UNDERGRADUATE ENGINEERING STUDENT MISCONCEPTION REGARDING COMPLEX CIRCUITS: THE CASE WITH SOLID-STATE DEVICE CIRCUITS

by

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ABSTRACT

Undergraduate engineering students usually face difficulties understanding electric circuit concepts. Some of those difficulties regard with misconceptions students bring into the classroom and develop during the learning process. Additionally, the increasing complexity of the topics along the fundamental electric circuit course constitutes another factor to those difficulties students experience. Another component we can add to this equation consists of the need of modernize and actualize the curriculum to meet the society's demands of the next taskforce. Therefore, it is important to investigate the conceptual difficulties students experience when they analyze complex electric circuits. In this dissertation, I identify what those conceptual difficulties are when undergraduate sophomore engineering students attempt to analyze solid-state device circuits. The context of this research comprises a modernized version of the traditional fundamental electric circuit course. This modernized version includes DC analysis, 1st order transient analysis, AC, and solid-state device analysis.

This dissertation took the form of three individual but complementary studies. Each study contributes to partially answer the overall research question. However, each study answered its own research problem. The first study attempted for identifying what concepts beginning students find challenging regarding semiconductors physics, diodes, and transistors. The second study identified student's misconceptions when they analyze two solid-state device circuits, one with a diode, and the other with a transistor. The final study looked for determining what misconceptions students use at both earlier and more advances stages along the course. This study also searched for understanding how students move through conceptual changes along the semester.

The general findings comprise three main points. First, students bring misconceptions into the classroom probably built from their previous experiences. Second, they also can develop those misconceptions through the learning process. This is particularly key regarding the relatively new and complex topics from student's perspectives. Finally, language plays an important role on the kind of misconceptions students develop. How students perceive the professional community use language contributes to either consolidate or modify old misconceptions or develop new ones.

1. INTRODUCTION AND LITERATURE REVIEW

1.1 Introduction

The electric circuits analysis is a difficult topic for engineering students to learn and understand. Student understanding of electric circuits has been an object of research in different fields such as education and sciences as well as in different levels from elementary to tertiary education (Cohen, Eylon, & Ganiel, 1983; Engelhardt & Beichner, 2004; McDermott & Shaffer, 1992; Shipstone, 1988; Wainwright, 2007). Moreover, interest in researching student understanding of electric circuits has been in place at least the last three decades. For engineering and engineering education, researching electricity is important for two main points. The first point relates to the social objective of engineering, namely solving social issues regarding modern technology. The second aspect points out to troubles engineering instructors face in helping students understand the nuances of electricity. Following, each one of these reasons is deeper explained.

Our society needs practitioner engineers in the workforce who can understand electricity and apply their knowledge to analyze electric phenomena, particularly electric circuits to provide adequate solutions to this society's problems. Undergraduate engineering students are the next generation of the engineering workforce. Engineers, in their social practice, usually work with great amounts of energy. Working with energy requires our society to demand future engineers understand at a high level how engineering and scientific concepts can and cannot be applied in the solution and understanding of the technological systems our society deals with nowadays. As an example, consider one issue our society faces. Only in the U.S., during the comprised period between 2012 and 2016, a total of 739 workers died at work as a result of exposure to electricity (Campbell, 2018a). Another 9,760 workers were injured through exposure to electricity during the same period (Campbell, 2018b). Here, this author illustrates how our society is facing issues related to the public health of the workforce when workers deal with electrical energy. Thus, it is important undergraduate engineering students are knowledgeable of electricity and use that knowledge to solve our social problems. Moreover, for the educational system, it is of imperative importance to understand how undergraduate engineering students are learning electricity concepts.

On the side of educational research, this field has found electricity is a difficult topic for four reasons. First, students and instructors at different levels bring into the classroom pre- and misconceptions regarding how electric systems work (e.g. McDermott & Shaffer, 1992). Electricity at home has been present in our society for at least one hundred years now. People in general and engineering students have operated appliances and other electric devices at their homes since they were very young children. Moreover, these students likely have received instruction regarding electricity in science courses at their secondary, and elementary schools. These factors indeed have helped to create some ideas related to how electricity works. Additionally, these ideas can or cannot be aligned with technological or scientific ways to understand and explain how these systems perform. Then, it is important to know what kind of pre- or misconceptions engineering students bring to the classroom if engineering instructors want to help them to be proficient as future engineer practitioners.

Second, electricity is a difficult topic for understanding and teaching given its abstract and complex nature (e.g. Bernhard, Carstensen, & Holmberg, 2013). Undergraduate engineering students consider electricity as one of the most challenging topics within the sciences and technologies subjects. Researchers have found one reason that supports these students' concerns consists of the high theorized and multi-faceted of the subject. Students struggle in making conceptual connections between what they know and the new material. Sometimes, they also need to build new ontological categories to accommodate the recently learned topic (Slotta & Chi, 2006). Then, it is very important engineering instructors understand the topic's learning hassles and the kind of difficulties it presents to engineering students.

Finally, constant change in technology requires curricular designers to modify engineering courses for keeping current and relevant to the curriculum. Modernizing and actualizing of engineering courses contribute with new challenges to both sides of the learning enterprise, namely instructors and students. For example, instruction regarding the new material can have been developed for more mature students but incorporating it in earlier stages can demand instructors to use of pedagogical tools not developed yet for these students, or push students to a ground where they can develop misconceptions for the new material. Consequently, it is worth to conduct research on how the nuances of modernizing and actualizing the curriculum have an impact on students' learning of the new content.

Considering all previous aspects, the problem this dissertation addresses consists of identifying what kind of conceptual difficulties sophomore undergraduate engineering students experience when they analyze electric circuits with solid-state devices. The difficulties emerge in the context of modernizing and actualizing the curriculum by incorporating solid-state devices to the traditional linear circuit analysis course. Then, the research question to answer is:

- What conceptual difficulties do sophomore undergraduate engineering students face when they analyze solid-state device circuits?

Moreover, the problem can be addressed from two different perspectives. First, looking for the pre- and misconceptions students bring into the classroom before they face traditional topics as well as solid-state circuit analysis. Second, identifying the difficulties the abstraction and complexity of the new and traditional topics introduce to the students' learning process of this topic. Addressing the problem through these lenses will provide an integrative landscape for understanding the problem regarding what conceptual difficulties sophomore undergraduate students face when they analyze solid-state device circuits, why those concepts challenge students, and how to address some of those difficulties.

1.1.1 Breaking down the problem

In addressing this problem, this dissertation takes the form of three stand-alone but complementary studies. Each individual study attempts to partially answer the overarching questions through one of the lenses discussed. The first study identifies how undergraduate engineering students understand solid-state electronics at an introductory level. The second study determines the pre- and misconceptions undergraduate engineering students use when they face solid-state device circuit analysis. The last study confronts how students' pre- or misconceptions regarding fundamental electric circuit concepts are predictive of students' difficulties on more complex electric circuit analysis.

1.1.2 Who can be benefited by the results of this project?

There are different stakeholders who can be interested in the results of this study. First, engineering instructors can benefit from the identified misconceptions, and they can design pedagogical interventions to address students' difficulties. In these ways, they can help students to improve their understanding of electric circuit concepts. These stakeholders also can be aware of other sources of difficulties for students such as textbooks or even instructors' discourses. Being aware that some resources can facilitate or promote students' misconceptions are also starting points for avoiding such kind of results.

Second, educational researchers have been interested in electricity as a subject topic because of its challenges for learning and teaching. Some of these difficulties consist of the topic's complexity and level of abstraction. Moreover, the pedagogical tools generally used during the teaching-learning process also contribute to such obstacles. The results of this study can provide educational research with insights regarding how undergraduate engineering students address the difficulties they find in this topic. Additionally, this research community also can use these results to inform research on similar challenging topics.

Third, the results of this study can provide curricular designers with key information to make the decisions related to how and when students should face the topics in a curricular program. Assessing the pertinence and timing of introducing and developing a specific topic should be a permanent element of curricular design. This study results can provide elements to determine students' difficulties in the context of their stage at their path through their curricular program. Curricular designers can use this information to build a better understanding of the learning process students have to pass through in their path to graduate from college.

Finally, our society will benefit from these results because future engineers will be better prepared for confronting the problems society needs to be solved. If the community can understand how our engineering students conceptually struggle with learning electricity, this community can design more appropriate curriculum, instruction, and educational research tools for the contexts students are developing. Designing better tools for helping students go through their learning experiences in college will contribute to having a stronger engineering workforce for solving the problems modern society faces. In such a way, future engineer practitioners can have a more favorable preparation for managing projects and developments where electrical energy is used as part of the process. They also can contribute to solving issues such as those related to the public health of workers dealing with electricity.

1.2 Literature Review and Conceptual Framework

In this section, a synthesis of the research regarding two main topics is presented. The first one concerns students' difficulties on the topic of electric circuit analysis. There, it is highlighted what researchers have found to be the most difficult concepts for students to grasp. On the second topic, a summary of what researchers have stated about conceptual change is stated. Conceptual change, as a framework, is the lens through which, in this project, the research analysis will be addressed looking at how students build concepts in their minds and how those recently built concepts can be modified.

1.2.1 Difficulties in understanding electric circuit topics

An electric circuit is a system used for transmitting energy or information between a source and a load. The transmission of electrical energy usually is achieved through a transmission channel. Frequently, this channel is controlled through devices. Then, a source, a transmission line, a control device, and a load compound the main parts of all electric circuits. Moreover, six physical variables interact on each circuit: voltage, electric current, electric charge, magnetic flux, power, and energy. Additionally, there are relationships between all these six variables, some of which are also considered variables by themselves, for example, resistance, capacitance, and inductance. Students tend to have particular difficulty understanding the interactions between all of these variables (Cohen et al., 1983). The challenges students have distinguishing the variables independently and their interactions have been studied by researchers for many several years (Cohen et al., 1983; Engelhardt & Beichner, 2004; Shipstone, 1988). In this section, a summary of what the research literature has found regarding students' difficulties for understanding electric circuits topics is presented.

Misconceptions regarding electric circuit concepts

This section portrays a general picture of the most challenging concepts for students to learn. The section is divided into two subsections. The first one relates to difficulties associated with basic concepts when students analyze linear electric circuits. In that subsection, concepts such as electric current, voltage, resistance among others are identified and explanations of why those concepts present difficulties are stated. The second subsection delineates concepts regarding more advanced topics such as Op-Amps, capacitors, phasors, phase, etc. It is also stated what researchers have recognized and their respective rational.

Basic electric circuit concepts

The research literature has focused mainly on some of the main physical variables, namely electric current, voltage (also named tension, potential, electric potential, or potential difference), resistance, power, and energy. McDermott & Shaffer (1992) describe four difficulties they classify regarding students' inabilities to apply formal concepts to electric circuits: 1) general nature difficulties, 2) difficulties with concepts regarding electric current, 3) difficulties with concepts dealing with potential difference, and 4) difficulties related to the concept of resistance (McDermott & Shaffer, 1992). With respect to the difficulties of general nature, McDermott & Shaffer (1992) state that they observe how students fail to differentiate among the different concepts they need to use when analyzing a circuit. For example, students indiscriminately assign properties from one variable to another, such as referring to current and power as though these variables were the same.

On the side of difficulties with electric current, Cohen, Eylon, & Ganiel (1983) studying high school students and their physics teachers find that both groups tend to use electrical current as of the only variable that matters over the other electrical variables such as voltage, power, resistance, etc. Cohen et al. (1983), McDermott & Shaffer (1992), and Wainwright (2007) also observe students believe both that electric current direction as well as elements disposition make a difference and that electric current is "used up" by circuit elements when their students analyze a simple series circuit. Another misconception regards with students' belief that electric current always is the cause of voltage and not the other way around (Picciarelli, Di Gennaro, Stella, & Conte, 1991b). This can be related to the observation done by Cohen et al. (1983) when most of their participants go through electric current calculations before they attempt to determine voltages even though this step is not always necessary. One potential explanation is that students may not be applying Ohm's law in these situations.

Regarding students' difficulties with the concept of potential difference, McDermott & Shaffer (1992) identify students do not recognize a battery maintains a constant potential difference between its terminals and fail to distinguish between potential and potential difference. Another issue the literature highlights is that students think batteries are constant electric current sources (Cohen et al., 1983; McDermott & Shaffer, 1992; Picciarelli et al., 1991b). Additionally, Wainwright (2007) stated students misunderstand the role of a battery in the circuit, students think a battery is a source of electrical charge instead of an energy source for moving those charges.

Concerning to the difficulties regarding the concept of resistance, Wainwright (2007) observing high school students interested in pursuing engineering programs, reports she observes how students analyze that adding more resistances to the circuit increases the net resistance no matter if those resistances are connected in parallel or series. Similarly, McDermott & Shaffer (1992) observe students have difficulties in identifying series and parallel connections.

Considering other concepts, researchers have found students experience difficulties when they are asked to integrate different individual concepts and when they attempt for connect the theory with the tangible world. For example, Wainwright (2007) realizes students exhibit similar misunderstandings previously reported by other researchers, such as lack of knowledge of the internal structure of a bulb and misunderstanding of the circuit as a system. Others such as Stetzer, Van Kampen, Shaffer, & McDermott (2013) state that advanced topics do not necessarily help students to overcome difficulties from topics developed in the early stages. For example, these authors notice that students who are familiar with the internal structure of a bulb may not understand the completeness of a circuit. They also observe students have difficulties understanding the bulbs' internal structure, analyzing short circuits' consequences, and understanding or correctly applying Kirchhoff's Current Law (KCL) in a single-loop circuit. Moreover, Adam, Harlow, Lord, & Kautz (2017) perceive students experience difficulties with electric current vs voltage (I-V) characteristics when they attempt to analyze electric circuits with conductors, isolators, and different kinds of semiconductors.

Summing up, the research literature has focused on some concepts, such as electric current, voltage, and resistance, where students struggle with when learning about electric circuits. Those concepts have been addressed from an individual perspective, however, there is little discussion about what kind of issues students experience regarding the interaction of those different concepts. More specifically, power and energy are marginally addressed in the research literature.

Advanced electric circuit concepts

In this subsection, a synopsis of the research literature regarding more complex concepts related to filters, AC circuits, and solid-state devices such as Operational-Amplifiers (op-amp) circuits analysis is presented. Concepts regarding these complex tasks interact with other more fundamental concepts such as electric current, voltage, power, energy, and resistance.

Regarding filters analysis, the literature shows that students have issues interpreting how RC circuits operate when the frequency of the source is changed (Coppens, Van den Bossche, & De Cock, 2017). These authors also have classified students' misunderstandings into two categories. First, students rarely recognize RC circuits as filters. Second, students fail to correctly apply Kirchhoff's laws and Ohm's law to arrive at a correct answer. Additionally, Carstensen & Bernhard (2009) in their study on how students approach transients in electric circuits, claim that "alternating currents and transient response are considered to be relatively complex topics in electric circuit theory, as the mathematics involved is rather advanced." (Carstensen & Bernhard, 2009, p. 390). To solve this issue, they propose providing students with opportunities to contrast different circuits' behaviors when some parameters are modified.

In the AC circuits analysis domain, Bernhard, Carstensen, & Holmberg (2013) observe students adding signal magnitudes without taking into account the phase of those signals. They also report students consider that the source's voltage and current must be in phase with the voltage across and current through the resistor in the circuit. Coppens, Van den Bossche, & De Cock (2017) notice students do not differentiate the frequency-dependence of some circuit elements and manifest there is no difference between AC and DC signals.

Dealing with the solid-state devices' concepts, Papanikolaou, Tombras, Van De Bogart, & Stetzer (2015) study how undergraduate students pursuing majors in physics and electronics engineering understand and analyze op-amps circuits. They find that students 1) do not correctly apply the concept of open circuit at the op-amp's inputs, 2) tend to assign a voltage drop to a resistor through which there is not current, 3) do not understand nor correctly apply the idea that there is no potential difference between the op-amp's inputs, and 4) consider there is no current at op-amp's output. Additionally, Scott, Peter, & Harlow (2012) develop a threshold-concept inventory in electronic where these authors observe students have issues with either circuit topologies and measuring variables such as resistance, current, and voltage. As can be seen, these studies illustrate how adding a new device to the circuit analysis topics can make it more complex because students must integrate concepts from other less complex levels.

All these studies together highlight the importance of assessing student's difficulties regarding advanced complex circuit concepts. Even though, research has identified some of the complex topics where students struggle, the reasons for understanding why those concepts constitute difficulties only describe that students lack integrating basic electric circuit concepts.

However, there can be other aspects such as managing mathematical tools, new or different approaches for the specific topic, previously learned concepts, etc., that add new challenges for students to understand the more complex concepts regarding electric circuits.

Models, analogies, and metaphors

In this section, an outline of what the research community has indicated as one of the aspects students describe as difficult in understanding electric circuits concepts is shown. This goal is achieved dividing the section into two aspects. First, how analogies and metaphors are used in the learning process by both students and instructors. Second, how the conducted research relates to different kinds of representations for analyzing and modeling electric circuits.

<u>Analogies and metaphors</u>

Analogies and metaphors are cognitive tools human beings use for facilitating learning and understanding processes. Regarding electric circuits, the most used analogy is comparing electric circuits with hydraulic circuits. Moreover, researchers have been interested in what kind of analogies and metaphors are used in different learning environments. For example, Pitterson, Perova-Mello, & Streveler (2019) report engineering students use analogies and metaphors when they learn electric circuits concepts. As a result, these authors describe having observed students use different types of analogies such as a direct comparison between the base domain and the target domain, a structural comparison between the two domains, or the use of a bridge concept to connect the base domain and the target domain. On the side of metaphors, these authors find students use two different kinds of these intellectual tools. The first one consists of introducing a degree of imagination as a step for visualizing abstract ideas. The other one is considered in the affective domain where students describe how they feel when they learn and understand a concept. In another study, Clement & Steinberg (2002) seek to understand how instructional practices induce conceptual change when instructors use analogies, discrepant events, and visual models. In their study, these authors observe a student during several tutoring sessions. In those sessions, the student experiences four different learning episodes. These authors notice how their student changed her conceptual understanding regarding electric circuits concepts using different tools such as analogies and visual representations. However, both studies report the most frequently used analogy was the hydraulic circuit.

In a different field within analogies, Steinberg (2008) conducted a study with high school students. He implemented a curriculum for the electric circuits course where he introduced Volta's original analogy. This analogy relies on a compressible fluid, such as air, to explain the concept of potential difference or voltage. He used a set of questions and asked students to think aloud when solving those questions. He found students can explain better electrical phenomena when they are exposed to this revived approach. As this subsection illustrates, different kinds of analogies and other cognitive tools such as metaphors are an important part of the process of understanding electric circuits concepts because these tools allow students to make connections between different but connected conceptual fields.

Representation regarding the kind of analysis

In this subsection, what the research community has pointed out regarding representing and modeling electric circuits for analysis purposes is presented. Considering a model as a system used to represent another system with a specific purpose, it is worth to highlight that the modeling system engineers use for analyzing electric circuits is very complex. Students need to learn to communicate and perform tasks such as analysis at the same time they are learning this new modeling system. Moreover, this modeling system can be considered to be a new language by itself. This language is composed of different kinds of graphs, diagrams, curves, algebraic expressions, symbols, and plain language, all of them interconnected. For example, when an electrical engineer listens to the expression *short circuit*, a complete set of symbols emerge in her mind. Symbols such as a straight line, zero volts, a specific I-V curve, among others. The research community has been interested in how students deal with learning this skill. For example, Adam, Harlow, Lord, & Kautz, (2017a) report half of the students did not use their previous knowledge to perform realistic checks in their circuit analysis. Additionally, these authors observed how their students use naive models to explain how electrical charges get distributed in a P-N junction and students do not use more advanced explanations such as band diagrams. Moreover, this study finds students do not use I-V curves to explain P-N junctions' behavior within an electric circuit. Other researchers, such as Bernhard & Carstensen (2002) notice students experience difficulties with topics related to AC, namely 1) measuring voltage and currents, 2) translating back and forth between the real world and mathematical representations, and 3) manipulating AC signals in different domains such as time, phasors, and graphically.

In another study, DesPortes, Anupam, Pathak, & DiSalvo (2016) investigate the kind of misconceptions computing engineering students experienced in the basic electric circuit course. These researchers test students' misconceptions using abstract representations accompanied by realistic images or actual circuits photos. Nevertheless, they report having observed similar kinds of misconceptions on students' ways of thinking than other studies. This study also claims that through exposing students to different but complementary circuit representations students are more likely to transfer knowledge between those different ways to represent these systems. The results of these studies illustrate how modeling and moving between those different models are important skills for understanding electric circuits concepts.

Another group of studies comprises experimental studies with pedagogical interventions. For example, Cheng (2002) conducts an experimental study with a control group and an experimental group that had a pedagogical intervention. The pedagogical intervention consisted of the introduction of AVOW diagrams (Amps, Volts, Ohms, Watts) during experimental group instruction. This study reports students in the experimental group outperformed students in the control group in different tasks regarding electric circuit analysis. For example, experimental students got better results in multiple-choice questions which assess conceptual understanding, the experimental group also used more frequently diagrams that support their analysis process during exams. Moreover, the experimental group also arrived at better explanations on tasks regarding the transfer of knowledge and problem-solving strategies. Finally, Moreno, Ozogul, & Reisslein (2011) develop a study consisting of three experiments. The experiments are set up for testing students' learning gains when they are exposed to different combinations of concrete and abstract visual representations of electric circuits. Along with the problem sets, these researchers also provide abstract and concrete cover stories to test students' problem-solving and near transfer skills. As a result, these researchers report that students exposed to abstract representations and to a combination of abstract and concrete representations outperformed students exposed only to concrete representations. They state "Our results suggest that problem solving is best supported when learners are eventually able to produce and use abstract visual representations to support the problem-solving process but that these representations should be scaffolded by concrete visual representations that connect their previous knowledge with the to-be-learned information." (Moreno et al., 2011, p. 44). As can be observed, exposing students to different kinds of representations can be helpful for developing a more complex and broad understanding of electric circuits concepts.

1.2.2 Conceptual change frameworks

In this section, what theorists say regarding how conceptual knowledge is developed on learners' minds and how those concepts are subject to change is illustrated. There are at least three distinct venues on the theories regarding the conceptual change. The first line of thought consists of a theory that holds the idea that student's misconceptions do not have any kind of structure. The second way of thinking states students' previous ideas have some structure which they compare to the pseudo concepts earlier scientists beheld. Finally, the last venue points towards students' knowledge are socially constructed through social interactions. Consequently, each of these lines of thought contributes to understanding what and why some electric circuit-related concepts are difficult for undergraduate engineering students. Following these different theories are explained in more detail.

First, fragmented theory establishes that students develop what is known as a facet. A facet is defined as a convenient unit of thought, understanding, or reasoning used by the student in making sense of a particular situation (Hunt & Mistrell, 1994). These theorists declare that students adapt their previous knowledge to a convenient way to express their understanding of a specific phenomenon. This theory also states conceptual change can be achieved through instruction if we consider the following aspects. 1) Deep learning takes time. 2) Deep learning requires learning in many contexts. 3) Helping students to build new knowledge based on their ideas facilitate the conceptual change (diSessa, 2008, p. 45). This theory claims that the conceptual change requires time, and other resources to achieve its goal. Through this kind of instruction, this theory affirms students can overcome their previous inaccurate understanding and reach a better knowledge of the topic.

From the side of Coherent theory, one subline of thought is led by Michelene Chi. This line is known as the categorical shift. In her theory, Chi (2008) describes that students' misunderstandings and learning unsuccessful attempts can be explained by at least one of two possible reasons. The first one occurs when the to-be-learned material does not fit within any previously learned schemas in the student's knowledge structure, activating an irrelevant former known schema. The second reason appears when the new topic activates an incomplete and under-development prior schema in the student's mind. As one possible explanation for the first reason, Chi's theory proposes that no fitting any previous schema forces students to use any other schema they have. In any case, Chi states that students' misclassification of those schemas can be solved by helping them to understand how and why students are assigning the new content to the wrong schema. Moreover, this author defines a categorical shift as the change in assigning the learned material to the correct schema.

Additionally, this theory considers understanding processes are related to narrative schemas. Through these narratives, people explain how they see events both in their everyday lives, or in their academic world (Chi, Roscoe, Slotta, Roy, & Chase, 2012). Through this theory, their authors have observed most of the narratives people give to everyday processes are related to what they call Direct Processes, instead of some other kind of processes that are known as Emergent Processes. These theorists claim that people use the schema of direct processes because of two reasons. First, students do not have acquired the schema for emergent processes. Second, some patterns of both processes can look very similar. This last reason adds to the complexity of some concepts making them difficult for students' understanding. This theory states showing students the discrimination between those two kinds of processes and helping students to build the emergent process schema is the way to address conceptual change (Chi et al., 2012, p. 15). This kind of intervention can help to build a better students' understanding however, time and resources are necessary to consolidate a deeper comprehension of the topics.

The second subline of thinking, within the Coherent theories, is directed by Stella Vosniadou. Vosniadou's theory is known as the Framework theory. Here, Vosniadou (2008) points out that learning science and mathematics is difficult because students try to understand these topics through a naïve framework. She describes those naïve framework theories as not fragmented and forming a relatively coherent explanatory system. However, those naïve frameworks are different from accepted math and scientific's theories academic communities use nowadays. Vosniadou also claims students' everyday experience molds the base of and constantly corroborates these naïve frameworks. Moreover, students who are not aware of the differences between the naïve and scientific frameworks usually utilize the enrichment approach. This approach consists of adding information to the student' previous knowledge structure. Just adding information to a previous structure without modifying that structure can contribute to creating misconceptions (Vosniadou, 2008).

In another study, Vosniadou, Vamvakoussi, & Skopeliti (2008) propose a theory that explains conceptual change based on theory-like organized learners' knowledge. They claim that "we need to move from thinking of conceptual change as involving single units of knowledge to systems of knowledge that consist of complex substructures that may change gradually and in different ways" (Vosniadou et al., 2008, p. 12). These authors suggest learners' knowledge is not a set of unconnected units but more like a complex interrelated system. They mention cognitive research has observed different groups of people consistently use ingenuous theory-like frameworks for explaining physics phenomena. Moreover, they claim conceptual changes are progressively reached and built. Additionally, speaking about instructional issues, these authors mention that if these conceptual changes are not adequately addressed, the student can develop fragmented cognitive structures or misconceptions. Thus, instruction can guide students to inadequate knowledge. Another important aspect of this theory is that it is not incompatible with sociocultural approaches. Those approaches claim that conceptual change happens within a socio-cultural environment which must be considered. These authors declare they are aware of sociocultural theorists' claim which affirms that conceptual change needs to consider cultural changes within the society, but they restate that conceptual change is not completely explained without individual accountability.

The last theory is the social activity theory, which states that concepts are repositories of human sense-making capacities and activities (Säljö, 1999). This theory also claims that concepts are linguistic phenomena that operate in concrete settings. It means that conceptual understanding is contextualized and situated in a specific environment. This author says the situated nature of human knowledge must be considered and that language is the medium that allows people to keep in contact with concepts. Moreover, that language and more general communication is a social and collective human activity (Säljö, 1999, p. 84). Additionally, this theory also claims that human artifacts such as diagrams, equations, charts, among others compose that language (Ivarsoon, Schoultz, & Säljö, 2002). When these theorists talk about conceptual change, that change happens when language is modified. It is possible to operationalize this change through instruction where new knowledge can be used in functional situations, and not only into the classroom's setting. It means that a situated kind of instruction can help to overcome conceptual difficulties and conceptual change.

Summing up, the described conceptual change theories constitute a theoretical framework through which students' understanding of electric circuit concepts can be analyzed. Moreover, through these theories, a possible explanation of why these students experience difficulties with basic and more advanced concepts when they attempt for analyzing electric circuits can be stated.

For example, some students can behold naïve scientific understanding of some concepts where those concepts are not connected nor form any coherent structure. In other cases, part of the students' population can have a more structured way of thinking where they can be using an incorrect schema to explain the process related to electric phenomena. Finally, given that learning is a social activity mediated by human communication, how the technical language is used can explain an amount of the difficulties a group of students experience when learning about electric circuit concepts. Thus, a combination of these three theories constitutes a good set of lenses for observing these students' difficulties in learning electric circuit concepts on solid-state device circuits.

2. ASSESSING STUDENT'S UNDERSTANDING OF SOLID-STATE ELECTRONICS IN THE FIRST INTRODUCTORY-LEVEL ECE COURSE

2.1 Abstract

This research paper presents the results of an explorative study to identify what concepts beginning students find challenging regarding semiconductors physics, diodes and transistors at an introductory electric circuits course. In order to prepare students for practically-important and application-relevant circuits and systems, there is a need to properly introduce semiconductors and solid-state electronics early in the electrical/computer engineering curriculum. Such concepts are not traditionally covered in the very first circuits course in most electrical/computer engineering programs. The purpose of this paper is to explore students' level of understanding of basic semiconductor physics, diodes, transistors and simple circuits that utilize such devices. To address the research purpose, we utilize a Design-Based Research (DBR) methodology. Design-Based Research is an iterative process where new theory is developed through applying research and theory to a specific educational problem, developing conjectures about the relationship between variables, testing and then revising educational intervention based on findings and then retesting. We analyze students' final exam scores (n = 99) to determine which topics were most challenging and then qualitatively analyze students' work to explore common errors. As more Electrical and Computer Engineering (ECE) programs look to modernize their introductory courses to include topics of semiconductor physics and devices, this research can inform instructional and curricular interventions.

2.2 Introduction

The very first linear electric circuit analysis courses offered in most electrical/computer engineering programs usually cover DC circuits, 1st and/or 2nd order circuits, and AC circuit analysis. Little attention is often paid to semiconductor physics, solid-state devices, or diode/transistor circuits. Such concepts are usually covered later in the curriculum. On the other hand, since virtually all practically important circuits and systems include semiconductors, such an approach may limit students' understanding. For instance, engineering students pursuing majors in fields other than electrical engineering are often only exposed to the very first introductory course thus missing concepts behind most modern circuits.

An attractive alternative approach is to introduce topics regarding modern technology earlier in the program. However, there is almost no research that informs what kind of difficulties students may experience when they attempt to understand semiconductor physics and devices in a fundamental circuits course. Therefore, the purpose of this study is to explore what concepts beginning students may find challenging regarding semiconductor physics, diodes, and transistors.

2.3 Literature review

Of the research on students' understanding of circuits, researchers have focused primarily on concepts related to comprehension of current, voltage, resistance, power, and energy and their relationships. Additionally, researchers have addressed how students interpret and translate different representations or diagrams when they analyze a circuit. For example, McDermott & Shaffer (1992) identify three big categories of students' difficulties, namely: 1) inability to apply formal concepts to electric circuits, 2) inability to relate formal representations and numerical measurements to electrical circuits, and 3) inability to reason qualitatively about the behavior of electric circuits. These authors also point out that students experience difficulties with concepts related to electric current, potential difference, and resistance. The population these authors focus on is undergraduate students pursuing a major or minor in physics when they took an introductory physics course.

Duit & von Rhoneck (1998) add to the discussion key aspects related to the everyday language used by students when they refer to electricity, and the role emotions play in conceptual change among these concepts. Moreover, these authors also notice that students tend to analyze circuits in one of three ways 1) *local reasoning* when students focus on one point in the circuit and ignore what is happening elsewhere, 2) *sequential reasoning* when a change in some part of the circuit only affects the "subsequent" elements but not the "predecesors" (after and before the current passes), and 3) *holistic reasoning* when students understand an electric circuit like a system where a change in some part of the system can affect the behavior on other parts.

Borges & Gilbert (1999) contribute with an alternative view of people's mental models for understanding electricity. They state people use the following models 1) electricity as flow, 2) electricity as opposing currents, 3) electricity as moving charges, and 4) electricity as a field phenomenon. Doing so, these authors add new understanding on how people conceive and explain what happens in an electric circuit. The target population, in this case, consist of very diverse groups of people, such as secondary students, teachers, and practitioners who work with electricity as part of their daily activities. Finally, Stetzer et al. (2013) go a step further when they observe contradictory findings regarding other studies (i.e. internal structure of bulbs and/or effect of short circuits). These authors suggest that advanced topics do not necessarily address difficulties found in early stages. In this case, the population is composed ofcorre undergraduate students of an introductory physics course in electricity and magnetism and their teaching assistants.

Just in the last fifteen years, researchers have started to conduct studies about concepts that are difficult for undergraduate engineering students beyond their first year. Bernhard & Carstensen (2002) study what misconceptions related to AC students had. They find similar problems addressed for basic DC concepts, such as current, voltage, resistance, power, and energy emerged in their studies. Additionally, they find three new exclusive aspects regarding AC. Students have difficulties 1) measuring voltage and currents, 2) translating back and forth between the real world and mathematical representations, and 3) manipulating AC signals in different domains (i.e. time, phasors, graphically). Simoni, Herniter, & Ferguson (2004) highlight that assessing solid-state electronics elements must consider their interaction in an electric circuit. As a consequence, usually misconceptions regarding basic electric circuits can emerge when assessing the behavior of solid-state devices in a circuit. Carstensen & Bernhard (2009) report a design-based-research assessing the effectiveness of using variation theory for improving students understanding of time-dependent responses. They focus on how students learn about transients in electric circuits when they expose students to experiences of contrasting different circuits' behaviors when some parameters are varied. These authors named this strategy variation theory. They also find most students use local and sequential reasoning attempting to explain transients when the pedagogical intervention does not use variation theory's principles rather than when they introduce it in their classes. Finally, Scott et al. (2012) conduct the development of a threshold-concept inventory in electronics. They find students struggle with circuit topologies and measuring electrical variables such as voltage, current, and resistance.

A final venue in the literature addresses more advanced engineering students and more complex topics. For instance, Guisasola (2014) proposes teaching electric current based on the model of electromagnetic fields. This author says "The proposal for teaching electric current based on the field model explicitly relates the measurements at a macroscopic level (voltage and current intensity) with a causal model at a microscopic level …” (Guisasola, 2014, p. 148). Adam et al. (2017b) study third-year electrical engineering students and find students have difficulties understanding and relating macroscopic and microscopic concepts of electrical current. Both of these studies address advanced topics regarding what happens inside of materials such as semiconductors, conductors, or isolators.

Currently, there is a gap in the research regarding how sophomore engineering students understand solid-state electronics at an introductory level. Hence, the purpose of this study is to explore students’ understanding of basic semiconductor physics, diodes, transistors and simple circuits that utilize such devices, as well as the common misunderstandings students have.

2.4 Methodology

2.4.1 Participants and setting

The 99 participants in this study were enrolled in the very first introductory circuits course offered during the sophomore year. All of them were electrical and computer engineering majors. The course covered some of the traditional topic of a linear electric circuit analysis course, such as DC analysis, first order transient analysis, and AC steady state analysis. This version of the course additionally introduced semiconductor physics, diodes, and single-stage transistors circuit analysis.

2.4.2 Data collection

This study consists of two stages, first quantitative and then qualitative. The first stage consists of a study of students’ final exam scores, including the test items’ difficulty and discrimination. The difficulty index measures the percentage of students that correctly answered the corresponding problem. The discrimination index gives information regarding how well a specific problem differentiates between high performing and low performing students with respect to the exam (Wang & Osterlind, 2013). These indexes are important for partially answering the research question because they allow us to narrow our attention over the questions where the students experience more difficulties. The first half of the exam was dedicated to linear electrical circuit analysis, and the second half assessed the topics introduced in this course, i.e.

semiconductors, diodes, and transistors. The second stage includes a qualitative phase where the data consisted of students' answers to two problems out of the sixteen exam questions. Each problem comprised of a simple electric circuit with a solid-state device. Moreover, students were required to choose one of the numerical answers provided through multiple-choice options. Partial credit was not available in these problems.

2.4.3 Data analysis

As a first pass to understand what areas students found particularly challenging, we examine the difficulty and discrimination indexes of each exam problem. We choose to focus our attention to the problems after we statistically examined students' answers to each final exam problem finding those couple of questions which showed the lowest combination of difficult and discrimination indexes. Problem 9 (question targeting understanding of diodes) had a difficulty of 61.62% and a discrimination index of 0.361 meanwhile, problem 12 (question targeting transistors) had a difficulty of 44.44% and a discrimination index of 0.335. Test items' statistics can be seen in Table 2.1. There we can observe problems 9 and 12 had the lowest difficulty indexes in combination with the discrimination indexes. Using this, we selected these two problems for the second stage. Both of these two problems are related to semiconductor devices. **Error! Reference source not found.** and Figure 2.2 illustrate the problems students answered.

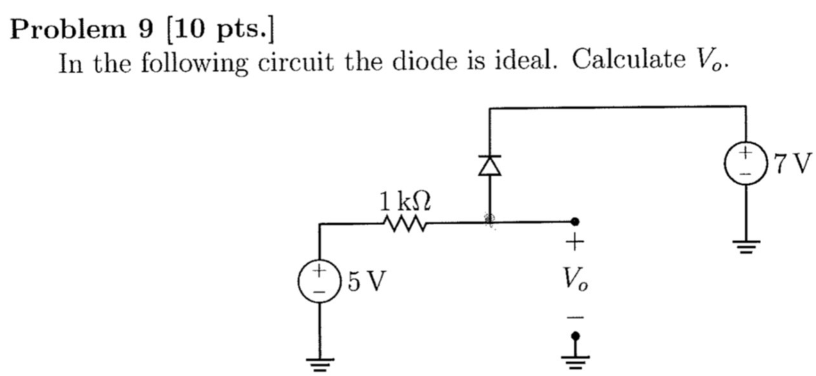


Figure 2.1. Problem 9 question

Table 2.1. Test Items' Statistics

Problem	Difficulty Index	Discrimination Index
1	0.919	0.168
2	0.687	0.577
3	0.889	0.428
4	0.646	0.486
5	0.646	0.555
6	0.778	0.289
7	0.646	0.320
8	0.687	0.377
9	0.616	0.361
10	0.768	0.525
11	0.747	0.535
12	0.444	0.335
13	0.737	0.623
14	0.737	0.495
15	0.808	0.467
16	0.848	0.518

Problem 12 [10 pts.]

For the following circuit calculate the resistance value R such that the transistor current is $2\,\mathrm{mA}$. Assume that $V_T = 1\,\mathrm{V}$ and $k = 1\,\mathrm{mA\,V^{-2}}$.

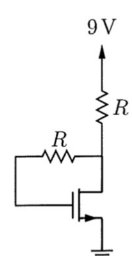


Figure 2.2. Problem 12 question

First, we went through a sample of 12 out of the 99 students answers for each problem for calibrating our human bias. Using this sample and what we found in the literature review, we developed a codebook which was used to qualitatively analyze the whole data. This codebook has four categories. In the first category, the device handling, we looked for evidence that students understand how the solid-state device works. In the second category, circuit handling, we observed if students performed the circuit analysis correctly. Here, we blended all the possible misconceptions, such as those previously discussed, into only one category since these questions were not designed to identify specific misconceptions. Additionally, we added an extra consideration to the problem 12 code book to assess if the students identify the gate as an open circuit. The third category (No Work) identified if the students did not show any procedure and they did not select the right option. The final category, Inspection, attempted to capture students' analysis by inspection. Here, students chose the right answer, but they did not illustrate details of their procedure for reaching their answer (students were not required to show their work since no partial credit was given). Due to the complexities of the transistor problem, problem 12, an additional category was added: region of operation. This means that the student was able to identify in which region of operation the transistor was operating. It is worth noting here that each of these problems had nine (9) possible answers and students were required to choose one of them. Thus, the probability of randomly choosing the correct answer is quite low. Table 2.2 and Table 2.3 illustrate both codebooks for each problem.

Table 2.2. Problem 9 codebook

Code	Description
Diode handling	The student correctly assesses the diode state.
Circuit handling	The student correctly analyzed the circuit behavior. (Using KVL, KCL, Ohm's law, etc.)
No work	The student answered incorrectly and did not show any procedure arriving at the incorrect answer.
Inspection	The student arrived at the correct answer apparently by inspection and did not show details of their followed procedure.

Table 2.3. Problem 12 codebook

Code	Description
Transistor handling	The student correctly assesses the transistor operation condition (saturation). S/he does not necessarily consider the gate as an open circuit.
Region of operation	The student verified the transistor's region of operation.
Circuit handling	The student correctly analyzed the circuit behavior. (Using KVL, KCL, Ohm's law, etc.). S/he correctly considers the gate as an open circuit.
No work	The student answered incorrectly and did not show any procedure arriving at the incorrect answer.
Inspection	The student arrived at the correct answer apparently by inspection and did not show details of their followed procedure.

Once we defined the codebook successfully, we applied it to the whole sample pool (n = 99). We developed the codification process verifying in meetings with the research team. The research team went through the data in an iterative process until we reach a level of agreement in the coding process. Next, we looked for students' handwriting of either mathematical expressions, formulas, diagrams, or marks on the problems prompt through which we could infer student understanding of the necessary steps to reach the answer. Then, we built a spreadsheet where we processed the coding. Here, it is worth noting the Device handling, Circuit handling and Region of operation categories are not mutually exclusive. However, if we use the Inspection category or the No Work category, we do not use any of the other categories. For all the categories, we assigned a one (1) if it was present and a zero (0) if not. Finally, the research team searches for common themes in students' responses. The themes found are related to students' similar way of thinking. Those themes are presented in the following sections of this document.

2.5 Results

Following, we describe the results we observed in the data which Figure 2.3 illustrates. The leftmost bar shows the number of students who got the right answer for each problem. The following bars are the number of students' answers classified into each of the categories. For describing what we found, we first illustrate our observations about Problem 9 and then for Problem 12.

Regarding Problem 9, Figure 2.3 shows that 48.5% of students displayed evidence in their answers of understanding about how a diode works. Moreover, 32.3% of students' answers exhibited a correct analysis of the circuit as a whole. Additionally, 14.1% of students neither mark any option nor provide any clue about their thoughts. Finally, 26.3% of students' answers were classified into the Inspection category. It can be seen that the percent of students who are able to handle a diode increases to 74.8% (26.3+48.5) if we assume that those who solved it by inspection did not guess, which is improbable (~11% chance).

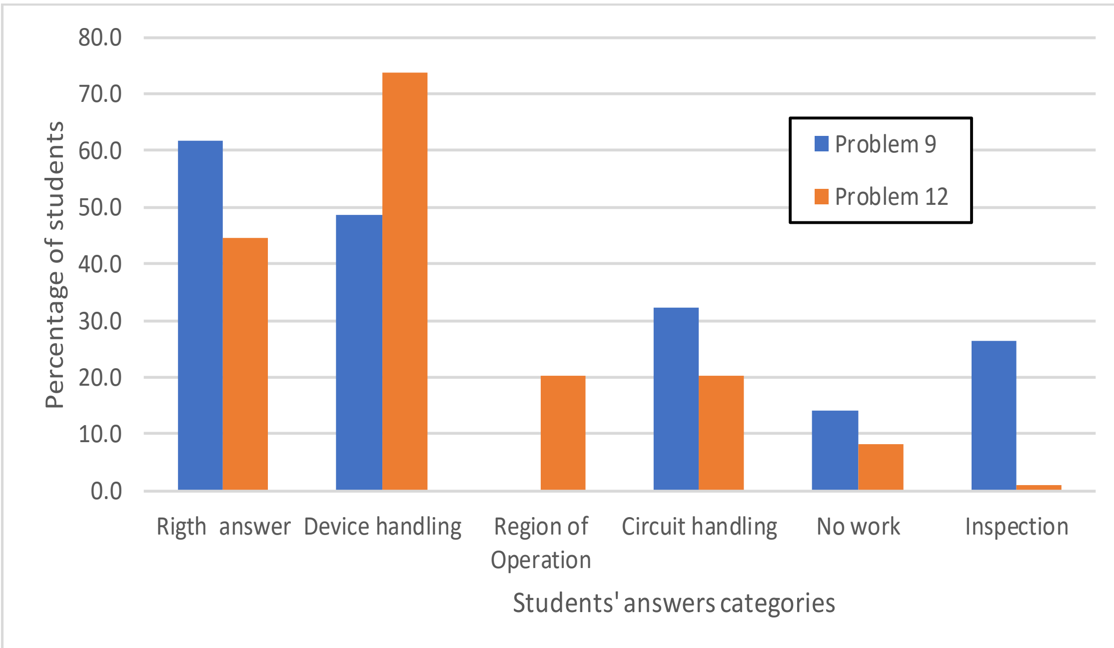


Figure 2.3. Percentage of students vs. answer's categories (n=99)

Regarding Problem 12, Figure 2.3 illustrates that 73.7% of students' answers showed students understanding of how they should analyze the transistor behavior. This percentage is larger than the percentage of students who correctly answered this question (44.4%). Regarding the circuit handling category, 20.2% of their answers matched what we classified as students understanding of the electric circuit's performance. Moreover, only 8.1% of students' answers classified into the No work category. Here, we observed only 1% of students' answer was classified in the Inspection category.

Using Figure 2.3 we can also compare how students' answers were classified between the two Problems. First, Figure 2.3 exhibits that a larger percentage of students' answers were classified as device handling for Problem 12 than for Problem 9. Second, the No work category obtained a greater amount for Problem 9 than for Problem 12. Finally, only 1% of student's answer got the Inspection category for Problem 12 even though 26.3% of students' answers reached that category for Problem 9.

2.6 Discussion.

We think the change in the course's content that focuses on exposing students to electronics earlier and particularly in their first circuit course is worth considering given the outcome of this study. Analyzing their responses to two key questions addressing these concepts has revealed that indeed students seem capable of handling these concepts.

In our analysis we also observed evidence that students responded correctly to simple diode circuits by solving the circuit by inspection. We think this for two reasons. First, each problem has 9 multiple-choice options which implies that the likelihood of answering correctly by chance is very low. Second, for the expected level of sophomore students, the diode problem (Problem 9) can be solved by inspection. This is not the case for the transistor problem (only 1% of students' answers was classified in this category).

2.7 Conclusion

The purpose of this study was to examine how well students understood topics related to solid-state electronics previously not taught until upper-level electronics courses. Overall, we find that students in the introductory course understood at a good level how a diode and a transistor work but struggled more with the analysis of the circuit as a whole. As other ECE programs look to reform their curriculum, our findings suggest that instruction regarding solid-state electronics can be introduced at the introductory level if instructors are aware of students' possible difficulties. Future research must consider how to support students' learning process of the interaction among solid-state devices with the rest of the circuit as a system.

3. COMMON MISCONCEPTIONS ABOUT BASIC CIRCUITS WHEN STUDENTS ANALYZE SOLID-STATE DEVICE CIRCUITS

3.1 Abstract

Contribution: This paper reports identified junior undergraduate engineering students' misconceptions when attempting for solving a couple of solid-state single device circuit problems.

Background: As more electrical engineering undergraduate programs include solid-state device topics early on their curriculum, undergraduate engineering students can face issues in understanding how complex circuits work. Identifying misconceptions students hold can inform instructors on how to help them to overcome with those issues.

Research questions: 1) What basic electric circuit misconceptions do students use when they analyze a single solid-state device electric circuit? and 2) How consistent is the use of the identified misconceptions among solving the two different single solid-state device electric circuit problems.

Methodology: Qualitative content analysis with both inductive and deductive coding was used over students' answers. Codebooks for each question were developed and emerging themes were identified.

Findings: Results indicate some students struggle understanding how the solid-state device works. Additionally, others illustrate misconceptions regarding how an open circuit operates and intertwin this issue with the device operation. Moreover, regarding a single diode circuit, students who correctly analyzed the circuit illustrated a variety of adequate approaches for solving it.

3.2 Introduction

Traditionally, the first fundamental electric circuit course covers linear electric circuit analysis under DC and AC signals and 1st and 2nd order transient responses. Solid-state devices such as diodes and transistors are usually discussed later in upper-level courses. This traditional approach delays students' opportunity to apply the understanding of modern technology into their academic programs and any internship or research experience early in the degree program. In addition, many engineering majors outside of electrical only take one course related to circuits. Thus, an alternative approach which introduces solid-state devices into the first electric circuits course could prepare a wider range of students to work with these concepts.

There is limited research regarding the effectiveness of introducing solid-state electronic devices at a beginning stage in their program. For example, many students have historically struggled in their first circuits course (Engelhardt & Beichner, 2004; McDermott & Shaffer, 1992; Shaffer & McDermott, 1992) and adding solid-state devices would require some content to be cut or rushed through. Even though researchers have acknowledged basic electric circuit concepts' learning is difficult for students, they have not addressed how such difficulties affect students' learning of more complex topics (Papanikolaou et al., 2015). The purpose of this study is to explore common misconceptions related to basic electric circuit concepts beginning students use when they analyze solid-state device circuits at the introductory electric circuit course.

3.3 Literature review

Conceptual understanding of fundamental electric circuit concepts has been a topic under research for at least two decades. Researchers have mainly focused on students' understandings related to basic electric circuits concepts (Cohen et al., 1983; McDermott & Shaffer, 1992; Picciarelli et al., 1991b). Even though these basic electric circuit concepts conform to the fundamental core of any electric circuit course, the research literature only has tangentially addressed how students use these basic concepts and their misconceptions when they attempt to solve more complex circuit problems (Papanikolaou et al., 2015; Stetzer et al., 2013). Students who experience difficulties understanding basic circuit concept then take those misunderstandings forward as they learn new topics.

Considering students understanding of basic electric circuit concepts, the literature shows students experience difficulties with fundamental electric concepts such as current, voltage, power, and resistance, among others. Cohen et al. (1983) describe how their participants use current as of the main concept in solving electric circuit problems. These authors also point out that a common misconception consists that people consider batteries are sources of constant current instead of sources of constant voltage. This misconception is also indicated by others (Picciarelli, Di Gennaro, Stella, & Conte, 1991a). They also observe most of their participants made unnecessary steps, such as calculating electric current, for determining electric potential differences. In a second case, Picciarelli et al. (1991b) notice students describe that electric current always produces voltage and not the other way around.

Researchers have focused on categorizing the different ways students tend to think about simple electric circuits. For example, researchers have found learners tend to struggle to assimilate electric circuits as systems where different elements interact and a resulting pattern is observed from that interaction. Duit & von Rhoneck (1998) classify students' ways of thought into three different categories: *local reasoning*, *sequential reason*, and *holistic reasoning*. Local reasoning refers to when students focus their analysis solely on a single point in the circuit but ignore what happens elsewhere. Sequential reasoning *is* when students describe a change in the circuit only affects elements that are connected "after" the electric current has passed the point of change but not the elements that are connected "before" that point. Holistic reasoning consists of the fact that students can analyze a circuit as a system where a change somewhere in the circuit has an impact on the circuit as a whole. Borges & Gilbert (1999) distinguish four different ways students tend to understand electricity: 1) electricity as a flow, 2) electricity as opposing currents, 3) electricity as moving charges, and 4) electricity as a field phenomenon. McDermott & Shaffer (1992) categorize three common mistakes when analyzing an electric circuit' operation: 1) inability to apply formal concepts to electric circuits, 2) inability to relate formal representations and numerical measurements, and 3) inability to reason qualitatively about the behavior of electric circuits. These authors also notice students experience difficulties regarding electric circuit concepts such as electric current, potential difference, and resistance.

More recently, researchers have begun examining students' difficulties related to more complex circuit analysis. In one of the first studies, Wainwright (2007) reports several new insights in observing high school students interested in pursuing engineering programs when they analyze electric circuits. She found students commonly used incorrect vocabulary to refer technical or scientific concepts, consider a battery is a source of electric charge instead it is a source of energy moving those charges through the circuit, and viewed connecting more resistances as always increasing the equivalent without regard if those new resistances are connected in series or parallel. Stetzer et al. (2013) assert that students learning advanced topics do not necessarily overcome difficulties developed in the early stages. For example, they found some students familiar with the internal structure of a bulb demonstrated they did not understand the completeness of a circuit, nor correctly apply Kirchhoff Current Law (KCL) in a single-loop circuit. In another case in the literature, Papanikolaou et al. (2015) notice students analyzing op-amp circuits illustrate misconceptions related to basic electric circuit concepts as well as misinterpretations regarding the op-amp's topic concepts. For example, they witness students 1) may not correctly use the concept of an open circuit at the op-amp's inputs, 2) tend to assign a voltage drop to resistors through which the current is 0A, 3) may not understand nor correctly apply the concept that the potential difference between the op-amp's inputs is 0V, and 4) may deem there is no current at the op-amp's output. Additionally, Coppens et al. (2017) describe how students have issues interpreting RC circuits' operation under sources' frequency changes. They categorize students' misunderstandings in two sets 1) it is rare students recognize RC circuits as filters, and 2) students usually fall short of applying Kirchhoff's and Ohm's laws to arrive at a correct analysis. Additionally, they also notice students illustrate issues previously observed on other studies such as electric current-based reasoning, weakness in differentiating the frequency-dependence of some circuit elements and not distinguishing between AC and DC signals. Finally, Adam et al. (2017a) report their students generally use naïve models to explain a P-N junction distribution of electrical charges. Moreover, they also observe students did not utilize previous knowledge to perform reasonable inspections, nor use I-V curves to explain P-N junctions' behavior within an electric circuit.

Currently, there is a gap in the research literature regarding what sophomore undergraduate engineering students' misconceptions related to basic electric circuits these students use when analyzing solid-state devices circuits at the level of an introductory electric circuit course. The literature has studied students' difficulties regarding basic electric circuits concepts, as well as inadequate ways of thinking about electric circuits as systems. Moreover, the literature has also focused on students' issues with more advanced complex circuits (Adam et al., 2017a; Coppens et al., 2017; Papanikolaou et al., 2015; Stetzer et al., 2013; Wainwright, 2007). Consequently, the purpose of this study is to identify 1) what basic electric circuit misconceptions these students use when they analyze a single solid-state device electric circuit 2) if the identified misconceptions are used in a consistent way when students solve two different single solid-state device electric circuits.

3.4 Methodology

3.4.1 Participants and setting

This study's participants consist of 99 sophomore undergraduate electrical and computer engineering students enrolled in the introductory electric circuit course. Students illustrated some explanation for their choices on 60 and 89 of each of the problems. The course is a modernized version of the traditional introductory circuit analysis course. The course covers these traditional topics: DC analysis, first order transient analysis, and AC steady state analysis. Additionally, the new topics to this course comprise semiconductor physics, and solid-state devices circuit analysis.

3.4.2 Data collection

This study builds from previous research (Perez, Fisher, Douglas, & Peroulis, 2019), where two topics related to solid-state device circuits were found to be the most difficult for students on their the final exam. For this study, the researchers selected out the responses for two questions where students described or illustrated their analysis process for choosing the option they consider is the correct answer. Each problem consists of an electric circuit with a solid-state device in a simple configuration. The researchers purposefully selected to focus on student responses where analysis was provided. Following, a description of each problem and the developed codebooks are presented.

Problem 9

The problem 9 asked students to calculate the voltage at the output of a relatively simple circuit involving a diode. After the first coding stage, the research team observed some of the students who correctly answered the question also illustrated different accurately approaches for developing their analysis. Also, other students illustrated a variety of misconceptions regarding different electric circuit concepts. The different categories developed at the end of the second iteration can be observed in Table 3.1. There, the first three rows describe the codes used for categorizing students' work that was correctly analyzed. The other rows illustrate the different misconceptions observed on students' procedures. The last code was utilized on cases where the student did not explicate how they arrive to the chosen option.

Table 3.1. Problem 9 codebook

Name	Code	Description
Logic test	LT	The student uses a zero/one (0/1) test to corroborate their analysis result.
Node analysis	NA	After correctly realizing how the diode is working, the student does a correct node analysis and determines if it makes sense.
Dual analysis	DA	The student does two analysis, one for each possible diode state, and determines which one makes more sense. It is an elimination process.
Diode issues	DI	The student incorrectly analyzes the diode's operation condition.
Open circuit implies 0V	OC0V	The student describes there is no current through the circuit which implies 0V at the output.
Open circuit implies a ▲V = 0V	OCD	The student describes an open circuit as having 0A and a potential difference of 0V. This implies 7V at the output.
Formula issues	FIS	The student attempts to use whatever available formula making mistakes such as summing quantities with different units in the same expression or forcing an expression that does not fit into the situation (voltage divider)
Open circuit vs short circuit	OCSC	The student confounds how an open circuit works with how a short circuit works.
No work	NW	The student does not illustrate enough information to be analyzed.

Problem 12

Problem 12 requested students to determine the resistance value for setting a specific electric variable at a particular quantity given a transistor circuit. This is known as a transistor DC bias. For this case, the different categories developed at the end of the second iteration can be observed in Table 3.2. There, only the first row describes the code used for categorizing students' work that was correctly analyzed. The other rows illustrate the different misconceptions observed on students' incorrect procedures. In this case, the last two categories were utilized for classifying student's work that was not feasible to be analyzed.

Table 3.2. Problem 12 codebook

Name	Code	Description
Correct procedure	CP	Correct and complete procedure for solving the problem.
Ig issues	Ig	There is a non-zero current through the gate resistance and into the gate. This implies the student does not understand the gate is an open circuit.
Ohm's law issues	Ohm	The student incorrectly applies Ohm's law, or any of the Kirchhoff's laws.
Current & voltage	C&V	The student confounds current and voltage.
Blind formulas	BF	The student blindly applies formulas. For example, voltage divider, current divider, among others.
Voltage source	VS	The student assumes the resistance voltage is the same than the source voltage V_R = 9V. This implies the voltage drop into the channel would be 0V.
VD issues	VD	The student speculates a value for the drain terminal voltage. Then, s/he does not confirm the real value for V_D.
Region issues	RI	The student does not verify how the transistor behaves and uses different expressions for determining the transistor operation region without success.
No work	NW	The student does not illustrate enough information to be analyzed.
No research analysis	NRA	The student illustrates different paths and attempts that it is not feasible to analyze the procedure.

3.4.3 Data analysis

The research team choose qualitative content analysis as the research method for interpreting and understanding the data. This method is used in engineering education research studies because as Mathis et al. point, "Qualitative content analysis (QCA) is a systematic way of analyzing documents, which may include transcribed communication, pictures, symbols, and written text to describe the meaning of the material." (Mathis, Siverling, Moore, Douglas, & Guzey, 2018, p. 429). Within the systematic way of conducting the qualitative analysis, Schreier indicates that researchers do QCA by assigning subsequent parts of raw data to categories of a coding frame (Schreier, 2012). This frame is the core of the QCA, and it includes all those descriptions and interpretations the researcher visualizes in the data. Another characteristic of this systematic approach consists of its iterative nature. Several stages must be conducted to understand meaning in the material. In the following paragraphs, the different steps developed for qualitatively analyzing the two final exam problems are described.

The first step consists of reviewing a sample of the data. The purpose of this stage is to have a general understanding of what students present as part of the process for solving each problem. Conducting this tread, the research team realize the kind of processes students should illustrate to correctly solve each problem. This stage is known as Open Coding (Schreier, 2012, pp. 111–112). For adequately conducting this stage, it was necessary to solve the problems using different approaches. A great variety of those approaches were observed from students' answers. The result of this step consists of an initial codebook for iterative refinement.

Second, using the codes developed in the previous stage, the research team observed the remaining responses. Different researchers separately codified the same sample of data. Coding in this way brings a greater degree of reliability on the observations the research process can state. Additionally, the lead author conducted two different coding processes, two weeks apart one of the other, over the whole data set. Then, the multiple codes were compared among each other to estimate the reliability of the process. At the end of this stage, each data point could be assigned to a category. This phase's results comprise the different categories and a spread sheet with the whole coded data. It is worth noting for each problem, some codes were applied on a non-mutually exclusive way. For problem 9, the first three codes, the ones that were identified as possible correct analysis, were used at the same student' work if it was illustrated any feature that indicate that strategy was utilized. Similarly, it was the case for the categories set that describe misconceptions. In the case of problem 12, the only codes set that were used in this way were the ones that describe possible students' misconceptions.

Finally, observing the emerging categories, the research next step consists of an analysis and developing of themes. It is at this stage that the research team can state what kind of patterns and possible ways of thinking students used for attempting to solve the two final exam problems. Also, it is here that the researchers can find links between what they are observing and what has been reported in the literature.

3.5 Results

This section is organized in two parts. First, a characterization of the categories on which each problem was classified is presented. Then, a counting of the different categories for each problem is illustrated. Each one of the student's answer sheets is consider a data point. Accordingly, to QCA, each data point can be named an artifact. These artifacts are considered as an instant image of what each student elaborated for approaching to the chosen answer. The artifact's analysis is based on the marks, equations, drawings, and illustrations each student elaborated.

3.5.1 Quantitative results

It has been observed students try different approaches when attempting to solve the assessed problems.

Problem 9

It is observed that artifacts associated with students who performed a correct analysis are done using one of three possible paths (LT, NA, DA). Some of the artifacts (2%) illustrate those students used one of the three paths and then, utilized another or the two others to corroborate the results. All the classified artifacts on these first categories group correspond to students who correctly answered the question. Together these three categories correspond to 32.3% of the data.

It is noticed that artifact classified into the next categories group (DI, OC0V, OCSC, FIS, and OCD) are associated with students who majority did not chose the correct answer. Similarly to the previous categories set, some of the artifacts (3.0%) can be classified to two or more of these categories. This implies the categories within this set are not mutually exclusive. Within this set, a small percentage of the artifacts correspond to students who choose the correct answer even though they conducted an incorrect analysis, and they work show misunderstandings (2.0%). These five categories together comprehend 28.3% of the data.

The last set within this section consists of the artifacts where students did not illustrate enough work to be analyzed. This category corresponds to 39.4% of the data. Moreover, this category is formed by 27.3% of students who arrived at the correct answer and 12.1% of who choose a wrong choice. This information is illustrated on Figure 3.1.

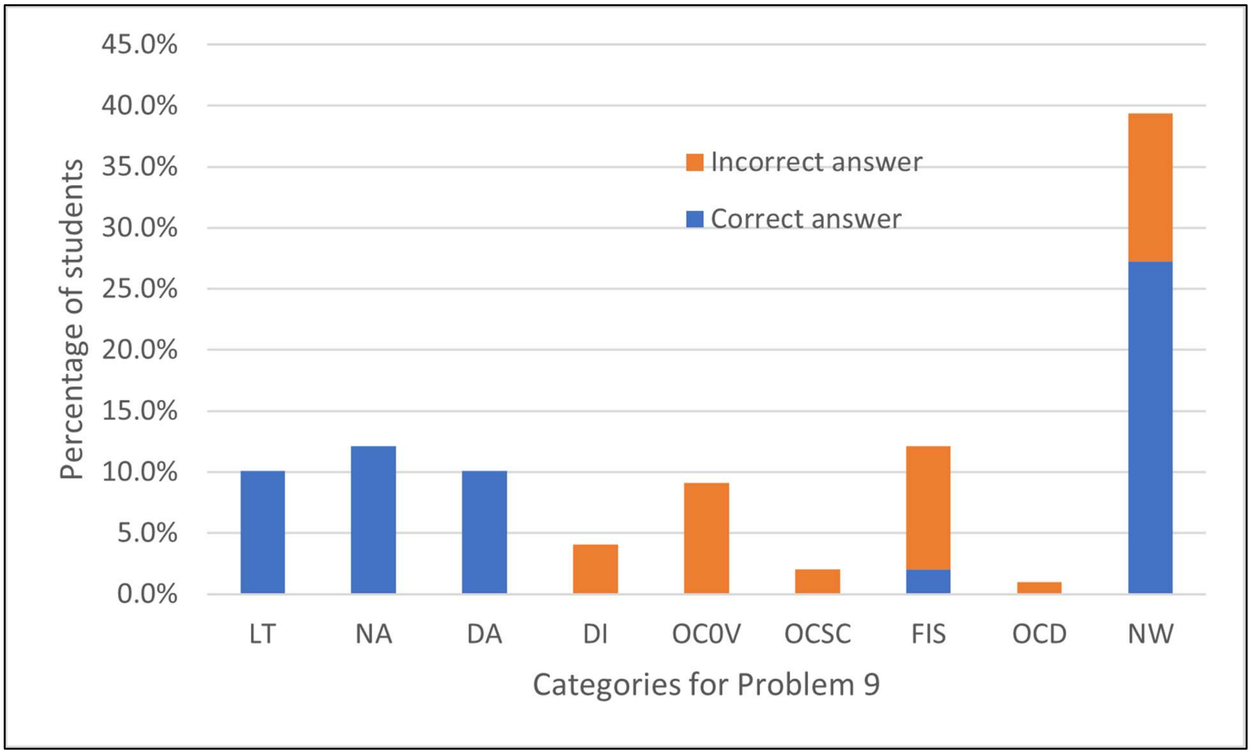


Figure 3.1. Percentage of students vs. categories for problem 9 (n=99)

Problem 12

Students reaching the correct answer:

It is observed that a small percentage of artifacts that illustrate a correct procedure and analysis (CP) (3.0%) reached the wrong choice. It seems these students incurred on a mathematical error, but their analysis corresponds with an overall correct procedure. This category corresponds with the only observed path in these artifacts set where students develop a comprehensive procedure for supporting choosing the correct answer. This bin comprehends a 19.2% of the data.

For the categories set related to misconceptions, it can be observed that these artifacts illustrate a broad variety of misconceptions. Within these categories, the artifacts show misconceptions regarding the following issues: a) the student states there is a non-zero current flowing into the gate (Ig), b) the student incorrectly apply Ohm's or Kirchhoff's laws (Ohm), c) the student confounds current and voltage (C&V), d) the student blindly applies formulas (i.e., voltage or current divider) (BF), e) the student assumes the resistance voltage is the same that the source voltage (V_R = 9V) (VS), f) the student speculates a value for the drain terminal voltage.

Then, s/he does not confirm the real value for V_D (VD), g) the student does not verify how the transistor behaves and uses different expressions for determining the transistor operation region without success (RI). This set comprehends the 60.6% of the data.

Within this categories' set, the proportion of students who choose the correct answer corresponds to 20.2% of the data. The remaining (40.4%) selected a wrong choice. Moreover, similarly to the same categories' set on the previous problem, some artifacts were classified on two (15.1%) or three (2.0%) different categories. This implies students' work can be identified as illustrating more than one kind of misconception.

Finally, two categories together were used for classifying artifacts where either the student did not illustrate enough information to be analyzed or the marks, equations, drawings, and illustrations were all over the place that it was not possible to clearly state the kind of misconception the student used. This set comprises an amount of 20.2% of the data. Within this set, 8.1% of students choose the correct choice meanwhile, 12.1% of them selected a wrong one. This information is summarized on Figure 3.2.

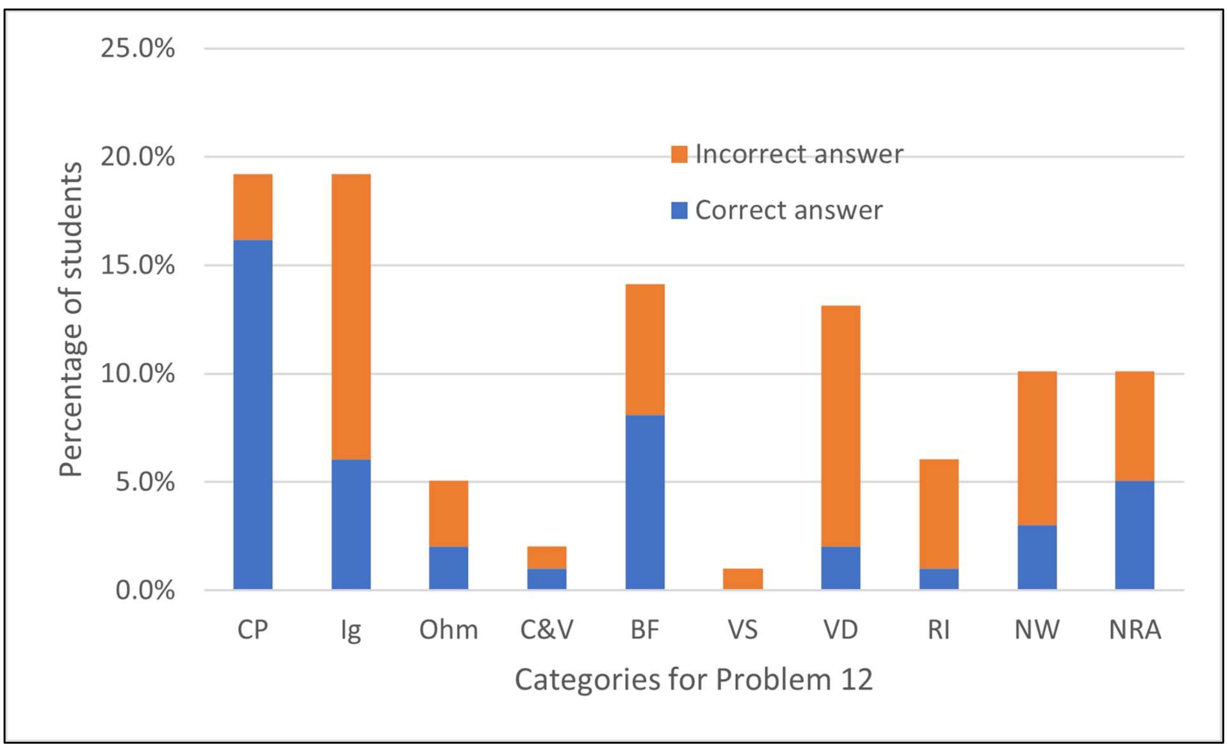


Figure 3.2. Percentage of students vs. categories for problem 12 (n=99)

3.5.2 Qualitative analysis

It has been observed students try different approaches when attempting to solve the assessed problems.

Problem 9

Theme 1: Correct analysis conducting to correct answer and choosing the correct choice.

The researchers observed on different artifacts that students did different marks when they analyzed the Problem 9's circuit. Those marks correspond to a combination of one of the following strategies 1) the student draw two different diagrams one for the diode operating as a short circuit and the other for the diode operating as an open circuit. Then, the student realized which one of the two possibilities makes more sense and determine the correct answer. This strategy is called dual analysis (DA), 2) The student conducted what the research team named a node analysis (NA). The student marked a circuit diagram with voltage values at the different nodes. It seems the student analyzed if those node voltages were adequately selected and concluded with the correct choice, 3) the student performed a logical test (LT). This test is like the node analysis, but it differs from the former on the student using 0/1 for determining if the diode is operating as a short circuit or as an open circuit. This last strategy was coded in this way because on the final exam students were asked questions regarding logic gates using diodes, which could be used by students to test their answers in Problem 9. Moreover, this context also guided the research team to state this code into the codebook.

Theme 2: Clear misconception manifestation

Subtheme 2a: Diode operation misunderstanding

This theme consists of artifacts where the student made a clear mark where the diode is operating as a short circuit and there is not any other mark where the diode is operating on the other condition. This suggests the student assessed the diode is operating in a condition that is not possible given the other circuit variables. All these artifacts were also associated to a wrong answer. Moreover, some of these artifacts also were categorized with other codes related to basic circuit misconceptions.

Subtheme 2b: Other misconceptions regarding basic circuit concepts

This categories' set consists of the artifacts classified on other categories different from the diode issues but where it was clear that there was at least a misunderstanding regarding basic electric circuits. An example of this kind of artifact can be seen on Figure 3.3. Here, the student clearly states that the diode's operation is off. However, it can be also observed this student wrote that the output node is "tied to ground = 0V".

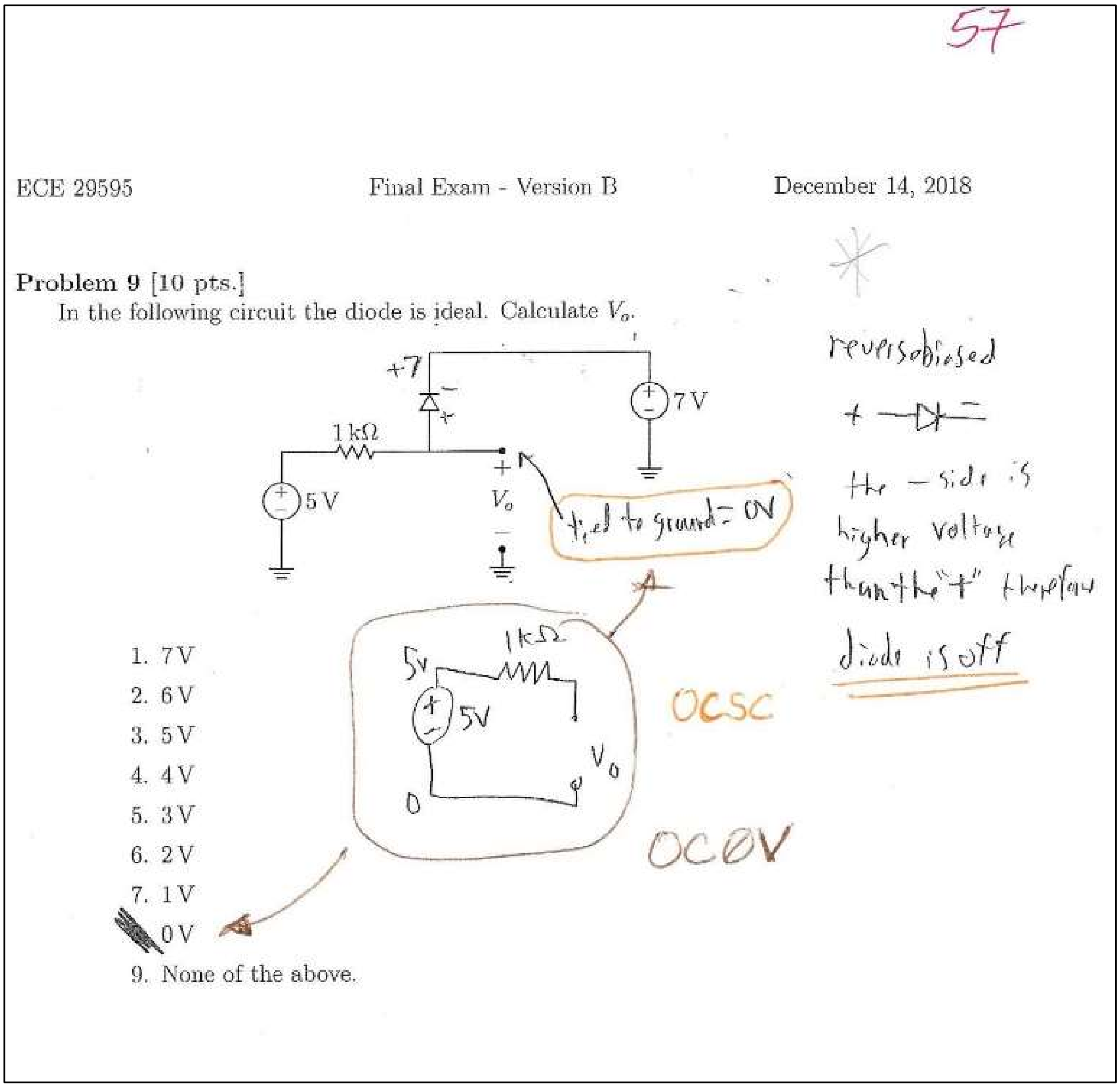


Figure 3.3. Basic circuit misconception example

Therefore, this artifact was classified as Open circuit vs. short circuit (OCSC) and Open circuit implies 0V (OC0V). This classification means that the research team considers this student illustrates issues regarding how an open circuit works.

Problem 12

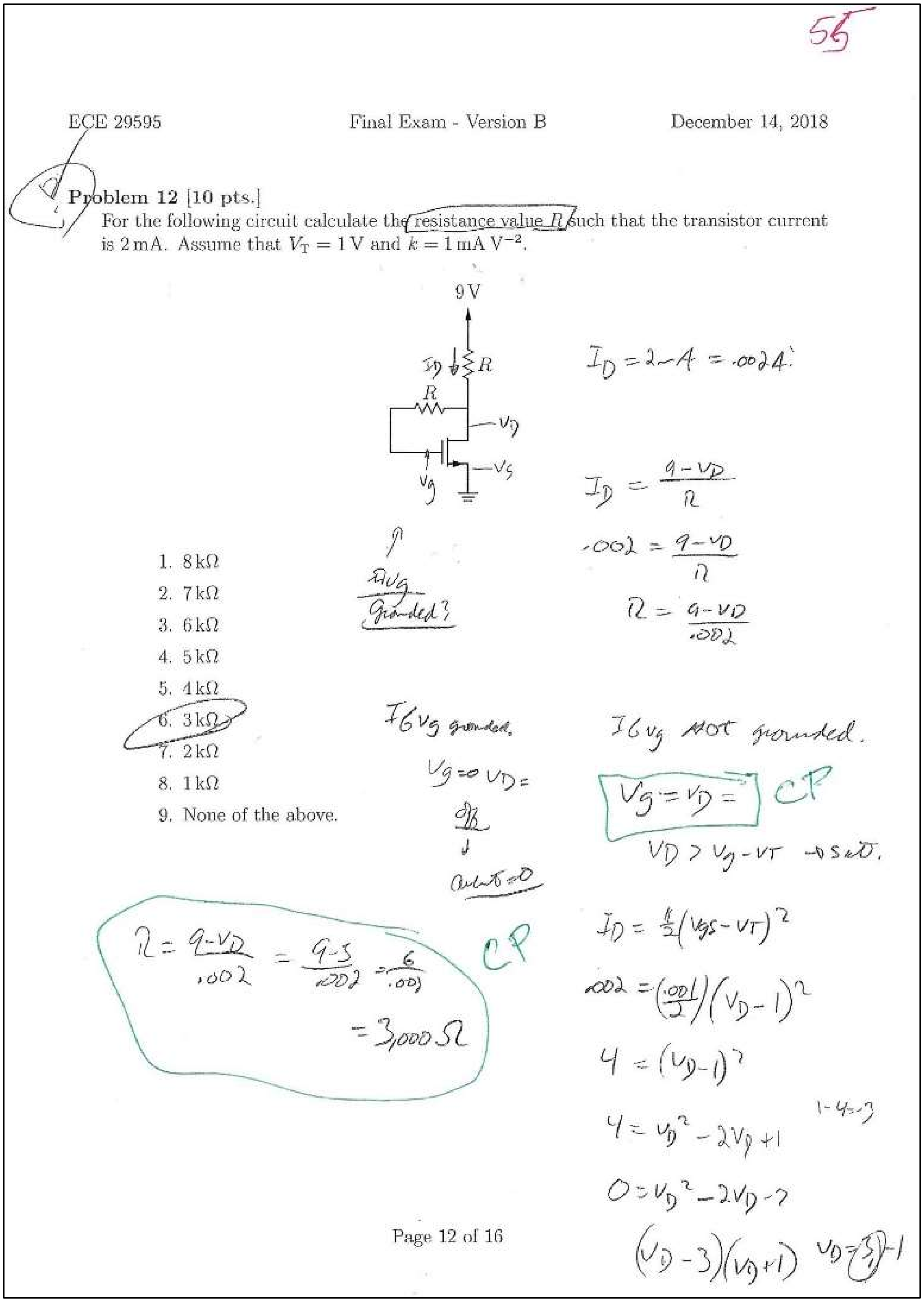
Students reaching the correct answer:

The researchers observed that students who conducting a correct analysis for Problem 12 basically followed a very structured steps set. Those steps were not always presented on the same order. These steps are a) realizing there is zero current (0A) into the gate and through the horizontal resistor, b) given the previous fact, the drain voltage and the gate voltage have the same value ($V_G = V_D$), c) realizing the source terminal is connected to the ground. Therefore, $V_S = 0V$, and $V_G = V_{GS} = V_D = V_{DS}$, d) using the transistor's saturation equation

$$I_D = \frac{k}{2}(V_{GS} - V_T)^2 \qquad (1)$$

the student can determine V_{GS} ($V_{GS} = 3V$), e) using Kirchhoff current law (KCL), it can be stated that the current through the vertical resistor is the same that I_D, the current through the transistor, f) using Kirchhoff voltage law (KVL), the student can determine the vertical resistor voltage $V_R = 9 - V_D$ ($V_R = 6V$), 7) finally, utilizing Ohm's law the student can determine the resistance value $R = V_R/I_D$ ($R = 3{,}000\ \Omega$ or $3k\Omega$).

For instance, the different steps for correctly solving Problem 12 are illustrated in Figure 3.4. There, this student states the current flowing through the vertical resistor is ID at the right of the circuit diagram. Below that, it can be observed that $V_G=V_D$ is expressed. Moreover, a confirmation or the transistor region of operation is evaluated ($V_D > V_G - V_T$). Then, putting the known values on the saturation equation, this student determines the V_D value. Given the quadratic characteristic for this equation, two values are obtained. The student chose only the positive value for this variable. Finally, bellow the nine possible answer choices the math for determining a value for R is calculated using Ohm's law.



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ECE 29595 Final Exam - Version B December 14, 2018

Problem 12 [10 pts.]

For the following circuit calculate the resistance value R such that the transistor current is 2 mA. Assume that $V_T = 1\,\mathrm{V}$ and $k = 1\,\mathrm{mA\,V^{-2}}$.

1. 8 kΩ
2. 7 kΩ
3. 6 kΩ
4. 5 kΩ
5. 4 kΩ
6. 3 kΩ
7. 2 kΩ
8. 1 kΩ
9. None of the above.

$I_D = 2\,mA = .002A$

$I_D = \frac{9 - V_D}{R}$

$.002 = \frac{9 - V_D}{R}$

$R = \frac{9 - V_D}{.002}$

Is V_g grounded?

If V_g grounded.

$V_g = 0$ $V_D =$

↓

cutoff $= 0$

If V_g not grounded.

$\boxed{V_g = V_D =}$ CP

$V_D > V_g - V_T \rightarrow$ sat.

$I_D = \frac{k}{2}(V_{GS} - V_T)^2$

$.002 = \left(\frac{.001}{2}\right)(V_D - 1)^2$

$4 = (V_D - 1)^2$

$4 = V_D^2 - 2V_D + 1$ $\quad 1-4=-3$

$0 = V_D^2 - 2V_D - 3$

$(V_D - 3)(V_D + 1)$ $\quad V_D = 3, -1$

$R = \frac{9 - V_D}{.002} = \frac{9-3}{.002} = \frac{6}{.002}$

$= 3{,}000\,\Omega$ CP

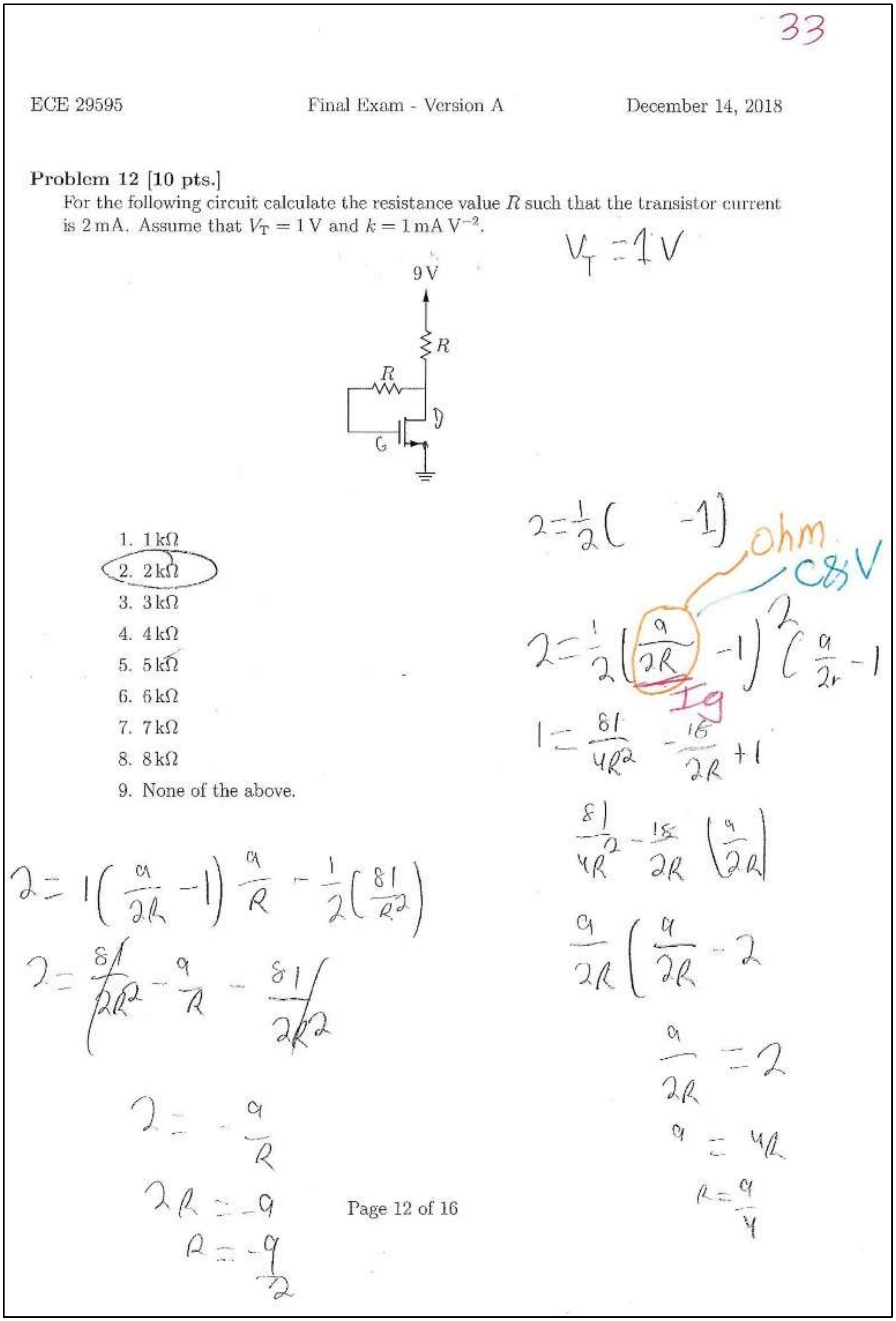
Figure 3.4. Correct analysis example

In this example, even though there are not explicitly illustrations of Kirchhoff's laws, it is evident from an expert's point of view that this student correctly applied the necessary steps for determine the correct answer and choose the correct choice. Thus, the research team classified this artifact in the correct procedure (CP) category.

Theme 2: Clear misconception manifestation

This theme consists of artifacts where students either did a clear mark or wrote an equation that clearly reflect they do have a misconception regarding how the transistor works or a combination of basic electric circuit mistakes.

The last example is shown in Figure 3.5. Here, this artifact allows to see different misconceptions. First, there are several parts where this student wrote "2R", which can be considered an indicative of current through the horizontal resistor and hence, into the gate. Second, this student put a math expression representing an electric current into the transistor formula where it is expected to ubicate a voltage, which indicates this person can confound the concepts of voltage and current. Finally, it is also exposed that Ohm's and Kirchhoff's laws are not correctly applied. The expression "9/(2R)", in several parts of this artifact, is an evident example this student did not use any of the Kirchhoff's laws for determining the voltage across and the current though the resistance for determining its value.



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ECE 29595 Final Exam - Version A December 14, 2018

Problem 12 [10 pts.]

For the following circuit calculate the resistance value R such that the transistor current is 2 mA. Assume that $V_T = 1$ V and $k = 1\,\mathrm{mA\,V^{-2}}$.

$V_T = 1V$

1. 1 kΩ
2. 2 kΩ
3. 3 kΩ
4. 4 kΩ
5. 5 kΩ
6. 6 kΩ
7. 7 kΩ
8. 8 kΩ
9. None of the above.

$2 = \frac{1}{2}(\quad -1)$

ohm

C&V

$2 = \frac{1}{2}\left(\frac{9}{2R} - 1\right)^2 \left(\frac{9}{2r} - 1\right.$

Ig

$1 = \frac{81}{4R^2} - \frac{18}{2R} + 1$

$\frac{81}{4R^2} - \frac{18}{2R} \quad \left(\frac{9}{2R}\right)$

$\frac{9}{2R}\left(\frac{9}{2R} - 2\right.$

$\frac{9}{2R} = 2$

$9 = 4R$

$R = \frac{9}{4}$

$2 = 1\left(\frac{9}{2R} - 1\right)\frac{9}{R} - \frac{1}{2}\left(\frac{81}{R^2}\right)$

$2 = \cancel{\frac{81}{2R^2}} - \frac{9}{R} - \cancel{\frac{81}{2R^2}}$

$2 = -\frac{9}{R}$

$2R = -9$

$R = -\frac{9}{2}$

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Figure 3.5. Misconception theme example

In this example, on the one hand, is evident this student considers there can be current through the horizontal resistor and into the transistor gate. Thus, this is also an example of misunderstanding regarding how the transistor works. On the other hand, this artifact illustrates two different but related misconceptions with respect to basic electric circuit concepts. First, there is a possible confusion between the concepts of voltage and current. Second, another issue regards the correct application of Ohm's and Kirchhoff's laws. Therefore, the research team classified this artifact within three different categories a) Ig issues regarding how the transistor works, b) current vs. voltage issues (C&V) for the confusion between these concepts, c) Ohm's law issues (Ohm) for the troubles applying Ohm's or Kirchhoff's laws.

3.6 Discussion

This research has illustrated different misconceptions students have when solving a single solid-state electric circuit. The themes suggest, on the one hand, students who correctly answer the first problem used different approaches. Additionally, artifacts where students had a correct procedure for the second problem followed a very similar procedure. This can be explained considering the second problem is more complex. On the other hand, the artifacts that illustrate students' misconceptions consist of two different subsets. The first one where students' work shows misunderstandings regarding how the solid-state device works. Here, in both cases, there are similar issues given these devices behave as open circuits. Second, the misconceptions related to basic electric circuit concepts can be classified into two groups. The first one consists of students using whatever formula as an attempt for reaching a feasible answer making mistakes on applying Ohm's or Kirchhoff's laws. The other one where students consistently confuse how an open circuit interact with the rest of the circuit.

The findings reached in this study are consistent with the reports made by other researchers.

3.7 Conclusion

The purpose of this study was to identify the misconceptions students used when solving a single solid-state device circuit. Overall, the data analysis could identify the most common kind of misconceptions are related to the open circuit concept. Other misconceptions have multiple sources such as the usage of any formula without regard it that expression can be applied. Going further on determining what other misconceptions students have within this category is one of the limitations this study has. These findings can support future instructional designs where students can receive support related to these kinds of identified misconceptions. Moreover, instructors can find this information useful for addressing possible students' misunderstandings.

4. BASIC CIRCUIT MISCONCEPTIONS INFLUENCING STUDENT'S PERFORMANCE REGARDING SOLID-STATE DEVICE CIRCUITS

4.1 Abstract

Studying electric circuit concepts is an important focal point in the engineering education community because they are sources of common misconceptions among engineering students. Identifying what those misconceptions are at both early and more advanced and complex stages can be paramount to understanding how to support student's success in their majors. Moreover, understanding what misconceptions can mostly impact other more complex topics will help focus resources on addressing key issues. This study identifies how misconceptions at an earlier stage impact student's performance on later topics. We found that students can use multiple misconceptions when answering different questions regarding the same problem. We also observed students' transit from a correct analysis to the usage of some misconceptions on other exams. Moreover, we consider there is a strong link between how language is used, and some misconceptions students illustrated.

4.2 Introduction

Some engineering students taking fundamental electric circuit courses experience difficulties understanding basic concepts at the beginning of the term. Electric circuit topics have been found one of the most complex for students to learn and understand (Yoon, Imbrie, Reed, & Shryock, 2018). As the semester advances, they face increasing challenges as the circuits' complexity increases (Adam et al., 2017a; Bernhard et al., 2013; Stetzer et al., 2013). For example, once students go through node analysis and Thevenin and Norton equivalents, they turn to RC circuits' transient analysis and steady-state sinusoidal analysis. Then, they immerse themselves in the calculations of solid-state electronic circuits. Engineering education researchers have investigated what kind of problems students have regarding understanding simple electric circuit concepts. However, it is necessary to research students' understanding of more complex circuits, given the specificity of the devices and tools under scrutiny. This study focuses on understanding how students longitudinally progress through the different electric circuit topics based on identified misconceptions in earlier stages during the electric circuit course.

Moreover, there is a gap in the literature concerning how students' misunderstandings regarding fundamental concepts relate to their later conceptions of complex circuit analysis. The purpose of this study is to understand how students who experience difficulties with basic circuit concepts perform later regarding more complex circuit analysis. Specifically, we ask the following research questions: 1) What are the conceptual difficulties that are most predictive of students' struggles with understanding more complex circuit analysis? 2) Are there misconceptions or difficulties specific to the different kinds of complex circuit analyses?

4.3 Literature review

This section describes some studies that have confronted issues regarding student's understanding of electric circuit concepts. Moreover, different theories on how conceptual change can be explained are addressed.

In STEM education research, student's misconceptions on DC circuits have been observed for at least three decades. Several studies have identified some students behold misconceptions regarding basic electric circuit variables such as voltage, current, resistance among others (Cohen et al., 1983; Engelhardt & Beichner, 2004; McDermott & Shaffer, 1992). Within these difficulties, they have highlighted how some students consider a battery is a source of constant current instead of a source of constant voltage (Cohen et al., 1983; Picciarelli et al., 1991b). Other researchers have also pointed to difficulties in understanding circuits as systems where the different elements interact producing an observable pattern (Duit & von Rhoneck, 1998). On a complementary line of thought, other studies have suggested students who attempt for more complex circuits analysis do not necessarily overcome more fundamental misconceptions (Adam et al., 2017a, 2017b; Scott et al., 2012; Stetzer et al., 2013; Wainwright, 2007).

Recently, researchers have reported studies considering how students understand increasingly complex circuit analysis. For example, Coppens, Van den Bossche, & De Cock (2017) studied students analyzing RC circuits as filters. Carstensen & Bernhard (2009), and Bernhard, Carstensen, & Holmberg (2013) conducted studies regarding students evaluating AC circuits. Papanikolaou, Tombras, Van De Bogart, & Stetzer (2015) observed students dealing with op-amp circuits analysis. All these studies found students struggle with the increasing complexity of those topics for different reasons. One of those reasons consists of wrongly applying basic laws or concepts such as Kirchhoff's laws or the concept of an open circuit. Another reason is that students have problems using the different models that experts use for conducting these complex analyses.

From the perspectives of conceptual change theories, three lines of thought dominate this field. First, diSessa (2008) has stated the fragmented theory. This theory states students use what is known as a facet. A facet consists of a convenient unit of thought or reasoning that the student utilizes to process a particular situation (Hunt & Mistrell, 1994). These researchers conceive those facets as independent units that do not have any kind of structure in students' minds. Another line of thinking declares that students' naïve understanding can have some kind of hierarchical structure (Vosniadou, 2008). A third possible explanation regards the idea that some learners could lack a taxonomical category through which they could approach the new content. This line of thought is known as a categorical shift (Chi, 2008). Finally, the theory known as social activity theory declares that knowledge is socially constructed (Säljö, 1999). Thus, only through the modification of social expressions, such as language, students can achieve a conceptual change in their mental structures.

4.4 Methods

4.4.1 Participants and settings

The population of this study consists of 142 undergraduate sophomore engineering students pursuing a major in engineering. These students were registered on one section of the introductory electric circuits course. During the Fall 2019 semester, the modernized version of the introductory electric circuit course was implemented for all registered students. This course's version comprises DC, first-order transient, AC steady-state analysis, semiconductor physics, and solid-state device circuit analysis.

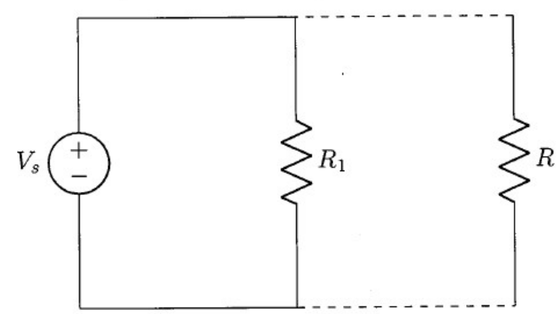
4.4.2 Data collection

Our research team worked with data collected on the modernized introductory circuits course at a Midwest Research University. The course was modernized by introducing semiconductor physics and devices, such as diode circuits and single-stage transistor circuits. Students pursuing majors in electrical and other engineering programs were enrolled in this course. We assessed students' data (n=142) to understand what misunderstandings they had regarding basic circuit concepts, as well as the kind of difficulties they displayed on topics such as transient circuit analysis, and semiconductor physics analysis.

Data was collected during the Fall 2019 term. It consisted of three data sets, each one of them is a midterm exam. On each midterm, the research team delivered three conceptual and interrelated questions. Those questions required analyzing a system under a change over it. Moreover, the students should justify their answers with either a short explanation or calculations. The first midterm question set assessed a simple DC circuit. The circuit consisted of an ideal voltage source feeding a light bulb. Then, a second bulb is connected in parallel to the original arrangement. Students were questioned regarding how the delivered power, original light bulb's power, and equivalent resistance change before and after the second bulb is connected. These questions are illustrated in Figure 4.1

Question 8-10 [10 pts. each]

When a finite-valued, non-zero resistor is placed in parallel with R_1, what will happen to the power delivered from the source (**question 8**), to the power delivered to R_1 (**question 9**), and to the resistance seen by the source (**question 10**)? ***You must explain your reasoning to receive full credit.***



Question 8

1. increases
2. decreases
3. stays the same

Question 9

1. increases
2. decreases
3. stays the same

Question 10

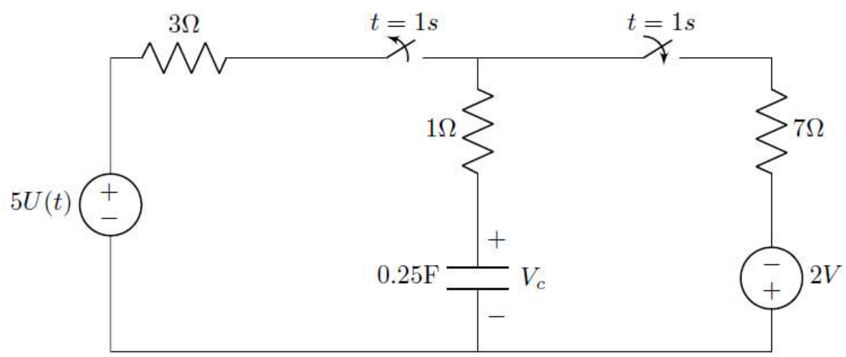
1. increases
2. decreases
3. stays the same

Figure 4.1: Questions from midterm #1

The second midterm exam questions asked about an RC circuit transient response. The circuit experiences twice a sudden change. Each change implies a change in the value in the capacitor voltage, and a change in the rate the capacitor's voltage reaches that value. The students were required to calculate the capacitor voltage at different instant times along the transient response. These questions can be observed in Figure 4.2.

Question 8-10 [10 pts. each]

Analyzing the circuit below, please find:
Question 8 – The approximate value of $V_c(1)$.
Question 9 – The value of $V_c(\infty)$.
Question 10 – The time ($t \neq 0$) where the capacitor has zero voltage.
In order to receive full credit, you must show all work and rationalize any assumptions.



Question 8 **Question 9** **Question 10**

Figure 4.2: Questions from midterm #2

The third midterm exam assessed student's understanding of fundamental semiconductor physics concepts. The questions were asked to identify how the carriers' concentration changes when some variables change. For example, the first question asks how the concentration is affected when the temperature increases. The whole third midterm exam's questions can be seen in Figure 4.3.

Question 8-10 [10 pts. each]

In order to receive full credit, you must show all work and rationalize any assumptions.

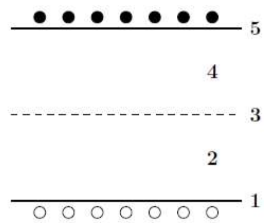
Question 8 – If the bandgap energy *increased* what would happen to the intrinsic carrier concentration?

1. increase
2. decrease
3. no change

Question 9 – For an intrinsic semiconductor, what would happen to the number of free carriers if the temperature were *increased*?

1. increase
2. decrease
3. no change

Question 10 – Please indicate where the conduction band is.



1. 1
2. 2
3. 3

Figure 4.3: Questions from midterm #3

4.5 Analysis methodology

To address the purpose of this study, we implement a mixed-method exploratory sequential research design. Exploratory sequential research studies begin with qualitative analysis and then seek to generalize the findings through quantitative studies (Creswell, 2009; Creswell & Plano Clark, 2018). For the qualitative part, we develop a content analysis applied to students' reasoning on each midterm exam answer. We then transform students' responses into categorical variables, as described below. Next, we assess how students' work was categorized on the different bins on the qualitative analysis for the following midterm exams. In this section, each of the different procedures used for analyzing and categorizing the data are described.

4.5.1 Qualitative analysis

Analyzing each midterm exam required a five steps iterative process. First, the research team solved each midterm exam problem taking each possible step for reaching a correct analysis of the system. Second, we iteratively went into the data looking for misconceptions previously reported in the literature, but with an open mind for new emergent insights. After some rounds, we consolidated a specific codebook for each midterm exam question set. Later, we codified the whole data set using the codebook. Finally, we made crosschecks with two different coders comparing a sample of each data set for assuring the consistency, validity, and reliability of the coding process. In the next subsections, a description of each developed codebook is explained.

Midterm #1 (MT1)

The codebook for the MT1 is presented in Table 4.1. This Table and the others which describe the other codebooks have a similar structure. At the left column, a name and a code are stated. At the right column, a comprehensive description of the category that students used in supporting their choices is declared. For this specific codebook, it can be observed the first five rows describe the codes used for the identified misconceptions. The last row comprises a correct analysis of the system.

Table 4.1: Midterm #1's codebook

Name	Description
Confusion of variables (CV)	The student describes current, voltage or any other variable as it were another one.
Blind formula (BF)	The student blindly applies formulas to solve the problems without consideration of the correct use of those expressions. This approach can be observed when the student says the power from the source decreases.
Power source (PoS)	The student mentions a change in the circuit does not change the supplied source's power.
Current source (CuS)	The student states that source's current is constant. Keywords on the explanation will be "split, sharing, 2 paths". This usually implies the power delivered to R1 decreases.
Parallel vs Series (PvS)	Adding a resistor in parallel increases the total equivalent resistance. This usually implies the power delivered from the source decreases.
Circuit as a system (SyS)	The student does a correct and complete analysis with the following descriptions: 1) the source power increases because either the Req decreases and V^2/R_{eq} increases or the source current increases, 2) the R_1 power stays the same because neither voltage, resistance, nor current varies, 3) the R_{eq} decreases because two or more resistances in parallel have a R_{eq} less than any of the original resistances.

Midterm #2 (MT2)

For the second midterm exam, the developed codebook is illustrated in Table 4.2. Here, the first code was used for student's work that cannot be assessed due to the lack of information. The next 6 rows describe the different misconceptions identified for this data set. The last row delineates what we consider was a neat, correct, and clear understanding of an RC circuit's behavior.

Table 4.2:Midterm #2's codebook

Name	Description
No Work (NW)	The student does not illustrate any work for analysis
Open Circuit/Short circuit (OC/SC)	The student considers either an open circuit has 0V or a short circuit has 0A.
Kirchhoff issues (KI)	The student has issues applying either KVL or KCL
R Thevenin (R_{Th})	The student has issues determining the R_{Th} for any of the time intervals.
Blind 1st order equation (B1o)	The student blindly uses a first order equation $V_c(t)=V_c(\infty)-[V_c(t_0)-V_c(\infty)]*\exp^{((t-t0)/\tau)}$ for describing the capacitor voltage. It can be across either for the full-time range or messing up the different values into the equation.
The circuit as a linear resistive circuit (Res)	The student analyzes the circuit as it were a linear resistive circuit. e.g., the student considers the capacitor either as an open circuit or as a short circuit at every stage s/he conducts an analysis.
Time issues (Time)	The student either does not correctly determine the initial voltage for each interval, does not use those values for further calculations, or does not consider the different switching events. This is also evident when it is no analysis for at least one of the time intervals of the circuit.
The circuit as 1st order system (SyS)	The student conducts an analysis considering all the time lapses, initial values, and time constants of the circuit.

Midterm #3 (MT3)

The third midterm exam questions assessed student's understanding of fundamental solid-state physics materials behavior. In this case, we used codes that emerged from the data. The codes are presented in Table 4.3. Some of those codes were related specifically to each question and others could be applied to the whole questionnaire. For stating a student's understanding of the system behavior, we had to assess how the student answered each question and how s/he justified their choices. In this way, we developed the code illustrated in the first row which can be applied if all the three following codes were present. The next four rows describe the misconceptions observed in this data set. In a similar way to the second midterm exam, it was needed to include a code to describe that a student did not elaborate on the choices s/he made, and we cannot assess that artifact.

Table 4.3: Midterm #3's codebook

Name	Description
Understanding the system (SyS)	(BGE-R) and (Temp-R) and (D-R)
Band gap energy right (BGE-R)	The student states that the intrinsic carrier concentration would decrease if the bandgap energy were increased. Their reasoning consists of that electric charges would find it harder to jump the gap or break the bonds.
Temp. right (Temp-R)	The student claims higher temperature implies more free carriers or electrons because of more energy, or kinetic energy, or more broken bonds, or excited molecules or electrons due to the increase in temperature. More electrons or freed carriers able to cross the bandgap because of the increase in temperature (energy).
Band gap diagram right (D-R)	The student relates the different band diagram components and states relationships among them.
Temp. wrong (Temp-W)	The student argues the number of intrinsic free carriers is independent or is inversely related to the temperature.
Math (Math)	The student clearly writes some mathematical expression or some text that resembles a dopped material.
Band gap energy wrong (BGE-W)	The student clearly states that the number of free intrinsic carriers (ni) is independent or directly related to the bandgap energy (EG).
Band gap diagram wrong (D-W)	The student does not correctly identify or support their choice regarding the conduction band diagram. The student has difficulties interpreting a band diagram.
No Work (NW)	The student does not expose their choices.

4.5.2 Quantitative analysis

For answering the research questions, the research team implemented a quantitative analysis as part of the analysis process. The quantitative analysis consisted of grouping student's artifacts into bins regarding how they were qualitatively classified on each midterm. Then, the research team observed how students moved between those categories on the second and third midterm exams. Artifacts were classified into two big bins regarding if those artifacts exposed either a coherent and systematic approach (SyS), or any kind of misconception (x). If the artifact was codified as not enough work for assessing, or if the student did not take the evaluation, the artifact was not considered for further analysis (NA). First, departing from midterm exam #1, we have two bins SyS and x. Then, moving to the next midterm evaluation, we obtained four bins SyS/SyS, SyS/x, x/SyS, and x/x. Finally, at the last midterm exam, we ended up with eight categories SyS/SyS/SyS, SyS/SyS/x, SyS/x/SyS, SyS/x/x, x/SyS/SyS, x/SyS/x, x/x/SyS, and x/x/x.

4.6 Results

4.6.1 Qualitative results

On midterm exam #1, we observe 50% of student's work was comprehensively and consistently elaborated in such a way that we could classify it with the SyS code. The other 50% presented at least one misconception. We noticed that 35 artifacts (~25%) showed more than one misconception. Regarding the second midterm, only 33 artifacts were classified with the SyS code, 80 presented at least one misconception, 19 did not illustrate enough information for being analyzed, and 9 students did not take this midterm exam. For the last midterm evaluation, 38 data points were codified with the SyS code, 76 had at least one misconception, 17 did not illustrate enough information, and 10 students did not take this exam. The most remarkable observation consists of student's usage of different misconceptions that, to the expert's knowledge, seem to be inconsistent. For example, some student's work regarding the midterm exam #1 states that the original resistance's power decreases meanwhile the source's power remains the same when the new resistance is connected. They argue that the original resistance's power decreases because the current of the source must be split between the original and new resistances. At the same time, they support that the source's power remains the same because the source is a power source then the power must be constant. Similarly, on the second and third midterm exams, we observe student's artifacts that were classified with more than one misconception have conflictive explanations to an expert's eyes.

4.6.2 Quantitative results

Following, we describe the observations that emerge from the quantitative analysis of the data. First, we analyzed how students made a transit from midterm exam #1 to midterm exam #2. We classified students in different bins regarding if their work was classified either as a correct analysis (SyS) or with some misconception (x). Figure 4.4 illustrates the transit of students from midterm exam #1 to midterm exam #2. On the Y-axis there is the number of students on each bin and on the X-axis is the grouping for midterm exam #1. The red color indicates the students' work that was classified as a correct analysis for midterm exam #2 and the yellow color refers to students' work that illustrated some misconception for the same midterm exam. The gray bins correspond to student's work that could not be assessed (NA) because either those students did not illustrate enough information, or those students did not take the second midterm exam.

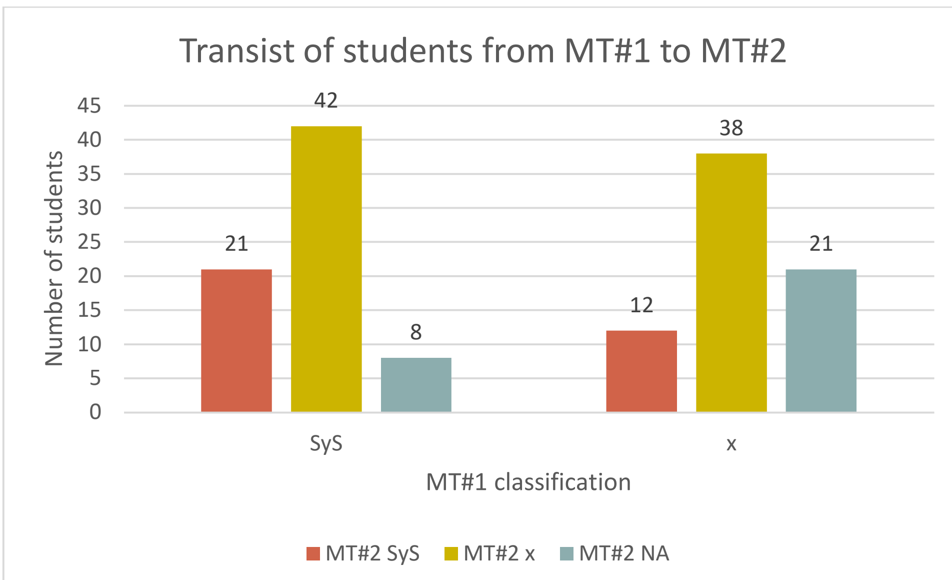


Figure 4.4: Transit of students from MT#1 to MT#2

Remarks:

- 71 student's work was classified as correct analysis for midterm exam #1. From those, 21 obtained the same classification for midterm exam #2 (30%).
- 42 students transit form a correct analysis on midterm exam #1 to illustrate at least one misconception on midterm exam #2 (59%).
- Also, 71 students were classified with some kind of misconception for midterm exam #1. Of those 12 (17%) made transit to a correct analysis on midterm exam #2.
- Lastly, 38 students illustrated misconceptions on both midterm exam #1 and midterm exam #2 (54%).

Second, we analyzed how students made a transit from midterm exams #1 and #2 together to midterm exam #3. This time the classification consisted of the bins described in the remarks above. For example, one student who did a correct analysis for both initial midterm exams (#1 and #2) was classified under the bin SyS/SyS. Meanwhile, a student who performed a correct analysis for midterm exam #1 and illustrated a misconception for midterm exam #2 was classified as SyS/x. We proceeded in a similar way to classify the other two possible combinations. Figure 4.5 shows the transit of students from midterm exams #1 and #2 together to midterm exam #3. On the Y-axis there is the number of students on each bin and on the X-axis is the grouping for the possible combinations of midterm exams #1 and #2. The red color indicates students' work that was classified as a correct analysis for midterm exam #3, the yellow color refers to students' work that illustrated some misconception for the same midterm exam, and the gray bins correspond to students' work that could not be assessed (NA) because either those students did not illustrate enough information, or those students did not take the third midterm exam.

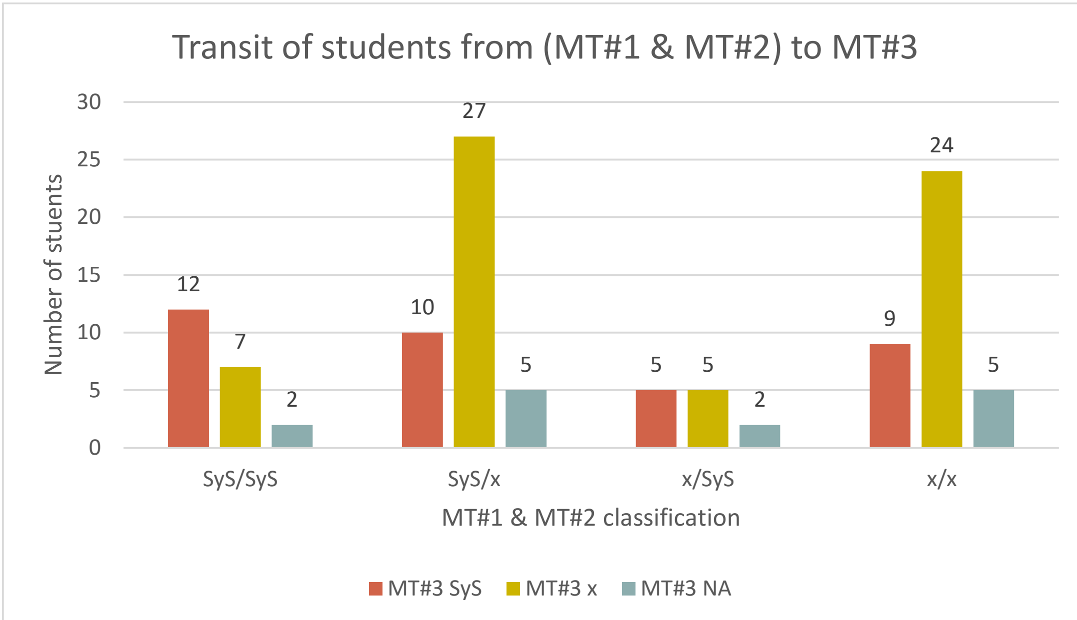


Figure 4.5: Transit of students form (MT#1 & MT#2) to MT#3

Remarks:

- 12 students maintained a consistent correct analysis through the three midterms (SyS/SyS/SyS). This corresponds to 57% of the students classified on the SyS/SyS (21 students) bin for the first two midterms.
- 7 students out of 21 made a transit from a correct analysis on the first two midterms to one where they illustrated some misconception on the last midterm (33%).
- 10 students out of 42 are classified on the SyS/x/SyS bin (23%).
- 27 students out of 42 belong to the SyS/x/x bin (64%).
- 5 students out of 12 get under the x/SyS/SyS bin (41%). The same number is categorized on the x/SyS/x bin (41%).
- 9 students out of 38 are classified under the x/x/SyS bin (24%).
- 24 students out of 38 belong to the x/x/x bin (63%).

It is worth noticing the last percentages are calculated based on the number of students on the transit from midterm exam #1 to midterm exam #2. This analysis allows assessing how students move through each transit.

4.7 Discussion

The exploratory sequential method implemented for analyzing the data allowed us to observe interesting findings. Taken together with the results from the qualitative and then use in a quantitative analysis suggest some implications for engineering instruction, research, and assessment. In this section, we summarize the finding, discuss connections with the literature, highlight some limitations, and consider future research projects in this area.

First, from the qualitative analysis of each midterm exam emerged student's misconceptions on the topics each exam assessed. Then, using the results of this qualitative step, we assessed how each student move from the first midterm exam to the second one and then, from there to the final midterm. From the qualitative results, we identified specific misconceptions on topics assessed on each evaluation. Some of those misconceptions can be found in different topics such as the blind application of formulas. Some others were previously reported in the literature. However, we found new misconceptions not described before such as the constant power source (PoS). From the quantitative analysis, we departed from the qualitative results for each midterm exam, we put together all the misconceptions for each midterm on one single bin and the correct analysis on another bin. Then, we assessed how students move between those bins through each midterm exam. We observe that there are movements in all the directions (e.g., from correct analysis to misconceptions, from misconceptions to correct analysis). However, it seems that it is easier that students move from a correct analysis to a misconception than the other way around. This could be partially explained by the fact of the increasing complexity of the topics. Moreover, it is a factor instructors must be aware of during their students' learning process.

Second, regarding how our findings connect with the literature, we have observed students utilized different misconceptions when answering different questions related to the same problem. For example, several students use the constant current source misconception and the constant power source misconception when they supported their choices in the first midterm exam. Some of those students use both misconceptions at the same problem. This observation can be linked to the fragmented theory. Moreover, the constant power source misconception could be associated with how the professional community uses language and the social activity theory. Additionally, the inconsistency on how students transition from coherent analysis to some misconception on the following midterms likely has a connection with the coherent theory regarding students' lack of a taxonomical category for associating how to analyze electric circuits as systems.

Finally, regarding the limitations and future research, we consider the size of this sample and the small number of students that were categorized into use specific misconceptions do not allow us to assess how students move between different misconceptions. Thus, the next steps on researching electric circuit misconceptions must consider assessing pedagogical interventions for helping students override those issues, designing assessment tools that allow easier ways to capture different misconceptions among other research projects that permit a better understanding of this issue.

4.8 Conclusion

The purpose of this study consisted of identifying the conceptual difficulties that most predict student's struggles with understanding more complex circuit analysis. We could identify that there is a combination of different misconceptions and other factors not fully uncovered, such as the inconsistency in analyzing electric circuits as systems. This can be observed longitudinally through the different midterm exams. This study's findings contribute to a better understanding of student's difficulties at different stages along their process of learning about electric circuit analysis. These findings also bring tools for students and instructors on addressing some of those difficulties.

5. CONCLUSION OF DISSERTATION

This chapter summarizes and highlights four main points for the dissertation. First, a paraphrase of each study's results is presented. Second, I illustrate how these three studies together contribute to answering the overall research question. Third, I describe how this dissertation's results can contribute to theory and previous studies. Finally, some possible future research areas and projects are described.

5.1 Results of each individual study

5.1.1 First study results

Regarding the first study's findings and results, we observe that students in the introductory course can understand at a good level how a diode and a transistor work. However, they struggle mainly with the analysis of the circuit at a fundamental level. This means that some students illustrated problems associated with the fundamental distinction between different electrical variables. The results of this first study encouraged us to explore those fundamental misconceptions students used when analyzing a solid-state device circuit.

5.1.2 Second study results

This second study attempted to identify what fundamental misconceptions students use when they analyze solid-state device circuits. We analyzed the same data for the first study but using this time a different lens. The data consisted of two circuit problems, the first one regarding a circuit with a diode as a solid-state device, and the second one assessing a more complex circuit comprising of a transistor. The following three remarks highlight the results we obtained. First, students who illustrated a correct analysis did so in different ways for the two problems. Regarding the diode's question, they performed a correct analysis using different correct approaches. However, the procedure they used for analyzing the transistor's question followed a more rigid structure comprised of a set of steps. It is necessary to highlight that the set of steps were not reached in the same order for different students. Second, students who developed an incorrect analysis of any circuit could illustrate more than one fundamental misconception. Third, the misconceptions some students illustrated can be classified as fundamental misconceptions and misconceptions regarding how the solid-state device works. However, we do not understand, yet, if there is another misconception level that relates to how the solid-state device circuit behaves as a system. Another aspect we found interesting, but we did not have any concluding remark consists of it seems students can use their knowledge for analyzing more advanced and complex circuits in analyzing relative simpler circuits. Doing so, it seems they are developing skills experts exhibit on performing complex analysis tasks. An example of this is the fact we observed a variety of correct alternatives for analyzing the diode circuit.

5.1.3 Third study results

The results from the third study confirm some of the observations we did in the previous two studies. Some students conducted correct analysis where they consider the circuit as a system. Other students illustrated different misconceptions and, in some cases, more than one misconception over the same problem. At different stages longitudinally the semester's evaluations, students illustrated misconceptions of the same kind such as blind usage of formulas. Moreover, we could identify misconceptions that seemed to be related to how the community uses language for describing how a circuit operates. Regarding how students move from one midterm exam to the next, we observed students transited in every possible direction (e.g., from correct analysis to misconceptions, vice versa, and kept into correct/incorrect bins). We also identified that it is easier that one student did a transition from a correct analysis to an incorrect one than on the other way around.

5.2 Taken together.

This section considers all the three studies together and takes their results for answering the overall research question. The overall research question looks to identify the conceptual difficulties sophomore undergraduate engineering students face when they analyze solid-state device circuits. Doing so, I can highlight three main reasons or causes that explain why students face difficulties when they analyze solid-state device circuits. First, students bring misconceptions to the classroom regarding how circuits work. A possible example of this situation consists of some students consider an independent voltage source provides a constant current value.

Second, they also can develop misconceptions on how some specific elements work when they are connected into a circuit. Even though I cannot differentiate which misconceptions students bring from previous experiences and which ones they develop during instruction into the electric circuit course, I consider that the instruction regarding relatively new elements or new complex circuits provides the fertile ground for misconceptions unfolded during instruction. For example, some students analyzed a capacitor as it was an open circuit without regard to the dynamic behavior of the capacitor and the whole circuit. Another example we observed consisted of some students applying Ohm's law to an open circuit. When they do this, they conclude that the potential difference on the open circuit terminals is zero volts because the current is zero amps.

Third, some other students have difficulties connecting different and complementary concepts for correctly analyzing an electric circuit as a system. For example, we observe some students attempt to blindly use different formulas such as voltage divider or current divider for analyzing circuits that do not correspond to those structures. Moreover, some other students interchange electrical variables such as voltage and current, thinking those are the same variable. We observe this situation when those students apply Kirchhoff's laws adding voltages and currents in the same equation.

Summing up, we can state there are three possible causes that bring students difficulties regarding electric circuit's conceptual understanding. They are misconceptions they bring into the classroom, misconceptions they develop during the learning process, and difficulties in connecting different and complementary concepts.

5.3 Concluding remarks

This section describes a summary of the themes that emerged from the different studies and the codebooks. These themes highlight the misconceptions that affect student's understanding of solid-state electronic device circuits. The data analyzed from the three studies consisted of two different solid-state device circuits, one DC circuit analysis, one RC transient circuit analysis, and one analysis of the fundamental solid-state physics materials behavior. The following paragraphs first outline the theme and its respective misconceptions. At the same time, I present the percentage of students who illustrated those specific misunderstandings. It is necessary to highlight that those percentages can be small numbers, but the purpose of this study consists of identifying student's difficulties no matter their frequency or prevalence. Then, some examples of what each misconception or the theme might look like are described. Next, I detail a possible way of student's thinking that can be underlying the theme. In some cases, some possible interventions that can address those issues are illustrated.

The first theme consists of some students have problems differentiating and correctly identifying the different electrical variables, such as voltage, power, and electric current. It can be observed, on different codebooks, that student's work was classified using the codes Confusion of Variables (CV 6.3%), Kirchhoff issues (KI 18.3%), and Current & voltage (C&V 2%). These codes, refer to considering different electric variables as if they were the same. These misconceptions can be observed when the student sums on the same equation or mathematical expression current and voltage. A possible way of thinking behind this misconception set would be that students do not have the emergent system behavior taxonomy (Chi, 2008; Chi et al., 2012). In this case, students can be exposed to reflect on how the different electrical variables are interrelated to override these difficulties.

On another theme, students illustrate previously reported misconceptions regarding the nature of batteries. They consider a battery as a source of constant current instead of a source of constant voltage. The code Current source (CuS 37%) refers to this specific misconception. Regarding this misconception, students describe a change in a circuit does not modify the current a battery provides. Instead, they incorrectly can state that the change affects other circuit elements' electrical variables, such as the power delivered to a resistor connected in parallel to the battery. The underlying behind this theme consists of students do not realize that the variable that a battery keeps constant is the voltage between its terminals. Several researchers (Cheng, 2002; DesPortes et al., 2016; Moreno et al., 2011) have suggested this kind of misconception can be overcome if students face different circuits with complementary elements. Students must compare how those circuits behave and reflect on what variables each circuit element keeps constant. An example of such circuits can be two resistive circuits, one of them fed by a voltage source and the other by a current source. Then those circuits are modified in the same way (e.g., adding another resistor). Finally, both circuits' behaviors are analyzed, compared, and contrasted looking for those electrical variables each element keeps invariant on each circuit.

Another group of students shows new misconceptions not previously informed in the literature. Within these new misconceptions, I highlight students describe batteries as sources of constant power (PoS 22.5%). Here, students state that a change on the circuit does not impact the power delivered by the battery. Even though this misconception is like the previously describe theme, I consider it has a complementary underlying way of thinking. In this case, the way experienced professionals utilize the technical language can be impacting how students understand the concepts. Usually, the lab personnel refer to the sources providing the main amount of energy for circuits to operate as the power sources. Other sources usually are considered signal sources. However, typically both kinds of sources are voltage sources. Thus, I hypothesize the technical language usage can help to develop misunderstanding on students' way of thought. A possible way for controlling this issue can be that instructors are aware of the different modes of language usage, and how, sometimes, this language is used on incongruent and incoherent patterns.

Another misconception regards how students apply Ohm's law. This misconception was observed on all the data sets but the analysis of the fundamental solid-state materials behavior. It mainly consists of students' usage of Ohm's law on circuits where the electric current is zero amps. The related codes to this misconception are Ohm's law issues (Ohm) 5%, Ig issues (Ig) 18%, Open circuit implies 0V(OC0V) 9%, and Open circuit implies a ▲V = 0V (OCD) 2%. Usually, students having this misconception describe there is a non-zero voltage between a resistor's terminals through which there is an electric current of zero amps. Others state the voltage between an open circuit's terminals is zero due to its electric current is zero amps. Within this last example, there are two possible variants. First, some students describe the zero volts is between the output terminals, such as the wall outlet. Second, others mention the zero volts is between the open circuit element equivalent's terminals, such as a diode's terminals operating on the reverse bias. The underlying way of thinking behind this misunderstanding can be students heavily rely on math as the most important model for describing an electric circuit. However, they lose focus on how the whole circuit interacts as a system. This misconception category can have a significant impact on how students analyze solid-state device circuits. Given the nature of some solid-state devices, under certain circumstances, these devices behave like open circuits. A possibility for succeeding over this misconception's category would be to ask students to determine all the electrical variables when they analyze a circuit. Additionally, they must determine how those variables are modified when a change is introduced in the circuit. In this way, they can better understand how the whole circuit is interrelated and operates as a system.

Finally, I consider there are two categories of misconceptions highly related among them. First, a significant number of students applied any formula in an attempt for reaching a sounding numerical answer. We describe this misconception as students blindly use different mathematical expressions. Those math equations usually do not match with the context of the system under analysis. The codes used for this category are Blind 1st order equation (B1o 36%), Blind formula (BF 14%), and Formula issues (FIS 12%). In this category, students try to apply formulas such as voltage divider or current divider into circuits where there is no such configuration. Other example we observe consists of students describing a capacitor voltage under two changes using only one math expression. Second, the last category consists of the misconception that a system analysis can be performed analyzing small and unconnected pieces of information. Codes such as Temp. wrong (Temp-W 21%), Bandgap energy wrong (BGE-W 32%), and Bandgap diagram wrong (D-W 41%) illustrate this specific misconception. Regarding the underlying way of thinking, students can have used the previously describe categories as part of a major issue. This issue would be the lack of understanding that any circuit is a system. Moreover, they also can incorrectly understand how a system works and interacts. For defeating this categories' issues, students must analyze how a system works integrating and interrelating the whole variables set. In this way they can develop the emergent system behavior taxonomy (Chi, 2008; Chi et al., 2012).

As a possible guide for instructors to help students override these and other emergent difficulties, I am describing three very general possible strategies. First, instructors must be aware of the misconceptions identified in this project and other misconceptions that can emerge during the interaction with students. Identifying misconceptions is an iterative process that can be better achieved with the students' help. It is also a key point for resolving student's misunderstandings they can hold or develop.

Second, asking students to reflect on their learning process is another step on going further regarding student's better understanding of the topic. It also contributes to the student's comprehension of their own learning. If students question their own way of learning and identify their used misconceptions on solving problems, they become aware of their own issues and can help themselves to override their difficulties.

Finally, instructors can research tools and strategies that help students to easier understand a specific topic. In such a way, instructors also can encourage students to approach the topic from different perspectives and use different and complementary models for analyzing a particular circuit or situation. Researchers such as Cheng (2002), DesPortes et al. (2016), and Moreno et al. (2011) have explore this strategy with encouraging results.

5.4 Contribution to theory

The findings of this dissertation support conceptual change theories and contribute to the knowledge body of electric circuit misconceptions. Following, I describe three pieces of evidence that link this dissertation's observations with the theory of conceptual change theories. First, we observed students use different misconceptions for analyzing the same circuit. This was more evident from the third study results when students had to answer different questions regarding the same circuit. However, in the second study, we also captured students using multiple misconceptions for analyzing the solid-state device circuits. I consider this can be linked to the pieces' theory (diSessa, 2008). It seems students can behold pieces of information relatively isolated they use for answering specific questions without considering how the circuit operates as a system.

Second, there is evidence that suggests some students do not have or have not developed yet a consistent scientific way of thinking for performing increasing complex analysis. We observe very few students consistently performed a systematic analysis (i.e., an analysis of the circuit as a system) longitudinally along to the three midterms in the third study. Most of the students illustrated misconceptions on at least one of the midterm exams. This observation can be interpreted in the light of coherent theories where students either are using an alternative category for classifying what they are learning or naïve frameworks for analyzing the problems (Chi, 2008; Vosniadou, 2008).

Third, students interact and develop their conceptual thoughts through language. One of the most interesting observations during this journey consists of some students mention a change in a parallel circuit does not impact the delivered power from the source. The limitations of this dissertation do not allow me to claim that this observation is linked on how students use language. However, it seems they could have developed this misconception from the way experts name voltage sources in the lab. If this is the case, this can be linked to the social activity theory that claims a modification on how the language is used contributes to a change in the conceptual structure of student's minds (Säljö, 1999).

Finally, we identified some misconceptions to add to the misconceptions' knowledge regarding the electric circuits' topic. The major misconceptions we identified are 1) students consider that a source can provide constant power, 2) students conceive a capacitor as always operating as an open circuit, and 3) students confound how an open circuit operates with how a short circuit operates.

Summing up, this work has contributed to the body knowledge in the field of engineering education. This contribution consists of two folds. First, it seems the results support what conceptual change theorists have stated. Second, through this dissertation, I have been able to identify new misconceptions regarding electric circuits.

5.5 Future research

I face the task of proposing possible research projects hand in hand with suggesting solutions to the issues I have previously highlighted in this chapter. Following, I describe three research ideas linked to how we can help students override those issues. First, instructional teams must be aware of misconceptions students have and can develop. Instructor-student and student-student interactions are great sources of information for identifying common or new misconceptions. If students actively participate in their knowledge development, they can also identify the misconceptions they are using for analyzing an electric circuit. Then, we can take advantage of the great source of information a classroom allows us to identify emergent misconceptions and confirm the ones found.

Second, designing activities where students can develop a consistent scientific set of tools for analyzing different circuits as systems. For example, educational researchers have designed activities where students must contrast and compare the behavior of two very similar circuits when one of the variables is modified. Others have tried complementary models such as the microscopic and macroscopic scale. Doing so, we can also assess the pedagogical interventions that better fit students' conceptual change.

Finally, instructional teams must be aware of how experts in their discipline use language both formally and informally to perform the tasks they usually do. Within the electrical engineering field, the colloquial use of language usually refers to a physical variable not clearly stated (e.g., the battery is charged usually means that the battery has enough energy, not necessarily electrical charges). Being aware of our own use of language can facilitate how we use it and how we help students to understand the way the academic and professional community uses that language. Moreover, we could research on how instructors, students, practitioners, and other stakeholders use and modify their language to achieve a conceptual change within a specific community.

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