Exploring undergraduate engineering students' conceptual learning of complex circuit concepts in an introductory course

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Abstract - **Some researchers have discussed that despite the implementation of active and engaging learning strategies to the teaching process, students still experience difficulties learning complex circuit concepts. Propositions from the literature credit the difficulty students face when learning circuit concepts to the following factors: 1. pre-conceptions students bring to the classroom which most times lead to the development of misconceptions, 2. the lack of engaging learning environments within which students can interact with the new material being taught, and 3. the difficult and complex nature of electric circuits. This study was designed to investigate how complex circuit concepts such as complex forcing function, phasors and sinusoidal steady-state analysis are taught in an introductory course. The research questions that guided this work were "*What are the instructional strategies used to teach complex circuit concepts in an introductory circuit course? What characteristics are emphasized as important in the learning of complex circuit concepts?*" The results of this study are significant to the field of engineering in that this study contributes to the body of literature on complex circuits and students' conceptual understanding.**

Index Terms – complex circuit concepts, conceptual understanding, instructional design, introductory course

INTRODUCTION

Across the spectrum of engineering, science and mathematics (STEM) education, the case has been made for the use of more innovative ways of teaching. This is aimed at actively engaging students in the learning process for increased achievement gains. Engineering education researchers have suggested, for the last twenty years, the benefits of implementing active learning approaches to engineering learning environments. Additionally, various studies have found the achievement gains have significantly improved when students take a more active role in their own learning [1], [2]. In traditional engineering classes, the mode of instruction is usually of the kind where the students are passive participants in the learning process. The instructor is the "sage on the stage" [3] while students basically go through the motion of listening and taking notes. However, many recommendations have been made to include student-centered activities or active learning environment designs to overcome this status quo. Researchers posit that students learn more when the environment is conducive to their active involvement [4].

Constructivist theorists have purported the learning process should be structured so that students are encouraged to employ real thinking and by extension engage themselves actively in their own learning. The implication for instruction is that the learning environment should be more learner-centered than teacher-centered [5], [6]. With the considerable attention given to active learning, much work has been done through the implementation of a wide array of active learning approaches. For example, problem based models, inquiry-based, cooperative and collaborative learning, various methods of inductive strategies, as well as discovery learning measures [7]. Basically, the main posit of active learning is to increase student participation and engagement through the use of concrete learning activities. The focus of these activities is the construction of knowledge in which students interact with the material and on some level each other.

In addition, an area of concentration has been on the impact learning environment design and the nature of instruction on undergraduate engineering education [8]–[10]. Nevertheless, there is a lack of studies on the design of learning environments in terms of the decisions made about the teaching of complex circuit concepts. Additionally, how these decisions are influenced by students' perceived prior knowledge needs further study. This is an important area to be researched as it helps to uncover the relationship between the techniques used to express information about these circuit concepts and possible barriers to students' understanding.

This work has the ability to explore the alignment of content, the manner in which the content is taught, what characteristics are emphasized as important for conceptual understanding and how great a role students' prior knowledge play in the dissemination of knowledge. This paper focuses on the teaching of complex circuit concepts in a compulsory introductory circuit course using a descriptive case study approach. The research questions that guided this study were:

a. What are the instructional strategies used to teach complex circuit concepts in an introductory circuit course?
b. What characteristics are emphasized as important in the learning of complex circuit concepts?

In this single descriptive case study with multiple embedded units guided by the pedagogical content knowledge (PCK) framework, the context of the learning environment was investigated through direct classroom observations to unearth decisions about how the content is taught.

Perspectives from Literature

The teaching and learning of concepts of an abstract nature such as electricity, often requires the use of varied strategies aimed at encouraging students to engage with the material on a deeper level. In keeping with the need to actively engage students, while helping them to come to an understanding of electric circuits, instructors sometimes feel the need to become creative in their approach to teaching. Numerous studies have been conducted to highlight the necessity of designing learning environments that encourage students to take on active roles in the learning process [11]–[15]. The conceptual change theoretical framework dictates the design of learning environments in which new concepts are introduced in that there should be multiple approaches through which the student has the ability to actively engage with the material [16]. This school of thought is based on the premise that the teaching of abstract difficult concepts should be approached using an active learning strategies. The assumption is that students will more likely recall information with which they had extensive engagement. Vosniadou, Ioannides, Dimitrakopoulou, and Papademetriou [17] suggests "learning environments should support active learning and guide the students towards the acquisition of self-regulated processes" (p. 382). In such a setting, students would be encouraged to construct their own knowledge and skills in learning these concepts by actively navigating their role in the learning process. Consequently, various studies have been conducted into methods of teaching and assessment that can be implemented in engineering learning environments aimed at increasing students' conceptual understanding [2]. The accepted approach to the teaching of any scientific concept is one in which students have more responsibility in the process in order for learning gains to be optimized [1].

The most general approach to learning complex scientific concepts utilizes the constructivist view of learning in designing environments. Researchers [11], [16]–[19] are of the belief that complex scientific concept learning is best achieved in environments that support the use of engaging learning activities, authentic tasks and giving students some level of autonomy over their own learning. These researchers commonly discuss the benefits of having students take ownership of their own learning and constructing meaning for themselves. This, they suggest, motivates students to learn the concept regardless of the perceived difficulty. However, the discussion is now more focused on whether students learn better together or alone or a mixture of both [20]. Along the continuum of active learning activities aimed at increasing students' conceptual learning gains, Chi [2] hypothesized that the most fruitful learning experiences and activities are those in which students interact with each other, material and instructor. According to Pea [22] meaning of concepts is negotiated when members within a community of learners collaboratively "construct common ground beliefs and understandings they share in activity as well as to specify their differences" (p. 268). However, this need of actively including the students in the process of learning can sometimes come at the expense of decreasing student interest in the material and engagement in the activity itself.

Engineering students' ability to learn introductory concepts is very important for their success in becoming experts in their respective disciplines or areas of study. More specifically "to develop competence in an area of inquiry students must have a deep foundation of factual knowledge, understand facts and ideas in the context of a conceptual framework and organize knowledge in ways that facilitate retrieval and application" [8]. The process of learning is characterized "in terms of comprehension, skill acquisition or both" [23, p. 440]. Engineering practice is theorized to consist of three components:

1. engineering as problem-solving, considering the systematic process that engineers use to define and resolve problems
2. engineering as knowledge, considering the specialized knowledge that enables to fuels the process
3. engineering as the integration of process and knowledge [24, p. 429].

In keeping with these three core areas, the root of electrical engineering expertise can be classified as:

a. a working knowledge of basic to complex circuit concepts which is transferred from course to course,
b. advanced mathematical understanding, and
c. the combination of content knowledge and mathematical skills which develops the ability to identify and solve for unknown circuit conditions.

Research however, has indicated students tend to have difficulty understanding these very basic concepts which then becomes problematic when more complex concepts are introduced [25]–[28].

The work of McDermott and Shaffer [28], [29] has been cited as one of the hallmark of research done of investigating difficulty students experience when learning direct current (DC) circuit concepts. Similarly, Bernhard and Carstensen [27] and Streveler et al. [30] have reported that a basic understating of the relationship among various electrical quantities is an important area of difficulty for students. Students tend to have difficulty envisioning quantities such as voltage, current and resistance acting interchangeably in a circuit yet still performing their own task toward the holistic operation of the circuit [31], [32]. In each case the recommendation has been made for the use of specific instructional strategies possessing the ability to help students' overcome these difficulties. This is based on the principle that students are to not only learn these basic introductory concepts but should possess the ability to apply them to more complex contexts such as other courses and the world of engineering practice. This involves the ability to transfer knowledge however it has been discussed that "one's existing knowledge can also make it difficult to learn new information" [8]. Transfer of knowledge is highly dependent on mastery of initial information which involves deep conceptual understanding rather than the memorization of facts. To achieve this deep conceptual understanding the ability to apply what is being taught, sufficient time to process and explore related connections to other concepts as exposure to various means of representation is a necessity [8], [33].

METHODOLOGY

Study Design

This study was conducted using a single descriptive case study with multiple embedded units. The case used was the introductory circuit course with three sections chosen as units of analysis. This approach was chosen as "subunits often add significant opportunities for extensive analysis, enhancing the insights into the single case" [34, p. 56]. To facilitate this in-depth analysis, data were collected in each unit for the same set of topics and each data set were first analyzed separately and then collectively.

Guiding Framework

The pedagogical content knowledge (PCK) as framework is used in research to highlight how knowledge and beliefs held by instructors influence their classroom practice. The premise of this framework is that as instructors blend their own knowledge about specific content and their experiences they tend to present content to their students in the form they believe best enables learning [35]. In addition, instructors use their PCK to determine what concepts are important for emphasis, teaching strategies that are most effective for teaching specific topics and activities necessary to foster conceptual understanding [36].

Study Context

Linear Circuit Analysis I is an introductory 3-credit circuit course compulsory for all undergraduate engineering majors and is a core course for electrical engineering majors at a Midwestern research-intensive university. This course is usually taken by sophomore engineering students. Pre-requisites for this course are ENGR131, PHYS172 and three semesters of calculus one of which can be taken concurrently. The main objectives of this course are to expose students to volt-ampere relationships and characteristics, the development of the ability to analyze first and second order linear resistive circuits with DC and AC sources, as well as being able to compute voltage, current, power and impedance values.

Participants

The participants were the three professors who instructed the sections chosen for the study. The professors' experience ranged from over eight years to one year of teaching the course. In relation to class size, the three sections ranged from large (over 150 students enrolled) to relatively small (60 students enrolled).

Data Collection

Fifteen (15) direct classroom observations, five from each section (unit), were conducted using the Teaching Dimensions Observation Protocol (TDOP) [37]. The TDOP was developed to have a validated observation protocol that can be used to collect information about the various factors leading to decision-making practices such as the teaching of content and specific classroom practices. The protocol consists of six categories namely: teaching methods, pedagogical strategies, cognitive demand, student-teacher interactions, student engagement and instructional technology. Within each category, a set of pre-determined codes were used to record data in two minute intervals. In addition to the codes, detailed notes were made at each interval and an analytic memo written following each observation. The elements of the Teaching Dimensions Observation Protocol (TDOP) [37] used to conduct and code the direct classroom observations for the three units are summarized in table 1.

Data Analysis

The frequency of observed data from each section (unit) were analyzed and reported separately then collectively to demonstrate the similarities and differences between units in answering the research questions.

TABLE 1
TDOP CATEGORIES AND CODES USED FOR DIRECT CLASSROOM OBSERVATIONS

TDOP Observation Protocol Categories and Codes		
Categories	**Codes**	**Definition**
Teaching Methods	L	Lecturing
	LW	Lecturing while writing
	LVIS	Lecturing from pre-made visuals
	WP	Working out problems
	AT	Administrative task
Student-Teacher Dialogue	IRQ	Instructor rhetorical question
	IDQ	Instructor display question
	ICQ	Instructor comprehension question
	SQ	Student question
	SR	Student response to teacher question
Instructional Technology	CB	Chalkboard
	OP	Overhead projector/transparencies
	PP	PowerPoint or other digital slides
	DT	Digital tablet
Pedagogical Strategies	HUM	Humor
	ANEX	Anecdote/example
	ORG	Organization
	EMP	Emphasis
Student Engagement	VHI	Very High (>75%)
	HI	High (between 50 and 75%)
	MED	Medium (between 25 and 50%)
	LO	Low (< 25%)

RESULTS

A. What are the instructional strategies used to teach complex circuit concepts in an introductory circuit course?

In all three units, the most common strategies used to impart knowledge about circuit concepts were lecturing and working problems. This is hardly a surprising finding since lecturing is the most preferred method of instruction in engineering classrooms [38]. The observed structure of the classes entailed the introduction of the topic followed by the corresponding equation then the demonstration of a solved problem related to the concept previously taught. In most cases, students were given alternate approaches to solving the sample problem. These problem-solving methods were related to previous methods taught in the course or prior knowledge the students were expected to have from other courses.

I. Unit one results

From figure 1 it can be seen that a high percentage of the observed sessions were conducted with a heavy reliance on classroom instructional technology and focused on problem-solving. This is evidenced by the 95% of time spent using display tablets (DT), 92% of time spent lecturing from pre-made visuals (LVIS) as well as the 59% and 40% time for overhead projector (OP) and PowerPoint (PP) slides respectively. In addition, 79% of the observed time was attributed to lecturing while writing (LW) and working problems (WP). These two codes, LW and WP, are typically recorded together as a recommendation from the TDOP. The observations uncovered that the classes were highly teacher-focused with very low interaction between students and the instructor. This is confirmed by the low percentage of student-focused dialogue since only 12% of the observed time were student responses (SR) to instructor questions and 3% for student questions (SQ). However, student engagement was very high (VHI) 53% of the observed time. In terms of pedagogy strategies 56% of the observed time was spent emphasizing (EMP) concepts and equation notation.

II. Unit two results

In figure 2 evidence of the vast use of classroom instructional technology is presented by the 99% of observed time in which the professor lectured from pre-made visuals (LVIS). This was also reflected in the combination codes of use of display tablet (DT) 98% of the observed intervals and 73% use of overhead projectors (OP). There was a significant proportion of the observed intervals spent lecturing while writing (LW) shown as 84% and working problems (WP) shown as 57%. This supports the theme that the sessions observed were primarily instructor-focused. In 60% of the observed time the professor would emphasized (EMP) the importance of concepts or equations being covered to either exams or to learn new and upcoming information. Student engagement in this section ranged from very high (VHI) at 42%, high (HI) at 24% and medium (MED) at 31%. This is also evident in the low percentage of student response (SR), 6%, observed.

III. Unit three results

In this particular unit, the primary method of presenting information to the students was by the professor writing on the chalkboard while lecturing. This can be seen from figure 3, the chalkboard (CB) was used 99% of the observed time as well as the 99% frequency of the lecturing while writing (LW) code. Contrary to the other two units, student engagement was significantly higher with very high (VHI) engagement being observed 97% of the time intervals. In addition, there were more observed instances of student questions (SQ) at 38% and student response (SR) at 7%. Another interesting observation was the high level of posed instructor comprehension questions (ICQ) which was observed 63% of the time intervals. This indicates there were more student-instructor dialogue than in the other two units observed. There was also more time spent emphasizing (EMP) concepts at 66% of observed intervals which can be attributed to the increase in the dialogue with the students.

B. What characteristics are emphasized as important in the learning of complex circuit concepts?

One of the core goals of the course is that students develop the necessary knowledge and even more importantly, problem-solving skills, to be successful in their future courses. Consequently, course activities were designed with this in mind. Among the other characteristics

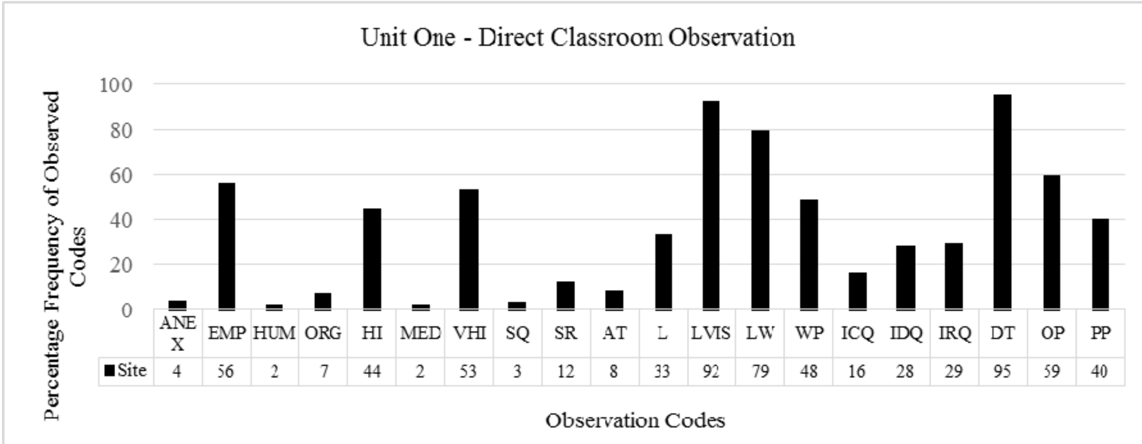

FIGURE I
PERCENTAGE OF OBSERVED CODES FOR UNIT ONE

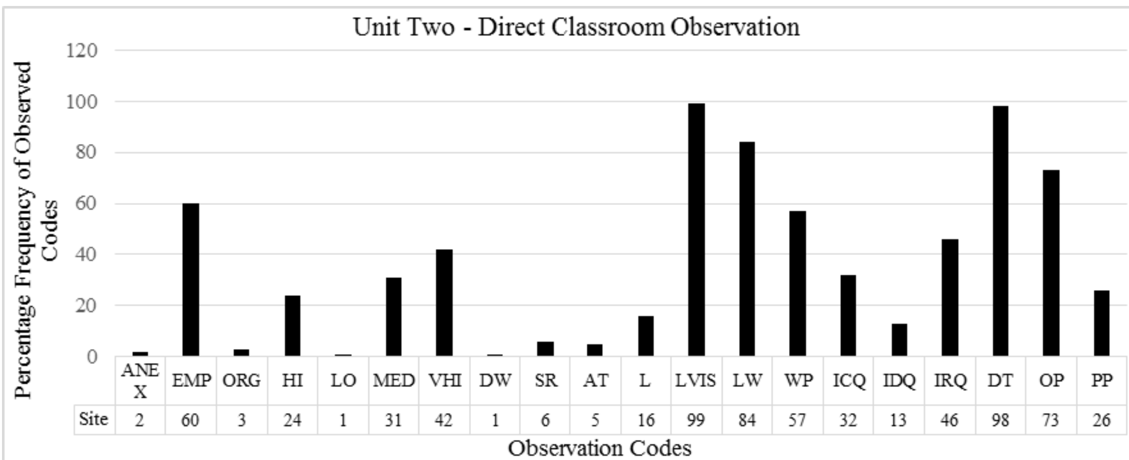

FIGURE II
PERCENTAGE OF OBSERVED CODES FOR UNIT TWO

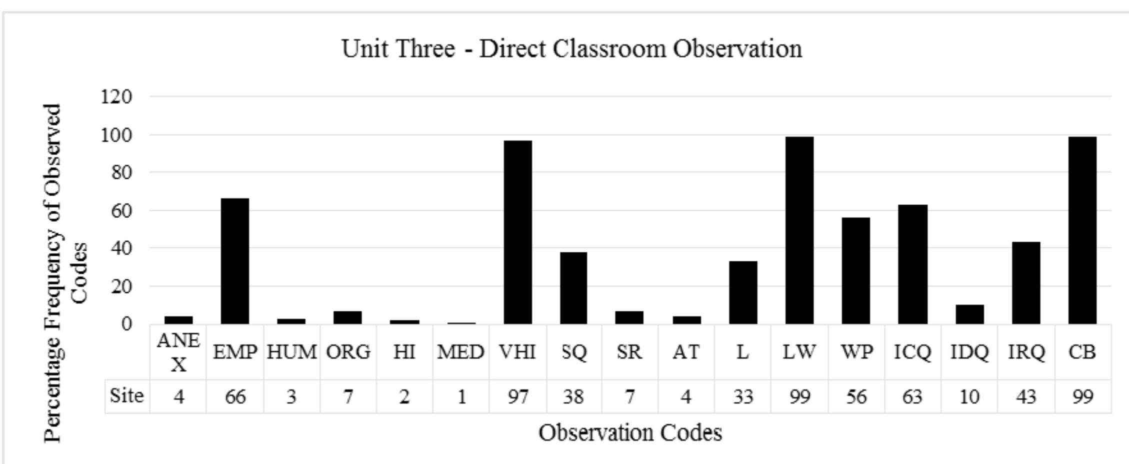

FIGURE III
PERCENTAGE OF OBSERVED CODES FOR UNIT THREE

emphasized was the development of problem-solving skills, being able to transfer their knowledge as they move to higher level courses, using a critical approach to problem-solving and in two of the units, using analogical reasoning. The two concepts discussed as the most important for success in this course were having the relevant pre-requisite knowledge and mathematical thinking and ability. In the course outline students were strongly advised not to enroll in the course until they have successfully passed the requisite physics and mathematics courses. In all three units, the professors accentuated conceptual learning of the content as the intent of the course and not memorization of formula.

To reduce students' tendency to attempt to memorize formula, they were given formula sheets for exams and were encouraged to practice the solution on their own repeatedly.

In table 2, the characteristics the professors discussed as important to the learning of complex concepts are summarized.

TABLE II
SUMMARY OF CHARACTERISTICS EMPHASIZED IN UNITS OF STUDY

Learning approaches	Unit One	Unit Two	Unit Three
Mathematical thinking skills	x	x	x
Importance of pre-requisite knowledge	x	x	x
Importance of repetitive practice	x	x	x
Development of problem-solving skills	x	x	x
Importance of knowledge transfer	x	x	x
Using analogical reasoning	x		x
Critical approach to problem-solving	x	x	x

DISCUSSION

The introductory course used in this study is designed with the intent to help students develop problem solving skills that can be transferred to higher level courses. It was also found that the primary approach to achieve course outcomes was through the derivation and application of mathematical equations. The findings indicate there are various intervening factors that help to determine how this course was designed and concepts taught to the students. It was found that the main emphasis of this course is providing students with the necessary information to develop a structured problem solving process that can be applied to the different circuit configurations. Deliberate repeated practice was strongly encouraged as a mean of ensuring the students not only understood the content of the class but most importantly for achieving a good grade on exams. A third major finding was the heavy reliance on mathematical knowledge and skills that was deemed necessary if the students were going to be successful in the course. All the professors discussed students would experience difficulty when they attempt to learn these concepts if, they lacked this prior knowledge or their understanding of these very core concepts was insufficient. This perceived inadequate prior knowledge then becomes problematic when professors attempt to use mathematical representation to convey information about the abstract concepts covered in the class.

The use of analogical reasoning, comparative language, mathematical proofs for equation derivation and graphical representation of concepts were all common components among the three units. It was found that analogies present the opportunity to discuss and represent abstract concept while having significant impact on students learning. The findings supported the use of these processes to convey knowledge about circuit concepts. Most commonly was the emphasis on the importance of having acquired mathematical skills and the ability to appropriately select and manipulate complex formulas. The nature of the content dictates this reliance on the use of mathematical models and graphical representation. There was a heavy and repeated emphasis on having the necessary mathematical experience in order to be successful in learning the content. Contrary to the findings of the studies, research has recommended an approach to the teaching of complex scientific concepts that equally recognizes the importance of mathematical, graphical and qualitative methods to disseminating knowledge.

Problem solving through the use of varied strategies was another aspect of information dissemination that was evident. The focus of introductory circuit courses is described as the means by which electrical engineering students develop the ability to troubleshoot, identify and solve required circuit parameters. Additionally, it was observed that a large percentage of the class sessions were spent working problems. Professors would show students alternate approaches to solving the problem however, the process of working problems used in the class was discussed as similar to what students would face on exams was one of the main approaches to teaching content.

The nonexistence of qualitative discussion and explanation of the assumed relationship between concepts was quite evident. Qualitative discussions should also be seen as a method of conveying knowledge that is of equivalent levels of prominence. The work of Johnstone [39] and Licht [40] speak to the significance of having an equal balance between the use of quantitative reasoning, graphical representations and qualitative discussions. Johnstone [39] suggests the design of learning experience which takes into consideration the alignment and importance of macro (tangible and visible) discussions about concepts, micro (the invisible represented by illustrations) and symbolics (use of mathematical formulas and equations).

CONCLUSION

The goal of this study was to describe how complex concepts are taught to engineering students enrolled in an introductory circuit course. From the findings it has been discussed that while the ideal situation is one which qualitative discussion, quantitative reasoning and visual representations hold equal sway, there tend to be a dominance on appealing to students' mathematical knowledge. These findings are supported by Vosniadou and Verschaffel [41] in relation to how instruction should be designed to incorporate the use of methods to help students develop an exploratory framework for the concept. Another key finding was that while the main goal of the course was to help students develop problem solving skills that can be transferred to more complex courses, students were assessed through the use of multiple choice items on exams. This indicates a misalignment between the goals of the course and the manner in which the course is designed and subsequently executed. The use of varied methods of assessment is discussed in the work of Svinicki [42] and Hansen [43]. There was no instance where students' mastery of this skill was evaluated beyond their ability to solve and select the correct answer on an exam. In addition, it was found students were not exposed to the open-ended problems they might encounter when they move beyond the classroom setting

A balanced approach such as the Lesh Translation Model (LTM) [44], [45], illustrated in figure 4, utilizes multiple representations of concepts that can have significant impact on students overall learning. Using this model allows instructors the ability help students understand complex concepts using a variety of representations. It is also theorized that by having students engage in the process of creating these various representations, for example drawing a schematic diagram of a circuit first, then representing that same circuit in a pictorial or layout diagram, has the power to strongly influence their learning. As students work on creating these different representations or are instructed using this model, they are being providing the opportunity to think about the concept in different ways as well as to develop an understanding of the underlying principles associated with the concept being studied.

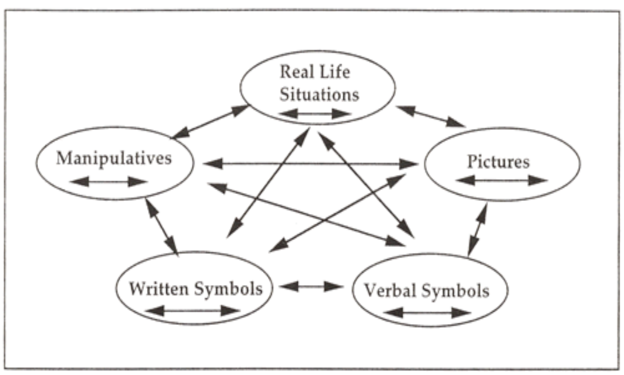

FIGURE IV
THE LESH TRANSLATIONAL MODEL [45, P.449]

This is an ongoing study. Since this paper we have interviewed the professors who taught the course sections that were observed, collected course documents such as lecture notes and course syllabi. In addition, we conducted a second set of observations in another semester. Our goal is to conduct a cross-case analysis using data from two different semesters (Fall the "on" semester for EE majors and Spring where the course is usually taken by non-EE majors). The focus of this work was not to assess student learning and achievement, instead we wished to study the pedagogical strategies used to teach these complex concepts and the decisions made by professors about concepts deemed important for emphasis. It was our intent to highlight differences in how professors communicate knowledge to the students as well changes in the learning environment. Another area for future study could be a replication of this descriptive case study in more complex courses using the same methods of data collection and guiding framework. This approach would provide interesting information on the similarity or difference in decisions made about the teaching of introductory and complex courses. Also, additional data could be collected to gauge student perception of content and learning environment design as well as student learning outcomes.

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REFERENCES

[1] K. A. Smith, S. D. Sheppard, D. W. Johnson, and R. T. Johnson, "Pedagogies of engagement: Classroom-based practices," *J. Eng. Educ.*, vol. 94, no. 1, pp. 87–101, 2005.

[2] M. T. H. Chi, "Active-Constructive-Interactive: A conceptual framework for differentiating learning activities," *Top. Cogn. Sci.*, vol. 1, pp. 73–105, 2009.

[3] P. Resta and T. Laferriere, "Technology in support of collaborative learning," *Educ. Psychol. Rev.*, vol. 19, pp. 65–83, 2007.

[4] R. J. Roselli and S. P. Brophy, "Experiences with formative assessment in engineering classrooms," *J. Eng. Educ.*, vol. 95, no. 4, pp. 325–333, 2006.

[5] J. Michael, "Where's the evidence that active learning works?," *Adv. Physiol. Educ.*, vol. 30, pp. 159–167, 2006.

[6] M. J. Prince and R. M. Felder, "Inductive teaching and learning methods: Definitions, comparisons, and research bases," *J. Eng. Educ.*, vol. 96, no. 2, pp. 123–138, 2006.

[7] M. Menekse, G. S. Stump, S. Krause, and M. T. H. Chi, "Differentiated overt learning activities for effective instruction in engineering classrooms," *J. Eng. Educ.*, vol. 102, no. 3, pp. 346–374, 2013.

[8] National Research Council, *How People Learn: Brain, Mind, Experience, and School. Expanded Edition*. Washington, DC: National Academies Press, 2000.

[9] National Research Council, *Reaching Students: What Research Says About Effective Instruction In Undergraduate Science and Engineering*. Washington, DC: National Academies Press, 2014.

[10] National Research Council, *Discipline Based Education Research: Understanding and Improving Learning in Undergraduate Science and Engineering*. Washington, DC: National Academies Press, 2012.

[11] R. Driver, H. Asoko, J. Leach, P. Scott, and E. Mortimer, "Constructing scientific knowledge in the classroom," *Educ. Res.*, vol. 23, no. 5, pp. 5–12, Oct. 1994.

[12] R. Anderson, R. Anderson, K. M. Davis, N. Linnell, C. Prince, and V. Razmov, "Supporting active learning and example based instruction with classroom technology," *ACM SIGCSE Bull.*, vol. 39, no. 1, p. 69, 2007.

[13] Z. Zacharia and O. R. Anderson, "The effects of an interactive computer-based simulation prior to performing a laboratory inquiry-based experiment on students' conceptual understanding of physics," *Am. J. Phys.*, vol. 71, no. 6, p. 618, 2003.

[14] M. Prince, "Does active learning work? A review of the research," *J. Eng. Educ.*, vol. 93, no. 3, pp. 223–231, 2004.

[15] R. M. Felder, D. R. Woods, J. E. Stice, and A. Rugarcia, “The future of engineering education II teaching methods that work,” *Chem. Eng. Educ.*, vol. 34, no. 1, pp. 26–39, 2000.

[16] C. Dede, M. C. Salzman, R. B. Loftin, and D. Sprague, “Multisensory immersion as a modeling environment for learning complex scientific concepts,” *Comput. Model. Simul. Sci. Educ.*, 1999.

[17] S. Vosniadou, C. Ioannides, A. Dimitrakopoulou, and E. Papademetriou, “Designing learning environments to promote conceptual change in science,” *Learn. Instr.*, vol. 11, no. 4–5, pp. 381–419, 2001.

[18] E. L. Smith, T. D. Blakeslee, and C. W. Anderson, “Teaching strategies associated with conceptual change learning in Science,” *J. Res. Sci. Teach.*, vol. 30, no. 2, pp. 111–126, 1993.

[19] C. Chin, “Teacher questioning in science classrooms: Approaches that stimulate productive thinking,” *J. Res. Sci. Teach.*, vol. 44, no. 6, pp. 815–843, 2007.

[20] E. Alfonseca, R. M. Carro, E. Martín, A. Ortigosa, and P. Paredes, “The impact of learning styles on student grouping for collaborative learning: A case study,” *User Model. User-adapt. Interact.*, vol. 16, no. 3–4, pp. 377–401, 2006.

[21] R. Pea, “Learning scientific concepts through materials and social activities,” *Educational Psychologist*, vol. 28, no. 3. pp. 265–277, 1993.

[22] M. T. H. Chi, N. De Leeuw, M.-H. Chiu, and C. Lavancher, “Eliciting self-explanations improves understanding,” *Cogn. Sci.*, vol. 18, no. 3, pp. 439–477, 1994.

[23] S. D. Sheppard, K. Macatangay, A. Cobly, and W. M. Sullivan, “The new century engineer,” *Educating Engineers: Designing for the Future of the Field*. pp. 2–227, 2008.

[24] D. Holton, A. Verma, and G. Biswas, “Assessing student difficulties in understanding the behavior of AC and DC circuits,” *ASEE Annu. Conf. Expo.*, p. 16, 2008.

[25] G. Biswas, D. L. Schwartz, B. Bhuva, J. Bransford, D. Holton, A. Verma, and J. Pfaffman, “Assessing problem solving skills in understanding and troubleshooting AC circuits,” vol. 298, no. 0704, pp. 1–39, 2001.

[26] G. Biswas, D. L. Schwartz, S. Brophy, B. Bhuva, T. Blanc, and J. Bransford, “Combining mathematical and everyday models of electricity,” in *Cognitive Science Society*, 1997.

[27] J. Bernhard and A.-K. Carstensen, “Learning and teaching electrical circuit theory,” *PTEE 2002 Phys. Teach. Eng. Educ.*, pp. 163–178, 2002.

[28] L. C. McDermott and P. S. Shaffer, “Research as a guide for curriculum development: An example from introductory electricity. Part I: Investigation of students understanding,” *Am. J. Phys.*, vol. 60, no. 11. pp. 994–1013, 1992.

[29] P. S. Shaffer and L. C. McDermott, “Research as a guide for curriculum development: An example from introductory electricity. Part II: Design of instructional strategies,” *Am. J. Phys.*, vol. 60, no. 11, pp. 1003 – 1013, 1992.

[30] R. A. Streveler, T. A. Litzinger, R. L. Miller, and P. S. Steif, “Learning conceptual knowledge in the engineering sciences: Overview and future research directions,” *J. Eng. Educ.*, vol. 97, no. 3, pp. 279–294, 2008.

[31] V. Picciarelli, M. Di Gennaro, R. Stella, and E. Conte, “A study of university students’ snderstanding of simple electric circuits part 2: Batteries, ohm's law, power Dissipated, resistors in parallel,” *Eur. J. Eng. Educ.*, vol. 16, no. 1, pp. 57–71, 1991.

[32] V. Picciarelli, M. Di Gennaro, R. Stella, and E. Conte, “A study of university students’ understanding of simple electric circuits part 1: Current in d.c. circuits,” *Eur. J. Eng. Educ.*, vol. 16, no. 1, pp. 41–56, 1991.

[33] R. W. Bybee and Ebrary, Inc, *Learning Science and the Science of Learning: Science Educators’ Essay Collection*. Arlington, VA: NSTA Press, 2002.

[34] R. K. Yin, *Case Study Research, Design and Methods*, 4th ed. Thousand Oaks, CA: SAGE Publications Inc., 2009.

[35] S. Magnusson, J. Krajcik, and H. Borko, “Nature, sources and development of pedagogical content knowledge for science teaching,” in *PCK and Science Education*, J. Gess-Newsome and N. G. Lederman, Eds. Netherlands: Kluwer Academic Publishers, 1999, pp. 95–161.

[36] M. L. Miller, “Pedagogical content knowledge,” in *Theoretical Frameworks for Research in Chemistry/Science Education*, G. M. Bodner and M. Orgill, Eds. New Jersey: Prentice Hall, 2007, pp. 86 – 102.

[37] M. Hora and J. Ferrare, “The Teaching Dimensions Observation Protocol (TDOP) 2.0,” Madison, WI, 2014.

[38] M. Borrego and J. Bernhard, “The Emergence of Engineering Education Research as an Internationally Connected Field of Inquiry,” *J. Eng. Educ.*, vol. 100, no. 1, pp. 14–47, 2011.

[39] A. H. Johnstone, “Why is science difficult to learn? Things are seldom what they seem,” *J. Comput. Assist. Learn.*, vol. 7, pp. 75–83, 1991.

[40] P. Licht, “Teaching Electrical Energy, Voltage and Current: An Alternative Approach,” *Phys. Educ.*, vol. 26, no. 5, pp. 272–277, 1991.

[41] S. Vosniadou and L. Verschaffel, “Extending the conceptual change approach to mathematics learning and teaching,” *Learn. Instr.*, vol. 14, no. 5, pp. 445–451, 2004.

[42] M. D. Svinicki, *Learning and Motivation in the Post Secondary Classroom*. Bolton, MA: Anker Publishing Company Inc., 2004.

[43] E. J. Hansen, *Idea-based Learning: A Course Design Process to Promote Conceptual Understanding*, 1st ed. Sterking, VA: Stylus, 2011.

[44] T. J. Moore, R. L. Miller, R. a Lesh, M. S. Stohlmann, and Y. R. Kim, “Modeling in Engineering: The Role of Representational Fluency in Students’ Conceptual Understanding.,” *J. Eng. Educ.*, vol. 102, no. 1, pp. 141–178, 2013.

[45] R. Lesh and H. M. Doerr, Eds., *Beyond Constructivism: Models and Modeling Perspectives on Mathematics Problem Solving, Learning, and Teaching*. Mahwah, New Jersey: Lawrence Erlbaum Associates, 2003.