Teaching Circuit Concepts Using Evidence-based Instructional Approaches: A Systematic Review

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Abstract

An educational strategy is evidence-based if objective evidence is used to inform the design of an academic program or guide the instructional practices. Studies show that the unsatisfactory performance of engineering graduates in competency-based examinations is due to a mismatch between teacher expectations and student learning. Since traditional lecturing is the most commonly used format for course delivery in electrical circuit courses, teaching and learning of abstract concepts such as electricity require the use of varied and efficient strategies aimed at encouraging students to engage with the material on a deeper level. In keeping with the need to actively engage the students while helping them understand electric circuits, instructors need to be creative and effective in their approach to teaching. The purpose of this systematic review is to survey and investigate the current research on evidence-based instructional practices (EBIPs) being done in teaching electrical circuits across undergraduate engineering education and science fields. We explore previous work on using EBIPs as an effective approach to teaching electrical circuits by trying to answer the questions "What evidence-based instructional practices have been reported to have the most impact on students' learning of circuit concepts? How are these practices implemented in engineering learning environments?" Also, common issues with the implementation of these strategies and continuous improvements were identified. Finally, a synthesis has been highlighted in this review that intends to provide a learner-centered, cognitive, flexible and varied approach to teaching electrical circuits with the use of existing instructional practices based on evidence of effective student learning.

Keywords: electrical engineering, circuit concepts, evidence-based instruction

Introduction

What is evidence-based practice?

A popular term in education, "evidence-based" refers to any strategy that is derived from or informed by educational research or any form of metrics of school, teacher, and student performance. Data-based, research-based, and scientifically based are also widely used modifiers when the evidence comprises largely or entirely of data used in or informed by educational research, or scientific findings. Simply put, an educational strategy is evidence-based if objective evidence is used to inform the design of an academic program or guide the instructional practices [1].

According to the International Reading Association (IRA), evidence-based instruction as an instructional practice is developed based on empirical research that has been found to be successful. In a sense, it is scientifically based on facts that are considered reliable indicators of effectiveness [2]. Moreover, educators' individual experiences resulting in professional wisdom can be a source of evidence as well [3]. Evidence-based instruction has five characteristics of evidence: objective and reliable (consistent collection and interpretation of data), valid

(adequately represented data), systematic (data derived from the rigorous design of observation and experimentation) and refereed (approved and reviewed data) [2].

Evidence-based practice started to emerge during the evidence-based medicine movement in England in the 1960s and a collaborative initiative to review the literature on medical practices based on scientific evidence. The Coalition for Evidence-based Policy suggests that in order to help evidence-driven progress in education, practitioners must effectively draw on objective evidence [4]. According to Groccia and Buskist, evidence-based teaching is:

> *"the conscientious, explicit, and judicious integration of best available research on teaching technique and expertise within the context of student, teacher, department, college, university, and community characteristics."* (p.8)

Moreover, evidence-based instructional practice (EBIP) is often referred to as pedagogical approaches or teaching methodologies that have proven successes over time in terms of student learning outcomes [5].

Evidence-based instructional practice in engineering

Several pieces of evidence show that the unsatisfactory performance of engineering graduates in competency-based examinations is due to a mismatch between teacher expectations and student learning. Groccia and Buskist argue that engineering faculty should play as experts of the discipline they are teaching and not just become course designers or teachers [5], [6]; carefully examining the issue from the perspective of the faculty and the pedagogical strategies they used. Moreover, to strike a balance between teaching and learning, instructional practices should be approached as both a systematic manner to be content-oriented in delivering knowledge to students and to be learning oriented or student-focused to facilitate the construction of knowledge among students. Hence, forming evidence of effectiveness in teaching and learning that can be integrated into instructional practices [7]. Traditional lecturing is the most commonly used format for course delivery in electrical circuit courses. However, in the emergence of new instructional approaches, its effectiveness has been called into question by several researchers in the field of engineering education due to lack of opportunities for the students to have active responsibility on the course itself, despite the huge amount of content delivered in a definite amount of time [8].

The teaching and learning of an abstract concept such as *electricity* often require 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 the students while helping them understand *electric circuits*, instructors need to be creative and effective in their approach to teaching. Numerous studies have been conducted that show evidence to highlight the necessity of designing learning environments that encourage students to take on active roles in the learning process [8], [9]. Additionally, the theoretical framework for conceptual change dictates the design of learning environments, wherein new concepts are introduced, provide multiple approaches through which students can actively engage with the material. This school of thought is based on the premise

that teaching of difficult abstract concepts should be tackled from an active learning framework as students are more likely to recall information if they take extensive engagement. Some scholars also posit learning environments should support active learning and guide the students towards the acquisition of self-regulated processes [10], [11]. In such a setting, students would, therefore, be encouraged to construct their own knowledge and skills by actively navigating their role in learning these concepts [12].

The purpose of this review is to survey and investigate the current researches on evidence-based instructional practices being done in teaching electrical circuits across engineering and sciences education field. A systematic literature review requires a more thorough and comprehensive procedure in synthesizing previous works when compared to traditional literature reviews. According to Borrego et al., a systematic literature review intends to open opportunities to discover areas in previous works that will try to provide various perspectives in answering the research questions, to summarize agreeing or contradicting issues on the subject matter found in the previous studies, and to highlight gaps and rooms for improvement that call for further studies [13]. This systematic literature review intends to address the questions:

- *What evidence-based instructional practices have been reported to have the most impact on students' learning of circuit concepts?*
- *How are these practices implemented in engineering learning environments?*

Particularly, this systematic review of literature will seek to investigate the types of evidence-based instructional practices (EBIPs) used to teach circuit concepts, their reported benefits, and which practices instructors can implement in their classrooms to improve learning of these concepts among students.

Method

A step-by-step framework of systematic research synthesis proposed by Cooper will be used in the search of past studies and the actual presentation of findings [14]. This framework follows the steps: formulating the problem, searching the literature, gathering information from studies, evaluating the quality of studies, analyzing and integrating the outcomes of studies, interpreting the evidence and presenting the results. In addition, Borrego et al. [13] propose a framework containing six steps in conducting systematic literature reviews in engineering education, namely: deciding to do a systematic review, identifying the scope and research questions, defining inclusion criteria, finding and cataloging sources, critique and appraisal, and synthesis. This study will use both the abovementioned frameworks as a guideline to systematically answer the research questions, similar to the method used by Pitterson and Streveler [15]. These frameworks will be used to examine prior studies that emphasize on EBIPs in terms of interactive engagement, formative feedback, and constructive alignment used to facilitate learning, and the use of EBIPs in teaching and assessment in engineering learning environments aimed at increasing students' conceptual understanding. These studies will be selected based on a pre-determined criterion involving the types of EBIPs used in circuit courses, and reports of assessment of students' learning of these EBIPs. The data extracted from the literature will be analyzed and the results discussed based on what EBIPs are reported to be more favorable among researchers in enhancing students' knowledge of electric circuits. The barriers to their

implementation will also be discussed. Finally, the researchers will propose a model that can be used in circuits courses that encompasses the strengths and weaknesses of each EBIP for optimal student learning.

Formulating the problem

This study intends to explore previous work on using EBIPs as an effective approach to teach electrical circuits and so, these research questions have been developed "What evidence-based instructional practices have been reported to have the most impact on students' learning of circuit concepts? How are these practices implemented in engineering learning environments?" Moreover, this study will be looking at the successes of the evidence used to facilitate more effective learning among engineering students, and how these pieces of evidence became the basis for designing instructional approaches in teaching circuit concepts.

Searching the literature

A comprehensive search was conducted using the Virginia Tech university library portal powered by Discovery Search using the keywords: *"evidence-based", AND instructional practices, AND "engineering OR physics OR sciences" AND "electrical OR circuits", AND undergraduate*. The use of boolean operators in the keywords was based upon the steps in undertaking a literature review by Cronin et al. [16]. Google Scholar was also used to compare the search results using the keywords set with Discovery Search and the search results turned out to be comparable. However, refining the search via Google Scholar was difficult, for instance, when showing the peer-reviewed articles only. So, to capture the most related and recent works, Discovery Advanced Search filter was used to refine the search based on:

- English language
- Books, conference, dissertation/thesis, and journal articles
- Engineering, physics, and sciences
- Peer-reviewed papers

The summary of the search is shown in Table 1.

Table 1. Summary of keyword and database search

Keywords used	Filter	Search results
"evidence-based" AND "instructional practices"	None	**317,414**
"evidence-based" AND "instructional practices"	✓ Book ✓ Conference ✓ Dissertation/Thesis ✓ Journal ✓ Peer-reviewed	**180,924**
"evidence-based" AND "instructional practices" AND "engineering OR physics OR sciences"	✓ Book ✓ Conference ✓ Dissertation/Thesis ✓ Journal ✓ Peer-reviewed ✓ English	**7,777**

"evidence-based" AND instructional practices AND "engineering OR physics OR sciences" AND "electrical OR circuits"	✓ Book ✓ Conference ✓ Dissertation/Thesis ✓ Journal ✓ Peer-reviewed ✓ English	**423**
"evidence-based" AND instructional practices AND "engineering OR physics OR sciences" AND "electrical OR circuits" AND 'undergraduate"	✓ Book ✓ Conference ✓ Dissertation/Thesis ✓ Journal ✓ Peer-reviewed ✓ English	**24**

It was our intention to include the keyword "evidence-based" to survey previous studies that defined and used this term quite similarly with how we described it in this review. We believe that this step was not a limitation to the scope of our research because we included the key phrase "instructional practices" in our literature search as well. In turn, this returned search results of instructional approaches that are evidence-based but are presented in various forms and names.

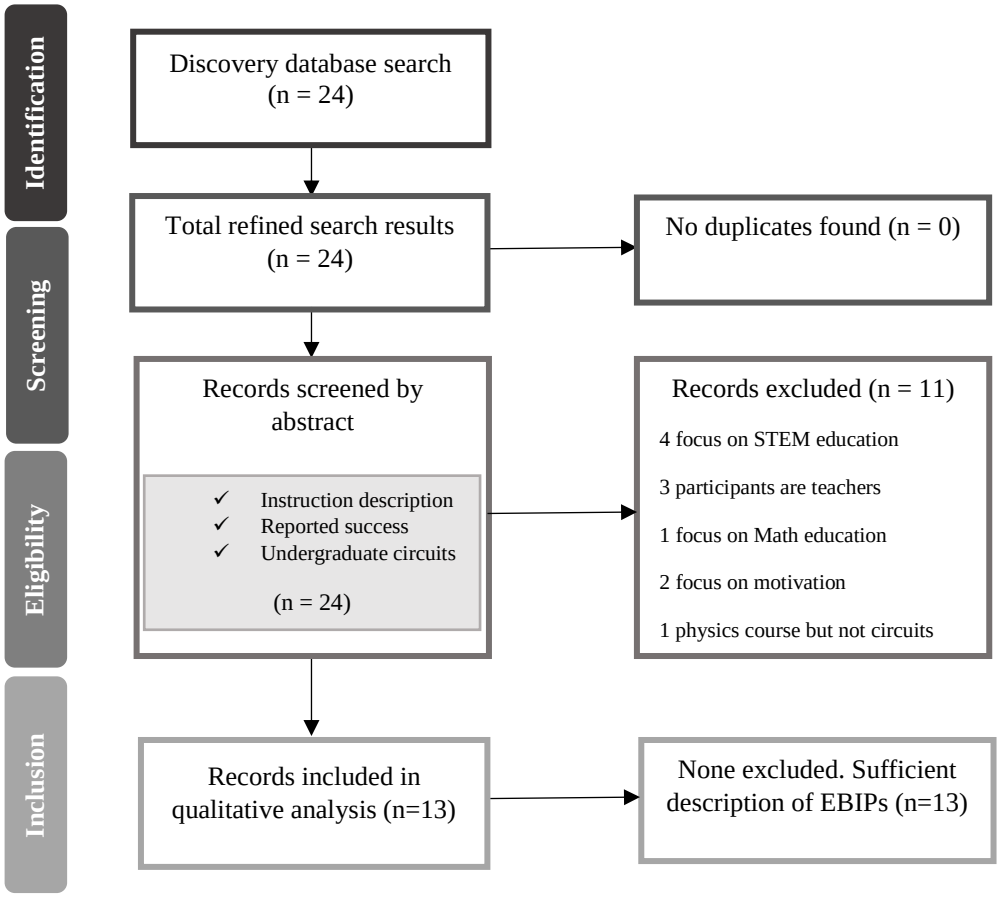

Figure 1. PRISMA flowchart [17]

After applying all the keywords and filters, the refined search results returned 24 articles. The abstracts and findings of the remaining papers were evaluated. A flowchart based on the PRISMA model [17] by Moher et al. , as shown in Figure 1, was constructed to guide the final

stage of inclusion/exclusion which follows the identification, screening, eligibility, and inclusion processes. A set of criteria was used for the inclusion/exclusion process of the 24 articles returned by the refined search. The criteria used were as follows:

- Description of the instruction used
- A reported measure of success/improvement in learning with the use of instructional practice
- Undergraduate circuit course (engineering or science focus)

Thirteen (13) papers were selected after the final phase of the inclusion/exclusion process guided by the PRISMA model. These records will be used for the final analysis and synthesis.

Gathering information from and evaluating the quality of the studies

This systematic literature review was conducted to investigate various existing instructional practices that are based on evidence of successes, as well as increased student learning in teaching circuit concepts. After applying the criteria for the literature search, data extraction process was established. The search ensured that the chosen studies were peer-reviewed dissertation, theses, conferences, reports, and journals. The instructional practices identified from the gathered literature were categorized as strategies used in teaching electrical circuit concepts based on student learning as manifested in their active roles and class engagement. These findings serve as indicators of success that will be classified as the evidence itself in EBIPs. Based on Cronin's work in undertaking literature review [16], studies obtained from the refined search according to the title of the paper, author/s, source and year for the first pass of literature search will be gathered.

Analyzing and integrating the outcomes of the studies

A thematic analysis was conducted for the initial search results. From the first pass of the literature search, the abstract and the findings were scanned and analyzed to ensure that the strategies used in the study comprise an evidence-based practice. After the second iteration of the inclusion/exclusion process, additional field columns in the table were created for the instructional practice used and major findings of the study (as shown in Table 2). This two additional information will help the researchers address the research questions set for this study in terms of investigating how these practices were implemented and identifying the most beneficial instructional practice towards students' learning of circuit concepts.

Interpreting the evidence and presenting the results

The idea behind EBIPs as an instructional strategy will be used to interpret the major findings of the gathered literature. Thus, as previously mentioned, the researchers investigated that the teaching strategies implemented in these studies were analyzed to make sure that at least one evidence of success has been seen to be exhibited. That means, there has been an improvement in learning circuit concepts among students. From this analysis, the researchers will come up with a theme or a framework to give an integrated representation of the most impactful EBIPs used to teach circuit theories and concepts to undergraduate engineering students.

Table 2 Summary of the literature search for final analysis

Title	Author/s	Source	Year	EBIPs used	**Major findings** (abstract excerpt)
Optimizing worked-example instruction in electrical engineering: The role of fading and feedback during problem-solving practice [18]	R. Moreno, M. Reisslein, G. Ozogul	Journal of Engineering Education	2009	Fading and feedback in problem-solving	"First, students who practiced by solving all problem steps and those who practiced by solving a gradually increasing number of steps starting with the first step first (forward-fading practice) produced higher near-transfer scores than those who were asked to solve a gradually increasing number of steps but starting with the last step first (backward-fading practice). Second, students who received feedback immediately after attempting each problem-solving step outperformed those who received total feedback on near transfer. Finally, students who learned with backward-fading practice produced higher near-and far-transfer scores when feedback included the solution of a similar worked-out problem."
Conceptual understanding of electrical circuits in secondary vocational engineering education: combining traditional instruction with inquiry learning in a virtual lab [19]	B. Kollöffel, T. de Jong	Journal of Engineering Education	2013	Lecture and inquiry learning in a virtual lab	"Results showed that students in the virtual lab condition scored significantly higher on conceptual understanding (Cohen's d50.65) and on procedural skills (d50.76). In particular, students in this condition scored higher (d51.19) in solving complex problems. This result occurred for both complex conceptual and procedural problems. Since students in the virtual lab condition acquired better conceptual understanding and also developed better procedural skills than students in the traditional condition, it appears that conceptual understanding and procedural skills develop in an iterative fashion."
Problem-based learning: influence on students' learning in an electrical engineering course [20]	A. Yadav, D. Subedi, M.A. Lundeberg	Journal of Engineering Education	2011	Problem-based learning	"Results suggested participants' learning gains from PBL were twice their gains from traditional lecture. Even though students learned more from PBL, students thought they learned more from traditional lecture. We discuss these findings and offer implications for faculty interested in implementing PBL. Given the limited research on the beneficial effects of PBL on student learning, this study provides empirical support for PBL. We discuss findings from this study and provide specific implications for faculty and researchers interested in problem-based learning in engineering."
An expanded study to assess the effect of online homework on student learning in a first circuits course [21]	K. Evans, P. Hummel, M. Gates	ASEE Conference	2016	Supplementary learning (online homework-based)	"The results suggest that the online homework, administered through the open-source WeBWorK, is at least comparable to paper homework for student learning. This is consistent with what other studies involving online homework in mathematics have revealed. Finally, the authors are looking to implement WeBWorK in higher level electrical engineering courses, so future educational studies to assess the impact of online homework on student learning in these courses will likely occur."
Comparison of traditional, flipped, and hybrid teaching methods in an electrical engineering circuit analysis course [22]	F. Kaleem, D.W. Jacobson, F. Khan	ASEE Conference	2016	Traditional, flipped, and hybrid	"A highly significant majority of students would not be interested in a Take-Home Hands-on Lab if they were offered the choice. Almost 2/3 of the respondents would not take an online section of the course if it were offered with a Take-Home, Hands-on Self Learning Kit. There was overall a greater level of confidence in performing various tasks by those in the hybrid and traditional sections than in the flipped classroom section. In particular, there was statistically significantly greater confidence for the following tasks: Understanding what the purpose or function of a presented circuit is. Building a circuit by choosing a set of resistors, capacitors and/or inductors based upon the results of design calculations. Students in the hybrid and traditional sections also had a much greater positive perception of the overall class quality in providing knowledge of circuits than the flipped

Title	Author/s	Source	Year	EBIPs used	**Major findings** (abstract excerpt)
					classroom section. The negative feelings in the flipped classroom section were primarily due to two factors: Pre-recorded lectures were too long. It required too much extra work to watch the pre-recorded lectures.”
Passive circuits for active learning revisited [23]	S.L. Post	ASEE Conference	2014	Real experimentation in the lab	“The decision was made to use the lead wires with alligator clips to make free-form circuits because it was believed this would help the students visualize the circuits and also because of the lower cost. Breadboards were used in the laboratories, and it was observed that students had difficulty visualizing the physical connections in the breadboards. In the course evaluations, students generally commented that the course was improved from what they had heard about the previous offerings with lectures without the active learning activities. Some of the more advanced students in the class complained that there were too many simple circuits that focused on Ohm’s law and they wanted to do some actual design of electronics. A design project would be a valuable addition to the class in the future. Since the instructor was on sabbatical and only taught the course once, there was not the opportunity to conduct assessments on student learning with the old and new versions of the course. Assessment of student learning outcomes would be a valuable addition to the literature.”
Improve learning efficiency with integrated math and circuit simulation tools in electrical and computer engineering courses [24]	C. Campbell, F. Saffih, K. Nigim	ASEE Conference	2006	Virtual experimentation	“This paper presents coupling the use of the TINA circuit simulation software with the Mathcad mathematical software. This coupling permits students to simply (1) enter a circuit in TINA diagrammatically, (2) export its symbolic solution y(t), or its transfer function, Y(s), to a Mathcad file, and (3) plot these solutions for multiple values of a parameter (e.g. R) on a 2-D or 3-D graph. The symbolic solutions and plots enhance understanding of both the physical and the mathematical foundations of the studied cases.”
Students' interest in their misconceptions in first-year electrical circuits and mathematics courses [25]	S. Bull, T.J. Jackson, M.J. Lancaster	International Journal of Electrical Engineering Education	2010	Computer-based feedbacking	“It was found that many first-year students held misconceptions in introductory electrical circuits and mathematics courses at some stage of their learning, and most viewed information about their misconceptions to assist them in identifying their problems. We suggest, therefore, that an approach of highlighting an individual's misconceptions can be found useful by students to help them recognize their knowledge, difficulties, and misconceptions to support self-assessment and facilitate their identification of an appropriate focus of their efforts, to meet their learning needs.”
Comparing and combining real and virtual experimentation: an effort to enhance students' conceptual understanding of electric circuits [26]	Z.C. Zacharia	Journal of Computer Assisted Learning	2007	Combining real and virtual experimentation	“Results indicated that the combination of RE and VE enhanced students' conceptual understanding more than the use of RE alone. Further analysis showed that differences between groups on that part of the curriculum in which the experimental group used VE and the control group RE, in favor of VE.”
When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment [27]	N. D. Finkelstein, W. K. Adams, C. J. Keller, P. B. Kohl, K. K. Perkins, N. S. Podolefsky, S. Reid	Physics Education Research	2005	Real vs. Virtual Experimentation	“Two groups of students, those who used real equipment and those who used a computer simulation that explicitly modeled electron flow, were compared in terms of their mastery of physics concepts and skills with real equipment. Students who used the simulated equipment outperformed their counterparts both on a conceptual survey of the domain and in the coordinated tasks of assembling a real circuit and describing how it worked.”
Activity-based education in electricity and circuit theory [28]	J. Bernhard, A.-K. Cartensen	Council for the Renewal of Higher Education	2003	Conceptual labs (math and circuit simulations)	“Analysis shows that the conceptual labs have been good at fostering conceptual understanding. By taken these conceptual labs one step further by merging problem-solving into the labs and systematically develop the task using the theory of variation we show that we have been even more successful.”

Title	Author/s	Source	Year	EBIPs used	**Major findings** (abstract excerpt)
Student learning in an electric circuit theory course: Critical aspects and task design [29]	A.-K. Cartensen, Jonte Bernhard	European Journal of Engineering Education	2009	Problem-solving lab (merges paper and pencil, simulations, and experiments)	"Researchers analyze and describe a novel learning environment design, the problem-solving lab, for learning transient response. This design merges problem-solving classes and labs, allowing students to engage in deep learning through the integrated use of tools like paper and pencil, MATLAB®, simulations, and experiments. A key element in this design is the systematic use of variation in line with variation theory. We describe critical features for learning transient response, and ways to facilitate the establishment of links between the 'worlds' of theories/models and objects/events for students. We contend that the integrated use of tools, and systematic use of variation, is crucial for learning and establishing these links."
Teaching circuit theory courses using team-based learning [30]	R. O'Connell, Pil-Won On	ASEE Conference	2012	Team-based learning	"The project is motivated by the desire to introduce students to self-directed independent learning and to learning in groups early in their programs. Team-based learning provides both of these features. Learning groups provide students with the opportunity to teach each other, which has been shown to produce deeper conceptual learning than listening to a traditional lecture. Also, while observing the group learning, the instructor can identify and correct learning difficulties on the spot, which is usually not possible with the standard traditional lecturing method. Despite the potential benefits, several practical challenges have been encountered while attempting to implement the strategy. These include motivating students to study and learn new material outside of class and before encountering it in the classroom; motivating them to engage appropriately in the specified group work process; and motivating them to engage in the formative/summative assessment examination processes used. The paper describes progress made over three semesters in overcoming these challenges."

Findings and discussion

As previously mentioned, a systematic literature review intends to discover areas of opportunities in previous work that will try to provide different perspectives in answering the research questions. It attempts to summarize agreeing or contradicting issues on the subject matter found in the previous studies, and it highlights the gaps and rooms for improvement that call for further studies [13]. In this section, these advantages of a systematic literature review will be discussed accordingly.

The first pass of refined literature search returned 24 papers. After an extensive evaluation of these gathered papers, the researchers obtained a total of 13 selected studies that were used for the final round of analysis (shown in Table 1). These 13 papers presented various instructional approaches that were studied and experimentally implemented to gauge student learning. Various instructional strategies used in these studies that were analyzed and evaluated as EBIPs with evidence of improvement in student learning are shown in Table 3.

Table 3. Summary of instructional strategies (EBIPs) used

Strategy	Number of studies
Fading and feedback (FF)	2
Problem-based Learning (PBL)	1
Supplemented Learning (SL)	1
Team-based Learning (TBL)	1
Real Experimentation (RE)	1

Virtual Experimentation (VE)	3
Real and Virtual Experimentation (RE + VE)	4

Instructional strategies and evidence of impact on student learning

In the 13 papers searched, we identified the strategies implemented in teaching circuit concepts as shown in Table 2. The strategies identified are fading and feedback (FF), problem-based learning (PBL), team-based learning (TBL), real experimentation (RE), virtual experimentation (VE), and the combination of real and virtual experimentations (RE and VE).

We found 2 papers [18], [25] that utilized *fading and feedback* (FF) strategy. FF is an instructional program that systematically provides instruction to the students on how an engineering problem is solved. Along with the problem-solving process, feedback is given on the spot when the students' near- and far-transfer are being experienced [18]. This study [18] shows that students learn more effectively with varying manner (forward or backward-fading practice) in relation to the instructional program when feedback is provided there and then. A proposition by Susan et.al. is to use a computer-based approach in promoting the learners' knowledge states, hence, the need for effective feedback. This approach is useful for students in their self-assessment processes when it comes to acknowledging their difficulties and misconceptions and what appropriate efforts to take to address these challenges [25].

Problem-based learning (PBL) is a learner-centered teaching approach. One paper [20] suggests, along with empirical support from previous studies, that electrical engineering students' learning gains are at least twice with PBL than with traditional lecture. However, the students also thought that they learned more from a traditional lecture than with PBL in terms of the amount of knowledge. Hence, PBL shows mixed findings when it comes to student learning impact in learning circuit concepts.

Supplemented learning (SL) has been used for quite some time in the field of engineering education. This includes tutorials, assignments, and homework, through the use of available learning tools such as the internet and another form of media. One study [21] iterates that homework provided online can supplement the students' learning because it maximizes efficient use of resources, especially if it is electronically delivered. The proponents of the mentioned study suggested the use of weBWorK, an open-source homework online delivery tool, as an alternative to traditional "paper" homework in the introductory circuits course. It was found to be at least comparable with the traditional homework, and thus, the online homework is being proposed to optimize resources for the students learning circuit concepts [21].

One paper [30] tackles *team-based learning* (TBL) as a strategy to teach circuit theories. It was reported that the use of TBL learning strategy in the sophomore circuit course assists students in self-directed learning when being exposed to learning in groups. Moreover, TBL has been shown to facilitate deeper conceptual understanding among students as opposed to traditional lecture. It is important to note that "while observing the group learning, the instructor can identify and correct learning difficulties on the spot, which is usually not possible with the standard traditional lecturing method. Despite the potential benefits, several practical challenges have been encountered while attempting to implement the strategy. These include motivating students

to study and learn new material outside of class and before encountering it in the classroom; motivating them to engage appropriately in the specified group work process; and motivating them to engage in the formative/summative assessment examination processes used." [30] (p.2)

Real experimentation (RE) and *virtual experimentation* (VE) are likened to physical and virtual manipulatives (PM and VM) in math education. However, in electrical engineering, RE and VE are terms that refer to conducting actual experiments and using simulations software in learning circuit concepts, respectively.

Post [23], in his study, proposes RE setup in teaching introductory circuit course to non-electrical engineering majors. Measuring instruments and electrical materials were used to conduct lab experiments but the findings say that students tend to have difficulty in visualizing physical connections, especially that the circuits were constructed on a breadboard as opposed to using terminal strips and free-from circuits with alligator clips. The more advanced students in class believed that some experiments were too simple, e.g. applications of Ohms' law, and wanted to do a more advanced physical electronics design.

On the other hand, 3 studies [19], [24], [28] were gathered in this review that argue that VE is a more effective strategy in learning circuit concepts. Kolloffel and de Jong suggest inquiry-based learning (textbook inquiry) that follows the procedural use of formulas and building circuits through the use of a virtual laboratory. Results show that students in the virtual lab acquired a much better conceptual understanding (solving complex problems) and a better grasp on procedural skills when compared to students in the traditional conditions [19]. Campbell et al. present a combination of the use of circuit simulation software and mathematical software to visualize and construct linear circuits through circuit diagrams, and understanding the mathematical aspect of the circuit such as transfer functions and circuit parameters [24]. This coupling is believed to elicit a better understanding of the physical, as well as mathematical foundations of circuits. In addition, Bernhard and Carstensen [28] propose an activity-based education through a "conceptual lab" in order to foster conceptual understanding of introductory and advanced circuit concepts, especially if students lack qualitative understanding of the problems which may result to difficulties in quantitative analysis. They argue that "[b]y taking these conceptual labs one step further, by merging problem-solving into the labs and systematically develop the task using the theory of variation, we show that we have been even more successful." [28, p. 2].

There were 4 studies [22], [26], [27], [29] in this literature review that presented both real and virtual experimentations (RE and VE) in strategizing instruction to teach circuits concepts. Kaleem et al. [22] compared three approaches to teaching circuits: traditional face-to-face, flipped, and hybrid. The competencies surveyed in the study include instruments used in electrical engineering, actual measurement of voltage and current using the instruments, building AC/DC circuits, circuit performance analysis and modeling using simulation tools, functions of circuit components, and building the actual circuit based on the simulated circuit design. Results show that students in hybrid and traditional sections have greater confidence than in the flipped classroom. Greater confidence was seen in tasks: understanding the functional components of a circuit, building the actual circuit using the actual electronic components from the simulated and calculated circuit design [22]. Zacharia investigated the value of combining RE and VE in the

changes in conceptual understanding of electric circuits. Results indicated that combining RE and VE improved the conceptual understanding among students when compared to the use of RE alone [26]. Finkelstein et al. [27] present a contrasting finding. They examine the outcome of replacing the use of computer simulations with a real laboratory of a large-scale introductory physics course. They found that students who used computer simulations had a better conceptual understanding of circuit concepts and more capable of manipulating real components. The virtual equipment was found to be productive for students in terms of understanding simple circuits, developing skills at manipulating components, and reasoning of the physical behaviors in the analysis of circuit concepts [27]. In the aspects of comprehending time-dependent circuit response, advanced familiarity with mathematical approaches is needed such as Laplace transform, say, solving transient responses. Carstensen and Bernhard presented a novel approach called "problem-solving lab" to address this concept in circuit theory [29]. This particular design integrates all the needed analytical processes of understanding circuits through actual drawings and solution, simulations, experiments and use of other tools such as MATLAB. It was found that using the variation theory, establishing the links between these process in understanding time-dependent responses had resulted to the establishment of "links between the 'worlds' of theories/models, and objects/events for students, allowing them to experience deep learning. Thus, the integrated use of these tools is crucial for students' learning of circuit concepts [29].

Issues with implementation and improvement

Common issues with the implementation of these strategies are identified. There is a lack of continuous research-driven improvement for carrying out an individual instructional practice, which is supposed to be the whole idea of EBIPS: to establish a proven effective instructional strategy for teaching electrical circuits. In addition, there is a lack of linking mechanisms between research output and the actual utilization of results. Conversely, there has been less innovative instructional practices seen in the area of teaching electrical circuits. Mainly because the supposed evidence that manifests as generated data from the learning outcomes or results of applied metrics on actual classroom instruction is rarely used for conducting further studies; especially, the necessary studies to investigate the impact of instructional practices used in teaching circuit concepts towards student learning. These barriers can be overcome if we create the necessary feedback in utilizing research outputs for improving actual teaching practice, i.e. evidence-based instructional practices. Henderson and Dancy [31] have raised an important point on this matter. In their investigation of the use of research-based instructional strategies, they have presented evidence that "major impediments to the spread of research-proven reforms are situational characteristics consistent with traditional instruction." (p.13), arguing that more effort is required to disseminate this reality. There has been an obvious disconnect between instructors' conceptions on these instructional strategies and their actual practice due to the difficulties encountered in translating abstract concepts and goals into tangible instructional actions. Thus, researchers tend to lean more on utilizing either established theories on learning and adaptability or form theories in order to guide and address such barriers.

Guiding models and theories

There is a long list of learning theories and models that relate to teaching and learning electrical circuit concepts. However, for discussion purposes, we only intend to note the relevant models

and theories that were prevalent and highlighted in the 13 papers presented in this review. These theories have been used in establishing instructional actions in accordance with how the engineering mind is constructed through active and experiential learning processes. These are the open-learner model [25], worked-example instruction [18], and variation theory. The relevance and significance of these guiding principles in teaching and learning circuit concepts using evidence-based approaches are briefly discussed in this section.

Open-learner model: Learner modeling has been used as a tool to diagnose misconceptions among learners. A computer-based learner model is patterned on learners' current understanding of the subject, storing data based on actual learners' encountered difficulties, misconceptions, and learned concepts. A study [29] presented in this review has proven that with the use of open learner model software called OLMlets, they were able to identify misconceptions among students in math and electrical circuits modules including "electrons carry positive charge, voltage and current generators are identical, resistance is reactive, current can change within the branch, etc." [29] (table 2, p. 314). In teaching electrical circuit concepts, it is with utmost importance that misconceptions are identified early in the process and not passed on and transferred to (as prior knowledge) learning the next advanced concept. Thus, identifying misconceptions and providing timely feedback will help the students learn more effectively.

Worked-example strategy: The 'worked example effect' has been coined to refer to the advantage of studying worked example problems when compared to independently solving problems [32]. A few studies have investigated the advantages of the worked-example strategy used to promote students' problem-solving transfer ability, especially in the area of electrical circuit analysis [33], [34]. Unlike solving problems by the traditional method, that is means-to-end and analytical practice approaches, example-problem (EP) practice (where worked-out problem examples are given to students followed by a practice problem) has significantly increased students' near transfer. For example,

> "You wire a subwoofer speaker with a resistance $R_1 = 16\ \Omega$ and a regular speaker with a resistance of $R_r = 8\ \Omega$in parallel and operate this electrical circuit with a $V = 6$ V battery. What is the total resistance of this electrical circuit?" and "The electrical system of a remote-controlled toy helicopter consists of a motor with resistance $R_m = 4.5\ \Omega$, and a control unit with resistance $R_l = 72\ \Omega$. These two components are wired in parallel and are connected to a $V = 9$ V battery. What is the total resistance of this parallel electrical circuit?" [18] (p.84)

It is important to promote the students near problem-solving transfer ability in learning circuit concepts wherein they use learned concepts in solving problems that share the same structure as the worked-out examples (given during instruction) but differs on the external characteristics. In addition, cognitive flexibility theory suggests that instructional practices, such as worked-example instruction, must show variations of examples, applications, and contexts in solving varying problems [35].

Variation theory: According to Carstensen and Bernhard, "[v]ariation theory states that the object of learning's critical features should be brought into the students' focal

awareness and that such critical features can be discerned through the use of systematic variation." [29] (p. 19) However, empirical research shows that this theory does not necessarily establish which features can be varied and what features are critical. In learning complex concepts such as in the area of electrical circuits, variation is key to conceptual understanding. In Carstensen and Bernhard's study, they proposed necessary varied tools such as paper and pencil for writing and drawing, simulation and mathematics tools such as MATLAB, Simulink, PSpice, and computer-based measurements were made available for students to use in an integrated learning environment design called problem-solving labs. They iterated that "… students need repeated practice in interpreting different aspects of circuit theory formalism and relating it to the real world and vice versa. This must be explicitly addressed in instruction since such links between theories/models and objects/events are difficult for students to establish by themselves." [29] (p.20) Thus, creating such a design of a learning environment is crucial to students' conceptual understanding of electrical circuits as a whole.

Synthesis and Conclusion

The number of studies gathered for this literature review indicates there is not much work done on investigating evidence-based instructional practices used in teaching circuit concepts, the studies presented here are evident enough to report that several practices were found to be successful in facilitating student learning of electrical circuits. The abovementioned 13 studies tackle the important aspects of learning circuit concepts. We can never discount the importance of exposing students to the actual building of circuits, i.e. while possessing a proper background on circuit theory and mathematics.

With the research questions, *"What evidence-based instructional practices have been reported to have the most impact on students' learning of circuit concepts? How are these practices implemented in engineering learning environments?"*, we emphasize that the strategies identified, presented, and analyzed for this review have been reported to be effective for teaching circuit concepts. However, we also recognize that there is still much work that needs to be done in documenting and assessing the overall effectiveness of instructional strategies and their alignment with learning outcomes.

Among the teaching strategies captured by this literature review, the implementation of real and virtual experimentation (RE and VE) environments are the most engaging learning experience for students when understanding circuit concepts, apart from achieving improved learning as mentioned in this review. Moreover, we would like to emphasize that this integration of physical and virtual exposure of students does not necessarily and directly relate to lecture and laboratory setup of the traditional electrical circuits course. As stated, RE and VE are linked and integrated together to facilitate a more holistic learning experience among students: VE being the necessary instrument to initiate proper understanding of circuits through simulations and mathematical software, RE being a validating instrument to secure the understanding of circuits via tangible and comprehensible manner of building an actual environment. In the aspect of nurturing student active roles, it is quite beneficial to work in teams to systematically solve circuit problems, as proposed by team-based learning (TBL) and problem-based learning (PBL) approaches. In the

aspect of inquiry learning, fading and feedback (FF) work as an effective instructional program and a feedback mechanism to address the complete cycle of learning and knowledge transfer in circuit courses. In addition, feedback has been recognized as one of the most relevant aspects of student learning because it promotes student awareness of errors and correctness, and better carry out problem-solving processes [36], [37]. This synthesis of strategies highlighted in this review has been proposed to provide learner-centered (open-learner model), cognitive (worked-example strategy), flexible and varied (variation theory) approach to teaching electrical circuits.
The findings from this work have significant implications for engineering educators, especially those who teach electrical circuits courses. Exploring the use of evidence-based instructional practices to teach circuit concepts is important to ensure that learning environments are designed to elicit conceptual understanding. Most importantly, understanding what practices are most suitable for implementation and what potential barriers exist is necessary information for educators and stakeholders who are eager to engage in the design of learning environments. The barriers in adapting such instructional strategies need to be overcome, both by instructors and students, by acknowledging what needs to be reformed for the better, that is providing mechanisms to use research-based outcomes into actionable instructional practices.

The findings and conclusions of this systematic review of literature are limited to evidence-based instructional practices in the context of teaching circuit concepts to undergraduate engineering students. Moreover, future research will be conducted in looking at the instructional practices in general and how the use of evidence of the success of various instructional strategies can be taken advantage of to further improve student learning in engineering and other disciplines. Additionally, the alignment between student learning outcomes and use of specific evidence-based instructional practices will also be studied.

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