Systematic Review of Rigorous Research in Teaching Introductory Circuits

Abstract

Systematic review is a meta-analytical framework for quantitatively searching, sorting, and synthesizing scholarly research on a particular topic. Systematic review techniques have recently gained traction in the field of engineering education. A systematic review performed over a specific area of practice can consolidate results from many studies into a synthesis of best practices.

This paper presents the best practices for teaching introductory circuits which were identified through a systematic review of prior research. Relevant publications were identified and appraised with a set of coding criteria generated by the researchers. The coding results were examined and used to write a mixed-methods synthesis of consensus, disagreement, quality, and limitations amongst studies identified by the systematic literature review. The results of the review may inform educational techniques employed in post-secondary introductory circuits courses.

Introduction

The purpose of this study is to identify and describe the best practices in teaching introductory electrical circuits. In recognition of the large body of existing literature on electrical circuits pedagogy, this study was conducted as a systematic literature review (SLR). Rather than devise an experimental research design, this study seeks to identify best practices in electrical circuits pedagogy by systematically collecting, reviewing, and synthesizing results from past educational studies on this topic.

The SLR presented in this paper aims to answer the research question, "What are the best practices in teaching introductory electrical circuits?". In this context, 'introductory electrical circuits' is taken to mean *any undergraduate* ***engineering*** *course which covers* ***linear circuits*** *(and possibly other content), and is taught* ***in-person***. This definition intentionally excludes online, high school, graduate, and advanced courses in electrical circuits. Since the meaning of 'introductory' may vary between instructors and institutions, linear circuits were chosen as the course subject which best captures the researchers' intention. The definition is left sufficiently open-ended to allow for courses which include additional topics beyond linear circuits — which may include digital circuits, signal processing, or three-phase power systems, depending on the course.

Systematic literature review is an emerging methodology in engineering education which aims to identify trends, consensus, and discrepancy amongst high quality studies in the field [1], [2], [3], [4]. SLRs differ from typical 'narrative' literature review (borrowing Borrego's terminology) in that it employs "transparent, methodical, and reproducible procedures" [1]. SLR is an appropriate technique for addressing our research question because it provides a systematic method for selecting and synthesizing the results of high quality studies from a large database. Furthermore, the field of research in pedagogical techniques for teaching introductory circuits is mature enough to warrant such a review, an important criteria for carrying out a successful SLR [1].

Writing about SLRs presents semantic challenges which necessitate clarity and consistency in the use of certain terms. Following the lead of Borrego, Foster, and Froyd, in this study, *researchers* and *reviewers* refer to the authors of this paper, *authors* refers to the authors of papers included in the SLR, and *studies* refers to the literature under review [2]. Furthermore, the *review database* refers to the database of studies collected by the researchers — not to be confused with a particular online database or the literature in general.

Background

Over the last decade, SLRs have been increasingly used in engineering education research. They have been used to study topics as diverse as the effectiveness of engineering student teams [5], student resistance to active learning [3], and the use of systematic literature reviews in engineering education research [1]. Like all established research methods, the best practices for completing systematic literature reviews have been extensively discussed elsewhere [2].

SLR is a research method with a variety of applications. An SLR can be used to broaden or strengthen the conclusions within a field of research by combining the findings from multiple studies. An SLR can also be used to inform researchers about the current state of a field and identify opportunities for future research [1].

Research into effective methods for teaching introductory electrical circuits has been taking place for over fifty years. It is difficult for engineering faculty to stay abreast of the high volume of research in the field, making introductory circuits education ripe for systematic literature review [1]. Researchers have previously used SLR to investigate students' perceptions of teaching activities in electric circuits courses [4].

More recently, another work sought to use SLR to establish which "evidence-based instructional approaches" have been used in circuits instruction [6]. This paper was narrow in the scope of its SLR, as the researchers used "evidence-based instructional practices", or EBIPs, as a keyword in their initial search of the literature (resulting in an initial paper pool of only 24 papers). The over-specificity of the search criteria used in [6] limits the scope of the SLR and provides an incomplete picture of research in introductory circuits education. Our paper strives to address this omission by reviewing all full, peer-reviewed research papers investigating the in-person instruction of electrical circuits at the undergraduate, introductory level.

Methods

The SLR methods used in this study are largely adapted from [1], [2], [3]. In this section, we describe these methods. A description of the papers identified by our methods is in the "Results" section below.

Search

In the search phase, online scholarly databases were queried to find as many relevant studies as possible. The researchers worked with a research librarian to formulate a set of keywords and search phrases that would fetch recent journal articles and conference publications on instructional techniques in introductory circuits courses. The librarian also aided the researchers in selecting high-quality databases to be included in the search. Table 1 shows the databases and search phrases used to conduct the search.

Table 1 — Search phrases used to query each database in the preliminary search for studies.

Database	**Search Phrase**
ERIC	(engineer OR engineering) AND (education OR educate OR educating OR pedagogy OR pedagogical OR teach OR teaching OR teacher OR learn OR learning OR learned) AND (circuits OR electronics) OR "best practices" OR introductory
IEEE Xplore	engineer* AND (educat* OR pedagog* OR teach* OR learn*) AND (circuits OR electronics) AND introductory
ASEE Peer	(engineer OR engineering) AND (education OR educate OR educating OR pedagogy OR pedagogical OR teach OR teaching OR teacher OR learn OR learning OR learned) AND (circuits OR electronics)
Elsevier Engineering Village	(((((engineer*) AND (educat* OR pedagog* OR teach* OR learn*) AND (circuits OR electronics)) WN ALL)) AND ((({ca} OR {ja}) WN DT) AND ((2019 OR 2018 OR 2017 OR 2016 OR 2015 OR 2014 OR 2013 OR 2012 OR 2011 OR 2010 OR 2009 OR 2008 OR 2007 OR 2006 OR 2005 OR 2004 OR 2003 OR 2002 OR 2001 OR 2000 OR 1999 OR 1998 OR 1997 OR 1996 OR 1995 OR 1994 OR 1993 OR 1992 OR 1991 OR 1990) WN YR)))

In keeping with the SLR methodology, the search phrases were constructed to fetch as many relevant studies as possible from each database. To increase breadth, search phrases included multiple variations of important keywords, or used wildcard characters to the same effect. The search was limited to recent papers (since 1990). This filter was applied via the graphical interface in three of the four databases, which explains its appearance in only one search phrase.

Citation data and full-length PDFs were exported from the online scholarly databases to create the *review database*. The review database was hosted using Zotero, a free and open-source reference management system. Zotero's remote synchronization feature conveniently allowed researchers to simultaneously access and edit the review database. Duplicate studies were manually removed from the database before continuing on to the selection phase.

Selection

After creating the review database from the results of the search phase, selection criteria were applied to identify only those studies relevant to the research question. Due to the unexpectedly high volume of studies captured by the search phase, the researchers elected to apply three rounds of selection criteria, described below in detail.

Table 2 — Description of selection criteria broken down by round.

	Tag	**Criterion Description**
Round 1	TE	Title or abstract mentions education
	TC	Title or abstract mentions circuits/electronics
Round 2 & 3	INTRO	Study concerns an introductory circuits course
	EMP	Study involves collection of empirical data on student learning
	MIN	If the study focuses on a demographic group that is underrepresented in engineering, data is also collected for students outside of that group
	WIP	Study is not a work-in-progress
	DATE	Publication date of study is 2005 or sooner

Criteria were applied to studies using Zotero's tagging feature. Each criterion was associated with a brief tag, which was added to the study's Zotero entry if it matched that criterion. This approach had the benefit of enabling database filtering based on selection criteria. Table 2 presents the selection criteria and their associated tags.

The INTRO criterion indicates that the study included work in an 'introductory circuits course,' as defined in the Introduction. The EMP criterion attempts to capture rigorous studies, and excludes descriptive or anecdotal studies. The MIN criterion selects studies about teaching methods intended for a general student population. The DATE criterion was shifted to a cutoff year of 2005, rather than the original 1990 cutoff used in the search phase. In the first round of selection, researchers noticed that a large number of papers from the 1990s and early 2000s describe educational technologies which are now commonplace — such as personal computers, software tools, and the Internet. The 2005 cutoff date focuses the research on studies which reflect the current relationship between pedagogy and technology. Furthermore, the selection of 2005 as a cutoff reflects the shift that occurred in the field of engineering education research in the early 2000s toward a more scholarly emphasis (Froyd, Lohmann, Johri, and Olds, 2014). For example, in 2003, the *Journal of Engineering Education* established new review guidelines for papers submitted to the journal which reflected the greater expectations for rigorous inquiry in the field ("History of JEE," n.d.).

The first selection round applied basic criteria intended to remove obviously irrelevant papers — those which do not mention engineering education or electrical circuits in their title or abstract. Round 1 was conducted by two researchers, who each evaluated half of the review database. Following Borrego's suggestion [1], the researchers began Round 1 with a 'calibration round' in which the pair jointly applied the first-round criteria to a subset of abstracts to establish inter-reviewer consistency. The remainder of the evaluation was performed individually. Studies which met both Round 1 criteria were passed on to the second round of selection, the remainder were discarded.

The second selection round applied more specific criteria to evaluate studies for rigor and relevance based on their title and abstract. Round 2 was conducted by two researchers in the same manner as Round 1. If a researcher was unclear about whether a study matched a criterion, it was flagged as ambiguous. At the end of Round 2, the researchers re-grouped to cooperatively review each flagged study. If the ambiguity still could not be cleared, the study was passed onto the third selection round with an 'Unclear' flag.

The third round of selection recycled the Round 2 criteria, but applied them to the full-texts. Round 3 was conducted by three researchers, who again met for a calibration round before individually evaluating their assigned studies. Round 3 criteria were applied using a new form which asked researchers to assign each study a mark of ‘True’, ‘False’, or ‘Unclear’ for each criterion. Any study which received no ‘False’ marks was passed onto the coding round. Round 3 helped the researchers settle ambiguities and double-check their work from Round 2.

Coding & Synthesis

The coding process consisted of evaluating the studies which passed all three rounds of selection. Evaluation of the full-texts was carried out using an online form created by the researchers, following the process of [3]. A condensed version of the form is presented in Appendix A. Three researchers jointly coded a subset of papers in another ‘calibration round’, then individually evaluated their assigned portions of the review database.

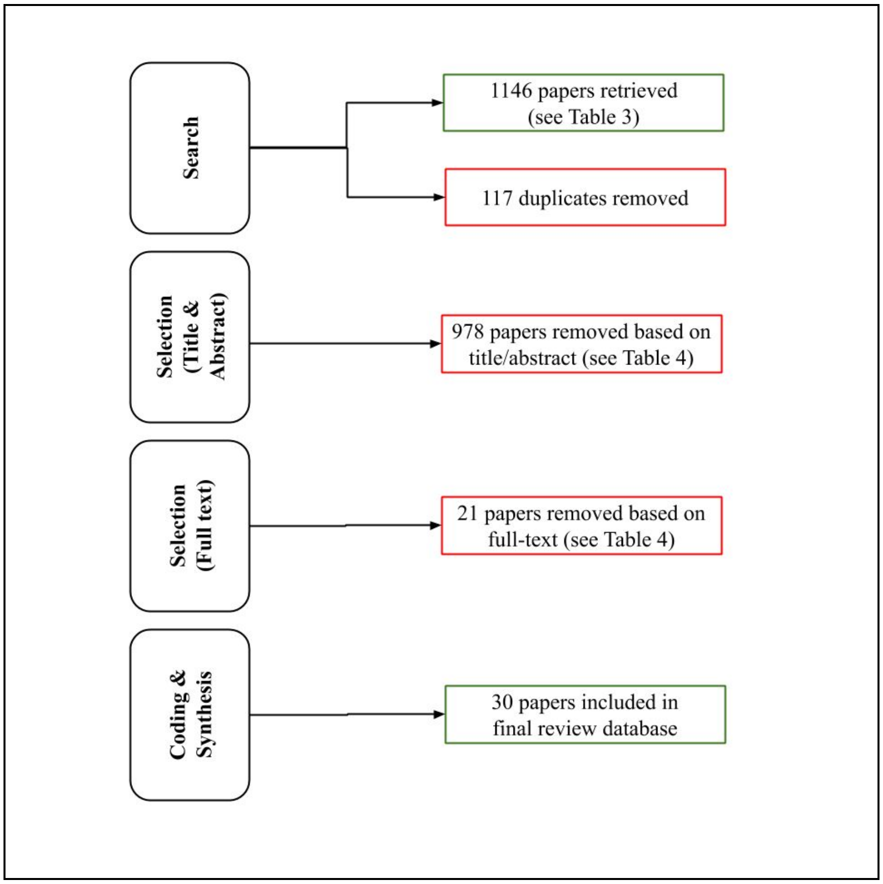
The coding form consisted of two types of questions: informational and quality-assessment (QA). Informational questions asked reviewers to provide descriptive details about the study in review — such as the location of the study and the type of data collected. QA questions (indicated by * in Appendix A) were formulated to indicate the quality of studies. Initially, the researchers intended to assign quantitative quality scores to studies based on responses to QA questions, following the “Yes/Somewhat/No/Not applicable” method used in [2]. However, researchers agreed that the method seemed somewhat arbitrary — “Should all QA questions be given the same weight?”, “How can ‘Not applicable’ responses be included in a meaningful way?”, “What QA score constitutes high quality?” — and abandoned it in favor of a *qualitative* assessment. The qualitative assessment took the form of a short written summary of the quality indicators present in each study.

Results were synthesized by examination of the completed coding forms. Studies were categorized by various measures, including category of teaching intervention, quality assessment score, research methods used, and impact on student learning. These categorizations were tabularized to allow researchers to examine trends within and across categories. Researchers produced a written summary of observations detailing the consensus, disagreement, quality, and limitations amongst studies identified by the systematic literature review.

Results

The flow diagram in Figure 1 (based on Figure 1 in [2]) presents a summary of the review process broken down by step. The organization of this section follows the methodological steps of the SLR. Each subsection of the Results reports the findings of a step in the SLR method, as described in the Methods section. Note that the results of the synthesis step of an SLR overlap significantly with the content typically included in the conclusion of a scholarly paper. Thus, readers wishing to identify the takeaways of our paper should take care to read both sections.

Figure 1 — Flow diagram summary of systematic literature review process, with callouts to indicate inclusions/removals from the review database at each step. Coloration is used to denote studies that were included in that round of the review (green) and removed (red).



Search

A total of 1,029 unique studies were retrieved from four scholarly databases. The initial search returned 1,146 studies, but 117 were found to be duplicates and removed from the pool of results. Table 3 provides a breakdown of results from each database.

Table 3 — Quantitative results of database search.

Database Name	Data Accessed	# Studies Retrieved
ERIC	9/11/2019	57
IEEE Xplore	9/30/2019	287
ASEE Peer	9/24/2019	301
Elsevier Engineering Village	9/11/2019	501
Total (all databases)	—	1146
Total (after removal of duplicates)	—	1030

Selection

As described in the "Methods" section above, selection was applied in three rounds: two rounds of title/abstract review, and one round of full-text review, the latter done in conjunction with the coding stage. The results from each round of review are shown in Table 4. Note that the totals are *not* the simple sums of their respective columns. To pass a round, a study needed to meet *all* criteria in the round. Equivalently, a study failed a round if it did not meet *any one* of the criteria in the round. The totals for the passed/failed bins report the number of studies that were kept or discarded at the end of each round. The totals for the 'unclear' bin include studies which had *at least one unclear criteria* and *no failing criteria*. The criteria listed use the abbreviations described in Table 2.

The selection process yielded a total of 30 relevant studies which were passed on to the coding and synthesis stages.

Coding — General Information

Most of the studies focused on a single course. Many included "Circuits" in the name of the course (n=13) or did not report the name of the course (n=8), though context clues allowed us to conclude that the class did include a focus on linear circuits. A significant proportion of studies examined multiple courses (n=4), some across multiple institutions. Most courses were taught in the department of Electrical Engineering or Electrical & Computer Engineering (n=17), with a significant minority being taught by a general Engineering department (n=5). Course size was extremely varied, with only two small courses (<25 students), and a roughly even split of medium (25-70 students), large (70-200 students), very large (>200 students), and unreported enrollments. Nearly all studies were conducted in the United States (n=27).

Table 4 — Results of the selection phrase. Note that totals are not simple sums. To pass a round, a study must meet *all* criteria in a round. To fail a round, a study must not meet *any one* of the criteria in the round.

	Criterion Tag	# Passed	# Failed	# Unclear
Round 1 (n = 1030)	TE	838	192	—
	TC	625	410	—
	Round 1 Total	450	579	—
Round 2 (n=451)	INTRO	137	277	36
	EMP	159	252	39
	MIN	436	14	0
	WIP	435	15	0
	DATE	267	183	0
	Round 2 Total	47	399	4
Round 3 (n=52)	INTRO	35	17	1
	EMP	47	6	0
	MIN	53	0	0
	WIP	53	0	0
	DATE	53	0	0
	Round 3 Total	30	21	0

Coding — Quality Assessment

The quality assessment results from the coding survey show that the selected studies constitute a mixed-bag. Quality assessment question 2.8 (as labeled in Appendix A) was discarded in the analysis after researchers experienced difficulty answering the question consistently across studies. Qualitative evaluations of each study were written by the lead researcher based on responses to the quality indicator question. A detailed quality assessment table is provided in Appendix B.

Quality assessment results for roughly half (n=16) of coded studies are ‘indicative of high quality’ or ‘mostly indicative of high quality’. The highest quality papers are characterized by replicability, the involvement of multiple researchers, and experimental design which guards against bias. Skromme et al is a particularly good example of control design: students from the same class section are randomly assigned to the experimental or control group, and data is collected from both student performance and student evaluation [7]. The design is strong because experimental and control groups are distinguished by a single variable (application of the teaching method), and a variety of data (grades, surveys) was collected to evaluate the experiment. Some studies introduce variability by using different instructors for the experimental and control groups [8], [9], while others (n=15) lacked a control group altogether. The researchers agreed to mark studies as ‘somewhat’ utilizing a control group (n=10) if results were compared to multiple experimental trials (with no true control), or compared to a poorly designed control group. Studies scored well on replicability, with a strong majority (n=22) scored as replicable from the authors’ description.

One common problem among coded studies is reliance on self-selected sample populations. Most (n=22) studies relied at least partially on written student feedback. Of those, 16 relied on voluntary participation, 5 were not discernibly voluntary or required, and one study did not feature an experimental component. Voluntary participation in data collection may lead to participation bias — students strongly affected by a teaching method are more likely to respond to an optional survey than students who are moderately affected. Since best practices in human subjects research mandate informed consent about research participation and the possibility to opt out of studies, it is difficult to avoid the possibility of participation bias in engineering education research. Participation bias risk can be mitigated by collecting data from both ‘required’ (e.g. course grades) and ‘self-selected’ (e.g. student surveys) sets — a practice adopted by six of the coded studies.

Of the studies which described experimental teaching methods, the majority concluded that the methods had a positive (n=14) or somewhat positive (n=9) impact on student learning. Positive experimental outcomes are not necessarily an indicator of high or low quality experiments — though they do indicate higher relevance to the research question. Rather, experimental outcome is included in the quality assessment because it can be indicative of bias. Studies which report high efficacy, but rely solely on a self-selected sample or single researcher, may suffer from participation bias or publication bias.

Synthesis of Best Practices

In the tables in Appendix B and Appendix C, studies are marked with a dagger (†) if their quality assessment coding is 'indicative of high quality'. We consider these four studies to be of the highest quality retrieved by the SLR. Studies are marked with a double dagger (††) if their quality assessment coding is 'mostly indicative of high quality'; there are 12 such studies. Despite variance in the context (in-class, out-of-class, lab, etc) of practice, the four highest quality studies share a focus on *how students construct knowledge*, rather than *how professors teach*. That is, they concern student-centric learning activities facilitated by instructors, rather than instructor-centric teaching performances.

The remainder of this subsection is organized paragraph-wise according to the context of teaching methods. Each paragraph contains a synthesis of studies concerning one context-area: out-of-class activities, in-class activities, projects/labs, or lectures.

Three of the four studies focus on **out-of-class methods** [5], [10], [11], while two concern in-class methods [12], [8] ([8] applies both in- and out-of-class). [5] and [9] both study the effect of online homework on student learning. [9]'s WeBWorK framework is a simple, open-source online homework platform which translates typical circuits problems into a digital context, randomizing values in problems to prevent cheating. The authors conclude that WeBWorK "is at least comparable to paper homework for student learning" [9], but ultimately has little effect on student learning. Meanwhile, [5] implements a step-based online homework system with multiple unique features including: (a) on-demand generation of an "unlimited number of topologically different circuit diagrams", (b) on-demand generation of fully-worked examples, (c) flexible input handling. The system is 'step-based' because it asks students to break problems down into steps, rather than working only towards a final answer [5]. Scaffolded problems, worked examples, and access to large example sets are all pedagogical techniques shown to improve student learning [13], [14]. Intertextual comparison of [5] and [9] suggests that online homework, in and of itself, does not improve student learning — but online homework can serve as a delivery vehicle for other pedagogical best practices. Another coded study concludes that online homework improves student learning, but relies on a self-selected sample population and lacks comparison to a control group — both indicative of lower quality results [15].

The **in-class methods** described in [10] and [8] share a focus on replacing lecture with active learning. [10] creates a studio format by uniting lecture and laboratory activities in a single class session, while [8] assigned students into groups which work on conceptual problems. Both studies report very positive impacts on student learning. Other studies which scored well in quality assessment — [6], [16], [17] — draw similar conclusions about the positive impact of active-learning in the classroom. Though active learning interventions vary between studies, there is consensus among high quality studies that active learning interventions improve student learning.

Half (n=15) of the coded studies examine **project- or lab-based learning**. This category is a comparatively mixed bag, with only 8 of the 15 studies indicated as high or mostly high quality. [18]–[20] each replace traditional labs or lessons with long-form projects. The latter does not draw any conclusions about the impact on student learning, but all three studies observe increased student motivation and interest in the project-based courses. Many studies on laboratory learning revolve around the use of a specific tool, rather than a pedagogical technique, making it difficult to establish consensus across the studies [9], [21], [22], [23], [24], [25].

Some studies (n=5) investigated augmentations to **traditional lecture formats**. Of these, two used active lecture note strategies to engage students during lecture [26], [27]. Neither study scored well on quality assessment, and they draw opposing conclusions on whether or not the method improves student learning. A lone study investigates the use of dialogue-based and problem-based learning in place of lecture, concluding that "no one instructional approach was identified as a [*sic*] providing a significant increase in student course attainment. Rather, a variety of approaches . . . appears to provide a robust experience that complements a variety of learning styles" [16]. Another study similarly concluded that introducing a variety of experiences — such as guest lectures and field trips — into a course enhanced student learning [28]. Based on these results, it is difficult to draw a consensus on the best methods for teaching introductory circuits during lecture sessions.

Discussion & Limitations

The systematic literature review method has several limitations. It is difficult to ensure that all relevant papers are captured during the search phase. The massive size of the initial database and inclusivity of the chosen search terms indicate that most relevant papers indexed by the chosen databases were captured — although it is certainly possible that some relevant papers were not caught by the search terms. However, only four online scholarly databases were included in the search. A future study may seek to expand the breadth of the database pool. Best practices in systematic literature reviews typically involve identifying relevant papers from other sources in addition to database searches, such as the recommendation of colleagues or a professional organization, neither of which were utilized in this work.

Inter-reviewer reliability is another problem endemic to systematic literature reviews, and this review in particular. Borrego and Crockett both advocate that each paper be cross-reviewed by multiple researchers [2], [3]. Due to the small size of our research team and the unexpectedly large pool of relevant studies, we relied on 'calibration rounds' followed by individual assessment of studies. The researchers typically found the results to be reliable between researchers (in one instance, two reviewers accidentally coded the same study and answered nearly every coding question the same), though some coding questions suffered from poor inter-rater reliability. For example, question 2.8 of the coding form was thrown out because the researchers realized that they had interpreted the question differently while coding papers, despite having participated in an inter-reviewer calibration round.

Systematic literature reviews are characterized by their systematic application of criteria and requirements to a large pool of literature, with the goal of identifying high-quality and relevant studies. While this approach is time-efficient and scalable, it involves a certain level of arbitrariness that at times raised questions amongst the researchers. The decision to remove studies published before 2005 was informed and justified, but it seems unrealistic to think that there are *no* relevant papers on circuits pedagogy published before that date. Similar arguments can be made about many of the selection criteria, but the researchers are unaware of a method to prevent such losses in the framework of a systematic literature review.

Lastly, it is very difficult to manage a review database of over 1000 academic papers. The researchers used certain precautions — such as tagging *and* refiling studies according to selection criteria — to prevent accidental miscategorization of papers. However, it is difficult to notice and take action against database mismanagement accidents when they occur. In one example, two copies of the same paper were accidentally included in the review database with slightly different citation data, and the mistake was not caught until the coding stage.

Overall, the primary limitation of a systematic literature review is that some high-quality, relevant studies may fall through the cracks of the review — whether due to database limitations, reviewer error, or arbitrary exclusion by selection criteria.

Conclusions

A systematic literature review of scholarly studies in introductory circuits education was performed in an effort to answer the question: "What are the best practices in teaching introductory electrical circuits?". The review followed a methodology adapted from [1], [2], and [3], consisting of four stages: search, selection, coding, and synthesis. A large review database was built from a query of four online scholarly databases. The review database was pared down via the application of specific selection criteria to each study, until only relevant studies remained. The remaining studies were coded to extract important information and appraise their quality. The coding results were examined and used to write a mixed-methods synthesis of consensus, disagreement, quality, and limitations amongst studies identified by the systematic literature review.

The Results section, in particular the subsection Synthesis of Best Practices, contains detailed synthesis of best practices described in the reviewed studies. The remainder of this section provides a brief summary of the SLR results.

Teaching methods were organized by area of implementation: in-class/lecture, project/laboratory, out-of-class, and other. Overarching trends emerged across methodological categories:

- Best practices focus on *how students construct knowledge*, rather than *how instructors teach*;
- Active learning interventions generally have positive impacts on student learning, especially when they replace (rather than supplement) lecture time;
- Project-based learning tends to increase student motivation in a course, though the impact on student learning may vary;
- A teaching method's impact on student learning is more strongly related to the pedagogical techniques employed, rather than the specific tools used.

Some studies were noted to contradict each other, lack high quality research methods, or lack conclusive results. It was difficult to identify best practice trends from such studies.
The systematic literature review method was successful in identifying high-quality, relevant studies, and extracting pertinent information from them. Researchers noted that the method was somewhat limited by the scope of queried databases, inter-reviewer reliability, and an element of arbitrariness in the coding process. Future work may involve a broader search, increased collaboration between researchers, and improved quality assessment metrics for studies under review.

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Appendix A — Tabular Coding Form

Number	Question
0.1	Title of study
0.2	Name of reviewer
Section 1	**Course Information**
1.1	What is the title of the course(s) described in the paper?
1.2	What discipline area/department is the course taught in?
1.3	What course format(s) does the paper discuss?
1.4	What is the approximate enrollment of the course?
1.5	At what institution or in what geographic region is the course taught?
Section 2	**Methodology**
2.1	Characterize the methods used in the study (quantitative, qualitative, mixed-methods, unclear)
2.2	What type of data is collected in the study?
2.3	Describe the specific data collection methods used (follow-up to previous).
2.4*	What is the sample size of the study? What percentage of the total population is involved in the sample?
2.5	What is the duration of the study?
2.6*	Are the results of the experimental teaching methods compared to data from a control group?
2.7*	Does the study provide enough methodological data for a third-party researcher to replicate the experiment to a reasonable extent?
2.8*	Are multiple researchers involved in the collection and review of data?
2.9*	Additional comments or notes on method and design of study
Section 3	**Results**
3.1*	Characterize the outcome of the teaching methods described in the completed study in terms of impact on student learning
3.2	Summarize the teaching methods described in the study
3.3	What is the intended outcome of the teaching method?

Appendix B — Quality Assessment Table

Title of Study	Impact of teaching methods on student learning	Student Participation	Replicable?	Compared to control?	Quality Overview
††Ferri, Harris, Weitnauer, and Majerich (2015). A feedback-based approach for evolving a blended class model for large enrollment, multiple section circuits courses.	Positive	Self-selected	Yes	Somewhat	Very positive results from a self-selected sample group may indicate bias. Mostly positive indicators.
††Shepard and Carlin (2014). A first-year soldering and analog music-to-light modulator electronics lab project.	Positive	Self-selected	Yes	Somewhat	Very positive results from a self-selected sample group may indicate bias. Mostly positive indicators.
Fares, Joujou, Khaddaj, and Kabalan (2012). A learning approach to circuitry problems using Matlab and PSPICE.	Somewhat positive	Self-selected (survey), unknown (quantitative)	No	No	Mostly negative indicators.
††Holland (2015). A mixed instructional methods approach to teaching a circuits and instrumentation course.	Positive	Required, self-selected (survey only)	Yes	Somewhat	Mostly positive indicators.
Sterian, Adamczk, and Rahman (2008). A project-based approach to teaching introductory circuit analysis.	Unknown	Unknown	Somewhat	No	Mostly negative indicators. Unknown conclusions and unclear methods indicate potential design flaws.
††Etchepareborda *et* al. (2018). A project-based learning method applied to an introductory course in electronics engineering.	Positive	Self-selected	Yes	Somewhat	Very positive results from a self-selected sample group may indicate bias. Mostly positive indicators.
††Skromme and Robinson (2015). Addressing barriers to learning in linear circuit analysis.	Positive	Required	Somewhat	Yes	Mostly positive indicators.

†Evans, Hummel, and Gates (2015). Assessing the effect of online homework on student learning in a first circuits course.	Unknown	Required	Yes	Yes	High quality indicators for study. Questionable quality of teaching methods.
Maheswaran (2015). Assessment and analysis of learning via a new approach! Teaching electrical circuits course by Mastering Engineering.	Positive	Self-selected	Yes	No	Very positive results from a self-selected sample group may indicate bias. Lacks control group. Mostly lacks indications of quality.
Connor, Schorch, Gullie, Newman, Armand, and Braunstein (2018). Experiment-centric pedagogy in circuits and electronics courses.	Somewhat positive	No coherent sample population.	No	No	Low quality indicators.
Connor *et al*., (2016). Experimental centric pedagogy in circuits and electronics courses at 13 universities.	Somewhat positive	Unknown	Somewhat	No	Mixed to negative quality indicators.
Timmermann and Kautz (2014). Investigating student learning of the voltage and potential concepts in introductory electrical engineering.	Negative	Required	Yes	No	Mixed quality indicators for study. Poor quality of teaching methods.
††Papanikolaou, Tombras, Van De Bogart, and Stetzer (2015). Investigating student understanding of operational-amplifier circuits.	Study did not involve the implementation of a teaching method.	Required	Yes	No	Mostly positive indicators.
Lawanto and Santoso (2013). Investigating students' self-regulated learning while learning electric circuit concepts with enhanced guided notes.	Somewhat positive	Unknown	Yes	Somewhat	Mixed quality indicators. Data collection methods not well-described.
Blanding and Meah (2014). Laboratory-based project-oriented	Positive	Required (grades), self-selected	Somewhat	No	Good data collection methods used by only one researcher. Overall mixed quality.

introductory course for electrical engineering.		(survey)			
Harbour and Hummel (2010). Migration of a robotics platform from a freshman introduction to engineering course sequence to a sophomore circuits course.	Somewhat positive	Self-selected	Yes	Somewhat	Mixed to positive quality indicators.
Parent (2017). Novel gateway stay/add policy used to increase student success rates in an introductory circuits class.	Somewhat positive	Required	Somewhat	Somewhat	Mixed to positive quality indicators.
††Sichel, Woolf, and Floryan (2014). Personalized intelligent software responses for engineering students.	Neutral	Required	Yes	Somewhat	Mostly positive quality indicators. Teaching methods ineffective but not harmful.
Nelms, Langford, and Halpin (2005). Problem-solving videos as an instructional aid for engineering education.	Unknown	Unknown	Somewhat	No	Mostly negative quality indicators.
††Delvicario, Lauria, Mellodge, and Yu (2018). Promoting critical thinking through troubleshooting exercises in fundamental electric circuits labs.	Positive	Required (grades), self-selected (survey)	Yes	No	Mostly positive quality indicators.
Bell and Horowitz (2018). Rethinking non-major circuits pedagogy for improved motivation.	Unknown	Self-selected (survey)	Yes	Somewhat	Study lacks necessary description. Mixed to poor quality indicators.
†Skromme *et* al. (2015). Step-based tutoring system for introductory linear circuit analysis.	Positive	Required, self-selected	Yes	Yes	High quality indicators.
††O'Connell and On (2012). Teaching circuit theory courses using team-based learning.	Positive	Self-selected	Yes	Somewhat	Very positive results from a self-selected sample group may indicate bias. Mostly positive indicators.

††Santiago and Abioye (2015). Teaching electronics to first year engineering students.	Somewhat positive	Self-selected	Yes	No	Possible self-selection bias. Mostly positive indicators.
†Benson and DePiero (2017). Teaching introduction to electronic circuits in a studio format.	Positive	Required (exam), self-selected (survey)	Yes	Yes	High quality indicators.
††Lord, Przestrzelski, and Reddy (2019). Teaching social responsibility in a circuits course.	Somewhat positive	Self-selected	Yes	No	Possible self-selection bias. Mostly positive indicators.
†Berry (2005). The re-design of an introductory circuits course based upon student demographics.	Positive	Required	Yes	Yes	High quality indicators.
Ferri, Majerich, Parrish, and Ferri (2014). Use of a MOOC platform to blend a linear circuits course for non-majors.	Somewhat positive	Required	Somewhat	No	Mixed quality indicators. Potential methodological flaws.
Weyten, Rombouts, Catteau, and De Bock (2011). Validation of Symbolic Expressions in Circuit Analysis E-Learning.	Unknown	Self-selected	Yes	No	No data was collected on student understanding. Mostly lacks indications of quality.
††Sichel, Woolf, and Floryan (2014). Web-based personalized laboratories for engineering students.	Positive	Required (grades), self-selected (survey)	Yes	No	Mostly positive quality indicators. Lacks multiple researchers.

Appendix C — Teaching Methods Summary Table

Article	Category of Method	Description of Teaching Method	Research methods	Findings to be highlighted
Bell and Horowitz (2018). Rethinking non-major circuits pedagogy for improved motivation.	Project/ laboratory	Project-based learning: seven week introductory course (for non-majors and even non-engineers) completely designed around introductory projects based on real applications (solar charger, EKG).	Reported student enrollment numbers and demographics (year, major) for the class and qualitative responses from student surveys.	Course was very popular with students.
†Benson and DePiero (2017). Teaching introduction to electronic circuits in a studio format.	In-class/ lecture; Project/ laboratory	Studio classroom (lecture merged with a laboratory to immediately apply concepts).	A survey was given to measure student comprehension and enjoyment. Final exam scores were compared to a previous class.	Students reported enjoying the studio format, finding the labs useful, and feeling confident in their decision of their major.
†Berry (2005). The re-design of an introductory circuits course based upon student demographics.	In-class/ lecture; Out-of-class	Cooperative learning: students were paired with a team to learn with inside and outside of classes.	Overall course grade was compared for students in a control group, collaborative course, and cooperative course. The effects of race, gender, and major were also controlled for.	"Significant improvement in the students' overall mean grade between the cooperative learning course and the control course… [and] between the collaborative course and the cooperative course. An improvement in course performance based upon gender as well as for African American students [was also seen]."
Blanding and Meah (2014). Laboratory-based project-oriented introductory course for electrical engineering.	Project/ laboratory; In-class/ lesson	Introductory laboratory-based and project-oriented course focused on introducing test equipment, teaching engineering design, and connecting students to the discipline.	End of semester practicum test, end of semester survey with quantitative and qualitative questions.	80% of students passed the practicum test. Positive student feedback.
Connor *et al*., (2016). Experimental centric pedagogy in circuits and electronics courses at 13 universities.	Project/ laboratory	Traditional labs are replaced with labs using an "ADB", or Analog Discovery Board.	Relied primarily on responses on student surveys re: the efficacy of the ADBs. Also included excerpts from student interviews and interviews with TAs and instructors.	Students reported positive benefits of the ADB on surveys related to their use and impacts on learning.
Connor, Schorch, Gullie, Newman, Armand, and Braunstein (2018). Experiment-centric pedagogy in circuits and electronics courses.	Project/ laboratory; In-class/ lesson	A studio lesson format featuring lecture, experiment, and simulation components. An alternative laboratory environment where weekly lab assignments are replaced with 3 long-term design projects called "beta labs".	Analysis of Piazza discussion forum interactions between instructors and students; written comments from a peer instructor who instructed/observed the course.	Limited findings.

Article	Category of Method	Description of Teaching Method	Research methods	Findings to be highlighted
††Delvicario, Lauria, Mellodge, and Yu (2018). Promoting critical thinking through troubleshooting exercises in fundamental electric circuits labs.	Project/ laboratory	Three "troubleshooting labs" were interspersed through the 12 lab periods of the semester to develop students' troubleshooting and critical thinking skills.	Created a rubric to assess students' troubleshooting abilities. Also administered a 10 question qual/quant feedback survey about the labs and looked for correlations.	Majority of students reported finding the exercises helped develop their troubleshooting abilities and that they were useful.
†Evans, Hummel, and Gates (2015). Assessing the effect of online homework on student learning in a first circuits course.	Out-of-class	Course homework is offered through the online homework platform, "WeBWorK," rather than in a traditional paper format.	In two sections of the course (each taught by different instructors), online and paper-based (the control) homework assignments were alternated. Then in-class quizzes were administered.	Online homework showed to be comparable to paper homework when measured by student quiz performance.
††Etchepareborda *et* al. (2018). A project-based learning method applied to an introductory course in electronics engineering.	Project/ laboratory	A traditional lecture course is replaced with a problem-based learning (PBL) course that centers around a semester-long circuits project. Class sessions are reorganized into 3 hour blocks which are mixed-purpose: they may involve lecture, experiment, and/or project work-time.	A quantitative survey and qualitative questionnaire were given to students at the end of the course semester about the perceived benefits and difficulties of the group project.	Impacts on student learning were not assessed.
Fares, Joujou, Khaddaj, and Kabalan (2012). A learning approach to circuitry problems using Matlab and PSPICE.	Project/ laboratory	A three-part circuit analysis lab was assessed: 1) A circuit is solved algebraically by hand. 2) The same circuit is simulated and analyzed in PSPICE. 3) Matlab is used to solve the equations generated in the first step.	Students were administered a mixed quantitative/qualitative course assessment survey which included some questions about the research. Other assessment data is referenced but not provided.	Limited findings reported.
Ferri, Majerich, Parrish, and Ferri (2014). Use of a MOOC platform to blend a linear circuits course for non-majors.	In-class/ lecture; Out-of-class	Flipped classroom in 8-9 different lectures using an online resource to deliver consistent information.	A pretest and posttest were assigned in the form of a modified concept inventory to compare learning between intervention sections and control sections.	Reported less variation between different sections of the course due to the MOOC.
††Ferri, Harris, Weitnauer, and Majerich (2015). A feedback-based approach for evolving a blended class model for large enrollment, multiple section circuits courses	In-class/ lesson	Blended learning - students watched video lectures and used in-class time for mini-lectures and group work.	Primarily relied on a student survey in which students ranked their self-perceived competence on a scale of 1 ("no understanding") to 4 ("solid understanding") for diverse course topics.	When taught in the blended mode, students reported higher levels of confidence compared to the traditional method for more complex topics. Blended learning was more effective when the class could move at a slower pace and with more motivated students.

Article	Category of Method	Description of Teaching Method	Research methods	Findings to be highlighted
Harbour and Hummel (2010). Migration of a robotics platform from a freshman introduction to engineering course sequence to a sophomore circuits course.	Project/ laboratory	Three lab exercises developed for this sophomore-level course to provide additional practice on hardware/tools introduced in the freshman year.	Likert scale survey to determine how confident students were in performing different lab skills sets.	Student self-reported confidence in performing specific tasks increased from pre-survey to post-survey.
††Holland (2015). A mixed instructional methods approach to teaching a circuits and instrumentation course.	In-class/ lesson; Project/ laboratory	Guided inquiry classroom technique -- structured activities/ conversation in the classroom in lieu of lecture. Laboratories focus on experiments and open-ended design. A partial flipped classroom provides lecture content and 'bonus content' -- including special topics, and extra examples done out on confusing topics.	Student demographics, average student grades on specific diagnostic assignments, overall course grades, comments on a student evaluation of teaching methods, formative assessment called the "Circuits Concept Inventory", and instructor observations. Collected semesterly.	Primarily describes the evolution of a course design over time. "No one instructional approach was identified as a [sic] providing a significant increase in student course outcome attainment. Rather, a variety of approaches … appears to provide a robust experience that complements a variety of learning styles."
Lawanto and Santoso (2013). Investigating students' self-regulated learning while learning electric circuit concepts with enhanced guided notes.	In-class/ lesson	Used enhanced guided notes (notes with blanks or omitted information, enhanced with frequent questions tied to metacognition and self-regulation) to replace traditional note-taking during a circuits course.	Self-regulated learning survey instrument developed using Butler and Cartier's SRL model; Holton's DC/AC Circuits Concept Inventory to measure students' conceptual understanding.	Increase in students' analytical abilities (e.g. solving circuits problems). Improved self-regulated learning (SRL).
††Lord, Przestrzelski, and Reddy (2019). Teaching social responsibility in a circuits course.	In-class/ lecture	A series of modules to help engineering students consider the social and ethical implications of electrical engineering. Related activities included field trips, guest lectures, and the introduction practical application.	Students were interviewed after modules. An end of class survey was given measuring student-perceived relevance and emotions during modules.	"Students felt that these modules enhanced their learning of circuits content and was relevant to their training as engineers."
Maheswaran (2015). Assessment and analysis of learning via a new approach! Teaching electrical circuits course by Mastering Engineering.	Out-of-class	Homework was offered via Mastering Engineering by Pearson, instead of as paper assignments.	A seven-question yes/no and one question free-response survey was administered to students at the end of the semester.	Minimal findings reported beyond a suggestion to adopt the teaching method.
Nelms, Langford, and Halpin (2005). Problem-solving videos as an instructional aid for engineering education.	Out-of-class	Problem-solving videos were made of the instructor solving example problems which the students could access from the web.	A survey with quantitative and qualitative questions was used to explore how the students used the videos.	Focused on student use of the videos rather than on learning outcomes.

Article	Category of Method	Description of Teaching Method	Research methods	Findings to be highlighted
††O'Connell and On (2012). Teaching circuit theory courses using team-based learning.	In-class/ lecture	Uses a mix of team and individual learning for in-class work. Modules are split into 2-3 week sessions where students do readings alone at the beginning, solve group problems in the middle, then finally are assessed at the end.	Surveys were given on various topics and students were asked if they agree or disagree. The instructor performing the experiment gave feedback on benefits and risks of the teaching strategy.	Limited findings on student learning.
††Papanikolaou, Tombras, Van De Bogart, and Stetzer (2015). Investigating student understanding of operational-amplifier circuits.	Other	No intervention – assesses current teaching practices rather than the implementation of a novel one.	Students were offered a formative quiz assessment after completing a unit on op-amps. Problems asked students to solve op-amp circuits and argue their reasoning for each response.	"Students in all populations struggled to analyze basic op-amp circuits after relevant instruction."
Parent (2017). Novel gateway stay/add policy used to increase student success rates in an introductory circuits class.	Other	A combination of: rearranging course topics, flipped classes, daily quizzes, stricter enforcement of prereqs, online homeworks, and required homeworks.	The impacts of various interventions (flipped class, problem-based learning, required homework completion) on DFW rates were investigated.	Requiring the completion of homeworks was found to be the most impactful intervention.
††Santiago and Abioye (2015). Teaching electronics to first year engineering students.	Project/ laboratory	Hands-on laboratory and group project to apply learning. Main goal to reduce attrition.	A survey was given to assess interest in the class.	"Module was well accepted by students."
††Shepard and Carlin (2014). A first-year soldering and analog music- to-light modulator electronics lab project.	Project/ laboratory	Project-based learning to increase student interest in an introductory course.	Post course surveys were given to students for them to rate their interest in the project on a scale of 1-5 and indicate how much time they spent inside and outside of lab.	Students reported high levels of interest in the project and reported using their final circuit outside of class.
††Sichel, Woolf, and Floryan (2014). Personalized intelligent software responses for engineering students.	Project/ laboratory	Lab-based tutoring software (CIRCE) to give students feedback as they progress through a lab.	Pre- and post- conceptual quizzes and grades on the individual labs.	On early units, scores on post-tests were lower than the scores on pre-, potentially showing the students were overwhelmed initially by the system. However, these scores improved as time progressed.
††Sichel, Woolf, and Floryan (2014). Web-based personalized laboratories for engineering students.	Project/ laboratory	Computer simulated laboratory with immediate feedback (CIRCE).	Students sent a pre and post lab Tweet, Likert Rating for surveys, and pre and post lab quizzes.	Improved lab grades, improved conceptual knowledge, and positive student affect all attributed to the feedback software.

Article	Category of Method	Description of Teaching Method	Research methods	Findings to be highlighted
††Skromme and Robinson (2015). Addressing barriers to learning in linear circuit analysis.	In-class/ lesson	A number of instructional methods are introduced to address common misconceptions and circuit topology topics.	The methods were implemented in one section of a large course, while the other sections continued with traditional methods. Implemented a pre/post concept inventory test to assess impacts and compared to non-intervention sections.	Addressed students' misconceptions directly through targeted models and explanations. Students in the intervention sections scored significantly higher on the post-test than students in non-intervention sections.
†Skromme *et* al. (2015). Step-based tutoring system for introductory linear circuit analysis.	Out-of-class	An intelligent homework software was developed to replace commercial homework software from textbook publishers. The software includes automatic generation of many types of circuits problems, detailed solutions and other pedagogical devices.	Students were randomly assigned to homework groups which use the Circuit Tutor (new method) or commercial method (control) to complete homework assignments. Students were also given surveys about their experience with the software. Homework grades were also factored into the evaluation.	Learning gains were ~10x higher for students using the Circuit Tutor vs. a control in one experiment. Student motivation also increased.
Sterian, Adamczk, and Rahman (2008). A project-based approach to teaching introductory circuit analysis.	In-class/ lesson; Project/ laboratory	Circuits topics are grouped into "theoretical" and "practical", and taught as two corresponding units in one semester (each unit being 1/2 of a semester). A design project is introduced in the lab component of the course -- two design projects and their results are described.	Unclear. Both written and verbal feedback is cited, but collection methods are not described. Instructor observations are relied on heavily.	Unknown. The study was unable to determine the effect of the methods on student learning.
Timmermann and Kautz (2014). Investigating student learning of the voltage and potential concepts in introductory electrical engineering.	In-class/ lesson	A scaffolded tutorial worksheet was used to teach students KVL concepts in lieu of a traditional lecture.	After application of the intervention, questions from the topics covered were presented in a recitation post-test, and a typical class exam. Data is collected from the results of those assignments.	The worksheets did not have the intended impact on improving students' understanding of these topics.
Weyten, Rombouts, Catteau, and De Bock (2011). Validation of Symbolic Expressions in Circuit Analysis E-Learning.	Out-of-class	Complementary electronic tutoring tool that gives students validation on equations.	Students ranked multiple aspects of the optional lessons the Likert Scale. The optional lessons' participation was recorded.	No data was collected on student understanding.