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A Comprehensive Review of Six Circuits Concept Inventories to Understand the Content Coverage and Their Merits

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Abstract

Circuits is one of the fundamental gateway courses not only required for Electrical Engineering students, but other engineering majors as well. Concept inventories are one approach that educators and researchers have used to quantify students’ conceptual understanding of a given topic. Several concept inventories have been developed over the years to measure conceptual understanding, diagnose misconceptions, and evaluate teaching effectiveness. In this study, we identified six concept inventories on circuits, explored their content coverage, reviewed psychometric characteristics, and discussed their application in the literature. The analysis showed that the majority of questions in all concept inventories except the Adaptive Concept Inventory in Introductory Electric Circuits (ACIIEC) are related to Kirchhoff’s laws. The Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT), Inventory of Basic Conceptions-DC circuits (IBCDC), and Simple Electric Circuits Diagnostic Test (SECDT) presented acceptable internal consistency reliability evidence. Four (DIRECT, IBCDC, SECDT, and ACIIEC) out of six concept inventories had validity evidence. Furthermore, ACIIEC’s questions showed on average high item difficulty and good item discrimination. While SECDT was the most frequently cited in all languages, DIRECT was the most frequently cited in English. The findings of this study provide educators and researchers with the knowledge that they need to wisely select from the variety of concept inventories available and implement them to achieve their unique research outcomes and specific educational goals and course objectives.

Keywords: Concept Inventory, Circuits, Electrical Engineering

I. Introduction

Circuits is one of the fundamental gateway courses not only required for Electrical Engineering students, but also other engineering majors, such as Aerospace Engineering, Chemical Engineering, Civil Engineering, and Mechanical Engineering, many of whom include a circuits course as part of their undergraduate curriculum [1]. Moreover, there have been a number of interventions in circuits aimed at improving students’ understanding and helping undergraduate students master the subject, which highlights circuits’ importance to many engineering fields [2]-[5]. Therefore, assessing students' understanding of circuits content and diagnosing their misconceptions are essential for instructors to monitor students' comprehension and inform their teaching practices.

Assessing students’ understanding can take different formats. One of these formats is using exams to evaluate students' learning. Interestingly, while students might do well in traditional exams, they might not do as well in a concept inventory related to the same topic [6]. This is because in concept inventories, students’ misconceptions of a topic are included as answers choices in a multiple-choice question. In traditional exams, however, it is possible that misconceptions are not included in the answer choices. Another reason is that traditional exams in a circuits class is likely to have more open-ended questions rather than multiple choice questions. This means that as long as a student has memorized how to solve that type of problem, they don't necessarily need to actually fully understand the underlying concept, whereas a concept inventory is specifically looking at their conceptual understanding and not their ability to solve a problem. Additionally, concept inventories can show the effectiveness of the instructors' teaching methods to illustrate what students learned in the course [7]. Finally, educators and researchers can assess and quantify students' conceptual understanding of a given topic using concept inventories [8].

In circuits education, researchers have developed several different concept inventories related to circuits. The first circuits-specific concept inventory published was the Electric Circuit Conceptual Evaluation (ECCE), introduced in 1996 by Sokoloff [9]. After that, a number of concept inventories related to circuits concepts were developed, such as the Circuit Concept Inventory (CCI) [10], the Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT) [11], the Signal and Systems Concept inventory (SSCI) [12], the Inventory of Basic Conceptions-DC circuits (IBCDC) [13], the AC/DC Concept Inventory (AC/DC) [14], the Electric Circuits Concept Inventory (ECCI) [15], the Simple Electric Circuits Diagnostic Test (SECDT) [16], the Adaptive Concept Inventory in Introductory Electric Circuits (ACIIEC) [17], and the Electrical Circuit Concept Diagnostic (ECCD) [18], listed in chronological order based on initial publication date. While these instruments may have similarities in the content coverage, each seems to have unique characteristics and applications in research and thus a potential different application within circuits education.

A. Purpose of the Study

We had several goals for this study. First, we identified concept inventories that could specifically be used for the circuits concepts usually taught in engineering, physics, or other similar courses. Second, as all concept inventories are not the same, we aimed to review their content coverage in circuits and psychometric characteristics, such as their validity and reliability evidence and their item characteristics. Finally, we explored the application of concept inventories by introducing three different application indexes (Alpha, Beta, and Gamma), which were used to quantify the degree to which each inventory has been used in the current literature. Therefore, the following research questions guided this study: (a) What concept inventories have been developed for circuits education?; (b) What content/topics in circuits were addressed in the concept inventories?; (c) What were the psychometric characteristics of each concept inventory?; and (d) To what extent did concept inventories contribute to circuits education and research?

II. Background Literature

A. Definition of a Concept Inventory and Its Common Roles

Understanding basic electric circuits concepts is foundational to many areas of engineering, making it essential for students to master this subject to be effective in their future profession. Therefore, the ability to reliably assess students' understanding of electric circuits concepts is crucial to identifying ways to improve students' knowledge of the subject. Concept inventories are one approach that educators and researchers have used to quantify students' conceptual understanding related to a specific topic. A concept inventory is an instrument that helps instructors assess their students' common beliefs and understandings of a concept [7]. Concept inventories are typically multiple-choice instruments where the answer to each problem consists of one correct answer and several distractors, with each distractor corresponding to a commonly held misconception about the concept [6].

The idea of concept inventories originated with the Force Concept Inventory in 1992 [7]. Since then, the approach has been adapted to a variety of topic areas, including basic electric circuits. The Electric Circuits Conceptual Examination (ECCE) debuted in 1996 [9]. Several additional concept inventories have been developed in the years since to measure conceptual understanding, diagnose misconceptions, and evaluate teaching effectiveness [10]-[16].

B. Past Reviews of Concept Inventories for Circuits Education

There have been several recent studies comparing several of the circuits concept inventories listed previously. Lindell et al. [19] reviewed the development methodologies of 12 concept inventories related to Physics and Astronomy. One of the concept inventories related to electrical topics was the DIRECT. The authors found that the definition of concept inventories is broad and needs to be better defined. This conclusion was made so that tests that did not follow the format and structure of concept inventories were not counted as concept inventories. The need to develop a guideline to design concept inventories was also emphasized [19].

Additionally, Sangam and Jesiek [20] reviewed four concept inventories in circuits. ECCE, CCI, DIRECT, and AC/DC were compared based on types and number of questions, number of questions on each concept, number of options for multiple choice questions, and questions' use of pictures and diagrams. The authors recommended useful scenarios for using each concept inventory. They also proposed suggestions for improvement of each concept inventory.

Furthermore, Ogunfunmi et al. [21] compared three concept inventories for circuits and systems courses. Two of these concept inventories, ECCI and SSCI are related to electrical circuits and the other one is related to digital logic circuits. The authors described the major topic of each concept inventory, the fundamentals of conceptual topics, and the possible application to each concept inventory [21].

Although previous reviews have benefited the engineering community, some gaps were found [19]-[21]. For example, content comparisons between the questions of concept inventories were not done. Additionally, IBCDC, SECDT, and ACIIEC were not included in previous reviews. Moreover, Sangam and Jesiek [20] compared the application of four concept inventories using a qualitative approach, but there is a need for quantifying the application of circuit concept inventories in studies to widen the comparison dimension and provide more validate information for the future users of these concept inventories. Therefore, this review study was conducted to address the aforementioned gaps in concept inventories in circuit education.

III. Method

To answer the research questions, we performed the following: (a) identified existing concept inventories for circuits education from the literature, (b) acquired copies of the concept inventories, (c) coded the content based on primary concept covered for each item included in the concept inventories, (d) located the articles they cited for references and articles that used the concept inventories, and (e) identified psychometric characteristics of the concept inventories found in the literature.

A. Identification of Existing Concept Inventories on Circuits

The first step in identifying the existing concept inventories in the literature was to perform a search in Google Scholar. After reviewing the studies found that introduced or developed a concept inventory for circuits education, we expanded our search by utilizing forward and backward snowball methods to identify additional concept inventories related to circuits education [22]. Our search resulted in the identification of 11 concept inventories that could potentially be used for circuits education, as listed in Table 1.

Table 1. Concept Inventories Related to Circuits in the Order of Development

Concept Inventory	**Acronym**	**Authors**	**Year**
Electric Circuit Conceptual Evaluation	ECCE	Sokoloff [9]	1996
Conceptual Survey in Electricity and Magnetism	CSEM	Hieggelke et al. [23]	2001
Circuit Concept Inventory	CCI	Evans et al. [10]	2003
Determining Interpreting Resistive Electric Circuits Concepts Test	DIRECT	Engelhardt & Beichner [11]	2004
Brief Electricity and Magnetism Assessment	BEMA	Ding et al. [24]	2006
Inventory of Basic Conceptions - DC Circuits	IBCDC	Halloun [13]	2006
AC/DC Concept Inventory	AC/DC*	Holton et al. [14]	2008
Electric Circuits Concept Inventory	ECCI	Rahman & Ogunfunmi [15]	2010
Simple Electric Circuits Diagnostic Test	SECDT	Pesman & Eryılmaz [16]	2010
Adaptive Concept Inventory in Introductory Electric Circuits	ACIIEC*	Espera & Pitterson [17]	2020
Electric Circuit Concept Diagnostic	ECCD	Hunsu et al. [18]	2022

Note. *The acronyms were given by the authors of this paper and not by the developer of the concept inventories.

B. Six Concept Inventories Reviewed for This Study

To obtain copies of the concept inventories listed in Table 1, we either contacted the authors of the concept inventories or collected them from PhysPort (https://www.physport.org/). As a result, we were only able to acquire six concept inventories for this study. The other five concept inventories were not used in this study because either more than half of their question were not specific to circuits (e.g., CSEM and BEMA) or we were not able to acquire them by January 2025 (e.g., CCI, AC/DC, and ECCD). For example, the majority of questions in CSEM are related to charges and Coulomb's law. Additionally, BEMA's focus is not specific to circuits' concepts. It included questions related to charges, Coulomb's law, electrical fields, and magnetic fields. As a result, these concept inventories were excluded from this study. Table 2 shows the summary of the six concept inventories, the method we used to acquire them, and the cost/condition for the acquirement.

Table 2. Method of Acquiring the Six Concept Inventories Used in This Study in the Order of Development

Concept Inventory	Acquirement Method	Cost
ECCE	Contacted the author. Then directed to the PhysPort website [25]	Free, but need to be an educator to register on the PhysPort website
DIRECT	Contacted the author. Then directed to the PhysPort website [25]	Free, but need to be an educator to register on the PhysPort website
IBCDC	Acquired by contacting the author	Free
ECCI	Acquired by contacting the author	Free
SECDT	Acquired by contacting the author	Free
ACIIEC	Acquired by contacting the author	Free

Table 3 shows student level, number of questions, types of questions, and time limits for each concept inventory. For the two concept inventories that were acquired from the PhysPort website [25], the student level was informed by PhysPort. As for other four concept inventories, the perceived student level was determined by studies using the concept inventory for students. Table 3 also includes the availability of administration directions and answer keys.

Table 3. Characteristics of the Six Concept Inventories on Circuits Used in This Study

Concept Inventory	Student Level	#Q	Question Type	Time Limit (Minutes)	Directions & Answer Key
ECCE	High School and Intro College	45	45 questions, each with 3-to-10 multiple-choices and 4 optional explanatory questions	60	Yes/Yes
DIRECT 1.2	High School and Intro College	29	29 questions, each with 4-to-5 multiple-choices	30	Yes/Yes
IBCDC	High School and Intro College	33	33 questions, each with 5 multiple choices	30	Yes/Yes
ECCI	Intro College	20 (35)*	15 3-to-5 multiple choice questions and 5 explanatory questions	-	No/Yes
SECDT	High School	12 (36)**	12 2-to-5 multiple choice questions	-	Yes/Yes
ACIIEC	Intro College	20	20 3-to-4 multiple choice questions	45	Yes/Yes

Note. #Q = The total number of questions; * ECCI has 20 questions, but since some of the questions have more than one sub-question inside them, both the number of questions (20) and the total number of questions (35) are mentioned; ** SECDT is a three-tier concept inventory with 36 questions for 12 circuits questions, 12 reasoning questions, and 12 confidence level question

C. Coding Concept Inventories for Content Coverage

To show the degree to which each concept inventory covers the full topics taught in a traditional Circuits I class, we first divided all the topics into 20 categories based on the order of appearance in the course syllabus in the circuits course taught at our institution, an urban public research university [27]. Table 4 lists the final 20 categories for content coverage used for this study.

Two of the authors of this study, who have a background in Electrical Engineering, determined the content coverage for all six concept inventories. Each author coded the questions individually based on the content categories defined in Table 4. It was decided that each question would only be assigned to the one category to which it is was mostly closely related. Once each author completed their independent coding of the questions for each inventory, they shared their findings with each other. Any discrepancies in the coding were discussed and a final coding for each question was determined based on the results of those discussions.

Table 4. Contents of the Circuits I Course

Category Number	**Category**
1	Basic electrical concepts (charge, current, voltage, power, energy)
2	Types of circuit elements (sources, resistors)
3	Ohm's Law
4	Kirchhoff's Current Law and Kirchhoff's Voltage Law
5	Series and Parallel combinations
6	Nodal and Mesh Analysis
7	Theorems: Linearity, superposition, source transformation, Thevenin and Norton equivalent circuits, maximum power transfer
8	Operational amplifiers (OPAMPs)
9	Capacitors/Inductors
10	First-order circuits
11	Second-order circuits
12	Sinusoids and Phasers
13	Sinusoidal steady-state response
14	AC power
15	Three-phase circuits
16	Magnetically coupled circuits (transformers)
17	Frequency response (resonance, filters)
18	Two-port networks
19	Laplace and Fourier transformations
20	Irrelevant questions to circuits

D. Searching Psychometric Characteristics of Concept Inventories

The next step was finding evidence for the psychometric characteristics of each concept inventory. This step started by locating the article published by the developers of each concept inventory. Later, the literature was explored for articles that cited each concept inventory. These were reviewed to find studies that used the instrument and reported psychometric characteristics. We categorized the evidence for psychometric characteristics based on the following: (a) reliability, (b) content validity, (c) construct validity, (d) convergent validity, (e) divergent (or discriminant) validity, (f) predictive validity, (g) concurrent validity, (h) item difficulty, and (i) item discrimination.

E. Coding Papers for Application Indexes

As a concept inventory can be used in many countries and cultures around the world, we devised three application indexes. Table 5 displays their definitions and the formula to calculate them. The first index is based on the number of citations of a concept inventory, regardless of the language of the citing paper. Based on the inability to read studies in languages other than English, we decided to define a second index, which only counts the number of citations of the articles written in English. The third index was to only count studies in English that actually used a concept inventory to assess student understanding. Therefore, if a study reviewed other concept inventories, it was counted as "cited" not "used." This process was achieved by reading all the articles in English that cited a specific concept inventory. As each concept inventory was developed at a different time, we added a time factor to calculate the application indexes because naturally older concept inventories were cited/used more often compared to recent ones. Note that self-citations by the developers/authors of the concept inventory were excluded in the index calculations.

Table 5. Application Indexes for Concept Inventories

Application Index	Definition	Formula
AI_Alpha	The total number of citations by articles in any language per year	$\frac{\text{The total \# of citations}}{(2025 - \text{the year that the CI was published})}$
AI_Beta	The total number of citations by articles in English per year	$\frac{\text{The total \# of citations in English}}{(2025 - \text{the year that the CI was published})}$
AI_Gamma	The total number of articles in English that used the concept inventory for students	$\frac{\text{The total \# of studies in English that used the CI}}{(2025 - \text{the year that the CI was published})}$

Note. AI = Application Index; CI = Concept Inventory; The year refers to the publication year of an article that officially mentioned the concept inventory.

IV. Results

The results were classified into three parts. First, the findings on content coverage for each concept inventory is presented. Second, the findings on psychometric characteristics of concept inventories are presented. Last, the application of each concept inventory using three AI indexes is presented.

A. Content Coverage

The content for each question in the concept inventories was determined and categorized using the content categories presented in Table 4. Table 6 presents the topical categories, the number of questions related to each category, and the percentage of the questions each category covered. As displayed in Table 6, none of the concept inventories covered all 20 topics. Additionally, all concept inventories except ACIIEC covered the topics related to beginning of the semester. Moreover, the most common concepts covered were Kirchhoff's Law (ECCE, DIRECT, IBCDC, ECCI, SECDT) and series and parallel elements (ECCE, DIRECT, IBCDC, ECCI), respectively.

Table 6. Content Coverage for Each Concept Inventory

	Topic Category	ECCE		DIRECT 1.2		IBCDC		ECCI		SECDT		ACIIEC	
		#Q	%	#Q	%	#Q	%	#Q	%	#Q	%	#Q	%
1	Basic Concepts			7	24.1	4	12.1			2	16.7		
2	Type of Elements			3	10.3	1	3.0	1	2.9				
3	Ohm's Law					7	21.2	1	2.9				
4	Kirchhoff's Law	25	55.6	13	44.8	12	36.4	10	28.6	10	83.3		
5	Series and Parallel	7	15.6	6	20.7	9	27.3	10	28.6				
6	Nodal and Mesh												
7	Theorems							2	5.7				
8	OPAMPs												
9	Capacitors/Inductors							4	11.4			6	30.00
10	First-order	6	13.3					6	17.1			6	30.00
11	Second-order											2	10.00
12	Sinusoids, Phasers											6	30.00
13	Sin SS Response												
14	AC power	7	15.6										
15	Three-phase												
16	Transformers												
17	Frequency RSP												
18	Two-port networks												
19	Lap and Fourier												
20	Irrelevant Qs to circuits							1	2.9				
	Total #Qs	45	100.0	29	100.0	33	100.0	35	100.0	12	100.0	20	100.0

Note. #Q = A total number of questions; Theorems include linearity, superposition, source transformation, Thevenin and Norton equivalent circuits, and maximum power transfer; OPAMPs = Operational amplifiers; Sin SS Response = Sinusoidal steady-state response; RSP = Responses; Lap = Laplace

B. Psychometric Characteristics of Six Concept Inventories on Circuits

Table 7 summarizes the evidence for reliability, validity, item difficulty, and item discrimination of six concept inventories in the literature.

Table 7. Summary of Psychometric Evidence for Concept Inventories

Concept Inventory	Vr	Reliability	Content Validity	Construct Validity	Convergent Validity	Item difficulty	Item Discrimination
ECCE	1.0	-	-	-	-	-	-
DIRECT	1.0	KR-20 = 0.71	[11]	[11]	-	0.15 to 0.89 Avg = 0.49	0.00 to 0.43 Avg = 0.24

		[11]				[11]	[11]
	1.1	KR-20 = 0.70 [11]	[11]	[11]	-	0.04 to 0.82 Avg = 0.41 [11]	0.01 to 0.43 Avg = 0.23 [11]
	1.2	-	-	-	-	-	-
IBCDC	1.0	Cronbach α = 0.79 [13]	[13]	-	[13]	-	-
ECCI	1.0	-	-	-	-	0.09 to 1.00 Avg = 0.80 [21]	-
SECDT	1.0	Cronbach α = 0.69 [16]	[16]	-	[16]	*0.22 to 0.77 Avg = 0.48 [16]	-
ACIIEC	1.0	KR-20 = 0.558 [28]	[25]	[25]	-	0.16 to 0.89 Avg = 0.44 [28]	0.08 to 0.67 Avg = 0.36 [28]

Note. – indicates that the evidence for that part was not reported or we were not able to find it. *Item difficulty for the first tiers which is related to circuits is mentioned; Avg = Average; Vr = Version; KR-20 = Kuder-Richardson Formula 20

B.1. Validity Evidence

For this study we were able to identify content, construct, and convergent validity evidence of concept inventories as follows.

Content Validity

Content validity evidence of IBCDC was established with the feedback from university professors and high school teachers, sampling validity of the taxonomies, and checking that items should measure what they are supposed to measure in the Taxonomy [13].

Content validity evidence of DIRECT 1.0 and DIRECT 1.1 was determined by item analysis through a panel that took the test, which covered all multiple-choice questions and open-ended questions [11]. Since the Questions for DIRECT 1.2 are the same as DIRECT 1.0, the content validity evidence of the previous versions can be applied to DIRECT 1.2 as well, but since it was not reported specifically, it was not mentioned in Table 7.

Content validity evidence of SECDT was determined by conducting interviews with two physics experts and instructors, creating and administrating open-ended questions to high school students, giving the modified test to instructors again to check the improvements, and finally administrating the final version of SECDT to students [16].

The content validity evidence of ACIIEC was determined by a pilot study with 18 Filipino students and 3 Filipino instructors and interviews with 5 Filipino students and 1 Filipino instructor [17].

Construct Validity

Construct validity evidence for DIRECT 1.0 was determined by identifying 8 factors using Exploratory Factor Analysis (EFA) [11]. However, construct validity evidence of DIRECT 1.1 was determined by identifying 11 factors using EFA [11].

As for ACIIEC, EFA indicated 8 latent factors and another round of factor analysis indicated 2 factors. Espera and Pitterson [28] addressed that questions about AC/DC circuit analysis were considered as a whole and also focused on analyzing electrical devices separately.

Convergent Validity

Convergent validity found through the search of studies were related to IBCDC and SECDT. For IBCDC, Pearson's correlated coefficient was calculated at $r = 0.780$ with Inventories of Basic Conceptions for Mechanics (IBC-Mechanics), and $r = 0.430$ with Views About Science Survey (VASS) [13].

For SECDT, Pearson's product moment correlation coefficient was estimated between combined scores from tiers one and two, and tier three scores on confidence levels with $r = 0.51$ with $p < 0.01$ [16].

B.2. Reliability Evidence

KR-20 and Cronbach's α are both measurements for internal consistency reliability [29], and were used for a number of these concept inventories. For IBCDC and SECDT, Cronbach α was calculated as 0.79 and 0.69, respectively [13], [16]. For ACIIEC, DIRECT 1.0, and DIRECT 1.1, the KR-20 was calculated as 0.56, 0.71, and 0.70, respectively [11], [28].

B.3. Item Difficulty

Engelhardt and Beichner [11] reported the evidence for item difficulty of DIRECT 1.0, DIRECT 1.1, and Espera and Pitterson [28] reported the aforementioned evidence for ACIIEC [11], [28]. The item difficulty of ECCI was calculated by the researchers of this study based on the data in Figure 10 of [21]. As for SECDT, Figure 4 in [16] showed the percentages of correct responses in terms of a number of tiers which is the same as the definition of item difficulty even though they did not directly mention item difficulty.

Engelhardt and Beichner [11] concluded that item difficulty for DIRECT 1.0 varied between 0.15 to 0.89 with an average of 0.49 for high school and university level students. They also concluded that the item difficulty for DIRECT 1.1 varied between 0.04 to 0.82 with an average of 0.41 [11] for high school and university level students.

ECCI was used for 23 students and the total number of incorrect answers was mentioned in one of the figures of the study [21]. Based on the numbers in Figure 10 (p. 21), we calculated that the item difficulty varies between 0.09 to 1.00 with an average of 0.80.

SECDT was used as a three-tier tool to find 124 students' misconceptions [16]. Based on the findings, they classified the item difficulty into three different categories. The first category was to evaluate answers on the first-tier questions. The second category was to evaluate answers on the first- and second-tier questions. The third category was to evaluate answers on all three tier questions. According to the findings of the study, item difficulty for just the first tier varied between 0.22 to 0.77 with an average of 0.48. As for the first and second tiers, the item difficulty varied between 0.02 to 0.59 with an average of 0.30. Additionally, item difficulty for all three tiers together varied between 0.02 to 0.48 with an average of 0.24 [16].

Finally, item difficulty for ACIIEC was determined to be 0.16 to 0.89 with an average of 0.44 [28].

B.4. Item Discrimination

Engelhardt and Beichner [11] reported that item discrimination for DIRECT 1.0 varied between 0.00 to 0.43 with an average of 0.24. They also shared that seven of the questions have a discrimination value of more than 0.3, 16 of them have a discrimination value between or equal to 0.20 and 0.29, and six questions have a discrimination value of less than 0.19. Engelhardt and Beichner [11] also mentioned that item discrimination for DIRECT 1.1 varied between 0.01 to 0.43 with an average of 0.23. They also mentioned that nine of the questions have a discrimination value of more than 0.3, 10 of them have a discrimination value between or equal to 0.20 and 0.29, and 10 questions have a discrimination value of less than 0.19 [11].

Espera and Pitterson [28] reported that the lowest value of item discrimination for ACIIEC was 0.08 and its highest value was 0.67 with an average of 0.36. Additionally, based on their report, 12 of the questions showed a discrimination value of more than 0.3, two of them showed a discrimination value between or equal to 0.20 and 0.29, and six questions had a discrimination value of less than 0.19 [28].

C. Applications of Concept Inventories

Figure 1 shows the number of studies we used to calculate each application index and the steps we took to classify studies during January 2025.

Figure 1. Flow Chart to Display the Number of Articles Cited and Used Each Concept Inventory for Each Application Index

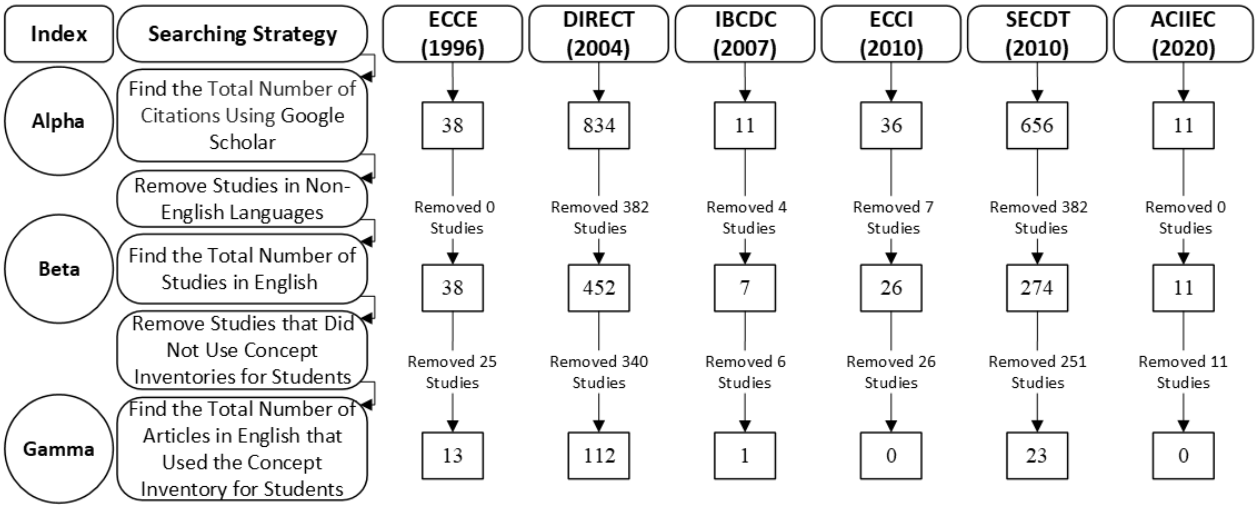

Table 8 presents the three application indexes calculated for each concept inventory when the time was factored in using the formulas presented in Table 5. DIRECT was cited the most with 834 citations and SECDT is ranked second with 656 citations as shown in Figure 1. However, since DIRECT was developed in 2004 and SECDT was developed in 2010, the AI_Alpha index for SECDT was higher. In both AI_Beta, "articles in English," and AI_Gamma, "used by studies in English," DIRECT recorded a greater number of studies. Even with an earlier development year, the AI_Beta and AI_Gamma index for DIRECT was higher compared to SECDT.

Table 8. Application Indexes for Concept Inventories

Application Index	ECCE (Sokoloff, 1996)	DIRECT (Engelhardt & Beichner, 2004)	IBCDC (Halloun, 2007)	ECCI Rahman & Ogunfunmi, 2010)	SECDT (Pesman & Eryılmaz, 2010)	ACIIEC (Espera & Pitterson, 2022)
Alpha	1.31	39.71	0.61	2.40	43.73	2.20
Beta	1.31	21.52	0.39	1.73	18.27	2.20
Gamma	0.45	5.33	0.06	0.00	1.53	0.00

Note. Self-citations by the developers/authors of the concept inventory were excluded in the index calculations.

V. Discussion

In this study, we reviewed six concept inventories that evaluate students' understanding of circuits concepts. For discussion, we elaborate more on the findings of the content coverage, reliability and validity evidence, item difficulty and discrimination, and the application of each concept inventory in research.

A. Content Coverage

Many of the concept inventories discussed have their origins in electricity and magnetism physics courses. While the origin of these inventories does not lie in the primary area of interest, the fundamental concepts covered in both contexts are the same, allowing for these inventories to be used in an engineering circuits course context. Our results indicate that based on Table 6, the majority of concept inventory questions are mostly related to Kirchhoff's current law and Kirchhoff's voltage law. For ECCE, DIRECT, IBCDC, ECCI, and SECDT, the amounts are 55.7%, 44.8%, 36.4%, 29.4%, and 83.3% respectively. However, for ACIIEC, none of the questions specifically focused on Kirchhoff's current law and Kirchhoff's voltage law.

Eight of the categories (e.g., three-phase circuits and operational amplifier) are not measured in any of the concept inventories. ECCE, DIRECT, IBCDC, ECCI, and SECDT focused more on the categories that will be taught to students at the beginning of the circuits course, such as basic concepts, Ohm's law, Kirchhoff's laws, and series and parallel combinations. ACIIEC covered more advanced topics, such as capacitors, inductors, first and second-order circuits, and sinusoidal steady-state response. Finally, our findings indicate that all the questions of the concept inventories are related to circuit concepts, except one question in ECCI. Question 19 from the ECCI concept inventory is a mathematics question that asks students to calculate a V (voltage) in an equation. Although this topic can be related to finding the voltage based on Kirchhoff's current law and Kirchhoff's voltage law, since there were no circuits concept presented in this question, it was counted as an irrelevant question to circuits concepts.

In order to address the gaps in coverage of topics typically covered in engineering circuits courses, the current concept inventories could be revised or a new concept inventory could be developed in order to include more advanced contents, such as OPAMPS, Sinusoidal steady-state response, three-phase circuits, magnetically-coupled circuits (transformers), frequency response (resonance, filters), and Laplace and Fourier transformations. In this case, the concept inventories, which specifically aimed at measuring students' conceptual understanding of circuits, can better align with the modern circuits curricula in engineering education. Additionally, for educators and researchers interested in understanding student's foundational knowledge, any of the inventories can work given their emphasis on KVL and KCL. However, the AEIICE inventory might be best used to investigate understanding of the broader collection of concepts covered in engineering circuits courses.

B. Reliability and Validity

Among the six concept inventories, four of them reported reliability evidence by either Cronbach's α or KR-20 for internal consistency reliability. DIRECT and ACIIEC used KR-20 as their measurement. Both Cronbach's α and KR-20 ranges from 0.0 to 1.0 and the closer it gets to 1.0 can show higher internal consistency reliability. Therefore, it can be concluded that DIRECT (KR-20 = 0.70 ~ 0.71), IBCDC (Cronbach $\alpha = 0.79$), and SECDT (Cronbach $\alpha = 0.69$) showed acceptable reliability evidence, but ACIIEC (KR-20 = 0.56) did not. Therefore, further reliability evidence would be necessary for ACIIEC.

The majority of concept inventories presented evidence for content validity. Only ECCE and ECCI did not present details of the content validity. DIRECT, IBCDC, SECDT, and ACIIEC presented at least two types of validity evidence including content validity evidence. DIRECT and ACIIEC had construct validity evidence for latent factor structures using exploratory factor analysis (EFA), which were inconsistent by studies, so further construct validity evidence using confirmatory factor analysis (CFA) would be necessary. The convergent validity for IBCDC was presented which compared the findings of IBCDC to two other concept inventories, IBC-Mechanics (Inventories of Basic Conceptions for Mechanics) and VASS (Views About Science Survey) using Pearson's product moment correlation coefficients.

C. Item Difficulty and Item Discrimination

Based on the comparison of item difficulty, DIRECT 1.0, DIRECT 1.1, ECCI, SECDT (first tiers), SECDT (all tiers), and ACIIEC have averages of 0.49, 0.41, 0.80, 0.48, 0.24, and 0.44 respectively. By just comparing the numbers, ECCI seems to be the easiest concept inventory and the SECDT seems to be the hardest concept inventory. However, as each concept inventory covers slightly different topics and students did not take all the concept inventories, comparisons of the six concept inventories using the item difficulty and item discrimination calculated based on the classical test are not plausible.

For example, since the average difficulty of ACIIEC is in the same area as DIRECT 1.0, DIRECT 1.1, and the first tiers of SECDT, at first glance, it can be concluded that their difficulties are in a similar range. However, according to the comparison of their content coverage, ACIIEC's questions were related to more advanced topics in Circuits compared to other topics, so comparing the averages of item difficulty across concept inventories seems not to be a good approach to understand the item characteristics presented in concept inventories.

Ranges for the item discrimination index (IDI) and their interpretation can be found in multiple studies [30]-[32]. Based on the information of these studies, and our need to distinguish the item discriminations found in these concept inventories, we defined Table 9 as the reference to interpret the IDI from the concept inventories on circuits.

Table 9. Item Discrimination Index (IDI) for Concept Inventories

Item Discrimination Index	**Interpretation**	**Recommendations**
IDI ≥ 0.3	Good Discrimination	Items are good. They can be kept
0.3 > IDI ≥ 0.2	Acceptable Discrimination	Items can be kept, but they are subject to improvement
0.2 > IDI	Poor Discrimination	Improve the subjects or reject them

The only concept inventories that reported the item discrimination indexes (IDI) were DIRECT 1.0, DIRECT 1.1, and ACIIED. Based on the findings from these concept inventories and Table 9, questions of these three inventories have been classified into three categories "Good Discrimination", "Acceptable Discrimination", and "Poor Discrimination". Table 10 shows the classifications of the questions.

Table 10. Classification of Questions on the Concept Inventories Based on Item Discrimination Indexes (IDI)

Interpretation	**DIRECT 1.0**		**DIRECT 1.1**		**ACIIEC**	
	#Q	**Questions**	**#Q**	**Questions**	**#Q**	**Questions**

Good Discrimination	7	4, 6, 14, 17, 21, 26, 27	9	3, 4, 5, 7, 9, 14, 17, 26, 27	12	4, 7, 9, 10, 11, 12, 13, 14, 15, 17, 18, 19
Acceptable Discrimination	16	1, 2, 3, 5, 7, 8, 9, 12, 15, 18, 19, 22, 23, 24, 25, 29	10	1, 6, 8, 12, 13, 15, 19, 22, 23, 24	2	16, 20
Poor Discrimination	6	10, 11, 13, 16, 20, 28	10	2, 10, 11, 16, 18, 20, 21, 25, 28, 29	6	1, 2, 3, 5, 6, 8

Note. #Q = A total number of questions

Most of the questions for ACIIEC have good discrimination in distinguishing high-performance students from low-performance students when it was given to 41 students [28]. However, as item discrimination indexes were calculated based on the classical test theory, further analysis using item response theory will be beneficial for understanding the difficulty levels of items within concept inventories.

D. Application of Concept Inventories

Each application index can be used to determine which concept inventory has contributed to literature more based on different scenarios. Based on Figure 1, the first conclusion might be that since the number of citations for DIRECT is higher than SECDT, overall, it was more popular. The problem with this conclusion is that DIRECT was published in 2004 and SECDT was published in 2010. Therefore, SECDT was not available for 6 years. That is the reason we defined a metric for time as well as the number of studies in application indexes.

Based on the findings in Table 8, as the Alpha index for SECDT was higher than DIRECT, SECDT was more popular overall. However, both Beta and Gamma indexes for DIRECT were higher than SECDT. Therefore, it can be inferred that DIRECT was more famous for articles that were written in English. Additionally, it can be concluded that DIRECT was used more in studies in English that use a concept inventory to evaluate students’ understanding.

Additionally, AI_Alpha and AI_Beta did not change for ECCE and ACIIEC, which indicates that studies in other languages did not use them. The overall AI_Alpha for ECCI and ACIIEC were in the same range even though ECCI was published 10 years earlier than ACIIEC. Overall, the highest AI_Alpha, AI_Beta, and AI_Gamma were for SECDT, DIRECT, and DIRECT, respectively. Moreover, the lowest AI_Alpha and AI_Beta indexes were for IBCDC, while the lowest AI_Gamma was for ECCI and ACIIEC.

E. Limitations and Future Directions

While we tried our best to collect all the articles that cited and used these concept inventories, it is possible that some of the studies were not collected. There is also a chance that the same study can be reported in more than one article, which may cause an inflation of the AI indexes. Additionally, the review of reliability, validity, item difficulty, and item discrimination has been only made between the studies that reported these psychometric measures.

In defining the application indexes, one of the indexes that could be defined was the "used" category regardless of its language. Since we did not have the resources to translate all the studies in different languages to English for reading, we defined the AI_Gamma index to only count articles in English.

Moreover, more concept inventories could be included in this study. In some cases, we were unable to locate copies of the concept inventories despite repeatedly contacting the authors, both of the original instruments and of papers that used them. Therefore, the review of concept inventories was only conducted for the six concept inventories for which we could obtain a copy.

Circuits include concepts that can be challenging for students to understand. Therefore, the need for a concept inventory that can help instructors on finding students' misconceptions in circuits is undeniable. The six concept inventories do not cover all topics usually covered by Circuits I course. Therefore, if there is a need to cover all topics to assess students' understanding of the concepts at the end of the course, then a future concept inventory could be expanded to include various topics in circuits class, such as OPAMPS, Sinusoidal steady-state response, three-phase circuits, magnetically coupled circuits (transformers), frequency response (resonance, filters), and Laplace and Fourier transformations. Additionally, it is also good to have a concept inventory that covers more of the topics typically introduced in an introductory engineering circuits course rather than just relying on those developed within a physics context. If this can be accomplished, it can help researchers to apply more precise interventions in Circuits I and Physics I classes to enhance student learnings.

F. Conclusion

In this study, we found six concept inventories that could be used in an introductory engineering circuits class to assess student understanding.-Except for ECCE and ECCI, we were able to find reliability and validity evidence to some degree for all the concept inventories. Most concept inventories covered the beginning topics of a typical circuits curriculum, which is because ECCE, DIRECT, IBCDC, and SECDT are basically concept inventories to assess students' understanding of circuits concepts in Physics class and are being used in circuits I class. ACIIEC covers more advanced topics. We were able to find item level characteristics to some degree for all the concept inventories except for ECCE, IBCDC, and DIRECT 1.2. Even though DIRECT 1.0 and DIRECT 1.1 had item-level characteristics, DIRECT 1.2 did not. Finally, based on the three application indexes that were defined in this study, it was concluded that SECDT is more popular in studies from all languages that cited Peşman and Eryılmaz [16] which originally introduced the instrument. However, DIRECT is more popular in studies in English that cited Engelhardt and Beichner [11] which originally introduced the instrument. Additionally, this study showed that DIRECT is more popular for being used as an assessment tool in articles that published their findings in English. Overall, it is recommended that DIRECT and SECDT be used in studies aiming to evaluate students' understanding of fundamental circuit topics, such as Kirchhoff's Current Law and Kirchhoff's Voltage Law. Conversely, if the goal is to assess more advanced topics—such as capacitors and inductors, first- and second-order circuits, and sinusoids and phasors—the ACIIEC can be used.

This study can help educators and researchers by providing details of concept inventories prior to using them inside their classrooms. Also, it can show the gaps in circuits concept inventories and motivates researchers to conduct research on providing remaining validity and reliability evidence of the circuits concept inventories.

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