What Does it Test? Psychometric Properties of the Electronics Concept Inventory with Data from Fourth-Year Electrical Engineering Students in the U.S.

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Abstract

This full paper seeks to contribute to course and curriculum design, improvement, and assessment. With the rise of electronic devices in our lives, electronics has become a key area in advancing technology and enhancing the quality of life. Understanding electronics fundamentals is crucial in many engineering fields, especially for electrical and computer engineering (ECE) students. The Electronics Concept Inventory (ECI), developed in 2004, can help educators identify students' misconceptions in electronics based on common misunderstandings. However, the literature lacks testing of ECI's validity and reliability. This study provided content and construct validity and internal consistency reliability evidence for the ECI through psychometric analysis rooted in the classical test theory. By comparing the ECI content with a common Electronics I textbook, three professors and one doctoral student with an electrical engineering background provided content validity evidence for the ECI. An exploratory factor analysis identified the latent factor structure of the ECI for construct validity evidence using the data from 210 fourth-year ECE students at a southern R1 public university from 2015 to 2017. The ECI included five questions assessing students' understanding of introductory circuits, rather than electronics. Questions about analog and digital integrated circuits are fewer than those about devices and basic circuits. Regarding construct validity, a 0.4 cut-off for factor loadings resulted in 19 items in a three-factor latent structure. Cronbach's α was 0.65 for the original 35-item concept inventory and 0.61 for the retained 19 items after excluding 16 items from the EFA. The findings of this study suggest room to improve the validity and reliability evidence of the ECI to identify students' misconceptions in understanding electronics.

Introduction

Understanding the fundamentals of electronics is essential across many fields of engineering, especially for electrical and computer engineering (ECE) students. Accordingly, electronics education is typically provided to ECE undergraduate students through two foundational courses, Electronics I and II. Often, ECE students take one or both of these courses in the second and third years of their undergraduate studies. Depending on the program's curriculum, students may also be required to take Electronics Laboratory I and II to deepen their comprehension of electronics concepts. Despite the central role of electronics and its integration across multiple courses and labs, students struggle to grasp key electronics concepts [1]-[3]. Hence, it is crucial to first identify the topics students struggle with and then design appropriate instructional practices to address those challenges.

Concept inventories are a common method for identifying students' misinterpretations in a subject [4]. These multiple-choice question instruments typically include one correct answer and several distractors, each associated with a common misconception about the concept [5]. Researchers have developed several concept inventories on fundamental electronics topics to identify students' misconceptions. According to the literature, Flores and Fabela [6] introduced the first electronics-related concept inventory, named the Concept Inventory on Basic Electronics (CIBE), in 2002. After that, a few more concept inventories related to electronics concepts were developed, such as the Electronics Concept Inventory (ECI) [7], Electronics Threshold-Concept Inventory (ETCI) [8], and Basic Electronics Concept Inventory (BECI) [9]. However, the literature consistently points to a notable absence of psychometric evidence for these concept inventories. In many cases, researchers reported limited or incomplete information about their development, validation procedures, or reliability estimates, making it difficult to determine whether the concept inventories accurately and consistently measure the intended students' conceptual understanding.

Purpose of the Study

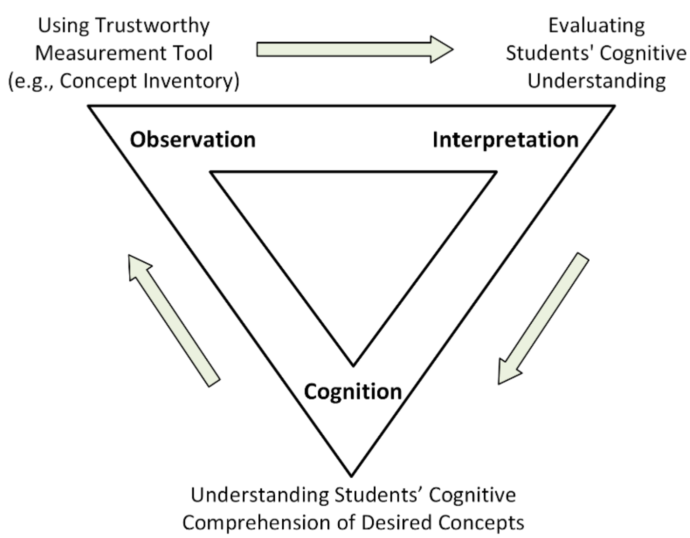
While there are several concept inventories on electronics, the purpose of this study is to provide content and construct validity and internal consistency reliability evidence for the ECI [7]. Therefore, the following research questions guided this study: (a) What content in basic electronics was addressed in the ECI?; (b) To what extent does latent factor structure support the construct validity of the ECI?; and (c) What is the ECI's level of internal consistency reliability?

Theoretical Frameworks

Assessment Triangle Framework

The assessment triangle framework is a model that represents how cognition, observation, and interpretation create the three corners of a trustworthy assessment [10]. Cognition is relevant to how students demonstrate their knowledge and become experts in a field. Observation refers to tasks, activities, and assessments that enable other experts, such as researchers or instructors, to monitor students' performance. Finally, interpretation refers to methods used to make judgments about students' cognition [10]. Figure 1 presents our adapted version of the assessment triangle framework, which aligns well with the application of concept inventories for this study.

Figure 1. Assessment Triangle Framework Adapted for Concept Inventory Implementation



Classical Test Theory (CTT)

CTT is one of the oldest theoretical frameworks used by researchers to develop measurement models, defining the observed test score as the sum of a true score and measurement error [11]. According to Traub [12], Charles Spearman laid the foundation for CTT. Since then, researchers, such as Louis Thurstone, Kuder and Richardson, Lee Cronbach, and Melvin Novick, have contributed to expanding the theory [12]. Using test scores from a trustworthy assessment helps evaluate students' understanding of a topic. Grounded in CTT, various psychometric analyses can be used to provide reliability and validity evidence, such as construct validity evidence using factor analysis and internal consistency reliability.

Literature Review

Concept Inventories as Assessment Instruments

Conceptual understanding is an individual's collection of concepts, beliefs, and mental models related to a topic [13]. Concept inventories are a well-established method for measuring students' conceptual understanding, typically using multiple-choice questions with incorrect responses that reflect the most common misconceptions. The idea of designing an instrument to evaluate students' conceptual understanding of specific concepts and to determine common misconceptions in those concepts originated with the Force Concept Inventory (FCI) in 1992 [4]. The FCI focused on assessing students' misconceptions in forces and kinematics. Since then, concept inventories have been designed for other fundamental topics, such as magnetism [14], signals and systems [15], calculus [16], kinematics and forces [17], waves and optics [18], light and spectroscopy [19], thermal and thermodynamics [20], mathematical reasoning in physics [21], and artificial intelligence literacy [22], to name a few.

A number of reviews of concept inventories in several fundamental topic areas, such as circuits [23]-[24], statics [25], cybersecurity [26], computer science subjects [27], and physics subjects [28] have helped to map the landscape of existing assessment tools, clarify how those concept inventories were developed, identify what constructs were developed, and note where significant gaps remain. Those reviews underscore the importance of evaluating the psychometric properties of these concept inventories, especially given their widespread use by instructors and researchers to identify students' learning gaps.

Electronics Concept Inventory (ECI)

Simoni et al. [7] designed the ECI to assess engineering students' understanding of introductory electronics concepts and to identify their common misconceptions in electronics. To do this, first, they conducted an informal survey of 20 engineering schools and found that, on average, each school required 1.5 semester-long courses in electronic circuit analysis and design. Therefore, the ECI was developed for implementation in the first course of a two-course sequence in electronics. To avoid complex calculations and focus on the underlying concepts, answers are mostly in graphical form. Each question offers four multiple-choice options, including one correct answer and three distractors that present common student misconceptions from the developers' perspectives. Additionally, the developers invited a number of external faculty members to evaluate the ECI. Each external faculty member wrote one new question for the exam and specified one question that should be excluded from the initial concept inventory. The final version of the ECI, consisting of 35 questions, is meant to be administered in a 50-minute time limit.

Although the ECI can be used to assess students' understanding of electronics concepts, data-driven evidence on its validity and reliability has not been reported by its developers or previous researchers. This gap points to the need for a rigorous psychometric evaluation of ECI.

Method

Participants

Participants of this study were fourth-year undergraduate electrical engineering students enrolled in the required 4.5 credit capstone course offered each fall semester from 2015 to 2017 at a Southern R1 public university. Of the 219 students in the course, 210 completed the ECI, resulting in a 95.9% response rate. Unfortunately, demographic information of participants was not directly collected. As an alternative, Table 1 presents the demographic profile of the entire undergraduate student population in the ECE department (includes second, third, and fourth year students who have declared the major), based on the assumption that the participants shared similar demographic characteristics. Consequently, the sample size for each year approximates one-third of the respective annual undergraduate population.

Table 1. All Undergraduate Students' Demographic Profiles in the ECE Department in 2015, 2016, and 2017

Category	Sub-Category	Year		
		2015(%)	2016 (%)	2017 (%)
Sex	Female	15.0	16.0	20.0
	Male	85.0	84.0	80.0
Race/ Ethnicity (Domestic student only)	Asian	25.6	19.4	23.5
	Black or African American	4.6	4.8	3.7
	Hispanic	5.0	6.7	6.2
	Multi-Race	5.0	6.0	6.6
	Unknown	6.7	8.3	9.9
	White	52.9	54.8	50.2
Residence	Domestic	94.0	94.0	94.0
	International	6.0	6.0	6.0
First-Generation	–	11.0	12.0	13.0
Total No. of Declared ECE Undergraduate Students		253	268	258
Capstone Course Class Size		70	71	78
Sample Size of this Study		65	67	78

Instrument

After examining the three electronics concept inventories, such as CIBE [6], ECI [7], and ETCI [8], available at the time of data collection, the ECI was selected based on student level (i.e., seniors). The instructor administered the ECI as an online survey to students toward the end of the semester to determine retention of electronics concepts from previous courses. In 2015, the instructor altered the question sequence by randomly reordering the questions, resulting in a different order from the original ECI item order. However, in 2016 and 2017, the original question order was retained. Table 2 shows the question sequence compared with the original sequence across all years. For example, the second question in the original ECI was the 19th question in the 2015 ECI.

Table 2. Question Order Comparison Between the Original ECI and the Order from 2015

Original Order	2015 Order	Original Order	2015 Order	Original Order	2015 Order	Original Order	2015 Order	Original Order	2015 Order
1	1	8	29	15	8	22	12	29	18
2	19	9	30	16	28	23	32	30	20
3	35	10	3	17	9	24	13	31	21
4	33	11	4	18	10	25	14	32	22
5	26	12	5	19	31	26	15	33	23
6	34	13	6	20	11	27	16	34	24
7	27	14	7	21	2	28	17	35	25

Data Analysis

Content Validity Analysis

A content analysis was conducted to assess evidence of ECI content validity. In this process, four authors of this study with backgrounds in electrical engineering, including three faculty members and one graduate student, identified the most relevant topic for each question on the ECI. These topics were derived from the table of contents of one of the reference materials for a typical Electronics I course [29] as presented in Table 3. According to the content organization by Sedra et al. [29] for their textbook, "*Microelectronic circuits*" *(8th ed.),* there are three categories: (a) Devices and Basic Circuits, (b) Analog Integrated Circuits, and (c) Digital Integrated Circuits. The four raters initially coded the ECI independently. Following the coding process, the researchers met to discuss and resolve any inconsistencies in their coding and to define new topics for questions that the topics from [29] did not specifically address.

Table 3. Categories and Topics of Electronics Textbook [29]

Category	Sub-Category	Topics
Devices and Basic Circuits	Signals and Amplifiers	Signals, Frequency Spectrum of Signals, Analog and Digital Signals, Amplifiers, Circuit Models for Amplifiers, Frequency Response of Amplifiers
	Operational Amplifiers	The Ideal Op Amp, The Inverting Configuration, The Noninverting Configuration, Difference Amplifiers, Integrators and Differentiators, DC Imperfections, Effect of Finite Open-Loop Gain and Bandwidth on Circuit Performance, Large-Signal Operation of Op Amps

	Semiconductors	Intrinsic Semiconductors, Doped Semiconductors, Current Flow in Semiconductors, The pn Junction, The pn Junction with an Applied Voltage, Capacitive Effects in the pn Junction
	Diodes	The Ideal Diode, Terminal Characteristics of Junction Diodes, Modeling the Diode Forward Characteristic, Operation in the Reverse Breakdown Region—Zener Diodes, Rectifier Circuits, Limiting and Clamping Circuits, Special Diode Types
	MOS Field-Effect Transistors (MOSFETs)	Device Structure and Physical Operation, Current–Voltage Characteristics, MOSFET Circuits at DC, The Body Effect and Other Topics,
	Bipolar Junction Transistors (BJTs)	Device Structure and Physical Operation, Current–Voltage Characteristics, BJT Circuits at DC, Transistor Breakdown and Temperature
	Transistor Amplifiers	Basic Principles, Small-Signal Operation and Models, Basic Configurations, Biasing, Discrete-Circuit Amplifiers
Analog Integrated Circuits	Building Blocks of Integrated-Circuit Amplifiers	IC Design Philosophy, IC Biasing—Current Sources, Current Mirrors, and Current-Steering Circuits, The Basic Gain Cell, The Common-Gate and Common-Base Amplifiers, The Cascode Amplifier, Current-Mirror Circuits with Improved Performance, Some Useful Transistor Pairings
	Differential and Multistage Amplifiers	The MOS Differential Pair, The BJT Differential Pair, Common-Mode Rejection, DC Offset, The Differential Amplifier with a Current-Mirror Load, Multistage Amplifiers
	Frequency Response	Low-Frequency Response of Discrete-Circuit Common- Source and Common-Emitter Amplifiers, Internal Capacitive Effects and the High-Frequency Model of the MOSFET and the BJT, High-Frequency Response of the CS and CE Amplifiers, Useful Tools for the Analysis of the High-Frequency Response of Amplifiers, High-Frequency Response of the Common-Gate and Cascode Amplifiers, High-Frequency Response of the Source and Emitter Followers, High-Frequency Response of Differential Amplifiers, Other Wideband Amplifier Configurations
	Feedback	The General Feedback Structure, Some Properties of Negative Feedback, The Feedback Voltage Amplifier, Systematic Analysis of Feedback Voltage Amplifiers, Other Feedback Amplifier Types, Summary of the Feedback Analysis Method, The Stability Problem, Effect of Feedback on the Amplifier Poles, Stability Study Using Bode Plots, Frequency Compensation
	Output Stages and Power Amplifiers	Classification of Output Stages, Class A Output Stage, Class B Output Stage, Class AB Output Stage, Biasing the Class AB Circuit, Variations on the Class AB Configuration, CMOS Class AB Output Stages, IC Power Amplifiers, Class D Power Amplifiers, Power Transistors,
	Operational-Amplifier Circuits	The Two-Stage CMOS Op Amp, The Folded-Cascode CMOS Op Amp, The 741 BJT Op Amp, Modern Techniques for the Design of BJT Op Amps,
	Filters	Filters and Tuned Amplifiers
	Oscillators	Signal Generators and Waveform-Shaping Circuits
Digital Integrated Circuits	CMOS Digital Logic Circuits	CMOS Logic-Gate Circuits, Digital Logic Inverters, The CMOS Inverter, Dynamic Operation of the CMOS Inverter, Transistor Sizing, Power Dissipation

	Advanced Topics in Digital Integrated-Circuit Design: Power, Speed, and Area	Implications of Technology Scaling: Issues in Deep-Submicron Design, Digital IC Technologies, Logic-Circuit Families, and Design Methodologies, Pseudo-NMOS Logic Circuits, Pass-Transistor Logic Circuits, Dynamic MOS Logic Circuits, Bipolar and BiCMOS Logic Circuits
	Memory and Clocking Circuits	Latches and Flip-Flops, Semiconductor Memories: Types and Architectures, Random-Access Memory (RAM) Cells, Sense Amplifiers and Address Decoders, Read-Only Memory (ROM)

Construct Validity Analysis

An exploratory factor analysis (EFA) provides evidence of the construct validity of the ECI and ascertains the appropriate number of underlying latent factors. The data were dichotomous, with each of the 35 ECI questions scored as 1 when students selected the correct answer and 0 when they selected a distractor. Therefore, the tetrachoric correlation matrix was initially derived. A scree plot of the eigenvalues identified the optimal number of factors to retain. By integrating the results from eigenvalues, the scree plot, and the factor loadings, the final number of factors and the number of retained items were determined, with justifications provided for the selected factor numbers. We used the *lavaan* package in *R* and subsequently verified the results in Mplus 8th ed [30].

Internal Consistency Reliability Analysis

Cronbach's α provides internal consistency reliability evidence of the ECI. The *psych* library in *R* allows for the evaluation of reliability for both categorical and continuous data. Data from all three years were pooled, and Cronbach's α was calculated for both the original concept inventory with 35 questions and for the retained items on the concept inventory after the EFA.

Results

Content Validity Evidence

Table 4 presents the results of the content analysis of the ECI, based on codes generated by the four researchers with backgrounds in electrical engineering, using the content shown in Table 3. For the initial coding, since all raters agreed on 21 of the 35 items, the percent agreement among the four raters is 60%. Subsequently, all four raters met to discuss inconsistencies in their initial coding. Through this process, an agreed-upon topic for the final coding was decided for each question. Because some questions were not limited to a single topic, the researchers defined new topics (e.g., Circuits Background) or synthesized topics (e.g., Feedback and MOSFET) that best described those questions.

Table 4. ECI Content Coding According to Initial and Final Codes from Four Researchers

#	Initial Coding			Final Coding
	Topic	Agreed	Disagreed	Topic
1	Other	4	0	*Circuits Background
2	Other	4	0	*Circuits Background
3	Other	4	0	*Circuits Background

4	Other	4	0	*Circuits Background
5	Signals and Amplifiers	3	1	*Amplifier Loading and Gain
6	Other	4	0	*Circuits Background
7	Operational Amplifiers	4	0	Operational Amplifiers
8	Semiconductors	4	0	Semiconductors
9	Diodes	4	0	Diodes
10	Semiconductors	4	0	Semiconductors
11	Diodes	4	0	Diodes
12	Diodes	4	0	Diodes
13	Diodes/Other	2	2	*Diodes and Circuits Background
14	Operational Amplifiers	4	0	Operational Amplifiers
15	BJTs	4	0	BJTs
16	BJTs	4	0	BJTs
17	MOSFETs	4	0	MOSFETs
18	MOSFETs	4	0	MOSFETs
19	MOSFETs	4	0	MOSFETs
20	Signals and Amplifiers	4	0	Signals and Amplifiers
21	BJTs	2	2	*BJT and Small Signal
22	No Specific Topic	0	4	*BJT and Small Signal
23	Transistor Amplifiers	3	1	*Small Signal
24	Transistor Amplifiers	3	1	Transistor Amplifiers
25	BJTs	3	1	BJTs
26	MOSFETs	4	0	MOSFETs
27	CMOS Digital Logic Circuits	4	0	CMOS Digital Logic Circuits
28	CMOS Digital Logic Circuits	4	0	CMOS Digital Logic Circuits
29	Transistor Amplifiers	3	1	*Small Signal
30	Transistor Amplifiers	3	1	*Small Signal
31	Transistor Amplifiers	3	1	*Small Signal
32	Transistor Amplifiers	2	2	Building Blocks of Integrated-Circuit Amplifiers
33	BJTs	3	1	BJTs
34	Feedback	2	2	*Feedback and MOSFET
35	Feedback	2	2	Operational Amplifiers

Note. *These newly synthesized topics were defined by the four researchers because the questions cannot be assigned to a single topic from Table 3.

Construct Validity Evidence

Tetrachoric correlation coefficients among the 35 items revealed that while there are more positive correlations than negative correlations, the mean of the item-item correlations was 0.086, and the standard deviation was 0.148. The item-item correlation ranged from -0.456 (between items Q22 and Q26) to 0.472 (between items Q8 and Q35), so there was no multicollinearity over 0.85 among items [31].

According to the Kaiser-Guttman rule, retaining factors with eigenvalues greater than 1.0 [32], was initially considered to determine the number of latent factors of ECI. Based on Figure 2, 14 factors could theoretically be retained. However, variables in social science research are often not continuous or metric, which can bias factor-analytic estimates, such as eigenvalues.

Therefore, although 14 eigenvalues exceed the eigenvalue of 1.0, selecting 14 factors for this instrument was deemed inappropriate.

By further examining Figure 2, the last substantial decline in eigenvalues, the "elbow" as defined by Cattell [33], occurs at the third factor, suggesting that a three-factor solution is appropriate. This conclusion is further supported by the factor loadings presented in Table 5. If only one factor were retained, 10 items would have significant loadings over 0.40; with two factors, 14 items would have significant loadings over 0.40; and with the three-factor model, 19 of the 35 items meet the loading cutoff criteria. Given this pattern and the location of the elbow at the third eigenvalue, a three-factor solution with 19 items was determined to be the most appropriate.

Figure 2. The Scree Plot of ECI

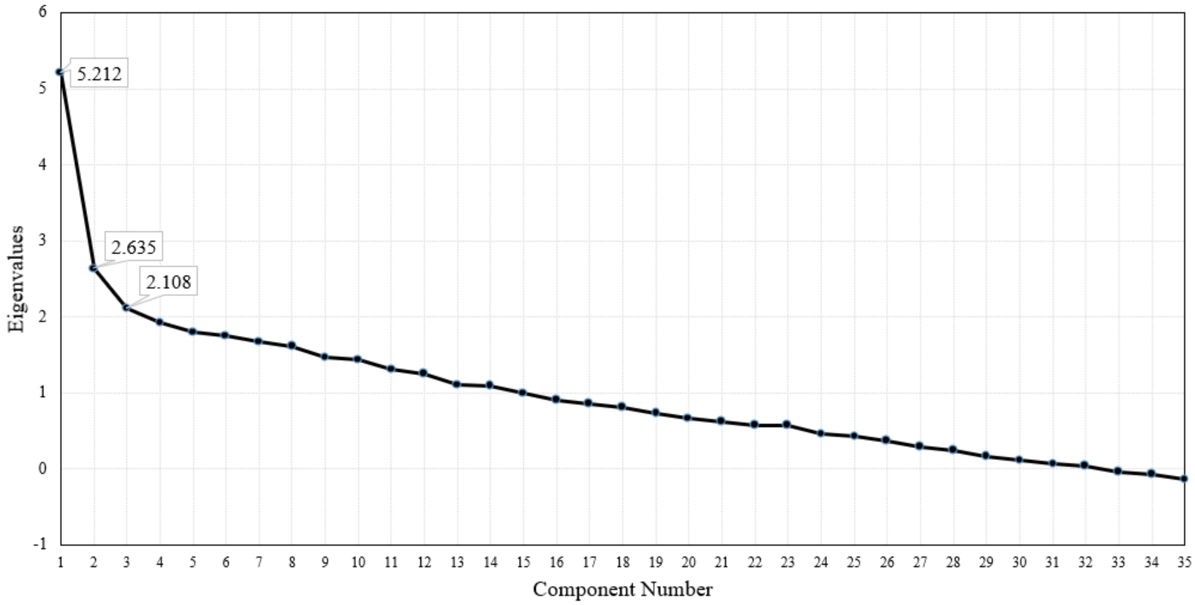


Table 5 presents the factor loadings from the three-factor model solutions for the ECI. A cut-off factor loading value of 0.40 was applied to identify meaningful factor loadings, and the statistical significance of each loading was also reported.

Table 5. EFA Factor Loadings for the Three-factor Model

#	Topics	Factor Loadings			Significant Loadings		
		F1	F2	F3	F1	F2	F3
1	Circuits Background	0.334*	0.029	0.216			
2	Circuits Background	0.617*	-0.003	0.108	0.617*		
3	Circuits Background	0.284*	-0.072	0.128			
4	Circuits Background	0.350*	0.252	0.064			
5	Amplifier Loading and Gain	0.057	0.030	0.498*			0.498*
6	Circuits Background	0.537*	0.015	0.038	0.537*		
7	Operational Amplifiers	0.099	-0.090	0.415*			0.415*
8	Semiconductors	0.007	0.592*	-0.028		0.592*	
9	Diodes	0.422*	-0.020	-0.071	0.422*		
10	Semiconductors	0.263*	-0.083	0.196			
11	Diodes	0.466*	-0.001	-0.265	0.466*		

12	Diodes	0.406*	0.159	0.184	0.406*		
13	Diodes and Circuits Background	0.267*	0.158	0.094			
14	Operational Amplifiers	0.614*	-0.322	-0.218	0.614*		
15	BJTs	0.480*	-0.319*	0.282	0.480*		
16	BJTs	0.341*	0.118	0.177			
17	MOSFETs	-0.109	0.325*	0.144			
18	MOSFETs	-0.174	0.060	0.011			
19	MOSFETs	0.250	0.253*	0.015			
20	Signals and Amplifiers	0.136	0.350*	0.164			
21	BJT and Small Signal	0.580*	0.182	0.009	0.580*		
22	BJT and Small Signal	-0.228	0.166	0.582*			0.582*
23	Small Signal	0.157	0.443*	-0.142		0.443*	
24	Transistor Amplifiers	0.158	0.108	0.164			
25	BJTs	-0.331*	-0.010	-0.040			
26	MOSFETs	0.148	-0.118	-0.204			
27	CMOS Digital Logic Circuits	0.403*	-0.003	-0.061	0.403*		
28	CMOS Digital Logic Circuits	0.460*	0.069	-0.317	0.460*		
29	Small Signal	0.212	0.222	0.025			
30	Small Signal	0.332	-0.006	0.511*			0.511*
31	Small Signal	0.479*	0.139	-0.021	0.479*		
32	Building Blocks of Integrated-Circuit Amplifiers	0.006	-0.131	0.571*			0.571*
33	BJTs	0.444*	0.227	-0.062	0.444*		
34	Feedback and MOSFET	0.056	-0.007	0.269*			
35	Operational Amplifiers	0.186	0.399*	-0.129			
No. of Retained Items					19		

Note. $^*p < 0.05$

Internal Consistency Reliability Evidence

To assess the reliability evidence and to determine whether different parts of the ECI yield consistent conclusions about students' understanding of electronics, Cronbach's α was calculated. The internal consistency reliability coefficient for the original concept inventory comprising all 35 items was 0.65. Conversely, the Cronbach's α for the retained 19 items was calculated as 0.61. Among the 19 retained items, removing items Q8, Q22, and Q32, respectively, would change Cronbach's α to 0.62, 0.63, and 0.62, respectively. Together, removing 16 items for EFA and removing all three items Q8, Q22, and Q32 will result in a Cronbach's α of 0.64.

Discussion

Content Validity Evidence

Evidence for the content validity of the ECI was established using two complementary approaches. The first approach was conducted by the developers of the ECI instrument [7]. In this process, the developers invited external ECE faculty members from various universities to review and critique the initial version of the instrument and to identify one question they believed should be removed from the exam [7].

The second approach to examining the instrument's content validity was undertaken by the researchers in the present study. According to the findings in Table 4, five ECI questions (Q1, Q2, Q3, Q4, and Q6) were not specific to electronics, as the developers designed them to evaluate students' prerequisites in electronics, specifically, a fundamental understanding of circuits. However, those five items were not grouped to be indicators of a factor, like understanding of fundamental circuit concepts.

The ECI was developed in 2004. Due to the rapid pace of technological advancements, concepts such as BJTs may no longer be covered in many Electronics I courses, as courses often focus on primarily MOSFET technologies. Hence, revising questions related to these topics (e.g., Q15, Q16, Q25, and Q33) is recommended.

Finally, 20 questions in ECI are related to the "Device and Basic Circuits" category. Of the 20 questions, 5 pertain to BJTs, 4 to MOSFETs, and 4 to diodes, respectively. This distribution excludes questions from other topics. Underrepresented topics include differential and multistage amplifiers, frequency response, output stages and power amplifiers, operational amplifier circuits, filters, oscillators, CMOS digital logic circuits, and digital design concerning power, speed, and area, alongside memory and clocking circuits. The exclusion of these topics may result in failure to identify students' misconceptions related to these topics. As a result, instructors might miss identifying conceptual challenges in these areas or designing targeted interventions to address these misunderstandings.

Construct Validity Evidence

According to Table 6, the items associated with the first factor pertain to fundamental circuits topics, characteristics of basic devices, such as operational amplifiers and diodes, as well as basic logic concepts, such as Boolean logic. The items related to the second factor are distinct in that they are word problems without any figures, graphs, or schematics. Finally, the items linked to the third factor involve the synthesis of various topics for their development, such as BJTs and Small Signal, and are application-oriented.

Table 6. Question Association with Factors

#	Topics	Factor Loadings		
		F1	F2	F3
2	Circuits Background	0.617*		
14	Operational Amplifiers	0.614*		
21	BJT and Small Signal	0.580*		
6	Circuits Background	0.537*		
15	BJTs	0.480*		
31	Small Signal	0.479*		
11	Diodes	0.466*		
28	CMOS Digital Logic Circuits	0.460*		
33	BJTs	0.444*		
9	Diodes	0.422*		
12	Diodes	0.406*		
27	CMOS Digital Logic Circuits	0.403*		

22	BJT and small signal			0.582*
32	Building Blocks of Integrated-Circuit Amplifiers			0.571*
30	Small Signal			0.511*
5	Amplifier Loading and Gain			0.498*
7	Operational Amplifiers			0.415*
8	Semiconductors		0.592*	
23	Small Signal		0.443*	
The Total Number of Retained Items		19		

Note. *Indicates the significance of the factor loading at $p < 0.05$

Considering that the ECI item order in 2015 differed from that of the original ECI, this may have influenced the EFA results and the grouping of items as an item order effect [34]. The item order effect refers to the influence that the sequence of questions in an assessment can have on the resulting outcomes. These effects may manifest in various ways, such as the possibility that earlier items consume the majority of students' energy or that students spend considerable time on them. Additionally, positioning more difficult questions at the beginning of the assessment may increase students' anxiety, potentially negatively impacting their performance. Furthermore, our preliminary review of the 35 questions showed that items addressing similar topics were often not positioned together within the test. Even in cases where related questions appeared consecutively, they were not ordered from the easiest to the most difficult. Such ordering issues can increase students' cognitive burden, which in turn may influence the EFA results. Overall, further psychometric analyses, incorporating item-level analysis, such as item difficulty and item discrimination, may supplement the evaluation of the construct validity evidence of the ECI.

Internal Consistency Reliability Evidence

The Cronbach's α =0.65 value for the ECI falls below the conventional threshold for acceptable reliability of $\alpha = 0.70$ [35]. While reliability estimates can vary with participant performance, and this single figure does not necessarily indicate a lack of reliability, the marginal internal consistency reliability evidence implies room for the enhancement of the ECI. Additional analyses, including item analysis, are necessary to examine item-level psychometric properties, such as item difficulty and item discrimination, as well as to identify items that may negatively affect the internal consistency of the ECI. These findings can then guide revisions to improve the ECI's reliability evidence.

Limitations of the Study and Suggestions for Future Research

The major limitation of this study is the generalizability of the findings, as the ECI was administered to ECE seniors at a single university rather than to a diverse group of students at various institutions. Hence, evidence for construct validity and reliability is based solely on responses from ECE students at a southern R1 public university. For future studies, it is recommended that data be collected from different universities and at different points in the curriculum. Second, confirmatory factor analysis (CFA) is essential to confirm the factors determined by EFA. As a future path for this study, CFA can be conducted on separate sample data.

Conclusion

This study provided validity and reliability evidence for the ECI. The ECI's content coverage was compared with a common Electronics I textbook, and a psychometric analysis of the ECI was conducted. It was concluded that five questions in the ECI are to assess students' understanding of introductory circuits, rather than electronics, and that more questions related to analog and digital integrated circuits could be included in the instrument.

Regarding construct validity, a three-latent-factor structure was identified for the ECI, and 19 out of 35 were retained as a result of EFA. CFA on a different dataset could determine whether the EFA factor model is confirmed. Although Cronbach's α is slightly below the commonly accepted threshold, the reliability evidence is likely to improve when the questions are reordered. Therefore, further analysis, such as item analysis, is needed to discuss more on how to improve the reliability evidence of the ECI.

The findings of this study inform possible future uses of the ECI to identify students' misconceptions in electronics courses. Consequently, educators can tailor their teaching to address those misconceptions identified by the instrument and, by providing reliability and validity evidence, researchers can use the ECI to evaluate the effectiveness of various interventions on students in electronics courses.

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Statement on Artificial Intelligence

No artificial intelligence tools were employed in the execution or communication of the work presented in this manuscript, except for Grammarly, which was utilized for grammar and punctuation verification. All procedures related to data collection, analysis, manuscript development, and revisions were carried out independently by the authors without the aid of AI.

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