AC 2010-876: CIRCUITS CONCEPT INVENTORIES: A COMPARATIVE ANALYSIS

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Circuits Concept Inventories: A Comparative Analysis

Keywords: circuits, comparative analysis, concept inventories, DC, electrical engineering, conceptual understanding

Abstract

In this paper we perform an in-depth comparative analysis of concept inventories in the area of electrical circuits: Determining and Interpreting Resistive Electric Circuits Concept Test (DIRECT), Circuits Concept Inventories (CCI), AC/DC Concept Test, and Electrical Circuit Conceptual Evaluation (ECCE). Comparison of these inventories is based on different categories of analysis: the specific concepts covered, the structure/presentation of each inventory, and other relevant features. Analysis of concepts covered includes classification of questions under AC concepts or DC concepts and identifying specific, fundamental concepts in each area. Comparison of each concept inventories' structure is based on types of questions, number of questions, number of questions on each concept, number of options for multiple choice questions, and question formalism (use of symbols, pictures, diagrams etc.). Other features that are compared include: nature of distracters, including types misconceptions that can be identified; reliability and validity; other applications; associated pedagogical interventions; and typical contexts in which each inventory has been used (high school, first year engineering, etc.). We conclude by recommending scenarios suitable for the application of each inventory, discuss opportunities for continued improvement of inventories in this domain, and identify some possible future directions for research. Our findings are of particular relevance for instructors wishing to administer a circuits concept inventory in their courses, and for those who are more generally interested in current research and development trends in the area of concept inventories.

Introduction

Interest in identifying misconceptions using concept inventories largely began with the advent of the Force Concept Inventory (FCI) in the 1990s.¹ Concept inventories (CIs) are assessment instruments that focus on fundamental concepts in a domain; concepts that are critical to building advanced knowledge in that domain. This provides a means of evaluating students' conceptual understanding and not just problem solving ability as typically assessed using other methods (ex. course exams). Results of administering FCI indicated that students did not understand basic concepts in mechanics; evidence of this, along with the knowledge that students have prior conceptions of concepts in physics², has created a need for concept inventories in different areas. Evidence of student misconceptions in the area of electrical circuits^{2,3,4}, and evidence that even students who can solve problems quantitatively struggle to qualitatively explain the underlying concepts⁵, reveal a need for effective instruments to identify student misconceptions and assess instructional approaches that aim to remedy those misconceptions.

Concept inventories are often used as assessment instruments for conceptual knowledge, both by being administered as a pre-/post-test to evaluate the effectiveness of instruction in teaching concepts and used as an in-class assessment tool for immediate feedback. This feedback is also

sometimes combined with other pedagogical methods to ensure students' understanding of key concepts. For example, immediate feedback may be combined with peer-assisted learning to reinforce student understanding.⁶

When administered as a pre-and post-test, a CI is typically given in-class using a pencil and paper version. For in-class assessment and immediate feedback, questions are often presented on a projector screen and student responses are collected using show-cards or clickers. Other ways of administering concept inventory include online hosting. Advantages of web-based administration and new methods of analyzing the concept inventory scores are discussed by Stief *et al.*⁷

This paper presents a summary and review of four CIs used to assess basic electrical circuit concepts: Determining and Interpreting Resistive Electric Circuits Concepts Test (DIRECT)⁸, Circuits Concept Inventories (CCI)⁹, AC/DC Concepts Test¹⁰, and Electric Circuits Concept Evaluation (ECCE).¹¹ We compare the four CIs based on commonly used specifications and make recommendations for using these CIs and describe opportunities for continued research and development in this domain.

Literature Review

Our work is inspired by similar analysis focused on other conceptual domains. Lindell *et al.* compare different Physics and Astronomy concept inventories based on the methodology used for development.¹² They analyze 11 concept inventories including DIRECT. In another review, Reed-Rhoads *et al.* discuss the role of CIs in engineering education, parameters that represent measurement quality of a CI, and propose creating a virtual community for CI developers and users.¹³ Streveler *et al.* present an excellent review of different aspects of learning for conceptual knowledge in engineering, ranging from cognitive theory perspectives to teaching for and assessing conceptual knowledge.¹⁴ This paper, though similar to the work of Lindell *et al.*, focuses on CIs for assessing conceptual knowledge of basic concepts in electric circuit theory.

Methods

Of the four concept inventories analyzed in this paper (DIRECT, CCI, AC/DC concepts test, and ECCE), none except DIRECT were published or publicly available. Access to all the inventories was obtained with permission from developers. Our primary interest lies in conceptual understanding in circuit theory. Other inventories commonly used in electrical engineering are focused on concepts in areas like electronics, electrical and magnetic fields and signals and systems.^{15,16,17,18,19}

We more specifically examine differences in concept inventories based on: instrument design methodology, type of questions, types of distractors used, application, method of results analysis, the value of statistical descriptors and recommended pedagogical interventions. These categories are described in more detail in the following sections.

Results/Findings

Electric Circuits Concepts

Research has indicated that in the area of electrical circuits, students commonly hold misconceptions about current, voltage and energy/power.^{2,20} McDermott *et al.* discuss some of the misconceptions and difficulties students have in the area of electric circuit theory³:

Student Misonceptions

- Current depends on direction and order of elements
- Current is “used up” in circuit
- Battery is a source of current

Difficulties

- Cannot differentiate between parallel resistance branches across a battery and some other place in the circuit
- Understanding difference between potential and potential difference
- Finding equivalent resistance of series and parallel connections

When creating concept inventories for assessing conceptual knowledge of circuit concepts, developers have included questions on: current, voltage and energy/power. In addition, since laws govern these concepts and their inter-relation in a circuit, they also contain questions on the governing laws. Holton *et al.* refer to the laws governing circuit behavior as invariants.²¹ Other sets of questions in the inventories are based on circuit behavior and interaction of concepts when circuit elements like resistors, capacitors, inductors and switches are introduced.

The questions in the circuit concept inventories may cover any of the following major concepts, invariants and/or elements: current, voltage, resistance, capacitance, inductance, power/energy, Ohm’s law, Kirchhoff’s Current Law (KCL) and Kirchhoff’s Voltage Law (KVL). DC circuit CI includes questions on current, voltage, resistance, Ohm’s law, KCL, KCL, power/energy, resistor-capacitor and resistor-inductor combinations with a DC source. In addition to these, AC/DC concept inventories include questions with a time-varying current or voltage source. Table 1 shows the number of questions in each concept inventory and whether the questions are based on DC circuits or both AC and DC (AC/DC) circuits.

Instrument Design Method

The design of an instrument can involve different steps depending on its purpose. A CI developed for evaluation of a particular course will contain questions based on the concepts covered in a textbook and/or other course material. On the other hand, if concept inventory is to be used for large-scale assessment, a more elaborate development method is used. An example of a method used to develop a general assessment tool is discussed in Engelhardt *et al.* and involves the following steps⁸:

1. Identify instructional objectives
2. Seek feedback from independent experts.

3. Develop open-ended format test to identify distractors through trial tests
4. Administer test to large sample size to eliminate sampling error
5. Perform statistical analysis on the test results to determine a measure of quality

Instrument design methodology for each of the CIs is indicated in Table 1.

Types of Questions and Distracters

Questions in concept inventories also depend on the types of assessment the instrument is intended for. Distractors are the incorrect options for a multiple-choice question. Questions can be differentiated based on: qualitative or quantitative, number of options (distractors), and representation. Qualitative questions assess students' ability to reason about a problem while quantitative questions focus more on calculations and have numerical answers. Options in multiple-choice questions on an inventory can vary in the number of options for each question. Options in some cases are also designed to identify a range of student understanding from partially correct understanding to completely incorrect understanding and specific misconceptions.¹³ Questions can be represented schematically, verbally or realistically, i.e. using diagrams that represent real life objects like bulbs, batteries etc. Table 1 discusses different attributes of questions and distractors. The total number of DC concept questions is identified for each inventory followed by the number of options for each question. Table 1 also indicates the basis for the choice of distractors and the type of assessment for which the instrument is designed. A sample from DIRECT CI is presented below as Figure 1.

Applications

Applications of CI include: curriculum assessment instrument, large-scale general assessment instrument and as a tool for in-class immediate feedback. Application of each CI is indicated in Table 1.

Statistical Descriptors

For a CI to be widely acceptable as a conceptual knowledge assessment instrument, the measurement quality should be acceptable. The following descriptors are often used to evaluate the quality of a CI⁸:

1. Reliability – measure of internal consistency of an instrument. The Kuder-Richardson formula 20 (KR-20) is used to determine reliability. A KR-20 value ≥ 0.7 is considered ideal. Average point-biserial correlation value (ideal value ≥ 0.2) measures the reliability of a single item on the test.
2. Discrimination – ability of a test item to discriminate between students who perform well versus students who don't perform well. Average discrimination index is the measure of discrimination and should have an ideal value of ≥ 0.30 .
3. Difficulty - proportion of students who choose right response, with an ideal value ≥ 0.40 -0.60.
4. Validity is a measure of a test's accuracy, i.e. its effectiveness in measuring conceptual knowledge. Content and construct validity of the instrument is of typical interest. For

content validity, independent panels of experts check the content and objectives of the instrument. Construct validity is performed by factor analysis and interviews to determine the interrelationships within the data and if questions are being understood as they were intended.

Table 1 indicates the type and values of statistical descriptors reported for each CI.

Analysis of Test Results

Depending on the application, different analyses can be performed on the results from administering a concept inventory. Results from pre- and post-test can be used to measure student conceptual gain and effectiveness of a particular instructional approach. When a CI has multiple questions for each concept, correlation between the responses to questions can be used to determine understanding of a specific concept. When each concept has only a single question, information obtained may be unreliable due to random error.⁷

Recommendations

When a CI is developed for assessing the effectiveness of a pedagogical technique, questions on the CI are closely tied to the instructional approach. In these cases, guidelines for using the CI comes with a recommendation of associated pedagogical techniques. When developing the instrument, developers usually have a target population in mind. Therefore, CI guidelines can also include recommendations for the target population.

Comparison of the four CIs based on the categories discussed above is presented in Table 1. Commonalities among these CIs include greater emphasis on DC questions and the source of distractors. Looking at published results for two inventories (DIRECT and AC/DC Concepts Test) reveals that they both have acceptable values for the statistical measure of the instrument. Differences among these include: varying number of questions and distractors, nature of questions (qualitative/quantitative), validity, problem representation, and recommended target populations.

Analysis of DC Circuit Problems

This section presents the results of comparison of DC circuit questions on the four CIs. Instructional objectives from Engelhardt *et al.* (developers of DIRECT instrument) are used as the basis for comparison.⁸ This was chosen as the basis of comparison because these objectives cover a wide range of problems in DC circuits, including all DC questions on the four instruments. Table 2 shows the results of the analysis.

Table 1. Summary Comparison of Circuits Concept Inventories

CI Comparison Criteria	DIRECT	CCI	AC/DC Concepts Test	ECCE
Instrument Design Methodology	Experts and field testing	Not known*	Student interviews and expert views	Not known*
DC concept questions/Total No. of questions	29/29	18/25	13/20	38/45
No. of options for each question	3-5	4	3-5	3-6
Basis for choice of distractors	Misconceptions (from literature)	Not known*	Invariants and Misconceptions	Not known*
Type of assessment used for	Qualitative assessment	Quantitative assessment	Qualitative assessment	Qualitative assessment
Application	Pre- and post-test results for assessment of curriculum or instruction, and students' conceptual understanding	Pre- and post-test to gauge knowledge prior to instruction, and assess instruction/curriculum	Pre- and post-test results for assessment of curriculum or instruction, and students' conceptual understanding	Not known*
Statistical reports of quality	<ul style="list-style-type: none"> ▪ KR-20 = 0.71 (reliability) ▪ Content validity ▪ Construct validity ▪ Point biserial correlation ▪ Discrimination index ▪ Difficulty index 	Not known*	<ul style="list-style-type: none"> ▪ KR-20 = 0.687 (reliability) ▪ Point biserial correlation ▪ Item difficulty ▪ Ferguson's Delta ▪ Item Discrimination index 	Not known*
Recommendations	High school and college/university students	Sophomore students	High school and early undergraduate	Not known*
Scope	DC resistive circuits	AC and DC circuits	AC and DC circuits	AC and DC circuits
Other	<ul style="list-style-type: none"> ▪ Uses multiple representation of problems (symbols, words, pictures) ▪ Questions are qualitative 	<ul style="list-style-type: none"> ▪ Uses only symbols ▪ Majority of the questions are computational (quantitative) 	<ul style="list-style-type: none"> ▪ Uses symbols, words and pictures ▪ Questions are presented in context (situated in everyday language) ▪ Revised for test-wiseness⁺ 	<ul style="list-style-type: none"> ▪ Uses symbols ▪ Questions are qualitative

* Information not found in published sources or personal communication.

⁺ Ability of students to do well in tests due to cues found in question wording.

Table 2. Classification of DC Circuit Problems Based on Instructional Objectives Presented by Engelhardt, *et al.*⁸ (Objectives reproduced verbatim with permission from Engelhardt, et al.)

Objective	*DIRECT Question #	CCI Question #	AC/DC Concepts Test Question #	ECCE Question #
(1) Identify and explain short circuit (more current follows the path of lesser resistance).	10,19,27	16		
(2) Understand the functional two-endedness of circuit elements (elements have two possible points with which to make a connection).	9,18			
(3) Identify a complete circuit and understand the necessity of a complete circuit for current to flow in the steady state (some charges are in motion but their velocities at any location are not changing and there is no accumulation of excess charge anywhere in the circuit).		11	1-3	
Objectives 1-3 combined	27			
(4) Apply the concept of resistance (the hindrance to flow of charges in a circuit) including that resistance is a property of object (geometry of object and type of material with which the object is composed) and that in series resistance increases as more elements are added and in parallel the resistance decreases as more elements are added	5,14,23	9,10	4	2-4, 14,
(5) Interpret pictures and diagrams of a variety of circuits including series, parallel, and a combination of the two	4,13,22	17	11, 14	9-16,23-26, 35-38
Circuit Layout (objectives 1-3,5)				
(6) Apply the concept of power to a variety of circuits	2,12			
(7) Apply a conceptual understanding of conservation of energy including Kirchhoff's loop ($\sum V=0$) rule and the battery as a source of energy	3,21			
(8) Understand and apply conservation of current to a variety of circuits	8,17	4,5,6,7,8	1,2,6,12	1-3,10, 27-34
(9) Explain the microscopic aspects of current flow in a circuit through the used of electrostatic terms such as electric field, potential differences, and the interaction of force on charged particles	1,11,20		2,5,12	
(10) Apply the knowledge that the amount of current is influenced by potential difference maintained by the battery and the resistance in the circuit.	7,16,25		9	4,6,8-10,12-14,38
(11) Apply the concept of potential difference to a variety of circuits including the knowledge that the potential difference in a series circuit sums while in the parallel circuit it remains the same	6,15,24,28,29	14,15		5,7,11
Current and voltage (objectives 8 and 11)	26			

The DC circuit questions in each of the concept inventories were categorized according to the instructional objectives indicated in Table 2. From the table it is apparent that objective numbers 4, 5, 8, 10, and 11 each have several questions per objective. More questions per objective ensure that the correct response is measured without random error, which in turn means that the CI can accurately identify if students have difficulties with those concepts, and possibly also the nature of their misconception. A larger number of questions for those objectives emphasize the relative importance. This trend is prevalent across other inventories.

8) Compare the current at point 1 with the current at point 2. Which point has the larger current?

(A) Point 1
(B) Point 2
(C) Neither, they are the same

Figure 1. A Multiple Choice Question from DIRECT1.0⁸ (Reproduced with permission.)

For example, consider a multiple-choice question from DIRECT CI as shown above in Fig. 1. Based on the categories of analysis discussed above, the question below can be characterized as shown in Table 3. The question targets common student misconceptions about current: current depends on direction and order of elements, and current is “used up” in circuit. Option (A) “Point 1” is a distractor that targets misconception that current supplied by the battery is used up in the resistor and therefore, current at Point 1 is larger than current at Point 2. Option (B) “Point 2” is also a distractor that targets misconception of current in a circuit depending on direction of elements. Option (C) is the correct response.

Table 3. Characteristics of DIRECT 1.0 Question 8 (shown in Figure 1)

Target concept	Current
Target misconception	<ul style="list-style-type: none"> ▪ Current depends on direction and order of elements ▪ Current is “used up” in circuit
No. of distractors	3
Basis for choice of distractors	Common misconceptions
Type of question	Qualitative
Question representation	Schematic

Conclusion and Recommendations

Though the end application driving the development of each inventory is different, they all target assessment of student understanding of key concepts in electrical circuits. Their uses range from general assessment of conceptual knowledge to assessment of a particular curriculum or instructional method. Distractors in the multiple choice questions are based on students’ pre-existing conceptions reported in the literature. With increasing interest in integrating cognitive theory knowledge in instruction, further research is needed to determine if CI design

methodology could also incorporate an understanding of how students' pre-existing conceptions are changed when they are exposed to instruction. Two popular theories of conceptual change based on "knowledge-as-theory" and "knowledge-as-pieces" can motivate different instructional approaches.²² It would be worthwhile to determine the effectiveness of CIs in evaluating instruction that is motivated by a conceptual change theory.

As discussed above, different formalisms are used in CI questions. Using multiple formalisms for a single concept will assess students' ability to understand and navigate between different formalisms. However, is an inability to do so an indicator of lack of a conceptual understanding? A single question represented in two different ways might have different student responses, which can decrease the correlation between the responses and decrease reliability of test results. A comparison of student responses to questions with different representation (same questions presented in different formalisms) can help instructors distinguish student difficulties with formalism versus with concepts.

A choice of CI for assessment depends on the target population. DIRECT is a fully developed CI with established statistical evidence. It would be suitable for high school students or first year engineering and science students. CCI is a quantitative instrument, which is suitable for second year engineering students in electrical engineering. It can be used to assess their ability to apply concepts to solve problems. ECCE and AC/DC concept tests use qualitative reasoning to assess students' understanding of AC and DC circuits. Statistical evidence for ECCE is not known to exist. AC/DC concept test has been tested for reliability and is being validated. We have currently not yet analyzed AC questions in the inventories; however, we infer that they can be useful for high school students and first year engineering and science students. ECCE has larger number of questions overall, and on DC circuits. Larger number of questions means longer test times, but depending on the instructor's needs, fewer questions can be selected.

This analysis, though limited to DC circuits and four instruments provides an in-depth comparative analysis of four CIs. We are hopeful that this summary will provide instructors with necessary insights to make an informed decision about the right CI for their needs, while also providing ideas and inspiration for further research in this domain.

Acknowledgments

The authors extend thanks to the developers of the four concept inventories discussed in this paper for their willingness to provide us with detailed information about their instruments.

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