AC 2012-4606: CONCEPTUAL UNDERSTANDING OF RESISTIVE ELECTRIC CIRCUITS AMONG FIRST-YEAR ENGINEERING STUDENTS

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Conceptual Understanding of Resistive Electric Circuits Among First-Year Engineering Students

Abstract

In this paper we present results from administering the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) concept inventory to first-year honors engineering students (n≈150). This study was coordinated around a one-week module on electrical circuit theory, with the concept inventory administered immediately before and after the module. Students were also given an open-ended questionnaire during the pre-test, and a survey to evaluate the instructional module with the post-test. We discuss details of the instructional module and present several findings from our analysis of the survey data. We find that while a majority of the students had completed Advanced Placement (AP) physics and/or electronics courses and were currently enrolled in college-level physics courses, they still had many difficulties solving basic problems involving resistive circuits and did not show significant improvements after completing the instructional module. Our findings highlight many of the persistent difficulties faced by students in this conceptual domain. Factors such as prior educational experiences and intended major (i.e., ECE vs. non-ECE) were shown to predict student performance on the concept inventory. We conclude the paper by first describing how this study has informed a new stage of research involving a more in-depth qualitative study of misconceptions in this domain, including across student levels (i.e., first-year to junior/senior). We also discuss how a number of insights from this study can help instructors and curriculum developers assess and improve conceptual understanding in the context of their own courses.

Keywords: circuits, concept inventory, conceptual understanding, DC, DIRECT, direct current, electrical engineering, student perceptions

Introduction

Extensive research on student understanding of physical science concepts has established that many students have deep-rooted misconceptions that are often difficult to change.[1] One-on-one student interviews are typically used to identify specific misconceptions, which in turn support development of Concept Inventories (CIs). CIs contain multiple-choice questions in a particular conceptual domain, with common misconceptions presented as "distracters." CIs are instruments of choice for in-depth and large-scale assessments of student conceptual knowledge. The feasibility of administering this kind of instrument on a large scale, as well as the relative ease of data analysis, makes CIs a valuable tool for both researchers and instructors.

In this paper we present results from administering the Determining and Interpreting Resistive Electric Circuit Concepts Test (DIRECT) concept inventory to first-year engineering (FYE) honors students (n≈150). The FYE course is offered as a two-semester course on engineering problem solving and provides an introduction to a number of different engineering disciplines. A one-week instructional module on electric circuits is included as a part of this course in the second semester. Our goal with this study was to assess FYE students' conceptual understanding of electric circuit theory and investigate the relationship between student understanding and their background and interests. We were also interested in finding the effect of a short refresher, in the form of a one week instructional module, on their conceptual understanding. To this end, we administered DIRECT before and after the instructional module. An open-ended questionnaire also accompanied the pre-test, and a survey evaluation of the instructional module was paired with the post-test.

This paper begins with a review of relevant literature, followed by a brief description of our circuits learning module, which featured a number of instructional innovations. We then discuss several findings from our analysis of the survey data, and conclude with a series of more practical implications and recommendations.

Literature Review

In the electric circuits domain, commonly used concept inventories include: Determining and Interpreting Resistive Electric Circuits Concept Test (DIRECT), Circuits Concept Inventories (CCI), AC/DC Concept Test, and Electrical Circuit Conceptual Evaluation (ECCE). In previous work, we presented a comparative analysis of these CIs based on development methodology, number of questions, basis for choice of distracters, type of questions (qualitative/quantitative), intended application, statistical reports of quality and scope (DC/AC & DC circuits).[2] Given these criteria, we found DIRECT to be most suitable for our own research. It covers DC resistive circuit concepts, and statistical measures of its reliability and validity have been established.

A survey of the literature reveals that apart from the results reported by developers of DIRECT[3], at least three other groups have reported the use of DIRECT as a conceptual assessment tool.[4,5,6] More specifically, DIRECT has been used to investigate the effects of simulations on pre-service elementary school teachers' understanding[4], to assess conceptual understanding of circuits concepts among first year engineering students[5], and to evaluate an instructional approach focused on electric potential and electric potential difference.[6] O`Dwyer used DIRECT to assess understanding of electric circuits among first-year, Level 7 (Bachelor's Degree level in Ireland), engineering students, primarily to gauge the diversity of abilities among incoming students at Dublin Institute of Technology. [5] However, this paper only presented preliminary results (percentage of correct responses) for 83 students and recognized the usefulness DIRECT.

Other studies have borrowed elements from DIRECT to develop their own assessment instruments.[7,8] For example, Smaill et al. developed their own assessment instrument and used it in conjunction with interviews to assess the level of understanding of first-year students at University of Auckland, New Zealand.[7] They found that students have similar difficulties with electric circuit concepts across national boundaries, but their understanding can be significantly improved with proper instruction. Pesman *et al.* developed a three-tier test consisting of multiple-choice questions, reasoning questions, and an assessment of students' confidence levels related to their responses to first two tiers. [8] The three-tier test was developed to compensate for the shortcomings of a regular multiple-choice test, and as a more convenient alternative to interviews.

In our study, we find that the questions from DIRECT align well with our goal to assess the academic preparedness of first-year engineering students at our university in the area of electric circuits. We are also interested in investigating whether a short instructional module on electric circuits can change their conceptions about electric circuits.

Methods

Study Context and Participant Population

The participants in this study were first-year honors engineering students (n~150) at our university who were enrolled in three different sections taught by three different instructors. Their selection was based on convenience sampling. Table 1 summarizes the different subject groups, including pre/post-test sample sizes for each.

Table 1. Sample sizes for pre-test and post-test for different sections

Section	Pre-Test Sample Size	Post-Test Sample Size
Section 1	n = 45	n = 52
Section 2	n = 38	n = 55
Section 3	n = 31	n = 47
Total	n_{total} = 114	n_{total} = 154

Data Collection and Analysis

We administered DIRECT as a pre/post-test to students. We also developed and delivered an instructional module based on conceptual change research that was implemented in only one section (Section 1). The students for this study were recruited by obtaining permission from the instructors and the study was carried out during regular class time. DIRECT was administered as a pre-test along with a perceptions survey before the beginning of the one-week module on electric circuit theory. After the instructional module, the post-test was administered, along with a student background and module evaluation survey. All appropriate human subjects research approvals were obtained and followed for this study. Student participation in the study was voluntary and their participation did not have an impact on their course grade.

Instructional Module

The first-year honors engineering curriculum includes a one-week module on electric circuit theory. The scope of coverage includes only an introduction to DC circuits and analysis methods. It amounts to one chapter in the prescribed course textbook.[9] For the instructional module implemented in Section 1, most of the lecture material and problems were borrowed from multiple textbooks, although the prescribed textbook was also referenced. The specific learning objectives for the module were:

1. Understand the meaning of charge, current, voltage, electrical energy, electrical power
2. Apply the concept of resistance
3. Apply conceptual understanding of conservation of charge and energy in electric circuit
4. Apply the concept of power to a variety of circuits

Our goal in designing the instructional module was to prevent misconceptions that can arise from improper usage of electric circuits vocabulary. We strived to present each of the concepts (current, voltage, resistance, etc.) as clearly and accurately as possible so that students understood the meaning and relevance of each concept. After establishing the relevance and context of electric circuits for all engineering majors, we introduced an electric circuit as an interconnection of circuit elements with current, voltage, power/energy as the circuit variables. Charge was described as the electrical property of matter that explains all electrical phenomena.

Student difficulties with concepts of current and voltage have been extensively researched. Table 2 presents typical student difficulties associated with each concept, along with a description of how we treated each of these concepts in class. [10] In addition to the above concepts, we also introduced the law of conservation of power and a procedure to compute power in an electric circuit. Research has also shown that students often have trouble correlating schematic diagrams with real-life pictorial diagrams.[11,12] To address this difficulty, we emphasized multiple representations of circuits, as well as the concept of a complete circuit.

Table 2. Treatment of common student difficulties in an in-class instructional module

Concept	**Difficulty/Misconception**	**Our Treatment**
Current	Current in a circuit depends on direction and order of elements	• Current is time rate of flow of charge • Used animation of a simple DC circuit with bulb and battery to show that current is the same everywhere at every instant of time
	Current is used up	• Emphasized conservation of Charge
	Battery is a source of current	• Battery is a source of energy and charge is a carrier of this energy, transferring energy from one point to another point in a circuit. • Battery does not contain stored charge
Voltage	Ideal battery maintains a constant potential difference across its terminals	• Irrespective of what is connected to the battery, it always maintains a constant potential difference, as demonstrated with simulations and examples
	Difference between potential and potential difference	• Electric potential at a certain point in a battery is the electric potential energy per coulomb • Potential difference is the difference in electric potential, and is calculated or measured with respect to two points in a circuit

To emphasize and reinforce all fundamental concepts, we used multiple instructional approaches: web-based simulations, contextual problems, design problems, qualitative problems, and hands-on experiential learning with breadboard and LEDs.[13,14]

Findings and Discussion

Performance on Concept Inventory

DIRECT was administered as a pre/post-test in each of the three class sections. Table 3 shows the average pre- and post-test scores for each section, and for all the sections combined. From this table it is evident that though the post-test scores were similar for the three sections, there was a higher pre/post-test gain for Section 1. Upon further examining student performance on each question, as presented in Table 4, it is evident that Section 1 had fewer questions with negative difference between post-test and pre-test scores and a larger number of questions with greater than 10% increase in performance. Tables 3 and 4 show a larger overall positive trend in student performance for Section 1.

Table 3. Average student performance on DIRECT, pre- and post-test

Section	Average Pre-Test Score	Average Post-Test Score	Pre/Post Change
Section 1	14.84 (51.17%) for n=45	18.63 (64.24%) for n=52	+13 %
Section 2	16.52 (59.02%) for n=38	17.29 (61.75%) for n=55	+2.73%
Section 3	16.87 (58.18%) for n=31	18.8 (64.86%) for n=47	+6.68 %
All Sections	15. 95 (55.02%) for n=114	18.2 (62.79%) for n=154	+7.77 %

Further examining individual questions we see that the three decreased performance questions for Section 1 were shared with at least one other section. These questions targeted: change in power delivered to a resistor when another resistor was added in series (Question #2), parallel connection of batteries (Question #16), and potential difference across an open switch (Question #28). Poor performance on questions #16 and #28 can likely be attributed to novel circuit arrangements, such that the limited learning experience provided in this short module on electric circuits was not sufficient for students to develop the ability to *transfer* their learning, i.e. the ability to extend what they have learned in one context to new context.[15]

Apart from nine questions with greater than 10% increase which were common between Section 1 and at least one other section, Section 1 exclusively saw an increase on seven other questions. Those seven problems covered: series-parallel resistance, multiple circuit representations, and properties of battery. Though there is no defining pattern to these questions, we believe that the increased performance can be attributed to the explicit conceptual-understanding approach that guided development and delivery of this instructional module. That is, the intentional and strategic organization and presentation of key concepts, as summarized in Table 2, likely helped student understanding as measured by their performance on the concept inventory. It further strengthens our hypothesis that conceptual-understanding based instruction can improve student conceptual understanding.

Table 4. Percentage of correct responses for each DIRECT question, pre- and post-test

Question No.	Section 1 (% of correct responses)			Section 2 (% of correct responses)			Section 3 (% of correct responses)		
	Pre-test	Post-test	Pre/Post Change	Pre-test	Post-test	Pre/Post Change	Pre-test	Post-test	Pre/Post Change
1	60	61.5	1.5	50	47.3	**-2.7**	74.2	57.4	**-16.7**
2	68.9	63.5	**-5.4**[*]	57.9	70.9	*13.0*	80.6	78.7	**-1.9**
3	35.6	59.6	*22.1*[**]	50	54.5	4.5	41.9	42.6	0.6
4	46.7	69.2	*22.6*	50	60	*10.0*	61.3	72.3	*11.1*
5	84.4	96.2	*11.7*	86.8	94.5	7.7	90.3	95.7	5.4
6	64.4	73.1	8.6	50	70.9	*20.9*	71	74.5	3.5
7	66.7	75	8.3	73.7	78.2	4.5	74.2	80.9	6.7
8	62.2	84.6	*22.4*	73.7	83.6	*9.9*	71	85.1	*14.1*
9	77.8	82.7	4.9	81.6	90.9	9.3	93.5	91.5	**-2.1**
10	44.4	53.8	9.4	63.2	61.8	**-1.4**	41.9	53.2	*11.3*
11	46.7	53.8	7.2	52.6	50.9	**-1.7**	51.6	61.7	*10.1*
12	15.6	23.1	7.5	21.1	21.8	0.7	9.7	14.9	5.2
13	95.6	96.2	0.6	97.4	100	2.6	93.5	95.7	2.2
14	66.7	82.7	*16.0*	50	83.6	*33.6*	48.4	74.5	*26.1*
15	51.1	53.8	2.7	57.9	50.9	**-7.0**	51.6	59.6	8.0
16	62.2	55.8	**-6.5**	52.6	41.8	**-10.8**	77.4	46.8	**-30.6**
17	33.3	53.8	*20.5*	52.6	54.5	1.9	48.4	66	*17.6*
18	57.8	88.5	*30.7*	65.8	76.4	*10.6*	41.9	63.8	*21.9*
19	62.2	75	*12.8*	18.4	7.3	**-11.1**	74.2	83	8.8
20	15.6	17.3	1.8	39.5	40	0.5	12.9	4.3	**-8.6**
21	42.2	61.5	*19.3*	39.5	40	0.5	74.2	66	**-8.2**
22	44.4	59.6	*15.2*	39.5	45.5	6.0	35.5	40.4	4.9
23	46.7	59.6	*15.2*	60.5	67.3	6.8	58.1	70.2	*12.1*
24	35.6	48.1	*14.7*	60.5	50.9	**-9.6**	51.6	46.8	**-4.8**
25	57.8	82.7	*27.1*	57.9	67.3	9.4	74.2	85.1	*10.9*
26	40	71.2	*33.4*	50	56.4	6.4	51.6	85.1	*33.5*
27	80	96.2	*18.4*	68.4	80	*11.6*	67.7	72.3	4.6
28	26.7	23.1	**-1.4**	34.2	10.9	**-23.3**	35.5	40.4	4.9
29	13.3	38.5	*29.6*	31.6	20	**-11.6**	22.6	19.1	**-3.4**

[*] Entries in bold indicate decrease in net percentage of correct responses from pre- to post-test.
[**] Italicized and underlined entries indicate a greater than 10% increase in correct responses.

For a random sample chosen in each section, the difference in performance and gain in performance of CI can be attributed to different teaching styles adopted by different instructors in each section. To evaluate the statistical significance of our inferences, we performed hypothesis testing using 2-sample t-test. Table 5 presents the hypothesis, as well as the details of the statistical tests performed.

The statistical results for our findings are limited by the small sample sizes. Despite a reasonable number of subjects in each section who completed the pre-test and post-test, the n for computing gain on test performance was relatively small since the same students were not present in the class during the pre- and post-test. For example, for Section 1, n=45 for pre-test and n=52 for the post-test, but there were only 38 students who completed both the pre- and post-test. The 2-sample t-test results show that there is a statistically significant difference between the average pre/post gain for Section 1 and Section 2, but not for Section 1 and Section 3. Though we are not fully aware of the details of the instructional approaches employed in Section 2 and 3, the above results do suggest that instructional strategies are likely pivotal to the process of developing conceptual knowledge in a particular domain. Though not conclusive from the above results, we believe a more elaborate and controlled experiment could be used to demonstrate the positive effect of conceptual-understanding based instruction.

Table 5. Summary of hypothesis test to determine the effect of 1-week instructional module

<table>
<tr><td colspan="6">Null Hypothesis: H_o – there is no difference between the average gain on test score between Section 1 and Section 2/3.</td></tr>
<tr><td colspan="6">Alternate Hypothesis: H_A – There is a statistically significant difference between the average test score between Section 1 and Section 2/3</td></tr>
<tr><td colspan="6">Significance level: $\alpha = 0.05$</td></tr>
<tr><td colspan="6">Tail – Right tailed test because we expect a positive difference between the Section 1 and Section 2/3 average gain</td></tr>
<tr><th>Case</th><th>h
(Null hyp rejected for h=1)</th><th>p
(probability)</th><th>ci
(confidence interval)</th><th>tstat
(test statistic)</th><th>df
(degrees of freedom)</th></tr>
<tr><td>Section 1 and Section 2</td><td>1</td><td>0.0164</td><td>[0.5801, Inf]</td><td>2.1783</td><td>69</td></tr>
<tr><td>Section 1 and Section 3</td><td>0</td><td>0.2142</td><td>[-0.9438, Inf]</td><td>0.7975</td><td>59</td></tr>
</table>

Effect of Student Perceptions and Background

To gauge student attitude and perceptions towards electric circuit theory, subjects were asked three open-ended questions after completing the pre-test:

1. Is electricity a difficult concept for you? Explain why?
2. Which of the problems on the diagnostic test were most difficult? Explain.
3. In your opinion, what is the most effective way to learn electricity concepts? For example, you can consider: textbooks, web-based simulation, lecture and discussion, projects, and problem practice.

To determine the relationship between student perception and performance, we used student responses for question #1 to compute a perception score (p-score). Representative responses ranged from "*difficult because hard to visualize*" to "*no it is just formula based*." Most respondents mentioned that it had been a long while since they last encountered electric circuit concepts or problems. We assigned p-score=0 for responses such *"yes it is difficult …"*, p-score=1 for responses like *"it is somewhat difficult …",* and p-score = 2 for responses like *"no it is not difficult …".* Unfortunately, we have not yet found any useful or usable information from student responses to the second and third questions on the perceptions survey.

A background survey was also distributed to students after the post-test to evaluate the instructional module and gather student background information. For module evaluation, we used a five-point Likert-style scale (1=strongly disagree, 3=neither agree nor disagree, 5=strongly agree) for each of the following criteria:

- Criterion 1: Increased my interest in electrical engineering
- Criterion 2: Improved my understanding of fundamental circuit concepts
- Criterion 3: Helped me realize/identify misconceptions about electric circuit concepts

Individual scores for each of these criteria were added to obtain a module score (m-score). The average scores (ranging from 1 to 5) for each of these criteria were relatively higher for section 1 where the conceptual-understanding-based instructional module was employed. Table 6 summarizes the average score for each criterion.

Table 6. Average score for each of the instructional module evaluation criterion

Section	Criterion 1	Criterion 2	Criterion 3
Section 1	2.84	3.75	3.47
Section 2	2.51	3.31	2.92
Section 3	2.6	3.04	2.7

Student background questions included their previous experience with electric circuits, their intended major and gender. We calculated the background score (b-score), by assigning the following scores for their past electric circuit experience:

0 = None
1 = Advanced Placement (AP) Physics course
2 = College Physics (PHYS 241, PHYS 272 offered at our university)
3 = High School Electronics course
4 = Introductory Electric Circuits course (ECE 201 offered by ECE Dept.)

Scores were also assigned for their intended majors (ECE=1and Non-ECE=0). For students who had completed more than one of the above listed background courses, the scores for all of them were added. For example, a student whose intended major is ECE and who had completed an AP Physics course and was currently enrolled in PHYS 241 had a total background score = 1 (ECE) + 1 (AP Physics) + 2 (college Physics) = 4. We did not assign any score to gender because of the relatively small number of female students (~ 30).

To study the effect of student perceptions of electric circuit concepts, their evaluation of the effectiveness of instructional module, and their background on concept inventory performance, statistical correlation coefficients were calculated. The computed Pearson's correlation coefficient ρ (rho) for the three scores is shown in Table 7. According to these computed values, there seems to be no significant correlation between student perceptions of difficulty and their performance. Though nothing can be said conclusively here, we believe that findings from more detailed studies can provide useful insights.

Table 7. Summary of correlation test results

Correlation Test	Computed value of ρ (rho)
p-score and pre-test	-0.2388
p-score and post-test	0.2615
m-score and pre-test	-0.1120
m-score and post-test	0.1127
b-score and pre-test	0.4711
b-score and post-test	0.5597

Nonetheless, it was encouraging that the students in Section 1 (where conceptual-understanding based instruction was implemented) rated the module higher. However, there was no significant correlation between student rating of the instructional module and their performance on the test, as indicated by the ρ (rho) = -0.112/0.1127 value, as presented in Table 7.

As would be expected, there is a slightly more significant relationship between student performance and their background as indicated by ρ (rho) = 0.4711/0.5597 in Table 7. Students who were concurrently enrolled in introductory circuits course offered by ECE department or who had completed an electronics course in high school performed significantly better. When we combined data of all three sections (for n=154), only 29 students scored greater than 80% on the post-test. When we further examined the intended majors of these 29 students, we found that 9 (out of a total of 22, i.e. ~40%) of them had indicated ECE as their major. On average, ECE students appeared to perform better.

Conclusions and Recommendations

It is apparent from student performance on the DIRECT concept inventory that a large majority of the students had persistent difficulties with fundamental electric circuit concepts, even at the university level. Their conceptions of electric circuits are often characterized as *naïve* and *robust.* With one week of instruction, their performance on the concept inventory only increased by 7%. It is encouraging to see that incorporating some research-based instructional measures seem to positively impact student conceptual knowledge. However, it appeared that concept inventory scores were neither influenced by student perceptions about electric circuits, nor their evaluation of the effectiveness of instructional module. As would be expected, students who had more experience with electric circuits in high school or college showed evidence of better conceptual understanding. Students who indicated ECE as their intended major also performed relatively better, which points to the role of motivation in relation to conceptual understanding.[16]

This study, though limited by time and sample size, shows some positive trends. It has also directly motivated two other studies, one investigating the role of textbooks in promoting conceptual understanding, and the other analyzing the evolution of student conceptions as they progress through an electrical and computer engineering curriculum. Findings from this study were used to develop evaluation criteria for the two studies. We are hopeful that findings from this study will be useful to other researchers who are interested in undertaking similar studies on a larger scale. We expect that when undertaken with even larger numbers of students, the data from multiple studies can help establish statistical evidence that confirms the effectiveness of conceptual understanding-based instructional approaches, while establishing how factors such as student background and interest/motivation influence student attainment of electric circuit concept knowledge.

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