AC 2008-542: ASSESSING STUDENT DIFFICULTIES IN UNDERSTANDING THE BEHAVIOR OF AC AND DC CIRCUITS

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Assessing Student Difficulties in Understanding the Behavior of AC and DC Circuits

Abstract

Students often have specific difficulties understanding basic electricity concepts.[1,2] Previous research has primarily been concerned with difficulties students have with direct current (DC) circuit problems. In the first circuit courses engineering undergraduates take, however, they must also understand the time-varying behavior of alternating current (AC) circuits that include components, such as capacitors and inductors. Over the past several years, we have been uncovering conceptual difficulties students have in the AC domain via interviews and test questions, and we have developed some instructional strategies for addressing these difficulties. The primary focus of this paper concerns our development of a reliable multiple choice instrument for assessing these difficulties, a concept inventory. We present the results from initial administrations of our test, the revisions we made based on analyses of reliability, discrimination, and test-wiseness, and the results of our most recent administrations of the revised test to engineering students *after* they had completed their beginning circuits courses. Our results so far suggest that students have specific difficulties understanding electrical circuit behavior that remain in spite of instruction, but we have begun to identify some strategies for addressing these difficulties, including the use of an animated circuit simulation and circuit problems that focus on qualitative understanding of circuit concepts.

Introduction

All undergraduate students who wish to pursue a degree in any branch of engineering in general, and electrical engineering in particular, are required to take one or more basic electricity and circuits courses that cover topics in DC and AC circuits. In most universities and four year colleges across the country, these topics are first introduced in physics courses, and then further developed in the first electrical engineering course. Here the emphasis shifts from basic understanding of concepts, individual laws, and simple problem solving to covering more advanced topics, that combine the use of multiple concepts and laws, particularly in applying them to solving real world problems.

There is a strong possibility that if students develop misconceptions in these courses that relate to the primary concepts of voltage, current, and charge, they will find it very difficult to extend their understanding to advanced topics such as AC currents and voltages, and how different components such as capacitors and inductors combine to define behaviors in electrical and electronic circuits. These difficulties may even dissuade students from pursuing further study in electrical engineering. Furthermore, the lack of basic electrical engineering skills are very likely to have a detrimental effect on preparing students to work in the 21st century global economy, where electronics, computational, and embedded systems will play a very important role in the design, development, and operation of engineering systems.

Therefore, assessing students' conceptual difficulties using concept inventories (conceptual multiple choice tests) and other assessment techniques, may help us improve the effectiveness of engineering education curriculum by catching and addressing their misconceptions and lack of understanding in the early courses, and thus help us retain more students in the electrical engineering program.[3,4,5]

Prior Research

Previous research has uncovered numerous misconceptions students have in understanding the behavior of DC circuits, but there has not been as much research on student understanding of AC or more advanced circuits. One of the primary difficulties students have when understanding DC circuits is the "current consumption" misconception, in which current is viewed as a substance that is "consumed" by a device, such as a light bulb or a resistor.[6] Students may conceive of a battery as a constant current source rather than a source of voltage, and fail to differentiate between current and voltage, and power and energy.[7] Since this and other previous research on student understanding has primarily focused on simple DC circuit problems, this may inadvertently guide one towards instructional decisions that that aren't as appropriate in more advanced circuit contexts. For example, analogies or visualizations of current flow which are useful in DC contexts may not work as well in AC contexts. So to extend this analysis to more advanced topics in electricity, we have researched student understanding of electric circuits in the domain of AC circuits. We were motivated by questions such as, to what extent do students exhibit the same misconceptions that they exhibit for DC circuits? How do students interpret time-varying phenomena?

In a protocol analysis of interviews with students working on DC and AC circuit problems, we found that students had greater difficulty understanding time-varying phenomena in circuits.[8] We uncovered new misconceptions specific to AC circuits, but also found evidence of well known DC misconceptions that carried over to the AC domain. We identified a variant of the "current consumption" misconception which we called the "empty pipe" model of current flow. Students conceive of wires as "empty" when a circuit is off, and when the circuit is turned on, charges flows out from the positive terminal of the voltage source sequentially passing each circuit component. This carried over to the AC domain in some students. Students would imagine current flowing out of the positive terminal during the positive section of an AC waveform, then going back into the voltage source (emptying), and coming back out the negative terminal during the negative part of the cycle. Other students even ignored behavior of the circuit during the negative parts of an AC waveform, or made no distinction between AC and DC behavior. One other AC-specific misconception which has similarities to previous research on graph understanding involved students interpreting AC waveforms spatially rather than temporally. That is, students viewed the waveform as representing voltage changes along the wire spatially, rather than at a point in the wire over time.

We also observed that students focus more on manipulating formulas during problem solving than on applying the underlying, unchanging principles (or *invariants)*, such as Kirchoff's and Ohm's laws, that govern circuit behavior. Table 1 contains a list of some of the invariant principles we identified that are important for students to understand in introductory circuits classes.

Table 1: Some of the invariant principles we identified as important in introductory EE courses.

Invariant	**Description**
Ohm's Law	For resistors, capacitors, and inductors the current through the component is directly proportional to the voltage across the component. The ratio of voltage drop to current is the impedance of the component. For a resistor, the impedance is the resistance value, R. For capacitor (or inductors) the impedance is a function of the capacitance (or inductance) and the frequency (i.e., the rate of change) of voltage and current.
Kirchoff's Current Law (KCL)	KCL states that the sum of the magnitudes of currents flowing into a node at any instant of time where a number of components are connected together must equal zero. Therefore, total current entering a node must equal total current exiting that node.
Kirchoff's Voltage Law (KVL)	KVL states that the voltage drops across all elements in a loop at any instant of time must sum to zero.
Effective Resistance (series/parallel circuits)	The effective resistance of a set of resistances connected in <u>series</u> is the sum of the individual resistances. So in a series combination, the effective resistance always greater than individual resistances The effective resistance of a set of resistances connected in <u>parallel</u> is given by the relationship: 1/Reff = 1/R1 + 1/R2 + ..., where R1, R2… are individual resistances In a parallel combination, the effective resistance is always smaller than the smallest resistance.
Charge held by an Capacitor	The charge held by a capacitor is directly proportional to the value of capacitance, C, and the voltage drop across it. (Q = C*V). Another way to express this relation is I = C * dV/dt, i.e., the current of a capacitor is related to the rate of change of the voltage across the capacitor.
Impedance of a Capacitor	The impedance of a capacitor is inversely related to the capacitance value and the frequency of the source. Specifically the impedance of a capacitor is given by the expression: X_C = 1/(2*pi*f*C), where f is the frequency, and C is the capacitance.
Impedance of an Inductor	The impedance of an inductor is directly related to the inductance value and the frequency of the source. Specifically the impedance of an inductor is given by the expression: X_L = 2*pi*f*L, where f is the frequency, and L the impedance.
Inductor and Flux	The flux held by an inductor is directly proportional to the value of inductance, L, and the current through it. Another way to express this relation is V = L * dI/dt, i.e., the voltage drop across an inductor is related to the rate of change of current through the inductor.
Power	To determine the power dissipated by a resistor one has to know at least two of the three quantities for the resistor: its resistance, the voltage drop across the resistance, and the current through it. (Mathematically the power consumed = V*I = V^2/R = I^2*R)

Developing an AC/DC Concept Inventory

Based on the analysis of the results our previous research, as well as an analysis of experts' approaches toward circuit analysis, we have developed a bank of multiple-choice test questions for assessing student difficulties with DC and AC circuits.[9] The questions focus on qualitative conceptual understanding, with both the correct answers and incorrect distracters designed to target specific invariants and misconceptions. Table 2 has a description of the most recent 20-item version of our test, which we'll refer to as the AC/DC Concept Inventory. Each item in the table is followed by a description, plus any invariants or misconceptions the item addresses. We cannot share the actual items themselves used in this concept inventory, as it would compromise future research findings.

In order to keep the time required for taking this test down as much as as possible, not all invariants and misconceptions are covered by this version of the test. The test takes on average 20 minutes for undergraduates to complete. Note also that some of the questions contain distracters designed to identify misconceptions, while other questions solely focus on student knowledge of invariant principles. Sometimes, we believe, student difficulties with circuits are not just a result of prior misconceptions, but simply a lack of understanding of the underlying invariant principles.

While other circuit concept inventories have been developed since we initially created our bank of conceptual test questions (e.g., DIRECT[10], ECI[11], CCI[12], SSCI[13]), our questions complement them by targeting a critical education period that bridges the high school level and the early undergraduate level, covering both DC and AC circuit concepts, yet not more advanced items such as transistors, op-amps, and diodes that are covered in the ECI (electronics) and SSCI (signals & systems) tests. The CCI test contains circuit problems with a large focus on mathematical calculations and is appropriate for students who have a grasp of the fundamental principles. This is in contrast to our concept inventory, where the focus is mainly on qualitative reasoning. While the DIRECT test primarily covers DC circuit textbook problems, we have incorporated one question dealing with the "empty-pipe" misconception from the DIRECT test in our test. This is a question about the reason lights come on so fast at home when we turn on the switch. Many students believe that the wires are empty, and when we flip the switch, the electrons race to our house at the speed of light from the power plant. We included the question because it is very much in line with the concepts we are testing.

Our own test questions have gone through many revisions, but below we focus on the revisions we most recently made to address issues of test-wiseness and reliability, and the results of our latest administration of the questions to students.

Table 2: A description of each item on our concept inventory, with the invariant principles it addresses, as well as misconceptions the item is designed to catch. The last column refers to whether an item requires students to consider the behavior of current over time.

Item	Description of Item	Invariants	Misconceptions	Temporal?
1	DC, bulbs in series	KCL	empty pipe	
2	DC, bulbs in series		empty pipe, negative charge flow	Yes
3	DC, bulbs in series	Ohm's	tests common knowledge about bulbs	
4	DC, bulbs	Effective Resistance		
5	Lights at home		empty pipe, speed of current	Yes
6	DC circuits	KCL	current consumed	
7	Capacitor in DC circuit	Capacitor Impedance		Yes
8	Inductor in DC circuit	Inductor Impedance		Yes
9	DC Heater	KVL, Ohm's		
10	DC Heater	Ohm's		
11	DC Heater	Power	More resistance means more power	
12	DC, LEDs in series		empty pipe, negative charge flow	Yes
13	AC fuse	KCL	empty pipe, negative charge flow	Yes
14	Bulbs, Power	Power	More resistance means more power	
15	AC Christmas Lights	KCL	current consumed, AC as spatial, neg	
16	AC Christmas Lights		AC as spatial, empty pipe, AC=DC	Yes
17	AC vs. DC Bulbs	Power	Ignore negative part of AC	Yes
18	AC Bulb		Ignore negative part of AC	Yes
19	AC RC	KCL	current consumed, AC=DC	
20	AC RC	Capacitor Impedance	Confuse low pass & high pass filters	Yes

First Iteration of the Concept Inventory

Participants. We first administered our 20-item version of this concept inventory in the spring of 2006 and 2007 to 100 students. 40 students were volunteers (engineering majors) for a circuit simulation study (described later) in the spring of 2006, who were enrolled in introductory circuits courses at a 4-year private university in the southeastern U.S. Students were not randomly selected, nor did they represent the entire cadre of students from a circuits class. These students were given the test questions as a pre-test and post-test. Their pre-test results are included in the data analysis here. Another 60 students represented the population of engineering undergraduates taking introductory circuits courses in spring 2007 at a small 4-year public university in the southern U.S. with a large minority enrollment. All students had already had instruction on AC circuits and capacitors and inductors before taking this test.

Procedure. We administered the test in paper and pencil form to students either individually outside of class (in the simulation study), or to the class as a whole during class-time. Students in the simulation study were paid a small fee for participating.

Data Analysis. We analyzed the test results using a combination of spreadsheets and R[14], a statistical analysis package. For classical test analyses, we used the R extension packages ltm[15], psychometric[16], and MiscPsycho.[17]

Results. Students scored an average 54% correct on the test items. Overall reliability of the test as measured by the Kuder-Richardson 20 statistic (KR-20) was 0.608. Ideally this value should be around 0.7 or higher. Adding more test items and testing more students may help increase the reliability, but we looked into revising the questions themselves to improve reliability. Approximately 7 of the 20 items on the test had low reliability, as measured by point-biserial correlation. Point-biserial correlation measures the relationship between scores on a test item with scores on the overall test. If people who did well on the test did well on the item, and people who did poorly on the test did poorly on the item, that item has a higher reliability. Some of these low correlations on our test are easily explained, as certain items on the test covered concepts that were very different from concepts covered by the other items on the test. However problems with other items are not as easily explainable. Thus for the remainder of this paper we will only discuss the revisions we made to the test and the more detailed results and analysis from our administration of the revised test.

Revisions for Test-Wiseness and Reliability

When more closely examining our questions yet again, we continued to find issues that may have affected test validity and reliability. The phrasing of a question or an answer choice can significantly influence how students respond. In effect, part of what we assess with a multiple choice test is not knowledge of the content but rather how good students are at taking tests (test-wiseness). Kirk Allen and colleagues in an ASEE 2004 paper on their Statistics Concept Inventory[18] cited 7 criteria that may lead students with good test-wiseness to figure out the answer. Building off of their work and others,[19,20] we generated 11 test-wiseness issues when designing multiple-choice tests of any sort, not just concept inventories (see Table 3).

Table 3: Test-wiseness cues.

Test-Wiseness Cue	**Description**
Categorical Exclusive	Distracters contain words such as "all", "always", or "every." If a choice contains the word "all" or "every", a student may more easily rule it out. Try not to use those terms in the question or in the choices.
Phrase-Repeat	The correct answer contains a key sound, word, or phrase that is contained in the question's stem.
Absurd/Implausible Answer	Distracters are unrelated to the stem. Some incorrect choices may be more obviously wrong and easier to eliminate.
Precision/Specificity	Correct answer is more precise, clear, or qualified than the distracters. It is very detailed and provides no room for ambiguity. That suggests it is the correct answer.
Length	Correct answer is longer than the distracters. Try to make each of the choices relatively equal in length.
Grammar	Distracters do not match the verb tense of the stem, or there is not a match between articles ("a", "an", "the").
Give-Away	Correct answer is given away by another item in the test. Sometimes the answer to question 2 can be found in the stem of question 1, for example.
Order of Answer	Don't use a predictable pattern for the answers (for example, making the correct answer usually be C).
Number of Options and Guessing	Out of a hundred multiple-choice items with three answer options each, a student with no knowledge of the content will get 33 correct simply by guessing blindly. However, the more choices you add, the more susceptible the question becomes to test-wiseness, hence four items is more common.[21]
Odd Man Out	If you make two or more choices difficult to distinguish from one another conceptually, that usually helps you rule them out. If three answers are very similar and one is very different, the different one may likely be the correct answer.
Spelling	Test authors are more likely to make spelling errors on incorrect choices, since they mainly review the correct answers.

We re-worded some of the questions, and replaced two others with other questions from our test bank. In the second iteration, we planned to give the concept inventory to more students, and use a population of students more generally representative of engineering students across the country.

Most Recent Administration of the Concept Inventory

Participants. Students were 126 undergraduate engineering majors, giving a representative sample of the entire cohort of students who had finished taking their first introductory circuits courses in Fall 2007 at an average 4-year public university in the western U.S. All students had finished instruction on AC circuits and capacitors and inductors before taking this test. Students were from one of 3 classes. One group of 24 students consisted of EE majors at the very end of their first circuits course covering AC circuits, including RLC circuits. Another group of 52 students consisted of EE majors in the middle of their Signals & Systems class, which was being taught by a graduate student. The last group of 50 students consisted of non-EE engineering majors at the very end of a circuits course designed for non-majors. This course covered all the relevant topics in the concept inventory, including AC circuits, capacitors, and inductors.

Procedure. We administered the test in paper and pencil form to the 3 classes in class. While the students were not paid to take the test, students in the Signals & Systems class were given homework credit. It took students on average 20 minutes to complete the test.

Data Analysis. As before, we analyzed the test results using spreadsheets and R,[14] with R extension packages ltm[15], psychometric[16], and MiscPsycho.[17]

Results

Overall students answered 65% of the questions correctly on the concept inventory. Students in the non-majors course scored an average 62% correct, beginning EE majors 69%, and Signals & Systems students 66%. Since there were not large differences in the results between classes (although there is a significant difference between EE & non-EE majors), the results are combined for the remainder of this paper.

Figure 1 on the next page depicts the responses by item, including what percentage of students chose each answer on the test. Figure 2 is a histogram of the number of students by how many questions they answered correctly.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
A	4%	10%	8%	1%	**34%**	2%	5%	4%	10%	**65%**	21%	**67%**	24%	**52%**	8%	21%	28%	1%	16%	**37%**
B	13%	15%	6%	2%	4%	6%	20%	**65%**	25%	21%	**74%**	18%	6%	42%	2%	4%	**61%**	1%	6%	22%
C	**82%**	**72%**	0%	**57%**	40%	**90%**	**69%**	13%	**65%**	14%	5%	13%	20%	2%	**83%**	10%	8%	28%	11%	32%
D	2%	3%	**86%**	40%	21%	2%	6%	17%	N/A	N/A	N/A	2%	**49%**	4%	6%	**63%**	0%	**67%**	**64%**	6%

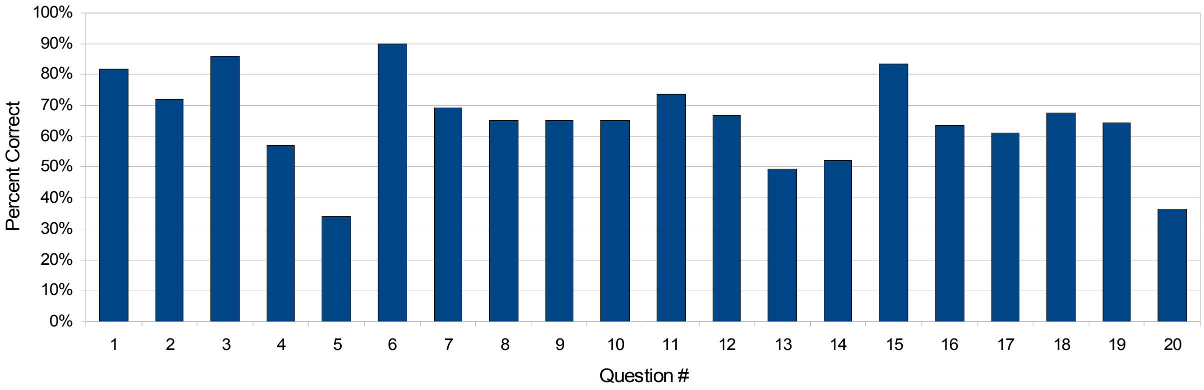

Figure 1: Table and graph with results on each item of the concept inventory.

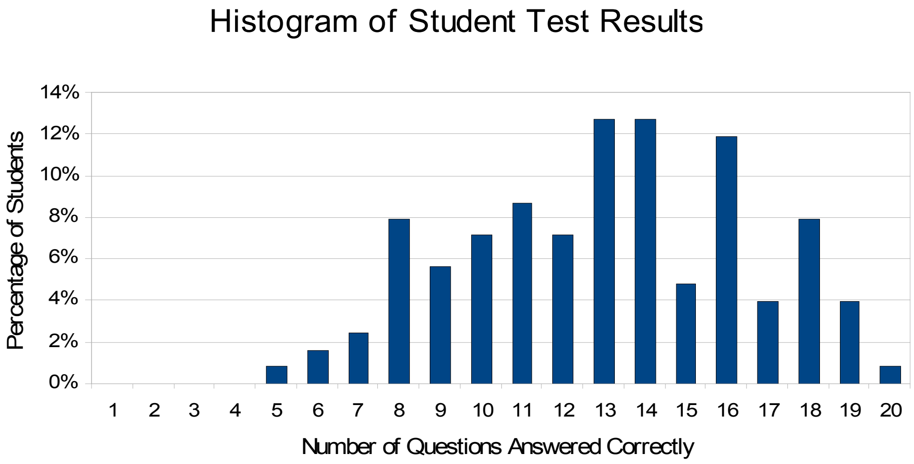

Figure 2: Histogram of students by how many items they answered correctly.

Reliability. Table 4 below summarizes the overall results of analyses of our test. The overall reliability of the test (KR-20) increased from 0.608 to 0.687. That is still not as high is recommended in psychometric texts (0.7). However, in this case the lower reliability of some of the items on the test are more easily explained below. Overall our concept inventory has acceptable values for the standard test statistics, despite the relatively low number of students tested (126).

Table 4: Summary of statistical test results

Test Statistic	**Description**	**Acceptable Value**	**Value Found**
Item Difficulty (P)	Percentage correct responses on the test.	Close to 50% for maximum spread of scores	65% - Note our results are with college students *after* they have had circuits instruction.
Kuder-Richardson 20 (KR-20)	Reliability, or internal consistency, of the whole test.	>0.70	0.687
Average Point Biserial Correlation	Reliability of a single item on the test. The correlation between correctness of a single item with correctness on the whole test.	>0.20	0.26
Ferguson's Delta	Ability of test to discriminate by how broadly it spreads out the scores.	>0.90	0.96
Item Discrimination Index (D)	How well an item discriminates between the top overall scorers (25%) and low scorers (bottom 25%)	>0.3	0.55

Analysis of low reliability items. Items 4, 11, 14, 16 & 20 have particularly low point-biserial correlations *and* few correlations with other items on the test (Table 5). Bold items in Table 5 indicate significant correlations.

Items 4 and 20 can be explained by the fact that individually they cover very distinct invariant principles from the other test items. Number 4 is the only question that tests one's understanding of effective resistance in series versus parallel circuits. Number 20 is the only AC-RC circuit question, testing one's knowledge of low-pass versus high pass filter circuits. The reliability of question numbers 11 and 14, however, at first appear curious because they are both about the invariant principle of power, and its relation to other factors such as resistance, current, and bulb brightness (an indicator of power). The fact that 11 and 14 are not significantly correlated with one another indicates that students may have been guessing on these questions. Most students were able to narrow down the choices from four to two (test-wiseness), but at that point they may have guessed. Approximately 75% of the students tested showed some error on these questions involving the concept of power. We have also found evidence for student difficulties understanding power in other pilot studies of our test questions, including test questions involving power calculations.[9] Finally, we may attribute the low reliability of question 16 about Christmas lights to poor wording of one of the distracters, which we will reword in the future.

When you plug in Christmas lights, they appear to glow steadily, and yet the AC voltage is changing constantly. The correct answer and distracter both sounded correct to some students.

Table 5: Item to item correlation matrix. Bold items are significant.

Item	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1	1	**.30**	-.08	-.12	-.01	.11	.08	.17	.08	-.04	.09	**.23**	.10	.04	**.45**	-.02	.00	.11	-.05	-.07
2	**.30**	1	.15	-.04	.11	.02	**.20**	**.21**	.10	.14	.07	**.50**	**.26**	.05	.10	.12	.01	.14	.13	.07
3	-.08	.15	1	.01	.05	**.23**	.12	**.18**	.08	.03	.07	**.19**	**.22**	.02	.06	.07	.05	.15	**.22**	.07
4	-.12	-.04	.01	1	.05	.13	.15	.14	.00	.07	-.08	-.17	.11	.01	-.17	.01	.10	.05	.06	.06
5	-.01	.11	.05	.05	1	.08	.08	.14	**.18**	.07	-.03	.15	.16	.15	.10	.09	-.04	.04	.08	.08
6	.11	.02	**.23**	.13	.08	1	.17	.08	.08	.03	.04	**.26**	**.28**	-.06	**.20**	.07	.05	**.32**	**.24**	.09
7	.08	**.20**	.12	.15	.08	.17	1	**.63**	**.27**	**.23**	-.01	.11	**.35**	.15	-.12	-.04	.17	**.23**	**.18**	-.06
8	.17	**.21**	**.18**	.14	.14	.08	**.63**	1	**.20**	**.20**	-.02	.12	**.29**	**.23**	.03	.00	.10	.17	**.18**	-.17
9	.08	.10	.08	.00	**.18**	.08	**.27**	**.20**	1	**.37**	-.17	.08	**.49**	.13	.03	.07	**.24**	.17	.15	.04
10	-.04	.14	.03	.07	.07	.03	**.23**	**.20**	**.37**	1	**-.28**	.05	**.35**	.20	-.10	**.21**	**.30**	.02	.15	.11
11	.09	.07	.07	-.08	-.03	.04	-.01	-.02	-.17	**-.28**	1	.15	.04	.01	.17	.11	-.10	.05	-.03	-.04
12	**.23**	**.50**	**.19**	-.17	.15	**.26**	.11	.12	.08	.05	.15	1	**.29**	.13	**.23**	.16	.02	.12	.14	.12
13	.10	**.26**	**.22**	.11	.16	**.28**	**.35**	**.29**	**.49**	**.35**	.04	**.29**	1	**.21**	.06	.15	.17	**.24**	.14	.01
14	.04	.05	.02	.01	.15	-.06	.15	**.23**	.13	.20	.01	.13	**.21**	1	.09	-.03	.09	.02	.09	.10
15	**.45**	.10	.06	-.17	.10	**.20**	-.12	.03	.03	-.10	.17	**.23**	.06	.09	1	.06	-.05	.10	-.02	-.06
16	-.02	.12	.07	.01	.09	.07	-.04	.00	.07	**.21**	.11	.16	.15	-.03	.06	1	-.13	-.14	.02	-.04
17	.00	.01	.05	.10	-.04	.05	.17	.10	**.24**	**.30**	-.10	.02	.17	.09	-.05	-.13	1	.14	**.22**	**.20**
18	.11	.14	.15	.05	.04	**.32**	**.23**	.17	.17	.02	.05	.12	**.24**	.02	.10	-.14	.14	1	**.30**	.10
19	-.05	.13	**.22**	.06	.08	**.24**	**.18**	**.18**	.15	.15	-.03	.14	.14	.09	-.02	.02	**.22**	**.30**	1	.05
20	-.07	.07	.07	.06	.08	.09	-.06	-.17	.04	.11	-.04	.12	.01	.10	-.06	-.04	**.20**	.10	.05	1

Analysis of high reliability items. We can learn even more by examining items with high test-item point biserial correlations and looking at the patterns in Table 2. We discovered two distinct patterns in the questions themselves and the correlations.

1. Approximately half of the test items force one to consider the behavior of the circuit over time (temporal understanding of current), whereas the other half are non-temporal in nature. For example, question 2 asked whether one bulbs lights up before another one in series when the circuit is switched on (empty pipe misconception). Other questions, however, were time invariant. For example question 1 asked if one of the bulbs was brighter than the other since it is closer to the positive battery terminal (current consumption misconception).
2. Some of the questions on our concept inventory test students' knowledge of invariant principles and have distracters designed to catch misconceptions, whereas other questions solely test one's understanding of invariant principles with no misconception distracters.

We found that students did worse on temporal questions than non-temporal questions: 51% to 72% (Figure 3). This is a robust effect we have seen in all administrations of our test questions. Students show a deficiency on questions involving considerations of current flow over time.

This is a skill not usually emphasized in traditional circuit courses. Given a circuit with a DC voltage source, a switch, bulb, and a capacitor in series (as in our question #7), students may know how to calculate the RC time constant or the voltage drops along the wire. But if you ask them "what happens" over time in this circuit – does the bulb light up at all, for example - some students may not know the answer. Similarly, our question #5 asked simply, why do the lights come on so fast when you turn on the switch? Only 34% of students answered correctly, with a large proportion of students showing evidence of the incorrect empty pipe model of current flow, believing the charge comes all the way from the power station to the bulbs in the instant *after* the switch is turned on.

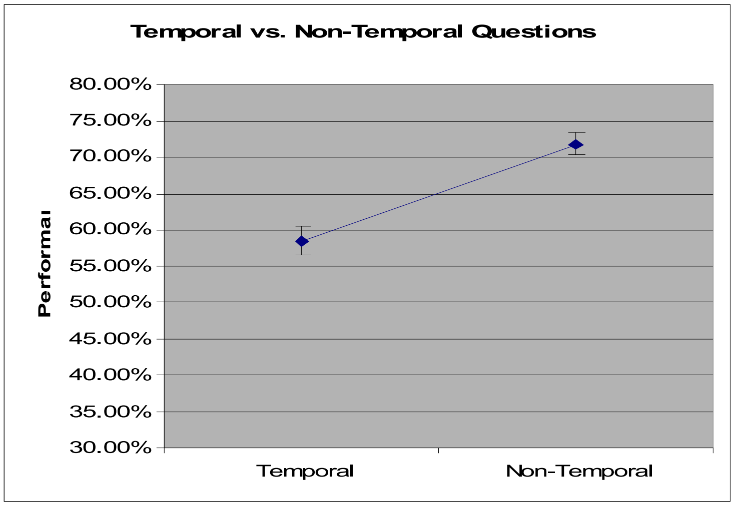

Figure 3: Performance (and variance) on temporal vs. non-temporal questions.

Comparing questions that had misconceptions distracters to those which did not (and solely focused on invariant principles), we found little difference: 64% on questions with misconceptions vs. 66% on invariant-only questions. However, separating those students who did worse on misconceptions questions from those who did worse on invariants questions, we found an interaction. Both groups did about the same on misconceptions questions (thus one may say that misconceptions about circuit behavior is a general problem with most all students), and yet there was a very large difference on invariants-only questions. Some students do appear indeed to be gaining a solid understanding of invariant circuit principles from traditional circuit courses, and yet some students seem to have a very poor understanding of the fundamentals. Further research is needed to explore the interaction between misconceptions and knowledge of invariant circuit principles, and the effects of instruction on both. However, from these initial results, in agreement with previous research, it appears that misconceptions are more resistant to instruction. Invariants are more closely connected to the instruction in existing circuit courses, hence the large difference in performance on those questions, with some students doing excellent and others doing poorly.

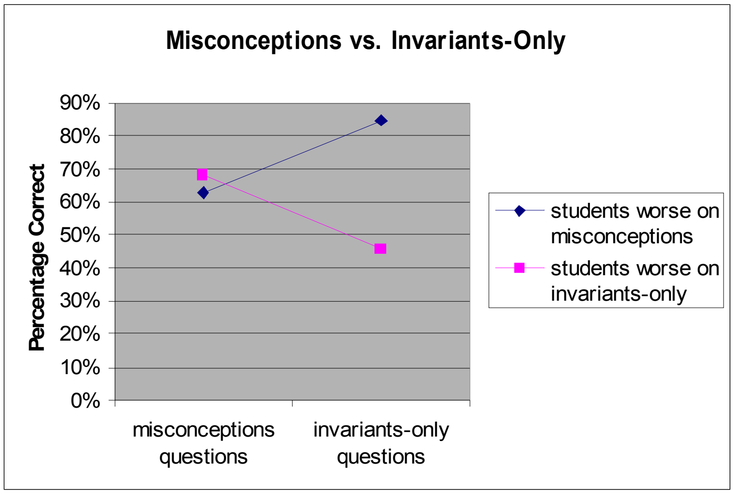

Figure 4: Students did about equally well on misconceptions questions, yet there was a large divide in student knowledge of invariant circuit principles.

Results by Specific Invariant and Misconception. Finally, we analyzed each students' answers for evidence of difficulties with specific misconceptions and invariant principles. Figure 5 breaks down the results. This chart shows what percentage of students showed as least some evidence of having difficulty with a particular invariant principle or misconception. The empty pipe misconception was most prevalent, with 78% of students showing at least one or more indications that they hold that model of current flow. Kirchoff's Current Law (KCL) is closely connected to that misconception (and the related current consumption misconception), and thus not surprisingly 73% of students showed a lack of understanding of the principle in at least one instance. 63% of students confused high vs. low pass capacitor filter circuits (our question #20), and 52% of students at least one ignored the negative part of the AC cycle or conflated AC with DC. Lastly, 75% of students showed at least some difficulty understanding the concept of power in electrical circuits.

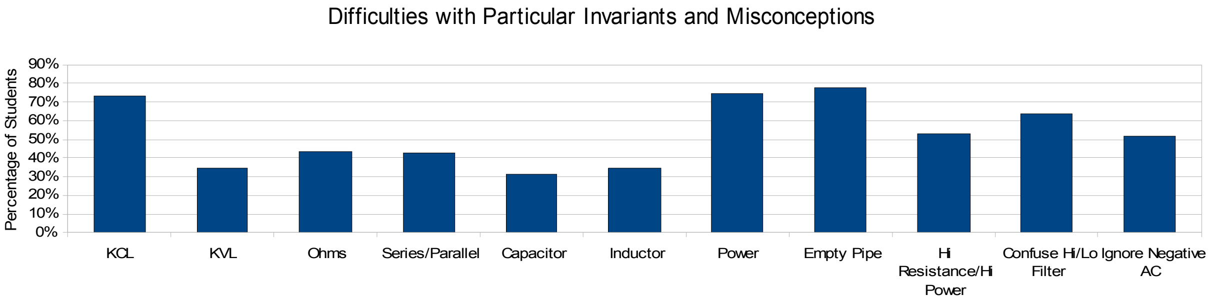

Figure 5: Prevalence of difficulties with specific invariant principles and misconceptions.

Conclusions, Implications for Instruction

We believe we have developed a reliable, useful concept inventory for assessing student conceptual understanding of DC and AC circuit behavior. We have made revisions to the questions to improve reliability and reduce susceptibility to test-wiseness issues. Administering this test to a cohort of engineering students after they completed their beginning circuits courses revealed conceptual difficulties that remain with students even after instruction. A large majority of students in particular have difficulties understanding the nature of current flow ("empty pipe" misconception) and have difficulties understanding the concept of electrical power.

We have begun to explore strategies for addressing these and other identified student difficulties with DC and AC circuits. Some of these strategies have included:
(1) an online dynamic assessment tool that provides feedback while answering qualitative circuit questions such as the ones on our concept inventory,
(2) challenge-based lab activities,[22] and
(3) an animated, real-time reactive circuit simulation.
In pilot studies so far, we have found that students using the dynamic assessment environment were able to improve their conceptual explanations of circuit behavior to more closely reflect the invariant principles we have identified.[9] Moreover, students tutored for a half hour with an animated circuit simulation improved their performance significantly on our test questions from pre- to post-test,[23] particularly on those questions that involved the behavior of current over time, which, as we noted earlier, students have the most difficulty. These results suggest that students' difficulties with understanding the behavior of AC and DC circuits can be significantly reduced by how we address them during instruction. In particular, the inclusion of qualitative reflection activities[24,25,9] and animated, controllable circuit simulation activities that reveal the behavior of circuits in real-time hold significant promise for improving the effectiveness of electrical engineering education.

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