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How Electrical Engineering Technology Students Understand Concepts of Electricity. Comparison of Misconceptions of Freshmen, Sophomores, and Seniors

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Abstract

Effective instruction in Engineering and Technology requires knowledge of how students understand or lack understanding of key concepts in these disciplines. Incorrect mental models, deeply rooted in everyday experience, can significantly affect student learning. Evidence suggests that students who learn new material may already have some understanding and preconceptions about the new concepts.

Misconceptions about electricity of novice students (college freshmen and first-semester sophomores) were analyzed and compared to the misconceptions of senior students. The study targeted: (1) correlation between student academic success (grades) and student misconceptions, and (2) understanding how student mental models and misconceptions change with increasing levels of competency and expertise during students' progression from the freshman to senior level. Non-equivalent groups of 20 novices and 22 seniors participated in this study. The mixed-methods research methodology included two phases. In the quantitative phase all students responded to the Concept Inventory [1] questions. During the qualitative phase 8 novices and 8 seniors were interviewed and responded to open-ended questions about their understanding of electricity.

The two most interesting and unexpected results deserve attention. First, in the novice group negative correlation between grades and misconceptions was stronger than in the senior group. Incorrect understanding of electricity in the senior group is frequently disguised by well-developed technical vocabulary. Even the brightest high-GPA students had numerous mistaken beliefs. The other unexpected result was that, despite significant improvements in understanding of electricity, seniors had more misconceptions (and were more confused) than novices about physical and fundamental electrical phenomena, such as 'charge' or 'electrical field'. Also, the two most widespread analogies among the students were between 'water flow' and electrical current, and electricity is a 'substance-that-can-be-used-up'. Identified as the most popular mental models, these analogies remained frequently used from the novice to senior levels.

Introduction

The shortcomings in STEM education in the U.S. attract great attention at the Federal and State levels. The focus on STEM (and in particular on Engineering and Technology) is closely related to concerns about the competitiveness of the United States in the global economy, and to the deficiency in numbers of domestic engineers, and qualified work personnel [2]. The problem [3], [4], [5] is that even high-performance engineering students (with high grades) after four years of college instruction continue to hold significant misconceptions about scientific concepts and have misinterpretations of phenomena (like electricity, force, light). The practical knowledge of engineering students is also limited and student ability to solve problems is weaker than desired. Even with increasing competency, while moving from freshman to senior level, students learn how to follow familiar algorithms (e.g., to solve equations) but often they are unable to explain why they followed those algorithms.

The present study focused on analysis of misconceptions of Electrical Engineering Technology (EET) freshmen, sophomore, and senior students studying the phenomenon of electricity. The field of electricity was chosen because it contains scientific, technological, and practical concepts, which are frequently misunderstood. Clear understanding of phenomena is particularly important for Engineering (and Engineering-Technology) students because new graduates become analysts, designers, and problem-solvers responsible for the entire spectrum of decisions at work places. Hence, inappropriate engineering decisions, some of which can result from lingering misconceptions about phenomena, may have critical consequences not only for the technological design of the particular product/artifact, but to impact negatively on whole society.

Background

Learning is inseparably linked to the process of creation /destruction of misconceptions. Previously cited studies in recent years have shown proof that many students do not understand concepts in science in the same way as experts and scientists. Concepts in science overlap in many ways with the concepts in engineering and technology. Thus, students' incorrect understanding of scientific concepts and natural phenomena affects engineering and technological performances. There is some evidence [6], [7], [8] that suggests when students learn new material, many of them already have some kind of understanding of the problem [9]. They also may have preconceptions or naïve theories about both new and familiar concepts. These pre-conceptions also are called alternative conceptions or misconceptions [10]. Usually such misconceptions are robust, very resistant to change, and deeply rooted in everyday experience.

Two of the major questions in research about misconceptions are: (1) why some concepts are more difficult to learn than others, and (2) why do students have misconceptions even after extensive instructions. Referring to a literature, the six most significant reasons were:

- The reasons some concepts are more difficult to learn may have developmental causes. However, this is not likely to be a key issue for engineering students [11], [12].
- Concepts are more difficult to learn when: (1) they are not directly observable, and (2) when a macroscopic pattern emerges from unobservable microscopic phenomena. The inability to directly observe key conceptual quantities such as force and energy almost certainly contributes to the difficulty in learning about them. Concepts that are most difficult to learn are often emergent processes which people misattribute to direct causation [13], [12].
- Ontological miscategorization: concepts are misunderstood when features of one ontological category are applied to another category [14].
- According to DiSessa [15], misconceptions are the product of a fragmented set of primitive mental constructs (phenomenological primitives or p-prims). "These are fundamental pieces of intuitive knowledge developed as a result of one's experience with the world. They are context-free constructs that are abstracted from prior experience and employed to rationalize other phenomena" ([16], p. 24). Misconceptions are generated by mistakenly activating a single p-prim, or a set of p-prims, in an inappropriate context.

- Ignorance is the other common reaction of learners on new information. There are seven distinct forms of response to unknowing information and anomalous data [17]: ignoring, rejecting, excluding, abeyance, reinterpreting, peripheral change, and theory change. Only one case in seven shows that new information is accepted and the learner is ready to reconsider his/her theories and ideas. In the other six ways, the new information (data) is ignored.
- Instructors' unclear understanding of natural phenomena and incorrect analogies that students are taught during the instructions is the final reason. For instance, frequent analogies between water flow and electrical current are very popular for instructors in introductory electrical courses. Some authors [18] expected to show proof that knowledge of hydraulics laws will help students better understand electrical circuits. The other example is the list of misconceptions about electricity [19] that are taught in middle and high school textbooks as correct scientific concepts. This issue raises two major questions: (1) the quality of science textbooks written for novice youth audiences, and (2) the professional preparedness of instructors teaching about natural phenomena and science in K-12 and beyond.

Misconceptions about electricity

The concept of electricity is usually difficult to understand because of human inability *to observe it directly* [13]. Numerous research studies diagnosed common student misconceptions in this field. Some studies [20], [12], [21], [22], [23], [24], [25] detected the following:

- Beliefs that a battery is a source of constant current. This is perhaps the most pervasive and persistent difficulty that students have with DC circuits;
- Failure to understand that an ideal battery maintains a constant potential difference between its terminals;
- The belief that current is consumed;
- Failure to distinguish between potential and potential difference;
- Failure to understand the concept of a complete circuit;
- Failure to differentiate between concepts of current, energy, power, and potential difference;
- Belief that 'current flow' is a sequential process that has a beginning and the end;
- Belief that current gets used up as it flows through the elements in a circuit;
- Confidence that the current through a given circuit element is not affected by the circuit modification introduced after the element ;
- Misinterpretations of Ohms law;
- Failure to recognize that an ideal voltage source maintains a constant potential differences between its terminals;
- Difficulty identifying series and parallel connections.

Research Questions and Hypotheses:

The purpose of the study targeted two directions:

- To investigate if there are any observable relationships between student academic success (grades) and their misconceptions of electricity.
- To explore how different are the nature and the number of student misconceptions of seniors comparing to novices (freshmen and sophomores)

The following three research questions guided the study:

1. Is there a correlation between student academic success (as represented by student grades in electrical/electronics courses) and the number of misconceptions about electricity?
2. Is there a difference in a number of misconceptions of novices vs. seniors?
3. How are seniors' misconceptions about electricity different from novices' misconceptions?

The study employed a mixed-methods methodology consisting of quantitative (RQs. 1-2) and qualitative (RQ 3) phases. Thus, the following hypotheses were developed for the quantitative analysis phase:

H01: There is no correlation between student academic success (grades) and the number of misconceptions.

HA1a: There is a positive correlation between student grades and the number of misconceptions. If the grade is higher, the number of misconceptions is larger.

HA1b: There is a negative correlation between student grades and the number of misconceptions. If the grade is higher, the number of misconceptions is smaller.

H02: There is no difference in numbers of misconceptions of novices and seniors.

HA2: Seniors have fewer misconceptions than freshmen.

Participants

There were 20 novices (the freshmen and first-semester sophomores enrolled in the introductory level course "Digital Fundamentals"), and 22 senior students (enrolled in the senior final project-design course) in the Electrical and Computer Engineering Technology program at Purdue University, Indiana.

Methods and Research Design

Concept Inventory

Despite the variety of accepted methods to detect and diagnose students' misconceptions, Concept Inventories (CIs) have attracted most of the attention in engineering education. This study employed an instrument entitled "Determining and Interpreting Resistive Electric Circuits Concepts Test", DIRECT, version 1.0 [1]. Previously, this test already had been administered to around 1200 students from high schools and universities across the United States. The reported [1] reliability (KR-20) of the test was 0.71. The CI contains 29 multiple-choice questions and takes approximately 30 minutes to complete. Every question of this CI provides of 3-5 multiple choice answers of which only one is the correct answer and all the others are distracters composed from previously identified common student misconceptions about electricity. The DIRECT CI was designed to test students' knowledge in: (1) physical aspects of DC electric circuits, which is the 'microscope' view of what goes inside the circuit; (2) current; (3) differentiation between current and voltage; (4) understanding of physical layout of the circuit and interpretation of circuit diagrams; (5) batteries that are in series or parallel; and (6) resistance.

Research Design Steps

The research design incorporated a synthesis of methods, such as descriptive, non-experimental, and correlational (in the quantitative phase) study. Its qualitative phase was based on the grounded theory principles. The research design includes three major steps presented below in Figure 1.

Step 1 Before taking the DIRECT concept inventory, a general demographic information was collected from each participant. That included gender, age, number of semesters in college, and pre-college experience with electricity. The novice sample consisted of 20 students in the age range from 19 to 25 years old. Novices' pre-college knowledge about electricity varied from a very basic high-school understanding to six years of military school and work experience. The sample of seniors consisted of 22 students and the age range varied from 21 to 26 years old. All senior students stayed in the same program for the last three years and did not change their majors. Also, all participants provided unofficial copies of their academic transcripts with lists of completed courses. Student were requested to highlight any course where concepts of electricity were taught. Gathering this information was necessary for the calculation of the Average Grade in Electrical Disciplines (AGED). Basically, AGED is an analogy of student GPA but only in 'electrical/electronics' disciplines without elective courses. Traditional student GPAs were not used because of the impact of elective courses on total GPA.

Step 2 (*quantitative phase*) was based on correlational research method. All 42 novice and senior participants responded to the CI questions. After collecting student responses, the numbers of correct and incorrect answers were calculated for every multiple-choice question. Since the distractors were adapting of existing misconceptions, when a student chose any distractor, she/he agreed and accepted a previously detected misconception. The observed numerical value of incorrect responses can be adapted as an indicator of the number of misconceptions. Correlation coefficients between AGED (grades) and number of incorrect responses (misconceptions) were calculated for both groups. To visualize findings, scatterplots were designed for each student group. Plotting the data showed the direction (positive or negative) and the strength of relationship. Subsequently an independent sample T-test (α=0.05) was performed to investigate significant difference in conceptual understanding of the novice versus seniors groups.

In Step 3 (*qualitative phase*). 16 volunteers (8 novices and 8 seniors) were invited for individual 30 minute semi-structured interviews. During the first 15 minutes students explained why they chose a particular answer in the DIRECT test. Participants were not informed that they were asked to explain only their incorrect responses. This approach avoided biases if students attempted to change their responses if they had known that they made a wrong answer. The next 15 minutes participants briefly responded on four questions about electricity that were not related to the DIRECT CI.

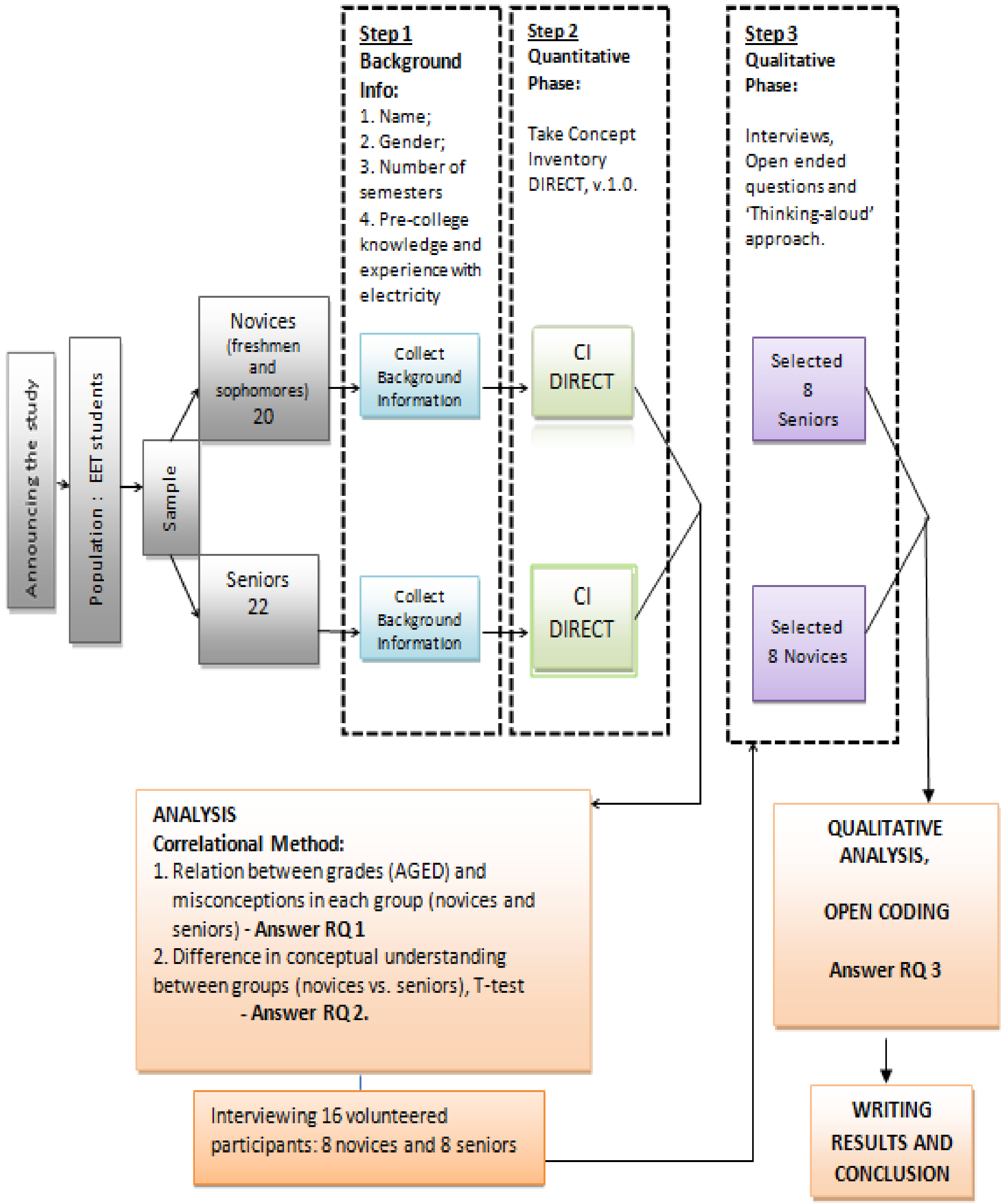

Figure 1. Flowchart: Research Design Steps

Those questions include the following:

1. How would you explain what is electricity?
2. From your perspective, what's the difference between voltage and current?
3. Explain in your words why batteries get "used up" and "go dead"
4. Comment on the statement: “The electric companies should not bill us since they take back all of the electrons they gives us”.

The purpose of question 1 was to detect the most frequent definitions that participants used to explain the phenomenon of electricity. Question 2 tested how well students differentiated between the two frequently misunderstood concepts of current and voltage. Question 3 (adapted from [19]) examined student ability to explain the “macro” event (the battery is dead) from the “micro-level” perspective (what is dead? what is happening inside of the battery? what exactly “used up”?) Words “dead battery” are used repeatedly in everyday language, but common explanations of “why it is dead” often consist of multiple misconceptions even for experienced professionals. Question 4 (also adapted from [19]) despite of its humorous formulation, allowed the researchers to probe student understanding of relationships between current, voltage, energy, and power. The interviewer did not judge correctness of responses but rather focused on attempting to understand how students think. During interviews participants were video-recorded. All interview protocols were transcribed and analyzed using open-coding technique.

Results

Quantitative Phase

Pearson Correlation Coefficients (r) were calculated for each group of students to investigate correlation between incorrect responses to the Concept Inventory and students’ grades (AGED). For the novice group **r** was equal -0.554 (P-value = 0.006< α=0.05), and for the senior group was **r** = -0.389 (P-value =0.037 < α=0.05). Both coefficients were negative which meant that as academic student performance (grades) increased there were lower numbers of misconceptions. However, even though the correlations for both groups were statistically significant, they were not strong. The squared correlation coefficients that measure how accurately grades predicted misconceptions for the novice group: $\boldsymbol{r^2}$nov.=0.307= 30.7 %, and for seniors $\boldsymbol{r^2}$sen.=0.151= 15.1%. On the freshman/sophomore level, grades may be considered as only a moderate indicator of students’ misconceptions. With an increasing level of expertise following to the senior level, misconceptions became more difficult to detect and were possibly hidden under scientific terminology and well developed scientific vocabulary.

Table 1. *Incorrect Responses to DIRECT CI and Grades (AGED) in the Novice and Senior Groups.*

Novices (Freshmen & First-semester Sophomores)		
Student Number	Number of Incorrect Responses to DIRECT CI	Students' AGED
1	5	3.62
2	7	3.46
3	3	4.00
4	17	2.47
5	12	3.70
6	5	2.09
7	14	2.46
8	17	2.18
9	14	3.17
10	15	2.46
11	13	3.33
12	13	3.26
13	14	3.41
14	15	3.53
15	10	3.43
16	21	1.77
17	8	2.75
18	12	2.46
19	17	2.00
20	17	2.46
	Mean=12.45	Mean=2.9

Seniors		
Student Number	Number of Incorrect Responses to DIRECT CI	Students' AGED
1	7	2.36
2	3	3.71
3	3	2.90
4	5	3.69
5	2	3.08
6	7	3.92
7	9	2.49
8	4	3.24
9	3	3.44
10	10	3.52
11	6	3.48
12	13	2.32
13	11	3.25
14	4	3.33
15	4	3.16
16	16	2.62
17	16	2.61
18	11	3.07
19	7	2.43
20	7	2.24
21	6	2.38
22	11	3.01
	Mean= 7.5	Mean=3.01

Table 2. *Correlation Between AGED and Numbers of Incorrect Responses.*

Novices		AGED
Incorrect Response	Pearson Correlation	$-.554^{**}$
	Sig. (1-tailed) P-value	.006
	N	20
Seniors		**AGED**
Incorrect Response	Pearson Correlation	$-.389^{*}$
	Sig. P-value (1-tailed)	.037
	N	22

*. Correlation is significant at the 0.05 level (1-tailed).

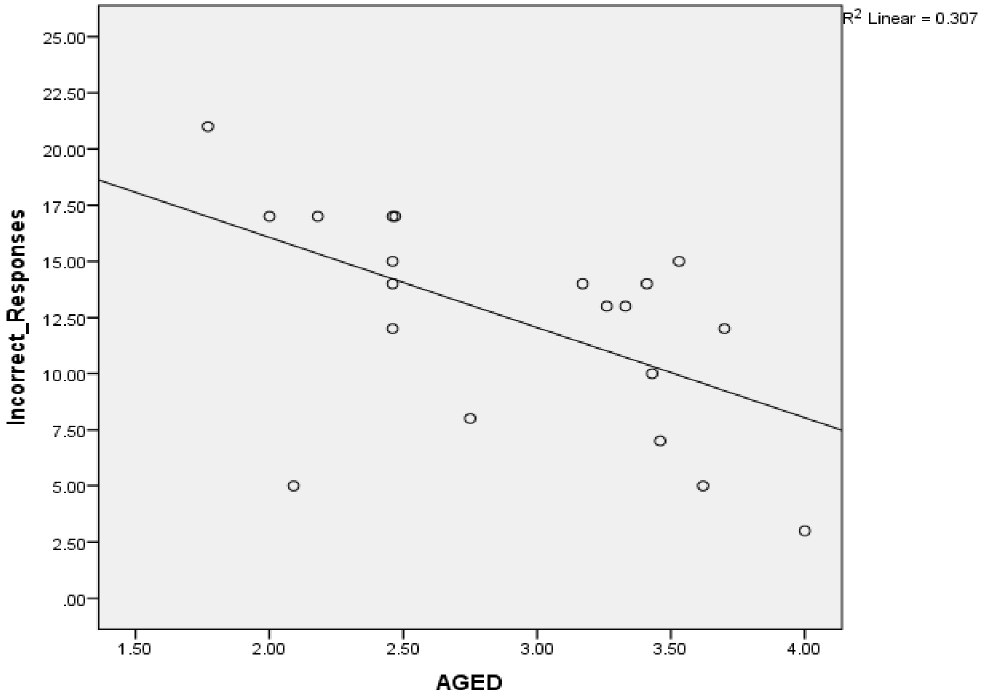

Figure 2. Linear Regression of AGED and Incorrect Responses in the Novice Group.

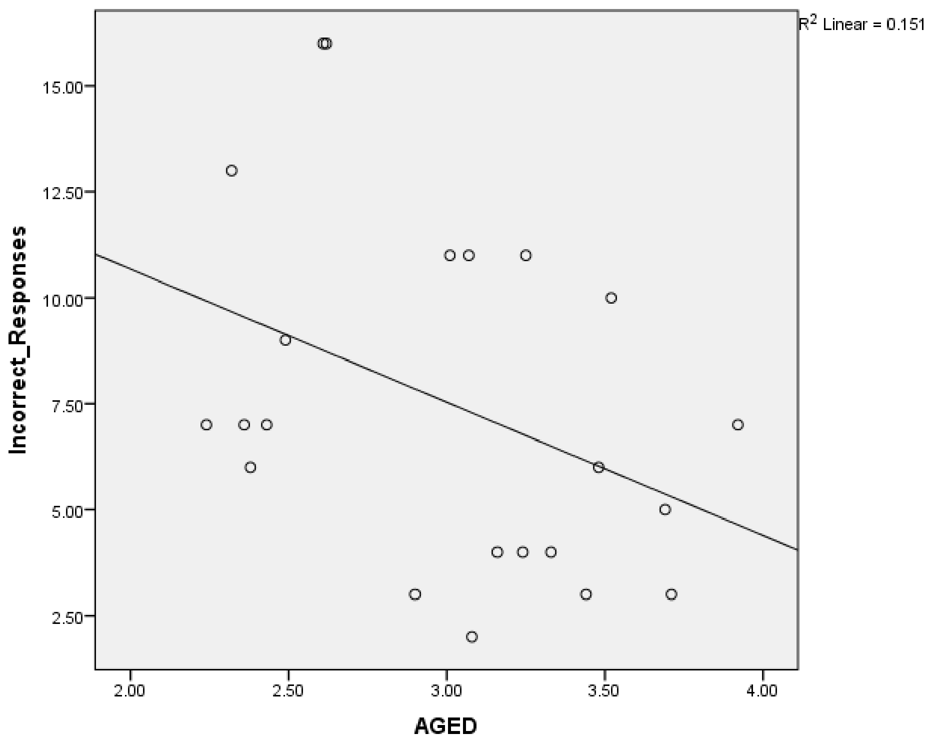

Figure 3. Linear Regression of AGED and Incorrect Responses in the Senior Group

The T-test for senior and novice groups shows a statistically significant difference between the population mean numbers of misconceptions between the two groups
(P-value = 0.006< α=0.05). Therefore, data provided sufficient evidence that seniors had fewer misconceptions than freshmen

Table 3. *Group Statistics of Senior and Novice Samples*

		N	Mean	Std. Deviation	Std. Error Mean
VAR01	Seniors	22	7.5000	4.13752	.88212
VAR02	Novices	20	12.4500	4.77356	1.06740

Table 4. *Independent Sample Test*

	T-test for Equality of Means					
					95% Confidence Interval of the Difference	
	t- statistics	Degree of freedom	P-value	Mean Difference	Lower	Upper
Equal variances not assumed	-3.575	37.844	.001	-4.95000	-7.75362	-2.14638

Figure 4 visually represents the difference between the two populations in terms of frequencies of students' incorrect responses. It shows that the peaks of the two distributions are located at different places. More specifically, most of the observations for seniors fall between 5 to 10 and that for the novices fall between 12 and 15 incorrect responses.

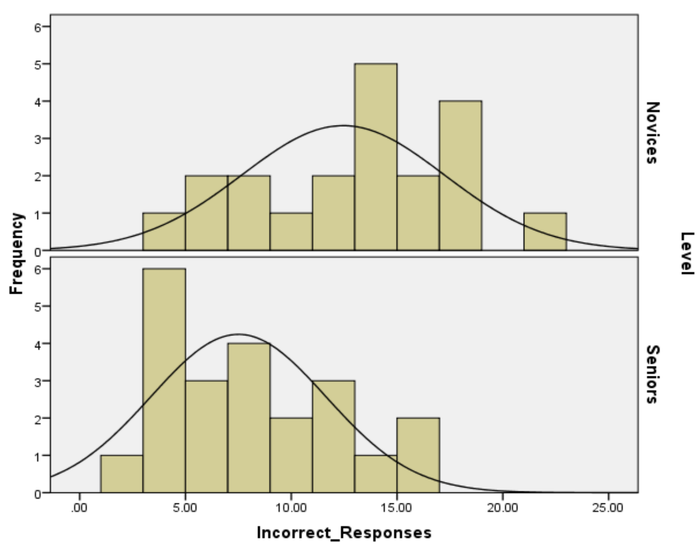

Figure 4. Frequency of Incorrect Responses of Novices and Seniors.

Table 5 presents overall results for the DIRECT CI for the both groups of participants. Seniors significantly improved their knowledge and were better able to interpret circuit diagrams, differentiate between current and voltage, and more clearly understand how arrangement of the circuit elements impacts the outcomes (voltage and current). However, some important concepts related to the physical 'micro-view' inside of the circuit and the 'nature' of electricity remained unclear for seniors as well as for novices. There were three questions (1, 11, and 20) where the percentage of seniors choosing the right response was lower than the percentage of novices. Questions 1 and 11 examined the understanding of the concept of charges; question 20 tested student knowledge about electrical fields inside the conductor. These results correspond with the extensive work of Chi [13], [26] which indicated that concepts are more difficult to learn when: (1) they are not directly observable, and (2) when a macroscopic pattern emerges from unobservable microscopic phenomena. The inability to observe directly key conceptual quantities such as force and energy almost certainly contributes to the difficulty in learning about them.

Table 5. *Overall Results for the DIRECT CI for the Groups of Seniors and Novices*

SENIORS							NOVICES						
Question #	Percentage % of Student who chose:					% of students who chose the right response	Question #	Percentage % of Student who chose:					% of students who chose the right response
	A	B	C	D	E			A	B	C	D	E	
1	36.4	9.1	31.8	22.7	n/a	22.7	1	35	10	25	30	n/a	30
2	4.5	90.9	4.5	n/a	n/a	90.9	2	0	80	20	n/a	n/a	80
3	4.5	9.1	59.1	4.5	22.7	59.1	3	0	20	55	0	25	55
4	0	0	9.1	81.8	9.1	81.8	4	20	0	25	45	10	45
5	4.5	95.5	0	n/a	n/a	95.5	5	0	90	10	n/a	n/a	90
6	9.1	0	0	9.1	81.8	81.8	6	35	0	15	15	35	35
7	86.4	9.1	4.5	n/a	n/a	86.4	7	80	10	10	n/a	n/a	80
8	4.5	0	95.5	n/a	n/a	95.5	8	15	5	80	n/a	n/a	80
9	0	4.5	0	95.5	0	95.5	9	35	10	0	55	0	55
10	0	0	27.3	0	72.7	72.7	10	0	0	50	0	50	50
11	22.7	13.6	45.5	18.2	n/a	22.7	11	55	20	10	15	n/a	55
12	40.9	9.1	0	50	0	50	12	50	25	5	15	5	15
13	100	0	0	0	0	100	13	95	5	0	0	0	95
14	13.6	86.4	0	n/a	n/a	86.4	14	15	70	15	n/a	n/a	70
15	22.7	0	77.3	n/a	n/a	77.3	15	55	0	45	n/a	n/a	45
16	9.1	4.5	86.4	n/a	n/a	86.4	16	15	35	50	n/a	n/a	50
17	0	9.1	18.2	63.4	4.5	63.4	17	0	10	50	35	5	35
18	0	0	100	0	0	100	18	0	0	85	15	0	85
19	0	0	90.9	0	9.1	90.9	19	0	30	50	5	15	50
20	4.5	4.5	72.7	18.2	n/a	18.2	20	0	0	75	25	n/a	25
21	4.5	0	4.5	77.3	13.6	77.3	21	0	5	45	45	5	45
22	0	72.7	4.5	0	22.7	72.7	22	0	50	15	5	30	50
23	4.5	22.7	68.2	4.5	n/a	68.2	23	15	15	55	15	n/a	55
24	18.2	0	9.1	59.1	13.6	59.1	24	30	0	15	35	20	35
25	95.4	0	4.5	n/a	n/a	95.4	25	85	0	15	n/a	n/a	85
26	13.6	0	9.1	77.3	0	77.3	26	30	0	0	70	0	70
27	0	95.4	0	4.5	n/a	95.4	27	0	95	5	0	n/a	95
28	9.1	0	13.6	77.3	n/a	77.3	28	15	0	25	60	n/a	60
29	27.3	45.5	13.6	9.1	4.5	45.5	29	20	25	10	45	0	25

Note. This table is read as follows (example): 35% of novices and 36.4% of seniors chose 1A. 10% of novices and 9.1% of seniors chose 1B, 25% of novices and 31.8 % of seniors chose 1C. 30% of novices and 22.7 % of seniors chose 1D. The same approach is applied to the rest of the table. Highlighted in orange questions are those where the percentage of seniors choosing the correct response is lower than a percentage of novices.

Qualitative Phase

First, students explained their incorrect responses to DIRECT CI, and then they briefly responded to four questions (presented above) about electricity. Table 6 presents a summary of detected in interview student misconceptions for both groups of participants.

Table 6. *Summary of Detected Misconceptions about Electricity for Novices and Seniors*.

Themes and Categories	Detected Misconceptions	How many students agreed: Novices N=8	How many students agreed: Seniors N=8
Physical aspects of DC electric circuits; "microview" of what happens inside the circuit.	Confusions about how to define "charge"	1	6
	Charge is energy; thus, charge may be converted to heat or light		2
	Replacing the meaning of "one charge" by the meaning of "one electron"	2	6
	Students refer to capacitors, because it is the only time when they heard about charges. "Capacitor can hold a charge". But students cannot explain what "hold" means.	1	1
	Charge is a moving "substance". Recognizing charges as "matter" that may be used up or can "store energy"	1	2
	Electricity is a matter/substance.	2	
	Electrical power can be sent somewhere like a material substance. Power goes through the bulb and bulb is "using up" power.	4	1
	Electrons travel fast with the speed of light	1	5
	Uncomfortable with the term 'electric field': "the term is vague"	2	2
Current	Current is "used up" by the first element in the circuit, and the rest of the current goes to the second element. Current "travels" in the circuit. (Students believe that change made at a particular point does not affect the current until that point. "A" stays the same because "B" is added in circuit after "A". Students do not recognize circuit as a "whole" system)	6	1
	Strength of the current depends on the direction of the "flow". As more elements in the circuit as lower current is, because current is "used up" and consumed by elements.	2	
	Confusion in interpretations of current vs. energy. Energy is used up by the first bulb and the second bulb in the circuit will get less	1	1
	Current causes electric field. (correct answer- current is a 'product' of the electric field)	7	5
Ability to differentiate between current and voltage	Voltage is "used up" by elements in the circuit. Examples of "used up" may include: The first component in the circuit had taken from the battery the "first source" and then the rest of voltage goes to the second component	11	3
	Analogy between water flow and "current flow" or "voltage flow". Voltage splits in a junction. Applications of hydraulics laws to the circuit	3	
	Confusion of current/voltage. Students assume one of the following: (1) that the potential difference is a property of the current; since there is no current, there can be no voltage, (2) when there is one, there is the other. They always come together or (3) current causes the voltage so you must have current to have voltage	3	3
	Voltage as a matter/substance that circulated inside of the circuit. If there is an open switch, there is no voltage in the elements after the switch.	2	1
	Confusion between power and potential difference (voltage)	2	2

Physical layout of the circuit and interpretation of circuit diagrams	Students identified series combination as parallel. Problems with interpretation of circuit diagrams	3	
	Do not recognize shorted out elements in the circuit	4	4
	Incorrect understanding of physical layout of the circuit. Do not understand schematic configuration	4	
	Unable to identify the need for two correct contacts from the battery to light the bulb	3	
	After turning on the switch, the light in our houses comes on immediately only because everything is wired in parallel (students refer to "observable" event)	1	1
Batteries that are in series or parallel	Batteries superposition: two batteries provide more current than one battery regardless of the battery arrangement.	4	2
	Considering battery as a constant current source	3	1
	Assuming that if one battery makes a bulb shine, then two batteries, regardless of the configuration, will make the bulb shine with "double brightness"	1	2
	For batteries connected in parallel, students use the same logic as for resistors. Total voltage should go down with an analogy of overall resistance in parallel connection	2	
	Battery "stores" both voltage and current; or the battery is a constant current source.	2	
	Misapplication of Ohms law: when one doubles the current through the battery, the potential difference across a battery is doubled. (Students do not have clear understanding that potential difference [voltage] is the property of the battery EMF = const.)	6	4
Resistance	Do not understand that in parallel connection the overall resistance of two bulbs halves; thus, current doubles	3	1
	Adding another resistor, regardless of configuration, increases the overall resistance, thus decreasing the current.	5	
	Added in series resistance increases current. Misapplication of Ohms law		2

Comparing responses of novices vs. seniors to the DIRECT concept inventory, a few important themes developed. Both groups of participants showed a limited understanding of physical aspects of circuits. Specifically, in the category of questions that tested knowledge of "insides of the circuit" (see Table 5), seniors showed worse results than that of novices. According to Table 6, both categories of students had an unclear understanding of the 'electrical charge' concept. For example, novices claimed that this term is vague and unfamiliar to them. Seniors, on the other hand, also complained about vagueness and ambiguity of 'charge' meaning. But after four years of instructions seniors automatically replaced the meaning of 'one charge' to the meaning of 'one electron'. This seemingly insignificant misinterpretation leads to many subsequent misconceptions. According to a scientific definition, current is a flow of charges. Many seniors understood the current as only the flow of electrons/particles. During instruction, the difference between these two terms must not have been elucidated and clarified. Charge is a 'property' of subatomic particles that allows them to attract or repel other particles by electric force. In the other words, one negative charge is a 'property' of one electron. Charges may be positive or negative and are 'measurable' in coulombs. Thus, current is not only the flow of negative electrons. It also may be a flow of positive 'holes', such as in a semiconductor. For better understanding, consider the next analogy. Someone can say that 'one ball' weighs 'one pound'.

A ‘pound’ is a property of ‘the ball’. It would be possible to say that ‘one ball is one pound’, but on the other hand, it is illogical to think that one pound is the ball. This variance in meanings refers to ontological differences of those two terms. ‘Ball’ belongs to the category of ‘matter’. One ‘pound’ is not matter, but a property of matter. When ontological features of one word-category are mistakenly applied to another word-category, it creates a fruitful source for very robust and resistant-to-change misconceptions [13], [14]. For example, understanding current not as a flow of charges but as a flow of electrons/particles, students often interpret electricity as a moving substance that can be ‘used up’.

In addition (according to Table 6), 7 out of 8 novices showed unclear understanding of the cause and effect relationship between current and electric field. They claimed that current caused electric field (correct answer: current is a ‘product’ of electric field). Similar responses were mentioned in the senior group, where 5 students agreed with the same statement. Another detected and widespread misconception (1 novice and 5 seniors), specifically on senior level, is that electrons travel in the conductor at the speed of the light. In reality, electrons move slowly; in AC circuits, they do not move but “vibrate”.

Problems interpreting circuit diagrams and layouts were usually resolved by the time students progressed to the senior level. Seniors showed clear understanding of schematic configurations. In the category of questions devoted to batteries in series and parallel, some concepts remained vague to seniors. They still do not have clear understanding that potential difference (voltage) provided by the source is the property of the battery (emf = constant). Students also may misapply Ohms law, considering two batteries in parallel as two resistors.

The key assertion that emerged from the present study is that the majority of Electrical Engineering Technology students perceived electricity as a traveling substance “that-can-be-used-up”. This incorrect understanding of the nature of electrical phenomena persisted from freshman to senior levels. Novices reported that this mental model already was created before entering college. The ‘product’ of such an incorrect understanding reflects the popular analogy of electricity and water. When learning new material about the ‘invisible’ world, students sought ‘visible’ analogies in the observable world. Often the water analogy was presented by instructors or in books or students made this assumption by themselves because it is “visible”. Although students understood that the water analogy cannot elucidate all electric properties, they repeatedly applied features of plumbing-systems to electrical circuits and diagrams. At the novice level, the water analogy is widely used but does not have yet a ‘common perspective’. Novices applied water similarities to a variety of electrical phenomena. For example, current is water flow; voltage is water flow too. Current also can be water pressure; voltage is ‘the height of water waves’. At the senior level, the water analogy has a ‘common agreement’ from students. The majority of seniors imagined current only as the amount of water, while voltage was perceived as water pressure in a pump.

In general, comparing changes in the nature of misconceptions of novices and seniors, the following conclusions can be drawn:

- In the category of questions characterized as ‘observable-world’ or ‘macro’ phenomena, seniors had significant improvement of their knowledge about electricity. Such “observable” phenomena included reading and interpreting of circuit diagrams, understanding of the relationship between current, voltage, and resistance that can be detected through the lab equipment, or any other hands-on lab experience that involves touching, hearing, or seeing.

- In the category of questions related to "invisible-world" or "micro-view" phenomena, where students demonstrated their knowledge of physical aspects of electricity, seniors performed worse than novices. Learning about "micro" phenomena, students often sought any understandable (but not always scientifically appropriate) analogy with "macro" phenomena. Seniors' mental models were more structured and more highly organized than those of novices' but still were incorrect and inconsistent with scientific views.
- Seniors' knowledge improvement about "observable-word" phenomena does not always show a deep conceptual understanding of those phenomena. Sometimes knowledge improvement occurs by learning how to follow familiar algorithms solving similar problems. Examples include seniors' applications and misapplications of Ohm and Kirchhoff laws. Students learned sequences of actions, but they were not always able to explain why they applied a particular equation to particular situation.
- When they needed to solve the 'unfamiliar' problem (compared to those solved in class or in homework), seniors did not apply recently learned knowledge, but primitive mental models and analogies carried over from the novice level. For example, the majority of seniors knew that the water analogy with electricity cannot explain all electrical features and laws in circuits. Usually they did not use this analogy to simple or familiar circuits. Although, applying to a more complicated problem, similarity with plumbing remembered from the novice level was the first concept utilized by the senior group.

Conclusion

The two of the most interesting and unexpected results found were the following. First, in the senior group, their correlation between grades and misconceptions was less than that of the novice group ($\boldsymbol{r}^2$ seniors =15.1 % comparing to $\boldsymbol{r}^2$ novices = 30.7 %). Before conducting the study, the researchers presumed that the correlation between grades and the number of misconceptions for the senior group should be stronger than for the novice group, expecting that students with high grades should have fewer misconceptions. The results showed the opposite: for seniors the link between grades and misconceptions was weaker than for novices. Incorrect understanding of electricity in the senior group frequently is hidden by well-developed technical vocabulary. Even the brightest high-GPA students had numerous mistaken beliefs. The researchers supposed that the main reason for such a case in the senior group was due to undetected (when seniors were freshmen) misconceptions. As a result, new knowledge was built on incorrect basic information. "If misconceptions are not recognized early in the course, the student will not only fail to understand much of the new material, but worse, s/he is likely to dress up his misconceptions in scientific jargon, giving the false impression that s/he has learned something about science" ([4], p. 1048).

The other unexpected result was that despite of significant improvement in understanding of electricity, seniors were more confused than novices about physical and fundamental electrical phenomena such as *charge, electrical field* and *current.* Students' responses to the DIRECT concept inventory were similar to research outcomes of the original author of the DIRECT test, Paula Engelhard. In her dissertation [27], reported the main source of the difficulty generally linked to current (the concept of 'something that flows'). Results indicate that students do not have a clear understanding of the underlying mechanisms of electric circuits. This is most likely the result of a weak connection between electrostatics and electrokinetics phenomena since this connection is only now beginning to be addressed in some of the newer textbooks (p. 159).

Also, the findings of the present study correlated well with the extensive cognitive research by Chi. According to the Chi's [13] work about *direct* vs. *emergent phenomena*, concepts are more difficult to learn: (1) when they are not directly observable, and (2) when a macroscopic pattern emerges from unobservable microscopic phenomena. The inability to directly observe the key conceptual quantities such as force and energy almost certainly contributes to the difficulty in learning about them [12]. Understandable analogies between observable and non-observable worlds often play a crucial role in the learning process, explaining the existence of the popular analogy between water and electricity among students and instructors. Also concepts are misunderstood when features of one ontological category are applied to another category [14]. One of the examples of ontological miscategorization detected in the present study was students' substitution of meanings of 'one charge' to 'one electron/particle' and, as a result, recognition of current as moving substance.

Cognitive motives of why seniors more than novices were confused about physical aspects of electricity need more investigation. In general, the researchers found a lack of literature devoted to changes in the nature of misconceptions as they relate to the level of expertise of adult learners. Questions regarding 'how misconceptions of beginners differ from misconceptions of experts' need additional research. Montfort, Brown, and Pollock [28] conducted a methodologically similar study to the present one when they compared conceptual understanding in mechanics of sophomores vs. seniors and graduate students. The authors stated that "graduate students demonstrated higher computational skill and confidence, but they were not significantly different from the sophomores in terms of conceptual understanding. Interestingly, the seniors showed markedly lower confidence in their ability to solve the problems posed in the interviews" (p.111). Those results corresponded with the results of the present study: under some conditions, seniors performed worse than expected. Montfort, Brown, and Pollock also indicated that "graduate students used the same basic approach as the undergraduates but were more often able to reason through how the equations they remembered would affect the interview questions" (p. 121). In other words, when solving a problem, students with a higher expertise level primarily referred to the familiar actions and algorithms (i.e., equations) than to deep conceptual understanding. The experience of following familiar algorithms was crucial for advanced-novices, which also may be called beginner-experts (i.e., seniors and graduate students).

Recommendations for Practice

The first recommendation for practice concerns pedagogical approaches for teaching novices about electricity. Demographics showed that novice students were a very diverse population with different backgrounds and pre-college knowledge. Therefore, students have various mental models and pre-conceptions about electricity. Yet, the majority of them are unaware of the scientific viewpoints about electricity. Perhaps when beginning their study, freshmen need an ungraded diagnostic assessment to detect their current knowledge about electricity? As a result, new college-level material would not be absorbed into undetected pre-college misconceptions. In addition, explaining to students the ontological nature of concepts (analogous to the study of

Slotta and Chi [7]), may significantly clarify students' misconceptions and initiate conceptual change.

The second recommendation for practice is devoted to instructors who teach Electrical Engineering Technology courses. As the interviews showed, sometimes misconceptions may be transferred to students by instructors or through text-books. A majority of people, regardless of their educational background and expertise level, hold various misconceptions about the natural world. The message to instructors is "do not make it worse". Sometimes, to simplify a new material, instructors attempt to use incorrect analogies (for example: water flow and electrical current). Although those analogies may be helpful for beginning learners, they will affect students' thinking in the long-term when students start to apply incorrect analogies to the variety of technical problems.

Limitations of the Study

In discussing conclusions of the present study, a few limitations need to be addressed:

1. All interviews and data analysis were conducted by one researcher. Thus, there is a possibility for biasing the data towards finding particular misconceptions. Although the researcher tried to avoid leading the students during the interviews, in motivating them to express their own opinions, a few occasions were noted in transcribing protocols. Students repeated exactly what was said by the interviewer. A few times the researcher had the impression that interviewees did not take seriously their responses, answering in a way to satisfy the researcher. To minimize such interviewees' responses, the researcher restated the question and asked the student to repeat aloud his/her thinking. To minimize a possibility for biasing towards specific misconceptions, the researcher asked three faculty members for their feedback and verifications.
2. The student sample only consisted of participants from one (Electrical Engineering Technology-EET) department at Purdue University in West Lafayette, Indiana. Therefore, attempts to generalize the results across a more diverse population or different settings would be not supportable without further research.
3. Concerning expertise development, longitudinal methodology would be more appropriate: the same student sample would be examined during two-three years for the purpose of their conceptual development. The present study was not longitudinal. Novices and senior students were not the same participants over time. Therefore, conclusions about changes in students' misconceptions during their progression from freshman to senior levels have a conditional limitation.
4. The results are applicable to only Engineering-Technology (ET) students but not to Engineering students. Historically, the purpose of Engineering Technology programs has been to educate engineers-practitioners. Thus, curriculum of ET students is more oriented towards hands-on experience in laboratory settings and has less commitments to pure theoretical knowledge. Also, it should be said that some students, which officially belonged to the novice group and were enrolled in the freshman/sophomore year at Purdue, already had extensive work experience or multi-year military school training. Thus, their knowledge about electricity was much more advanced compared to their novice peers directly after high school.

Future Research

The researchers also deem that further research exploring the following themes would be advantageous:

1. Conducting a methodologically simple but longitudinal study about changes in students' misconceptions would give more accurate information about expertise development and conceptual understanding of students. In such a study, the novice sample should be more homogeneous (for example, only freshmen after high school), excluding advanced-level novices with extensive pre-college work or schooling experience.
2. Knowing how the misconceptions of Electrical Engineering Technology (EET) seniors are different compared to the misconceptions of Electrical Engineering (EE) seniors would also be interesting and potentially valuable given the differences in the instructional approaches in these two disciplines. The results of such a potential study would show how different educational approaches impact students' understanding and their mental models about electricity.
3. Further investigation is needed of what occurs when seniors responded correctly to a simple, yet potentially familiar problem. Their responses were aligned with scientific views about the problem. However, when they met a similar but more complicated problem, they rejected recently obtained and more advanced knowledge, referring their explanations to primitive analogies or misconceptions from earlier education (or even childhood). Basically, it showed how decision-making in ill-defined settings can be different from decision-making in familiar classroom settings. Specifically, this is important for future engineers since their professional life will typically require working in ill-defined settings and constraints.

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