Common Misunderstandings of Electricity: Analysis of Interview Responses of Electrical Engineering Technology Students

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***Abstract*—In the recent decade the wide body of research on misconceptions focused on establishing understandable schemes of why some scientific concepts are so difficult to understand for students in various Engineering Technology majors. The present interview-based, qualitative study of two student groups opened some interesting insides and explains common struggling of learning the basic electrical concepts. It had been observed that progressing from a freshman to a senior level, students developed strong technical/terminological vocabulary, but often they were unable to clear explain what those terms mean. Both student cohorts (from freshmen to seniors) continuously applied incorrect "water-analogy" to the concepts of current flow. Also, in majority of cases, they perceive electricity ontologically incorrect as a "Substance-that-can-be-used-up".**

***Index Terms*—Misconceptions about Electricity, Problems in Learning, Engineering Technology**

I. INTRODUCTION

The quality of STEM education through K-12 and Postsecondary Levels is the main concern of many scholars in American Academia. It leads to the clear understanding that a percentage of jobs required postsecondary education in technological fields is dramatically increased [1]. Therefore, clear understanding of scientific concepts and natural phenomena by recent Engineering Technology graduates is essential for the entire spectrum of technological and safety decisions that they will make at new working environments. But on the other hand, extensive research confirms that majority of students do not have an ability to explain physical phenomena clearly learning in college just how to "solve equations" or to follow familiar algorithms [2], [3], [4].

The present qualitative study confirms that undetected-on-early-stages (during a freshmen year) misconceptions grow into more-sophisticated forms on a senior level. Students won't decline their old beliefs after completing multiple courses becoming seniors. Roots of incorrect analogies, such as "electricity is a water" or "electricity is a substance" from the first year of college, usually transform into fogy concepts that students carry towards graduation. Despite of that, students' self-confidence of "knowing something" and an ability to employ scientific vocabulary highly increased.

II. BACKGROUND

The concept of electricity is usually difficult to understand because of human inability to observe it directly [5]. Several studies detected common student misunderstandings in this area [6], [7], [8], [9], [10], [11], [12] such as:

- Confidence 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;
- 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 differentiate between concepts of current, energy, power, and potential difference;
- Failure to distinguish between potential and potential difference, as well as a belief that current is consumed.
- Failure to understand that an ideal battery maintains a constant potential difference between its terminals.

There are a few acceptable cognitive theories that explain possible reasons for difficult understanding of scientific concepts by students. It includes Ontological miscategorization [13], occurrence of phenomenological primitives or p-prims [14], [15], ignorance [16], and inability to observe the phenomena directly [5], [7]. More detailed summary of possible explanations for learning difficulties can be found in [17].

III. RESEARCH QUESTIONS

The purpose of the study targeted to explore how different is a nature of student misconceptions of EET seniors comparing to novices (which was the mixed group of freshmen and sophomores). The research questions that guided this study were:

- If misconceptions of senior students about electricity different from the misconceptions of novices?
- And if yes- how?

IV. PARTICIPANTS

There were 8 novices (freshmen and first-semester sophomores enrolled in the introductory level course "Fundamentals of Electronics"), and 8 senior students (enrolled in the senior final project-design course) in the Electrical and Computer Engineering Technology program at the Large Public Midwest University. Since in qualitative studies, the sample size is not as critical as in quantitative studies [18], the primary concern of the author was to allow participants freely explain their mental models and conceptual chains during interviews.

Before taking interviews, 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 was 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 a six years of military school and work experience. The age range of seniors varied from 21 to 26 years old.

V. METHODOLOGY

In this study, the clinical interview method was used under the ground theory framework. In total, sixteen volunteer students were invited for individual 30-minute semi-structured interviews where they briefly responded to four questions about electricity. Those questions include the following:

1. How would you explain what electricity is?
2. From your perspective, what is 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 author 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. All participants were video-recorded. Interview protocols were transcribed and analyzed using open-coding technique. The goal was to understand students' mental models about electricity and what lead them to the answers. Comparison of novice and senior responses helped explain the "development" and transformations of mental schemes and misconceptions from freshman to senior levels.

VI. A FEW WORDS ABOUT CLINICAL INTERVIEW METHOD

As it was said above, the clinical interview method was used for data collection. Patton in [18] states that this method is appropriate for the studies guided by the ground theory methodology. Clinical interviews were introduced by the Swiss psychologist, Jean Piaget, in the 1920's, and initially were developed for investigating the nature and extent of children's knowledge. According to [20]:

…this method consists in letting the individual talk and in noticing the manner in which his/her thought unfolds itself. The novelty consists in not being content simply to record the answers given by the child to the questions which have been put to him, but letting him talk of his own accord…Clinical interviewing is directed toward the information- gathering function. The chief goal is to ascertain the nature and extent of an individual's knowledge about a particular domain by identifying the relevant conceptions he/she holds and perceived relationships among those conceptions (195-6).

Clinical interviewing has two major functions: (a) it allows eliciting and collecting detailed information, and (b) it allows the interviewee to take the lead, encouraging him/her to talk more freely. Clinical interviews have their own positive and negative aspects. On one hand, this method is a highly flexible technique that allows a researcher "to probe the areas of the knowledge domain of particular interest and to let subjects speak freely, while constantly checking his/her spontaneous remarks for those that will prove genuinely revealing" [20] . On the other hand, interviews take a lot of time and there may be significant difficulties in interpretation of the data gathered through the interview. Five types of possible subject responses during interviewing are:

1. *Answers at random*- may be given by a subject uninterested in the question at hand; they represent what first comes into his/her head.
2. *Romancing*- spontaneous answer given for the sake of amusement but without conviction; it is an invented answer which the subject does not really believe or believes only by the force of saying it.
3. *Suggested conviction*- stimulated or suggested by the questioner's choice of words or sequence of questions; or one that is given in an effort to satisfy the examiner.
4. *Liberated conviction* – "neither spontaneous nor suggested; it is the result of reasoning, performed to order, but by means of original material…and original logical instruments. Despite its being necessarily influenced by the structuring of the interview situation, the liberated conviction is "an organized product of the child's thought" [21].
5. *Spontaneous conviction*- result of previous original reflection on the part of the subject; it is one for which he/she has no need of reasoning, because it is either already formulated or capable of being formulated [20].

Practitioners assessing cognitive structure through clinical interviewing face a real danger in possible misinterpretation of responses. Piaget [21] stated that the psychologist must in fact make up for the uncertainties in the method of interrogation by sharpening the subtleties of interpretation [20]. Although *answers at random* and *romancing* would be rare and easy to detect from adult subjects, the possibility of *suggested, liberated,* and *spontaneous convictions* remains high. Nuances in phrasing a particular term or the selection of questions can stimulate *suggested convictions*. Thus, recommendation to the interviewer is to make counter suggestions after a short lapse in the interview [21]. *Suggested convictions* are unstable and can be discovered in this fashion. Also, lack of connectedness of a particular response to the subject's other conceptions may be an indication of its possible suggested nature. Problems of interpretation, however, can be undeniably thorny [20]. The five possible interviewee's responses described above helped the author to develop a behavioral strategy of how to communicate with participants during the interviews. For example, questions that lead interviewees to answer in a way that satisfies the interviewer should be avoided. Three recommended effective strategies that can be used during clinical interviews were:

a. Use general open-ended questions for ascertaining a student's current conceptual scheme;
b. Ask to solve problems during the interview and think aloud;
c. Check comprehension: students were presented with detailed written solutions to complex problems. Then students were asked to reconstruct the solutions as well as they can. Those aspects of the explanations students remember or fail to remember and the way in which students change an explanation are informative to the kind of scheme the students bring to the comprehension task [20].

VII. DATA ANALYSES TECHNIQUES

In qualitative research, the purpose of the study guides the analysis. As it said above, the present study is conducted under the grounded theory framework. According to [22], grounded theory is a 'cyclical' method. Analyzing data the researcher constructs tentative theoretical statements about the relationships among constructs and explores these statements through further data collection and new literature review. This cyclical process of comparing new data with tentative theoretical statements continues until the comparative analysis no longer contributes anything new (theoretical saturation). Because of time-limitations, the present study consisted only from one 'cycle'.

The open coding technique was used to analyze protocol interviews. Developing some manageable classification or coding scheme is the first step of analysis [18]. Coding of the data began with open coding, which requires data to be broken into discrete parts before being closely examined and compared. Open coding should be performed on each individual participant's data set. All relevant data needs to be broken into data 'bits' and be grouped by emerging themes. These themes will lead to concepts and categories that are not necessarily conceptually congruent. After concepts and categories were developed, the process began again.

After transcribing the interviews, the researcher read the transcripts three times. Every interview protocol been read carefully attempting to get a holistic view of the phenomenon [23]. For the first reading, the researcher simply read without taking any notes or memos. During the second reading, the researcher highlighted the repeated words that caught her attention. Reading through the third time, the researcher formulated codes by indicating major words or lines. Also, the researcher employed a color coding technique: similar meanings from interview protocols were highlighted in the same color. The main goal of this stage was to identify meaning units and their central themes [23]. These themes allowed the researcher to develop assertions and to describe findings.

VIII. VALIDITY

In qualitative studies guided with grounded theory framework, the term *validity* alternate with the term *verification*. The responsibility for establishing verification in a study rests with the researcher. Verification in grounded theory studies is an active part of the research process and becomes the part of the standards one should judge the quality of the study [24]. To avoid a possibility for biasing the data towards finding particular misconceptions, we tried to evade leading the students during the interviews. Our goal was to motivate students to express their own opinions. Although, a few occasions were noted, when students repeated exactly what the researcher said, answering in a way to satisfy the researcher. To minimize such responses, we restated the mentioned above question(s) and asked the student to repeat aloud his/her thinking. Such technique was used in agreement with [20] recommendations. After data analysis, the researcher asked three faculty members for their feedback and verifications for the purpose of minimizing a possibility for biasing towards specific misconceptions.

IX. RESULTS

In this section we present responses of novices and seniors on four open-ended questions.

A. *Responses to the first question (How would you explain what electricity is?)*

About fifty percent of novice students defined electricity as a "flow of electrons". Basically, they substituted the meaning of "electricity" to the meaning of "current". This statement is correct, but only for metallic conductors. Most commonly, students' definitions of electricity are linked to the "water analogy", which is a consequence of the reasoning that "electricity is a moving substance". Some freshman interviewees explained why this analogy is valuable and useful. They also provided information about how and where the "water analogy" was introduced to them. The "history" of this analogy will be discussed further.

Responding to the first question, some seniors had difficulties articulating their knowledge. More than twenty five percent of seniors responded explicitly that they were not informed about what electricity is because "we haven't really studied the physical properties of electricity". All of those students had high academic achievement, and a high GPA. Our observation was that a "water analogy" remained very typical among seniors. For example, during interviews, about thirty percent of seniors immediately switched their discussions towards such an analogy. They employed features of a plumbing system to explain an electron flow in the circuit. Furthermore, one student attempted to explain the working principles of transistors applying a similarity with water. He indicated that this analogy was presented in textbooks.

Interviewer: *Uh…what is the 'history' of this water analogy for you? I mean…if someone taught you this way? Or books said that? Or maybe something else?*

Respondent: *Mm… some of the books have analogies like that.*

Interviewer: *Some books have that analogy?*

Respondent: *Yea. Like the way a transistor works… They… you have to trigger the base in order for the power from the collector flows through the emitter.*

In addition, data shows that seniors repeatedly substituted meanings of "one electron" to "one charge". The majority of students is uninformed about the difference.

Such unawareness leads to statements like: "Electricity is the charge in electrons moving through some sort of vacuum" or "Charges are getting excited to produce energy…it goes through and produces electricity". Students stated memorized sets of words, but they cannot explain the meaning. One example is the explanation of electricity given by one senior.

Respondent: *Um… well, I've never been asked that so…since my freshman year…I was mentioning earlier it would be just the charge in electrons moving through some sort of vacuum …um… and these charges getting excited to produce energy… and when it's applied to like certain metallic or something like that, it actually goes through.*

Interviewer: *Um… that's a very interesting statement 'getting excited'… can you clarify what do you mean by 'getting excited'?*

Respondent: *in chemistry (laughs) when I think there is… the want of the electrons, or something and like atoms or…… that's sort of that…*

Interviewer: *Uhum… back to chemical processes?*

Respondent: *... basically, back to chemical processes, and it is trying to even itself out, and so… it is going through a circuit…it wants to even out, and like the voltage wants to go from 12 to 0, and so it wants to flow down through that… and even itself out…(sighs)*

B. Responses to the second question
(From your perspective, what is the difference between voltage and current?)

Responding to the Question-2, novice students frequently defined voltage as water pressure, but current as the amount of water flowing through the conductor. Another two students said: "Voltage is the 'how much' and current is 'where it was going'. Voltage is the amount of electrons and current would be the strength of the flow". Another interesting definition is that current is water pressure and voltage is the height of the wave. A few additional misconceptions had been detected by question 2 as well. One of them states that current and voltage cannot exist separately and voltage is the by-product of current. One participant explained currents as energy and voltage as a force. In general, freshmen showed unclear understanding of current and voltage; these two phenomena were misinterpreted frequently.

Seniors' understanding of current and voltage varied as well. They agreed that current and voltage are related. But frequently they were not able to clarify how these two phenomena are related. For example, some students announced that current is a by-product of voltage; another participants argued the opposite, saying that voltage is a by-product of current.

C. Responses to the third question
(Explain the concept of a "dead" battery)

Question 3 tested how well students can interpret the "macro" phenomenon ('used up' and 'dead' battery) from the inside "micro" perspective. The majority of novices understood that the condition of the 'dead' battery refers to the chemical processes inside of the battery. Freshmen with more advanced electrical background (such as a work experience or a military school) gave more plausible explanations than students with 'no' or 'basic' pre-college experience with electricity. For example, one student compared the insides of the battery with overflowing liquid from the cup. Other misconceptions detected by question 3 include (a) electrons and charges are used up inside of the battery like a matter, and (b) energy is stored inside of the battery.

During interviewing seniors, there were a tendency of describing processes inside of a battery similar to the "used up substance" analogy. Other misconceptions detected by this question include: (1) energy stored inside of battery, and (2) misinterpretations between power and electromotive force.

D. Responses to the fourth question
(Commented the statement: "The electric companies should not bill us since it takes back all of the electrons it gives us").

Laughing was a common students' reaction after they heard that statement. Yet, the majority of novice students had difficulty articulating their own perspectives. Fifty percent of novices were not sure if this statement is false or true. Thirty seven percent of novices claimed that the statement is false and other thirty eight percent of novices agreed with this statement saying it is true. Fifty percent of students argued that "we have to pay, just because someone has to pay". Sixty two percent of novices displayed misconception that electrical companies sell to us a power. Students again applied features and properties of matter and substance to electrical power: "it can be sold or sent somewhere". Explaining their reasoning, twenty five percent of novices employed an analogy with the hydraulic system.

The most common explanation of seniors was the statement that "*someone has to pay for their burned resources (coal, nuclear, etc*)". Sixty two percent of seniors answered in that way. Also, fifty percent of seniors argued that *"electrical companies bill us for a power; we use their power for our house equipment"*. Seniors' common mental model was "*power provided to customers as a flowing substance through electrical cables"*. In reality, electric companies "provide" voltage (potential difference) only. Power consumption in particular households depends on the overall load resistance of the household equipment. This idea was never explicitly explained by students. A full description of student responses on four open-ended questions can be found in [26].

X. DISCUSSION

Table 1 summarizes and compares misconceptions of novices vs. seniors detected by four open-ended questions. Students' responses allowed to conclude that the 'water analogy' and thinking that electricity is a matter/substance remained powerful mental models from the freshmen to the senior levels. Usually, freshman students did not formulate yet the 'common perspective' on how to use this analogy. They applied a water-similarity to any electrical phenomena, such as: current is a water flow; voltage and power can be

XI. THE 'HISTORY' OF WATER-ANALOGY

The origins of the water analogy are similar for both student categories. Two freshmen and two seniors indicated that this concept was introduced by instructors; one senior mentioned that his father taught him that, because the father is electrical engineering. Basically, the last statement shows that robust misconceptions can be transferred through generations. One senior and one freshman said that a "water analogy" was presented in books. Another four students (two freshmen and two seniors) explained that they created this idea themselves because "it is visible". One student indicated that he started to use this analogy when he needed to explain electrical fundamentals to people without a technical background. Table 2 is a brief summary of "history" of water analogy.

XII. LIMITATIONS OF STUDY

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

- Some concerns might be raised about the size of the sample, such as only 16 interviews, eight students in each category. But it should be noted that methods for data analysis, as well as theoretical frameworks, in quantitative and qualitative studies vary significantly. According to [18], the minimum sample size for qualitative studies may be equal to 1. It means that even one person might provide valuable responses if his/her data analyzed correctly using appropriate theoretical framework.
- The present study was not longitudinal. Novices and senior students were not the same participants over the time. Therefore, conclusions about changes in students' misconceptions during their progression from freshman to senior levels have a conditional limitation.
- 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 commitment to pure theoretical knowledge. Also, it should be said that a few interviewed students, which officially belonged to the freshmen group already had extensive work experience or multi-year military school training. Thus, their knowledge about electricity was more advanced compared to their freshman peers directly after high schools.

XIII. FUTURE RESEARCH

We 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.

XIV. CONCLUSION

Findings of the present study correlated well with the extensive cognitive research [5]. 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 [7]. 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 [13]. 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.

The other unexpected result was that seniors were more confused than novices about physical concepts such as *charge, current and electrical field.* Cognitive motives of why seniors more than freshmen 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 in relation to the level of expertise of adult learners. Questions regarding 'how misconceptions of beginners differ from misconceptions of experts' need additional research. A methodologically similar study [25] 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". Those results corresponded with the results of the present study: under some conditions, seniors performed worse than expected. "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"[25]. 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).

TABLE I.
SUMMARY OF DETECTED MISCONCEPTIONS OF NOVICES VERSUS SENIORS

Categories	Detected Misconceptions	Number of students agreed with that statement	
		Novices	*Seniors*
Explaining current, students use water-analogy or applications of plumbing systems	Electricity has a water analogy; students applied features of plumbing systems to explain circuits	7	8
	Voltage is water pressure; current is amount of water	3	6
	Voltage is the amount of electrons. Current would be the strength of the flow. Voltage was the 'how much' and the current was 'where it was going'	2	-
	Current is water pressure that is going through the wire…voltage is "just how high your wave is going through"	1	-
Electricity is a substance that can be "used up"	Electricity is matter and substance	6	4
	Electricity is a flow of current, where current is the substance, so electricity is a flow of substance	1	
	Energy is stored inside of the battery	2	3
	When electrons inside the battery are "used up", there's no electrons left to flow	1	
	Battery is dead when all charges are used up	1	
	Electric companies do not get all electrons back because electrons are transferred into the ground	1	3
	Electrons flow inside of the electrical cord	1	-
	Electric companies are leasing us workers (electrons)	1	-
	Electric companies provide us and bill us for the usage of power; power is sent to us as a substance	4	4
	Circuit elements take "juice" from the battery		1
Understanding of current and voltage	Current is energy and voltage is a force	1	2
	You need current in order to make voltage (voltage is by-product of current). Current and voltage cannot exist separately	1	2
	Substitute meanings of "one charge" to "one electron"	5	3
	Current is more important than voltage because current is actual "flow"; voltage is difference between two points	-	2
	We have to pay electric companies because someone has to pay for their burned resources (coal, nuclear, etc.)	4	5

TABLE II.
'HISTORY' OF WATER- ANALOGY

History of water analogy	How many students mentioned it	
	Novices	*Seniors*
Water analogy was presented by the instructor (in high-school, college, military school)	2	2
Student made this assumption by himself and stayed with this idea because "it is visible"	2	2
Presented in high school or college textbooks	1	1
"My dad told me that; he is an electrical engineer"		1

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