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Engineering Habits of Mind: How EE Majors Talk About Their Knowledge of Circuits

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Abstract

The preparation of future engineers is often characterized as ensuring students possess technical knowledge and the ability to apply that knowledge to solve problems. Researchers often advocate that emphasis is placed on using instructional strategies aimed at improving the way students develop this technical knowledge, and that they are provided opportunities to use it. Also, the goal of engineering and science education is to encourage students to employ various modes of thinking about concepts rather than passively duplicate what they have been exposed to. The purpose of this paper is to highlight the spontaneous habits of mind demonstrated by undergraduate electrical engineering students when asked to explain the phenomena of electric current in basic circuits. Engineering habits of mind are defined as a unique set of values, skills and attitudes associated with engineering depicted by one's ability to make informed choices when faced with uncertainty in problem solving. The habits of mind framework used to guide this study was first published in the Project 2061 initiative led by the American Association for the Advancement of Science (AAAS) and further developed by the National Academy of Engineering (NAE). This exploratory work was guided by the following question: *What habits of mind do undergraduate electrical engineering students use when answering conceptual questions about electric current?* The data for this study were student interviews conducted using a think aloud protocol. The questions on the protocol were aimed at uncovering students' conceptual knowledge and possible misconceptions about basic circuit concepts. The findings from this work can potentially address key questions relating to curriculum design in engineering as well as to suggest ways in which teaching in engineering classrooms can be improved for maximum benefit to both instructors and students.

Background

One major goal of engineering education is to prepare students who possess disciplinary knowledge, technical skills, and are capable of identifying and applying solutions to complex problems [1]. These engineering traits have also been recommended in publications such as The Engineer of 2020 [2]. In this report attributes of the future engineer are explicitly described as possessing strong analytical skills, practical ingenuity, creativity, good communication, leadership roles such as in business and management, demonstrated levels of ethics, professionalism, dynamism, agility, resilience and flexibility. These attributes may otherwise be classified as habits of mind. Habits of mind are broadly defined as outcomes of engineering education whereby students develop into competent problem solvers with the ability to transfer these skills to other similar or new contexts. In 1989, the American Association for the Advancement of Science (AAAS) published a report on the goals of science, mathematics and technology education called Project 2061: Science for All Americans. Among their recommendations to the National Council on Science and Technology Education was the strategic goal of determining "what habits of mind are essential for all citizens in a scientifically literate society" [3, p. 3]. The purpose of this committee was to contribute to the development of increased scientific literacy in U.S. education. Project 2061 defined habits of mind as a set of scientific skills, values and attitudes that "relate directly to a person's outlook on knowledge, learning, and ways of thinking and acting" [3, p. 133]. In more recent literature [4], habits of mind are described as possessing the necessary intellectual authority to make choices, conscious or unconscious, to employ a certain mode of thinking when faced with uncertainty in problem solving. The Project 2061 initiative and other scholars who have applied this framework [5]–[8] suggest a conceptual change approach in engineering and science teaching whereby students are engaged in different types of learning activities. This multi-faceted approach to instruction is aimed at supporting students' understanding of one concept in various ways that also incorporates their prior knowledge and experiences. It is only through such an integrated manner that students will be able to not only learn, but grow to appreciate the development of salient values, attitudes and skills in science, engineering, mathematics and technology.

The values associated with these habits of mind comprise of students possessing the ability to apply different strategies of "intellectual behavior" [3, p. 17] to various educational settings. Engineering or scientific habits of mind further suggest the development of attitudes among students related to their appreciation for the rigor of scientific and mathematical thinking, teamwork and understanding beyond rote memorization. Thinking skills consist of computational and manipulation and observations skills. Computational skills include basic number, calculator and estimator skills, while manipulation and observation skills comprise of communication and critical-response skills. Thinking skills are considered necessary facets of students' ability to not only solve problems, but to developing critical understanding for various contexts around which the problem might exist as well.

Project 2061 [3] discussed that the purpose of science education is to disseminate knowledge in such a manner that common values and skills be developed among scientists, mathematicians and engineers. In 2009 the National Academy of Engineering (NAE) reinforced this mandate by proposing three overall principles for K-12 engineering education. These were:

Principle 1: Emphasize engineering design,

Principle 2: Incorporate important and developmentally appropriate mathematics, science, and technology knowledge and skills, and

Principle 3: Promote engineering habits of mind [9, p. 6]

Since the publication of Project 2061 and the NAE report, other researchers have expanded this idea of habits of mind and have made suggestions for specific pedagogies to develop these habits [9]–[13]. Most importantly, the NAE outlined six engineering habits of mind which are systems thinking, creativity, optimism, collaboration, communication and attention to ethical considerations [9, p. 8]. The purpose of this paper is to highlight the *spontaneous* habits of mind, categorized in terms of values, attitudes and skills, demonstrated by undergraduate electrical engineering (EE) students when required to explain the phenomena of current in basic circuits. This study was guided by the question: *What habits of mind do electrical engineering students use when answering conceptual questions about electric current?* The data used in this paper were collected using think aloud interviews. A deductive content analysis of the data was conducted whereby the three categories of habits of mind were used to analyze the data. The findings indicate students' unprompted reliance on habits of mind when faced with open-ended problems.

Method

The study presented in this paper utilized a qualitative inquiry approach where undergraduate engineering students were interviewed using a think aloud protocol. To gain a deeper understanding of how students conceptualize electric current as well as how they approach learning about circuits, a think aloud interview was considered an appropriate data collection method. Students were presented with a think aloud protocol compiled by researchers (one is an author on this paper) and the instructor of an introductory circuit course from which the questions were drawn. The protocol consisted of two parts. Part one consisted of basic and complex electrical circuits. Students were expected to discuss how the circuits operate, the function and operation of individual components and how current was manifested at each component. Part two of the protocol required students to discuss current and voltage in a real-world context. For example, students were given examples of workers on machinery or herds of cattle in a field that were directly affected by current or voltage. Additionally, all students were asked to discuss why they chose engineering as a major and what prior experiences, if any, assisted them in making this decision. Sample items from the protocol are included in the appendix.

Participants

The data used in this study were a subset of data collected from engineering majors at a Western US university. The broader study for which the data were collected was aimed at uncovering engineering students' potential misconceptions about common circuit concepts [14], [15]. The interviews were conducted after the proper IRB forms were filed and approved. The students were undergraduate junior and seniors who had taken at least two circuit courses. The students were identified and recruited by the instructor who was a part of the research team and had taught the introductory circuits course. This instructor was also instrumental in creating the think aloud protocol using sample questions from the course text and other course related materials. Nineteen (19) students volunteered to participate in the study of which nine were a combination of junior and senior electrical engineering students. The nine transcripts were used for this paper. The students' academic aptitude was not a determining factor in their recruitment to the study as their participation was purely voluntary. In the interview, students were expected to explain their thought processes as they solved the given open-ended questions. Students were assigned pseudonyms and all audio recordings were destroyed after the interviews were transcribed. The transcripts were cleaned to remove any personal identifying information thereby ensuring the students were anonymous.

Analysis and findings

The data were analyzed using the three categories of habits of mind as defined by Project 2061. Initially, two of the authors coded one interview transcript independently to determine their level of agreement. The researchers then met to review their analysis of the transcript together. For the first transcript analyzed there was over 80% agreement and the researchers discussed where differences in their coding existed. This discussion led to the resolution of differences. Following this meeting, the two researchers separately coded the other eight transcripts and then collated their results in one shared Google document. The following table shows a description of the habits of mind framework used to guide the analysis and subsequent discussion about the results.

Table 1. Habits of mind definition based on Project 2061

Habits of mind	Definition
Values	- Making decisions about what concepts are relevant to their understanding and how to gauge conceptual scientific knowledge.
Attitudes	- How past knowledge and experiences shape/form their current understanding about science/engineering learning.
Skills	Computational - Performing simple calculations and possessing the ability to employ the correct type of mathematical thinking to a problem - Knowing not only when to use equations and formulas but having in depth understanding of what they mean. Manipulation and observation - Completing lab work by applying theoretical knowledge to practical situations - Can articulate one's thoughts and knowledge about concepts beyond the use of mathematical and graphical representation.

Across our data set we found statements that were indicative of habits of mind as defined in Table 1. All nine of the students interviewed used habits of mind in their discussion of the questions; however, some students used more variation than others. For example, we found instances of all categories of habits of mind in five of the nine interviews while the other four had combinations of values and attitudes or values and skills. Table 2 shows examples of values, attitudes and skills that were found in the transcripts. The participants from which the examples were taken verbatim are presented.

Table 2. Examples of habits of mind from think aloud transcript

Habits of mind	**Example from Participants Transcripts** *(pseudonyms assigned by researchers)*
Values	So, I, I had an idea of what I should get, and then just doing the equations made it a little more clear on, you know, what effects you ought to see from that ~ Jerry Like, seeing it on paper's one thing, but actually doing it makes a lot more sense. You can screw around with it and like make sure that you're right, and test everything that you do ~ Pat Well I don't think I, like, here at school they're real worried about how you analyze things; as opposed to learning how the actual device or whatever works. And it's, oh okay, you know, plug in this, plug in this, plug in this, you know, I can, I used to be able to solve all these problems with no problems at all. But, not understanding like how, you know, the basics of how it works and why you're learning to see this. So I think just not having the, you know, hands on type of thing, is why I've forgotten everything. 'Cause I've struggled ~ Joey I think for me it's been more of a hands on, like in a lab I do a lot of just tinkering. Like I started playing with electronics when I was real young ~ Donald So I think I kind of have a better understanding if I can, you know, look on an

Habits of mind	Example from Participants Transcripts *(pseudonyms assigned by researchers)*
	oscilloscope and see it. As opposed to, you know, looking at all the equations, the differential equations, and the relationships between them. ~ Gerald
Attitudes	**(**What got you interested in this?) I think my dad. Because he likes to do, yeah, he made some electronic boards and stuff and I played with. So, yeah. ~Kevin Like, I know most of it, but whatever I don't know I can look up and like re-learn it really fast. Like I'm pretty familiar with it. So like I forget things, but they're easy to remind myself of later. Yeah. It's like it's all based on stuff that's been ingrained in my mind at least. ~Brad I was going to be an electrical engineer just because, I guess my dad also played a part in that. He's pretty knowledgeable on electricity and, and, and what not. He's actually a mechanic. But as far as electricity goes, I mean he, like he'd be able to fix anything-- ~Keith
Skills	I just remember the formula, not necessarily because it's, I remember the formula because it's easy, not because the formula helps me realize how to do it. ~Tyler Okay. So, the general idea of this is basically we're going to have, well, I guess we'd have to make some estimation for sure ~ Pat If you say this equation or that equation, they're like oh yeah! But if I do, like if I talk to my little sister who's in middle school, she's like, "Oh, what does that mean?" And I'm like, huh. I don't know. I'll have to get back to you on that. So it's just talking with the general population who are not engineers that it's not as easy to describe ~ Jerry

For the values category, we found that students tend to prioritize the importance of hands on experiences to help them develop an understanding of the concept. The students indicated they wanted to see something concrete, like an output of an oscilloscope, to explain the phenomena. In general, students perceived Electrical Engineering as a practical discipline that gave them the opportunity to approach problem solving from a more applied rather than conceptual manner. Additionally, they discussed that classroom experiences should ideally incorporate practical applications.

For the attitudes category, we found students commonly identified familial influence as the impetus for their interests in engineering. For example, all participants responded to the question of what got them interested in engineering that one or both of their parents were engineers or had scientific careers. The participants explained that through their parents they were exposed to the idea of engineering at a very early age. Students also discussed their aptitude to easily recall prior knowledge or having the ability to draw on past experiences when confronted with a topic they have not engaged with for a long time as an academic strength.

For the skills category, we found students frequently used an estimation approach as a first step in problem solving. Students expressed wanting to have a "general idea" about the problem before getting into complex mathematics. Participants also tended to view equations as a way to conceptualize the relationship among variables on a surface level. For example, one of the students commented "If *you can memorize an equation that at least helps you form at least some relationship about it.*" In general, all the students in our study demonstrated all three categories of habits of mind as described in framework shown in Table 1. Hands on experiences were most frequently declared as an integral approach to learning in engineering along with the value of memorizing formulas in identifying relationships among variables.

Discussion

In this study, the questions on the think aloud protocol were derived from a basic introductory circuits course and the participants were junior and senior EE majors who had exited the course two or three years prior. It is important to note that the protocol was not designed to assess habits of mind. Instead, the data were collected to identify possible misconceptions students might have about electric current and circuits in general. The focus on habits of mind in this paper was to investigate if the students would spontaneously use examples of these values, attitudes and skills in their discussion of circuit concepts. This work is purely exploratory. Consequently, we do not seek to make any generalizable claims about habits of mind in relation to engineering students' academic aptitude. Rather, the intent of this work was to highlight that habits of mind are not widely studied in engineering though they have been recommended as intended outcomes of engineering education at various levels. Additionally, we aim to illustrate that think aloud interviewing is a viable approach to uncovering the same.

In this preliminary study, we found that though habits of mind form the core of engineering education, it is not a topic that is currently being widely researched. Thus, we conclude that it is important to develop an understanding of variables that comprise habits of mind for an engineering discipline. Our analysis confirms that students do verbalize values, skills and attitudes during think aloud problem solving. Therefore, our findings can be seen as a proof of concept for engineering education researchers that habits of mind provide viable categories for coding students' responses.

Frequently, engineering curriculum design tend to favor one type of habit over another often overlooking the importance of a holistic approach to engineering teaching and learning [4]. The goal of engineering training should be not only to teach students the specific traits of the profession, but to help them develop a mindset of an engineer in order to be successful in the field [3]. Habits of mind, when approached from a curriculum stand point as enduring understandings/outcomes [16], would assist students in becoming a part of the culture of their respective discipline. Curriculum designers can ask themselves: What *kinds* of values, skills and attitudes do we want to inculcate in students during their education as engineers? How can undergraduate engineering programs leverage existing course structures and activities to further develop these habits of mind? What key educational experiences can foster and sustain their development? We theorize that the answers to these questions might be achieved by using and evaluating instructional activities aimed at helping students to develop certain values, attitudes and cognitive skills directly related to the said discipline. We also suggest that research with engineering practitioners to elicit their habits of mind when solving complex, real-world problems, would greatly enhance our understanding of engineering workplace culture and help to bridge the gap between academia and practice. We posit that understanding innate qualities of a discipline would help instructors develop activities to provide students with consistent exposure to engineering culture.

Our study suggests that through interviews one may be able to track how habits of mind, such as values, skills and attitude change as students progress through their academic career. In addition, since this work has highlighted significant gaps in research as this phenomenon of habits of mind is a topic that has not been widely studied, this preliminary study will serve as an impetus for the subsequent research on the topic. Our goal is to work on refining our methods to capture other variables that comprise and define more holistically habits of mind for an engineering discipline as well as to investigate how habits of mind relate to students' implicit scientific knowledge.

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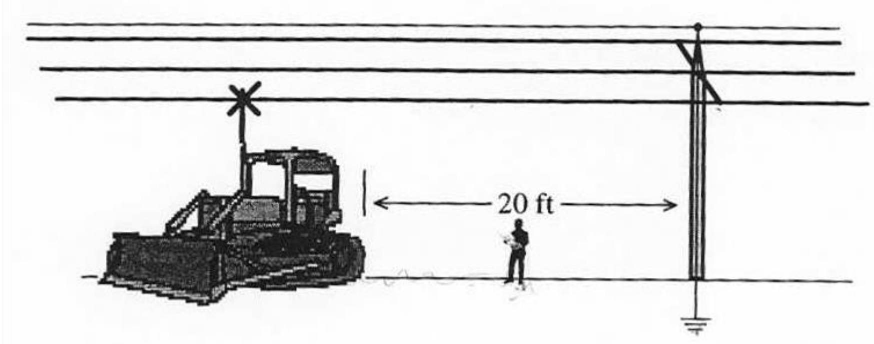
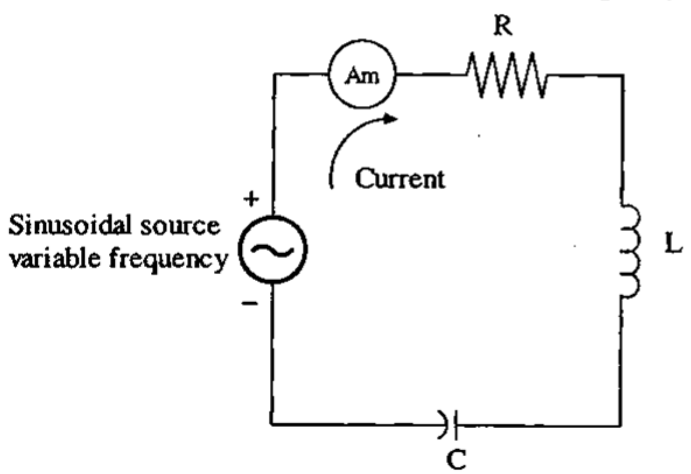
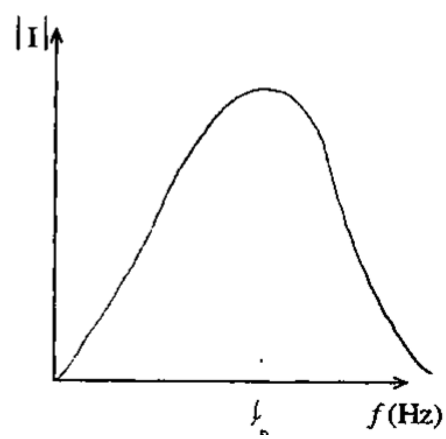
Question 2: A bulldozer operator working in some muddy soil inadvertently contacts an energized 7.97-kV overhead power line. The overhead neutral wire is grounded at the power pole. The bulldozer operator is unhurt. However, the construction worker who is standing nearby takes a step towards the dozer and is electrocuted. Why did this happen?



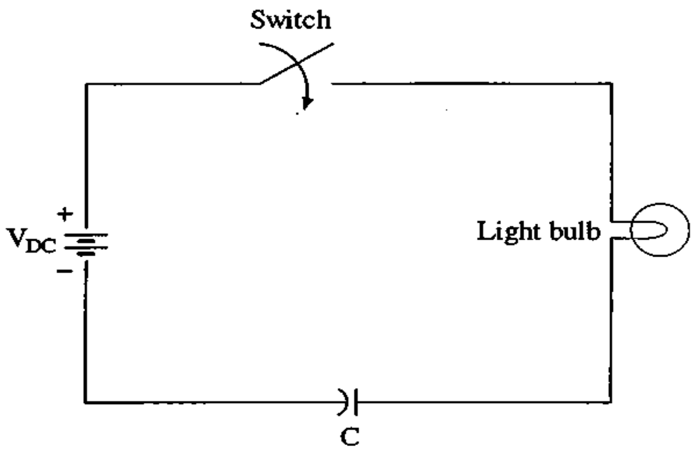
Question 3: Why is the majority of electric power used worldwide generated, transmitted, and utilized in a three-phase AC form? Defend your answer (i.e. explain your reasoning).

Question 4: An ac signal generator produces a sinusoidal voltage. The ac source voltage is applied to the circuit shown below and the current flowing is measured as the frequency of the signal is changed. Predict what the current magnitude will look like as a function of frequency. Defend your answer (i.e. explain your reasoning).

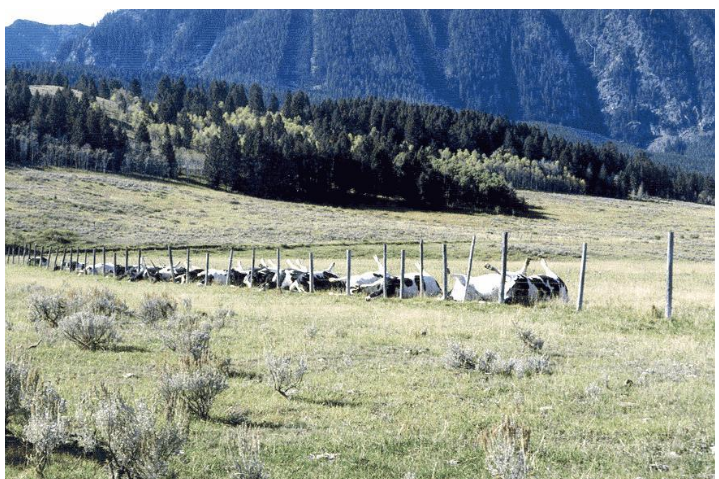




Question 5: The dc circuit below contains a battery, a capacitor, a light bulb, and a switch. The switch is initially open and the capacitor is uncharged. Explain what happens to the light bulb after the switch is closed. Defend your answer (i.e. explain your reasoning).



Question 2a: The following pictures are posted on the National Weather Service Lightning Safety web site. Animals are frequent victims of electrocution by lightning. Explain what happened to this group of cattle. Defend your answer (i.e. explain your reasoning).



Question 2c: The picture below shows the preferred body position and location during an electrical storm.

A mountaineering guidebook makes the following suggestions of what to do in the event you are caught in an electrical storm while hiking.

- Never lie down.
- Do not put your hands down.
- Put your elbows on your knees.
- Crouch on the soles of your feet.
- It is better to stand on dirt than rock and avoid water.

Why do these suggestions improve your chances of surviving if lightning strikes nearby? Defend your answer (i.e. explain your reasoning).