International Journal of Engineering Education Vol. 35, No. 1(A), pp. 2–14, 2019
Printed in Great Britain

0949-149X/91 $3.00+0.00

Engineering Students' Use of Analogies and Metaphors: Implications for Educators*

NICOLE P. PITTERSON
Department of Engineering Education, Virginia Tech, Blacksburg, VA 24060, USA. E-mail: npitters@vt.edu

NATASHA PEROVA-MELLO
School of Civil and Construction Engineering, Oregon State University, Corvallis, OR 97333, USA. E-mail: nperova@gmail.com

RUTH A. STREVELER
School of Engineering Education, Purdue University, West Lafayette, IN 47907, USA. E-mail: rastreve@purdue.edu

Circuit concepts are abstract in nature and have been proven to be difficult for students to understand. Instructors often rely on the use of analogies and metaphors to help students associate what is being taught with their prior knowledge or experiences. This study was guided by the following research questions: (1) What types of analogies and metaphors do students use to explain basic circuit concepts? and (2) What characteristics of *constructive analogies* are most common in electrical engineering students' discussion of circuit concepts? A think aloud protocol consisting of conceptual questions about circuits was used to interview nine participants who were juniors or seniors majoring in electrical engineering at a selective public university in the Western United States. The protocol was initially developed to assess students' misconceptions about introductory circuit concepts. However, a second round of analysis indicated students spontaneously used analogies and metaphors in their discussion of these concepts. The students' use of analogies and metaphors also highlighted lingering common misconceptions about the nature of current and the faulty interchangeability of voltage and current. Additionally, the most common characteristic of analogies used by the students was the basic surface comparison of features between the base and target concept. These findings support the use of the teaching with analogies (TWA) model and can inform instructional strategies used in circuit courses where students are exposed to the concept for the first time. This work also highlights implications for current and future instructors of introductory circuit concepts.

Keywords: analogies and metaphors in instruction; conceptual understanding; circuits; scientific models

1. Introduction

Engineering students' inability to verbalize knowledge about key circuit concepts they are capable of proving mathematically is a significant area of research interest [1–4]. The perceived difficulty experienced by students is often attributed to issues that arise when these concepts are first introduced in a formal instructional setting. The abstract nature of the concept dictates emphasis on the use of mathematical approaches to make them relatable. On one hand, researchers often advocate for multiple contextual representations such as tables, diagrams, graphs or equations to illustrate scientific concepts [5]. On the other hand, the need for qualitative understanding for the relationship among variables is also important for conceptual understanding [6]. Consequently, two common instructional tools used to help students develop qualitative understanding of circuits and the interaction of circuit parameters are analogies and metaphors [7]. The argument for the implementation of analogies and metaphors in scientific instruction suggests students' formal prior knowledge of the electricity and circuit concepts is minimal. While researchers do not dispute that students enter the learning environment with preconceived notions about scientific concepts such as heat or energy, they are often only exposed to specific references to basic electric concepts such as current, voltage or resistance when they enter introductory physics courses [8].

The teaching of scientifically complex concepts often requires the use of other related concepts to help students make sense of the new information [9, 10]. In scientific instruction, an analogy is the use of a comparative argument whereby a known concept (also referred to as the base concept) is used to explain an unknown concept (also referred to as the target concept) having similar attributes [11]. For example, a common analogy used when describing the movement of electrons within a circuit is the comparison to how water flows through a pipe. The similarities that exist between these two concepts are usually a good example when teaching students how current behaves in a circuit. The assumption is that students already have some practical knowledge of how water moves through a pipe. Scientific metaphors, on the other hand, are "the main mechanism through which we comprehend abstract concepts and perform abstract reasoning" [12, p. 244]. Though metaphors are most often thought of in

* Accepted 1 August 2018.

literary terms, in science learning a metaphor introduces an analytical attribute to a theoretical construct. The phrases the microprocessor is the brain of the circuit or the brain is a computer are common examples of scientific metaphors. This microprocessor example specifically conveys to students the complexity of the operation of a microprocessor and its control over the entire circuit with the assumption that they have some basic idea of how the brain controls all function of the body.

When combined, the use of analogies and metaphors help to foster the development of scientific models about the target content. Bailer-Jones [13] defines scientific models as "an interpretative description of a phenomenon that facilitates access to that phenomenon" [p. 108]. By using analogies and metaphors, instructors can provide their students with complex information and assist them in interpreting this information by relating the new content to something they already know. Interpreting complex and abstract concepts involves simplifying, idealizing and comparing these concepts to literal or empirical concepts. For example, using the solar system to describe an atom or using the mathematical equations to illustrate concepts or instructing students to imagine current beginning at the source and moving to all circuit components instantaneously. Consequently, scientific models link students' imagination, prior knowledge and experience to prepare them for the new material they are about to be presented with.

In addition, analogies and metaphors help students to conceptualize the new information by cognitively mapping what they are already familiar with (the base) to the unknown and abstract concept being taught (the target). As a result, analogies and metaphors are valuable tools when teaching abstract circuit concepts [14]. The main benefit analogies and metaphors provide to instructors and students is the ability to create relationships between concrete and abstract concepts. While analogies help learners categorize and better understand abstract and non-observable concepts such as electricity [11, 12], metaphors are the mechanisms whereby learners are able to reconcile the difference between their intuition and formal conceptions [17]. In most cases, the use of scientific metaphors is a mediator of analogical thought. This means metaphors "are like analogies in the sense that they can be reduced to comparison statements that try to indicate some structural similarity between a target and a source" [10, p. 82].

This study is aimed at investigating electrical engineering undergraduates' spontaneous use of analogies and metaphor when discussing current, voltage and resistance in electric circuits. To achieve its goal, the research was guided by the following questions:

(a) What types of analogies and metaphors do students spontaneously use to explain basic circuit concepts?
(b) What characteristics of constructive analogies are commonly used in electrical engineering students' discussion of circuit concepts?

Transcripts from a think aloud interview conducted with electrical engineering majors was conducted.

The questions were conceptual in nature, meaning students were expected to discuss their understanding of basic introductory concepts rather than to provide a numerical answer. Students were instructed to verbalize their thoughts as they solved each problem. This approach was aimed at eliciting students' conceptual understanding of current, voltage, resistance and power as well as how these variables interact in the basic operation of a circuit. Findings from this study can inform instructional strategies especially in introductory engineering circuit courses where students are exposed to fundamental circuit concepts that form the base of their core understanding.

2. Background

2.1 Analogies and metaphors in instruction

Circuit concepts are inherently abstract, and students tend to have very little pre-conceptions about how circuits work. Unlike other scientific concepts such as heat, temperature and energy, students often hold no prior knowledge about voltage, current, resistance or power. Consequently, their first engagement with these concepts occur in introductory physics and circuits courses. To combat the level of difficulty associated with these concepts, instructors often resort to the use of analogies and metaphors in instruction. In scientific learning, analogies are used to develop insights into hypotheses, questions and explanations of a target phenomenon that is often unobservable [18]. Analogies represent explicit measures whereby the learner is encouraged to make connections between or across two specific domains. A metaphor, on the other hand, is an implicit comparison where the basis of the comparison must be created by the concept to which it is applied [19, 20]. For example, comparing the charge held by a capacitor to water stored in a reservoir. The explicit comparison of the capacitor and reservoir storing charge and water respectively is the analogy while the implication that electricity and fluid are stored in similar ways is implicit comparison i.e. the metaphor. In other words, analogies afford instructors the opportunity to tap into students' prior knowledge and directly map what they are familiar with to the new information being taught while metaphors foster the ability to compare the known and the unknown using a hidden yet rational approach. Meaning, analogies compare concepts literally while metaphors compare concepts symbolically.

Sfard [17] argues scientific metaphors are inherently intuitive knowledge developed through experiences or prior conceptions about how the world works that in turn shape learning or understanding of formal scientific conceptions. Though analogies and metaphors are two different constructs, their effect on the learning of scientific concepts should not be considered as mutually exclusive. This means metaphors in most cases, utilize a comparative approach between two concepts in a manner similar to analogies. It is through this comparative approach that "the generative characteristics of metaphors can stimulate the construction of analogical relationships and facilitate conceptual change" [21, p. 716]. Consequently, the constructivist approach to learning supports the use of analogical thinking and metaphors. This perspective posit learning is more meaningful when learners can construct similarities between their prior knowledge and new information [7, 17, 22, 23]. Additionally, as learners' prior knowledge is engaged in the learning process, they are afforded the opportunity to transfer what was learned or experienced in context to a similar or novel context.

The use and development of mental models holds significant benefits for deep learning. For example, introducing analogies and metaphors when teaching unfamiliar and difficult concepts has the potential to motivate students by linking the material to concepts they can easily identify and renders the target concept easier to comprehend [18, 24]. Additionally, analogies and metaphors are also beneficial to learning since abstract ideas can be presented in an imaginative manner thereby requiring the learner to engage in thought provoking activities. These activities have the ability to appeal to students' cognitive and affective knowledge [25]. The general assumptions about learning when analogies and metaphors are used to explain a concept are explained in seven steps [9]:

1. The student has little knowledge or understanding of the target situation and would find a comparison to a more familiar situation helpful.
2. The base concept is understood by the student.
3. The student accepts the analogy as sound which could be due to acceptance of the analogy as appropriate or the level of authority ascribed to the teacher.
4. The student makes the correct comparison between the elements of the base concept and the target concept.
5. An expert would view the analogy as sound, meaning the elements of both concepts are similar enough that use of an analogy would benefit students' understanding.
6. The student is motivated to accept the comparison.
7. The outcome of the use of the analogy is aimed at conceptual growth.

The application of analogies and metaphors under these assumptions is directly aimed at knowledge acquisition where the intent is to use students' prior knowledge and experience to make sense of new incoming information [6]. For example, the water flow analogy, the most common analogy used to introduce the concept of electron flow, satisfies all seven assumptions. Additionally, by referring to the movement of electrons as *flow* intimates a fluid-like attribute to electrons. However, a more fruitful approach to the use of analogies and metaphors would seek to elicit conceptual understanding of the target concept that goes beyond an ability to easily recall what is being taught. This approach would not only leverage students' understanding of the analogy or metaphor when mapped to the target concept but also highlight cases when the use of analogies and metaphor foster the development or reinforcement of misconceptions.

In the classic book *Metaphors We Live By* [26], Lakoff and Johnson suggest our conceptual nature is fundamentally metaphorical. This implies at the base of human cognition is the tendency to use metaphorical and comparative language to give meaning to concepts. Reddy [12] also highlights language functions like conduit and is used to convey meaning in a figurative way. Consequently, there is an important caution on role of language in the use of analogies and metaphors and the way comparisons are made. Lakoff and Johnson [27] posit that by focusing on how students justify their overall understanding of particular concepts researchers can understand how these underlying conceptions impact students' learning. Similarly, since conceptual systems are metaphorical in nature, metaphors have the power to influence "how we perceive, how we think and what we do" [28, p. 454]. For example, an extensive review conducted by Reiner, Slotta, Chi and Resnick [29] highlighted how the use materialistic language was found to reinforce students substance-based preconceptions about force, heat, light and electric current. These authors contend that "instruction should attempt to introduce a new language of processes while shunning any language that uses the ontological attributes of material substances" [29, p. 30]. One suggested model for instruction was the use of analogies as explanatory tools in bridging the abstract with the concrete [22, 29]. By this approach, instructors would tap into the comparative power of the analogy while also helping students to understand that the comparison being made between the two concepts is only representational.

Through language, that is, the words used to describe scientific phenomena such as electricity, an abstract concept derived from a concrete entity takes on meaning to become an entity as real as the concrete concept [30]. Similarly, the language used to discuss specific concepts can steer the learner down a path where the understanding of one concept systematically leads to the understanding of another which may exists in a seemingly unrelated conceptual domain [17]. Conceptual change researchers [31–33] discuss at length the potential for misconceptions when analogies and metaphors are used to describe abstract concepts. These researchers claim that in the process of making a concept relatable, the main idea which is the concept being taught, becomes overshadowed by the analogy or metaphor. On the other hand, some empirical studies have reported students' learning showed significant increase in cases where analogical thinking and metaphor use were encouraged when thinking about the material. This, they discussed, was mainly due to the fact that learners were able to think of these concepts within contexts with which they could relate [19, 34]. In addition, researchers have theorized that the use of analogical thinking activities have significant influence on conceptual growth for two main reasons. Firstly, analogical thinking helps students to understand concepts and secondly, students can form associations between various concepts using the same system of analogies and metaphors [14, 19, 35].

To combat the potential for reinforcing or developing misconceptions, it is recommended that instructors be intentional about their use of analogies and metaphors. This is particularly important because "while analogies are frequently encountered in daily life, there is no compelling justification for assuming that students will necessarily understand how they work" [18, p. 168]. In addition, instructors often operate under the premise that because students are familiar with the base concept, they understand the analogy or metaphor being used. Brown and Salter [18] suggest students should be taught about analogies just as they are routinely taught about other forms of figurative language. The analogy or metaphor should be explained in detail since it is not often obvious from the words used how comparison works and at what point it no longer works. Consequently, instructors should be deliberate not only about their use of analogies but also how they teach students about the analogy and how it aligns with the target concept. The teaching-with-analogies (TWA) model demonstrates how instructors can use analogies and metaphors as powerful instructional tools while reducing their potential for misconceptions. This model provides a six-step approach to using analogies to teach complex or abstract concepts:

1. Introduce target concept,
2. Cue retrieval of base concept by reminding students of what they know about it,
3. Identify relevant features of target and base concepts,
4. Connect the similar features of the concepts,
5. Draw conclusions about target concept based on the base concepts,
6. Indicate where the analogy between the base and target breaks down [36, p. 230].

The most important implication of the TWA model lies in step 6. It is pertinent that instructors explicitly communicate to their students the point at which the analogy differs from the target concept. The strength of the analogies lies within its ability to explain the domains of the abstract concept. Therefore, it is necessary for students to understand that as the attributes of the analogy are mapped to that of the target concept there are features of the analogy that no longer apply. For example, consider the current taking the path of least resistance is like finding alternative routes when driving through peak hour traffic analogy. Assuming that the comparison is taken as "resistance is like traffic", the objects in the analogy are the vehicles and the relation between them is the speed or ease at which the driver can move. The movement of each vehicle would be dependent on how fast they are each moving as well as the presented road conditions. However, as with all analogies, the example of traffic does not completely map all of the relevant attributes of resistance. For example, whereas there might be exits along the highway where vehicles get on or off which changes the dynamic of how many vehicles will be on a particular road at any given time, resistance in any particular circuit is often fixed unless the circuit is designed with variable loads in mind.

2.2 Constructive analogies

The recommendation for the application of analogical reasoning in scientific learning also comes with the caution of using analogies that are considered "good" or otherwise called constructive analogies [36]. As mentioned earlier, the nature of making comparisons between two similar yet different concepts can come at the expense of reinforcing misconceptions. Consequently, instructors are encouraged to ensure that the analogy used is appropriate for the concept being explained. A good analogy is measured by the following three characteristics:

1. *The number of features being compared*—the power of the analogy to explain the target concept increases significantly when there are numerous features of the analogy in alignment with the concept being explained.
2. *The similarities of the features being compared*—an analogy must possess the ability to map important features that are similar in the base and target concept.
3. *The conceptual significance of the features being compared*—an analogy is beneficial to enhancing students understanding only when the analogy is able to explain the concept in terms that the students already understand [36].

Knowledge and use of constructive analogies are important to science learning because, if explained correctly, constructive analogies can "predict aspects and behavior of the target concept" [26, p. 227]. Since the analogy describes the new concept in ways students are familiar with it, the explanatory power of analogies can lead to the development of conceptual systems in understanding complex scientific concepts.

In the science education literature, much research has been done one the use of analogies and metaphors in instruction [37, 38]. Also, researchers have cautioned about their use and have developed models for how analogies and metaphors should be introduced and applied to the learning of scientific concepts [13, 39]. However, within engineering and more specifically electrical engineering where most concepts are abstract in nature, there is a dearth of work around how students are taught using analogies and metaphors. While engineering instructors and researchers often promote the value of analogies and metaphors as teaching tools, they are often unacknowledged. This study seeks to add to the body of knowledge about analogies and metaphors by aiming to answer the following questions:

(a) What types of analogies and metaphors do students spontaneously use to explain basic circuit concepts?
(b) What characteristics of constructive analogies are commonly used in electrical engineering students' discussion of circuit concepts?

3. Methodology

3.1 Study design and data collection

The data used for this study was part of a larger project aimed at uncovering engineering students' misconceptions about common scientific concepts [40, 41]. In the context of that study, junior and senior engineering students were interviewed using a think aloud protocol designed by the researchers in collaboration with course instructors. The questions posed in the protocol were developed by the course instructor and were drawn from the course textbook and other course related materials. Two interviewers (one of the authors and one other interviewer) were trained by the instructor to recognize correct answers but were in no way related to the courses from which the students were selected. The students were invited to participate in the study through an email that was sent to all engineering majors. The original sample size were 19 participants, however for this study only the transcripts of the electrical engineering students (n = 9) were re-analyzed specifically exploring the students' unprompted use of analogies and metaphors. The analysis was conducted by the other two authors who were not a part of the interviews.

In the protocol, students were presented with simple electric circuits and tasked with explaining the operation of the circuit based on the voltage applied and the current through the various components in the circuit. Students were instructed to talk aloud as they solved the examples to gauge their understanding of the concepts presented in the document. The interviewers asked students probing or clarifying questions where necessary. The protocol also consisted of real-life examples of electric circuits and the students were instructed to explain how the results observed could be explained by circuit parameters such as current, voltage, and resistance. For example, students were presented with a picture of a line operator that was electrocuted and asked to explain how current, voltage, and resistance played a role in that event.

3.2 Data analysis

The data were analyzed in two phases using a combination of inductive and deductive content analysis. Initially, the transcripts were read multiple times by two of the authors separately and all the statements perceived to be analogical were highlighted. Following the identification of the use of analogies in the participants' response, an exploration of literature was conducted to categorize and define the different types of analogies and metaphors in a coding framework. Using these defined typologies from the literature, codes were created and then used to code the data under these broad headings. The data were then analyzed by taking a count of the number of analogy and metaphor types that were present in each participants' transcript.

The findings are reported further in the paper under these derived typologies.

For phase two, the three characteristics of constructive analogies were used to assess how often students expressed these characteristics and the quality of the participants' conceptual understanding of the concept being discussed. The transcripts were read using the three characteristics as a guide. Instances of each characteristic was recorded, and the findings discussed in terms of the significance of the characteristics on the participants' conceptual understanding of circuit concepts.

3.2.1 Phase one—types of analogies and metaphors

Initially, two researchers read through the think aloud transcripts repeatedly to get a sense of the whole. In the second reading of the interviews, personal notes were made and comments to each other in a Google document about initial impression of analogical thought in the students' responses. Broad examples of analogical language that emerged from transcripts were highlighted. To refine the analogical examples into smaller categories, a search and synthesis of literature was done from which a coding framework was developed.

3.2.1.1 Development of coding framework

To develop a coding framework, insights from the work of ten studies on analogies and metaphors were used [6, 8, 9–16]. These studies were the most highly cited work on the use of instructional analogies and metaphors. The work of authors such as Lakoff and Johnson [26], Brown and Clement [9], Glynn [11], Gentner [42] and Ortony [12] are fundamental in science education research around how analogies have been used to foster conceptual understanding of abstract concepts. One model [19] described analogies as having two levels: 1) the direct mapping of two concrete structures (i.e. type one or direct comparison analogies) and 2) the comparison of identities or parts of structures (i.e. type two or structure comparison analogies). In this framework [19] the comparison speaks directly to the analogy and the target concept. Figures 1 and 2 demonstrate how an analogy maps the base and target concepts [11].

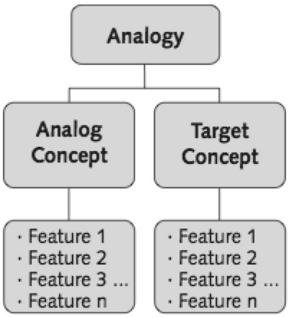

Fig. 1. A conceptual representation of an analogy, with its constituent parts.

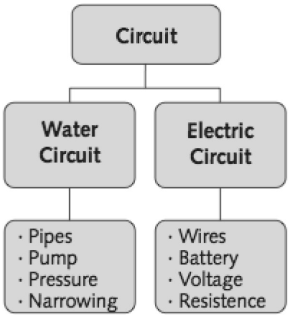

Fig. 2. A conceptual representation of a water-electric circuit analogy.

Another study [20] introduced the idea of an intermediary concept that links the abstract and the target via a "bridge". The use of analogies in both cases follows some logical progression from one point (abstraction) to another (concrete knowledge). This supports the notion that analogies are indicators for explicit learning [19]. However, even with the introduction of the intermediate concept [20] there is still the assumption that students' understanding of the target concept will be logically sequenced. The assumption that students' learning of scientific concepts will always be logically sequenced is a limitation of the previous work done on the use of analogies. This limitation however, can be accounted for by not only looking at students' use of analogies but also examining their use of metaphors. The use of metaphors can strengthen claims about the benefits of analogies. While analogies are characterized by the mapping of structural similarities between the base and target concept, metaphors support a deeper explanation of the target concept. Metaphors provide evidence of specific attributes of the base that can be mapped on to the target concept [42]. Metaphors in science teaching are usually of two distinct types: 1) the link between new and existing knowledge (that in most cases takes the form of an image associated with the concept) and 2) the influence of one's intuition on their cognition [9, 16]. This is aligned with the two main principles of scientific metaphors described in broader literature; the visualization of abstract concepts [13] and the association of thinking and feeling [16].

Finally, revisions to the coding framework were made based on the work of Gentner [43] and Brown and Clement [9]. This resulted in the modification of the metaphor section to be subtitled "representative models". Table 1 shows the types of analogies and metaphors that emerged from the literature. This framework was used for phase one of data analysis to answer the first research question.

Table 1. Coding framework used in phase one

Types of analogy	Definition
Direct comparison (A1)	The relation between two domains of reality. Meaning the use of a tangible domain to describe an abstract domain e.g., water in a pipe (base) compared to current in a circuit (target).
Structure comparison (A2)	The relation between identities or parts of a structure. Meaning the comparison of attributes within the base and target concept e.g., how water pressure changes in a pipe (base) and the varying force associated with a changing voltage source (target).
Bridge analogies (A3)	The use of an intermediate concept (bridge) that links initial analogy and target. If A is analogous to B and B is analogous to C, hence A is analogous to C, which is the breaking down of one large concept into two smaller ones that make it easier to understand e.g., water in a pipe always flows directly out from the tap, water in a pipe is like current in a circuit, current always flows out directly from the source (base—water flow, target—conventional current flow).
Types of metaphors/representative models	**Definition**
Imaginative (M1)	Introduces a degree of imagination that helps with visualizing abstract ideas e.g., using Kirchhoff's current law and the loop graphic to demonstrate current in a node.
Level of comfort (M2)	Links thinking with feeling (bridges the gap between cognitive and affective domains) e.g., how the level of comfort experienced when learning a concept made it easier to understand.

3.2.2 Phase two—characteristics of constructive analogies

To answer the second research question the characteristics of constructive analogies [36] were used to conduct phase two of data analysis. These were:

- *Characteristic 1*: The number of features of the target concepts to which it is compared.
- *Characteristic 2*: The similarity of the features being compared.
- *Characteristic 3*: The conceptual significance of the features compared.

The findings are discussed based on how many examples of analogies had all three characteristics evident and the participants' conceptual understanding of the concepts to which the analogy was applied.

4. Results

4.1 What types of analogies and metaphors do students use to explain basic circuit concepts?

In the transcripts, eight of the nine participants used some combination of analogies and metaphors spontaneously in their discussion of the circuit or individual component operation due to the presence of an electric current. One participant, Brad, used no concrete type of analogy or metaphor as defined by the coding framework. However, implied comparisons that were not explicit enough to be classified as level one analogies such as *"When you have a—when you have a larger area, there's just, they're traveling on more material because the circumference is larger"* were found in Brad's transcript. Here it can be seen that there is some comparison being made to how electrons travel given the size of the conductor. However, the analogy is not overtly said or discussed.

The following discussion will be focused on the other eight participants that spontaneously used analogies and metaphors in their discussions. All eight participants used direct comparison (A1) analogies; three participants used structure comparison (A2) analogies while none used bridge (A3) analogies. For the metaphors, eight participants used imaginative metaphors (M1) and five participants used level of comfort metaphors (M2). The findings are summarized in Table 2.

Within the transcripts there were several instances of students using comparative language to justify their thought processes on a question for the interview or when probed by the interviewers to clarify something they had previously said. Some students attributed their use of analogies to previous instructors or professors that used these analogies to convey meaning of the abstract concept during instruction. From the results of Table 2, direct comparison analogies (A1) were the most frequent type of analogies used by the participants.

Table 2. Use of Analogies and Metaphors by Participants

Participant*	A1	A2	A3	M1	M2
Donald	5	1		1	0
Kevin	2	0		3	3
Gerard	4	0		1	0
Tyler	6	1		1	1
Jerry	3	0		4	2
Keith	4	1		2	1
Joey	2	0		3	0
Pat	5	0		5	2
Brad	0	0		0	0

* Pseudonym assigned by researchers.

This is not surprising since using a tangible domain to describe an abstract concept is the most common type of analogy used in instruction.

Eight participants used direct comparison (A1) analogies which is the use of a tangible domain to describe an abstract concept. Common examples of direct comparison analogies were the water flow or pipe model used to describe the movement of electrons, the changing diameter of the pipe or being in traffic to discuss the concept of resistance, or a spring to describe an inductor. The use of this type of analogy by all but one of the participants indicates students had, whether through their own personal experiences or instruction, developed a tendency to liken an unknown to a known concept. For example, some students discussed the use of analogies was a skill they learned from their instructors.

Examples of structure comparison (A2) analogies being used to show the relationship between parts of a concept were also found. While direct comparison analogies compare two concepts based on their overall similarities, structure comparison analogies delve deeper to compare distinct characteristics of the concepts. For example, one of the students compared resistors to shrinking the pipe and another participant compared water pressure to voltage. These are classic examples of structure mapping between two somewhat similar concepts.

Participants relied on the use of metaphors to help them explain difficult concepts often with the help of formulas and graphical representations. For example, when asked about a three-phase power source one of the participants discussed repeatedly trying to "visualize the concept" and having a related image coming to mind. This is an example of imaginative (M1) metaphor. In addition, there were several instances of level of comfort (M2) usage where participants attempted to link their thinking with their emotions. For example, Joey in talking about his experience learning about circuits described it as being hard because he had no interest in the concept being taught and as a result he did not put much effort into it. In other examples, several participants discussed how an external influence, such as having a good teacher, had a positive impact on their learning. Examples of the coded analogies and metaphors are shown in Table 3.

The absence of supporting examples of bridge three analogies may be attributed to two specific reasons. The first is that this type of analogy assumes students have a logical and sequenced understanding of the target concept based on their ability to make direct associations between two smaller concepts. The second reason deals with the idea that this type of analogy was developed through the use of intended instructional strategies that the students who participated in this study might not have been exposed to [44]. The latter explanation supports this study's purpose in that the researchers hoped to find that students would naturally use analogies and metaphors when talking about circuit concepts without being prompted to.

Table 3. Examples of analogies and metaphor from participants' transcripts

Direct comparison (A1) Analogy:

I think it's the inductor that behaves like a spring, because it will store energy and release energy—*Tyler*

Well resistance is easy. That other ones just like, you know kind of putting, like putting the scarf over your mouth to breathe—*Pat*

So basically with, with DC power, or direct current, it's kind of like a fire hose, so as you're pushing a fire hose through, let's say a small tube, or even a larger tube, it doesn't really matter, you're going to have the water that kind of clings to the walls essentially. That's kind of the general idea of resistance—*Donald*

Structure comparison (A2) Analogy:

Like you could think of potential as like if you have a battery is basically like a reservoir in that high altitude. And you get like so much pressure or whatever at the bottom of the dam, that's your potential—*Tyler*

And like resistors are like shrinking the pipe, and inductors are, let's see—like fluid flow, probably like a storage, no that would be a capacitor would be a storage tank, and I don't remember what the inductor was. But they did have any analogy that like, 'cause most people take just fluids, they take fluids beforehand—*Keith*

Imaginative (M1) Metaphors:

I'm trying to visualize what the three-phase power is. And I keep getting this, I keep getting either a star or Y-system in my head. I can't really visualize what a one-phase system is. I guess it would probably just be a single sinusoid with the, with the wires coming off of it. I'm not positive on that—*Pat*

Yeah, I'm visualizing it basically. I know that a voltage through a wire creates a current basically. I'm always looking for ways to, to visualize something a little bit better. I think being able to visualize what the different components were intending to do, rather than just hoping your equations works out right—*Kevin*

Level of comfort (M2) Metaphors:

And, just kind of really easy equations. And you know, and then, it got real complex, and it got a little bit harder. And I don't know, I was just able to pick up on it relatively quickly and felt that would be my best fit. So, that was I think more or less why I chose my major—*Jerry*

If you can't have any tangible grasp in your head on it, then I think it definitely can help in that sense. So I guess for me I always try and understand it first, 'cause I always want to understand things—Just because I relate really well to the algebra side of it—*Kevin*

Similar to the use of analogies, all but one participant used imaginative metaphors. This finding can be attributed to the fact that in circuits courses the introduction of a concept is usually followed by a graphical illustration or a mathematical equation. Research suggests multiple ways of representing a concept as necessary since it is impossible for students to see the movement of electrons or the operation of a capacitor [3, 5].

4.2 What characteristics of constructive analogies are most common in electrical engineering students' discussion of circuit concepts?

In phase two, the transcripts were analyzed using the three characteristics of a constructive analogy: number of features between base and target concepts, similarity of features being compared and conceptual significance of compared features. Twenty-nine (29) examples of analogies that had at least one or a combination of the three characteristics of a constructive analogy were found. There were three examples in which only characteristic 1 was evident and two that were only characteristic 2. There were no examples where only characteristic 3 was present. In terms of the combination of more than one characteristic, there were eight examples of characteristic 1 and 2, one example of characteristic 1 and 3, one example of characteristic 2 and 3. There were 15 examples that had characteristic 1, 2 and 3. Eleven of these 15 examples were characterized as constructive analogies in that the use of the analogy aided the students' conceptual understanding of the target concept to which the analogy was applied. For example, Gerard in discussing how current tends to follow the path of least resistance used the following analogy:

> "It will go easier. It's kinda' like which is a good analogy, would you pick 5:00 o'clock traffic on the [main street] going into [the city], or coming out of [the city]? Coming out of [the city] is probably going to be a lot busier than going into [the city], because everyone's trying to get out. It's easier for you to go into [the city], than it is to go out. So, it's actually easier if you go through the least amount of traffic, than the greater one."

From the example, the path of current flow is directly compared to driving on a road (characteristic one), then the constraints associated with traffic movement alludes to resistance (characteristic two) and finally the participant arrives at the conclusion that like choosing a roadway with least traffic current will follow in the path of least resistance. Using this analogy Gerard demonstrated how a constructive analogy enhances conceptual learning.

In a similar example one participant, Jerry, uses traffic to describe resistance:

> "So, as they—any time an obstacle, like other atoms or electrons, that's the resistance in their flow. So, they're—they're basically, it's like a—like being in traffic. Like sometimes you can jump out into a spot, and get a little farther down, but then you run into something else".

The characteristics manifested here are: resistance is like traffic; movement restrictions are like obstacles posed by resistors in a circuit and the idea of traffic captures resistance well. While the presence of all three characteristics indicate the use of a constructive analogy, these characteristics on their own does not prevent against students' ability to develop or reinforce existing misconceptions.

Analogies used in instruction that are not explicitly discussed and explained can lead students to develop misconceptions about the nature of the concept being taught. There were four instances where the use of analogies showed the presence of misconceptions in the students' conceptual knowledge. One participant in discussing the movement of electrons in a circuit using the water flow model described how water flowing in a broken pipe is similar to electrons still flowing when the circuit becomes open. The following is an example from Pat:

> "Okay. So initially if the switch is closed, we're going to have a voltage flowing through our circuit. You'll have a current flowing around here. And, it's just flowing, flowing, flowing actually—and then when the switch opens, it's still wanting to flow through it. And so that's what causes that initial arc. So suppose that you have your pipe and you broke the pipe, the water's still going to flow through it. So it's, it wants to keep going. And so the arc is actually just the flow of electrons continuing. . ."

This example shows that not only does this student interchange the concepts of voltage and current, which is a common area of difficulty identified by other researchers [28] but has a persistent misconception of how current behaves in an open circuit. There were also misconceptions present assumed to have been reinforced or developed by the substance property that is typically associated with electricity. For example, Brad discussed the following:

> "So, when that's cut off that flow of electricity is stopped, and there's just sorta' like a—it acts like a volt—or a battery. And it increases voltage until it has a way to disperse it through either an electrical arc to the ground, if it gets high enough. Or, someone touching the vending machine or anything like that".

The obvious misconception here is that even with the removal of a load or the breaking of a circuit, there is a build-up of voltage until there is a way to get rid this excess voltage. The correct reasoning in circuits as it relates to voltage is that the value of the voltage applied to the circuit is constant as it is directly supplied by a source. Consequently, unless the source is manipulated the value of the voltage is unlikely to change regardless of what is happening elsewhere in the circuit. A basic understanding of Ohm's law and the relationship that exist between voltage, current and resistance would expose the idea of voltage build-up as incorrect one since the law clearly states that voltage is always constant however the value of the current is likely to change based on the load or resistance value. This finding also provides evidence to the claim that students tend to use voltage and current interchangeably when they lack a proper understanding of the obvious and fundamental difference between these two variables.

Another common misconception associated with learning about circuits is students' inability to correctly distinguish between potential and potential difference. In the following example, Donald explains why a line operator was electrocuted while making obvious misrepresentations of the concept of potential difference:

> "Like when you have like power line operators, that's what they have to do. Is, they'll get out of their, whichever, like the cherry picker thing, and like they have to attach themselves to the line. And, they have to charge their body up to that voltage so if they, so they're at that voltage, so if they were to say, take a rod, and contact another line that's right beside them, they'd be electrocuted because they'd get that line to line voltage across them."

Researchers have suggested that the use of analogies or terms associated with analogies such as "it is just like this" or "if you think about it like that" are so ingrained in human conversations it is easy to develop the ability to compare two similar concepts. However, being able to go beyond the comparison of similar concepts gives evidence to higher order conceptual understanding of the target concept [36]. Therefore, the three characteristics discussed as indications of constructive analogies are important to be included in the analogies used when teaching scientific concepts. Since more than half of the analogical examples found had all three characteristics, the conclusion can be made that there are constructive analogies in the students' knowledge base. These examples demonstrate that while analogical thinking or reasoning can be considered commonplace in scientific contexts, when these participants learned or were exposed to these analogies all three characteristics were included. In addition, the participants' ability to not only identify similar features in the two concepts being compared but to also discuss how these features map unto each other is a strong indication of their conceptual understanding of the concepts.

These findings support the claim that analogies are "double-edged swords" [36] in that analogies can be both beneficial and detrimental to the learning of scientifically complex concepts. When the aim is to elicit conceptual understanding of complex concepts, instructors may often resort to the use of analogies and metaphors because of their benefits to teaching abstract concepts. However, the findings of this study indicate there are significant implications for how and when analogies and metaphors are used in instruction.

5. Discussion

The results of this study provide evidence for the spontaneous use of analogies and metaphors by students when discussing electric circuit concepts. This is an interesting finding because the larger study for which this data were collected was aimed at identifying students' misconceptions about scientific concepts associated with circuits. The protocol used to collect data was not designed to lead students to express their understanding of circuit concepts using analogies and metaphors. However, these results show that even after students have progressed in their courses of study, when asked to describe their knowledge of these concepts, they default to the use of analogies and metaphors they were most likely exposed to in their introductory courses. The use of analogies and metaphors when teaching circuit concepts is a common instructional strategy because of the level of abstraction associated with the concept. The authors contend that while analogies are effective teaching tools for abstract concepts their use can have significant impact on students' learning. In most cases, the instructor will attempt to use analogies to help students to create a visual, relatable representation of electricity. However, the researchers have found that the use of the analogies and metaphors can lead to even more complex and deeply rooted misconceptions that are harder to repair.

Discussion of the base and target concepts should be done in a manner that communicates to students their similarities while explicitly identifying where the analogy is no longer applicable to the concept being taught. Researchers refer to this as the point at which the analogy breaks down. For example, when students talked about *voltage build up in the frame of the vending machine* or *electrons building up behind an open switch* are classic examples of misconceptions associated with the capacitor as a container analogy. The substantive property attributed to electrons by word *flow* leads students to deduce that in circuit electrons maintain fluid-like attributes. A proper conception or understanding of current in a circuit would result in students knowing that once the complete path of the circuit becomes broken, whether by a loose connection or opening of a switch, electron movement and the manifestation of current would immediately discontinue. The general rule of current not being present in an open circuit of any kind should be reinforced as well as the fact that there is no operation of circuit components in an open or broken circuit should be emphasized.

The authors posit that analogies and metaphors are appropriate methods for introducing a concept, however over time students should be guided to understanding the concepts through other instructional means such as using multiple modes of representation (e.g., qualitative discussions, graphical illustrations and quantitative measures). For example, Licht [45] and Johnstone [3] proposed models for teaching complex scientific concepts that illustrate equal emphasis on qualitative discussions, graphical illustrations and mathematical equations. The implication for instructors is that whenever an analogy is used to discuss a concept, direct measures should be taken to ensure that students understand the purpose of the analogy, (i.e., the conceptual idea it is being used to convey) and why the analogy is being used (i.e., what conceptual features render the analogy applicable). In addition, when an analogy is being used, intentional effort should be made to ensure the base concept corresponds with the target concept. Misconceptions arise when students intentionally compare features between base and target concepts that do not correspond. Consequently, this research supports the use of the teaching with analogies (TWA) model, previously discussed in the background section.

Throughout the transcripts evidence of students use of language associated with substantive reasoning were found. There were three main categories of substantive reasoning. These were repeated discussion of (1) electricity or current traveling, passing through a component or jumping from one area to the other, (2) voltage, charge or electrons building up and, (3) current or voltage having transitional characteristics meaning it can be moved or chose to move from one location to the next. These findings align with Reiner, Slotta, Chi and Resnick's [19] discussion of a substance schema which highlights the tendency of learners to attribute substantive properties to abstract concepts. These properties they discuss "are learned very early in development and persist throughout life as useful generalized knowledge of the attributes and behavior of material objects and substances" (p. 5). This supports the argument of current and previous work that the abstract nature of the circuit concepts warrants the use of mental models on the part of the students to aid their understanding. A key implication for instructors is the need for an instructional model that builds on students' initial knowledge about circuits, while helping them to create more robust understanding of circuit concepts. In the absence of concrete ways to demonstrate how components in a circuit operates holistically instructors and students rely on analogies and metaphors to make the concepts more relatable. However, instructors should be deliberate and intentional about their use or the ways in which they apply analogies and metaphors. Finally, to guard against misunderstanding and misconceptions, instructors should design classroom discussions or assignments to gauge or scaffold students' understanding of or thought processes about concepts introduced using analogies.

6. Conclusions

The benefits of analogies and metaphors in the teaching and learning of scientific concepts cannot be understated. Their advantages as significant teaching tools lie in their ability to not only convey facts about abstract concepts but their role in presenting abstract information in a connected manner that leverages students existing knowledge. For instructors, it is easy to rely on analogies and metaphors because they provide the opportunity to add meaning to what would have been otherwise unrelated. However, it is important that instructors guard against students arriving at the conclusion that the base concept is an exact representation of the target concept. It is necessary that students are taught to regard an analogy as nothing more than a physical representation of the target concept. If students are not made aware of the fact that analogies do not always map directly onto the target concepts, this may lead to the development of misconceptions that are difficult to repair or to the strengthening of existing misconceptions. Future research endeavors include studying the role of language in making meaning and fostering conceptual understanding of abstract concepts. Additionally, the authors suggest further exploration of other instructional strategies can be used to make abstract concepts more relatable without developing or reinforcing misconceptions. We also recommend that future studies can be focused on alternative analogies generated by students and how effective these are to students' understanding. A limitation of this study was that there were only nine think-aloud interviews used as the data. This study could be conducted using a larger sample size with other electrical engineering students at different institutions as well as students in other engineering and STEM disciplines to determine if students will spontaneous use analogies and metaphor when discussing introductory concepts in their respective disciplines as well as what types of analogies and metaphors they use. We believe a larger sample size would also provide the opportunity to validate the findings of this study on a wider scale.

Acknowledgments—The data analyzed in this article was originally collected as part of the Difficult Concepts project for Center for the Advancement of Engineering Education (CAEE). We wish to thank the National Science Foundation for funding CAEE through grant ESI-0227558.

References

1. A.-K. Carstensen and J. Bernhard, Student learning in an electric circuit theory course: critical aspects and task design, *Eur. J. Eng. Educ.*, **34**(4), 2009, pp. 393–408.
2. R. Duit and C. von. Rhöneck, Learning and understanding key concepts of electricity, *Connecting Research in Physics Education with Teacher Education*, 1998, pp. 55–62.
3. A. H. Johnstone, Why is science difficult to learn? Things are seldom what they seem, *J. Comput. Assist. Learn.*, **7**, 1991, pp. 75–83.
4. D. Holton, A. Verma and G. Biswas, Assessing student difficulties in understanding the behavior of AC and DC circuits, *ASEE Annu. Conf. Expo.*, p. 16, 2008.
5. S. Ainsworth, The educational value of multiple-representations when learning complex scientific concepts, in *Visualization: Theory and Practice in Science Education*, 3rd ed., J. K. Gilbert, M. Reiner, and M. Nakhleh, Eds. Surrey, UK: Springer Science and Business Media, 2008, pp. 191–208.
6. N. P. Pitterson and R. A. Streveler, Increasing students' conceptual understanding of AC circuits: An application of Licht's model, in *American Society for Engineering Education*, 2014, pp. 1–8.
7. S. Bishop, Using analogy in science teaching as a bridge to students' understanding of complex issues. In J. F. Meyers & R. Land (Eds.), *Overcoming barriers to students understanding: Threshold concepts and troublesome knowledge*, pp. 182–194. London and New York: Routledge, 2006.
8. G. Biswas, D. L. Schwartz, S. Brophy, B. Bhuva, T. Blanc and J. Bransford, Combining mathematical and everyday models of electricity, in *Cognitive Science Society*, 1997.
9. D. E. Brown and J. Clement, Overcoming misconceptions via analogical reasoning: abstrat transfer versus explanatory model construction, *Instr. Sci.*, **18**, 1989, pp. 237–261.
10. J. Bernhard and A.-K. Carstensen, Learning and teaching electrical circuit theory, *PTEE 2002 Phys. Teach. Eng. Educ.*, pp. 163–178, 2002.
11. S. M. Glynn, Making science concepts meaningful to students: Teaching with analogies, *Four Decad. Res. Sci. Educ. From Curric. Dev. to Qual. Improv.*, 2008, pp. 113–125.
12. A. Ortony, Ed., *Metaphor and Thought*, 2nd ed. Cambridge, NY: Cambridge University Press, 1993.
13. D. M. Bailer-Jones, Models, metaphors and analogies, in *The Blackwell Guide to the Philosophy of Science*, P. Machamer and M. Silberstein, Eds. Malden, Massachusetts: Blackwell Publishers Inc, 2002, pp. 108–128.
14. D. F. Treagust, R. Duit, P. Joslin and I. Lindauer, Science teachers' use of analogies: Observations from classroom practice, *International Journal of Science Education*, **14**(4), 1992, pp. 413–422.
15. R. Duit, D. F. Treagust and A. Widodo, Teaching science for conceptual change: Theory and practice, in *International handbook of research on conceptual change*, S. Vosniadou, ed. 2008, pp. 629–646.
16. J.-J. Dupin and S. Joshua, Analogies and 'modeling analogies' in teaching: Some examples in basic electricity, *Sci. Educ.*, **73**(2), 1989, pp. 207–224.
17. A. Sfard, On Two Metaphors for learning and the Dangers of Choosing Just One, *Educ. Res.*, **27**(2), 1998, pp. 4–13.
18. S. Brown and S. Salter, Analogies in science and science teaching," *Adv. Physiol. Educ.*, **34**, 2010, pp. 167–169.
19. R. Duit, On the role of analogies and metaphors in learning science, *Sci. Educ.*, **75**(6), 1991, pp. 649–672.
20. J. Clement, Using bridging analogies and anchoring intuitions to deal with students' preconceptions in physics, *J. Res. Sci. Teach.*, **10**(10), 1993, pp. 1241–1257.
21. K. Tobin and D. J. Tippins, Metaphors as seeds for conceptual change and the improvement of science teaching, *Sci. Educ.*, **80**(6), 1996, pp. 711–730.
22. J. Clement, Role for explanatory models and analogies in conceptual change, *International Handbook of Research on Conceptual Change*, 2013, pp. 412–446.
23. J. Clement, Model based learning as a key research area for science education, *Int. J. Sci. Educ.*, **22**(9), 2000, pp. 1041–1053.
24. W. F. McComas, ed., *The Language of Science Education: An Expanded Glossary of Key Terms and Concepts in Science Teaching and Learning*, Rotterdam, The Netherlands: Sense Publishers, 2014.
25. Z. R. Dagher, Review of studies on the effectiveness of instructional analogies in science education, *Sci. Educ.*, **79**(3), 1995, pp. 295–312.
26. G. Lakoff and M. C. Johnson, *Metaphors We Live By*, Chicago, Illinois: University of Chicago Press, 1980.
27. G. Lakoff and M. Johnson, The metaphorical structure of the human conceptual system, *Cogn. Sci.*, **4**, 1980, pp. 195–208.
28. G. Lakoff and M. Johnson, Conceptual metaphor in everyday language, *J. Philos.*, **77**(8), 1980, pp. 453–486.
29. M. Reiner, J. D. Slotta, M. T. H. Chi and L. B. Resnick, Naive Physics Reasoning: A Commitment to Substance-Based Conceptions, *Cogn. Instr.*, **18**(1), 2000, pp. 1–34.
30. D. Heywood, The place of analogies in science education, *Cambridge Journal of Education*, **32**(2), 2002, pp. 233–247.
31. M. Forišek and M. Steinová, Metaphors and analogies for teaching algorithms, *Proc. 43rd ACM Tech. Symp. Comput. Sci. Educ.—SIGCSE '12*, p. 15, 2012.
32. M. Limon, On the cognitive conflict as an instructional strategy for conceptual change: A critical appraisal, *Learn. Instr.*, **11**, 2001, pp. 357–380.
33. E. L. Zirbel, Teaching to Promote Deep Understanding and Instigate Conceptual Change, *Bull. Am. Astron. Soc.*, **38**, 2006, p. 1220.
34. R. K. Coll, B. France and I. Taylor, The role of models/and analogies in science education: implications from research, *Int. J. Sci. Educ.*, **27**(2), 2005, pp. 183–198.
35. D. F. Treagust, G. Chittleborough and T. L. Mamiala, Students' understanding of the role of scientific models in learning science, *Int. J. Sci. Educ.*, **24**(4), 2002, pp. 357–368.
36. S. M. Glynn, R. H. Yeany, and B. K. Britton, Eds., *The Psychology of Learning Science*, Hillsdale, New Jersey: Lawrence Erlbaum Associates, Incorporated, 1991.
37. P. Machamer and M. Silberstein, eds., *The Blackwell Guide to the Philosophy of Science*. Malden, Massachusetts: Blackwell Publishers Inc, 2002.
38. F. Hallyn, ed., *Metaphor and Analogy in the Sciences*, Vol 1. Belgium: Springer Science and Business Media, 2000.
39. T. L. Brown, *Making Truth: Metaphor in Science*, Urbana-Champaign, Illinois: University of Illinois Press, 2008.
40. M. A. Nelson, M. R. Geist, R. A. Streveler, R. L. Miller, B. M. Olds, C. S. Ammerman and R. F. Ammerman, From practice to research: Using professional expertise to inform research about engineering students' conceptual understanding. In *American Educational Research Association*, pp. 1–15. Montreal, Canada, 2005.
41. R. Streveler, M. Geist, R. Ammerman, C. Sulzbach, R. Miller, B. Olds and M. Nelson, Identifying and investigating difficult concepts in engineering mechanics and electric circuits, In *American Society for Engineering Education*, 2006.
42. D. Gentner, Structure-mapping: A theoretical framework for analogy, *Cogn. Sci.*, **7**(2), 1983, pp. 155–170.
43. D. Gentner and D. R. Gentner, Flowing waters or teeming crowds: Mental models of electricity, in *Mental models*, D. Gentner and A. L. Stevens, Eds. Hillsdale, New Jersey: Lawrence Erlbaum Associates, Incorporated, 1983, pp. 99–129.
44. L. H. T. West and A. L. Pines, Eds., *Cognitive Structure and Conceptual Change*. San Diego, CA: Academic Press, Inc, 1985.
45. P. Licht, Teaching Electrical Energy, Voltage and Current: An Alternative Approach, *Phys. Educ.*, **26**(5), 1991, pp. 272–277.

Nicole P. Pitterson is an assistant professor in the Department of Engineering Education at Virginia Tech. Her research interests include eliciting conceptual understanding of complex circuit concepts using active learning strategies. Nicole holds a PhD in Engineering Education from Purdue University and degrees in Manufacturing Engineering (Western Illinois University) and Electrical and Electronic Engineering (University of Technology, Jamaica).

Natasha Perova-Mello is currently a Postdoctoral researcher at Oregon State University in the School of Civil and Construction engineering. She received PhD in Engineering Education from Purdue University, MS in Mathematics, Science, Technology, and Engineering education, and MS in Electrical Engineering from Tufts University, and BS in electrical engineering from Suffolk University. Dr. Perova-Mello's research interests and experience in Engineering Education are in the areas of *educational technology* (computer-based instruction, blended and distance learning) and *instructional methods* (collaborative learning, cooperative learning and team-based learning).

Ruth A. Streveler is a Professor of Engineering Education at Purdue University. Before coming to Purdue, she was the founding director of the Center for Engineering Education at the Colorado School of Mines. She has a long-standing research interest in how students understand difficult concept in engineering science.