# Abstraction and Problem Solving in an Undergraduate Electrical Engineering Circuits Course

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*Abstract*— **The ability to solve problems is a critical skill in all undergraduate engineering curricula. Students' capacity for problem solving is complicated by the fact that higher level reasoning skills, including the capacity for abstraction, are not innate in a person until the mid-twenties or later. The results of an exploratory study that looked at students' episodes of reasoning when solving problems in a sophomore level electrical circuits course are presented. Students' problem solving attempts are analyzed using the representation mapping framework developed by Hahn and Chater that is based on store representations of knowledge and how they are applied. This framework distinguishes between similarity and rules-based cognitive processes, and accounts for memory-bank, rules-based, similarity-based and prototype types of reasoning. Students were asked to think aloud when solving specific problems selected by the course instructor. The interviews were recorded, transcribed, and analyzed in detail to identify the types of reasoning and the degree of abstraction in the students' problem solving attempts. This study demonstrated that representation mapping is useful framework for studying students' problem solving skills in electrical engineering**.

***Keywords—abstraction, engineering curriculum, problem solving.***

## I. Introduction

Many of the critical skills that industry is asking for in engineers relates to their ability to solve complex problems. When engineers start working in industry, companies are expecting them to work on problems with solutions that require the application of knowledge from different domains [1]. Proficient problem solvers are highly valued by an industry that looks for engineers to attack problems involving technological challenges and resource sustainability [2,3]. To prepare students for a career in engineering problem solving, educators must adapt the curriculum in terms of its structure, contents, learning attributes, learning tools, and assessment methods [4]. It has long been recognized that undergraduate engineering curricula that rely on traditional pedagogical techniques often fail to encourage deep-learning of the content or go beyond simple short-term memorization thus failing to fully develop students' problem solving capabilities [4]. Many researchers and curriculum developers have worked on designing curricula based upon constructivism and experiential learning principles to better prepare future engineers for the modern engineering workforce [5,6,7,8,9]. They have considered problem solving as the most authentic and relevant learning activity that a student can be engaged in [10, p. xvii].

However, when considering undergraduate engineering students and curricula, problem solving is complicated by two issues:

- Many theories of human development hold that high-level reasoning and abstraction skills are not reached until one reaches the mid-20s or later [11]. This is after students have completed the undergraduate curriculum.
- The process of problem solving for some problems in the undergraduate curriculum require the ability to abstract a specific problem to a more generalized one, and then translate the results from the generalized problem back to the specific one.

We hypothesize that many undergraduate engineering students do not have fully developed reasoning and abstraction abilities (i.e., their *cognitive supply* is not fully developed), and that there may exist in some undergraduate engineering curricula a point at which the disciplinary content and its associated problems have a *cognitive demand* that exceeds the students' current capacity for abstraction.

In our experience over two decades teaching undergraduate electrical engineering course, we have observed that students who successfully solve complex problems hold multiple abstractions in their mind, manipulate them, and apply rationales to determine which abstraction is valuable when approaching a specific problem. We define *abstraction* when solving a problem as the ability to consult multiple similar scenarios stored in the mind, extract relevant features, and apply conclusions about them to the problem at hand [12]. Moreover, we define *abstractness* as the degree of abstraction present in the way in which a person stores relevant knowledge about a problem.

The overall goal of our project is to assess the cognitive demand of the problems being posed to them as they progress through an undergraduate electrical engineering curriculum and the cognitive supply students bring to problem solving. *Cognitive demand* may be defined as the level of thinking required of students in order to successfully engage with and solve a specific problem [13]. It includes the definition of the operations to be completed during a problem-solving episode. For example, *Bloom's Taxonomy* has been used as a tool for characterizing the cognitive demand of problems [14]. We are still in the process of formulating our method for assessing the cognitive demand of problems. *Cognitive supply* represents the mental processes that students bring to a problem solving episode. In this paper, we present the results of a preliminary study that assessed the cognitive supply of students when solving problems in a sophomore circuits course for electrical engineering majors. The cognitive supply is assessed using the representation mapping framework developed by Hahn and Chater [15]. The sophomore year is a critical period for engineering students because research has shown that about two-thirds (perhaps as much as 90 percent for cognitive skills) of the gains college students make in reading, math, science, the social sciences, and cognitive skills occur in the first two years of college [16].

## II. Framework

### A. Problem Solving in Engineering

Many researchers have described various models to explain the process of problem solving, factors that have impacted the performance of problem solvers, and problem solving contexts. Much research has focused on the differences between expert and novice problem solvers. Experts have been shown to be four times faster when solving problems, spend more time in representing the problem, exhibit different approaches when solving a problem, organize their knowledge and information differently, and demonstrate a larger chunking of information than novices [18,19,20]. While experts are better problem solvers, their approaches do not necessarily transfer to novices due to the cognitive demand of their strategies [21].

In the beginning of the undergraduate curriculum, engineering students have limited experience solving problems and tend to access information stored in memory in one piece instead of using a more systematic or organized approach [22]. While some strategies may help students alleviate the cognitive demand of problem solving, such as problem decomposition, students may apply them inappropriately, leading to poor performance. Several researchers and developers of curriculum have attempted to improve problem solvers' performance by promoting awareness of performance errors and personalizing instruction [23]. Other researchers have focused on the search for a clear and concise statement of the problem along with the effective generation, selection, and implementation of alternatives in order to facilitate problem solving [24].

Hahn and Chater [15] propose a distinction between rule- and similarity-based cognitive processes, in terms of how the representation of stored information is matched with the representation of a new item. They use this to describe four types of reasoning based on the abstractness in the representations of knowledge and type of cognitive process being used when solving a problem. We choose the Hahn and Chater framework to analyze students' problem solving episodes because it had features consistent with our observations of students' capacity for abstraction when problem solving. In the remainder of this paper, we describe the representation mapping framework of Hahn and Chater and present preliminary results of its application to student problem solving episodes in a sophomore level circuits course.

### B. Representation Mapping Framework of Hahn and Chater

During problem solving, cognitive supply is related to the mental representations that maybe described using cognitive processing models based on how knowledge is organized and accessed [15,25,26]. Many researchers in the area of cognitive psychology have identified two long-standing traditions in cognitive processing, rules-based and similarity-based. Rules-based cognitive processing suggests that mental activity involves facts applied to specific cases [27,28]. On the other hand, similarity-based theories claim that cognitive processing occurs when comparing problems with stored past problems [15,25,26].

The framework of Hahn and Chater [15] is based on representations of knowledge and the distinction between rules-based and similarity-based cognitive processes. As shown in Figure 1, this results in four types of reasoning based on representations of knowledge and the cognitive processes applied to that knowledge.

| | Partial matching (Similarity processes) | Strict matching (Rules processes) |
|---|---|---|
| Difference in abstractness between stored knowledge representation and new instance representation | ***Prototype reasoning*** | ***Rule-based reasoning*** |
| No difference in abstractness between two representations | ***Similarity-based reasoning*** | ***Memory bank reasoning*** |

Fig. 1. Representation mapping model by Hahn and Chater [15].

A "representation" of knowledge is a description of how a student organizes ideas and concepts. When a student is solving a problem, there is an initial representation of knowledge that they bring to the problem, and a final representation of knowledge when the problem solving episode is finished. In Figure 1, the vertical axis represents a measurement of the difference in the degree of abstraction between the initial and final representations of knowledge. Therefore, if a student demonstrates either prototype reasoning or rules-based reasoning, then they have a final representation that is significantly more (or less) abstract than the initial representation. A student demonstrating either similarity-based or memory bank reasoning has initial and final representations with little difference in the degrees of abstraction.

The distinction between rules-based and similarity processes is based on whether or not knowledge representations are being strictly matched (rules-based) or partially matched (similarity-based). In rules-based processes, existing knowledge is stored as rules. If the antecedent of a rule is satisfied, then the category in the consequent applies. The *matching is strict.* In similarity-based processes, knowledge is stored as a set of past instances with category labels. The *matching is partial* and a matter of degree, and representations of the new instance and the existing knowledge that it is compared to are *equally specific.* We now present some preliminary results of the use of the Hahn and Chater framework to analyze students' problem solving episodes.

## III. Research Method

The purpose of this preliminary study was to determine whether the representation mapping of Hahn and Chater could be successfully applied to students' problem-solving attempts in a sophomore-level electrical circuits course. In this study, participants were interviewed while they were solving problems using a talk-out-loud protocol. Interviews were audio recorded and the students' problem solutions were recorded using a LiveScribe pen. The audio and LiveScribe recordings were then analyzed using the Hahn and Chater model [15].

### A. Couse Selection

The course selected for this study was Electrical Circuits I. It is a sophomore course of the undergraduate electrical engineering degree program at the institution where the study took place. The purpose of the course is to introduce students to electrical engineering circuit theory: Kirchhoff's law, circuit analysis theorems, transients in circuits with resistors, capacitors and inductors, and sinusoidal steady-state circuits. We selected this course based on its content as much more abstract than basic courses of physics as part of the electrical engineering curriculum. Therefore, it might be a course where the cognitive demand of the material is higher than the cognitive supply of the students.

### B. Participants

Participants were recruited from a traditional, large-sized university in the Midwest United States. A total of six students enrolled in the course during the fall 2014 semester volunteered to participate in the preliminary study. They were identified as sophomore, and the average age was 20. The participants were informed in detail of the purpose of this study during the recruitment process, and they signed the IRB-approved informed consent form before starting the process of data collection. Participants who completed the interview process were given a $20 electronic gift card.

### C. Data Collection

We asked the instructor of Electrical Circuits I to select and provide two problems of the test and one additional problem from the course as indicator of the students' understanding of the material as part of the curriculum of the class. The problems were identified as problem #1, #2, and #3 (see Fig. 2). Because of the exploratory nature of the research, we conducted semi-structured interviews with the participants. The advantage of this kind of interview is its adaptability: researcher may obtain more information than a structured survey, thus allowing the researcher to clarify vague thoughts [29].

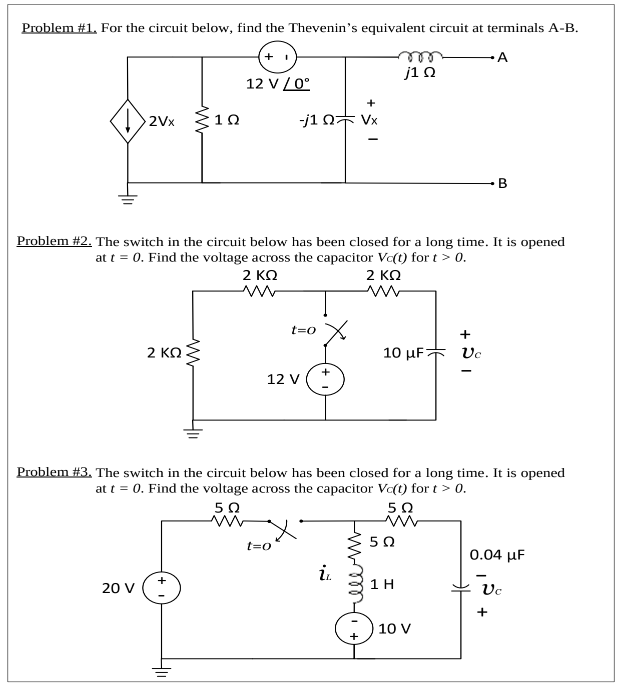


Fig. 2. Problems of Electric Circuits I used in the study.

The protocol of the interview chosen for this study was developed by the researcher in collaboration with a colleague who had previously used similar protocols for studies of Chemistry students. Interviews were conducted using a LiveScribe pen to simultaneously capture hand-written solutions and spoken explanations. The items of the interview protocol were designed to elicit the thinking process when solving problems. Below some examples used in the interview:

- *What are the things you first noticed about the problem?*
- *What was your first approach to solving the problem?*
- *Can you walk me through and explain each of the things you did and your thoughts as you were solving this problem?*
- *What was the most difficult part of this problem?*

The instructor of the course was interviewed before students took the exam. The instructor discussed the major ideas and concepts involved in each of the problems that were used for this study, and how a proficient student would be expected to solve the problems. Participants were interviewed within 1 week after taking the exam. They were asked to solve the problems and to verbally explain (think aloud) their thoughts while solving the problems.

### D. Data Analysis and Findings

When the participants finished solving the problems from the test and the additional problem, the interviews were transcribed, segmented, and coded. The researcher and a postdoc research associate verified the data-coding process in order to ensure the inter-rater reliability. The postdoc was also trained in the IRB process and the protocol of this study. Problems were coded and evaluated according to the following steps:

a) We assessed the cognitive supply of the participants by analyzing the episodes of reasoning in their problem solving attempts.
b) We decomposed the structure and logic of the episodes of reasoning in order to identify any cognitive process of the participants (similarity- or rules-based reasoning).
c) We decomposed the structure and logic of the episodes of reasoning in order to identify any level of abstraction used by the participants (from no abstraction to abstraction).

After the steps described above, the researcher identified the participants' reasoning in the representation mapping quadrants (see Fig. 1), from (1) memory-bank to (2) rules-based reasoning, and (3) similarity-based to (4) prototype reasoning. The representation mapping framework served as a reference to identify the students' processes and degree of abstractness during problem-solving activities. The differences between similarity and rules process is whether the matching is "partial" or specific for similarity, or "strict" and not specific for rules. Regarding the abstractness, if during the process of solving the problem there is a large difference in strict matching between the stored knowledge and the new instance representation, then the type of reasoning is rules-based. If the difference is in partial matching, then the type of reasoning is the prototype. If the difference is small or no difference between the stored knowledge and the new instance representation, both have low levels of abstractness (low/low) or high level of abstractness (high/high).

For the purpose of this preliminary study, three problems of three different participants were reported. Participants were randomly identified as students X, Y, and Z. For each participant, we recognized characteristics that appeared to differ in terms of reasoning process and degree of abstractness. First, we wrote a summary of the interview in order to identify relevant aspects to be considered during the analysis. Second, we identified the stored knowledge, new instance representation, and actions taken by participants. Third, we identified the type of matching and reasoning. Below the results of the three problem solving approaches.

Student X, problem #1, Figure 3:

Summary:

*He started by noticing what the problem was asking to find the Thevenin equivalent circuit. He stated explicit features of the problem. Then, he recalled the steps of how to find the Thevenin impedance $Z_{TH}$ shorting the voltage sources and trying to find the impedance between the terminals A and B. At this point, he had to figure out how to find the $Z_{TH}$, identifying explicit aspects of how to simplify the circuit. He recalled the concepts of impedances in series and parallel. He also recalled how to mathematically operate impedances in phasor and rectangular forms, and found the value of $Z_{TH}$. To find the Thevenin voltage $V_{TH}$, he recalled the procedure of how to find the short circuit current, $I_{SC}$. After that, he decided to use mesh analysis to find the value of $I_{SC}$. He identified some explicit features of how to deal with current sources in mesh analysis and recognized the value of the current $I_1$ in terms of the dependent voltage source. The value of $I_3$ is the same as $I_{SC}$. He applied Ohms' law and found the value of $V_{TH}$.*

Stored knowledge:

- Theorem of Thevenin equivalent circuit.
- Circuit analysis technique: mesh analysis.
- Ohm's law and series/parallel impedances simplification.

New instance representation:

- Noticed explicit features and numeric values stated in the problem.

Actions:

- Applied stored knowledge about Thevenin equivalent circuit.
- Applied mesh analysis to find unknown values in the circuit.
- Applied series/parallel impedances simplification
- Applied Ohm's law.

Strict matching:

- Recognized this problem as a case of finding the Thevenin equivalent circuit.
- Determined specific numerical values needed to find the solution.
- No need to discard any extraneous information.

Abstractness:

- Low/low, rules-based reasoning.

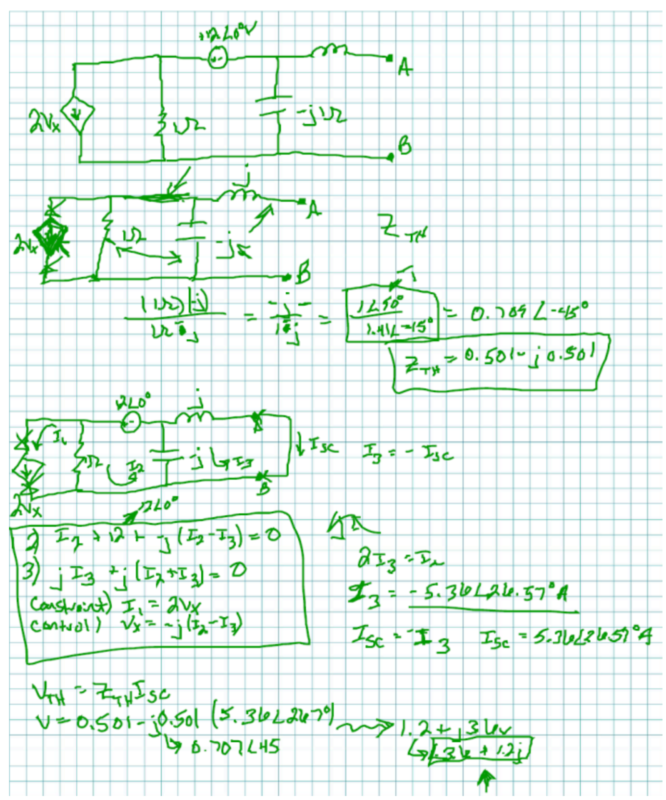

Fig. 3. Solution of student X to problem #1.

Student Y, problem #2, Figure 4:

Summary:

*He started by noticing that this is a problem related to capacitors. He stated explicit features of the problems redrawing the circuit. He recalled the behavior of the voltage across the capacitor $V_C$ at steady state, and when closing/open the switch. He said the value of $V_C$ was the same of the voltage source at $t = 0^-$ and $t = 0^+$. He performed similar steps in finding the $V_C$ at steady state (infinite) stating that the capacitor is acting as an open circuit with no current and the value of $V_C$ dropped to zero volts. After that, he recalled the formulas to find the value of the time constant of the circuit and the values of A and B. Finally, he stated the equation of the $V_C$ as a function of time.*

Stored knowledge:

- Capacitor's behavior in RC circuit as function of time, time constant (first order circuits).

New instance representation:

- Noticed explicit features and numeric values stated in the problem.

Actions:

- Applied stored knowledge about capacitors to find the initial conditions of the circuit, time constant, and the value of $V_C$ as function of time.

Strict matching:

- Recognized this problem is a first order RC circuit.
- Determined specific numerical values needed to find the solution.
- No need to discard any extraneous information.

Abstractness:

- Low/low, rules-based reasoning.

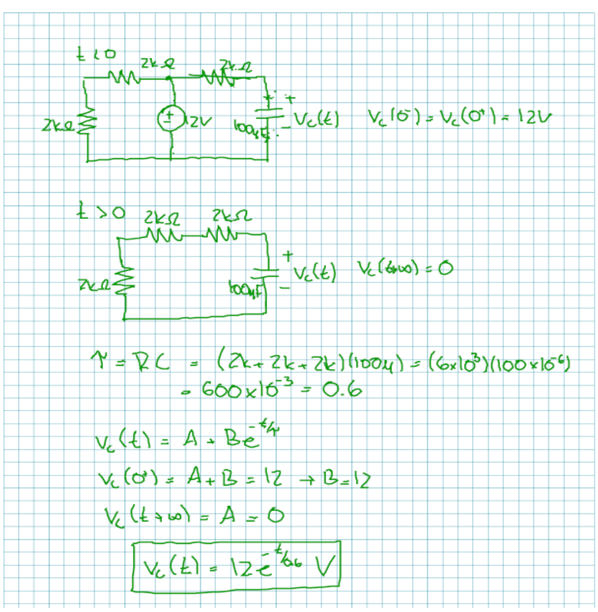


Fig. 4. Solution of student Y to problem #2.

Student Z, problem #3, Figure 5:

Summary:

*He started by recalling that he needs to work on finding the initial conditions for the voltage in the capacitor $V_C$ and the current in the inductor $i_L$. He said that, for $t < 0$, the capacitor will be open circuit and the inductor will be a short circuit. He identified some implicit features, and started redrawing the circuit. Then, he applied Ohm's Law and Kirchhoff's voltage law to find the values of $V_C$ and $i_L$. After that, he identified some implicit features in the circuit and mentioned that it was easier than the analysis for $t > 0$ because there is a simple circuit. He applied the same concepts for the capacitor and inductors as open and short circuits in order to find the values of $V_C$ and $i_L$. He noted the changes in polarity for $V_C$ and $i_L$. Then, he recalled the formulas to find the values of alpha "α" and omega "ω". With these results, he started reasoning that this was the natural response of the circuit and he identified the circuit as a "critical damped". He wrote again the values of $i_L$ for $t = 0^+$ and infinity and related them with the constant values $A_0$, $A_1$, and $A_2$ of the equation of $i_L$. Then, he applied Kirchhoff's voltage law in the circuit. He derived the equation of $i_L$ and evaluated it for $t = 0^+$ in order to arrive at another equation based on $A_0$, $A_1$, and $A_2$ because these are the values needed to find and complete the equation of $V_C$ and $i_L$ as a function of time. After applying mathematical calculations and solving the equations for $A_0$, $A_1$, and $A_2$, he found the values of $V_C$ and $i_L$ as a function of time.*

Stored knowledge:

- Capacitor and inductor behavior in RLC circuits as function of time (second order circuits).
- Different techniques to analyze a circuit depending of its configuration, Kirchhoff's voltage law.

New instance representation:

- Noticed explicit and implicit features and numeric values stated in the problem.

Actions:

- Applied stored knowledge about capacitor and inductor to find the initial conditions of the circuit, natural response, and the value of $V_C$ and $i_L$ as function of time.
- Applied Kirchhoff's voltage law.
- Applied techniques of derivation.

Strict matching:

- Recognized this problem is a RLC second order circuit.
- Determined specific numerical values needed to find the solution.
- No need to discard any extraneous information.

Abstractness:

- High/low, rules-based reasoning.

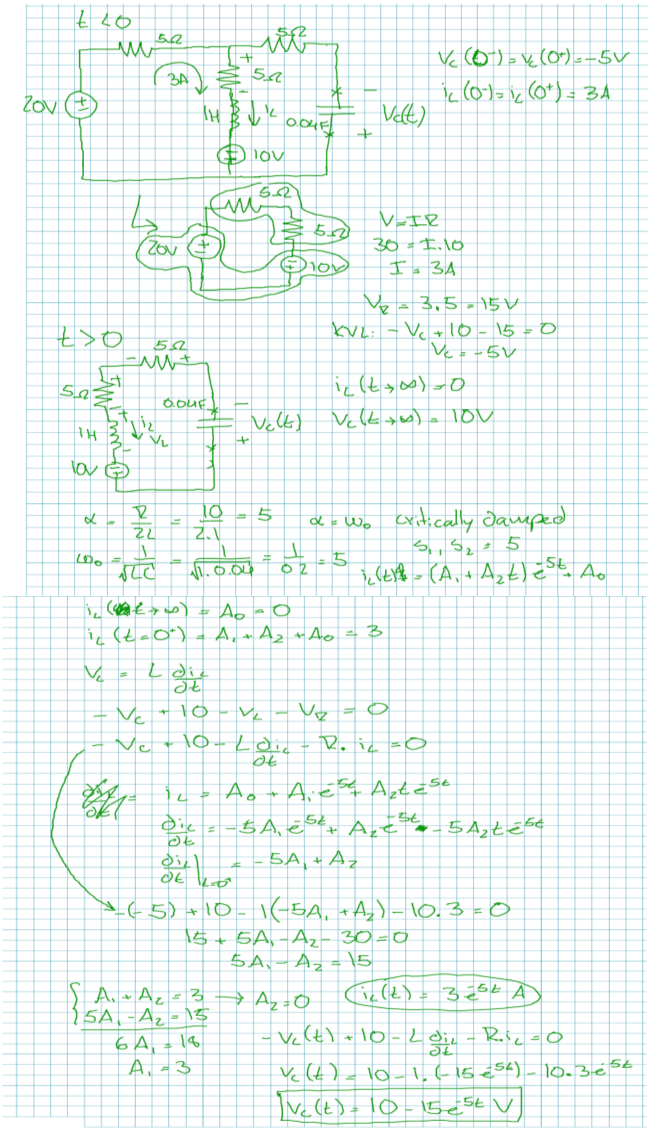


Fig. 5. Solution of student Z to problem #3.

Student X solved the problem using rules-based reasoning because he remembered several rules of the analysis of electrical circuits and focused on a specific instance in every step before finding the solution. His stored knowledge consisted of the steps in finding the Thevenin voltage and impedance. He made a common mistake in the process of finding the solution because he treated the dependent current source $2V_X$ as an independent source. The representation of the concepts that he remembered were used in a strict matching manner: for Thevenin's voltage, open the terminals *A-B* and find the open-circuit voltage and, for Thevenin's impedance, short voltage sources and open current sources to find the equivalent impedance from the terminals *A-B*. Similarly, student Y solved the problem using rules-based reasoning. His stored knowledge consisted in recalling the behavior of RC circuits. He used strict matching of the concepts: find the initial conditions before and after opening the switch, and find the constants of the equation for the voltage across the capacitor $V_C$. Student Z also solved the problem using rules-based reasoning because he remembered several rules for the analysis of RLC circuits and focused in specific instances related to the inductor (L) and capacitor (C). Similar to student Y, he used strict matching of the concepts: find the initial conditions for L and C before and after opening the switch, and find the constants of the equation for the voltage dropped in the capacitor $V_C$ and the current across the inductor $i_L$. He noted some implicit features realizing that the problem was more abstract than his stored knowledge. He had to identify that the circuit was "critically damped" and then go forward and backward in order to find the constants $A_0$, $A_1$, and $A_2$ to complete the equation of the current $i_L$.

## IV. Conclusions

The purpose of this preliminary study was to determine whether or not the representation mapping framework of Hahn and Chater could be applied to analyze students' problem-solving attempts in a sophomore-level electrical circuits course. In the examples given in this paper, we were able to characterize the different types of reasoning used by students as they solve problems in sophomore level circuits course. We have identified that some students use abstraction to solve problems, although they were not necessarily successful at solving the problem correctly. Actually, depending of the type of problem, it is not always necessary to use abstraction to solve the problems proposed by the instructors in Electric Circuits I. Also, we identified that similarity-based and memory bank are the most common reasoning used by students when attempting to solve the problems.

The results of this preliminary study help us develop more clear lines of research. The developers of curricula may identify sets of appropriate problems that require a high level of abstractness and help students in identifying the types of reasoning according to the representation mapping model in order to improve their problem-solving skills. Instructors may focus on how to teach rules-based and similarity-based processes and their associated types of reasoning, and how to approach the problem depending on the type of reasoning that may be applied. We are continuing to collect additional data and analyzing the cognitive demand of the problems being posed in sophomore and junior courses in Electrical Engineering major.

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