



## **Conceptual Understanding of the Electrical Concepts of Voltage and Current: A Pilot Study of a Method to Create Representations of Students' Mental Models**

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## **Introduction**

In any educational activity, it is generally assumed that the ultimate goal is that someone learns something. So, to determine the effectiveness of an educational program, it is necessary not only to choose what things are to be learned, but also to be able to tell whether, in fact, learning has taken place. In this study, I am exploring the development of a method to create representations of individual students' mental models of electrical phenomena. These mental models are internal cognitive structures that individuals use to think about, make predictions, and solve problems involving specific concepts<sup>1,2</sup>. Schoenfeld<sup>3</sup> has demonstrated that it is possible by observation and interviews to discern the mental models used by classroom teachers, leading to a greater understanding of their decision making processes. He then went on to demonstrate that this could be done in other domains as well. My intention in this paper is to apply this idea in the domain of electrical engineering. Specifically, I am using interviews and textual analysis to explore students' mental models of the concepts of voltage and current. I have chosen to study students who are near to completion of an undergraduate course of study in Electrical Engineering (EE), so that they will have had maximum exposure to a course of study designed to produce understanding in this domain. This study will then provide a basis for the use of this method for a larger study exploring the types of mental models that students construct for themselves as they pursue a course of study in Electrical Engineering.

## **Methods**

### **Interview Protocol**

The goal of the analysis of each interview is to develop a representation of the mental model of the concepts of voltage and current held and used by each participant. The mental models literature has shown that, in general, most people are not aware of their own internal mental models<sup>4,5</sup>, and are thus not able to accurately create representations of them. Thus, to ask directly the question, "draw a concept map of the way you think about voltage and current" would not be particularly helpful<sup>6</sup>.

The need for an alternative approach has led to the development of an interview structure that allows the researcher to gather data by observing the working of the participant's mental model indirectly by prompting a general discussion of electrical phenomena and experience. The interview structure consists of asking the same four questions about several of the most common types of components used in electrical design: resistors, capacitors, inductors, diodes, transistors, and op-amps. The questions for each component are of the form:

1. What is it?
2. What does it do?
3. How does it do that?
4. How would you use it to solve design problems?

This structure is based on the four kinds of knowledge described by Schoenfeld<sup>3</sup> in *How We Think*. He defines these kinds of knowledge as:

1. Facts, or isolated pieces of knowledge – These can be definitions, formulas, physical laws, etc. (i.e., “knowing that”),
2. Procedural knowledge, how to do things – Following protocols or algorithms, such as how to solve a quadratic equation (i.e., “knowing how”),
3. Conceptual knowledge, the intellectual rationales that explain how things fit together and why things work the way they do – Cause and effect relationships, interaction of physical properties (i.e., “knowing why”),
4. Problem solving strategies, also known as heuristics or rules of thumb for solving problems – Specifically, knowing which methods or rules should be applied to specific problems (i.e., “knowing when”).

In discussing the various components that form the overall structure of the interview questions, the participant will of necessity need to use ideas that reflect their understanding of the concepts of voltage and current from several perspectives: definitional, functional, underlying principles, and application to solving circuit design problems. By not posing specific design problems to be solved in a “think aloud” format, the discussion can be more free-ranging and focus on principles, rather than the specifics of a particular problem.

### Data Analysis

Each individual transcript is read in its entirety to get an overall view of the participant’s modes of expression. Then, instances of the usage of key terms (e.g., voltage, current, power) are analyzed by the ways in which they are used, both grammatically and conceptually. The codes used, shown in Table 1, are based on the grammatical usage of the word in the sentence.

**Table 1. Coding by grammatical usage**

<b>CODE</b>	<b>Meaning (Usage of key word)</b>
ADJ	Used as an adjective
ADO	Used as an appositive to a direct object
DO	Used as the direct object of a transitive verb
PA	Used as a predicate adjective to a “being” verb
PADJ	Used in a prepositional phrase that is used as an adjective
PADV	Used in a prepositional phrase that is used as an adverb
PN	Used as a predicate nominative to a “being” verb
SB	Used as the subject of a “being” verb
SI	Used as the subject of an intransitive verb
ST	Used as the subject of a transitive verb

Table 2 below shows a sample of the grammatical analysis, in which each occurrence of a key word (such as voltage) is analyzed by how it is used in a sentence, what other words it is related to, and the context.

**Table 2. Sample Word Usage Analysis.**

Item	Form	CODE	Usage	Context	Comments
1	voltage	DO	Direct object (DO) of "drop"	"It (a resistor) can be used to drop voltage".	Agent: resistor
2	volts	DO	DO of "use"	"we'll just use 5 volts dc. "	As a quantity Agent: We
3	voltage	ADO	Appositive to value, DO of "jump up to"	"the line will jump up to that pull up resistor value, The voltage on the other side of the resistor, here (pointing)."	voltage as a property of a point. Agent: line
4	volts, potential	PADV	"as in zero volts" modifies "floating"	"It's floating above earth ground as in zero volts or zero potential."	Explaining zero volts as at a reference point. Equated to "potential."
5	volts, potential	PN	Predicate nominative to "a floating ground"	"So, a lot of times, it's considered zero voltage or zero potential on ground, but that's not always the case depending on how you are looking at it."	Explaining a floating ground
6	potential	PA	Predicate Adjective (PA) to "Energy," i.e., an adjective modifying energy.	"Energy itself is, can be kinetic or potential, so in terms of a capacitor, it stores potential energy"	
7	voltage	ADJ	adjective modifying "difference", as a P.N. to "charge"	"charge itself in a capacitor is generally a voltage difference across a capacitor."	"voltage difference" is equated to "charge difference"

Then, statements are analyzed at the conceptual level. Some statements are directly definitional, stating what something is (in the view of the speaker) such as:

- “Voltage is the amount of energy that electrons have”
- “Current itself is the measure of how many electrons are moving at a given time.”

Frequently, synonyms are used, that is, terms are used interchangeably, indicating they are viewed as being essentially the same thing. For example, “Zero voltage or zero potential on ground”, indicates that voltage and potential are seen as equivalent. When used as a noun, is the concept something that acts, or is acted upon, or both? In either case, what verbs are used to express this action? Some examples of this include:

- “A resistor can be used to drop voltage”, i.e., voltage is something that can be “dropped”.
- “I have used resistors to limit current”, i.e., current is something that can be “limited”.
- “On an oscilloscope, you’re watching how voltage moves”, i.e., voltage is capable of moving.
- “It’s the current that kills you.”

When a term is used as an adjective, the kinds of things that it can modify illustrate the relationship between those things. In this category, we have things like voltage followers, voltage roll-off, and voltage protection (do you need voltage protection if it’s the current that

kills you?). On the other hand, when a term is used as a noun, what kinds of adjectives can modify it? Is it something quantifiable (High voltage, low current, reverse voltage, etc.)?

“How much current is present;”

“We can measure the voltage;”

Finally, how do the concepts being discussed relate to each other in the context?

“Power itself, it’s both the combination of voltage and current,  $P = E \cdot I$ ”

“You need both your voltage and your current there to move electrons to do work.”

Results from the above analysis are then used to construct a concept map (CMAP), which is a pictorial representation of the concepts that shows their characteristics (e.g., definitional, functional) and their relationships to other concepts<sup>7</sup>. The goal of each concept map is to come as close as possible to a representation of the structure and functionality of the internal mental model of the concepts that is held by the participant.

### **Pilot Study Participants**

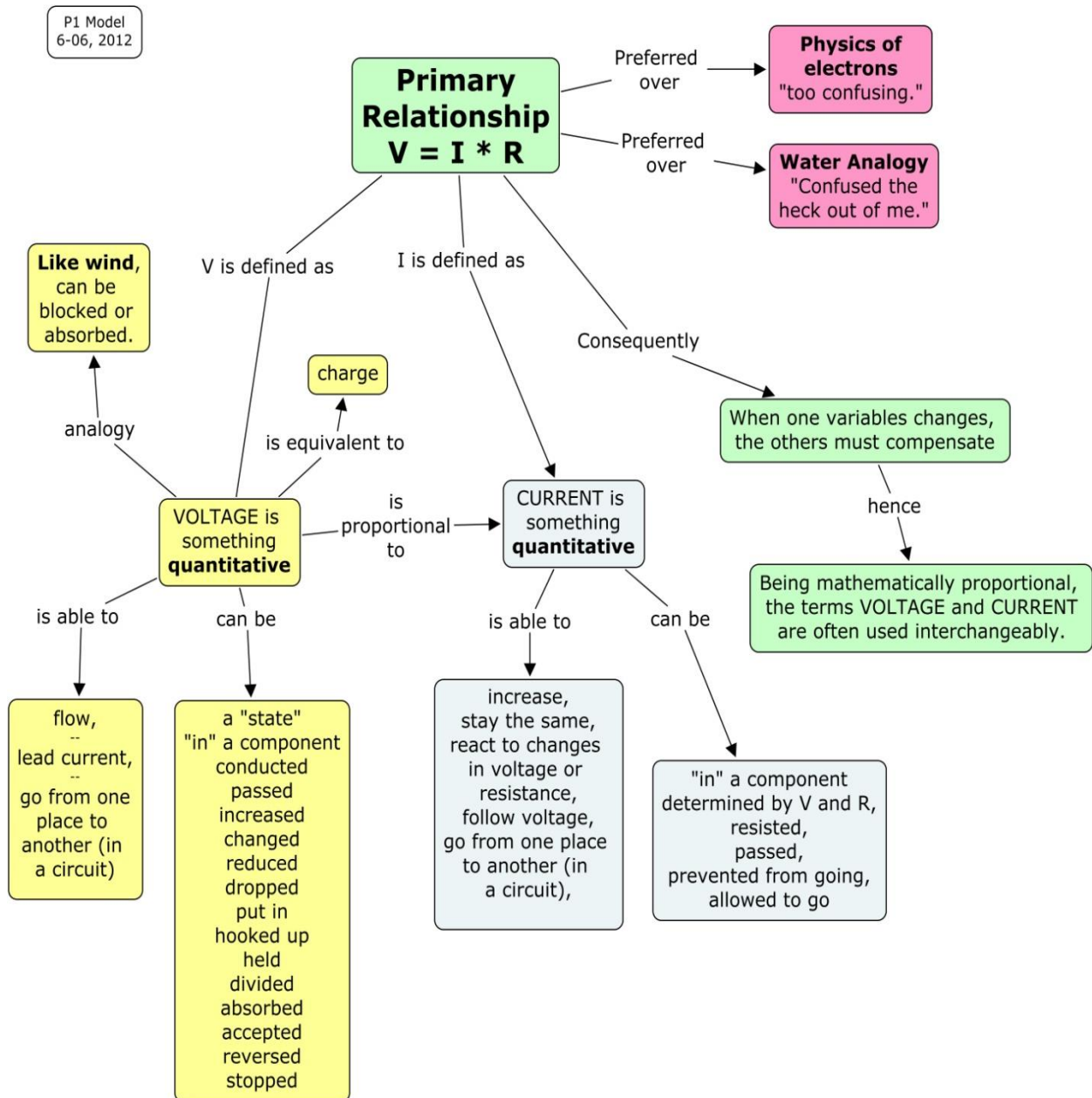
To test the method proposed above, two students with very different characteristics were chosen for this pilot study. Participant P1 was a non-traditional student who had struggled over several years to reach senior status, occasionally needing to repeat courses due to poor performance. Participant P2, on the other hand, was a top performing traditional student who took heavy course loads and achieved a high GPA. Since the time of the interviews, both have graduated and are employed in engineering positions.

## **Results**

### **P1’s Mental Model**

The concept map representation of P1’s mental model is shown in Figure 1. The focus of P1’s model of voltage and current is through the mathematical relationship,  $V = I \cdot R$  (where  $V$  = voltage,  $I$  = current, and  $R$  = resistance), or its permutation,  $I = V / R$ . The three variables in the equation are treated as mathematical quantities, with no direct reference to anything physical. Thus, in the first equation, when  $V$  changes,  $I$  must change proportionately; but in the second equation, if  $I$  increases, then  $V$  must increase and  $R$  must decrease. P1 states that this only works some of the time, but P1 does not know what to do when it does not. The terms “voltage” and “current” are often used together, with the idea that they do essentially the same things, so they are effectively interchangeable. However, P1 does make one distinction in the case of a diode, in which voltage and current are seen to do essentially the same things (flow, or be stopped), but in opposite directions. Another difference is that while voltage can be put in, or hooked up to a circuit, the current usually follows the voltage. Voltage and current are quantities that can be increased, decreased, or divided; but they can also move around in a circuit by being conducted or passed. P1 does not relate voltage or current directly to any physical phenomena. P1 states that when instructors tried to explain electricity in terms of electron flow, P1 rejected it as too confusing. P1 similarly rejected the analogy to water flow, also as being too confusing.

**Figure 1. CMAP of Student P1's Mental Model.**



**P1:** “When I first started, and learned about this, they explained it (electricity) as water going through a valve. But that confused the heck out of me, so I quit thinking about that one. And then they tried to equate that to also electrons and electricity and I was like ‘Don’t do that, I don’t get it.’ So I quit thinking about that because it was just too confusing.”

Having rejected these two views, P1 has chosen to view voltage as something quantitative that can be manipulated. It can be “in” a component, or it can be moved or changed. It can be conducted, passed, increased, reduced, dropped, etc. Also, acting on its own, it is able to “flow” from one place to another. The one analogy that P1 does find useful is that voltage is like wind (air flow), with resistance being like a screen that can block or absorb some of the wind, only allowing some of it to pass through. Current is able to do many of the same things, such as go from one place to another in a circuit, increase, stay the same, or follow the voltage. Since voltage and current appear in the equation  $V = I * R$ , they are treated as being essentially the same thing, with R being little more than a proportionality constant that determines the quantitative value. As a result, the two terms, voltage and current, are regularly used interchangeably as representing essentially the same thing.

The action of the other passive components (capacitors and inductors) is not understood in any physical sense, but can only be used by mathematical transformations that convert them into forms resembling resistance.

## **P2’s Mental Model**

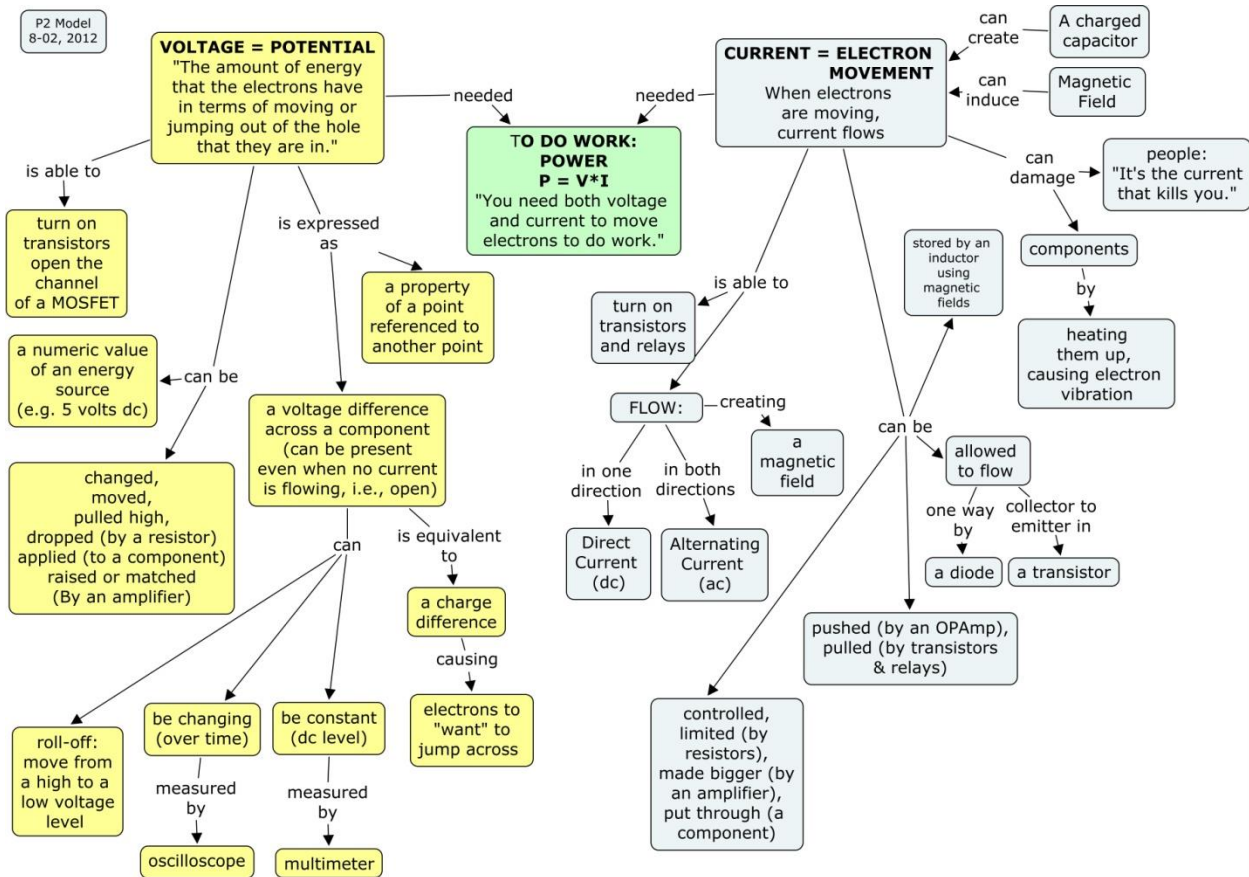
The concept map representation of P2’s mental model is shown in Figure 2 below. For P2, voltage and current are all about electrons and their movement. Electrons are the things that are moving; current refers to the measure of that movement, which is spoken of as a “flow.” This flow can either be in one direction, referred to as dc, or in both directions, called ac. Current can be caused to flow by a difference in charge between two points, with the negatively charged electrons being attracted by the positively charged side of the source. Current can also be induced by a magnetic field, following the “right-hand rule.” Conversely, electron flow will also create a magnetic field by the reverse of the same rule. The magnitude of a current flow is affected by the resistance of the material through which it flows. This resistance is determined by the amount of free electrons that are available in the material. The movement of electrons increases vibrations at the molecular level, resulting in heating of the material. Excessive heating can damage components.

P2 uses the terms “voltage” and “potential” interchangeably because P2 sees voltage as the potential energy that electrons have. This potential can be present even when no current is flowing and can be thought of as a difference in charge between points. When there is a charge difference between two points, the electrons “want” to jump from one of the points to the other and will then flow when a circuit is connected. Voltage is spoken of usually as a difference, but sometimes as the property of a point. But when speaking of it as at a point, P2 then states that this is in reference to some other point, such as ground. Voltage can be a constant, referred to as a “dc level”, such as when speaking of a power source. This level can be measured by a multimeter. Voltage can also vary over time, and this variation, thought of as “movement,” can be viewed with an oscilloscope.

Voltage and current are very closely linked to each other. Applying voltage to a circuit causes current to flow, thus both must be present to move electrons and do work.

**P2:** “Power itself, it’s both the combination of voltage and current,  $P = EI$ , and power is what does work at the end of the day. You need both your voltage and your current there to move electrons to do work. If we don’t have that, then we’re not really getting anything done.”

**Figure 2. CMAP of Student P2’s Mental Model.**



**Discussion**

While both P1 and P2 see voltage and current as related to each other, the differences between their models are striking. P1’s model focuses on the quantitative, mathematical relationship between voltage and current. In this model, voltage and current are seen as being almost the same thing. Both are capable of doing the same things, the main difference being a proportionality in magnitude represented by the factor R. Neither physics nor analogy has a significant place in this model. This lack of connection reduces the usefulness of this model for P1, so that while P1 recognizes that the model is not very effective (sometimes it works, and sometimes it does not), there is no perceived path to overcome the limitations.

In contrast, P2’s model focuses primarily on the physics of electron movement. Voltage and current, while related, are clearly differentiated. Voltage is seen primarily as the potential energy



that electrons have that allows them to move, while current refers directly to that motion. The presence of both is represented as energy, or work being done. As shown in the concept map (Figure 2), the things that voltage and current can be or do are markedly different from each other in P2's model. For instance, voltage can be present across a component even when no current is flowing.

This method was able to identify two very different models of voltage and current. This gives some encouragement that in the application of this method to the larger study, additional model types and variations will be discernible. Interviews have begun for the larger study, and while analysis is not complete, it is already evident that there is a wide range of student models.

## Conclusion

These preliminary results show that this interview protocol and concept mapping analysis can be effective at revealing the thought processes, or mental models, that students use in thinking about voltage and current. This pilot study indicates that applying this method to a larger population of students could advance our knowledge of the varied types of mental models that EE students develop over the course of their studies. The results of the larger study could then be used to impact instructional methods to enhance the development of more desirable student outcomes. The conceptual change literature<sup>8</sup> has shown that students usually come to the educational setting with already constructed "naïve" models of how the world works. These models can be very resistant to change, since they are often based on a lifetime of experience. So to bring about change, it can be much more effective to understand the models that students already have, and then use the features of those models as a foundation from which to guide them in refining, developing, and when necessary, altering their own models. The method presented in this paper could be employed to create a representation of a student's model both before and after instruction to aid in determining what, if any, changes occur as a result of the particular instruction or instructional method that is being evaluated.

In this study, the method was applied in the domain of electrical engineering, but it could also be applied to other concepts in this domain, as well as in other domains. To apply the method, it would be necessary to identify one or two concepts to focus on, sometimes called "key" or "threshold" concepts<sup>9</sup>. Then a discussion could be structured, as here, around aspects of the domain that would facilitate the application of the concepts being studied, guided by the four types of knowledge described by Schoenfeld<sup>3</sup> as discussed above.

## Bibliography

1. Craik, K. *The Nature of Explanation*; Cambridge University Press: Cambridge, U.K., 1943.
2. Johnson-Laird, P. N.; Girotto, V.; Legrenzi, P. (1998). *Mental Models: A Gentle Guide for Outsiders*. Retrieved from <http://www.si.umich.edu/ICOS/gentleintro.html>
3. Schoenfeld, A. H. *How We Think: A Theory of Goal Oriented Decision Making and its Educational Applications*; Routledge: New York, 2011.
4. Johnson-Laird, P. N. *Mental Models: Towards a Cognitive Science of Language, Inference, and Consciousness*; Harvard University Press: Cambridge, MA, 1983.
5. *Mental Models*; Gentner, D.; Stevens, A., Eds.; Lawrence Erlbaum Associates: Hillsdale, NJ, 1983.
6. Heywood, J. *Engineering Education: Research and Development in Curriculum and Instruction*; Wiley-Interscience: Hoboken, NJ, 2005.
7. Novak, J. D.; Canas, A. J. *The Theory Underlying Concept Maps and How to Construct and Use Them*, 2008.

8. Vosniadou, S., Baltas, A., & Vamvakoussi, X. (Eds.). (2007). *Re-framing the Conceptual Change Approach in Learning and Instruction*. Oxford, UK: Elsevier.
9. Meyer, J. H. F., & Land, R. (2006). *Overcoming Barriers to Student Understanding: Threshold Concepts and Troublesome Knowledge*. London: Routledge.