

# **Designing Animated Simulations and Web-based Assessments to Improve Electrical Engineering Education**

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## **Abstract**

Over the past decade, our research group has uncovered more evidence about the difficulties undergraduate students have understanding electrical circuit behavior. This led to the development of an AC/DC Concept Inventory instrument to assess student understanding of these concepts, and various software tools have been developed to address the identified difficulties students have when learning about electrical circuits. In this chapter two software tools in particular are discussed, a web-based dynamic assessment environment (Inductor) and an animated circuit simulation (Nodicity). Students showed gains over time when using Inductor, and students using the simulation showed significant improvements on half of the questions in the AC/DC Concept Inventory. The chapter concludes by discussing current and future work focused on creating a more complete, well-rounded circuits learning environment suitable for supplementing traditional circuits instruction. This in-progress work includes the use of a contrasting cases strategy that presents pairs of simulated circuit problems, as well as the design of an online learning community in which teachers and students can share their work.

## **Keywords**

dynamic assessment, concept inventory, circuit simulation, circuit analysis, animation

## **Introduction**

Students often have specific difficulties understanding basic electricity concepts (e.g., Duit, et al., 1984; Caillot, 1991). One of the primary difficulties students have in learning about and understanding circuit behavior is the *current consumption model*, where current is viewed as a substance that is “consumed” by a device, such as a light bulb or resistor (Reiner et al., 2000). Students may conceive of a battery as a

constant current source rather than a source of invariant voltage (Engelhart & Beichner, 2004). Students may also fail to differentiate between current and voltage, and power and energy (McDermott & van Zhee, 1984). Previous research has primarily been concerned with simple direct current (DC) circuit problems, and this may inadvertently guide one towards instructional decisions that reinforce misconceptions and difficulties students have when learning in other contexts. As part of an Office of Naval Research (ONR) funded project at Vanderbilt University, we extended research of student understanding of electric circuits into the domain of alternating current (AC) circuits. We were motivated by questions such as, to what extent do students exhibit the same misconceptions that they exhibit for DC circuits? How do students interpret time-varying phenomena?

## Student Interviews

In interviews with students working on electrical circuit problems, we found that students had much greater difficulty understanding time-varying phenomena in circuits. We also found that students focused on manipulating formulas and performing numerical calculations during problem solving, and not applying the underlying principles or *invariants*, such as Kirchoff's or Ohm's laws, that govern circuit behavior. Analyzing common student difficulties that we identified, and by studying expert problem solving behavior, we developed a web-based tool (Inductor) for assessing and guiding students' learning of DC and AC circuits. Using Inductor we explored an additional research question: What are the effects of automated, invariants-based feedback on self-assessment and learning of electric circuit behavior? We found that by using this feedback students improved their problem solving performance in a short time, and were able to better explain their understanding of electric circuits.

Our protocol analysis of interviews with students solving circuit problems brought to light a number of difficulties students exhibit in both DC and AC circuit domains (Schwartz, et al., 2000; Biswas, et al., 2001). The misconceptions appeared to fall into three general categories: (i) those specific to particular AC or DC concepts (such as believing an AC voltage varies in space along the wire rather than in time), (ii) general difficulties (such as a failure to differentiate concepts, or incorrect simplifying assumptions when multiple invariants have to be applied to analyze circuit behavior), and (iii) lack of basic circuit knowledge, such as when to apply particular invariant properties and laws of circuit behavior, and in analyzing the behavior of dynamic elements, such as capacitors. We created a list of misconceptions related to understanding AC circuits (Table 1).

Table 1: List of Misconceptions Related to AC Circuits

1. **Spatial AC misconception.** The sinusoidal AC voltage and current waveforms are not a representation of variation of these variables at a point in time. Rather they depict a variation of their magnitudes along the length of the wire in which the current is flowing. For example, students said that a string of identical light bulbs in series when connected to an AC source would light up in sequence, and some of the light bulbs may be on when others are off. At the same instant of time, the brightness of the bulbs would vary depending on their position in the circuit.

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2. **Negative part of AC cycle is just a mathematical artifact.** No current flowing in circuit or power delivered during negative part of AC cycle. For example, a number of students said that a light bulb only lights up during the positive part of the sinusoidal cycle. Others said that there could be “no such thing as negative current. That is just a mathematical artifact. If current reverses, the electrons would reverse direction too. They would then run into each other, stopping flow, which implies there could be no current.”
3. **Alternate form of this misconception.** The negative current "cancels" out the positive current. So bulb will never light up when you connect to true AC source.
4. **Empty pipe misconception.** During AC cycle electrons stop, turn around, and go the other way. In some cases when you have very long wires, they may never reach the light bulb connected to the end of the wire. Students thought that you would need two fuses to provide protection in an AC circuit, where you could do with one in a DC circuit.
5. **Incorrectly importing DC models to explain AC.**
  - Students often surmised that the alternating current going through a resistor was constant in time.
  - Students often hypothesized that a capacitor behaved the same in AC and DC circuits.
6. **Difficulties understanding circuit behavior when AC and DC signals are combined.** Students had difficulty “separating” or recognizing the AC and DC components of a signal in problems in which the midpoint of a sinusoidal voltage was not zero.
7. **More generally, difficulty thinking of circuit behavior when multiple waveforms, frequencies are combined.** Even advanced students stated that the number of channels you can get from cable TV was a function of the number of wires in the cable, or the thickness of the cable.

*General classes of difficulties that are not specific to AC.* (Schwartz, et al. 2000)

- **Failure to differentiate among concepts.** Examples, voltage and current, series and parallel configurations, role of capacitor in DC versus AC circuits.
- **Minimum causality error.** (Incorrect simplifying assumptions). Single change in outcome must be a result of single change in cause. (e.g., a 10W bulb must have greater resistance than a 5W bulb).
- **Overly local reasoning.** Not thinking of global constraints, invariants.
- **Bad framing.** Incorrect generalizations, trouble switching from equations to physical explanations to analogical models.
- **Experiential impoverishment.** Electricity is invisible except for its end products.

*Lack of basic circuit knowledge.*

- **Lack of Ohm's law** (how resistance affects current when voltage is constant)
- **Lack of KCL** (current through all components of a loop must be equal).
- **Lack of KVL** (the voltage drop across components of a loop must sum to zero).
- **Lack of knowledge of the behavior of capacitors** (such as  $C=Q/V$ )
- **Lack of knowledge of Capacitor and Inductor impedance as a function of frequency.**
- **Topographic misunderstanding of the circuit** (e.g. unable to differentiate series from parallel).

## AC/DC Concept Inventory

The catalog of student difficulties had performing circuit analysis formed the basis for the development of a set of multiple-choice questions to assess student understanding with larger groups of students: the AC/DC Concept Inventory (Holton, Verma, & Biswas, 2008). The questions asked for qualitative (not

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quantitative) answers, and unlike traditional multiple choice tests in which only the correct answers matter, these questions have foil responses that are specifically linked to particular misconceptions our group and others have identified. The correct answers to our test questions matter as well, because they are written to specifically target core invariant principles of circuit behavior that experts use (see Table 2 below). We can analyze both correct responses and incorrect responses for information about students' understanding of invariants, their misconceptions and other learning difficulties.

Table 2: AC & DC Circuit Invariants List

<i><b>Invariant</b></i>	<i><b>Description</b></i>
a. Ohm's Law	For resistors, capacitors, and inductors the current through the component is directly proportional to the voltage across the component. The ratio of voltage drop to current is the impedance of the component. For a resistor, the impedance is the resistance value, R. For capacitors (and inductors) the impedance is a function of the capacitance (or inductance) and the frequency of voltage and current.
b. Impedance of a Capacitor	The impedance of a capacitor is inversely related to the capacitance value and the frequency of the source. (Specifically the impedance of a capacitor is given by the expression: $X_C = 1/(2\pi fC)$ , where f is the frequency, and C is the capacitance).
c. Charge held by a Capacitor	The charge held by a capacitor is directly proportional to the value of capacitance, C, and the voltage drop across it. ( $Q = C \cdot V$ ). Another way to express this relation is $I = C \cdot dV/dt$ , i.e., the current through a capacitor is related to the rate of change of the voltage across the capacitor.
d. Impedance of an Inductor	The impedance of an inductor is directly related to the inductance value and the frequency of the source. (Specifically the impedance of an inductor is given by the expression: $X_L = 2\pi fL$ , where f is the frequency, and L the impedance.)
e. Inductor and Flux	The flux held by an inductor is directly proportional to the value of inductance, L, and the current through it. Another way to express this relation is $V = L \cdot dI/dt$ , i.e., the voltage drop across an inductor is related to the rate of change of current through the inductor.
f. Power	To determine the power dissipated by a resistor one has to know at least two of the three quantities for the resistor: its resistance, the voltage drop across the resistance, and the current through it. (Mathematically the power consumed = $V \cdot I = V^2 / R = I^2 \cdot R$ )
g. Kirchoff's Laws of Conservation	<u>Kirchoff's Voltage Law (KVL):</u> Consider a closed loop consisting of one or more components. KVL states that the voltage drops across all elements in the loop at any instant of time must sum to zero. This relation holds universally for any set of components, and is independent of the frequency of the voltage and current. <u>Kirchoff's Current Law (KCL):</u> KCL states that the sum of the magnitudes of currents flowing into a point where a number of components are connected together must equal 0. (Current flowing away from the point is given a negative value). This relation holds universally at any point in time, and is not dependent on the frequency of the voltage and current.
h. Effective resistance	(a) Resistances in Series: The effective resistance of a set of resistances connected in series is the sum of the individual resistances. So in a series combination, the effective resistance always

increases.  
 (b) Resistances in Parallel:  
 The effective resistance of a set of resistances connected in parallel is given by the formula:  $1/R_{\text{effective}} = 1/R_1 + 1/R_2 + \dots$   
 In a parallel combination, the effective resistance is always smaller.

We administered a paper and pencil version of the multiple-choice test to twenty 2nd year electrical engineering students. We found that students had the most difficulty with the invariant principles underlying dynamic elements, such as capacitors (45% correct vs. 62% correct on questions not involving capacitors). Students appeared to have a better understanding of other invariant principles, such as Ohm's law, and applied them more correctly in circuit problems (63%). An analysis of incorrect answers revealed a significant number of misconceptions and difficulties (see Figure 1). Eight of twenty student answers indicated they possessed a current consumption (or "empty pipe") model of current, in which current flows from the positive side of a voltage source (DC or AC) sequentially and is consumed by the components. Five students revealed an "electron flow" model similar to the current consumption model except that flow starts from the negative terminal. Three students revealed a lack of knowledge about the relationship between power (light bulb wattage) and resistance, and six students tended to ignore the role of a capacitor in a circuit altogether. Students had the most difficulty with AC capacitor circuits (or filter circuits). The concepts of power (via bulbs) and the behavior of capacitors would thus later become a focus of the fourth phase of research utilizing an animated circuit simulation.

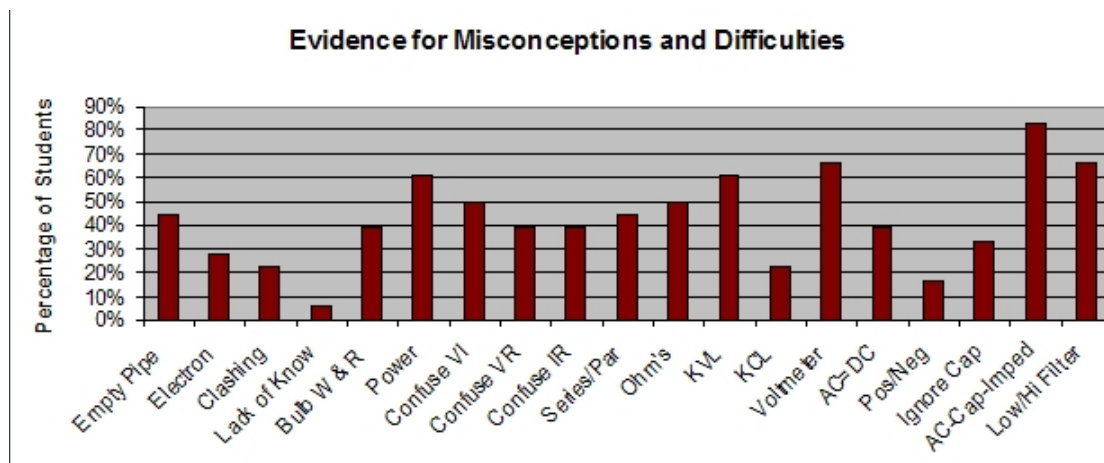


Figure 1: Range of Circuit Misconceptions Seen on Misconceptions Test

The context-dependent nature of students' knowledge of circuit behavior suggests that the difficulties students have in understanding electrical circuits are directly linked to instruction. Härtel (1982) believed that many learning difficulties can be traced to the fact that instruction is done in a piecemeal fashion, and students are never taught how to analyze a circuit as a system with interdependent components and

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constraints on behavior. This plus our own observations led us to develop an invariants-based framework that we believe experts apply in problem solving tasks, and we turned to a dynamic assessment approach (Campione and Brown, 1985, 1987; Bransford, et al, 1987; Magnusson, Templin, & Boyle, 1997) that focuses on how to prepare students to learn through instruction.

## **Inductor: Web-Based Dynamic Assessment Tool**

Inductor was designed to be an online assessment tool in which students answer multiple-choice questions, select the invariant principle best applies to the circuit problem, and finally write an explanation for their answer. What makes Inductor a *dynamic assessment* environment is that students were provided opportunities to learn from outside resources while taking the test. Inductor not only provided instruction for remediating misconceptions, but it taught the invariants technique for circuit problem solving. After choosing the invariant principle involved in a problem and then selecting an answer, a student who is incorrect on either the invariant or the answer receives immediate feedback in the form of expert hints and explanations emphasizing the invariant properties of the circuit in the problem, and links to outside resources such as circuit diagrams and tutorials. Students could look up resources, then revise their answers or choice of invariant principles involved, and finally view a video of an expert explanation for the solution to the circuit problem.

In a related study, Leonard, Dufresne, and Mestre (1996) had physics students describe the principles involved in physics problems and write a justification for their answer. The instructors also discussed problem-solving strategies during their lectures, much like the invariant-based explanations and techniques for problem solving that we present through Inductor. They found that the students who were taught problem solving strategies generated more correct answers to problems, were less-dependent on surface features of problems for selecting the principles that governed problem solving, and better recalled the major principles covered in the course months later. The effort those instructors put into carefully reviewing and grading all the students' writings during the course provided valuable feedback and learning opportunities for the students, but also undoubtedly represented a significant investment of time and effort on the part of the instructors. The Inductor tool made a trade-off by providing automated feedback in the form of hints, expert explanations, and learning resources to students. Our focus was on self-assessment and providing Inductor as a supplementary resource to classroom instruction.

## **Pilot Study with Inductor**

We ran a test study of the Inductor tool using our DC and AC test questions with a small group of first year electrical engineering students (N=6). All students completed two 14 item multiple choice tests using the online Inductor tool. The items in both tests were matched so that they both had the same level of difficulty. We wanted to see if performance improved from the first test to the second test, and also collect evidence for students' improving their explanations of circuit behavior.

## Overall Results from Pilot Study

Overall, the participating students scored an average 61% correct answers on the first test, and 82% correct on the second test, an improvement of 21%. Five of the six participants showed an improvement from the first to second test. As in earlier research our group conducted, we found that students, at least initially, had the most difficulty with problems dealing with capacitors and other dynamic components. In this study, however, by the second test students were performing well in all categories, showing the largest improvement with DC capacitor circuit problems.

### Student Explanations

Students initially revealed misconceptions ("higher resistance means more power is absorbed," "internal resistance rises," "the internal resistance is lower for low frequencies," "John's battery will be required to work harder to push current through the larger resistor"), errors ("after long time, all voltage will be across capacitor," "since they are in series the voltage should be the same across all of the bulbs"), and admitted to making some guesses. The responses of students who received invariants prompts and instruction revealed they more often attempted to revise and correct their misconceptions:

#### Example 1:

- 1<sup>st</sup> explanation: "Since frequency and current are related linearly, and increase in frequency will increase current."
- 2<sup>nd</sup> explanation: "Actually, current and frequency have no relation so current does not change with frequency."

#### Example 2:

- 1st explanation: "More current flows through the bulbs when they are in series. this makes a brighter light."
- 2nd explanation: "More voltage through the bulbs in parallel will make for brighter bulbs."
- 3rd explanation: "Power is what determines the light intensity. More power makes for more intensity."

The students also articulated some of the invariant principles they learned:

- "There is only one path for the current to flow through and both bulbs lie on this path."
- "With low frequencies most of the voltage is across the capacitor since its impedance is high when frequency is low."
- "because the lower resistance in Peter's circuit will result in more power consumption. lower resistance = more power"
- "since it is in series connection, the same resistances and current will produce the same power for all the bulbs.  $p=i^2R$ "
- "when you go from parallel to series, the intensity will decrease since the voltage is split across both bulb 1 and bulb 2."
- "because the lower resistance will need more power."  
"the lower resistance will result in more power being dissipated because  $p=v^2/R$ "

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It was clear that after receiving feedback on invariants, most students attempted to revise and correct their misconceptions.

### **Invariant Selection Analysis**

For each circuit problem, our experts selected and agreed upon the invariants that were most relevant and helpful for solving the problem. They also identified which invariants were clearly irrelevant. The impedance of an inductor, for example, is irrelevant for a circuit with only capacitors. The remaining invariants were placed in a third category. These invariants were technically involved in the circuit's behavior, but were not necessarily useful for solving the problem asked about the circuit. Ohm's law, for example, is involved in many of the circuits used in our tests, but is not always an important one for answering a particular question about the circuit.

We needed a way to quantify how well students selected invariants for a particular problem. In this case a simple percent correct measure is insufficient for characterizing students' use of invariants, and would reward students who select more invariants regardless of their importance to the problem. To control for such response biases, we utilized a nonparametric discrimination measure known as Yule's Q. Nelson (1984) contrasted simple percentage correct measures,  $d'$  measures and Yule's Q, and advocated Yule's Q over  $d'$  on the basis that it was thought to make weaker assumptions about the data and required fewer observations. For our purposes this measure rewards the selection of invariants our experts agreed were appropriate for a problem, while controlling for the selection of clearly irrelevant invariants.

The Yule's Q measure was constructed first by calculating the percentage of invariants a student chose out of those invariants experts chose as relevant ( $h$ , or hit rate) as well as the percentage of invariants a student chose out of those invariants experts deemed clearly irrelevant ( $f$ , or false alarm rate). Invariants that are technically correct but less relevant to a problem were ignored in this computation. The Yule's Q score was then calculated by the formula:  $(h-f)/(h-2fh+f)$ . A Q of one implies perfect discrimination of the relevant from irrelevant invariants, and zero implies chance performance.

### **Results of Invariant Selection Analysis**

The average discrimination of invariants (as calculated by Yule's Q) when a correct answer to a circuit problem was chosen was 0.53. The average discrimination when an incorrect answer was chosen was 0.39. Thus students were more likely to select those invariants that experts deemed relevant on questions they answered correctly.

We found, however, that students' selection of relevant invariants declined from the beginning of the tests to the end. The graphs below reveal this pattern across each of the categories of questions and across both classes. Different explanations may be provided for this pattern of results. One is that the questions grow more difficult from the beginning to the end of a test. Another explanation is a fatigue or indifference factor. Students may have been concentrating only on getting the correct answer to questions, and gradually paid less attention to the invariant selection.

### **Student Survey Responses**

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After completing both tests, students answered questions on a follow-up survey. The students responded that they liked and used the outside resources and the hints we provided after answering incorrectly. One student even suggested, "I was very impressed with the information provided to learn from mistakes. I think that that information should be provided regardless of whether the answer was right or wrong so that if the answer was just a guess I could solidify my understanding."

Students also mentioned they thought the test questions helped reinforce concepts they had learned and better apply what they had learned. When we asked those participants who received instruction on invariants what they believed invariants are and how they are used, the students primarily thought of invariants as a method for solving a problem. When asked what is an invariant, one student responded: "A circuit invariant is a certain method of circuit analysis needed to solve the problems presented.(ex: ohms law, power, etc)." When asked why it is useful to analyze a circuit by considering the invariants, that student also responded: "It gives the student an idea of where to start the problem." Other students also responded: "It lets you know how to solve the circuit and how to solve like circuits in the future," and "It allows one to find and use the necessary method of solution quicker."

## **Problems with Inductor**

We identified certain problems from our tests of the Inductor environment as well. The student participation rate in our pilot studies was low, which we believe was partly due to the fact that use of the tool was not connected to their current class work. We found the outside resources used were not sufficient for addressing many of the difficulties students had in applying invariants to solve problems. Ultimately, Inductor was still primarily a "test", and not an engaging, motivating environment for learning about circuit behavior. We believe that the inclusion of more open-ended challenge problems that include diagnosis and design questions will motivate the students to think deeper and begin to see the importance of understanding how the bridges between invariants help to better structure problem solving tasks. First, however, our focus was on creating a better interactive resources for qualitatively understanding the dynamic behavior of electrical circuits – an animated circuit simulation.

## **The Design of an Animated Circuit Simulation**

As mentioned above, the outside resources used in Inductor to provide feedback to students while they worked on circuit problems were not sufficient. Students still were not given a sense of how particular circuits behave in real-time. This motivated the creation of an animated circuit simulation. An interactive simulation environment may allow students to develop a more "voltage-centered" model of circuit behavior that experts use to understand the flow of current (Frederickson and White, 2000). Also, allowing students to experiment with a simulation will allow them to develop multiple context-dependent interpretations of the invariant laws that govern circuit behavior. Furthermore, from a design perspective, students can explore the role of circuit components by adding and removing them from the circuit, or by

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changing their values in a circuit. By showing an animation of current flow through a circuit in real-time, students can see Ohm's law (voltage equals current times resistance) in action and see the effects of more advanced components like capacitors and inductors on current flow.

This simulation can model DC and AC analog circuits, including components such as capacitors and inductors and transistors. There are two major design features however that distinguish it from existing simulations. One is that current flow is visualized as a single moving chain of dashes to help students understand the behavior of the various circuits they learn in introductory classes. From interviews we found that students knew the mathematical formulas related to circuits with capacitors, for example, but could not answer basic qualitative questions such as what happens in a circuit with a capacitor, light bulb and DC voltage source. Our circuit simulation shows them this behavior. Second, our circuit simulation uses a technique known as *enactive modeling* that allows for manipulating variables in real-time and immediately seeing their effects. Thus for example students can 'wiggle' the voltage and see its effects in a circuit with a capacitor or inductor, thereby helping students induce invariant principles related to the impedance of these components with respect to frequency changes. The enactive modeling strategy is described in more detail below.

## **Enactive Modeling**

Scientists have routinely employed causal and mechanical models to help reason about events and communicate their understanding to other scientists (Salmon, 1998; de Regt & Dieks, 2002; Gooding, 1992), even if they later eschew these models for purely quantitative/mathematical descriptions. James Clerk Maxwell for example used a mechanical-fluid analogy for electro-magnetic fields that may have helped him deduce the quantitative relationships now known and taught as Maxwell's laws (Nersessian, 2002).

Researchers in the learning sciences and cognitive science are beginning to uncover more about the underlying basis for people's natural and informal reasoning about both physical and social events, and why people show a preference for causal and mechanical models. There appears to be a connection between our informal reasoning and the embodied nature of our thoughts and actions. We are beginning to pay attention to the role of one's body and intentional actions ("embodied cognition", "enactive learning") in order to better characterize the contextual constraints involved in natural reasoning about events. This applies to computer simulated events as well. Roth and Lawless (2001) note for example that students' "gestures are an important means in the construction of perception and communication as students interact over and about a computer software environment." They suggest that learning environments that do not support students' use of body and gesture can limit what and how students learn.

Educational researchers have found evidence linking students' kinesthetic behavior to their understanding of dynamic systems. Clement (1994) and Reiner (2000) have found that both students and experts may sometimes "describe a system action in terms of a human action" and use gestures that depict changes happening in a system. They have interpreted these "self-projections" as evidence that a person is mentally enacting or simulating aspects of a system. Monaghan and Clement (1999) observed students

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performing hand motions and visualizations while using a relative motion simulation. Other researchers have referred to these kinds of self-projections as anthropomorphic reasoning (Zohar & Ginossar, 1998) or anthropomorphic epistemology (Sayeki, 1989).

Sometimes these self-projections may even underlie some of the misconceptions students have in science, but they can also be used positively, as a starting point for instruction. Susan Goldin-Meadow and others have found that teachers using gestures or attending to student gestures can make math instruction more effective (Goldin-Meadow, 1999). Physics education researchers have also found that kinesthetic real-time participation is a key component responsible for the success of microcomputer-based labs (MBL) in fostering understanding of physics concepts and graph interpretation skills (Beichner, 1990; Mokros & Tinker, 1987). In MBL activities, students use computers with sensors attached (distance, force, temperature, etc.) to explore the changes that occur in physical phenomena.

### **Enactive Modeling Hypothesis**

Our hypothesis was that these kinesthetic activities are helping foster - yet also constrain - how students “intentionalize” the phenomena about which they are learning. They are connecting their natural, embodied experience of phenomena to the constraints and rules operating in scientific representations of the phenomena, and conversely, abstract scientific concepts are converted into embodied metaphors which students can use. This “exemplifies what we call symbolizing: a creation of a space in which the absent is made present and ready at hand” (Nemirovsky & Monk, 2000). More generally speaking, Roth and Lawless (2002), like Piaget, have argued that gestures can serve as a bridge between our everyday experiences in the physical world and the abstract scientific thinking that is a goal of science instruction.

If anthropomorphic reasoning, gestures, and self-projection help signify students’ understandings and misunderstandings of complex systems, then it is possible that students may benefit by instructional interventions that facilitate and constrain their enactive participation with a complex system. For this research, I explored a new learner-centered simulation design strategy that may be uniquely suited to helping students understand complex changes happening in physical systems – *enactive modeling*.

A simple example of this enactive modeling strategy has been applied in physics education. Students have difficulties understanding how Newton’s third law operates in static situations. Given a situation in which a book lies atop a table, students may recall that gravity pulls the books down, but they neglect the equal and opposite upward force that the table exerts on the book. Various strategies have been used to help students recognize this “passive” force, but an example of an enactive modeling (or enactive participation) strategy is for students to lie down on their backs and hold books up on their hands (Freudenthal, 1993). In a sense the students are enacting the role of the table and can sense that they have to push up harder if more books are added.

With more complex and simulated physical systems, however, determining how to facilitate such participation is more difficult. Most computer-based simulations are *symbolic* simulations, encapsulated representations of an external physical system such as an electric circuit. In contrast, *experiential* simulations are simulations in which the user or learner is a functional element, or agent, in the situation

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or system being modeled. An example of this is Model U.N., in which students from various schools take on roles of different countries in pretend meetings of the United Nations. The question I pursued though is can students learn by participating in simulations of complex *physical* systems as well as social systems. Does enacting the physical and temporal constraints that operate within a system help one understand the behavior of the system as a whole?

## **Enactive Modeling Interface for a Circuit Simulation**

We applied the enactive modeling strategy to the design of an animated simulation of electrical circuit behavior. As mentioned before, electricity is one of the most difficult subjects for students to understand, and there are a great deal of misconceptions about circuit behavior. Particularly difficult are behaviors that change over time, as in alternating current (AC) circuits. In an AC circuit, the voltage changes very quickly, often switching from positive to negative values. Further complicating matters, some circuit elements such as capacitors and inductors respond differently based on the rate of change in voltage or current. A capacitor in an alternating current (AC) electrical circuit exhibits qualities similar to a resistor, a virtual impedance, but unlike a resistor, the impedance of a capacitor varies inversely with the frequency of the AC voltage source. This law of circuit behavior has consistently proved to be one of the most difficult concepts for undergraduate students to learn, and is also very difficult to represent visually or explain verbally to students. Most students may only memorize a formula or a shortcut and never understand how or why a capacitor exhibits this impedance, or how this impedance characteristic is useful for designing or troubleshooting circuits (such as radio tuners), or how it is related to other invariant constraints on circuit behavior such as Kirchoff's laws or Ohm's law.

Imagine there is an interface to a circuit simulation that allows you to directly vary the voltage applied to a circuit, and the circuit responds in real-time. You could alternate the voltage from positive to negative just like an AC voltage source does, with zero voltage being the middle, or resting point. Imagine also that you could both feel the resistance of the circuit (Ohm's law), and see resistance in the form of reduced current flow. A circuit with high resistance would resist your applying voltage, and a circuit with low resistance would be easy to apply voltage. The flow of charge (current) through the circuit would also be visually depicted as an animation, to redundantly specify current and resistance.

A force-feedback steering joystick or steering wheel (commonly available as interfaces for computer games and simulations) may help students embody and understand the constraints of an AC voltage source. One may move the joystick or wheel to the right to increase the voltage positively, and to the left for negative voltages. Instead of setting the frequency of an AC voltage source by entering a numeric value or moving a slider control, students enact a change in frequency by changing how fast they move the steering wheel from side to side. The force feedback component allows one to make the joystick or steering wheel harder to move if there is a higher circuit resistance (or impedance), and easier for lower resistance. In the aforementioned AC capacitor circuit, the law governing how a capacitor's impedance varies inversely with frequency can be experienced directly, by sensing that the steering wheel is easier to move the faster you turn it and current flows faster, and harder to move and current flows slower when turned slowly or held at one position (as in a DC circuit). An inductor circuit component has the opposite relationship with frequency as a capacitor, and when combined with a capacitor may form a tuning

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circuit, in which there is one particular resonant frequency with the lowest resistance, or where the steering wheel turns the easiest.

Two sets of electricity misconceptions identified in earlier research also helped lead to the choice of a joystick or steering wheel for the input device to use with the circuit simulation. One set of misconceptions relates to AC circuits. Students may believe AC voltage varies spatially along a wire rather than temporally. Also, they may not understand what happens to current when voltage is in the negative part of a sinusoidal cycle. Another set of misconceptions concerns the relationship between resistance and current. For example, despite having two resistors instead of one, a parallel circuit can have lower total resistance than a circuit with only one of those resistors in series, and for many students this is counter-intuitive. Students may not even distinguish between voltage and current, and a constant voltage source versus constant current.

## **Pilot Study with Nodicity**

A pilot study tested the use of this animated circuit simulation on individual undergraduate students, and assessed its effects of students' intuitive conceptions about circuit behavior. The study involved a mixed methods experimental design employing both quantitative and qualitative methodologies and analyses. The quantitative component consisted of a 20 item multiple choice circuit quiz derived from other quizzes. Students took the test as a pretest and posttest. The pretest helped show what preconceptions individual students had about electrical circuit behavior coming into the study. After a individual tutorial session with the circuit simulation led by the first author, students took the same test again as a post-test. This revealed how students' conceptions may have changed as a result of instruction. As will be discussed in more detail below, some students used the simulation with a joystick interface to control voltage in real-time, while a second group of students used the simulation with only an on-screen graphical slider control to change voltage. The pretest and posttest measures allow one to quantitatively compare and contrast these two groups of students, to see what effects the joystick had. Furthermore, the students were videotaped during the session while using the computer simulation, capturing the computer screen and interface devices, the student, and the first author (acting as a tutor or guide) for later qualitative analysis. This allows for exploration of any potential links between particular events and actions by the student and myself to specific learning outcomes as measured by the test. With a qualitative analysis of the video, one may see if the students use gestures while using the simulation, and if there connections between what the students said or did and their developing understanding of electrical circuit behavior.

Participants consisted of 40 undergraduate electrical engineering majors recruited from introductory courses. Students were asked to volunteer to try out the animated circuit simulation during a tutoring session outside of class, and were paid approximately \$15 for participation.

The entire tutoring session with each student lasted not more than an hour. This is a very short time for an instructional intervention, however, there were two factors influencing this time decision. One is practical. Few students have volunteered in previous studies even when their only commitment was to take a couple of short quizzes online on their own time. Secondly, the real-time reactive control feature

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this simulation has that allows for controlling voltage over time is most similar in spirit to microcomputer-based labs (MBL), and research on MBL has shown surprising learning gains in very short periods of time. In MBL, students for example might move a car back and forth, while a computer graphed its motion in real-time via a sonic distance sensor. Heather Brasell (1987) has shown marked improvement in younger students' graphing skills after just 40 minutes of instruction, and Linn et al. (1987) show that this improvement asymptotes rather quickly at about the 70% level even after a year of experience with MBL. Abbott et al. (2000) actually have examined the effects of one 2-hour active learning laboratory in electrical circuits (students worked with real bulbs and circuits). They did find some significant learning gains using a pretest and posttest as well.

## **Results from Pilot Study with Simulation**

This study showed significant conceptual change gains, despite the short intervention. Overall, the gains were weak, with only a 12% increase in test scores, however, eight of the twenty questions on the misconceptions test showed more significant and larger gains (highlighted in bright red in Figure 2 and bright green in Table 3). These eight questions did not have any structural characteristics in common. They included questions involving DC, DC capacitors, AC, and AC capacitor circuits. Some of the questions were very similar to the circuits explored in the simulation, and some were not (far transfer questions). What is the connection between the seemingly unrelated eight questions on which students showed significant gains? The connection appears to be that some questions on the test may force one to imagine the behavior of the circuit over time. A post-hoc analysis identified ten questions on the test that involve considerations of circuit behavior over time. Eight of these questions are the same eight questions identified before which showed significant gains. Figure 3 shows performance on these ten time related questions versus the ten which were not time related. As the graph illustrates, students did worse on time related questions on the pretest than non-time related questions (53% vs. 68% correct, respectively). By the posttest, students answered on par in both categories (73% vs. 71% correct). Thus students showed a gain on time-related questions, yet not on non-time related questions. An ANCOVA analysis using the pretest as a covariant showed a difference between the two categories ( $F(1,77)=9.81$ ,  $p=.0025$ ).

### Total Test Scores (N=40)

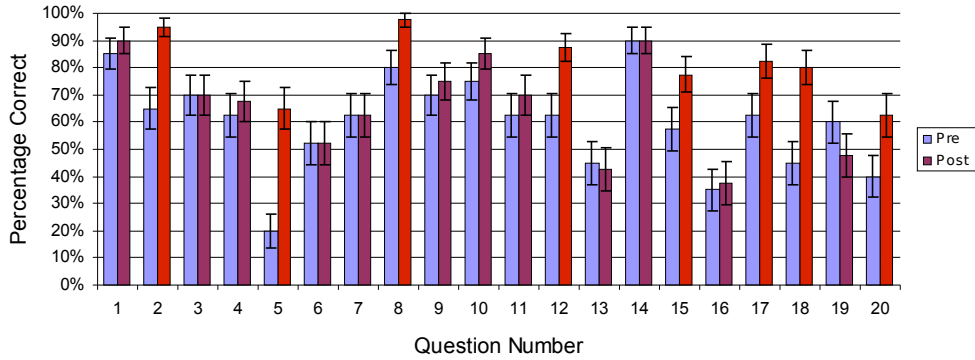


Figure 2: Scores on Individual Test Questions

Table 3: Chi Square Analysis of Individual Test Questions

Test Question:		1	2	3	4	5	6	7	8	9	10
Pre	Correct	34	26	28	25	8	21	25	32	28	30
	Incorrect	6	14	12	15	32	19	15	8	12	10
Post	Correct	36	38	28	27	26	21	25	39	30	34
	Incorrect	4	2	12	13	14	19	15	1	10	6
Chi Square Result:		.2918	.0000	1.0000	.4996	.0000	1.0000	1.0000	.0000	.4652	.0765

Test Question:		11	12	13	14	15	16	17	18	19	20
Pre	Correct	25	25	18	36	23	14	25	18	24	16
	Incorrect	15	15	22	4	17	26	15	22	16	24
Post	Correct	28	35	17	36	31	15	33	32	19	25
	Incorrect	12	5	23	4	9	25	7	8	21	15
Chi Square Result:		.3006	.0000	.7491	1.0000	.0025	.7440	.0009	.0000	.1134	.0033

## Time vs. Non-Time Related Questions

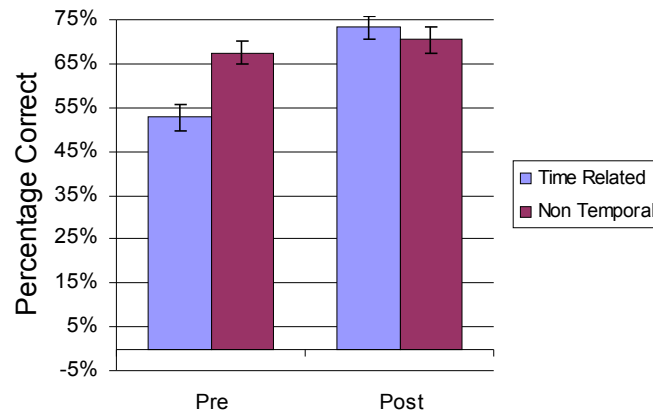


Figure 3: Time vs. Non-Time Related Questions

## Limitations of the Circuit Simulation

Students using our animated circuit simulation did not show improvement on *all* our concept inventory test questions in our pilot. In particular they showed no improvement on the non-temporal test questions. We believe part of the difficulty students have with these questions lies in the conflation of different variables (such as voltage vs. current) or a lack of distinction between components (capacitor vs. inductor) and circuit configurations (series vs. parallel). We have previously referred to this student difficulty as *undifferentiated concepts*. Students may either conflate or mix-up different concept pairs, such as voltage and current, voltage and power, AC and DC, series and parallel, capacitors and inductors, and low pass and high pass filter circuits. We have often observed that students have to resort to memorization to remember these distinctions, which means they may still not understand the inherent underlying reasons for these distinctions.

What then is required to get students to attend to these important distinctions and possibly improve on *all* the questions in our AC/DC Concept Inventory, including the non-temporal test questions? We describe an instructional strategy that we are in the process of pursuing known as *contrasting cases*.

## Future Directions

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Our ultimate goal is to develop a complete learning environment that facilitates student understanding of electrical circuit behavior and principles, including all the invariant principles we identified as important for understanding analog electrical circuits. Holton (in press) has reviewed how, with the right supporting instructional strategies, simulations such as ours can serve as a foundation for a well-rounded learning environment that addresses knowledge-centered, learner-centered, assessment-centered, and community centered issues as delineated in the framework provided in the book *How People Learn* (Bransford et al., 1999).

However, as mentioned above, students only showed improvement on some of our test questions when using our animated circuit simulation. Furthermore, students in real classrooms still need a reason (*raison d'etre*) to use our simulation, as well as our dynamic assessment tool. Two additional strategies will be being pursued to address these issues and hopefully create a more well-rounded environment for learning about electrical circuit behavior. One is the contrasting cases strategy, and another is the creation of an online challenge-based community for learning about electrical engineering.

## **The Contrasting Cases Strategy**

We believe difficulties on the non-temporal questions in our AC/DC Concept Inventory primarily revolve around students' lack of distinctions between different circuit components and behaviors. As mentioned above, students often conflate various variables such as voltage and current and various components such as capacitors and inductors and circuit configurations such as series versus parallel. Sometimes students even ignore the fact that a circuit is AC rather than DC.

One strategy for helping students notice and make new distinctions is contrasting cases (Bransford, Franks, Vye, & Sherwood, 1989). Using this strategy, one shows learners two related cases at a time, rather than one at a time. This approach has theoretical roots in ecological psychology and perception and action research (Gibson, 1979). Essentially one can direct attention to a feature by showing two cases side by side that differ by that very feature on which attention needs to be focused. Contrasting cases has been shown to be an effective strategy in other domain areas such as algebra (Rittle-Johnson & Star, 2006; Derry, Wilsman, & Hackbarth, 2007) and psychology (Schwartz & Bransford, 1998). However, it has not been tested in the domain of engineering or science education before. Related research has also found giving students contrasting cases activities or simulation activities is more effective when employed *before* a class lecture rather than afterward (Brant, Hooper, & Sugrue, 1991; Schwartz & Bransford, 1998). That supports the notion that a supplementary online resource for learning and investigating circuit behavior may be effectively integrated into a circuits class, especially when students explore the simulation before hearing a lecture about the related concepts and formulas. Even though students may or may not fully understand the model underlying the simulation they use, they may form questions or strategies for learning about the domain after exploring the circuit. So even when a simulation is not completely understandable to a student, it may engender a preparedness for future learning, and the students may become more curious or attentive when presented with a subsequent lecture or other learning activity (Schwartz & Bransford, 1998).

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There are also other instructional techniques that are quite similar to contrasting cases but have different theoretical foundations and differences in their implementation. These include:

- *Analogies* (e.g., Gentner & Gentner, 1983; Clement, 1993) – show a system or scenario that is analogically isomorphic to the target domain being learned. This strategy has roots in cognitive information processing models and mental models research.
- *Variation strategy* (e.g., Marton & Pang, 2006; Pang & Marton, 2005) – show students variations in a scenario along one dimension while keeping other aspects invariant. This approach has roots in phenomenology.
- *Multiple representations* (e.g., Kozma et al., 1996; Schnotz & Bannert, 2003) – provide multiple linked representations of phenomena, such as graphs and pictorial and textual representations. This strategy has roots in multimedia learning theory and human-computer interaction (HCI) research.
- *Embodied metaphors and gestures* (e.g., Glenberg et al., 2004; Núñez, Edwards, & Matos, 1999; Goldin-Meadow, 2005) – Essentially use one's own body and actions as an analogy to or enactment of the target domain. The aforementioned enactive modeling strategy falls in this category, as well. These approaches have roots in embodied cognition (Gibbs, 2006).

This plethora of independently-derived instructional approaches raises numerous research questions, however. For not only do each of these techniques have distinct theoretical roots, they also have specific differences in how they have been applied to instruction. Moreover only the analogies technique has been sufficiently researched in domain areas involving misconceptions that are resistant to traditional instruction, including electrical circuits (e.g., Gutwill, Fredericksen, & White, 1999). The limitations of the analogy strategy have been well identified (e.g., limitations of using the water analogy to electrical circuits, Gentner & Gentner, 1983).

We will be conducting future meta-analyses and pilot studies that explore how presenting circuit simulation problems in pairs rather than one at a time may better facilitate student understanding and noticing of critical features in electrical circuit problems.

## **Online Challenge-based Community**

One other larger challenge for our research is addressing student learning of electricity concepts at the K-12 level. Currently most high schools only spend a week or two on electrical circuits over the course of four years of instruction. Curricula exist for more in-depth learning about digital and analog electrical circuits (such as Project Lead the Way), yet it also may have limitations. One is that the curricula is very expensive and not openly available to the public. Only schools in richer school districts may adopt specialized technology education courses on electrical circuits. Also, this leaves out not only poorer schools, but the ever-increasing number of online virtual high schools. More and more high school students in the United States and elsewhere are beginning to take more, if not all, of their courses online. Existing technology education curricula are designed for face-to-face courses only, and use expensive and dangerous equipment that could not be utilized by students on their own from home.

We have proposed the creation of an online/blended learning community for students learning science, technology, engineering and math (STEM) concepts known as BOOSTEM. Students can use animated simulations such as our own, and also collaborate and compete with one another on engineering and design projects and problems. Similar online portals have been developed for science education, including the ITSI project at the Concord Consortium and the EU-funded SCY project (Science Created by You).

## Conclusion

This chapter has discussed initial tests of two software tools for facilitating student understanding of electrical circuit behavior: the Inductor dynamic assessment tool and the Nodicity animated circuit simulation software. The design of both tools and the impetus for much our work is improving student performance on a qualitative multiple-choice questionnaire – the AC/DC Concept Inventory. Students using the simulation showed improvement on approximately half the questions, those involving temporal considerations of circuit behavior, and our group is beginning to research strategies such as contrasting cases to improve performance on the other, non-temporal questions. The ultimate goal is creating a complete, well-rounded environment for understanding how to analyze, design, and troubleshoot electrical circuits. Hopefully, the data and lessons learned that are presented in this chapter will help others attempting to design better instruction in engineering and science.

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## **Support Material**

### **Questions and Answers**

1. What is the overall problem(s) in this case?

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The central problem of this case concerns how to help students overcome conceptual difficulties understanding the behavior of electrical circuits in order that they may become better electronic troubleshooters and designers.

2. What are the factors affecting the problem(s) related to this case?

Some factors affecting this problem includes the fact that much electrical behavior is complex and occurs and at a microscopic scale outside our natural level of perception.

3. Discuss managerial, organizational, and technological issues and resources related to this case.

Such microscopic circuit behavior is not easily conveyed via the texts and lectures traditionally used for instruction. The curriculum used in beginning circuits classes also has not changed very much over the last several decades.

4. What role do different players (decision-makers) play in the overall planning, implementation and management of the information technology applications?

Ultimately individual college instructors control what is taught in circuits courses, but they are constrained by ABET standards for engineering education and the circuit analysis textbooks currently on the market.

5. What are the possible alternatives and pros and cons of each alternative facing the organization in dealing with the problem(s) related to the case?

One alternative solution that has been proven successful is tutoring individual students with the assistance of computer software; however, this solution does not scale well. Giving students individual supplementary activities using computer software and other technologies may work nearly as well though without the need for employing individual tutors for every student.

6. What are some of the emerging technologies that should be considered in solving the problem(s) related to the case?

Different emerging technologies one might consider for addressing student conceptual difficulties understanding circuit behavior include animated applets for visualizing circuit behavior, online assessment tools that allow instructors to assess qualitative understanding and allow students to get feedback on their own understanding of circuit behavior.

7. What is the final solution that can be recommended to the management of the organization described in the case? Provide your arguments in support of the recommended solution.

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The solutions presented in this chapter included 1) an online dynamic assessment environment for assessing student qualitative knowledge and allowing students to learn from experts and other online resources while answering test questions, and 2) a java-based animated circuit simulation that allows students to visualize and control complex circuit behavior. A third solution is proposed to overcome the weaknesses of the second one – using the contrasting cases instructional strategy to present circuit problems and scenarios in pairs rather than one at a time, so that students may better attend to and discover the essential distinguishing features of these cases.