ENACTIVE MODELING AS A CATALYST FOR CONCEPTUAL UNDERSTANDING: AN EXAMPLE WITH A CIRCUIT SIMULATION

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Dedicated to the memory of my father Lee Holton

and

To my wife Laura, my son Reed, and the rest of my family.

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CHAPTER 1

INTRODUCTION

This research explores how allowing students to actively control an electrical circuit simulation in real-time helps them better understand the complex behavior of electrical circuits. Many students even at the college level have misconceptions about electricity that make the subject more difficult to teach and learn via traditional methods such as lecture or textbooks. A unique control interface to an animated circuit simulation is presented that allows students to enactively model how an AC voltage source controls the current flow in a circuit. Enactive modeling is not to be confused with more general "hands-on" learning or with other forms of modeling, such as constructing physical models or social modeling in which people learn from observing or imitating others. In enactive modeling, the student is an agent participating in the behavior of a dynamic system, and is controlling one or more temporal aspects of the changes occurring in the system. This enactive modeling interface to a circuit simulation may allow students to better relate to complex aspects of circuit behavior without having to over-simplify the simulation.

Organization of This Paper

This paper begins in the next chapter by situating the research I and others at Vanderbilt have conducted on learning electrical circuit behavior in the context of other intuitive physics research and theories. Our research may contribute to this existing body of research by helping improve instruction in the area of electrical circuits and by progressing the field of intuitive physics research in general by venturing into a relatively unexplored area (AC circuits) and testing a new theoretically rooted instructional strategy (enactive modeling).

Chapter three describes in more detail the research I have previously helped conduct on student understanding of AC circuit behavior. This research has progressed through three phases: interviews with students about their circuit knowledge, the development and testing of diagnostic misconceptions tests, and finally the development of a web-based assessment tool that provided students with feedback while they worked on problems on the tests. This research has not been previously published, and so chapter three provides more details about the materials, methods, and data analysis used in these studies.

The next chapter introduces the motivation for the fourth and current phase of this research, the design and testing of an animated circuit simulation. Chapter four reviews some of the techniques and research concerning educational computer simulations and their effectiveness for conceptual learning, and introduces background to the hypothesis that an enactive modeling strategy may prove useful in the design of the simulation and instructional activities.

Next, the methodology is described for testing this new circuit simulation with students and the procedure for employing the enactive modeling strategy. A multiple choice conceptual quiz based on earlier tests we have developed was used to measure the concepts that students learn during a tutoring session with the simulation. Some measurable learning effects occurred in a very short time, and the final section explores implications for the enactive modeling strategy and for the redesign of the simulation and instruction.

CHAPTER II

INTUITIVE PHYSICS RESEARCH

A body of educational research known as “intuitive physics” or “misconceptions research” provides three decades worth of examples of the difficulties students have understanding and applying scientific concepts. One of the most dramatic examples is a video of Harvard engineering students on the day of their graduation (PBS, “A Private Universe”). Students were given a light bulb, a battery, and wire and were asked to make the bulb light up. Many students did not succeed despite having plenty of physics and engineering instruction. There are countless other examples across all areas of science, math, history, and other disciplines. This research has established that students often have their own intuitive conceptions about the subject matter taught in schools, and these preconceptions are typically resistant to instruction, especially traditional lecture and textbook-based instruction. Examples drawn from intuitive physics research are often used as a hook near the beginning of major books in the fields of education and psychology, such as *The Design of Everyday Things* by Donald Norman (1988, p. 36, airplane drop example), *The Unschooled Mind* by Howard Gardner (1991, p. 3, coin in air example), and *How People Learn* by John Bransford and others (1999, p.15, notes how intuitive physics research has provided one of the key sets of findings of the learning sciences).

Intuitive physics research has been identifying important problems concerning learning and instruction, and yet one could argue that not as much progress has been made over the last decade or so in this field. By progress I mean progress in scientific and educational research, which involves expanding research into relatively unexplored areas and addressing anomalies or theoretical disagreements in previous research. That is how Laudan defines scientific progress: "The aim of science is to maximize the scope of solved empirical problems, while minimizing the scope of anomalous and conceptual problems" (1977, p. 66). Intuitive physics research has tended to study only simplistic problems, such as simple Newtonian physics examples or basic electric circuits that only consist of bulbs, batteries, and resistors. While focusing on simple problems highlights the fact that students have misconceptions in even the simplest scenarios, it may not apply as well to instruction involving more complex problems. There remain many unexplored domain areas that could help instruction and progress our understanding of student learning difficulties.

There are also some anomalies and theoretical disagreements in previous intuitive physics research, although the anomalies have gone mostly unnoticed. McCloskey (1983) found that students erroneously believe than an object dropped from a moving airplane falls straight down, instead of in the correct parabolic path. He gave a visual perception-based explanation for this phenomenon: students were reasoning based on an incorrect visual perspective of the problem. From the perspective of the airplane moving along with the object, the object does appear to fall straight down. However, later research utilizing animations found cases where this explanation did not fit the data. If an animation showed an object being shot or thrown forward from the airplane instead of merely dropped, then students could accurately recall the motion of the object. No further research or theoretical analysis has been done with respect to this case. However another example that has received significant theoretical attention and disagreement is known as the curved tube (or spiral tube) problem. A ball travels through a curved tube lying horizontally and then exits out of one end. Students erroneously believe the ball will continue to travel in a curvilinear path after exiting the tube. Students' beliefs in this case cannot possibly be based on previous visual experiences. Various cognitive explanations have been offered yet they have recently been shown to also be unsatisfactory (Kerzel, 2003). Kerzel found a better explanation utilizing recent advances in perceptual-motor theories and paying more attention to the actions of the participant (in this case, eye movements). This approach is part of a larger body of research emerging recently from traditional cognitive and perceptual approaches that has been variously labeled as an embodied or enactive approach. In the embodied cognition or enactive learning tradition, one examines how the biological constraints and physical actions and movements of a person can contribute to the shaping of one's understanding and learning. I will explore this theoretical approach further below and later in the section on simulation design.

Intuitive physics research became established during the 1980s, when traditional cognitive and visual perception theories were dominant. When applying this cognitive research to education and instruction, we have tended to focus on the individual student in an isolated learning context. It has inspired new instructional strategies and technologies such as intelligent tutoring, computer microworlds, and 3D visual learning environments. More recently however two theoretical derivatives of the traditional cognitive approach have emerged. One is the situated cognition perspective, which places more importance on the social and real-world contexts of cognitive activities, and has inspired new instructional techniques such as problem-based learning and anchored instruction. Educational research in this area has analyzed learning in the social context of classrooms and in complex real-world contexts, and has explored the educational aspects of more social technologies such as online chat rooms and multi-user games. A second perspective to emerge recently is the embodied cognition or enactive learning approach. As explained before, this approach takes a person's biology and actions into account when explaining learning phenomena. This approach has not been applied very much to the development of new and more interactive instructional techniques or educational technologies. There have however been observations and analyses of student and teacher gestures (hand motions) while learning or teaching particular concepts in math and science, which will described in further detail at a later point.

The purpose of the new research presented in this paper is to extend previous intuitive physics research into new areas involving more complex problems, and apply a new interactive instructional technology inspired by theories of embodied and enactive cognition in hopes of progressing the field of intuitive physics and improving instruction. The next section describes some previous research the author helped conduct which extended intuitive physics research into the more complex and relatively unexplored domain of AC (or alternating current) circuits, including circuits with capacitors and inductors. This research has not been previously published, and so the next section will go into some more depth about the methods, data analysis, and materials used during these prior studies. Afterward, the author's current extension to this research is described, which utilizes an animated circuit simulation and employs various perceptual and enactive strategies to help students understand the dynamic behavior of electrical circuits more quickly and accurately.

CHAPTER III

EXTENDING INTUITIVE PHYSICS RESEARCH: AC CIRCUITS

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 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?

In protocol studies, 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.

Previous Phases of Our Research on AC Circuits

Our research at Vanderbilt into student understanding of circuit concepts evolved through three phases. First, we used interviews to generate a list of common misconceptions and difficulties students exhibited when involved in problem solving tasks. This list was used to design multiple choice and fill-in-the-blank tests, where students applied qualitative reasoning mechanisms on invariants to generate answers. Lastly, we incorporated the questions into a web-based self-assessment tool, and tested what students learned using that tool. Research the author helped conduct with that project has not been published, and it is described it in some detail below. Following that project's completion, the author followed up with a fourth phase of research described in this paper involving the design of an animated circuit simulation and the testing of new strategies for helping students understand the behavior of AC circuits and components such as capacitors and inductors.

Phase 1: Interviews

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.

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.**
    a. Students often surmised that the alternating current going through a resistor was constant in time.
    b. 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 got 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]

8. **Failure to differentiate among concepts**. Examples, voltage and current, series and parallel configurations, role of capacitor in DC versus AC circuits.

9. **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).

10. **Overly local reasoning.** Not thinking of global constraints, invariants.

11. **Bad framing.** Incorrect generalizations, trouble switching from equations to physical explanations to analogical models.

12. **Experiential impoverishment.** Electricity is invisible except for its end products.

Lack of basic circuit knowledge.

13. **Lack of Ohm's law** (how resistance affects current when voltage is constant)

14. **Lack of KCL** (current through all components of a loop must be equal).

15. **Lack of KVL** (the voltage drop across components of a loop must sum to zero).

16. **Lack of knowledge of the behavior of capacitors** (such as C=Q/V)

17. **Lack of knowledge of Capacitor and Inductor impedance as a function of frequency.**

18. **Topographic misunderstanding of the circuit (e.g. unable to differentiate series from parallel).**

Phase 2: Misconceptions Test

The catalog of student difficulties with circuit analysis formed the basis for developing a set of multiple-choice questions (see Appendix A.1) to study their effects on problem solving behavior. The questions asked for qualitative 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. Hunt and Minstrell (1994) used this technique with their DIAGNOSER assessment tool to provide instruction that targets misconceptions students' display in physics. 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

Invariant	***Description***
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*f*C), 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*V). Another way to express this relation is I = C * 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*f*L, 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 * 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*I = V^2/R = I^2*R)
g. Kirchoff's Laws of Conservation	Kirchoff's Voltage Law (KVL): 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. Kirchoff's Current Law (KCL): 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: $1/R_{effective}$ = 1/R1 + 1/R2 + ... 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.

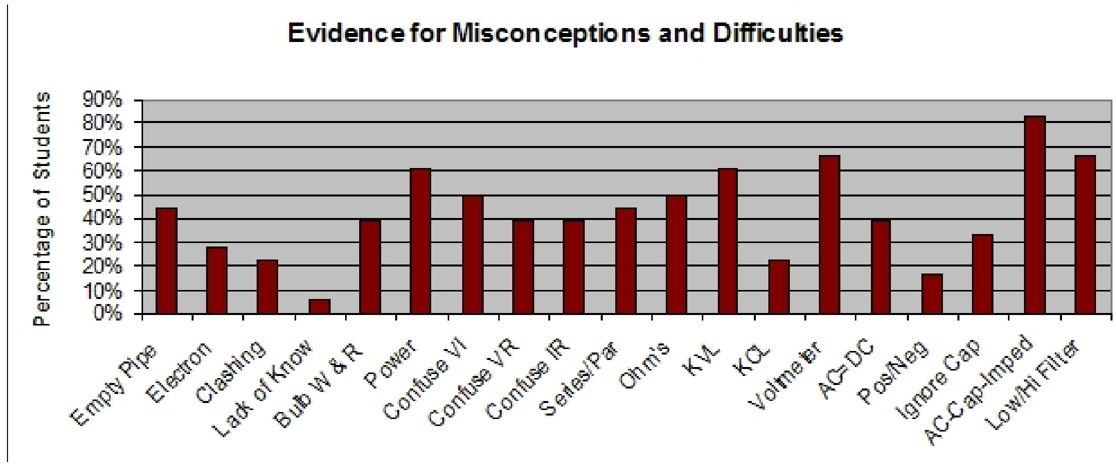


Figure 1: Range of Circuit Misconceptions Seen on Misconceptions Test

A few weeks later, we gave eighteen of the same students a second, fill-in-the-blank test (see Appendix A.2), in which they were required to work through a sequence of steps to generate solutions. These questions were similar to questions on their homework assignments and tests. The only difference was that the emphasis was not on numeric computations, but on their choosing and applying the right invariant laws in deriving their solutions. In comparison with the results of the multiple-choice test, student performance declined significantly (only 43% correct vs. 59% on the multiple choice test). Students again showed significant difficulties in understanding invariant principles related to Kirchoff's laws and capacitor behavior. Particularly surprising was their performance on a multi-part question involving light bulbs and power, which required them to link invariant laws related to power and Ohm’s law. Students’ averaged only 23% correct on this question, despite the fact that many of the same students did not show difficulties on the multiple choice test with questions targeting concepts of power or resistance. The lack of significant correlation between performance on the power questions in the multiple-choice test and performance on the question in the second test indicated perhaps that the *bridge* between the power and Ohm's law through resistance remained inert when problem-solving in the second 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 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.

Phase 3: Web-based Assessment Tool.

Our early version of Inductor was designed to be an online assessment tool in which students answer multiple-choice questions and select the invariant principles that apply to the circuit to justify their answer. Inductor not only provided instruction for remediating misconceptions, such as another assessment tool known as DIAGNOSER did (Hunt & Minstrell, 1994), but it taught the invariants technique for circuit problem solving. After submitting their answer, students received 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 simulations and tutorials. Students could look up resources, then revise their explanations, and finally view 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 professors 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.

In a pilot test of Inductor, we found that students' answers to questions improved with instruction. Students took two online tests in a row using Inductor, borrowing multiple-choice questions from the tests developed earlier on DC and AC circuits. The two tests were constructed to be similar in difficulty yet using different questions. An earlier pilot study established the difficulty of the items and allowed us to equalize the two tests and refine the wording of the problems. Students initially had difficulties with their answers, but by the second test performance increased substantially. Part of this increase could be attributed to superficial similarity between questions on the two tests, but detailed analysis of students' explanations more clearly revealed what the students learned while using Inductor. Students initially revealed a number of misconceptions ("*higher resistance means more power is absorbed*", "*John's battery will be required to work harder to push current through the larger resistor*"), and errors ("*since they are in series the voltage should be the same across all of the bulbs*"), and admitted to making guesses. However, it was clear after receiving feedback on invariants, most students attempted to revise and correct their misconceptions.

Analysis of Students' Choice of Invariants. In order to analyze how well students did at choosing the invariants, or circuit principles, while answering questions in Inductor, we compared their choices to those of experts. or each circuit problem, we used three experts to select the invariants that were most relevant and helpful for solving the problem. After initial selection they met to come to a consensus about the relevant invariants for each of the questions. They also identified the invariants that were clearly irrelevant. The impedance of an inductor, for example, is irrelevant for a RC circuit. The remaining invariants were placed in a third category. A link could be drawn between these invariants and the circuit behavior, but they were not particularly useful for solving the problem asked about the circuit. Ohm's law, for example, applies to all circuits with resistive components, but it is not always necessary for a particular question about a circuit.

We needed a way to quantify how well students selected invariants for a particular problem. In our case, a simple percent correct measure is insufficient for characterizing students' use of invariants, because it rewards 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 that our experts agreed were appropriate for the 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: $\frac{h-f}{h-2fh+f}$. A Q of one implies perfect discrimination of the relevant from irrelevant invariants, and zero implies pure chance performance.

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.

However, we found that students' selection of relevant invariants declined from the beginning of the tests to the end. Students performed much worse on questions involving capacitors in both DC and AC contexts. The graph in Figure 3 reveals this pattern across each of the categories of questions and across both classes. Clearly students are not understanding the behavior and invariant principles involved with capacitors in circuits. However, other explanations may have contributed to this pattern of results as well. One is that the questions grew more difficult from the beginning to the end of the tests. 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.

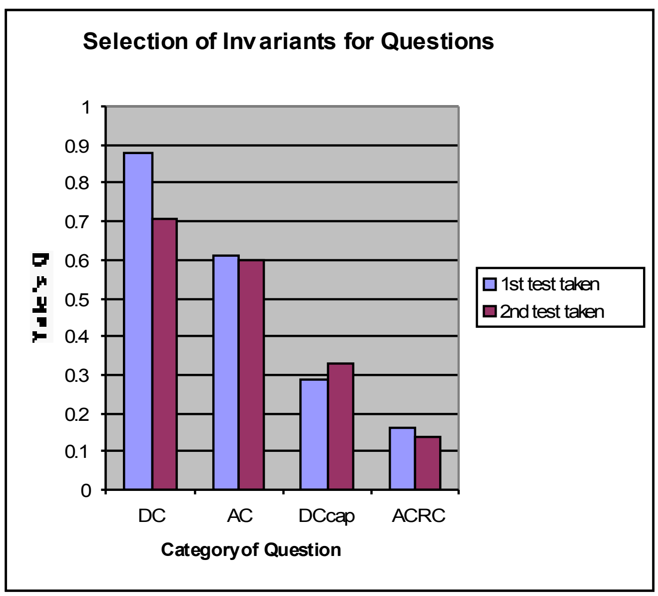


Figure 2: Student Selection of Invariant Circuit Principles

We identified other 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. Also, 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.

Towards Phase 4: Using an Interactive Animated Circuit Simulation

As mentioned above, the outside resources we used 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 use of an animated circuit simulation in my dissertation research. 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 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. In the next section, I describe some of the research on educational simulations that informed the selection and design of an interactive circuit simulation used in phase four of this research.

CHAPTER IV

DESIGNING A COMPUTER SIMULATION

As science and technology advance, the fields of study for education are becoming more and more complex. Students have many difficulties learning about complex and dynamic phenomena. There is a growing need for more powerful tools to assist students and teachers in understanding dynamic systems, including modeling tools and computer simulations. Simulations may also be useful for instruction targeting intuitive or informal reasoning about these more complex phenomena. But still largely unanswered is not only the question of why simulations may be useful for helping students better understand scientific concepts, but *how* simulations may be designed to more effectively achieve this purpose.

A simulation is a dynamic, manipulable model of a system that recreates some of the properties and behavior of the system it is modeling. The primary design principle that characterizes simulations as representations is *fidelity*. Simulation fidelity is the similarity between a simulation and the system it is modeling. The higher the fidelity of the simulation, the more trustworthy its behavior may be to an expert familiar with the actual system, in the sense that experiences using the simulation more closely resemble real-world experiences.

Educators and students have used computer simulations for many of the same practical reasons as experts, such as cost and safety. There are however penalties associated with learning from high fidelity simulations. The more closely a simulation models a complex dynamic system, the more difficult the simulation is for someone to learn and understand how to use. The same design principle of fidelity that makes simulations more effective for experts may hurt the effectiveness of simulations in pedagogical contexts. Instead of providing more knowledge to a learner, like a textbook or video, higher fidelity simulations *require* more knowledge from a learner to be used and understood.

Accordingly, many trainers have argued for the use of low fidelity (or simplified) simulations at the beginning of training in order to help students learn the basics more quickly and gradually increase the fidelity as learning progresses. While this strategy has been sufficient for procedural learning tasks such as learning to fly an airplane, the results have been mixed when the goal of instruction is a deeper level of understanding of the system being modeled. In these contexts, students approach simulations with their own ideas that often may conflict with an expert's understanding of the underlying domain. In these domains the effects of fidelity in a simulation may present a larger hurdle to successful understanding on the part of the learner, for the closer the simulation resembles an expert's model of the dynamic system, the farther the simulation may be from the learner's model and understanding of the system. I refer to this as a tension between simulation fidelity and "learner fidelity."

Learner Fidelity: What and Why

Despite the influence a learner's knowledge and beliefs has on the effectiveness of simulations, a typical symbolic simulation focuses on fidelity to the system it is modeling irrespective of the prior understanding or beliefs of the user. This is why many educational researchers have argued for the need to add various forms of support to simulations to help students overcome difficulties in learning with understanding (de Jong & van Joolingen, 1998; de Jong & Njoo, 1991; Njoo & de Jong, 1993; Wiser, 1995; Rieber, 1992). Examples include helping students with generating hypotheses, designing experiments, and interpreting data. Thus there are alternatives to lowering a simulation's fidelity in order to help students understand the system being modeled. In fact one does not necessarily have to sacrifice simulation fidelity in order to improve learner fidelity.

What specifically is involved in a person's conceptions of events that a computer simulation is modeling, and how does it differ in nature from the representations a simulation uses? The primary difference is that people generally understand systems qualitatively, not quantitatively:

> For teaching purposes, the main drawback of quantitative simulation is its inability to give a full account of the causality underlying its inferences. Causality is pedagogically important because it is the main ingredient of the kinds of explanations human students can understand. In a troubleshooting context, causality, more than information content, drives the diagnostic reasoning and the decision to perform measurements. (Wenger, 1987, p.62)

This is true for scientists as well as students. 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 accounts. 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).

Numerous sources of research help better specify how people naturally and informally reason about both physical and social events, and why they might show a preference for causal and mechanical models. In addition to the aforementioned reference to student misconceptions, there is relevant research on perception, action, and mental imagery, on embodied cognition, on causal and anthropomorphic reasoning, and on the connection between gestures and understanding. Only a few of the most relevant excerpts of this literature will be discussed here, but it is worth noting that researchers in these fields are all beginning to pay attention to the role of one's body and intentional actions in order to better characterize the contextual constraints involved in natural reasoning about events. This applies to 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.

The Link Between Learner Fidelity and Gestures

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 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 David Tall have found that teachers using gestures or attending to student gestures can make math instruction more effective (Goldin-Meadow, 1999; Tall, 1999, 2001; Tall & Watson, 2001; Watson & Tall, 2002). 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.

Hypothesis: Enactive Modeling Strategy

The hypothesis guiding the research presented below is that these kinesthetic activities are helping foster - yet also constrain - how students “intentionalize” the phenomena about which they are learning. Students may make a connection between their natural experience of phenomena and the constraints and rules operating in scientific representations of the phenomena. In a sense abstract scientific concepts may be 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 indicate 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. The following research explored a new learner-centered simulation strategy that may be uniquely suited to helping students understand complex changes happening in physical systems – enactive modeling (or enactive participation).

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 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 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 pursued in this research is can students learn by participating in simulations of *physical* systems as well as social systems. Does physically perceiving and acting under the physical constraints that operate within a system help one understand the behavior of the system as a whole?

Utilizing Enactive Modeling with a Circuit Simulation

The enactive modeling strategy was applied to a computer simulation of electrical circuit behavior. Electricity is one of the most difficult subjects for students to understand, and as mentioned before there are a great deal of misconceptions about circuit behavior. Behaviors that change over time are particularly difficult, as in alternating current (AC) circuits (Holton, Biswas, Bhuva, Brophy, & Schwartz, 2003). 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 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 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.

Enactive Interface. 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 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 earlier in particular 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.

Other Instructional Strategies Employed by the Simulation

Other instructional strategies were also employed by this circuit simulation and by the instructor besides the use of an enactive control interface, including contrasting cases, multiple representations, analogies, animations, and other graphical techniques. This section just describes some research supporting the use of the strategies, the particular details of their implementation in the simulation and in the design of the instruction are discusses in the next chapter.

Multiple representations. Presenting multiple representations of the same phenomena or contrasting cases of similar but different phenomena may encourage students to consider multiple perspectives when forming their own understanding of a system. This strategy can be useful when a concept is difficult to represent and cannot be easily understood from a single visual depiction or description. Electrical current is a good example, for if one represents current only as moving particles or as water in a pipe then this may reinforce an erroneous "current as substance" misconception. Kozma et al., (1996) found significant gains in understanding chemical processes with a simulation environment that provided multiple linked representations of the phenomena. If the representations are *not* linked, then students may choose the representation that is least explanatory and easiest to understand (Linn & Songer, 1991). An important strategy Kozma et al. (1996) used was to use at least one representation that connects to everyday experience (using real-world objects and interactions), and linking it to other more abstract and symbolic representations.

Analogies. Analogies may also be helpful to learners by connecting to their prior experiences. One may use a technique of "bridging analogies" by beginning with a system that students have correct intuitions in understanding, such as pressing a spring on top of a floor. Clement (1994) gradually made connections from this model to a model of a book lying on a table that was consistent with Newtonian static forces, a concept about which students had difficulty understanding correctly. As mentioned with the example of electrical current, however, analogies are never perfect and sometimes are not effective strategies, particularly in areas in which students have little or no experience.

Visualization and animation. Visualization and animation may also be effective strategies for assisting learners in understanding the underlying model of a simulation. Rieber (1996) found that students learned more tacit knowledge about the Newtonian physics of motion when provided with animated feedback rather than textual feedback in a simulation. The real-time visual feedback a simulation provides can help students overcome misconceptions engendered by static representations such as textbook graphics (Sadler et al., 1999). Monaghan and Clement (2000) compared students using a relative motion simulation which provided either animated feedback or numeric feedback. Learning occurred in both conditions, but students in the numeric feedback condition sometimes used faulty algorithms to solve problems. Students in the animated feedback condition showed evidence for using mental imagery to solve problems.

Graphical devices. Visual representations such as arrows and highlighting are additional methods to help students attend to particular aspects of a simulation. Mayer (2001) summarizes the cognitive effects of many of these techniques. An important consideration is not to cognitively overload a user with these methods. There are limits to the amount and type of information a person can process. Certain strategies, such as placing text captions directly next to the visual representation of the object to which it is referring, greatly assist in learner's conceptual understanding. Comprehension may also be facilitated by using multimodal representations incorporating combinations of textual, graphical, or auditory modes of information presentation.

The use of arrows and pointing plays an important role in visual simulations and other visual representations of physical systems. Heiser and Tversky (2002) have found that arrows in particular can enrich structural diagrams to depict functional information. When asked to describe a bike pump or car brake or pulley system based on a diagram, students viewing a diagram with arrows wrote about functional and behavioral properties more than students who viewed a diagram without arrows. Conversely, other groups of students who were given functional descriptions of each system constructed diagrams with arrows, whereas students given structural descriptions did not.

Interestingly, the above list of instructional strategies that one may use to facilitate learning with understanding from simulations is very similar to strategies shown in previous cognitive studies to facilitate transfer. Duncker's radiation problem is a task in which students are asked to generate a method for destroying a bodily tumor without damaging the surrounding tissue using rays of radiation. Typically a small percentage of students are successful in solving this problem, even after hearing the solution to an analogical problem that uses a similar solution strategy. Researchers have found however that certain techniques such as visually highlighting important aspects of a problem or presenting animated diagrams may facilitate transfer and problem solving success on the task (Grant & Spivey, 2002; Pedone, Hummel, Holyoak, 2001). This provides further evidence for the connection between learning with simulations and learning for transfer (Thomas & Hooper, 1991).

CHAPTER V

METHODOLOGY

Rationale

The study presented here tested the use of an 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 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 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 myself (acting as a tutor or guide) for later qualitative analysis. This allows for future 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 qualitivate 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

Participants consisted of 40 Vanderbilt undergraduate engineering students recruited in the latter half of the semester from four introductory electrical engineering courses: two EECE 112 Electrical Engineering Science courses (N=20), one EECE 213 Network Theory class (N=14), and one EECE 116 Digital Logic class (N=6). The last class is an optional elective usually taken before the other two classes. 14 of the students were female, 26 were male.

Selection of the students for the study was not random. Students were asked to volunteer to participate, and were given $15 each for such participation. The participation rate was rather low despite the large number of students in each class (~80), which is why I went to multiple classes to ask for volunteers. This meant that students had different levels of knowledge of about electrical circuits coming into the study, however the use of a pretest can control for such differences.

Materials

Circuit Quiz. The quiz used to assess students is in Appendix A.3. It is a 20 item multiple choice test with items borrowed from earlier quizzes developed at Vanderbilt. I selected items to provide a broad yet brief coverage of the main circuit misconceptions we have found in earlier studies, including questions concerning power and the impedance of a capacitor in an AC circuit, which were two main focuses of instruction. Also, two questions (numbers 6 and 7) were borrowed from Engelhart and Beichner's (2004) DIRECT test of basic DC circuit concepts. I added these questions to strengthen the coverage of power on the quiz and to assess how voltage-centered students' understanding of circuit behavior was.

Circuit Simulation. The primary material used consisted of an animated computer simulation of electrical circuit behavior. I am developing a circuit simulation with the same name as the aforementioned web-based assessment tool, Inductor. Due to time constraints however I took an existing animated computer simulation instead and modified it for my needs and for use with this study. The original version of the circuit simulation is a java applet created by Paul Falstad (2006).

Paul Falstad's circuit simulation contains many of the aforementioned strategies that are useful in designing educational simulations. It makes the invisible visible, such as showing current as a line of dots moving through the wires. The speed of the dots indicates the level of current in a particular wire. The simulation is a general purpose circuit simulator, allowing the simulation of many different circuits, including those you design yourself. It can simulate DC or AC circuits, resistors, capacitors, inductors, op-amps, gates and many other circuit components and combinations all in real-time (actually, a slowed down version of what happens in the circuit in real-time). The circuit simulation presents information in multiple different ways redundantly and at the same time. For example, scrolling graphs can show voltage, current or power over time. Voltage also appears as color changes in the wires and components. Green depicts positive voltage and red depicts negative voltage. Another very useful feature of the simulation is that multiple circuits can be run side by side in the same window. This allows the use of the contrasting case technique (Bransford, Franks, Vye, & Sherwood, 1989) to highlight certain aspects of circuit behavior.

I modified the simulation in various ways such as adding "live" voltage sources that could be controlled in real-time by the student via an on-screen slider or a hardware joystick or steering wheel interface. A spring-like force feedback effect was computed for the joystick based on the current flow through the voltage source being controlled. Faster current flow had lower force and vice versa. I found after some testing that the difference between weaker and stronger force feedback effects was not as salient as I would have hoped, but still utilized these effects in the study. Other force feedback devices such as force feedback pens may provide more sensitive changes that are more noticeable to the user. I also added a bulb component to the simulation which visually showed changing brightness and power. The scrolling graphs I modified to use equivalent scales to make for more accurate comparisons. Lastly, I changed the applet to an application in order to allow interfacing with the joystick via the jinput library (https://jinput.dev.java.net/), as well as to be able to load and save circuits to text files on a hard drive. A screenshot of the customized circuit simulation is below.

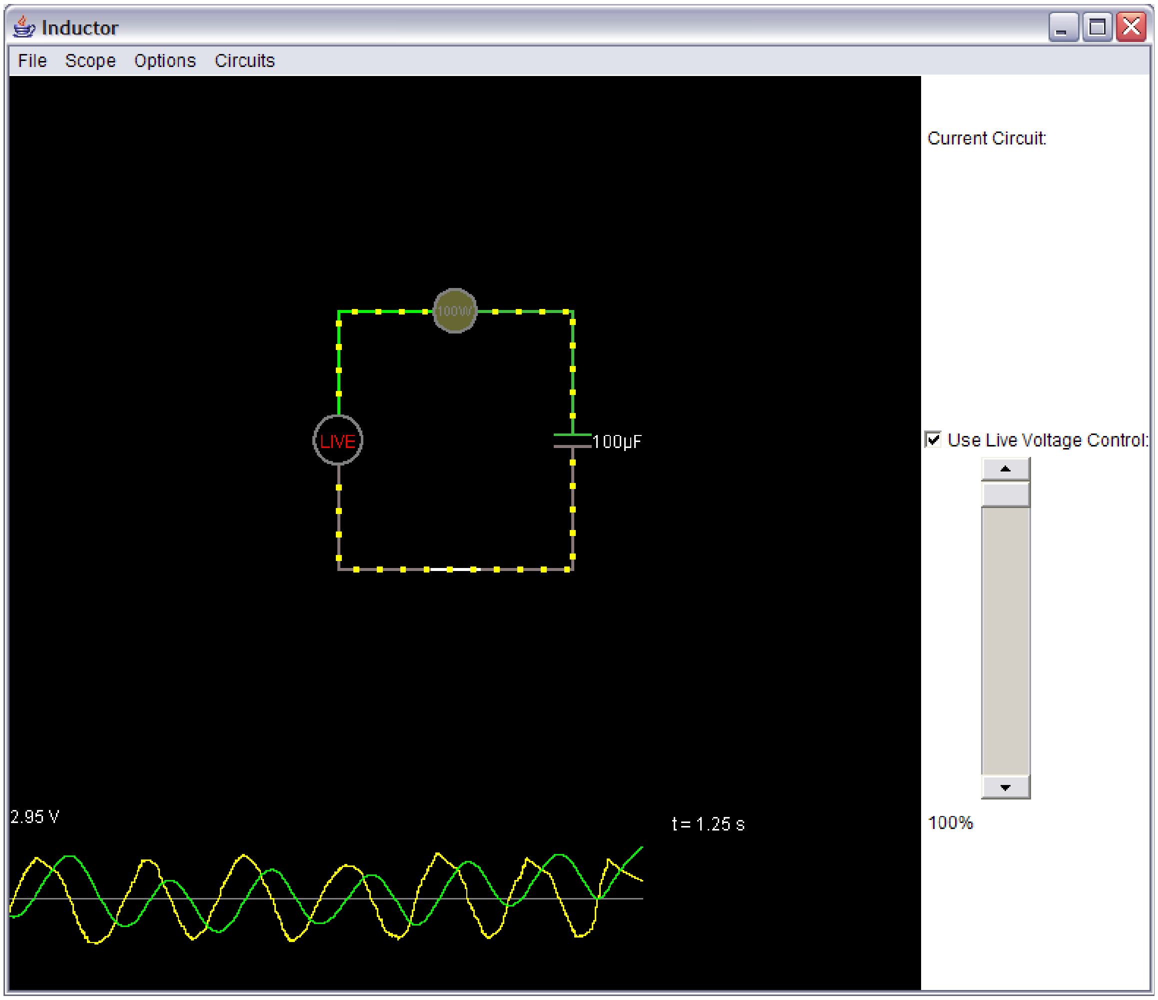


Figure 3: Screenshot of the Circuit Simulation.

Procedure

Before each student arrived to the circuit simulation session, I assigned each student pseudo-randomly to either the joystick or slider condition. It was not exactly random because I wanted to keep a balanced number of students from each class in each condition to help control for differences in experience levels. I also kept a balance between males and females in each condition. Also, there was a miscommunication with the EECE 116 students about how many students could sign up for each time slot, and so

I ran four of the students in pairs of two. One pair used the joystick and one used the slider control. I allowed both students to take turns controlling the voltage.

After signing a consent form (Appendix B) and completing the pretest (Appendix A.3), which took an average of 15 to 20 minutes, I led students through an approximately 30 minute tutoring session with the circuit simulation, going over some of the concepts covered on the exam.

Argument for such a short tutorial session. 30 minutes 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. I did not feel that keeping students in a cubicle to use the circuit simulation for much longer period of time would be desirable, especially considering compensation was only $15, which is not a great deal of money to most Vanderbilt undergraduates. Secondly, the real-time reactive control feature this simulation had that allowed for controlling voltage over time is most similar in spirit to microcomputer-based labs (MBL), research on which 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.

Due to our previous work which showed that students had the most difficulty understanding power and bulbs, as well as AC circuits with capacitors and inductors, I spent the most time in the tutoring session covering those concepts. Following the tutoring session, students took the same test again, and afterward I paid each student $15 and wrote down the address of Paul Falstad's circuit simulation so that students could try the simulation more on their own.

Details of the Tutoring Session.

For the tutoring session, I first started with a simple loop circuit consisting of the voltage source, resistor and a 100W bulb, to familiarize the students with the interface and controls, and to cover some of the basic DC circuit concepts. I started with explaining how this circuit simulation was different in that the student could control voltage in real-time. I then verbally and gesturally described how they could control voltage via the slider or joystick. The student then tried out the controls and saw current begin to flow in the circuit. I explained what the moving dots were depicting, and what the scrolling graphs represented. I pointed out that the dots were travelling at the same speed throughout the loop, an illustration of Kirchoff's current law. Also, when changing the voltage (via the slider or joystick) from the zero point to a non-zero point, the dots all started moving at the same time. The current did not start at the voltage source and then travel through the rest of the circuit, as in the current consumption misconception.

Following some other basic observations I preceded to cover four points about bulbs and power. I asked them to observe how the bulb got brighter as more voltage was applied (positive or negative). The bulb lit up even when the voltage and current were negative. I related this to the equations of power most of the students (except from EECE 116) had already been exposed to ($P=I*V=I^2*R$). In the I^2*R formula, negative current is canceled out by the squaring, and in the I*V formula, both current and voltage are negative and thus cancel out, leading to positive power output from the bulb. I also noted that even though a 100W bulb was depicted, if they moved the mouse over the bulb, the simulation showed that the bulb wasn't actually using 100 watts of power. It was a much lower figure (I noted that this was only an approximation to how much power an actual 100W bulb consumes, as the simulation was still being redesigned and improved). I noted that 100W is not how power a bulb necessary uses, but rather a maximum power rating that should not be exceeded. I then related students to their everyday experience with bulbs. A 100W bulb is usually brighter than a night-light bulb or other smaller wattage bulbs. I asked the student what he or she thought that meant with respect to the resistance of a 100W bulb vs. a smaller wattage bulb. Does a 100W bulb have higher or lower resistance that for example a 40W bulb? While they gave their thoughts about this, I added a second 100W bulb in parallel to the first one in the circuit. I then changed the wattage from 100W to 40W and let the student observe how that affected brightness and current flow. I asked the question about resistance again and then gave an explanation for how a 100W bulb counter-intuitively has a lower resistance than a 40W bulb, again referring to the power equations. Even though a 100W bulb has a lower resistance, it has more current flow, and since current is squared in the power equation, this led to much higher power from the 100W bulb despite having less resistance than a 40W bulb.

Following explanations about bulbs and power, I preceded to ask students what they noticed about the current flow in the parallel circuit with two bulbs. The current flows faster through the lower resistance component, and fastest from the voltage source. I preceded to switch to another circuit that contained three bulbs and two switches, that allowed the student to switch back and forth between one bulb alone, two bulbs in parallel, and two bulbs in series. I used this circuit to help students notice behavior related to Kirchoff's voltage and current laws.

Following the lessons on series vs. parallel circuits, I introduced a simple capacitor circuit. Before allowing students to manipulate the voltage, I asked students what they thought would happen in the circuit if they moved the voltage to a positive level and then held it there, like a DC circuit (the current will flow for a short period and then gradually come to a stop as the capacitor is charged up). This is another example of the predict-observe-explain instructional strategy that helps students reflect better on what they are learning. The student preceded to manipulate the voltage and observe the results. I asked students to continue to try different manipulations of the voltage, including changing the voltage similar to how an AC sinusoidal voltage source changes voltage. I noted that as long as the student kept changing the voltage, they could keep th current moving. I then changed the capacitance of the capacitor to a larger value and asked the student to reflect on how the behavior was different (the current flows faster and longer before stopping). At this point I also offered a visual story to explain what is happening with the capacitor, given that the simulation showed no animation of the capacitor itself. I explained how they might think of the capacitor as two plates that are filling up with charge. When the plate is filled up, current stops, and a larger plate has more room and thus takes longer to fill up. I explained how this might be a possible area of redesign in the simulation.

I then changed the capacitance to a very small value. Now the current stops very quickly. I asked students again to try to simulate how an AC voltage source behaves, and had students try changing the voltage slower (like a low frequency AC source) and faster (like a higher frequency source). Here I do not believe the changes in the force feedback effects were strong enough to be noticeable, however the graph of current flow was very helpful in pointing out that current flowed faster (the peaks in the graph were higher) when the student changed the voltage faster, and the peaks were lower when the changes were slower. I now told the student that this circuit configuration, when a capacitor is in series with the voltage source, can be known as a high-pass filter circuit. In other words, at higher frequencies, more current flows, meaning there is less resistance or impedance, and that signals can pass through more easily. I related this behavior to the impedance formula for capacitors which they learn in the 112 and 213 classes (Xc = 1 / (frequency * capacitance)). I also used the visual story again of what might be occurring inside the capacitor. They might imagine that at faster frequencies, you are not giving the capacitor enough time to fill up with charge and thus resist the current more. At lower frequencies, the capacitor does have more time to get filled up and thus impede current flow more.

I then used the contrasting cases technique to illustrate aspects of how a capacitor circuit behaved. Three circuits exactly like the previous capacitor circuit were shown one above another, except they differed by their capacitance values. The top circuit had a larger capacitor, down to the bottom circuit which had the smallest capacitor. The joystick or slider controlled the voltage in all three circuits simultaneously, and there were three scrolling graphs at the bottom of the screen showing current flow in each circuit. Force feedback effects could only be applied to one circuit at a time, however, and so I chose the bottom circuit to use for calculating force effects, but again, I do not feel it made much of a difference in the experience. The circuit which is being used to calculate force effects is distinguished by a red font for the word "LIVE" on the voltage source rather than a green font. After more experimenting with the three capacitor circuits, I again related the circuit behavior they were seeing and controlling to the formula for the impedance of a capacitor, noting that the dots were moving much more in the circuit with the larger capacitor. Thus not only a higher frequency but also a higher capacitance value means lower impedance or resistance. Students tried manipulating the voltage like different frequency AC sources as well.

Following these explorations of capacitor circuits, I let the computer take over voltage control. The computer simulated sinusoidal voltage sources for the three circuits so that it was easier to see via the graphs that the current was higher in the circuit with the largest capacitor. Next three circuits were shown in which the frequency rather than the capacitance was varied. This more closely demonstrated how these circuits were high pass filters.

I then went through the exact same sequence of activities using circuits that had inductors instead of capacitors. I helped show how these circuits were low-pass filters. The slower you change the voltage, the higher the current. Note however, there were actually no questions about inductors on the circuit quiz. It has been assumed in previous research as well that the difficulties students have understanding capacitors and inductors are virtually the same. One difference with instruction on capacitors, however, is that with inductors I gave an analogy with physical mass and momentum. I explained how the coils of wire in some inductors creates a magnetic field which keeps pushing on the current and keeps current flowing for a while even after the voltage source has gone back down to zero. When showing the circuits with different sized inductors, I made an analogy of a bus vs. a car. Once up to speed, a bus takes longer to come to a stop than a car, just like the larger inductor. Also, a bus takes longer to get up to speed from zero, just like a larger inductor. Capacitors have a physical analogy of a spring, however, I did not use that analogy during the main instruction because it would have been too confusing. I did use the spring analogy with some students with whom I had time to show an RLC oscillator circuit at the end of the session.

At the end of the tutoring session I went through a quick rundown of some other circuits the simulation could simulate, to show how it may relate more closely to the circuits they use and learn about in 112, 116, and 213. Not all of the students saw all of the circuits listed below due to time constraints and individual differences in the time taken to take the test and explain the earlier concepts. I did show all the students other examples of passive filter circuits in which there were multiple AC voltage sources added together and in which the capacitor or inductor was in series or in parallel with the voltage sources (I related this to the stereo system circuits developed in the 213 lab that for example send lower frequencies to a woofer speaker and higher frequencies to a tweeter). I briefly showed an RLC oscillator circuit and op-amp inverting and non-inverting circuits (studied in 112), diodes with and without capacitor filters (not studied in any of the classes), and a few logic circuits (studied in 116), including and gates, nand gates, flip-flops, and an LED decoder display. These circuits and many more were all already included with the simulation by Paul Falstad.

Data Analysis

For testing the experimental contrast between the joystick and slider conditions, I can perform t-tests to determine 1) if there is a significant difference in overall scores from the pretest to the posttest and 2) if there are significant differences between the two groups on the pretest and posttest. If there are differences between the two groups of students on the pretest, I can instead perform an ANCOVA analysis of the post-test scores between the two experimental groups, using the pretest as a covariate to control for preexisting differences between the groups. Following that analysis, I can analyze on which individual test questions students showed the most gains, and which, if any, of the questions the students show no gain or possibly even negative performance.

Interpreting the t-test Results. There are four potential outcomes that may be interpretable. One is that the joystick group shows less misconceptions on the posttest than the group without the joystick interface. This result coupled with qualitative observations may support the hypothesis that facilitating enactive modeling and participation with a computer simulation helps students understand the complex behavior of the system being modeled. A second potential outcome is that there is no significant difference between the two groups on the posttest, but both groups do significantly reduce the misconceptions they had about electrical circuit behavior. In this case, the qualitative data becomes even more important. For although one must be careful in interpreting a null effect, the qualitative observations may allow me to ask such questions as were students in the control condition using the slider to control voltage in a manner similar to how students used the joystick? If so, then enactive participation and control may still be hypothesized to play a role in facilitating student understanding, and a follow-up study may be employed that compares students given analog control over voltage (with a slider) versus symbolic, or numeric control over voltage. If instead the qualitative data does not show students using the slider in a manner similar to the joystick, then social and perceptual features of their interaction with the simulation may better account for student learning. A third potential outcome is that students in the no joystick condition perform better than those in the joystick group. This also would signify that social and perceptual factors are playing a role in their learning. It should be noted that in none of the outcomes am I ruling out social or perceptual influences; I believe they are very much involved and very important to students' learning with this simulation. But I am trying to see if I can "rule in" factors specific to students' embodied, enactive control over the simulation. A fourth potential outcome is that both groups do not significantly reduce their misconceptions at the time of the posttest and this indicates that the intervention was too weak or ineffective. I may have not allowed the students enough time with the simulation or there are flaws in the design of the simulation and tutoring instruction.

CHAPTER VI

RESULTS

Pre-Post Test Results

Pretest. There was no significant difference between the two groups of students overall on the pretest. Both groups answered an average of 60% of the test questions correctly on the pretest. As will be shown later, some of the basic DC questions at the beginning of the test were perhaps too easy for students at this level. 90% of the students on average answered question 14 correctly as well, indicating they did not have the misconception that bulbs located physically closer to a voltage source would be brighter than another identical bulb.

Gain on Posttest. Students on the whole showed an average 12% gain from pretest to posttest, to 72% correct. This gain was only marginally significant and not as large as had been hoped. A paired t-test comparison of pretest to posttest scores resulted in a t-statistic of 1.19 (39 degrees of freedom), with a p-value of 0.12. A later analysis of gains on individual test questions, described in more detail below, showed more significant gains on eight particular questions in the test.

Class Differences. There were some differences between students based on their experience with circuits, although this is more difficult to analyze due to the smaller number of students in each group and the non-random selection. The six 116 students, who had no previous undergraduate experience with analog circuits, averaged 49% on the pretest and 58% on the posttest. The twenty 112 students, who mainly had only the experience from their current class, averaged 63% on the pretest and 75% on the posttest. The fourteen 213 students showed no significant difference with the 112 students despite having more experience. They averaged 60% on the pretest and 74% on the posttest.

Test of the Experimental Manipulation. There was no overall difference between the two experimental groups on the tests (see Figure 4). Both groups had identical pretest and posttest scores. There was however one difference on question 18, which along with question 20 were the only questions about the behavior of a capacitor circuit in response to frequency. The joystick group had larger gains on this question, and outperformed the slider group on the posttest. This result will be analyzed in more detail below.

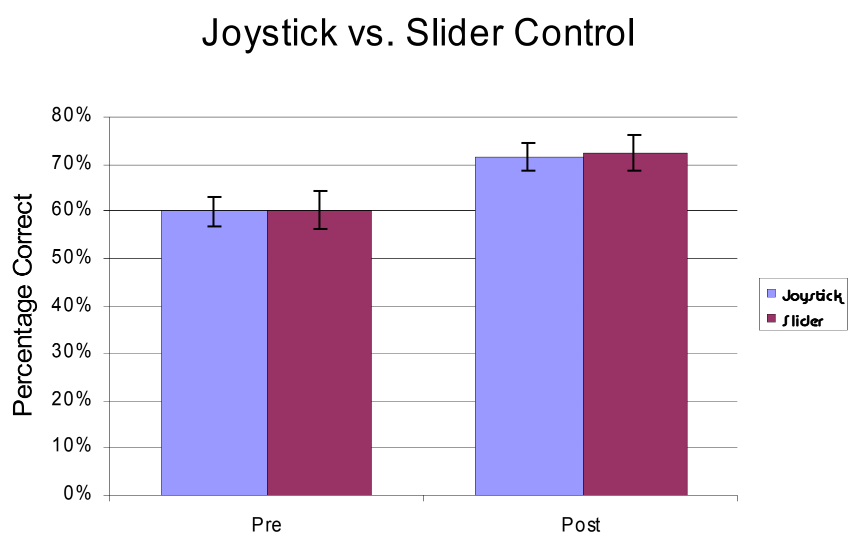


Figure 4: Joystick vs. Slider Group Test Results

Gains on Individual Test Questions

Figure 5 shows the performance on individual questions on the circuit quiz from pretest to posttest. The two experimental groups are collapsed into one (group of 40) since there was no significant difference on any of the questions (except number 18). The brighter red bars indicate the eight questions on which there were significant gains (as revealed by a chi square test, see Table 3) . Please see Appendix A.3 for the test questions to which the numbers refer. First I will examine the questions that showed gains, and then I will analyze the questions which perhaps should have shown more gains but did not, including question 19, which actually showed some decline from pretest to posttest.

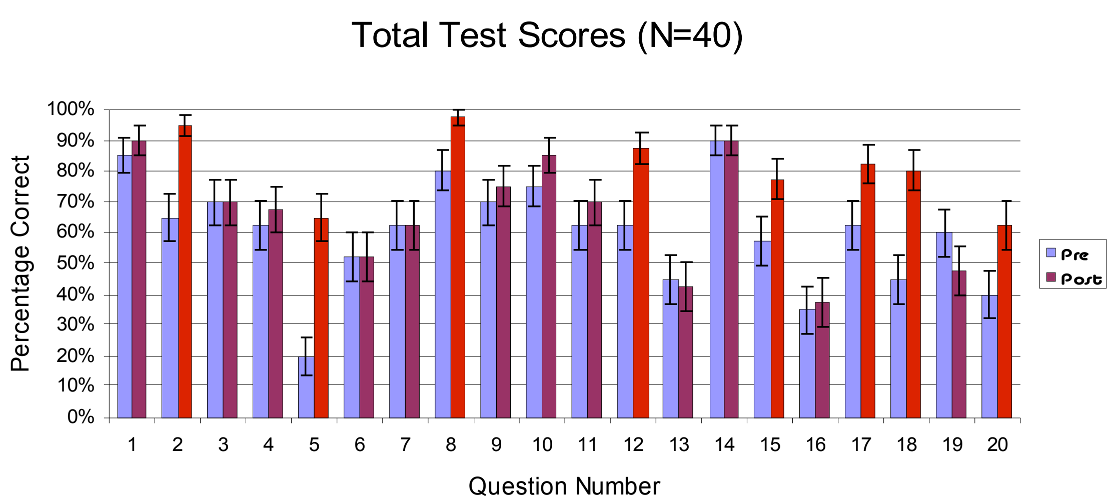


Figure 5: Scores on Individual Test Questions

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

Questions 2 and 12. These questions both involved a current consumption model. Some students believed that current flowed sequentially from the voltage source to each component one after the other. The animated dots showing current flow combined with the real-time control over voltage may have helped students develop a more accurate conception of current flow. The correct answer to question 2 is C, and for question 12 is A. Twelve out of the fourteen students who missed question 2 on the pretest answered it correctly on the posttest. Only two students out of 40 missed question 2 on the posttest. Nine out of the fifteen students who missed question 12 on the pretest answered it correctly on the posttest.

Question 5. Question 5 related to our everyday experience with electricity, and asked why lights in our homes come on almost instantly. Students mostly gave C or D as incorrect answers to question 5 on the pretest. The dot velocity animation of current flow no doubt helped students reason about this question better on the posttest as well. The correct answer is A. Seventeen students who missed this question on the pretest answered it correctly on the posttest. Fourteen students missed the question on the posttest.

Question 8. Question 8 concerned the behavior of a capacitor in a DC circuit. I took to prompt students for what they believed happened in a DC capacitor circuit, and this was evidently the most effective concept taught in the tutoring session. Every student but one answered this question correctly on the posttest, including the students from the 116 class who had little or no prior experience with capacitors. The correct answer is C. The one student who answered incorrectly on the posttest had answered correctly on the pretest, indicating perhaps either guessing or fatigue may have been a factor.

Question 15. This question targeted the spatial misconception of AC voltage circuits. That is, that the voltage varies spatially along the length of the wire rather than temporally throughout the circuit. The dot velocity animation along with the real-time control I believe had an effect in helping students understand the behavior of AC circuits better. The correct answer is D. Ten of the seventeen students who missed this question on the pretest answered it correctly on the posttest. Three students answered the question correctly on the pretest yet incorrectly on the posttest, which again may be attributable to fatigue or guessing.

Question 17. This question targeted mistaken conceptions about bulbs and voltage, in the context of AC circuits. Those students who answered incorrectly on the pretest (N=15) tended to answer B (bulb only lights up when voltage is positive) or E (never lights up because average voltage is 0). The correct answer is C. Nine of the students who answered this question incorrectly on the pretest answered it correctly on the posttest. One student was correct on the pretest but incorrect on the posttest.

Question 20. This last question on the test showed a low pass filter circuit with a capacitor and AC voltage source. However, it should be noted the circuit diagram is different from that primarily utilized during instruction. It did resemble the combined AC sources low pass filter circuit I briefly showed students at the very end of the tutoring session. The students in the 213 gained the most on this question. 50% got it correct on the pretest and 83% on the posttest. This is a circuit they already have covered in their class and labs, and so it is surprising they did not score better on the pretest. The students from the 116 class showed no gain on this question, averaging 50% correct on the pretest and posttest. Evidently covering everything from simple DC circuits up to more advanced capacitor filter circuits in 30 minutes was too much for the unexperienced students to handle. However, the 116 students did show gains on question 18 (discussed below), and thus the fact that the configuration of the circuit in question 20 looked different than the circuit explored in the simulation may contributed to their lack of transfer. It is interesting however that 116 students still averaged 50% correct, which is the same as the 213 students did on the pretest. Looking at the choices for answers on that question, one could probably guess that the answer is either A or B, ruling out C and D due to the wording (the correct answer is A). Thus a 50% correct score may be an indication of chance performance, or guessing. And indeed I do believe that 213 students often confuse low and high pass filter circuits with one another. The real-time voltage control interface and the sequence of activities and contrasting cases I did with the capacitor and inductor circuits may have helped make the differences between the different kinds of filter circuits less arbitrary (and learned only via rote memorization).

Question 18. Question 18 concerned the behavior of current in capacitor circuit as the frequency of voltage was manipulated. This was perhaps the concept I targeted most in the design of the circuit simulation voltage control interface and in the design of the tutoring instruction. Thus it is fortunate that students showed large gains on this question, going from 45% correct on the pretest to 80% correct on the posttest. Students from all three classes showed similar gains on this question. The correct answer in B. Fourteen of the 22 students who answered this question incorrectly on the pretest answered it correctly on the posttest. Ten of these fourteen students were in the experimental joystick group.

Question 18 thus also revealed for the first time some differences between the joystick and slider control groups. In the experimental joystick group, 33% of the students got this question correct on the pretest, while 85% of the same students got the question correct on the posttest. The slider group gained from 55% to 75%. Figure 6 and Table 4 show these figures in more detail.

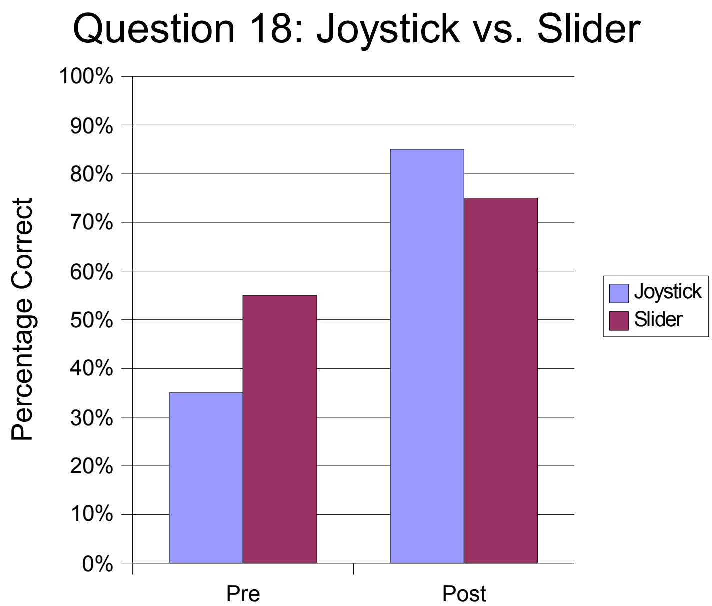


Figure 6: Joystick vs. Slider on Question 18

Table 4: Chi Square Between Group Analysis of Question 18

Question 18:		
Joystick	Gained	10 (out of 13)
	No Gain	3
Slider	Gained	4 (out of 9)
	No Gain	5
	Chi Square:	.0017

Thus the joystick may have indeed provided some assistance to students in modeling the behavior of current in an AC-capacitor circuit. A large part of this difference is due to the differences between the group on the pretest. The difference between the two groups on the posttest is not significant if you do not account for pretest differences, and so I am not interpreting this as strong support for the hypothesis that the joystick was "better" than the slider for helping students understand the behavior of capacitor circuits. However, the results are somewhat encouraging. Perhaps trying "exaggerated" enactive controls such as joysticks may be more effective with younger students and in instructional sessions that do not cover so many different concepts in a single session as I did.

With respect to the test and instruction used in this study, however, I believe the joystick and slider control conditions were too similar to show significant overall differences. I could have compared the simulation with joystick real-time control to a condition in which only traditional DC and AC voltages sources were available, and students could only manipulate voltage indirectly by setting numerical voltage and frequency values. However, I did not want use a learning environment that was intentionally deprived. It would have required significant changes in how I tutored the students as well as other changes. Given the brevity of the instruction and number of concepts covered, students in this hypothetical control condition may have not shown any significant learning gains at all.

<u>Non-Gains on Individual Test Questions</u>

Referring again back to figure 5, some questions on the test did not show any student gains from pretest to posttest. This section explores these questions in more detail exploring possible reasons for the lack of improvement. In general however, these lacks of gains may be due to factors such as the tutoring session being of a short duration and not covering all matters covered on the test, student fatigue, lower student motivation to work through questions on the posttest, guessing, bad or tricky wording of questions, or ceiling effects (high pretest scores) which reduce the room in which to improve.

Questions 1 & 14. Some of the questions did not show much perhaps because of a ceiling effect. Only six students missed question 1 on the pretest, four on the posttest, and one of those four students had answered it correctly on the pretest. 90% answered question 14 correctly as well. Students were not tricked into believing that a bulb is brighter than another equal bulb if it is placed spatially closer to the voltage source.

Questions 3 & 4. Questions 3 and 4 were primitive troubleshooting and design questions. The first asked what happened to a circuit if a bulb burned out, and the second asked students to rearrange the circuit configuration to make the bulbs burn brighter. At the time I originally proposed this study to be conducted in a high school lab class, I was planning to incorporate design and troubleshooting activities which may have helped students more when reasoning through these questions. Instead, like many teachers when confronted with a large amount of topics to cover in a short period of time, I primarily focused on analysis activities and questions instead (analyzing what a circuit is doing). It is also perhaps a limitation of the circuit simulation that it cannot show a bulb that fails. It is possible to rearrange and add or delete components from a circuit however, which is an activity I did not give students time to do in the tutoring session.

Questions 6 & 7. Questions 6 and 7 were more standard textbook type questions borrowed from the DIRECT circuit test created by Engelhart and Beichner (2004). Question 6 concerned the relationship between voltage and power. Students in the tutoring session only explored power via bulbs, not voltage sources. Also this question has somewhat tricky wording by asking for which circuit provided the least amount of power (not most), and providing two circuits which deliver the same amount of power. Question 7 concerned the taking of a "voltage-centered" perspective when analyzing a circuit's behavior. It was a tricky question because double the current through a battery does not change the potential difference (or voltage) of a battery. I had hoped the tutoring session would help more students answer this question correctly, however it did not. My only partial explanation is that perhaps students did not make the connection between potential difference and voltage (they are different words for the same concept). Also perhaps the use of the term "battery" makes students think of it as merely another passive component in a circuit that can be affected by other components, rather than thinking of the battery as a "voltage source" that is controlling voltage in the circuit.

Questions 9, 10, and 11. These questions were about a heater with two heat settings. It involved understanding the relationships between heat and power, current and resistance and voltage (Ohm's law), and current and power. Students who did not answer this question correctly on the pretest did not appear to transfer what I tutored them about power and light bulbs to the context of a heater. Transfer in this manner is difficult to achieve in such a short tutoring session. In these cases I would primarily put the blame on the shortness and weakness of the instructional intervention. Giving students more time to experiment with changing and redesigning circuits, prompting more reflection, and showing them a wider variety of circuit configurations are just some of the things which may have helped students perform better on these questions.

Question 13. Question 13 is a question about the proper placement of a fuse in a circuit. We have used this question in earlier research, and it also appeared to trip up students. It jibes with both their possible misconceptions about current flow (that it is like a substance coming out of the voltage source) as well as their possible everyday experience with fuses, which in some cases are placed before an electrical component or important circuit (like a surge protector, or a house's fuse box). D is the correct answer. According to Kirchoff's current law, the current is the same at all points in a series circuit. Once the current exceeds an acceptable level, a fuse would break, regardless of where it is placed in the circuit. I had thought perhaps the animation of the dots flowing in a series circuit would help students intuitively figure out the correct answer to this question. However, only 43% answered this question correctly on the posttest, which was no gain from the pretest. The incorrect answers were spread between A, B, and C, each of which is designed to catch certain misconceptions. Students answering B might think the question is a trick one, because technically electrons flow from the negative terminal of a voltage source when current is positive. Students might have answered C (use two fuses) because it appeared to be the safest bet. I cannot fault the wording or design of this question, nor the design of the circuit simulation for the poorer student performance on this question. My only recommendation would be to show students how actual fuses work. Despite being very simple to describe, perhaps students have an incorrect model of how a fuse actually protects a circuit, just like students often had an incorrect model of how a bulb works. This would require explicitly adding a “fuse” component to the circuit simulation that can be added to circuits.

Question 16. Question 16 I believe was a bit vague in its wording to the point that it did not help students reason correctly about the problem. The question is asking about one's general perception of a bulb's brightness over time, not the actual brightness at specific time points. There has been research showing students' confusions between concepts such as average vs. instant velocity, and perhaps this is a related yet unexplored issue. Students may confuse average vs. instant brightness levels, or perhaps the question could be reworded to make the distinction more clearly. This question also reveals a limitation of the enactive modeling approach, however. Students can simulate the behavior of a bulb in an AC circuit, but at a greatly reduced time scale. In real world AC bulb circuits, you cannot even see notice changes in a bulb's brightness, because the frequency is so fast. This is similar to issues of understanding the relation between graphs of sound waves vs. our everyday perception of sounds. Perhaps students should be asked an additional, related question about bulb brightness. Is a bulb brighter if the frequency of a voltage source is doubled? The answer is not so straightforward, because the maximum current flow does not change.

Question 16 and the proposed new test question have revealed another area for misconceptions research, as well as an important limitation of the enactive modeling approach tested in this study. That limitation again is timescale. With enactive modeling, students model certain changes via their own actions. This requires those system changes to be done on a human spatial and/or temporal scale. When changing the scale of certain changes, they may lose some qualitative aspects. You cannot easily perceive whether a bulb in a high frequency AC circuit is qualitatively brighter or dimmer on average than a bulb in a lower frequency AC circuit. At this point, one can either have the student step back from the circuit, stopping the enactive control strategy, and let the computer simulate the different frequencies for them on a more realistic timescale, or one can allow enactive control over frequency directly instead of voltage.

Students can play with a circuit that has a bulb and an AC voltage source, and change in the real-time the frequency of the AC source to see any effects on brightness.

Question 19. Lastly, Question 19 is a very important question to analyze. It is a question that appears to involve the most important concepts I was teaching (capacitors in AC circuits), and it is the only question in which students actually did worse on the posttest than on the pretest (60% pre to 48% post). As it turns out, this question was a bit of a trick question for students. You can answer this question correctly without having any understanding of AC circuits or capacitors because the question involves Kirchoff's current law. The current at the two points in the circuit are the same. Where the tutoring session may have hurt students' performance on this question is the fact that if one adds a "voltage out" line at the top right of the circuit, then the correct answer would have been A, which is the most common incorrect response. In fact, the AC capacitor filter circuits I showed students during instruction did measure voltage output at the top right corner of the circuit, which is how it is typically depicted in some textbooks as well. Thus this question was a bit tricky for students, and yet still I would have hoped students would be able to pick up on the subtle differences in this question. I believe only allowing students more time to explore more varied circuit configurations would help students confront tricky near transfer questions such as this one. This is an example of how quick-paced instruction (as seen in normal classroom contexts as well) can actually hurt students' ability to transfer their understanding to different contexts, especially contexts which have superficial (only) similarities to problems they learned in class and in textbooks.

What is the Connection?: Time

What is the connection between the seemingly unrelated eight questions on which students showed significant gains? Why do seemingly related questions, such as questions 1-3 (which all refer to the same circuit) show differing results? The questions are not connected by their structural features, such as AC or DC or the presence of capacitors (Figure 7). There is relatively equivalent improvement across all the structural types of questions. Transfer vs. non-transfer questions were also analyzed. Some questions presented circuits and problems which were very similar to the circuits explored during tutoring. Six questions though involved a farter transfer of learning to different problem scenarios (questions numbered 5, 9, 10, 11, 13, and 16). For example, although we spent the first half of tutoring learning about power and resistance in the context of light bulbs, three questions concerned power in the context of a heating element instead. The underlying principles are the same, however students did not show significant improvement on these questions, nor the other transfer questions (Figure 8) except one, question number five, which asked why do the lights come on so quickly in our homes. Previous research has shown that transfer takes time and is very difficult to achieve. A short instructional intervention will not give students enough time to develop an understanding that can transfer to different situations. I believe in a more naturalistic learning environment, one could employ more strategies to assist transferable learning, such as metacognitive guidance and reflection prompting, challenge or problem-based instruction, and so forth. Regardless, in this intervention, neither the structural characteristics of the questions nor the amount of differences between the questions and the learning context explained what students gained from this instruction.

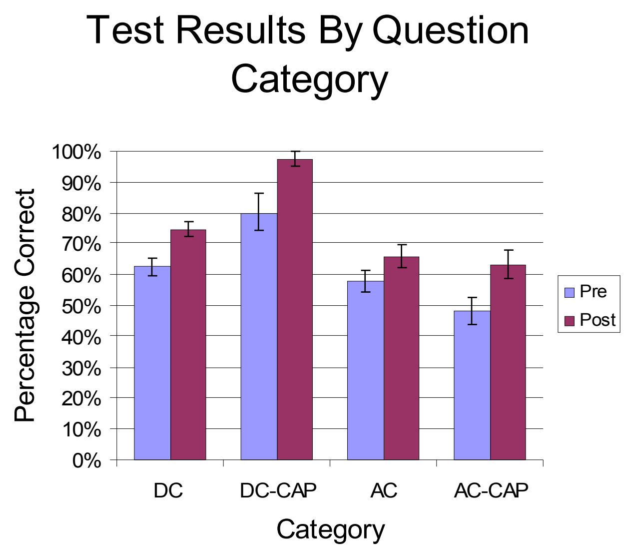


Figure 7: Test Results by Structural Category

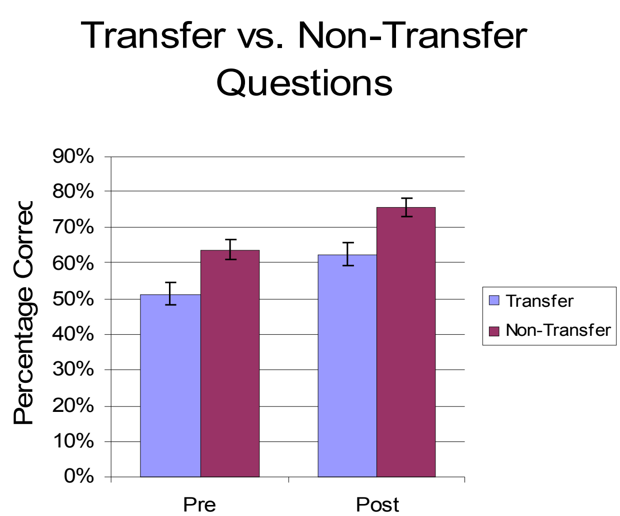


Figure 8: Transfer vs. Non-Transfer Questions

The connection instead appears to be that some questions on the test may force one to imagine the behavior of the circuit over time. If you compare question 1 to question 2, for example, question 1 addresses the "current as substance" misconception, yet one does not need to imagine current flow over time to answer it. Question 2 forces one to consider the changes and behavior of current across time. Question 5 relates to why it takes so little time for lights in our home to turn on. One has to have some mental model of why that is so. Either you may imagine the current traveling at light speed from power station to the house, or you can have a model similar to the one presented by the simulation, in which charges (dots in the simulation) are already in the wires even when there is no current flow. Question 8 also explicitly asks students about the behavior of a bulb in a DC capacitor circuit over time. Questions about AC circuits generally involve considering time-varying behavior as well.

Post-hoc analysis. Overall, ten questions on the test appear to involve considerations of circuit behavior over time. Eight of these questions are the same eight questions identified before which showed significant gains. An additional question in this category which did not show gains is question 16. As discussed earlier, this question involved considering circuit behavior on a time scale far different from the one explored in the simulation. One had to consider the average brightness of a bulb on the timescale of everyday experience, instead of the timescale of milliseconds as in the simulation. The tenth question in this category is question 19, which showed a marginally significant decline in performance from pretest to posttest. As discussed before, this question tricked students because of the lack of a voltage output branch in the top right corner.

Figure 9 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).

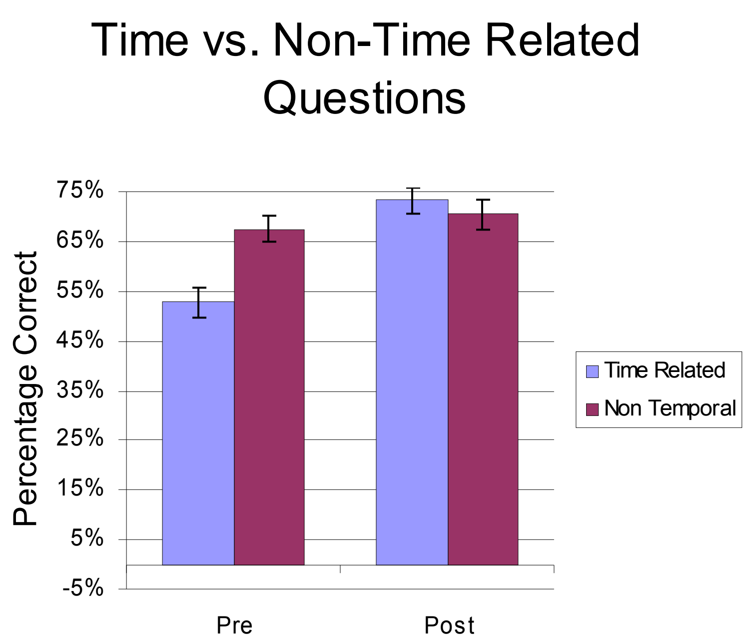


Figure 9: Time vs. Non-Time Related Questions

Qualitative Observations

I have not closely analyzed the videotapes of the tutoring sessions, however I do recall some things I observed overall while conducting this study. Students in the joystick group were sometimes surprised that they would be using a joystick with the simulation. These are college students, and devices like joysticks or force feedback controls are a far cry from the typical instructional technology interfaces they have used. The standard circuit simulations students use in college only allow voltage control indirectly and numerically. Students in these simulations enter a frequency value for an AC source, and then run a transient analysis of the circuit, and the simulation would then produce a static graph of the voltage or current over time. Joysticks and steering wheels are more commonly used by either younger students in video games, or some adults in very narrow and specific contexts such as flight simulations and racing games. Thus the age-appropriateness of joystick interfaces may not be so good for older students.

I did notice however that students using the joystick controller required much less encouragement from me to try changing the voltage in real-time. Often students using the joysticks would oscillate the voltage back and forth before even being prompted to do so. I also believe students using the joysticks did more unprompted manipulations of voltage than the students using the mouse and slider control. I had to encourage the students using the mouse and slider more to try changing the voltage in a manner similar to how an AC voltage source does.

The use of the joystick control also allowed me to use the mouse while students were manipulating the voltage. I used the mouse to point out things happening in the circuit or graphs, and also to make changes to the circuit. In the mouse and slider condition I had to physically point with my hand or a pen to items on the screen to help students notice them. Also I had to ask permission each time I needed to take over the mouse control temporarily.

Most of the students were enthusiastic about the computer simulation, and could see the value it would have to their studies in the 112, 116, and 213 classes. One student did not appear to think the animations of current were as helpful as doing the analysis with equations and other traditional means. Afterward I checked his test score and he had answered every question on the pretest correctly except one, which he did answer correctly on the posttest. Thus he appeared to already be very knowledgeable about the circuit behavior.

Some students were definitely more reflective about what they were learning during the tutoring session, although this was not very common. These students would sometimes also explain a concept the simulation was showing them before I had a chance to explain it.

CHAPTER VII

CONCLUSION

This research explored how students may learn about the behavior of electrical circuits by enactively participating and controlling a circuit simulation. This was tested in two ways. A computer simulation was developed that allowed for real-time reactive control of the voltage. Secondly, two different forms of control over the voltage in the circuit were tested. One manner of controlling the voltage was via an on-screen slider (or scrollbar) control, and the other method of control was via a force feedback joystick. After only a 30 minute tutoring session with the circuit simulation, students did gain in their understanding of some difficult concepts about circuit behavior, as measured by a multiple choice conceptual test. In particular there was significant evidence that students were quickly able to overcome a common misconception about the temporal behavior and flow of electrical current. Current does not flow like a substance in an empty pipe from the voltage source to each component sequentially over time. Instead, charge is already in the wire, and current is the uniform flow of that charge.

The form of input control used with the circuit simulation did not make a significant difference. Both the slider and joystick were more or less equivalent in their effects on students' abstract understanding of dynamic circuit behavior. I believe both the joystick and slider interfaces provided a gestural medium by which to communicate to students such difficult circuit concepts as frequency, current, capacitance, and inductance. In effect the joystick and slider may both gave more weight and meaning to such words and symbols. Frequency is not just a number anymore, but a behavior or an action. The enactive participation both these forms of control enabled had a catalyzing effect on student learning, allowing students to construct an understanding of the behavior underlying these concepts much quicker than with traditional instruction via lectures, textbooks, and formulas.

Both the slider and joystick interfaces afforded the same interactions and manipulations possible with the simulation. However, our history of experience with both forms of control are very different. With joysticks and steering wheels we can naturally imagine using them to oscillate side to side, or up and down. But the standard mouse and on-screen slider controls are traditionally used for very different purposes. Sliders and scrollbars are almost solely used for scrolling text (down) on screen. We do not typically use scrollbars for real-time control of dynamic on-screen behaviors. Computer mice are also very poor for use with controlling real-time changes. They are best used for only one purpose: pointing at some location on the screen. Motion of the mouse is typically non-linear and not as predictable when used in other non-pointing contexts. However in this study, through my (the tutor's) encouragement, students were able to re-adapt the use of these control interfaces for the purpose of changing the animated behavior of the on-screen circuit simulation. It remains an open question though, of how well these forms of control may work in a more normal educational setting such a classroom where a teacher or other student may not always be there to encourage particular interactions with the simulation. In such situations and especially with younger students in K-12 schools, it may possibly benefit to use an exaggerated form of voltage control such as a joystick or steering wheel, with which students may explore the behavior of the simulation with less encouragement. Other considerations for changes that might be made to the simulation and to the instruction before applying to classroom are discussed in more detail later in this section. First, however, a general overview of the theoretical implications this research may have for the field of intuitive physics research is presented.

Implications for Intuitive Physics Research and Applications

This research was a small first step in expanding the field of intuitive physics into a new direction. It has explored students' intuitive understanding of more complex circuits than were previously studied (including circuits with AC voltage sources, capacitors, and inductors), and it tested a new instructional technique, enactive modeling, based on research on embodied and enactive learning. I would like to connect the experience gained from this study to some of the previous research discussed in the introductory sections.

Some of the applications this research may have to previous educational research are only speculations, because I did not test the simulation in a regular classroom setting. For example, Susan Goldin-Meadow and others have shown that students use gestures when trying to explain and learn certain math concepts, and that teachers using gestures while explaining these concepts to others are more effective. I believe using the circuit simulation with a joystick would be beneficial because the joystick facilitates observable and shareable gestures. Students can easily empathize and imagine what another student or teacher is doing when they see that person is doing while controlling the simulation. Also, I believe the gestures would add a new vocabulary that the teacher could employ to teach these more advanced concepts of circuit behavior such as the frequency of an AC voltage source. A teacher could use the gesture of turning an imaginary joystick or steering wheel side to side slowly when discussing low frequency behavior and gesture faster when discussing an increase in frequency. Again, this adds more weight and meaning to the concept, frequency, which is typically only presented as a static visual symbol (omega) or just as a word.

There are implications from this study for others who have previously tried force feedback devices and other forms of real-time reactive control in educational contexts, including microcomputer-based laboratory (MBL) research with motion sensors and other sensors. These researchers have primarily applied the use of these devices for instruction on Newtonian physics or for example to let you "feel" what a complex molecule feels like. A force you feel in the input device corresponds to a force in the simulation. There is a spatial connection between the movement of the input device and the movement being simulated. I think the study presented here demonstrates that there in fact does not need to be a direct spatial correspondence between the form of input and the behavior being simulated. In the circuit simulation tested here, there is no literal or mechanical connection between moving a joystick (or slider) and changing voltage. There is only a temporal connection (changes occur immediately), and a symbolic connection (the direction you move the input device creates more or less voltage). I believe that this opens up the number of symbolic simulations where one can apply an enactive modeling or participation strategy considerably. Consider one example below.

Another domain in science besides electrical circuits that is a common target for simple animated computer simulations is thermodynamics. In particular, there have been many simulations made of Charle's and Boyle's laws. Given a container filled with molecules, these laws express the relationships between pressure, volume, and temperature. These simulations typically use numeric inputs and slider controls to change the variables, and students view an animation of the molecules for feedback. Temperature, however, is a concept with which students have a great deal of difficulty understanding in the same sense that expert scientists understand it. Just as students often think of current as a substance, many students think of temperature (or heat) as a substance as well, instead of increased molecular kinetic energy. To apply the enactive modeling strategy to this case, imagine students can grab a molecule in the chamber (symbolically using the computer mouse) and "wiggle" it around, instead of merely inputting a different numeric value for temperature. This wiggling motion has the effect of adding kinetic energy to the other molecules via collisions. This technique combined of course again with other techniques such as contrasting cases and predict-observe-explain activies may help students more intuitively gain a scientific understanding of temperature.

Lastly, as one other area in which this study may have theoretical implications, I did not mention in the introduction one particular theoretical dispute in the intuitive physics research community, because it has spanned decades now and would require a separate and more in-depth analysis. There has been a long running dispute about the nature of students' intuitive conceptions in science and other domains. One position advocated by Michelene Chi and others has noticed a resemblance between the ideas about physical phenomena expressed by novices and early (or pre) scientific theories about physics, biology, and other domains. For example, in medieval times, a common belief was that the world is flat, and that the sun and the rest of the objects in the sky rotate around the earth rather than the other way around. Some young students have the same conceptions early on in life. Researchers argued that students develop their own intuitive theories about things happening in the world, just as pre-scientific cultures did. Another position advocated by Andrea diSessa and others however is that students' knowledge is not so coherent and organized as medieval theories were. Rather, their knowledge is "in pieces," as diSessa phrases it, because it is closely connected to the superficial features of the context. Studying the verbal explanations given by students while solving problems in science and other domains, one may find them often giving self-contradictory explanations for phenomena, which indicates students may not be employing an underlying, consistent theory in their reasoning. diSessa termed the different "pieces" of knowledge students employed in their reasoning p-prims, or phenomenological primitves. Some examples include "force as effort", "force as mover", and "force as resistance." These are primitive ideas students have about force in different contexts. Their ideas appears to be completely unrelated to one another, despite the fact that scientifically, the same force principle applies in all those contexts. As yet, there has been little direct public discussion between the two perspectives about their differences, nor has one ever been shown to be clearly more correct or more useful for instructional applications.

Enactive learning and embodied cognition theories I believe provide a better explanation for students' intuitive reasoning about physical phenomena. Furthermore I believe both diSessa and Chi in their later writings are converging upon action as a common basis for many of students' misconceptions. diSessa later begain clustering various p-prims together and acknowledged that those involving action, agency, and force appeared to be most central. Chi has focused on helping students acquire a cognitive schema to better understand emergent, acausal processes such as current flow and molecular diffusion to replace the “substance-like” schema students often incorrectly use to reason about such phenomena. As it happens, action is often a basis for the underlying schemas we use while performing tasks or reasoning, and Chi (2005) acknowledges that our innate, embodied understanding of causality (seen even in infants) may have something to do with our difficulty understanding emergent processes like diffusion. However, both diSessa and Chi have tended to give disembodied accounts of students' understanding, ignoring the potential role of gestures and other actions.

I do not believe I have enough of an empirical basis yet to draw any strong conclusions, but the enactive learning and perceptual-motor theories that inspired the design of this circuit simulation and instruction may help lead us to better theoretical frameworks and guiding metaphors for understanding and alleviating students' misconceptions about natural phenomena. This does not involve abandoning or disputing previous research in intuitive physics. Take for example this quote from Chi (2005):

> Our approach, based on our proposed explanation, would be to focus on teaching the underlying causal structure of emergent processes via the ontological attributes. The idea is that if we can help students build a general structure or schema of emergence first (in the context of using simulations and role-playing activities), then presumably learning, in the sense of assimilating and integrating new knowledge with existing knowledge, can be more easily undertaken because the relevant cognitive structure will already have existed.

An enactive learning and modeling approach can help fill in some of the blanks in this approach. For example, how to design simulations and role-playing activities such that they encourage the formation of particular action schema that are more helpful for understanding particular scientific concepts. Again, however, there is not enough space nor is there enough evidence yet from this study to warrant the full exploration of how to apply enactive and embodied learning theories to the wealth of pre-existing research in intuitive physics. In the following sections, I digress and just look at the small changes that could be made to the simulation and to instruction in order to possibly enhance its effectiveness with students.

Improvements to the Design of the Simulation

I was often reminding the students in this study that the circuit simulation was still in progress. I only had time to make a few changes to the original simulation. I told the students that my interviews with them were helping me think of other ways to improve the interface, animations, and other features of the circuit simulation, and indeed it has. In fact, most of the suggested ideas listed below for improving the simulation I was able to ascertain after tutoring only a few students.

1. Use the same scale for graphs. By default I believe when there are multiple graphs on the screen, they should use the same scales and maximums for the y-axes.
2. Put graphs near component they are measuring. Many students suggested this themselves, that instead of putting all the graphs on the bottom of the screen, the graphs might be more easily understandable if they were placed near the

component they were measuring, such as the voltage source or capacitor. This is in line with much cognitive research in educational psychology and human-computer interaction.

3. Visualize difference in component values. I believe it might be helpful to make different resistors, or different capacitors and so forth more visually distinguishable. A 100 ohm resistor and a 200 ohm resistor look exactly the same in this circuit simulation. Perhaps, especially for younger students, it might be helpful to show larger resistors as longer, and bigger capacitors and inductors as larger. Of course this does introduce two potential problems though. One is that it might engender new misconceptions about these components. Also, it would require more space on screen and make the layout of more complex circuits look visually awkward.
4. Capacitor and inductor animations. Above all else I believe some type of dynamic animation depicting what happens in capacitors and inductors may be of help to students. A capacitor could be shown as two plates which the dots fill up, or else perhaps a tank that gets filled up with charge. An inductor can be shown as a coil of wire with arrows running through the middle to depict the magnetic field with pushes on the current.
5. Allow enactive control over other variables besides voltage. As discussed earlier regarding question 16 on the test, it may be helpful to allow students to manipulate other variables in the system in real-time besides voltage. Allow students to continuously change the frequency of an AC source, for example, via either a slider or perhaps some other other enactive form of control that has a

connection to the meaning of frequency such as tapping a key or button, or moving the mouse around. Students can explore the effects of frequency on bulb brightness, impedance, and other qualities. Other variables students could be given control over could include maximum amplitude of an AC source, resistance of a resistor, capacitance of a capacitor, and so forth. Giving students more direct control over an AC voltage source's frequency and/or amplitude can allow them to explore more advanced concepts and behaviors such as AM and FM signal modulation.

6. Allow enactive control over multiple system variables simultaneously. I believe allowing multiple students (or perhaps "simulated" students or agents) to control various aspects of the system at the same time may also be beneficial. A simulation with multiuser features could support either multiple mice and other input devices and/or multiple remotely connected users, as in multiuser online games. This opens up new possibilities for games and other problem or challenge-based learning contexts one could design for students. Imagine for example two circuits, one with a resistor and one with a capacitor. One student controls the voltage of both circuits simultaneously, while another student controls the resistance of the resistor in the first circuit. Graphs of the voltage output of both circuits are shown side by side. As the student controlling the voltage oscillates the voltage like an AC source at different frequencies, the second student could try changing the resistance so that the output of both circuits matches. It would be difficult to impossible to perfectly match the impedance characteristics of the capacitor, but as long as the students get a sense that with

faster changes (higher frequencies) you need to lower the resistance of the resistor to match the other circuit (and vice versa), I believe it may be a useful learning experience.

7. More modern circuit design interface. The current simulation requires right clicking to make any changes or additions to the circuit. Also to edit the values of a single component you have to right click and edit values in a floating window. Most modern development environments and circuit simulations show the components alongside the left side or top of the window in a toolbar, and let you drag and drop components onto the designer pane. Also, many development environments use a property editing pane on the right side of the window when you select a single component to edit, rather than using a floating window.
8. Age appropriateness. Other than the above issues, this simulation is primarily designed for undergraduate electrical engineering majors. It is very different from other animated simulations designed for younger students, which show more realistic depictions of batteries and bulbs. In fact this simulation originally did not contain bulb components at all; I added them myself, however the visual depiction of the bulbs and bulb brightness could be improved. One other simulation for example shows lines of light emanating from the bulb rather that changing color from black to yellow as I did. Perceiving color changes is more difficult than detecting spatial changes, especially when the brightness changes exponentially as it does with the power consumed by a bulb.

Improvements to Instruction

I would recommend the testing of this simulation in a more natural classroom or circuit laboratory setting, as well as more informal learning settings, such as museums or the home. Especially in classroom or laboratory-based settings, one could create various problem or challenge-based activities for students to do with the simulation. Such activities encourage more reflection from students, and help them make more connections in their understanding, leading to transfer of their understanding to different scenarios. The use of the joystick or steering wheel may also help in contexts when multiple students are using the computer at the same time. One student can try changing the voltages while another edits other parameters in the circuit or redesigns the circuit. Here are some simple examples of the activities younger students might do, and the concepts linked to these activities. Some of the activities are short enough that they might also work as interesting activities for students to do on their own in informal learning settings, such as when using an educational computer kiosk at a museum, or using a computer at home.

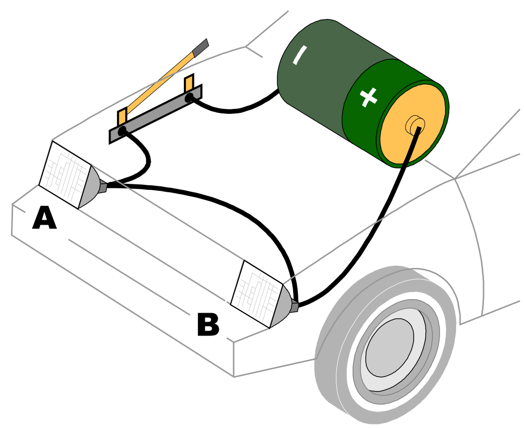
1. Build a flashlight. This involves learning such concepts as the necessity of a complete circuit for current to flow, and the components needed for a basic circuit (voltage source, wire, and a resistive load, the bulb). Here students may also switch between putting a battery (constant voltage source) in the circuit, and controlling voltage themselves with one of the enactive interfaces, be it joystick, steering wheel, or the slider.

2. Build car headlights. Now they can see the difference when two bulbs are in the circuit. The resistance is higher. To emphasize the concept of resistance, they can try to make the headlights have a "high beam" and "low beam" mode.
3. Broken headlight. If one of the headlights goes out, both go out. In a real car (and other examples such as Christmas lights) this is not the case. How can the circuit be redesigned so that both do not go out. This involves learning about series vs. parallel circuits.
4. Design a fading car door light. Design a circuit that emulates the behavior of a car door light, that gradually fades out when the door is closed. This involves using a capacitor in the circuit.

APPENDIX A: CIRCUIT QUIZ

Test on Electrical Circuit Behavior

Please clearly circle your choice for the best answer to each question.
Questions 1-4 refer to the picture below.
The headlights on a toy auto are wired in series to the battery as shown here:



1.) Circle the statement that best describes this arrangement. When the switch is closed,

a. The headlight A on the left will be brighter than headlight B.

b. Headlight B will be brighter than headlight A.

c. Both headlights will be equally bright.

d. Neither headlight will light at all.

2.) When the switch is first closed,

a. Headlight A lights before headlight B.

b. Headlight B lights before headlight A.

c. Both headlights light at the same time.

d. Neither headlight lights at all.

3.) If Lamp A burns out,

a. Lamp B burns more brightly than it did before the burnout.

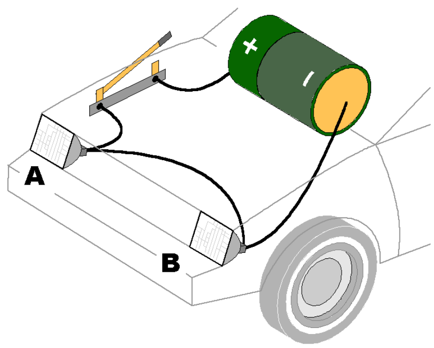
b. Lamp B burns just as brightly as it did before the burnout.

c. Lamp B lights but burns less brightly than it did before the burnout.

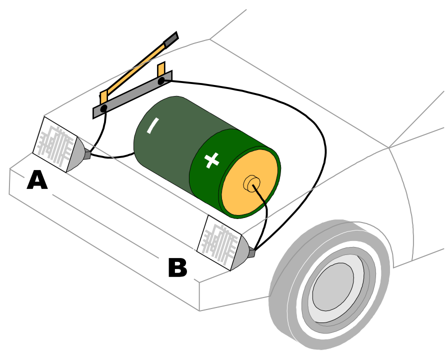
d. Lamp B does not light.

4.) An engineer wants to redesign the car in such a way that the headlights burn more brightly. Which of the following designs will make the headlights burn more brightly?

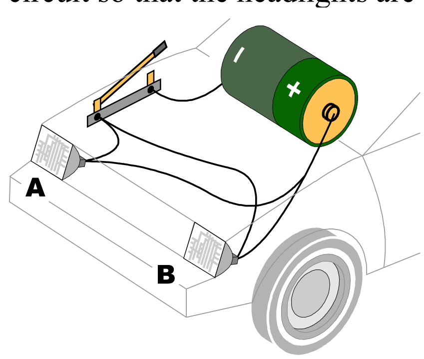
a. Reverse the way the battery is connected:



b. Move the battery so that it is in between the two headlights.



c. Rewire the circuit so that the headlights are in parallel with the battery.



d. The brightness cannot be increased without changing or adding batteries or using different headlight bulbs.

5.) Why do the lights in your home come on almost instantaneously?

a. Charges are already in the wire. When the circuit is completed, there is a rapid rearrangement of surface charges in the circuit.

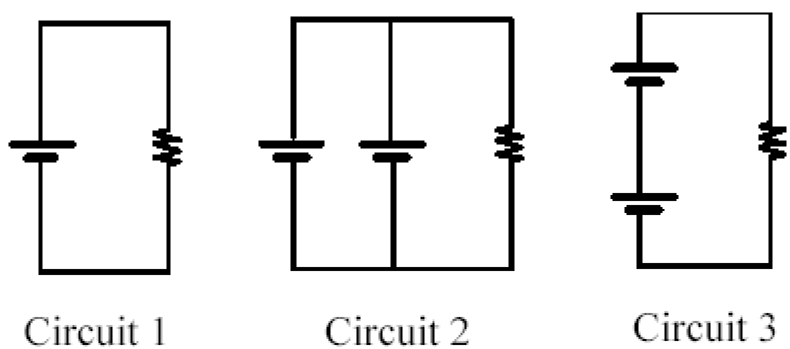
b. Charges store energy. When the circuit is completed, the energy is released.

c. Charges in the wire travel very fast.

d. The circuits in a home are wired in parallel. Thus, a current is already flowing.

6.) In the figure below, all batteries and resistors should be considered equal.

Consider the power delivered to each of the resistors shown in the circuits below. Which circuit or circuits have the least power delivered to it?



a. Circuit 1
b. Circuit 2
c. Circuit 3
d. Circuit 1 = Circuit 2
e. Circuit 1 = Circuit 3

7.) If you double the current through a battery, is the potential difference (voltage) across a battery doubled?

a. Yes, because Ohm's law says V = IR.

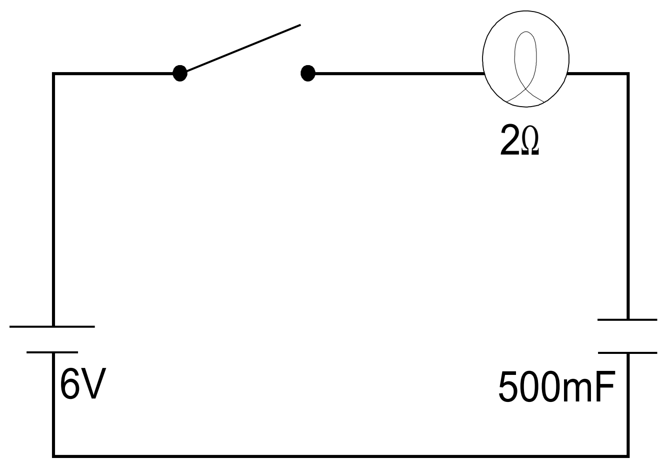
b. Yes, because as you increase the resistance, you increase the potential difference.

c. No, because as you double the current, you reduce the potential difference by half.

d. No, because the potential difference is a property of the battery.

e. No, because the potential difference is a property of everything in the circuit.

8.) A battery, a large capacitor, a switch, and a lamp are wired in series, as shown below:



Initially the capacitor is discharged. What happens when the switch is closed?

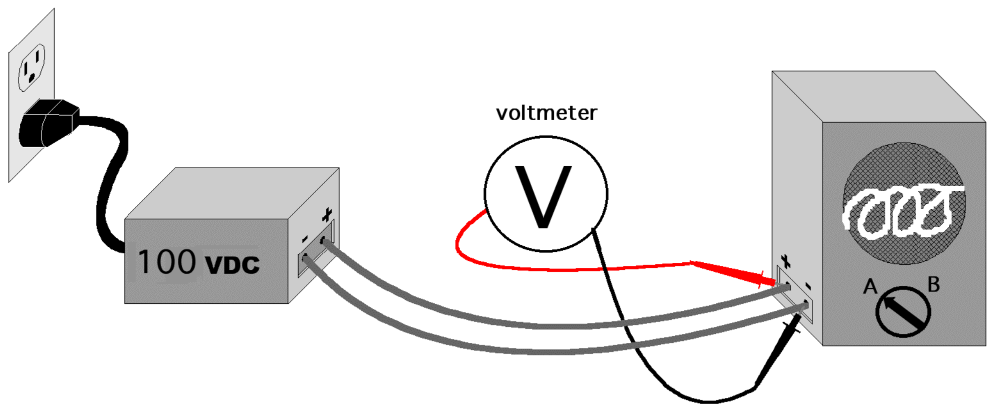
a. The lamp will not light up at all.

b. The lamp will gradually grow brighter and brighter.

c. The lamp will glow brightly at first, then gradually dim and go out.

d. The lamp will glow steadily all the time.

Questions 9-11 refer to the picture below.



An electric heater uses a 100 volt DC power source. When the heater is at one setting (A), it draws 3 Amperes current. At another setting (B) it draws 4.5 Amperes current.

9.) We measure the voltage across the poles of the heater at the two heat settings. How do these readings turn out?

a. The voltage is greater at the A setting than the B setting.

b. The voltage is greater at the B setting than the A setting.

c. The voltage is the same at both settings.

10.) The power supply is disconnected, and the resistance across the heater's power terminals is measured with an Ohm meter. How do these readings turn out?

a. The resistance at the A setting is greater than the resistance at the B setting.

b. The resistance at the B setting is greater than the resistance at the A setting.

c. The resistance is the same at both settings.

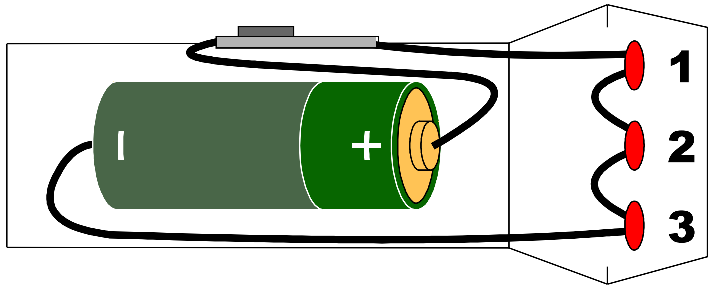
11.) Which setting generates the most heat?

a. Setting A

b. Setting B

c. Both settings generate the same level of heat.

12.)A battery powered game controller has three decorative LEDs connected in series through a switch to the battery.



What happens when the switch is closed?

a. All three LEDs light at the same time.

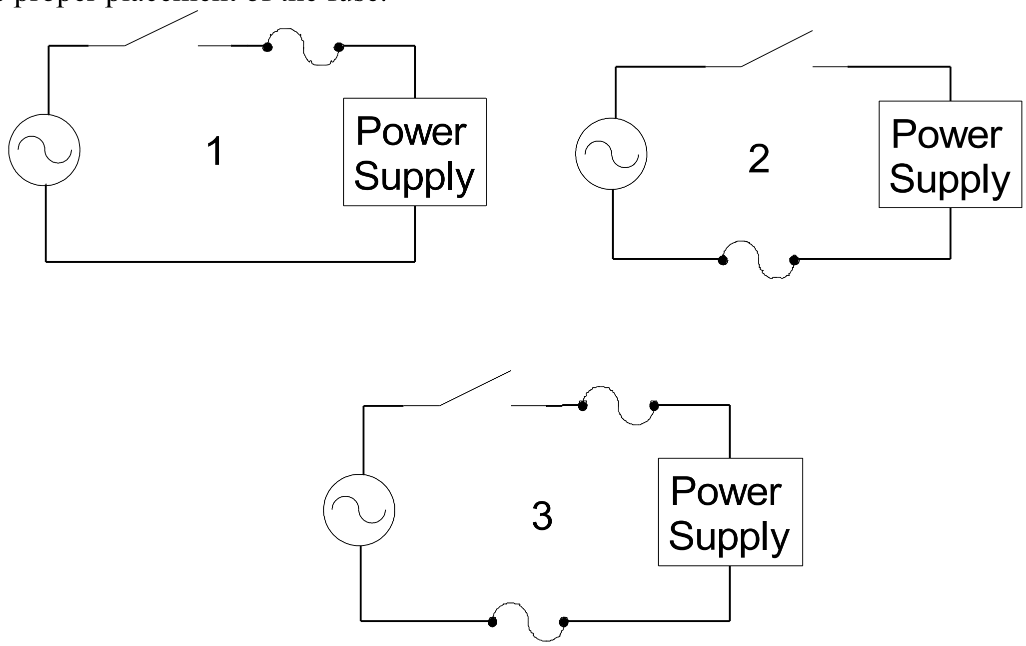
b. LED 1 lights, then LED 2, then LED 3.

c. LED 3 lights, then LED 2, then LED 1.

d. LEDs 1 and 3 light, then LED 2 lights.

e. LED 2 lights first, then LEDS 1 and 3 light.

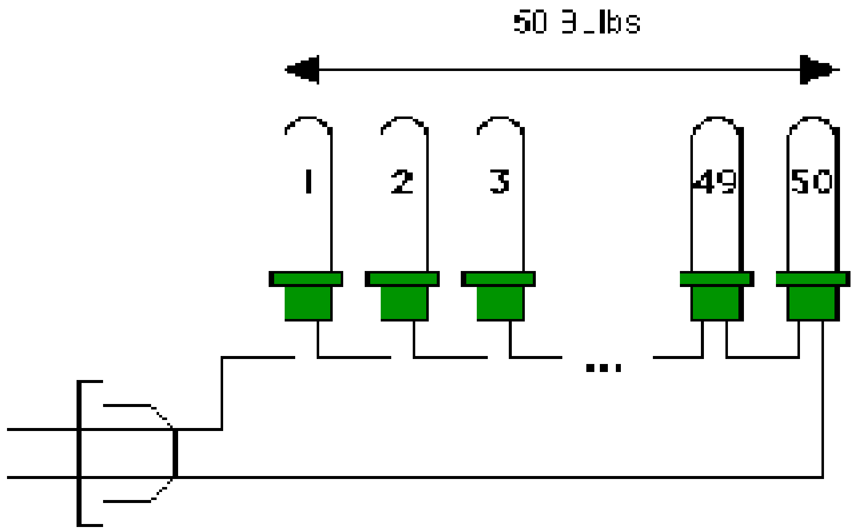
13.) An expensive power supply is connected to an AC power source. A decision has to be made on where to place fuse(s) to protect the power supply electronics from AC power surges. Examine the three circuit diagrams below and decide which describes the proper placement of the fuse.



a. Circuit 1 places the fuse in the right position to protect the sensitive load, and it is the only position where the fuse can be placed to protect the load.
b. Circuit 2 places the fuse in the right position to protect the sensitive load, and it is the only position where the fuse can be placed to protect the load.
c. Circuit 3 with two fuses is the only one that will protect the sensitive load.
d. It does not matter where you put the fuse in the circuit, but you need only one fuse.

Questions 14 and 15 refer to the picture below.

A Christmas light bulb string with 50 lamps is connected to an AC wall outlet.



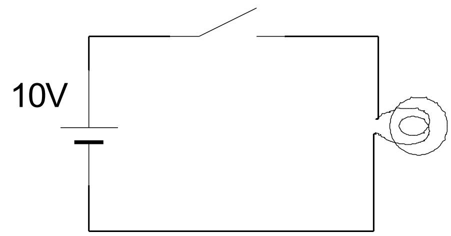
14.) Which bulb will be brightest?

a. Bulb 1 is the brightest.
b. Bulb 50 is the brightest.
c. All bulbs are equally bright.
d. The brightness of the bulbs decreases from the first bulb to the 50^{th}.

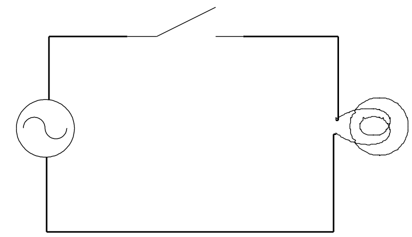
15.) The string of lights is plugged into a special device that provides them with a 1 Hz source of AC power. When the string is first plugged in to this device:

a. All 50 lights burn steadily when they are plugged in.
b. Bulbs 1 and 50 light up first, then Bulbs 2 and 49, then Bulbs 3 and 48, etc.
c. Bulb 1 lights up first, then Bulb 2, then Bulb 3, etc.
d. The lights flash on and off, all at the same time.

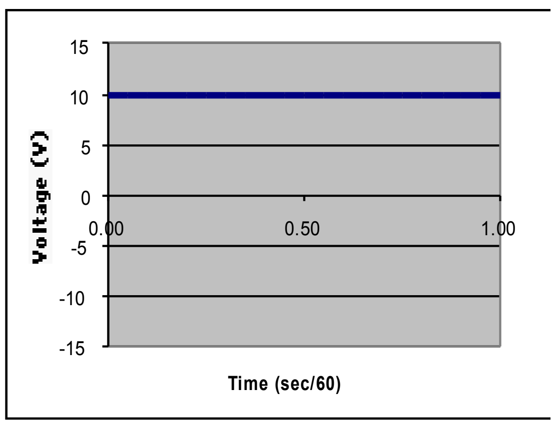
16.) Circuit A consists of a lamp connected to a 10V DC power source. Circuit B consists of an identical lamp connected to a 10V peak, 60 Hz AC signal generator. The following shows each circuit and the voltage waveform of the corresponding power source.

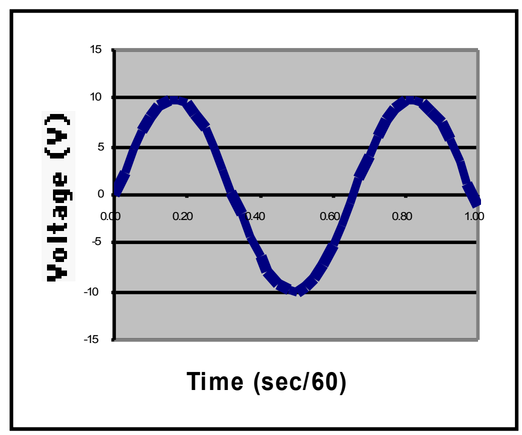


Circuit A



Circuit B

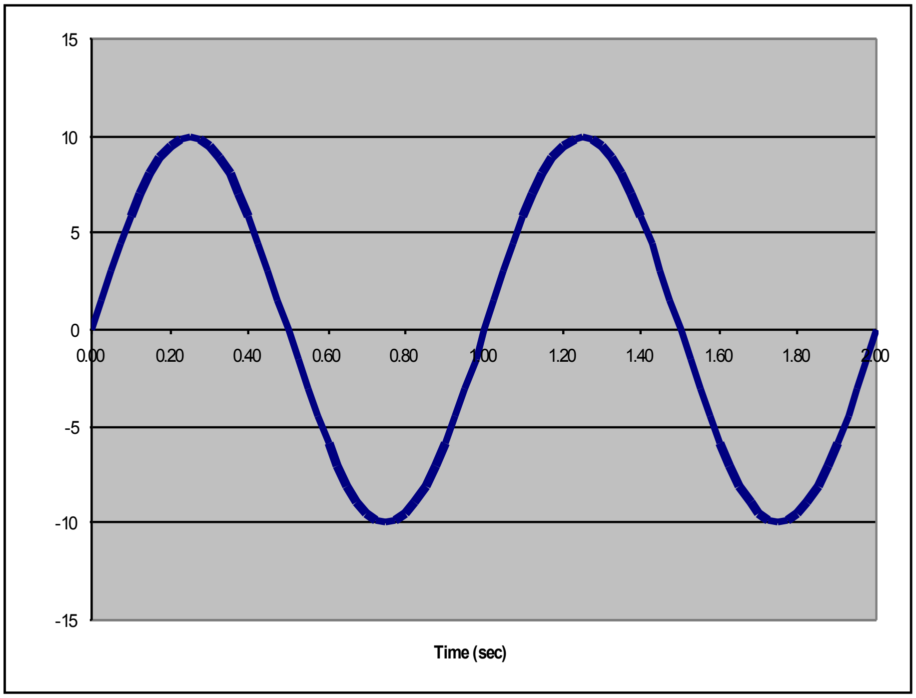




Are there any differences between the brightness of the bulbs in the two circuits (when the switch is closed)?

a. The two bulbs are equally bright.
b. The bulb in Circuit B is the brighter.
c. The bulb in Circuit B is the dimmer, but it still lights.
d. The bulb in circuit B does not light.

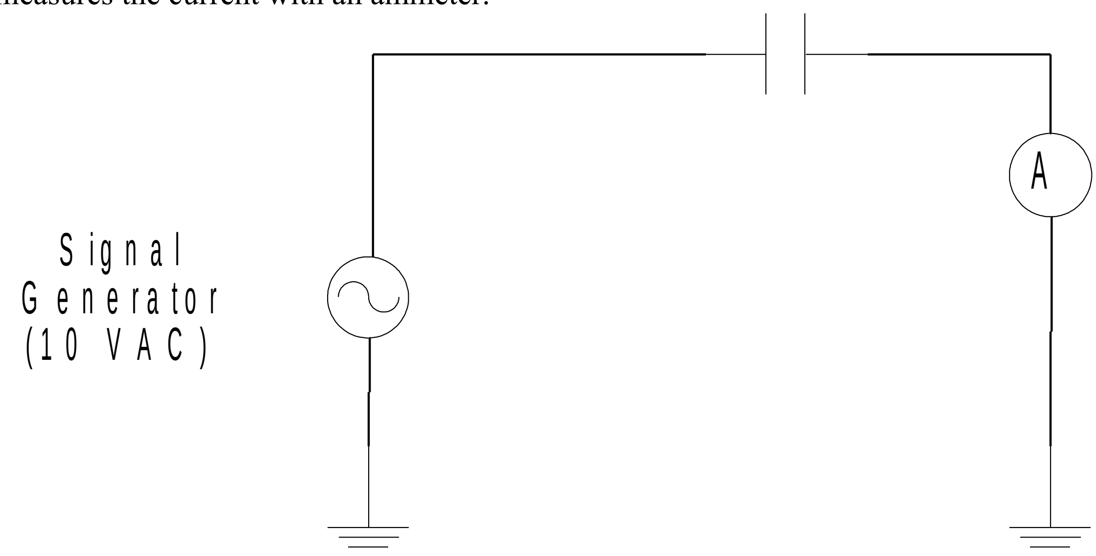
17.)A low frequency (1 Hz) AC source has an output voltage like that shown below.



If the source is used to light a lamp, how many times in two cycles (2 sec) will the bulb reach maximum intensity?

a. Once
b. Twice
c. Four times
d. Eight times
e. Never, the average voltage is 0.

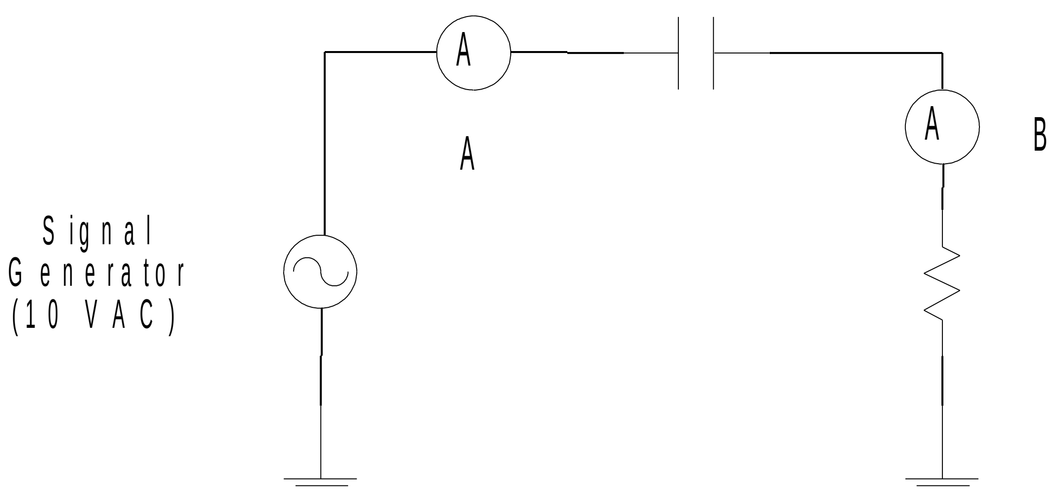
18.) An engineer connects a capacitor to a variable-frequency signal generator and measures the current with an ammeter.



At 60 Hz, he finds that the ammeter reading is about 1A. When he cranks the frequency to 120 Hz, he finds that the ammeter reading is now

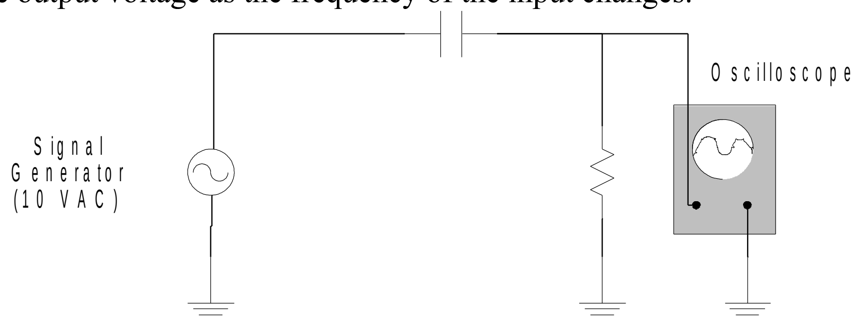
a. about the same value.
b. about twice the value.
c. about half of the previous reading.
d. 0 A.

19.) The technician inserts a resistor in series with the capacitor. He places two AC ammeters in the circuit as shown below. What can you say about the two ammeter readings?



a. The reading on Ammeter A will be greater than that of Ammeter B.
b. The reading on Ammeter A will be 0. The reading on Ammeter B will be greater than 0.
c. The current reading for both ammeters is 0 A.
d. Both the current readings are identical and greater than 0.

20.) With the signal generator providing a 10V input, we use the oscilloscope to measure the output voltage as the frequency of the input changes.



How does the output voltage change with the frequency of the input signal?

a. The higher the frequency, the higher the output voltage.
b. The higher the frequency, the lower the output voltage.
c. There is no change in the output voltage as the frequency of the source signal is changed.
d. The output voltage is zero for all frequency settings.

APPENDIX B: IRB CONSENT FORM

Name of participant: ____ Age: ______

The following is given to you to tell you about this research study. Please read this form with care and ask any questions you may have about this study. Your questions will be answered. Also, you will be given a copy of this consent form.

You do not have to be in this research study. You can stop being in this study at any time. If we learn something new that may affect the risks or benefits of this study, you will be told so that you can decide whether or not you still want to be in this study.

1. What is the purpose of this study?

You are being asked to take part in this research study because you are enrolled in an electrical engineering course at Vanderbilt University. The purpose of this study is to explore strategies for using a computer simulation to assist students in learning about the behavior of electrical circuits. This will help us design better instruction and tools for learning about circuits. In particular, this will help improve the design of the circuit simulation tool you will be using.

2. What will happen and how long will you be in the study?

You will be working through some circuit problems using the simulation. Before and after using the simulation, you may complete a short quiz consisting of multiple-choice questions, none of which require math calculations. The entire study will take approximately 1 hour. The researcher (Doug Holton) will act as a facilitator during the study to answer any questions you have and guide you through the activities. The activities with the simulation will require you to dynamically interact with the computer via a mouse or force-feedback joystick.

While using the circuit simulation you will be videotaped so that we may analyze how students are using the simulation and how to improve instruction. These videotapes will be kept indefinitely by myself and shared in research presentations and publications, but your name and other personal information will be kept confidential. Neither your instructors nor anyone else aside from myself will be able to see your personal information. Your instructors will not see any videotape until after you have completed the EECE courses in which you are currently enrolled.

3. Costs to you if you take part in this study:

None

4. Side effects and risks that you can expect if you take part in this study:

The potential risks, discomforts, or inconveniences associated with this study are minor. None of the work you do as part of this study will have any effect on your grades in your courses. If using the computer simulation causes you any discomfort for any reason, you may stop participation at any time. The quiz you will take before starting and after finishing is relatively short, multiple-choice only, and involves no mathematical calculations.

5. Risks that are not known:

None

6. **Good effects that might result from this study:**

a) The potential benefits to science and humankind that may result from this study include helping make electrical circuit behavior more easily understandable to students and people in general. Also the computer simulation that you are using will be redesigned and improved based on an analysis of how you and others learn while using it. The simulation is available online to download and use for free by anyone – thus your participation in this study will benefit others learning about electricity too.
b) The potential benefits to you from this study include making the concepts involved in your EECE courses more easily understandable. Your experiences using the simulation (which you are welcome to continue to use anytime after the study, I will provide you with a URL to download it) may help you in your current and future EECE courses and future experiences designing, troubleshooting, or analyzing electrical circuits.

7. **Payments for your time spent taking part in this study or expenses:**

You will be compensated with $15 upon completion or partial completion of the simulation activities and quizzes. You will also be provided with access to the computer circuit simulation to download and use.

8. **Reasons why the study doctor may take you out of this study:**

I will ask you myself to stop participation if there is a technical problem with the computer or video camera or any other technical or outside disruption of our interview. You will still receive $15 for participation. Any tapes and data collected by the researcher will be erased or deleted.

9. **What will happen if you decide to stop being in this study?**

You may withdraw from participation at any time without any risk to you by notifying the principal investigator verbally or in writing. You will still receive $15 if you have at least partially completed the second quiz. Any tapes and data collected by the researcher will be erased or deleted.

10. **Who to call for any questions or in case you are injured:**

If you should have any questions about this research study or if you feel you have been hurt by being a part of this study, please feel free to contact **Douglas Holton** at **799-7859** or my Faculty Advisor**, Dr. Bob Sherwood** at **343-2596**.

For additional information about giving consent or your rights as a person in this study, please feel free to call the Vanderbilt University Institutional Review Board Office at (615) 322-2918 or toll free at (866) 224-8273, or email at http://mcapps01.mc.vanderbilt.edu/IRB/WkshpReg.nsf/Suggestion Form?OpenForm.

Confidentiality:

All reasonable efforts will be made to keep the personal information in your research record private and confidential but absolute confidentiality cannot be guaranteed. Your information may be shared with institutional and/or governmental authorities, such as the Vanderbilt University Institutional Review Board, if you or someone else is in danger or if we are required to do so by law.

STATEMENT BY PERSON AGREEING TO BE IN THIS STUDY

☐ **I have read this consent form and the research study has been explained to me verbally. All my questions have been answered, and I freely and voluntarily choose to take part in this study.**

____________________ ____

Date Signature of patient/volunteer

Consent obtained by:

____________________ ____

Date Signature

____

Printed Name and Title

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