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Reductionistic Conceptual Models and the Acquisition of Electrical Expertise

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Abstract

Our objective has been to determine whether working with reductionistic models reduces students' misconceptions, and increases the coherence and flexibility of their expertise as they solve problems and generate explanations. We conducted experimental trials of an interactive learning environment that provides models of circuit behavior. In these trials, we examined students' performance on a variety of circuit problems before and after they worked with either (a) a "transport" model alone, or (b) the transport model augmented with explanations of its processes in terms of a "particle" model. The posttest results reveal that, while both groups performed well on a wide range of tasks, students who received the particle-model explanations achieved higher levels of performance on tasks that require an understanding of voltage and its distribution. We conjecture that this is due to the particle model providing students with a mechanistic model for charge distribution that is consistent with the behavior of the transport model and that inhibits the construction and use of certain common misconceptions.

Introduction

Computer-based models can embody different perspectives on system operation. For instance, models can reason about circuit behavior at the macroscopic level; that is, they can incorporate reasoning about circuit behavior through the application of a set of laws that govern the distribution of voltages and currents within a circuit. Alternatively, they can represent the behavior of circuits at a more microscopic level. For instance, one can imagine seeing how electrical forces within a circuit cause mobile charged particles to be redistributed when, for example, a switch is closed. When internalized, such models enable students to simulate mentally and to explain domain behavior (Gentner & Stevens, 1983; Spoehr & Horvath, in press).

Our hypothesis is that physical domains, such as electrical circuits, cannot be understood from a single perspective, rather, they must be conceptualized from multiple perspectives. Further, in order for expertise to have explanatory depth and consistency, these alternative perspectives must cohere. The question we thus address is how can a set of models be designed to show the linkage between microscopic and macroscopic conceptualizations of system behavior? Further, does working with such a set of linked, reductionistic models help students to understand and reason about the behavior of electrical circuits?

In this article, we introduce three perspectives on circuit behavior: (1) *microscopic*, (2) *macroscopic*, and (3) *intermediate* (which models circuit behavior at a level that is intermediary between the other two -- see White 1993 for a discussion of "intermediate models").

1. The Microscopic Perspective -- reasoning about interactions among particles. The first conceptualization we introduce, called the "particle model," focuses on the behavior of mobile, charged particles within a conductive medium and their changes in position and distribution over time. In this model, conductive materials are divided into small slices, and the primitive process is the Coulomb interaction between particles (like charges repel, unlike charges attract). Thus, if one puts two slices next to one another, and if there is a difference in their initial net charges, then there will be an electrical force exerted on the charged particles within the two adjacent slices. This can be thought of as due to the negative charges repelling one another and the positive charges attracting the negative charges. These forces will accelerate the mobile charges (i.e., the electrons), causing them to migrate (i.e., be redistributed) from the more negatively charged slice to the more positively charged slice until both slices have the same net charge. The model can be elaborated to explain resistance in terms of obstacles that affect the motion of charged particles.

2. The Intermediate Perspective -- reasoning about local flow of charge. In order for students to investigate the properties of a system that incorporates a mechanism like the Coulomb interaction, it is useful to move to a higher level of abstraction. To facilitate such investigations, we created the "transport model," which incorporates a more abstract representation of the charge of a slice (the vertical bars shown in Figure 1) and of the flow of charge from one slice to another (the horizontal arrows shown in Figure 1). For instance, Figure 1 shows two slices of a resistor; the resistor slice on the left is neutral and the one on the right has a negative charge. If one connects these two resistor slices, one can watch what happens over time. The primitive process in this model is a transport or "local-flow" process that governs the movement of charge within each time interval. (In the model, time is quantized as discrete intervals.) In each interval, the amount of charge moved depends on the difference in charge between adjacent slices. As this model runs, one can see that in each time increment, adjacent slices go part way towards reaching equilibrium. By observing this process, one can watch the system settle into a steady state. Thus, in the example shown in Figure 1, initially there is a large difference in the charge density of the two slices, and this causes a large current flow between the two slices. As one continues to step through time, one sees that the difference in charge density of the two slices becomes smaller and smaller and the current flow between the two slices becomes correspondingly smaller and smaller until finally the two slices have the same charge density and current no longer flows. By the use of this representation, and stepping through time, one can infer the simple causal relationship that the larger the difference in charge densities of adjacent slices, the greater the current flow between those two slices.

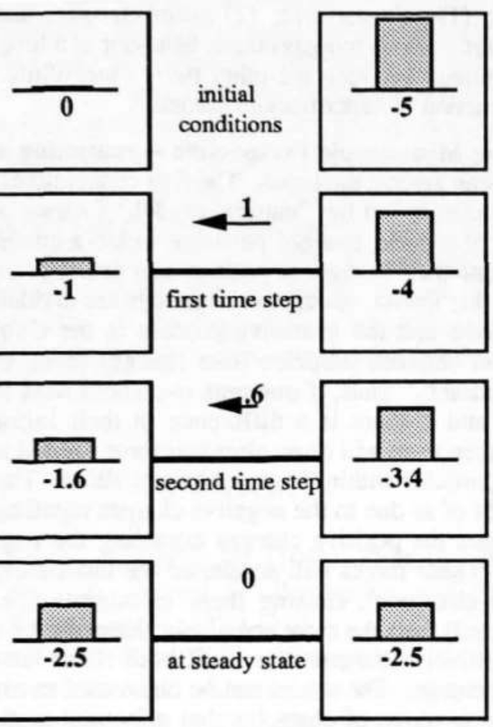

Figure 1. Using the transport model to illustrate charge redistribution across time. The model uses the difference equation: flow(t) = k x Δcharge(t) where Δcharge is the difference in charge between connected slices at time t and flow is the amount of charge transfer at time t. The parameter k is set to .2 in the simulation. Note that there is no distinction between amount of charge and charge density in this model since all of the slices of conductive material are the same size.

With this model, one can increase the resistance of a resistor by putting more and more of these slices next to one another. The charge on a given slice affects only those of adjacent slices; it does not affect the charges on slices that are further away from it. (The mechanism ignores interactions among widely separated charges.) A battery is modelled as a device that reacts to maintain a constant difference in charge between its positive and negative terminals. If one assembles these components into a complete circuit like the one shown in Figure 2 and lets the process run, the process can be seen to eventually reach a steady state in which the distribution of charge throughout the circuit has stabilized. By observing this process run, one can see how Ohm's law and Kirchhoff's laws emerge from a system that behaves in accordance with this local-flow mechanism. In the example presented in Figure 2, the equilibrium will be a dynamic equilibrium (unlike that shown in Figure 1): The net charge on a slice of a resistor will remain the same, not because there is no longer a current flowing, but because the current flow into each slice will exactly equal that leaving the slice. Thus, Kirchhoff's current law emerges from the behavior of the simulation. In this way, the transport model (based on the local-flow equation) provides a model of transient as well as steady-state circuit behavior and thereby illustrates the origins of the steady-state circuit laws.

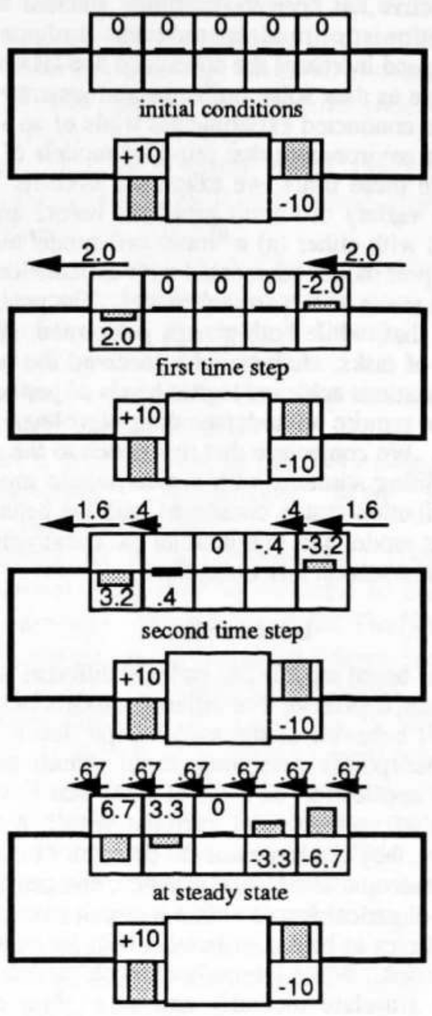

Figure 2. The transport model applied to a simple circuit containing a battery and a resistor. Note that many time steps have occurred before steady state is reached.

3. The Macroscopic Perspective -- reasoning about steady-state circuit behavior. In order to solve a wide range of circuit problems (such as circuit design and prediction problems), students need to derive principles or rules that enable them to determine steady-state circuit behavior. Students can work with the transport model to develop such rules in qualitative or quantitative form. For instance, in our prior instructional research (White & Frederiksen, 1990), we created computer-based models that use qualitative rules to reason about circuit behavior at the macroscopic level. These models determine the distribution of voltages within a circuit via a set of qualitative rules of the form "If you have a circuit with an open in it, the only voltage drop in that circuit will be across the open; whereas, if you have a circuit that is a complete conductive loop, there will be voltage drops across resistive devices in that circuit." The rules are, in effect, qualitative expressions of the laws of quantitative circuit theory. Students in the present study had to develop such rules from working with the transport model (as opposed to working with qualitative or quantitative models that explicitly articulate such rules).

Together, this set of reductionistic and macroscopic perspectives provides a hierarchical decomposition such that emergent behaviors at one level of the hierarchy become the primitive processes for reasoning at the next, higher level. The lower level models provide an explanation for (they unpack) processes that are considered primitives within the higher level models. For example, within the particle model, particles are seen to migrate over time into adjacent, connected regions of a circuit at a rate that is proportional to the difference in charge densities between the regions. This process, represented at a higher level of abstraction, becomes the primitive process governing the flow of charge within the transport model. Likewise, within the transport model, voltages have a certain distribution across a resistive network when the model reaches a steady state. Rules for describing these outcomes, in turn, govern the reasoning that operates at the next level in the hierarchy, that is, macroscopic reasoning about steady-state circuit behavior.

When we surveyed physics textbooks, electrical-engineering textbooks, and technical textbooks (used in training electrical technicians), we were unable to find a dynamic, physical model such as the transport model (Frederiksen & White, 1992). The fact that we did not find such a mechanism presented in any of the textbooks suggests that, from the perspective of physicists, either it is unnecessary to develop a model of transient phenomena within DC circuits, or that such models, presented in the form of differential equations, are so complex that they confuse rather than enlighten.

However, while physicists may accept abstract, algebraic presentations of circuit laws, most students find that mathematical abstractions make sense only after they understand the domain in mechanistic terms. If a dynamic, physical model is not supplied, they will attempt to invent their own, or to interpret circuit behavior in terms of their prior conceptions of electricity (Collins, 1985; White & Frederiksen, 1990). In either case, misconceptions and inconsistencies develop. For instance, one prevalent misconception is the "current-as-agent model" in which batteries are viewed as current sources, rather than voltage sources, and current seeks the path of least resistance as it finds a way through a circuit (Cohen, Eylon, & Ganiel, 1983). Our hypothesis is that the formation and use of such misconceptions can be avoided if students are presented with an alternative, causal account of circuit dynamics. For these reasons, we created the particle and transport models, that each embody simple mechanisms, to help students acquire dynamic, physical models for the origins of steady-state circuit behavior. Introducing students to the particle and/or transport models, which differ in level of mechanism and degree of abstractness, will allow us to investigate this hypothesis and to determine the characteristics that conceptual models need to posses to enable students to acquire coherent, flexible expertise.

Experimental Trials

We are conducting experimental trials of a computer environment that embodies this set of models. In these trials, we are varying the number of hierarchical models that are given to groups of subjects. The purpose of the research is to determine the properties of models that foster learning and, more specifically, to investigate whether learning a reductionistic model (or models) (a) reduces students' misconceptions, particularly their adherence to the current-as-agent model, and (b) increases the coherence and flexibility of their knowledge as they solve circuit problems and explain circuit phenomena. The experiment reported here involved a comparison of students' performance on a variety of circuit problems before and after they had learned either (a) the transport model alone (the TM group), or (b) the transport model augmented with explanations of its processes in terms of the particle model (the PM group). We compared performance on problems for which the current-as-agent model is sufficient with performance on problems that require a full understanding of how voltages are created and distributed within a circuit.

Subjects. The TM group and the PM group included 10 and 9 subjects, respectively. The subjects were all undergraduates at Brown University who had taken no previous courses in electricity, who professed to be naive about the subject, and who scored below a cut-off value on a screening test of knowledge of electricity.

Learning Sessions

Students in the two groups learned how to conceptualize circuit behavior from working with an interactive simulation that embodies the transport model. The learning environment incorporates a carefully designed sequence of models and problems for developing the basic principles of DC circuit functioning. This sequence of problems is based upon a progression of successively more elaborated versions of the transport model that begins, in level 1, with a simple model of the flow of charge between two slices of purely conductive material. The sequence next introduces, in level 2, the concept of resistance and portrays the iterative process of charge redistribution that occurs between resistive slices (e.g., Figure 1). Next, in level 3, a model of a battery is presented, and students observe the effect of a battery on simple series circuits containing a battery, a switch, and a resistor (e.g., Figure 2 with a switch). In the remaining three instructional levels, students learn about the behavior of more complex circuits. These include: in level 4, more elaborate series circuits containing multiple resistors of varying lengths (i.e. voltage dividers); in level 5, parallel circuits; and, in level 6, hybrid series-parallel circuits. In these later levels, students are encouraged to abstract the steady-state circuit laws that form the foundation of our qualitative, macroscopic models (White & Frederiksen, 1990) and of quantitative circuit theory.

In addition to the simulation software, students are given a workbook to accompany each of the six levels in the sequence. The workbooks begin with explanatory material for introducing the new concepts and principles at each level. This is followed by a series of activities to be carried out using the software. In each activity, the student first sets up a problem on the computer and then is asked to simulate the problem mentally and make some written predictions. The student next runs the simulation on the computer and compares his or her predictions against the simulation results. The student then reads some interpretive material and seeks to resolve conflicts and amend any misconceptions. He or she can then (optionally) rerun the simulation and ask it to generate explanations for its behavior, or can run a variant of it using different initial charges. Finally, the student is asked to formulate rules that summarize the results and that will help in making predictions in future activities. These include both qualitative and quantitative rules useful for determining steady-state circuit behavior.

Subjects in the PM group received descriptions of the particle model within levels 1 and 2 when the idea of flow of charge was introduced. Subjects in the TM group received alternative descriptions that did not unpack the flow process in terms of the particle model.

Assessment Sessions

To determine the effectiveness of these instructional materials on students' understanding and problem solving, the following assessment tasks were administered before and after instruction:

(a) Understanding of circuit concepts. In these tasks, subjects were asked to make judgements or generate explanations concerning basic circuit concepts such as voltage, current, and resistance (e.g., "What is meant by the term voltage?").

(b) Predicting circuit behavior. In the circuit behavior tasks, a set of circuits, some of which are similar to those used in the instructional sequence, was presented in schematic form. The subjects were asked to predict whether or not a light would be on when particular switches within the circuit were open or closed. In addition, for each item, they were asked to give an explanation as to why that particular behavior would occur. Finally, they were asked to rate their confidence in their predictions of circuit behavior.

(c) Designing circuits. In the circuit design tasks, subjects were asked to design, using a given set of components, a circuit that would exhibit a particular behavior (e.g., "Design a circuit with a battery, a switch, and a resistor such that when the switch is closed, the resistor is hot."). The circuits to be designed included circuits of greater complexity than those contained within the curriculum, such as circuits containing two switches that jointly affect the behavior of lightbulbs within the circuit.

In addition to the above assessments, three additional assessments were administered only as posttests. These allowed us to assess subjects' understanding of the transport model, and their ability to reason about the voltages and currents obtained when a circuit reaches a steady state, that is, to reason about the emergent behaviors resulting from the operation of the transport model.

(d) Understanding of the transport model. A set of multiple choice and quantitative problems required subjects to demonstrate their mastery of the transport model and to perform the local-flow calculations entailed in its operation.

(e) Reasoning about relative magnitudes. In the relative magnitudes tasks, students were asked to compare voltages or currents for two components within a circuit, or across two separate circuits, in order to determine if one or the other was larger or if both were the same. This assessment provides the most direct test of subjects' abilities to reason about voltages and the dependence of current on voltage.

(f) Quantitative circuit analysis. In the quantitative tasks, students were asked to calculate voltages and currents for series and parallel circuits that vary in complexity.

Experimental Findings

There were no significant differences between the PM and TM groups on any of the pretest measures, nor were there significant differences in study times for the two groups (the average study time was 4.5 hours). The two groups of subjects thus appear to have had comparable initial knowledge of electrical circuits and to have spent similar amounts of time reading the workbook materials and using the computer simulations. The effects of learning using the circuit simulations and workbooks were significant for both groups of subjects for nearly all of the assessment measures administered before and after learning. For the PM group, there were significant effects of learning for all measures. For the TM group, there were significant improvements on the circuit concept and circuit design assessments; however, for the circuit behavior tasks, there were significant improvements for the total correct, but not for the rationales or confidence scores.

Our major source of information about the cognitive effects of learning the particle and transport models was a set of comparisons of performance for the PM and TM groups carried out for the assessments administered following learning.

(a) Understanding of circuit concepts. Significant group differences were found when subjects were asked to generate explanations for electrical concepts ($t_{17} = 1.75$, $p < .05$; PM group 86% correct, TM group 77% correct). Furthermore, a content analysis of subjects' responses showed that PM subjects had a better understanding of voltage than did TM subjects ($t_{17} = 3.35$, $p < .002$): PM subjects were more able to provide explanations of charge flow in terms of the charge gradients, and were more apt to describe batteries as voltage sources (i.e., devices that maintain a constant difference in voltage across their terminals). Finally, they were more apt to provide a physical mechanism in explaining the effect of resistance on current flow ($t_{17} = 4.49$, $p < .001$), as in, for example, "resistance inhibits charge from flowing freely through a substance by atoms that it encounters and collides with within the material."

(b) Predicting circuit behavior. Both groups showed high levels of performance in predicting circuit behavior (PM group 84% correct; TM group 83% correct). While there was no significant overall difference between the two groups on the total number of correct predictions for the circuits presented, or on the correctness of rationales that subjects provided for their predictions, this may be due to the nature of the circuits employed in this assessment. Since the predictions involved qualitative statements of whether or not a light would be on when a switch within a circuit was open or closed, most of the problems could be solved by reasoning solely from a current perspective, that is, by tracing paths for current to follow. However, when we analyzed performance for two circuits that require reasoning about voltages within the circuit and for which the current-as-agent model is insufficient, we found a significant difference between the PM and TM groups, with the PM group (mean of 39%) outperforming the TM group (mean of 20%; $p < .05$ using the Fisher exact test). This result, that the particle model provided a more solid understanding of the difficult concept of voltage distribution within a circuit, received further substantiation in the relative magnitudes assessment.

(c) Designing circuits. Both groups of subjects were able to design circuits involving a single switch with a high degree of success (97% correct for the PM group and 87% correct for the TM group). While performance was poorer for more difficult two-switch problems, the two groups continued to show a substantial degree of success on this unfamiliar task (58% for the PM group and 65% correct for the TM group).

(d) Understanding of the transport model. Both the PM and TM groups demonstrated a high degree of mastery of the transport model concepts and the calculations entailed in its operation. On a set of qualitative, multiple-choice questions, the PM group had an average of 91% correct and the TM group had 80% correct ($t_{17} = 1.18$, $p = .13$). On a set of quantitative calculations similar to those carried out within the transport model, both the PM and TM groups correctly completed 73% of the items.

(e) Reasoning about relative magnitudes of voltages and currents. There was a significant group difference in judging the relative magnitudes of voltages or currents within a circuit or between two circuits ($t_{17} = 2.16$, $p < .02$) with 81% correct for the PM group and 66% correct for the TM group. An analysis of variance revealed that this difference between groups was due entirely to their performance on series/series-parallel circuits as opposed to single resistor and parallel circuits ($F_{2,34} = 4.25$, $p < .02$, for the interaction of subject group and circuit type). Successfully judging relative magnitudes within these circuits cannot be accomplished solely through reasoning about current flow; such judgements require thinking about how voltages are distributed within a circuit. Again, the difference in performance between groups for this particular class of circuit problems provides evidence that the particle model has successfully dealt with the current-as-agent misconception and has improved understanding of the most difficult aspect of steady-state circuit behavior, that is, understanding the distribution of voltages within circuits.

(f) Quantitative circuit analysis. The final task assessed how well subjects in the two groups could calculate the actual values of voltages and currents within a circuit. The voltage and current relationships that are needed in this task represent emergent properties of the transport model of circuit behavior. Because the transport model provides quantitatively correct solutions for voltages and currents within any circuit that it simulates, subjects have been exposed to the relevant relationships. However, while the workbook exercises endeavored to draw attention to some of these relationships, the algebraic forms of circuit laws were not explicitly presented, and subjects were not given any quantitative problems to solve that utilize these laws. Nonetheless, we found that subjects given the transport model were able to solve a fair number of the quantitative problems. Despite large variability within groups, there is some evidence that the PM group again outperformed the TM group ($t_{17} = 1.51$, $p < .07$; PM group 43% correct, TM group 28% correct).

Discussion of Results

The posttest results reveal that both the PM and TM groups achieved a high level of performance on a wide range of problems. However, the PM group subjects, who received a particle model explanation for the basic concepts and processes of the transport model, achieved a level of performance that was superior to the TM group on problems that require an understanding of voltage and its distribution. We conjecture that this is due to the particle model explanations providing students with a mechanistic model for voltage and its distribution that is consistent with the behavior of the transport model, and that inhibits the construction or at least overrides the use of the current-as-agent conception.

To elaborate, in the current-as-agent conception, students, seeking a causal account for circuit behavior, invent a model in which current wants to flow into regions that offer it the least resistance as it finds its way from one side of the battery to the other. In some versions of this conceptual model, current is thought to carry energy to devices it encounters along the way, causing lightbulbs to light and resistors to become hot. The battery is regarded as the source of current and energy for the circuit. Unfortunately, this conception is inadequate for dealing with problems that require reasoning about relative magnitudes of voltages and currents.

The transport model represents an attempt to provide students with an alternative, local, causal account of current flow by showing how differences in charge densities on connected sections of a circuit cause a local flow of charge to occur. This account was designed to focus students' attention on voltages as the causative agent in understanding circuits, and was therefore expected to help students overcome the limitations and difficulties associated with the common current-as-agent conception.

We have seen, however, that despite evidence that students have mastered the transport model, the transport model alone was not sufficient for overcoming the limitations of current-as-agent conceptions. For example, subjects given only the transport model continued to show difficulties in solving series circuit problems that required them to reason about voltages, and did not provide explanations for circuit concepts that incorporated voltage and charge gradients. However, when we introduced an additional model to unpack the basic flow equation (flow = constant x Δcharge) in terms of charged particles repelling one another, the picture changed. Subjects no longer showed greater difficulty in solving problems that required them to reason about the distribution of voltages within a circuit. They were also able to generate explanations using voltage as the cause of current flow.

Our conjecture is that these improvements in performance are due to two predilections that students have in creating conceptual models for understanding electrical circuits: (a) they prefer mechanistic, causal models in which individual objects act as local agents of change; and (b) they strive for consistency in their causal accounts of circuit phenomena.

Objects as local agents. We argue that the particle model differs from the transport model by providing a causal mechanism that includes objects that are active agents in determining the flow of charge. Within the particle model, individual, mobile, charged objects exert and react to repulsive forces that cause them to move away from one another. This results in a flow of charged particles away from crowded areas into less crowded areas. Subjects who are given this causal mechanism can then accept the transport model as a more abstract and efficient way of representing the local flow of particles. In contrast, subjects who are exposed only to the transport model are given a causal account solely in terms of the flow of aggregate charge, much as are students who are given a water analogy for electricity. In either case, local differences in pressure within the charge, or fluid, could be thought of as causing current flow; however, there is no mechanism involving individual agents, only an abstract notion of "pressure difference." Such a model did not provide subjects with a causal mechanism that they could accept in attempting to understand circuit behavior. They therefore continued to use the limited current-as-agent model.

Causal consistency. Our findings are that students who have been given the particle model are able to transfer their understanding of voltage and voltage distribution from the context of local charge transfer to an account of steady-state circuit behavior. Thus, students who were first given the particle model did not invoke the current-as-agent model when they later attempted to understand the behavior of circuits in the steady state. Our conjecture is that this unwillingness to invoke the current-as-agent theory in their model of circuit behavior was a manifestation of their general desire for parsimony and consistency within their conceptual models of electricity. That is, we conjecture that they did not introduce the current-as-agent model in explaining steady-state circuit behavior because that would have involved introducing an alternative mechanism that conflicts with one they had already accepted, namely, that differences in charge density cause the movement of mobile, charged particles. This conjecture assumes that students strive for parsimony and consistency in constructing theories. If it is true, it implies that coherence among models within a progression of linked models is essential for learning and understanding.

Conclusions. The findings of this study support the hypothesis presented in the introduction: In order to achieve coherent, in-depth expertise one needs to acquire a set of linked models (such as the particle model, the transport model, and the steady-state model) in which the emergent properties at one level become the primitive properties of the next level. This reductionistic sequence of models grounds abstractions (such as Ohm's Law) via a mechanistic unpacking of the physical phenomena. Without such a reductionistic unpacking down to the microscopic level, students develop inconsistent views of circuit behavior, and their performance in solving problems at the macroscopic level is significantly impaired.

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