Combining Mathematical and Everyday Models of Electricity

Gautam Biswas, Daniel Schwartz, Sean Brophy, Bharat Bhuva, Tamara Balac, & John Bransford
Learning Technology Center, Vanderbilt University
Nashville, TN 37203 USA
biswas@vuse.vanderbilt.edu

As part of a larger project exploring people's concepts of alternating current (AC), we have been appraising people's knowledge of direct current (DC). Because DC is taught before AC, ideas developed for DC may influence AC understanding. Our research indicates that in electricity most conceptions and misconceptions come through instruction. People do not come to the domain of electricity with a virile set of preconceptions. Whereas people may naturally be inclined to be "naive physicists," they are not inclined to be "naive electrical engineers." In part, this may be because people have no direct perceptual experience with the primitives of electricity. They can, for example, see that a 10 watt bulb is brighter than a 5 watt bulb, but they do not feel the currents and resistances causing this effect in the same way that they can feel gravity affecting different masses. While the lack of perceptual experience may prevent entrenched misconceptions, it also makes instruction a challenging endeavor. Students need to learn a complex and invisible domain. In the work described here, we consider some of the moves that novices and experts make to help them learn and problem solve. In particular, we will describe how they use mathematical and causal descriptions.

Different instructional methods in electricity emphasize mathematics to varying degrees. Nonetheless, mathematics may play an important role in understanding electricity both because electricity is structurally complex , and because it is largely invisible. Despite the common belief that mathematical models can be too abstract and bereft of content, and that people learn about things qualitatively and causally first, mathematics seemed very important to all of the participants in the following study. Using a number of simple circuitry problems, we conducted interviews with applied and theoretical experts, college students with one or two semesters of instruction, and Navy recruits at various stages in their basic electricity training course. Here we describe the results for a single problem. Participants were shown a simple DC circuit that included a battery and a 5 watt light bulb. They were then shown an identical circuit except that the light bulb was 10 watts. Their task was to explain the differences in outcomes, if any, in terms of the basic constructs of electricity such as voltage, current, resistance, and power.

The question of why the 10 watt bulb burns brighter is deceptively difficult. One reason is that we think of more resistance as causing more light, much like more friction causes more heat. Consequently, one might be tempted to reason that the 10 watt bulb must have a higher resistance if it extracts more power. In fact, the 10 watt bulb has less resistance. Given a fixed voltage source, this allows more current to flow through the bulb. This increased flow causes more "power extraction." But, if the amount of resistance and current flow were in a direct proportion, then the increase in current would be offset by an equal decrease in the resistance that draws power from the current. According to this line of reasoning, changing the resistance gets you nowhere. The answer is that power has a linear relation to resistance but a square relation to current. Notice that in the preceding description, we combined causal and mathematical explanations. For example, we say resistance *causes* power extraction. At other points, we wrote about the quantitative *structure* of the relationship between resistance and current. Our interviews also reveal these combinations.

Participants often moved to mathematical notions when the relationships between elements could no longer be expressed according to a linear causal chain. This happened frequently. One reason people used math is that it provided a notation that could help them recall relationships among the elements of voltage, resistance, current, and power. Many participants also jumped to equations and numbers when they wanted to check whether they had construed the structure appropriately and had included the relevant elements. The mathematics also provided a way to express structures that are difficult to keep in mind (e.g., non-linear relationships among three variables; $P=I^2R$). And finally, the non-experts lacked strong causal models or analogies that could support reasoning about complex problems. When asked to explain structural mappings, they often began with an analogy (e.g., water flow) but quickly left it behind when the relationships became complicated. This is not to say that people did not continue to rely on analogies and causal explanations. They frequently gave causal interpretations to their equations, often incorrectly. Starting with $V=IR$, for example, they might reason causally that the current could not change if it were coming from a constant voltage source. Therefore, the only way to change the system was to change the voltage, and this must be what the different light bulbs do. We develop these findings further to motivate a form of instruction that capitalizes on students inclination to merge mathematical and causal descriptions of electricity.

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