Understanding Electricity with an Augmented Circuit Exhibit

Elham Beheshti and Michael Horn

Northwestern University, Evanston, IL

ABSTRACT

Electrical circuits are difficult to understand. Novices tend to have inadequate understandings of what happens at the level of atoms and electrons, leading to difficulty predicting the outcomes of electrical circuits at the level of wires, resistors, and light bulbs. In this paper, we describe an augmented science museum exhibit that enables visitors to make circuits on an interactive tabletop and observe a simulation of electrons flowing through the circuit on a separate handheld device. We used augmented reality to couple the electron simulation with the circuit simulator. We then discuss findings from a pilot study with family visitors at a science museum that highlight the learning benefits of integrating an electron-level simulation into a circuit building environment.

INTRODUCTION

Understanding the flow of current in electrical circuits can be challenging for learners of all ages (Grotzer & Sudbury, 2000; Osborne, 1983; Shipstone, 1984; Tarciso Borges, 1999). Research in Learning Sciences has documented a variety of mental models that novices rely on as they struggle with concepts like resistance, current, and voltage drop. One stream of studies has shown that novices have an insufficient understanding of what happens at the level of atoms and electrons in a circuit (Chi, Roscoe, Slotta, Roy, & Chase, 2012; Reiner, Slotta, Chi, & Resnick, 2000; Sengupta & Wilensky, 2009). Learners might think of current as something like water in a pipe that flows out of the battery and encounters each component in turn (Reiner et al., 2000). Or, they might think of current as a substance that gets consumed by things like lightbulbs and resistors. And, while these models have some value for understanding electrical phenomena, they differ from the scientific understanding in ways that makes it difficult to predict things like the relative brightness of lightbulbs in a series circuit.

One promising strategy to help learners understand circuits is to provide dynamic visual representations of electrical concepts (Frederiksen, White, & Gutwill, 1999; Sengupta &

Wilensky, 2009). For example, Frederiksen et al. explored different ways of visualizing the concept of voltage for learners by relating it to the distribution of charged particles in a circuit (Frederiksen et al., 1999; Gutwill, Frederiksen, & White, 1999). In another example, Sengupta and Wilesnky (Sengupta & Wilensky, 2008) created an *agent-based* representation of current based on Drude's model. In this model, a cloud of free electrons has a net movement through a circuit when a potential difference is applied. Simple kinetic interactions between free electrons and ions in conductive materials result in emergent properties that approximate Ohm's law. Research has shown that this kind of electron-level representation along with structured curriculum can help students develop more sophisticated understandings of simple circuits (Sengupta & Wilensky, 2009, 2011).

In this paper, we present *Spark,* an augmented circuit exhibit to help learners better understand the fundamental concepts in circuits, such as current and resistance. *Spark* combines a circuit building environment with electron-level simulation of current flow, which enables learners to interact with electrical circuits at two levels. At one level, visitors can create and test a variety of circuits by wiring together the circuit components (circuit representation). At another level, visitors can inspect a simulation of electrons moving through these components (electron representation). The primary goal of our design is to enhance children's understanding of electrical current and resistance by enabling them to develop meaningful connections between the two representations. Our research question is: *does coupling the electron simulation with the circuit representation enhance children's learning*? To study the learning benefits of our approach, we tested a prototype of *Spark* with parent-child dyads at the Museum of Science and Industry in Chicago. Our findings show that children who had access to the electron simulation did significantly better on a post-test interview compared to a control condition with no electron simulation.

DESIGN OF *SPARK*

Through an iterative design process, we developed an interactive exhibit that enables visitors to construct circuits and then see a simulation of electrons moving through the various components. The system consists of two main components (Figure 1): (1) a DC circuit simulator that allows visitors to build simple electrical circuits by dragging and connecting circuit components (wires, batteries, resistors, and lightbulbs) on a multi-touch tabletop display. The current and voltage drop for each component are calculated every time a visitor makes a change to the circuit.; and (2) an electron-based 3D visualization of current flow on. Inspired by NIELS simulation environment (Sengupta, 2009) and based on Drude's free electron theory, we developed a simulation that shows the flow of electrons throughout the circuit. In this model, electrical current and resistance can be thought of as phenomena that emerge from simple kinetic interactions between electrons and ions in the conductive materials such as wires and resistors. We used augmented reality techniques to display the simulation on a tablet computer that visitors hold above their circuit. This creates the illusion of peering inside the circuit. The model is updated every time a visitor makes a change to the circuit. On the tablet display, visitors can tap on the components to see the electrical measures such as current and resistance, and a brief textual description of the underlying concepts. Visitors can also tap on a "watch an electron" button to track the movement of a random electron through the circuit (see Figure 2).

METHODS AND DATA SOURCES

To evaluate the learning benefits of our approach, we conducted a museum study with parent-child dyads who were visiting the Museum of Science and Industry in Chicago. We designed a between-subject study with two conditions: a control condition in which visitors could create and test circuits on a tabletop screen, but without the electron model (Figure 3). In the second condition (experimental condition), we displayed the electron simulation on a tablet device that visitors hold above their circuits. This created the illusion that the tablet was a lens that could peer into a circuit (Figure 4). We tested each condition with 20 parent-child dyads (a total of 40 families) with children between the ages of 10 and 14 years old. The study sample was generally representative of the museum population, which is predominately white (Caucasian). We used matched sampling to balance boy/girl ratios across our three conditions. There were 25 boys and 15 girls in the study (12 boys and 8 girls in condition 1 and 13 boys and 7 girls in condition 3). These ratios reflected the visitor population as a whole; around 65% of children who visit the museum are boys. The age of children in the study ranged between 10 and 14 years (M=11.85 and SD=1.42 for the control condition and M=11.75 and SD=1.41 for the experimental condition).

Procedure

After introducing the study and obtaining informed consent, we invited dyads to use the interface for their condition. The researcher then asked families to use the exhibit to complete a series of tasks. We asked participants to pretend the researchers were not in the room and to use our design as they would use any other exhibit. Upon the completion of this phase, we interviewed the child about electricity understanding while the parent filled out a demographic questionnaire. Participants were compensated with a $10 gift certificate to the museum store. Sessions were video recorded and took around 25 minutes to complete.

Data

Data took the form of children's post-interview responses. To assess children's understanding of circuits, we first transcribed video recordings and then coded for the presence or absence of target concepts about electricity. We inductively developed the coding scheme based on literature (Grotzer & Sudbury, 2000; Osborne, 1983) (Table 1). We identified three main dimensions for children's mental models: (1) current path models dealing with the direction of current flow; (2) models that attempt to explain cause and effect relationships in a circuit; and (3) current lowering models that include thinking of current as a substance being consumed or as a flow that is slowed down. Table 1 shows the list of codes for each dimension. One researcher conducted the majority of the coding. Two assistants coded 20% of the transcripts to establish inter-rater reliability. We achieved an agreement of 94% for the first research assistant (Kappa = 0.78), and 93% for the second research assistant (Kappa = 0.72).

FINDINGS AND DISCUSSION

In this section, we present our findings on children's conceptions of current and resistance in the post-interviews.

Current Path

To assess children's understanding of current path, we grouped the first three codes together (Table 1); these three models are considered incorrect or non-scientific, whereas the fourth model, unidirectional current, is considered correct. Figure 5 shows the differences in usage of incorrect and correct conceptions for current path in each condition. We found that 6 children in control condition evoked an incorrect conception of current path, compared to one participant in the experimental condition. A chi-square test showed a significant difference between the two groups ($p = 0.037$).

Current Flow Mechanism

We then studied children's conceptions of the underlying mechanism of current flow (second dimension of the coding scheme). We identified four different models in this category based on our review of the literature and inductive coding of children's responses in our study. The models in this category seem to suggest a sequence of conceptions that progress towards a more scientific understanding of causal relationships in circuit. The first model (*sequential*) views current as a substance that fills up an initially empty circuit one component at a time. Children who hold this model think that a component placed in a circuit after the bulb cannot affect the brightness of bulb. Second, in the *traffic jam* model, current can be jammed behind a resistor after a lightbulb and hence the resistor can increase the brightness of lightbulb (in reality it decreases the brightness). Third, the *cyclic model* is a progression from sequential model towards concurrent model; it includes a reasoning that current flows in the circuit in a cycle. As a result, a change in circuit after a bulb can still affect the bulb in the next cycle through the circuit. But, there is still a temporal relationship between cause and effect. Fourth, the *concurrent* model is the correct model in this category. This model indicates a non-sequential relationship: a change in any part of the circuit affects the whole circuit instantaneously, and there is no real beginning or ending.

We considered the cyclic model as an intermediate model towards the correct model. In addition, in some cases it was unclear whether the child is using a cyclic model or a concurrent model. For these two reasons, we grouped these two models together as "progressed" conceptions. We observed children in control condition mostly used a sequential model to reason about circuits. We also found an increase in number of times that children used either of the progressed models in the experimental condition (Figure 6) and a chi-square test shows that this increase is significant ($p = 0.025$).

We then reviewed the interviews and compared the completeness of responses qualitatively. Our observations show that in the experimental condition, children were more likely to provide an elaborate explanation for their responses. Moreover, we observed that children frequently used electron-based language in their explanations.

Current Lowering Models

Previous studies suggest that children commonly think of current as a substance that is being used up by the components in circuit (*consumption* model) (Grotzer & Sudbury, 2000;

Reiner et al., 2000). In this model, adding more resistance to a circuit makes the current weaker by decreasing its quantity. However, a more scientific model describes current as a flow that can be slowed down by the resistive materials in the circuit (*slow-down* model). In this model, the focus is on rate.

In our study, we observed that some children used both models in their explanations for different parts of the interview. In other cases, children did not evoke either model. Therefore, for this measure we counted the number of times that each code was used across all interview responses. We found no significant difference between the two groups: children in control condition used the consumption model 9 times and the slow-down model 12 times (57% use of slow-down model). This ratio was 9 to 17 for condition 3 (65% use of slow-down).

CONCLUSION

In this paper, we presented the design and evaluation of a science museum exhibit that enables visitors to make circuits on an interactive tabletop and observe a simulation of electrons flowing through the circuit which conveys basic concepts of current and resistance. Our findings from a between-subject study with family visitors show that having access to the electron simulation could benefit children to better understand the concepts of electricity, such as current and resistance. Moreover, we observed that children in the experimental group commonly attended to the electron simulation and the behavior of electrons moving in the circuit. This research leads to an increased understanding of novices' learning about electrical circuits through using an agent-based model of current flow. In the future, we will continue our research to further investigate how children (and their parents) interacted with each component of the exhibit and made sense of circuits in their explorations.

References

Chi, M. T. H., Roscoe, R. D., Slotta, J. D., Roy, M., & Chase, C. C. (2012). Misconceived Causal Explanations for Emergent Processes. *Cognitive Science*, *36*(1), 1–61. https://doi.org/10.1111/j.1551-6709.2011.01207.x

Frederiksen, J. R., White, B. Y., & Gutwill, J. (1999). Dynamic mental models in learning science: The importance of constructing derivational linkages among models. *Journal of Research in Science Teaching*, *36*(7), 806–836. https://doi.org/10.1002/(SICI)1098-2736(199909)36:7<806::AID-TEA5>3.0.CO;2-2

Grotzer, T. A., & Sudbury, M. (2000). Moving Beyond Underlying Linear Causal Models of Electrical Circuits. Retrieved from http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.43.2787

Gutwill, J. P., Frederiksen, J. R., & White, B. Y. (1999). Making Their Own Connections: Students' Understanding of Multiple Models in Basic Electricity. *Cognition and Instruction*, *17*(3), 249–282. https://doi.org/10.1207/S1532690XCI1703_2

Osborne, R. (1983). Towards Modifying Children's Ideas about Electric Current. *Research in Science & Technological Education*, *1*(1), 73–82. https://doi.org/10.1080/0263514830010108

Reiner, M., Slotta, J. D., Chi, M. T. H., & Resnick, L. B. (2000). Naive Physics Reasoning: A Commitment to Substance-Based Conceptions. *Cognition and Instruction*, *18*(1), 1–34. https://doi.org/10.1207/S1532690XCI1801_01

Sengupta, P. (2009). *Designing across Ages: Multi-Agent-Based Models and Learning Electricity*. ProQuest LLC.

Sengupta, P., & Wilensky, U. (2008). *NetLogo Current in a Wire model*. Center for Connected Learning and Computer-Based Modeling, Northwestern University, Evanston, IL. Retrieved from http://ccl.northwestern.edu/netlogo/models/Electronsink

Sengupta, P., & Wilensky, U. (2009). Learning Electricity with NIELS: Thinking with Electrons and Thinking in Levels. *International Journal of Computers for Mathematical Learning*, *14*(1), 21–50. https://doi.org/10.1007/s10758-009-9144-z

Sengupta, P., & Wilensky, U. (2011). Lowering the Learning Threshold: Multi-Agent-Based Models and Learning Electricity. In M. S. Khine & I. M. Saleh (Eds.), *Models and Modeling* (pp. 141–171). Dordrecht: Springer Netherlands. Retrieved from http://www.springerlink.com/content/p887223317845665/

Shipstone, D. M. (1984). A study of children's understanding of electricity in simple DC circuits. *European Journal of Science Education*, *6*(2), 185–198. https://doi.org/10.1080/0140528840060208

Tarciso Borges, A. (1999). Mental models of electricity. *International Journal of Science Education*, *21*(1), 95–117. https://doi.org/10.1080/095006999290859

FIGURES AND TABLES

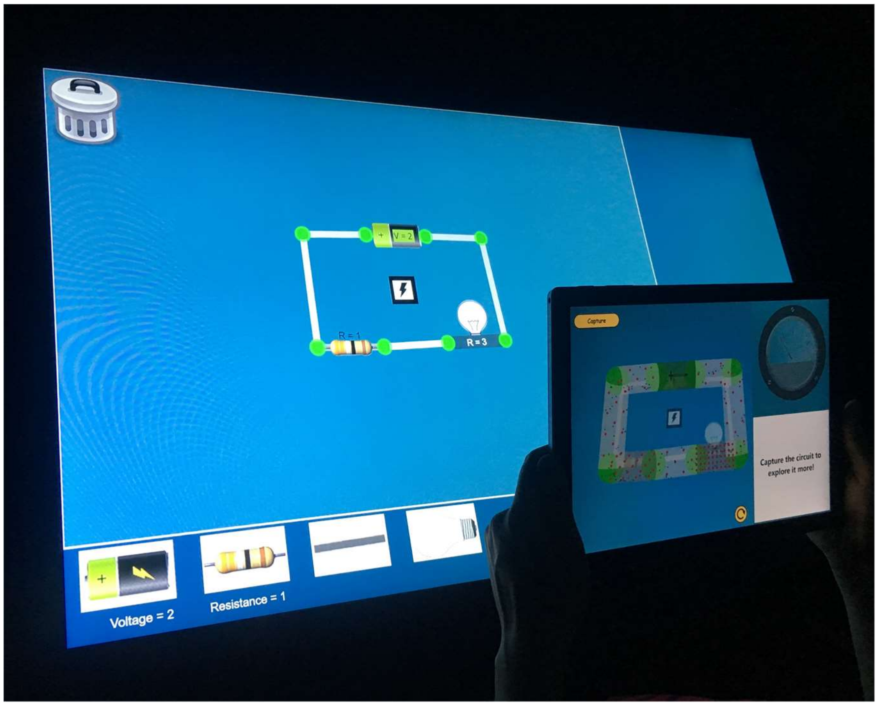


Figure 1. ***Spark*** **interactive tabletop exhibit.**

Figure 2. Electron model display. The blue dots are moving electrons and the red dots represent ions in conductive materials. Resistors have higher ion densities than wires.

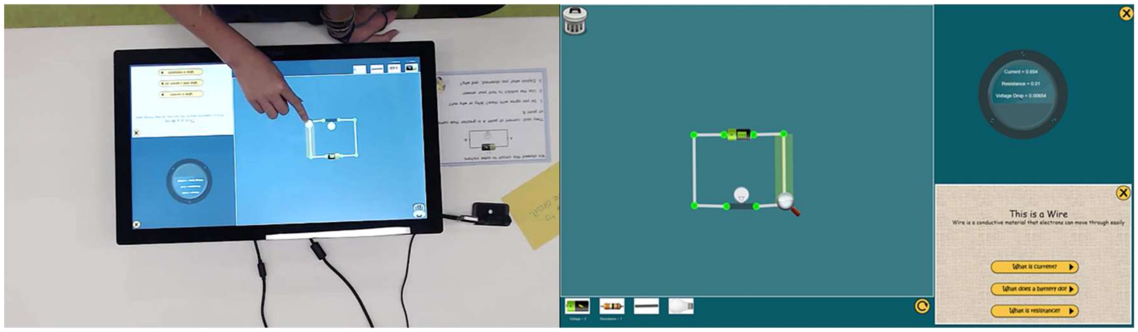


Figure 3. A parent-child dyad using the exhibit in the control condition

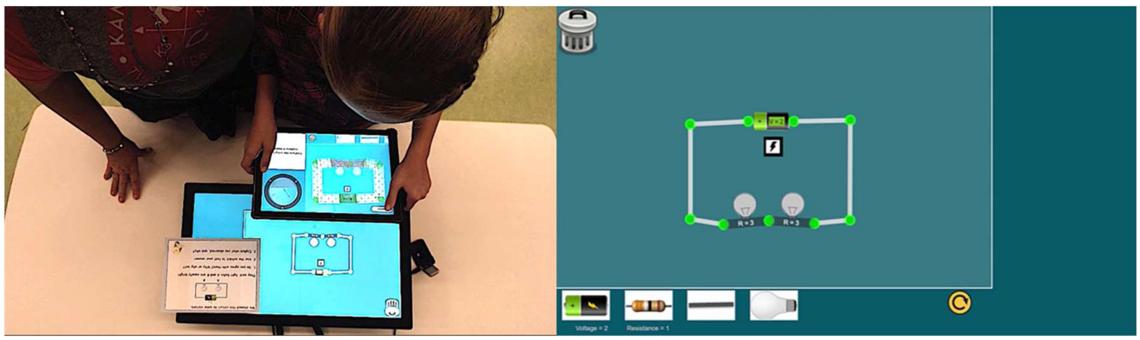
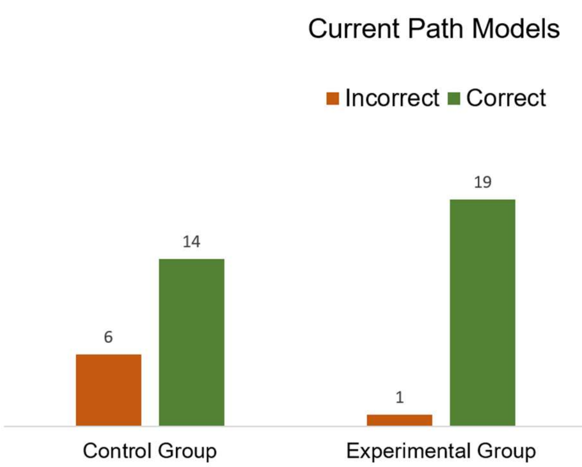


Figure 4. A parent-child dyad using the exhibit in the experimental condition



	Code	
Current Path Models	No current in return path	Incorrect models
	Clashing currents	
	Bidirectional currents	
	Unidirectional current	Correct model

Figure 5. Children's mental models of current flow path in control condition and the experimental condition (with electron simulation).

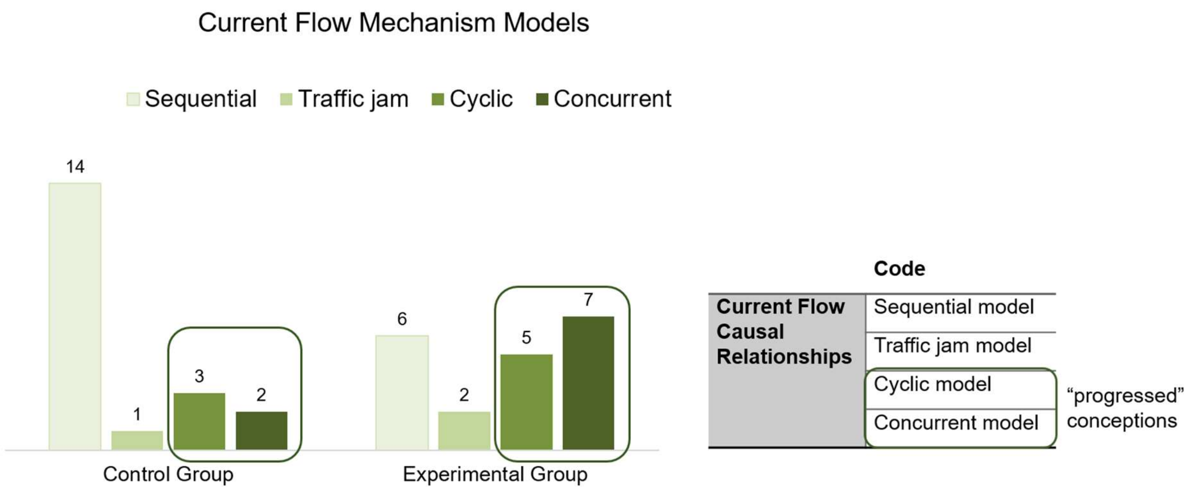


Figure 6. Children's mental models of mechanism of current flow with cyclic model and concurrent model grouped as "progressed" conceptions.

Table 1. Coding scheme for children conceptions of current and resistance.

	Code	Description
Current Path Models	No current in return path	Current leaves one terminal of battery and is completely consumed by the circuit and no current remains in the return path
	Clashing currents	Current travels from both terminals of battery and clashes at the bulb or resistor
	Bidirectional currents	Current flows around the circuit in both clockwise and counter-clockwise directions
	Unidirectional current	Current flows in one direction around the circuit
Current Flow Causal Relationships	Sequential model	Current travels from point to point and affects each component in turn as it is encountered with the circuit (domino-like effect)
	Traffic jam model	Similar to sequential model, current travels point to a point, but can be slowed down by traffic congestion ahead
	Cyclic model	Current travels around the circuit in repeated cycles
	Concurrent model	The effect of a change in the circuit affects the circuit as a whole. In other words, a local change causes a global effect which affects the entire circuit simultaneously
Current Lowering Models	Consumption model	Current is consumed in components of the circuit
	Slow-down model	Current is slowed down in components of the circuit