Looking Inside the Wires: Understanding Museum Visitor Learning with an Augmented Circuit Exhibit

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ABSTRACT
Understanding electrical circuits can be difficult for novices of all ages. In this paper, we describe a science museum exhibit that enables visitors to make circuits on an interactive tabletop and observe a simulation of electrons flowing through the circuit. Our goal is to use multiple representations to help convey basic concepts of current and resistance. To study visitor interaction and learning, we tested the design at a popular science museum with 60 parent-child dyads in three conditions: a control condition with no electron simulation; a condition with the simulation displayed alongside the circuit on the same screen; and an augmented reality condition, with the simulation displayed on a tablet that acts as a lens to see into the circuit. Our findings show that children did significantly better on a post-test in both experimental conditions, with children performing best in the AR condition. However, analysis of session videos shows unexpected parent-child collaboration in the AR condition.

Author Keywords
Electrical circuits; multiple representations; augmented reality; agent-based modeling; design; interactive surfaces; museum learning.

ACM Classification Keywords
H.5.2 Information Interfaces and Presentation: User Interfaces - Interaction styles

INTRODUCTION
Understanding the flow of current in electrical circuits can be challenging for learners of all ages [17, 28, 36, 39]. 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 [9, 30, 34]. For example, learners might think of current as something like water in a pipe that flows out of the battery and encounters each component in turn [30]. 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 (e.g. Figure 5).

One promising strategy to help learners understand circuits is to provide dynamic visual representations of electrical concepts [15, 34]. 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 [15]. In another example, Sengupta and Wilesnky [34] 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 (see [34]). Research has shown that this kind of electron-level representation along with structured curriculum can help students develop more sophisticated understandings of simple circuits [35].

In this paper, we present the design and evaluation of *Spark*, an augmented circuit exhibit for science museums (Figures 1-3). *Spark* combines a virtual circuit building environment with a simulation of current flow based on Sengupta and Wilensky's instantiation of Drude's model. Visitors drag and connect circuit components (wires, batteries, resistors, and

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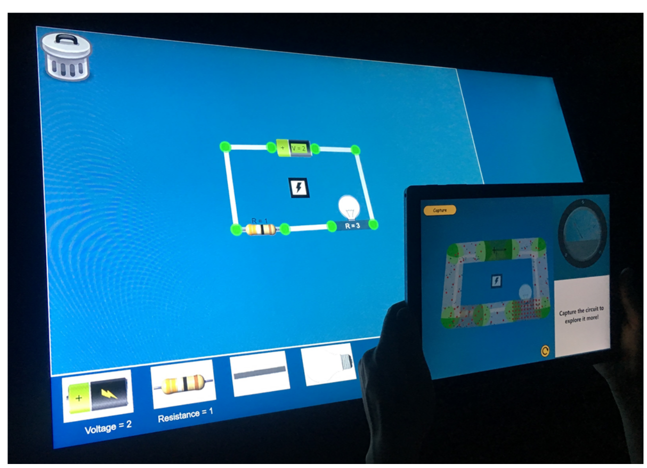


Figure 1. ***Spark*** **interactive tabletop exhibit.**

lightbulbs) on a multi-touch tabletop display. As they make changes to their circuit, they can explore an electron simulation that gets updated in real time. In one version of the exhibit (Figure 2a), the simulation is displayed alongside the circuit on the same display. In another version (Figure 2b), we use an AR Toolkit [42] to display the simulation on a tablet computer that visitors hold above the table. This creates the illusion of peering inside the circuit (Figure 1). *Spark* enables visitors 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 model). At another level, visitors can inspect a simulation of electrons moving through these components (electron simulation).

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. Prior research suggests that using multiple representations can improve learning but that they are difficult to design [1, 16]. If two representations of a scientific concept are not appropriately linked, learners can misinterpret the connections between representations based on unrelated surface features instead of scientific concepts. One important design consideration of a multi-representational simulation environment is how to support *translation* between the two representations [1]. In this study, we aim to investigate different ways to *dynamically link* the circuit representation with the electron simulation to support an effective translation between the representations.

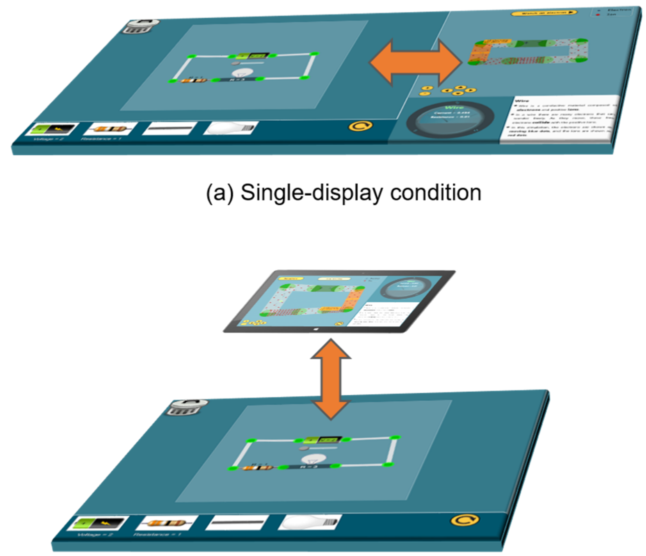
To study visitor interaction and learning, we recruited 60 parent-child dyads at the Museum of Science and Industry in Chicago to participate in three conditions: a control condition with no electron simulation (condition C1); a condition with an electron simulation displayed on the same screen as the circuit model (C2); and an augmented reality condition with the electron model displayed on a separate handheld tablet device (C3). Our research questions are: does the combination of the two circuit representations enhance children's learning? And, are there differences in the two experimental conditions? Second, we were interested in how parent-child dyads interacted with the exhibit and made sense of circuits in each condition.

We discuss findings from our investigation of visitor interaction and learning in each condition. Our findings have implications for design of interactive exhibits with multiple representations and considerations for improving the family experiences with interactive tabletop exhibits.

BACKGROUND

Existing Learning Environments

There are several computational environments and activities that allow children to investigate simple circuits. Examples include the Circuit Construction Kit from the PhET project, which simulates the behavior of simple circuits [14]; and LightUp [8], which uses augmented reality to project a simple representation of current flow on top of an image of the physical circuit. NIELS [34] is an example of an agent-based modeling environment that shows how electrical concepts such as current and resistance emerge from the interactions between electrons and ions in a conductive material. NIELS directly inspired the design of electron simulation in *Spark*.



(a) Single-display condition

(b) AR condition

Figure 2. Linking two representations of a circuit (a) side-by-side on one display and (b) with AR on a second display.

Museum Learning

Research in museums and other informal settings has shown that it is possible to increase learner interest and engagement around scientific phenomena [19, 23, 41]. Recent studies suggest that interactive exhibits containing novel technology can be attractive to visitors, promote enhanced understanding of content [2], and engage people for extended periods of time [31]. Other studies highlight the potential that museums have in changing individuals' conceptual understandings of scientific ideas and processes of science [13].

Researchers have also explored factors that facilitate or hinder collaborative family learning in museums [2, 7]. This work has revealed that factors such as the height of displays and the accessibility of interactive elements to multiple family members can impact enjoyment, depth of engagement, and learning behaviors like identifying, describing, and interpreting information [22]. Other studies explored how increasing the visibility of different types of information can affect the authority and accountability of family visitors [24].

Learning with Multiple Representations

Even though the idea of combining multiple representations in one learning environment seems promising, studies have demonstrated that learners fail to gain from multiple representations if they are not carefully designed [1, 16, 21].

Ainsworth [1] suggests that multiple representations require learners to understand each individual representation, a complex process in its own right, in addition to the relationship between representations. Moreover, learners tend to treat representations in isolation and find it difficult to integrate information from more than one resource [1, 16]. These studies suggest that it is critical to support a fluid and meaningful transition among the representations in a learning environment.

Affordances of AR in Learning

Recent studies have investigated the affordances of augmented reality for learning in different settings [11, 27, 37, 40, 41]. Augmented reality can enable learners to see the world around them in novel ways and engage with dynamic processes within contexts in which they are already familiar [11]. Furthermore, augmented reality fosters interactivity, which provides users with control over their learning and thus tailors to the need of each learner [33].

Museums have also started to explore the use of augmented reality; however, much of the research has been focused on usability rather than learning outcomes [12]. The few existing studies have promising findings. For example, Yoon and colleagues conducted several studies finding that the addition of digital augmentation resulted in significant learning gains [40] and lead to increased engagement and group participation [41]. Asai and colleagues found that their augmented reality lunar surface navigation system helped facilitate collaborative interactions between parents and children in an informal environment [3]. AR interfaces have also been shown to aid in capturing visitor interest: Hall and Bannon found that interest and engagement increased when children interacted with digitally augmented museum artifacts [18], and Szymanski and colleagues demonstrated that visitors of a historic house were more likely to explore augmented objects [38]. One of our primary goals in the current study is to study the use of AR to help families make meaningful connections between representations.

DESIGN OF SPARK

Through a three-year iterative design process [5, 6], 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 four components (Figure 3): a DC circuit simulator, an agent-based model of current flow, a virtual multimeter, and a brief textual description of basic concepts on electricity. We briefly describe each of these parts.

Circuit Simulator

In *Spark*, visitors can build simple electrical circuits by dragging and connecting components from a toolbox menu on a multi-touch display. Each component has three variables: voltage drop, current, and resistance. The lightbulb has a fourth variable of brightness factor. The voltage of batteries and resistance of resistors can be changed adjusting with a slider. We calculate current and voltage drop for each component every time a visitor makes a change to the circuit.

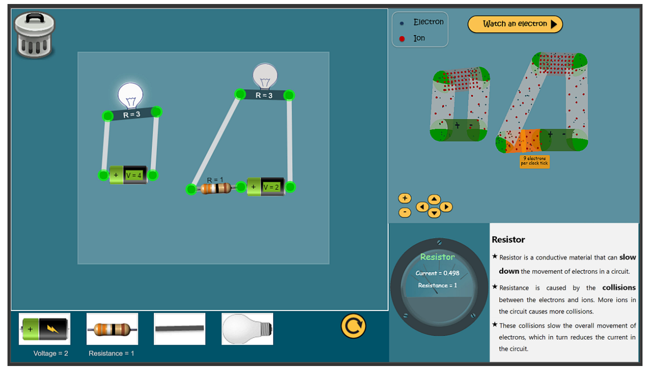


Figure 3. Snapshot of *Spark* system in the single-display condition.

Figure 4. Electron model display in the AR condition. The blue dots are moving electrons and the red dots represent ions in conductive materials. Resistors have higher ion densities than wires.

Electron Model

We developed a 3D visualization of current flow using Three.js [43], a browser-based JavaScript library based on WebGL. *Spark* electron model is inspired by NIELS simulation environment [34] and is based on Drude's free electron theory in which electrical current and resistance can be thought of as phenomena that emerge from simple kinetic interactions between electrons and ions in the conductive materials. Here, resistance is modeled by the collisions between the electrons and ions. Thus, more ions in the circuit cause more collisions resulting in higher resistance (see the example in Figure 4). These collisions slow the overall movement of electrons, which in turn reduces the current in the circuit.

The model is updated every time a visitor makes a change to the circuit. Visitors can tap on a "watch an electron" button to track the movement of a random electron through the circuit (see Figure 4). Visitors can also tap on a component to see its electrical measures, a textual description about the component, and also a counter that shows the "electrons per clock tick" rate. This measure indicates how many electrons pass by the cross section of the component over a certain

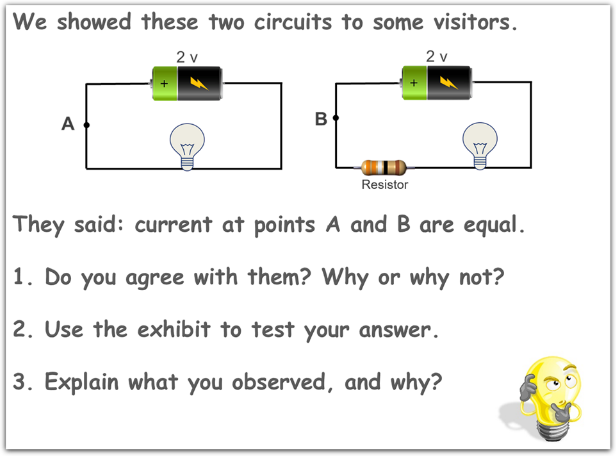


Figure 5. Final task (task 3) in the series of tasks.

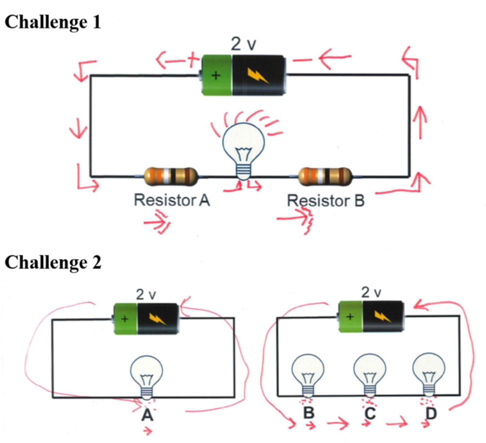


Figure 6. Post-interview questions and two examples of children's drawings to show the flow of current.

time, which is directly proportional to the measure of current in that component. Finally, visitors can zoom and pan the display using direct touch interaction or buttons in a toolbar.

Multimeter

The third component of the exhibit is a multimeter that shows the variables (current, voltage, resistance) of each component. These variables are updated every time there is a change in the circuit.

Information Window

The last component of the exhibit is a window that contains brief textual descriptions of the underlying concepts of an electrical circuit, such as current and resistance. Four short scripts are provided for each component type to describe what is inside a wire, what a battery does, what is current, and what is a resistor. The descriptions provide simple explanations of the concepts based on the electron model and do not include any explicit notion of circuit equations or laws such as Ohms law (V = IR).

METHODS

Conditions

We recruited 60 parent-child dyads who were visiting the science museum to participate in one of three conditions.

Condition 1: Control Condition

In the control condition visitors could create circuits, use the multimeter, and read textual descriptions. But the simulation of electrons flowing through the circuit was not visible. Visitors could drag a magnifying glass icon over a component to see its measures.

Condition 2: Single-display Condition

In condition 2, we introduced the electron simulation. The simulation was shown alongside the circuit on the same display (see Figure 3). With every change to the circuit, the electron simulation was updated in real time.

Condition 3: AR Condition

In condition 3, we displayed the electron simulation on a separate handheld tablet device using the JSARToolKit library [42]. The tablet's rear-facing camera was used to track the position of an AR tag displayed on the tabletop. This created the illusion that the tablet was a lens that could peer into a circuit. Visitors could zoom in to focus on a specific segment of circuit or zoom out to have a view of electrons moving around the whole circuit. Visitors used a capture button to pause and resume tracking of the AR tag. When paused, visitors could explore the simulation by tracking an electron or tapping on a component to see its electrical measures and textual description.

Apparatus

We used a 21×12-inch multi-touch monitor as the tabletop screen. The monitor was placed flat on a table and connected to a laptop that ran the simulation. For the AR condition, we used a Microsoft Surface Pro 4 with a 12×8-inch display to run the electron model. This display size allowed us to keep the size of the electron simulation consistent across both experimental conditions.

Participants

We tested each condition with parent-child dyads who were visiting the Museum of Science and Industry in Chicago. For each of the three conditions in the study, we recruited 20 parent-child dyads (a total of 60 families) with children between the ages of 10 and 14 years old. We approached any group of visitors (with minors within the target age range) who passed the exhibits nearby the space where our design was setup and asked them if they were interested in participating in the study. The study sample was generally representative of the museum population, which is predominately white (Caucasian). Based on the self-report data driven from the demographic questionnaire, in condition 1, 6 of the families reported non-white ethnicity, whereas 2 families for each of condition 2 and condition 3 reported non-white ethnicity. The median education level of families in all conditions was 4-year college degree, and the distribution of education level across the three conditions was not statistically different. We also asked parents how much they knew about electrical circuits and how much they thought their children knew about electrical circuits. There were no significant differences on either of these measures across conditions.

We used matched sampling to balance boy/girl ratios across our three conditions. There were 37 boys and 23 girls in the study (12 boys and 8 girls in condition 1; 12 boys and 8 girls in condition 2; 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 condition 1; M=11.65 and SD=1.27 for condition 2; and M=11.75 and SD=1.41 for condition 3).

Procedure

The study took place over 8 weeks of summer. To avoid distractions from other museum visitors, we set up our exhibit in a relatively quiet activity room and recruited families who passed nearby. After introducing the study and obtaining informed consent, we invited dyads to use the interface for their condition. Before using the interface, the researcher gave a one-minute demo of the interface to make sure that all the families are aware of the different features of the design. Our intention was to limit the effect of prior experience with touch screens. 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. We also asked participants to talk out loud while interacting with the system. 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 from two different camera angles. In total, the sessions took around 25 minutes to complete.

Tasks

We asked families to use the interface to complete a series of tasks (e.g. Figure 5). The tasks were printed on paper cards and were handed to families one at a time. We designed the tasks as a way to focus families' attention to certain target concepts, such as the idea that current is the same throughout a simple series circuit, or that adding resistance decreases the current. To make sure that all families knew how to make a complete circuit, we first asked them to make a simple circuit to turn on a lightbulb. If families could not complete this task after 2 minutes, we handed them a hint card that instructed them on how to make a complete circuit. This warm-up task was followed by three additional tasks. Each of the tasks had three parts: it opened with a statement about the circuit in question and asked families to agree or disagree with the statement (prediction); then to test their answers (exploration); and finally, to explain what they observed (explanation).

Figure 7. Snapshots of parent-child dyads using the exhibit in the single-display condition (left) and the AR condition (right)

The first task involved comparing the relative measure of current before and after a lightbulb. The second task asked families to compare the brightness of two bulbs in series. The third task explored the effects of adding a resistor to a circuit. The focus in task 3 was on the concept of resistance, and the relationship between resistance and current in a circuit (see Figure 5). Task 3 was the most difficult task for families to complete, as it required comparing two circuits and understanding the relationship between current and resistance. If families constructed a better understanding of current in the first two tasks, they were more likely to offer a correct prediction for task 3. It took families 13:06 minutes on average to complete all the tasks in condition 1, 13:16 in condition 2, and 16:24 in condition 3.

Post-Test Interviews

To assess the effect of exhibit on children's conceptions of electric current and resistance, we interviewed children in all conditions with a set of two challenges (Figure 6). In the first challenge we asked children to predict the effect of changing the resistance of two resistors on the brightness of a lightbulb placed between them. We also asked children to use a pen to draw the current flow on the circuit. The second challenge involved comparing the brightness of four lightbulbs in two series circuits. We designed the challenges to help us understand mental models that children evoke in their explanations and whether there is a difference in these models across the conditions. Children's responses to the challenges were transcribed and coded.

Data

Data took the form of video recordings from families' interactions with the interface, children's post-interview responses, and field notes. We used two camera angles, to capture both the parents and children body expressions and gestures and the families' interactions with the interface including touch interactions, points, and gestures. We also recorded the screen of the interface. Figure 7 illustrates two snapshots of the synchronized video recordings.

	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

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

RESULTS

In this section, we first report on children's conceptions of current and resistance in the post-interviews. We then examine videos of parent-child interaction with the exhibit.

Post-Test Interviews

To analyze children's interviews, 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 [17, 28] (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).

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. We did not see any instances of the first incorrect model (no current in return path). This was likely because the diagrams in the challenge questions provide a hint that one needs two wires to have a circuit. Figure 8 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 each of the experimental conditions. A chi-square test showed that the two experimental conditions differed significantly from the control condition ($p = 0.027$). This was not surprising as the electron simulation shows current flowing in one general direction when the circuit is closed.

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. For both

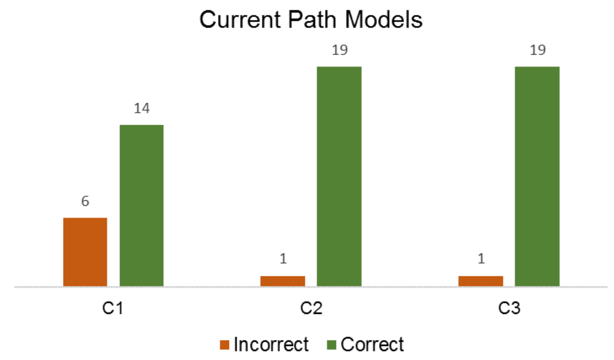


Figure 8. Children's mental models of current flow path in control condition (C1); single-display condition (C2); and AR condition (C3).

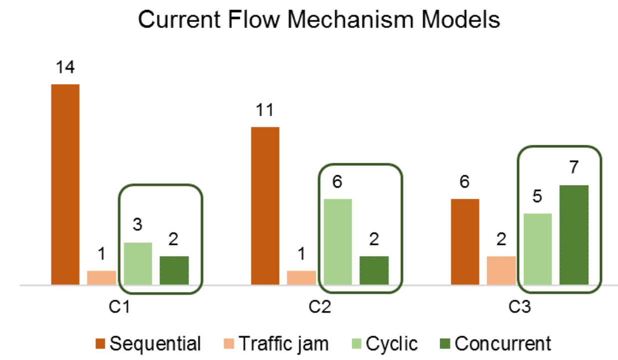


Figure 9. Children's mental models of mechanism of current flow with cyclic model and concurrent model grouped as "progressed" conceptions.

experimental conditions, we observed an increase in number of times that children used either of the progressed models (Figure 9). Children in control condition mostly used a sequential model to reason about circuits. A chi-square test shows that this increase is significant from condition 1 to condition 3 ($p = 0.025$), but not significant from condition 1 to condition 2.

We then reviewed the interviews and compared the completeness of responses qualitatively. Our observations show that children's explanations increased in completeness for both experimental conditions, with most complete responses in condition 3 (AR). In condition 3, children were more likely to provide an elaborate explanation for their responses. The following excerpt demonstrates a child's conception of current in the AR condition:

[Researcher shows the circuit in Challenge 1]
Researcher: In this circuit, if I increase the resistance of resistor A [the resistor before the lightbulb], what do you think happens to the brightness of lightbulb?
Participant: Um, I think it's going to get less bright. It's gonna get dimmer.
Researcher: Can you tell me why?
Participant: Because it slows the amount of electrons going through, with more collisions, so they [electrons] slow down and then that's less electricity going through every second, so then it would be dimmer.
Researcher: And what happens if I increase the resistance of resistor B?
Participant: Well, based on what we saw [reference to experience with the exhibit] where the resistor kind of affects all the way through the circuit [kid motions his hand in circles around the circuit diagram], I think the same effect would happen with what happens with resistor A, where it would slow down the amount over the whole circuit.
Researcher: And so does it make the lightbulb dimmer or brighter?
Participant: dimmer.

In this excerpt, the child relies on his experience with the exhibit and provides a relatively complete explanation of how a resistor affects the circuit as a whole (concurrent model). Moreover, we observed that children in this condition used electron-based language more frequent than children in single-display condition. For example, we observed that children in the AR condition used the concept of electrons being slowed down due to collisions with ions more frequently than children in single-display condition (11 and 6 times, respectively).

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) [17, 30]. 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.

We coded the interviews with regard to these two models. 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 a similar pattern across all the three conditions: 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 10 to 13 for condition 2 (57% use of slow-down) and 9 to 17 for condition 3 (65% use of slow-down). There was no significant difference across the conditions.

Parent-Child Learning and Interaction

We analyzed videos of visitor sessions to investigate how families learned from and interacted with the exhibit. We examined discourse, physical interaction, and the shifting roles of parents and children in the activity. We share findings that focuses on understanding how families learned about the concepts of electricity using the exhibit.

Assessment of Dyad Learning

To assess learning with the exhibit, we examined the prediction part of task 3. In task 3 (Figure 5), families are shown two circuits; the first circuit has one lightbulb, and the second circuit has one resistor and one bulb after the resistor (assuming a counter-clockwise direction of current flow). The question asks visitors to agree or disagree with a comparative statement about two points on these two circuits placed before the resistor and bulb: the current at points A and B is equal. The correct answer is that current is greater at point A because the resistor in the second circuit slows down the current in the whole circuit. Applying a sequential model results in concluding that the currents at points A and B are equal because the current has not yet encountered the bulb or resistor.

We chose to examine task 3 to assess the learning process for two reasons: first, when starting task 3, families have had several minutes of interaction time with the exhibit. Second, task 3 was the most difficult task as it required families to construct a relatively complete understanding of current to predict the correct answer. Therefore, we saw performance on the prediction part of the final task as a good gauge for the quality of dyads' explorations of circuits.

We coded families' verbal and nonverbal actions while predicting the answer for task 3 and categorized the sessions into three separate groups: (1) incorrect prediction; (2) correct prediction with no explanation; and (3) correct prediction supported with some explanation. Depending on parents' engagement in the prediction task, answers (and explanations) were offered by the child, parent, or after dialogue between parent and child. One family in the control condition did not offer a prediction, and one family in condition 3 gave conflicting predictions: the parent gave an incorrect answer while the child disagreed with her by predicting the answer correctly. We coded this instance with correct prediction since we consider children as the primary users of the interface. Figure 10 shows the number of incorrect and correct predictions in each condition.

We found that families in condition 2 performed significantly better than the other two groups. We applied chi-square tests for the number of correct (with or without explanation) versus incorrect predictions and found a significant difference between condition 1 and 2 ($p = 0.002$) but no significant difference between condition 1 and 3. We also found a significant difference between the two experimental conditions ($p = 0.005$).

These findings suggest that families in the AR condition did only slightly better than families in control condition. On the other hand, most of the families in single-display condition predicted the answer correctly. This was surprising for us as our earlier analysis on post-test interviews suggested that children in the AR condition perform better than the other two groups and significantly better than the control condition.

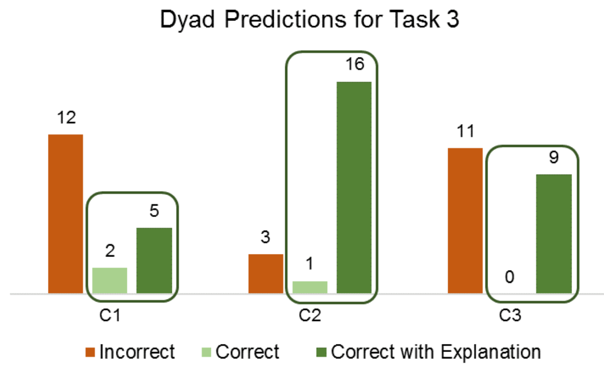


Figure 10. Parent-child dyad predictions for task 3.

To make sense of this trend, we re-examined the videos of families' predictions for task 3, however this time we focused our attention on the process through which the predictions were formed. We observed that parents in the control condition and single-display condition frequently let their child to come up with an answer by prompting questions and leading a conversation to assist the child. Parents in these two groups were less likely to tell what they believed the correct answer was. However, unlike the other two groups, parents in the AR condition actively articulated ideas and conceptions, and were more likely to offer what they thought. This change in behavior led to an increase in number of incorrect answers, as parents actively influenced the process. We found three different scenarios for the influence of parents resulting in incorrect answer: (1) after reading the question, the parent offered an answer before letting the child express his opinion. The child said nothing and started on building the circuit to test his parent's answer (one case); (2) the child initially predicted correctly, but then the parent offered an incorrect answer and thus the child changed his/her mind to comply with the parent's opinion (3 cases); (3) the child was trying to come up with the answer and the parent directed the child's attention to a misleading conceptualization of the circuit in question (2 cases). The following episode illustrates an example of the second scenario:

Child: [after reading the question] I don't think that A and B is equal, because one has a resistor and one doesn't.
Dad: but I am going to say they will be equal because the resistor is after, if it is flowing this way [motions a counter-clockwise path from the positive end of battery]. Should we test it?
Child: what?
Dad: should we try it?
Child: [keeps looking at the question]
Dad: See, I think because there is a resistor that lowers [the current] and so if it is flowing this way [counter-clockwise], point B is before the resistor. So, I think B and A will be the same.
Child: Oh!
Dad: but if you were to measure the [brightness of] lightbulbs those will be different.
Child: [nods head] yeah, yeah, B and A will be the same then.

Dad: should we try it? [dad and child start building the circuit together.]

In this vignette, the child starts her articulation with a correct answer but then her father immediately disagrees with her and offers his idea about comparing the two circuits. He provokes a sequential model and thinks that current affects the circuit point by point. The child seems to be confused by her father's explanation at first, but after the second time that her father articulates his idea, the child finally agrees with him.

It is important to note that the parents' active engagement did not always result in an incorrect prediction. In two cases, the parent initiated the prediction by providing the correct answer and the child either said nothing, or agreed with the parent. In two other cases, parent's engagement resulted in a conversation between parent and child to come up with correct reasoning.

Shift in Parental Engagement

To further investigate parental engagement, we extended our video analysis to look at family interaction while completing task 2. We were interested in finding out whether a similar pattern could be observed for a shift in parents' engagement in the AR condition. For this purpose, we narrowed our analysis to the two experimental conditions. We first open-coded the videos for all the families in both groups and formed a coding scheme with four distinct parental roles (see Table 2). We then coded the session video. The primary researcher worked with one of the two research assistants. Each of the researchers coded the video sessions separately and then compared the codes and resolved disagreements.

For each family, we identified the dominant role for parents. In some cases, we could identify a secondary role for parents, but for this analysis we only looked at the primary role of parents in the session. Figure 11 illustrates the distribution of parental roles in each group. As demonstrated in the graph, we found that parents in single-display conditions mostly took the role of *educator* or *observer*. On the other hand, parents in the AR condition, were commonly engaged in a collaborative learning process. Chi-square tests show a significant relationship between the type of interaction and parental role ($p = 0.001$). This observation is consistent with our earlier analysis for shift in parents' engagement in the final tasks predictions. In sum, we observed that parents were acting more collaboratively in the AR condition, leading to more incorrect predictions in task 3.

DISCUSSION

Our findings show that children did significantly better on a post-test in both experimental conditions, with children performing best in the AR condition. Moreover, our analysis of both the video sessions and post-test interviews suggest that children in the AR condition were more likely to attend to the electron simulation and the behavior of electrons moving in the circuit. This finding is in agreement with previous studies that suggest AR can enhance learning in various ways

Code	Description
Absent	Parent has no interaction with the exhibit or content of tasks
Observer	Parent has some interaction, but the extend of interaction excludes learning
Educator	Parent tries to teach the child by prompting questions, directing child's attention, and providing explanations
Co-learner	Parent is engaged in the learning process with the child and offers ideas

Table 2. Coding scheme for parental roles

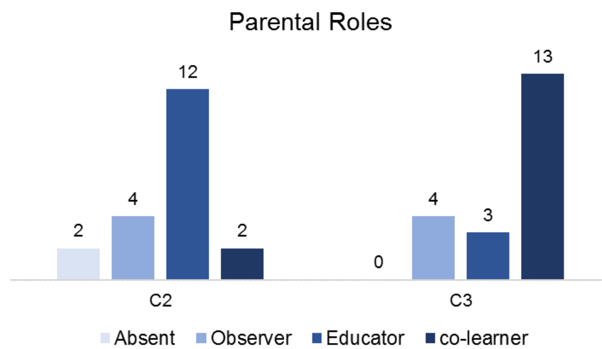


Figure 11. Different types of parental roles in task 2 in the single-display condition (C2) and the AR condition (C3).

[40, 41]. Here, one affordance of AR on learning is that it can support a better transition between the two representations, as it allows visitors to naturally inspect the circuit components using the tablet as a lens that sees *through* the circuit. In other words, it can enhance the coupling between the two representations. On the other hand, visitors have the option to ignore the tablet display allowing them to physically decouple the two representations, possibly making exploration less confusing for novice learners.

We also examined parent-child interactions with the exhibit in the single-display condition and the AR condition. Extensive museum studies show that parents often take on the role of educators during the museum visit and use specific mediating behaviors [10, 29]. These studies suggest that teaching occurs as a fundamental aspect of interactions of family members in science museums. In accordance with these studies, we observed that parents in the single-display condition commonly took the role of educator while using the exhibit; they instructed their children by means of three common actions: prompting questions; directing child's attention to components of the exhibit; and explaining how circuits work. However, we observed that parents in the AR condition were significantly less likely to take on the role of educator and instead acted as a co-learner.

This was an interesting finding for us. We have two plausible explanations; the first argument is that due to the novelty in technology being used in the AR condition, parents became less comfortable with their role as educators. A 2009 study by Barron and her colleagues identifies seven different types of roles that parents play to support their children with activities that involve computers and new technologies, "Teacher" and "Collaborator" being two of these roles [4]. This study suggests that most of these roles did not require parents to have greater technical expertise than the child. We observed that, when being introduced to the exhibit, parents made comments about the technology, saying "*this is the type of things that you [child] know better than me*". In other words, inclusion of AR technology might have affected the parents' level of comfort leading to a more collaborative role.

Second, holding the tablet device might result in a perception for child that he/she has control over the interaction with the exhibit. In other words, the tablet acts as a tool that allows the child to control the experience with the exhibit; In most cases, the child is responsible for holding the tablet, capturing the electron model, and then interacting with the model. Having control over the investigation could have raised the child's status or power in parent-child interaction. This explanation aligns with [24], which suggest that appropriating different resources and making different types of information visible can help children claim authority over their activity in a museum environment.

CONCLUSION AND FUTURE WORK

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 show that having access to the electron simulation could benefit children to better understand the concepts of electricity. We also observed that coupling the electron simulation through augmented reality significantly enhanced the learning benefits of the exhibit. Moreover, an analysis of session videos shows an interesting shift in parents' engagement. We observed that parents in the AR condition no longer acted as an educator and instead toke the role of co-learner. These findings raise the question for us that what factors could account for this shift in parental engagement. We will continue our research to further investigate this question.

Moreover, we are interested in studying the effects of working with physical circuit components (tangibles) instead of a digital circuit simulator. Research has shown that physical manipulatives can support science learning [26, 32]. Recent museum studies also suggest that physical manipulative are more inviting than their virtual counterparts [20, 25]. We are currently working on designing and testing a tangible prototype of the system (Figure 12). In the future, we will recruit family visitors to examine the effect of tangibles on parent-child learning and interaction.

Working Prototype

The design of physical components is inspired by the work of Chan and colleagues on LightUp [8]. Similar to LightUp, the electronic components of the circuit are attached to each other with magnetic connectors. The physical components

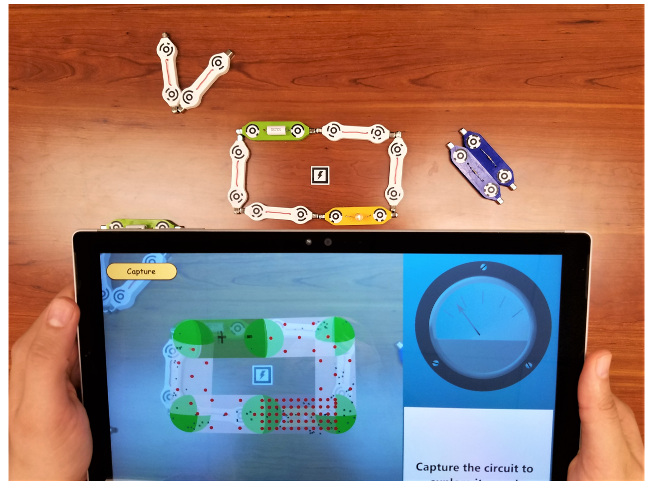


Figure 12. A demonstration of Tangible *Spark*.

include wires, batteries, resistors, and lightbulbs (Figure 12), similar to the digital circuit simulator. To detect the circuit components and render the corresponding electron simulation of circuit, we use Top-Code markers [44] on both ends of each component. We use a Microsoft Surface Pro 4 for running the computer vision code and then rendering the electron simulation. The computer vision code analyzes the capturing video stream and uses a series of algorithms to detect the components in the frame along their corresponding connections. This data is then passed to the electron simulation that runs on the tablet.

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REFERENCES

1. Shaaron Ainsworth. 2006. DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction* 16, 3: 183–198. https://doi.org/10.1016/j.learninstruc.2006.03.001
2. Sue Allen. 2004. Designs for learning: Studying science museum exhibits that do more than entertain. *Science Education* 88, S1: S17–S33. https://doi.org/10.1002/sce.20016
3. Kikuo Asai, Yuji Sugimoto, and Mark Billinghurst. 2010. Exhibition of Lunar Surface Navigation System Facilitating Collaboration Between Children and Parents in Science Museum. In *Proceedings of the 9th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry* (VRCAI '10), 119–124. https://doi.org/10.1145/1900179.1900203
4. Brigid Barron, Caitlin Kennedy Martin, Lori Takeuchi, and Rachel Fithian. 2009. Parents as Learning Partners in the Development of Technological Fluency.

International Journal of Learning and Media 1, 2: 55–77. https://doi.org/10.1162/ijlm.2009.0021

5. E. Beheshti, A. Aljuhani, and M.S. Horn. 2014. Electrons to light bulbs: Understanding electricity with a multi-level simulation environment. In *2014 IEEE Frontiers in Education Conference (FIE)*, 1–8. https://doi.org/10.1109/FIE.2014.7044047
6. Elham Beheshti, Mmachi Obiorah, and Michael S. Horn. 2015. “Let’s Dive into It!”: Learning Electricity with Multiple Representations. In *Proceedings of the 14th International Conference on Interaction Design and Children* (IDC ’15), 263–266. https://doi.org/10.1145/2771839.2771892
7. Minda Borun, Margaret B. Chambers, Jennifer Dritsas, and Julie I. Johnson. 1997. Enhancing Family Learning Through Exhibits. *Curator: The Museum Journal* 40, 4: 279–295. https://doi.org/10.1111/j.2151-6952.1997.tb01313.x
8. Joshua Chan, Tarun Pondicherry, and Paulo Blikstein. 2013. LightUp: An Augmented, Learning Platform for Electronics. In *Proceedings of the 12th International Conference on Interaction Design and Children* (IDC ’13), 491–494. https://doi.org/10.1145/2485760.2485812
9. Michelene T. H Chi, Rod D Roscoe, James D Slotta, Marguerite Roy, and Catherine C Chase. 2012. Misconceived Causal Explanations for Emergent Processes. *Cognitive Science* 36, 1: 1–61. https://doi.org/10.1111/j.1551-6709.2011.01207.x
10. Judy Diamond. 1986. The Behavior of Family Groups in Science Museums. *Curator: The Museum Journal* 29, 2: 139–154. https://doi.org/10.1111/j.2151-6952.1986.tb01434.x
11. Matt Dunleavy, Chris Dede, and Rebecca Mitchell. 2008. Affordances and Limitations of Immersive Participatory Augmented Reality Simulations for Teaching and Learning. *Journal of Science Education and Technology* 18, 1: 7–22. https://doi.org/10.1007/s10956-008-9119-1
12. Committee on Learning Science in Informal Environments, Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education, and National Research Council. 2009. *Learning Science in Informal Environments: People, Places, and Pursuits*. National Academies Press.
13. John Howard Falk and Susan Foutz. 2007. *In Principle, in Practice: Museums as Learning Institutions*. Rowman Altamira.
14. N. D. Finkelstein, W. K. Adams, C. J. Keller, P. B. Kohl, K. K. Perkins, N. S. Podolefsky, S. Reid, and R. LeMaster. 2005. When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physical Review Special Topics - Physics Education Research* 1, 1: 10103. https://doi.org/10.1103/PhysRevSTPER.1.010103
15. John R. Frederiksen, Barbara Y. White, and Joshua Gutwill. 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
16. Susan R. Goldman. 2003. Learning in Complex Domains: When and Why Do Multiple Representations Help? Commentary. *Learning and Instruction* 13, 2: 239–44.
17. Tina A Grotzer and Margot Sudbury. 2000. Moving Beyond Underlying Linear Causal Models of Electrical Circuits. In *annual meeting of the National Association of Research in Science Teaching*, New Orleans, LA.
18. T. Hall and L. Bannon. 2006. Designing ubiquitous computing to enhance children’s learning in museums. *Journal of Computer Assisted Learning* 22, 4: 231–243. https://doi.org/10.1111/j.1365-2729.2006.00177.x
19. Michael Horn, Zeina Atrash Leong, Florian Block, Judy Diamond, E. Margaret Evans, Brenda Phillips, and Chia Shen. 2012. Of BATs and APEs: An Interactive Tabletop Game for Natural History Museums. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI ’12), 2059–2068. https://doi.org/10.1145/2207676.2208355
20. Michael S. Horn, R. Jordan Crouser, and Marina U. Bers. 2011. Tangible interaction and learning: the case for a hybrid approach. *Personal and Ubiquitous Computing*. https://doi.org/10.1007/s00779-011-0404-2
21. Robert B. Kozma. 1994. Will media influence learning? Reframing the debate. *Educational Technology Research and Development* 42, 2: 7–19. https://doi.org/10.1007/BF02299087
22. Gaea Leinhardt, Kevin Crowley, and Karen Knutson. 2003. *Learning Conversations in Museums*. Taylor & Francis.
23. Gaea Leinhardt, Karen Knutson, and Kevin Crowley. 2003. Museum Learning Colloborative Redux. *The Journal of Museum Education* 28, 1: 23–31.
24. Leilah Lyons, Michael Tissenbaum, Matthew Berland, Rebecca Eydt, Lauren Wielgus, and Adam Mechtley. 2015. Designing Visible Engineering: Supporting Tinkering Performances in Museums. In *Proceedings of the 14th International Conference on Interaction Design and Children* (IDC ’15), 49–58. https://doi.org/10.1145/2771839.2771845
25. Joyce Ma, Lisa Sindorf, Isaac Liao, and Jennifer Frazier. 2015. Using a Tangible Versus a Multi-touch Graphical User Interface to Support Data Exploration at a Museum Exhibit. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction* (TEI ’15), 33–40. https://doi.org/10.1145/2677199.2680555
26. Taylor Martin and Daniel L. Schwartz. 2005. Physically Distributed Learning: Adapting and Reinterpreting Physical Environments in the Development of Fraction

Concepts. *Cognitive Science* 29, 4: 587–625. https://doi.org/10.1207/s15516709cog0000_15
27. Tom Moher, Brian Uphoff, Darshan Bhatt, Brenda López Silva, and Peter Malcolm. 2008. WallCology: Designing Interaction Affordances for Learner Engagement in Authentic Science Inquiry. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (CHI '08), 163–172. https://doi.org/10.1145/1357054.1357082
28. Roger Osborne. 1983. Towards Modifying Children's Ideas about Electric Current. *Research in Science & Technological Education* 1, 1: 73–82. https://doi.org/10.1080/0263514830010108
29. Sasha Palmquist and Kevin Crowley. 2007. From teachers to testers: How parents talk to novice and expert children in a natural history museum. *Science Education* 91, 5: 783–804. https://doi.org/10.1002/sce.20215
30. Miriam Reiner, James D. Slotta, Michelene T. H. Chi, and Lauren B. Resnick. 2000. Naive Physics Reasoning: A Commitment to Substance-Based Conceptions. *Cognition and Instruction* 18, 1: 1–34. https://doi.org/10.1207/S1532690XCI1801_01
31. Cody Sandifer. 2003. Technological novelty and open-endedness: Two characteristics of interactive exhibits that contribute to the holding of visitor attention in a science museum. *Journal of Research in Science Teaching* 40, 2: 121–137. https://doi.org/10.1002/tea.10068
32. B. Schneider, J. Wallace, P. Blikstein, and R. Pea. 2013. Preparing for Future Learning with a Tangible User Interface: The Case of Neuroscience. *IEEE Transactions on Learning Technologies* 6, 2: 117–129. https://doi.org/10.1109/TLT.2013.15
33. Stephan Schwan and Roland Riempp. 2004. The cognitive benefits of interactive videos: learning to tie nautical knots. *Learning and Instruction* 14, 3: 293–305. https://doi.org/10.1016/j.learninstruc.2004.06.005
34. Pratim Sengupta and Uri Wilensky. 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
35. Pratim Sengupta and Uri Wilensky. 2011. Lowering the Learning Threshold: Multi-Agent-Based Models and Learning Electricity. In *Models and Modeling*, Myint Swe Khine and Issa M. Saleh (eds.). Springer Netherlands, Dordrecht, 141–171.
36. D. . Shipstone. 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
37. Kurt Squire and Eric Klopfer. 2007. Augmented Reality Simulaions on Handheld Computers. *Journal of the Learning Sciences* 16, 3: 371–413. https://doi.org/10.1080/10508400701413435
38. Margaret H. Szymanski, Paul M. Aoki, Rebecca E. Grinter, Amy Hurst, James D. Thornton, and Allison Woodruff. 2007. Sotto Voce: Facilitating Social Learning in a Historic House. *Computer Supported Cooperative Work (CSCW)* 17, 1: 5–34. https://doi.org/10.1007/s10606-007-9067-y
39. A. Tarciso Borges. 1999. Mental models of electricity. *International Journal of Science Education* 21, 1: 95–117. https://doi.org/10.1080/095006999290859
40. Susan A. Yoon, Karen Elinich, Joyce Wang, Christopher Steinmeier, and Sean Tucker. 2012. Using augmented reality and knowledge-building scaffolds to improve learning in a science museum. *International Journal of Computer-Supported Collaborative Learning* 7, 4: 519–541. https://doi.org/10.1007/s11412-012-9156-x
41. Susan A. Yoon and Joyce Wang. 2013. Making the Invisible Visible in Science Museums Through Augmented Reality Devices. *TechTrends* 58, 1: 49–55. https://doi.org/10.1007/s11528-013-0720-7
42. *JSARToolKit library*. Retrieved from https://github.com/artoolkit/jsartoolkit5
43. *Three.js library*. Retrieved from http://threejs.org/
44. *TopCode library*. Retrieved from http: //users.eecs.northwestern.edu/˜mhorn/topcodes/