

Developing Accessible Physics Simulations for Students with Vision Impairments

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Defended March 18, 2016

Abstract

Interactive science simulations, built by the PhET Interactive Simulations Project at the University of Colorado, rely heavily on visual representations to achieve their learning goals. This prevents students with visual disabilities from using those simulations. This paper examines one simulation, Capacitor Lab: Basics, as a case study on the implementation of keyboard navigation and auditory descriptions in PhET simulations. By manipulating a parallel DOM, it was possible to provide HTML equivalents of every Javascript element of the simulation, allowing a screenreader to access the descriptions. Keyboard navigation and auditory descriptions were designed and refined based on interviews with screenreader users. Through these think-aloud interviews, students' ability to learn concepts related to capacitors was assessed. The interviewees explored how to light the lightbulb and change the capacitance of the capacitor, and were successful in both goals. Findings suggest that these designs can support students with visual impairments to successfully learn from the simulation.

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1 Acknowledgments

Emily Moore, the PhET Director of Research and Accessibility, has been invaluable in guiding this project, conducting interviews, and designing the accessible features. Amy Rouinfar, one of PhET's science specialists, also provided her expertise throughout the design process. On the code side, Jesse Greenberg, a software developer with PhET, created the libraries for accessibility that Capacitor Lab: Basics used for keyboard navigation and screen reader accessibility. With the help of Jonathan Olson, another PhET developer, he built and tested the parallel DOM. Finally, Professor Clayton Lewis provided design guidance and valuable feedback throughout the process.

Funding for this work came from a University of Colorado ASSETS grant.

2 Introduction

The PhET Interactive Simulations Project at the University of Colorado [15] designs and develops educational simulations that address numerous topics in science and mathematics. They are aimed at grade levels K to 16. The simulations, of which there are over 130, are run over 75 million times a year, in classrooms across the country, but are currently inaccessible to students with visual or motor disabilities. The former may use a screen reader, while the latter may need alternative input methods, neither of which is supported by the PhET simulations at this time. This paper investigates the design and implementation of accessibility features in one simulation, Capacitor Lab: Basics, which is used as a case study for the implementation of these features in PhET simulations.

Students who are blind or have visual impairments are often at a disadvantage when it comes to educational achievement. The American Printing House for the Blind reported 60,393 legally blind students ages 3 to 21 in the American school system in 2014 [18]. The number of children under age 20 with visual disabilities is much higher, according to the American Community Survey: 694,300 children reported a visual disability in 2013 [4]. Children with visual disabilities are much less likely to graduate high school or complete college; 24% of adults ages 21 to 64 with a visual disability never graduated high school [18], while only 11.4% of the general population has less than a high school diploma [4]. Only 13.7% of adults with visual disabilities have a bachelor's degree or higher, while 30% of the total population has attained that level [4]. The most recent available NAEP (National Assessment of Educational Progress) science assessment indicates that only 11% of 8th grade students with disabilities scored “at or above proficient”, compared to the 34% of students without disabilities who received the same score. Even more alarming, two-thirds (66%) of all 8th grade students with disabilities scored “below basic” (i.e., the lowest) level of science achievement, compared to 31% of 8th grade students without disabilities [12].

When it comes to learning science, students with visual impairments are particularly disadvantaged. They are often forced into a passive role, where their sighted partner completes the lab experiment and then describes the results. This impedes their ability to learn the science – the NAEP shows a correlation between higher scores on the NAEP science assessment and the

amount of time students spent performing hands-on activities [13]. In general, students with visual disabilities have less access to experiential learning, which is a valuable component of learning in the sciences. Tools such as PhET simulations can provide such experiential learning, which is why they need to be accessible to all students.

More generally, the requirements for accessible technologies have been shifting towards equivalent interactions, so scenarios wherein a sighted student performs an exercise and then describes the results is becoming less accepted as a reasonable accommodation [5]. Legislation passed in 2013 requires that educational agencies use the principles of universal design for learning to ensure that all students have “equitable access to high-quality curriculum, instruction, assessments, technology and digital learning” [7]. Thus the goal for Capacitor Lab: Basics is to create a simulation that conveys equivalent experiences for users no matter their disability status.

3 Background

PhET simulations rely on the visual layout and implicit scaffolding to “support student learning through exploration and experimentation” [11]. Text is rarely used to cue interactions; instead, object placement, color, and other design choices are utilized [16]. The interactivity of the simulation is essential, as “learning goals are parameterized into interactive representations” [16], which are movable or changeable elements that provide dynamic feedback as the student interacts with them. All of these design choices make accessibility features more difficult to design and implement within the confines of the existing PhET infrastructure.

3.1 Infrastructure

PhET simulations use a modified Model-View-Controller pattern to structure the simulation architecture, as shown in Figure 1. The model represents the physics of the simulation: the speed at which the capacitor discharges, the calculations for stored energy and capacitance, the state of global variables, and more. All changes in state are handled by the model. So when the user drags the voltage slider, for instance, the view notifies the model of the change, and the model then updates the value of the battery voltage variable, which is stored as a `Property` of the main model class. `Property` is a class created by PhET developers to store changeable physical values of the simulation. The model also updates the values of the variables for the plate charge, stored energy, and electric field, which are `Property` objects as well; it then notifies the view of those changes.

The view classes, which also take on the controller role, draw the simulation and handle user input. They describe the various visual attributes of the view, which is structured using the composite design pattern, shown in Figure 2. In this design, every view class inherits from a class called `Node`. `Node` objects must have a parent, and can have any number of children. For example, the class that draws the circuit in the capacitance screen is called `CapacitanceCircuitNode`. It is a child of the screen view, which tells the simulation to how to draw the circuit; its children include an object of class `BatteryNode`, an object of class `CapacitorNode`, and several objects of class `WireNode`, among others. These classes draw the battery, capacitor, and circuit wires, and

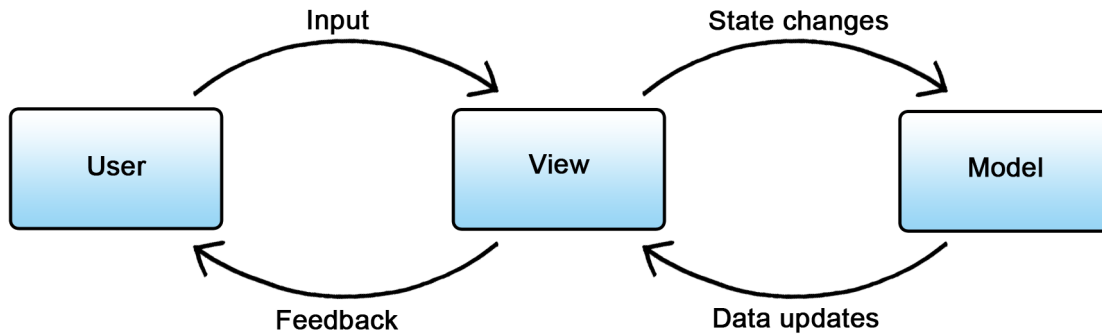


Figure 1: Modified Model-View-Controller architecture as used by PhET; simulations lack an explicit set of Controller classes.

handle user interaction with those elements.

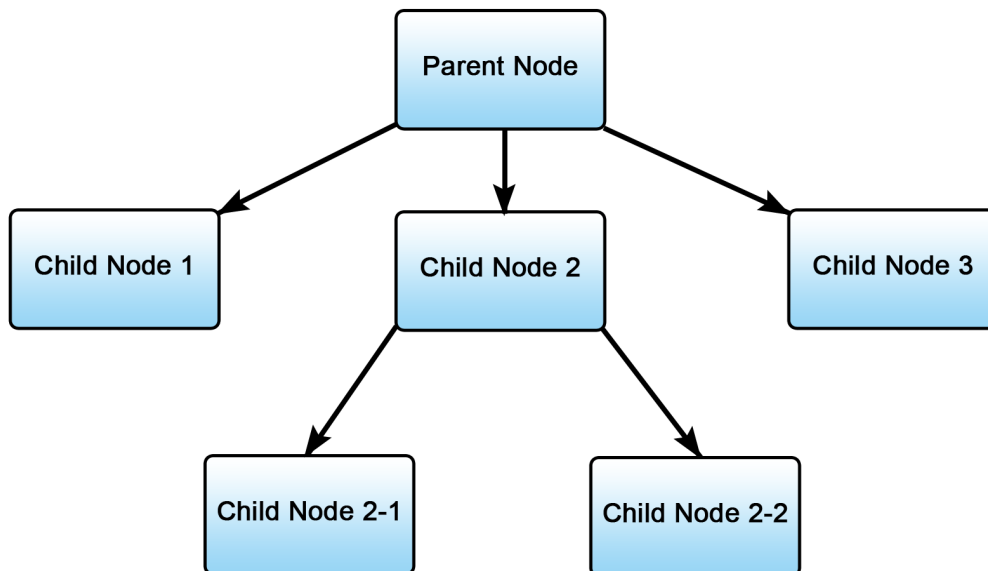


Figure 2: Example of the composite design pattern.

The view classes pass user input to the model via the observer pattern. In the observer pattern, pictured in Figure 3, the view classes take on the observer role, while the model classes are the classes that the view observes. When the model changes state – more specifically, when the `Property` objects in the model change state – it notifies the observer classes in its list of observers of that change. View classes can add themselves to that list, so they only listen for changes to properties that concern them. For example, the `BatteryNode` class listens for changes to the `Property` that describes the voltage of the battery, but it doesn't care about changes to any other

variables. When a view class observer is notified by a subject that a variable changed, it then updates the visual representations shown to the users.

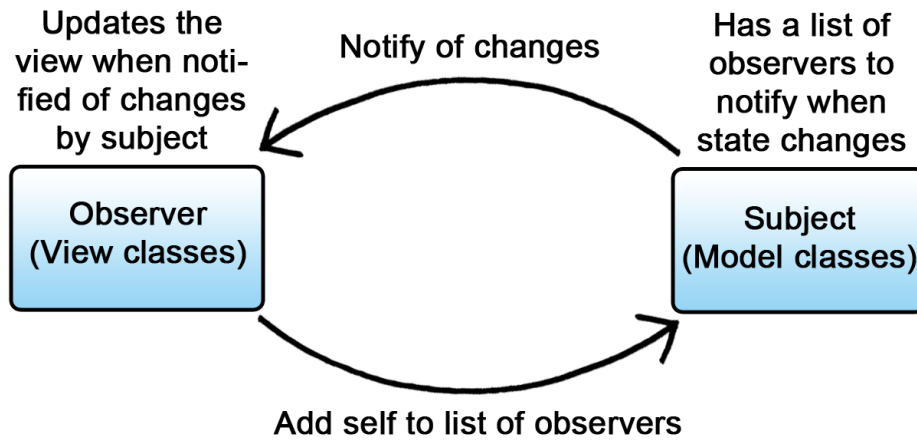


Figure 3: Example of the observer design pattern.

4 Capacitor Lab: Basics

Capacitor Lab: Basics is a simulation designed to support students in learning how a capacitor functions in a circuit. It has two screens, which guide the student through the concepts necessary to understand capacitors.

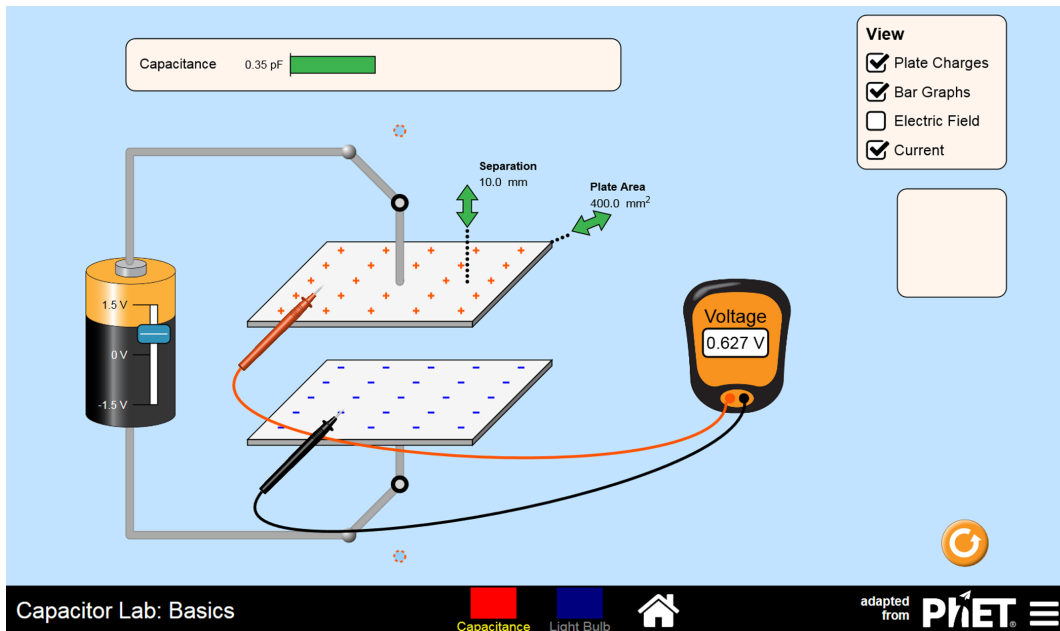


Figure 4: Capacitance screen of Capacitor Lab: Basics, with voltmeter in use.

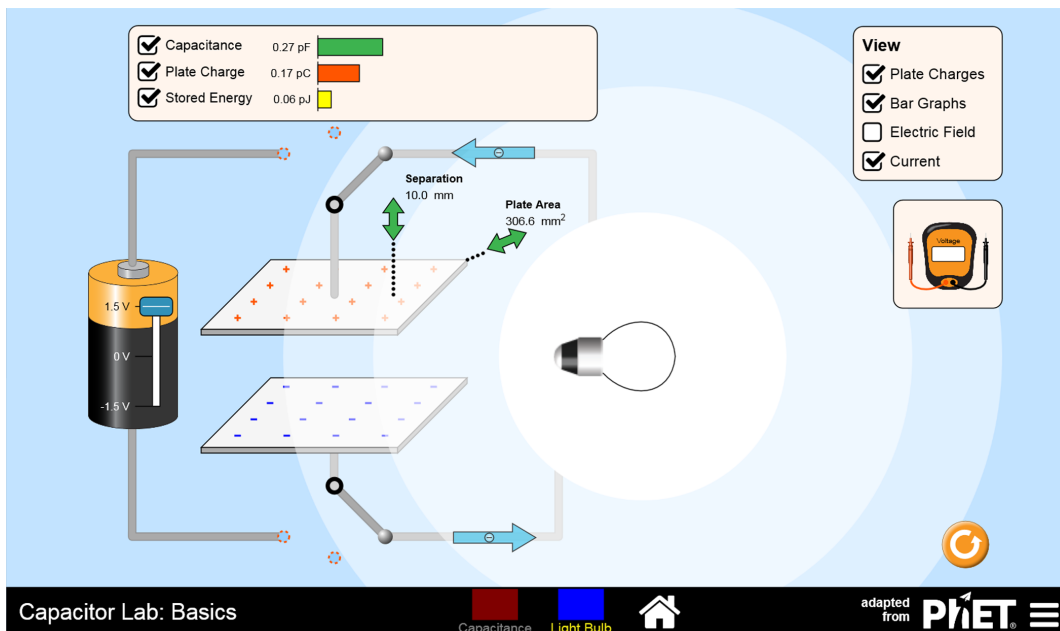


Figure 5: Lightbulb screen of Capacitor Lab: Basics, with lightbulb lit.

In the capacitance screen, which is the first one that students generally encounter, there is a

lone capacitor connected to a battery, along with a voltmeter and a bar graph that displays the value of the capacitance. Students can change the voltage of the battery and discover how the charge on the capacitor and the electric field change.

The second screen of the simulation, the lightbulb screen, adds a lightbulb to the circuit. The capacitor can be charged by connecting it to the battery, and discharged by connecting it to the lightbulb. The graph of capacitance is joined by a graph of the plate charge and a graph of the stored energy of the capacitor.

4.1 Interface design

The user interface for Capacitor Lab: Basics is designed to support three specific learning goals:

1. Explain the relationships between voltage, charge, stored energy, and capacitance
2. Predict how capacitance changes when the plate area or plate separation change
3. Describe how charge drains away from a capacitor into a lightbulb

The sequence of the screens guides students to initially explore the first two learning goals, as the third learning goal is only apparent in the second screen. The complex concepts are broken down into manageable pieces so the student is not overwhelmed by information [16].

In Capacitor Lab: Basics, students usually interact first with the circuit, as its importance is highlighted via its placement in the screen. The initial interaction provides motivation [10] for productive simulation usage by motivating the student to ask questions and by providing immediate feedback from their actions [16]. In the circuit, the slider on the battery and the arrows next to the capacitor allow them to change the battery voltage, as well as the plate area and plate separation. The use of such affordances guides students without the need for explicit instructions [11].

When they change the voltage, there is immediate feedback from the charges on the capacitor; changing the capacitor dimensions produces feedback from the graph of capacitance. This leads students towards exploring the first two learning goals without explicit instructions within the simulation.

5 Challenge: Designing for Vision Impairment

Accessibility features need to be consistent with web standards, and need to support learning through exploration and inquiry. The Web Content Accessibility Guidelines (WCAG) from the World Wide Web Consortium require that every non-text element has a text equivalent and the equivalents for dynamic content are updated as the dynamic content changes [2]. The PhET project requires that the accessible content supports the implicit scaffolding used to guide the student exploration and conveys the necessary information for students to achieve the learning goals. Capacitor Lab: Basics is used as a case study of how to be consistent with the WCAG design guidelines while satisfying the PhET project's goals of exploration and inquiry. Rather than designing a version of the PhET simulation specifically for students with vision impairments, the goal is to design features that will allow any group of students to work with the same simulation.

The WCAG guidelines were created to provide developers with standards for creating basic web pages. They include many useful rules, including the ones described above. Other guidelines include ensuring sufficient contrast within pages and using header elements to convey document structure [2]. However, while many of the guidelines are useful, WCAG designed its rules to apply to ordinary web pages, not complex Javascript simulations. Many of the rules, such as “Organize documents so they may be read without style sheets” [2], simply do not apply. Others, such as the requirement to provide text equivalents – such as alt text for images – for non-text elements, are good to follow, but do not provide any specific information. While it is fairly straightforward to provide alt text for images and videos in a normal website, alt text alone is not sufficient for a PhET simulation.

The lack of specificity is one reason why the design process for Capacitor Lab: Basics was relatively complicated. The WCAG standards do not cover all of the scenarios that users encounter in the simulation, so much of the work was done in previously-unexplored territory. Furthermore, the standards are not consistently implemented across all browsers – some support more accessible technology than others – so the simulation design needed to work around those issues as well. Adhering to the PhET project requirements for exploration and learning was just as important as working within the WCAG standards, and guided much of the design when the WCAG failed to

provide sufficient guidance.

6 Design Process

Current PhET simulations do not allow for keyboard navigation or screen reader descriptions without modification, as every element is dynamically generated with Javascript. That means that the typical elements a screen reader looks for, such as links and headings, do not exist. Similarly, there are no simulation elements that are naturally navigable via the keyboard. The WCAG require that every element in the page must be accessible via the keyboard, as users with visual or motor disabilities often cannot use a mouse [6]. So modifications to the simulation must support both keyboard navigation and auditory descriptions.

To design and implement those modifications, an iterative design process was used. The structure of the keyboard navigation and auditory descriptions was sketched out and refined on paper, leading to a document that described a sample path through the simulation. At each step, the active keys and their effects was listed, along with the auditory descriptions that would accompany each key press. A sample set of interactions is shown in Table 1.

Interaction	Secondary Action	Outcome	Screenreader Description
Tab		Keyboard focus moves to battery slider	Slider - Battery voltage
	Up arrow key	Voltage increases	Voltage is [insert value]
	Down arrow key	Voltage decreases	Voltage is [insert value]
Tab		Keyboard focus moves to top wire connector	Toggle - Circuit wire
	Space bar	Toggle connector from connected to disconnected position	Circuit disconnected

Table 1: Sample interaction set from first implementation of keyboard navigation and auditory descriptions.

Once the paper draft was completed, implementation began. To allow screenreaders to access the content of the simulations, a parallel DOM was created by PhET developers. It contained all of the common-code elements of the simulation, such as the reset button and the PhET menu button, but did not include any of the objects that were created specifically for Capacitor Lab: Basics. Then, by altering the specific parallel DOM structure of Capacitor Lab: Basics, each interactive element of the simulation was given an HTML equivalent. This allowed the screenreader to control the keyboard navigation when a screenreader was in use, and gave the screenreader access to descriptions of each element.

7 Methods for Evaluating the Design

The initial implementation was tested using a think-aloud interview with a volunteer who identified as blind and regularly used a screenreader but had little knowledge of physics. She will be given the pseudonym of Megan. Megan was a recent college graduate, who had not pursued a degree in any physical science or mathematics. She was asked to explore the simulation while describing her thought process to the interviewer. This type of interview allows interviewers to discover how the users interpret various components of the simulation [3]. It also reveals any plans, hypotheses, or revelations they have as they manipulate the simulation, so the interviewer can assess how well they understand the physical concepts being presented. Misconceptions can be found through this process as well; if multiple users misunderstand the same component, that suggests that it needs to be redesigned.

Megan worked with Capacitor Lab: Basics for approximately twenty minutes. The interview was videotaped so that both her discourse and her interaction with the simulation could be analyzed. That analysis, combined with her feedback, was used to create another iteration of the design. A similar redesign process occurred, wherein the design was first created on paper and then implemented.

The new design was tested via two longer think-aloud interviews – one with Megan and one with another student who will be given the pseudonym Anna. Anna was a senior in college, majoring in a non-science field, who also identified as blind. Like Megan, she regularly used screenreader technology. Megan worked directly with the simulation for a total of 21 minutes, while Anna used the simulation for 29 minutes; both women were asked three questions before and after their use of the simulation:

1. What happens to the charge on a capacitor when the voltage is increased? Explain.
2. In a capacitor, how can you change plate area and plate separation to achieve maximum capacitance? Explain.
3. What happens when a charged capacitor is connected to a lightbulb?

These three questions capture essential elements of the learning goals described above. Neither interviewee knew the answers to any of the questions prior to using the simulation, although both

guessed that the lightbulb would light up when connected to a charged capacitor.

Their answers to these questions were analyzed along with the videos of their interaction with the simulation. The results are presented below.

8 Initial Design and Implementation

In the first iteration of the design, each interactive element was given an `accessibleContent` property and a tab order of 0. That tab order designation allowed the PhET architecture to handle the traversal of the nodes, focusing on them in their rendering order when the user pressed the tab key. When a screenreader is in use, it takes over from the PhET architecture and handles the traversal, following the same order as the PhET architecture.

The order in which the elements are navigated must follow the logical flow of the page, according to the WCAG [6]. In Capacitor Lab: Basics, the layout of the screen guides the order in which students interact with objects [16], so the initial keyboard navigation path followed that order. First, focus went to the elements in the circuit, then the graphs, and then the checkboxes controlling aspects of the view (all pictured in Figure 4.) Focus is denoted with a magenta box around the object in focus, as shown in Figure 6. If the focused object was movable, arrow keys allowed the user to move it.

Initial auditory descriptions focused solely on the interactive elements, so elements such as the circuit or the capacitor were not given descriptions. Only elements such as the slider on the battery, pictured in Figure 4, had auditory descriptions. Those descriptions were minimal; e.g., the battery slider read “Slider - battery voltage.” No indication of how to use the objects was provided. This approach was chosen because sighted students focus primarily on the interactive elements, which are designed to provide pedagogically-beneficial interactions [16]. The lack of explicit instructions in the simulations is designed to give students a sandbox in which to explore, rather than give them a set path to follow. By focusing the descriptions on the interactive elements, the design was intended to encourage students to explore the simulation by discovering what each interactive element did. However, this approach was modified after the initial interview, as described below.

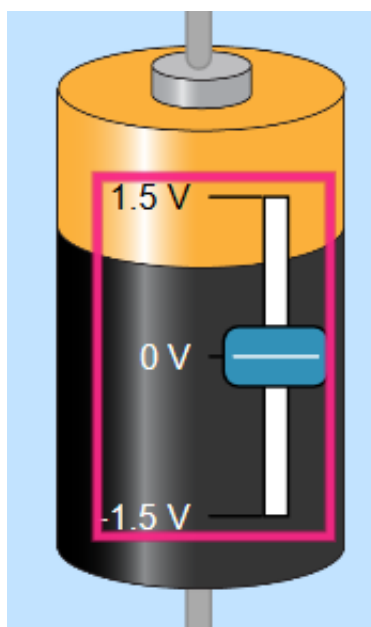


Figure 6: Focus box around the voltage slider on the battery.

8.1 Initial Interview

The first interview contained numerous technical challenges, and served to identify areas where the simulation could be improved. Megan began by using screenreader shortcuts to search for headings, and did not find any, as the original version of the parallel DOM only included divs, paragraphs, and input elements. She informed us that most screenreader users navigate first through the headings to see what the page contains, in the same manner that a sighted user briefly skims the page. Without the headings, and lacking a simple description of the simulation contents, she found it difficult to understand what was happening in the simulation. This led to the introduction of the scene description, accompanied by headings, paragraphs, and other structures, as described in the Current Design and Implementation section. These new features give screenreader users an overview of the simulation.

Megan had to be prompted to switch into forms mode and use the tab key to navigate through the elements. Once she did so, she was able to interact with the simulation, but did not know how to manipulate the interactive elements. Her feedback led to changes in the auditory descriptions, some of which are described in Table 2.

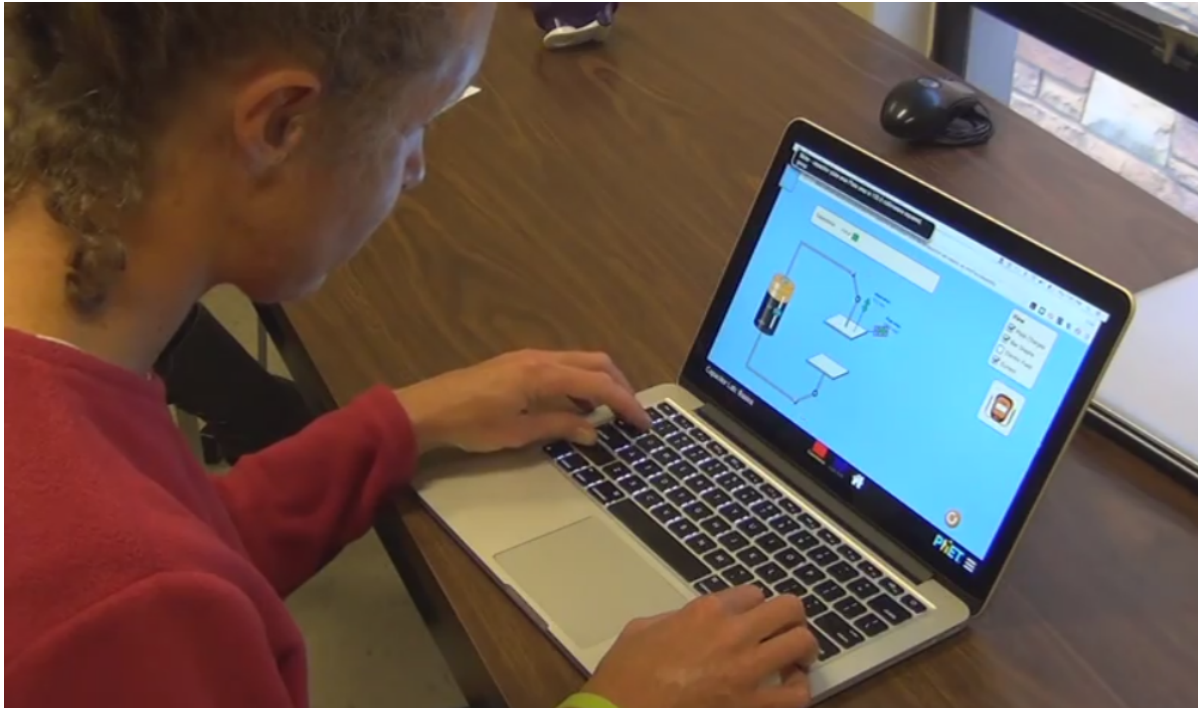


Figure 7: First interview, user trying to increase voltage.

Simulation Element	Initial Description	Modified Description
Battery Slider	Slider - battery voltage	Slider - battery voltage. Use arrow keys to change voltage
Toolbox	Menu - toolbox	The toolbox contains a voltmeter, which measures voltage. Press enter to use the voltmeter
Voltmeter Probe	Voltmeter probe	Voltmeter probe 1. Use arrow keys to move probe

Table 2: Sample descriptions of interactive simulation elements before and after the initial interview.

8.2 Infrastructure Redesign

As a result of the changes suggested by the first interview, the infrastructure that created the parallel DOM needed several modifications.

Some elements of the simulation change dynamically, and that must be announced through

the auditory descriptions [2]. For those elements, ARIA live regions are used. WAI-ARIA is a framework that allows developers to make their web applications, especially ones with dynamic content and advanced user interfaces, more accessible to people with disabilities [19]. It provides methods for developers to add extra attributes to elements so a disabled user can identify their current state and their relationship to other elements. Live regions are specifically created for dynamic content, so a change in the content will be announced to the user no matter which object is currently in focus [8]. To create a live region, the element in the DOM tree must be tagged with the `aria-live` attribute. Significant changes to the infrastructure were made to support live regions, as well as a wider range of HTML elements such as headings.

The initial implementation of the parallel DOM did attempt to support live regions, but did not communicate them clearly to the screenreader, so numerous bugs were present. Many changes were announced multiple times: e.g., if the voltage changed to 0.30 volts, the user would hear “Voltage is 0.30 volts” repeated up to four times. Other live regions simply failed to announce any changes. Bugs were highly browser-specific and system-specific, with different browsers having varying levels of support for live regions. The infrastructure redesign mainly utilized Firefox, as it had the most native support for all ARIA attributes. By revealing more of the parallel DOM structure to the browser and screenreader, the PhET architecture was able to bypass some of the problematic interactions that were causing the repetition or omission of strings.

8.3 Cuing Interaction

Implementation was designed to be compatible with NVDA, a free screen reader for Windows [14]. A 2015 survey conducted by WebAIM revealed that 41% of respondents commonly use NVDA, but only 14.6% use it as their primary screenreader [17]. JAWS, a commercial screenreader for Windows [1], was the most popular, as 44% of respondents commonly use it, and 30.2% use it as their primary screenreader. However, its market share has declined in recent years, as users trend towards free or low-cost screenreaders [17]. This study used NVDA to test the simulation’s implementation of auditory descriptions because of its cost and relatively high – and increasing [17] – market share.

NVDA has two modes: browse mode, which allows users to navigate through headings, paragraphs, and text content; and forms mode, which allows users to manipulate interactive elements. Browse mode is the default mode for NVDA, and forms mode disables most of the key shortcuts that allow screenreader users to efficiently navigate a document [9]. In forms mode, the application handles most of the key events, while browse mode strictly limits the amount of control that the application is given. Because of the differences between the modes, and the different information accessible from each one, the simulation needs to provide information to the user about which mode to be in. Once users switched into forms mode, it needed to explain which key commands would produce the desired effects. Early interview feedback suggested that strings such as “Use arrow keys to change voltage” would be helpful when an element like the battery voltage slider is in focus, so those were added. A help menu was also added to provide a list of active keys and their effects. Using the ‘H’ key brings up the help menu so long as focus is somewhere within the main body of the simulation. Either the escape key or the tab key returns focus to the previously-focused element when the user is finished with the help menu.

The keys used in the simulation are shown in Table 3.

Key	Description Given in Help Menu
Tab	Navigates through elements
Enter	Enters groupings of elements
Escape	Leaves groupings of elements
Spacebar	Toggles checkboxes
Arrow keys	Move moveable objects like sliders
H	Brings up help menu

Table 3: Descriptions of keys used in the simulation.

9 Current Design and Implementation

The current design utilizes the new architecture to provide information for both forms mode and browse mode, the two modes common in screenreaders, although the majority of interactions are completed using forms mode. The terms ‘browse mode’ and ‘forms mode’ are specific to NVDA – not all screenreaders use the same terms, although most have similar modes. Because NVDA was the primary screenreader used to test the simulation, this paper will use those terms.

The parallel DOM is organized into sections and divs, with headings to describe the purpose of each area, which are accessible in the browse mode of the screenreader. The level 1 heading and its associated paragraphs, which are the first thing many screenreader users encounter, provide a high-level overview of the features of the simulation; the level 2 heading describes the play area. Every element within the simulation is then described with lower-level headings and paragraphs. Both `aria-describedby` and `aria-labelledby` attributes are used to convey this information to the screenreader.

For example, the parallel DOM element for the circuit in the first screen looks like this:

```
1      <div id="circuit-widget" aria-labelledby="circuit-label" aria-
      describedby="circuit-description">
2      <h3 id="circuit-label">Circuit</h3>
3      <p id="circuit-description">The circuit contains a capacitor and a
      battery. The capacitor is currently connected to the battery.</p>
      >
4      <div id="battery-widget" aria-labelledby="battery-label" aria-
      describedby="battery-description">
5      <h4 id="battery-label">Battery</h4>
6      <p id="battery-description">The battery has a slider on it that
      controls voltage. The current voltage is 0 volts. Use the
      arrow keys to change the voltage of the battery.</p>
7      </div>
8      <div id="capacitor-widget" aria-labelledby="capacitor-label" aria-
      describedby="capacitor-description">
```

```

9      <h4 id="capacitor-label">Capacitor</h4>
10     <p id="capacitor-description">The capacitor is represented by two
      rectangular plates, one on top of the other, separated by a
      small space. It has a slider above it that controls the
      separation of the plates, and a slider next to it that controls
      the area of the plates. There are no charges visible on the
      plates.</p>
11     </div>
12     <div id="switch-widget" aria-labelledby="switches-label" aria-
      describedby="switches-description">
13         <h4 id="switches-label">Switches</h4>
14         <p id="switches-description">The circuit has two switches, above
      and below the capacitor, that connect and disconnect the
      capacitor from the battery.</p>
15     </div>
16 </div>

```

The circuit contains a battery, a capacitor, and two switches, each of which is represented by their own `<div>` element. As shown above, the `<div>` for the circuit is given the id of “circuit-widget”, as well as the `aria-labelledby` and `aria-describedby` properties. The `aria-labelledby` property is assigned the value “circuit-label”, which is the id of the heading which labels it as ‘Circuit,’ while the `aria-describedby` property is assigned the value “circuit-description”, which is the id of the paragraph that provides a longer description of the circuit. Every `<div>` element contained in the circuit is given the same properties.

When the screenreader is in forms mode, the first element in the focus order is the circuit, which is a group containing the battery voltage slider, the wire connectors, and the capacitor dimension controls. The user can either choose to enter the circuit grouping or continue to navigate through the simulation. If they choose the latter, navigation proceeds in a clockwise manner.

Pressing enter brings the focus inside the group to the battery slider. Subsequent presses of the tab key will allow the user to navigate among the elements of the group, with the arrow keys

changing the values of the sliders. Pressing the escape key brings the focus back to the circuit group, from which the student can navigate among the rest of the simulation.

Navigation proceeds in a clockwise manner around the screen after the circuit loses focus. In the Light Bulb screen, the panel containing bar graphs also acts as a group, but otherwise the two screens behave in an identical manner. Tasks such as lighting the lightbulb can be accomplished in a few number of key presses, as shown in Figure 8.

Numerous elements, such as the bar graphs and lightbulb, are ARIA live regions. WAI-ARIA live regions are special elements that announce any changes in state to the user, no matter which element is in focus [8]. This allows a blind user to receive feedback for their actions comparable to the feedback seen by a sighted user. Because “well-designed feedback is foundational to effective interface design,” [16], the feedback provided through the accessibility features must convey all of the information that the visual changes do.

9.1 Second Round of Interviews

During the second round of interviews, both interviewees accessed a description of the screen and formed a concept of the layout. They both navigated sequentially through the scene description; Megan listened to all of the element-level descriptions provided, while Anna listened to most of them. They then proceeded to explore the simulation. After interacting with most of the interactive elements, both women chose a specific conceptual problem to explore. Megan focused initially on changing the voltage, then explored the plate area and plate separation controls, with the goal of determining what effect those changes would have on the capacitance. Anna decided to focus on the voltmeter and attempted to determine which factors would change the voltage reading.

Megan encountered no technical challenges while interacting with the circuit elements, but Anna ran into multiple usability issues while working with the voltmeter. She spent a significant amount of time attempting to figure out how to productively use the voltmeter, which impeded her ability to engage conceptually with the simulation. She was eventually prompted by the interviewer to access the lightbulb screen, pictured in Figure 5, and immediately focused on lighting the

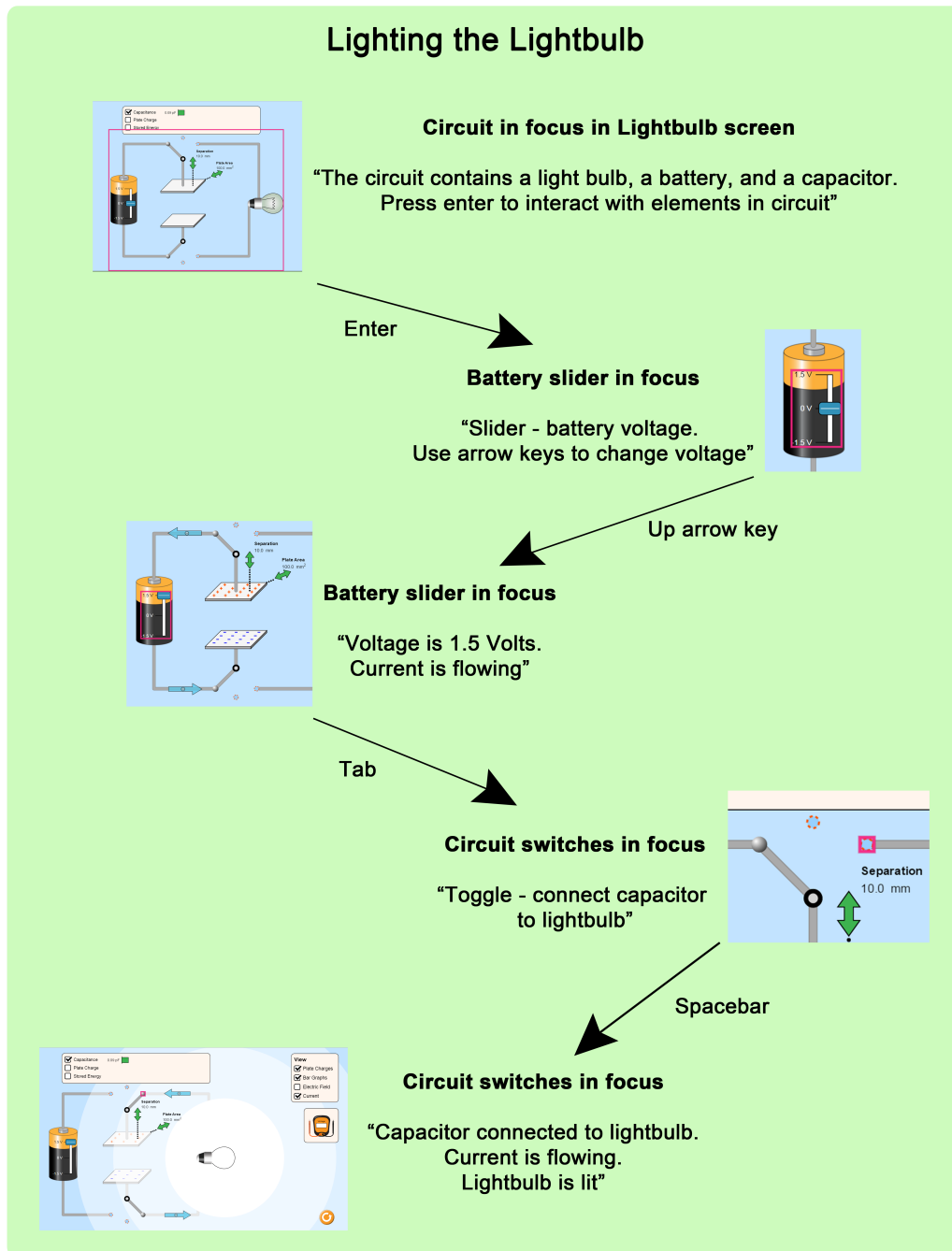


Figure 8: Auditory descriptions and keyboard navigation path used to light the lightbulb.

lightbulb. To do so, she needed to follow the path shown in Figure 8 – first, increase the voltage of the battery to charge the capacitor; then, connect the capacitor to the lightbulb. Within her first three minutes on the lightbulb screen, she able to successfully charge the capacitor and light the lightbulb, which pleased her.

Megan, on the other hand, was able to focus on the relationship between the circuit elements

and capacitance from the beginning, without interference from usability challenges. She spent the majority of her time on the capacitance screen, exploring how changes to the voltage, plate area, and plate separation affected the capacitance. Due to this deeper exploration, she did not have time to explore the lightbulb screen. However, she successfully learned that voltage does not affect capacitance, while both a smaller separation and larger plate area increase it.

In the end, both interviewees were able to conceptually engage with features of the simulation. Despite technical issues, they could access the scene descriptions as well as the interactive elements. That allowed them to explore the simulation and successfully learn some of the learning goals which are described above. Megan successfully met the learning goals for the capacitance screen, while Anna was able to learn one of the main goals of the lightbulb screen. More detailed results will be presented below.

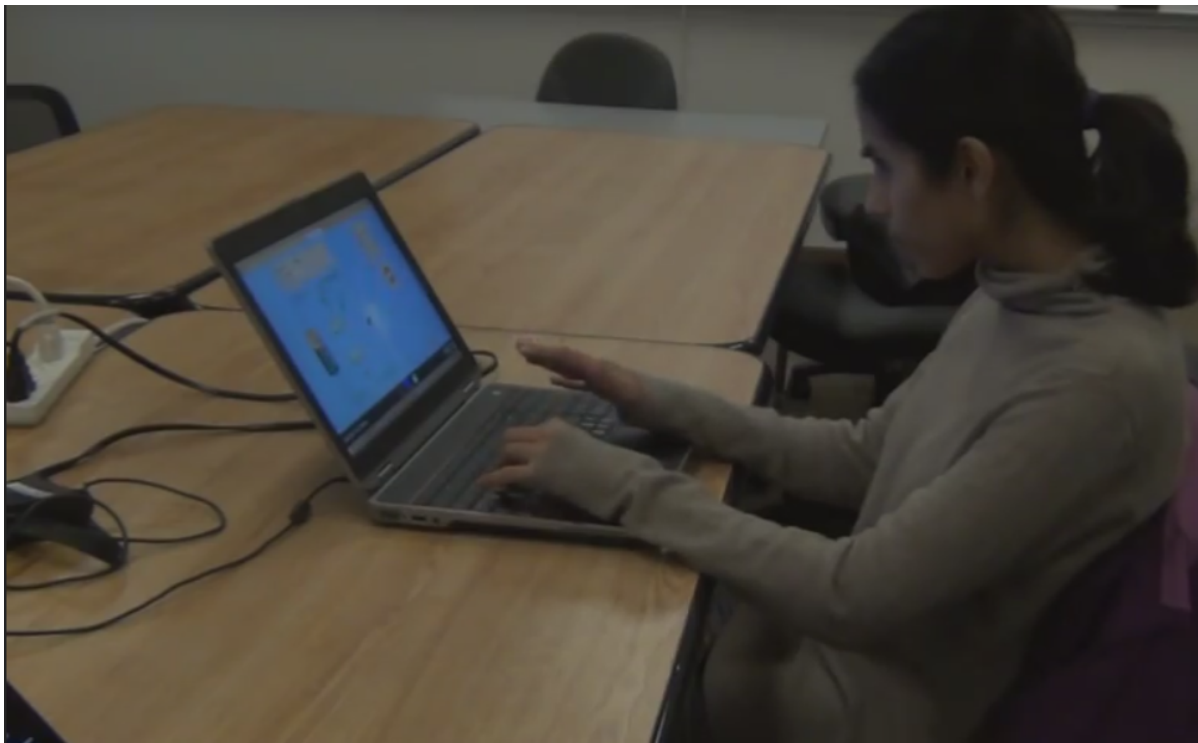


Figure 9: Third interview, user lighting the lightbulb.

10 Results: Learning Physics

In order to discuss the results of the second round of interviews in more depth, excerpts from the interview transcripts will be presented. The time will given in min:sec format, and will be followed by a brief summary of the user's interactions and verbalizations. Summaries will be used for lengthy interaction patterns or long quotes.

The first learning goal of Capacitor Lab: Basics is to explain the relationship between voltage, charge, stored energy, and capacitance. To measure it, both interviewees were asked, "What happens to the charge on a capacitor when the voltage is increased? Explain." Unfortunately, neither user was able to successfully answer the question, as feedback about the plate charges is only provided in the second screen. In the lightbulb screen, there is a graph depicting the plate charge, which, as a live region, gives feedback about the value of the graph. But the only representation of charge in the first screen is the visual accumulation of red positive charges and blue negative charges on the plates of the capacitor. A sighted user can see the accumulation of charges on the plates, but feedback for that visual representation was not provided.

This made it impossible for Megan to realize the relationship between charge and voltage, since she was never given any information about charge. She guessed that the voltage had no effect on charge, but was quite uncertain about why, probably due to the lack of information. While Anna was given some information about charge when she explored the second screen, she was not focusing on that information. When asked the question, she replied, "I don't know, because I don't think I actually got it to read." She then guessed that an increase in voltage decreased the charge, but admitted that it was "a complete guess." This is an area for future work.

The second learning goal of Capacitor Lab: Basics is to predict capacitance changes when plate charge or plate area change. This is the goal that Megan chose to focus on, without prompting on during her exploration. After listening to all of the descriptions of the various elements, which took a bit over four minutes, she announced, "Okay. I think I more or less know the parts." After prompting from the interviewers, she then switched into forms mode, allowing her to manipulate the interactive elements, and began to explore the circuit group. She started by changing the plate separation, then plate area, before returning both to the default values and exploring the circuit

switches, then the voltage slider. Here is the transcript of that interaction:

- 8:24 Changes capacitor plate separation, plate area, battery voltage, and navigates through all of sims interactive elements.
- 11:05 Switches into browse mode and begins listening to the scene description.
- 11:39 Says “I’m looking for where it would tell me... so if I can control voltage, I can control size and I can control distance...so that all goes together to... so what’s the output?”
Continues listening through description.
- 13:20 Listens to description of capacitance graph, which reads “Capacitance Graph, measures the capacitance of the capacitor”. Says “I guess I’m looking for capacitance.”

In this way, she realizes that a goal of the simulation is to learn about capacitance. The capacitance graph is a live region, which means that it should read out the value of capacitance whenever it changes. Unfortunately, due to a bug in the simulation that appeared during the interview, the capacitance graph was not properly functioning during Megan’s interaction with the plate separation and plate area sliders, so she was not receiving appropriate feedback. To address this, the interviewer offered to tell Megan the value of capacitance whenever she wanted. Megan then began to explore the elements with the goal of determining how capacitance changes, as shown in the sample transcript below.

- 14:25 Makes an initial prediction before interacting: “I assume that if I push the voltage up, the capacitance is also going to go up, but it might stay the same because it might not be dependent on I don’t know, so I’m going to check.” Navigates to the voltage slider, increases the voltage, and asks “How many picofarads?”. Capacitance was 0.11 pF. Megan says “Okay, so its the same. So voltage does not impact okay.”
- 15:29 Navigates to the plate area slider, currently with a value of 121 mm². Says, “Okay, so I had it at 121.” Increases area to 144 mm²., and says, “Okay, so if I go up, then what is it?” Interviewer informs her that capacitance is 0.13 pF. Megan increases area to 169 mm², and asks, “Okay, what is it there?” When informed that capacitance was 0.15 pF, says, “Okay, the size of the capacitor is increasing, umm, I don’t know if exponentially is the right word.” Explains her ideas about the relationship between plate size and capacitance.
- 18:01 Says, “I’m going to take the size back down to where the default was.” Decreases the plate area back to 121 mm² and navigates to the plate separation slider. Decreases plate separation, then increases it back to the maximum. Asks, “Okay, so it’s back to 0.11 there, right?” Interviewer informs her that she’s correct. Megan then decreases the plate separation from its maximum to its minimum in the 0.5 mm increments available to her through keyboard presses, asking for the capacitance readout with each change. Then she explains her ideas about the relationship between plate separation and the capacitance.

Through her explanations of the relationship between capacitance, plate area, and plate separation, it was clear that Megan had figured out that decreasing plate separation increased capacitance, while increasing plate area did the same. She also learned that voltage has no effect on capacitance. This realization was a significant accomplishment, as she was able to learn one of the major learning goals of the simulation without the visual cues that sighted students rely on. Her new knowledge allowed her to confidently answer the question regarding how to change plate area and plate separation to achieve maximum capacitance when it was asked at the end of the interview.

The third learning goal of Capacitor Lab: Basics relates to the functioning of a lightbulb in a circuit containing a capacitor. The lightbulb can be found in the second screen of the simulation, pictured in Figure 5. The PhET project has found that the introduction of a lightbulb, when appropriate, provides users with a clear goal: light the bulb. The interview with Anna showed that users with visual impairments also immediately realize the purpose of the bulb.

Anna worked with the capacitance screen for approximately 23 minutes, spending most of the time struggling with the voltmeter. At that point, the interviewer suggested that she switch over to the lightbulb screen, which she did. She then proceeded to explore the screen with the clear goal of determining how to light the lightbulb, and was successful within approximately three minutes. Here is a transcript of her interactions:

- 23:32 The interviewer suggests switching to the Light Bulb screen, indicating that it has the same features as the Capacitance screen “and a few more”. Anna says “Yeah!” and the interviewer helps her navigate to the screen.
- 24:27 The lightbulb screen opens. Anna navigates around the interactive features, finding the circuit group but not entering the group. After changing the screen reader from focus mode to browse mode, she begins listening to sections of the scene description, but does not get to the description of the bulb. She changes the screen reader back to focus mode.
- 25:22 Navigates to the voltage slider and increases the voltage, then navigates to the circuit toggle switch. The switch connects the capacitor to either the lightbulb or the battery – the capacitor starts connected to the battery. She explores connecting and disconnecting the battery.
- 27:02 Toggles the circuit to connect the capacitor to the lightbulb, which lights the bulb. “Hooray, the lightbulb lit!”

When the interviewer asked Anna the third question, “What happens when a charged capacitor is connected to a lightbulb?” she immediately answered that it turns the lightbulb on. She then remarked, “Most exciting thing that I’ve done so far is when the lightbulb turned on.” She later said that the lightbulb was her favorite part of the simulation.

Anna also said that “As soon as you said there is a lightbulb page, I’m like, I know what I’m

supposed to do.” This is a positive sign that the lightbulb representation is serving its function in guiding student exploration. Sighted users focus on the lightbulb as an obvious indication of the goal of the simulation; that Anna did the same implies that the nonvisual representation of the lightbulb also gives a clear indication of a goal. This shows that the implicit scaffolding desired by the PhET project [16] can translate reasonably well into an auditory version of the simulation.

11 Challenges

11.1 Description Clarity

The keyboard navigation and auditory descriptions allowed both interviewees to engage with the simulation on a conceptual level, setting up experiments to answer questions such as ‘What affects the capacitance?’ and ‘How do I light the lightbulb?’ However, a lack of appropriate descriptions and feedback impeded the interviewees’ ability to accomplish all of the learning goals of the simulation.

For instance, the voltmeter contains two probes, one red and one black. These are described in the initial description of the voltmeter, but the probes themselves are only identified as probes; they are not identified with their color. Without that indicator, Anna found it difficult to keep track of the probes. As both probes need to be on the wires or the capacitor plates for the voltmeter to provide a reading, this proved to be problematic.

The voltmeter also frustrated Anna by repeating “Voltage cannot be measured.” The voltmeter is a live region that announces its state every time a probe moves. If both probes are on the wires or the capacitor plates, it will announce “Measured voltage is x volts,” where x is the voltage gap between the probes. However, if one or both of the probes is somewhere other than the wires, it informs the user that it cannot measure the voltage. A sighted user receives the same information visually, as depicted in Figure 10.

Anna wanted to figure out how to measure the voltage, and simply being told “Voltage cannot be measured” did not explain why she could not measure the voltage, so she grew frustrated with it. If the voltmeter had announced “Voltage cannot be measured. Try moving the probes,” that might have been more useful.

The auditory descriptions related to current were another set of cues that neither interviewee in the second round understood. The simulation announces “Current is flowing” when the current starts to flow, and “No current is flowing” when it stops. A sighted user sees Figure 11 when the current begins to flow; the blue arrow then slowly fades out as the current decreases to zero.

Both interviewees said that they chose to ignore the information about the current, as neither

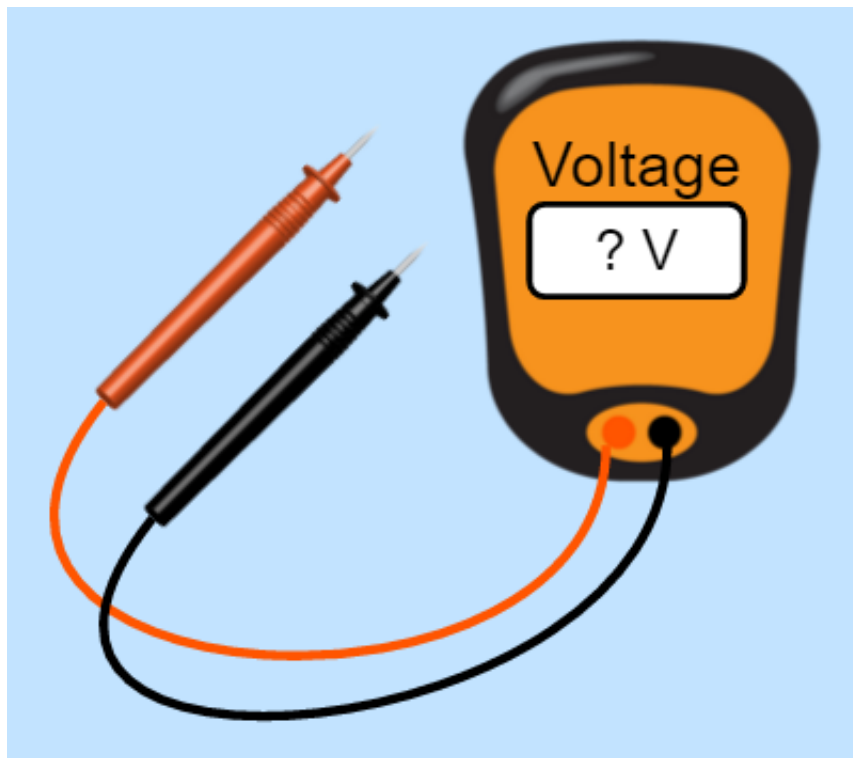


Figure 10: Voltmeter and probes, currently unable to measure voltage.

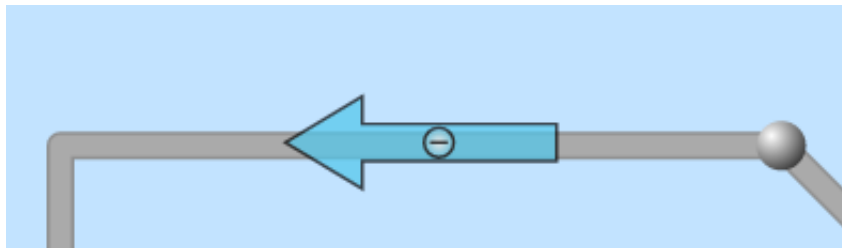


Figure 11: Depiction of current flowing through the circuit.

understood what it meant. Here is a sample interaction from Megan’s interview:

12:22 Voltage changes; simulation announces “Current is flowing.”

12:30 Simulation announces “No current is flowing.” Megan remarks, “Current is flowing... and then no current is flowing. So I don’t, um... But I assume the current is actually flowing, um... that the ‘no current is flowing’ is just, um, an extra... it shouldn’t really be there.”

She had said earlier that she didn’t understand what was happening when the simulation announced the changes in current. As can be seen from this interaction, Megan did not understand that the current starts to flow when the voltage changes, but stops flowing as soon as the capacitor

is charged. So she chose to interpret the string ‘No current is flowing’ as a bug in the simulation, rather than valid information.

Sonification of the current, as will be discussed in Section 12.1, may clarify the representation, as it would provide a representation of the slow decrease of current. However, it would not explain what current is, or why it’s flowing, which appear to be the main source of Megan’s confusion. More interview data would be necessary to determine the best way to represent the current.

11.2 Technical Challenges

Screenreaders such as NVDA have both a browse mode and a forms mode; browse mode is used to navigate “complex read-only documents,” while forms mode allows the user to manipulate the elements such as text boxes [14]. The screenreader should switch into the correct mode, depending on which elements are present on the page. Capacitor Lab: Basics was originally built to work only in forms mode, as nearly every element takes user input. However, in complex applications like simulations, the screenreaders do not automatically recognize when to switch into that mode. It was necessary to tell interviewees to manually switch, as that was not always obvious.

Navigating Capacitor Lab: Basics in browse mode provides some information, but does not allow users to interact with the elements. The parallel DOM contains various sections and headings, which sort the content into semantically-relevant groupings and give users a high-level overview of the contents of the simulation. We found that screenreader users tend to search first for those headings, and then explore deeper into the document.

Because this work pushed the boundaries of current standards for implementing accessible content, many standards are not yet developed, and no comparable examples exist. Some improvements are still needed for a seamless interface between the simulation and browse mode of the screenreader, and some current bugs caused the interviewees some frustration.

12 Future Work

Though significant progress has been made in making Capacitor Lab: Basics accessible for students with visual impairments, a number of improvements are in progress to ensure that all features of the simulation are easily accessible with a screenreader.

12.1 Sonification

The current design uses ARIA live regions to provide feedback when dynamic content changes. For some situations, this can work well – e.g., announcing the change in capacitance when the plate area or plate separation change. However, in other situations, it can be clunky and obtrusive without conveying all of the necessary information. For example, the lightbulb in the second screen lights up when the charged capacitor is connected to it. That light immediately begins decreasing as the capacitor discharges, until the lightbulb is dark again. Using live regions, the user receives feedback when the lightbulb is lit, and again when it goes dark, but receives no information about the time in between. So this does not convey the physical processes that occur as the capacitor discharges.

Sonification would remedy that problem. To sonify the lightbulb, a sound – possibly a hum like that generated by a fluorescent bulb – would be chosen to represent it. The magnitude of that sound would represent the magnitude of the light being emitted. So when the user connected the charged capacitor to the lightbulb, the sound would turn on, then decrease in sync with the dimming of the light. That would convey to the user what is happening during every point in the process, rather than giving discrete points of feedback.

Near the end of the interview with Anna, she said that she enjoyed working with the physical circuits during a class in middle school because she could actually perform the experiments. She went on to say that “There’s actually a sound component to when the lightbulb turned on, it also played a sound [when in a physical circuit].” She wanted to know if there would be a way to incorporate that sort of feedback into the simulation. If her view is common among screenreader users, that suggests that sonification would be quite effective.

Other elements such as the current and plate charge could be sonified as well. As discussed

above, both interviewees struggled to understand the representation of current – sonification might alleviate some of their confusion. In the case of the charges, which currently lack any form of auditory representation, the value of sonification is less clear, but it could still be useful. The charges do not dynamically increase or decrease in the same way that the light or the current do; charge changes in discrete intervals as a function of voltage and capacitance. So a numerical representation, similar to that of capacitance, might be just as valuable. It will take further user testing to determine which is better.

12.2 Browse Mode

The simulation needs to interface seamlessly with both browse mode and forms mode. Browse mode is especially important, as it is the initial mode that people use. Because the two modes behave quite differently, users need to be clear about which mode they need to be in. Forms mode, for instance, disables most of the keyboard shortcuts that are commonly used in browse mode. As both modes contain essential features for interaction with the simulation, users will need to comfortably toggle between modes. Future work will implement cues for users that inform them that they may need to switch into a different mode to interact with a certain element, and will strive to make such switching as seamless as possible.

13 Conclusion

Although many technical challenges remain, this work demonstrated that students with vision impairment can successfully use and learn from a PhET simulation. The implicit scaffolding that guides a visual learner through the simulation was mirrored in the descriptions in the parallel DOM, and proved, on the whole, successful. Both visual and nonvisual users react to elements such as the lightbulb in the same way: they figure out how to turn it on. The majority of the interviewees' play focused on the circuit, as does the majority of play among visual users, so the relative importance of different elements was also maintained.

This supports the idea that a diverse group of students can use the simulation together in a classroom environment, even if a student has low or no vision. They can still interact with the simulation and learn the requisite concepts, though they cannot see the screen the way their peers can. The learning of their peers is not impeded, as the accessibility features do not disable the features used by sighted students. So all students can work together to discover the various physical concepts presented in the simulation.

The use of the parallel DOM illustrates the necessity of well-designed auditory descriptions, and depicts a way of providing those descriptions for dynamically-generated content. Using such a structure, even websites purely composed of Javascript can be accessible to screenreader users.

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Appendices

Sample Parallel DOM

```
1 <!doctype html>
2 <html lang="en">
3 <head>
4   <title>Capacitor Lab: Basics </title>
5 </head>
6 <body>
7   <header role="banner" aria-labelledby="scene-label" aria-describedby="
      scene-description">
8     <h1 id="scene-label">The Scene for the Capacitance screen of Capacitor
      Lab: Basics </h1>
9     <div id="scene-description">
10      <p>A capacitor, represented by two rectangular plates, is in a circuit
      with a battery. The battery is to the left and the capacitor to
      the right.</p>
11      <p>There are switches above and below the capacitor to connect and
      disconnect it from the battery. It is currently connected.</p>
12      <p>There is a graph labeled "Capacitance" above the circuit.</p>
13      <p>There is a control panel that controls the visibility of the
      charges on the capacitor plate, the bar graph, the electric field,
      and the current. All but the electric field is currently visible
      .</p>
14      <p>There is a toolbox containing a voltmeter, which measures voltage
      .</p>
15      <p>Select Tab for next item, and enter to go inside groups of items.
      Select H for keyboard help.</p>
16    </div>
17  </header>
```

```

18 <main>
19   <section id="play-area" aria-labelledby="pa-label" aria-describedby="
      pa-description">
20   <h2 id="pa-label">Play Area</h2>
21   <p id="pa-description">Place to play with a capacitor in a circuit
      with a battery</p>
22   <div id="circuit-widget" aria-labelledby="circuit-label" aria-
      describedby="circuit-description">
23   <h3 id="circuit-label">Circuit</h3>
24   <p id="circuit-description">The circuit contains a capacitor and a
      battery. The capacitor is currently connected to the battery.</p>
      >
25   <div id="battery-widget" aria-labelledby="battery-label" aria-
      describedby="battery-description">
26   <h4 id="battery-label">Battery</h4>
27   <p id="battery-description">The battery has a slider on it that
      controls voltage. The current voltage is 0 volts. Use the
      arrow keys to change the voltage of the battery.</p>
28   </div>
29   <div id="capacitor-widget" aria-labelledby="capacitor-label" aria-
      describedby="capacitor-description">
30   <h4 id="capacitor-label">Capacitor</h4>
31   <p id="capacitor-description">The capacitor is represented by two
      rectangular plates, one on top of the other, separated by a
      small space. It has a slider above it that controls the
      separation of the plates, and a slider next to it that controls
      the area of the plates. There are no charges visible on the
      plates.</p>
32   </div>
33   <div id="switch-widget" aria-labelledby="switches-label" aria-

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```

    describedby="switches-description">
34    <h4 id="switches-label">Switches</h4>
35    <p id="switches-description">The circuit has two switches, above
        and below the capacitor, that connect and disconnect the
        capacitor from the battery.</p>
36    </div>
37 </div>
38 <div id="toolbox-widget" aria-labelledby="toolbox-label" aria-
        describedby="toolbox-description">
39 <h3 id="toolbox-label">Toolbox</h3>
40 <p id="toolbox-description">The toolbox contains a voltmeter, which
        measures voltage. Press enter to use the voltmeter.</p>
41 <div id="voltmeter-widget" aria-labelledby="voltmeter-label" aria-
        describedby="voltmeter-description">
42 <h4 id="voltmeter-label">Voltmeter</h4>
43 <p id="voltmeter-description">The voltmeter has two probes, one
        red and one black, connected to the body of the voltmeter with
        wires. The body of the voltmeter displays the voltage measured
        by the probes: the current display is a question mark.</p>
44 </div>
45 </div>
46 </section>
47 <section id="graphs" aria-labelledby="graph-label">
48 <h2 id="graph-label">Graph Panel</h2>
49 <div id="capacitance-graph-widget" aria-labelledby="capacitance-
        graph-label" aria-describedby="capacitance-graph-description">
50 <h3 id="capacitance-graph-label">Capacitance Graph</h3>
51 <p id="capacitance-graph-description">The bar graph of capacitance
        measures the capacitance of the capacitor</p>
52 </div>

```

```

53     </section>
54     <section id="control-panel" aria-label
55 edby="cp-label">
56         <h2 id="cp-label">Control Panel</h2>
57         <div id="view-widget" aria-labelledby="view-label" aria-describedby
58             ="view-description">
59             <h3 id="view-label">View Panel</h3>
60             <p id="view-description">The view panel controls the visibility of
61                 the capacitor plate charges, the bar graphs, the electric field,
62                 and the current. All but the electric field are currently visible
63                 .</p>
64         </div>
65         <div id="reset-widget" aria-labelledby="reset-label" aria-
66             describedby="reset-description">
67             <h3 id="reset-label">Reset Button</h3>
68             <p id="reset-description">The reset button resets the experiment to
69                 the original state.</p>
70         </div>
71     </section>
72 </main>
73 </body>
74 </html>

```