Access, Action, & Agency: Inclusive Design for the Non-visual Use of a Highly Interactive Simulation

by
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Declaration

I hereby declare that I am the author of this Major Research Project (MRP). Chapters 3 and 4 are conference papers co-authored with my advisors, Clayton Lewis and Emily B. Moore.

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Abstract

Interactive computer simulations are effective learning tools commonly used in science education; however, they are inaccessible to many students with disabilities. In this Major Research Project, we present findings from the design and implementation of accessibility features for the PhET Interactive Simulation, *Balloons and Static Electricity*. Our focus was access for screen reader users. We designed an interaction flow that connected keyboard interactions with reactions in dynamic content. Using a Parallel Document Object Model (PDOM), we created access for screen reader users to simulation content and interactive sim elements. We conducted interviews with 12 screen reader users to evaluate our progress on verbal text description and keyboard access, and to understand better how blind users engage with interactive simulations. We share findings about our successes and challenges and the insight we have gained in making an interactive science simulation more inclusive.

Keywords

web accessibility, usability, blind users, inclusive design, non-visual user interface, parallel Document Object Model (PDOM), keyboard interaction, text description, educational simulation, interactive science simulation

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- External Advisor: Dr. Emily B. Moore, Director of Research and Accessibility, PhET Interactive Simulations, Department of Physics, University of Colorado.

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Anand.

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Introduction

This Major Research Project examined one highly interactive science simulation and designed accessibility features for it. These accessibility features make it possible for students with vision impairments, who use a screen reader, to interact with and explore the science concepts in the simulation. We developed a description strategy framework that can be used to help make other simulations accessible and engaging for students who use screen readers. We have created access to a valuable learning tool for screen reader users, where no prior access existed.

1.1 Rationale

Interactive computer simulations are commonly used as science education resources. Science simulations have been shown to be highly effective in supporting student learning [8, 42]. Interactive simulations allow students to investigate scientific phenomena across a range of size and time scales, and allow for experimentation when physical equipment is either not available or not accessible to the student. While the use of simulations has been shown to benefit student learning, they are often inaccessible to students with disabilities. Interactive simulations are generally highly visual and designed for mouse- or touch-driven interactions – making them particularly inaccessible to students with vision loss who use a screen reader and keyboard while using a computer.

1.2 Target User

The target users for this project were students with vision loss who engage with a desktop computer or laptop using a screen reader and keyboard. At the beginning of this project this target group had no access to the sim. The visual representations of the simulation were not presented in a mode that was perceivable to students who cannot see and none of the interactions were operable via keyboard, the preferred interaction device for students who use a screen reader with a desktop or laptop computer.

1.2.1 Significant Numbers of Students with Vision Loss

Every student should have the option to study science. The website of the National Federation of the Blind (NFB) states that there are 694,300 children (ages 4 through 20) in the United States who identify as having a visual disability (Erickson, 2015) [32]. The NFB's statistics on blind children come from reports developed by the American Printing

House for the Blind. The 2014 Annual Report states there are 60,393 legally blind children (through age 21) enrolled in elementary and high school in the United States. There are many barriers that reduce access to STEM education for students with disabilities resulting in a disparity in their achievements in science (NCES, 2011 in [30]). Designing science simulations that are accessible to students who use screen readers provides a way to explore science content independently when other environments such as laboratories are not accessible. More importantly, it allows students to learn and engage with the science content along side their student peers.

1.2.2 How Screen Reader Users Use the Web

An important part of designing for inclusion is understanding not only what users may need, but what they are used to. Many blind students rely upon screen readers to use their computers, and to access digital materials including websites and web applications. Screen readers are sophisticated software programs [49] that not only convert the text on the page to synthesized speech, but also communicate information about the content's structure and purpose. Screen readers provide many navigational tools and shortcuts that enable the user to explore content in different ways by listening. Sighted users look (and perhaps read) before they interact, while screen reader users listen first and then interact [9, 23]. Much like sighted users skim and scan with their eyes by reading headings and other visually prominent content, screen reader users use the functionality of their screen readers to skim and scan with their ears. The screen reader allows the user to scan for and jump to different types of content such as headings, lists, links and forms controls. This helps a user who cannot see form a picture of how the page is organized and what content is for reading and what content is for interacting (i.e., actionable). It is the structure of the web application (the HTML code) that allows a blind user to skim and scan efficiently, skipping over repetitive content such as menus and page headers and enables them to find the path they seek. This structure enables them to interact successfully.

1.3 Background: About PhET

The PhET Interactive Simulations project [37] has created a popular suite of over 130 interactive science and mathematics simulations. These highly interactive simulations (or"sims") are run over 75 million times a year by teachers and students around the world. In this project in inclusive design, we present findings from the design and implementation of accessibility features for the PhET sim *Balloons and Static Electricity* [36].

1.3.1 PhET Sim: Balloons and Static Electricity

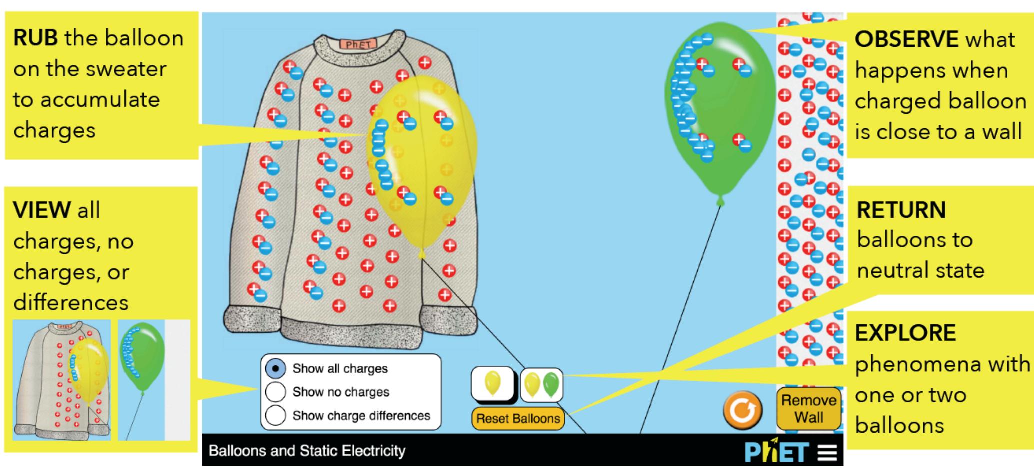

Figure 1.3.1: The PhET Simulation, Balloons and Static Electricity after some student interaction. One negatively charged Balloon (the yellow one) sticks to the Sweater, the other Balloon (green and negatively charged) sticks to the Wall. Image reproduced with permission from PhET Interactive Simulations.

The *Balloons and Static Electricity* sim (Figure 1.3.1) can be used to support student learning of topics related to static electricity, including transfer of charge, induction, attraction, repulsion, and grounding. This sim is used in classrooms from middle grades up to introductory college level, with students from age 10 to adult. Upon start-up, the user encounters the sim's Play Area, containing a Sweater on the left side, a centrally located Balloon, and a Wall on the right side. Representations of positive and negative charges are shown overlaying all of these objects. At the bottom of the screen is the Control Panel area, including: on the left, a set of three radio buttons that control what charge representations are shown (all charges, no charges, or charge difference), in the middle, a toggle switch that allows the user to change between experimenting with one Balloon or two, a Reset Balloons button that can be used to reset the Balloons to their original position and neutral state, on the bottom right, a reset all button that resets the sim to its initial state, and also on the right, a Remove Wall button that allows users to conduct experiments with or without the presence of the Wall.

The Balloon can be moved and rubbed against the Sweater (resulting in a transfer of negative charges from the Sweater to the Balloon) and the Wall (resulting in no transfer of charges). Once charged, releasing the Balloon results in the Balloon being attracted to the Sweater or Wall, depending on the total amount of charge present on the Balloon and its proximity to either the Sweater, or the Wall. For example, rubbing the Balloon on the Sweater results in a transfer of negative charges from the Sweater to the Balloon, and the now negatively charged Balloon, upon release from the middle of the Play Area is attracted to (moves toward and "sticks" to) the now positively charged Sweater. Releasing the Balloon near the Wall may result in the Balloon attracting to the neutral Wall (Green Balloon in Figure 1.3.1) or attracting back to the positively charged Sweater (Yellow Balloon in Figure 1.3.1).

1.4 Web Accessibility & Interactivity

Web standards and methods for making web content and moderately interactive web applications accessible to non-visual users are well-known and well-documented [18, 25, 44]; however, inclusive practices for creating accessible websites and web applications continue to be a challenge for many [10, 16, 26, 27, 40]. In spite of accessibility challenges, interactivity of websites and web applications continues to increase. Web standards such as HTML5 and WAI-ARIA [2, 4, 17] continue to evolve to provide developers with advanced tools to make interactive web applications accessible to people with disabilities, including people with vision loss who use screen readers.

New PhET sims are built in HTML5 and run in a web browser. To make the sims accessible to students with vision loss who use screen readers we look to the Web Content Accessibility Guidelines [1] and its four foundational principles for making web content accessible. These are the "POUR" principles:

- **Perceivable:** "Information and user interface components must be presentable to users in ways they can perceive."
- **Operable:** "User interface components and navigation must be operable."
- **Understandable:** "Information and the operation of user interface must be understandable."
- **Robust:** "Content must be robust enough that it can be interpreted reliably by a wide variety of user agents, including assistive technologies."

For a screen reader user, this means we will need to present the visual representations of the sim's scientific model (the sim's content) and the sim's interactive elements (the sim's controls) in a mode that the user can perceive (e.g., text or sound). The content and controls must be made navigable and operable via the keyboard in a way that the user can connect their actions with changes in the content. The operation of the controls and the delivery of content both need to be understandable so the user can engage in sense making of the scientific concepts and learn from their experience as they engage with the sim. Our solution must be robust enough, so that the sim remains accessible even as screen readers and user agents (i.e., browsers) change and improve.

1.5 Design Challenge: Access, Action, & Agency

In the original sim all interactions, including moving the Balloon and activating buttons and radio buttons, were mouse or touch events. No verbal description of visual representations or dynamic changes were provided. The design challenge of this work was to create:

- **Access:** Descriptions of visual representations in a mode perceivable to the user gives them access to those representations.
- **Action:** Buttons and interactions that are operable via the keyboard allows the user to take action.
- **Agency:** Descriptions and interactions that are understandable and make sense when accessed in different ways (i.e., using diverse navigational strategies) enables the user to self-direct their own learning.

1.6 Implicit Scaffolds for Non-visual Access, Action, & Agency

PhET's design framework is termed *Implicit Scaffolding*, which aims to guide the student on how to use the sim with the bare minimum of explicit instruction using visual cues [39]. The framework is grounded in research in education, human-computer interaction and how students learn. For example, in the *Balloons and Static Electricity* sim, visual students immediately recognize, without being told, that the Balloon is the central object in the sim due to its large size, bright color, and central location.

Implicit Scaffolding has worked very well for the design of the current visual sims. The philosophical goal of this work is to create implicit scaffolds for the non-visual user that address our design challenge: to create access, action and agency for the non-visual user.

1.7 Research Questions

Making a highly interactive web application such as a PhET sim accessible to students who use screen readers is new and challenging work. In this work, we address three research questions aimed at enabling students with vision loss who use screen readers to interact with a PhET sim:

1. How can we make an accessible and engaging learning experience for students with vision impairments who use a screen reader to interact with a PhET simulation?
2. What are the technical challenges to designing accessible features for screen reader access to a PhET simulation?
3. What are the *implicit scaffolds* for the non-visual user of a PhET simulation?

We addressed these questions through an iterative user-centered design process to create a working prototype. We conducted a series of interviews with 12 screen reader users to test our progress. Between interviews we made modifications to the software in response to users' experiences.

1.8 Summary

We have introduced the rationale for our research, and situated it within the larger PhET Interactive Simulation project. We have introduced the simulation that we worked on, our target user, and our design challenge. We introduced principles of web accessibility, and PhET's design framework of implicit scaffolding. Finally, we listed our research questions and how we addressed them.

In Chapter 2, Research Design, we describe our design processes and methods. In Chapter 3 and Chapter 4, we outline and discuss our findings in two conference papers. In Chapter 3, we discuss key accessible design features that have successfully addressed several barriers to access for students who are blind and we also discuss the challenges that we faced. In Chapter 4 we analyse more closely our design for verbal text descriptions. Our initial analysis of our design features confirmed that we made progress towards realizing the POUR principles introduced in Section 1.4: the sim's content and interactions were made **perceivable** and **operable**, but we still had some work to do on making the content (all verbal description) and the flow (the story of the sim) more **understandable**. We developed a framework for description that we found to be very helpful for organizing different aspects of description in a highly interactive sim. In Chapter 5 we discuss how web standards, our design and our thoughts are evolving. Finally, in Chapter 6 we conclude with our contributions to inclusive design and ideas for future research.

2

Research Design

The goal of this work was to design inclusive features that support non-visual use (screen reader access) of the highly interactive simulation, *Balloons and Static Electricity*. In this chapter, section 2.1 describes the iterative idea phase, and section 2.3 lays out and describes the methods we used to evaluate our progress on the prototype. The overall iterative process was informed by the co-design process established by the PhET project [24].

Early aspects of our design process were aided and informed by informal discussions with an expert screen reader user, and experts in web accessibility, inclusive design, science education, human-computer interaction and software development. In order to test and refine our designs, we conducted a series of interviews with screen reader users. We asked users to explore the sim and, while interacting, to "think aloud" [3, 28]. Between interviews we made modifications to the software in response to user experiences.

2.1 Ideas & Prototype Design Phase

2.1.1 Experimental Play: Live Installation of a Science Simulation

To begin the work on possible text descriptions, the author of this report had the opportunity to create a real-life representation of the PhET Interactive Simulation, *Balloons and Static Electricity*. During the showing of the installation, we asked people to play with real balloons (with and without helium) and to mark down their observations about what they saw, heard and felt. The installation (shown in Figure 2.1.1) was beautiful and a lot of fun to design, and even though it did not produce much usable data, it provided valuable scientific insights to an Inclusive Design researcher with little background in science.

2.1.2 Cognitive Walkthroughs

Early design ideas were tested using a text-based cognitive walkthrough technique [28]. Using this technique, the designer steps through the design interactions, literally step by step. This technique is very useful for identifying problems in design logic, missing steps in an interaction, potential implementation issues and inefficiencies in keyboard navigation. In the text of the walkthroughs we also documented the rough (estimated) screen reader verbalizations to gain a fuller understanding of what a non-visual user

Figure 2.1.1: Experimental Play: A live installation of the PhET Interactive Simulation, *Balloons and Static Electricity. Shown at OCAD University's Graduate Gallery on the afternoon of June 26, 2015. Photograph by author.*

would hear while interacting with the simulation.

To gain an understanding of how a screen reader user might hear the simulation, we created a static hierarchical representation of the simulation in plain text using HTML content and form markup. Early versions of this simple non-interactive prototype was tested with JAWS and NVDA, two popular screen readers. The author of this report tested it in JAWS and an expert screen reader user tested it with NVDA. Initial testing helped gain some understanding of how WAI-ARIA attributes might be applied in a more interactive prototype - especially for labels and descriptions. Iterations on this initial structure eventually formed the basis of hierarchical content and interaction layer for the actual interactive prototype. This content layer is referred to as the *Parallel DOM* and is discussed elsewhere (see section 3.5).

After text-based cognitive walkthroughs, simple visual cognitive walkthroughs were presented to experts on the PhET team (content, design, development, screen reader user experts). The visual process helped iron out more details about our initial designs for keyboard interactions. Implementation work began once the keyboard interactions were clear and we had a plan for basic text description.

2.2 Method for Testing Descriptions

The first prototype for *Balloons and Static Electricity* included all keyboard interactions, all static labels and descriptions and dynamic descriptions for charge levels in Sweater and Balloon. The initial prototype did not contain dynamic descriptions for balloon behaviour. Due to very dynamic behaviour between the balloons and the surrounding objects, the Sweater and the Wall, the description challenge for balloon position, movement and velocity is complex. These dynamic descriptions were challenging to write, design and prioritize. They would be equally challenging to implement. Thus, we decided to test the descriptions for the dynamic aspects of balloon position, balloon movement, balloon velocity and charge behaviour in the wall with an adapted live *Wizard of Oz* method [15, 21, 48]. We describe this as an adapted *Wizard of Oz* method because, it would be obvious that the "wizard" describer was not the computer. The "wizard" would not be *behind the curtain*, but in the room with the user.

The interviewer wore two caps during the interview, the interviewer cap and the wizard cap. The interviewer encouraged the user to think aloud, the wizard filled in verbalized dynamic text descriptions that were not yet implemented. Some descriptions were scripted and some were unscripted. While this proved to be difficult to execute consistently especially in the first interview, the method did appear to work. Important aspects about description were exposed and confirmed, such as wording, verb tense, length, order (see Chapter 4 for full discussion on text description). Having a trained "wizard" dedicated to description would have been more ideal, so the interviewer could focus on the interview.

The interviews were not scripted and the participants were given minimal instructions, only to pretend like they were in science class and learning about static electricity. We "framed" [41] the interview as a learning activity rather than a usability test. We asked them to explore and to see what they could learn about static electricity and by doing so see if they could figure out how to use the sim while listening to and interpreting the combined verbalizations of the screen reader and the live descriptions provided by the interviewer (i.e., the "wizard"). The semi-structured, improvisational nature of the interview allowed for a lot of flexibility [41] in where to ask questions about the participants understanding of the science and about the usability of the sim.

A *Think Aloud Protocol* (TAP) [28, 34] style interview was used to gain insight from the users as they used the simulation. In the first interview, it was challenging to get the user to think aloud. This may have been due in part to the inexperience of the interviewer, technical issues with the simulation or perhaps due to conflicts in dual processing as discussed by [3]. In subsequent interviews, we explained the protocol more clearly, engaged the user in a practice *think aloud* exercise, as suggested by [19], and attempted to vary the prompts, adding a suggestion to pause the screen reader to think aloud. Chandrashekar (2006) [3] suggests asking the user to reflect aloud. It is likely difficult to listen to screen reader input and think aloud at the same time [51].

2.3 Method for Iterative Usability Evaluation

2.3.1 Recruitment

To recruit participants with vision loss we connected with community organizations that support people with disabilities and or people with vision loss, and Memorial University's students with disabilities office, the Glenn Roy Blundon Centre. We asked organizations to share with their networks an invitation to participate in our study. In St. John's the local chapter of the Canadian National Institute for the Blind and staff at Memorial University responded graciously and we were able to recruit 4 screen reader users. In Toronto, we were able to send an invitation to a large community email list that supports people who are blind and very quickly recruited another 8 diverse screen reader users for interviews.

2.3.2 Interviews

Apparatus and Equipment

People who use assistive technology such as screen readers may customize their environments. We gave the 12 participants the option to use a computer we provided or to use their own computer, their preferred screen reader, and when possible their browser of choice. Overall the hardware and software setups were varied:

- **Hardware:** desktop PCs (2), Mac Air (2), Surface Pro 3 Tablet (1), Lenovo E541 (1), Lenovo T520 (6)
- **Screen readers & Browsers:** Chrome & JAWS 17 professional (1), IE11 & JAWS 17 Home (1), Firefox & JAWS 17 Home (1), Firefox & JAWS 17 demo (5), Firefox & JAWS 15 (1), Safari & VoiceOver (2) and Firefox & NVDA 2015 (1)

To record the interviews we used one of two video cameras, a large semi-professional-style Cannon with built-in microphone and a small portable Canon Camcorder with an external microphone. We positioned the camera to capture the participant's hands on the keyboard and the screen. We made an audio recording on an iPhone as a backup which proved to be useful because in one case we neglected to turn on the external microphone. Furthermore, the audio recording on the phone provided a higher quality (higher volume) because of its proximity to the computer speakers.

Procedure

The sequence of activities with each participant was:

1. **Describe the process** and outlines the order and components of the rest of interview.

2. **Ask background questions** regarding interests in science or education, demographics, educational background, system specifications, habits on daily computer use, use of assistive technology (AT), level of expertise with AT, and a question on online education. (usually 5-8 minutes)

3. **Explain the state of the prototype** that we would be using. For example, it was necessary to explain that the prototype was fully keyboard accessible, but that some parts of the planned verbal descriptions were not yet implemented. Thus information about the sim would be coming from both the screen reader and from the interviewer, playing the part of the screen reader for to-be-implemented features. This aspect was inspired by the Wizard of Oz method [15, 48]; however, in our case, the "wizard" and the interviewer were one and the same and the wizard was not "hidden behind a curtain." While speaking out the live description, the "wizard" followed a description script where possible, but improvisation was required at times.

4. **Describe the Talk Aloud Protocol (TAP) and conducted a TAP warm-up exercise** to help participants learn to use it. Following Hughes, 2012, we asked participants to count the number of windows in their house and to think aloud as they counted.

5. **Introduce use of the simulation as a learning activity**. To do this, we asked participants to imagine they were back in middle school science class starting a unit on static electricity and that their teacher had given them this simulation to explore ideas about how static electricity works.

6. **Provide access to the prototype** via a link provided through a personal email, a simple URL, a saved bookmark, or a downloaded file on a USB key. (1-2 minutes)

7. **Ask the participant to freely explore** the simulation for 20 to 40 minutes and to *think aloud* while doing so.

    (a) **Provide live description** of unimplemented dynamic content during the participant's use.

    (b) **Remind the participant to think aloud** or asked for their thoughts.

8. **Ask follow-up questions to gain an understanding of their perspective** and thoughts on the experience and for suggestions to improve the design.

2.3.3 Inclusive Protocols

In addition to these procedures for data taking, we were mindful to make our recruitment and interviewing process as inclusive as possible. Graham's protocol [14] for working with blind participants is an excellent resource and contains an extensive check list that

Figure 2.3.1: Interview set-up at IDRC, Toronto. Photograph by author.

researchers can use to design and execute inclusive interviewing methods while working with people who are blind or who have severe vision loss.

We checked our consent forms to make sure that they could be read while using a screen reader. Only one out of thirteen participants had trouble opening the electronic word document. For that participant we did the informed consent verbally at the beginning of the interview. We invited participants to use their own computers and to be interviewed at a place that was convenient to them. We offered to meet them at a convenient location, the nearest transit station and arranged to collect them and return them to that location. For participants who used our computer equipment, we asked in advance what screen reader they would need and made sure we could provide a set-up that worked for them. For signing procedures we allowed them to confirm electronically

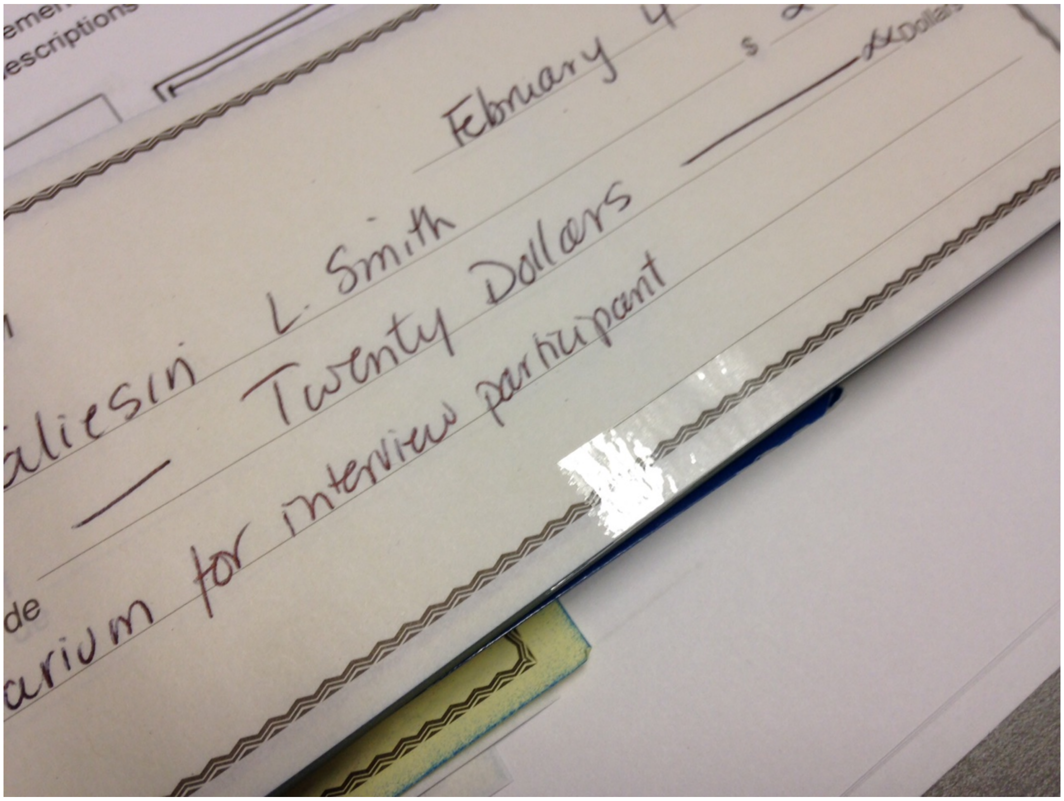

Figure 2.3.2: Inclusive Signing Procedure: Paper consent forms and receipts that needed to me signed were marked in advance with cello-tape to provide a tactile marker just below the signature area. Participants were asked to sign above the tape. Photograph by author.

through a plain text email, or if they preferred they could sign on paper. We had one document, the receipt for the honorarium, that had to be physically signed. Taking the idea of a tactile marker used by Lazar's 2007 study [27], we used clear cello-tape to mark all the paper receipts and consent forms (shown in Figure 2.3.2). This procedure was very convenient as participants could easily find the spot to sign on their own with little to no assistance from the interviewer.

2.4 Research Design Analysis

To analyse the data we transcribed and described parts of interviews. The transcripts included verbalizations of the participants, the screen reader and the interviewer (both as the interviewer and the "wizard"). The transcripts also included descriptions of associated interactions. We examined the transcripts, but found that we had to continually return to the recordings to fully understand the interactions. We made notes in the data through repeated examinations to understand and analyse the participants actions more clearly. In this way we identified usability issues and gained a better understanding of the interactive listening environment for non-visual users.

2.5 Summary

In this chapter we discussed our research design and how we conducted our interviews.

In the next chapter two chapters we discuss our findings in two conference papers. In Chapter 3 we discuss the successes and challenges of our accessible design features. In Chapter 4 we examine the descriptions of the prototype more carefully and a description strategy framework emerges from this analysis.

3

Successes & Challenges

3.1 About this Chapter

This chapter contains an accepted conference paper for HCI International 2016, Toronto, Canada, 17 - 22 July 2016. The paper is part of the invited session, Designing User Experience for Human Diversity: Lessons from Inclusive Design and Personalization. The text of the paper is presented, here, as it was in the conference submission with the only differences being formatting and the location of references. The references are part of the main bibliography.

The full title of the paper is ***A Balloon, a Sweater, and a Wall: Developing Design Strategies for Accessible User Experiences with a Science Simulation*** and it was co-authored by Taliesin L. Smith (author of this report) and my advisors, Clayton Lewis and Emily B. Moore.

The paper introduces four accessible design features that we made to the PhET Simulation, *Balloons and Static Electricity*, and our initial analysis of what worked well and where we faced challenges.

3.2 Abstract

Interactive computer simulations are effective learning tools commonly used in science education; however, they are inaccessible to many students with disabilities. In this paper, we present initial findings from the design and implementation of accessibility features for the PhET Interactive Simulation, *Balloons and Static Electricity*. Our focus: access for screen reader users. We designed an interaction flow that connected keyboard interactions with reactions in dynamic content. Then using a *Parallel Document Object Model (PDOM)*, we created access to simulation content and interactive sim objects. We conducted interviews with screen reader users to evaluate our progress, and to understand better how they engage with interactive simulations. We share findings about our successes and challenges in the design and delivery of dynamic verbal text description, of efficient keyboard navigation, and the challenges we faced in making a keyboard accessible drag and release mechanism for a highly interactive simulation object, a Balloon.

Keywords. web accessibility, usability, blind users, inclusive design, non-visual user interface, parallel Document Object Model, keyboard interaction, text description, educational simulation, interactive science simulation

3.3 Introduction

Interactive computer simulations are commonly used science education resources shown to be effective in supporting student learning [8, 42]. Interactive simulations allow students to investigate scientific phenomena across a range of size and time scales, and allow for experimentation when physical equipment is either not available or not accessible to the student. While the use of simulations has been shown to benefit student learning, they are often inaccessible to students with disabilities. Interactive simulations are generally highly visual and designed for mouse- or touch-driven interactions – making them particularly inaccessible to students with vision loss.

The PhET Interactive Simulations project [37] has created a popular suite of over 130 interactive science and mathematics simulations. These highly interactive simulations (or "sims") are run over 75 million times a year by teachers and students around the world, and are pushing the capabilities of web technologies and standards to their limits. In this paper, we present findings from the design and implementation of accessibility features for the PhET sim *Balloons and Static Electricity* [36]. Our goal was to make this sim accessible and usable by screen reader users. In the process, we addressed challenges in the delivery of dynamic content and interactions, design of efficient keyboard navigation and operation, and user interaction with complex sim features. We conducted interviews with screen reader users to evaluate our progress, and to understand better how screen reader users engage with interactive simulations. We found that when access is successful, user engagement and learning can take place.

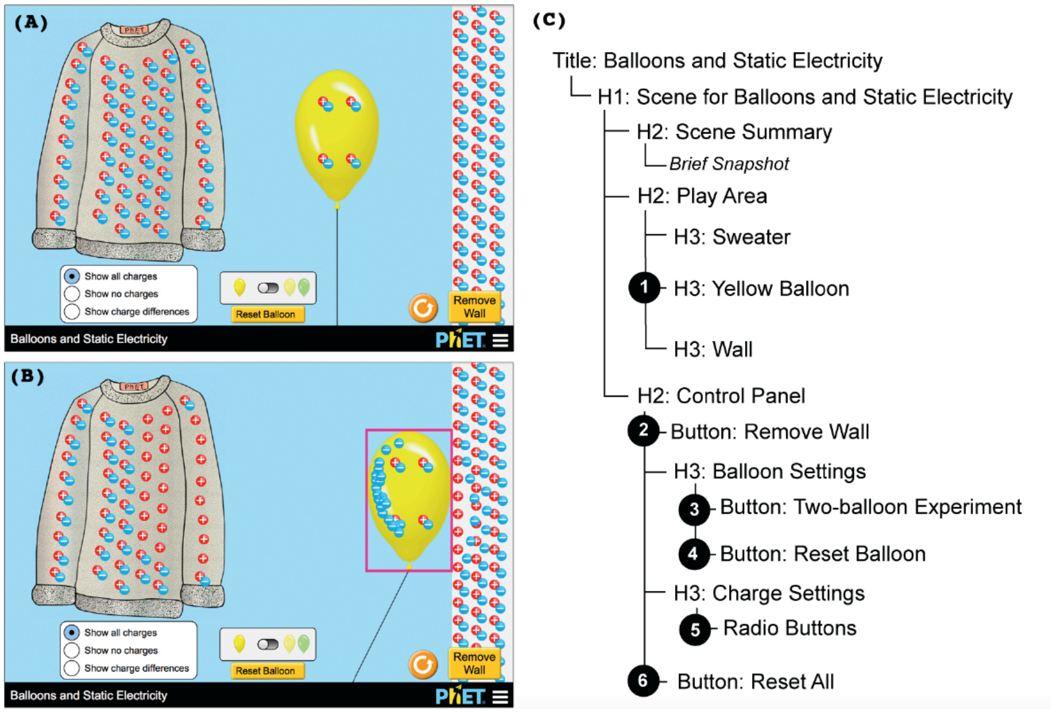

Figure 3.4.1: (A) *Balloons and Static Electricity* sim on page load, before interaction. (B) Sim while Balloon has keyboard focus (pink box), released and attracted to Wall. (C) Simplified *Parallel DOM* shows heading hierarchy (H1 to H3) and tab order (circled numbers). Images reproduced with permission from PhET Interactive Simulations.

3.4 PhET Sim: Balloons and Static Electricity

The *Balloons and Static Electricity* sim (Figure 3.4.1A, Figure 3.4.1B) can be used to support student learning of topics related to static electricity, including transfer of charge, induction, attraction, repulsion, and grounding. This sim is used in classrooms from middle grades up to introductory college level, with students from age 10 to adult. Upon start-up, the user encounters the sim's Play Area, containing a Sweater on the left side, a centrally located Balloon, and a Wall on the right side. Representations of positive and negative charges are shown overlaying all of these objects. At the bottom of the screen is the Control Panel area, including: a set of three radio buttons that control what charge representations are shown (all charges, no charges, or charge difference), a toggle switch that allows the user to change between experimenting with one Balloon or two, a Reset All button that resets the screen to its initial state, and a Remove Wall button that adds or removes the Wall.

The Balloon can be moved and rubbed against the sweater (resulting in a transfer of negative charges from the Sweater to the Balloon) and the Wall (resulting in no transfer of charges). Releasing the Balloon results in the Balloon being attracted to the Sweater or Wall, depending on the total amount of charge present on the Balloon and its proximity to either the Sweater, or the Wall. For example, rubbing the Balloon on the Sweater results in a transfer of negative charges from the Sweater to the Balloon, and the now negatively charged Balloon, upon release from the middle of the Play Area is attracted to (moves toward and "sticks" to) the now positively charged Sweater. Releasing the Balloon near the Wall may result in the Balloon attracting to the neutral Wall (Figure 3.4.1B) or attracting back to the Sweater.

In the original sim all interactions, including moving the Balloon and activating buttons and radio buttons, were mouse or touch events. No verbal description of visual representations or dynamic changes were provided.

3.5 Accessible Design Features

To provide access for screen reader users, we implemented the following enhancements.

3.5.1 Access to Sim Content and Interactions

To make the content and interactions of the sim accessible to assistive technologies (AT), we designed a semantically rich HTML-based hierarchical representation of the sim that describes all objects and interactions. We refer to this accessible feature as the *Parallel Document Object Model* (or "PDOM"). The reasoning for the PDOM approach has been addressed previously [35]. In this work, we enhanced the PDOM with the rich semantics available in HTML. Through native semantics, the use of headings, and the linear order of elements, we created a hierarchy that conveys the spatial layout of the sim and the relationships among the sim objects. This structure makes it possible for screen reader users to perceive these relationships as they explore the sim, gaining an understanding of how the relationships relate to the interactions in the sim. For example, the Play Area contains three objects: the Balloon, the Sweater, and the Wall. We communicate that the objects have an important relationship through their heading structure. Each object's label (or name) is marked up as an H3 heading. The heading for the Play Area is an H2, conveying that it is the parent of these sibling objects. Details about each object are contained in a paragraph under each of the respective objects' headings. Design features that provide visual users with clues, within the design itself, on how to interact with the sim are referred to as"implicit scaffolding" [39]; providing hierarchical structure and a *Tab order* (Figure 3.4.1C, circled numbers) that is based on pedagogical importance is an attempt to provide implicit scaffolds for screen reader users.

3.5.2 Keyboard Navigation and Operation

The PDOM described in the previous section provides meaning through heading hierarchy. It also provides a mechanism for efficient keyboard navigation and operation via navigable elements such as landmarks and regions. With screen reader commands, users can efficiently navigate by landmarks, regions, or headings. In *Balloons and Static Electricity*, the Scene Summary, Play Area, and Control Panel were coded as navigable regions (HTML section element) that each start with an H2 heading. With this structure, a screen reader user can navigate to the Play Area either with the region command or via the heading, thus providing efficient navigation from anywhere in the sim. We employed native HTML form controls and standard interaction design patterns [43], in order to create interactive sim objects that were findable and operable by users. For example, all interactive sim buttons are real HTML buttons and recognized by screen readers as such. They are reachable via the keyboard with the *Tab key* and can be operated upon (activated) by pressing either the *Spacebar* or the *Enter key*.

3.5.3 Timely Description that Connects Interactions with Dynamic Content

Descriptions of changing information such as Balloon charge, Balloon position and Balloon behavior (direction and velocity during attraction and repulsion) must be delivered in a timely fashion while minimizing disruption. Our approach involved announcing dynamically changing charge information using ARIA live regions [4]. Live regions provide a way for screen readers to present new information that occurs away from where the user is currently reading (or has *focus*). For example, when a user rubs the Balloon on the Sweater, a transfer of charge occurs causing changes in the descriptive content associated with both the Balloon and the Sweater. Through the use of live regions the user is made aware of changes in charge levels for both objects, even though the user technically is only "reading" the Balloon. In designing our descriptive text strings, we aimed for brevity, consistency and clarity [20].

3.5.4 Keyboard Interaction and Engagement with Balloon

In order to explore the sim with a screen reader, the learner needs to be able to grab the Balloon, drag it to different locations, rub it on the Sweater (or Wall), and release it (to see how it attracts and repels) using keyboard interactions. To achieve this, we created the following mechanisms:

1. **Grab, Drag & Rub Interaction.** These interactions are integrated into one

(similar to the mouse-driven grab, drag, and rub interaction). To grab, drag, and rub the Balloon, the user navigates keyboard focus to the Balloon and then presses one of a set of four directional movement keys, the *W, A, S, or D keys*. These keys correspond to up, left, down, and right movements of the balloon, respectively. These keys were selected as they are commonly used for directional movement in the computer gaming community. The sim includes a description of the interaction so it can be used (learned) without prior gaming experience. Note, our initial design utilized *Arrow keys* for directional movement, but unfortunately, the *Arrow keys* already have assigned meaning (as *cursor keys*) essential to screen reader control.

2. **Release mechanism.** We provided three ways to release the Balloon: *Spacebar*, *Control + Enter* and *Tab*. The *Spacebar* was chosen for its alignment with the established interaction of submitting a form. Pressing *Control + Enter* is another standard way to submit a form, so for consistency this key press combination was implemented as a release for the Balloon. Pressing the *Tab key* moves focus away from the Balloon, and as a result (intentional or unintentional) must release the Balloon so that the non-visual interactions (and representations) remain in sync with the visual representations.

3. **Balloon interaction keyboard shortcuts.** We implemented the *Shift key* as a semi-modal acceleration key so that the user can make the Balloon move in larger increments (in the chosen direction). We also designed four, letter-based (non-case-sensitive), hot key combinations to *jump* the Balloon to pedagogically strategic locations in the Play Area: *JW* (to <u>W</u>all), *JS* (to edge of <u>S</u>weater), *JN* (to <u>N</u>ear Wall) and *JM* (to <u>M</u>iddle of Play Area). By using pairs of keys for the hot keys, we avoided conflicts with browser hot key functionality [29]. To address

other potential conflicts with screen reader functionality, we used the ARIA role *application* on the Balloon. The *application* role informs the screen reader to pass key presses to the web application (the sim) for an alternate purpose. Note, this approach does not work for the *Arrow keys*, but does work for letter keys – many of which are used as hot keys for screen reader navigation.

3.6 Iterative Usability Evaluation

In order to test and refine our designs, we conducted a series of interviews with blind users. We asked users to explore the sim and, while interacting, to "think aloud" [3, 28]. Between interviews we made modifications to the software in response to user experiences.

3.6.1 Methods

Participants. We recruited 12 screen reader users to participate in interviews – and conducted 11 in-person interviews and 1 remote interview. The users, 5 women and 7 men, spanned a diverse age range (19 years to 61 years). Users demonstrated a diverse level of expertise with their screen reader: one user used both a refreshable Braille display and a screen reader. All users had at least some post-secondary education, the youngest being in their first year of college.

Apparatus. We gave the 12 users the option to use their own computer or one that we provided. Overall, the hardware and software setups were varied:

- **Hardware:** desktop PCs (2), Mac Air (2), Surface Pro 3 Tablet (1), Lenovo E541 (1), Lenovo T520 (6)
- **Browsers & Screen readers:** Chrome & JAWS 17 professional (1), IE11 & JAWS 17 Home (1), Firefox & JAWS 17 Home (1), Firefox & JAWS 17 demo (5), Firefox

& JAWS 15 (1), Safari & VoiceOver (2) and Firefox & NVDA 2015 (1)

Each interview was video recorded, with the camera positioned to capture the participant's screen and keyboard.

Procedure. Most interviews took approximately 1 hour. Each interview proceeded as follows:

1. **Describe the process** and outline the order and components of the interview.

2. **Ask background questions** regarding interests in science, demographics, educational background, system specifications, habits on daily computer use, use of AT, level of expertise with AT, and online education.

3. **Explain the state of the prototype** that we would be using. For example, it was necessary to explain that the prototype was fully keyboard accessible, but that some parts of the verbal descriptions were not yet implemented. Thus, information about the sim would be coming from both the screen reader and the interviewer, who would be playing the part of the screen reader for yet-to-be-implemented descriptions. This aspect was inspired by the Wizard of Oz method [15]. While speaking out the live description, the "wizard" followed a planned description script (where possible), but improvisation was required at times.

4. **Describe the Think Aloud Protocol** (TAP) and conduct a TAP warm-up exercise.

5. **Introduce use of the sim as a learning activity** by asking users to imagine they were in middle school science class starting a unit on static electricity and that their teacher had given them this sim to explore.

6. **Provide access to the sim prototype** via a link or a downloaded file.

7. **Ask the user to freely explore** for 20-40 minutes and to think aloud while doing so. As the user explores, the interviewer/wizard provides live descriptions of unimplemented dynamic content, and occasionally reminds user to think aloud.

8. **Ask follow-up questions to gain an understanding of their perspective** and thoughts on the experience and suggestions for how to improve the design.

3.7 Discussion & Results

Analysis of user interviews provided significant insight into effective (and ineffective) design approaches for making the interactive sim, *Balloons and Static Electricity*, accessible to visually impaired users. We describe here, for each inclusive design feature described in Section 3.5, what worked well and what challenges were found.

3.7.1 Access to Sim Content and Interactions

We found the *Parallel Dom (PDOM)* to be an effective approach for providing access to sim content and interactive (i.e. controllable) sim objects.

What Worked Well.

- Some sim content is static, meaning it does not change or changes very little, and some content is dynamic and changes a lot (see Section 3.7.3). Users were able to easily access, review and locate all static content and some dynamic content in the sim. All users accessed content successfully with the *Arrow keys* line by line. Most used a combination of strategies in addition to the *Arrow keys*. Access to this content is a significant achievement that allowed most users to explore, ask their own questions, and experiment to answer their own questions.

- When first encountering the sim, most users employed a strategy that consisted of first listening and then interacting. This behavior of listening before interacting is consistent with prior research with blind users [9, 23]. Some users listened just to the brief Scene Summary that introduces the sim and then took the suggested navigation cue (*Press Tab for first object*) at the end of the Scene Summary. Some listened to everything in the sim at least once before interacting with the *Tab key* or activating one of the buttons in the Control Panel. Both strategies were effective.

Challenges.

- Some users encountered challenges that they were not easily able to overcome. For example, one user's navigational approach involved listening to descriptions (sometimes listening to descriptions in full, other times listening to descriptions minimally), then using the *Tab key* to navigate quickly around the sim, and then listening again – without seeming to set any specific goals for exploration. In this case it seemed the descriptions were not supporting the user to find a productive path of exploration so her navigation seemed aimless.

- Browser implementation inconsistencies led to some confusion about interactions. For example, with Safari, VoiceOver reads out the Balloon as, "Application 3 items. Yellow Balloon". Upon hearing a number of items, one user tried, unsuccessfully, to interact with the Balloon as if it were a list.

- We learned how to optimize *label* and *description* text as we understood more fully how the interactive objects were read out by screen readers. *Label* text is the essential information for the control and is always read. *Description (or help)* text is additional information that can help the user understand what to do with the interactive object. Descriptions can be read out by default along with the *label* text or not. Changes to label and description text were made throughout the project and these changes improved the auditory experience in two ways: reduced screen reader verbosity and improved clarity. We found it useful to optimize *label* text to reduce the use of *help* text.

3.7.2 Keyboard Navigation and Operation

In this category, we also found the PDOM approach to provide affordances that supported effective keyboard navigation and operation.

What Worked Well.

- The PDOM approach allowed users to employ strategies developed from past experience to explore and interact with the sim. With the content structured and accessible in familiar ways, users were provided full agency to independently solve problems that arose – including science learning and technical challenges. For example, one user utilized the *Tab key* to navigate through the sim twice, while listening minimally to descriptions. Without the descriptions, she did not have enough information to successfully explore, and eventually changed her strategy. Her second strategy involved using a screen reader command to bring up a list of all headings. From there, she chose to navigate to the Scene Summary and began listening, ultimately resulting in her proceeding along a more productive path. In an example of a strategy change in response to a technical issue, one user encountered a technical issue where using *Tab* or *Shift-Tab* did not appropriately navigate away from the Reset All button. In one case the user made use of the *Arrow keys* to navigate away from the button, while in another case they used a screen reader navigation command (the *B key* in the JAWS screen reader) to navigate to the next button.
- In general, users found navigation and operation of common controls (e.g., buttons

and dialog box) to be straightforward. If the label text was clear and read out correctly by the screen reader, the users seemed to know how to interact based on prior web experience.

Challenges.

- Navigation cues (telling the user explicitly what to do) were sometimes helpful, but significantly increased screen reader verbosity. Some users missed navigation cues by not listening long enough. Providing cues on demand may be a better approach.
- Some navigational cues were poorly placed which led to unsuccessful interaction attempts. We found that navigational cues need to be operable at precisely the same time that they are delivered.

3.7.3 Timely Description that Connects Interactions with Dynamic Content

We found that connecting interactions with changing content helped to create a successful interaction flow.

What Worked Well.

- All users understood that *something* changed when they rubbed the balloon on the sweater. Most perceived and understood that the overall charge had changed from neutral to positive (Sweater) or negative (Balloon). Only some noticed the charge description update, "a few more", "several more" and "many more". We chose this three-point relative scale to convey charge levels because it is the relative amount of charge, not the total number of each charge type, that is foundational to the underlying concepts. One user commented that a relative scale was useful, but another participant commented that the difference between "several more" and "many more" was too subtle. At least two users said that a numerical value for the level of charge would be more useful.

- Live description, though difficult to execute, worked well to test out a complex description plan for comprehensibility, usability and effectiveness before implementation. As part of the live description, some sound effects were produced by rubbing an actual balloon to indicate Balloon on Sweater and hitting the balloon to indicate reaching the Wall. These sounds received positive reactions from some users. However, live sounds were difficult to execute, and were not presented consistently. Further research will explore the use of sounds to augment verbal descriptions.
- Announcing changes to the Play Area when a user activated a button (e.g. "Wall removed from Play Area") was clearer to users than listening only to the changed button text.

Challenges.

- We found certain descriptions were particularly challenging for some users, and need to be refined. The description including "no more negative charges than positive ones" was interpreted by one user as no charge at all, rather than a net zero, or neutral charge. Not describing positive charges caused some users to think that the balloons had no positive charges at all, rather than the intended goal of cueing users that the negative charges were more relevant than the positive charges for exploration. The description of induced charge in the wall was misunderstood by a few users. These users thought that the Wall was actually repelling the Balloon when they heard "[…] negative charges in the wall are repelling away" from the negative charges in the Balloon.

- There were some implementation issues that need to be addressed. For example, one user was confused when they came across the Wall via the *Arrow keys* directly after intentionally removing it. Details in the Scene Summary sometimes led to confusion as they were not implemented to update dynamically. If users re-read the brief Scene Summary after interacting, the information was no longer aligned with the current sim state.

- Some descriptions needed to be more succinct and new or changed information needed to come first. Details about charges were missed if a user did not listen to the full update. One user said, "There is a lot of talking going on. I have to be honest, I tend to tune it out." This user repeatedly stopped dynamic updates prematurely, and as a result sometimes missed important details.

- We found capturing certain object behavior in strings of text to be particularly challenging. For example, a Balloon with a small net negative charge will attract to the Sweater slowly at first, speeding up as it gets closer. This behavior involves continuous change over distance and time, while text is better for describing change occurring in discrete units

3.7.4 Keyboard Interaction and Engagement with Balloon

The Balloon object presented an interesting interaction design challenge. Ultimately, we want users to easily understand how to grab, drag, rub and release it with as little explanation as possible. The challenge is that there is no single HTML form control (or ARIA role) that provides a way to increment and decrement two separate values (Balloon position x and y) by simply operating the *Arrow keys*. In other words, it is difficult to represent the Balloon in code in a way that users will intuitively understand how to interact with it. We tried different types of HTML input controls, all in combination with the ARIA role application, to achieve the required keyboard interactions. All users were eventually successful in grabbing, dragging, rubbing, and releasing the balloon – though several needed guidance from the interviewer. An analysis of how to optimize implementation of the Balloon and how to best describe the interactions is ongoing.

What Worked Well.

- We found the directional movement keys (*W, A, S, and D*) to be an understandable alternative to the *Arrow keys*. Three users needed no additional explanation; some users were curious about our choice of these keys, but nevertheless easily used them. One user exclaimed, "Oh, they are just like the Arrow keys!" commenting on the layout of the keys on the keyboard. Only the first user trying these keys had significant trouble mastering their use. An improvement to the description of the interaction seemed to improve understanding for subsequent users.

- The *Spacebar* and *Tab key*, as release mechanisms, were quickly learned and used repeatedly by all users. Other than some surprise with the Tab key, e.g., "I keep forgetting that when I tab away, I release the balloon," the interaction was understandable. There were no issues with the *Spacebar*. One user mentioned that *Spacebar* is used in some computer games to pick up and drop objects, confirming our choice for the *Spacebar* as a useful release mechanism for the Balloon.

- The jump hot key combinations, (e.g. *JS*, *JW*) appear to be quite understandable and memorable. One user commented "It's like using *J* like a *Shift key*. Those commands make sense." This user did not actually employ the hot keys; regardless, during the wrap-up questions, they were able to correctly recall three out of four of the hot keys. Another user made extensive use of the jump hot keys.

- The Balloon acceleration operation (*Shift key* plus a direction key) showed promise as a useful way to move the Balloon more efficiently; however, its initial effect was found to be negligible. We have since increased the amount of acceleration the *Shift key* provides.

Challenges.

- The pronunciation of "*W, A, S, and D keys*" in the interaction cue was not clear with a high screen reader speed. "*D*" sounded like "*T*".
- Neither, the jump hot keys nor the accelerator key were easy to find. They were only available at the bottom of the Keyboard Commands help dialog. Moving the information to the top of the dialog will likely improve discoverability.
- Screen readers announce aspects of the Balloon that are not directly meaningful to users. For example, "Application. Yellow Balloon. Three items", or "Application. Yellow Balloon. Draggable. Read-only." Some users were more tolerant of this verbosity than others. Decreasing this verbosity by improving the Balloon's representation in code is currently in progress.

3.8 Conclusions

We faced a number of challenges in the design of a screen reader accessible interactive science simulation, *Balloons and Static Electricity*. The main challenges, determined by a study of 12 blind users, related to the delivery of complex descriptions in dynamic situations, and the lack of a native role for the main interactive sim object, the Balloon. In spite of the challenges reported here, all the users were excited about the research and their participation in the research.

The web standards (HTML and WAI-ARIA) that pertain to making highly interactive web applications accessible are complex and evolving. These standards are implemented inconsistently by browsers and screen readers, complicating our implementation approaches. Cases where native elements and roles could be directly applied to interactive sim objects seemed to be the easiest for users to discover and utilize.

The outcome of our efforts, thus far, is an interactive simulation prototype that is entirely operable by keyboard. Visual users who use alternative input devices such as a switch or joystick to browse the web can now access, operate, and learn with our prototype. Many sim features are now technically and functionally accessible for visually impaired users. Future work will focus on sonification (the use of non-speech sound to convey information), complementing ongoing work on a more complete description strategy.

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3.9 References

References are part of main bibliography.

4

Complex Description

4.1 About this Chapter

The contents of this chapter contain a technical paper written and submitted for the 2016 SIGACCESS Conference on Computers and Accessibility. The text of the paper is presented, here, as it was on April 22, 2016 in close to final draft just prior to the time of submission. Differences in the version presented here include formatting of the document such as the numbering of headings and the layout of tables and figures, and the references for the paper are included as part of the main bibliography and the end of the report.

The full title of the paper is ***Complex Description within a Highly Interactive Science Simulation***. The paper was co-authored by Taliesin L. Smith (author of this report) and my advising committee, Clayton Lewis and Emily B. Moore.

The focus of the paper is on verbal text description for a highly interactive environment, the PhET sim, *Balloons and Static Electricity*. We discuss the challenges we faced within the context of current guidelines for description, *Recommended Practices for Verbal Description for Interactive Scientific Graphics* [20] (ISG Practices) . We share insights on the description of a complex interactive element, the Balloon, that we feel are not yet part of the existing guidelines. Through an analysis of our design process, we identify strategies for description in highly interactive environments that may be helpful for others working in this area.

4.2 Abstract

Interactive learning tools span a broad spectrum in complexity, from simple tools consisting of static representations and linear interactions to more complex tools, with highly dynamic representations and nonlinear, sometimes nonstandard, interactions. This range of complexity presents challenges for making these tools accessible. In the case of designing verbal descriptions (e.g., for screen readers), existing guidelines for interactive scientific graphics provide a foundational framework for interactive learning tools, particularly at the simpler end of the spectrum of complexity. We demonstrate here, in the context of a PhET simulation, that highly interactive learning tools present unique challenges. In particular, we found that designing and implementing verbal descriptions within the PhET simulation *Balloons and Static Electricity* presented complex description challenges related to the description of complex interactive elements (the

Balloon) and maintaining cohesion across descriptions when content is accessed in multiple ways. From this work, we have identified specific description strategies for complex interactive learning tools.

4.2.1 CCS Concepts

K.4.2 [Computers and Society]: Social Issues – Assistive technologies for persons with disabilities; K.3.1 [Computers and Education]: Computer Uses in Education; H.3.4 [Systems and Software] Performance evaluation; H.5.2 [User Interfaces] Natural language.

4.2.2 Keywords

Description; Accessibility; Visual Impairment; Usability Study; STEM Education; Interactive Science simulation; PhET Simulation

4.3 Introduction

Interactive learning tools can be complex, resulting in challenges for accessible design and implementation of accessibility features. For complex interactive learning tools, like interactive science simulations, a range of interactions may be present in one tool, such as the pressing of buttons, selecting or setting a range of values (numerically or with sliders or tweakers), and dragging and dropping of interactive elements. The content and feedback provided to students is often highly visual. Providing accessible descriptions of visual representations, interactions, and feedback within these tools is important for students with disabilities, including students who are blind, or have vision impairments.

A diverse range of prior work in the development of descriptions (verbalized natural language descriptions) has addressed access challenges in scientific images [33], graphs

[6, 11, 12], charts [52], and molecular chemical diagrams [46]. The report *Interactive Scientific Graphics: Recommended Practices for Verbal Description* [20] (which we refer to as ISG Practices) provides guidance on creating effective verbal descriptions for blind and severely visually impaired students using interactive scientific graphics – defined as "images that will change their appearance in response to actions taken by an external agent" (p.9).

While these resources provide useful suggestions for some aspects of the description problem, we found that challenges in providing descriptions for highly interactive simulations require additional guidance. We discuss the strategies that emerged from our design process and demonstrate how we used them or can use them to improve the design.

4.4 PhET Interactive Simulations

This work focuses on our efforts to increase the accessibility of an interactive science simulation, *Balloons and Static Electricity* [36], developed by the PhET Interactive Simulations project [37].

The PhET project has created a popular suite of over 130 interactive science and mathematics simulations. These highly interactive simulations (or "sims") are run over 75 million times a year by teachers and students around the world. Each sim is designed to be visually rich, highly interactive, and to support multiple productive learning pathways for students to investigate.

4.4.1 Balloons & Static Electricity

The Balloons and Static Electricity sim (Figure 4.4.1) can be used to support student learning of topics related to static electricity, including transfer of charge, induction,

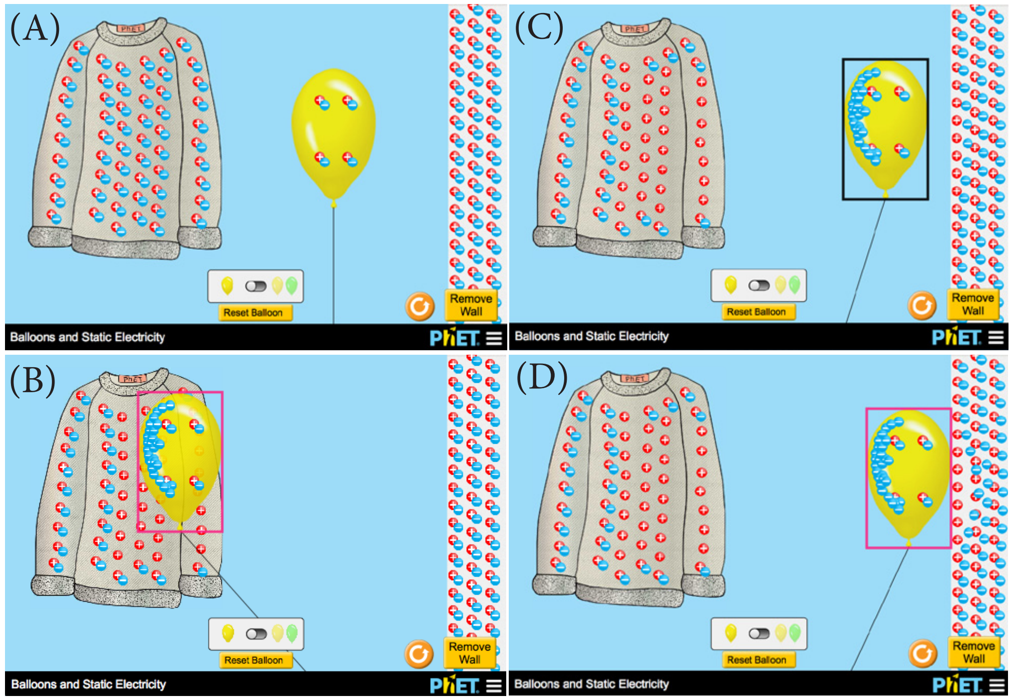

Figure 4.4.1: PhET Sim, Balloons and Static Electricity. (A) Sim on page load. (B) Negatively charged Balloon sticking to positively charged Sweater. (C) Negatively charged Balloon, in a grabbed state, and positioned near the Wall. (D) Negatively charged Balloon, in a released state. The Wall is showing the effect of an induced charge with negative charges in the Wall being repelled away from the Balloon.

attraction, repulsion, and grounding. This sim is used in classrooms from middle grades up to introductory college level, with students from age 10 to adult.

Upon start-up (Figure 4.4.1 A), the student encounters the sim's Play Area, containing a Sweater on the left, a centrally located Balloon, and a Wall on the right. Representations of positive and negative charges are shown overlaying these three objects. At the bottom of the screen is the Control Panel area, including: a toggle switch (toggle button) that allows the student to investigate using one Balloon or two, a Reset Balloon(s) button to reset the charges on the Balloons, a Reset All button that resets the entire screen to its initial state, and a Remove Wall button that enables the student to investigate with or without the presence of the Wall on the right side.

Interacting with the Balloon

In this sim, the Balloon is the primary interactive element. It is a focusable element and can be grabbed, dragged, and rubbed against the Sweater (resulting in a transfer of negative charges from the Sweater to the Balloon (Figure 4.4.1 B) and the Wall (resulting in no transfer of charges). Students can release the Balloon at different locations in the Play Area and observe what happens. The Balloon may be attracted to either the Sweater or the Wall, depending on the total amount of charge present on the Balloon and its proximity to the Sweater or Wall. For example, upon sim start-up, rubbing the Balloon on the Sweater results in a transfer of negative charges from the Sweater to the Balloon, and the now negatively charged Balloon, upon release from the middle of the Play Area is attracted to (moves toward and "sticks" to) the now positively charged Sweater (Figure 4.4.1 B). Releasing the Balloon near the Wall (Figure 4.4.1 C) may result in the Balloon attracting to the neutral Wall (Figure 4.4.1 D) or attracting back to the Sweater (Figure 4.4.1 B), again depending on the net charge of the Balloon.

Key Accessibility Structures for the Sim

In the original sim (inaccessible by screen reader users) all interactions were mouse or touch events. There was no mechanism to provide access for students who used screen readers; the sim's *Document Object Model (DOM)* [22] was composed of the canvas element[1] and svg (*scalable vector graphics*) elements[2], which on their own, provide no structure or information that a screen reader can use.

To increase the accessibility of the sim, we designed and implemented a prototype containing a content and interaction layer that represents and describes the visual and

[1] The canvas element, introduced in HTML 5, allows developers to build complex dynamic applications by drawing the graphics directly on the screen.

[2] Scalable vector graphics, are plotted graphics, rendered dynamically in the web application.

interactive elements of the sim. We refer to this layer as the *Parallel DOM* (PDOM) [35, 45]. The PDOM was designed with a robust HTML structure that supports non-visual exploration and interaction with the sim. For example, a student can listen by using the screen reader cursor keys (arrows keys), listen by skimming and scanning for typical structures such as headings or buttons, navigate using the Tab key (or by other screen reader navigation commands) and operate interactions using common key presses. The design of the PDOM is crucial to supporting these strategies.

With the PDOM we have significantly increased access by making the content and interactions perceivable and operable by a student who uses a screen reader and keyboard. However, the challenge then arises, how should the elements in the PDOM be described so that the screen reader user can understand what they are? Further, how can the screen reader user know what actions are supported, and how can they understand the effects of their actions? We report here our efforts to address these challenges, including our approaches to introducing the sim's starting scene, providing help text and navigation cues, emerging strategies for description, and design improvements and ideas.

4.5 Method

To understand how dynamic verbal descriptions would be interpreted and understood by screen reader users, we conducted a series of interviews where we asked screen reader users to explore a sim prototype while thinking aloud [3, 28] while using it. We made iterative improvements to the design as we learned of issues from these interviews. A combination of fully implemented descriptions read by the screen reader, and scripted and unscripted live descriptions were used, allowing for flexible testing of description variations.

4.5.1 Participants

We recruited 12 screen reader users to participate in interviews – conducting 11 in-person and 1 remote interview. The participants, 5 women and 7 men, spanned a broad age range (19 years to 61 years). Participants demonstrated differing levels of expertise with their screen reader, and one participant used both a refreshable Braille display and a screen reader. All participants had at least some post-secondary education, the youngest being in their first year of college.

4.5.2 Description Procedure

Our prototype was fully keyboard accessible. Descriptions implemented within the sim, and read by the screen reader, included: all static content (content that does not change) and some dynamic content (content that changes as a result of interaction). The static content consisted of the content for a Scene Summary, all element names (headings and labels), descriptive help text for control elements (buttons, etc.), and static descriptions (e.g., the Wall's charge). The dynamic content consisted of descriptive phrases describing the amount of charge on the Sweater and the Balloon.

Descriptions provided by the interviewer were either scripted, or unscripted. Scripted descriptions included descriptions of Balloon movement (position in the Play Area while being dragged), descriptions of induced charge in the Wall, and the Balloon's "sticking" states. Descriptions for Balloon's behavior upon release (position changes and velocity during attraction) were unscripted.

Using a combination of scripted and unscripted live description allowed us flexibility to test wording, order of details, and length of the description for understandability. This approach also allowed us to identify particularly challenging areas of description and refine approaches prior to full implementation. The approach also helped us identify aspects of the sim where descriptive text, alone had trouble conveying the full meaning of a physical event.

4.6 Results & Implications

In this section we illustrate some of the description challenges in the sim, and how we addressed them. We focus on issues surrounding the Balloon, the most pedagogically important element, and the most difficult element to access and use while using a screen reader.

4.6.1 Introduction to Balloon - Scene Summary

PhET sims utilize a design approach called implicit scaffolding to visually cue students towards productive interactions [39]. The design and layout of the visual sim layer in *Balloons and Static Electricity* cues students towards interacting with the Balloon. Due to the Balloon's large size, bright color, and central location, students typically recognize this object as a starting point for interaction. Without instruction, they quickly grab the Balloon and move it around the screen.

Screen reader users listen before they interact [9, 23]. We created a *Scene Summary* as an introduction to the sim and placed it at the very beginning of the sim's hierarchical structure, to support this listen-first interaction pattern. The Scene Summary briefly describes the Play Area and Control Panel areas, and what is in each of these areas. The description includes details about the charges on each of the elements in the Play Area, a description of what the student can do with the control elements in the Control Panel. At the conclusion of the Scene Summary, students are cued to interact with the Balloon with the instruction, "Tab for next object," with the Balloon being the first object in the Tab order of the sim.

From interviews, we found that the Scene Summary provided essential information to help participants establish an overview of the sim. All but three participants started by listening to the Scene Summary. Participants who started with structural search commands (such as pressing *F6* for headings using the Jaws screen reader), rather than cursor keys, recognized the Scene Summary as a good place to start. One participant, after listening to the list of headings, selected "Scene Summary" from the list in the screen reader dialog and said, *"Scene Summary? I am going to check this out."* Some participants also identified the Scene Summary as a place to return to throughout sim use. Some participants returned to the Scene Summary for help or re-orientation and some returned to check for updated details about changes to the sim.

To use the sim for learning, a student using a screen reader must transition from listening (e.g., browsing with cursor keys) to interacting with focusable items such as the Balloon and the buttons and switches in the Control Panel. Table 4.6.1 shows three participants' verbalized responses regarding the navigation cue intended to cue them to encounter the Balloon.

Table 4.6.1: Participant responses to initial navigation cue

Participant	**Think Aloud Data**
P3	[VoiceOver User] *'Tabbing' is usually a Jaws navigation thing, so would that still work here?*
P7	*Since it told me to me to 'Tab to the next object' maybe I'll try that [Presses Tab key].*
P13	*I'm just thinking if I was younger, I wouldn't know what an object is...and maybe give it a bit more context.*

Based on participant responses, the Scene Summary might be improved by providing more context, especially in the wording of the first navigation cue in order to highlight more explicitly the importance of the Balloon.

As mentioned earlier, placing the Balloon first in the Tab order provided some indication of its importance. But a more explicit cue, that mentions that the student should actually interact with the Balloon, might be helpful. This context may help a student using a screen reader understand the importance of transitioning from browsing to interacting. It may also be helpful to include the location of more detailed information on how to use the sim (e.g., the location of a detailed *How to use this sim* document) within the Scene Summary.

The fact that some participants returned to the Scene Summary throughout their use of the sim raises an additional issue for the description. Rather than being a static description of the initial state of the sim, the Scene Summary needs to dynamically update to continuously reflect the current state of the sim.

A dynamically updating Scene Summary results in redundancy of the information students have access to. When the student takes an action, for example, rubbing the Balloon on the Sweater, the sim needs to provide a description of what the effect of that action is at that moment in time, in this case, moving charges from the Sweater to the Balloon. The resulting change in amount of charge on the objects will also be reflected in the Scene Summary. If the two descriptions, that of the effect of the action, and of the modified sim scene, were the same, that may seem needlessly repetitive. Considered in the context of sim use the two descriptions would be used quite differently. The description of the effect of an action focuses on only the single action. The Scene Summary should summarize the state of the sim scene providing the *big picture* view of what is represented onscreen.

As mentioned earlier, the ISG Practices [20] provides guidelines on many aspects of descriptions, such as providing a general overview. Here, the "contextual" requirement is of special importance. As we showed, in complex simulation contexts, descriptions are needed to both explain specific actions and for conveying the big picture. Additionally, cueing the most pedagogically relevant actions is a further role for descriptions to be considered within learning tools. These description attributes currently fall outside of the list of attributes emphasized in the ISG Practices.

4.6.2 Help Text & Navigation Cues

For elements in the Control Panel (typical form-like control elements), the help text provides an explanation of the purpose of the element (i.e., how and why a student would want to use it). Help text was a useful way to provide further context intended to encourage investigation. For example, the Remove Wall button's help text was initially "Toggle to conduct experiments with or without the wall," lightly cuing students that they are "conducting experiments" and that the Wall might have an effect worth investigating. The wording of the button's label is a form of *implicit scaffolding*. The help text provides guidance for students accessing the sim non-visually, while avoiding saying exactly what to do.

We found the cue to "toggle" the button was unnecessary. All participants knew implicitly how to operate the button by pressing either the Spacebar or the Enter key. In this case, the familiar structure itself is an implicit scaffold for screen reader users. As a result, we shortened the help text to "Conduct experiments with or without the Wall."

Initially, we implemented all help text to be read out automatically (using the *aria-describedby* attribute). We learned quickly that the PDOM supported the implicit operation of common control elements (buttons and radio buttons) and providing automatic help text was not necessary. Participants knew how to operate the control elements, and with a clear label participants knew what the control elements could be used for.

As a result, we removed automatic help text from all control elements – except for the Balloon (an uncommon control element). The removal of automatic help text significantly reduced screen reader verbosity. We supported on-demand access to help text with the down cursor key (i.e., down arrow). In subsequent interviews, we found very few participants accessed the on-demand help text.

The Balloon cannot be operated by standard key presses; automatic descriptive help text was needed to support successful interactions with the Balloon. Unfortunately, the lack of standard key presses results in a lengthy description. We do not yet have a satisfactory way to address the verbosity challenge presented by the Balloon element description. One approach would be to provide concise, minimal automatic help text, while supporting on-demand access to additional help text, as we have done with the common control elements described previously. Due to technical incompatibilities outside of our control it is not currently possible to support use of the down cursor key or down arrow (the common screen reader command to access on-demand help), while the Balloon element has focus. As a workaround, we are investigating the approach of providing a general, *How to use this sim* resource that can be accessed from anywhere in the sim through hot keys. This resource would include information about operating the Balloon. The Balloon's description would then only include its general description, and general automatic help text rather than the lengthy instructions on how to move the Balloon. A navigation cue is likely unnecessary. This would reduce the length of the original description to what is shown in Table 4.6.2.

To summarize, for common elements in an interactive simulation we found providing help text on-demand rather than providing help text automatically was effective. This finding for common elements aligns with recommendations in ISG Practices. In the case

Table 4.6.2: Potential description components for the Balloon

General Description	General Automatic Help Text	Navigation cue
Balloon has a net negative charge, a few more negative charges than positives ones.	Press H key for hot keys and help.	None.

of uncommon control elements, e.g., the Balloon element, the operation of a control element does not follow a common interaction design pattern and has no associated key presses that are already familiar to screen reader users. An approach combining general description, automatic help text and opportunities for further help may address this challenge.

4.6.3 Strategies for Interactive Description

Describing a complex interactive science involves the description of the sim's interface, how to use the sim's features, real-time interactions, the results of those interactions, and the big picture overview. Additionally, screen reader users can access many of the descriptions in numerous ways (e.g., browsing with cursor keys, navigating with the Tab key), resulting in many different access pathways through an already non-linear sim investigation. We found that sim elements and sim descriptions could be sorted into distinct categories (Tables 4.6.3 and 4.6.4), which supported our understanding and consistent design of the descriptions.

In the following two sub sections we discuss the types of elements and categories of descriptions (content) and their implications on the design of the non-visual interface (listening environment).

Table 4.6.3: Categories for Sim Elements

Category	Definition	Examples
Dynamic Sim Objects	An element containing a visual representation(s) of the underlying physics model that changes as a result of student interaction, but is not directly controlled by the student.	Sweater and Wall
Interactive Sim Controls	An element that is directly controlled by the student to manipulate parameters of the underlying physics model and/or how representations are presented to the student.	Buttons in Control Panel
Dynamic-Interactive Sim Control	A complex element that is directly controlled by the student to manipulate parameters of the underlying physics model, **and** also contains visual representations of the underlying physics model. This type of element may also effect changes on other elements.	Balloon

Categoriess of Sim Elements: Objects & Controls

We found the first two categories of elements, *dynamic sim objects* and *interactive sim controls* to be relatively straight forward to describe. Dynamic sim objects, e.g., the Sweater and the Wall, are not interactive. For objects in this category, we describe the object and how it changes, and ensure that the description would be appropriate across all contexts in which it can be accessed. *Interactive sim controls*, e.g., the Remove Wall Button, require clear label text. With clear label text, participants effectively operated interactive sim controls. We found that interaction alerts that support understanding of the interaction can be important in the use of interactive sim controls (see Section 4.6.4).

The Balloon emerged as a unique category of element. The Balloon consists of

Table 4.6.4: Categories for Sim Descriptions (Content)

Category	Definition
Static Description	Names and descriptions for elements that do not change. *Static descriptions are available to screen reader users at all times.*
Dynamic Description	Descriptions for elements that change due to interactions. These descriptions represent changes in the underlying scientific model. These descriptions appear as part of the individual elements and as part of the scene summary. *Dynamic descriptions are delivered dynamically as changes happen and the descriptions are also available to screen reader users at all times as they navigate the sim in different ways.*
Interaction Alert	An alert is a static description that is delivered dynamically to support interaction or to support the delivery of dynamic descriptions. *Alerts are presented only through the verbalization tied to a specific interaction and are not available at other times.*s

Table note: An *alert* here is a "special case" live region [4]. It has the same "politeness level" as aria-live assertive which is used for the dynamic description updates.

dynamic visual representations of charges (like the Sweater) and it is interactive and operable like a control. Like the Sweater, it has a basic value for amount of charge (net negative charge), but unlike the Sweater, its position changes. The student can do several things with the Balloon (grab it, drag it, rub it, and release it) and the Balloon does several things in response to the student's interactions (collects negative charges, attracts or repels from other objects). This complexity makes a sim element like the Balloon difficult to describe. We refer to the Balloon as a *dynamic-interactive sim control*.

To address the description complexity of the Balloon we considered all of its different states and the information a screen reader user needs as they interact and move through these states. The Balloon states, or *perspectives* (Table 4.6.5), directly affect the information and the order of information that the student needs verbalized during the interaction.

Table 4.6.5 lists the Balloon's perspectives and the details that form its description when it is in that perspective. We are continuing to optimize the description order and wording based on what we learned from interviews.

Table 4.6.5: Balloon perspectives & action descriptions

State	**Student Action**	**Announcements at action**
Focused (Ready to grab)	Student Tabs to Balloon object.	- Balloon's Name - Balloon's charge - Balloon's position - Description of closest objects (Sweater or Wall) *- How to grab and drag*
Grabbed & dragging	Student grabs Balloon by using movement keys	- Balloon grabbed state - Direction of movement - Progressive orientation announcements - Arrival at important locations - Live updates of description changes when the Balloon touches another object *- How to release*
Released (still has focus)	Student activates release mechanism (Spacebar or Enter key)	- Balloon release state - Release position - Reaction in past tense - Resting position - Description of closest object (Sweater or Wall) - Balloon's charge *- How to grab*

Table note: The last italicized item in each list are a navigation cue which were provided as live scripted descriptions during interviews.

The resulting three perspectives, rather than one dynamic description, makes the

Balloon significantly more complex to describe than the other two categories of elements we identified. We anticipate that nearly all PhET sims contain at least one complex element like the Balloon.

We compared our categories in Table 4.6.3 with the ISG Practices [20]. The ISG Practices divide the description task into two component parts: guidance for describing the actual dynamic graphic, and guidance for describing the digital control element that changes the value represented in the graphic. This is very practical – and in our opinion one of the strengths of the ISG Practices – because the description strategy for each is unique.

For similar reasons, the three categories of elements we identified in *Balloons and Static Electricity* were a useful approach to addressing the description challenges we faced with this sim. The ISG Practices were also helpful in developing descriptions for individual elements of the sim. For example, the ISG Practices' guidelines for describing a "digital control object" are directly applicable to an *interactive sim control*, like the Remove Wall button. In addition, many aspects for describing a "dynamic scientific graphic" can be applicable to an element like the Sweater, however, even the Sweater has more complexity than a simple dynamic graphic. It has only one visual representation actively changing as the student rubs the Balloon on it – its net positive charge increases – but the location of its remaining negative charges is crucial for subsequent interactions. Strategies for addressing this level of complexity are not yet fully represented by existing guidelines and best practices for verbal description.

Categories for Sim Descriptions

For descriptions we found it essential to distinguish between the descriptions that are static (do not change), and descriptions that are dynamic (change as a student interacts). We also found that we needed a third category of static descriptions, which we call

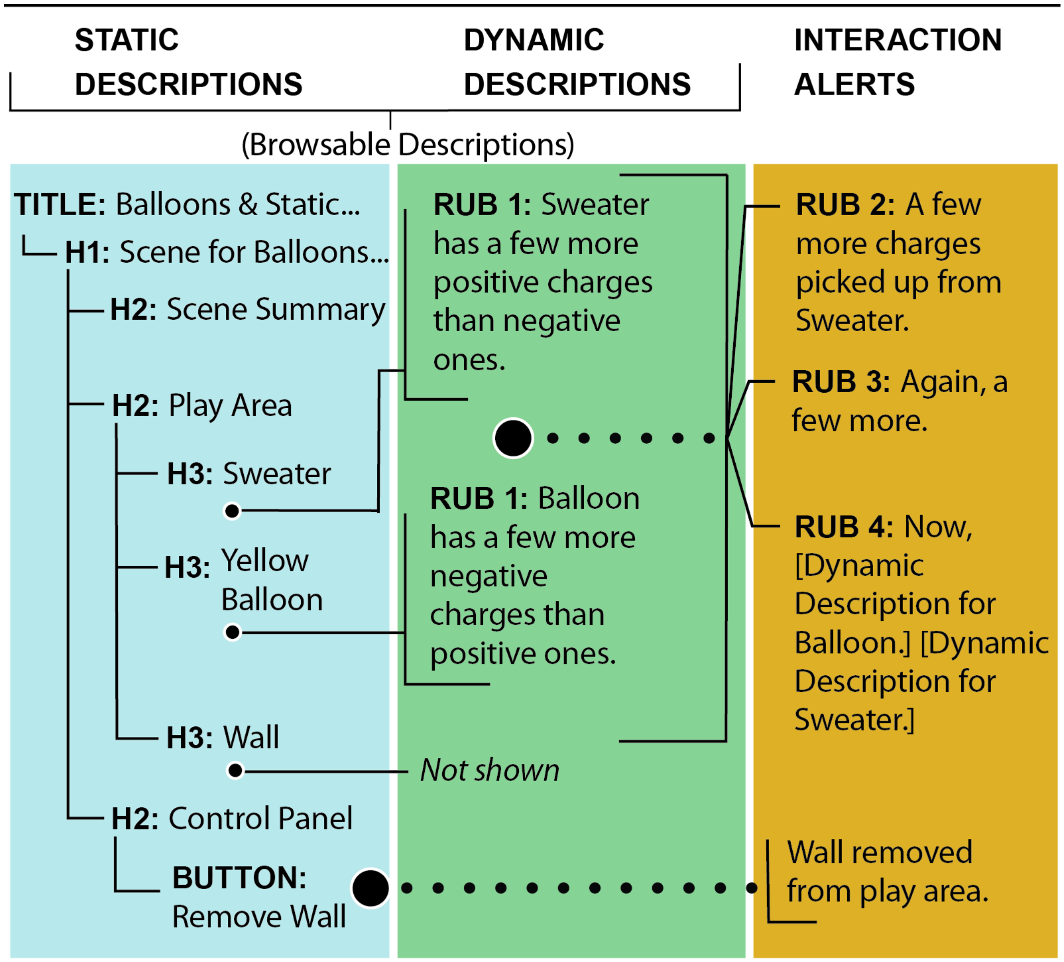

Figure 4.6.1: Description Categories with simplified Parallel DOM.

interaction alerts. Interaction alerts are descriptions that directly support interactions rather than describe elements.

As we examined how we were using these categories we noticed interesting patterns. The static and dynamic descriptions essentially make up the main ingredients (pedagogical content) for the sim. The static descriptions (element labels and descriptions) form an outline of the sim and provide context. The dynamic content provides the changing details that provide the essential content about the scientific concepts that students are investigating. Dynamic and static descriptions are always accessible to the student, either directly through interaction with live updates[3], through browsing with the cursor keys, or through the use of screen reader commands for skimming and scanning.

Interaction alerts, on the other hand, are not accessible at all times. Interaction alerts are delivered to students as they interact to indicate the success of an interaction, such as moving left towards the Sweater, or adding a second balloon to the Play Area. These descriptions are not part of the description of a sim element, and thus are not stored in a location where the student can review or repeat the content at a later time. An interaction alert only makes sense in the storyline of the sim at the exact time of interaction when it is delivered.

The ISG Framework states that the "delivery" of descriptions need to be "apt", "synchronous" and "controllable". More specifically changing features must be identified; they must be delivered in a timely manner; and they should describe information from the general to the specific. While this guidance is accurate and relevant, it does not provide any guidance on how to approach describing multiple changes. Our description categories fill this gap and can be used to help organize the design and delivery of descriptions that are apt, synchronous and controllable.

In the next section we discuss how we used alerts to support student interaction and to improve the design.

4.6.4 Design to Reduce Verbosity & Repetition

Because screen readers read out the structural and state information of the interactive sim controls as a student navigates to them, the verbalizations that are delivered tend to be verbose and repetitive. We observed that verbosity and repetition cause clutter in the

[3]Live updates are delivered using WAI-ARIA live regions [4, 7, 43], a system that alerts users of content changers that are outside their current cursor focus.

listening experience and may make the content or the interaction difficult to understand. A few participants would silence the screen reader before they heard the important part of the description because it sounded like it was repeating something they had already heard. Reducing verbosity and repetition even a little bit may make significant improvements making description more understandable.

Label Text, Part of the Story

Here is an example of a redesign that produced a full verbalization (label text plus structural and state information) that was shorter, clearer, and more contextual. The sim starts with a single balloon in the Play Area, but the participant can add a second, green, balloon later on. In the Scene Summary, the Green Balloon is not specifically mentioned by color. In our initial implementation of the prototype, the participant controlled the number of balloons using a pair of radio buttons, one to add the Green Balloon and one to remove it. Radio buttons contain a lot of structural information that a screen reader needs to convey to the user. In addition to the control type and the label text, the screen reader provides the checked state of the radio button and the count of the radio button within the group, and it does this for each radio button as a screen reader user navigates through the group. That information becomes partially redundant, and might seem confusing if the label text does not read well with the state information. While the verbalizations for the radio buttons (see Figure 2) were understandable to the first participant, we found the verbalization verbose, awkward, and slightly out of context.

To reduce verbosity, we replaced the group of radio buttons with a single toggle button which would behave more like an on-off switch. We first used the label "Add green balloon" which is read out in its unchecked state as "Add green balloon, toggle button" with Firefox and JAWS, and "Add green balloon, unchecked, toggle button" with Safari

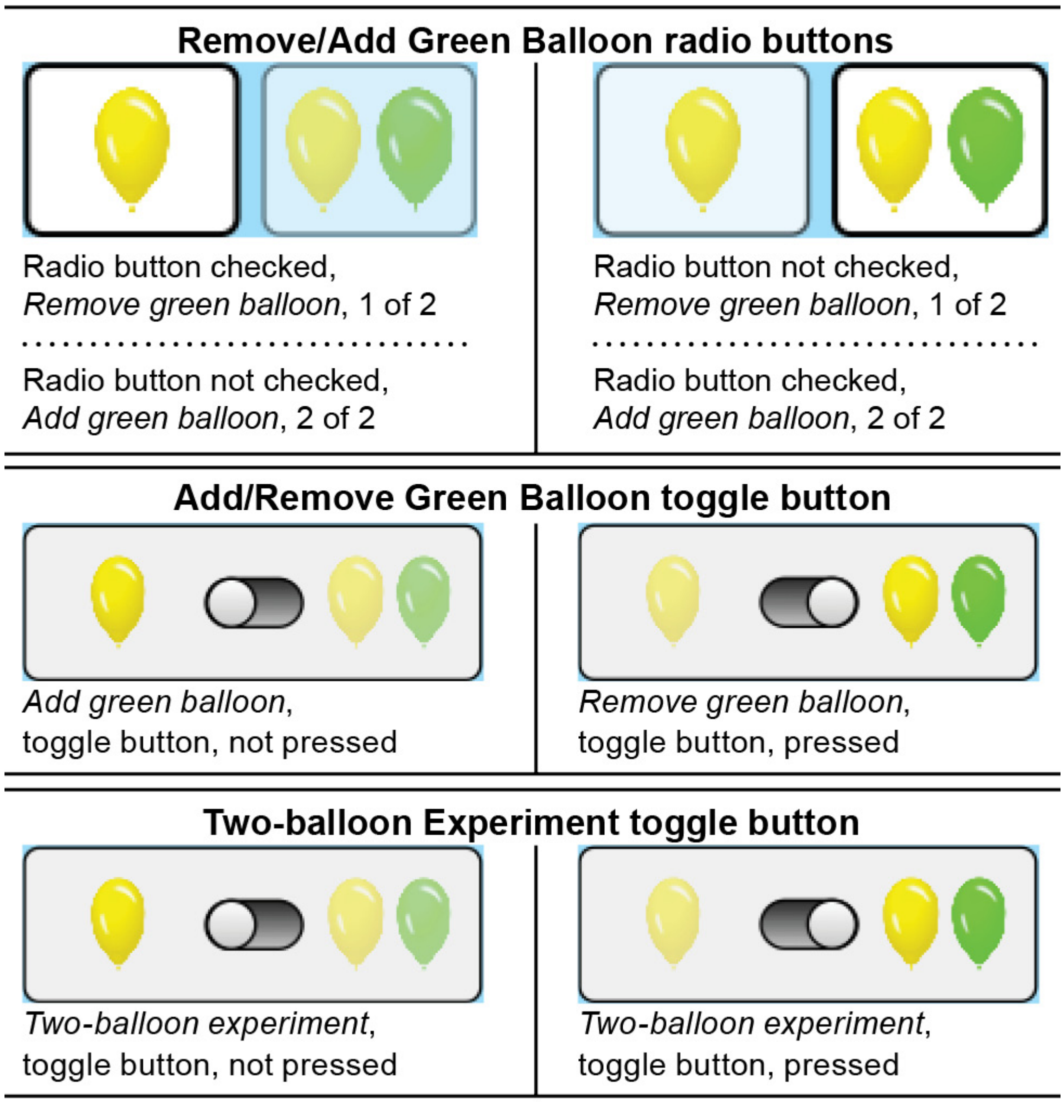

Figure 4.6.2: Verbalization comparison for labels and control types (approximate verbalization).

and VoiceOver. While less verbose, the verbalization still seemed awkward and out of context to us. Finally, we changed the label text to a single noun (two-balloon experiment); something that can be logically switched off or switched on (see also Figure 4.6.2).

The entire verbalization was now much shorter (one element and one label). The wording was clearer; the purpose of the label text was now describing a parameter rather than an action. It was more contextual because participants were no longer being asked to add or remove an unknown Green Balloon. Having an on-off switch2 for a parameter (i.e., "not-checked" or "checked") made more sense than having an added balloon "checked" or "not-checked". The interaction was now clear, concise, contextual, and we believe more understandable.

The first two participants (P5 and P6) to encounter the new label text, expressed very clear understanding of the interaction. A snippet from P5's interview is in Table 4.6.6. P6 became particularly engaged by the interaction. Fifty seconds of P6's interview follows showing their engagement:

- **P6:** *Remove Wall?* [sounds curious]
- **Interviewer:** Uh-huh [nods]
- **P6:** *Aaah, like from the experiment?*
- **Interviewer:** You can do that.
- **P6:** [Tabs again, and hears the screen reader read the label text, "Two-balloon experiment"] *Two-balloon experiment. Two...Aaah! So these are new experiments!* [sounds excited]
- **Interviewer:** Uh-huh.
- **P6:** *Ok. Two balloons instead* [Tabs between Remove Wall button and

Two-balloon experiment button]. *Can I choose this one, or do you want me to choose the previous one* [Remove Wall]?

- **Interviewer:** You can do whatever you like.
- **P6:** *OK.* [Tabs quickly to the next 2 buttons, then into the Browser toolbar, then quickly uses Shift-Tab to come back to the Two-Balloon experiment button].
- **Interviewer:** And just think about what you are doing aloud.
- **P6:** *Yes, yes. Oh, sorry. I am just exploring to see what options I have and to see what looks a bit more interesting. I think I will use the Two-balloon* [P6 presses Shift-Tab moving focus to Remove Wall button, hears label text and realizes she is not where she wants to be.]
- **P6:** *Remove Wall. No.* [Presses Tab again, hears "Two-balloon experiment, button."] *Two-balloon experiment, to see how they interact and with the Sweater.*

Before encountering the Two-balloon Experiment toggle button, P6 had already experienced a successful investigation with the Balloon and the Sweater. Upon finding more options (Remove Wall, Two-Balloon Experiment, Reset Balloon, etc.), they chose the Two-balloon Experiment and engaged (excitedly) in a new task. P5 had had trouble initially with the first balloon because they did not understand the instructions on how to move the Balloon; however, after activating the Two-balloon Experiment button the participant set a task to find the Green Balloon and with so doing began a more productive path of inquiry which lead to rubbing the Green Balloon on the Sweater and witnessing a transfer of negative charges. Though we have little data for comparison, we think the combination of the words "two", "balloon" and, "experiment" provided context and made more sense within the story of the sim.

Interaction Alerts to Communicate Success

While the changes just described helped some participants engage and take action, we found that they were not always certain of the result of their actions. For the Two-balloon Experiment interaction, state change information (*checked* or *not-checked*) was delivered inconsistently by browsers, leaving some participants unsure about the success of their interaction (see P3 and P4 in Table 4.6.6). Similarly, the label text on the Remove Wall button changed to Add Wall. That gives only an implicit indication of the Wall's removal to non-visual users, though that is obvious to visual users. We added alerts to communicate the success of these actions more explicitly. Based on the more certain responses from P5 and P7 (see Table 4.6.6), we feel the explicit alerts were more effective at communicating the success of the interaction. The interaction was now more clear in most cases; however, we still experienced some technical issues with browser inconsistencies and live regions[4]. In the next example, we propose that interaction alerts might also be helpful to reduce content verbosity and repetition during multiple dynamic description updates that occur often in highly interactive science sim (e.g., rubbing on the Balloon on the Sweater).

Multiple Updates & Repetitive Phrasing

In our original design we constructed phrase templates for the descriptions, so words could be swapped in and out as needed without changing the entire description. For example, we used the same template to describe the charge on the Balloon and on the Sweater: "Sweater has a net positive charge, a few more positive charges than negative

[4]WAI-ARIA live regions are used to deliver updated information which is outside the user's focus: changes in element descriptions (dynamic descriptions) and the supportive interaction alerts. It is possible the ARIA alert role, a "special case" live region is more appropriate for the alerts [4, 7, 43]. Alerts also have a politeness level of "assertive."

Table 4.6.6: Alerts for buttons make success more clear

Participant	**Certainty/Uncertainty in Think Aloud Data**
P3 (Uncertainty with no Alert)	[VoiceOver screen reader: "Add green balloon, unchecked, toggle button"] *So, you can add a green balloon? So I will try doing that.* [hits Spacebar] [VoiceOver: "Checked, Remove green balloon, toggle button."] Uuum… [presses something and gets the on-demand help text associated with the toggle button. VoiceOver: "Toggle to conduct experiments with two balloons or just one." P3 then navigates with the Tab key.]… So I am just tabbing to try and find the green balloon.
P4 (Uncertainty with no Alert)	OK, so I can remove the wall. [Hits spacebar]. I removed the wall, but I didn't get feedback. [Interviewer jumps in with a live description "Wall removed from Play Area"] Ah, ok. Cool. So wall removed. [Screen reader says "Add Wall, button"]. Oh, so it is changed to add wall. Cool.
P5 (More certainty with an Alert)	[Activates the Two-balloon Experiment button and hears "Green balloon added to play area."] *Green balloon, so, I got that added to the play area.* [P5 then re-listens to the button]. *So it tells me that it's toggled and it's in the Area.* [P5 then asks about the Balloon Reset button and then goes looking for the Green Balloon].
P7 (More certainty with an Alert)	[Activates Remove Wall button, and hears "Wall removed from play area."] *All right* [Understands that the Wall is removed]. *So, I'm going to try tabbing again to see what happens.*

ones," and "Balloon has a net negative charge, a *few more* negative charges than positive ones." These descriptions seemed appropriate in isolation, and served as an initial starting point. When read together back-to-back, as they are when a participant rubs the Balloon on the Sweater, the repeated wording obscured the actual change in wording resulting in different levels of understanding of what was happening. Participants were always intrigued by the dynamic description update as they moved the Balloon onto the Sweater. They immediately knew *something* they were doing was causing a change involving charges; however, *only some participants* understood exactly what about the charges was exactly changing.

The repetitiveness of the description continued as the participant rubbed on the Sweater. Each move (or rub) that touched negative charges resulted in two dynamic descriptions being updated, and thus verbalized; one for the Sweater and one for the Balloon: "Sweater has a net positive charge, *several more* positive charges than negative ones," and "Balloon has a net negative charge, *several more* negative charges than positive ones."

This repetition problem also cropped up when participants used either of the two reset buttons. The act of resetting can cause changes to multiple sim elements simultaneously. Descriptions of these changes would then be read out sequentially, resulting in a verbose set of descriptions that requires significantly longer amount of time to listen to than the actual act of resetting the sim. An alert that simply says that everything has been reset is considerably shorter and clearer.

4.6.5 Summary of Findings

We began our work with the approach of describing the things in the sim, and their state. Our experience implementing descriptions within the *Balloons and Static Electricity* sim and interviews with screen reader users has led us to a new understanding of descriptions within interactive sims.

- The Scene Summary is an essential accessible design feature, that was used by participants more than we expected. It sets the scene, and provides a *big picture* overview of the sim; something that students without vision impairments have at all times.

- The Balloon is not a standard control. It is a combination of a dynamic object, and an interactive control. Students need specific information about how to interact with it. This information is best delivered on-demand after initially provided upfront.

- Static descriptions, dynamic descriptions, and interactive alerts that support interaction need to be considered together, but require different approaches to design because they have unique roles to play. Because static descriptions form a base content outline for the sim as well as a focusable navigational outline, they warrant careful focus for nuances around accuracy, contextual relevance, and clarity. Dynamic descriptions are essential for learning about the science concepts, so finding ways to minimize their complexity while at the same time staying true to the learning objectives of the sim are crucial. Descriptions for interaction alerts require a focus on connecting the student's interactions with the changes in science content so the design can be engaging.

- Simple interaction alerts are more effective for communicating the success of a sim control activation than relying on passive changes to label text changes (e.g., remove/add) or control state changes (e.g., not pressed/pressed).

- Multiple dynamic descriptions are often read out in close sequence, which means that descriptions that seem clear and to the point in isolation can be confusing and repetitive in context. Designing a system of alerts that can provide a summary to replace some multiple individual dynamic descriptions during interaction may be more effective.

- Multiple descriptions (live content updates) are often read out in close sequence, which means that descriptions that seem clear and to the point in isolation can be confusing and repetitive in context. Alerts that provide a summary of the effects of actions can be more effective than relying on automatic reading of live content updates of separate sim elements.

4.7 Discussion

In our initial work on designing descriptions for an interactive science sim we found specific and general aspects of the ISG Practices [20] that apply nicely to describing an interactive sim. For example, sim controls that have a natural HTML equivalent can be described using the same best practices for describing digital control objects (a component category in the ISG Practices). More generally, we found the guidelines to be an excellent tool that provide a good starting point and a useful way to evaluate individual descriptions.

However, as just summarized, we found that we faced a number of description challenges in our work that reflect the complexity of a simulation with many interactive and interacting elements (Balloons, Sweater, Wall, Charges), and many interactive control elements. We believe the categories we proposed for sim elements and for sim descriptions, may be useful additions to the space of guidelines.

We feel it will be possible to improve on our results, by exploring how alerts can be made to depend on context within an interaction. For example, when a student rubs the Balloon repeatedly, an alert for a second rub could describe the transfer of charge rather than a full update of the Sweater and Balloon: "A few more charges picked up from Sweater," and the alert for a third rub could trigger an even shorter alert: "Again a few more." A system of interaction alerts describing what is happening in the moment may provide an interaction-centered view [13] of the simulation that may be a way to enhance understanding and encourage engagement.

In an interactive simulation where content can be delivered and accessed in multiple ways, a strategy for handling multiple descriptions for the same thing can be very useful. It may seem counterintuitive to have multiple descriptions for the same thing, but the description should be slightly different, depending on a particular moment in the interaction and the way in which the student is receiving and accessing the description (via automatic update or browsing). The student needs brief differentiated updates when actively engaging, but then needs a full description when browsing an individual object element, and then needs a summary of all elements in the Scene Summary. This kind of description management creates a level of complexity for the description of interactive simulations that does not exist when describing simple dynamic interactive graphics.

4.8 Conclusion

In this work, we shared what we learned about a complex description problem in a highly interactive science simulation, that we tested in a study with 12 individual participants with vision loss and who use screen readers. Through the analysis of their comments and an analysis of our design process, we learned that there are dimensions of description for a highly interactive sim that are not covered by current description guidelines for interactive graphics. We introduced a description strategy framework that can be used in addition to existing guidelines, and that may be helpful for others describing highly interactive learning tools. Our organizational framework emerged as we worked on describing one PhET sim, *Balloons and Static Electricity*. We will take what we learned from this sim and see how it can be applied to other PhET sims that present similarly complex description problems.

4.9 Acknowledgments

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4.10 References

References for this paper are incorporated into the main references section.

5

Evolving Standards, Design, & Thoughts

In this chapter, we discuss how the design of inclusive sims might be affected by evolving standards, design and thoughts. First, promising upcoming changes in web standards have implications for future work. Second, an important interaction change has been implemented since our interviews which will affect sim design. Finally, we reflect on how we have addressed aspects of our research questions while working on *Balloons and Static Electricity*.

5.1 Evolving Standards

Some of the challenges we faced in designing accessibility features for *Balloons and Static Electricity* were due to the current shortcomings of the web standards HTML5 [17] and WAI-ARIA 1.0 [4]. These are robust technologies that provided us the tools to implement accessibility features that addressed significant access barriers for this sim. In fact, using the native elements and attributes of the specifications, and the defined keyboard interaction design patterns in the WAI-ARIA Authoring Practices document [43], we created a robust Parallel DOM (Figure 3.4.1, Chapter 3) that provides access for screen reader users to all the basic elements and interactions of the sim. As discussed in Chapters 3 and 4, we did not have a native way to address the challenges that a complex sim element like the Balloon presented. Based on what we learned we have options and ideas for other customized designs (discussed in Section 5.2 below). We are confident that we can make the Balloon interaction more understandable while the work on HTML5.1 [38] and WAI-ARIA 1.1 [5] continues.

Work on HTML5.1 has begun. The new plan for the standard is to publish updates approximately once per year [50]. The stated goals for the standard look very promising for organizations that design and develop highly interactive simulations:

> "The core goals for future HTML specifications are to match reality better, to make the specification as clear as possible to readers, and of course to make it possible for all stakeholders to propose improvements, and understand what makes changes to HTML successful." [50]

Having an HTML standard that "matches [the] reality [of interactive sim elements] better", and provides an open process that makes it "possible to for all stakeholders to propose improvements", both sound extremely promising to us. Part of what we learned from our research on this project is that while standards took us very far, improvements are still needed.

We hope that future work on HTML5.1 will define ways that will allow us to design the Balloon interaction so that it is as implicitly intuitive to use as other interactive elements in the sim. Something along the lines of a 4-way slider to create a keyboard accessible drag-and-drop interaction would be quite helpful.

WAI-ARIA 1.1 is now in a working draft and accepting comments. In the editor's draft there are several changes that will directly affect our next steps with this sim, and generally benefit future work on making interactive sims accessible. While a complete review of the new definitions in WAI-ARIA 1.1 will be part of our future work, we feel it is worth noting some changes that are immediately relevant to our work on *Balloons and Static Electricity*. We comment on some of the changes and their potential implications below.

- **Drag and Drop attributes:** Likely due to poor browser implementation for the aria-dropeffect (property) and aria-grabbed (state) [1], these attributes are expected to be replaced by a new feature in a future version of WAI-ARIA. The attributes are to be treated as deprecated in WAI-ARIA 1.1."Deprecated" means that no further work will be done on these attributes and that the working group has determined that a new approach is needed to better define this interaction. The attributes will continue to work as-is, but it is likely that user agents (browsers) will not improve implementation until a new standard is defined. We have implemented these attributes on the Balloon and many other interactive sims have drag-and-drop interactions. A truly intuitive keyboard accessible drag-and-drop interaction is still part of the future. While this may not sound like great news, we feel it is a positive step forward. The attributes have been identified as not working that well and are

[1] Personal discussion with WAI-ARIA expert Joseph Scheuhammer, Inclusive Design Research Center, OCAD University, Toronto, Ontario, March 1, 2016

in need of attention for the next version of the specification.

- **application (role):** There are significant changes to the definition of the application role. This role is meant to define a way to create complex custom elements with custom interactions like the Balloon. The main difference to the new definition is that the role's "superclass" has been changed from *landmark* to *structure*. In more general terms this means that an element with the role application will now be more like other typical structural elements (e.g., divs, headings, paragraphs) rather than behaving like a special landmark region element. This change should greatly improve the way the Balloon is read out by screen readers and should result in reduced screen reader verbosity. With our current prototype screen readers verbalized irrelevant information along with the Balloon's accessible name. A typical verbalization went something like, "Yellow balloon, Application, Region, Draggable". With the specification change, a screen reader might just read out, "Yellow Balloon, Draggable," and provide an audible indication that the screen reader has switched to an "application" browsing mode. Some participants that we interviewed noted there was a mode change, often an audible popping sound, when their keyboard focused moved to the Balloon.

- **aria-roledescription (property):** This new property allows us to define "a human-readable, author-localized description [sim-localized description] for the role of an element" [7]. Together with changes in to the application role, a way to better describe the Balloon should greatly improve its usability. Any reduction in the irrelevant information read out by screen readers about the Balloon (e.g., "Application, Region") should improve usability and provide an experience that may make it more clear how to engage with the Balloon.

- **switch (role):** defines "A type of checkbox that represents on/off values, as

> opposed to checked/unchecked values.” PhET sims employ a lot of switches. This role will be very useful for many sims. For *Balloons and Static Electricity*, the switch role might better describe the toggle button we used for the Two-balloon Experiment button in this project. Ideally, a screen reader would say something like, “Two-balloon Experiment, Switch, Off.” This may be more clear than “Two-balloon Experiment, button not-pressed,” which is the approximate verbalization of the current design.

Of course, as new standards are defined, it is up to user agents (browsers) and screen reader manufacturers to interpret and implement the standards. We are hopeful that the time line for the full cycle of how standards become reality might be getting shorter. Even as we write this, some changes have already occurred. At a recent development meeting, PhET software developer, Jesse Greenberg, reported that the screen reader NVDA when used with the Firefox browser allows for the use of the Arrow keys to move the Balloon. This is a sign of encouragement and evidence that perhaps the reason why the Arrows keys do not work while using the JAWS screen reader is in fact a bug and that we need to file a bug report to the manufacturer.

5.2 Evolving Design

As discussed in Chapters 3 and 4, we found that some participants had trouble easily engaging with the Balloon. The complex nature of the Balloon resulted in unfamiliarity for the interaction and severe verbosity in the Balloon’s overall description. Successful engagement with the Balloon is fundamental to achieving the learning goals of the simulation, making it a top priority to improve.

In the prototype, the grab-drag-rub interaction was integrated as one interaction. While this provided efficiencies in the number of key presses to start the Balloon interaction, it also meant that a lot of information about the Balloon and about how to operate it was provided all at once. In iterations since the interviews, we decided to split the the grab-drag-rub interaction into a two-step process: first a clear and simple grab interaction and then the more complicated drag-rub interaction.

This design change has several clear benefits for accessibility and usability.

- The grab interaction has been implemented with a native HTML button, an element that users will implicitly know how to operate.

- The new label for the button, "Grab Balloon" is clear, concise, action-oriented, and not obscured by information about the Balloon being an "application" or a "region" or "draggable".

- The new button is the first focusable item in the Tab order for the sim, greatly clarifying the first and most important interaction. The text, "Grab Balloon" makes sense after hearing the Scene Summary and may even make sense for a user who has skipped the Scene Summary.

- Creating a separate grab interaction also makes the interaction of grabbing more intentional. This intention may have the affordance of preparing the user for what is to come, a browsing mode change which involves a highly interactive Balloon.

- Using a native HTML element (i.e., button) for the grab interaction also means we can provide an on-demand description containing help text for the button. This help text can be made available to the user in a standard way (i.e., down cursor/arrow key). This paragraph of help text could strategically provide some instruction or advanced notice about what is to come when the button is activated, potentially addressing other usability issues around verbosity and the Balloon.

- A separate grab interaction reduces overall complexity of the Balloon and its description by dividing the the delivery of content up, even if just a little bit.
- By splitting the interaction, the Balloon itself is removed from the Tab order which may make the focusable outline of interactive elements more clear and understandable. The new list is: Grab Balloon, button; Remove Wall, button; Two-Balloon Experiment, toggle; Reset Balloon, button; Reset All, button [2].

The drag-rub interaction will remain somewhat complex; however, we think that setting the interaction up with more clarity and more intention may provide enough context to improve the overall interaction, making it easier for a user to understand how to engage with the Balloon. As discussed above (Section 5.1), changes to the definition of the application role should also contribute to the design of a more usable and understandable Balloon interaction.

5.3 Evolving Thoughts

In this work we set out to answer the following three questions about how to make an interactive sim accessible and engaging for a student who uses a screen reader.

1. How can we make an accessible, engaging and effective learning experience for students with vision impairments who use a screen reader to interact with a PhET simulation?
2. What are the technical challenges to designing accessible features for screen reader access to a PhET simulation?
3. What are the *implicit scaffolds* for the non-visual user of a PhET simulation?

[2] The radio group for the Charge View Settings is not in the list as they are hidden from view in the current prototype.

In the beginning we were really not sure how we would do it. As discussed in Chapters 3 and 4 we had many successes. A robust Parallel DOM created access to all implemented descriptions and made all sim interactions operable via the keyboard. A set of hot keys provided efficient ways to engage with the sim in addition to the ways that screen reader users typically navigate and interact with web applications. Together with the "live *wizard* descriptions", this access provided enough information to the participants for them to engage with the sim in meaningful ways. We feel that adjustments to descriptions, and to how they are delivered, will improve the level of understanding. It is hoped that this will foster a deeper level of student engagement.

The Balloon interaction presented the biggest technical challenges, and ideas for that interaction are evolving. The Parallel DOM supported user interaction in a way that made many interactions implicitly understood. Familiar structure and operations are key *implicit scaffolds* for screen reader users. Verbal description is, by nature, more explicit than visual imagery, but the goal is to discover nuances in descriptions that guide the student with as little explicit instruction as possible. Thus, we have discovered that PhET's design framework of *Implicit Scaffolding* [39] which has worked so well in the visual design of the PhET sims, can be extended effectively to non-visual modes [31].

In this project, and in our exploration of the *Balloons & Static Electricity* sim, we designed and partially implemented the first of many layers that PhET has planned to make their sims (currently numbering more than 130) more inclusive to all learners.

5.4 Summary

In this chapter we discussed the changing design space for interactive sims, a new interaction for the Balloon and reflected on our research questions. In the next chapter we conclude with our achievements for this project, our contributions to inclusive design, and our intentions for future work.

6

Conclusions

This work has created access to a highly interactive science simulation, *Balloons and Static Electricity*, for students who use screen readers where no prior access for these students existed.

To make the sim accessible to screen reader users, we designed, implemented and evaluated a prototype containing a content and interaction layer that represented and described the visual and interactive elements of the sim. This accessible (or inclusive) layer is referred to as the *Parallel DOM (PDOM)* [35] and was designed with a robust HTML structure that is very effective at supporting non-visual exploration and interaction with the sim using a keyboard. All basic static descriptions (descriptions that do not change) were made fully perceivable, operable and understandable to screen reader users. The custom (non-standard) keyboard interaction patterns and hot keys that we designed, once learned, were operable and provided efficient use of the sim. The interactions connected participants' actions with changes in the descriptions of the changing visual representations in the sim allowing screen reader users to explore the sim, ask their questions about static electricity, set tasks for themselves and find answers to their questions.

An initial analysis of our interviews helped us identify what worked well and where we had challenges (see Chapter 3). Through further analysis of our interview data and an examination of our design process for designing descriptions, we were able to create a description strategy framework that can be used in the description design process for other PhET sims (see Chapter 4). This framework may be useful for other highly interactive learning tools and nicely compliments existing guidelines for the verbal description of interactive scientific graphics [20] which we found helpful in our work.

6.1 Contributions

This study has contributed to the three dimensions of inclusive design[47].

1. **Recognize diversity.** All students deserve the chance to learn about science. We focused on the needs of students with vision loss who use screen readers. These students face significant barriers to STEM content that is often highly visual and where real access to lab equipment is often limited or not possible. We made a popular interactive science simulation accessible so that a separate segregated solution is not necessary. By making the sim navigable and usable with the use of a screen reader we have maintained interoperability with a commonly used assistive

technology with which students who are blind are familiar. Access to the sim allows students to explore independently and potentially along side and together with other students using the same sim. The design of the inclusive layer leaves full agency to the student to explore and navigate the sim in a way that works for them.

2. **Inclusive processes and tools.** Along with an accessible prototype, the results of the study offer a description strategy framework that may help others who are working on making interactive learning tools accessible to students who use screen readers.

3. **Broader beneficial impact.** By focusing on the needs of screen reader users we have made the sim fully keyboard accessible. Now that the sim is operable via the keyboard it is also operable with other alternative switch-operated input devices often used by sighted students with dexterity impairments who do not use a mouse. While keyboard access is the obvious curb-cut effect resulting from our design, we suspect that the descriptions we have designed may benefit learners other than those with visual impairments.

6.2 Future Research and Work

While successful in many in ways, we did encounter challenges (discussed in Chapters 3 and 4) that we will address in future work. Some of these challenges include:

- **Completing and implementing complex descriptions for *Balloons and Static Electricity.*** Not all descriptions have been implemented. Based on what we have learned from the evaluation of our implemented, scripted and unscripted live descriptions and the description framework that emerged from our analysis, we can immediately move forward with the completion and implementation of descriptions for this sim. This will include strategic use of interaction alerts that can improve understandability of the current descriptions by reducing repetitiveness (see Chapter 4 for details).

- **Addressing technical challenges.** As described in Chapter 5 standards are evolving, and so is our design for *Balloons and Static Electricity*. A careful review of recent changes to the WAI-ARIA specification will be done in order to see what we can use to improve the Balloon interaction.

- **Providing help in more flexible and findable ways.** We are investigating ways to provide on-demand help for the Balloon interaction and have already improved the discoveraability of the list of keyboard hot keys. When found and accessed, participants found the hot keys useful and employed them.

- **Investigating sonification features.** We found capturing the behaviour of some sim elements in strings of text particularly challenging. For example, velocity changes as a Balloon attracts to the Sweater, and the induced charge effect in the Wall increases as the Balloon approaches the Wall, both involve change over distance and time. Text-based descriptions are best for describing changes that occur in discrete units. This work has identified areas of the design that can be augmented by sonification features (the use of non-speech sound to convey information). Future work will involve exploring which sonification features can enhance meaning and potentially reduce the need for some description.

- **Applying the description framework to other sims.** Work continues to make more PhET sims accessible and we can immediately take what we have leaned from this sim and see how it can be applied to other sims that present similarly complex description problems.

The PhET Interactive Simulation project has long-term goals to transform their growing suite of interactive sims into the most inclusive learning tools possible [35]. Work on this project has contributed significantly to this effort.

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Appendix A: Colophon

This Major Research Project report was typeset using LaTeX, originally developed by Leslie Lamport and based on Donald Knuth's TeX. The above illustration is OCAD University's logo and was created by Bruce Mau Design. In the frame of the logo is a pen sketch of a balloon by Taliesin L. Smith, author of this report. The document template was adjusted from the original to meet OCAD University's Open MRP Guidelines. The body text is set in 12 point Arno Pro, designed by Robert Slimbach in the style of book types from the Aldine Press in Venice, and issued by Adobe in 2007. The original template, which can be used to format a thesis with this look & feel, has been released under the permissive AGPL license, and can be found online at github.com/suchow/Dissertate or from the author at suchow@post.harvard.edu.