Board 202: Assessing the Design of an AR-based Physics Exploratorium

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Introduction

Concepts covered in introductory electricity and magnetism such as electric and magnetic field vectors, solenoids, and electromagnetic waves are difficult concepts for students to visualize. Part of this difficulty may be due to the representation of three-dimensional objects on the two-dimensional planes of course textbooks and classroom whiteboards. The use of two-dimensional platforms limits the visualization of phenomena such as the vector field of a point charge or test charges traveling in the three-dimensional space of an electric field. In addition, working in two dimensions may add to students' difficulties orienting their body correctly to use the right-hand rule when determining the direction of a magnetic field. These difficulties in visualization may limit the conceptual understanding of these fundamental topics.

To promote conceptual understanding of electromagnetism we are cyclically developing and researching three spatial computing 3D environments covering electric fields, magnetic fields and electromagnetic waves. Each environment will be developed and tested in both augmented and virtual reality. The first of our environments, the electric field, has been built and tested in augmented reality (AR) with introductory physics students in the Fall 2023 semester. Our study is currently in phase IV of the National Science Foundation's Design and Development Cycle. Data collected during phase II is being analyzed to support revision to the environment as well as data collection protocols. This article will outline findings from qualitative data gathered during the AR experience as well as during student post interviews following participation in the electric field space. These findings are characterized and then responded to with recommendations for the design team regarding content and testing procedures.

In what follows, we first present a framework listing current knowledge regarding students' difficulties learning electric fields and how these guided our design of this electric field augmented reality environment. We next present themes that emerged from discussions during the experience as well as the post interviews. We conclude with suggestions to inform our second round of environmental design.

Literature Review

The abstract nature of electric fields--and their 2-dimensional representations-- makes forming conceptual understandings very difficult. Thus, it seems logical that students might visualize these ideas using concrete and familiar conceptions. This "confusion by representation," [1], is a cause of student confusion about the characteristics of electric fields. One of the most well-documented examples of this tendency is the finding that students view field lines as physical entities that transport charges [1, 2, 3]. Tornkvist et al. [1], described this as students' tendency to "attach far too much reality to the field lines and often treat them as isolated entities in the Euclidean space". In a similar vein, Picovi and Finley [4], document introductory electromagnetism students treating field lines as distinct physical constructs capable of transporting, containing and interfering with charges. They report that students in their study did not understand that the field line representation is only a sample of an infinite number of field lines. When asked to describe the force acting on a charged particle positioned between two field lines in an electric field students responded that no force would act because there is no field line there [4].

A second challenge for understanding these ideas is that students have difficulty understanding the assumptions inherent in the different representations. In particular, many reports have documented the tendency to conflate field lines, force vectors and trajectories [1, 3, 5]. For example, Tornkvist et al. [1], documented introductory electromagnetism students' belief that force vectors can be drawn with curved arrows as field lines can be curved. They supported this claim by reporting that students had a high tendency to predict the trajectory of a particle with zero initial velocity as erroneously following field lines. This conflation of representations was also evidenced in interviews of students drawing arrows to represent both force and a charge's trajectory [3], and a tendency to explain field lines as the forces a particle would experience.

These two main challenges, constructing models of abstract ideas with real-world referents, and the confusion among properties inherent in standard representations, form the cornerstone of our design and research efforts. However, other reported student difficulties that have also informed our work and research include explaining whether field lines may cross during construction [6, 7]; accounting for multiple charges in the same field [8, 9], and connecting electric field lines' density to the relative magnitude of the field [1, 7, 9, 10]. These findings have led us to pursue the following questions:

1. In what ways do students' descriptions of electric fields after engaging in the AR space differ from previously documented conceptions that rely on two-dimensional constraints?
2. In what ways does exploration in an augmented reality environment support or hinder students' efforts to differentiate the properties of common symbolic representations used in introductory classes?
3. What types of properties or rules did students ascribe to the unique representations in the field they experienced?

Methods

The literature review above mentions studies that were conducted using a wide array of methods ranging from large-scale paper-and-pencil surveys that rely on multiple choice [7], or drawings and open-ended explanations [5, 11], to smaller, more nuanced student interviews where students were asked to draw and explain their thinking [1]. One commonality among these approaches is that they all relied on 2-D representations of 3-D phenomenon. Therefore, our goal was to first design an augmented reality environment that might lead to alternative interpretations and then to examine if some of the same conceptions revealed in prior studies were still evident when students are exploring electric field representations using augmented reality.

We first describe the design of the AR space and the interview setting. We then present findings that emerged from a qualitative analysis of 33 video-recorded and transcribed student experiences and subsequent interviews. We conclude with recommendations for revisions to both the augmented reality space and interview protocol.

The Electric Field Space. The electric field lesson is a 37-screen AR experience. With each screen there is a corresponding slide within the point of view containing informative and/or instructional text. Twenty-five of the slides ask the students a question while the remainder have informative statements or directions to interact with the AR. For example, a slide may ask students to predict the motion of a negative test charge through an electric field. The content starts with point charges and motion of test charges released or launched into their electric fields. The content then builds up to line and planar charges and the movement of test charges launched with initial velocities. Students that work in pairs have their augmented reality experiences synchronized. Advancing slides, selecting predictions, and launching test charges advances the experience for both students simultaneously. The slides can be moved within the screen during the experience by dragging it with the touchscreen. Dragging and dropping slides to new locations within the environment affects the screen of the individual student only.

Research Context and Participants. This project took place within a large, four-year research institution in the southwest US during the Fall 2023 semester. Students from an introductory electricity and magnetism physics course were recruited to participate in an electric field AR lesson in exchange for extra credit. The course is the second in a three-semester series of calculus-based physics courses. Prerequisites are integral calculus as well as the first physics course in the series which covers the fundamentals of mechanics.

Students signed up for one-hour time slots with two students for each slot. There were 40 time slots made available for students to participate over a three-week span. At the outset, all 80 time slots were quickly filled. However, due to attrition, 33 of the 40 scheduled interviews took place. The span of data collection was over three weeks. During each session a research assistant was present to help students navigate technology, answer questions, and conduct post-experience interviews. The sessions took place in a small room on campus with dimensions of approximately 10 feet by 12 feet.

Students were introduced and briefed upon arrival. With a few exceptions, students met for the first time during the briefing process. Each student was given an iPad to participate in the lesson. They were instructed to take turns reading the slides aloud and to follow the directions within. Students are encouraged to think aloud throughout the lesson and communicate with their partner. They are also instructed to work at their own pace. Several students did not attend their sessions and therefore some students participated without a partner. Thirty-three sessions occurred in total with 15 sessions having two participants and 18 of the sessions having one participant for 48 total students. A recording from the point of view of each iPad was taken as well as a wide angle recording from the corner of the room. Time of completion for the experience varied from around 15 up to 40 minutes. At the completion of the lesson students were interviewed regarding their experience. They then completed a task with Likert scale and multiple-choice content questions. The students' discourse during the experience as well as the interviews were transcribed and coded for common themes. The transcriptions form the data corpus of this report.

Results

Q1: In what ways do students' descriptions of electric fields after engaging in the AR space differ from previously documented conceptions that rely on two-dimensional constraints?

Results that align with Q1, conceptions that appear to leverage the 3-D aspect of the experience are grouped into three categories, "Pictures in my head", "Walk around it", and "Real World".

Pictures in My Head. During the post interview students reported that the experience contributed to the "pictures in [their] head." Table 1 exhibits examples of students' responses during the post interview session. This category included comments where students compared their visual images with the animation presented in the experience. Other comments referred to how the experience increased the clarity of their mental imagery.

Walk around it. Repeatedly students mention that they could walk or move around the objects presented in the augmented reality space. Students claimed that being able to move around the objects 'helped [them]", "gave [them] more of a stronger knowledge" and allowed them to "really see like how it like acts." There was no expansion on the statements from students in regard to how, in particular, moving around helped or what knowledge was strengthened.

Real World. Another common theme found throughout the coded interviews is students' reference to the augmented reality experience as the "real world" or "real life." As seen in Table 1 a student states the experience was "a great way to learn how it actually is in the real world." Another student states after the electric field lesson they "can visualize it how it actually would look in real life if it was like totally blown up." In both examples students' statements suggest confusion between reality and the models that represent it.

Table 1 Exhibits student quotes from the post interview relating to Q1.

Category	Example Quotes
Pictures in My Head	• "Seeing this in 3D, really like really helps. It's like oh wow, this is how it's supposed to be. In my mind this is how I saw it. This is awesome. They also see it this way and this is really awesome." • "It's just it's a lot clearer. Like the picture I have in my head is very vivid now just because of going through this whole session." • "I think it's helpful to see and like understand because now I can see like the pictures in my head. So it'll help me remember better. Like where the lines for the electric field go." • "Like, yeah, obviously I only have it in my head, like in class. So I think being able to like actually, like put it into like my, like in front of me, like literally right in front of me like that. Like expanding my imagination of it like, tenfold."

Walk Around It	● "I think it was dope. I'm like a visual learner. So like just seeing like a 3D model, like where everything's going and I was able to walk around like it gave me more of a stronger knowledge, only how the e-fields, work." ● "I find it useful because I feel like it's hard to draw an electric field, like just on paper. It's like being able to, like, really move around, helped me." ● "I also, like, like when you walk around it, you can see how it's different. Like, especially for the line charges. Like you can really see like how it like acts."
Real World	● "I think it's a great way to learn how it actually is in the real world. If you're looking at a textbook, you might think it's just in two dimensions or you might get confused" ● "I can visualize it how it actually would look in real life if it was like totally blown up."

Q2: In what ways does exploration in an augmented reality environment support or hinder students' efforts to differentiate the properties of common symbolic representations used in introductory classes?

Students' comments relating to Q2 indicate mixed results. Some students were able to better understand the properties ascribed to vectors and field lines while others reported interpretations similar to those found in research from 2-D representations. A common theme throughout the post-experience interviews was that the experience made them realize that the vector fields point in all directions. Students mentioned the experience allowed them to imagine the electric field vectors "pointing out in like an infinite amount of directions" and brought them to the realization that "There's like, other ways to go" when drawing vector arrows. A student mentions that previously they "thought there was space in between each one" referring to electric fields. For these students the electric field representation supported the realization that the electric field exists at all points. Table 2 exhibits examples of quotes from students relaying understanding of the completeness of an electric field.

Despite statements from students that the electric field experience supported the realization that the electric field does exist at all points in space, a subset of students took the field line placement as literal. Consistent with findings from Picovi and Finley [4], students in this subset comments reveal conceptions that the test charges would not be affected by an electric field if it was released between field lines. This conception was particularly evident in slide sequence 27-28. Within this sequence students are shown an infinite line of charge. The line of charge is represented by a red cylinder with four white plus signs. A line of spaced red disks with the same radius as the cylinder radiates from either side, implying the continuation of the charged line. Ten sets of orthogonal field lines radiate from the red cylinder at regular intervals. Students are prompted to choose between three green lines representing possible trajectories of a positive test particle released above the line of charge with an initial velocity parallel to the line of charge. While the majority of students correctly predicted a forward and upward trajectory for the test charge, some proposed that the test charge could pass by the field lines and not be affected by them. One student explicitly verbalized the difficulty interpreting a sample of field lines for the infinite line of charge as a field existing at all points in space. The student states that the representation caused them to pause because "the charges were drawn to where it's like only going in five or six maybe directions. But in reality it's like a whole field. So it just kind of confused me for a moment." Another student did not trust their intuition regarding the representation of the field lines. Although they initially interpreted the field lines pointing in every direction, they predicted the trajectory of the test charge incorrectly with the explanation "because like the electric field is pointing in every direction could be wrong. So I'm just going to say it will move straight ahead, pass this cylindrical charge." Other students predict the trajectory of a test charge correctly with the problematic explanation that they "can see for that arrow, it's still going to conflict" implying a conception that the field does not exist in all space.

Furthermore, a student noted an inconsistency in the written and visual language of the infinite line of charge and questioned the representation. In slide 26 the text on the slide refers to the image as an infinite line of charge. Students are then prompted to choose a trajectory for a given positive test charge launched with an initial velocity in Slide 27. The language on the selections, however, refer to a cylindrical charge, not an infinite line of charge. "it was shaped like a cylinder, but it said line charge in the first thing, line of charge, and then cylindrical and then next slides, which was kind of confusing, but I mean, yeah, cause like if it has a volume, if it has height, then it will be cylindrical. But then that's different from the line charge."

Hinderances in the AR Environment. Our analysis also revealed three main aspects of the environment that may have hindered students' experiences. The first was regarding the slides within the AR experience. Students complained that the slide placement was "a little bit funky", sometimes blocked the electron, and challenging to move. The second area of criticism from the students was the lack of resolution for some questions. "And then if I get a question wrong, just maybe elaborate why it's wrong or like, why that's the right answer". There was also a request to explain the connection between the lesson and the Van De Graph generator that is the last visual of the experience. The student explained "I don't necessarily know, like whats going on with that." Finally, two students complained of the weight of the iPads, commenting that holding it for the duration of the experience made them tired.

Table 2 Exhibits student quotes related to Q2.

Category	Example Quotes
Vector Representation	• "when I think of an electric field now, I can visualize it a lot better than I was before because I can now imagine, like all the different like electric field vectors pointing out in like an infinite amount of directions." • "in class, we just draw arrows and we're like, All right, whatever. It goes that way. I guess, like now that I saw that, like, it can go like that way, that way, that way, that way. I'm just like, Oh, s***[sic]. There's like, other ways to go." • "like before this lesson, like, I didn't realize that, like, I guess in this, like, never thought about how, like, electric fields point, like, in every single direction. I thought there was space in between each one." • "Yeah, I was, I was a little bit confused about like, how it all jutted out of, like, objects. This made it more clear exactly how it's happening."

Q3: What types of properties or rules did students ascribe to the unique representations in the field they experienced?

One of the challenges of creating novel AR environments is designing effective 3-D representations. Designers wrestle with questions such as *should we use textbook conventions with 3-D enhancements, or leverage affordances of 3-D environments that incur the construction of new interpretations?* Our current approach is to choose the former and this analysis provides support for this choice. That is, students' responses can be interpreted to suggest that the conventions used in the AR environment helped confirm their understanding of the properties suggested in the 2-D representations.

Students appeared to enter the experience with the general understanding that opposite forces attract, while like-charges repel. This fundamental understanding led some students to more fully interpret the convention that arrows point away from positive point charges and point towards negative charges. We plan to follow up with this hypothesis in the next round of interviews by asking students to use paper arrows and styrofoam balls to indicate charge polarity in before- and after-interviews.

A second example of understanding of representational conventions that appeared to emerge is the use of color gradations and vector sizes to indicate relative strength of the electric field of a point charge. In slide 8, the red sphere of positive fixed charge becomes larger, and the field lines become longer than in slide 7. The text on slide 8 asks the students what this change represents and if they notice anything else. Students often responded that the electric field had become "stronger" or "bigger." Students described the field lines as "arrows", "rays", "lines", "the field", "spikes", "vectors", and "stringy things that are coming out." The change in the field lines was characterized as "bigger", "more pronounced", "longer", and "greater." Slide 9 the representation of a positive charge goes back to original size before subsequently becoming smaller in slide 10. The text of slide 10 asks if the field strength is stronger or weaker than the field in slide 9 and how could they tell. The students responded weaker because "it's more condensed", "all the arrows don't point out as great", "the arrows kind of pulled in", and "the arrows got smaller." In sum, these findings point to the mismatch between what instructors assume students ascribe to representations and what they may interpret. This suggests that the design of the environments must be consistent with the textbook representations but leveraged to enhance students' proclivity to notice the implications of the ideas.

Recommendations

This work is divided among two teams: an educational design research group and a technical development group. This section suggests four recommendations for design and two for development, and one for the intersection of the two teams regarding the fundamental idea of representations of lines in 3-D space. This analysis has revealed many potential avenues for further study. Each of these will require more nuanced, follow-up questions to probe deeper into students' thinking during the post interview. It is not enough for students to verbalize "seeing this in 3D" or "being able to, like, really move around" helped them. We want to know *how* it helps them. What was it about moving around that changed their thinking? Future interview protocols will include a pre and post interview regarding electric fields of a point charge and research assistants will probe deeper into student thought with advancing how and why questions.

There are several recommendations regarding the AR environment interface. It is recommended that the physical device used be reconsidered. As several students complained of fatigue from the weight of the larger iPad that many needed both hands to support. This may also inhibit the use of gestures. Therefore, the use of smaller iPads or even cellular phones might alleviate this. In addition, the Altoura(c) platform enables the use of virtual reality headsets so future iterations of interviews might free students' use of more gestures. It is recommended that the design team consider solutions for slide positioning. The largest quantity of complaints from the students were regarding the slides being positioned poorly and awkward to move. Dealing with the slides hinders the students' focus on the material and may reduce learning.

The first recommendation for the educational content team is to define test particles when they are first encountered in the electric field experience. Although the number was low, a few students did expect the point charge to move instead of the test particle. Test particles are still new concepts for introductory physics students and familiarity with them should not be assumed. A second educational content recommendation is to consider the possibility of altering the space to allow students to select the sign, position, and initial velocity of the test charge in a field space. This will provide more autonomy for students to investigate individual curiosities and reinforce concepts within the AR space. In addition, results indicate that directions could be more explicit regarding the reasons behind motion of test particles, naming relationships such as Gauss' Law, and explaining connections between the physics concepts and real-world objects such as the Van De Graph Generator. This will help to provide resolution to questions that otherwise leave students wondering. The fourth recommendation for the educational design team is to explicitly remind the students to move around the space in the slide directions. Students are used to staying in one place during instruction and they tend to stay stationary unless reminded to change perspectives.

A final recommendation is directed at the intersection of these two teams. Both educators and programmers need to revisit the representation and language used during the infinite line of charge representation. Although most of the students understood that the field lines point orthogonally in all directions, there was still some confusion among several students. As Gire and Price [6] note, although the electric field exists everywhere, representation requires a sampling of the field for practical reasons. This will lead both teams to consider questions such as: *Is there another sampling scheme that would better relay the notion of a complete field to the students? What is an effective way to represent a line that exists in 3-D space if not using a cylinder?* As the student pointed out, "if it has a volume, if it has height, then it will be cylindrical. But then that's different from the line charge." If such a change is made, the design team will have to revisit the language used and consider replacing any mention of "cylindrical charge" with "line of charge" to reinforce the representation. These questions drive our further research.

Conclusion

The purpose of this project is to support conceptual understanding of introductory physics concepts such as electric fields. This preliminary exploration of students' responses to the electric field AR experience provided insight into the interpretation of visual representations of concepts such as point charges, field lines, trajectories, and infinite lines of charge. In the post interviews analyzed here, students often struggled to describe exactly how the experience shifted their conceptions of electric field spaces that were based on the 2D constraints of conventional learning platforms. They could not verbalize how their understanding changed, and instead gave somewhat superficial responses such as "better" and "clearer pictures" in their head due to the benefit of walking around and seeing it in real life. Although we believe that the 3D environment of the AR experience supported student understanding of the completeness of field lines, we have realized that a baseline measure of their understanding is needed to confirm their conceptual changes.

The results raised further questions such as how to best represent 1 dimensional objects such as a line, in this 3 dimensional space. Furthermore, questions arose regarding how technology such as this can best be deployed. Navigating the environment including the slides on the touchscreen and holding a sometimes heavy iPad during the experience may deter focus on content and hinder learning. Students came into the experience with previous knowledge regarding electric fields and point charges. This previous knowledge supported the students' investigation of the electric field environment. Coupled with the 3D affordances of the AR experience students created rules and properties of the representations such as longer vectors indicating stronger fields. As previous knowledge gained through 2D representations supported students' interpretation of this 3D space, it is our hope that reciprocally the knowledge gained through these 3D interactions supports students' understanding and interpretation of the 2D representations encountered in the classroom. Investigations to come will provide further insights into the benefits of these 3D environments.

Future Analyses. In response to recommendations from the fall 2023 testing of the electric field experience described here, a new interview protocol was deployed in spring 2024 that included a novel approach for determining students' baseline understandings of theoretical physics objects in space. In part one, the students are asked about their understanding of 2D representations found in typical physics textbooks. Students are shown a paper with two representations of electric fields of a positive point charge hung at eye level on a corkboard. The two images both represent an electric field, but one features vectors that decrease in size as the distance from the charge increases, while the second uses field lines. Students asked to draw any conclusions about the images based on their familiarity and knowledge of these common representations.

Part two of the interview is designed to establish a baseline understanding of students' conceptions of these objects in 3-D space. They are shown several 3-D props hanging on the wall and asked to use any they like to model the same idea as that shown in the images discussed in part one. The props include styrofoam balls glued on wooden dowels to represent point charges. The balls were painted either red or blue and adorned with + or - signs in black ink to indicate positive or negative charges respectively. In addition, yellow arrows of varying sizes were cut out of paper and glued on chopsticks. The yellow arrows were purposely hung on the cork board in no order. The interviewer presents the crafted red positive charge to the students and asks them to represent the electric field of the object using their hands and/or the arrows available. The goal here is to collect data on their understanding of the 3-D nature of the fields which they have only ever seen in 2-D at this point. The interviewer then replaces the red ball with the plus signs with the blue ball with the negative signs. The students are asked if they would change anything with the new prop in place. Following the electric field lesson and several post interview questions, the students are again asked to represent the electric field of a point charge in 3D space. The videos of pre and post interviews are going to be coded for both verbal and visual communication by the students of their understanding. Of particular interest are any differences in understanding that may occur between the pre and post interview questions that provide insights into shifts in understanding of electric field from a point charge.

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