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Virtual Reality Laboratory Experiences for Electricity and Magnetism Courses

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Abstract

A solid understanding of electromagnetic (E&M) theory is key to the education of electrical engineering students. However, these concepts are notoriously challenging for students to learn due to the difficulty in grasping abstract concepts such as the electric force as an invisible force that is acting at a distance, or how electromagnetic radiation is permeating and propagating in space. Building physical intuition to manipulate these abstractions requires means to visualize them in a three-dimensional space. This project involves the development of 3D visualizations of abstract E&M concepts in Virtual Reality (VR) in an immersive, exploratory, and engaging environment.

VR provides the means of exploration, constructing visuals and manipulable objects to represent knowledge. This leads to a constructivist way of learning, in the sense that students are allowed to build their own knowledge from meaningful experiences. In addition, the VR labs replace the cost of hands-on labs, by recreating the experiments and experiences on Virtual Reality platforms.

The development of the VR labs for E&M courses involves four distinct phases: (I) Experiment Design, (II) Experience Design, (III) Software Development, and (IV) User Testing. During phase I, the learning goals and possible outcomes are clearly defined, providing context for the VR laboratory experience, and identifying possible technical constraints pertaining to the specific laboratory exercise. During stage II, the environment (the world) the player (user) will experience is designed, along with the foundational elements, such as ways of navigation, key actions, and immersion elements. During stage III, the software is generated as part of the course projects for the Virtual Reality course taught in the Computer Science Department at the same university, or as part of independent research projects involving electrical and computer engineering students. This reflects the strong educational impact of this project, as it allows students to contribute to the educational experiences of their peers. During phase IV, the VR experiences are played by different types of audiences that fit the player type. The team collects feedback and, if needed, implements changes.

The pilot VR Lab, introduced as an additional instructional tool for the E&M course during Fall 2019 and Spring 2020, engaged over 100 students in the program, where in addition to the regular lectures, students attended one hour per week in the E&M VR lab. Student competencies around conceptual understanding of electromagnetism topics are measured via formative and summative assessments. To evaluate the effectiveness of VR learning, each lab is followed by a 10-minute

multiple-choice test, designed to measure conceptual understanding of the various topics, rather than the ability to simply manipulate equations.

This paper discusses the implementation and the pedagogy of the Virtual Reality laboratory experiences to visualize concepts in E&M theory, with examples for specific labs, as well as challenges and student feedback with the new approach. We will also discuss the integration of the 3D visualizations into lab exercises, and the design of the student assessment tools used to assess the knowledge gain when the VR technology is employed.

Introduction

Concepts in electricity and magnetism (E&M) are notoriously challenging for students to learn[1], due to the difficulty in grasping abstract concepts such as the electric force as an invisible force that is acting at a distance, or how electromagnetic radiation is permeating and propagating in physical space. The sources of these difficulties are a lack of intuitive familiarity with the phenomena, physical principles and mathematical relations, and the three-dimensional (3D) nature of the concepts that do not translate well to two-dimensional platforms. Building physical intuition to manipulate these abstractions requires means to visualize electromagnetism concepts in a three-dimensional space, which is key to building strong theoretical foundations. This project involves the development of 3D visualizations of abstract physics concepts in Virtual Reality (VR), in an **immersive, exploratory, and engaging environment**, curating customized experiences for learners that would pave their paths to a firm knowledge of physical principles, coupled with a strong critical-thinking proficiency.

Why Virtual Reality?

Today's engineer is expected to possess 21st century skills such as creativity, critical thinking, and technological literacy. However, teaching these skills in a traditional classroom setting, in which instruction relies primarily on transmissionist methods such as blackboard lectures, is becoming increasingly ineffective. When the transfer of knowledge is isolated from context, it causes students to becomes passive and disengaged, as many struggle to see the relevance of a theoretical course in a "real life" context[3]. The majority of teens and young adults are online daily, playing video games, interacting with various social media platforms, and participating in technology-mediated experiences[4], which

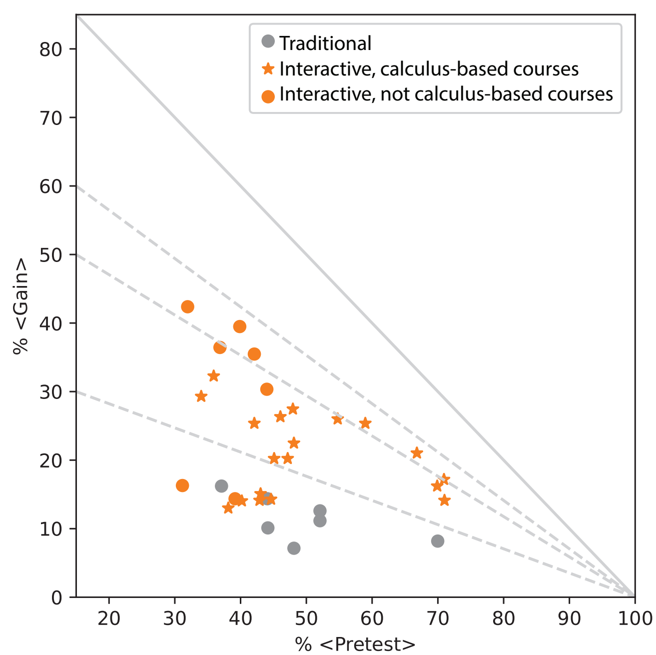

Figure 1: %Gain vs % Pretest scores for 16 college courses enrolling a total of 597 students. Figure digitized and adapted from Hake[2] (Figure 3(c)).

makes them accustomed to learning environments that are diverging from the traditional way of learning. These findings suggest that a shift in the way teaching is done now might be necessary. For instance, efforts to reform introductory physics instruction, augmented by cognitive science and research in physics education, have shown that knowledge retention increases dramatically when interactive-engagement teaching methods are employed, as compared to traditional teaching methods that primarily rely on passive-student lectures, recipe labs, and algorithmic-problem exams[2]. Figure 1 shows that retention increases from $\sim 20\%$ in the traditional method case to $\sim 50\%$ when interactive engagement methods are used.

The way we teach has evolved over time, from a time when teaching was done in a "one size fits all", which is known as the **Industrial Revolution Model**, to when the amount of information that was transferred was prioritized, and this is referred to as the **Information Age**, to recently, when technology provides alternative way of learning by immersion (see Figure 2). The last learning model is known as the **Experience Age**. In this experience age, the joy of exploration and discovery through Virtual Reality experiences could act as a very powerful motivator for learning, and can guide students to develop both rigor and problem-solving skills, and thus empowering them to become independent learners.

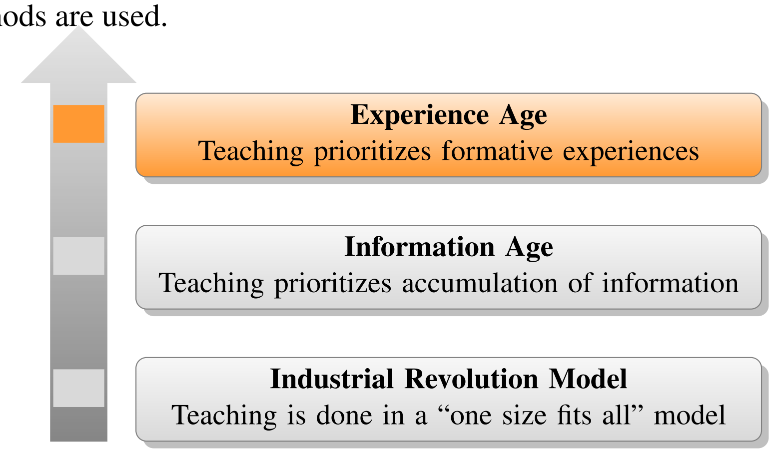

Figure 2: Learning Models

Virtual Reality provides a disruptive platform for teaching and learning, in an immersive, realistic and, most importantly, interactive three-dimensional environment. There are many advantages for using VR as an immersive teaching tool, as it has the potential of addressing many challenges traditional teaching usually faces, and can lead to increased student engagement while removing some of the anxiety students experience in active learning environments[5].

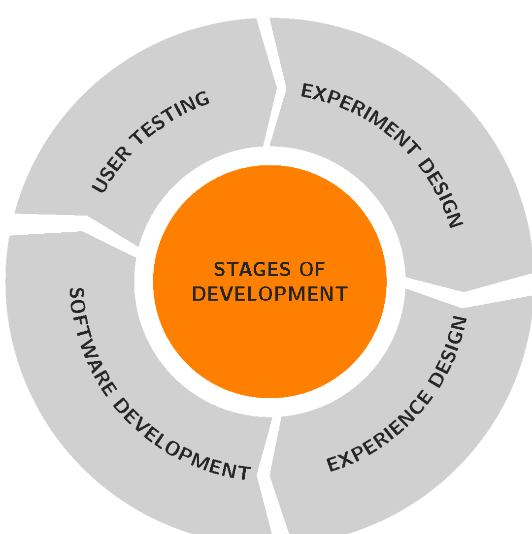

Figure 3: Stages of development for the Virtual Reality experiences.

Virtual reality provides the means of exploration, to construct visuals and manipulable objects to represent knowledge. This leads to a constructivist way of learning, in the sense that students are allowed to build their own knowledge from meaningful experiences. In this project, we use the VR technology to visualize difficult E&M concepts, which in turn affords creativity and provides experiences that impact student identity. In addition, the VR labs replace the cost of hands-on labs, by recreating the experiments and experiences on virtual reality platforms.

Development of the VR Experiences for E&M Courses

The VR labs for visualizing concepts pertaining to E&M theory are currently under development. The software development involves four distinct phases, as illustrated in Figure 3. A detailed description of the development stages is provided in Table 1.

STAGES	DESCRIPTION	STUDENT INVOLVEMENT
Experiment Design	• Involves the design of the physics experiment. • Learning goals and the possible outcomes are clearly defined, to help provide context for the VR experience, and discovery. • Determine what are/could be some of the technical constraints pertaining to the specific laboratory exercise. • The team documents the plan and the lab design, as well as the assessment task that is aligned with the lab's instruction.	✗
Experience Design	• The team designs the environment (the world) the player (user) will experience. • Foundational elements, such as ways of navigation, key actions in the experience, are defined. • Key considerations are given for the user experience, the user types, and relevant immersion elements.	✓
Software Development	• The experiences for the E&M course are generated by **engineering undergraduate students**, either as part of course projects for the Virtual Reality course taught in the Computer Science Department at the same university, or by electrical and computer engineering students for research experience under the PI's guidance. • This reflects the strong educational impact of this project, as it allows **students to contribute to the educational experiences of their peers**. • Students are trained to develop reusable modular code, following software development standards aligned with industry standards, which can be easily ported to the development of a different VR laboratory exercise.	✓
User Testing	• The VR experience is played by different types of audiences that fit the player type. • The team collects feedback and, if needed, implements changes.	✓

Table 1: Description of activities during each of the Development Stages.

Example Laboratory Exercise in Virtual Reality: Gauss' Law

A snapshot from the "Gauss' Law" laboratory scene is presented in Figure 4. The laboratory experience is set in a space that is meant to resemble Gauss' office in Göttingen, Germany. This *fantasy* room is decorated with period objects that "hide" quiz questions and information regarding Gauss' scientific legacy. The set is designed to intrigue and enhance student participation, and the experience gamification is intended to maximize the time students spend inside the VR exercise, to learn and engage with the experiment.

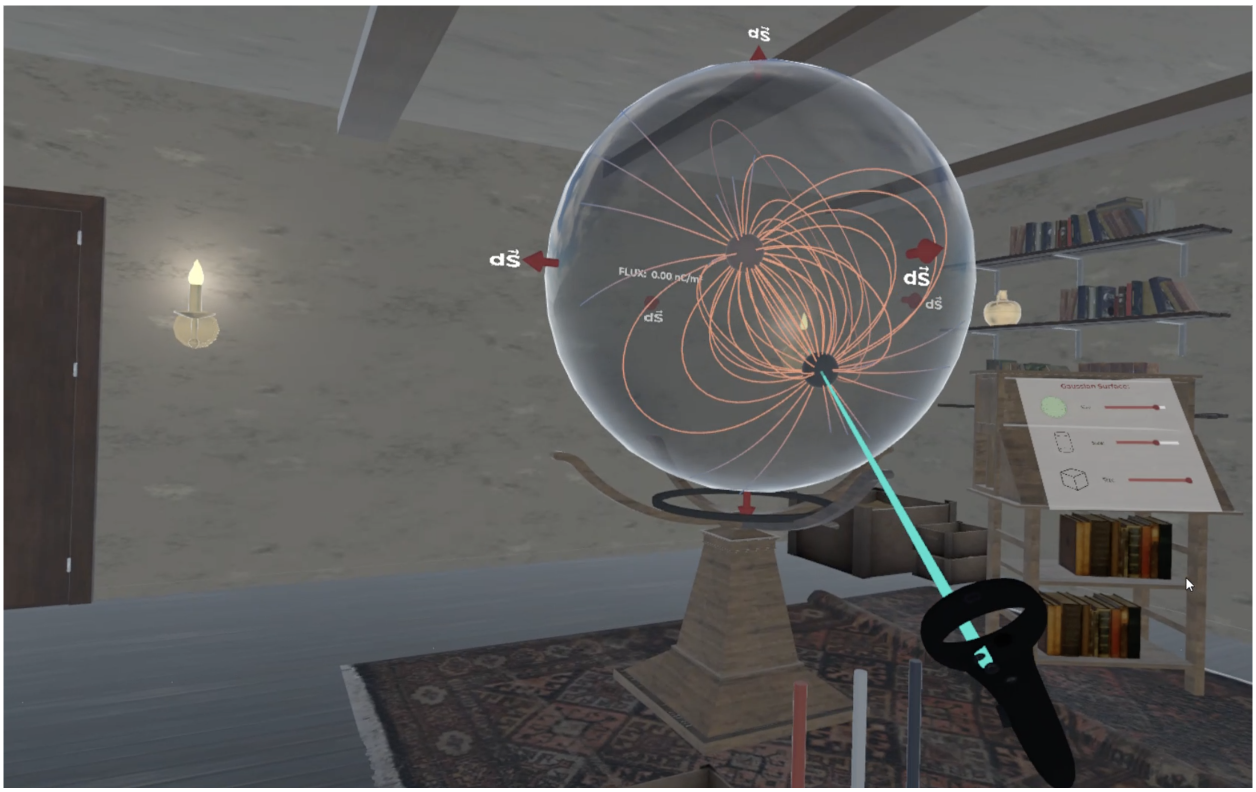

Figure 4: Scene from the VR "Gauss' Law" exercise illustrating the visualization of an electric dipole and the calculation of electric flux through a spherical Gaussian surface. The unit surface elements $d\mathbf{S}$ are also shown.

This VR-based experiment was designed to not only allow students to view the three-dimensional nature of electric fields and Gaussian surfaces from multiple perspectives, but also to allow students to interact with these phenomena. Specifically, in this lab students can:

(i) create a variety of charges of various polarities;

(ii) visualize the resulting electric fields from individual static charges, or from the distribution of charges;

(iii) calculate the electric flux through various Gaussian surfaces (rectangular box, sphere, cylinder);

(iv) build their own experiments and visualize in real time how changes in the charge

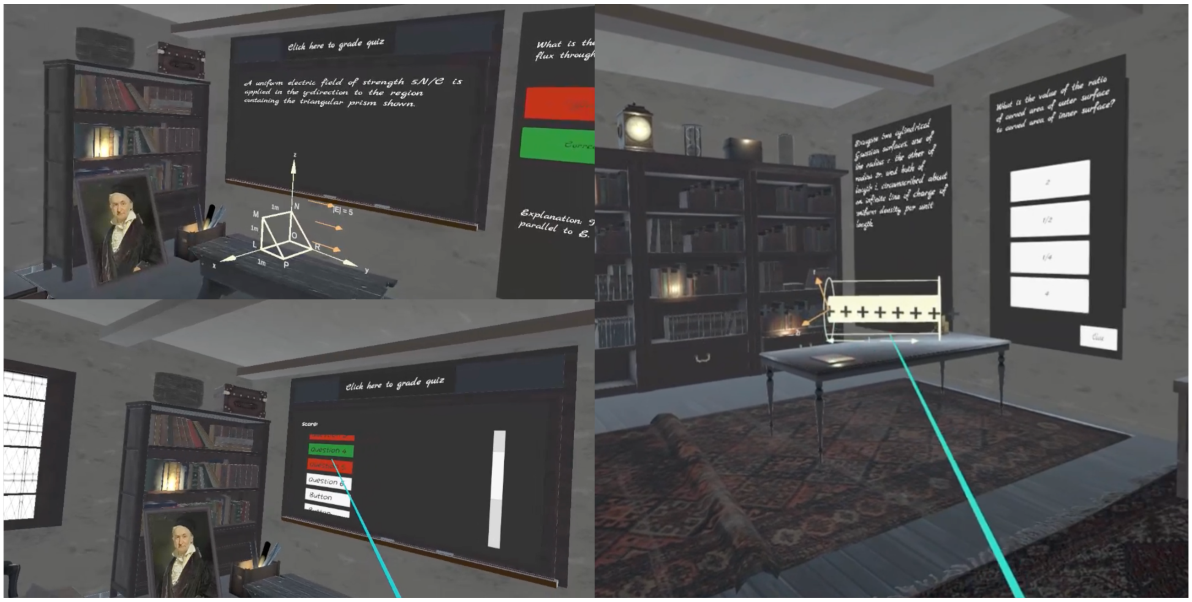

Figure 5: Sample multiple choice conceptual questions from the Quiz accompanying Gauss' Law lab inside the VR experience.

distribution alter the superposed field;

(v) explore the laboratory space and discover "Did You Know" facts that provide context for the lesson, and for the scientific discovery;

(vi) answer conceptual questions centered on the lab's instruction. Students are not only allowed, but encouraged to play with the experiment, to build their own experiment that will help them discover the answer to the quiz questions.

Figure 5 shows conceptual questions that were administered part of the VR lab, and grading and explanations are provided at the end of the testing period.

In addition, the team is planning the development of software that will track student behavior inside the VR experience in order to assess where and how time is spent inside the lab experience, which will lead to a better understanding of how learning is done.

VR Labs Under Development

We have started the development of VR Laboratory Experiences for Electromagnetism in Spring 2019, and since then we have completed the development of 9 Virtual Reality Lab experiences for the electricity and magnetism course. In addition to "Gauss' Law" lab described above, we have developed the following experiences, designed to enhance student's understanding of electromagnetism concepts. Snapshots from each experience are presented in Figure 6.

a. Introduction Module As with any video game, we designed a startup scene of the Virtual Reality Laboratory, which is set in a gallery-like space, where artwork such as portraits of physicists like Gauss and Coulomb provide the gateway to the VR experience, but also some

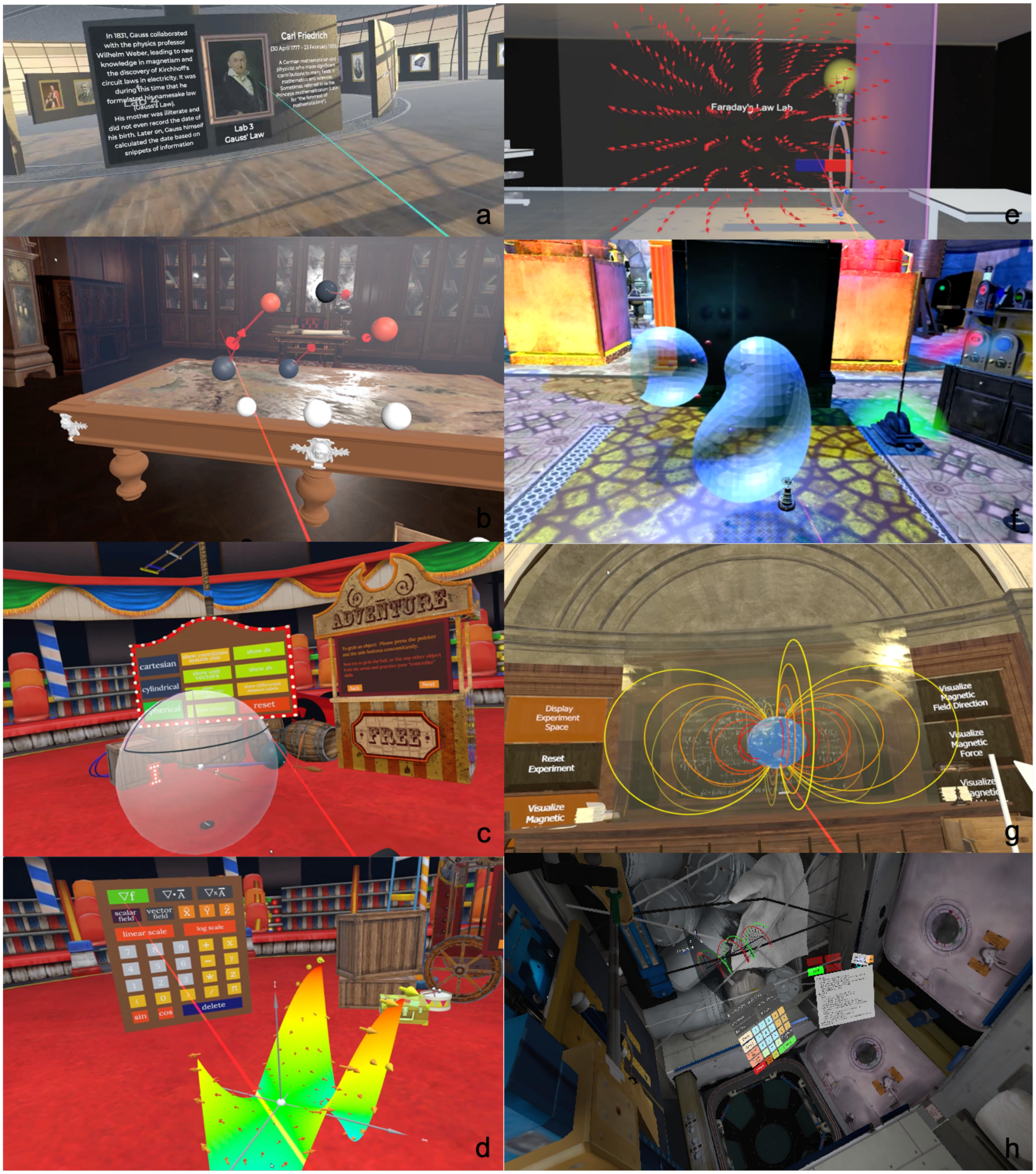

Figure 6: Snapshots of scenes from 8 VR experiences that were used for instruction during the Spring 2020 and Spring 2021 semester: a) Introduction Module, b) Coulomb's Law, c) Math Module: Coordinate Transformations, d) Math Module:Vector Calculus, e) Faraday's Law, f) Electrostatic Potential, g) Ampere's Law, h) Wave Polarization.

historical context. Also, within this module, an introduction to the course is provided, together with a tutorial on the use of the VR equipment.

b. Coulomb's Law In this lab students can visualize the direction and magnitude of electrical forces between various charged objects of different polarities, as they are being moved within a specified space.

c. Math Module: Coordinate Transformations We have developed a VR lab to visualize concepts pertaining to coordinate transformations and visualization of surface and volume elements in different coordinate systems. This lab facilitates understanding of these abstract mathematical concepts, which are central to most physics and engineering courses.

d. Math Module: Vector Calculus In this VR lab, students can visualize concepts pertaining to elements of vector calculus. Students encounter difficulties understanding the nature of operators such the gradient, curl and divergence. This lab facilitates understanding of these abstract mathematical concepts, which are central to most physics and engineering courses.

e. Faraday's Law This lab was designed to illustrate both Faraday's and Lentz's Laws. Students can visualize the direction of the current induced in a loop due to changes in the local magnetic field, as well as the magnitude and direction of the resulting electric field.

f. Electrostatic Potential This VR experience allows students to visualize the electric potential due to any configuration of electrical charges.

g. Ampere's Law In this VR lab, students can visualize the magnetic field due to infinitely long current wires, loops of current, current sheets, solenoids, and the terrestrial magnetic field.

h. Wave Polarization This VR experience is built to allow users to create "their own wave", using an easy to use interface, and visualize the propagation and also the polarization properties of the said wave.

Please note that while all the VR labs developed so far could be and have been used for instruction, the team continues to work on the gamification aspect of each of the lab, and implement changes and improvements based on the students' feedback.

Assessment

The **pilot VR Lab** was introduced as an additional instructional tool for the E&M course during the Fall 2019 semester, and continued (partially) during Spring 2020 semester. Over 100 students were enrolled in the VR section during these semesters. In addition to the regular lectures, students attended one hour per week in the E&M VR lab with TA instruction, but were granted access 24/7 to the space. During the instruction lab period, students worked in teams of two or three, and at the end of the laboratory session, they completed a quiz of the type described above, while allowed to go back to the VR experience for guidance. We did not however track the use of the space outside of class period, but is is something we will consider starting Fall 2021 semester.

At the end of the Spring 2020 semester we interviewed students on their perception of efficacy of the VR experiences for learning. Due to the global pandemic, only 2 students participated in the interviews, which were conducted via Zoom. Students indicated that they really liked the VR lab and that they thought it was a great addition to the electromagnetism course. They indicated that the VR labs really helped with their conceptual understanding of electromagnetism, and helped them answer conceptual questions in the exams, but did not help with math-based questions. Both students reported that the use of controllers were confusing at times (a problem the developers were aware of, and continue to work on and improve). Another important issue that was raised was the limited amount of time (1 hour) that was available to complete all tasks in the lab period.

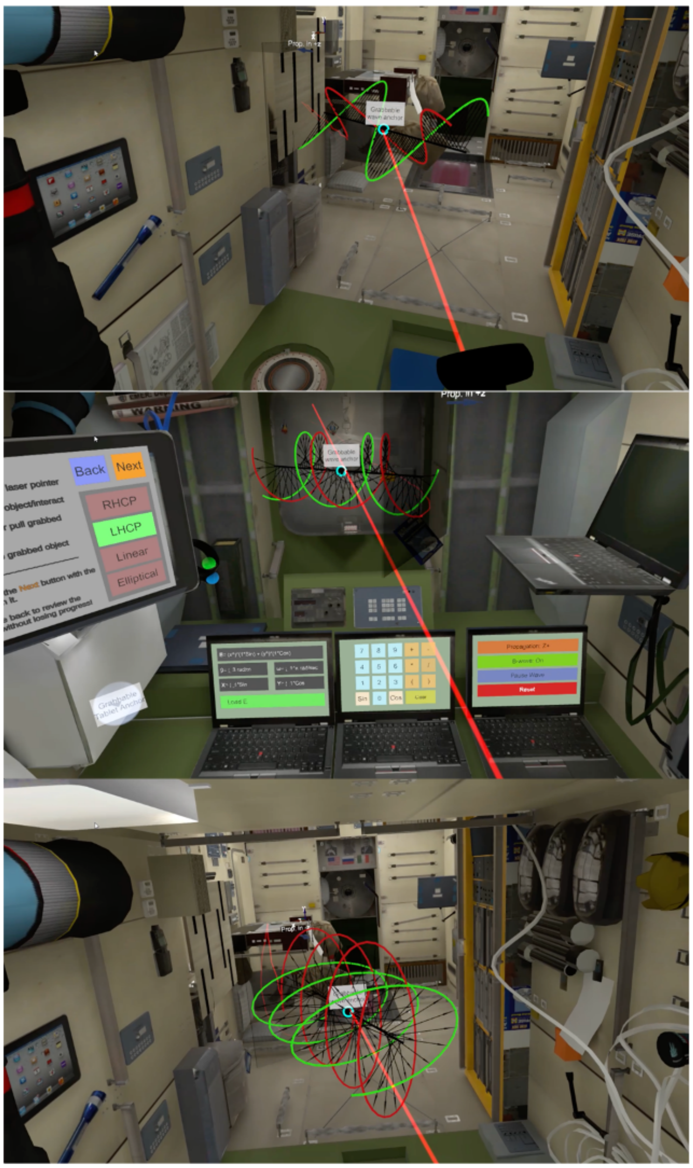

Figure 7: Snapshots from the Wave Polarization VR Lab showing and example of a linearly polarized wave (top), circularly polarized wave (center), and elliptically polarized wave (bottom).

During the Spring 2021 semester, student competencies around conceptual understanding of electromagnetism topics, as well as their understanding of mathematical concepts, will be measured via formative and summative assessments. To evaluate the effectiveness of VR learning, each VR experience will be followed by a short 10-minute multiple choice test. Questions are designed to primarily measure conceptual understanding of the various topics, rather than measuring the ability to simply manipulate equations, and are tied to the specific contexts and topics of that lab's instruction. This will help inform the research team of how well the visualizations are working, and provide more timely feedback on instruction throughout the semester. After the development of the VR labs is completed (anticipated in Spring 2022 or earlier), a pre- and post-test survey adapted from *Conceptual Survey of Electricity and Magnetism (CSEM)*[1] will be used to summatively measure the knowledge gain on general conceptual learning of electromagnetism topics throughout the semester.

Figure 7 shows snapshots from the Wave Polarization VR lab where students can visualize the electric and/or magnetic field of various wave-forms as they propagate in space, and are able to assess the wave polarization for each case by visualizing the trace of the electric field vector on a plane perpendicular to the direction of the wave propagation. The Wave Polarization Lab is set on the International Space Station, in an effort to provide students context and "real life" examples of application of the concepts covered in the lab. The VR experience starts with several guided exercises that use pre-coded wave-forms, where the polarization concept is demonstrated. After completion of said exercises, students can use an interface to *build their own wave*, alter the wave number and frequency, as well as direction of propagation. The lab is followed by a quiz where students are asked to:

- Construct a linearly polarized wave and provide the instantaneous and the phasor form for the electric and magnetic field.
- Construct a right hand circularly polarized (RHCP) wave and provide the instantaneous and the phasor form for the electric and magnetic field.
- Construct a left hand circularly polarized (LHCP) wave and provide the instantaneous and the phasor form for the electric and magnetic field.
- Construct a left hand elliptically polarized wave and provide the instantaneous and the phasor form for the electric and magnetic field.
- Construct a right hand elliptically polarized wave and provide the instantaneous and the phasor form for the electric and magnetic field.
- Alter the magnitude of ω and β in the VR lab experiment. What is the impact to the wave propagation when you change ω and β to different values?

A preliminary survey was distributed to eight students who are currently enrolled in the E&M course and the VR lab, and completed the Wave Polarization VR experiment, and 5 students responded. Students rated the degree to which this VR lab helped their understating of wave polarization concepts, using a scale of 1 (Strongly Disagree) to 5 (Strongly Agree). Survey questions and results are presented in Table 2.

Survey Question	**Average**	**Std. Dev**
After completing the Wave Polarization VR Lab, I think I acquired a good understanding of the linear polarization concept.	4.8	0.4
After completing the Wave Polarization VR Lab, I think I acquired a good understanding of the circular polarization concept.	4.6	0.49
After completing the Wave Polarization VR Lab, I think I acquired a good understanding of the elliptical polarization concept.	4.6	0.49
Visualizing the changing electric and magnetic field as the wave propagates helped me better understand the concept of wave polarization.	4.6	0.8
The VR environment enhanced your learning experience of wave polarization.	4.4	0.8
Did it help to see the Wave Polarization experiment in 3D?	4.2	0.98
The Wave Polarization VR lab helped you answer the quiz questions.	4.4	1.2

Table 2: Students' Assessment of Wave Polarization VR Lab Experiment Effectiveness in Meeting Learning Objectives.

The team will collect data on the design process for the VR-based visualizations and their integration into the curriculum of the undergraduate science and engineering courses. We will analyze the data on the pre/post assessment of students' conceptual knowledge in the VR-based condition compared to test outcomes of students' that did not use the VR-based visualizations. We will also conduct interviews with students that participated in the VR labs to understand more about their uses of the visualizations and implications for our design decisions.

Figure 8: E&M VR lab during instruction.

Equipment

The E&M VR Lab consists of 10 stations equipped with gaming grade GPUs and Oculus Rift S headsets. While the cost of each station is relatively high (∼$3000 for the GPU and $400 for the headset), these stations are used both for the software development and for instruction. After the development of all VR labs is completed, the software will be made freely available and ported to un-tethered headsets, such as the Oculus Quest, which does not require a GPU machine, therefore reducing the cost of operation to the headset's cost only ($500). Figure 8 shows students in the enrolled in the E&M VR section participating on "Gauss' Law" VR experience.

Summary

Virtual reality (VR) simulations and learning environments can support student learning in many ways, based on the various affordances of the VR technology[6]. One of the affordances is that the immersive nature of VR can facilitate the use of multiple perspectives from which the student can view an object or scene. This is aligned with the fact that nowadays, the primary cognitive channels for young adults are audio and video only.

For E&M fields and related phenomena, that are three-dimensional in nature, this multiple-perspective-taking and immersion that VR allows can aid students in better understanding EM fields, charge distributions, charged surfaces, and the behavior of charged particles in these various spaces. The team is working on implementing assessment based on student interviews and outcomes analysis of in-lab quizzes. This project seeks to build a learning infrastructure to be adopted by physics and engineering departments across the country.

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