Visualizing Fundamentals of Electric and Magnetic Fields in Virtual Reality

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1 Introduction

In the first half of the 19th century, Michael Faraday studied electricity and magnetism. He hypothesized that a changing magnetic field can generate a current. He tested his hypothesis by conducting numerous experiments, most notably the coil and magnet experiment. He created a coil by wrapping a paper cylinder with wire, connected the coil to a galvanometer, and moved a magnet back and forth inside the coil. He noticed that the galvanometer showed there was a current induced when the magnet was in motion.

Faraday theorized that a current was induced because there were magnetic lines of force around the magnet. He demonstrated the existence of these lines of force by conducting the iron filings experiment. He poured tiny pieces of iron filings to coated sheets of paper placed on top of bar magnets. The iron filings were attracted to form a shape that resembles that of the magnetic lines of force. The iron filings' formation showed that the magnetic lines of force were curved and not straight as Newton conceptualized. After this experiment, Faraday began to visualize magnetic field lines as a collection of lines, each of which has a certain direction. These visualizations have transformed Faraday's ideas into more precise mathematical and physical concepts that provide more insights to people who study magnetic and electric fields.

There is one problem that new learners face in learning magnetic and electric fields. They are presented with two-dimensional visualizations when, in fact, these fields are three-dimensional. These visualizations are not only confusing but also prone to misinterpretation. I aim to tackle this problem by creating immersive experiences in visualizing electric and magnetic fields in Virtual Reality. I harnessed the power of GPU, computer graphics, and virtual reality technologies to create a new way of learning the two fields that make use of physical movement and gestures in a fun and engaging way. I developed four experiences, each illustrates magnetic and electric fields in different scenarios. **The Simple Moving Magnet Experience** visualizes the magnetic and electric fields around a bar magnet as it moves back and forth. **The Interactable Magnet Experience** allows users to directly interact with the magnet by holding it and seeing the magnetic and electric fields generated by the magnet. **The Coil and Magnet** experience is a recreation of Faraday's experiment in which users can move a magnet inside a coil to generate a current that will turn on a light bulb. The last experience, **The Two Magnets Experience**, visualizes the magnetic and electric fields between two bar magnets.

In the next four sections of my paper, I describe the details of each of the four experiences as well as the process of designing and developing them. In the following section entitled **Game Instructions**, I walk through how one can engage in the virtual experience using the HTC Vive VR headsets. In the next section entitled **Rendering the Fields**, I explain the algorithms used to render the fields. Finally, I reflect on my learning experience in working on this project and share my future visions on how this project can be improved.

2 The Simple Moving Magnet Experience

The Simple Moving Magnet Experience is the first experience that a user encounters when entering the virtual experience. The purpose of this experience is to give the user a first dive into the theory of magnetic and electric fields. In this experience, the user is presented with a magnet that oscillates in the x-axis based on a cosine function. As the magnet moves, the user can see a dynamically-rendered field that is computed based on the position of the magnet. The key concept illustrated in this experience is how and why the vector at a certain point in three-dimensional space around the magnet change its direction and magnitude when the magnet moves from one point to another.

2.1 Description

The user is provided with a tablet and a panel to help them study the key concept. The user can choose to see either the magnetic field or the electric field by pressing a button on the tablet. The tablet has a pause button which, if pressed, stop the magnet. This feature allows the user to observe the field more closely as they can pay attention to the vectors that are away from the magnet which may not be visible when the magnet is in motion. The tablet is also equipped with a slider that the user can use to position the magnet as they wish. If the slider is slid to the left, the magnet will move in the same direction. This feature is implemented to immerse the user in the experience, allowing physical movement to see changes in the displayed field.

While a field is displayed, the user can go to a nearby panel to have a read on the fundamentals of the displayed field. The panel has two buttons that can be used to navigate through the pages. One can think of the panel as a text book containing two short chapters on magnetic and electric fields. The panel is placed in front of the moving magnet so that the user can identify the name, definition, and formula of the displayed field. The panel minimizes the need to take off VR headsets to read about the fields and wear them again to see the visualizations. The benefit of having such a panel is that the user can have the various learning resources they need to study the two fields in one place.

2.2 Fundamentals of Magnetic and Electric Fields

THIS SECTION NEEDS TO BE DONE In this section, I will present a brief introduction to the fundamental concepts of magnetic and electric fields. These fundamentals motivated the emergence of the study of vector field in mathematics about 60 years after 19th century scientists started drawing field lines to visualize forces around magnets.

2.3 Development

I began the development of this experience by creating a magnet prefab.

Definition 2.1. A prefab in Unity is a special type of component that allows fully configured GameObjects to be saved in the Project for reuse.

I created two cubes, colored one cube red and the other blue, and stick them together as a prefab. I decided to make a magnet prefab so that I can reuse the prefab instead of making a magnet from scratch for future virtual experiences. Prefabs reduce time spent on not only creating objects from scratch but also modifying objects. If the prefab is modified, the modification is applied to all of the prefab instances across all scenes. Once the prefab is created, adding a magnet into the scene can be done by dragging the prefab into the hierarchy window.

The second step in developing this experience is adding a game object of type *VectorField* into the scene. The *VectorField* object reads the charges and positions of the two poles at each frame. It uses the two inputs to render a field of the user's choosing. A complete walk through of how the fields are rendered will be given in the section entitled **Rendering the Fields**. The size of the rendered field is configured to be larger than the magnet itself because larger visualizations are easier to understand and helpful in illustrating magnetic force at a point far from the magnet.

The next step is writing the *MoveMagnet.cs* and *GUIPanel.cs* scripts. These scripts enable the magnet to move if the play button on the tablet is pressed. Else, the magnet is paused and the slider is activated, allowing the user to move the magnet by moving the slider. The two scripts communicate with each other through the UI slider. The UI slider acts as an interface that sends a *float* value based on the position of the slider within the interval. When the magnet is not paused, the *Update()* function in the *GUIPanel.cs* script increments the value of the slider by 0.05 in each frame. The *MoveMagnet.cs* script reads in the slider value and computes it into a cosine function that returns the x-coordinate of the magnet displayed in the following frame.

3 The Interactable Magnet Experience

The purpose of the Interactable Magnet Experience is to allow the user to interact with the magnet in a way that gives much more freedom than the first experience. In this experience, the user can move the magnet in any direction as opposed to moving it along the x-axis only. The idea behind the creation of this experience is once the user has a basic understanding of magnetic and electric fields, they can try to move, rotate, and flip the magnet to see the different visualizations of the magnetic or electric field.

3.1 Description

In this experience, the user is presented with a smaller bar magnet placed on a small table. A *VectorField* game object sits on a big table to the left of the small table. The user can grab the magnet with either their virtual left or right hand. Once the magnet is in the user's virtual hand, they can approach the bigger table where the field of their choosing is located.

There are three ways in which the user can move the magnet and observe a change in the field. The user can wave the virtual hand that is holding the magnet. This way of moving the magnet is recommended when the user chooses to visualize the magnetic field. When the user wants to see the electric field, it is recommended that the user holds the magnet and touch the left trackpad to move the virtual character or touch the right trackpad to rotate the character's head around. The differences in the recommended ways of moving the magnet arise because, in theory, the magnet generates an electric field only when it is moving. In practice, however, we can only move our hands for a few seconds before stopping. It can be observed that as soon as the user stops moving their virtual hand, the magnitude of the electric forces at all points in the field is zero. While the visualization is theoretically correct, there is not much to see in the short few seconds we move our hands. A continuous movement such as translation or rotation of the virtual character in any direction keeps the electric field on display long enough.

There is a common problem with visualizing the magnitudes of magnetic force in text books. It is that there is no indication of existence of magnetic force at some points far from the magnet. These kinds of visualizations can be confusing as they do not convey the nature of magnetic force in real life. This experience uses the affordances of virtual reality to let the user gain an intuition of the magnitude of magnetic force using a magnet and their virtual hands. When the user is located within the field, the process in which the arrows change their magnitudes becomes more visible. It can be observed from the inside of the field that even when the magnet is far from a particular arrow, the arrow does not completely disappear but appears in a minuscule size. The minuscule size of the arrow implies that there is still some magnetic force at the point despite having a relatively small magnitude.

A similar kind of problem can be found in the visualizations of electric field too. It is often not clear whether a magnet is moving or not when it generates an electric field in a visualization. One may misunderstand the visualization and think that an electric field can be generated regardless, which is not correct. In this experience, the idea that the magnet needs to move to generate an electric field is made clear, allowing the visualizations of electric field to be as accurate as it gets.

3.2 Development

I developed this experience in a short amount of time. I dragged the magnet prefab created in the past into the scene and decrease the size to be about a reasonable size of object that can be held. Then, I downloaded and imported a free Unity asset containing home furniture prefabs from the asset store. I created two instances of the table prefab and resized them such that one is significantly bigger than the other. The idea of having a smaller table came about because a physics component that applies gravity is attached to the magnet. The small table allows the user to pick the magnet from a convenient height, minimizing the need to pick the magnet from the floor.

Once the objects are set up, I added another *VectorField* game object into the scene. I set the length and width of the field to be about the same as the length and width of the big table. An important lesson that I learned from developing this experience is that the *VectorField* game objects cannot use the same material. Thus, I duplicated the material used by the *VectorField* game object in the previous experience, renamed it, and attached it to the second *VectorField* game object.

The last but most important steps in developing this experience is attaching the XR Grab Interactable component to the magnet and attaching the XR Interactor component to the hands. The former component allows the game object it is attached to be picked up by the virtual hands. The latter component allows the hands to pick up game objects containing the former component.

4 The Coil and Magnet Experience

The third experiment is grounded on Faraday's coil and magnet experiment in 1831. He did not only discover electromagnetic induction but also had a good understanding of what makes electromagnetic induction possible. The explanation behind electromagnetic induction is summarized by Faraday's Law.

Definition 4.1. Faraday's Law states that a changing magnetic field creates an electric field.

This experience is grounded on the idea of recreating Faraday's coil and magnet experiment. I believe that doing an experiment that a scientist like Michael Faraday did brings more excitement in learning about electric field. Playing with the Coil and Magnet Experience may also give the user an insight to the reasons why Faraday thought what he was thinking or a deeper understanding of how a changing magnetic field generates an electric field.

4.1 Description

The user is presented with five game objects in this experience: a magnet, an electric field, a coil, a light bulb, and a panel. The only game object that the user can interact in this experience is the panel. The panel has a slider that controls the position of the magnet in the scene. If the slider is slid to the left, the magnet will slide to the left. The key idea illustrated in this experience is as follows. When the magnet moves, there is a change in the magnetic field. The change in the magnetic field generates an electric field and results in a flow of current that turns the light bulb on. resembling Faraday's experiment. The difference is that Faraday used a galvanometer to read the magnitude of the resulting current whereas the experience used a light bulb to indicate whether there is a flow of current or not.

4.2 Development

THIS SECTION NEEDS TO BE DONE I started creating this experience by making a coil model in Blender first. When the design was finished, I exported the file in the .fbx format and imported it into Unity. I assigned a material to give the coil a color.

I added another *VectorField* game object into the scene. This time I scaled the size of the arrows up up to give better visualizations. I also scaled the size of the field down to create a visual illusion that the arrows "come out" of the coil.

5 The Two Magnets Experience

The Two Magnets Experience presents a scenario in which the north pole of a magnet and the south pole of another magnet generate a magnetic field. The purpose of this experience is to visualize the changes in the field when a magnet is moving into or away from the other magnet. I find that visualizations of a magnetic field between two magnets in physics text books can be misleading. One can interpret that there is a constant number of magnetic field lines between two magnets. A key concept this experience illustrates is that the number of magnetic field lines is not constant.

5.1 Description

The user is presented with three game objects in this experience: a dynamic magnet, a static magnet, and a panel. The dynamic magnet can be moved along the z-axis using a slider attached to the panel. When the dynamic magnet is moved away from the static magnet, more arrows will be rendered to fill in the space in between the magnets. The increase in the number of arrows illustrates that magnetic field lines are continuous and exists at any point in space.

Another key concept demonstrated in this experience is the concept of electrostatic force which is summarized by Coulomb's Law .

Definition 5.1. Electrostatic force is the force between two point charges.

Definition 5.2. Coulomb's Law states that the magnitude of the electrostatic force of attraction or repulsion between two point charges is directly proportional to the product of the magnitudes of charges and inversely proportional to the square of the distance between them.

In this experience, the positive point charge is represented by the north pole, and the negative point charge is represented by the south pole. The magnitude of the electrostatic force between the two poles is displayed on the panel. In observing the panel, the user is expected to notice that the magnitude of the electric force increases as the distance between the poles decreases as stated by Coulomb's Law.

The magnitude of the force is computed by the *TwoMagnet.cs* script. The script reads in the positions of the poles in every frame. It finds the distance between the poles and compute the electric force using the formula

$$|F| = \left| \frac{k * q_1 * q_2}{r^2} \right| \tag{1}$$

where k is the Coulomb constant, q_1, q_2 are the charges of the poles, and r is the distance between the poles. Once the magnitude is computed, it sends the the result in the *float* number data type to the display panel.

5.2 Development

I started creating this experience by adding two magnets prefabs into the scene. I fixed one of them to a wall and the other to a hollow cylinder that moves along the z-axis. I attached ONE OF THE SCRIPTS to the dynamic magnet to move it closer and far away from the static magnet.

Once the magnets were set up, I added another *VectorField* object and scale it down enough to occupy the space between the two magnets when they are spaced out. While testing out the experience, I noticed that when the magnets are close to each other, some arrows appear from behind the dynamic magnet. It is as if there exists some invisible charges that produce magnetic force around the dynamic magnet.

I modified the *TwoMagnetsShader.shader* file to overcome the problem. I called the clip function inside the *ConfigureSurface()* function. The clip function controls how many arrows in the *VectorField* object gets rendered. It takes in the z-coordinate of the plane that divides the dynamic magnet. Then, it renders the arrows that are in front of the plane and discard the arrows that are behind the plane. As a result, more arrows get rendered as the distance between the two magnets increase and vice versa.

I wrote the *TwoMagnet.cs* script to complete the experience. The script calculates the electrostatic force between the magnets.

6 Game Instructions

In this section, I provide instructions on how to move around the virtual space and interact with the game objects inside it. These instructions will use the HTC Vive controllers as an example. I developed my virtual reality using the OpenXR platform to support various kinds of hardware and platforms without additional limitations. I expect that the following instructions should apply to other kinds of controllers.

6.1 User Movement

There are two kinds of movement in my virtual reality: position and rotation. Position refers to the position of the virtual character at a specific frame whereas rotation refers to the virtual character's head rotation. The position movement is implemented to enable users to play in a relatively small space in reality whereas the rotation movement is implemented to minimize the need to rotate the user's head when looking at an object in the virtual reality.

The left controller's trackpad can be used to move the virtual character. To move forward, one can touch the upper part of the trackpad. Similarly, touch the bottom part of the trackpad to move backwards. The benefit of implementing this movement is that the user can "walk" about the virtual world without actually walking in the real world.

The right controller's trackpad can be used to rotate the head of the virtual character. To rotate right, one can touch the right part of the trackpad. To rotate left, touch the left part of the trackpad. The character's head can only rotate right or left. To rotate the head upwards and downwards, the user needs to rotate their own head. In designing the virtual reality, I placed all of the game objects at eye level, minimizing the need to move the user's head up and down.

6.2 Grabbing Interaction

There are two game objects that the user can grab with their virtual hands: the tablet and the interactable magnet in the second experience. Both of these objects are designed in a way that makes learning more engaging as they motivate the user to move their own hands and be more active. In designing the grabbing interactions, I decided to enable either hand to grab game objects from within arm's reach but only use the left hand to grab objects from afar.

The tablet can be grabbed from within arm's reach and from afar. To grab from within arm's reach, the user can move closer to the tablet and press the trigger button on the desired hand controller. To grab from afar, the user can lift their virtual left hand up and point it towards the tablet until a blue ray appears. The blue ray indicates that the tablet can be pulled into the user's left hand. While the blue ray is in display, press the trigger button on the left hand controller twice to grab it from afar.

The interactable magnet can only be grabbed from within arm's reach. T

6.3 UI Press interaction

7 Creating the Virtual Environment

8 Conclusion