
Work-in-Progress: Gamification of Electromagnetism for Engineering Education

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Ayush Garg is a student at UIUC, where he is pursuing a Bachelor's degree in Electrical Engineering. With a passion for merging technology and education, Ayush is a developer at the Immersive Labs at UIUC. His focus lies in leveraging Virtual Reality to enhance comprehension of electromagnetic theory and its applications. Through his work, Ayush aims to bridge the gap between theoretical concepts and practical understanding, ultimately striving to make complex subjects more accessible and engaging for students in the field of electrical engineering.

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Racula Ilie is an Assistant Professor at UIUC and specializes in high-performance computational models for near-Earth space, focusing on geomagnetic storms. With a Ph.D. in Space and Planetary Physics from the University of Michigan, she integrates theoretical and observational research to advance predictive tools for solar wind-magnetosphere-ionosphere dynamics. Formerly an NSF Postdoctoral Fellow at Los Alamos National Laboratory, she contributed to the TWINS NASA space mission. Prof. Ilie's accolades include the Air Force Young Investigator Program (2017), NASA Heliophysics Early Career Investigator (2019), and NSF CAREER (2019) awards. Her work informs operational warning systems and hazard mitigation efforts.

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1 Motivation

Encompassed by four equations¹, the theory of Electromagnetism (E&M) holds a central role in Electrical Engineering education, offering students insights into the fundamental behavior of electromagnetic fields and waves, knowledge that is required for effective design and innovation. Mastery of E&M principles fosters a deep physical intuition, enabling engineers to navigate complex systems with confidence. Beyond its direct applications, E&M education cultivates a versatile intuition that proves invaluable across diverse engineering domains. However, students often face challenges in grasping the abstract nature of these concepts, particularly in visualizing three-dimensional fields through two-dimensional media, and therefore, struggle to effectively apply their theoretical knowledge to real-world situations^{2,3}. Recognizing the need for innovative educational approaches, our research builds on the idea of using Virtual Reality in classrooms⁴ to address these challenges. This paper details the development and implementation of VR technology to visualize and conceptualize one of the most abstract and complex laws of electromagnetism: Faraday's Law of Electromagnetic Induction.

Faraday's Law, discovered by Michael Faraday in 1831 (and independently by Joseph Henry in 1832) is one of the four laws that encompass the theory of electromagnetism; it forms the cornerstone of many engineering principles and most modern technology. By leveraging VR technology, we aim to create an environment that allows students to witness the practical implications of Faraday's Law in a visually compelling manner, providing them the tools to observe the interaction of these abstract fields as it happens.

2 Faraday's law: theoretical description

Faraday's law states that time varying magnetic fields act as sources of electric fields

$$(\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t})$$

where \mathbf{E} and \mathbf{B} denote the electric and magnetic fields, respectively. An alternative definition involves the electromotive force (EMF, $\mathcal{E} = -\frac{d\Phi_B}{dt}$) defined as electromagnetic work done on a unit electrical charge, and states an EMF is induced in a conductor if the magnetic flux (Φ_B) through the surface enclosed by the conductor varies in time:

The direction of the electromotive force is given by Lenz's law. These concepts are foundational in various engineering disciplines, including electrical and electronic engineering. The practical

applications of Faraday's Law range from supplying power through transformers to more common household devices like wireless chargers.

3 Designing laboratory experiments using virtual reality

The methodology employs the Unity 3D game engine to create a visually compelling and interactive learning environment. The software development is done by teams of undergraduate students at the same University, as part of research projects. Enabling interaction within the VR environment is made possible through the integration of Unity XR scripts. These scripts, written in C#, establish the connection between the VR headset and the scene, allowing users to immerse themselves in the learning experience, as well as dictate the behavior of elements within the scene, ensuring dynamic responses to user actions. For example, the main experiment, featuring a bar magnet and conducting coil, is brought to life through carefully crafted C# scripts. Figure 1 presents an example view of the Unity game engine and Blender 3D software, used to create custom 3D models of objects in the scene.

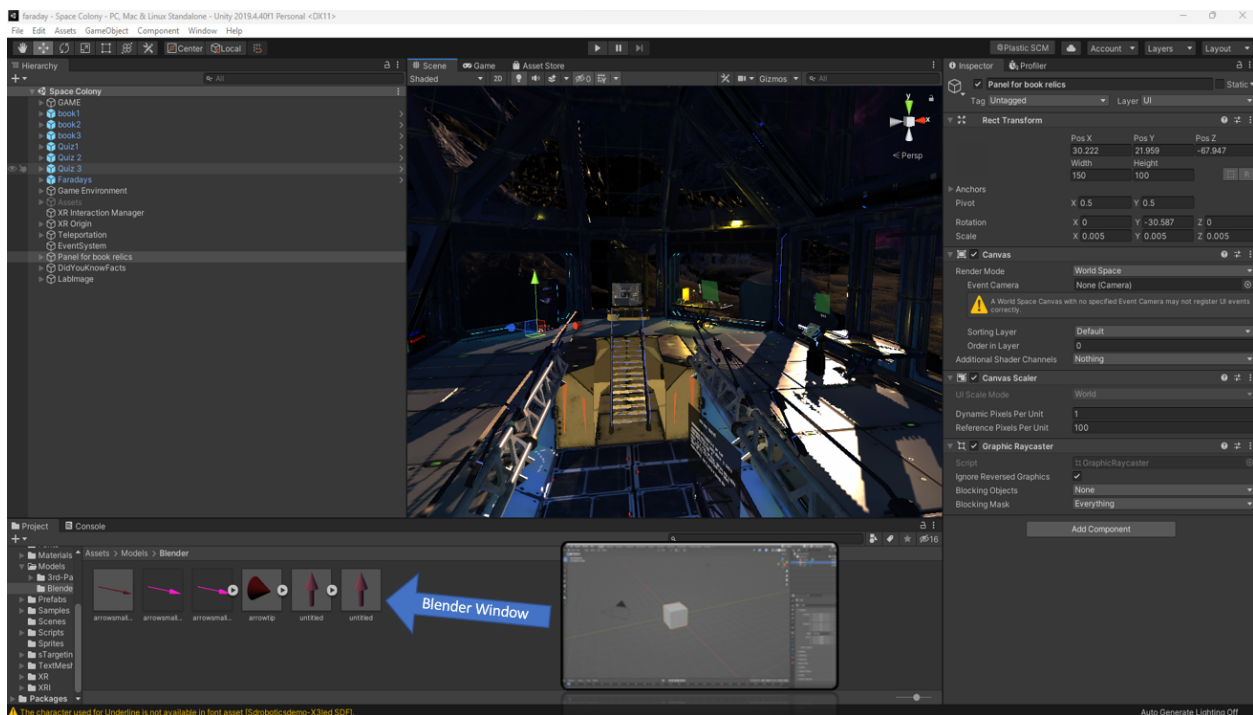


Figure 1: Composite screenshot showcasing the Unity game engine (top) and Blender 3D modeling software (bottom).

3.1 The physics experiment

At the core of the Virtual Reality laboratory experience is the primary experiment which is designed to demonstrate the physics law, in this case Faraday's law, where students can visualize the underlying principles through a dynamic and visually rich interaction. The learning objectives for this laboratory experience are to: (i) understand Lenz's law, (ii) understand how the EMF is induced from linked magnetic flux variations, (iii) relate the curl of an electric field to its

circulation, (iv) relate the time varying magnetic field with the curl of the electric field, (v) understand the implications of Faraday’s law of induction.

A snapshot of the experiment setup is shown in Figure 2, which includes a combination of physical elements (bar magnets and a light bulb attached to a conductive coil), and several visualization tools (3D domain to visualize the bar magnet’s magnetic field, a 2D plane that is used as a canvas to display the curl of the induced electric field as governed by equation ??, a graphics interface that allows to visualize in real time evolution of the magnetic flux through the coil). The latter is provided to reinforce the principles of Faraday’s Law in a more classical, mathematical sense.

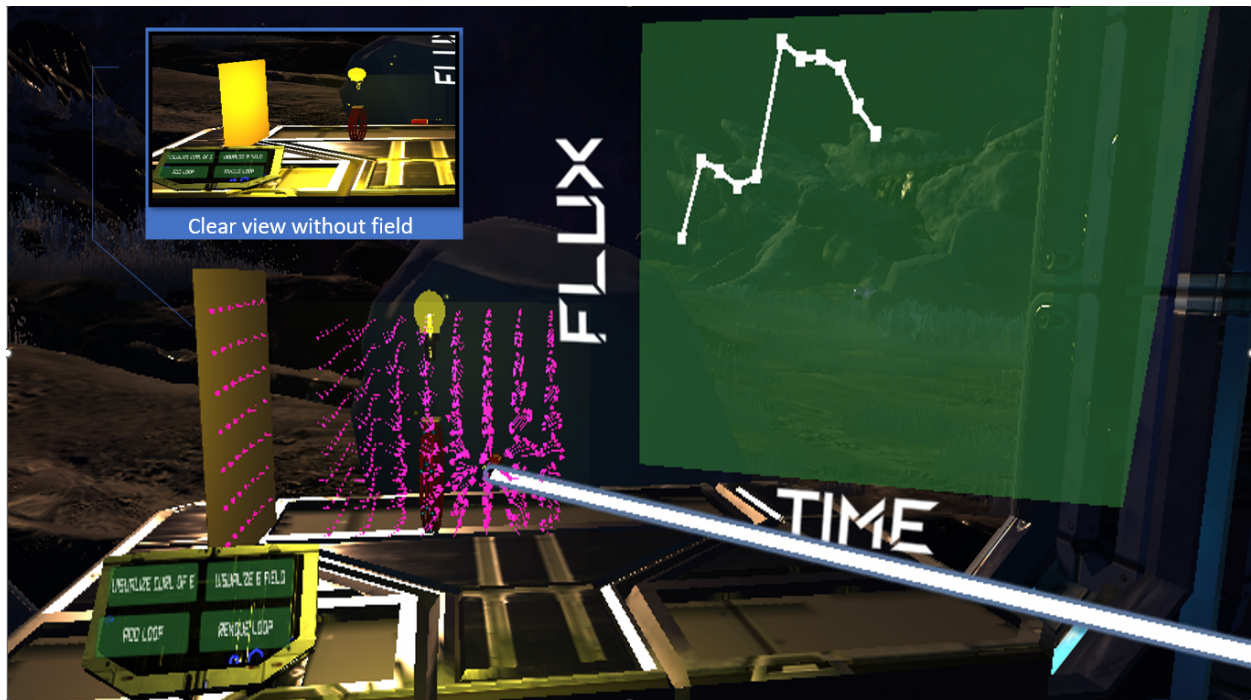


Figure 2: In game screenshot showing the elements involved in the physics experiment: the bar magnet, light bulb and coil (seen best in the top left insert), the graphics interface (showing the evolution of the magnetic flux with time), the 3D visualization of the magnetic field (shown as magenta arrows), the 2D plane that allows visualization of the curl of the electric field, the "in game" control panel which allows students to select various actions.

The experiment space includes several actions that are designed to provide experiential knowledge of the physical law, while also making the connection to the mathematical constructs, with the goal of building a solid conceptual understanding of these processes. Several actions are available for the player engagement, and the primary ones are detailed below:

1. Visualize the 3D magnetic field vector sourced by the magnet. As the magnet moves, the relative magnetic vector field is calculated at points around the magnet by using the formula : $\frac{3xz}{R^5} \hat{x} + \frac{3yz}{R^5} \hat{y} + \frac{3z^2 - R^2}{R^5} \hat{z}$, where R is the distance from the magnet and (x,y,z) represent the coordinates of each point in space around the magnet. Calculated value of the magnetic field is

used to scale the 3-D model of an arrow, placed at each point in the experiment space, representing a magnetic field vector in the experiment space.

2. As the bar magnet is moved relative to the coil, observe that the light bulb illuminates. The light bulb intensity is directly proportional with the rate of change of the magnetic flux passing through the coil's surface area. Note that the flux calculation takes into account the rotation of the magnet relative to the surface that bounds the coil ($\Phi_B = \mathbf{B} \cdot \mathbf{A}$, where \mathbf{A} is the surface area bounded by the coil). Numerically, this proportionality is expressed via a list that stores the values of the magnetic flux at the centre of the coil. The magnetic flux is calculated using the values of the field at the centre of the coil and the direction along which the coil faces. The intensity of the light bulb is recalibrated by a factor proportional to $\frac{\Phi_B^{current} - \Phi_B^{last}}{\Delta t}$, where Δt represents a fixed time step.
3. The experiment includes visualization aids that respond dynamically to changes in magnetic flux. The current flow inside the conductor is visualized by the motion of charge carriers (denoted by blue spheres in the game) inside the conductor as a result of change in magnetic flux. The link between the changes in the magnetic flux and the change in direction of the electrical current allows for a real time visualization of the principles behind Lenz's law. To do so, the magnet's position is tracked throughout the scene, and whenever a change is detected in the magnet's position, the position of the charge carriers is updated. This is achieved by changing their angles relative to the centre of the coil, by an amount proportional to the distance by which the magnet has moved.
4. The player has the option to add or remove turns in the coil which exemplify the direct proportionality between the number of turns and the change in flux ($\Phi_B \propto n$).
5. A vertical plane is used to display the curl of the induced electric field as governed by Maxwell's equation. Similar to the rate of change of flux calculations, a list is used to store the value of the magnetic field vectors at every point in the experiment space. The curl is represented using arrow 3-D models on the vertical plane laid out corresponding to points in the experiment space. The arrows are scaled by a factor $\frac{|\vec{B}_{current} - \vec{B}_{last}|}{\Delta t}$, where Δt represents a fixed time step. The arrows are made to point in the direction opposite to $\vec{B}_{current} - \vec{B}_{last}$.
6. As the experiment is ongoing, the temporal evolution of the magnetic flux through the coil is visualized to reinforce the principles of Faraday's Law in a more classical, mathematical sense through the use of a flux vs time graph. The graph is composed of circular 2-D objects, representing flux measurements, against a transparent panel. The y-coordinate of a plot point is scaled according to the flux at the centre of the coil at a corresponding point in time; the x-coordinate is scaled according to the time at which the point is visualizing the flux.

3.2 Learning Assessment

Ongoing research suggests a possible correlation between challenge based learning and students' ability to become reflective and flexible thinkers⁵. This VR learning experience integrates quiz questions to allow students to challenge their conceptual knowledge in application-based scenarios through guided experimentation. Each quiz question has a corresponding panel of instructions and the appropriate apparatus to implement those instructions. Figure 3 showcases

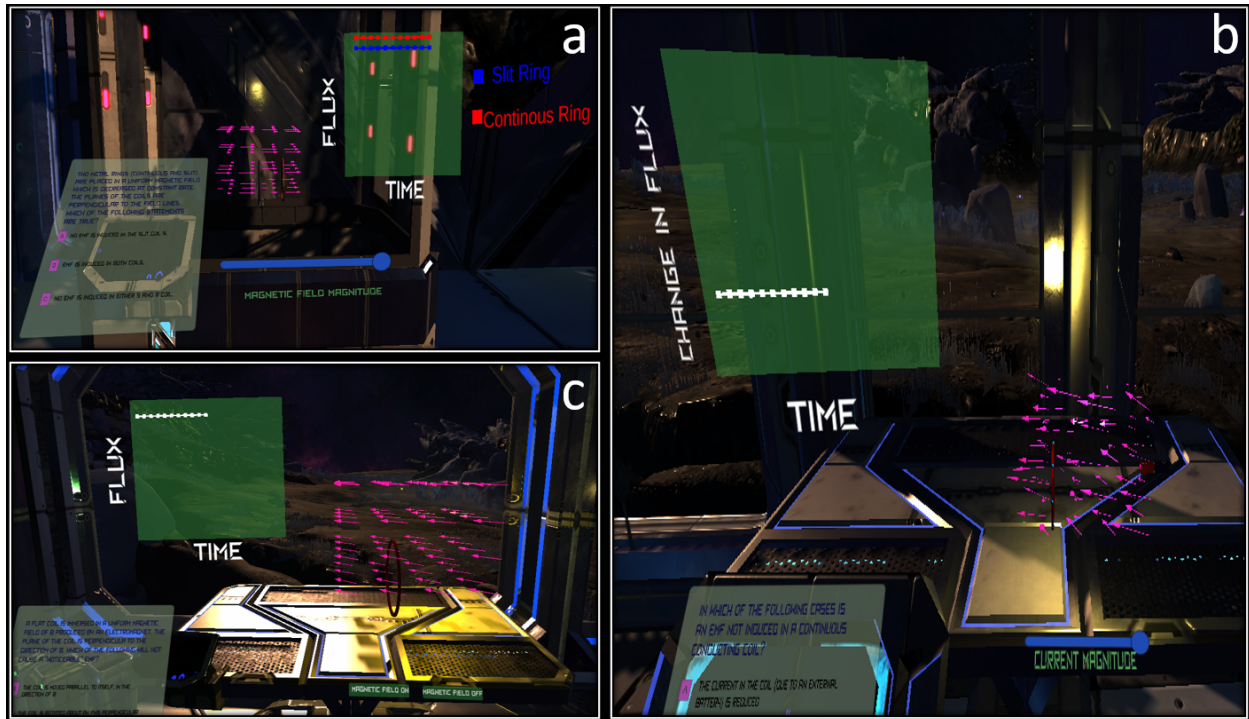


Figure 3: Snapshot depicting in game conceptual quizzes that allow guided experimentation: a) EMF induction in split coil, b) Identifying non-inductive scenarios, c) Altering flux through a coil

three examples of such conception question designed to reinforce key concepts:

a. EMF induction in split coil

- *Apparatus:* Experiment space showing a uniform magnetic field in 3D, split and continuous coils, slider to vary magnetic field magnitude.
- *Graph Interface:* Plots flux through split and continuous coils over time.
- *Experimentation:* Students manipulate the slider and observe changes in the values plotted on the graph accompanying the visual flux changes in the field projected through the coil.
- *Activity:* Students deduce if EMF is induced in either, both, or neither of the coils.

a. Identifying non-inductive scenarios

- *Apparatus:* Experiment space showing a non-uniform magnetic field, controls to turn field on/off, conducting coil, blue spheres representing the coil's free electrons, bar magnet, slider to manipulate magnitude of current (visualized through the angular velocity of the blue spheres) through coil.
- *Graph Interface :* Plots flux through the conducting coil.
- *Experimentation:* Reduce current in the coil, plunge a magnet into the coil, move the coil in random directions in a non-uniform magnetic field.

- *Activity* Students physically engage with each experiment, observing flux variations and deducing the scenario where an EMF is not induced.

a. Altering flux through a coil

- *Apparatus*: Experiment space with uniform magnetic field, controls to turn field on/off, flat conducting coil.
- *Graph Interface*: Plots flux through the conducting coil.
- *Experimentation*: Turn off magnetic field, rotate the coil about an axis perpendicular to B , move the coil parallel to itself in the direction of B .
- *Activity*: Students explore each option, observing flux changes and determining which options do not induce EMF.

3.3 Headset tracking software for attention monitoring

Understanding how students engage with the VR scene is crucial for optimizing the learning experience. Implementing a headset tracking software will identify areas of the virtual scene that attract or may distract students. This data will allow us to make informed decisions to enhance the students' focus on key educational components while maintaining an engaging and immersive experience.



Figure 4: Abandoned space station exterior (gameplay backdrop) overlaid with interior view.

3.4 Gamification/Immersive Elements

To enhance student engagement and captivate their attention, the virtual laboratory is set in an abandoned space station. Figure 4 provides a view of this scene, selected to facilitate the introduction of immersive element to enhance the learning experience. The player is able to move freely around the environment through means of teleportation. The team is in the process of implementing an engaging plot in order to provide a narrative context that complements the educational content, making the learning process more engaging. The plot is designed to seamlessly integrate with the main experiment and the quiz questions, and create a sense of adventure and discovery. As we progress with the plot implementation, we anticipate that it will contribute significantly to the overall appeal and effectiveness of the VR learning experience.

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