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Seeing Electromagnetic Induction: Student Sense Making with Augmented Reality

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Abstract

This study maps the process of students' conceptualization of magnetic flux and induction of electric current using visualizations in the MARVLS Augmented Reality App. We also use the mathematical sense making (MSM) framework to map students' reasoning about mathematical relationships within this context. We present this process and content in a series of semi structured think-aloud guided interview questions. Students manipulate the AR visual objects including a copper ring and magnetic field within the AR models to explore their conceptions of magnetic flux and how the direction of induced current is related to changes in magnetic flux. The MSM framework is used to analyze how students manipulate these elements in the AR model to build their conceptual model of electromagnetic induction.

Interview results suggest that the AR model of electromagnetic induction within the MARVLS App promotes a deeper and more nuanced understanding of how a change of flux creates an induced current. The results indicate that many students are not sure what flux means and needed scaffolding to determine how to create changes in flux. For example, students were prompted to move a copper ring away from or toward a magnetic field within the visualization, to move the copper ring from left to right through the magnetic field, or to rotate the cube such that the magnetic field lines were rotated about the copper ring. In addition, some students needed additional scaffolding to link the direction of the current to an increasing or decreasing flux. The insights gained during the interviews and analyzed with the MSM framework contribute to curriculum development concerned with using AR models to engage students in physics learning.

Introduction

Reasoning about electromagnetic induction requires students to coordinate multiple concepts, including electric current and its direction, changing magnetic fields, the right-hand rule, and magnetic flux as it varies with changes in loop area, field strength, and the relative orientation between the loop and the field [1-4]. Research on embodied cognition suggests that coordination between abstract conceptual understanding and physical representations of these concepts can be facilitated through perceptuo-motor actions [5].

The MARVLS smartphone App employs AR with a Merge© cube to support students' understanding of abstract physics concepts [6,7]. Using a smartphone or tablet camera, the system registers the Merge© cube as a physical reference and renders interactive 3D models on top of the cube. It allows students to rotate, translate, and reposition the augmented scene components in real space with the cube. Prior work has shown that interactional coupling allows learners to examine how changes in orientation and position alter key relationships represented in physics equations, articulate the physical meaning of the represented variables, and support connections between two-dimensional representations and three-dimensional spatial models

[8-11]. Because the visualization updates continuously in response to students' manipulation of the cube, it can be explored as an interactive representation rather than a fixed 2D diagram. An example of the student using their smartphone to view the AR induction model for the interview is shown in Figure 1.

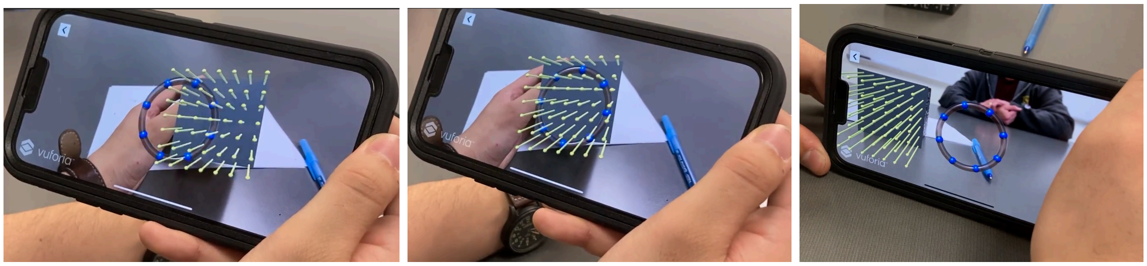

Figure 1. Example from the interview of a student moving the loop from left (left image) to center (middle image) to the right (right image) of the magnetic field.

The AR environment supports learning by coupling students' physical movements with dynamic 3D models viewed through a mobile device. Prior research has shown that such sensorimotor interaction can support conceptual understanding by allowing learners to reason about abstract phenomena through spatial action and perception [12]. By manipulating the 3D model through changes in position and orientation, as well as through on-screen controls, students explore how these interactions affect the relationships shown, supporting connections between spatial reasoning, visual representations, and the mathematics used to describe the system. In the example shown in Figure 1, a student moves a conducting loop from left to center to right relative to a magnetic field, observing corresponding changes in the visualization as the loop passes through the field region. This model allows students to observe relevant representations, such as field direction, charge motion, angle between the loop and the field, and associated variables, supporting connections between the visualized spatial relationships and the underlying physics concepts.

Gifford and Finkelstein [13-16] developed the mathematical sense-making (MSM) framework, a collection of modes of sense-making as shown in Figure 2. These modes define the tool and the object that a student uses to understand the object. The triangles in the figure are a representation of mediated cognition, where the student uses a tool to interact with an object or interacts with the object directly. Individual nodes and triangles come together into a reasoning structure.

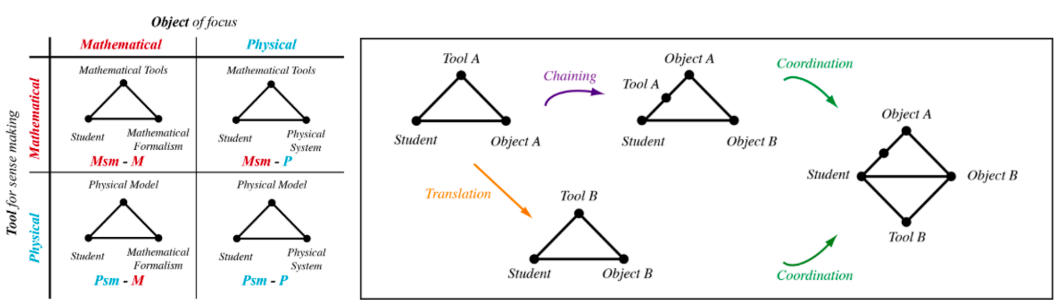

Figure 2. Left: the four modes of the MSM framework, defined by the tool and the object of sense-making. Right: a sense-making diagram, showing the processes of translation and coordination that lead to a coordinated reasoning structure called a molecule of sensemaking.

While Figure 1 illustrates the structure of sense-making observed across interviews, Table 2 provides a summary of how frequently each MSM mode was used by students.

Within the MSM framework, students' reasoning can be characterized by the nature of the tools they use and the type of object they are attempting to make sense of. Reasoning within the framework is distinguished by both the type of tool employed and the nature of the object being considered. In some cases, mathematical tools mediate engagement with mathematical objects (Msm-M) or with physical phenomena (Msm-P), while in others, physical tools mediate reasoning about mathematical ideas (Psm-M) or direct interaction with physical systems (Psm-P). The diamond structure in the box on the right in Figure 2 is an example of the coordinated use of individual reasoning structures that make up the molecule of sensemaking.

Prior work in physics education research has shown that productive sense making often involves movement among these forms of reasoning rather than reliance on a single mode. The framework further accounts for how students integrate these forms of reasoning through dynamic processes such as shifting attention between representations, sequencing multiple tools during problem solving, and coordinating physical and mathematical perspectives into a coherent explanation. Research on representational competence and coordination supports the view that learning emerges as students translate between representations, chain reasoning steps across tools, and integrate multiple modes into stable reasoning structures.

The goal of the study is to determine whether students are connecting the physical objects like the arrows and the copper loop with blue spheres as representations of the magnetic field and the current, respectively. For the MSM framework, most of the modes will be a physical tool to a physical object. However, there may also be a connection between the physical tool and a mathematical object for a conceptual understanding of Faraday's Law and Lenz's Law. For Faraday's Law, current is non-zero when the flux changes. For Lenz's law, a negative sign in the equation represents a change in the opposite direction. However, we did not introduce equations for Faraday's Law or Lenz's Law explicitly in this AR model.

Methodology

Fourteen semi-structured interviews were conducted to examine how undergraduate students reasoned about electromagnetic induction while interacting with an augmented reality (AR) model. Participants were students who had completed or were currently enrolled in a calculus-based introductory electricity and magnetism course, representing a range of STEM majors and varying levels of prior experience with electromagnetic induction. Interviews included over-the-shoulder screen recordings of students' interactions with their mobile phone to view and interact with the AR model and follow-up explanations without the App present. Three images of a student moving the loop into and out of the magnetic field during an interview are shown in Figure 1. Interview prompts focused on how students generated, interpreted, and explained the concept of electromagnetic induction including induced current, magnetic flux, current direction, and opposing flux.

Interview data were analyzed using an inductive qualitative approach. Analytic codes were developed iteratively through repeated review of the interview recordings and notes, with attention to students' verbal explanations, gestures, and interactions with the AR model. The resulting coding scheme captured how students interpreted visual representations, reasoned about magnetic flux and its parameters (field strength, area, and angle), articulated current directionality and mechanism, and used embodied or visual resources during explanation (Table 1). Codes were applied across all interviews to identify recurring patterns and contrasts in student reasoning. Results are reported descriptively, while interpretive claims and instructional implications are presented.

Table 1. Codes used to analyze interviews of students using the MARVLS App and the Interactive Mode Induction AR Scene

Analytic Focus	Code	Brief Descriptions
Representations	Charges as current	Interprets blue spheres as moving charge or current
	Field as arrows	Interprets yellow arrows as magnetic field
Flux reasoning	Changing flux → current	Links induced current to changing magnetic flux
	Constant flux → no current	Identifies no current when magnetic flux is constant
Flux parameters	Field strength	Varies flux by increasing or decreasing magnetic field strength
	Area	Varies overlap between loop area and magnetic field region
	Angle	Rotates loop relative to magnetic field direction
Directionality	CW/CCW control	Intentionally produces clockwise and counterclockwise current
Mechanism	Opposing field	Describes induced magnetic field opposing flux change (Lenz's law)
Interaction	Orientation error	Loop initially oriented parallel to magnetic field
Embodied reasoning	Gesture use	Uses hand or body gestures to represent current or field
Reflection	Mental visualization	Reports visualizing AR model during explanation

Finally, we sort the student responses by the MSM framework to identify which of the four modes the student was using for each of the concepts. To provide a summary of how students engaged with the different modes of the MSM framework, Table 2 presents the distribution of primary modes observed across interviews.

Table 2. Distribution of MSM Modes Across Interviews (N = 14)

MSM Mode	Description	# of Students	Typical Use
Psm-P	Physics tool → physical object	14	Interpreting AR model (flux, current, direction)
Psm-M	Physics tool → mathematical object	2	Using physical model to reason about equations
Msm-P	Mathematical tool → physical object	2	Using equations to explain AR behavior
Msm-M	Mathematical tool → mathematical object	0	Not observed

While all students engaged in Psm–P reasoning during interaction with the AR model, only a small subset coordinated their reasoning with mathematical representations of induction.

Results and Discussion

Students differed in whether the AR model functioned as a tool for justification, validation, or procedural interaction. Analysis of student interactions revealed distinct patterns in how the augmented reality (AR) model was used to reason about electromagnetic induction. Students who demonstrated a deep conceptual understanding consistently used the AR model as a justificatory tool, coordinating features of the visualization. For example, they easily oriented the magnetic field, the face of the loop, and the movement of the loop with respect to the magnetic field to explain induced current in terms of changing magnetic flux. In contrast, students who did not develop a deep understanding interacted with the same AR model in one of three qualitatively different ways. Some required substantial scaffolding, including explicit definitions of magnetic flux and changing flux, before the model became productive. Others used the AR model primarily to validate existing but incomplete ideas, treating the visualization as confirmation rather than as a resource for generating explanations. A third group interacted with the AR model at a surface level, manipulating parameters without attending to the underlying physical relationships and, as a result, did not develop a coherent understanding of electromagnetic induction.

Across all interviews, students reliably interpreted the moving charges in the loop as electric current, the yellow arrows as the magnetic field, and the blue spheres as charged particles. However, analysis of the interviews revealed clear differences in how students with varying levels of conceptual understanding used these representations to reason about electromagnetic induction. Students who demonstrated robust conceptual understanding consistently connected the induced current to both changing magnetic flux and the resulting induced magnetic field that opposes the original field. In contrast, students with developing or limited conceptual understanding typically associated induced current with changing flux but did not articulate the opposing-field mechanism described by Lenz’s law. This distinction was consistent across interviews and is summarized in Table 3.

Table 3. Student Identification of Key Induction Concepts (N = 14)

Concept Identified	# of Students
Changing flux produces current	14
Direction of current (CW/CCW)	14
Opposing magnetic field (Lenz's law)	3

While all students identified changing flux and current direction, only a small subset explicitly articulated the opposing-field mechanism described by Lenz's law.

All students reported that they found the AR scene very useful for understanding the concepts. When asked at the end of the interview to summarize the concepts without using the app, all students relied heavily on gestures, using their fingers or hands to represent induced current and, in some cases, in-and-out motions to illustrate the magnetic field. Each student explicitly stated that they were visualizing the three-dimensional AR model while describing the phenomena, indicating that the spatial features of the AR environment continued to support reasoning even after the model was removed.

Differences were especially evident in how students appropriated the AR model during the interview. Students with robust conceptual understanding immediately recognized the model as a resource for testing and validating their ideas, consistently using disciplinary vocabulary such as current, magnetic field, and changing flux. These students oriented the loop perpendicular to the magnetic field vectors, explored multiple ways of inducing particle motion, and demonstrated that increasing and decreasing magnetic flux produced currents in opposite directions. They also explicitly described the induced current as generating a magnetic field opposing the original field, with one student systematically testing this relationship across multiple cases.

In contrast, students with limited conceptual understanding engaged with the AR model in more constrained ways. One student rarely used disciplinary vocabulary (eg. current, magnetic field, flux), instead referring to features of the visualization using non-specific terms. Two students initially oriented the loop parallel to the magnetic field vectors; one asked clarifying questions about the orientation and subsequently made conceptual progress, while the other did not. These observations suggest that providing instructors or interviewers with real-time visibility into student interactions with the AR model could support more productive guidance, such as prompting attention to loop orientation.

Based on the responses of students with a robust level of understanding, we used the MSM framework to identify the process these students used to describe their understanding of electromagnetic induction. The MSM sense-making modes are all of the Psm-P variety, meaning that they use a physical tool to describe a physical phenomenon. As illustrated in Figure 3, there are two branches that were identified in their sensemaking including identifying a changing flux and identifying an induced current. To identify changing flux, students needed to recognize that flux can change through variations in magnetic field strength, loop area, or the angle between the field and the loop. Most students used the number of B field vectors through the loop to represent flux and a changing number of arrows as a changing flux.They interpreted the arrows through the loop as magnetic flux and changes in the number of arrows as changes in flux. Most students recognized current flowing and linked that to changing flux. Those with robust understanding also linked the current to the creation of an opposing magnetic field. This missing coordination step highlights a key representational gap in the current AR model, which does not explicitly visualize the magnetic field generated by the induced current, limiting opportunities for students to coordinate these elements within the MSM framework.

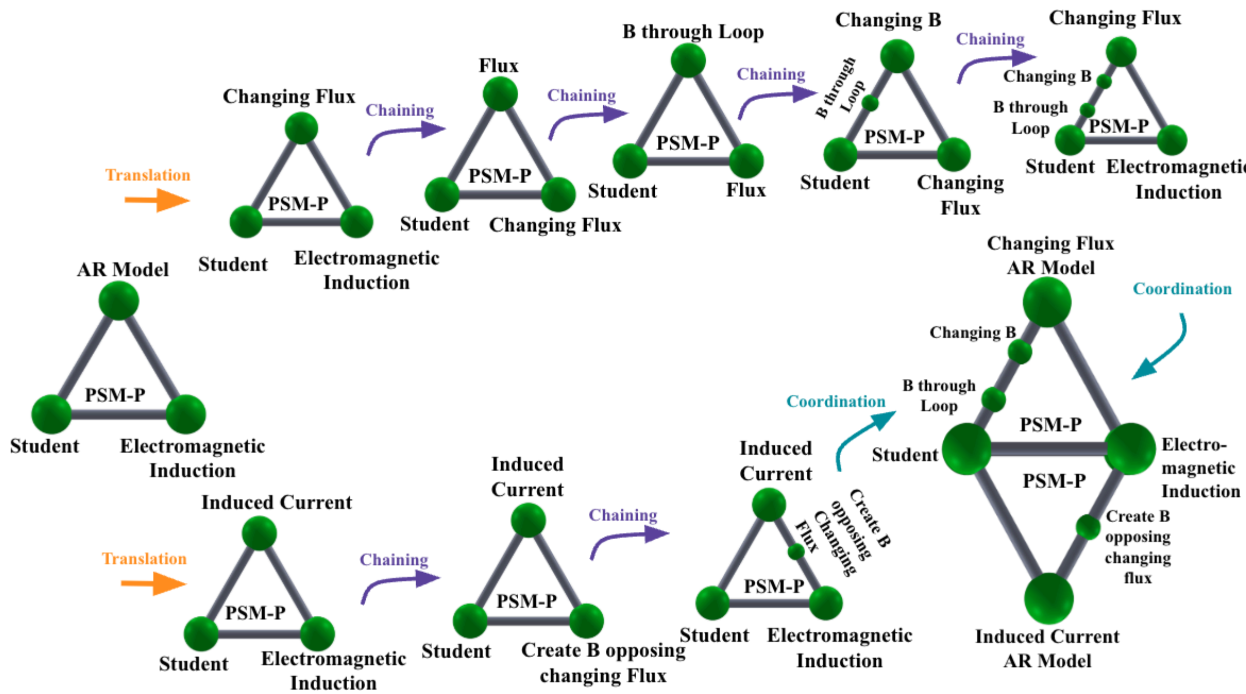

Figure 3. MSM sense-making structures observed in student interactions with the AR induction model. A subset of students identified that induced current generates a magnetic field opposing the change in flux (Lenz’s law).

A few of the students mentioned Faraday’s Law and Lenz’s law and were able to describe these equations using the AR model referencing the change in current direction related to increasing and decreasing flux. A few also linked the induced current to the creation of an opposing magnetic field.

Conclusions and Future Work

This study examined how students reason about electromagnetic induction while interacting with an augmented reality (AR) model, with particular attention to how the model supports or constrains conceptual and mathematical sense-making. Across interviews, students consistently interpreted the motion of charges as current and used the AR visualization to identify when current was present and to control its direction. Most students recognized that current arises from a change in magnetic flux and were able to generate clockwise and counterclockwise current by manipulating the loop and magnetic field. However, fewer students articulated the mechanistic role of the induced magnetic field described by Lenz's law, often moving directly from "changing flux" to "current flows" without explaining how the induced current acts to oppose the change. These findings suggest that while the AR model effectively foregrounds dynamic features of induction and supports spatial reasoning, it underrepresents key mechanistic and representational links necessary for deeper understanding.

From a Mathematical Sensemaking (MSM) perspective, the AR environment supported students' ability to recognize and reason about change but less consistently supported coordination between physical representations and the mathematical relationships governing induction. Students frequently relied on perceptual cues, gesture, and mental visualization when explaining induction, indicating that the AR model served as a durable representational resource. At the same time, interaction-level challenges—such as loop orientation and the salience of particle speed over direction—highlighted the need for more explicit scaffolding to guide students toward mechanistic and mathematical explanations. Together, these results position AR not simply as a visualization tool, but as a powerful medium for eliciting student reasoning and revealing conceptual gaps that may be obscured in traditional instruction.

Future work will focus on extending the AR induction environment to better support conceptual and mathematical sense-making, particularly for students with limited prior knowledge. Interview results indicate that the current induction scene omits key representational and instructional elements, including explicit links between visual features and the variables in Faraday's and Lenz's laws. To address this, future versions will incorporate dedicated AR scenes that embed these equations directly within the environment and dynamically link each variable to its corresponding physical component in the model (e.g., magnetic field strength, loop area, orientation, and induced current). These equation-linked scenes are intended to create explicit opportunities for students to use mathematical expressions as tools for representing physical ideas and, conversely, to interpret physical changes in terms of mathematical relationships—an alignment central to the Mathematical Sensemaking (MSM) framework. Additional visual overlays will be developed to make the induced magnetic field created by the current visible, clarifying the mechanistic role of Lenz's law and reducing students' tendency to reason directly from "more field lines" to "more current" without attending to change. To reduce extraneous cognitive load, early instructional scenes will constrain interaction and highlight only one flux-changing mechanism at a time (field strength, area, or angle), before transitioning to the fully interactive induction scene. Design refinements will also include prompts for incorrect loop orientation, clearer indicators of current direction (CW vs. CCW), and representational cues that emphasize direction over particle speed. Finally, the induction scene will be reframed as a diagnostic or mastery check: students who demonstrate difficulty coordinating flux, directionality, or mechanism will be guided to targeted prerequisite AR scenes that explicitly introduce representations of charge, current, magnetic field, and flux before re-engaging with induction.

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