MSM Framework: AR Model of the Force on a Charge Moving in a Magnetic Field

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In this case study, the MARVLS augmented reality app is utilized to study students' understanding of the direction of the magnetic force encountered by a charged particle moving through a magnetic field (Lorentz force). This study uses the tools developed in the MARVLS app and integrates the mathematical sense making (MSM) framework to facilitate the process of students' understanding of mathematical relationships and physical concepts. We present this process and content in a series of semi structured think-aloud guided interview questions and map the MSM framework to diagrams, concepts, symbols, and equations of the Lorentz force. The interview results suggest using the tools (e.g. equation info box) developed within the MARVLS app along with the Merge© cube promotes a deeper understanding and an increased speed in answering the Lorentz force cross product (thus the right hand rule) 3D conceptual questions. The insights gained during the interview process also contribute to further curriculum development around these models and the MSM framework.

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I. INTRODUCTION

Students often struggle with magnetism concepts in their introductory physics courses [1–3] as well as upper-level courses [4]. Students commonly struggle with unfamiliarity with vectors [5], abstract topics that are introduced in rapid succession [6], confusion between electric and magnetic fields [7, 8], disconnect between lecture materials and laboratory exercises [9], and trouble with accurately using the right hand rule (RHR) [8, 10]. Magnetism concepts can be illustrated using conceptual diagrams and can be represented using symbols and mathematical equations. However, even after seeing the diagrams and learning how to manipulate the symbols and equations, it can still be difficult to truly understand these concepts without providing a hands-on learning experience to interact and observe the consequences of the interaction in real-time. To aid students in developing an intuition about important aspects of magnetism and help them link 2D representations they see in texts to a 3D visualization, the first author created an augmented reality (AR) App where a 3D model is projected onto a Merge© cube (images on the cube orient the cube and the model in space). AR has been shown to be an effective learning tool in science and specifically for magnetism concepts in physics [11–15]. The learner holds the Merge© cube in their hand and moves and rotates the cube to maneuver the 3D model around as they view the model through the screen on their smartphone.

II. MARVLS

The Manipulable Augmented Reality Visualizations to Learn Spatially (MARVLS) smartphone Apps use augmented reality (AR) and Merge© cubes to allow students to hold the diagrammatic representations of the abstract science concepts, rotate and move them around in space, and investigate the connections between the 2D and 3D models and the mathematical formulas [16–18]. Each model includes a help menu that directly associates labels with aspects of the model, for example, highlighting which finger represents which vector in the right hand rule.

III. THE MSM FRAMEWORK

In this study, we are using the mathematical sense making (MSM) framework developed by Gifford and Finkelstein [19–21]. Their framework is based on the sense making work of Odden and Russ and the ideas of mediated cognition of Vygotsky [22, 23]. The MSM framework blends scientific sense making and mathematical sense making and provides a set of tools to understand how students make sense of physics concepts and mathematical relationships. The basic units of sensemaking are four modes where each mode is represented by a triangle with the student located on the left vertex, a tool located at the apex, and an object located at the right vertex of the triangle. The MSM framework consists of four sense making modes (also called reasoning structures) which are: mathematical sensemaking of a mathematical object (Msm-M), mathematical sensemaking of a physical object (Msm-P), physical sensemaking of a mathematical object (Psm-M), and physical sensemaking of a physical object (Psm-P). Gifford and Finkelstein provide examples where they have applied the MSM framework to one group of students working through a problem on the photoelectric effect from a modern physics course. Finally, the MSM framework consists of three different ways these modes can be constructed and combined for more complex sense making. These include translation, chaining, and coordination. translation happens when there is a change in the tool or the object being considered. Chaining occurs when the objects become tools and objects and tools stack together for a more complex mode. Coordination is bringing modes together into molecules of sense making resulting in a complex coordinated reasoning structure. As Gifford and Finkelstein demonstrate, coordinated reasoning (a mix of Msm-M and Psm-M) is necessary for students to be able to draw or identify the correct plot of the kinetic energy versus wavelength plot of the photoelectric effect [24].

A. Why MSM and MARVLS and a moving charge in a magnetic field?

One of the challenges associated with introducing 3D concepts (such as right hand rule and cross product) on a 2D screen is lack of depth and details in a 2D model. Students need to mentally picture and understand spatial relationships in a 2D model and cognitively convert the information from a flat screen into a 3D space [10]. Before developing the MARVLS app and the AR models, the magnetism concepts of a moving charge, a magnetic field, and a magnetic force were introduced during class. This magnetism concept was taught using representations in the textbook and a slide presentation, demonstrated with clever physical objects, and some problem solving work to identify the vector quantities. This progressed into (re)learning the right hand rule and the cross product equation that was taught in the previous semester on the topic of torque. The right hand rule approach to cross products has been shown to improve retention of the topic [25], but there are some challenges associated with applying it to the Lorentz force [7, 8, 10]. Next, the Lorentz force equation ($\mathbf{F}$ = q$\mathbf{v}$ x $\mathbf{B}$) is introduced and the variables in the equation are matched up with the cross product equation ($\mathbf{C}$ = $\mathbf{A}$ X $\mathbf{B}$) and the right hand rule. With this knowledge and experience, a student should be able to determine any one of the three vectors in the Lorentz force equation given the other two.

To help students develop this sense making knowledge, an AR model was developed in the MARVLS app. The first step was to develop a 3D model that includes a charge which is represented as a sphere, an arrow for the velocity vector of the charge, an array of arrows for the magnetic field vectors, and an arrow for the force vector on the charge. Next, two 2D representations were added into the model so that students could map each of the 2D representations onto the corresponding projection in the 3D model. The Lorentz force equation was added to the screen of the app and finally buttons were added to the screen. The buttons are labeled with the variables in the Lorentz force equation. When the buttons are pressed and held, the physical object in the 3D AR model is highlighted by changing its color to green. When the buttons are pressed and held, the corresponding representations in the 2D images are also highlighted allowing students to link the use of x's and dots to represent vectors into and out of the page, respectively.

Because of the complexity of this Lorentz force concept and the many resources and sense making that students must utilize to determine the motion of a moving charge in a magnetic field (cause-and-effect relationship), the authors believe the MSM framework is a valuable tool to assist us in the development of curricular materials to accompany the AR model. Upon first analysis, the AR model (visualized through the smartphone app) is a physical tool to understand the physical object which is the concept of the force on a moving charge in a magnetic field (Psm-P). The right hand rule is a physical tool to determine the physical direction of the force (Psm-P). The Lorentz force equation is a mathematical tool to understand the direction of any one of the variables in the AR model (Msm-P). The direction of the force is a physical tool to understand the motion of the charge in the magnetic field.

The motion of a charged particle in a magnetic field is dependent on the Lorentz equation. To use the Lorentz force equation effectively, the student needs to recognize the relevant physical magnetism concepts, be skilled with the right hand rule, and understand how the RHR can be used with the cross product to determine a vector direction. This process of sense making maps well onto MSM's coordinated reasoning that includes translation, chaining and coordination. Recent developments push this further to include a mix of MSM modes in the coordination of the reasoning elements [24].

IV. METHODOLOGY

The data presented here comes from one of a series of 27 of semi structured think-aloud interviews that involved students that had used the app in class and some that saw it for the first time. Students were guided by the interviewer (one of the authors) through a MARVLS AR model. The student in the case study presented in this paper, Jennifer (pseudonym) is a rising junior physics major who took the calculus-based introductory courses during her freshman year and served as a group tutor for that course during her sophomore year. Jennifer had experience using the MARVLS App during her introductory physics course to visualize magnetism concepts. Lessons to guide the exploration with the AR models had not been developed when she took the course. Three reviewers watched and categorized the modes in the videos independently.

In the chronologically-ordered transcripts that follow, the interviewer is guiding the student as she is using the MARVLS App, asking questions and making suggestions as needed. The evolution and construction of the modes is discussed in the next section. In each interview the student is guided to an AR model to review the right-hand-rule where the thumb represents the resultant vector. This interview was chosen as the student spent more time with this RHR model and vocalized how she was connecting the fingers to the gesture and the gesture to the cross product.

Psm-P

I: Tell me what you know about the Lorentz Force Law.
J: When a charged particle or charged object is in a magnetic field it feels a force and that causes it to move in typically circular motion (gestures a curve with her finger).
I: Now let's go into the app to Lorentz force on a moving charge.
J: *Jennifer is viewing the AR model through the screen on her phone and manipulating the cube to bring the model closer and rotating the cube to rotate the model as shown in Figure 1(a).*
I: Tell me what you see.
J: There is a particle, it has a positive charge. There are three vectors coming out of it, the force, the velocity, and the magnetic field. There are also some 2D representations of the velocity in the magnetic field and I think just a projection of the magnetic field again but with arrows coming perpendicular to how they are on the other 2D view.
I: Why do you think we have the arrows there on the particle?
J: Sort of like with the RHR how you have your force, field, and flow. I guess those three are representing that. But more so because those are forces or the things that are acting on it that cause it to move the way that it would in a magnetic field.
I: Do you remember the RHR?
J: Yeah. I think so.

Psm-M

I: Do you remember the equation for the Lorentz Force?
J: Oooh, (pause) that's a good question.
I: There's a little question mark (on the app screen). If you click on that (pause)
J: Oooh, yeah, yeah. That's sick.
I: You can push on those buttons.
J: *Jennifer is pressing and holding each of the buttons and seeing which arrows are highlighted in green in the 3D and 2D image as shown in Figure 1b by rotating the cube to see the AR model from different angles. She presses each button several times and views the highlighting changes in the AR model.*
I: Can you tell me what you are seeing?
J: When I press each term in the equation, different parts of the diagram light up so it really just illustrates which part of the equation maps onto the real-life forces that are affecting

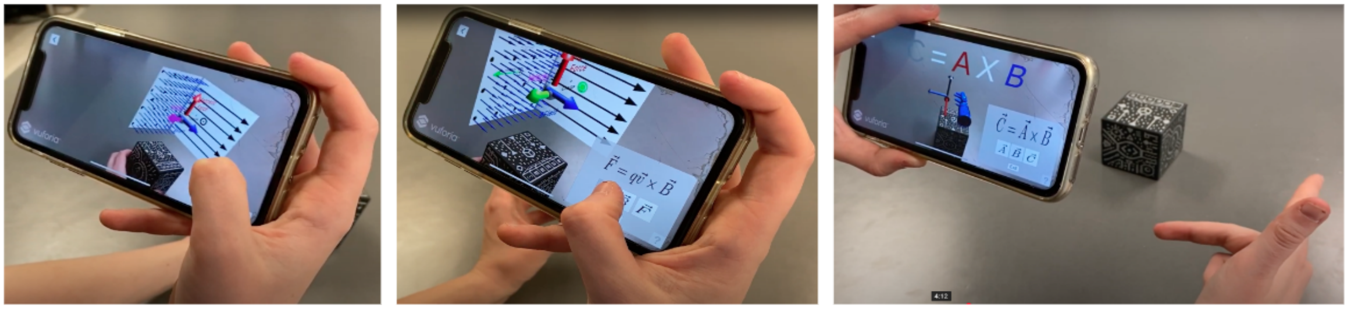

FIG. 1. (a) AR Lorentz force model, (b) addition of equation and highlighting of velocity vector in green, and (c) RHR AR model with student demonstrating their RHR gesture.

the particle. Oh, that's really cool, and it also lights up on the 2D representation. So if you're seeing it on a piece of paper you can also visualize it a lot better.
I: So you know the right hand rule?
J: Yes.
I: Can you show us the RHR?
J: Yeah, yeah, yeah, RHR. Flow field and force was I think the way where if this is the direction. *At this point Jennifer has her right hand extended and is showing the RHR and is pointing to her thumb as the flow, pointer finger as field, and middle finger as force.*
I: Let me back you up. Let's go back to the RHR model. Go back in the app and choose RHR as a refresher of the right hand rule.
J: *As she's rotating the cube to see the cross product equation in the right orientation (see 1(c)), she whispers A cross B. She clicks on the question mark to display the cross product equation. She starts pressing and holding the buttons.*

Coordinated Psm-M and Msm-P

J: The hand changes to show you which (pause) That's really nice. So for the different terms in the equation, you can see which finger corresponds to which term. That's really nice.
I: So practicing a little bit, how would you demonstrate that with your own right hand?
J: I would say like if this is two vectors being crossed (pointing to her thumb and her pointer finger) to form this one (pointing to her middle finger), this (pointing to her thumb) would be A, (pointing to her pointer) B, and (pointing to her middle finger) C.
I: Okay. We usually do 1, 2 and 3, like A, B, and C (interviewer is pointing to her own fingers). So try it and see if it makes sense.

Psm-P and Msm-P

J: *Jennifer holds up her right hand displaying the RHR gesture. She then points to her pointer, then her middle finger, then her thumb and whispers A, B, C. Jennifer presses and holds the A, B, and C buttons on the phone screen and views the green highlighting of the fingers and the arrows in the AR model for each of the terms in the cross product equation. Then she places her hand alongside the phone screen aligned with the RHR hand in the AR model. She's looking at the screen and her hand. She first points her thumb up - identifying her thumb as C. Next she has her pointer finger pointed to the left and her index finger pointed forward. She realizes that is not correct and opens her hand so that her pointer finger points forward and her middle finger points left as she views the AR model of the RHR. And then she's holding her hand and rotating it forward slightly to indicate she's pointing forward.*
J: Oh, that does make sense. That makes alot of sense.
I: So do we want to go back?
J: Back to moving charge?

Psm-P

J: *Jennifer is viewing and rotating the AR model of the charge in a magnetic field shown in 1(b). She whispers, there she is!*
J: Alright then, in the case of this for the RHR, you would have the force represented by the thumb, q times v as the first finger and the magnetic field as the second finger.
J: *While she is describing what she sees, she orients her hand into the RHR gesture. And as she describes the AR example, she wiggles her pointer finger in a little circle pointing forward, points her middle finger to the left for the B field and her thumb up for the force. However, the vectors in the AR model are NOT aligned with her RHR gesture! The interviewer does not know that her fingers are not aligned with the AR model and goes on.*
I: Does that make sense?
J: Yeah!
I: So now what I want you to do is to take the cube and and I want you to put it in a different orientation.
J: *Turns the cube to the side. Using her RHR she correctly points her pointer finger up in the direction of the velocity, her middle finger towards herself in the direction of the magnetic field, and her thumb to her right in the direction of the force.*

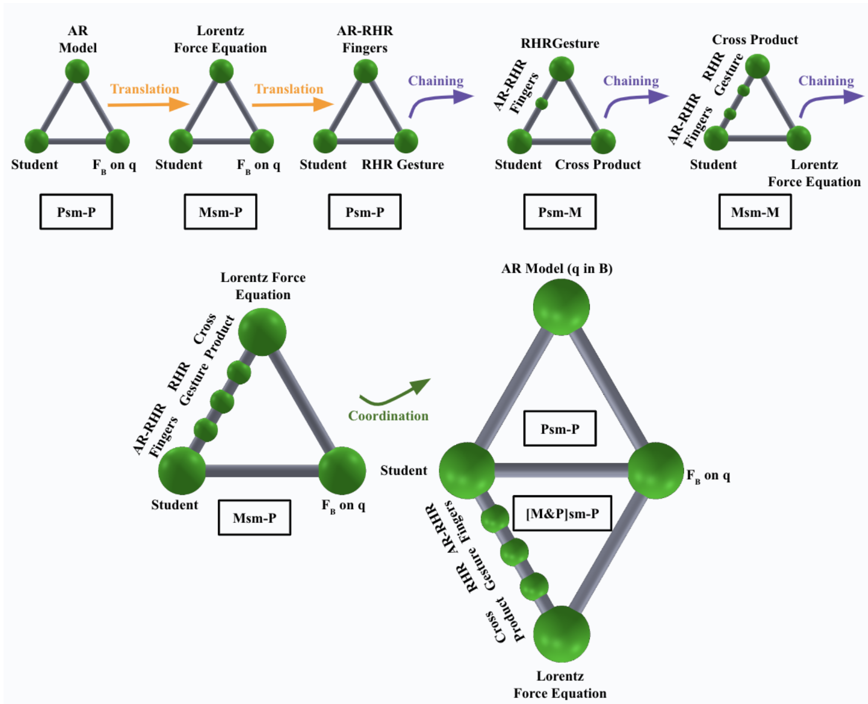

FIG. 2. Sense making modes, translations, chaining and coordination.

V. DISCUSSION & CONCLUSION

In Figure 2, the authors attempted a sense making diagram similar to the ones created by Gifford and Finklestein [19–21, 24]. The sense making diagram starts out in a Psm-P mode with the AR model as the tool and the concept of force on a moving charge as the object. There's a translation to the Lorentz force equation as new tool and new mode of Msm-P. There is a second translation to a new AR model of the RHR and the specific fingers used in the gesture as the tool and also a change of object to the RHR gesture which is back to a Psm-P mode. Three chaining steps occur with changes of the tool from the RHR fingers (Psm-M) to the cross product equation (Msm-M) to the Lorentz force equation (Msm-P) as the final tool to understand the force on a moving charge in a B field as the object. This sense making molecule is joined with the sense making atom that we started with which is the AR model as the tool and the concept of the force on the moving charge in the B field as the object. Studying the chaining process to get to the Lorentz force equation as a tool, we determined that the sense making mode was a coordinated M and P tool as described by Gifford and Finklestein as [M&P]sm - P [24].

When Jennifer is using Psm-P and Msm-P with the RHR, she is using the fingers highlighted in the AR model (tool) and matching her own fingers in her RHR gesture (object) while also considering the cross product equation and how the terms match her fingers. This is consistent with our sense making model in Figure 2. She seems to be using Psm-P more than Msm-P as she is comfortable with the cross product. Asking her to switch to a new RHR gesture is difficult and she's relying mostly on Psm-P to build her confidence with the RHR gesture.

Direct interaction with the AR model provides real-time feedback for the intended use of the RHR as compared with the delayed feedback received on a conventional worksheet assignment. In the case described in this paper, Jennifer needed very specific instruction to develop the skill to use a different RHR gesture than she used previously. However, she was able to use the new RHR gesture to determine the directions of the velocity, magnetic field, and force when she returned to the AR model of a charge moving in a magnetic field.

Assessments, student work, and these interviews are informing further curriculum development around the AR models. This interview will inform the development of questions to help students connect the proper RHR gesture with the velocity, magnetic field, and magnetic force vectors necessary to understand the Lorentz force. Other interviews revealed a useful suggestion to have students place their hand in the field of view while working with the model.

Our recorded think-aloud interviews provide rich data to analyze the MSM framework applied to different magnetism concepts and differently prepared students.

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