Leveraging scientific modeling to engage pre-med undergraduates in physics lab courses

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Undergraduate students on track for medical school are often required to take general physics lab courses. Many of these students carry an attitude of obligation into these courses which can make it challenging for instructors to engage students in course material. We address the question: How does engaging with medically based models in introductory physics labs affect pre-med undergraduate perceptions of the modeling process and their perceptions of science? We redesigned an electricity and magnetism lab in an introductory physics lab course, where approximately 70% of the undergraduates reported plans to attend medical school. We situated the lab in the mechanics of MRI magnetic resonance and collected data on the participants' experiences through surveys and lab submissions. As a part of the analysis, we modified a rubric to evaluate engagement in modeling and applied grounded coding theory to the survey responses to develop themes of the participants' understanding of scientific modeling. The participants' understanding and engagement in scientific modeling increased during the newly developed lab and remained high for subsequent labs. We recommend that instructors of undergraduate nonmajor labs consider the demographic of their student population and design lab experiences situated within their interests and focus on central science practices like modeling.

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I. INTRODUCTION

For pre-medical undergraduate students enrolled in general physics courses, scientific modeling can be the bridge that connects the physical sciences to the life sciences. The difference between the physical and life sciences can be difficult to reconcile for students and teachers alike. The approaches to these sciences can be dissimilar, and when people are familiar with one approach, it can be challenging to see the value or application of any other. Because this disconnect has been apparent in introductory physics courses for nonmajors in many colleges [1], including our own, we sought to address the stumbling block. At the heart of any scientific practice—no matter the approach—there is a foundation of scientific modeling; biologists use models just as often as physicists do to test hypotheses. Knowing that scientific modeling skills can be beneficial in any field, including the medical field, we chose to adjust our approach to part of an introductory physics lab course to emphasize scientific modeling practices for the high concentration of pre-med students enrolled. More specifically, we applied models for physics in a medical context and looked for answers to the following research question:

> How does engaging with medically based models in introductory physics labs affect pre-med undergraduate perceptions of the modeling process and their perceptions of science?

II. LITERATURE REVIEW

In the following sections, we discuss pre-medical students and their involvement in physics courses, the central role of scientific modeling in authentic science, and our theoretical framework.

A. Physics and pre-med students

In our introductory physics lab courses for nonphysics majors, about 70% of the students are on track for medical school or other professional schools such as dental school [2,3]. Often, the attitude that pre-med students carry into a required physics course is an obligation to fulfill the requirements for their medical school applications but little interest in the actual subject matter [1]. Because a physicist's approach to science may be different from a medical student's approach, such as a differing dependence or focus

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on mathematical reasoning, there are often situations where pre-med students doubt the relevance of physics to their future careers while enrolled in physics courses [1]. This lack of connection is concerning because there actually is a significant amount of overlap between physics and the life sciences. The scientific practices that are developed in lab courses are applicable to every type of science. For example, the ability to make conclusions (or diagnoses) based on data collected during an experiment is a skill frequently implemented by physicians and physicists alike. The physics courses that pre-med students participate in should therefore be focused on not only helping students gain a better understanding of basic physics principles but also teaching them higher levels of problem-solving and scientific modeling skills [4]. One such method that proves valuable in teaching physics is an investigative science learning environment (ISLE) in which students learn by participating in activities that replicate real physics practices and require authentic reasoning tools [5]. According to the American Association of Physics Teachers (AAPT), the target learning outcome in these entry level physics lab classes for nonphysics majors should be to expand the students' understanding and ability to participate in experimental investigations because science is interdisciplinary in nature [6]. We used this target learning outcome as the foundation of our course goals.

B. Scientific modeling and its role in the classroom

Within introductory lab courses across the world, it is common to find assignments and experiments that are set up in a traditional "recipe" style [7,8]. In such an approach, a teacher presents students with a set of lab instructions for them to follow step-by-step while aiming for a specific result (such as confirming the acceleration of gravity or verifying some other constant). While this method of teaching is convenient and informative for both teachers and students, it is not the most effective way to equip students with the skills necessary to excel in the world of scientific research [9]. One flaw of this recipe style is the lack of authentic investigative experience; the labs are hands-on but not heads-on [10]. In fact, instruction settings with this verification structure have been found to provide no statistically significant benefit to students regarding their performance or course content comprehension [11]. Recipe style labs address the need for data analysis and communication, however, the experience of designing an experiment and formulating scientific models is often undervalued in those labs. Classroom experiments should be used to provide practice and experience with scientific modeling [12]. To better address course goals, as recommended by AAPT, many educators have begun implementing a model-based method of teaching instead. In a report giving recommendations for undergraduate physics laboratories, AAPT depicts different science practices as overlapping [6]. The overlapping nature of the practices represents a shift away from the linear representation of the scientific method. A central science practice, noted by Kozminski *et al.* [6] report and other national standards (e.g., the Next Generation Science Standards [13]), is scientific modeling.

Scientific modeling is a method in which students are challenged to use and create representations of specific scientific phenomena that are both familiar to them and that provide grounds for them to predict further outcomes [14,15]. They should engage in progressive cycles of modeling as they build, validate, and refine the conceptual models they are working on [16,17]. This method of scientific exploration should not be limited to advanced scientific researchers who have years of experience; the modeling approach should be integrated into science classrooms at every stage of education [18,19]. Students who engage in actual scientific practices develop a better understanding of—and proficiency in—the decision-making process involved [20]. From the work of Passmore *et al.* [21], we incorporate two ways of having students engage in the modeling practice. The first is using models as tools. This is where students are provided with a model and then they use it to reason with, make predictions about, and collect data for a given scientific phenomenon. The second is having students develop their own models. This involves using data and analysis to create a model (e.g., mathematical, conceptual, representation) that students can use for their own sensemaking [22].

C. Theoretical framework: Situated learning and scaffolding

This work is built within the framework of situated learning theory. Similar to the ISLE approach [5], situated learning theory, as visualized in Fig. 1, takes place when students can explore and practice the applications of class

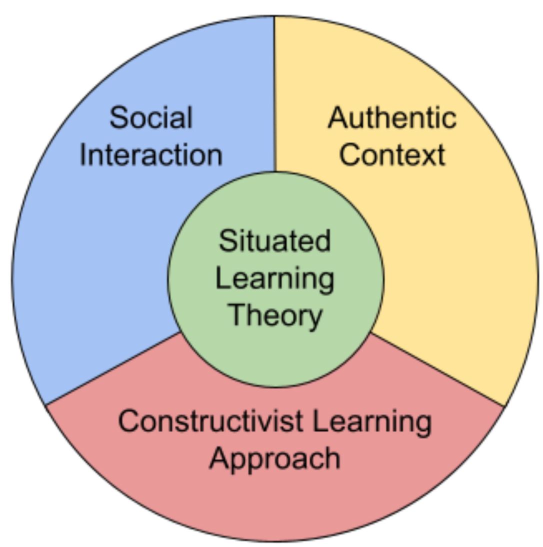


FIG. 1. The main tenets of situated learning theory (adapted from Green *et al.* [23]).

material in authentic contexts alongside other students to better foster constructivist learning [23]. The constructivist learning theory supports the idea that there is no such thing as knowledge without a learner; students construct meaning and knowledge for themselves [24]. Providing authentic and applicable contexts is also beneficial to students because they have the opportunity to develop the skills needed to apply what they learn rather than simply gaining knowledge of seemingly abstract principles [25]. For premed students in particular, these biomedical contexts foster student interest while furnishing authentic environments to engage with scientific practices [4,26]. Billett [27] proposed that learning is closely linked to the circumstances and context of the learning environment and that students may have difficulty transferring their experiences and knowledge to spaces different from that original context. In other words, experiments centered on affirming constants or other inauthentic projects can undermine the goals of the course because it is not a transferable experience. Moreover, social interactions between students help foster learning because interacting with other people is a significant source of developing knowledge [28]. This interactive development of knowledge is supported by the constructivist learning approach where students are given the opportunity to express their thought processes, learn by inquiry or problem solving, and add new knowledge to the foundational understandings they already had [29].

As is the case with any area of growth, there is a zone of proximal development (ZPD) between a student's independent abilities to engage in scientific modeling and a higher level of ability that requires guidance [30]. Instructors who foster learning within this ZPD enable their students to more confidently progress from one level of performance to the next [31]. Distributed scaffolding is one way to engage students in the ZPD and includes access to multiple tools, resources, and—much like situated learning theory—social interactions [32].

In one of our introductory lab courses for nonphysics majors, we explored the impact of situated learning on premed students and their scientific modeling practices. We redesigned an electricity and magnetism lab to include an investigation of a simplified analog of a magnetic resonance imaging (MRI) machine. By using the context of an MRI machine, our students were able to engage with the scientific phenomena of solenoids, gradient magnetic fields, and magnetic resonance within a context that is meaningful to them. We tracked their engagement and understanding of scientific modeling before, during, and after the MRI lab to better understand how situating their learning in this way impacted how sophisticatedly they engaged in scientific modeling.

III. METHODS

We used a structured open coding approach [33] to address our research questions because we wanted to compare the student perspectives and performance before and after our adjustments to the lab. We redesigned the electricity and magnetism lab in an introductory physics lab course for nonmajors from a traditional (recipelike) approach to an exploration of a situated model of an MRI machine. Because many of the other labs fit a more traditional profile, we were able to carry out a cross-case analysis of student reasoning with models. The following sections provide a description of the context of the study, the MRI lab rebuild, and our analytical methods.

A. Context and participants

The introductory physics lab course for nonmajors (PHSCS 108) in our study covers electricity, magnetism, waves, and optics. Students in this lab must be concurrently enrolled in a companion lecture course or have previously taken a lecture course. This lecture course is a traditional content-driven electricity and magnetism course (with a little bit of modern physics) that teaches problem solving. Teaching science practices such as modeling, planning investigations, and scientific argumentation are not included in the lecture course's student outcomes. The content taught through the labs and lectures is not aligned so while students are often able to apply principles from the lecture to the labs, there are times when they are using the labs to explore scientific phenomena for the first time. For example, a main content theme of the MRI lab is magnetic resonance, this topic is not introduced in the lecture course (although they do look at basic magnetism). Following AAPT recommendations for the learning outcomes of nonphysics majors [6], we recently adjusted the course goals of the PHSCS 108 lab course to teach scientific thinking, modeling practices, and experimental design skills. In the process of adjusting the labs of the course, we are leveraging this opportunity to study student outcomes.

In an average semester, the course has 12–15 sections with roughly 20–30 students per section. Each section meets once a week for a 2-h period in which the students work through experimental physics labs in groups of 3 to 4. While there is one professor who oversees the progress of each section, there are one or two teaching assistants (TAs)—usually undergraduate students who either are physics majors or have previously taken the PHSCS 108 course themselves—to monitor and instruct each section more closely. The professor and TAs meet once a week for 2 h to go through the upcoming labs themselves, troubleshoot equipment, solidify their own understanding, receive teaching instruction, and address areas of potential confusion. While the TAs receive no formal pedagogical training, these students are ones who have successfully navigated this course as students or who are physics and astronomy majors with excellent lab skills. This arrangement gave us confidence in our restructuring of the magnetism lab because we knew the TAs would receive training in the lab's implementation. For the new labs, the

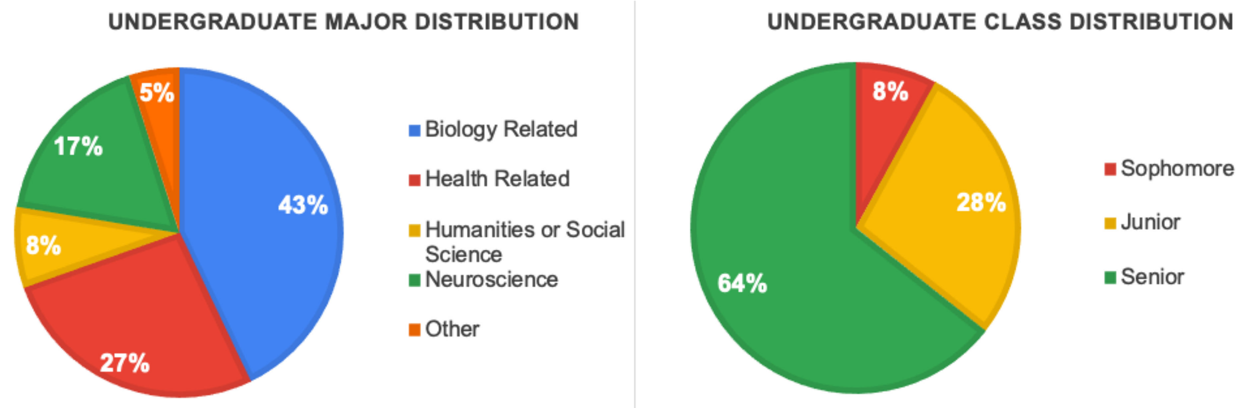


FIG. 2. The major and class distribution of students in the lab course ($N = 305$).

training the TAs receive is crucial because the students need a different level of support than when they are following traditional lab instructions.

During the semester of the study, 305 undergraduates enrolled in the lab course. They came from various majors and colleges across the university. Figure 2 shows the major and class distribution of the students in the course. In the U.S., sophomores are typically second-year students, juniors are third-year students, and seniors are fourth- or fifth-year students. We simplified some of the majors to reduce the total number of majors reported (biology related—biology, bioinformatics, genetics, microbiology, …; health related—exercise and wellness, exercise science, health science, …; humanities or social science—human development, languages, psychology, …; other—open major, business, education, …). While the biology major is one of the only life science majors to require an introductory physics lab, many medical schools require the experience of physics lab courses [34]. We also note that the majority of the students were in their senior year at the time of the course. The students reported that they often delay the physics courses to take them closer in time to their qualifying medical school exams (e.g., MCAT).

According to the Colorado Learning Attitudes about Science Survey for Experimental Physics (E-CLASS) for the undergraduates in our study, just under 70% of the students had plans for medical school, 30% for other professional schools (such as dental or physical therapy schools), and no students declared plans for physics graduate school (see Fig. 3). This point is important to emphasize because unlike physics undergraduates, who are enrolled in heavily math-based science classes and primarily unscaffolded lab courses, these pre-medical students are most likely unfamiliar with a physicist's approach to experimentation and science learning.

B. Description of the MRI lab

The MRI lab sequence begins as the fourth lab within the course lab sequence. See Table I for a brief description of

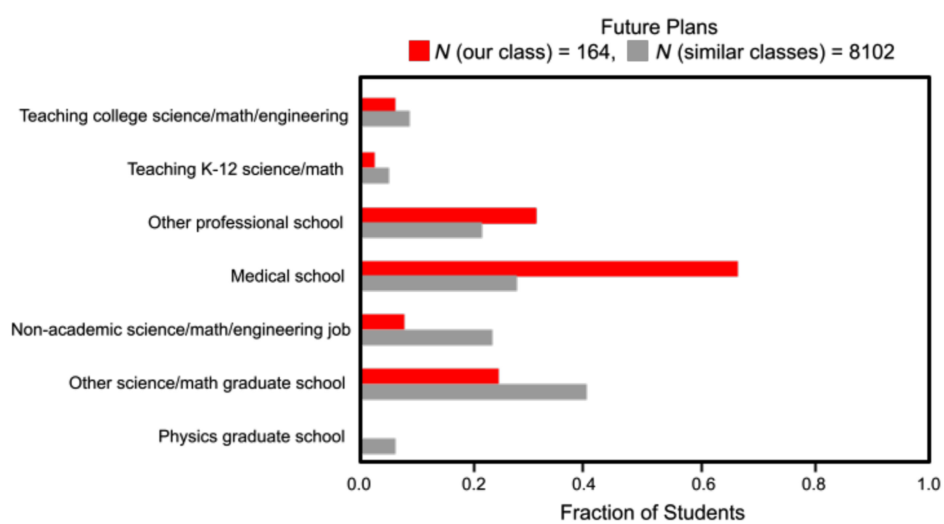


FIG. 3. E-CLASS detailing undergraduate future plans where the top bar in each set of responses is from our class and the bottom bar is from other similar classes from colleges across the nation.

TABLE I. A description of the sequence of course labs.

Lab	Description	Learning style
L1—Electrostatics	Students are introduced to the basic concepts of charge, static forces, conductors, and insulators.	Traditional
L2—Fields and potentials	The students use electrically conductive paper to study how electric potentials change over distance. They are given models that physically represent the phenomenon to reason with.	Traditional
L3—Electricity and circuits	Students use Ohm's law to explore electric circuits. They collect measurements to confirm the relationships between resistance, current, and voltage.	Traditional
L4—Magnets and fields	Students use Hall probes to investigate the behavior of magnetic fields of bar magnets and current carrying wires. They are also introduced to the concept of resonant frequency	Traditional
L5—MRI lab D1	Students use solenoids to model an MRI machine. Using this model, they plan and conduct their own investigation of the resonance of a bar magnet (or hydrogen atom) within a gradient magnetic field.	Situated learning
L6—MRI lab D2	Students share the results (mathematical or conceptual models) they found the previous day. They defend their findings in small group discussions.	Situated learning
L7—Optics D1	Students explore the behavior of light through various lenses and develop an initial model around the thin lens equation.	Traditional
L8—Optics D2	Students study possible limitations of the thin lens equation (color, angle, aperture). They design their own experiment within the parameter and report their results by revising their initial models to accommodate the limitation.	Inquiry
L9—Refraction	Students use physical models of the human eye to explore the refraction of light as it transitions through mediums like air, glass, and water. They continue to apply principles of lens optics from the previous labs.	Traditional
L 10—Lab final D1	Students choose from among several experiments (diffraction and thickness, spectra of elements, light absorption by color, …) to design an experiment for the course final. Within this project, they design their own experiment and reason with their analysis to come to a conclusion (scientific explanation or model)	Inquiry
L 11—Lab final D2	Students continue their work on the lab final. This day is focused more on data analysis, collecting possible additional data, and writing the final report.	Inquiry

each lab along with the learning style at the time of the study. We also note that at the time of this research, we are in the beginning stages of rebuilding the course labs to transition them from more traditional over-scaffolded versions to labs that teach science practice (such as modeling, explanations, and conducting student-designed investigations) through situated learning environments. The MRI lab is the second lab to undergo revision, and we hope to continue the revision process, incorporating what we learn from this study into future labs.

The full sequence of the MRI experience happens over three sessions. First, the students went through a scaffolded exploration of magnetic fields by following instructions to use a Hall probe to plot field lines on magnets, current-carrying wires, and observations on magnetic resonance (see Supplemental Material [35]). On the second day, we introduced the context of an MRI machine with two short videos and the following foundation of a model for them to work with:

> It is clear that MRI is a very complicated area of both medicine and physics... but you can explore the concepts of magnetic resonance with a simplified model of an MRI machine and a bar magnet that represents a single hydrogen atom in the body.

Within this basic overview of an MRI machine and using the model of an MRI, we provided (one dc current solenoid, an ac current solenoid, and a mounted bar magnet), the undergraduates could design their own experiment to test their own hypotheses (see Supplemental Material [35]). This gave them the opportunity to engage in a more authentic scientific process both using a model as a tool for inquiry and then developing their own mathematical or conceptual models to make sense of their data. The limited scaffolding we provided includes the simple model just described, recommended settings for measurement tools, and examples of variables they might test in their experiment. The shift in scaffolding between prior labs and the MRI is evident in the differences between the labs found in Supplemental Material [35]. The earlier labs walked students through an investigation prompting them to do certain tasks that had expected outcomes. In the MRI lab, the scaffolding shifted to guidance on how to build and conduct their own investigation. They could ask questions where the outcome of the experiment was uncertain and where they would be required to make sense of their data

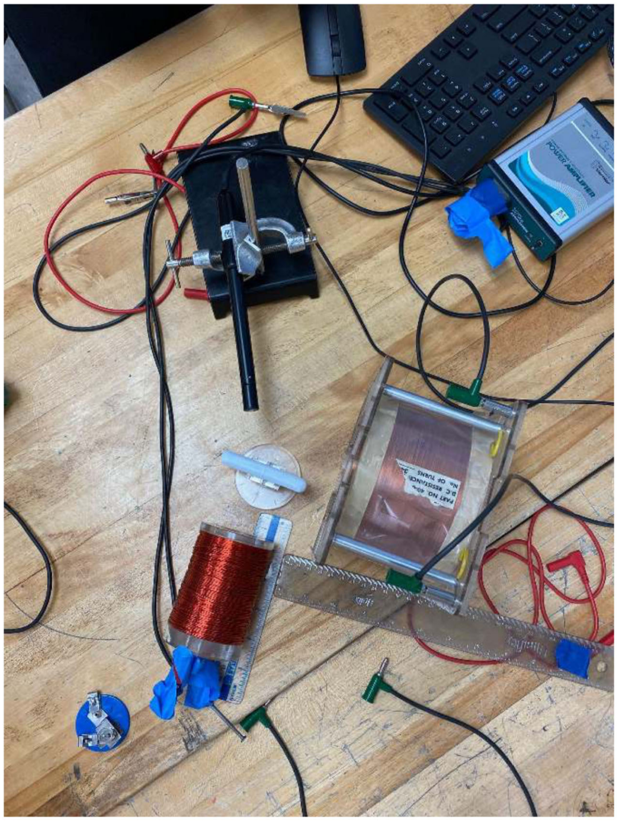


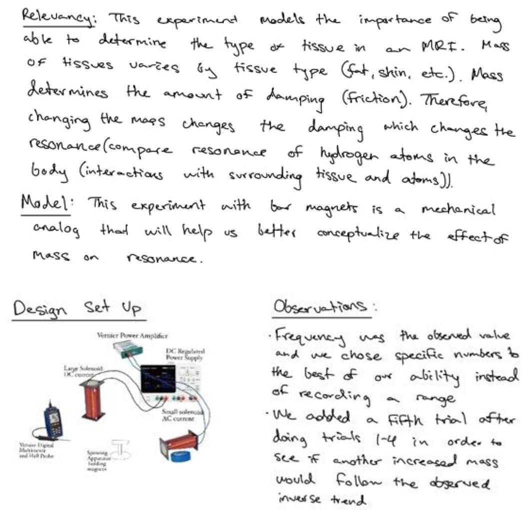
FIG. 4. An example of student's lab configuration for the MRI lab. Students modeled an MRI with a large dc powered solenoid and a smaller ac powered solenoid to investigate the properties of resonant frequencies of a bar magnet.

through modeling (either mathematical or conceptual). Figure 4 shows images of what two groups of students used for their lab setup.

As an example of what student work could look like, we provide three examples from the student notebooks (see Fig. 5). In these examples, the students show evidence of scientific modeling and reasoning when they describe the relationship they observed between their tested variables and use it to predict the relationships.

While this small sample cannot capture the wide variety of student responses from our study, we can observe here the conceptual work the students engaged in. Student 1 spoke in more general terms about their data, but they did note the importance of the model to predict outcomes. Student 2 noted that their original hypothesis of a linear relationship was wrong. This student was able to adjust their model through data analysis and mathematical reasoning. Student 3 used graphical methods to model their data and went as far as including the uncertainty of their model.

Student 1:



Relevancy: This experiment models the importance of being able to determine the type of tissue in an MRI. Mass of tissues varies by tissue type (fat, skin, etc.). Mass determines the amount of damping (friction). Therefore, changing the mass changes the damping which changes the resonance (compare resonance of hydrogen atoms in the body (interactions with surrounding tissue and atoms)).

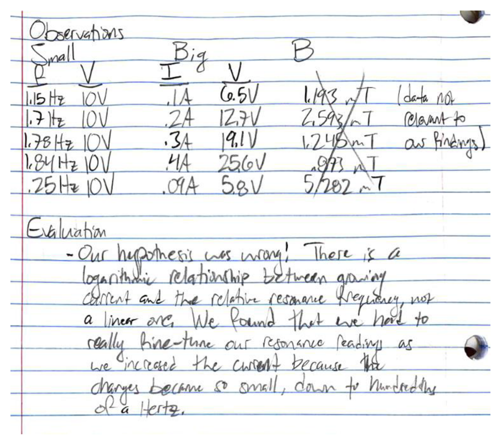
Model: This experiment with bar magnets is a mechanical analog that will help us better conceptualize the effect of mass on resonance.

Design Set Up

Observations:

- Frequency was the observed value and we chose specific numbers to the best of our ability instead of recording a range
- We added a fifth trial after doing trials 1-4 in order to see if another increased mass would follow the observed inverse trend

Student 2:



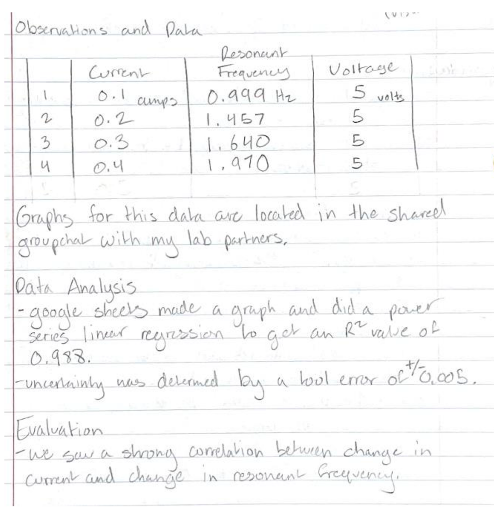
Observations

Small f	Small V	Big I	Big V	B	
1.15 Hz	10V	.1A	6.5V	1.193 mT	(data not
1.7 Hz	10V	.2A	12.7V	2.593 mT	relevant to
1.78 Hz	10V	.3A	19.1V	1.245 mT	our findings)
1.84 Hz	10V	.4A	25.6V	.973 mT	
.25 Hz	10V	.09A	5.8V	5.282 mT	

Evaluation

- Our hypothesis was wrong! There is a logarithmic relationship between growing current and the relative resonance frequency, not a linear one. We found that we had to really fine-tune our resonance readings as we increased the current because the changes became so small, down to hundredths of a Hertz.

Student 3:



Observations and Data

	Current	Resonant Frequency	Voltage
1	0.1 amps	0.999 Hz	5 volts
2	0.2	1.457	5
3	0.3	1.640	5
4	0.4	1.970	5

Graphs for this data are located in the shared groupchat with my lab partners.

Data Analysis

- google sheets made a graph and did a power series linear regression to get an R^2 value of 0.988.
- uncertainty was determed by a tool error of +/- 0.005.

Evaluation

- we saw a strong correlation between change in current and change in resonant frequency.

FIG. 5. Examples of student work and scientific modeling and reasoning from the MRI lab.

TABLE II. Sources of data.

Source	Available	Used	Description
E-CLASS responses	164	164	Student learning attitudes about science
Lab 3 student notebooks	295	89	Scaffolded lab notebook on electricity and circuits
MRI lab reports	25	25	Student reports completed by groups detailing their MRI exploration
Lab 8 student notebooks	293	89	Guided lab notebook on lenses and optics
Pre- and postlab questionnaires	95	95	Student responses to the distributed application questions

C. Data collection and analysis

To answer our research questions, we collected the following data: E-CLASS results, lab notebooks, lab reports, and in-course surveys (see Table II). To complement the E-CLASS survey, we wrote two additional survey questions and distributed them to the students before they participated in the MRI lab and again after the lab:

1. What is scientific modeling and why is it significant to experimentation?
2. How can engaging in physics experimentation prepare you for your future academic and career interests?

The E-CLASS survey was taken by the students outside of class at the beginning and end of the semester. The students were offered a small amount of extra credit for completing it. The above additional survey questions were included as part of their pre- and postlab questionaries. Each lab has a short set of pre and postlab questions that prepare the students for their lab experience so they would not have found the questions out of the ordinary and likely had only a small influence on their perceptions of modeling.

Table II also indicates how many of each data source we had available to us and how many we used in our analysis. The number of available sources reflects the total number of students who participated and turned in their work for that source. The MRI lab report is an exception to this because the students submitted these as a group (3–4 students) rather than individually. The samples we used for the MRI lab report only included students who participated in lab 3 and lab 8, giving us a sample size of 89 undergraduates. As comparison labs, we chose labs 3 and 8 for specific reasons. We selected lab 3 because it was a traditional design that included opportunities for the students to engage in modeling. This gave us an opportunity to see their unscaffolded efforts with scientific modeling. We chose lab 8 as a follow-up because labs 7 and 8 were designed as inquiry labs with a modeling emphasis. Lab 8 provided the students with the greatest opportunity to showcase their modeling skills as they were given time in this lab to revise previous work. Lab 8 did not include an intentional situated context like the MRI lab and so could also serve as a comparison where modeling scaffolding was provided but not fully integrated in an intentionally relevant context.

To understand how the students defined scientific modeling, we used grounded theory and open coding [33] to track student responses to the survey questions. From those open codes, we developed the themes presented in Table III. Grounded theory requires the coders to allow the participant responses to be the source of the categories or themes rather than applying a set of preconceived codes to the participants' work. We used these themes to track how undergraduate perceptions and applications of modeling changed between the first and second sets of survey responses.

TABLE III. Recurring themes coded for in student descriptions of scientific modeling.

Theme	Description	Student example
Tool	Modeling is used as a tool that provides some assistance or benefit to their experiments.	"Models can help us see and understand difficult concepts."
Process	Modeling is used as a process through which new information can be attained. Includes the recognition that revision is an important step.	"It is important that scientists test their models and be willing to improve them as new data comes to light."
Multiple types	Student acknowledges multiple types of models and/or ways to model.	"Physical or mathematical representation of a phenomenon." "Using data, math, stats, theory, to represent observations."
Misconceptions	Incorrect assumptions or ideas regarding modeling.	"You are trying to create a perfect model for the principle you are studying."
Limitations	Student limits the purpose or function of modeling.	"Models are used when it is either impossible or impractical to create experimental conditions where scientists can directly measure outcomes."

TABLE IV. Elements of the modeling sophistication rubric used to code student work.

Origin	Element	Description
NGSS	Scientific principle	Parts of the model are explicitly linked to scientific principles
NGSS	Patterns	Describes relationships and/or patterns in the data
NGSS	Predicts	Model makes predictions about phenomena
NGSS	Limitations	Identifies limitations of the model
NGSS	Sensemaking	Students determine whether their results are reasonable
AAPT	Assumptions	Addresses or acknowledges assumptions made in the model
AAPT	Multiple models	Uses multiple types of models (mathematical, visual, etc.)
AAPT	Complete analysis	Work begins with research question and finishes with evidence-based model(s), including revisions
AAPT	Systematic error	Discusses how systematic error and biases affect the model

To assess how the participants engaged in modeling in each lab, we used an *a priori* coding approach [36]. This allowed us to measure student performance against predetermined criteria. Table IV provides a description of the criteria used to construct the modeling sophistication rubric (MSR). The MSR divides attributes of modeling into two categories: the first are skills attributed to modeling that occurs in secondary science settings, and the second are skills prescribed for undergraduate physics courses. We sourced these from the modeling progressions described in the Next Generation Science Standards [13] and used in previous research studies [37,38]. The undergraduate skills come from the AAPT college level modeling recommendations [6]. We used these sources to develop these scientific modeling themes or skills, and they were further refined through coding student work and discussions within the research group. Table V breaks down how we assigned levels of modeling proficiency to the students' lab work.

For each student's response to the labs of interest, we applied the descriptions in Table IV to the submitted lab reports. We assessed how many of the NGSS- and AAPT-aligned elements each response contained. These were tallied and we then applied the rubric in Table V to assign a relative level of modeling. For example, from all the work submitted by student 2 in Fig. 5, we found three NGSS elements and one AAPT element. This resulted in a level 3 (advanced secondary) modeling sophistication score.

We grouped each modeling score for the participants by the labs they engaged in to track the group's progress over the course. We also looked at how their changes in modeling sophistication changed for different majors and class level of students within our population. These results are presented below. The MSR's highest level of sophistication is likely unachievable for our sample of students, but it does allow for it. It is not that these students are not capable of that level of engagement, but rather that it takes time and practice (more time than can be found in one semester long lab course) to develop sophisticated skills in scientific modeling [38]. Finally, we verified the coding method through rounds of interrater reliability. Approximately 20% of the data was coded by a second coder and their codes were compared to those of the first coder. We continued the double coding process until the percent agreement between the two coders reached a minimum of 80%. Where the codes disagreed, consensus was found through discussion until we achieved 100% agreement [39].

D. Limitations

While the results of this research have supported our application of situated learning, it is important to recognize our limitations. Because our sample only includes undergraduates attending one institution, the results may not be

TABLE V. Scoring criteria used with the modeling sophistication rubric. Note that it is uncommon for there to be cases with few secondary modeling traits and many college level traits. The few we found were coded on an individual basis.

Score:	Criteria:
Level zero modeling:	Meets no benchmarks
Level one modeling(introductory secondary modeling)	Meets one to two NGSS benchmarks
Level two modeling (intermediate secondary modeling):	Meets three NGSS benchmarks
Level three modeling (advanced secondary modeling):	Meets three to four NGSS benchmarks and one AAPT benchmark
Level four modeling (introductory college modeling):	Meets four or more NGSS benchmarks and two or more AAPT benchmarks
Level five modeling (intermediate college modeling):	Meets four or more NGSS benchmarks and three or more AAPT benchmarks
Level six modeling (advanced college modeling):	Meets all benchmarks

generalizable outside of this context. Kanim and Cid [40] suggest that most physics education research samples oversample undergraduates in calculus-based physics courses. Our sample does not fit this trend as the majority of our students are nonphysics majors. Our sample does represent a case that can be tested in other contexts.

Additionally, the data we were able to collect were restricted to written work because of institutional review board (IRB) constraints. In the future, with more comprehensive approval from IRB, video recordings of students working through labs could be collected to add further insight to the findings. This additional method of monitoring student work more closely would also help triangulate results. With more sources of evidence, we could bring to light the lesser-known effects that additional factors have on scientific modeling, such as the varying extent of scaffolding in each lab [32]. We also note the difference in the submission type of the MRI lab compared to labs 3 and 8. The MRI was a more formal lab report done in teams while the student work evaluated from the others was more scaffolded lab notebooks. While this difference could confound the results of the study, we note that the changes observed in the MRI lab did not disappear in the following lab (see the lab 8 results). This gives us confidence that the students did make progress with their modeling skills. Finally, the study introduces both scientific modeling strategies and a medically situated context in the same lab. The effects of these two changes are likely entangled. We argue that this kind of entanglement is unavoidable for work of this nature. First, in order to provide rich modeling opportunities, instructors need to situate their lab work in meaningful contexts. Second, modeling is a science practice central to the work of all scientists. In order to situate the work of students in authentic labs, their work will lead to some level of modeling.

IV. RESULTS

We aligned the results with the study's research questions. First, we present our findings for the changes in undergraduate perceptions of scientific modeling. Second, we show the development of undergraduate performance in the scientific modeling process.

A. Changes in undergraduate perceptions

One way to estimate the undergraduate's changes in perceptions comes from the E-CLASS survey. This survey is a series of questions, given at the beginning and close of the semester, that collected data on the degree to which students personally related to a statement compared to how "experts" related to the same statements. We present the responses to four inquiry and modeling related statements (see Fig. 6) that showed movement for our students. The score indicates the fraction of students with "expertlike" responses. In other words, as scores approach 1, more students are responding like experts. The dots indicate where the responses were at the beginning of the semester while the arrows indicate how much the responses shifted by the end of the course. This iteration of the course only included two modified labs so we did not expect large changes, but these results provide both an indication of the progress we have made and where additional work could be done. While there was an increase in expertlike responses to questions 14 and 29, there was a decrease in questions 27 and 28. The decrease in these two categories could indicate students' difficulty in working

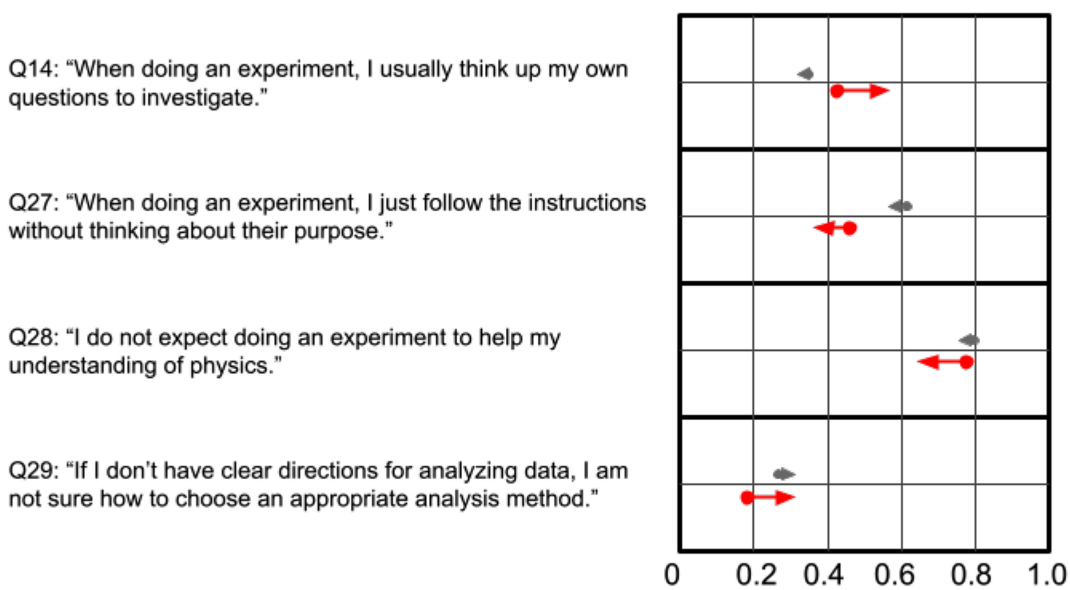


FIG. 6. Data from E-CLASS results. The line above the center represents the average national change and the line below the center is our class change. The dot represents the starting point and the arrow shows the change. The scale on the bottom shows the proportion of students who think similarly to experts.

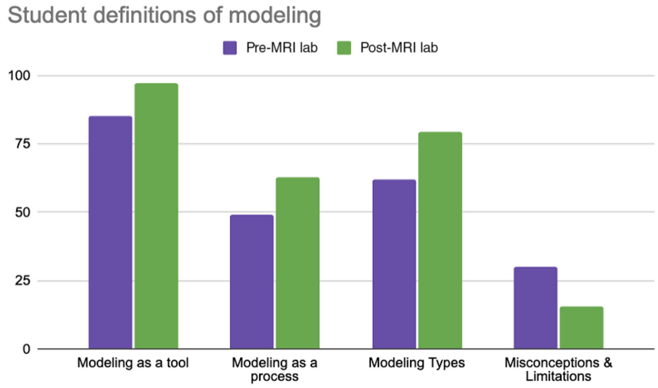


FIG. 7. Student descriptions of scientific modeling before and after the MRI lab. The scale represents the number of instances each definition occurred.

with open-ended labs and a desire to have more scripted lab experience. The dot and arrow above the center line represent undergraduates in similar courses from a national sample, and the dot and arrow below the line represent undergraduates from our sample.

From our own survey data, given immediately before and after the MRI lab, student responses revealed an increase in how the participants defined modeling and the applications for its use, as well as a decrease in the misconceptions and limitations associated with modeling (see Fig. 7). For example, participant's 1271 response to the question, "What is scientific modeling and why is it significant to experimentation?" shifted in the following way:

> Before the MRI lab: I believe scientific modeling is addressing something that is difficult to capture since it is not easily visible. But the best way to learn it is with experimenting.
>
> After the MRI lab: Scientific modeling uses models and examples to explain and predict the behavior of real objects or systems. Modeling is significant to experimentation because it can help to provide hypothetical models as part of experimental design and can be adjusted/corrected after experimentation to explain results of an experiment in a more concrete/applicable way to both experimenters and to the general scientific community (participant 1271).

While their first response described using models when systems are "not easily visible," which could limit the use of modeling to those types of systems, their second response captures a more inclusive definition that highlights the ability to make predictions for any experimentation. We found that 65% of the participants experienced a similar shift in the positive direction.

While the changes in each category are not large, the data suggest that experiencing student-designed and modeling-focused laboratories can improve student perception and understanding of the modeling practice. To better understand the misconceptions and limitations the undergraduates had, we analyzed the undergraduate's responses that were coded as deficient in some way. Distinguishing limitations from misconceptions, we considered unnecessary constraints on modeling to be limitations while incorrect statements about modeling were categorized as misconceptions. For example, when participant 9618 stated, "Scientific modeling uses physical representations to explain a concept," they were not necessarily incorrect, but they did limit models to being

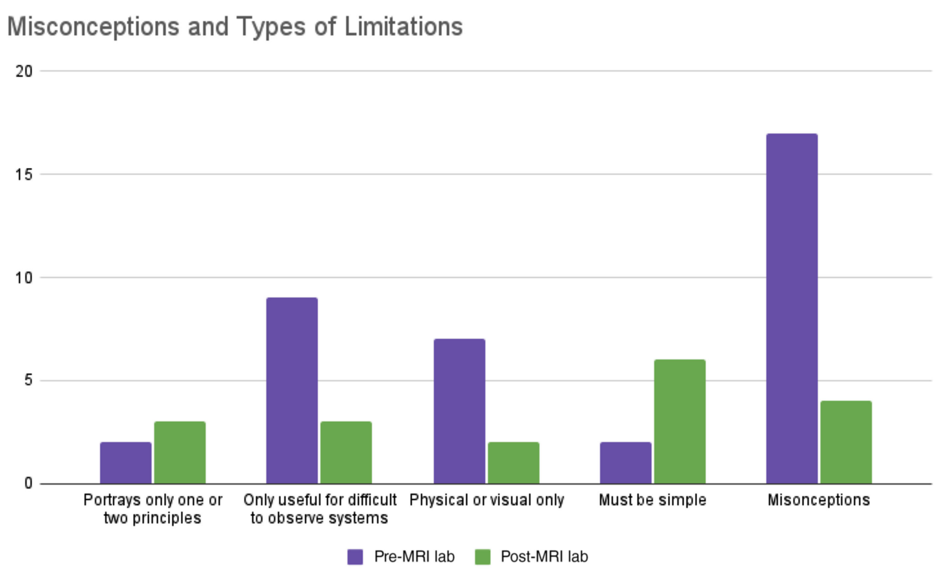


FIG. 8. The changes in limitations and misconceptions students associated with modeling. The scale represents the number of instances each type of limitation or misconception occurred.

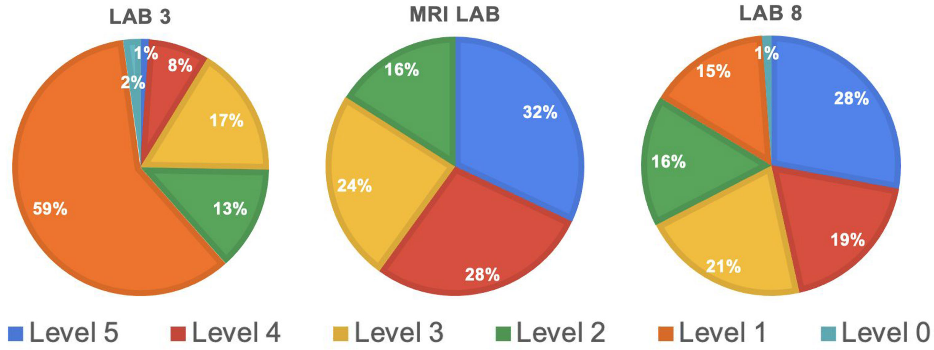


FIG. 9. Student modeling sophistication rubric (MSR) levels of performance for lab 3, MRI lab, and lab 8. Levels 1–3 are secondary levels and levels 4–6 are college level modeling. There were no instances of level 6 modeling.

physical representations and thus could have excluded the possibility of mental or mathematical models. Figure 8 evidences a decrease in student-held limitations that scientific models are only useful in difficult to observe systems and that models are primarily physical or visual representations of those systems. Simultaneously, however, there was also an increase in two of the limitations: models only portray one or two principles and models can only be simple. While it is good practice to use simple and familiar models, they are not necessarily constrained to simplicity. The most frequently occurring limitations shifted from the idea that models are only useful in difficult to observe systems to the stipulation that models must be simple. One participant's (3621) change in response looked like this:

> Before the MRI lab: Models are used when it is either impossible or impractical to create experimental conditions where scientists can directly measure outcomes. A model allows them to ignore the uncertainty and not have to deal with the potential legal or ethical problems, and still observe phenomenon.
>
> After the MRI lab: Scientific modeling is when you take a concept or phenomena that is difficult to view directly and create some sort of simplified version or model of it in order to view the effects. We will be using physical models as well as mathematical representations (participant 3621)

B. Changes in undergraduate modeling performance

To understand the level of scientific modeling that students performed before, during, and after the MRI lab, we used the MSR rubric outlined in the methods section to categorize students into six levels of sophistication. Because PHSCS 108 is an introductory physics course for nonmajors, we expected students' physics modeling skills at the beginning of the semester to be primarily at the secondary level of scientific modeling.

Figure 9 displays the proportion of students who achieved a given level of sophistication in their modeling work. The data show that most of the sampled students performed at the introductory and advanced secondary levels of modeling (levels 1–3 of the rubric) in lab 3. In the MRI lab, levels of student modeling performance increased to primarily introductory and intermediate college levels of modeling (levels 4 and 5). Observing the improvement in both the quality and quantity of student scientific modeling validated our efforts to both expand the inquiry nature of the labs and situate the learning within models that interest them. Wanting to verify that the modeling practices the undergraduates learned in the MRI lab could persist, we also assessed the participants' modeling sophistication in lab 8. While some students did drop back down to lower secondary levels of modeling (levels 1–3) in lab 8, 47% maintained the introductory and intermediate college levels of modeling (levels 4 and 5), with only 31% of students in the lowest levels of secondary modeling.

To further our analysis, we separated the analyzed sample into groups based on declared major and their class (senior, junior, sophomore). For the majors, we sorted the sample into four groups: biology, neuroscience, health, and humanities and social science. Treating the level of sophistication score as a continuous variable (an assumption that can limit the following results), we calculated averages and standard errors for each lab and gave the results in Table VI.

TABLE VI. MSR rubric results for analyzed samples separated by major and class. Note that results represent a mean score followed by the standard error in parentheses.

	Lab 3	MRI lab	Lab 8
Biology ($N = 36$)	1.69 (0.17)	3.62 (0.17)	3.59 (0.26)
Neuroscience ($N = 20$)	1.75 (0.24)	4.00 (0.26)	2.83 (0.34)
Health ($N = 27$)	1.77 (0.22)	3.97 (0.18)	3.16 (0.30)
Humanities and social science ($N = 6$)	1.50 (0.50)	3.86 (0.40)	3.67 (0.49)
Senior ($N = 59$)	1.71 (0.14)	3.88 (0.14)	3.23 (0.22)
Junior ($N = 24$)	1.75 (0.24)	3.62 (0.20)	3.52 (0.25)
Sophomore ($N = 5$)	1.60 (0.40)	4.17 (0.30)	3.20 (0.58)

TABLE VII. The percent of individual elements of MSR found across all students in each lab.

	Science principle	Patterns	Predicts	Limitation	Sense making	Assumptions	Multiple models	Complete analysis	Systematic error
Lab 3	86	85	44	0	11	2	32	9	12
MRI	100	100	68	96	64	32	68	40	76
Lab 8	92	87	58	98	18	42	82	38	53

Within any of the grouped lab averages (either the majors group or the class group) for a given lab, the set shows no significance within group differences using an analysis of variance test. Meaning that none of the averages within the group is significantly different than the others. Within any of the categories (either major or class), the results of the MRI lab and lab 8 are significantly different than the lab 3 results. While the lab 8 scores are slightly lower than the MRI scores, in most cases that difference is not significant. We note that while the MSR rubric scores are not continuous and the sample size for sophomore and humanities and social science are smaller than allowed in the model assumptions, we find these results instructive and that they show a general pattern of gaining skill in modeling and maintaining that skill over time.

Finally, we include the percent of the individual elements of the MSR we found for the undergraduates across each of the analyzed labs (see Table VII). We note that differences in percentages from one lab to another can change because different types of lab work can require different analyses, but we find some of the shifts instructive. For example, moving to an inquiry and model drive lab (for both the MRI and Lab 8) drastically increased the undergraduates' consideration of limitations in their models. We also note, how many more students engaged in sensemaking with their MRI models when the learning was situated in a context they could relate to.

V. DISCUSSION

For pre-medical undergraduate students, engaging in scientific modeling can be an enhanced learning experience when labs are appropriately scaffolded and situated to applications in the medical field. The following sections discuss the importance of modeling and situated learning in classrooms, how scaffolding benefits students, and suggestions for implementation in each section.

A. The importance of modeling in science classrooms

Based on our previously outlined learning goals for nonmajor physics college courses, we hope to see students engage with scientific modeling in a way that describes specific scientific phenomena in simple ways that are both familiar to them and can provide grounds for predicting outcomes [14,15]. The shifts in limitations and misconceptions in Fig. 8 show students aligning more closely with that expectation after participating in the MRI lab. These improvements were made without direct instruction on the importance or application of scientific modeling. Students learned the principles by first, using modeling as a tool through the provided model of the MRI lab; and second, constructing their own models (mathematical or mental) through analysis and making sense of their data [9]. The MRI lab also included a day where the students presented their results to the other groups in their sections. As a part of these presentations, each group was able to see different ways of modeling the data they worked with. Exposing the students to a broader view of modeling in this way could have caused the decrease in misconceptions we found in the data. We suggest that introductory lab courses build modeling into their curriculum by providing both relevant and interesting models for the students to work with and by encouraging the undergraduates to construct their own models to describe the phenomena they are studying.

The fraction of expertlike responses from our class to the statement, "When doing an experiment, I usually think up my own questions to investigate," (see Fig. 6) increased over the course of the semester, and it did so when other similar courses usually experienced a decrease. This increase may be attributed to the opportunities to create and experiment upon their own questions and models (found in both the MRI lab and lab 8) that helped the students better utilize scientific processes in their work [12].

B. Scaffolding modeling in introductory labs

Participation in scientific modeling, as measured by the MSR, appeared to change given the amount of scaffolding present in each lab [32]. Lab 3 was traditionally scaffolded and did not provide much room for students to freely explore the models presented. For example, they were asked to complete specific tasks with the models that had expected outcomes. We designed the MRI lab on the other end of the scaffolding spectrum. We encouraged scientific modeling in a way that allowed the undergraduates to define, design, and experiment on their own. We built lab 8 with similar freedoms in the design process and opportunities to model. In this lab, we included a more guided inquiry style of scaffolding to help the students in a new aspect of modeling which engaged them with opportunities to revise their models. For example, the scaffolding in lab 8 prompted the undergraduates to challenge their initial models by collecting extra data, looking for inconsistencies in their model, or adjusting their procedures to account for possible procedural error. For introductory lab courses, we encourage instructors to follow a similar pattern, asking their students to engage in more and more of the modeling process as the semester progresses.

The decrease in expertlike responses for questions 27 and 28 may indicate that the cognitive load of diving into the scientific process without the traditional step-by-step scaffolding of a “cookbook” style lab may have been a frustrating experience for the students [41]. There is a balance that science teachers must find between providing too much scaffolding and not providing enough. An appropriate amount of scaffolding is a powerful tool, especially when used in a situated learning environment [28].

C. Situated learning and student interests

The MRI lab situated the student learning in an environment relevant to the student’s future careers. This relevant context was likely one of the factors that helped the students perform at a higher average MSR level than they did in labs 3 and 8. For example, the improvement in modeling measured from lab 3 to the MRI was an increase from only 9% of the students modeling at the higher levels of the rubric to 60% of them showing this proficiency. In lab 8 (a lab with the modeling scaffolding but a less relevant context), we only measured 47% of the students to be in the higher levels. Here we see some evidence of the possible impact of the relevant context on the undergraduates’ modeling skills. Further work needs to be done to see if this difference holds in different contexts.

Situating the learning of these pre-medical undergraduates likely improved their ability to understand and engage with scientific models and construct further knowledge in their own fields of interest [23]. We propose that because the MRI lab is related to a relevant topic of interest, our students learned principles that will remain applicable to them [25]. For example, our physics class of pre-medical students may have benefited from a lab on MRI machines, but a class of civil engineers might have benefited more from a lab on power lines and city electrical grid systems. In this study, the change in the situated nature of the lab was entangled with the change of also giving the students more freedom in the design and structure of the lab (more inquiry based). The student-centered nature of the MRI lab is part of the situated learning the students experience. The inquiry and open nature of the lab is more authentic to real practice and cannot be cut away without also breaking down the opportunities to do authentic modeling.

VI. CONCLUSION

From our findings, we suggest that physics teachers working with nonphysics majors encourage active participation in scientific modeling, and prioritize giving students scientific skills more than scientific facts [10]. We also encourage these instructors to scaffold and situate their labs and investigations within the interests and career aspirations of their students. We plan to continue this work with our students as we continue to track the student demographics and shift our lab experiences to be both authentic science experiences and situated in the interests and aspirations of the attending students. This will help the undergraduates because they will likely be working with those contexts in their futures and will be better able to recall the principles they used in those learning environments [27].

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