Supporting Scientific Practice through Model-Based Inquiry: A Students'-Eye View of Grappling with Data, Uncertainty, and Community in a Laboratory Experience

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ABSTRACT

Modeling is a scientific practice that supports creative reasoning, motivates inquiry, and facilitates community sense-making. This paper explores students' perspectives on modeling in an undergraduate laboratory course, Authentic Inquiry through Modeling (AIM-Bio), in which they proposed, tested, and revised their own models. We conducted comparative case studies of eight students over a semester. Students described using models to support multiple forms of scientific reasoning and hypothesis generation. They recounted the challenges of dealing with uncertainty and integrating diverse ideas. They also described how these challenges pushed their thinking. Overall, students reported feeling a sense of scientific authenticity and agency through their modeling experience. We additionally provide an in-depth look at two students whose unique experiences in AIM-Bio emphasize the variable ways modeling can support inquiry learning. We claim that modeling emerged as a legitimate practice among students, because the AIM-Bio curriculum encouraged diversity in students' models, provided opportunities for students to grapple with uncertainty, and fostered collaboration between students. We suggest that biology educators consider how model-based inquiry can allow students to participate in science, as a way to support interest in, identification with, and ultimately persistence in science, technology, engineering, and mathematics fields.

INTRODUCTION

Human creativity and our desire to explain the natural world are key drivers in the process of science. A central challenge for science educators is making room for these aspects of science in our classroom learning environments. By understanding the "practices" that scientists' use to do their work, we can learn ways to capitalize on students' social and cognitive resources for authentic participation in science (Ford, 2008; Lehrer and Schauble, 2015; Manz, 2015; Berland *et al.*, 2016).

One such scientific practice, *modeling*, is at the heart of the process of science (Giere, 1988; Frigg and Hartmann, 2006). Scientists use models as tools to form predictions, to make sense of experimental findings, and to generate ideas (Odenbaugh, 2005; Passmore *et al.*, 2009). While traditional accounts of the scientific process emphasize a linear application of deductive logic, research has shown that additional forms of model-based reasoning are often necessary to make the creative leaps used to explain novel phenomena (Nersessian, 2002). Modeling is also a social practice, as model representations can serve as shared resources for communicating, questioning, and refining scientific explanations (Latour, 1999; Nersessian, 2017). Given the ways that modeling supports creative and social reasoning among scientists, it is important to consider how this scientific practice may be beneficial for students.

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In this paper, we aim to motivate attention of biology education researchers to engaging students in the practice of modeling at the undergraduate level. To do that, we first describe what it means to conceptualize modeling as a scientific "practice" and review the opportunities for learning that this conceptualization affords. We then present empirical data from a classroom study of students' experiences with and perceptions of modeling practice. We use these data to enumerate and illustrate how modeling supports students' creativity, agency, and collaborative sense-making. We end by discussing the instructional implications raised by these data.

Modeling as a Scientific Practice

The practice of modeling in science has been well documented by cognitive-historical, psychological, and ethnographic studies of scientists in practice (Giere, 1988; Morrison and Morgan, 1999; Nersessian, 1999; Odenbaugh, 2005). This work has also been used to motivate the importance of engaging learners in modeling (Nersessian, 1995; Svoboda and Passmore, 2010; Lehrer and Schauble, 2012). In the remainder of this section, we briefly summarize what studies of scientific modeling have revealed about how this practice supports the intellectual and social work of scientists.

First, modeling is a highly *creative practice*. In constructing models, scientists decide which features of reality to include and which to ignore—what to "show and hide" (Lehrer and Schauble, 2010). This aspect of modeling emphasizes that models are not made to literally represent the world, but rather are sense-making tools that must be flexibly adapted to specific epistemic tasks (Passmore *et al.*, 2014). Modelers also decide *how* to represent the features of reality included in their model, taking aspects of the world and converting them into diagrams, symbols, or computer code (Knuuttila, 2005). Such decisions are made in accordance with the modelers' aims and priorities, such as building explanations, making predictions, exploring new ideas, or posing questions (Odenbaugh, 2005).

Second, modeling is a *community practice*. Whether working alone or in collaboration, modelers depend on the ideas and feedback of the scientific community to inform their work. Scientists use model representations to make their explanations visible to other scientists, opening the way for communication, critique, and refinement of ideas (Dunbar, 1999). Through participation in modeling within a scientific community, researchers act as both critics and constructors of knowledge, two central aspects of scientific practice (Ford, 2008).

A third major theme emphasizes how models function as tools for supporting various forms of *scientific reasoning*. One such form of reasoning is *visual-spatial*. For example, simple drawings translate microscopic entities into visible icons and relate objects separated in space or time. Three-dimensional molecular models enhance visibility of relevant entities and promote reasoning about spatial relationships (Nersessian, 2008). While models make some features more visible, they make other features less visible, reducing the details of reality to amplify the most salient aspects for explanation (Latour, 1999). Abstraction facilitates *analogical reasoning* across different problem contexts, allowing scientists to build new explanations based on existing models (Dunbar, 1999; Nersessian, 1999). Famously, James Maxwell built a model for electromagnetic fields through analogical reasoning about the mechanics of spinning wheels (Davies *et al.*, 2005). In biology, models can abstract away from specific organisms to reveal more general mechanisms. For example, a biologist might use a mechanistic model that explains the actions of a protein in *Saccharomyces cerevisiae* to begin to explain the involvement of a homologous protein in human disease (Dunbar, 1999). In addition, scientists use models to engage in *simulative reasoning*, or making their ideas "playable" in the mind (Nersessian, 2008). For example, models in molecular and cellular biology often include drawings of mechanisms composed of entities (e.g., ribosomes) having particular properties (e.g., composed on macromolecules with certain structures) that allow them to perform activities (e.g., translation of mRNA to protein; Machamer *et al.*, 2000; Darden, 2002; van Mil *et al.*, 2013). When reasoning through a model, scientists use simulative reasoning to mentally animate the relevant mechanism (Hegarty, 2004; Nersessian, 2008). In such episodes, a scientist often "plays" the mechanism from initial or starting conditions to termination conditions, using causal reasoning to connect ideas (Machamer *et al.*, 2000; Darden, 2002). In the case of protein synthesis, a scientist might say,

> First, the small subunit of the ribosome scans the mRNA until it find the start codon, which causes the recruitment of the large subunit of the ribosome, so then a tRNA enters the A site and because its anticodon is complementary to the next codon it binds, which brings in an amino acid…

Similarly, computational models extend the limits of the mind to allow scientists to explore how model outcomes change over a range of parameters or over time (Nersessian, 2009; Morrison, 2015). Simulative reasoning is an important aspect of scientific creativity, serving as a way to use models to generate new ideas and hypotheses and to examine the plausibility of those ideas (Duncan, 2007; Nersessian, 2008; van Mil *et al.*, 2013; Southard *et al.*, 2017).

Finally, models include a blend of elements of the world (i.e., data and direct observations of phenomena) and elements of our theories about the world (Morrison and Morgan, 1999). Because models include select elements of both data and theory, but are not completely tied to either, they allow scientists to *reason across these domains*. For example, data are used to iteratively refine models, improving their accuracy. Thus, some models will attain relatively high fidelity to the world; but models need not be completely accurate to be useful in scientific endeavors (Odenbaugh, 2005). Modeling is often considered productive for its ability to foster generative reasoning, serving as a conceptual framework to motivate further experiments (Odenbaugh, 2005). Thus we may conceive of models as a hybrid space, bringing together data and theory, for the purpose of creative reasoning about phenomena.

In sum, the practice of modeling requires and therefore stimulates opportunities to exercise a variety of forms of scientific reasoning. For this reason, many have argued that students can benefit from engaging in this practice, and a variety of forms of model-based instruction (MBI) are becoming more popular. Yet teaching modeling as a practice is challenging; unlike skills, practices cannot be directly taught (Ford, 2008, 2015). Taking a "science-as-practice" view acknowledges that, in order to teach modeling in context, educators should be open to introducing students to more authentic scientific experiences in which they must creatively and flexibly collaborate to solve problems (Lehrer and Schauble, 2006). In the next section, we briefly review forms of MBI most relevant to undergraduate biology education and where modeling as practice fits into this prior work.

MBI in Science Education

MBI takes a variety of forms in science education supporting different learning purposes.

One main strand of work in undergraduate biology education leverages the visual and organizational power of modeling to help students build, change, or reinforce conceptual understandings (Dauer *et al.*, 2013; Dauer and Long, 2015; Speth *et al.*, 2014). In this type of instruction, students draw and revise conceptual models, which are similar to concept maps, in order to represent their current understandings of biological ideas or processes (e.g., evolution and the genetic origins of variation). The purpose of this activity is to help students externalize their current understandings of how various ideas relate. Once these connections are externalized, both students and instructors can evaluate and refine them. Over time, this process can help students build and retain more connections among core biological concepts (Dauer and Long, 2015).

A second line of work, which has roots in K–12 education, aims to support students' own modeling practice (Lehrer and Schauble, 2005; Windschitl *et al.*, 2008; Passmore *et al.*, 2009; Schwarz *et al.*, 2009). This form of instruction, often termed *model-based inquiry*, is grounded in understandings of how scientists use models. Here, models take the form that is appropriate to the inquiry at hand (e.g., mechanistic drawings or mathematical models) and are used primarily as reasoning tools for students as they build and refine explanations from observation or experimentation.

A main difference between the two approaches is that the former is primarily concerned with helping students attain more normative conceptual understandings, while the latter is more concerned with supporting students in building and reasoning with models that support their scientific investigations. In classrooms where the primary purpose is enrichment of conceptual understanding, students' models are expected to change to include a greater number of scientifically accurate connections (Dauer *et al.*, 2013) or to more closely resemble target understandings (Speth *et al.*, 2014). This is made possible through assessment and feedback that is designed to improve model correctness. In classrooms where the primary purpose is for students to engage in scientific practices, models may also become more scientifically correct over time, but arrival at a specified target model is not the classroom goal (Svoboda and Passmore, 2013; Hester *et al.*, 2018). Instead, instructors focus on students' ability to justify their modeling decisions with evidence and to distinguish the plausibility of competing models (Svoboda and Passmore, 2010).

Educators may often value both conceptual understanding and learning modeling practice. However, the two purposes often trade off against one another. When students and instructors understand the goal of modeling activities as arriving at a particular set of ideas, the conditions necessary to support modeling practice may be undercut. Students who perceive modeling to be about recreating canonical knowledge may be less willing to propose or explore their own ideas, deferring to instructors or textbooks rather than engaging with reasoning and evidence (Berland *et al.*, 2016; Miller *et al.*, 2018). Similarly, instructors who have a correct target model in mind can miss opportunities to engage with students' thinking, focusing on getting students to a predetermined end product rather than on the process of revising ideas (Gouvea and Passmore, 2017; Miller *et al.*, 2018; Guy-Gaytán *et al.*, 2019).

Engaging Students in the Practice of Modeling

The rationale for engaging students in the practice of modeling stems from a body of work that describes the benefits of doing so. Instruction that makes use of models as a thinking tool often supports students' ability to generate ideas. Asking students to create a model first supposes that students *have* ideas worth documenting and builds on a long history of instructors asking students to construct their own explanations through modeling (Passmore and Stewart, 2002; Lehrer and Schauble, 2005; Louca and Zacharia, 2012). Taking students' ideas into account when they are developing an explanation for a phenomenon is likely to signal to students that their prior experiences and personal reasoning matter, potentially leading to enhanced engagement and learning (Rivet and Krajcik, 2008; Berland *et al.*, 2016; Miller *et al.*, 2018).

Engaging students in modeling also means inviting them into a scientific community (Brewe *et al.*, 2010). In this community students can learn to refine their thinking about particular phenomena as well as to participate in negotiations with peers and instructors about how evidence supports models and the purpose of models (Lehrer and Schauble, 2005). Mutual engagement by participants in this community of practice can lead to recognition, a sense of belonging and demonstrated competence that can contribute to participants' identity as "scientists" (Wenger, 1999; Carlone and Johnson, 2007; Le *et al.*, 2019).

Finally, modeling is likely to support students' use of visual-spatial reasoning, abstraction, and simulative reasoning as they engage in the task of generating explanations of the world (e.g., Svoboda and Passmore, 2013; Wilkerson-Jerde *et al.*, 2015).

In these ways, prior work has made a compelling case for the promise of engaging students in the practice of modeling and forms the rationale for the design of Authentic Inquiry through Modeling in Biology (AIM-Bio). In this study we examined this potential from the perspective of the students themselves, by asking students to tell us about their experiences as modelers.

RESEARCH QUESTION

Our study takes place in the context of an introductory undergraduate biology laboratory course. Students were engaged in the AIM-Bio curriculum, which provided them opportunities to collaboratively propose models to explain observable biological phenomena and to revise those models after conducting experiments that they designed. We asked the following research question: How did students experience modeling in the AIM-Bio curriculum?

Although much is known about how scientists use models, relatively little is known about the modeling practices that undergraduates might use in an inquiry setting. We wanted to understand how such practices could authentically emerge in unique ways among students. Therefore, our approach to data collection and analysis was intended to allow themes to emerge

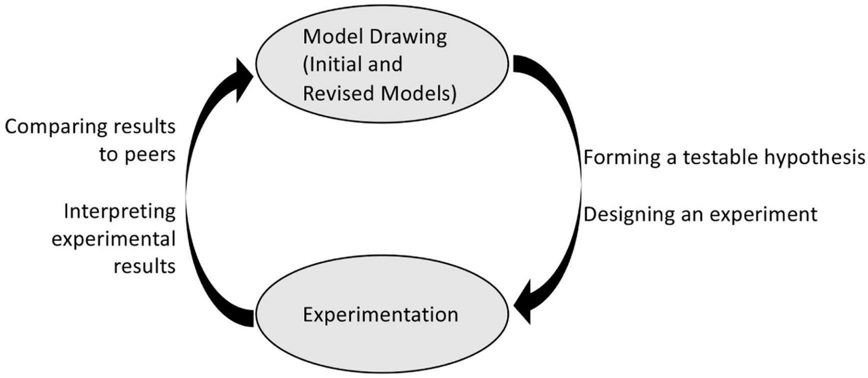


FIGURE 1. Modeling cycle in the AIM-Bio curriculum.

from students' experiences. We placed value on understanding students' own perceptions of their experiences (Nurani, 2008). Therefore, we conducted repeated interviews in which we asked AIM-Bio students to describe their own modeling practices, prompted by discussion of their own model drawings and lab reports.

INSTRUCTIONAL CONTEXT

AIM-Bio is a curriculum developed to bring aspects of an authentic research experience to the laboratory classroom by centering on the scientific practice of modeling (Hester *et al.*, 2018). In developing the curriculum, we worked with collaborating scientists to use biological systems and methods of experimentation that relate to ongoing research, but much of the scientific process was left to the students to develop. Our previous study documented the following outcomes for AIM-Bio students: 1) a greater sense of project ownership, as compared with students in the traditional laboratory curriculum; 2) greater expressed science identity, as compared with students in the traditional laboratory curriculum; 3) increased skills for doing science; and 4) increased understanding of the nature of science (Hester *et al.*, 2018).

Students participate in five units, each lasting 2 or 3 weeks and each focusing on a different biological system. The curriculum is organized around cycles of modeling in which students create initial models, test their models through experimentation, and revise models based on experimental results (Figure 1). The purpose of this activity is to give students practice with proposing, testing, and revising their own models. Students' models often increase in validity as they revise them to fit data; however, matching a specific expert explanation for each phenomenon is not the goal. Each unit scaffolds students through aspects of the modeling cycle, with increased autonomy as the semester progresses. Throughout the semester, students are asked to work in groups to create or revise model drawings with prompts like "Working in your group, draw a model that you can use to explain to your classmates what you think causes the outcomes you observed?" Biological systems were chosen such that a group of undergraduate students were likely to have multiple plausible models, paving the way for classroom model diversity.

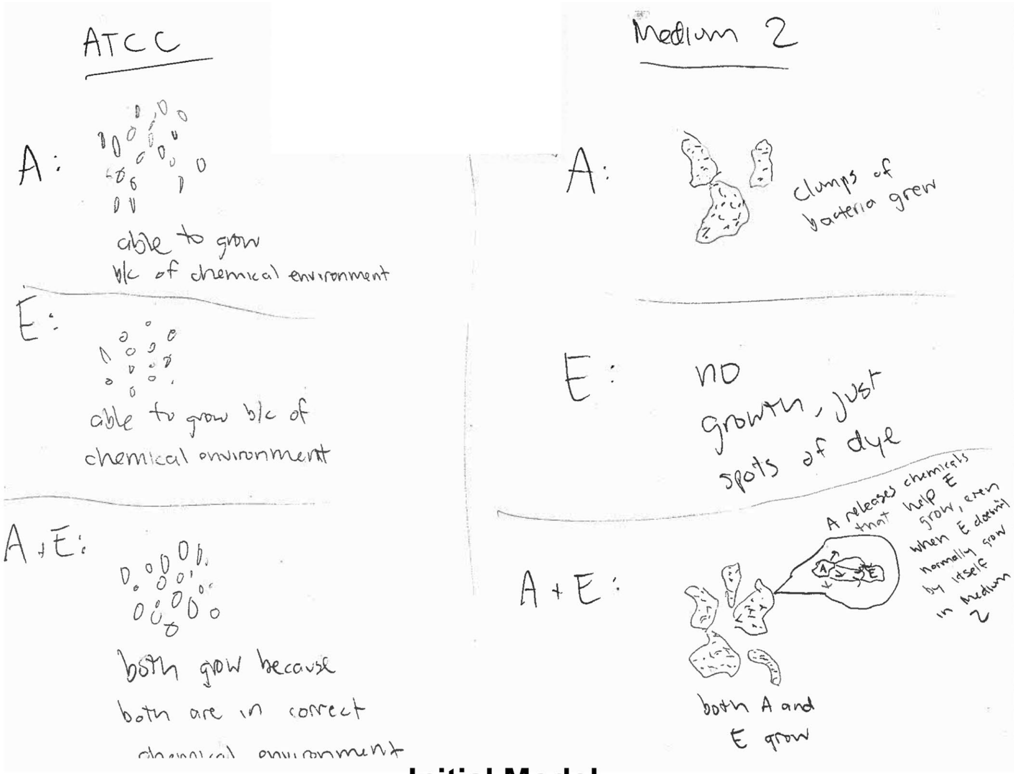
The student interviews that are the focus of this study were performed following three different units. The "Membrane Transport" unit (weeks 2 and 3) asked students to construct and revise models to explain their observations of different cell types in solutions with varied tonicity; laboratory procedures were prescribed. The "Bacterial Growth" unit (weeks 4–6) asked students to construct and revise models to explain a puzzling phenomenon of codependent growth of two different bacterial species; students designed their own experiments to test their hypotheses. The "Genetic Pathways in Yeast" unit (weeks 12–14) asked students to construct a model to explain some aspect of mating in *Saccharomyces cerevisiae*, given mutants in the pathway that led to expression of the *fus-1* gene and the ability to observe the visible "shmooing" phenotype; students posed their own questions and designed experiments to test their own hypotheses.

Figure 2 depicts the initial and final model drawings for one group of students in the Bacterial Growth Unit. In this unit, students observe that, in a rich media (ATCC), two species of bacteria (A and E) can grow independently or together. In a minimal media (medium 2), which contains colominic acid as a carbon source, species A thrives but species E does not reproduce unless species A is also present. This set of observations is a primary focus of the students' initial model. In the final panel of their initial model (bottom right corner), the group provides a hypothesis to explain the puzzling growth pattern: "A releases chemicals that help E grow." These students went on to test their hypothesis by attempting to grow species E in medium 2 that previously contained species A. Positive growth implied that the media contained something from species A that enabled species E to grow. Other groups discovered that species A was able to enzymatically cleave colominic acid. These experimental results formed the basis for the revised model, which depicts a mechanism whereby species A breaks down colominic acid into "nutrients" that are taken up by species E, fostering growth of the bacteria in medium 2. These model drawings show how students' ideas developed by gathering evidence from experimentation. They also show how students used icons, arrows, and words to illustrate the entities and actions within an explanatory mechanism, especially in the revised model.

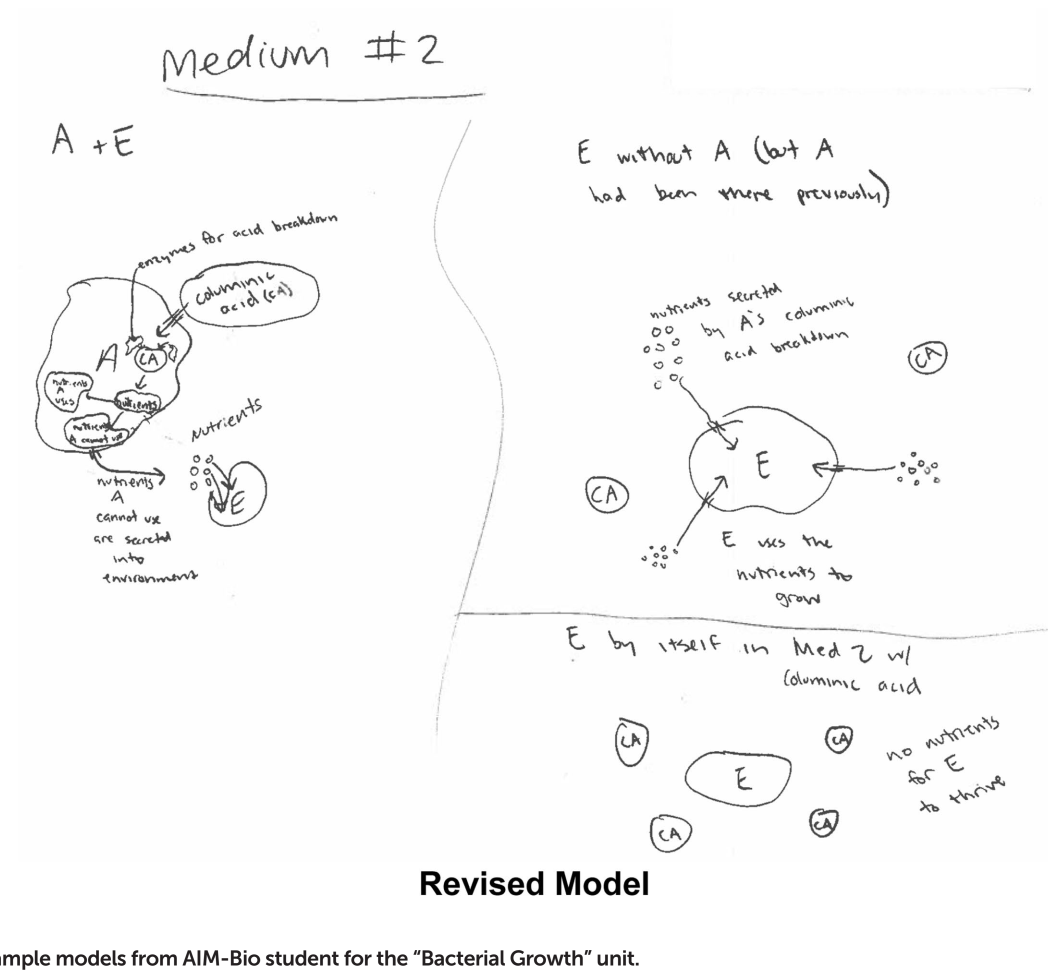
METHODS

Data Collection

Subjects were enrolled in Introductory Biology 1 lab, a one-semester, one-unit course that accompanies the Introductory Biology 1 lab lecture course (MCB 181). Both courses focus on topics in molecular and cellular biology. The course was taught at the University of Arizona, a large, research-intensive, and Hispanic-serving institution. Science, technology, engineering, and mathematics (STEM) persistence is a key challenge among this student population. The DEW (final grade of "D," "E," or course withdrawal) rate for MCB 181 is consistently above 30%. This course is offered within the College of Science, where 22% of underrepresented students do not return to the university after their first year and only 52% of these students have graduated after 5 years.



Initial Model



Revised Model

FIGURE 2. Sample models from AIM-Bio student for the "Bacterial Growth" unit.

Data were collected from a total of 14 consenting students across two sections of the laboratory course utilizing the AIM-Bio curriculum during the Fall 2018 semester. One laboratory section enrolled 22 students, the other 24. Two instructors taught the curriculum during this semester. Interviews were conducted with students who volunteered to participate outside class after each of the three AIM-Bio units were complete; all volunteers were included in the study. Students were compensated for the interviews with small gift cards. Data were collected according to protocols approved by the Institutional Review Board for Human Subjects at our institution.

Interviews were semistructured and focused on students' experiences of modeling in the classroom. All three interviews were anchored by the lab report the student had submitted for the preceding unit. Specifically, students described their final models, explained what changes they made from the initial to final model, and what led them to make those changes. A few specific questions were added to learn more about students' experiences in each unit. The third interview also asked students to reflect back on their experiences during the semester. Interview protocols are provided as Supplemental Material (see Appendix A). We also collected and made copies of consenting students' written work. This work included student model drawings and lab reports after the end of each unit. We refer to the interviewed students with pseudonyms.

Qualitative Data Analysis

To address our research question, we took a case study approach (Yin, 2014). Our goal was to understand the perspective of each research subject with regard to the student's experiences with modeling in the curriculum. Each interview provided an in-depth view of each subject's perspective at a given point in time. However, a subject's perspective is likely to be influenced by the specific context of a particular instructional unit, and we anticipated that subjects' experiences would change over time. Therefore, we decided to include only subjects who participated in two or three interviews (eight students), excluding six other students who participated in only one interview. A total of 21 interview transcripts were analyzed.

Our analysis took place in three phases. During the first phase, we constructed analytic summaries for individual students, drawing on both their interviews and written work. To construct these summaries, we used a constant comparative method (Kolb, 2012) to identify themes from the data. This phase included independent noticing by two researchers (M.S.B. and J.B.O.) and regular meetings to discuss our developing understanding of each case. The first pass through the data was inductive. We took this approach because we wanted to understand students' perspectives on their own experiences in the lab. We then compared these inductive themes with categories derived from the literature on scientific modeling. Through these comparisons, we found that some emergent themes (e.g., students' descriptions of reasoning) aligned well with ideas in the modeling literature, while others captured students' local experiences in the course (e.g., students' responses to uncertainty).

The second phase included a cross-case analysis (Khan and Van Wynsberghe, 2008) in which we discussed similarities and differences between cases. A cross-case analysis can be useful to build greater explanatory power (as one case makes more sense in light of another) and to move toward generalizations. This phase of analysis led to the identification of themes that emerged to describe important ideas across our data set.

In the third phase, we extended our analysis for two case study students, Joan and Sofia, chosen because they described different experiences. In this phase, we sought to provide a narrative description of the experiences of each student. Whereas our initial case studies were bounded only by the research question ("How did students experience modeling in the AIM-Bio curriculum?"), the final phase was more constrained. Specifically, we used each student's responses to exit interview questions to determine which aspects of the AIM-Bio experience the student found most salient. After making this determination for each individual, we reanalyzed each case through this lens. This allowed us to provide a narrative of how a single, salient aspect developed over time.

Case Study Subjects

Table 1 presents the eight students who were the subject of this study, referred to by pseudonym. We present basic information available to the instructor (year of study and major); no informed consent was obtained for collection or presentation of any further demographic data. Previously, we presented outcomes of the AIM-Bio curriculum among a larger population of students (Hester *et al.*, 2018). To provide context for the case studies, we summarize these same pieces of information about each participant in Table 1.

First, our previous work found that AIM-Bio students scored higher on the Project Ownership Survey (POS; Hanauer and Dolan, 2014) than students in the same course experiencing a traditional curriculum. Published scores for AIM-Bio students were similar to those previously reported for research-based laboratory curricula (Hester *et al.*, 2018), suggesting that different forms of curricula that relate to authentic research may foster this outcome for students. Case study subjects POS scores were similar to the average for AIM-Bio students (Table 1). Note that lower scores on this instrument indicate higher ownership. Some subjects' scores suggested greater than average ownership; two subjects' scores indicated lower than average ownership. However, this instrument was designed to measure aggregate student responses across a population and may not be appropriate for drawing conclusions at the individual level.

Second, our previous work (Hester *et al.*, 2018) found that AIM-Bio students' scores on an adapted version of the Classroom Test of Scientific Reasoning (Benford and Lawson, 2001) improved after instruction. This instrument is intended to measure students' general facility with scientific reasoning (e.g., drawing logical conclusions from experimental data, correctly controlling variables, and reasoning about proportions) in a context appropriate for introductory-level science students. Typically, scores on this instrument do not increase following introductory course work (Johnson and Lawson, 1998; Benford and Lawson, 2001). The ways in which students may participate in authentic scientific reasoning with models in a classroom setting are much more complex than what can be measured with this instrument; however, we present scores for each participant to provide context for the cases. Table 1 suggests

TABLE 1. Case study students

Case	Class standing, major	POS score[a]	Pre, Post assessment[b]	Exit survey response to "Have you ever felt like a scientist?"
Michelle	Junior, engineering	1.75	100%, 96%	"I took O Chem 1 lab, which was very hands on. Also, getting to design our own experiments I this lab makes me feel like a scientist because I have to actually think about the process and what I am testing."
Joan	Senior, engineering	2.38	100%, 100%	"Yes, in this lab. We observed something, made a hypothesis about what we thought was happening, then designed an experiment, tested our hypothesis, and wrote a report explaining what the process was and the results of the process."
Nicole	Junior, life sciences	2.94	56%, 40%	No data
Jasmine	Sophomore, agriculture science	1.81	64%, 72%	"Yes, because of the experiments we have done in this class. I felt like an actual scientist when we had to come up with a model and different experiments to try to find a scientific explanation for the phenomena we've seen."
Kyle	Senior, engineering	1.81	92%, 96%	"Yes, in this lab of course!"
Mike	Senior, agriculture sciences	2.56	60%, 68%	"Yes, every time I test a hypothesis and get conclusive results."
Sanjay	Junior, life sciences and physical sciences	1.50	No data, 88%	"This lab makes me feel like a scientist in that we were able to come up with our own hypotheses and models regarding phenomena we observed."
Sofia	Sophomore, life sciences	1.69	76%, 80%	"Being in this class has made me feel like a scientist. I feel that being a scientist means being able to form educated explanations, test them, and view whether it's supported. And if it isn't then reflect off the data. I did exactly these things in the MCB lab."

[a]Previously published mean POS score for students in the AIM-Bio curriculum was 2.40 compared with 2.77 for the traditional curriculum (significance confirmed by a Welch's two-sample t test, $p < 0.0001$).
[b]Previously published skills assessment average was 66% pre and 72% post for AIM-Bio students (significance confirmed by a Welch's two-tailed, paired t test, $p = 0.032$).

that the general trend for small improvements in scores pre–post is similar among case study students and the general AIM-Bio population. In addition, case study students ranged widely in their scores. The mean pre-score for case study students was 78.3% with an SD of 17.6 (80.0% ± 18.7 for post scores). While it is difficult to know whether a student's score on this instrument would impact how they might engage in scientific modeling, scores do suggest that students entered the course with different levels of prior experience with formal logic in science.

Third, in our previous work, we analyzed written responses to the question "Have you ever felt like a scientist?" as an informal window into students' perspectives on science identity (Hester *et al.*, 2018). We found that AIM-Bio students were more likely than those in the traditional curriculum to answer "yes" and to indicate experiences in the course that they viewed as authentic scientific experiences. We provide the response to this question for each case study student from an exit survey given during class (Table 1). All case study participants who completed the survey (seven) stated that they did "feel like a scientist," specifically indicating experiences in the course (in all but one case).

RESULTS

The question guiding our study was "How did students experience modeling in the AIM-Bio curriculum?" In the sections that follow, we present five themes that emerged from our eight case studies, highlighting both the commonalities and variation of experience. We indicate the pseudonyms of each student, which will allow the reader to follow each individual case. We end the *Results* section with an elaboration of two cases.

Theme 1: Students Faced Uncertainty and Unexpected Results when Modeling

The AIM-Bio curriculum placed students in the position to make hypotheses and predictions based on their initial models of a system. All interviewed students reported having experimental results that were unexpected or puzzling. However, they reacted in different ways to these results.

Unexpected data often evoked a sense-making process involving the adjustment of prior models or explanations. Jasmine explained how this process occurred. First, she described the sense-making that she and her peers engaged in when they did not see what they expected.

1. **Jasmine:** I was surprised when it happened, but I think
2. afterwards as I was thinking about it, it made sense in my head…
3. **Interviewer:** And how did you react when you didn't see
4. what you first predicted? How did you react and how did
5. you figure out what to do next? Or how to proceed?
6. **Jasmine:** So, it really was like a little bit surprising, um, kind
7. of made me think about it but, um, I don't know, it was
8. just weird. Like I had to think about it a lot in order to
9. figure out why that was happening in the oocyte versus like
10. what happened in the elodea leaf and the red blood cell. (Quote A)

When Jasmine's group encountered an unexpected result, they found it "just weird," which provoked Jasmine to try to explain the new observation (lines 8–10). Next, the interviewer asked Jasmine whether this sense-making was connected to her process of model revision.

1. **Interviewer:** Okay. Um, after finding out that it didn't
2. match your predictions and being surprised, did you think
3. at all about your model and how that could possibly be
4. modified or was it more just like in yourself thinking about
5. like why it did make sense or didn't make sense?
6. **Jasmine:** At first it was more in myself like trying to figure
7. out like why. What was going on? Um, but then when we
8. sat down and looked at our initial model, that's when I
9. realized that like oh, we did something wrong, there was
10. something missing in our model. (Quote B)

Here, we see that the process of revising her initial model prompted Jasmine to rethink her explanation for the phenomenon. Specifically, she revised her model to include a transport protein in order to more fully explain the movement of water across the plasma membrane.

Students did not always react to unexpected results with sense-making leading to model change. In some cases, unexpected results were viewed as confusing by students, and unexpected results were sometimes dismissed. For example, Michelle explained that when another group had an experimental result that she did not expect (in the Bacterial Growth Unit), she ultimately decided the other group had done "something wrong":

1. Well, [the Bio Babes] said that when they grew species E
2. and A in colominic, or in medium with no acid that nothing
3. grew. So, I don't know if that was just like, if they did
4. something wrong or what because I expected like at least
5. A would grow since there was no colominic acid for A to
6. break down … —Michelle (Quote C)

When we further followed Michelle's description of this episode, we found that, rather than consider what unexpected data might mean, she dismissed it as an error. Whereas a scientist might use this as an opportunity to repeat her experiment, Michelle did not have this opportunity due to the limitations of time in the curriculum.

In a few cases, students chose to disengage rather than to explain a puzzling result, for example:

1. **Interviewer:** And how did you react when you didn't
2. see what you predicted? And what did you, what did you do next?
3. **Nicole:** Like we were we were shocked at first like we
4. didn'tknow like what else to do like. So we just like we just
5. we didn't go into it further. We're like OK this is what
6. happened. So, we just like did [what] we have to do,
7. cleaned up and then we just went back to our desk and
8. just talked about like the experiment in general. (Quote D)

Through Nicole's experience, we can see that unpredicted experimental results could be legitimately confusing for students. This uncertainty was not necessarily resolved at the end of a lab period or even at the end of a lab unit.

Overall, while not all uncertainty was resolved, we found that uncertainty often afforded opportunities for sense-making. Sense-making frequently began with interpreting unexpected experimental results. Then, through a process of reconciling data with different predictions and hypotheses, uncertainty prompted some students to adapt their explanations through modeling.

Theme 2: Students Experienced Modeling, Experimental Design, and Data Interpretation as Connected Scientific Practices

One of the features that distinguishes scientific practice from an isolated skill is the interconnection between multiple scientific activities (Lehrer and Schauble, 2006; Ford, 2015; Berland *et al.*, 2016). That is to say, when scientists or students authentically engage in solving a problem, they fluidly apply the different scientific practices that are needed to solve that problem. The AIM-Bio curriculum is designed to scaffold students' use of science practices, as units revolve around a modeling cycle that sequentially moves from model creation to experimental design and finally to data interpretation and model revision. However, during interviews, we found that students referred to these activities as interrelated practices, not only as isolated classroom tasks. For example, when asked, "Will you walk me through your final model please?" Kyle responded (emphasis added to highlight practices):

1. Basically, the revised model, we're looking at an
2. environmental explanation for why E was able to survive,
3. when it was with A in the colominic acid solution. So, we
4. hypothesized that when we had a colominic acid solution
5. that A was added to (reference to the experiment Kyle
6. designed), A changed the solution in such a way that E was
7. able to survive in it. And based on the testing and evidence
8. that we gathered, we also hypothesized that what's being
9. changed in the solution was the colominic acid is being
10. broken down into, chemicals, we don't know what that
11. chemical is, but we know it's a broken down form of
12. colominic acid. And then when, even when you take A out
13. of that solution, because it has been altered by A, um, E can
14. survive in that solution.—Kyle (Quote E)

When asked about his model drawing, Kyle responded by referring to at least four different scientific practices: modeling (line1), hypothesizing (lines 4–8), experimental design (lines 3–7), and data interpretation (lines 7–14). His explanation moves fluidly through these practices in an interrelated way. This integration of multiple scientific practices around modeling was common in the cases we analyzed but seemed to be more fluid in the experience of some students than others. Students were not necessarily conscious of the way they were integrating multiple practices, but one student, Joan, did articulate in her last interview how the process of modeling evolved from a classroom requirement to an ongoing part of her inquiry process:

1. I mean, I guess by the end by this last project I feel like my
2. group and I spent a lot of time like we were really
3. conscious of the models that we were eventually going to
4. have to draw. So, I feel like we thought like instead of
5. waiting until the end of the experiment to like sit down
6. and draw the model we were like planning the model as
7. we were going like makes us like since we knew it was
8. coming, we were like … it made us almost like engage a
9. little more in like the experiments we were doing…. So, we
10. were like preplanning it [with] the chalk before she even
11. gave us the assignment to do it. We know it's going to
12. happen. So, let's use what we know like in the moment,
13. like what we're curious about in the moment too because
14. it's hard to remember that later when you're trying to write it.—Joan (Quote F)

Here we see that classroom scaffolds, the requirement to draw models and reflect on model revision in lab reports, pushed Joan to engage in model use. However, by the end of the semester, the process of modeling had become ingrained in the investigations she did in class. Though Joan's view of modeling still included elements of a classroom requirement, she had started to use it earlier in the modeling cycle, during the process of experimental design (at times when model drawing was not prompted by the curriculum or instructor). She found that the modeling allowed her group to "engage a little more" in their experiments (lines 8–9). She described creating unprompted model representations with chalk (lines 9–11) and associated the process of modeling with "what we're curious about in the moment." This example suggests that, for Joan, modeling became an integrated scientific practice that was personally useful as she engaged in the process of experimentation.

Joan was unique in the way she explicitly reflected on the integration of scientific practices within the course. However, we saw evidence that all case study students integrated multiple scientific practices (e.g., modeling, experimental design, and data interpretation).

Theme 3: Students' Experience of Modeling Was Socially Complex

A major theme that emerged from our analysis was the highly social nature of modeling for AIM-Bio students. In each unit, students were asked to collaborate with peers in their groups to create model drawings and to design and conduct experiments. These groups were composed of two to four students and were typically stable throughout the semester. Students were also asked to share the results of their experiments with students in other groups before creating a final model. Students were welcome to confer with other student groups at any point during the modeling cycle. During interviews, we saw evidence for the influence of both intragroup and intergroup interactions on the modeling process.

Students often reported that their final models were influenced by intergroup interactions. For example, Michelle was asked to compare her experiences in the second AIM-Bio unit (the first full modeling cycle) and the first unit (which did not include experimental design). She noticed how shared data from the classroom community were more helpful in the second unit:

1. I feel like there was more, like coverage, because different
2. teams do different experiments. So when you, when you're
3. able to do all those experiments, like in one lab and get those
4. results, it makes it easier to like understand what's going on
5. rather than having the like just your experiment… as
6. opposed to the last lab report the last set of labs we did it
7. was more like guided everybody kind of did the same
8. thing.—Michelle (Quote G)

In this example, we see that Michelle valued the diverse contributions from other student groups, because they increased the extent of the available data and were useful in "understanding what's going on."

While all interviewed students relied on intergroup interactions to obtain experimental data or make conclusions at some point, there were also examples of this aspect of modeling being challenging for students. When asked to compare the second unit to the first, Sofia (similar to Michelle) noted the opportunity to compare diverse experimental results. However, she found this to be a more challenging modeling task:

1. **Sofia:** Um, the previous one was, I feel like more…
2. straightforward. I feel like there is more … since everybody
3. just kind of did a streamed lined [*sic*] experiment with
4. their models, everybody's models kind of lined up in the
5. end. We all kind of knew what we were looking for. While
6. with this, you had different teams going off on like, oh I'm
7. going to find if CA is what's killing it, I'm going to see if the
8. proteins are, there were so many different variables with
9. different teams, it made it hard to compare results at the
10. end. Because, you were looking at, everybody was looking
11. at what they thought was right even though we had
12. different models…
13. **Interviewer:** And I'm curious you said that it was more,
14. fewer variables. Do you think that, like, are you saying that
15. is a good thing or a bad thing?
16. **Sofia:** It makes for a more interesting experiment if there is
17. [*sic*] more variables and everybody is doing whatever they
18. want but, um, when it comes together with data collection
19. and actually bringing this all together, that's the hard part.
20. Like that's what like throws everybody under the bus. I was
21. like oh my gosh, what do we do? [Laughs.] (Quote H)

Here, Sofia described sense-making during the process of model revision in an environment with diverse student ideas. Reconciling the different hypotheses and variables into a single, coherent model was cognitively challenging and at times seemed to be overwhelming for Sofia, though at the same time she found diverse ideas more "interesting."

In these examples, students emphasized intergroup collaboration in model revision. In other instances, students described their intragroup interactions with peers as they drew models or designed experiments. When asked to describe the model drawings that they included in their individual lab reports, students often described a social process, typically referring to "we" instead of "I."

In most cases, students reported on the collaborative modeling process in terms of the group consensus, but in some cases, they revealed a more complex view of disagreement and negotiation within their groups. For example, Kyle reported on the different initial ideas held by the members of his group when they formed their initial model and testable hypotheses:

1. So, my group kind of had two different ideas as far as what
2. our initial model was going to be. The two other group
3. members I had, thought that it was actually like the contact
4. of A and E. Like the physical contact that they were growing
5. next to each other…. It had more to do with A used
6. colominic acid for nutrients and the by-product from that
7. metabolic pathway was then able to be used by E.
8. —Kyle (Quote I)

In this case, Kyle and his group members were able to use evidence from more than one experiment to draw conclusions about which model had greater support.

In another case, Sofia reported being simply overruled in a model drawing episode:

1. Yeah, um, but we disagreed mainly on what actually to
2. present [in our final model]. Because, I was like oh, we
3. should also, um, put in the actual protein of the GFP, to

4. illustrate that in there to at least show some sort of like the
5. procedure that was going on before we found these results
6. and they were, like, “No, that’s dumb,” and I was, like, okay.
7. [Laughs.] So, we didn’t do that. Yeah, I’ll probably like redo
8. [the model drawing] on my own time.—Sofia (Quote J)

Sofia’s ideas were not fully utilized when her group came to consensus at the end of the unit. However, Sofia maintains agency of her ideas, suggesting that she can simply redo the model on her own.

Though disagreements within a group were likely frustrating at times, we found some evidence to suggest that overcoming these disagreements could be an emotionally positive experience for students. For example, in a later portion of his last interview, we asked Sanjay, “So, thinking of the models and experiments you created during the semester, is there one that you personally feel proud of?” His response illustrates the importance of social interactions in his modeling experience.

1. Um … probably the *Chlamydomonas* experiment. Like,
2. mostly the experiment itself, because I was just like, thinking
3. in my head, or I was able to—me and my partner were both
4. able to come up with, like, two different types of experiment
5. but then, like, figure out how to combine them into one
6. without disrupting any of the controls or stuff like that.
7. So, it was really interesting to figure out how to do that.
8. —Sanjay (Quote K)

Sanjay and his partner had different ideas for the experiment they wanted to conduct to test their initial model; they were able to resolve this potential conflict by developing an experiment that combined their ideas. While Sanjay did not provide a detailed description of this experience, the fact that he singled it out 4 weeks later as the episode that he was “personally proud of” suggests that negotiation of diverse ideas in a social context was important to him.

Overall, we found that students experienced modeling as a social practice. The ideas and perspectives from peers served as a source of cognitive and affective tension, while at the same time serving as an essential resource for knowledge construction.

Theme 4: Students Engaged in Scientific Reasoning with Models

Scientists use models as an aid to make sense of questions they explore. Model-based reasoning has been demonstrated to incorporate a number of mental processes (Nersessian, 2008). Likewise, we found that AIM-Bio students described using models as a sense-making tool. For example, when asked what the purpose of models were in the lab course, Kyle stated, “So, I think it was practice with like the critical thinking aspect of trying to make an explanation for something rather than just be given it and then using it.” In addition, we observed students using various forms of reasoning as they described their models and modeling processes, including: visual-spatial reasoning, simulative reasoning, mechanistic reasoning, and deductive logic.

When students described their models during interviews, it was possible to observe the way that visual representations in model drawings were a part of students’ reasoning about scientific explanations. Specifically, we noted how representations encoded spatial relationships and visual features and were used by students to support reasoning (Hegarty and Kozhevnikov, 1999). For example, when explaining his model (Figure 3), Sanjay provided the following description:

1. Okay, so essentially what [the model] says is as time goes
2. on, it like describes the development of zygotes. So, you
3. start off with two cells, the A cell and the alpha cell and then
4. as time goes on, both of them shmoo, and you get those
5. genotypic changes in which like *fus1* is more active than, or
6. not genotypic, phenotypic change in which *fus1* is more
7. active in this phase. And then they come together to fuse
8. together then form the zygote. What ended up happening is
9. that due to that, the process, the DNA is actually able to flow
10. from one of the cells to the zygote.—Sanjay (Quote L)

In this model drawing (Figure 3), we can see that Sanjay used icons to represent A and alpha cells (the two mating types of *Saccharomyces cerevisiae*). He highlighted phenotypic changes (in drawing and in words) that occurred during the process of mating. He used an arrow and spatial organization to represent “time,” as temporal ordering of events was a primary feature of this explanation.

While visual-spatial reasoning seemed to be used by all students to some extent, there were notable differences in other forms of reasoning that students used, specifically the reasoning they used to make sense of relationships between experimental data and their explanatory models.

We found several instances in which different students used *simulative* and *mechanistic reasoning* as they described their models. Simulative reasoning is an extension of visual-spatial reasoning in which someone imagines combinations and spatial transformations that could occur (e.g., imagining the movement of gears in a picture; Nersessian, 2002). Mechanistic reasoning entails considerations of the processes that underlie cause–effect relationships, including accounting for how the activities of the constituent parts (“entities”) affect one another (Bolger *et al.*, 2012). Mechanistic reasoning often employs mental simulations to imagine the actions of various underlying entities (Russ *et al.*, 2008). Thus mechanistic and simulative reasoning are used together as part of the generative process of “figuring out” how a complex process might occur.

Joan’s case illustrates how she combined visual-spatial, simulative, and mechanistic reasoning to generate her own ideas about yeast reproduction. In her model drawing (Figure 4), Joan arranged icons in space to represent a biological mechanism. Circles, triangles, and squares represent molecular entities (signaling molecules), and small arrows represent actions of those entities (release from cell into the culture medium). Cellular entities also change their properties (from circular to “shmoo” shaped) over time, represented as two boxes in a cartoon. The large arrow represents causality, as events in the first box lead to events in the second box.

When asked to describe her model at the end of the semester, Joan responded as follows. In this example, bolded words emphasize the temporal and causal nature of the explanation. Underlined words emphasize the tentative or hypothetical aspects of the explanation.

1. So, this side is sort of, like the, if like <u>what we think</u> is there
2. isn’t there. And this is like <u>what</u> <u>we think</u> the normal
3. process is. So, <u>we think</u> that there’s two signaling proteins
4. specifically in the A cell, the A strain, that secretes

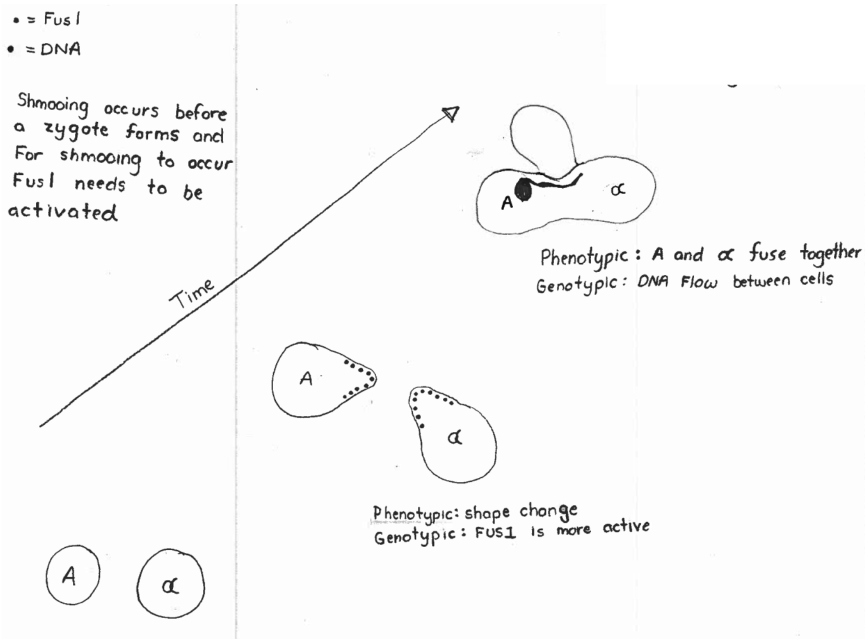


FIGURE 3. **Sanjay's model drawing, highlighting the use of visual representation to support reasoning.**

5. some sort of signal into like the medium wherever it is
6. **that then causes** both of the cells to start shmooing
7. **and then** like mating. **And then if** they don't have the
8. signaling proteins, either of them, it doesn't happen
9. no shmooing no mating.—Joan (Quote M)

When describing her model, Joan "played" the mechanism as a story evolving over time from the initial event (the "a" strain secretes signaling molecules) to the final event (mating; Machamer *et al.*, 2000). We interpret this explanation as a mental simulation of a simple molecular mechanistic model, evidenced by the way Joan described the mechanism as playing out over time and by her use of causal language to connect ideas. The tentative nature of her description also suggests that generative reasoning—the formation of novel hypotheses—was at work. Her use of simulative reasoning to mentally animate the activities in her model is a key aspect of model-based reasoning that is often associated with the creation of new ideas or hypotheses (Nersessian, 2008). Further, simulative reasoning with an iconic, mechanistic model drawing (like Joan's) can help a scientist to visualize gaps in the mechanism that disrupt causal flow and to compensate by inventing hypothesized elements (Van Mil *et al.*, 2013; Southard *et al.*, 2017). We see an example of idea generation in the signaling molecule that is released outside the cell in Joan's model, which she refers to as "some sort of signal" (lines 4–7). This is a hypothesized entity that was constructed by Joan and her group and was never directly observed or described in course materials. Joan revealed more about how she made the signaling molecule hypothesis when she was asked about the process of constructing her model.

1. Well, we used our data initially, which
2. was the plate growth mating assay,
3. and basically saw that without the
4. mutants either "1" or "2," it's like the
5. triangle or the square (drawn in the
6. model), there was no mating. And
7. then there was another group that
8. [describes shmooing results] … that's
9. how we created that bridge of like
10. mating and shmooing and then the
11. ideas of like it, the signals being
12. released into the medium it was from
13. the group. I want to say they did the
14. beta gal assay and they used the
15. [supernatant from shmooing cells]
16. and they found that [if they were
17. placed in the supernatant] like there
18. was still shmooing. So, that's how we
19. knew that it's secreting something
20. [into the supernatant] that like both
21. of them are reacting to.—Joan
22. (Quote N)

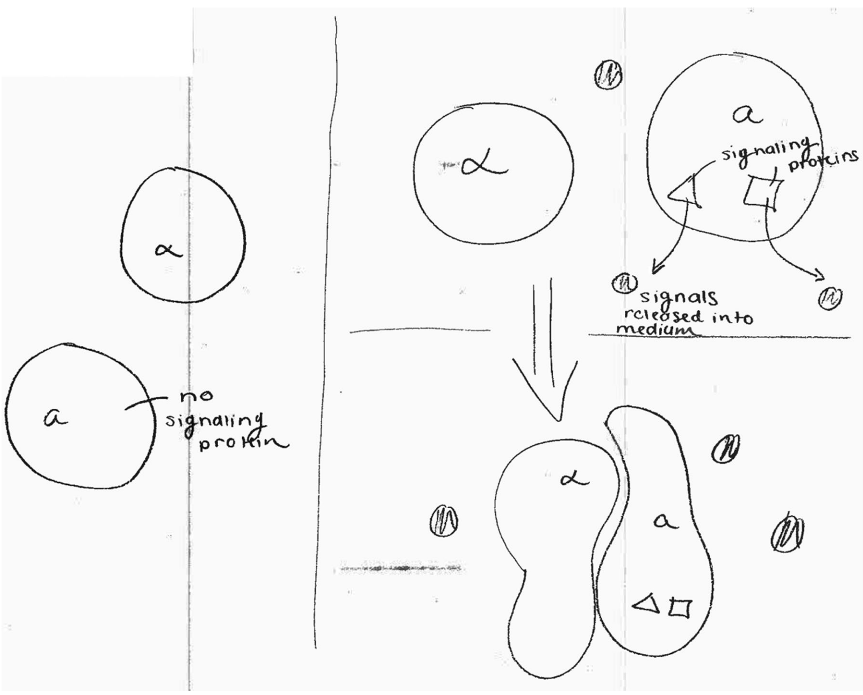


FIGURE 4. **Joan's model drawing used in episode of stimulated reasoning and generative mechanistic reasoning.**

This explanation shows how the signaling molecule hypothesis provided a mechanistic link to complete Joan's explanation. By interpreting data, they "knew that it's secreting something" (lines 18–19). Specifically, Joan's experiment demonstrated that cells with a mutation in a signaling cascade (mutants "1" and "2") were unable to mate (lines 1–6). Another groups' data showed that extracellular material (supernatant) was able to induce shmooing (lines 6–18). Joan's group integrated these pieces of data using the mechanism in their model. In so doing, they generated the hypothesis that secreted signaling molecules (that were missing in each mutant) caused cells to shmoo (as shown in their model [lines 18–21]).

In addition to integrating multiple pieces of data, Joan's explanation and model also integrate elements of theory and data. This aspect of Joan's case mirrors expert modeling practice (Morrison and Morgan, 1999). Within her explanation, she mapped together entities from her explanatory model (i.e., the triangle and the square) with components of her experimental results (i.e., mutants 1 and 2 [lines 3–6]). While the model drawing is rather abstract, preserving few literal features of experimental results, Joan still viewed each aspect as connected to specific experiments. For example, she viewed the results from a beta-gal assay as the evidence that allowed her group to add the release of a hypothesized signaling molecule to their explanation: "secreting something" (lines 18–19).

In contrast to the form of model-based reasoning just described, we found that some students used models primarily as a tool for logic-based scientific reasoning. Specifically, we found instances in which students reasoned using *deductive logic*. This form of reasoning primarily involves applying deductive algorithms to a set of propositions to determine whether each is true or false (Nersessian, 2008). When asked to describe the process of model revision, Sofia seemed to rely primarily on deductive logic:

1. In our experiment we tested 2 hypotheses. The first one
2. had to deal with the proteins being exchanged between the
3. 2 bacteria. The second hypothesis had to deal with um see
4. ing if A actually broke the CA and whether or not E
5. survived in it afterwards.… So, the new um, model came
6. from our findings which proved the protein hypothesis was
7. wrong since when we actually incubated E in the solution
8. that has already been exposed to E that has previously
9. been exposed to A and then putting E in the solution, it still
10. died, there was dead bacteria that we viewed underneath
11. the microscope … So, we knew it was something to do to
12. deal with the CA, not necessarily the proteins themselves
13. that were being effected since that was ruled out from our
14. protein hypothesis, so instead we settled to the CA was
15. definitely the main um, indicated in our model and we also
16. obtained this from other groups when we did the whole
17. sharing group thing.—Sofia (Quote O)

In this example we can see that Sofia viewed the modeling process as testing two competing hypotheses (lines 1–5). Based on experimental findings, she deduced that one hypothesis was wrong (lines 5–7). Ruling out the "first hypothesis," she and her group "settle" on their second hypothesis, which was supported by the evidence described by Sofia (lines 11–17). She explained that their new model was primarily based on findings that logically excluded their first hypothesis.

Further evidence of Sofia's deductive orientation is the way she organized her model drawing (Figure 5). The model is structured around the four different experimental conditions tested by Sofia, for example "E in #2 w/ CA." In this way, the model drawing is very closely tied to the experimental design and results, with no obvious hypothesized elements. A closer examination suggests that the model primarily seeks to illustrate variation between two variables: state of the colominic acid (enact or broken) and state of the bacteria (dead, alive, or missing). By tracking the change in variables between the different experimental conditions used to test Sofia's hypotheses, the model supports the logical reasoning she used to draw conclusions.

We saw several other instances in which other students reasoned about their models in ways similar to Sofia. Students used words like "proves," "wrong," and "evidence" and seemed to draw a single conclusion from data, often based on whether or not it fit with their predictions. Students' use of models in these logic-based episodes clearly supported them in making evidence-based decisions. However, their reasoning was often constrained to a linear process or to a set of binary (i.e., true or false) conclusions.

Overall, we found that students used model representations as a tool for scientific reasoning. This reasoning took various forms, adapted to the aspect of sense-making on which the student was focused. Because we wanted to provide details about the forms of reasoning that we observed, we focused primarily on two students, Joan and Sofia, in this section. However, it is important to note that we observed these same forms of reasoning among other students. Specifically, Jasmine and Kyle exhibited generative mechanistic reasoning similar to Joan. Michelle and Mike exhibited deductive logic similar to Sofia.

Theme 5: Students Felt a Sense of Agency and Scientific Authenticity within the Modeling Cycle

Through the modeling cycle, students felt a sense of agency over their actions and a sense of ownership of their ideas. They often emphasized their ability to design their own experiments, for example:

1. I mean the fact that we were able to create our own
2. experiments and stuff like design our own experiments and
3. then carry them out and then having this copious amount of
4. data to sift through and make conclusions out of was really
5. nice.—Sanjay (Quote P)

In addition to designing their own experiments, students expressed enthusiasm for the opportunity to test their own hypotheses. For example, Kyle described his experience in the AIM-Bio course:

1. I think it was probably the first lab where I was able to kind
2. of form my own hypothesis and design an experiment. Of
3. course, there were tools that kind of had a guideline, but
4. you still had the option to choose which tool you wanted to
5. use. So, that was cool. But also, kind gave you the
6. opportunity to totally like bomb an experiment if you're, if
7. you had a bad design or if your hypothesis wasn't very
8. good. But I think that's probably a better representation of
9. what science is, as opposed to like other labs where they
10. say okay add a and b and then it turns blue and you write

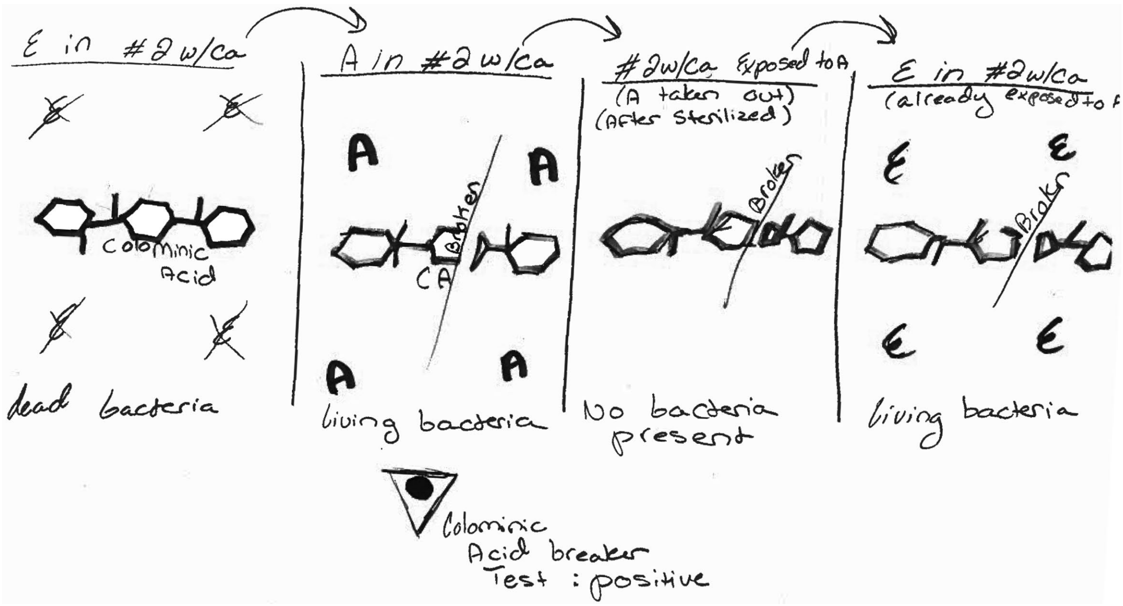


FIGURE 5. Sofia's model drawing used in episode of deductive logic reasoning.

11. about that. And it's like that's not … I don't think that's
12. really going to prepare students for you know going to grad
13. school and having to do their own research stuff like
14. that.—Kyle (Quote Q)

Kyle connected his own agency in the laboratory course, and the chance of failure, to authentic science. Specifically, he felt that the opportunity to engage in more authentic science was good preparation for research or graduate school. Similarly, Joan compared her AIM-Bio experience to her previous work during a research internship:

1. I feel like models. I feel like it was a way for us to work as
2. we would in a real lab. Because I also did an internship at
3. a lab here. So, I feel like, I vaguely remember it was a while
4. ago, but … that's kind of like the process, like you look at
5. something or like you read about something and you're like
6. okay that's like pretty cool. And then you like run some
7. experiments just to like see it, if you did it. And then you
8. like go to your P.I. and you're like this is what I want to do
9. and this is how I'm going to do it so, can I do it? And then
10. when they say yes you just kind of like do it until you get
11. results so it's like or like you can draw a model essentially.
12. I don't think it's as simple as that, but I think this [lab] is
13. like a really good way to show us what it would be like to
14. do research for real on something that you can't just like
15. find on the Internet.—Joan (Quote R)

In this example, Joan highlighted the authenticity of her experience, comparing it to a "real lab" (lines 1–3). As she compared her experiences, she highlighted the role of agency in authentic science: "you like go to your PI and you're like this is what I want to do and this is how I'm going to do it." Finally, throughout her interview, Joan was very aware of modeling as a key scientific practice. When asked what stood out to her about the course, she responded, "I guess when I, like, think about this lab, the only word that comes to mind is like model." The idea of modeling is also present in the above example. Specifically, Joan connects her use of models in the AIM-Bio curriculum to the process of generating knowledge in a research laboratory as opposed to finding it "on the Internet" (lines 12–15).

While many students viewed their classroom experiences as related to authentic science, the reasons for this connection were not all the same. As we saw earlier, students noted their agency over their actions, the ownership of their ideas, or the opportunity to engage in practices they viewed as authentic to science. In other cases, students focused on the authenticity of the social interactions in the AIM-Bio classroom, for example:

1. It was more like a research group is what it felt like instead
2. of, just being in a regular lab doing experiments and going
3. home. Instead, like at the end of the day, everybody came
4. together and was like, what are you presenting, what are
5. you presenting, what are you presenting? Yeah, so I feel like
6. this was more like a lab group.—Sofia (Quote S)

Sofia's experienced authenticity of the scientific community, referring to her classmates as her "research group" and "a lab group." She emphasized a sense of engagement with the sharing of diverse ideas (lines 3–5) and contrasted this with a "regular lab" in which students are simply completing experiments and going home (lines 1–3).

Together, our case studies suggest that authentic scientific practices emerged when students worked together in cycles of modeling. In this environment, students found different aspects of the experience to be salient and indicative of an "authentic" experience.

The results we have presented thus far point to common themes across the experiences of case study students, as well as several differences in their experiences. One affordance of the case study approach is the ability to understand the perspective of an individual student and how that student's experience may evolve over time. In the next section, we return to two case study students, Sofia and Joan, to further elaborate on their individual experiences as modelers in the AIM-Bio curriculum and illustrate the possibility that authentic science learning can take multiple forms in this curriculum.

A Comparison of Two Cases: Sophia and Joan

In this final section, we focus on two case study students: Sofia and Joan. Sofia was a sophomore life sciences major. She readily engaged in course material through collaboration with two other students in her small group. Within the study population, Sofia was notable for a greater than average project ownership score (see Table 1). Joan was a senior, completing the introductory biology course as a part of her major in engineering. She had previous experience in a research internship, which she related to her experience in AIM-Bio during her interview. Compared with her peers, Joan scored well on the skills assessment (Table 1).

Through data that we have presented thus far, it is evident that both Sofia and Joan experienced the opportunity to author and revise their own explanations through modeling in the laboratory course (quotes O and N). We know also that both students felt a sense of scientific authenticity in their experience, but for different reasons. Sofia felt a sense of an authentic scientific community that differed from a normal lab (quote S). Joan saw connections between the process of modeling and the work she had previously done as a research intern (quote R). Our results also showed differences in the forms of reasoning used by Sofia (deductive logic) and Joan (generative mechanistic reasoning) when modeling. Their model drawings (Figures 4 and 5) further point to differences in their modeling approaches. Throughout the semester, Sofia's drawings were consistently more closely tied to observations and data, whereas Joan's drawings frequently depicted more abstract, theory-based explanations. Despite these differences, we contend that both students experienced the AIM-Bio curriculum in ways that they found personally fulfilling and that were productive from our perspective.

To present the experiences of Joan and Sofia more coherently as a case, we present a narrative account highlighting some aspects of each student's experience. At the beginning of an exit interview, each student was asked two open-ended questions: "Looking back at the semester what stands out to you about this lab course?" and "What do you think you learned in this lab?" We interpreted the way Joan and Sofia responded to these questions as the features of the experience that were most salient to each student. We then used these salient features to frame our analysis of all interviews for the narrative accounts presented here. We also provide the full transcripts for Sofia and Joan's interviews in the Supplemental Material (Appendices B and C, respectively), should the reader wish to see more of the context for each provided quotation.

Sofia: The Case of Becoming Part of a Scientific Community. When asked what stood out about her experience in the laboratory course, Sofia focused on how the course felt different from a typical lab class. Specifically, she felt that the way students shared ideas in the course was "more like a research group" (see quote S). The interviewer then asked Sofia what she had learned from the course:

1. **Sofia:** Overall, I learned that it is better to work with
2. people who share their results.
3. **Interviewer:** So, yeah, so being in a collaborative space is
4. more productive?
5. **Sofia:** Yes, being in a collaborative space is more productive
6. than just single groups. (Quote T)

From these questions during the interview, we learned that Sofia was attuned to the social interactions in the class that allowed students to function as a scientific community. When we followed Sofia's case over time, we saw evidence of how Sofia came to participate in the classroom community. We do not suggest that Sofia necessarily changed her perspective on social interactions through the semester, but rather that, as a classroom community emerged, Sofia's social experience was enriched. Further, this aspect of modeling practice seemed particularly important to Sofia.

Sofia's first interview was immediately following the first full unit of the course, about 3 weeks into the semester. At this point, Sofia described coming to conclusions as an individual:

1. Yeah, I think that was it. From what we gathered from the
2. lab and what we did the reading.
3. This was the only thing that allowed me to come to this
4. conclusion. (Quote U)

Sofia often referred to "I" rather than "we" in her first interview (see annotated transcript in Appendix B in the Supplemental Material), suggesting a focus on individual over group reasoning. Within this first interview, there was one significant instance in which Sofia switched to describing a collaborative reasoning with her team:

1. The blood cells, so what our team predicted before was that
2. it would just swell. They wouldn't actually burst but with the
3. information that we saw in the lab, when we added it into a
4. hypotonic solution they actually, we didn't see anything. We
5. were like what's going on? [Laughs.] We were like oh my
6. gosh. (Quote V)

It is notable that the only collaborative episode that Sofia recalled during this interview was one that occurred in response to an unexpected result. It seems that this uncertainty caused the team to work collaboratively to find a solution.

Sofia's second interview was quite different from her first. At this point, after completing another modeling cycle, Sofia's language was primarily dominated by "we" instead of "I." The interview included frequent descriptions of collaborative discovery and sense-making (see annotated transcript in Appendix A in the Supplemental Material). For an example, see earlier quote O. In addition to working collaboratively with her group, Sofia begins to describe how sharing ideas between groups contributed to sense-making.

1. So, instead we settled to the CA was definitely the main, um,
2. indicated in our model and we also obtained this from other
3. groups when we did the whole sharing group thing.…
4. There was only one group who did a similar product to
5. ours and their results backed up ours. While the other
6. groups took out the CA and yeast still died even without
7. CA they hypothesized that CA was what was killing E, but
8. instead I guess the solution itself was killing E. So…our

9. results of CA breaking and E surviving in the broken CA
10. supported their, what they couldn't conclude.
11. (Quote W)

Sofia's group used data from other groups obtained during "the whole group sharing thing" to support their revised model. She also indicated interdependence between groups when she said that another group's results "backed up ours" and that their results "supported" what another group could not conclude.

Sofia's collaborative modeling within the AIM-Bio curriculum was not without challenges. When asked to compare her experience in the second unit to that of the first unit, Sofia described the difficulty of processing so many different ideas as feeling like "being thrown under the bus" (see quote H). Despite the success Sofia felt after the second unit, this was not the case for every unit. During the final interview, Sofia explained how she and her group had struggled to make sense of the biological phenomenon in the fifth and final unit:

1. So, we were really like, wow, I need to slow down. So, I
2. didn't really know where to start and our group didn't know
3. where to start so we were like what are we doing? So, we
4. had to get help and we were like, what are we even doing?
5. So, we asked the TA and she was like, well you should do
6. this, and we were like wow, we should do that. (Quote X)

After this same unit, Sofia described the difficulty of navigating social challenges within her group during modeling (see quote J). Importantly, even though her group had difficulty making sense of data and agreeing on a model in this final unit, Sofia was still engaged in authentic modeling practice. She understood that her purpose in generating a model was to explain a biological phenomenon, and she was able to self-assess her groups' model along these lines:

1. **Sofia:** So, what we did overall [in our model] was we just illustrated day 1 and then we illustrated day 3 that was literally, we shouldn't even call this a model, it's just, it's just…
2. **Interviewer:** Data
3. **Sofia:** Yeah, it basically is. Like it's not explaining a phenomenon like, we aren't explaining how they shmoo, we're just explaining, oh we saw them shmoo. (Quote Y)

Overall, Sofia's case suggests that participation in modeling in an inquiry setting can provide opportunities to participate in a scientific community. Within this community, uncertainty and sense-making play a role in positioning students as legitimate participants in modeling practice. As a participant in practice, Sofia experienced social interactions as both a challenge and an asset.

Joan: The Case of Buying into Modeling Practice. When asked what stood out about her experience in the course, Joan focused on using models:

1. I guess when I like to think about this lab, the only word that
2. comes to mind is like "model." Like that's all we've been
3. doing, which is true. I feel like it's an interesting take on like
4. a biology lab because like I had them in high school and
5. everything. So, this is my first one at a university but in high
6. school we had labs like we didn't really talk about models
7. but it's sort of like, I think it's a really good way to actually
8. be thinking about the science and not just like chugging
9. through an experiment. (Quote Z)

From this response, we conclude that the experience of modeling was the most salient feature of Joan's laboratory experience. Perhaps it is not surprising that modeling was so important to Joan. In earlier results, we demonstrated how Joan used models to support generative, mechanistic reasoning and hypothesizing (see quotes M and N). Further, Joan was notable in the extent to which she explicitly described modeling as an integrated practice that came to infuse all the work that her group was doing by the time of the exit interview (see quote F). However, an examination of Joan's case over the semester reveals that some aspects of her engagement in modeling practice had to develop over time.

Joan's first interview immediately followed the first full unit of the course, about 3 weeks into the semester. At this point, Joan seemed comfortable in a laboratory course setting. She understood that models should explain, and she readily adapted her model to the data that were presented in the course. We also note that the lab seemed relatively unproblematic for Joan:

1. **Interviewer:** So what data or was there anything that led
2. you to come up with this mechanism?
3. **Joan:** Yeah was this, this one [refers to published data provided to students]. What we were given in class.
4. **Interviewer:** Oh, okay, cool, so the worksheet in class.
5. **Joan:** Yeah the worksheet in class
6. **Interviewer:** And how did that give you the mechanism?
7. **Joan:** Well we could see like with the protein and then
8. without the protein, it sure showed like how the volume
9. was changing like of the water coming in and out so it was
10. like well, that sort of leads the conclusion of like with
11. the protein water can go in, without the protein it can't.
12. (Quote AA)

Joan's language, in lines 7–11 suggests that the conclusions she drew from the provided data were relatively straightforward. At another point in the interview, Joan described what occurred when her group encountered a result that they did not predict. She reported their response as, "Yeah, like what? Like are we supposed to know something that we don't." This is evidence that Joan seemed to have the expectation that there are explanations and ideas that the curriculum or teacher intends for students to know or uncover. The way Joan's group handled the unexpected result further supports this interpretation. Joan explained that they trusted their results and expanded their model:

1. Like not really, like our model was wrong more just like
2. there's a case now that we have to add. That's what we
3. thought like, "We're not wrong." And then when we did the
4. blood cells we were like, "Okay, see we're not wrong."
5. (Quote BB)

Here Joan's reasoning suggests an emphasis on being right or wrong in her modeling process. It is not surprising that Joan, who later reported that she had "taken lots of labs," might think about a laboratory course in these ways. An emphasis on confirming scientifically correct ideas is a common expectation in many laboratory courses.

In Joan's second interview, we see evidence that her initial expectations for laboratory courses does not fit well with her experience in the second unit. At this point, Joan has just experienced a modeling cycle in which students were expected to have different models and to design and conduct different experiments to test those models. At the end of the unit, groups were expected to share experimental results and to revise models based on available evidence. Joan was able to revise her model in a reasonable way in response to new data and drew conclusions in part from the data from other groups (as evidenced in her laboratory report; data not shown). However, the format of the unit was clearly not what Joan expected. When asked to compare this unit to the first she responded:

1. The first [unit] was way more straight forward. I could see
2. the end goal that I was supposed to be getting to. I mean
3. like in terms of biological knowledge I was supposed to
4. understand it, that's what I mean, not like the
5. experimental end goal. Like I understood the overall topic
6. like this [second unit] I was sort of, like I feel like I didn't
7. get, like a biological understanding of something. Because
8. it felt like there was like no direction we were supposed to
9. go in and like everybody went in different directions which
10. is like fine but then when I was like trying to talk to them
11. about, like other groups about their experiment like they
12. kind of didn't pertain to my experiment and even though
13. they did like maybe a similar test, it wasn't the exact same
14. test so I was kind of like I don't know how to like make
15. conclusions on everybody else's stuff because it had
16. nothing to do with mine. (Quote CC)

There are several things to note in Joan's response. First, Joan seems to have continued to expect that a laboratory unit will lead her to a particular biological understanding. Further, she expected that there was an experimental direction that she was "supposed" to follow, presumably dictated by the curriculum or instructor. Such a direction was not clear to Joan in the second unit. This was further emphasized to Joan by the complexity of the diverse directions and experiments taken by other student groups. Because Joan seemed focused on finding the expected, correct understanding, she viewed this complexity as a barrier to sense-making, rather than an asset. Joan had yet to recognize the value of diverse hypotheses and models, stating that she could not draw conclusions from others' data, "because they had nothing to do with mine." We also note that Joan's language in this instance is focused on individual, rather than collaborative, sense-making.

In her final interview, Joan expressed a very different view of modeling. At this point, after having completed five model-based units, Joan did not appear to be looking to the instructor or curriculum for a correct understanding. Instead, she seemed to have fully embraced her role as an explanation generator through the practice of modeling. Furthermore, during this final interview, Joan readily talked about collaborative sense-making with her group and fluidly integrated experimental evidence and ideas from other groups when explaining her model (see quote N). When asked to compare the final unit to previous units she responded:

1. **Joan:** I feel like I liked [this unit] more than all the other
2. ones. Yeah… I feel like I genuinely learned more from all
3. the other groups and I think that's where it was like, cool.
4. Whereas like in all of the other labs like sometimes I didn't learn new things because like we were doing too similar of
5. like experiments and it was sort of like okay.
6. **Interviewer:** And you liked that?
7. **Joan:** Yeah, I liked it because we realized that we were
8. making assumptions where we shouldn't have been. But
9. like other groups' conclusions then let us make those
10. assumptions. Which was like, cool, sort of. It was also sort
11. of, like, "Oh wait you can't just assume," because we were
12. like yes shmooing means mating. But it's like, okay like
13. does it? And then the other group was like yes it does and
14. you're like oh okay. Yes, it does. Now we can say yes. So, it
15. was cool. (Quote DD)

At this point, Joan valued the diverse ideas and experiments of her classmates as an asset to her learning. She also felt that data from other groups further validated assumptions made in her model. In this way, examination of Joan's perspective over time suggests that she shifted her expectations of a laboratory class as she began to engage in more authentic modeling practice. There is evidence throughout Joan's case that this shift also included a change in focus from being "right" to being "curious." We can see evidence of Joan's curiosity throughout her final interview, for example, in the way that she described being curious "in the moment" during spontaneous modeling with chalk (see quote F). Importantly, Joan's curiosity was not limited to the investigations of her group, but extended to the work of her peers in other groups:

1. I mean I guess it wasn't even my project that kind of made
2. me curious but the project. I think it was the [beta gal
3. experiment], when [another group] had the condition
4. medium that really sort of, like, my group all of us were like
5. "What?" because our test didn't do that. So, we were just like
6. "oh that's like super cool" that like, oh. That's like really what
7. initially sparked our model … that's where the coolness
8. came in towards the end and it wasn't even ours. (Quote EE)

Overall, Joan's case suggests the significant potential for the generation of scientific ideas through authentic modeling practice in a classroom setting. However, the case also illustrates how unlocking this potential is likely to require shifting students out of a frame for what is expected in a traditional laboratory course to embrace a role as knowledge generators.

DISCUSSION

This paper reports on students' descriptions of and reflections on their activity in a model-based inquiry laboratory course, AIM-Bio. Students' descriptions reflect engagement in core aspects of the practice of scientific modeling that, we argue, support important opportunities for learning. As modelers, students described proposing and exploring their own scientific ideas. Students' ideas and decisions drove the science forward, giving them practice exercising their scientific creativity and agency. They also described participating in a scientific community in which ideas from their peers often pushed them to revise and expand their own thinking. Finally, students described engaging in multiple forms of scientific reasoning not typical of the undergraduate laboratory experience.

In what follows, we discuss how modeling functions to support student thinking and why variation in modeling practice should be expected and embraced. We then examine how the particular design elements of AIM-Bio were able to support the emergence of students' modeling practice. Finally, we discuss the potential for MBI as an instructional model that can provide opportunities for students to participate in and persist in science.

How Did Modeling Support Students' Scientific Reasoning?

Among scientists, modeling is a tool for reasoning. Models help scientists to visualize, to abstract, and to engage in thought experiments (Nersessian, 1999). Models combine features of the natural world with elements of a scientist's explanation of the world, drawing together data and theory (Morrison and Morgan, 1999). In this study, we presented evidence for all of these elements of model-based reasoning within the population of AIM-Bio students. The results we have presented make it clear that students used model drawings as a sense-making tool. Here, we unpack how students used models to make sense of data and to hypothesize novel ideas.

First, we found that students used models as a hybrid space to translate their observations of the world into explanations or theories. This is similar to the way scientists use models to build explanations (Morrison and Morgan, 1999). Evidence that students reasoned in this way included the fact that their models often contained explanatory elements intermixed with observed elements. For example, a model might combine theoretical molecular entities with observed results for different experimental conditions. Further, when students described their model drawings and their process of model revision during interviews, stories of collecting and unpacking data were at the forefront. We suggest that, by placing students in the position to create their own explanations based on experimental results, the AIM-Bio curriculum drew attention to the relationship between theory and data. Models then became a useful tool for sifting through data and hypotheses to make assertions of possible meanings.

Second, we found that students used representations with varied levels of abstraction to make sense of data. The scientific process of abstracting explanations from observations is not linear or direct and typically involves multiple, diverse representations (Latour, 1999). In this process, representations typically become more abstract as the scientist's understanding grows, moving from literal representation of observation to an abstracted representation of explanation. In keeping with this aspect of scientific practice, AIM-Bio students invented their own model representations. These model representations varied in their degree of abstraction, some focused on observations, seeming to serve as a way to reason about data rather than theory or explanation. This was also evident when students talked about their models, seeming to use them to make sense of experimental results. In other instances, students integrated theoretical and empirical aspects, using models to depict their abstract explanations. These results are reminiscent of the findings from another study in which elementary students were asked to make their own representations of an elbow (Penner *et al.*, 1997). Students' elbow representations shifted from perceptual to functional models, that is, models that literally looked like an elbow to models with mechanisms that worked like an elbow. This shift in representation followed children's changing ideas for what made a model valuable. We suggest that a similar mechanism may explain variation in model representations in our study. Namely, AIM-Bio students, similar to practicing scientists and to students in other studies of MBI (Latour, 1999; Lehrer and Schauble, 2005), developed model representations with the level of abstraction that they found appropriate within their nonlinear process of building explanations. This suggests that, if models are to be a tool for scientific reasoning, instructors should allow students to be decision makers in the nature of their representations.

Third, we found that students used models to reason about mechanisms in a way that supported generation of novel ideas. Specifically, models facilitated thought experiments in which the mechanism in a model drawing was animated through simulative reasoning. This is similar to how scientists reason with models to support simulative reasoning, that is, manipulating a set of icons or entities to imagine how they might interact (Nersessian, 2008). By imagining what could be happening within a proposed mechanism, students began to hypothesize novel molecular entities that could enhance their explanations. Among molecular biologists, simulative reasoning about mechanisms, also known as "generative mechanistic reasoning," supports the creation of hypothesized entities and actions within a mechanism (Darden, 2002; Van Mil, 2013). Case studies of AIM-Bio students revealed episodes in which students put into motion the molecular entities within a proposed explanatory mechanism. This supported their generative reasoning through the formation of hypothesized entities and activities that enhanced the explanatory power of their models. Similar episodes of reasoning have been described for scientists (Darden, 2002; Van Mil, 2013) and students solving problems in an interview setting (Duncan, 2007; Southard *et al.*, 2017). Others have reported that this type of reasoning is challenging to support among secondary and undergraduate biology students in an instructional setting (Duncan, 2007; Van Mil *et al.*, 2016). Our study demonstrates that generative mechanistic reasoning can emerge in a classroom context. We suggest that curricula and instructors can support this type of reasoning by positioning modeling as a central practice when students are asked to build explanations through self-driven inquiry.

How Should We Think about Variations in Students' Modeling Practice?

While we argue that all of our case study students participated in scientific modeling practice, there was variation in how they experienced modeling. We found differences in how students' responded to unexpected results, reasoned with models, and participated in social interactions. Our case study approach allowed us to see that these differences were not only between individual students, but also between different contexts for an individual over the course of the semester.

We presented case studies of Sofia and Joan to illustrate two examples of varied experiences with modeling. We found that both students believed that they had authentically participated in science during the course, but for different reasons. For Sofia, the most salient feature of the AIM-Bio course was participation in a scientific community. For Joan, the most salient feature was building and revising models. Both students connected these salient aspects to the practices of "real-world" scientists. Case studies also revealed the extent to which modeling experiences took time to develop. Sofia's engagement with her peers for the purpose of building models grew over the course of the semester. This engagement was not without challenge, but ultimately

Sofia viewed the importance of sharing ideas as a personal learning outcome. Joan began the semester with a traditional view of her role in a laboratory course but grew to engage fully in the creative process of building explanations through modeling. Initially, the way she framed her role seemed to interfere with how she viewed the purpose of collaborative model building. Ultimately, she viewed modeling as an integrated practice that framed her collaborative, sense-making work.

A key claim of this study is that modeling practice enabled students to engage in authentic inquiries. We argue that variation is inherent in authenticity and that the possibility for students to experience authentic science in different ways may be considered a strength of model-based inquiry.

Why Did Modeling Practices Emerge in the AIM-Bio Classroom?

Our study describes the emergence of scientific practices in an undergraduate biology classroom. In this section, we discuss the elements of the course design that may have contributed to this emergence.

First, AIM-Bio curricular materials and instructors explicitly framed modeling as a shared enterprise of making sense of phenomena. Curriculum developers purposely selected biological phenomena for which students and biologists might propose a variety of plausible explanatory models rather than for the purpose of demonstrating canonical models to students. We believe this design choice functioned in two important ways. First, the complexity of the phenomenon ensured that students had a role as idea generators. Situations in which one obvious model presents itself do not problematize the need to test competing models (Stewart *et al.*, 2005). Second, we found that, when students saw the plausibility of multiple ideas, the legitimacy of their role as investigators was reinforced. This finding is aligned with prior research suggesting that tasks which elicit variation in students' hypotheses and models allow for greater engagement in scientific practices (Engle and Conant, 2002; Lehrer and Schauble, 2005).

Instructors reinforced the legitimacy of the students' role as modelers in the ways that they treated students' model drawings in the classroom. Though models were a communication tool through which students' articulated their ideas, instructors did not treat model drawings as a classroom assessment tool. Instead, they used models as a means to discuss students' developing ideas and how these related to experimental data. Rather than assess the correctness of students' model drawings, instructors evaluated students' lab reports on the basis of how well they explained the ways their models were supported by empirical evidence. By positioning students as modelers, instructors avoided some of conflicting messages that have been shown to undermine the emergence of scientific practices in other studies (McNeill *et al.*, 2017; Guy-Gaytán *et al.*, 2019)

Second, because students made their own hypotheses and their own decisions for how to test their models, they frequently experienced unexpected results. We suggest that these opportunities problematized the task of explanation and provided the context for authentic modeling practices to emerge. Previous work has suggested that "material resistance"—evidence from the world that is not expected—is central to scientific practice both for scientists and for science students (Pickering, 2010; Manz, 2015). In our study, when students encountered results that they did not predict, they often responded by attempting to make sense of the biological phenomenon in question. This provided them with a legitimate purpose to seek ideas or additional data from peers. The authentic challenge of explaining the unexpected provided a frame for students to engage in the various scientific practices that were part of their cycles of modeling.

Third, like scientists, students experienced modeling in the context of a community in which social practices served shared goals. A focus on science as a "practice" emerged within the field of science studies (i.e., philosophers and social scientists who study natural scientists) as a shift to emphasize more detailed investigations of how scientists actually engage in their day-to-day scientific work, including the social context in which that work takes place (Soler *et al.*, 2014). Educators have translated the idea of scientific practices to a classroom setting and have viewed this concept primarily through the lens of social practice in a community of learners (Wenger, 1999; NRC, 2012; Ford, 2015). Findings from our study support the idea that scientific practices emerged in the AIM-Bio classroom as a social endeavor. As has been reported in other modeling contexts, students often viewed the sense-making process of building and revising models as dependent on interactions with peers (i.e., sharing data, ideas, or feedback; Brewe *et al.*, 2010). Importantly, interactions among students were also a source of diverse and often conflicting viewpoints. Diverse ideas produced cognitive conflict that authentically pushed students to negotiate, reason with evidence, and construct explanations. All of these aspects of scientific inquiry were carried out by students through the social practices that emerged in the classroom.

While a legitimate scientific community cannot be imposed upon a group of students, design features of the AIM-Bio curriculum likely supported community emergence. Students were required to work in small groups through the semester to construct, revise, and test models. Tasks were designed to be challenging enough that students were likely to prefer collaboration. Finally, while groups of students were encouraged to take different approaches, the entire class was investigating different aspects of the same phenomenon. This meant that sharing experimental results and ideas between groups was beneficial to students for generating robust explanatory models. Finally, the practice of sharing data was explicitly encouraged by the curriculum and instructors.

How Can Model-Based Inquiry Support Opportunities for Students to Participate in Science?

There is currently an increased national emphasis on providing opportunities for undergraduate students to engage in authentic inquiry experiences (Altman *et al.*, 2019; Aikens, 2020). One reason behind this push is the significant evidence that participating in authentic inquiry through mentored undergraduate research experiences (UREs) can positively influence students' decision to persist in STEM, particularly among students from minority groups underrepresented in STEM (Nagda *et al.*, 1998; Jones *et al.*, 2010; Hernandez *et al.*, 2013). However, student access to mentored UREs is limited, and the potential for disproportionately low access by students from underrepresented groups has led to calls for new models for authentic research engagement (Lopatto *et al.*, 2008; Wei and Woodin, 2011; Bangera and Brownell, 2014). Classroom-based research experiences can increase the number of students who can participate in authentic inquiry and provide more equitable access to these opportunities (Bangera and Brownell, 2014). Participation in classroom-based research can also influence rates of undergraduate persistence (Jordan *et al.*, 2014; Rodenbusch *et al.*, 2016).

We suggest that model-based inquiry can be a fruitful model for creating opportunities for students to participate in science that may support interest in, identification with, and ultimately persistence in STEM fields. Previously, we reported that participation in the AIM-Bio curriculum positively impacted students' science identity and feelings of project ownership (Hester *et al.*, 2018). Based on previous research, outcomes like these are important determinants in students' decisions to persist in STEM (Estrada *et al.*, 2011; Graham *et al.*, 2013; Hernandez *et al.*, 2013; Hanauer *et al.*, 2017). The current work begins to unpack *how* students' experience in model-based inquiry may influence factors related to persistence.

First, students saw themselves as legitimate participants in activities that they viewed as authentic to the practice of "real" science. Second, they had many opportunities to make their own scientific decisions in terms of what they would "do" in experiments, but also in terms of what they would "think" in building explanations. Positioning students as legitimate participants in a scientific enterprise and giving them the chance to make decisions and be included as competent members of a scientific community are both mechanisms that are likely to have a positive impact on students' science identity (Lave and Wenger, 1991; Wenger, 1999; Kim, 2018). Third, as students participated in authentic inquiries, they had the chance to overcome challenges. Failure and the opportunity for iteration have been described as essential aspects of undergraduate research that promote patience and perseverance in the face of setbacks (Thiry *et al.*, 2012; Brownell and Kloser, 2015). Further, this type of opportunity may serve as an "enacted mastery experience" that may positively impact students' self-efficacy (Usher and Pajares, 2008). Along with science identity and ownership, self-efficacy is thought to be one of the most important predictors of STEM persistence (Estrada *et al.*, 2011; Graham *et al.*, 2013).

In our view, there are multiple, possible ways for undergraduates to engage in authentic inquiries. This may include mentored undergraduate research opportunities, course-based undergraduate research experiences (CUREs), and authentic inquiry courses like AIM-Bio. When considering course-based opportunities, it is important to note the potential affordances of different approaches.

The AIM-Bio curriculum is a carefully constructed inquiry setting, with many scaffolds to support student learning and engagement. In this setting, students have opportunities to participate in all parts of an inquiry, asking and answering their own questions and proposing and defending their own explanations. However, AIM-Bio students are not contributing to authentic biological research, and students' experimental results do not have an audience beyond the classroom. This is in contrast to a CURE approach, which often seeks to provide this type of authentic connection to practicing scientists (Brownell and Kloser, 2015; Corwin *et al.*, 2015). Collectively, our work and that of others suggest that there are likely to be different mechanisms whereby curricula may support students in developing a sense of authentic participation in science (Corwin *et al.*, 2018).

Finally, the AIM-Bio curriculum was structured to not only give students the opportunity to engage in authentic inquiries, but also to scaffold their success. Modeling was an integral component of how students were supported in the classroom. In this paper, we have provided evidence that models aided students in the forms of reasoning that were necessary in the inquiries they performed. Further, we have illustrated how modeling was as a central, organizing feature of the integrated scientific practices that emerged to support students' efforts. Finally, modeling was a social enterprise that allowed students to support each other in a shared goal of generating explanations for novel phenomena.

Limitations

There are limitations to our methodological approach. First, our decision to focus analysis on individual case study students provided in-depth information about the experiences of a few students, but those experiences were not necessarily representative of the experiences of most AIM-Bio students. Our analysis focused on themes that emerged as commonly relevant among interviewed students, but we cannot report on the experiences of those students who chose not to be interviewed, nor do we make claims about the frequency of the various experiences that students described. Second, by using student interviews as our primary data source, we made the intentional decision to filter our analysis through the lens of students' own experience. Though we could make inferences about how students demonstrated model-based-reasoning during interviews, most of our claims should be viewed as representing how students perceived their experiences with modeling, not necessarily how modeling events actually evolved. Future work could follow students during classroom episodes and compare students' perceptions of modeling practices with the perceptions of a research observer.

CONCLUSION

There are many examples of MBI in undergraduate classrooms across science domains (Mattox *et al.*, 2006; Khan, 2007; Brewe *et al.*, 2013; Speth *et al.*, 2014; Zwickl *et al.*, 2015; Zagallo *et al.*, 2016; Bierema *et al.*, 2017; Hester *et al.*, 2018). Instructors enlist models for different purposes in their classrooms, ranging from building conceptual understanding, to assessing students' ideas, to supporting students' scientific inquiries. Our study suggests that the way models are positioned within a classroom by instructors is likely to influence the purpose they will serve for students.

In this paper, we make a specific argument for instruction that encourages students to engage in modeling as practice by proposing, testing, and refining their own models about uncertain phenomena. The AIM-Bio curriculum prioritized the development of students' creativity, agency, and ability to contribute to a scientific community. The decision to engage students in this type of curriculum impacts not only how students may view themselves as scientists, but also how we as educators are preparing them to *be* the scientists or the science advocates of the future. We suggest that engaging in modeling as a practice can foster students' curiosity and build their experience with scientific inquiry.

By examining a model-based inquiry experience through the eyes of individual students, we revealed the cognitive, social, and emotional complexity of this type of learning environment. Unsurprisingly, individuals' experiences were not uniform. The open-ended nature of an inquiry experience allows students the agency to investigate and learn in their own way. As educators, we advocate for curricula that provide students this space. Specifically, we suggest building curricula that facilitate and encourage multiple entry and exit points for student learning over the course of a semester.

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