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Article

Context Dependence of Students' Views about the Role of Equations in Understanding Biology

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Students' epistemological views about biology—their ideas about what "counts" as learning and understanding biology—play a role in how they approach their courses and respond to reforms. As introductory biology courses incorporate more physics and quantitative reasoning, student attitudes about the role of equations in biology become especially relevant. However, as documented in research in physics education, students' epistemologies are not always stable and fixed entities; they can be dynamic and context-dependent. In this paper, we examine an interview with an introductory student in which she discusses the use of equations in her reformed biology course. In one part of the interview, she expresses what sounds like an entrenched negative stance toward the role equations can play in understanding biology. However, later in the interview, when discussing a different biology topic, she takes a more positive stance toward the value of equations. These results highlight how a given student can have diverse ways of thinking about the value of bringing physics and math into biology. By highlighting how attitudes can shift in response to different tasks, instructional environments, and contextual cues, we emphasize the need to attend to these factors, rather than treating students' beliefs as fixed and stable.

INTRODUCTION

In the past decade, policy makers and professional organizations have emphasized the need to incorporate more fundamental physics and mathematics into biology courses (National Research Council, 1999, 2003; American Association for the Advancement of Science–Howard Hughes Medical Institute, 2009; Labov *et al.*, 2010; Brewer and Smith, 2011). In response, biology and physics instructors are starting to broaden their focus (Matthews *et al.*, 2010). These interdisciplinary reforms bring not only new content but also new ways of thinking and learning about biological phenomena into introductory courses. In particular, the reformed courses increasingly ask students to reason and to build biological knowledge using equations and other mathematical representations of physical concepts.

To assess whether and how these reforms are making a difference, researchers need to study not only students' conceptual understandings but also their epistemological views about biology—their ideas about what "counts" as learning and understanding biology. Students' epistemological views, along with their expectations about what kinds of knowledge and understanding their courses reward, are important for understanding how they respond to interdisciplinary reforms. For instance, if a student is thinking of physics concepts in biology class as just another set of things to memorize, the student may resist engaging in the kinds of interdisciplinary thinking these reformed courses seek to foster. By contrast, if a student is viewing physics equations as expressing biologically relevant physical meaning, the student is not likely to use equations as mere "plug-and-chug" tools.

Given the likely importance of students' epistemological views in interdisciplinary biology courses, the question for researchers then becomes: How can we best conceptualize and study these views? Most biology education research on students' views and attitudes relies on pre–post surveys

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claiming to measure whether students' beliefs changed in response to instruction (Hoskins *et al.*, 2011; Semsar *et al.*, 2011). While these studies provide a coarse-grained read on whether students' attitudes changed on average, they are often interpreted in terms of students possessing beliefs that either do or do not change over the course (Hoskins *et al.*, 2011). In this paper, we argue that students can hold multiple sets of beliefs about learning biology. We show that a student, when probed more deeply than is possible with surveys, can express diverse, context-dependent views about the role of physics equations for learning and understanding biology, even in the same interview.

This result, we argue, has implications for both researchers and instructors. Researchers should supplement their survey-based studies by using interviews and/or classroom observations to examine students' epistemological views in biology and how those views vary in different contexts. This basic research will provide a richer understanding about why students respond as they do to interdisciplinary learning environments. Furthermore, if context dependence in students' epistemological views is indeed widespread, as the growing body of research in science education suggests, then instructors can develop new approaches to changing students' views, tapping into and trying to stabilize the *productive* epistemological stances that students initially exhibit in some contexts but not others.

LITERATURE REVIEW: MOTIVATING ATTENTION TO CONTEXT DEPENDENCE IN STUDENTS' EPISTEMOLOGICAL STANCES

Our review of relevant literature comes in three parts. First, we briefly situate the emerging research on biology students' epistemological views within the broader education research literature on student epistemologies. Then, using studies that connect students' epistemological views to their academic performance and their approaches to learning, we argue for the importance of attending to these views in introductory courses. Finally, we use a related pocket of literature to argue that the epistemological views students display in interdisciplinary biology courses are likely to be context-dependent, motivating the interview analysis in *Data and Analysis*.

In what follows, *epistemologies* refers to students' views about the nature of knowledge and knowing (e.g., what counts as understanding biology); *expectations* refers to students' views about what kinds of learning and understandings are rewarded in their courses (or in a particular course); and *epistemological stance* refers to how a student views and approaches knowledge and learning in a particular context. So, a student's epistemological stance while studying for a biology exam might depend on both his or her epistemology and his or her expectations about the course.

Emerging Research on Biology Student Epistemologies

Originally, researchers tended to conceptualize epistemologies as discipline-independent developmental stages through which students progress from less-sophisticated to more-sophisticated worldviews (Perry, 1970; Belenky *et al.*, 1986; for a review, see Hofer and Pintrich, 1997). More recently, researchers started studying students' epistemologies in specific disciplines, such as math (Schoenfeld, 1988) and physics (Hammer, 1994; Roth and Roychoudhury, 1994). Both the domain-general and discipline-specific lines of research have documented that many students express naïve views about what counts as knowing and understanding, about what kinds of knowledge and learning their courses are trying to teach, and about how to learn that knowledge. For example, many physics students often view physics knowledge as composed largely of formulas rather than as concepts *expressible* by these formulas (Hammer, 1994; Redish *et al.*, 1998). These kinds of discipline-specific epistemologies and expectations have been documented using a variety of methods, including surveys such as the Maryland Physics Expectations Survey and the Colorado Learning Attitudes about Science Survey (CLASS; Redish *et al.*, 1998; Adams *et al.*, 2006); multiple interviews with students (Hammer, 1994; diSessa *et al.*, 2002;); and analyses combining classroom observations with interviews (Lising and Elby, 2005).

Building on previous research on discipline-specific epistemologies in math and science, more systematic work is beginning in biology education. For example, Hall *et al.* (2011) documented introductory students' epistemological stances in interviews. They found that several students expected biological knowledge in the class to consist of narrow facts provided by authority (professor and textbook). Walker *et al.* (2008) documented essentially the same epistemological stance: students expressed the idea that learning is "the accumulation of unambiguous facts" (p. 365) that the instructor needs to impart. At the University of Colorado, Semsar *et al.* (2011) adapted the CLASS to conduct larger-*N* studies of these epistemologies and expectations. The CLASS-Bio measures whether students report making connections between biology and the real world and recognizing relationships between biological concepts. Semsar *et al.* (2011) found that in five of the six introductory biology courses in which the CLASS-Bio was administered before and after instruction, students' average responses shifted from more to less favorable. From these results, the authors claim that students "become more novice-like in their beliefs during their introductory biology courses" (p. 273). Other studies have examined student beliefs as an outcome of their course reforms. Hoskins *et al.* (2011) found that student responses to Likert-scale survey items about their epistemological beliefs improved after taking a C.R.E.A.T.E. (Consider, Read, Elucidate hypotheses, Analyze and interpret data, Think of the next Experiment) biology course in which students dissect a series of research papers and propose possible follow-up experiments. In particular, more students responded that scientific knowledge can be uncertain and changeable and that abilities in science are not innate. The authors claim that their results reflect changes in students' beliefs as a result of experiences in this course, particularly because these beliefs tend to remain stable. In examining different implementations of an interdisciplinary introductory biology course, Matthews *et al.* (2010) compared student responses to postsurvey questions about the importance of math in biology. They claim that, as a result of their reforms, students gained a positive attitude about the role math plays in learning biology. These studies mark the first steps toward unpacking common discipline-specific epistemological stances in introductory biology courses.

Student Epistemologies Are Consequential for Interdisciplinary Reforms

Previous work suggests that students' epistemologies affect how they approach learning and their performance in their courses and on conceptual assessments. For example, Songer and Linn (1991) observed higher scores on a postinstruction thermodynamics test for eighth-grade students who indicated (on a survey) that scientific knowledge is dynamic and integrated with their everyday experiences than for those who indicated that scientific knowledge is static, factual, and divorced from everyday life. Schommer *et al.* (1992) tested college students' comprehension of the ideas explained in a textbook-style passage about math after giving the students an epistemology survey. They found that students who viewed knowledge as complex and interconnected outperformed students who viewed knowledge as simple and piecemeal, even after controlling for students' grade point averages (GPAs). Additionally, Schommer (1993) found that secondary students' GPAs correlated strongly with their responses to epistemological survey questions, even after controlling for IQ scores. May and Etkina (2002) coded college physics students' written "learning journals" and compared students' reflections with their pre–post gains on conceptual assessments, namely the Force Concept Inventory (Hestenes *et al.*, 1992) and Conceptual Survey of Electricity and Magnetism (Maloney *et al.*, 2001). They found that students who reflected on constructing their own knowledge and documented their own reasoning in their observations and experiments achieved greater gains than did students who reported relying on authority as a source of knowledge, rarely mentioned inferences in their observations, and described experiments without much interpretation.

Case studies shed light on causal mechanisms underlying these correlations. For example, Lising and Elby (2005) documented that Jan, a life sciences major, displayed two types of reasoning in physics: formal, technical reasoning and intuitive, everyday reasoning. However, she kept these two types of reasoning separate in her thinking. Lising and Elby argue that this epistemological "wall" contributed to Jan's difficulties in the course. For instance, during collaborative group work in a discussion section addressing geometric optics, Jan tuned out her classmates' productive everyday/intuitive explanations when she was expecting formal "physics-oriented" explanations. Her incorrect responses to the homework questions on this topic suggested that she had failed to learn the material well. This and other evidence suggests that Jan's epistemological "wall" prevented her from making connections between the formalism and her intuition—an integral part of learning physics—although, in interviews, she displayed the capabilities of using everyday/intuitive and formal/mathematical reasoning separately. Similarly, in his study of introductory physics students' epistemologies, Hammer (1994) documented Roger consciously disregarding his own correct intuitive reasoning, because he did not expect such knowledge to cohere with formal physics knowledge (e.g., with what the equations were telling him).

Some biology education researchers and instructors suspect that these kinds of connections also exist between *biology* students' beliefs/attitudes (epistemological and otherwise) and their learning. Indeed, from written comments, conversations with students, and in-class observations, biology instructors have documented negative student attitudes and used them to motivate course reforms (Freeman *et al.*, 2007; Walker *et al.*, 2008; Armbruster *et al.*, 2009; Ueckert *et al.*, 2011). For example, instructors noticed that their students tend to express more concern with test scores than with understanding the material in their traditional introductory courses (Armbruster *et al.*, 2009). Others have observed that their students underestimate the time commitment required to succeed in the course and seem to be passive in their learning (Freeman *et al.*, 2007; Ueckert *et al.*, 2011) Furthermore, Armbruster *et al.* (2009) found that some introductory students did not "recognize the importance of the course content to their education as biologists" (p. 204). The authors asserted that these attitudes motivate their course reforms and that they suspect improving student attitudes will lead to improved learning outcomes. In short, these observations highlight the importance of attending to biology students' approaches to learning and certain aspects of their epistemologies, specifically, a view of learning as absorbing information (passive learning) and a view of "textbook knowledge" as disconnected from what they will need to know as biologists.

These studies and observations, indicating a relationship between student epistemologies and their course performance, motivate more systematic work in examining students' epistemological stances in introductory biology courses. We see a second motivation, too. In courses that emphasize the role of physics in understanding biology, fostering students' epistemological sophistication about interdisciplinary learning—in particular, helping them see the value of physics concepts and equations in understanding biology—can be an instructional goal for its own sake (Redish and Cooke, 2013). In other words, at the heart of many course reforms is the need to change how students think about and approach biology (Handelsman *et al.*, 2004; Allen and Tanner, 2005). By introducing new tools, such as physics principles and equations, instructors are asking students to learn biology in ways to which they are not accustomed. Documenting students' epistemological stances in these courses is therefore an important part of assessing whether we are succeeding at helping them productively approach their learning of biology with these new tools.

A few studies have begun taking up this agenda of documenting biology student epistemologies in reformed interdisciplinary courses. In their study of a *BIO2010*-inspired introductory course, Matthews *et al.* (2009) found that some of their students bring "strong beliefs about the nature of mathematics and science from secondary school," noting that many students with weak preparation did not see how the mathematics connected to biology or to real-life issues. Similarly, Hall *et al.* (2011) found in interviews that many students in a reformed introductory class took the stance, "the role of math and physics in biology is useful at some level, but not necessary." For example, Judy expressed the idea that math rarely "comes into play" when reasoning about biological phenomena, with a few exceptions related to statistics and blood flow through the heart.

Context Dependency of Epistemologies

So far, we have used previous literature to argue that students' epistemological stances in reformed biology courses are both important and feasible to study. The remaining issue is, how best to conceptualize and study those stances?

Most of the research on biology students' attitudes relies on survey data, comparing student responses either before and after instruction or across courses with different classroom interventions, as discussed in *Emerging Research on Biology Student Epistemologies*. While epistemology surveys offer useful coarse-grained information about a class of students, they do not capture an individual student's epistemology, unless the student has *a* coherent set of epistemological views. To illustrate why, we will imagine an epistemology survey that probes, among other things, students' views about the role of physics equations in understanding biology. The survey includes a cluster of items probing this issue, and the students receive cluster scores determined by summing or averaging over their responses to the individual items in the cluster. The result is *a* singular score corresponding to *an* epistemological level of sophistication. But if the student's epistemological stance toward the role of physics equations in biology depends on contextual factors, such as the biology topic, the complexity of the equations involved, or even the particular task under consideration, that score does not capture the complex reality of the student's views.

Therefore, we need to understand whether biology students' epistemological stances, especially their stances toward the role of physics (and chemistry and math) in biology, are context-dependent. If they are, then researchers would benefit from supplementing epistemology surveys with interviews, videotaped classroom observations, and/or other techniques for exploring students' epistemological stances.

Research in science education shows that students' epistemologies can indeed be dynamic and context-dependent. For instance, in the case study discussed earlier, Lising and Elby (2005) documented that, *in class*, Jan relied almost entirely on formalisms and "physics-y" vocabulary. However, in a series of interviews outside the physics building, she adopted a different epistemological stance, using everyday commonsense reasoning to talk about physics phenomena and problems (while also using formal reasoning when she felt it was appropriate). Leach *et al*. (2000) found that students' representations of the nature of science, as inferred from their written responses to two prompts, differed in ways connected to contextual features of the two tasks. Epistemological stances can also shift in the moment. For instance, Rosenberg *et al*. (2006) documented that a group of eighth graders initially approached a task, modeling the rock cycle, as a matter of making an ordered list of vocabulary terms, drawing almost entirely on knowledge from their classroom worksheets. But then, in response to the teacher's brief injunction to "start with what you know," the students switched to constructing causal explanations of the underlying processes, drawing in part on their own physical intuitions and using the worksheets to help them build explanations rather than treating the worksheets as the answers (Rosenberg *et al*., 2006). Studying introductory college physics students, Scherr and Hammer (2009) used student talk, gestures, and body positioning to document shifts between *answer-making* stances, trying to figure out the answer the instructor wants, and *sense-making* stances, building and refining their intuition to develop causal accounts of physical phenomena. Tuminaro and Redish (2007) also documented in-the-moment shifts between different epistemological stances taken by upper-division physics students completing their homework.

This body of research highlights that students' epistemological stances can vary by context in physical science. If biology students in reformed introductory classes show similar variability in their epistemological stances, there are several implications for researchers and instructors. We discuss those implications more fully after our analysis. Here, we briefly note that, as Lising and Elby (2005) illustrate, students might have productive epistemological stances they preferentially display *outside* class. Therefore, their survey responses might not capture these stances. More generally, pre–post surveys and other coarse-grained measures of the effects of interdisciplinary reforms cannot capture the kinds of context sensitivity we just discussed. Students who express negative attitudes toward the new interdisciplinary focus of introductory biology in some contexts may express more productive views in other contexts.

In this paper, we show how during a single interview, a student takes two distinct epistemological stances toward the role of physics equations in her biology course. This work adds to biology education research on student attitudes by:

1. providing an existence proof that biology students can exhibit context dependence in their epistemological stances toward interdisciplinary learning;
2. illustrating how interviews can display this context dependence; and
3. emphasizing the need for instructors and curriculum writers to attend to these contextual factors that influence how students engage with biology–physics integration, rather than treating students' beliefs as robust across contexts.

DESCRIPTION OF ORGBIO

This study examines an interview with a student, Ashlyn (a pseudonym), enrolled in Organismal Biology (OrgBio) at the University of Maryland. To set the stage for this analysis, we now give an overview of the OrgBio course and describe in more detail the particular course activities Ashlyn brought up when discussing her views about the role of equations in biology.

Overview of OrgBio

This was the third and last course in the introductory biological sciences sequence, covering the diversity, structure, and function of organisms. The prerequisites were 1) cellular and molecular biology and 2) evolutionary and ecological biology, or advanced placement (AP) credits for these courses. Ashlyn took OrgBio in the spring semester, along with ~150 other students. About two-thirds of these students were sophomores. The rest were mostly freshmen (15–20%) and juniors (15–20%), with only a few seniors enrolled. The course met for 50 min, three times a week.

The instructors reformed OrgBio to avoid a "forced march through the phyla," focusing more on conceptual understanding that integrates basic principles from biology, chemistry, physics, and mathematics. Several of these principles incorporated such physics concepts as diffusion, fluid flow, scaling, and lever mechanics to demonstrate organismal development and diversity. In addition to these curricular changes, the instructors introduced group active-engagement exercises (GAEs) to replace approximately one-third of the lectures. These exercises often centered on interdisciplinary concepts and involved a range of activities, including small-group discussions, in-class demonstrations, and data collection and synthesis. Students completed weekly homework assignments based on the GAEs. The activities and homework asked students to use mathematics in diverse ways (Watkins *et al.*, 2012).

Description of the Math/Physics GAEs

To convey an understanding of the nature of the interdisciplinary activities in which students engaged, we describe two of the GAEs and associated homework assignments that Ashlyn discussed in her interview. Our descriptions draw from the in-class worksheets and homework assignments, discussions with the instructors, in-class observations of and discussions with students, and review of videotapes of students working in small groups. (We do not, however, have recordings of Ashlyn engaging in these activities.)

Diffusion GAE and Homework. The diffusion GAE, which took place approximately one-third of the way through the course, was one of the first class sessions to use mathematical representations and quantitative reasoning. The GAE opened with groups of two to three students using a computer simulation that depicted random motion of individual dots representing particles. The dots began at the center of a circular bulls-eye, and the simulation showed that the random movement of individual dots resulted in net movement to the less densely populated outer circles (Figure 1a). The simulation allowed students to change parameters, such as the number of particles, and it displayed nested circles to help students see how far the dots had moved from the center.

In class, students first were asked to change the number of particles starting at the center of the circle, which their worksheet indicated was a measure of concentration gradient, and, after running the simulation for 20 s, to count the number of particles that reached the outermost circle. Each small group entered its result in a shared spreadsheet. When the graph revealed a linear relationship between the total number of particles and the number that reached the outermost circle after 20 s, the instructor briefly lectured on Fick's First Law: $J = D\frac{\Delta C}{\Delta x}$. He linked the number of initial dots to concentration gradient, and particle number in outermost circle to rate of diffusion.

Returning to the simulation, students next kept the number of particles constant and then recorded the particles' average distance from the center in 20-s increments. Plotting the class data showed a curvilinear relationship between time elapsed and diffusion distance. In Ashlyn's class, this activity ran long, so the lecturer only briefly related the graph to Fick's Second Law, the Einstein-Smoluchowski relation. This equation highlights a squared relationship between the root mean squared[1] time to diffuse and the distance, which the instructors represented as $t = \frac{\Delta x^2}{2D}$.

[1]Root mean square: $t_{rms} = \sqrt{\frac{t_1^2+t_2^2+\cdots t_n^2}{n}}$. Note that this course did not unpack the differences between this quantity and average time.

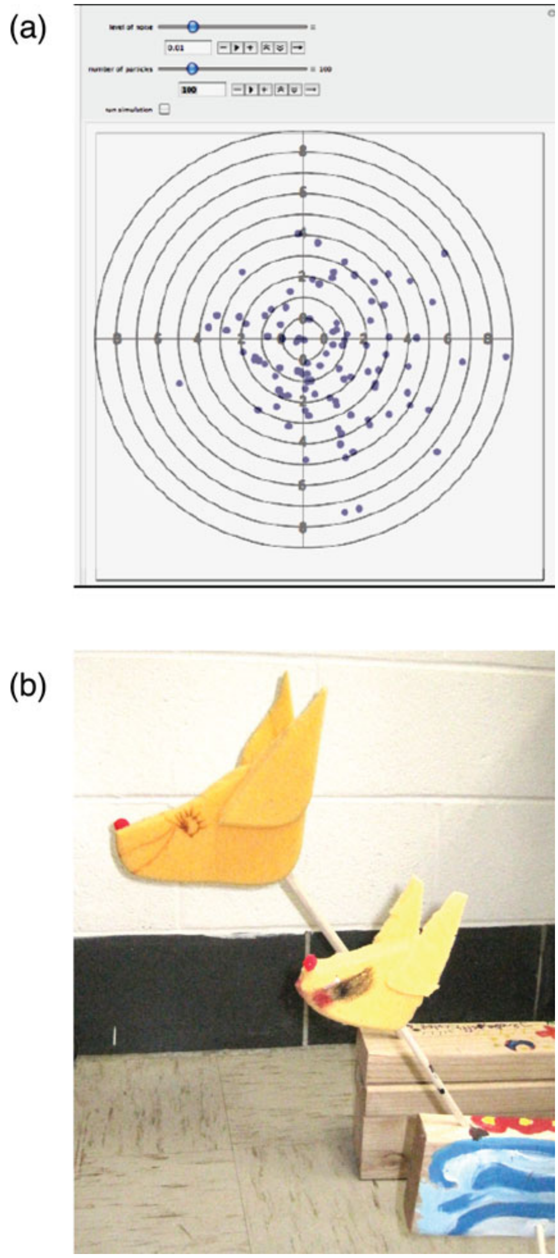

Figure 1. Images from diffusion and scaling GAEs. (a) Screen shot of diffusion simulation. (b) Photograph of two wooden horses supported with dowel legs; the horse shown in back is twice as large in every dimension as the horse shown in front.

For homework, students were asked to plot by hand the class means from the two tasks, describe the resulting curves, and relate the curves to the equations given. For Fick's First Law, they answered multiple-choice questions about the relationships between the variables, such as "If the concentration gradient decreases, then the diffusion rate will 1) increase, 2) decrease, or 3) remain the same." For Fick's Second Law, the students were asked to use the equation to calculate the time it takes a molecule of oxygen to diffuse across a cell membrane, a eukaryotic cell, and a human heart wall. They used the latter answer to discuss the role of coronary heart vessels. The last homework problem also had them calculate and compare the time it would take oxygen to diffuse from the surface to the center of flatworms and roundworms. They were asked whether these organisms could survive without circulatory systems and to describe the constraints on the size and shape of the worms.

Scaling GAE and Homework. The scaling GAE occurred a week after the diffusion activity. It started with a demonstration and discussion. The instructor held up two wooden "horses" with planks for the body and dowels for the legs. One horse was twice the size of the other in every dimension (Figure 1b). Students were asked to think about whether the horses could stand. The instructor then showed that the small horse could stand, while the larger horse's legs broke off underneath him. Students then discussed these results in small groups, with the instructor prompting them to think of the physical relationships that could be responsible for the outcome. In a whole-class discussion, the idea arose that volume and weight scale differently than surface area and that the increased weight of the larger horse caused its collapse. The instructor then turned to another demonstration, showing the temperature decrease of two beakers filled with hot water. Once again, one beaker was twice the size of the other in each dimension. When temperature versus time was plotted, the graph displayed a greater rate of decrease in temperature for the smaller beaker. Students again discussed the results in small groups, and then the instructor led a whole-class discussion about the impact these mathematical parameters and relationships have on physiology. After a short discussion, the instructor showed a short clip from an old horror movie about a monster-sized spider and "debunked" the biology behind this fictional creature. He then showed slides with three different bones of the same length but different diameters and asked which came from the largest animal. After discussing their intuitive understanding that the largest diameter corresponded to the largest animal, he used PowerPoint slides to review the mathematical relationships among length, area, and volume with the simple example of a cube. He used a pictorial representation (Figure 2) of small cubes being combined to form larger cubes of various sizes to highlight the nonconstancy in the ratio of surface area to volume and how that ratio decreases as the size of the object increases. To reinforce this point using another representation, he also compared graphs of surface area versus length and volume versus length to underscore the different scaling relationships.

After discussing these mathematical relationships, the instructor then transitioned to talking about their biological

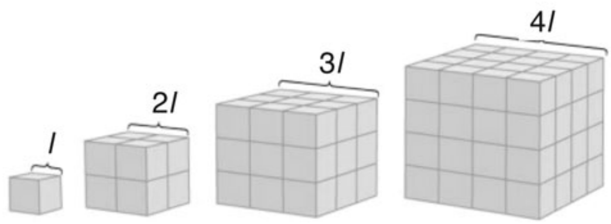

Figure 2. Pictorial representation of the scaling relationship between surface area and volume used in the GAE slides.

implications and other physical challenges and opportunities organisms face. For the remainder of the class, small groups considered a hypothetical organism with a specified nutritional strategy, environment, size, and mobility characteristics; they had to discuss the design of this organism, figuring out what solutions were compatible with its form and function.

The homework was an extension of the last in-class activity. Small groups were given an actual organism to research and write about these needs and constraints related to gas exchange, locomotion, nutrient uptake and transport, and sensory/nervous systems. Note that, in contrast to the diffusion activity, this homework called for no explicit calculations.

DATA AND ANALYSIS: ASHLYN'S DIFFERENT STANCES TOWARD EQUATIONS IN ORGBIO

Ashlyn was a general biology major taking OrgBio in her second semester at the university. She received AP credit for the two prerequisite courses and did not take biology in her first semester. Ashlyn was one of 20 students interviewed as part of a National Science Foundation (NSF) project to implement and evaluate pedagogical and curricular reforms in OrgBio. While the primary focus of the grant was curriculum development, we used interviews (5–10 per semester) to gain insight on how students were responding to the reforms and to start exploring their epistemological views toward learning biology. We chose to interview Ashlyn because her small group interacted energetically during the math- and physics-intensive GAEs, suggesting that she was engaged in the course and might therefore provide useful feedback. We chose Ashlyn's interview to analyze in this paper, as it was an especially clear example of context dependence in epistemological views about learning biology in an interdisciplinary context. However, as briefly discussed below, many other interviewees also displayed context dependence in their epistemological stances, Ashlyn was unusual only in how articulate she was in expressing her stances.

A graduate researcher involved in the project interviewed Ashlyn a little more than halfway through the class, after the second of three "midterm" exams. The interviewer and Ashlyn had interacted only briefly during the OrgBio course. The interview protocol was semistructured, with only a few preplanned questions designed to get Ashlyn talking about her experiences in the course. The first part of the interview focused on Ashlyn's general experiences in the course. Ashlyn talked about how she felt she needed to get used to biology again, since she had not taken it recently. She expressed concern about her performance on the exams and contrasted her study habits in this course to how she succeeded in her organic chemistry course. In OrgBio, instead of studying "straight out of the book" and memorizing, Ashlyn focused on understanding "*the concepts and generalizations*," such as form and function. Though she liked the course and found it interesting, she was annoyed about her grades, which were just below and just above the class mean on the first and second exams, respectively.

In the next part of the interview, the interviewer invited Ashlyn to talk about the role of equations in the course and in biology as a discipline. In the following subsection, we document her epistemological stance toward the use of equations when talking about diffusion. She expressed the view that equations provide little value for her learning of biology; they are merely a way to summarize conceptual ideas that she can understand just as well without using mathematical formalism (and to complete course assignments requiring calculations).

We then show, however, that her epistemological stance looked dramatically different only 10 min later in the interview, when the topic of conversation shifted to the GAEs. Talking about the GAE on scaling, she articulated that a mathematical relationship could help her develop a greater understanding of biological phenomena.

Ashlyn Discusses the Diffusion Example

"I just don't like it—biology is not about numbers and variables." The interviewer initiated discussion of the physics and mathematics in OrgBio by asking about the recent class sessions that included equations. Ashlyn had an immediate negative reaction to the use of "numbers and variables" in this course:

> Interviewer: . . .they showed a lot of equations recently, I feel like, right? And I want to talk to you a little about this. How is this working out for you?
>
> Ashlyn: Well, I've kind of blocked out the equations.
>
> Interviewer: Really? Okay.
>
> Ashlyn: I don't like to think of biology in terms of numbers and variables. I feel like that's what physics and calculus is for. So, I mean, come time for the exam, obviously I'm gonna look at those equations and figure them out and memorize them, but I just really don't like them.
>
> Interviewer: Okay. So you've blocked them out and you don't like them, keep going.
>
> Ashlyn: I understand, like, what they're used for, what they do, but the actual—
>
> Interviewer: And that is?
>
> Ashlyn: —placement, like for diffusion and gas exchange and stuff, but I don't remember precisely what the variables and what the equation is.
>
> Interviewer: Do you think that's important?
>
> Ashlyn: Yeah, it is important, I just don't like it, which is why I don't really think about it.

Ashlyn expressed a negative view of equations; they are something she "kind of blocked out," because "I just really don't like them." Her dislike of equations is why she does not "really think about it," except when she needs to "figure them out and memorize them" for exams. She acknowledged the importance of remembering "precisely what the variables and what the equation is," but in this and other exchanges, the importance *to her* was confined to completing course assignments and preparing for exams.

Her comments here revealed more than just her negative affect toward the mathematics in the course. She also expressed the epistemological view that "numbers and variables" belong in physics and calculus, setting biology apart from those other disciplines. She also started to discuss her stance toward learning the equations in this course: she's going to "figure them out and memorize them." Although "memorize" may indicate a stance of just trying to absorb the information without understanding it, "figure them out" could mean many things. Still, these first few comments begin to reveal her epistemological stance toward equations in this course. Her stance involves not only her ideas about learning biology generally ("I don't like to think of biology in terms of numbers and variables"), but also her expectations about succeeding in this course ("come time for the exam, obviously I'm gonna look at those equations"). We look to her subsequent comments in the interview to unpack these views about how to learn and use equations in biology.

"I'll memorize how the letters fit together, but the only function of equations in biology is to 'put the concept into words.'" Ashlyn went on to state that she understood what the equations are used for, but had trouble remembering the placement of the variables and what they represent. When asked whether memorizing the variables posed problems for her, Ashlyn elaborated on her views about the role of memorization in learning equations:

> Ashlyn: It's memorizing how they fit together. If you give me, like, for example, like, the diffusion equation on the last exam, if you gave me the units, I could figure it out for the most part, but the equation with the letters that stand for numbers, sometimes I can't remember which letters stand for what, and where they go, but I do remember, like, what goes where. I know that distance goes on top, and the—
>
> Interviewer: You want to draw it?
>
> Ashlyn: Hold on. It was x squared over $2D$, and distance goes on top and that's the diffusion constant, and I remember that because I just looked it at before coming here, but if I hadn't done that, then I would just know that the distance that it travels goes on top, and I would not necessarily remember the letters that go in that place, so I guess I have a more, like, broad and less detail-oriented knowledge of the equations.
>
> Interviewer: So do you think the equations are necessary to understanding how diffusion works?
>
> Ashlyn: Kind of, I mean, it's basically a way to put it, put the concept into words. I think that's what the only function of the equations are. It's just to help you write it down. If you understand that the distance that it goes is on—like, if you just look at it in terms of units even, it would be easier for me to remember than just to write down a couple of letters—That equals time.

Here Ashlyn discussed her struggle with remembering what different variables represent and how they are arranged in the equations. Talking about these difficulties, she clarified her expectation that learning the equations in this course is partly a matter of learning what the symbols stand for and where they go in the equation. Alongside this expectation, however, Ashlyn expressed the epistemological view that these equations have meaning behind them—they "put the concept into words." This epistemological stance differs from the one taken by many physics students, that equations are mere problem-solving tools that carry little conceptual meaning. By contrast, Ashlyn said that instead of simply remembering all of the letter placements in the time-to-diffuse equation, she could figure the equation out based on knowing that the distance "goes on top" (i.e., in the numerator).

While acknowledging that equations represent conceptual meaning and are needed for calculations, Ashlyn also expressed the view that equations have limited purpose in understanding biology. She stated that they are "just to help you write [the concept] down." In this epistemological stance, the "only" function of equations is as a bookkeeping device—and Ashlyn indicated that they are not particularly effective in this role, as units are easier to remember than "a couple of letters." In the next part of the interview, Ashlyn expanded on why she saw little value for equations in biology.

"Biology is supposed to be tangible and understanding the actual concept behind the equation is sufficient." When asked why she was unhappy using the equations, Ashlyn noted that she was tired of math and chemistry, two courses she took the previous semester. She explained that she had a bad experience with her Calculus 2 course and that she expected biology to be different:

> Ashlyn: All right. I haven't taken—I took [Calculus] 2 last semester, and it was not pleasant. It was basically a—like, I had a bad professor, no TA because it was an honors version, and it was just not fun. I got a bad grade. Well, it was a B, but I did—I was doing really well and then all of a sudden my grades plummeted because the professor was really bad, and his speaker broke, so we couldn't hear him, and he had really illegible handwriting and he did not go by the book at all. So I guess most of it is just a bad experience, so that's why I'm sick of math and equations and having to memorize them and having to prove them, etc., etc. And like I said, I think that biology is just—it's supposed to be tangible, perceivable, and to put that in terms of letters and variables is just very unappealing to me, because like I said, I think of it as it would happen in real life, like if you had a thick membrane and you try to put something through it, the thicker it is, obviously the slower it's gonna go through. But if you want me to think of it as this is x and that's D and then this is t, I can't do it. Like, it's just very unappealing to me. . .
>
> Ashlyn: Yeah, the main thing is just that I don't like it. If I liked it, I'm sure I would remember it better, but I guess understanding the actual concept behind the equation is enough to get me by. . .
>
> Ashlyn: So the equation, like I said before, like, I will memorize it because I have to, but knowing that, it's—the time is directly proportional to distance and indirectly proportional to the diffusion constant, I think in my mind is enough.
>
> Interviewer: Okay. Fair enough.
>
> Ashlyn: And if you're actually doing the calculations, though, obviously you have to know what the—what do you call it—equation is, so that's why I always make a point to remember them. I just don't enjoy doing it.

With prompting from the interviewer, Ashlyn explained her negative attitude toward mathematics in OrgBio, tying it to her recent bad experiences in Calculus 2. In her complaints, she again expressed expectations about what she needs to do with equations, namely memorize and use them. Using calculus as a contrast, she then elaborated on her disciplinary views about the role of equations in biology. She connected her view that biology is supposed to be "tangible, perceivable" to both her negative affect toward equations and her epistemological stance about their lack of utility in understanding biology. She described the biological and physical concepts underpinning the time-to-diffuse equation, stating that "the thicker it is, obviously the slower it's going to go through." She then expressed distaste for using letters to represent this idea. In her next comments, she explicitly articulated that "understanding the actual concept behind the equation" is "enough." In other words, she thinks that expressing the concept in equation form does not add to her understanding, though of course she needs the equations to carry out calculations on course assignments. This stance toward equations persisted in the interview as Ashlyn went on to talk about other OrgBio class sessions, including the one on circulation. She continued to state that she did not like the equations and described that she just "wrote them down . . . and forgot about them."

Ashlyn's epistemological stance in this part of the interview conflicts with the instructors' goal of using mathematical representations to make meaning in biology. While Ashlyn connected the equations to concepts, she stated that they did not add value to her understanding of the relationships involved in diffusion and other physical and biological phenomena. This stance, which likely reinforces and is reinforced by her negative affect toward equations, could hinder her engagement with the interdisciplinary activities in the course. Indeed, she stated that she tried to "block out" the equations and memorize them only for exams. This "blocking out" may help to explain why she did not attend to the nonlinear relationship between distance and time in the time-to-diffuse equation; she described the relationship as proportional, despite the x^2 in her equation.

Mathematical Relationship Helped Her Better Understand the Biological World

Less than 10 min later in the interview, the discussion had turned away from equations to other topics. When asked what she liked about the course, Ashlyn's affect became more positive. She said she liked the course's focus on the "big picture" in organismal development rather than her previous high school biology courses' emphasis on details. She stated that she gained an appreciation for the focus on unity and diversity in biology and liked learning how different organismal features function to achieve the same goal. With this more positive attitude, Ashlyn continued to praise the course, even when asked what she thought could be improved. During this discussion, we find a drastic difference in her attitude toward the inclusion of mathematics in the course:

> Interviewer: Is there anything in this class that you think could really be improved to maybe help students understand more?
>
> Ashlyn: With regards to the lecture, not really. The GAEs, I think are really helpful. It's just the exams that I have problems with. . .
>
> Interviewer: Were any of them [GAEs] particularly helpful for you?
>
> Ashlyn: Okay, well, the wooden horse demonstration?
>
> Interviewer: Yeah.

> Ashlyn: The little one and the big one, I never actually fully understood why that was. I mean, I remember watching a Bill Nye episode about that, like they built a big model of an ant and it couldn't even stand. But, I mean, visually I knew that it doesn't work when you make little things big, but I never had anyone explain to me that there's a mathematical relationship between that, and that was really helpful to just my general understanding of the world. It was, like, mind-boggling.
>
> Interviewer: Could you explain it to me now?
>
> Ashlyn: Yeah. There's not a uniform increase in both volume and mass, so when volume increases, mass also increases, but disproportionately—at a disproportionately larger rate. So if you had a one-unit increase in mass—or, in volume, the mass would increase by another power of that one unit, so it's just really disproportionate, and that's why certain organisms only—can only be so big, because then that makes more work for internal transport, gas exchange, and stuff like that.
>
> Interviewer: Right.
>
> Ashlyn: It was really, like, it blew my mind.

Ashlyn appreciated the in-class activities, particularly the demonstration and discussion on scaling. As described earlier, the instructor held up two horses, one twice the size of the other in every dimension. The smaller one could stand on its own, while the larger one could not. The instructor then launched a discussion about how surface area and volume (and hence mass) scale differently as length increases, using a cube as a simple mathematical example. In her recollection, Ashlyn conflated volume and surface area; replace "volume" with "surface area" and her description becomes both conceptually and mathematically accurate. We lack evidence to decide whether this mistake reflects a temporary reasoning glitch, a deeper misunderstanding of the relevant scaling concepts, and/or a tendency toward imprecision about mathematical details (reflected also, perhaps, in her glossing over the distance-squared dependence in Fick's law). Under any of these interpretations, however, the following analysis of her epistemological stance still holds.

Ashlyn linked this GAE on scaling to her memory of a similar phenomenon seen on a televised science program. She described how she never had a satisfactory explanation for *why* ants could not get big without other structural changes to the organism. She then expressed a positive affective and epistemological stance toward the use of mathematics in explaining this phenomenon: "there's a mathematical relationship between that, and that was really helpful to just my general understanding of the world." In contrast to her earlier attitude, Ashlyn smiled as she talked about this use of mathematics. Epistemologically, she explicitly pointed to the value of mathematics not simply for representing intuitive ideas but for adding to her "understanding" of the world.

In summary, in two different segments of the interview, Ashlyn expressed two different epistemological stances toward the use of mathematics in biology. When discussing the role of equations, using diffusion as an example, Ashlyn said that the conceptual meaning expressed by equations adds little or nothing to intuitive conceptual ideas she can understand adequately without mathematics. By contrast, when discussing a GAE she enjoyed, Ashlyn spontaneously laid out how a mathematical relation describing scaling adds to her understanding, contributing to a "mind-boggling" aha moment that "blew [her] mind."

We highlight Ashlyn's multiple stances toward mathematics as an existence proof of the context dependence that may exist in biology students' epistemological stances. While her interview provided an especially clear example of this context dependence, other interviewees in this project also exhibited multiple stances toward biology learning. For example, Harry, a student in an honors section of OrgBio, used mathematical variables primarily as a referent to underlying physical quantities and concepts ("it talks about…," "in order to maximize this whole thing…") when discussing the diffusion equation. In contrast, when talking about the Hagen-Poiseuille equation, which relates the flow rate of a fluid through a pipe to the pipe's dimensions, the difference in pressure at its ends, and the viscosity of the fluid, he leveraged the algebraic form (functional relationships) of the mathematical representation.[2] Specifically, he used the r^4 dependence of the fluid resistance to understand the compounded effect of a change in artery/vein radius on blood flow and pressure. While he did not make statements about the usefulness of the mathematical representations or exhibit the same affective responses that Ashlyn did, his epistemological stances were similar to Ashlyn's. When discussing the diffusion equation, he primarily used the formal mathematics as a way to point to the underlying concepts. By contrast, when discussing the Hagen-Poiseuille equation for flow, he used the functional relationships to help him make sense of the biological phenomena.

We also observed context dependence in interviewees' epistemological stances toward issues besides the role of equations in biology. For instance, Joe discussed studying for his OrgBio exams as a matter of memorizing the material in such a way that he can spit it back in the way the professor wants to see it. In organic chemistry, by contrast, he thought mere memorization played less of a role: "If you memorize your reactions it's not gonna be—you don't know how to string them together. If you understand mechanisms and how to move around atoms and reconstruct molecules then you'll be able to say okay well I can go from here to here because I can move this around and make sense to it and back and forth…"

In brief, by using Ashlyn as an existence proof of context dependence in biology students' epistemological stances, we are illustrating a phenomenon that is not unique to Ashlyn. However, we note that our analysis does not provide evidence that Ashlyn's particular epistemological stances are common among introductory biology students. An in-depth analysis of a single student cannot characterize the span of epistemological stances that students may adopt in response to the use of mathematics and physics in biology. Instead, we can use this analysis to illustrate a particular phenomenon, the context dependence of biology students' epistemologies, or, as we illustrate next, the mechanisms by which these contextual differences arise.

[2]The Hagen-Poiseuille equation as presented in the GAE: $\frac{V}{t} = \frac{\Delta p}{R} = \Delta p \frac{\pi r^4}{8l\eta}$, where $\frac{v}{t}$ is the flow rate through the pipe, Δp is the change in pressure across the pipe, R is resistance, r is the radius of the pipe, l is the pipe length, and η is the viscosity of the fluid.

UNPACKING THE CONTEXTUAL DIFFERENCES OF ASHLYN'S ATTITUDES

So far, we have argued that Ashlyn's epistemological views about the role of mathematics in biology are context-dependent, not stable "beliefs." That is the main result of this paper, and it has implications for both research and instruction. One such implication is the need to tease out the contextual factors that support students such as Ashlyn to tap into, refine, and adopt more generative versus less generative epistemological stances toward the role of mathematics, physics, and chemistry in biology. In this section, we use Ashlyn to motivate some hypotheses about these contextual factors, hypotheses to be explored in later research.

Affect

In our data, Ashlyn's epistemological stances toward bringing physics equations into biology are coupled to her emotions. In discussing the different OrgBio activities, Ashlyn is happy with mathematics in biology when she sees it as explanatorily useful, and unhappy with the mathematics when she sees it as useful only for writing the concepts down and doing calculations. This epistemological and affective coupling may have impacted both how she interpreted her experiences in the course and her expressed views about the role of particular mathematical relationships in biology. For instance, Ashlyn's positive affect and epistemology around her "aha" moment with scaling, both in the OrgBio GAE and in her later recollection during the interview, may have influenced her explicitly articulated views about the usefulness that this mathematical relation has for understanding biology. Understanding that affect can play an integral role in students' epistemological dynamics has powerful implications for instruction. For example, biology instructors can use these kinds of affectively charged aha moments as not just conceptual but also *epistemological* teachable moments, using the mathematically infused conceptual insight as a springboard to have students reflect about the role of physics equations in understanding biology.

Framing

Differences in how Ashlyn experienced the diffusion and scaling classes and associated homework assignments might have contributed to the different stances she took toward mathematics in those two contexts. The diffusion GAE was one of the first classroom activities incorporating physics and mathematics. Students ran simulations of randomly moving dots and were asked to plot average distance from the starting position as a function of time. From the resulting curve, they then were taught about the equation, with little time for discussion about its biological relevance. While the biological importance of diffusion was discussed in prior and subsequent lectures, the introduction of the mathematical equations in this GAE was motivated by a computer simulation of randomly moving dots. The diffusion homework then foregrounded the mathematical relationships, asking students to relate graphs to the equation and to use the equations to make calculations, much like those required in a mathematics or physics course. From this succession of activities, Ashlyn may have framed the latter part of the classroom activity and/or the homework as *introducing an equation for its own sake*, an equation she perceived the course as emphasizing. (Her statements about the equation's importance for completing course assignments but its limited importance for understanding biology are consistent with this interpretation.) Viewing the diffusion equation's introduction in this way could support an epistemological stance in which equations are viewed as having a limited role in understanding the biological concepts.

By contrast, the scaling GAE started with the wooden horse demonstration and the heat loss demonstration. The relevant biological phenomena motivated a presentation and discussion about the mathematical relationship between surface area and volume. Students were then asked to apply this relationship qualitatively to questions about organismal form and function. The scaling homework foregrounded biological form and function, with no explicit calculations required. Furthermore, the scaling GAE apparently cued Ashlyn to recall her own curiosity about similar phenomena she had seen on a television program. So, with both the GAE and the homework assignment presenting the mathematical scaling relations to explain biological phenomena in which Ashlyn was interested, and with no calculations involved, Ashlyn may have framed the latter part of the classroom activity and/or the homework as *explaining biological phenomena*. This framing supports an epistemological stance in which the mathematical relation is viewed as biologically relevant, not as something introduced for its own sake.

Of course, our speculations about Ashlyn's framing of the diffusion versus the scaling activities/assignments are based on limited information. Our broader point, however, is that how students interpret the purpose and nature of their classroom activity can affect how they view the role of the physics equations or other mathematical formalism introduced.

Conceptual Factors

As discussed above, Ashlyn thinks she already understands diffusion adequately without equations, which could trigger and/or reinforce the epistemological stance that equations have no role to play in explaining biological phenomena. By contrast, she did not think she (already) understood why human-sized ants are impossible, and she therefore was engaged in understanding the relationships involved in making "little things big." This attitude could help her view mathematics as explanatorily useful in this conceptual context.

Interview Context and Dynamics

To the extent that students' epistemological stances are context-dependent, we hypothesize that contextual features of the interview itself can affect students' stances (Russ *et al.*, 2012). In Ashlyn's case, the interviewer prompted the initial discussion about mathematics by noting that there had been "a lot of equations" recently in the course and asking for Ashlyn's reaction to this observation. This question followed their discussion about Ashlyn's general experiences in the course, including her struggle on exams and how she engaged with the material during lectures. Considering "a lot of equations" against the background of reliving her troubles with course exams may have primed Ashlyn to take a negative stance (affectively and epistemologically!) toward equations. In contrast, the later discussion of mathematics arose from a conversation about what Ashlyn liked about the course. This conversational dynamic could lead an interviewee to express more favorable views toward the mathematics, as a part of describing her positive experiences in the course. (We do not think this dynamic fully explains Ashlyn's view toward the mathematics of scaling, however.)

IMPLICATIONS FOR RESEARCH AND INSTRUCTION

With the increased attention to student attitudes in biology education, particularly in interdisciplinary reforms, how we conceptualize students' epistemologies becomes important for understanding learning in biology. Shifting from a more unitary conception of student epistemologies to one that considers the multiplicity and context dependence of these views has implications for both biology education research and instruction.

Implications for Biology Education Research

Most biology education research on student attitudes relies on student responses to survey questions. However, the contextual, dynamic nature of student epistemologies raises issues for this methodology. While surveys can be a useful coarse-grained measure for assessing the impact of a course on average, they have limited value in unpacking 1) the nuanced content and 2) the fluidity and context dependence of student epistemologies in biology. Research claims from these surveys need to take into account that students' scores provide only one slice of their epistemological beliefs. Students may hold other beliefs that they do not express on the instrument, and summing/averaging over students' responses within a given cluster washes out rather than illuminates whatever context dependence the survey *is* capable of revealing. Furthermore, the context in which students report their attitudes on a survey differs greatly from the context in which they study and learn biology. Consequently, the epistemological stance students adopt when taking a survey may differ from the one they adopt "in the heat of the moment," when participating in class or studying for an exam. Therefore, we argue for broadening the methodological tools used in biology education research. In particular, in-depth case studies using interviews and in-class observations can allow for examining student epistemologies either in the course context or in a context more closely aligned to that of learning biology. A full case study of Ashlyn's views about the role of equations in learning biology, for instance, would triangulate between interviews of the type we conducted and in-class observations of her engaging in GAEs with classmates. (As noted above, this study is an existence proof of context-dependent epistemological stances in biology, not a full case study.)

Furthermore, the research community needs to do more than just document how students' views differ from those of experts; it needs to unpack the fine-grained epistemological resources within students' views. By "resources," we mean the finer-grained epistemological ideas or seeds of ideas that can be leveraged to form productive epistemological stances for learning biology. Examining these epistemological resources can help us learn more about what comprises students' stances and how these resources might play a role in activating more productive stances. For example, even in Ashlyn's negative stance toward the mathematics of diffusion, she exhibited the productive resource that equations express conceptual meaning. This resource was then an integral part of her productive stance about the mathematics of scaling. Students have likely developed many different epistemological resources from their myriad learning experiences in everyday life and in different disciplines. Therefore, particularly in the context of interdisciplinary reforms in biology education, more basic research is needed on both the coarse-grained and fine-grained epistemologies students exhibit in biology.

In addition to investigating the form and substance of students' epistemologies, researchers also need to understand under what conditions students express the various pockets of their epistemological views. Understanding when and how students adopt different epistemological stances involves taking a closer look at the contexts in which these stances arise. By unpacking not just student views, but the contexts in which these views are expressed, researchers can address critical questions about how different tasks, instructional environments, and contextual cues can support different epistemological stances toward, for instance, the role that physics and mathematics play in learning biology. As discussed in our analysis above, this work engenders rich avenues and hypotheses for education research, such as examining the relationship between affect and epistemology in student learning.

Implications for Instruction

We begin this section by noting that our analysis of Ashlyn's views yields limited instructional implications. Rather, our point is to motivate a line of research that we think *will* produce rich, detailed information for instructors and curriculum developers. Still, even without the details filled in, the context dependence of student epistemologies can provide instructors with new ways of thinking about student learning. In particular, this perspective can change how instructors diagnose their students' epistemologies. Rather than seeing a student's epistemological belief as a stable, fixed attribute of the person, instructors can think of the stance as one of many stances toward biology learning that the student may take, one that is tied to the context in which it was expressed. In the former view, changing a student's epistemology appears to be a daunting task; instructors need to either accommodate their students' beliefs or completely transform or replace them. The latter view highlights how students can take multiple context-dependent epistemological stances, some of which are productive for biology learning. Therefore, instructors can focus on noticing the productive epistemological resources students exhibit and how to elicit and promote these in their courses.

Redish and Hammer (2009) describe how they developed their introductory physics course for bioscience majors guided by this model of student epistemologies. They detail how they tried to "tap" into students' productive epistemological resources for learning physics. For example, to promote students thinking of their own knowledge as consisting of many resources from which they can draw, Redish and Hammer talk about "shopping for ideas." Similarly, Hammer *et al*. (2005) describe how they ask students to explain their ideas as if they were talking to an intelligent child or a nonscientist roommate. They postulate that this move may encourage students to use their resources for everyday sense making and to rely on their intuition and experiences. These different instructional moves have met with success in encouraging productive epistemological stances (Redish and Hammer, 2009) and highlight the importance of thinking of student epistemologies at finer-grained sizes.

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