How Knowledge-in-Pieces Informs Research in Math-Bio Education

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Abstract: Recent growth in Discipline-Based Educational Research presents opportunities for extending and refining theory from the Learning Sciences. I present two investigations that leveraged Knowledge-in-Pieces approaches to add theoretical specificity to characterizing the challenges and opportunities undergraduate biology students experience when coordinating knowledge of mathematical and physical models. Clinical interviews demonstrated that students do use knowledge of equations to dynamically assemble an intuitive but productive understanding of physical quantities. Moreover, student reasoning stabilized around the equation. Think-aloud protocols illustrated that using a multi-representational learning technology (NetLogo) to problematize students' reasoning de-stabilized their knowledge to shift them towards constructing the productive understanding and conferred a learning benefit on a multi-representational assessment. These investigations illustrate that Knowledge-in-Pieces approaches can inform the design of undergraduate biology education learning environments that aim to use mathematical representations.

Introduction

Biology reflects a domain central to understanding conceptual change. Biology students tend to make statements that construe biological phenomena in anthropomorphic (human-centered), essentialist (invisible causes), and teleological (goal-oriented) terms. For some, these frames conflict with mechanistic biology (Coley & Tanner, 2015). Recent growth in undergraduate Biology Education Research (BER), however, reveals the emergence of a theoretical debate. The debate concerns whether or not to characterize such *statements* as evidence that students' *knowledge* is a modular set of stable and coherent misconceptions as opposed to a dynamic system of context-sensitive competing elements (Gouvea & Simon, 2018). We have seen this conversation unfold in the Learning Sciences (LS) only to achieve no consensus (Smith III, diSessa, & Roschelle, 1994). BER, however, presents a unique opportunity for interdisciplinary collaborations because of the community's current drive to augment teaching and research. Such interfacing offers LS new contexts for extending and refining theory and methods.

Biology education research is an emerging discipline

Among the areas of Discipline-Based Educational Research (DBER), biology education research has bloomed in recent years (Lo et al., 2019). LS and science education scholars have long conducted research on biology learning. Here I refer instead to a specific community that focuses primarily on *undergraduate* teaching and learning. The scholars tend to be trained in biological—not educational—research and their research most often focuses on small-scale interventions in classroom teaching practices (e.g. implementing clickers).

This, however, is changing. In addition to augmenting research designs by borrowing theory and methods from LS and sister disciplines, leaders in BER have crafted new visions for undergraduate learning (Woodin, Carter, & Fletcher, 2010). This vision includes re-imagining the content and delivery of undergraduate education. Chief among the innovations is the push to include mathematical approaches to meet the changing demands of professional biology. How students will meet this apparent demand, however, remains unknown.

This curricular reform problem intersects with intellectual challenges. One such challenge involves situating any particular problem within a coherent framework that dovetails with the communities' values, goals, and epistemology. As the community grows, epistemological conflicts emerge (Leonard, Kalinowski, & Andrews, 2014). A central challenge concerns how to characterize student knowledge. The characterization matters because educators' beliefs about student knowledge informs their instructional decisions. Some scholars characterize student knowledge as "right or wrong" in absolute terms but others suggest that students' intuitions are more or less "productive" depending upon the context of their use (Elby, 2000). It is in this latter regard that LS offers value to the BER community. Mathematical approaches in biology education will necessitate new modes of learning as students must construct new knowledge vis-à-vis novel *representations*. Guiding science students to learn *with* representations has long been an area of interest central to scholarship in LS (Parnafes, 2007).

Knowledge-in-Pieces informs BER with models of representational learning

Knowledge-in-Pieces (KiP) refers to a set of theoretical approaches that model knowledge as a complex system of elements (Smith III et al., 1994). Such approaches have appeared in biology education to address issues similar to the one at hand but the goals, era, and communities differed (e.g. Southerland, Abrams, Cummins, & Anzelmo, 2001). As opposed to addressing the conceptual change debate (Smith III et al., 1994), I aim to leverage KiP to identify students' challenges and resources for coordinating their knowledge of mathematical and physical models that represent biological cells. By modeling student's knowledge as a system of dynamically competing elements that cue and assemble in context, I position the investigation to determine *when and how* students connect productive intuitions (inarticulate knowledge) and heuristics (mental short-cuts) to features of external representations such as equations (Parnafes, 2007).

A KiP approach holds merit because many models of conceptual knowledge fail to account for learning *with* scientific representations of mathematical concepts and physical quantities (Elby, 2000). KiP approaches have developed this specificity by theorizing that students learn about these concepts and quantities by coordinating *extraction and readout strategies* (i.e. how they perceptually notice features and determine information in representations) to construct inferences vis-à-vis representations (Parnafes, 2007). Such models better predict and account for empirical findings regarding students learning with representations than do competing models (Elby, 2000). Because leaders in BER desire to transform undergraduate education by implementing interdisciplinary, mathematical approaches, the opportunity is ripe for jettisoning classic cognitivist framings of the conceptual change debate—such framings underemphasize the role that representations play in cueing and shaping students' productive reasoning and overemphasize students' readouts as nonproblematic evidence of accurate or misconceived knowledge. Therefore, I pose the following guiding research questions:

- How do students coordinate knowledge of math and physics with representations in biology?
- How can representational learning environments support students' knowledge coordination?

Study 1—Identifying knowledge elements via conceptual dynamics

Study 1 aimed to assess students' understanding of a quantified biological concept—*the resting membrane potential*. This concept refers to a physical property of all cells of the body, namely a *voltage* or potential difference. In physiology, it is often called an electrical gradient. This disciplinary context provided a rich domain that afforded students opportunities to coordinate knowledge of mathematical and physical representations of cells. Moreover, the domain's complexity taps both students' intuitive and school-based knowledge.

Methods

Population. 10 undergraduate biology major students (of 50 enrolled in the class) who had completed a 200-level biological science course titled *Homeostasis: The physiology of plants and animals*.

Disciplinary context. The resting membrane potential refers to a quantified biological phenomenon that emerges from two competing influences—the concentration and electrical gradient (see Figure 1). The concept therefore belongs to a class of phenomena related to dynamic equilibrium. A *chemical concentration gradient* for an ionic species and a *selectively permeable membrane* will result in the diffusion of that species down its concentration gradient and thus, will result in the separation of oppositely charged particles at the membrane (i.e. an electrical gradient). The system may be modeled ideally as when one species dominates. Thus, the Nernst equation—$\frac{60}{z} \times log_{10}\left(\frac{ion_{out}}{ion_{in}}\right) = E_{ion}$—describes these conditions when the cell's membrane potential is the same as the equilibrium potential for a given ionic species. The right variable (E_{ion}) represents the predicted voltage that will balance the left variables and parameters that represent the concentration gradient for an ionic species.

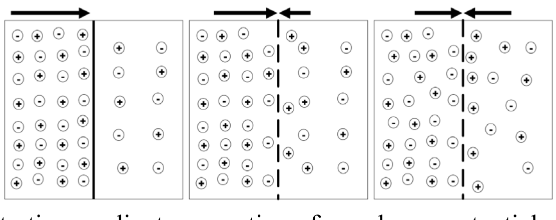


Figure 1. Left to right: concentration gradient, generation of membrane potential, and dynamic equilibrium. As a selectively permeable membrane permits one ionic species to diffuse, it separates from its counter ion to generate a transmembrane voltage that balances the tendency for the ion to diffuse.

Procedure. One-on-one clinical interviews structured to elicit knowledge of physical mechanisms and quantitative relations regarding membrane potentials. Four segments included explaining personal understanding, drawing and explaining, explaining a simple equation (Nernst equation), explaining a complex equation (not discussed here). Segment 1 only presented here. The protocol followed procedures common to Knowledge Analysis approaches as described by Sherin, Krakowski, and Lee (2012). Students were recruited 1-5 weeks after the course ended and if they had received a passing grade. Questions were designed to probe for primitive knowledge (i.e. when students bottom-out by saying statements such as, "that's just the way things are") or repeat previously documented key phrases that students described as ineffable (e.g. "Things just have a stability point, I don't know, it's hard to say").

Analysis. Video and audio were captured to construct transcripts. The case presented here was selected by identifying a productive shift. The shift was operationalized as a student who *first* described the resting membrane potential in terms of the knowledge element EQUILIBRIUM or *natural stability within parameters* and then BALANCE or *two competing influences in balance*. To detect such shifts, I employed Knowledge Analysis techniques described elsewhere (Elby, 2000; Parnafes, 2007; Sherin, Krakowski, & Lee, 2012).

Results and discussion

Knowledge of an equation constrains and stabilizes Frank's productive reasoning

Prior studies in BER suggest that students "construe" biological phenomena within conceptual frameworks that impede learning (Coley & Tanner, 2015). In contrast, other work in BER demonstrates that students reveal dynamic knowledge with sensitivity to contextual factors such as question wording (Gouvea & Simon, 2018). This study extends dynamic knowledge claims by tracking students' conceptual dynamics from *moment-to-moment* as they coordinate knowledge of mathematical and physical models in cellular physiology. This work therefore continues the extension and refinement of theory from LS in BER contexts.

To accomplish this aim, I modeled students' knowledge—as it manifests *first*—as setting the "initial conditions" of the knowledge system. But, critically, a conceptual dynamics approach will not privilege this initial knowledge as *the* knowledge. The stability of the knowledge must be tested. One student, Frank, provides an illustrative case. Below, he was first asked to explain what he means when he describes the membrane potential.

> I: [...] when you say, "Resting" what do you mean by resting?
>
> F: When you're just kind of like breathing normally. When you're not having to actually exert any type of energy. So, I guess, like me right here just sitting down as opposed to like if I had to get up or something or if say I was like just thrown into some really, really super-cold environment or super-hot environment where I would have to actually adjust or like the body has to adjust in order to actually be satisfied in those conditions […]

Frank's first explanation demonstrates that "resting" cues the knowledge element EQUILIBRIUM (*i.e. stability)* as "normal" and non-problematic (i.e. needing no explanation). The key point is that he first describes "resting" as normal but not as dynamic equilibrium. I invite Frank to describe his thinking in relation to cells as opposed to his entire body. He maps his intuitive knowledge between the levels without a problem.

> I: What I would like for you to do is think down all the way to that cellular level. […] so, what does it mean that's going on with that cell when you say, "resting"?
>
> F: Well, I just remember like there's a certain value for like different ions. […] So, […]—what is it? So, like just normal ions that are being moved in and out of the membrane is what's occurring as opposed to like if it was not at rest […] but at rest the basic ionic movement is like potassium leak channels that are moving [potassium ions] out of the cell generating like a negative voltage value I think.

Frank's description may read as incomprehensible. He does not appear to hold a stable explanation (e.g. "What is it?"). Instead, Frank assembles a series of equilibrium-related intuitions (e.g. "normal" and "basic") with terms he learned from his class (ion and leak channels). From a disciplinary stance, Frank presents inaccurate and problematic knowledge. From a conceptual dynamics perspective, however, his thinking is germane to how learners' construct explanations (Sherin et al., 2012). I ask him to elaborate.

> I: [...] What does equilibrium mean in this context?
>
> F: That the ions flowing in and the ions flowing out are essentially the same. So, while there is still, there's still ionic flow, there's no like net movement.

Note that when the interviewer re-cast *resting* as *equilibrium*, Frank then delivered a near text-book definition for dynamic equilibrium. Physiologists accept his characterization (i.e. no net movement or flux) as accurate. Thus, here we see a shift from intuitive knowledge to school-based knowledge—this result holds theoretical value because it reflects a dynamic and productive shift and illustrates how a KiP approach detects such moments.

> I: Just to clarify, because earlier you were saying that potassium ions are going out and sodium ions are coming in. Is that equilibrium?
>
> F: If I remember correctly what happens is so I think each ion has its own equilibrium potential value. So, OK, so if potassium is flowing from in to out like we said earlier there's more of like a negative charge building in the inside of the cell so the more and more potassium that flows in to out the greater the negative charge is but then there's like a certain point where that negative charge is great enough that is sort of attracts back the potassium sort of like back into the cell. So that's like that point where you're starting to get potassium to start to come back in again. I'm pretty sure like that's the point where that's like the equilibrium potential where it can't get more negative than that value because then it will start to pull back potassium back into the cell. I think that's the general idea of the [Nernst] equation.

Frank earlier referred to "negative [or] positive values" for ions. Here he unpacks his reasoning further by beginning to specify ionic mechanisms ("attracts"). He continues by coordinating his knowledge of physical mechanisms with his knowledge of an equation—the Nernst equation. This knowledge is similar to OVERCOMING or *one influence overpowers another* as has been observed in physics education. The Nernst equation predicts or specifies the electrical gradient (voltage) needed to balance the chemical gradient (diffusive entropy). Frank coordinates temporal dynamics where the two influences each can "get their way" one after the other.

We later transitioned to the next task where Frank illustrated how a cell generates a resting membrane potential. In this context, I ask him about a feature (arrows) of his drawing. This is when Frank coordinates a full shift from EQUILIBRIUM to BALANCE and he does so by organizing his knowledge around the physical quantity (-61 millivolts) represented in his inscription and that he understood was from the Nernst equation.

> I: [...] and then it looks like you have another arrow pointing at the arrow that says, 'generates negative membrane voltage'.
>
> F: Yes. So, like we said earlier how when your positive ions are leaving from the inside to the out, you're losing positivity inside the membrane. So, then it generates like I think the value was like -61 millivolts. [It] is the value that the inside will get to, which is like the Nernst equilibrium value. So, it can't really go past that [voltage] because once that much potassium has gone to generate like -61 millivolts inside then it's strong enough to bring back potassium. So essentially there is no net movement then. So, I think that's why it like stops at that value which is the Nernst equilibrium value.

In contrast to frameworks that characterize students' knowledge as stable, this exchange illustrated how traditional biology tasks such as defining terms and explaining phenomena, led Frank to cue knowledge elements dynamically. His initial elements (EQUILIBRIUM) held less utility for learning physiology concepts such as homeostasis and dynamic equilibrium than his later elements (BALANCE). By spontaneously cuing disciplinary knowledge of the Nernst equation and its associated physical quantities, Frank was able to shift and stabilize his reasoning around this more productive knowledge.

Demonstrating students' capacity to spontaneously make this shift by organizing knowledge around an equation presents a potential pathway for coordinating knowledge of mathematical and physical models and promises the possibility of equations as serving productive roles in student learning. But was Frank's shift representative of the sampled population?

No (see Table 1). Unlike his peers, Frank was the only student to reason about influences "overpowering" each other. Instead, students fell into two groups—those who saw balance and those who saw equilibrium. Although students who saw balance also saw equilibrium, no students cued OVERCOMING as a path between the two modes of reasoning. Franks case thus provides a productive but non-representative path. The question is whether a learning environment can induce students to shift from less to more productive modes of reasoning. That was the aim of Study 2.

Table 1: Frank's shift represents a productive but a non-representative case of conceptual dynamics

Student	Equilibration	Equilibrium	Overcoming	Balance	Imbalance	Canceling
Frank	3	1	2	5	1	3
Sum (n=9)	31	21	0	18	14	13

Study 2—Promoting shifts in knowledge by problematizing reasoning

Study 2 aimed to assess design principles for recapitulating the shift Frank presented in Study 1. To accomplish this aim, I designed a multi-representation learning environment in NetLogo (Wilensky, 1999) and a think-aloud protocol that problematized students' reasoning. The inspiration for this approach came from Parnafes (2007) who illustrated learning mechanisms vis-à-vis computational representations. She described how students learn to *distinguish* between two different classes of physical quantities—this reflected students' challenge of seeing one not two distinct influences on dynamic equilibrium.

Methods

Population. The participants were from the same population as that of Study 1.

Disciplinary context. The same as Study 1.

Procedure. One-on-one think-aloud protocols that followed the approach of Study 1— describe the target concept, interpret the mathematical representations, and then coordinate the meanings of the two arguments. See Parnafes (2007) for a full description of the "challenging mechanism" that inspired this design. Students were recruited after their first exam that covered relevant content. They participated during weeks 5-15 of the semester. The protocol was segmented into an orientation, reflection upon initial conditions or concentration gradient with no electrical gradient, transient transport mechanism observed silently, and then reflection upon final conditions or dynamic equilibrium. The segments were designed to assess how students read out (i.e., determined) dynamic equilibrium and the concentration and electrical gradients as a function of time. A sampling method was used to select 10 of 30 students for participating in video recording and eye-tracking (see Figure 2 for a screenshot). All 30 students participated in the same think-aloud protocol and experienced the same HCI process. The only difference lies in that 10 students were video recorded for later analysis. A pre-/post- assessment was delivered.

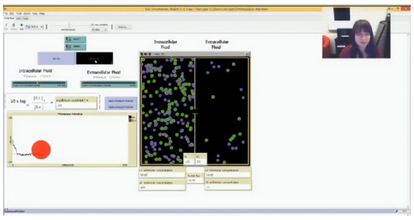


Figure 2. NetLogo model of the membrane potential with student (upper right) and eye tracking red dot (left).

Instruments. A multi-representational assessment (7 multi-part questions) was developed from interview questions and students' responses. The items demanded that students explain, illustrate, and interpret different facets of the resting membrane potential as well as calculate with equations and analyze graphs. Cronbach's alpha across pre- and post-tests was .71 and .75, respectively. Pearson product-moment correlation coefficient was computed to assess the relationship between students' short answers on their class exam that covered membrane potentials and their pre-test scores. There was a positive correlation between the students' (N= 30) performance on the multi-representational assessment and their short answer scores (r= .452 p= .012).

Analysis. Think-aloud protocols were the same as Study 1. Test items were scored as 0, .5, or 1 point on a total of 25 items across the 7 sub-parts. For example, if a student explained that a membrane potential was generated by a concentration gradient but did *not* include the selectively permeable membrane, they earned a .5.

Results and discussion

Problematizing Sally's reasoning de-stabilizes her knowledge but promotes a productive shift

In Study 1, Frank illustrated that the word "resting" cued natural stability as opposed to BALANCE influences in dynamic equilibrium. He did so first in the absence of any external representational resources. Therefore, Study 2 aims to first determine the existence of parity in the presence of a multi-representational learning technology. To present conceptual dynamics and make a shift similar to Frank, a student must cue similar knowledge.

Sally does just this. After a first simulation run is completed, I ask her to read the property of "resting" out of the simulation. During this exchange, the simulation does, in fact, show a resting potential.

> I: Is the membrane potential resting right now?
>
> S: I think so because now it's staying pretty steady at a single value and it matches the equilibrium potential of potassium [ions].
>
> I: And what does "resting" mean to you?
>
> S: Something staying pretty constant.

Sally's language of "something staying pretty constant" is consistent with seeing stability as Frank did. Again, she does not mention anything akin to two competing influences. I begin to problematize her reasoning by drawing attention to the idea of different kinds of potentials.

> I: […] From what we are seeing right now, is there any potential there in the visualization […] is there any potential, as you understand it?
>
> S: Yes, because there's more potassium on one side than the other, which means that if it can, it will flow out to where there's less potassium. So, all the ones that haven't come out yet represent the potential that they could come out.

Sally's reasoning suggests that the visually salient characteristic is "more potassium [ions] on one side than the other"—this coordinates the same chemical species with itself and with its same charge. This language describes the chemical but not the electrical gradient. I therefore problematize her reasoning further by drawing attention to the temporal dynamics before and after the transient generation of the electrical potential and the incongruity between her earlier prediction that all of the ions would "come out" and the observed non-equal concentrations between fluid compartments.

> I: Let's see if you agree with this - it looks to me like [the membrane potential] started off at 0 [millivolts] and then potassium ions left [the cell] and that made the cell more negative inside. […] And then all of sudden, it seems like it started to level off and now it's just oscillating around -60 millivolts. Do you agree with that?
>
> S: Mhmm. [Nods yes.]
>
> I: What do you think caused it to stop at -60 millivolts and I'm asking this because earlier you told me that it would go to be about approximately equal […] and now I'm looking at the concentrations and I'm seeing that they're not equal […] So why did they stop moving […], specifically at -60 millivolts.
>
> S: Maybe […] well I know they move because of a chemical gradient. You know, you want high concentration goes to low concentration but maybe there's an electrical gradient now that's in the opposite direction that's preventing them from moving further. Just because charge-wise, they're getting repelled from moving in that direction.

This exchange reflects the critical turn in our dialogue that is structurally similar to the spontaneous conceptual dynamics Frank presented. Unlike when she first defined resting, Sally now distinguishes between the two distinct influences of the concentration gradient (i.e. "high goes to low") and the electrical gradient (i.e. "repelled"). But she does not do so explicitly. I therefore invite her to reflect and re-apply her current reasoning to *resting*.

I: OK, so then by that logic, if let's say another positively charged potassium ion happened to move from that intracellular fluid to the extracellular fluid. What would it experience?

S: It might experience some force that would push it or another potassium ion back into the cell.

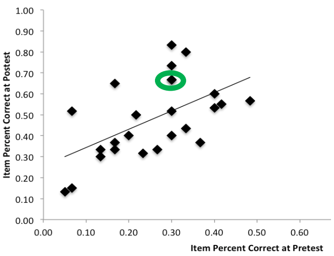
I: OK, based upon that logic […], what does the resting membrane potential mean to you, using that kind of thinking?

Sally: Oh, it means the resting potential occurs where you've got equal and opposite forces between the electrochemical - the electric side and the chemical side of gradients.

Sally now explicitly re-defines the meaning of the resting membrane potential in terms of opposite forces—thus, like Frank, she sees two influences competing in this case of dynamic equilibrium. This exchange also reflects the second time that Sally exclaimed, "Oh," and thus, it is unlikely that Sally *acquired* these ideas in this activity. Instead, she likely possessed the cognitive resources to understand the resting membrane potential but the knowledge was not organized and connected to external representations. What she did likely construct during our exchange was a strategy to extract and coordinate knowledge of the relevant physical quantities.

Frank was a non-representative case of the students who participated in the clinical interviews. Was Sally a similar case? No. Among the students who participated in video recording, 4 of the 10 presented similar conceptual dynamics by shifting from stability-based reasoning to balance-based reasoning. But did Sally's experience reflect an unusual case of prior-knowledge or did her insight result in her making non-representative gains relative the entire population sampled?

No (see Figure 3, left). Sally is representative of the sample. The four students who shifted as Sally did had average scores of 44 and 61 percent at pre- and post-test, respectively—an increase of 17 percent. The 6 students who presented emerging but non-sufficient evidence of a shift had average scores of 19 and 36 percent at pre- and post-test, respectively—also an increase of 17 percent. So, relative to students' prior knowledge, the modest simulation intervention did not achieve equity in *outcomes* but it did achieve parity in learning *gains*.



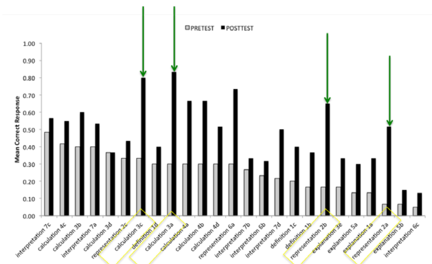


Figure 3. Left: Sally's prior knowledge and learning gains (green circle) were representative of the sample. Right: Students presented pronounced growth on the calculation and drawing tasks (green arrows).

How might this be so? The goal here was not to demonstrate efficacy of the intervention but illustrate how the design of the environment might engage learning mechanisms. To determine this, pre-test assessment items were plotted in increasing difficulty to observe how students learned (see Figure 3, right). Students struggled to draw how a cell generates a resting membrane potential but at post-test they improved at representing initial conditions and the dominant transport mechanism more so than other items. This makes sense because they were required to readout when the membrane potential was resting before, during, and after it was generated. But, despite having not received instruction on calculation items, they also improved on these items more so than others. This pattern supports the claim that students can spontaneously coordinate knowledge of mathematical and physical models as assessed by distinct calculation and drawing items. This finding is consistent with models of student knowledge in KiP (Sherin, 2001) but conflicts with models that draw modular dichotomies between mathematical procedures and conceptual knowledge (e.g. Nakhleh & Mitchell, 1993).

Conclusions and implications

Undergraduate BER represents an area of DBER ripe for productive interfacing with LS. The pair of studies presented illustrates how theory and methods from LS offer resources for informing the design of instruction in undergraduate biology education. In particular, because of the recent shift in emphasis toward mathematical approaches, efforts to design student-centered learning environments could benefit from cognitive models of how learners coordinate knowledge of mathematical and physical models. This set of studies demonstrated that micro-analytic attention to how students' knowledge elements cue and dynamically assemble from moment-to-moment provide insight into productive paths for coordinating knowledge of mathematics, physics, and biology. Providing students opportunities to coordinate knowledge across multiple representations may stabilize their readout strategies and support their understanding of different but related physical quantities (Parnafes, 2007). Last, insights into how students capitalize upon the resources (i.e. multi-representational technologies) delivered during interventions sharpen models of student cognition and research questions regarding them. As opposed to accepting Frank's or Sally's first answers as evidence of their only knowledge, I pursued further evidence and, in the process, observed dynamic shifts to new and productive modes of reasoning (Sherin et al., 2012). The takeaway is that (1) even short (<30 mins) training studies suggest that students present both naïve intuitions and accurate biology knowledge and (2) learning with mathematical representations can raise the priority of the accurate knowledge and, in turn, shift students towards distinguishing between physical quantities—drawing this distinction appears to confer a benefit to calculation accuracy despite students experiencing no explicit calculation training. These results invite tapping and engaging biology students' intuitions when the goal is coherence and coordination between mathematical and physical models.

Since its inception, LS has championed its interdisciplinarity. As burgeoning fields like BER embark upon their agenda to understand the complexities of student learning, existing interfaces, such as those between LS and physics education, offer guideposts for forging productive collaborations and research designs. The recent history of BER demonstrates a recapitulation of theoretical debates from LS regarding the nature of student knowledge (Smith III et al., 1994). This investigation offers evidence that in undergraduate biology education, it can be productive to model students' knowledge less like a set of theory-like, stable, and robust misconceptions and more like a manifold set of dynamic heuristics. The enthusiasm in BER for evidence-based practice offers a fruitful opportunity for extending and refining theory and methods from LS. But the fruit will likely only bear if we recognize biology students' intuitive knowledge as the seeds that eventually bear the fruit.

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