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Supporting the development of curricular knowledge among novice physics instructors

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In this paper, my aim is to problematize the invisibility (to instructors) of the purposes of particular exercises within research-based instructional materials (RBIMs) and to provide one possible solution to this problem that other teacher educators may adapt for their institutional contexts. In particular, I show that many RBIMs anticipate and respond to *particular* (often incorrect) learner ideas, that teachers often do not recognize this, and that not recognizing this can cause teachers to miss opportunities to build on learner ideas and/or engage students in scientific practices. I share an instructional activity I designed that is meant to support teachers—including university physics Learning Assistants—in recognizing the purposes of particular questions or sequences of questions within RBIMs, and I illustrate that this activity can be a productive starting place for conversation about RBIMs.
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I. INTRODUCTION

The instructional activity I describe in this paper grew out of an observation I made in my course for undergraduate Physics Learning Assistants (LAs), who are intellectually and relationally competent students that support reform-oriented instruction in introductory physics courses.[1] Learning Assistants at my university, Seattle Pacific University, support introductory physics courses that use *Tutorials in Introductory Physics,*[2] research-based instructional materials (RBIMs) that are designed to develop students' conceptual understanding and address specific misunderstandings.[3–5] The development of these instructional materials is extensively documented (e.g., Refs. 3, 4, 6–22), such that a well-informed physics education researcher can see that particular exercises are designed to address specific, documented misunderstandings, or to progressively lead students to particular conclusions about how motion, tension, waves, etc., work. However, when my LAs (originally) look at these materials, these design choices and strategies are often invisible to them. For example, several years ago, in our weekly content preparation meeting, I asked LAs to identify the purpose of specific sequences of questions within a *Tutorial* about electric fields. Nearly all of the LAs answered that the questions were meant to help students understand electric fields; none of them identified that a question or sequence of questions were meant to elicit and address a particular misunderstanding, or to iteratively build a specific idea within students' understanding of electric fields. For example, in looking at an exercise that asks students to rank the electric field at points P and Q (Fig. 1), LAs told me that this exercise was designed to "enhance student understanding of electric fields," even when I knew the question was designed to address *specific* student misunderstandings (e.g., that the electric field at a point is indicated by the density of the electric field lines, not the proximity of the point to a field line). As someone who is deeply committed to teacher agency and choice, it concerned me that LAs did not seem to understand the motivation for particular *Tutorials* exercises but were still willing to implement them with fidelity. I wanted to empower them to partner with the *Tutorials* and to make local decisions about the appropriateness of particular *Tutorials* exercises for specific students in specific moments in time.

In a separate paper,[23] I present a case study that documents how I—then the instructor of our preparatory and pedagogy courses for LAs—supported one cohort of these students in developing knowledge of the purpose of particular questions or sequences of questions within RBIMs, proposing this knowledge as a new component of Shulman's curricular knowledge,[85] defined by him as "a particular grasp of the materials and programs that serve as 'tools of the trade' for teachers."[24] The process of developing this knowledge for this cohort of LAs was rigorous and extensive, spanning the course of an entire academic year. In *this* paper, I present an instructional activity that I later designed on the basis of the insights I gleaned from that year-long process. The instructional activity is meant to make visible that exercises within RBIMs are designed for particular purposes, and that these purposes can be inferred from the structure and content of the exercises. I used the activity in my courses for LAs in the following three years that I taught the course, and I found that it streamlined the process of curricular knowledge development, such that in two or three class sessions LAs generated insights that it took my first cohort a full quarter to develop.[86]

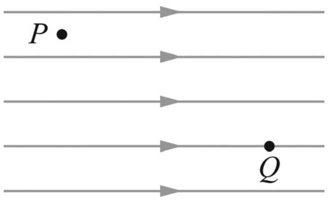

Fig. 1. Reproduction of electric field from "Electric Field and Flux," Sec. III. Reproduced with permission from McDermott *et al.*, *Tutorials in Introductory Physics,* Preliminary 2nd ed., 2011, Pearson, p. 95.

There are many different perspectives about what teachers need to know or be able to do to teach well.[24–29] Here I take the perspective that teachers (including university physics Teaching and Learning Assistants) need to develop curricular knowledge—in particular, knowledge of the purposes of particular questions or sequences of questions within the curricula they use—and I provide one possible way of beginning that process. In what follows, I situate this perspective in the literature. I then share the instructional activity that I developed and give examples of how novice instructors have interacted with it. My aim in writing this paper is to both (a) problematize the invisibility of the purposes that RBIMs are designed to serve and (b) provide a possible solution to this problem that others may adapt for their own institutional contexts.

A. Some research-based instructional materials anticipate and respond to student ideas

As in the example illustrated by Fig. 1, many RBIMs in physics anticipate and respond to student ideas.[87] As a second example, the *Physics and Everyday Thinking* curriculum[30] includes an activity in which students are asked to (1) draw a model representing the inside of a magnetized nail, (2) predict what will happen to the magnetic properties of the (magnetized) nail when it is cut in half, and then (3) perform the cut-the-nail-in-half experiment. This experiment is intended to address a particular, incorrect model for magnetization: as in Fig. 2, learners often predict that like "magnetic charges" congregate on opposite ends of the nail.[31] If the original magnetized nail had "N" charges congregated in one half and "S" charges congregated in the other, cutting the nail in half would result in an all-"N" and an all-"S" half. Each of these halves would not behave like a magnet—i.e., would not have differently interacting ends. However, when learners perform the cut-the-nail-in-half experiment, they find that each half of the nail *does* behave like a magnet, challenging the incorrect model. In the curriculum, learners are asked to reconcile their predictions and observations, and then to revise their original model for the magnetized nail if the two conflict.

Similarly, the "Conservation of Momentum in One Dimension" *Tutorial*[2] includes a sequence of questions intended to address the canonically incorrect understanding of momentum as a scalar.[8] The *Tutorial* poses a hypothetical situation in which a less massive glider, A_1, moving to the right, collides with a more massive glider, B_1, that is initially at rest. Figure 3 (reproduced from the *Tutorials*) depicts what happens to the motion of the two gliders after the collision. Given this information, students are asked to predict whether the magnitude of the final momentum of glider B_1 is greater than, less than, or equal to the magnitude of the final momentum of the system of both gliders. If a learner consistently thinks of momentum as a scalar, they would determine the magnitude of the momentum of the system by *adding* the magnitudes of the momenta of gliders A_1 and B_1, and would thus predict that the magnitude of the final momentum of the system is less than that of glider B_1. The *Tutorial* seeks to elicit this misunderstanding with the particular scenario it offers. It addresses this misunderstanding by (1) asking students to draw "qualitatively correct" vectors for the initial and final momenta of glider A_1, glider B_1, and the system, providing them the grid in Fig. 4, and then (2) suggesting that their vector diagrams should be (a) consistent with the principle of conservation of momentum and (b) consistent with their earlier prediction of the relative magnitudes of the momenta of glider B_1 and the system.

In both of these examples, RBIMs anticipate that learners will use particular misunderstandings in thinking about magnetism or momentum, and the materials are designed to elicit and then address these misunderstandings. These purposes are communicated to us (the readers) by the structure and content of the materials themselves: we can make sense of the sequence of activities and the specific directions given to students in light of the purpose of addressing particular misunderstandings. However, without an overt awareness that RBIMs are designed to anticipate and respond to student ideas, these purposes are often invisible to curriculum users; I turn to this next.

B. Curriculum users may not recognize that RBIMs anticipate and respond to student ideas

Many studies have explored curriculum *use*—which may draw on curricular knowledge—in science and mathematics classrooms, primarily focusing on: articulating the inevitability of curricular adaptation;[32–42] modeling the types of adaptations teachers make;[35,36,41,43–51] and determining what factors influence teacher adaptations.[41,43–46,48–50,52–54] However, to my knowledge, there is very little in the literature that speaks to the development of teachers' knowledge of the *purposes* of particular questions or sequences of questions within RBIMs. Harlow's[55,56] characterization of two teachers' use of the "Models of Magnetism" *Physics and Everyday Thinking*

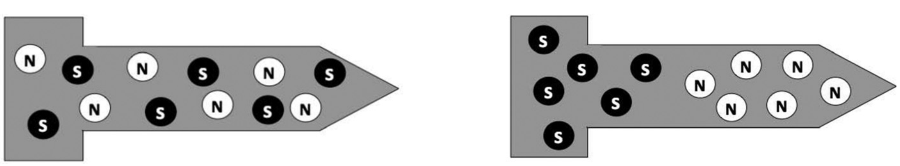

Fig. 2. Common adult learner model for unmagnetized (left) and magnetized (right) nails. Reproduced with permission from D. B. Harlow, "Uncovering the hidden decisions that shape curricula," in Proceedings of the 2010 Physics Education Research Conference, edited by C. Singh, M. Sabella and S. Rebello. Copyright 2010, AIP Publishing LLC.

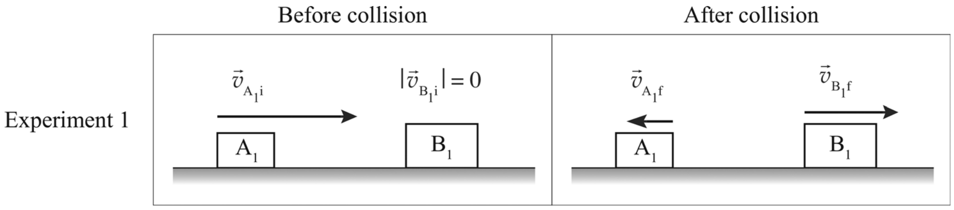

Fig. 3. Collision depicted in the "Conservation of Momentum in One Dimension" *Tutorial*. Reproduced with permission from McDermott *et al.*, *Tutorials in Introductory Physics,* Preliminary 2nd ed., 2011, Pearson, p. 50.

module (described in Sec. I A) is one notable exception. In her papers, Harlow compares the implementation of this module in Ms. Shay's and Ms. Carter's elementary school classrooms. Whereas the curriculum anticipates that learners will model a magnetized nail as having like "magnetic charges" congregated at the two ends of the nail (Fig. 2), students in these two teachers' classes modeled the magnetization process as transferring magnetic dust to the nail (Ms. Carter) and as activating something within the nail (Ms. Shay). Ms. Carter recognized the mismatch between (1) the experiment proposed by the curriculum and (2) the model that her students were using, and she deviated from the curriculum, encouraging her students to test their idea by rubbing their magnetized nails with their fingers to wipe off the dust. Ms. Shay, on the other hand, followed the curriculum as written and instructed her students to cut the nail in half. However, the cut-the-nail-in-half experiment does not respond to or challenge the "activation" model for a magnetized nail; in fact, it confirmed this canonically incorrect model for Ms. Shay's students. The contrast between these two teachers, Harlow says, highlights the "hidden"-ness of the "decisions that shape curricula." She writes:

> *"Looking carefully at the actions of the instructor and curriculum, it is not surprising that Ms. Shay and other teachers may not recognize that cutting the nail is in response to the model proposed by the learners in PET. In fact, the responsive action of the curriculum is hidden from learners. The learners do not know that the curriculum developers anticipated that they would propose this particular model."*[55]

On the basis of her analysis, Harlow advocates for more transparency on the part of curriculum developers with respect to the decisions that influence the structure and content of research-based instructional materials, and for more intentional focus on this dimension of teacher understanding in teacher education programs:

> *"In particular, [teachers] need to learn to recognize when the planned activities are not appropriate and to make real-time instructional decisions…Making the knowledge that goes into designing activities transparent to teachers may help teachers recognize the underlying structure of the activity."*[56]

Harlow's work sheds light on what can happen when teachers—like Ms. Shay—do not recognize the purposes of particular exercises within RBIMs. She proposes that recognizing these purposes supported Ms. Carter in successfully modifying the curriculum to meet the needs of her own students, facilitating these students' enactment of sophisticated model-building practices. My own work in supporting LAs in developing curricular knowledge in the context of the *Tutorials* [documented in Robertson *et al.* (submitted)[23]] suggests that: (a) the purposes of particular exercises within RBIMs are not necessarily obvious to novice instructors (see earlier in Sec. I), and (b) developing curricular knowledge can support novice instructors in enacting flexible instruction,[57–60] in ways that are consistent with recent STEM education reforms[61–63] and best-practices in STEM education pedagogy. By "flexible instruction," I mean instruction in which the "actual learning trajectory" differs from the "planned learning trajectory,"[60] in ways that respond to learner ideas. For example, developing curricular knowledge in the context of the *Tutorials* supported LAs in:

- prioritizing particular parts of the *Tutorial* on the basis of their assessment of their students' proximal needs;
- recognizing when students were demonstrating the misunderstandings the *Tutorials* were eliciting, and then partnering with the *Tutorials* to address these misunderstandings; and
- deviating from the *Tutorials* when the conjectures the curriculum made were incorrect for specific students.

As an example of the latter, one LA's decision to tell her students to skip the remainder of a particular

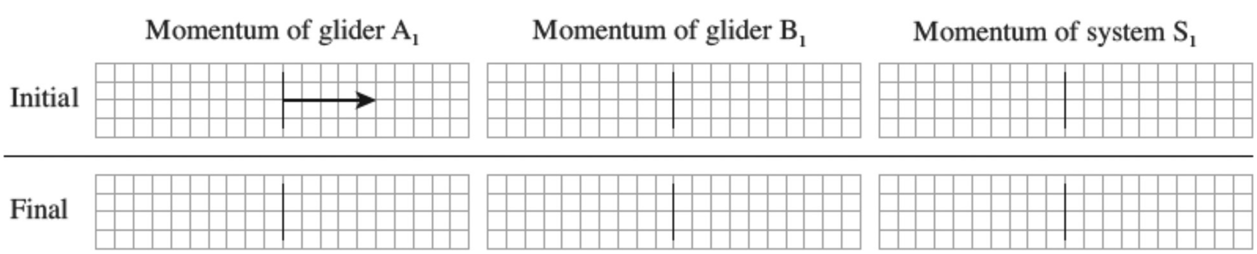

Fig. 4. Grid for drawing momentum vectors for the collision depicted in Fig. 3. Reproduced with permission from McDermott *et al.*, *Tutorials in Introductory Physics,* Preliminary 2nd ed., 2011, Pearson, p. 50.

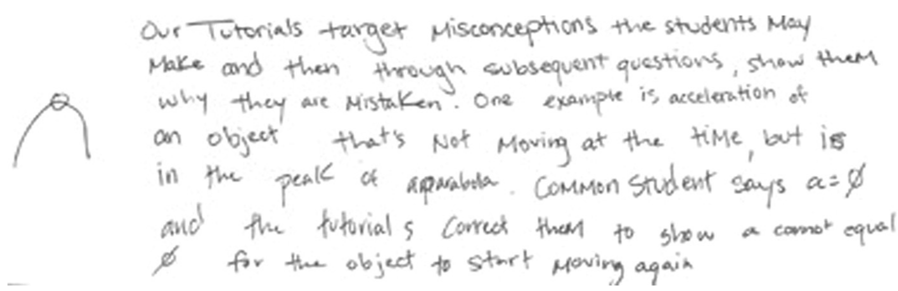

Fig. 5. Zach's response to question 6.

Tutorial section was tied to her sense that students were not experiencing the misunderstanding it was meant to elicit, confront, and resolve. [For more detail, see Ref. 23.]

These examples illustrate that though it may not be obvious to teachers that RBIMs are anticipating and responding to student ideas, teachers can develop such knowledge, either by reflecting on their own experiences, like Ms. Carter did, or by intentional engagement in the development of curricular knowledge, as my cohort of LAs did. Further, these examples illustrate that this knowledge can be consequential to student learning, and that teacher partnership with RBIMs can be a powerful means by which to accomplish the purposes of RBIMs. I continue to flesh out the importance of this kind of knowledge next.

C. It is important for curriculum users to recognize that RBIMs anticipate and respond to student ideas

By design, many RBIMs embed pedagogical content knowledge:[24–29] they anticipate and respond to common learner ideas, and they use representations and sequences of questions that "work" for many students. But what if students present unanticipated but fruitful lines of inquiry, or what if the ideas students bring to bear are different from the ones anticipated by the curriculum? Instructors (like Ms. Shay) who do not recognize that the curriculum anticipates and responds to learner ideas may miss out on opportunities to engage their students in scientific practices or to build on learners' productive (but unanticipated) ideas.

Yet we know that building on learners' productive ideas[59,64,65] and engaging students in practices that center on the articulation and refinement of ideas about scientific phenomena[66,67] are important. Opportunities to practice science are central to the vision of recent reforms,[61] and instruction that is grounded in students' thinking is consistent with what we know about how people learn.[68–70] Further, teaching that treats students as capable sense-makers have the potential to dismantle traditional systems of privilege[71,72] by challenging a "dichotomous view" of student thinking (e.g., correct versus incorrect) and instead focusing on the "potentially profound continuities between everyday and scientific ways of knowing and talking."[73] In fact, literature on curriculum use explicitly acknowledges the importance of balancing responsiveness to students and use of the curriculum as written.[34–36,42,43,49,51,53,74,75] For example, Brown and Edelson[35] treat the balance between curricular adaptation and fidelity as a tension at the center of classroom practice. Ben-Peretz[34] advocates for a view of "curriculum potential"—i.e., that there are a vast range of possible uses of any given curriculum, and it is the teacher's role to "uncover" the curriculum's potential for any given moment, depending on the situation.

Teachers' recognition of the purposes of particular questions and sequences of questions within RBIMs also has implications for *fulfilling* those purposes, or partnering with the curriculum to accomplish specific instructional goals. Both the literature and my own experience with LAs offer examples that support this. For example, Goertzen *et al.*[76] studied university physics Teaching Assistants' beliefs and practices as they facilitated students' completion of worksheets from *Maryland Open-Source Tutorials in Physics Sense-Making*.[77,78] They observed one TA's—Alan's—interactions with students in the context of tutorials that were designed to support students in reconciling formal physics concepts/principles with their "common-sense" ideas. The authors note that Alan regularly constrained the conversation, "fail[ing] to elicit students' ideas…despite the tutorial's emphasis on eliciting and refining students' common sense thinking." Likewise, in my own observations of LAs' teaching practice (and in approximations of their practice), I noticed that LAs would often correct students in the midst of an extended sequence that was meant to build understanding of a particular concept, pre-empting the conceptual development intended by the curriculum. In Ref. 23, we show that LAs' development of curricular knowledge supported them in choosing when to intervene; often, it supported them in *waiting* to intervene until students had an opportunity to experience the curriculum as written. For example, one LA, Ellie, wrote in her teaching reflection:

> *"One group had a question about a difficulty that I knew was about to be addressed later in the tutorial. So I had them work through it and I came back to see if they were still having trouble, but they no longer were. So I used what I knew about the tutorials to decide if I should answer their question now or later."*

Remillard[42] presents a vision of curriculum use as *participation with the text,* which assumes "that teacher and curriculum materials are engaged in a dynamic interrelationship that involves participation on the parts of both teacher and text." Such a perspective differs from a conceptualization of curriculum use as "following or subverting the text," where teachers are often seen as "conduits" of externally designed curricula. The former of these—participation with the text—is more consistent with the possibilities I name above, where teachers take up opportunities to build on their students' thinking, to engage their students in the refinement of scientific models, and, when appropriate, to partner with the curriculum to accomplish its purposes. We saw this in the case of Ms. Carter, whose participation *with* the curriculum supported her students in refining their own model of a magnetized nail. The latter of these—"following or subverting the text"—may cause teachers to miss such opportunities, or rely exclusively on the curriculum to provide such opportunities. I feel that such partnership—and all of the potential therein—requires teachers to understand the purposes of the questions and sequences of questions within the curriculum, or to develop the kind of curricular knowledge I propose.

II. SUPPORTING LAs IN THINKING ABOUT THE PURPOSES OF PARTICULAR EXERCISES WITHIN RBIMs

In my own work as a teacher educator, I have supported Physics LAs in developing curricular knowledge in the context of the *Tutorials in Introductory Physics*[2] curriculum, discussed above. In this section, I present an instructional activity that I use with my LAs that is based on the insights I have gleaned over the past five years. In Sec. III, I will share examples that illustrate how LAs engage with this activity. Before I do either of these, I briefly offer some context that may be important for readers' understanding (and potential use) of this activity.

A. Context

As I briefly say above, Physics Learning Assistants (LAs) at my university—Seattle Pacific University (SPU), a private liberal arts institution in the Pacific Northwest United States—are relationally competent students that support reform-oriented instruction in university physics courses. Like LAs at other institutions, LAs at SPU take a pedagogy course that focuses on educational theory and best-practices in facilitating dialogue amongst students. Learning Assistants also take a "prep" course, where they meet to go over the materials that they will teach in the subsequent week. The instructional activity I describe in this section was used in our "prep" course. Unlike LAs at many other institutions, SPU Physics LAs (during the time I was the course instructor) enroll in prep and pedagogy courses each quarter that they serve as an LA (i.e., not only the first semester or quarter that they serve as an LA). Many—though not all—of our LAs go on to become K-12 teachers. For those interested, Refs. 23 and 79–83 further describe SPU's Physics LA Program.

B. Instructional activity to develop LAs' curricular knowledge

The instructional activity I use with LAs is grounded in examples from the *Physics and Everyday Thinking* (PET)[30] "Models of Magnetism" module (discussed extensively above) and from Harlow's[55] paper that compares Ms. Carter's and Ms. Shay's implementation of this module. (In what follows, boxed text indicates pieces of the activity itself.) The activity starts with an overview:

> **Pre-Assignment: Thinking About How the Structure and Content of Curriculum Communicates its Purposes**
>
> The primary goal of this assignment is to get us thinking about the *purposes* of particular curricular exercises. Most research-based curricula have the general goal of supporting the development of conceptual understanding, but each one goes about doing this in particular ways that communicate additional purposes and/or values. One of the things we'll do this quarter is to think about the purposes of specific questions (or sets of questions) in the *Tutorials* being covered each week; I'm hoping this assignment kick-starts that process.
>
> The first set of questions pertains to an activity from the curriculum *Physics and Everyday Thinking,* in which students develop a model for magnetism. I won't ask you to do the entire activity, but I do want you to get the gist of what students would be asked to do.
>
> The important thing in answering these questions is that you understand what the students are being asked and that you've thought about your answer. Just write down what you think, intuitively. (We're not so concerned about the "right" answer as about the content and structure of the curriculum, and you are definitely not being graded on the basis of whether or not your answer is canonically correct.)
>
> In Activity 1 (stated purpose pasted below), students do a series of experiments and observe that an (originally) un-magnetized nail that has been rubbed by a magnet becomes magnetized (i.e., starts to act like a magnet once it has been rubbed).

The worksheet proceeds with an excerpt from the "Models of Magnetism" PET module, which states the purpose of Activity 1:

> *"In Chapter 3 Activity 1, you studied some properties of the magnetic interaction, in particular how one magnet can affect another magnet. In that activity you discovered that only certain materials (ferromagnetic metals) will interact with a magnet. To remind you of these properties, take a moment to review the Scientists' Ideas from that chapter relevant to magnetism."*
>
> *But what gives a magnet its properties? Are magnets made of special material and how are they made? What is it about ferromagnetic materials that allows them to interact with magnets? The purpose of this activity is to investigate how you can make a magnet yourself, and to explore in greater depth some additional properties of the magnetic interaction. During the remainder of this chapter, you will use this information to construct a model to explain magnetism." (p. 4–3, Ref. 30)*

My worksheet then gives LAs the first instruction:

> 1. In Activity 2, students develop a model for a magnetized nail. **Complete the following two pages of this worksheet, which correspond to the first two pages of Activity 2.**

LAs complete pages 4–15 and 4–16 in PET, which instruct them to:

(1) Sketch "what you think might be different about the nail" in the "rubbed" and "unrubbed" conditions, giving them two outlines of a nail on which to do so (p. 4–15); and
(2) Explain how their model accounts for their observations that: (a) "rubbing an unmagnetized nail with a magnet can *magnetize* it"; and (b) "the magnetized nail has north and south poles" (p. 4–15).

LAs are then told to complete two more pages (4–19 and 4–20) of the PET "Models of Magnetism" module:

> 2. The next two pages of Activity 2 ask students to discuss their drawings and predictions with their peers and to decide on a "best model" for the rubbed nail (i.e., a consensus model from their group).
>
> Students then predict the behavior of their rubbed nail (i.e., after it has been magnetized) when it is cut in half. **To get a sense for the predictions that this curriculum is asking students to make, complete the following two pages of this worksheet**.

Pages 4–19 and 4–20 of PET ask students to reproduce their sketch of the magnetized nail, assuming that "the pointed end was a north pole" (p. 4–19). Students are then given an outline of a nail that has been cut in half and told to draw "what [their] model above suggests would be inside the two halves" and to "label each end of each piece according to whether it should be a north pole (N), a south pole (S) or have no pole (NoP)" (p. 4–19). They predict what would happen if "the north pole of a rubbed nail was brought near each of these four ends: *attract, repel,* or *nothing"* (p. 4–20) and explain their predictions using their model.

In my instructional activity, after completing pages 4–19 and 4–20, LAs see:

> 3. Students then do the experiment, observe the results, and modify their models of the rubbed nail if necessary.
>
> **Follow the prompts on the attached two pages, corresponding to the activity described above. In particular, answer the question asking you to compare your observations and predictions, and draw your current model of the rubbed nail.** (Notice that I've added the results you would observe if you conducted the experiment, assuming — as the worksheet states — that the rubbed nail was labeled with an "N" at the pointed end and an "S" at the flat end.)

They complete PET pages 4–22 and 4–23, which: (a) provide them with the results of the cut-the-nail-in-half experiment (i.e., for each half of the nail, one end is attracted to a magnetized nail and the other end repelled), (b) ask them to compare their observations with their predictions, and (c) if their observations are inconsistent with their predictions, "consider how [they] might change [their] model so it can explain both [their] new observations **and** [their] previous observations" (p. 4–23).

After working through the PET module themselves, LAs complete the remainder of the worksheet, which is intended to "make visible" that RBIMs anticipate and respond to learner ideas:

> 4. **Thinking about the structure and content of PET Activities 1 and 2 (which you completed above), what do you think was the purpose of the cut-the-nail-in-half experiment? (i.e., Why did the authors of this curriculum put *this* experiment in *this* spot?)**
> 5. Please read the two sections (1) "From Learning to Teaching" (including the two sub-sections) and (2) "Discussion" of the paper "Uncovering the Hidden Decisions that Shape Curricula," included in the Blackboard folder with this assignment. (You can ignore Fig. 3, making this about two-pages-worth of reading).
>
>   **Per your reading, what does Harlow (the author) say is the purpose of the experiment in the PET activity you just (partly) did?**
>
>   **What do you think Ms. Carter saw in/ understood about the curriculum that Ms. Shay did not?**
> 6. Harlow says that this activity *anticipates* that students will propose a particular model of the rubbed nail and then *responds* to this model with a specific experiment, as though the curriculum makes decisions or has a mind.
>
>   **What kinds of decisions do you think the Tutorials (used in our intro physics courses) make? Give an example and explain your thinking.**
> 7. **What questions does this assignment raise for you about the *Tutorials* curriculum?**

In particular, question 4 is intended to both (a) highlight that specific activities within an RBIM serve specific purposes and (b) elicit their ideas about what might be the purpose of the experiment in the PET "Models of Magnetism" module. Question 5 is meant to introduce LAs to Harlow's comparison of Ms. Carter's and Ms. Shay's implementation of the PET module, focusing their attention on her proposal for what the experiment was designed to do. In answering questions 6 and 7, LAs start to think about how these insights might apply to the RBIMs that they use in their own classrooms.

To be clear, in my courses, this activity is framed as a starting place for dialogue about "how RBIMs work;" the conversation does not stop when LAs complete the worksheet. The specific form that this dialogue takes depends on the ideas and questions that LAs bring to bear, in the spirit of participating with my own "curriculum." For example, three years ago, we used the "decisions" LAs proposed (in response to question 6) as a starting place for developing a model for the instructional strategies used by the *Tutorials;* this model became the center of our discourse for several weeks, and we used it to "dissect" *Tutorials* and identify which parts corresponded to which strategies in our model. Two years ago, we spent two weeks discussing LAs' models for magnetized nails, using this as a platform to talk about what kinds of questions might support learners in developing their own models. We then discussed how the experiment proposed in the PET curriculum responded to these models. And then we sought to answer the question, "Are there parts of the materials [we're] using that are anticipating particular ways of thinking from students? What are they? Are there other specific purposes that the materials are serving?" In every case, I've found the experience of using the activity to be meaningful and productive for supporting LAs in both (1) recognizing that RBIMs anticipate and respond to learner ideas and (2) identifying specific instances in which they do so. I will give examples of what this can look like in Sec. III.

III. ILLUSTRATING LA THINKING ABOUT THE PURPOSES OF PARTICULAR EXERCISES WITHIN RBIMs

In this section, I will provide excerpts from LAs' responses to the instructional activity I described in Sec. II, as a way of showing that engaging in this activity can be a rich starting place for discussion about the purposes of particular activities within RBIMs. More generally, these excerpts—and my own experience of working with novice instructors around the development of this kind of knowledge[23]—suggest that novice instructors *can* develop curricular knowledge of the type I propose. Though I will not claim that these quotes are representative, neither are they idiosyncratic; at least half of my LAs responded in ways that I consider to be equally sophisticated.

In particular, it is not uncommon, in the context of this instructional activity, for LAs to recognize the purpose of the cut-the-nail-in-half experiment as addressing a particular (canonically incorrect) model for the magnetized nail. For example, in response to question 4, LAs wrote:

> *"The purpose of the experiment was to bring the learner to a greater understanding of the workings of a magnet. It would be easy to incorrectly believe that all the (+) gathered on one side and the (-) gathered at the other. If this model was used then it would cause the nail, when split, to repel both at one side and attract to both of the other side of the split nail. However, when actually done we see that it is not possible to create an 'all N' [or all (+)] chunk of magnet. It always works in pairs. Also, [the experiment] allowed for the learner to go through the process of creating and checking something, which will allow them to be reminded to check their assumptions as they move forward, especially if their initial diagram was faulty or insufficient." (Rusty)*[88]

> *"I think that the reason the authors put it in there was to address the misconception of magnetic monopoles contributing to magnetization of an object. Giving students no instruction, it is fairly reasonable to assume that there are charge-like equivalents to magnetic poles, especially if you've just done electric polarization. So it is important to address this misconception." (David)*

In these responses (and others like them), LAs not only name the function of the experiment as addressing an incorrect idea, they also identify the specific idea that the experiment is meant to problematize. Further, this idea—that like "magnetic charges" would congregate at either end of the nail (or that "magnetic monopoles would contribute to the magnetization of an object")—is sensible to them; they recognize this as a reasonable idea for students to bring to bear, given their own experiences.

In reading and responding to Harlow's analysis, many LAs understood the role of curricular knowledge that she proposed. For example, in response to question 5, LAs wrote:

> *"Ms. Carter knew that by challenging the students with the second piece of information, she would prompt them to reconsider their ideas and think of how they could change their models to make sense of the new observations. Ms. Shay showed them how to create a model or idea, but not how to revise or develop it when given secondary information." (Eddie)*

> *"Ms. Carter understood that the purpose of cutting the nail in half was to test the model where charges separate to the ends. If students propose another model, then cutting the nail in half would not help their understanding. So Ms. Carter instead made up a different experience that was targeted to the misconceptions in her student's initial model." (Maddie)*

Both Eddie and Maddie highlight that Ms. Carter's instructional choices were responsive to her students' models in ways that the cut-the-nail-in-half experiment was not.

Several LAs articulated ways in which the curriculum they implement—*Tutorials*—anticipates and responds to learner thinking. For example, responding to question 6, LAs wrote:

> *"The Tutorials also follow this model and assume that there will be a general flow of thought. It will ask 'leading questions' hoping that the student will answer a certain way. It will often tell the learner to make a prediction and then will go through a series of steps and ask the learner to then review their prediction and revise it if necessary. This series of steps can be extremely helpful in developing the thinking of the learner but it also cannot, because of its concrete nature due to being printed on the page, alter itself to help the learner. This is why it is important to understand what the tutorial is attempting to do in order to help facilitate learner participation and maximum benefit from the classes!" (Rusty)*

Rusty's response draws attention to the fixedness of the curriculum and the role this carves out for instructors: since the curriculum cannot "alter itself to help the learner," instructors need to understand "what [the curriculum] is attempting to do" so that they can carry out these purposes in the context of a dynamic learning environment. Zach's response, illustrated in Figure 5, uses a specific example to illustrate how the *Tutorials* anticipate and respond to learner ideas: the curriculum anticipates that learners may think that an object at rest is not accelerating, and responds to this in the context of an object on a parabolic trajectory.

Finally, many of the questions that LAs proposed in response to question 7 reflected the kind of awareness I was hoping to foster, such as what to do when students have ideas that are different than the ones the curriculum anticipates, or what kind of research supports curriculum developers in anticipating student ideas. The first of these is consistent with the kinds of questions that I raised earlier (in the Introduction)—e.g., what if the ideas that students bring to bear differ from those anticipated by the curriculum—and could serve as a "way in" to considering a framing of curriculum use as participation *with* the text (rather than curriculum use as following or subverting the text). The second question communicates to me that LAs are becoming aware that the curriculum is *designed with intent,* which also represents a step toward considering their own role in relationship to the curriculum.

In sum, these examples are meant to illustrate: (a) that it is possible for novice instructors to recognize the purposes of particular questions or sequences of questions within RBIMs, and (b) that the instructional activity I describe can be a productive starting place for conversations about such purposes. Many of the responses in this section speak to the importance of understanding the purposes of RBIMs, in the ways I articulate earlier: LAs acknowledge that students may bring to bear ideas that differ from the ones that the curriculum anticipates; they recognize that Ms. Carter's deviating from the curriculum provided students with opportunities to refine their models; and their vision of their own roles is consistent with curriculum use as participation with the text. Teacher educators could use each one of these as a launching point for more conversation—e.g., pressing more deeply into each idea, providing opportunities to ground the ideas in particular curricular contexts, etc.

IV. DISCUSSION

In this paper, my aim has been to problematize the invisibility (to teachers) of the purposes of particular exercises within RBIMs and to provide one possible solution to this problem that other teacher educators may adapt for their own institutional contexts. In particular, I have shown that many RBIMs anticipate and respond to *particular* (often incorrect) learner ideas, that teachers often do not recognize this, and that not recognizing this can cause teachers to miss opportunities to build on learner ideas and/or engage students in scientific practices (whereas recognizing this has had powerful outcomes for my own LAs and for Ms. Carter). I shared an instructional activity I designed that is meant to support teachers in recognizing the purposes of particular questions or sequences of questions within RBIMs, and I illustrated that this activity can be a productive starting place for conversation about RBIMs.

My own aim in supporting LAs in developing curricular knowledge of this type is to empower them to make informed, real-time instructional decisions: I want them to know what the curriculum is trying to accomplish and to decide if that purpose is what is best for the particular students in front of them. This is important to me for reasons of teacher agency—I want teachers to feel capable of and free to teach in ways consistent with their intuitions and their values. It is also important to me for reasons of student achievement and empowerment—I want students to see their ideas as influential in the direction that their learning takes. Other teacher educators—with similar goals as mine and/or who prepare instructors to use RBIMs—may wish to use or adapt my instructional activity for their local contexts.

Some may object to my focus on the development of curricular knowledge amongst LAs, arguing instead that another focus—such as the development of pedagogical content knowledge (PCK)[24,29,84] or content knowledge—would be more appropriate. Certainly teacher educators—including those who prepare LAs and TAs—must choose among competing instructional goals, and I do not wish to dispute the importance of PCK or content knowledge for teaching. However, I do wish to point out that physics RBIMs themselves embed both PCK—e.g., in choosing representations to support student learning of *x* idea—and content knowledge—e.g., in pressing for deep conceptual understanding of *y* idea. Thus, seeking to engage with these materials so as to understand what they are designed to accomplish—i.e., developing curricular knowledge—necessarily provides opportunities for teachers to deepen their content knowledge and PCK.

Physics education researchers and curriculum developers can support the development of curricular knowledge by:

- not only providing Instructor's Guides and other materials that make visible the decisions that influence curricular design,
- but also by supporting users in developing curriculum-specific curricular knowledge of the kind I advocate for here. In other words, researchers and curriculum developers could work with users to see *that* RBIMs anticipate and respond to common learner ideas and/or are meant to develop particular understandings in specific ways.

These recommendations are consistent with Harlow's call for curriculum developers to "mak[e] the knowledge that goes into designing activities transparent to teachers" for the purpose of "help[ing] teachers recognize the underlying structure of the activity."[56] However, the second recommendation goes beyond Harlow's suggestion; I am bidding that curriculum developers support users in *constructing* context-specific curricular knowledge, rather than (primarily) *disseminating* that knowledge through instructor's guides or other facilitation materials.

The instructional activity introduced in this paper draws on my own (and Harlow's[55,56]) thinking about two physics RBIMs—*Physics and Everyday Thinking (PET)* and *Tutorials in Introductory Physics*. The "Models of Magnetism" module in *PET* was sufficiently similar in purpose to the *Tutorials* my LAs were planning to teach that I felt it an appropriate starting place for the development of curricular knowledge in my context. However, I acknowledge the growing diversity of RBIMs in physics; as our field continues to develop research-based instructional materials, the purposes, structure, and scope of these materials will undoubtedly continue to proliferate. In fact, *PET* and the *Tutorials* serve very different audiences—future elementary teachers versus university physics students—and, in many cases, different purposes. This paper is not meant to "cover" the space of RBIM-specific curricular knowledge; instead, I mean to make visible *that* RBIMs anticipate and respond to learner ideas, and to get us thinking about how to support teachers in developing the knowledge and skills to see this in the curricula they use. I hope we can broaden this conversation to include more RBIMs, and to consider the implications of curricular diversity for the development of curricular knowledge.

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[84]D. L. Ball, M. H. Thames, and G. Phelps, "Content knowledge for teaching: What makes it special?," J. Teach. Edu. **59**(5), 389–407 (2008).
[85]Throughout this paper, I use the word curriculum consistent with the definition issued by Remillard,[42] to mean "printed, often published resources designed for use by teachers and students during instruction"—e.g., the *Tutorials* themselves, in a *Tutorials*-supported university physics course.
[86]To be clear, this streamlining has advantages with respect to how long it takes novice instructors to develop this kind of knowledge. However, as I share in Robertson, Gray, Lovegren, Rininger, and Wenzinger (under review), taking the time to *invent* this knowledge had substantive

advantages for the original cohort (e.g., authentic ownership of their curricular knowledge).

[87]Many such curricula—and all of the examples I use in this paper—anticipate and respond to student *mis*understandings. However, some RBIMs in physics are explicit about their choices to build on students' productive resources (e.g., Maryland Open Source Tutorials[77,78]). Others, including the *Tutorials,* though perhaps not explicit, presume students will be able to iteratively build conceptual models (e.g., for extended light sources) using existing ideas, thus implicitly treating these existing ideas as productive resources. I draw on misunderstandings-oriented examples here for rhetorical simplicity—because the instructional activity I developed for LAs and the literature's treatment of teachers' understanding of RBIMs rely on such examples.

[88]All names are pseudonyms.

Ellipsoidal Conductor

Lines of force are always perpendicular to the surface of a conductor, and the electric field is largest where they cluster closely together. The distribution of charge on the conducting surface of this ellipsoidal conductor is largest near its point. This can be shown by removing a small amount of charge with a proof plane (a small metal ball on an insulating handle) and using this to charge an electroscope. This was a standard piece of demonstration equipment, and typically sold for a few dollars in the first part of the 20th century. This example is at Cornell University. (Picture and Notes by Thomas B. Greenslade, Jr., Kenyon College)