A case of resources-oriented instruction in calculus-based introductory physics

Lisa M. Goodhew
Department of Physics, University of Washington, 3910 15th Ave NE, Seattle, WA, 98195

Amy D. Robertson
Department of Physics, Seattle Pacific University, 3307 3rd Ave W, Seattle, WA, 98119

Paula R. L. Heron
Department of Physics, University of Washington, 3910 15th Ave NE, Seattle, WA, 98195

Many research-based instructional materials in physics have been informed by investigations of common student difficulties – thinking that is inconsistent with canonical understandings. Our research team is beginning to develop instructional materials that elicit and build on common conceptual *resources* – ideas that may be continuous with formal physics. These materials are open-ended and emphasize on building from students' thinking, in contrast with other research-based materials that aim to address specific difficulties or scaffold toward well-specified conceptual understandings. We expect that resources-oriented materials like ours place different demands on instructors, and that the instructional practices that are effective in this context may differ from other research-based approaches. In this paper, we use classroom video from preliminary resource-oriented instructional materials on pulse propagation to analyze a *case* of resources-oriented instruction in introductory physics, to explore what knowledge, skills, and/or dispositions may support instructors in implementing this kind of instruction.

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I. INTRODUCTION

Resources theory conceptualizes knowledge use as context-sensitive, in-the-moment activation of *resources:* cognitive units that can be of smaller grain size than a scientific concept, theory, or skill. *Learning,* in resources theory, is a cognitive process in which resources are activated, refined, and connected. Learning, then, "requires the engagement and transformation of prior productive resources" [1], which may involve reusing them in new contexts, connecting resources to one another, or changing the conditions for activation [1–3]. Resources theory directs instructional attention to the ways in which student thinking is sensible and fruitful in some contexts [1,3,4]. This perspective contrasts with instructional strategies that aim to address common difficulties or misconceptions [5,6], which have had a pronounced impact on university physics education in recent decades.

Examples of instructional approaches that are consistent with a resources perspective on learning are characterized by: (a) an emphasis on understanding the substance of student thinking, (b) attention to the connections between students thinking and disciplinary concepts, and (c) flexibility in pursuing student thinking in the moment [7–12]. In line with resources theory, instructional approaches of this kind aim to support students in articulating, refining, and building from their own ideas [3].

The research we present here is part of a broader effort to support implementation of resources-oriented instruction in university physics courses (e.g., [13]). We are in the early stages of developing and testing instructional worksheets that are designed to elicit and refine common conceptual resources. These materials do not aim for a single, predetermined conceptual outcome; the goal is to facilitate the refinement of students' own thinking through metacognition and experimentation (Section III includes a more detailed description of an example). The materials are designed to be implemented in small-group sessions in university physics courses, which are often led by graduate or upper-division undergraduate teaching assistants (TAs). As we iteratively test and refine these materials, we are beginning to ask what preparation may support TAs in effectively implementing them. The answer to this question is not obvious because (i) instruction using these materials is likely different than the kind of instruction TAs have experienced [14], (ii) TAs have different preparation than the experienced K-12 teachers who are the subject of literature on resources-oriented instructional approaches, and (iii) most existing TA studies have been done in the context of materials that motivate different instructional action (e.g., Socratic questioning to address specific misunderstandings). In this paper, we present a case study to explore the question: *What knowledge, skills, or dispositions might support instructors in effectively implementing resources-oriented instruction in a university physics course?* Our aim is to inform recommendations for TA preparation in resources-oriented contexts, and to explore the extent to which the knowledge, skills, and dispositions posed by existing literature generalize to this context.

II. OVERVIEW OF LITERATURE

Literature on teacher professional development suggests that certain kinds of preparation support teachers in effectively implementing instructional approaches consistent with resources theory. These suggestions include: practice in noticing and responding to the substance of students' ideas [15,16], a commitment to listening to and understanding student thinking [12,17], or content knowledge that helps to see the connections between student thinking and disciplinary concepts [10,18]. However, the bulk of these suggestions have been primarily developed through the study of instructors in K-12 classrooms, who bring different expertise and training (*e.g.*, teacher certification) and respond to different sets of student expectations and content goals than typical instructors in a large university physics course.

Other literature focuses on recommendations for instructors preparing to teach with existing research-based instructional materials or approaches for university-level physics (*e.g.*, [19]). This literature emphasizes a need for both content knowledge and pedagogical content knowledge [20], which includes awareness of students' common misconceptions or difficulties, knowledge of effective pedagogical practices, and familiarity with research-based instructional materials and strategies [5,21,22]. Some research highlights the importance of instructor buy-in and appropriate epistemological framing of activities [23], or emphasizes attention to instructors' beliefs and goals [23,24]. Because our instructional materials are open-ended and focus on refining students' own thinking, we anticipate that this kind of resources-oriented instruction may place different demands on instructors than other research-based instructional strategies.

The differences between (a) TAs and K-12 teachers, (b) university and K-12 instruction, and (c) existing research-based instructional materials and our resources-oriented worksheets raise questions about the degree to which existing recommendations are appropriate for resources-oriented university physics contexts with open-ended content goals. This study begins to explore what knowledge, skills, and/or dispositions university TAs need to implement resources-oriented instruction, by looking at a *case* of such instruction in our local context.

III. METHODOLOGY & EXCERPT SELECTION

The video data for this study was collected at a large, selective research university. The university's Office of the Registrar reports that during the term in which we collected this data, the overall student population was: 54.5% female, 45.5% male; 40.6% Caucasian, 25.7% Asian, 16.8% International, 8.1% Hispanic/Latinx, 4.0% African-American, 1.1% American Indian, 0.9% Hawaiian/Pacific Islander, and 2.6% did not indicate ethnicity. The episode we selected for this study comes from a set of video-recorded small-group sessions in the calculus-based introductory physics course, which primarily serves engineering and physical science majors. These weekly, 50-minute sessions are a required part of the introductory physics course, and typically groups of students work through one worksheet from *Tutorials in Introductory Physics* [19].

In the video for this study, students worked on a preliminary worksheet developed by our team, which was designed to elicit and build on some common conceptual resources for mechanical pulse propagation that had been identified in our earlier work [13] (see Section III). As we watched the video, we looked for *cases of* resources-oriented instruction [25]. Our criteria for calling an episode "resources-oriented instruction" was that it loosely satisfied the three characteristics we articulate in the Introduction.

For this analysis, we chose a 16-minute conversation between a group of three **s**tudents – **S**am, **S**arah, and **S**eung (pseudonyms) – and a graduate **t**eaching assistant – **T**homas – in which they discuss a mechanism for pulse propagation. We originally selected this clip to share in a group meeting because it was a sustained interaction between the students and instructor in which they are engaged with the physics content of this worksheet. We went on to analyze the clip more carefully because it contained clear instances in which the TA asked what the students were thinking and adapted his responses based on the ideas the students voiced (i.e., the TA was engaged in resources-oriented instruction), and because we saw the students making conceptual progress over the course of the conversation (i.e., students were learning in the context of resources-oriented instruction).

We used an inductive approach [26] that drew on elements of interaction analysis [27] to identify some of the knowledge, skills, and dispositions that Thomas brought to bear in this interaction. The analysis involved an iterative process of watching and discussing this clip in our research team, each time refining our focus toward particular interactions and characteristics [26,27]. This process led us to highlight instances where we inferred that Thomas was drawing on his knowledge of physics content and practices and where he made instructional moves consistent with particular commitments or dispositions. In Section IV, we seek to make visible the meaning we make of the interactions between Sam, Sarah, Seung, and Thomas [25].

The purpose of our analysis is to articulate some of the knowledge, skills, and dispositions that are integral to real-time deployment of instruction that is consistent with resources theory. Our aim is *hypothesis generation,* in service of local decision-making and contributions to scholarship about TA preparation. For these purposes, a case study is appropriate [25].

IV. RESOURCES-BASED WORKSHEET

Our team developed a preliminary worksheet intended to elicit and build from common resources for mechanical pulse propagation. The worksheet is designed to be open-ended to accommodate a breadth of context-sensitive resources that students may use for making sense of propagation. The goal of the worksheet is the articulation and refinement of these resources through experimentation and metacognition, not a particular content outcome.

At the beginning of the worksheet, students observe a demonstration of a pulse generated by flicking the end of a spring up and down (experiment 1). Then, the tension is increased, and a pulse is generated using the same hand motion (experiment 2). Students are asked to explain why a pulse moves faster on a higher-tension spring, and then to find someone who has a different explanation and record both. Next, the worksheet presses students to describe the mechanism for pulse propagation that is implied by each of their explanations. Finally, students generate hypotheses based on these mechanisms for new pulse propagation experiments. The learning goal of this worksheet is that students should construct a physical mechanism from their own ideas. This mechanism should address causal questions about propagation experiments ("*why* does this happen?") by identifying the relevant physical entities and activities [28] and should support predictions about new propagation experiments. The worksheet does not guide students toward a specific, correct mechanism.

V. ANALYSIS

Leading up to the episode we selected, Sam, Sarah, and Seung discussed two different explanations for why increasing the tension increases the speed of a pulse on a spring. Their first explanation was based on something they recalled from lecture and focused on forces: with more tension in a spring, there is less force in the transverse direction and more force the longitudinal direction, making the pulse move faster.[1] The second explanation focused on energy and was suggested to the group in an earlier conversation with another TA. Specifically, the group agreed that when there is higher tension in the spring, there is more potential energy, which is then available to be converted into kinetic energy associated with the pulse's motion.

Just before the excerpt we chose, Thomas joined the group and Sarah asked what is meant when the worksheet asks for a "mechanism" for pulse propagation. Thomas responded with an example of a mechanism for why the capacitance of a parallel-plate capacitor changes as area

[1] An explanation based on the width of the pulse and the relative magnitudes of the transverse and longitudinal components of the tension force at the leading edge of the pulse is described in the course text ([28] - see Ch. 16) and was discussed in the lecture section of the course.

changes. He recapped his example by saying that *the explanation for a particular outcome builds off of the underlying mechanism.* We analyze the conversation between Thomas and the students that follows as they work to articulate a specific mechanism based on their understandings of pulse propagation. In this excerpt, most of the conversation is between Thomas and Sarah, who summarizes the group's previous conversation and contributes new ideas.

A. Seeking to understand student thinking

In the video, Thomas appears to cut his capacitor example short before finishing, perhaps because he perceives that the example is not satisfying Sarah's question. He shifts course and asks the students what their explanations for the tension question are. This shift seems to signal a commitment to understanding and building on student thinking, because it refocuses the conversation on the students' own ideas. It is also responsive to the question the worksheet is asking – "What is the underlying mechanism implied by *your* explanation?"

Sarah answers Thomas' question by drawing on the energy explanation they discussed earlier, saying that when the spring is tauter, there is more potential energy in the system, which means there must also be more kinetic energy in the system. In response, Thomas first re-voices Sarah's idea and affirms the explanation, then he presses it further:

(1)[2] *Okay, so you're saying as I increase the tension then that increases the potential energy, which in turn increases the kinetic energy...Okay, um, so, I think that this explanation has a lot of good stuff going for it. There's some assumptions that are in here. So why does the kinetic increase if the potential energy increases?*

Thomas notices and validates Sarah's resourceful ideas about how energy affects pulse speed (which are similar to documented resources for pulse propagation [13]). His question presses into Sarah's thinking by inviting students to articulate the assumptions that their explanation makes; he is asking them to "say more," of a particular kind of thing. This move suggests a commitment[3] to understanding and building from student thinking. Thomas' question does not clearly address the question of what is meant by a mechanism for pulse propagation. However, as the conversation continues, Thomas asks questions – building on the one in line 1 – that both press into Sarah's understanding and point toward a mechanistic description of propagation:

(2) *Sarah: Because it's a closed system, so all the kinetic energy comes from the—potential energy?*

(3) *Thomas: So, but why doesn't the increased potential energy just stay as potential energy? Why does it have to become kinetic energy?*

(4) *Sarah: Because then there's no energy [moving]?*

(5) *Sam: Because it moves?*

(6) *Thomas: Because it moves. Okay we've got a question mark here but somehow, somehow potential becomes kinetic energy. Alright, um—Okay, so I think this is a good explanation, I think that the mechanism um…that you wanna explain is um, how does U get converted to K. Right, and how does T connect, or T change U.*

In this exchange, Sarah begins by stating an assumption that their energy explanation makes – the idea that potential energy turns into kinetic energy relies on the system being closed (or the energy being conserved). In response, Thomas asks *why* potential energy must become *kinetic* energy. This clarifies his question in line 1 (why does kinetic increase if potential does?) in a way that points toward a mechanistic explanation. That Thomas intends his questions to point students toward a mechanism becomes clearer in line 6: he acknowledges that the group has a good explanation that they can build from, *and* that there is room for clarification that will support a mechanistic description. These instructional moves continue to enact a commitment to understanding and building from students' own thinking.

In line 6 above, Thomas suggests that the group consider a specific mechanism that builds from the ideas Sarah has already articulated: one that explains how potential energy (U) is converted to kinetic energy (K), and how changing tension (T) changes potential energy. The connection between tension and potential energy is Thomas' addition to the conversation and suggests that he sees it as an important part of a mechanism for propagation. From this we infer that Thomas draws on knowledge that tension and potential energy depend on a shared variable. In the conversation that follows, Thomas more overtly draws on his knowledge of the forces involved in propagation as he responds to the group.

B. Guiding toward a mechanism

Sarah answers Thomas' suggestion to consider how tension is connected to potential energy (line 6) by saying that there's an equation that includes the spring constant (k) and displacement of the spring (Δx). Thomas names the equation for potential energy in terms of these variables ($U = \frac{1}{2}k\Delta x^2$). Then, Sarah asks:

(11) *Sarah: Is that enough, to say that, like, because the tension relies on delta x, and delta x goes up, the potential goes up, is that a mechanism?*

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[2] The parenthetical numbers denote line numbers in the transcript of this conversation. In the transcript excerpts included in the main body, dashes (—) indicate pauses in dialogue. Ellipses (…) indicate the authors' editing of the transcript to remove unimportant (um, uh) or repeated utterances. Words in square brackets are the authors' inferences about inaudible parts of the video.

[3] Consistent with resources theory, we assume Thomas' knowledge, skills, and commitments may be constructed in the moment of the conversation. We do not expect that these are stable and consistently applied.

(12) *Thomas: yeah, so that's a mechanism for how increasing tension would increase potential energy.*

Here, we see Thomas responding directly to Sarah's question about mechanism by clarifying *what* her response is a *mechanism for,* linking back to the group's original question. This move is consistent with instructional goals of answering Sarah's questions and supporting her in refining her thinking.

Following this dialogue, Sarah double-checks that the group needs a second mechanism to answer the worksheet's question. Thomas affirms this and offers his own ideas about the mechanism for pulse propagation:

(14) *Thomas: Yeah exactly—I think it's kinda like, that next level down—So there's…this energy way of thinking about it, and then you can also approach it from like a forces standpoint, where you can think about breaking your spring down into a series of points, and looking at… the force on the individual points as the wave propagates. So you initiate the wave by pulling up on one here, and then looking at the impact that that has on the neighbors as you go down. So this is…your energy, and this is …the forces buildup…this one feels more fundamental to me.*

In this move, Thomas draws on his understanding of a mechanism for propagation as he guides the conversation: the wave is initiated by pulling up on one particle which impacts the adjacent pieces of the spring and so on. For him, a mechanism based on the forces acting on and between particles of the spring in more fundamental; it is a deeper explanation, "one level down." Importantly, the specific mechanism he articulates extends a particular concept – tension – within the mechanism that Sarah began to articulate previously ("*because the tension relies on delta x, and delta x goes up, the potential goes up"*).

Following line 14, conversation between Thomas and the students continues for three and a half more minutes as Sarah explains that the group's first explanation had to do with forces on the spring. Thomas encourages the group to come up with a mechanism for propagation based on whichever explanation they prefer, and he reiterates what a forces-based mechanism could look like. This prompts Sarah to say that she doesn't understand how to explain *why* increasing tension means there is more force in the horizontal direction and less in the vertical direction (referring to the group's original forces-based explanation for the tension question). Thomas asks for clarification about this explanation. After some discussion with Sam about the group's force-based explanation, Thomas again suggests the group think about a mechanism based on the connections between small parts of the spring. He suggests that they use this mechanism to make a prediction about the next experiment in the worksheet and says he will return to discuss the prediction.

VI. DISCUSSION & CONCLUSIONS

In this case study we explore the question: *what knowledge, skills, or dispositions might support instructors in effectively implementing resources-oriented instruction in a university physics course?* Our analysis suggests to us that resources-oriented instruction is supported by a commitment to understanding and building from student thinking and by flexibly deployed knowledge of scientific concepts and practices. In particular, the structure and sequencing of the guidance that Thomas offers throughout the episode we analyzed is consistent with a commitment to understanding and building from students' own thinking. He gives more specific guidance toward a mechanism only after understanding and pressing into Sarah and Sam's ideas. Thomas' enactment of this kind of instruction appears to be supported by knowledge of physics content – about energy and the mechanics of pulse propagation – and practices – particularly knowledge of how mechanistic explanations are used in scientific discourse. Importantly, Thomas guides Sarah to understand what a mechanism is in a way that simultaneously presses student thinking forward and inserts elements of the scientific process.

The findings from this case study affirm suggestions from the literature that a commitment to noticing, understanding, and building from students' ideas [12,17] – which has not been emphasized as much for other research-based strategies – is important for resources-oriented teaching. Our findings also affirm suggestions that relevant content knowledge is important for both resources-oriented teaching and other research-based instructional strategies [5,12,18,21]. Our analysis specifically suggests that instructors should be prepared with a breadth of content knowledge such that they can adapt this knowledge as they respond to student thinking in the moment. This case study also places emphasis on instructors' knowledge of disciplinary practices (e.g., Thomas' understanding of physical mechanisms), especially those latent in the instructional materials used.

These findings may guide decisions about how to prepare instructors to use resources-oriented instructional materials like those we are developing. In particular, this case study suggests that resources-oriented instruction may be supported by TA preparation in which TAs discuss multiple ways to think about the physics content covered in the worksheet, and what scientific practices might be used to carry student thinking forward. Investigating the most effective way to prepare instructors (including graduate TAs) to use materials like those we are developing is the subject of future work.

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