Resources-oriented instruction: What does it mean, and what might it look like?

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Resources-oriented instruction in physics treats student thinking as sensible and then seeks to connect what students are saying and doing to physics content and practices. This paper uses an illustrative case to make progress toward answering the instructional questions: "What does resources-oriented instruction in physics look like?" and "How can I do it?". We analyze an interaction between a university TA and a group of four introductory physics students completing a worksheet about mechanical wave propagation. We show some of the ways in which the TA's instructional moves supported students in making conceptual progress, even though several of the students' ideas would not be accepted as correct by many physicists.

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I. INTRODUCTION

The resources theoretical framework[1–4] emerged in the early 1990s, alongside and in conversation with misconceptions research.[5–7] Whereas misconception research focused on student ideas that were incorrect, positioning these ideas as *barriers* to learning, resources theory framed student thinking as fundamentally sensible and as including "seeds" or "beginnings" of formal physics reasoning, and thus *integral to* student learning.

In physics education research (PER), early misconceptions- and difficulties-oriented work focused on identifying student misunderstandings about a variety of physics topics and on developing instructional materials that address the misunderstandings identified (e.g., Refs. 8 and 9). Early resources research focused on illustrating theory with case studies, showing, for example, that student thinking is context-dependent and that students have conceptual and epistemological resources for understanding physics.[3,10,11]

This paper draws on resources theory to build instructor awareness around a *pragmatic* instructional question, one that is often asked of researchers doing resources theory work in PER and one that has not yet been extensively explored in physics.[12] That is: "What does resources-oriented instruction look like?" and "How can I do it?" By resources-oriented instruction, we mean instruction that takes up the *orientation toward student ideas* reflected in the resources framework. Resources-oriented instruction in physics treats student thinking as sensible and then seeks to build bridges between what students are saying and physics content and practices. It often relies on the assumptions that students have good ideas and that students can make conceptual and epistemological progress on the basis of what they already know and are doing, even if their ideas would not be considered correct by many physicists.[13–15]

In this paper, we use a case of resources-oriented instruction from an introductory physics course at a large university to illustrate what this kind of instruction looks like, including what kinds of instructional moves support it. We chose this case not only because it exemplifies what we think of as resources-oriented instruction but also because it addresses some of the concerns that we hear when we talk to instructors who are enthusiastic about resources-oriented instruction but worried about their students' learning.[16] For example, instructors may ask, "What if students bring in incorrect ideas? I care about my students arriving at correct physics understandings." Or in imagining resources-oriented instruction, they may think it is the job of the instructor to affirm every idea they hear, equally, in ways that don't clearly draw on their physics expertise.

The analysis in this paper responds to these concerns. The focal episode shows students making conceptual progress in their understanding of mechanical wave propagation. The students' TA affirmed and built on students' thinking—including incorrect physics ideas—in ways that supported this conceptual progress. We analyze the episode in detail in Sec. III, and we summarize the students' conceptual progress and the TA moves that supported it in Fig. 3. The TA's support relied on his own deep conceptual and epistemological understandings and communicated the value he saw in students' ideas while also inviting them to be more specific or clarify aspects of their thinking.

II. INSTRUCTIONAL CONTEXT FOR FOCAL EPISODE

The case we document here is drawn from an introductory physics course at a large university in the Pacific Northwest U.S. The university is not representative of the U.S. in terms of racial and/or ethnic demographics or wealth demographics, as described in more detail in supplementary material.[17] Though this case study is meant to illustrate what is possible, which does not require a representative sample, Kanim and Cid rightly point out that if physics education research continues to under sample from universities that serve Black, Latinx, and Indigenous groups, and/or students with less wealth, the results of PER will continue to underserve these populations of students.[18] Our team is working to understand the relationship between university- and course-level demographics to contribute to the field's understanding of this dynamic.[19]

The episode we selected for this study took place in a small-group session associated with the third quarter of the calculus-based introductory physics course sequence, which primarily serves engineering and physical science majors and focuses on waves and optics. The weekly 50-min small-group sessions are a required part of the course. Typically groups of students work through one worksheet from *Tutorials in Introductory Physics*.[20] In this case, students worked through the *Representing Pulse Propagation* worksheet, developed as part of a research grant focused on identifying and building on students' conceptual resources. In our team's research on common conceptual resources for mechanical wave propagation,[21] we noticed that students often answered questions about mechanical wave propagation by articulating what pulse propagation *is,* or by describing nascent models for pulse propagation. In response, we designed the *Representing Pulse Propagation* worksheet (see the supplementary materials[17]), whose objective was for students to construct a model for mechanical pulse propagation that could accurately predict and explain the outcome of unfamiliar wave propagation experiments. There is no single model toward which the worksheet scaffolds. Students sometimes use macroscopic models that focus on how changes to the spring affect "resistance" to the pulse's motion in the spring, and they sometimes use microscopic models that consider how changes to the spring affect the speed of a point moving up and then back down (and so on). The aim of the worksheet is to support students in engaging in the process of articulating and refining a *mechanism* for pulse propagation that is predictive and explanatory.[22]

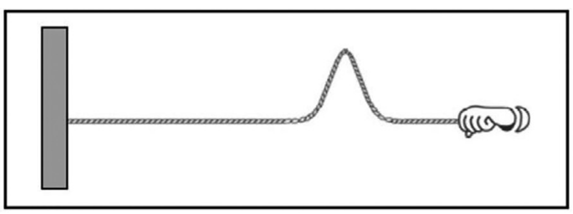
The interaction we focus on in this paper is an approximately-eight-minute interaction (full transcript available as supplementary material[17]) between four students, Sal, Seth, Song, and Sam (pseudonymed with names beginning with "s" to indicate "students"), and the TA, Teddy (pseudonymed with a name that begins with "t" to indicate "TA"). Most of the interaction centered on the *tension pulse flick* question (Fig. 1), which asked why pulses move faster on higher-tension springs. In the original research, this question reliably elicited a variety of resources for understanding pulse propagation, such as "the speed or duration of transverse motion affects the speed of the pulse" and "the speed of the pulse is affected by its energy."[21] Before students answered the first question (Fig. 1), they observed a demonstration of the phenomenon of interest from their course instructor.

Our model for mechanical pulse propagation is described in detail in Goodhew *et al.*[21] To summarize: We model a spring as a series of small beads connected by massless strings of equal length and equal tension (see Fig. 2). In this model, a propagating pulse is the sequential, transverse disturbance and return to equilibrium of individual beads (or, in the continuum limit, segments of the medium). The motion of neighboring beads/parts is coupled by the tension between them. Propagation speed, in this model, is determined by properties of the medium that affect the transverse acceleration of the small segments of the medium. We observe that the pulse propagates without dispersion, so that it maintains the same shape as it moves. Increasing tension increases the magnitudes of the forces acting on a bead in a given location within the pulse, which act in the directions θ and $\theta + d\theta$. Thus, for a given difference in angle between the two tension forces $d\theta$, the net force on the bead increases, causing a larger acceleration, so each "bead" completes its displacement and return to equilibrium more quickly, and the pulse propagates faster.

We chose the focal episode in this paper for the reasons stated in Sec. I: It exemplifies resources-oriented instruction at the college level; it demonstrates that such instruction relies on rich and deep physics understandings; and it shows that students can make significant conceptual progress in resources-oriented instructional contexts. We analyzed the transcript piece by piece using discourse analytic techniques, which are meant to help analysts understand the meaning that actors are making of their interactions.[23] In this paper, we interpret what we think students meant and some of the ways in which Teddy's instructional moves seemed to shape

Consider the following two experiments:

Experiment 1: Your instructor creates a pulse on a spring by flicking the end of the spring, as in the figure at right.



Experiment 2: Your instructor pulls the spring tighter than in scenario and then creates a pulse using the same hand motion as in scenario 1.

The pulse in experiment 2 travels down the spring faster than the pulse in experiment 1.
Why does it make sense for a pulse to move faster on a higher-tension spring?

Fig. 1. The *tension pulse-flick* question from the *Representing Pulse Propagation* worksheet. An audio description of the contents of this figure is provided online in the multimedia. Multimedia view: https://doi.org/10.1119/10.0009796.1

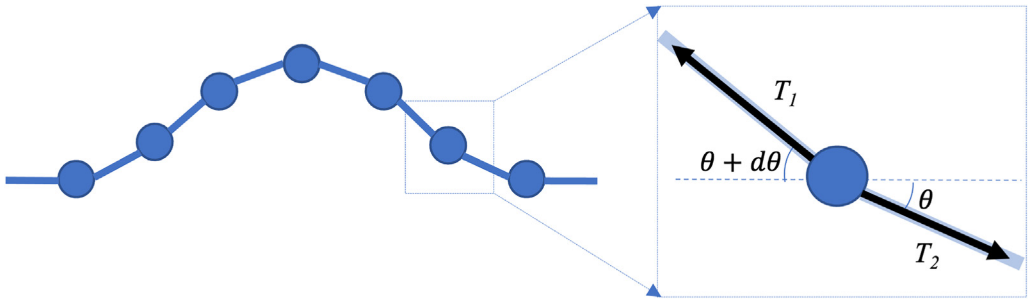


Fig. 2. String-and-bead model for pulse propagation. The transverse acceleration of each bead is due to the net force acting on it, which is the sum of the transverse components of two tension forces. It is assumed that the net force in the longitudinal direction is zero. An audio description of the contents of this figure is provided online in the multimedia. Multimedia view: https://doi.org/10.1119/10.0009796.2

the conversation. We make the claim that Teddy's questions and revoicing of student ideas were integral to the students' progress. This is in some sense a causal claim and relies on a process theory of cause, wherein cause is inferred by a visualizable sequence of events that plausibly links local causes and effects.[24,25] In this way of thinking about cause, "E, the phenomenon to be explained, arose because D came before, preceded by C, B, and A. If any of those earlier stages had not occurred, or had transpired in a different way, then E would not exist or would be present in a substantially altered form from E, requiring a different (but equally credible) explanation."[26]

In the remainder of the paper, our aim is to walk you through the interaction, to show you how it is an example of resources-oriented instruction as we have defined it, and to suggest that this kind of instruction can support students in making progress toward more sophisticated and more correct understandings. Case studies that draw on process theories of cause produce insights that are necessarily local; they are not reproducible in that the same instructional moves may produce very different outcomes in another context. But that does not mean that the insights do not generalize.[27–29] In fact, they concretize broader themes so that readers can expand their awareness of what is possible and *how* certain processes happen. Early work suggests that our case is not unique, in that students do often make progress, but as they use this worksheet, their awareness of the progress they are making seems to depend at least in part on the instructional support they receive.

It is worth noting that the primary speakers in this episode were Seth, Sal, and the TA; Song entered the discussion for a short period, and Sam spoke very little. Our analysis has been limited to the ways in which Teddy noticed and built on the *conceptual ideas being raised by the students*. An analysis of power or equitable team dynamics would certainly highlight different points, and may not position this as an exemplary interaction.[30–32]

III. RESOURCES-ORIENTED INSTRUCTION IN INTRODUCTORY PHYSICS: AN EXAMPLE FROM WAVE MECHANICS

In this section, we document an example of resources-oriented instruction, where a TA, Teddy, listened to and supported students in building on their ideas about mechanical wave propagation. (Figure 3 in Sec. IV summarizes this interaction.) In the three minutes preceding the interaction we document, the students began the *Representing Pulse Propagation* worksheet, answering the *tension pulse flick* question in Fig. 1. Seth talked first, proposing that increasing the tension stretches the spring out so that "there's less mass because the spring is less condensed." Thus, the mass density is less, such that "the force [the spring is] gonna exert to counteract that wave motion is less."[33] Here we see Seth drawing on the conceptual resource that lower mass density means less force resisting the motion of the pulse,[21] almost as though the pulse is an *object* moving through a medium that has been made less dense.[34]

Sal answered, "that definitely makes sense," and then went on to propose a second explanation: that "the more taut the spring," the stronger the restoring force and thus the faster the acceleration of the spring. As the students paused to write their answers on the worksheet, Teddy, the TA, approached. He asked the group if they would share how they were making sense of the demonstration from the start of class, which illustrated the phenomenon described in the *tension pulse flick* question.

Seth was the first to answer Teddy, recounting his mass density explanation: pulling the spring means that the length is longer but the mass stays the same, so "mass per unit length is less." With a lower mass density, the "inertia of it is going to be less resistive," so the pulse will "travel quicker." Seth's explanation here includes several correct elements. If the spring stretches under the increased tension, then its mass density μ decreases, and the propagation speed $v = \sqrt{T/\mu}$ increases. In the language of our model above, the inertial mass dm of each length dx is reduced, so the transverse acceleration is increased, and the pulse propagates more quickly. However, Seth's model cannot explain why a pulse would propagate more quickly on a string whose mass density is nearly unaffected by tension. Teddy revoiced Seth's answer with discursive moves in the form of "Okay, so you said…" and "Okay, so…".

Seth then brought in "particles" of the spring for the first time, saying that when the tension is increased:

> "So, when the whoever, uh, hits the spring or string, the individual particles…will be less resistive to the force of the person so it will propagate through the quickest."

Teddy simply said, "Okay," and Seth continued, bringing in Sal's explanation about the restoring force:

> 10. Seth: Yeah. And we also said, uh, when you have a more tense string there's going to be like stronger restoring force, so ummm then that force is greater, so…since force equals mass times acceleration, the acceleration will be fas—greater, and it will propagate quicker.

11. Teddy: Okay.

12. Sal: Are those valid points?

13. Teddy: I mean that's making sense to me. It sounds like you've come up with some way of kinda like explaining a correlation between… tension and higher wave speed.

14. [Seth and Teddy begin to talk at the same time, Teddy signals for Seth to go ahead.]

15. Seth: I was going to ask a question but finish what you were going to say.

16. Teddy: Oh, sure. I guess, ummmm, yeah. Okay. So, what's the restoring force here? Like, what's the force that you're thinking of? Like what's F equals ma?

17. Sal: I was thinking of like the force, uh, like, if the-. It's like a point on the wire displaced from the line, it's like the force that like brings it back to the line. And because the force is greater, the acceleration that will bring it up is greater.

18. Teddy: Okay, and increasing the tension means that the force that brings it back to that equilibrium position is greater?

19. [Sal nods]

In line 10, Seth offered Sal's explanation to Teddy, layering on Newton's second law: There will be a "stronger restoring force" in a "more tense spring," and a higher force means a higher acceleration. At this stage, this explanation appears to be a macroscopic: The *spring* experiences a stronger restoring force. Sal sought confirmation from Teddy for this answer, and Teddy responded by revoicing the activity that the students were engaged in: They were coming up with a way to explain the "correlation between…tension and…wave speed." Rather than confirming or disconfirming the correctness of their answer, Teddy said "that's making sense to me."

Teddy then (line 16) pressed the group for elaboration of their thinking, using more technical physics language—specifically, asking them what they are identifying as a restoring force? This question prompted Sal to bring in the beginnings of a microscopic model for pulse propagation: The restoring force is the force that brings *displaced points* on the wire back to equilibrium. As the restoring force increases, Sal said, "the acceleration that will bring it up is greater." We call this the "beginnings of a microscopic model for pulse propagation" because it names one step in a mechanistic chain:[35,36] It explains the relationship between the tension and the acceleration of a particle in the spring, but it does not yet state the connection between individual particles' motion and the speed at which the disturbance propagates.

Teddy's next question (line 18) further clarified and connected the students' thinking to the physics canon: "increasing the tension means the force that *brings it back to that equilibrium position* is greater?" (emphasis ours, highlighting what Teddy added). Seth answered Teddy, bringing in Hooke's law:

20. Seth: We thought, like kx, y'know? Like by increasing the tension you'd be like manipulating the negative kx thing, so like the negative k-constant would increase, so your force restoring it would [signals up for increase].

21. Teddy: Okay, so we're changing the k, that's how you're thinking about it? …increasing the tension, you're saying makes the k bigger.

22. Seth: Yeah.

23. Teddy: Okay.

24. Seth: Hmmmm. Actually, the problem with that is, like, wouldn't you have the same, like uh, wouldn't that counteract-. It'd actually counteract, because you'd also be experiencing a greater force by the wave propagating away from–, your, minimum. 'Cause when you go this way [signals toward the wall] you have like the force of the spring, like the restoring force counteracting your movement, so like if we were to increase that constant by like stretching it, then we'd have that same, it'd like balance out, you know what I'm saying? Because if there's tension here and we're experiencing like a spring force from that Hooke's law, it's going to exert a force that's opposite of its motion since when you first hit it it's moving this way, you're going to have a force going that way which would be slowing down the wave, and then when it's going back it's going in the direction this way so it's increasing it, so it's kinda like balancing it out. Which is why I like kinda don't know if it makes sense.

In response to Teddy's question (line 18), Seth connected the tension in the spring to Hooke's law. (We will get to hear more about why Seth associated a higher tension with a higher spring constant later.) Though the specific association (between T and k) that Seth made is not particularly effective for describing pulse propagation from a physics perspective, Teddy did not focus on this but instead revoiced Seth's reasoning and asked if he had heard Seth correctly: "increasing the tension, you're saying makes the k bigger." He posed this as a question: "that's how you're thinking about it?" Importantly, Teddy neither *suggested that this answer was correct,* nor did he step in to correct it.

This interaction made room for Seth to then identify a vexation point (line 24), which Odden and Russ define as "a critical moment [in the sensemaking process] when the students articulate an inconsistency or gap in their understanding, the thing that doesn't 'make sense' to them."[37] Importantly, Odden and Russ find that this moment often "kicks off the sensemaking frame," where students "transition from recalling previously learned knowledge to actively building new knowledge or connections between new ideas."

In line 24, Seth started to zoom out from (a) focusing only on the pulse and the restoring force on the pulse to (b) talking about the spring and the phenomenon as a whole. When he said, "…when you go this way you have like the force of the spring, like the restoring force counteracting your movement," we think he was referring to two forces: (1) the force the hand exerts on the spring to create the pulse ("go this way" and "your movement") and (2) the restoring force of the spring. (It may be instead that he is talking about the transverse motion of points and the restoring force that pulls points back down to equilibrium.) He suggested that these forces will "balance out," and he was right, in a sense; these two forces are a Newton's third law pair, so they *are* equal, even though they are being exerted on different entities (one on the spring, the other on the hand). After this point, we become less sure what he was referring to, but what *is* clear is that he was naming something he was confused about; he even said, "I like kinda don't know if it makes sense." Teddy's response was to again revoice what Seth said rather than correct him, and then ask for clarification:

> 25. Teddy: Okay, so I heard you mention a couple of forces, specifically you talked about the tension and the spring force. So, what are the forces here?
>
> 26. Seth: The wave force? The, like, pull?
>
> 27. Song: Isn't that just tension?
>
> 28. Seth: But there's also the force that starts the wave.
>
> 29. Teddy: Okay, so there's something about starting the wave. You asked, isn't it just tension? Ummmm, so we could look at like, just part of the spring, right? And ask like what are the forces on it?
>
> 30. Song: So, like $F = -kx$, and ummmm, even though you probably displaced the same amount, so the x stays the same, but like umm but the spring constant increased because the spring was like harder.
>
> 31. Teddy: Okay, so like a more stretched spring is kind of like a harder spring, you're saying?
>
> 32. Song: Yes.
>
> 33. Teddy: So, it's going to like to bounce back more. So, like also adding to that explanation for how or why you'd expect k to change when you change T.

Teddy's question in line 29 brought Song into the conversation in a substantive way for the first time. When Seth responded in line 26 that "the pull" ("wave force") is the force on the spring, Song asked, "Isn't that just tension?" and Seth answered that "there's also the force that starts the wave." Teddy revoiced their thinking in line 29, drawing attention to Song's question ("*you* asked…," emphasis ours), and then narrowed the scope of his original question, inviting students to focus on "just part of the spring." Teddy's suggestion here invited Song and Seth to look at the problem in a formal physics way: He asked about a small part of the system that can be treated as a point-like object (e.g., Refs. 38–40).

Song then (line 30) revoiced and added to Seth's earlier reasoning about the relationship between increasing the tension and changing the spring constant, saying "the spring was like harder." (He also associated x, the displacement in Hooke's law, with the displacement of the spring during pulse generation.) Teddy (line 30) again revoiced and added, saying "a more stretched spring is kind of like a harder spring, you're saying?" When Song agreed, Teddy named the knowledge-building activity students were engaging in: They were explaining "how or why you'd expect k to change when you change T."

Seth then began to articulate a second vexation point:

> 34. Seth: Okay, but now I'm, like, confused by this. I can draw it [draws a circle, representing a unit of mass]. You have a unit of mass representing some point on the spring, when the wave is travelling this way [down the spring] it's [unit of mass] going to go up and then like back down, right?
>
> 35. Teddy: I agree. Yes.
>
> 36. Seth: Okay, so as it's travelling up it's going to be feeling the force of whatever the thing that hit it was-.
>
> 37. Teddy: Uhhh.
>
> 38. Seth: Or does that like not make sense?
>
> 39. Teddy: Well how-, let's see.
>
> 40. Seth: Okay. Okay, I'll skip over that part.
>
> 41. Teddy: Like what is exerting the force?
>
> 42. Seth: I'll skip over that part.
>
> 43. Teddy: You said-. This is an interesting point. You've raised an interesting question in that you know that it's going to go up and down somehow, and some force is going to do that. [few moments of silence]
>
> 44. Seth: Okay. So maybe, what's happening is like you have like a chain of like particles, and the initial force is going to knock this, like up here, right. And it's going to be like that now, but these are kind of connected and there's going to be tension between them, and that's going to pull this up, and this is going to end up here, and in so doing, this is going to get pulled up and like down the line as it's pulling. So, the only force then is like this force in-between like individual particles, and if there's more tension we'd have that like kx relationship where k is increasing. So the force that each individual particle is putting on each other is larger, and since $F = ma$, then mass stays the same, but acceleration has to go up, so each one of these individual particles is going to accelerate faster which allows the process of like pulling up to go faster.

Seth began articulating another vexation point (indicated by "I'm, like, confused by this…") in lines 34–36: As the wave propagates down the spring, a point on the spring moves up and down, and as it does it will be "feeling the force of whatever the thing that hit it was…" We do not get to hear what Seth was "confused by" (line 34) because he seemed to perceive from Teddy that what he is saying "[did] not make sense." When Seth offered to "skip over that part," Teddy pressed him to continue, affirming and revoicing the parts of Seth's reasoning that Teddy understood: "You've raised an interesting question in that you know that it's going to go up and down somehow, and some force is going to do that."

Seth did continue; after a short pause, he articulated a microscopic model for pulse propagation that was more correct than his earlier one from line 17. Here, Seth said that "particles" in the string pull on one another, and increasing the tension in the string increases the "force that each individual particle is putting on each other…so each one of these individual particles is going to accelerate faster which allows the process of…pulling up to go faster." This mechanism builds from an individual particle moving up and down faster in a higher-tension spring (earlier explanation) to a chain of particles that put forces on one another, making progress toward an explanation that connects the transverse motion of particles in the spring to the forward propagation of the pulse. Further, as Seth explained his thinking, he notably transitioned from describing an initial force that "knocks" the particles to describing pulling forces between particles.

Teddy then invited comments and additions from the group:

45. Teddy: Okay. Is this making sense to other people at the table?

46. Sal: Yeah, that makes sense.

47. Teddy: Different thoughts? Additions?

48. Sam: Are you talking about like…I didn't really understand the $F = ma$…

49. Seth: Ok, if you imagine the string, the string is easier to think about, for me at least, and that's also what this one says. If you think about the string as like a whole bunch of smaller particles, they start [Teddy slowly walks away] off like that basically [pointing to a drawing of connected particles in a neutral position, $y = 0$], and what happens is you apply an initial force at the top, but that force isn't propagating through. What happens is you apply the force then this moves here [points to first particle, indicates moving up], and essentially that force you applied is no longer relevant, it's done, but because it's here [in a raised position] there's going to be like these units of mass are all connected, so it's kinda like that, pulled up here so you can ignore that part of it. There's tension between those two units of mass [first two particles in drawing]…

50. Sam: It's like stretched out more?

51. Seth: …and we know that Hooke's law is the negative kx relationship, and since it's here it's going to put a force on it which pulls it upwards. So, you have that force of one unit pulling it up and then it like keeps going all the way through. And since force is equal to kx and we've increased k then the force is increasing. Because what tension does is it increased the hardness, like you said, or like tension in the string. Ummm, so like now the force is greater, and since the force is greater, the acceleration of each particle has to increase so like the whole process now, like each thing is accelerating faster, so it goes-.

52. Sam: Ok.

53. Sal: Are you good with that?

54. Sam, Song: Yeah.

55. Seth: I think the assumption is, or like the mechanism is like everything is operating like smaller particles and they're all affected by each other.

56. Song: Yeah.

In this final exchange, Sam asked clarifying questions about the mechanism that Seth proposed, and Seth explained his thinking in more detail. His final explanation included multiple correct elements that we see coalescing toward a useful and more complete mechanism, even if not all the way there yet. Here, Seth noted that the role of the initial hand force is to pull up on the particles at the end of the spring, and is then "no longer relevant," which feels to us like a resolution of the vexation he articulated in line 24 (i.e., whether the pulse-generating force and the restoring force co-exist/balance in the spring). The pieces pull on one another "and then it keeps going all the way through." Though incorrect, he brought into coherence the group's thinking about Hooke's law: Increasing the tension increases k, since the spring is harder.[41] They ended this dialogue with a statement of their mechanism in line 55: "everything is operating like smaller particles and they're all affected by each other." This mechanism builds even further toward the correct mechanism than earlier ones the students articulated by emphasizing that the particles in the spring pull on one another as they move up and down, which is an additional piece in the chain connecting higher tension to higher pulse propagation *down the spring*.

The group went on to use this mechanism to make predictions about what would happen if the mass of the spring changed, and then if they flicked the pulse faster. They continued to name and then sense-make about vexation points as they went.

A. Summary

In this extended interaction, we see Teddy engaged in resources-oriented instruction. This kind of instruction treats student thinking as sensible and seeks to build on the connections between students' ideas and accepted physics explanations. Teddy routinely chose not to correct student thinking and instead revoiced it and asked questions that clarified or pressed students to be more specific or more concrete. Teddy's questions often pointed to something students were already doing—naming forces, articulating a relationship—and then asked them to extend that thinking or become more specific—which forces, on what parts of the spring. This was not observational listening, which Empson and Jacobs define as "listening with an attempt to hear the [student's] thinking but with nascent formulations about what is heard and few active attempts to support or extend that thinking."[42] It was not "anything goes" or "everything's great." Teddy actively intervened to guide the students' thinking, and his responses relied on and reflected (i) careful attention to what the students were saying and (ii) flexibly-deployed knowledge of physics content and practices. In our view, students made significant progress in and through this interaction; we'll briefly recap this next.

IV. STUDENTS' CONCEPTUAL PROGRESS IN RESOURCES-ORIENTED INSTRUCTION

In this extended, 8-min interaction, we see students' ideas progressing toward more sophisticated, mechanistic, canonically correct understandings of mechanical wave propagation. We summarize the progression in their thinking in Fig. 3.

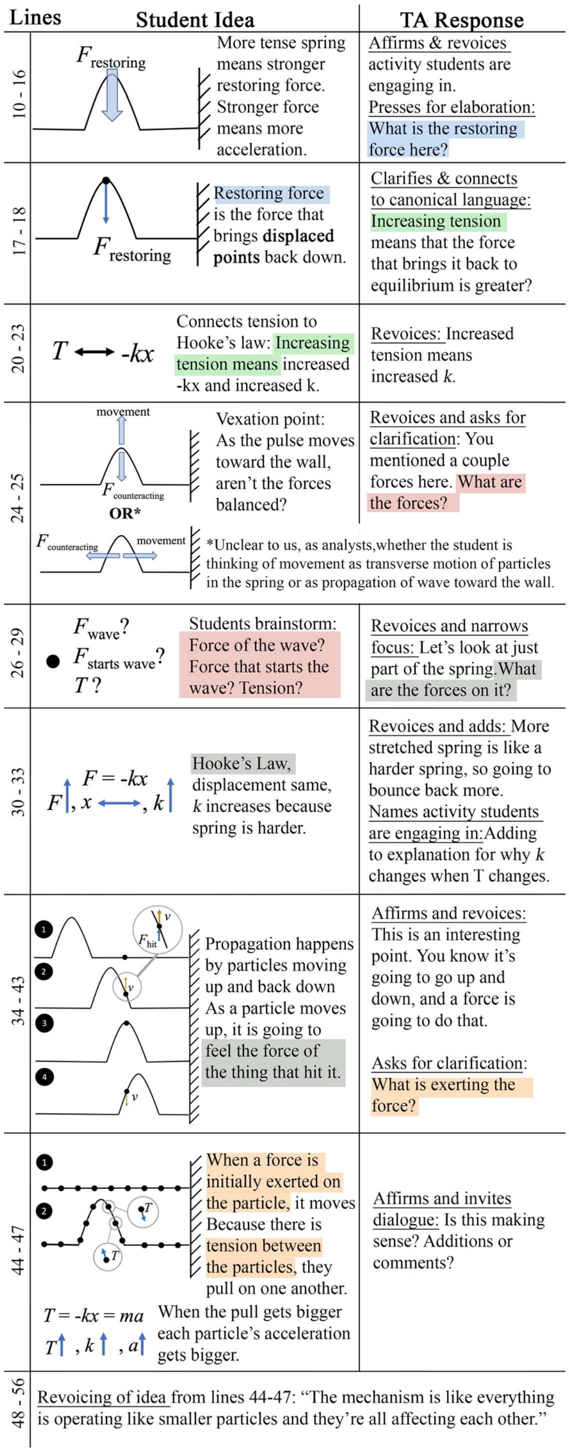


Fig. 3. Progression in students' ideas over eight-minute classroom interaction. Embedded figures are our (analysts') best guesses as to what students mean. The underlined text indicates the instructor move we see the Teddy employing. Highlighted text indicates connections between TA's response and students' next ideas. The color of the highlighting (online only) tracks which TA response maps to which student response. An audio description of the contents of this figure is provided online in the multimedia. Multimedia view: https://doi.org/10.1119/10.0009796.3

Like most forms of collaborative learning, the progression of this group's thinking was nonlinear. However, Fig. 3 makes visible that the TA's instructional moves played a role in how their ideas unfolded and that the students' model for pulse propagation became increasingly specific and integrated more abstract and mechanistic representations for motion.

For most of the interaction, the group iterated on Sal's (line 10) restoring force idea, which was originally framed macroscopically as "the restoring force goes up, so the (unspecified) acceleration goes up." When asked by Teddy *which* force they were thinking of, Sal (line 12) brought in a microscopic definition: The restoring force is the force that brings displaced points on the spring "back to the line." Whereas Seth (line 20) answered the same question—Which force is the restoring force?—with a relationship: It's "kx." Both Sal's and Seth's latter responses were more mechanistic than their previous ones.[35,36] Here, Sal and Seth moved from "higher tension means higher restoring force which means more acceleration" to articulating a means by which the restoring force translates into higher acceleration (Sal) and describing the restoring force more specifically (Seth). The former explanation connected higher tension to higher transverse acceleration of points on the spring, but did not yet articulate a relationship between the transverse acceleration of points on the spring and the horizontal motion of the pulse, nor did it highlight the relationship between parts of the spring—students seemed to be focused on the up-and-down motion of a single point.

As Seth continued to get clearer and more specific in his thinking, he named a vexation point (line 24), which we see as part of his sorting through his thinking about the role of the hand force in the propagation of the pulse. Teddy's response—to ask the group to name the forces on the spring and then on a part of the spring—pressed the students to issue explanations that were even more mechanistic than before. Seth's (line 20) reasoning about the relationship between increasing tension and increasing k was deepened by Song (line 30): increasing tension makes the spring "harder," which corresponds to a higher k. And Seth (lines 34, 36) began really parsing the relevant forces (lines 26, 28), identifying a relationship between the transverse displacement of the points on the spring and the forward propagation of the wave. Teddy's revoicing of Seth's reasoning—"you know that it's going to go up and down somehow, and some force is going to do that"—prompted Seth's pulling everything together into a microscopic mechanism for pulse propagation that included particles pulling on one another, such that increased tension means increased pulling and faster propagation.

In this, we see movement from ambiguity to clarity, toward more mechanistic, more canonically correct reasoning. (Though not yet completely correct; students still seemed to think that increasing tension increases the spring constant.) As the students became more specific, they named (and then resolved) places of confusion, added pieces to their model, and used physics language. We see this progress as shaped by—indeed, inseparable from—the questions Teddy asked, which often pressed for specificity, reflected back students' thinking in physics language, and encouraged epistemic practices like sense-making that are thought to be central to productive physics engagement. Importantly, students made progress toward *more correct* answers without *being corrected;* indeed, Teddy *revoiced and gave attention to* ideas that were incorrect throughout.

V. CONCLUSION

We said at the start of this paper that our aim was to answer a pragmatic instructional question: What does resources-oriented instruction look like, and how can I do it?

Table I. Teddy's instructional moves.

Instructor moves	Example
Affirming	"I mean that's making sense to me" (line 13) "I agree. Yes." (line 35)
Revoicing	"…increasing the tension, you're saying makes the k bigger." (line 21)
Connecting to physics language or definitions	"Okay, and increasing the tension means that the force that *brings it back to that equilibrium position* is greater?" (line 18)
Naming/reflecting activity students are engaged in	"So, like also adding to that explanation for how or why you'd expect k to change when you change T." (line 33)
Narrowing focus	"…so we could look at like, just part of the spring, right? And ask…what are the forces on it?" (line 29)
Asking for clarification/ pressing for elaboration	"So, what's the restoring force here? Like, what's the force you're thinking of?" (line 16) "Okay, so I heard you mention a couple of forces… So, what are the forces here?" (line 25)
Inviting dialogue	"Different thoughts? Additions?" (line 47)

The focal episode in this paper is one example of what resources-oriented instruction can look like, including concrete examples of discursive moves an instructor might make as they try on this kind of instruction.[43–45] Table I summarizes the discursive moves made by Teddy, which could serve as a guide for instructors who want to test out resources-oriented instruction.

This case may support instructors who ask, "What if students bring in incorrect ideas? I care about my students arriving at correct physics understandings," by suggesting that students can make conceptual progress during resources-oriented instruction, even when they begin with ideas that would not be seen as correct by many physicists, and even when their instructor does not directly intervene to correct these ideas.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts of interest to disclose.

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