Taking teachers' ideas seriously: Exploring the role of physics faculty in preparing teachers in the era of the Next Generation Science Standards

Amy D. Robertson, Lane Seeley, Orlala T. Wentink, and Stamatis Vokos

Citation: American Journal of Physics **87**, 57 (2019); doi: 10.1119/1.5082286
View online: https://doi.org/10.1119/1.5082286
View Table of Contents: http://aapt.scitation.org/toc/ajp/87/1
Published by the American Association of Physics Teachers

PHYSICS EDUCATION RESEARCH SECTION

The Physics Education Research Section (PERS) publishes articles describing important results from the field of physics education research. Manuscripts should be submitted using the web-based system that can be accessed via the American Journal of Physics home page, http://web.mit.edu/rhprice/www, and will be forwarded to the PERS editor for consideration.

Taking teachers' ideas seriously: Exploring the role of physics faculty in preparing teachers in the era of the Next Generation Science Standards

Amy D. Robertson, Lane Seeley, and Orlala T. Wentink
Department of Physics, Seattle Pacific University, Seattle, Washington 98119

Stamatis Vokos
Department of Physics, California Polytechnic University–San Luis Obispo, San Luis Obispo, California 93407

(Received 27 January 2018; accepted 17 November 2018)

The Next Generation Science Standards (NGSS) call for K-12 science instruction that centers on and substantively takes up students' science ideas. In this paper, we explore the question, "What role might physics faculties play in preparing teachers in the era of NGSS?," as we also consider our field's adage that "most teachers tend to teach as they were taught." In particular, we propose the importance of teacher education experiences that take teachers' own physics ideas seriously. We argue that physicists can play a critical role in this work by designing and facilitating teacher preparation and professional development that (1) elevates and maintains a focus on teachers' physics ideas and (2) collaboratively subjects teachers' ideas to the kinds of tests to which we subject our own ideas. We ground these considerations in two illustrative episodes from our local context: Focus on Energy professional development for elementary teachers. We highlight particular professional development instructor moves that take teachers' ideas seriously, and we discuss questions and implications that emerge from our analysis. Although the focus of our analysis is on taking teachers' ideas seriously, we suggest that most of our arguments also apply to taking students' ideas seriously in pre-college and university physics courses.
https://doi.org/10.1119/1.5082286

I. INTRODUCTION

The Next Generation Science Standards (NGSS)[1] lay out a bold vision in which K-12 students learn core disciplinary content and cross-cutting concepts, co-integrated with their learning about and participating in central practices of science. At the heart of this vision is that students would *do* science as science is done professionally—that is, their own science ideas and curiosity would drive their classroom pursuits—and that they would feel and see that they are (all) capable of doing so. This vision is as much about an *experience* as it is about outcomes; it is about what students do, and how they feel as they do it.

The challenges of enacting the NGSS are at the center of national conversations about curriculum (e.g., Refs. 2–4), assessment (e.g., Refs. 5–7), and teacher education (e.g., Ref. 8). This paper is meant to contribute to conversations about the latter, by discussing the question:

> *What role might physics faculty play in preparing teachers in the era of NGSS?*

The PER community has been discussing the question of how to prepare physics teachers for decades. We have theorized extensively about what physics teachers need to know to teach physics, including in our list: content knowledge,[9–18] pedagogical content knowledge (including knowledge of student ideas),[15,16,18–24] scientific reasoning skills and/or an understanding of scientific processes and practices,[14–18,25] and epistemological beliefs or beliefs about teaching and learning.[26–28] We have considered how to support teachers in learning or developing these things, and we have designed courses, curricula, and tools that translate these considerations into action.[10–12,15,16,22,29–31] Teacher preparation and professional development (PD) are central to what our community does.[32–36]

However, we would argue that the shifting tide of national standards toward inquiry around *students' own science ideas* calls for a particular conversation among educators of physics teachers. That is, if we take seriously the adage that most teachers tend to teach as they were taught,[11] then we need to be asking ourselves if our work with teachers, as they learn physics, is preparing them to center K-12 instruction around their students' physics ideas in generative ways. In other words, consistent with our adage, are *teachers* experiencing physics PD and teacher preparation as centered on and emerging from *their* ideas?

We (the authors of this paper) cannot answer this question *for* teachers, nor would we want to. But if we look at the PER literature on teacher preparation and PD, our sense is that the focus has been on teachers developing particular, often pre-determined, understandings, following prescribed instructional trajectories that we know work for getting learners to the places we want them to go. And this is important! We do not mean to suggest otherwise; we cannot dispute the ever-growing body of evidence that teacher knowledge matters.[37–39] But such learning experiences, in which teachers follow pre-determined trajectories toward externally articulated instructional targets, are unlikely to prepare them for the kind of emergent pursuit of students' science idea that the NGSS calls for.

We take the position in this paper that there is a special—and critical—role of physics faculties in preparing teachers in the era of NGSS. In particular, the idea-centered science classroom envisioned by these standards is messy and emergent, yes, but not a boundary-less free-for-all.[40,41] It is a classroom that is messy and emergent in the ways that *science* is messy and emergent—where the pursuit of curiosity is disciplined and generative and where we make progress together on ideas. Furthermore, doing physics involves discipline-specific instantiations of science practices. We take the position that, in NGSS parlance, physics disciplinary core ideas developed through science practices differ from life science disciplinary core ideas developed through the same practices, and not just through the differences inherent in the underlying concepts. There are physics-y ways of explanation and argumentation.[42]

In *this* vision, we argue that physicists can participate generatively in the preparation and professional development of teachers of physics. Specifically, physicists can design and facilitate learning experiences in which they *take teachers' physics ideas seriously* by both (1) elevating and maintaining a focus on teachers' physics ideas and (2) collaboratively (with teachers) subjecting teachers' ideas to the kinds of tests to which we (physicists) subject our own ideas (e.g., designing a thought experiment to test the accuracy or generality of an idea, or drawing on models or other experiences to check for consistency). In this paper, we advance the conversation by grounding this possibility in two examples from our local context, a PD course about energy for elementary teachers. We show what it looks like for PD instructors to take teacher participants' ideas seriously in the two ways that we highlight above. That is, we use episodes from our local context in which PD instructors both (1) elevate and maintain a focus on teachers' ideas and (2) with these teachers, test the ideas that they are putting forth. Further, we (briefly) draw on excerpts from interviews with teacher participants to highlight that the experience of having their ideas taken seriously was consequential for them. Our aim in making these considerations concrete through examples is to start a conversation in the PER literature. (Others, e.g., Refs. 43 and 44, have expressed similar aims for teacher PD in other literatures/forums.) Although the focus of our analysis is on taking teachers' ideas seriously, we suggest that most of our arguments also apply to taking students' ideas seriously in precollege and university physics courses.

Before we share our examples (starting in Sec. III), we offer some details about our instructional context and research methods.

II. INSTRUCTIONAL CONTEXT AND RESEARCH METHODS

The two episodes we introduce in Secs. III and IV were captured during a five-day (30-h) summer professional development course for elementary teachers at Seattle Pacific University (SPU). The course was a part of the NSF-funded Focus on Energy (FoE) project, which is a research and development collaboration between TERC, SPU, Tufts University, Facet Innovations, LLC, and Boston College. The partnership has designed curriculum that supports elementary students in learning about energy (see https://foeworkshop.terc.edu for more details). In the PD, facilitators support teachers in working through the curricular materials and in pursuing the questions that arise for them as they do so. The "fan episode" and "convection episode" come from the 2015 summer PD; eight teachers participated in the project that summer, many of whom had participated in SPU-led teacher preparation or PD (e.g., Energy Project PD[45–50]) in previous years. The primary selection criteria for these two episodes were that PD instructors took teachers' ideas seriously. In particular, we selected episodes

(a) in which we saw evidence that PD instructors' responses took up teacher participants' ideas in substantive ways, i.e., not to evaluate or correct these ideas but instead to understand, maintain the focus on, and advance these ideas and
(b) for which we could conceivably characterize PD instructors' responses in terms of discourse moves from the literature on responsive teaching (e.g., Refs. 51–55), i.e., instruction that embodies careful attention to and pursuit of student ideas.[41,56–58]

In our analysis, we break each episode into chunks corresponding to specific PD instructor moves, to support us in discussing the question we name in the Introduction: What role might physics faculty play in preparing teachers in the era of NGSS? For each chunk, we

- interpret the physics ideas of the PD participants, who are elementary teachers. We try our best to make visible what they mean by what they are saying, using analytical tools from conversation analysis[59] and the interpretive research tradition.[60]
- characterize the PD instructor's move in terms of how it takes teachers' physics ideas seriously in physics-y ways. That is, we say what "kinds of tests" the PD instructor is subjecting teachers' ideas to, whether it be a thought experiment, a test for coherence with other physics ideas, or a connection to an experimental test that has already been done.
- suggest ways in which the PD instructor's move supported teachers in making progress, by looking at what happened just before and just after the instructor move.[61] For example, if teachers started to discuss an idea of one of their peers after a PD instructor move, but did not observably attend to this idea before the PD instructor move, we suggest that the instructor move drew teachers' attention to that idea.

In each case, our aim is to highlight how PD instructors *take teachers' ideas seriously*, to inform the conversation that we elevated in the Introduction.

The interviews we excerpt in Sec. V were conducted during the summer of 2016, during a short two-day workshop for teachers who had participated in the 2015 Focus on Energy PD. These interviews were conducted by the first author (ADR) and asked teachers to (1) describe if and how they used the FoE curriculum in their classes during the previous academic year and (2) name "some of the significant experiences that have shaped [their] thoughts and feelings about science." We noticed that a number of teachers identified their experiences with SPU PD as among their significant science experiences, and they articulated the PD instructors' focus on their own thinking as part of that significance. We selected excerpts that illustrated the latter for this paper.

III. PROFESSIONAL DEVELOPMENT FACILITATORS TAKE UP THE SUBSTANCE OF TEACHERS' SCIENCE IDEAS IN THE FAN EPISODE.

In this section, we present the first of two video episodes that illustrate teachers' ideas being taken seriously by FoE PD instructors. The fan episode occurred during the morning of Day 4 (of 5) of the Summer 2015 Focus on Energy PD course. The teachers had completed the motion and thermal energy units (see https://foeworkshop.terc.edu) and are in the midst of the electrical energy unit. Their work drew on the Energy Tracking Lens[62] and representational tools such as Energy Cubes and Energy Theater.[48,49,63,64] Their model for energy included kinetic energy, elastic energy, thermal energy, and electrical energy.

Just before the start of the episode, the teachers read a transcript of a discussion among elementary students, centering on the question, "How could this [cup of water] have gotten hot? What happened here?" As the teachers discuss this transcript, Brian,[84] the teacher whose question launches the fan episode, recalls a question he wanted to discuss. He says out loud, "Oh my gosh, I had a really good energy question that came to me; I want to write it down (inaudible) ask (inaudible)." Brian does not have an opportunity to ask the question before the class moves on to another topic. As the conversation begins to lull, Brian asks Isabelle (a PD instructor) if the class is going to talk more about the video transcript; he says he has a question but does not want to "derail" the conversation and can ask later. Isabelle prompts Brian to ask his question, which is where the episode begins.

The fan episode features four teachers prominently: Grace, Brian, Will, and Mia. Brian and Will have participated in previous energy-related PD offered by our research team, and Mia was a former student from a course for preservice teachers at SPU. Grace is a first-time participant in physics PD at SPU. Two additional, off-screen teachers, Pam and Natalie, participate briefly in the conversation. Four PD course instructors participate in the episode: Ilana, Isaac, Isabelle, and Imogen, all names that start with "I" to indicate that they are PD *instructors*. Both Isaac and Isabelle are physics faculty at SPU; both Ilana and Imogen are science teacher educators at TERC. A full transcript and video of the fan episode can be found at goo.gl/zWXxBW.

The episode begins when Brian poses the question,

> "So, I'm using fans. Fans involve moving air. Fans cool you down; they don't heat you up. Why does a block of moving air…why does that cool me down? It's adding movement energy to my face. Why do I feel cooler?"

In the next several talk turns, Will, Mia, and Pam propose several different mechanisms by which a fan could cool someone down: "it's evaporating water from your face…taking heat" (Will, line 4); "it's blowing the moisture off so your skin can breathe" (Mia, line 10); "the molecule of water is leaving your face and taking some of your heat with it" (Will again, line 15); and "it pushes the heat you radiate away from you" (Pam, line 18).

A. Ilana describes an experiment that answers to (1) Will's observation and (2) Brian's original question.

Will (in lines 21–23 in the full transcript) then points out that though "you're feeling cooler," this process would "hea[t] up the room." Perhaps in response to this comment from Will or perhaps in response to Brian's original disbelief that the fan's "adding movement energy to [his] face" (line 3) will *cool him down*, Ilana, a PD course instructor, describes an experiment done by one of her colleagues. She says

> "I wanna say something, a little experiment that [my colleague] did. Um, he took one of these Styrofoam boxes and he had a little fan inside it, and the motor was on the outside so that it didn't heat up things, and he just turned it to move the air inside the box, and there was a temperature probe in, and the temperature of the air went up. Is that what you want to hear?"

Ilana's description of the experiment done by her colleague *takes the teachers' ideas seriously* in a way that physicists take their own ideas seriously. The experiment she describes responds to the substance of Will's and Brian's ideas: Both Will and Brian have pointed out that the fan would contribute motion energy to the room/their face, increasing the temperature of the room. Ilana's colleague's experiment measured this very thing, confirming that the motion energy from the fan does increase the temperature inside an insulated box. The participants on the camera are visibly impressed, saying, "Whoa!" Brian affirms that "that's what I want to hear" and goes on to elaborate (lines 36 and 44) that "it's really a perception issue…Why does a fan cool me down? It doesn't. And the answer is 'no it doesn't.'" Will then initiates a dialogue (lines 46–56) that extends his original claim, corroborated by Ilana's description of her colleague's experiment, in which Will describes how his roommate, John, leaves the fans on in their home to "cool down the house," whereas Will thinks this increases the temperature of the house.

B. Isaac connects Brian's question to a familiar phenomenon.

Brian then brings the group's attention back to two of the proposed mechanisms by which fans cool you down (line 57), asking,

> "So is this water evaporation an important part of the story or is it more like Pam is saying, the thermal energy is going into the air. Is it going via these water particles?"

Here, Brian synthesizes across two possible mechanisms, asking if any of the following are relevant to the story: (a) evaporation, (b) thermal energy being dispersed into the air, or (c) thermal energy being dispersed into the air *via* evaporation. These mechanisms, represented by the first three boxes in Fig. 1, become the centerpiece of the group's conversation for the rest of the fan episode. Will answers Brian's question—"Is it [the thermal energy] going via these

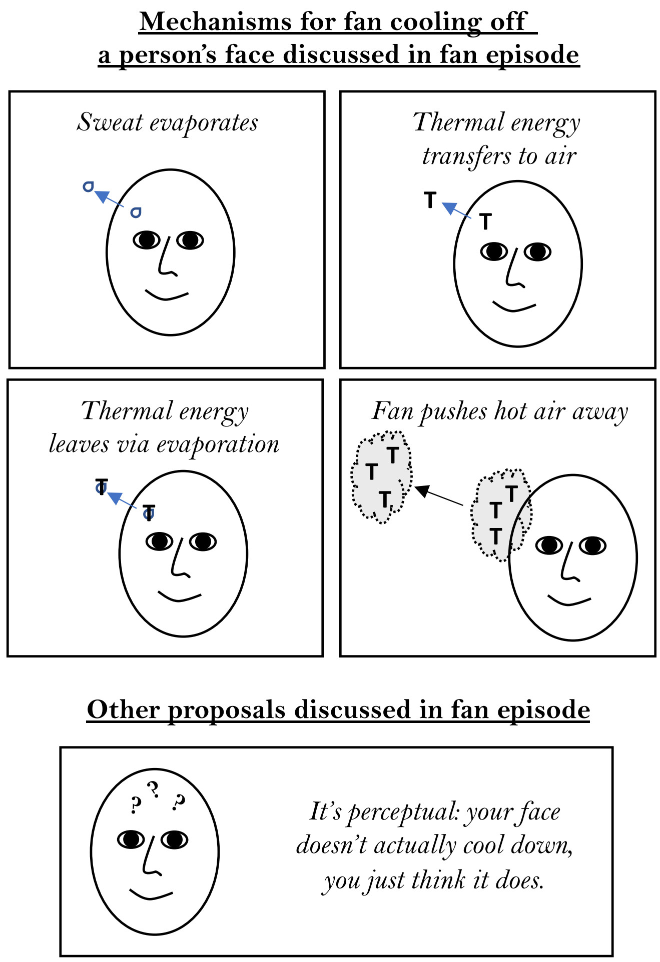

Fig. 1. Mechanisms for a fan cooling off a person's face discussed in the fan episode.

water particles?"—affirmatively, saying "I think it is," and then he invites the PD instructors to comment. Isaac (PD instructor) responds,

> "I think a good question to sort of push that question along…would be… recently it's gotten pretty hot in Seattle, but it never- I don't think it ever actually exceeded body temperature, did it?" (lines 62–65)

When the teacher participants affirm that it did not, Isaac continues,

> "And so…I think a question which is related to Brian's question, is why does it feel hot, why does the air feel so hot when it's still below body temperature. You know what I mean?" (line 70)

In this instructor move, Isaac connects the conversation to a familiar phenomenon, providing the teachers an opportunity to use their shared experience of Seattle weather to narrow the contexts in which fans cool people down. In particular, Isaac wants[85] to support the group in establishing that fans cool people down *when the surrounding air has a temperature below body temperature*. Further, he wants them to connect the phenomenon they are examining to their shared model for energy, in which thermal energy transfers from warmer objects to cooler objects. Thus, if the air temperature is below body temperature, thermal energy will spontaneously transfer into the surrounding air. The fan does not cause this transfer; it merely expedites a thermal transfer that already exists. Isaac's interjection *takes Brian's question seriously* by refining the context over which Brian's question is valid: Fans cool you down when the outside temperature is below body temperature. As the discussion progresses, the group increasingly focuses on the fan's role in enhancing thermal energy transfer away from the body.

C. Isaac proposes an analogy that distinguishes between the mechanisms the teachers have proposed.

Will responds to Isaac's question by proposing why it may feel hot to humans even though the outside temperature does not exceed body temperature. Namely, he proposes that

> "we evolved to have our bodies put out so much heat to combat temperatures that are milder than [hot temperatures in Seattle], and so…even though it's not body temperature outside, it feels hot to us 'cause our body is still producing, is generating heat, you know, use the term transforming our food energy into heat energy, and it doesn't leave your body as easily when the room is warmer." (lines 73–75)

We interpret Will to be suggesting that the temperature difference between our bodies and the air around them matters for how "easily" the thermal energy we produce through metabolism leaves our body. Because humans evolved in cooler climates, where the temperature difference was big, our bodies are "conditioned" by large temperature differences. If the magnitude of the temperature difference matters for how easily thermal energy leaves our bodies, it may be difficult for heat to leave our bodies when the temperature difference is small. Brian takes Will's idea up, calling this conditioning a "trick," saying that our bodies "trick our brains to not feel heat so we don't" (line 78).

Isaac (PD instructor) challenges Brian's interpretation of Will's mechanism, proposing an analogy to computers, and in doing so draws attention to the three mechanisms Brian proposed in line 57:

80. **Isaac:** I would say that we put fans in computers.
81. **Will:** It sounds good.
82. **Brian (to Isaac):** Right, right.
83. **Isaac:** Right. And I mean I don't think computers are trying to trick their brain.
84. **Brian:** Yeah.
85. **Isaac:** They really and so it must, it seems like if we put fans in computers to cool them off, and computers don't sweat as far as I know.
86. **Ilana:** See I was thinking [laughing].
87. **Brian:** Right, okay. So this is a good point.
88. **Mia:** Or is their form of sweating thermal energy?
89. **Brian (to Isaac):** That's a good point, because the fan is not evaporating water on the—on the hard drive to make the hard drive feel cooler.

Here, Isaac starts by challenging Brian's interpretation of Will's evolutionary mechanism, saying that "we put fans in computers" to cool them down, and the mechanism is not "tricking [the computer's] brain." He goes on to problematize sweating—or evaporation—as the mechanism for fans cooling us down, harkening back to Brian's question (line 57) about whether the evaporation itself (the water leaving) or the carrying away of thermal energy is the mechanism by which a fan cools you down. Mia inserts the question of whether computers' "form of sweating" is thermal energy, suggesting that the mechanism underlying sweating may *be* the dispersal of thermal energy.

This analogy, like Isaac's just-prior invitation for the teachers to consider recent Seattle temperatures, *takes the teachers' ideas seriously* by (a) mapping closely onto Will and Brian's exchange about evolutionary conditioning and (b) responding to Brian's question in line 57 about what *matters* in this scenario. Isaac does so in (what we think is) a distinctly physics-y way: he constructs a thought experiment that behaves similarly (cools something down) but that pulls out and tries on a *single mechanism*, rather than considering multiple mechanisms at once. In other words, Will and Brian's conversation centers the transfer of thermal energy in a *human* context, and Isaac's example problematizes this: He proposes a scenario in which a *machine* supports cooling, removing evolutionary and perceptual mechanisms. In choosing a scenario in which sweat plays no role, he re-centers the conversation on Brian's question in line 57 about which mechanism is at play as a fan cools off our face.

The computer example launches the group into the final exchange of this episode, where Brian, Will, and to some extent Mia land on a mechanism by which fans cool you down:

91. **Brian:** It's literally cooling it down.
92. **Mia:** It's taking the thermal energy that the computer's putting off and moving it farther away from it.
93. **Brian:** But now energy is matter when you do that.
94. **Mia:** Hmm?
95. **Brian:** You're making energy into matter it seems like when you do that.
96. **Will:** Like-
97. **Ilana:** It's called convection.
98. **Mia:** No, you're just redistributing the thermal energy.
99. **Isabelle:** Yeah, you're moving therm-
100. [Brian and Grace laughing together.]
101. **Will:** So there's—there's air in the computer, there's air pockets in the computer. Yeah, that makes sense.
102. **Brian:** So it's moving into the air.
103. **Will:** And then it's just moving that hot air out.
104. **Brian:** But, you're, okay,
105. **Will:** (Transferred from the computer.)
106. **Brian:** So here's some hot air cause here are the molecules right [gesturing moving particles in a single location in space].
107. **Will:** Yeah.
108. **Brian:** A fan hits it with a bulk of air and it takes those….
109. **Will:** And it blows that away…
110. **Brian:**…hot molecules over there [gesturing moving particles moving to a different location in space].
111. **Will:**…into the room.
112. **Isabelle (PD instructor):** And then what replaces that air?
113. **Imogen (PD instructor):** And then what happens next?
114. **Will:** Then more—more air comes in.
115. [Brian is doing a breaststroke-like gesture.]
116. **Candy:** More air comes in.
117. **Brian:** This? Is this a thing?
118. [Laughter.]
119. **Brian:** The breaststroke. That's what happens next.

In this exchange, Brian starts by challenging evaporation as a mechanism. Following from his last utterance above, he's saying that "the fan is not evaporating water on the hard drive to make the hard drive feel cooler…it's literally cooling it down." Mia, building on her statement in line 88, presses on this, articulating a way in which evaporation and cooling are similar: either way, thermal energy is dispersed. She says, "It's taking the thermal energy that the computer's putting off and moving it farther away from it." Brian challenges her idea, suggesting that Mia is "making energy into matter…when you do that," pointing out the substance metaphor[48] implicit in Mia's proposal. However, shortly thereafter, Will provides a mechanism by which the energy can move *with* the matter, saying that the fan is moving the hot air out of the computer (fourth box in Fig. 1). Brian takes this up, summarizing their argument as:

> "So here's [in the computer there's] some hot air cause here are the molecules right [gesturing snapshots 1–3 in Fig. 1]. A fan hits it with a bulk of air [gesturing snapshots 4–7 in Fig. 2] and takes those hot molecules over there [gesturing snapshots 9–10 in Fig. 2]."

After Brian offers this explanation, two PD course instructors—Isabelle and Imogen—ask him "what replaces that [hot] air" and "what happens next," respectively. Both Will and Candy (off screen) answer that "more air comes in." Brian elaborates with a repetitive "breaststroke" gesture, indicating that the process is cyclical—that the hot air that moves out will be replaced by cool air moving in, which will then move out to be replaced again.

Another participant bids that they return to a discussion of the curriculum, and Isaac (PD course instructor) wraps up by suggesting that "Mia gave us a really good, uh, sort of foothold on…an answer that [the fan is] carrying away the air…with your thermal energy in it." Brian and Will affirm this, and the class turns its attention back to the curriculum.

D. Discussion

In this section, we have highlighted three instructor responses that *take teachers' ideas seriously* in the fan episode. In particular, Ilana's sharing of her colleague's experiment, Isaac's asking why we feel hot in Seattle when the temperature is still lower than body temperature, and Isaac's analogizing to computer fans all take up and advance the substance of Brian's original question and his peers' subsequent conversation about why fans make us feel cooler when they are adding motion energy to our faces. Importantly, Ilana's and Isaac's responses not only maintain a focus on teacher participants' ideas, keeping these ideas at the center of the class' collective work, but do so in a way that is consistent with how physicists take their *own* ideas seriously: by constructing experiments to test these ideas and by drawing on examples that bring single variables or mechanisms into focus so that we can consider *what matters* for relevant processes.

We speculate that these instructor moves supported the substantive progress that the teachers made toward a rigorous answer to Brian's original question. By sharing an experimental result, Ilana confirmed the idea that fans add energy to the air. Her confirmation provides an endorsement of the scientific merit of Brian's questions. Crucially, Ilana endorses Brian's question scientifically rather than

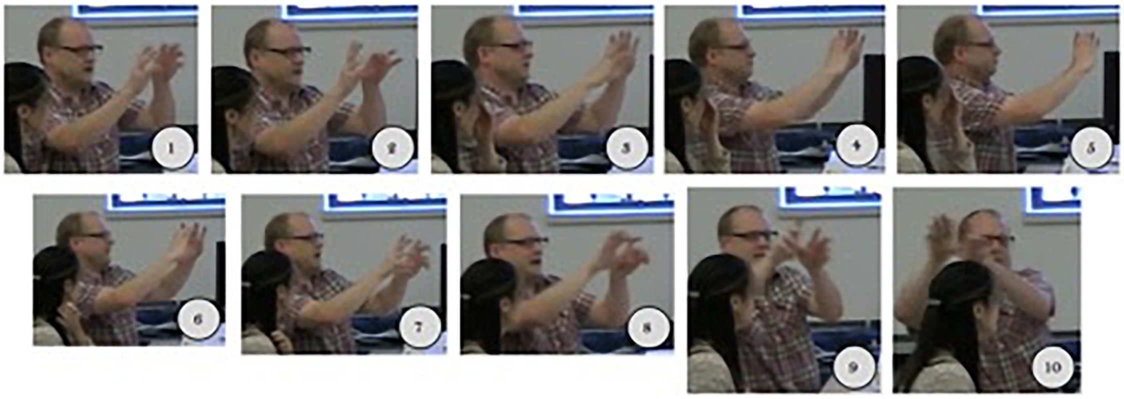

Fig. 2. Brian's gestures as he explains what happens when the computer fan blows the hot air inside the computer. In snapshots 1–2, Brian wiggles his fingers to depict hot air (quickly moving gas molecules) in the computer. In snapshots 3–6, Brian turns his body and orients his hands around an object—the bulk of air that is going to encounter the molecules. In snapshots 7–10, Brian is again wiggling his fingers to depict the hot air, which is being pushed away from its original location by the bulk of air from the fan.

rhetorically. She doesn't simply say, "that's a great question," she *treats it* as a great question by citing relevant experimental evidence. Isaac references a shared experience, Seattle temperatures, in order to refine the contexts in which Brian's question is valid. This allows the group to focus their thinking on mechanisms by which a can could expedite the transfer of thermal energy to the lower temperature surrounding air. Finally, by drawing an analogy to a computer fan, Isaac supports the group in focusing on a single mechanism from which a coherent energy story is constructed.

IV. PD FACILITATORS TAKE UP THE SUBSTANCE OF TEACHERS' IDEAS IN THE CONVECTION EPISODE.

The convection episode takes place on Day 3, the day before the fan episode, in the same Focus on Energy PD course, and illustrates another way in which PD instructors can take teachers' ideas seriously: By elevating and then lending credence to an idea, articulating its coherence with other concepts, and suggesting experimental evidence that supports it. Before we describe this episode, we offer some context.

On Day 2, the day before the convection episode, the teachers were introduced to Energy Theater, a representational tool in which people embody units of energy and "act out" the energy transfers and transformations in a complex physical scenario.[64] Throughout the afternoon of Day 2, the entire class of teachers negotiated and performed Energy Theater for a stopper popping out of an empty soda bottle that has been partially submerged in warm water.[86] As part of their negotiation, the teachers agreed on three objects that the energy transforms within and transfers among in this scenario: the warm water, the air in the bottle, and the stopper. They also agreed that the scenario begins with several units of thermal energy in the water and some units of thermal energy in the air. Most of their discussion centered on two primary questions: (1) What is the difference between thermal and kinetic (motion) energies?, and (2) What is causing the stopper to pop out of the bottle, thermal or motion energy, and by what means? Their negotiation of question (2) intersected with a third question, which they needed to answer to perform Energy Theater: (3) *Where* does the change from thermal energy (present at the start of the scenario) to motion energy of the stopper happen—in the air in the bottle, or in the stopper? This question is not resolved by the time they need to act out Energy Theater, and so, they act out two parallel stories: Some teachers turn from thermal to motion energy in the air, and others do so as they move from the air to the stopper. Day 2 ends without a consensus, and they agree to return to the discussion on Day 3.

Importantly, in the midst of the discussion on Day 2, one teacher, Pam, repeatedly hinted that convection may be the mechanism by which the stopper pops, though she does not use this word. She is one of the first to propose that it is *motion* energy in the air that transfers to the stopper, making it move. She says, "Doesn't the air that's moving push it?…The air, once it heats up, it starts to move." She affirms Ron, another teacher participant, in "rebel[ling]" against the teachers who think that the T (thermal energy) turns to M (motion energy) in the stopper. Later, Mia proposes that "maybe what's happening in the bottle is the creation of wind energy," and Pam draws a connection between their ideas, saying that such energy comes from "the hot air and the cooler mix[ing]."

The convection episode takes place on Day 3, as the teachers return to their discussion of the stopper scenario from the previous afternoon. Isabelle (a PD course instructor) prompts the teachers to continue their conversation in their smaller table groups. Brian, Pam, and Gwen—the three teachers in the convection episode—have varying degrees of experience with SPU PD. Brian is a returning participant; Pam and Gwen are first-time participants. The three teachers revisit questions (1) and (2) from Day 2, starting with the latter: what is it that is forcing the stopper out of the bottle, thermal or motion energy, and by what means? In their discussion, Pam brings in her idea from Day 2 of "wind created when the cold air and the warm air mix" as a mechanism for the stopper popping. Brian names this idea "convection," but it does not become a focus of the teachers' conversation at this point. Instead, the teachers shift their focus to question (1)—whether thermal and motion energy are the same kind of energy. Gwen "sees kinetic energy in the whole [scenario]," and Brian frames the identification of energy forms in terms of indicators, such that it "makes more sense" to talk about motion energy for the moving stopper, whereas "both things [heat and movement] were in play" in the air. This is when Isla (PD instructor) enters the conversation, and our analysis of the convection episode begins.

The convection episode[87] starts with Isla's question:

> "So I wanna look at the moving of particles and the moving—the bulk movement. At what point does the movement of particles change to bulk movement of the air?"

Brian and Pam both respond—Brian by pointing to a location in the group's Energy Tracking Diagram, and Pam by proposing a mechanism by which the air moves, saying,

> "I don't know, but I think the hot water, so it's warmed up the air down here and so then the heat always wants to warm up the cool, and so I think when they start to mix, that's my total guess."

These two mechanisms—Isla's suggestion that (random) motion of air particles becomes bulk motion of air and Pam's convection proposal—feature prominently in the remainder of the conversation and are presented in Fig. 3. Brian follows Pam's proposal by noting that her answer has consequences for their diagram: "So you want maybe another, another kind of thing that looks sort of like this?" It is at this point that Isla makes her next instructor move.

A. Isla compares (a) the mechanism inherent in Pam's model and (b) the mechanism implied by her group.

Isla then revoices[65] Pam's proposal in disciplinary terms, saying:

7. Isla: Oh so the hot air, I see, you are talking about convection.
8. Pam: Yeah.

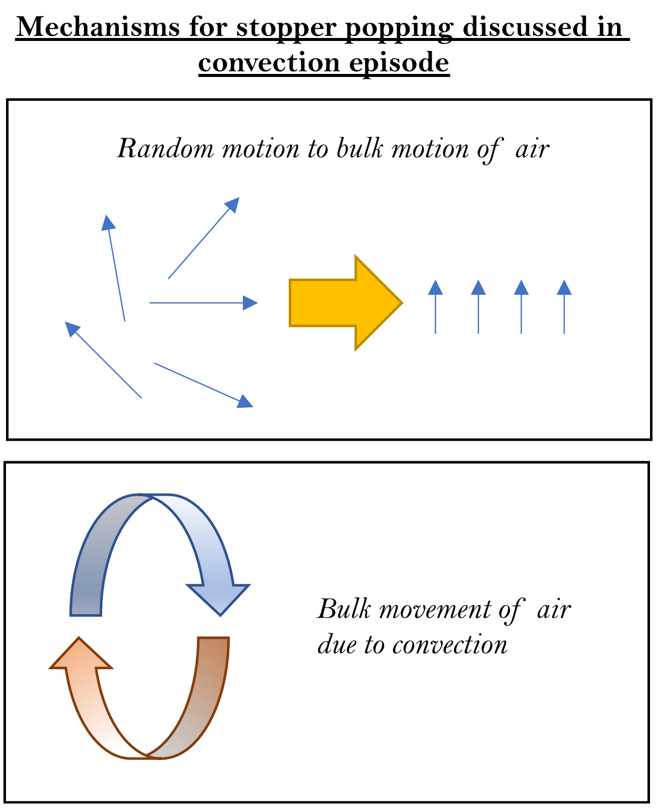

Fig. 3. Mechanisms for stopper popping discussed in the convection episode.

9. Isla: So then you actually do get movement of air en masse, bulk air, moving from here to here.
10. Pam: Yeah.
11. Isla: On a macro scale. What do you think about that Gwen?

In this exchange, Isla identifies the mechanism that Pam is proposing (line 7). She then clarifies that Pam's mechanism is different from the one she (Isla) identified at the start of the episode, highlighting that, in Pam's mechanism, "you actually do get movement of air en masse," rather than particle motion becoming bulk motion (line 9). Then, she elevates Pam's idea for collective consideration (line 11). Each of these moves *take Pam's idea seriously*, in a way that embeds physics practices and discourse. In particular, in these moves, Isla articulates a central difference between the *mechanisms* that Pam and her group are using to explain how the stopper pops, that is, (1) that the stopper pops because of bulk movement of air due to convection (Pam) versus (2) that the stopper pops because of a transformation of random motion into bulk motion just under the stopper (Pam's group, revoiced by Isla).

In the exchange that then ensues (lines 12–29), we see that Isla's moves in lines 7–11 draw Gwen's attention to Pam's ideas for the first time: Gwen notes that she "ha[d]n't thought of that," even though Brian had named Pam's idea as convection earlier in the conversation. Isla's question to Gwen in line 11 also invites her to identify what she is confused about. Gwen says,

> "Yeah, I'm just really hung up on—because these, the air in here is moving. Like it's moving before you even put the bottle in the water, so I just don't understand."

We interpret her to be saying that their conversation about "the movement of air" is confusing because there is movement in the air before the scenario even begins. Gwen's statement initiates a series of talk turns in which Isla clarifies the difference between "the air itself moving" and "the particles moving," or, in Brian's words, "the difference between bulk movement and particle movement."

Isla ends the clarifying exchange with the following statement in lines 28–30:

> "Yeah, in an organized way. It's just this randomness that you can, I mean, there's air moving here, but I'm not feeling anything…Because the particles are so tiny and there's so much empty space between them that I can't say that this chunk of air right here has moved over here. I can with your convection because now this temperature differentiation has made a mass of it move, perhaps. And so I can buy that."

Here, Isla re-elevates convection, highlighting it as a mechanism by which the stopper could pop—"this temperature differentiation has made a mass of it [air] move"—and lends her support, saying "I can buy that." She continues to contrast the bulk motion of air with the random motion of air particles, responding to Gwen's stated confusion. In this sense, she *takes both Pam's idea and Gwen's identification of her confusion seriously*.

B. Isla adds to Pam's convection mechanism.

Isla's statement in lines 28–30 draws Brian's attention back to Pam's convection mechanism, prompting him to say:

31. Brian: And so, in maybe your scenario, and I know, this is where, uh, mass and energy start being together 'cause I wanna start talking placement, but right, we have thermal energy kind of at the bottom of the bottle that moves towards the top switching to a movement energy.
32. Pam: Yeah they do, they wanna mix, the heat wants to warm up the cold.
33. Brian: No I don't think that's the wrong answer.[88]
34. Isla: Well I think it's a matter of density too, is that the cold air is heavier, so-
35. Brian: Mhmm.
36. Isla: -that moves to the bottom and then gets heated up.

In line 31, Brian highlights that "in Pam's scenario," matter and energy move together—as the warm air moves upward, so does the thermal energy. Connecting across a number of things Brian said during the PD, we interpret him to be thinking that Pam's proposal deviates from other scenarios that the teachers have considered with Energy Theater, where matter and energy are intentionally represented as distinct entities: Objects are represented by the stationary ropes on the floor, and energy is represented by people that move within and between the ropes. In line 32, Pam responds to Brian, proposing a reason that the air moves in bulk—that the "heat [hot air] *wants* to warm up the cold" (emphasis ours). Isla then adds to Pam's convection mechanism, suggesting that "it's a matter of density too"—that the "cold air is heavier" and so "moves to the bottom and then gets heated up." In other words, she *takes Pam's idea seriously by* pointing out that this idea coheres with other fundamental concepts, in this case, density and buoyancy.

Isla's addition prompts Pam to articulate her original question, which she restates in line 37 as "at what point does thermal energy turn into energy of motion." Gwen seeks clarification on what Pam is proposing, asking, "Are you saying that there's heat energy that transforms into wind energy that transforms into motion energy when the stopper comes out?" Brian and Isla respond to this in turn, with Brian suggesting that they "get rid of the idea of wind energy" and then shifting the conversation away from Pam's idea, proposing that what is happening in the bottle is "not about whole bunches of air at once…[but instead] thermal energy bumping around a lot and it gets so much that it switches here [at the stopper]."

C. Isla proposes a thought experiment that lends credence to Pam's convection mechanism.

In the next talk move, Isla draws the group's attention back to Pam's idea, saying in line 44, "And I could buy the convection thing too." She then goes on to propose a thought experiment that lends credence to convection as a mechanism for the movement of air in the bottle, saying:

> "I was thinking, what if we put water in there and actually do the same thing and put dye in there and watched it…And then we'd actually see the water moving the dye around because the water's actually moving."

She continues to elaborate, saying that she's "taking that model of what water does, and air is—is matter too and it would do the same thing." Though Isla quickly turns her attention to Gwen, whom she feels "concerned about," her move in lines 44–50 *takes Pam's idea seriously* in a similar way as did her offering density as a means by which the hot and cold air mix. That is, Isla is voicing a multitude of ways in which she can imagine Pam's idea being not only reasonable but also correct, for this scenario, even though she (Isla) entered the conversation with a very different mechanism in mind. Again, this embodies a physicist's orientation toward ideas, considering them through the lens of experimentation and coherence with other concepts.

D. Discussion

Throughout the convection episode, Isla's instructional responses take Pam's convection idea seriously by revoicing, elevating, and elaborating on her idea. She takes it seriously as a *physics* idea by considering its consistency with experimental evidence and its coherence with other core concepts. We speculate that Isla's doing so was significant to Pam's idea getting taken seriously by her group. In particular, both the day before and the morning of the convection episode, Pam had articulated her idea that convection was the means by which the stopper popped, but in neither case did it get taken up by her peers.

Further, Isla *continues* to take Pam's idea seriously. After attending to Gwen, Isabelle (another PD instructor) approaches the table, and Isla asks Pam to recap her thinking to Isabelle. Pam recounts her idea, saying,

> "Well the water was hot, and…the air in the bottle was cooler. And so then when you stick the bottle [in the water], and of course it heats the air in the bottle…And then, when the air is suddenly heated here, then there's a kinda convection 'cause it's the cooler air here, and then they mix and then it turns to movement and it pops off the [stopper]."

Isabelle affirms Pam's idea, saying, "I had not thought about creating convection in there, and I don't see a reason why that's inaccurate."

Canonically speaking, Pam's convection idea is not the correct mechanism for the popping of the stopper. In particular, convection involves energy transfer through mass transfer, which occurs because there is a mass density difference in a gravitational field. However, the stopper in this scenario would pop even in the absence of a gravitational field: energy associated with random motion in the water is transferred to the air in the bottle as random motion in the air (i.e., thermal energy). This increase in the random particle motion in the bottle increases the collisions of the particles with the stopper, which transfer motion energy to the stopper via tiny pushes, so much so that the stopper eventually pops out. Nonetheless, Pam's proposal and the correct answer have in common that the motion of the air will push the stopper out. Isabelle and Isla's instructional moves throughout the convection episode suggest that they see this "seed of science"[66–68] in Pam's thinking.

V. TEACHERS IDENTIFY OUR "TAKING THEIR IDEAS SERIOUSLY" AS A SIGNIFICANT SCIENCE LEARNING EXPERIENCE

The following excerpts are from interviews conducted in June 2016 with Brian and Candy, both elementary school teachers enrolled in the summer 2015 Focus on Energy PD and both participants in previous iterations of SPU PD. As we will show, both Brian and Candy spontaneously identified

SPU PD—including the summer 2015 FoE workshop—as "significant experiences that shaped [their] thoughts and feelings about science." They elaborated that part of what was significant about these experiences was having their ideas treated as valid starting places for joint pursuit.

When asked to share "some of the significant experiences [he's] had that shaped how [he] think[s] and feel[s] about science," Brian responded, "Thi-SPU." When the interviewer (ADR) asked, "Yeah?," Brian emphasized, "Number one, absolutely." He went on to elaborate:

> ".being challenged in a really safe place to think about science as an adult was just a—was huge. I have always really appreciated the way the folks here validate where you come from with your thoughts. It was some of the first times that I had felt like my experiences were enough to begin talking intelligently about science. Especially with someone who, who studies science for a living you know, like, I felt like there was gonna be such a huge language and mathematical gap that I would either just feel stupid the whole time, or—or that we just wouldn't understand each other. But the amount of like, wait time that was given as you're trying to explain something…And just this feeling of respecting your idea and using that as a starting place, which I know is all part of the philosophy. But it was hugely powerful and really frustrating at first the first year."

He went on to say that

> "…by the end of that first energy course I thought wow,…I learned—I felt capable of pursuing curiosity in a realm of science that I had never felt like was my business to mess around in…And it wasn't until these classes that I felt justified and like (inaudible). I mean right now I'm listening, and I'm not fully understanding but I don't care, to this book on tape about the Higgs boson and what that's all about, right, and I don't think I would have even checked something like that out years ago. But now I think, 'Well, I'll probably understand some of it.' And it's just a whole new, a whole new way."

Here, we hear Brian reflecting on the experience of having his ideas taken seriously: that the instructors "validate[d] where [he] c[a]me from in [his] thoughts" and "respect[ed his] idea and us[ed] that as a starting place." Importantly, we hear him saying that it was one of the "first times that [he] had felt like [his] experiences were enough **to begin talking intelligently about science"** (emphasis ours) and that through his experiences in PD, he began to feel "capable of **pursuing curiosity in a realm of science that [he] had never felt like was [his] business to mess around in"** (emphasis ours). These specific outcomes that Brian describes seem plausibly tied not only to his experience of having his ideas taken seriously, in a broad sense, but also to the experience of having his ideas taken seriously *in the way that physicists take their ideas seriously*, as we have reiterated in this paper. That is, Brian describes a shift in his perception toward thinking of his ideas as the beginnings of scientific activity and of his curiosity as something that he can pursue and toward thinking of science as a place he can mess around. These ways of talking about ideas are not only (a) deeply aligned with the vision of NGSS but also (b) fundamentally consistent with how *physicists* treat ideas, as starting places for "messing about."[69]

Candy, when asked the same question as Brian, also identified her experience in SPU PD as significant, and then reflected on the impact this had on how she thought about her own teaching:

> "Isaac is an amazing…listener. He makes you feel like you are, your ideas, as harebrained as they might be, might have some validity, and he listens carefully enough so, then he questions, and so the art of listening and the art of questioning is something that I saw developed here. And when I first was taking the class I was determined to be very scientific and wanted more cut and dry answers…And then seeing how that could develop thinking was an eye opener…"

Candy, like Brian, reflects on the significance of having her ideas treated as though they "might have some validity." Further, she reflects on the *ways* in which Isaac, her PD instructor, treated her ideas as valid—not only by listening but also by *questioning* them, in the ways we illustrate in Sec. III.

VI. DISCUSSION

We launched this paper with a question, "What role might physics faculty play in preparing teachers in the era of NGSS?," an era in which standards are increasingly calling for students' own science ideas and curiosity to be the driving force in classroom instruction. We suggested that one answer to this question is that physicists can design and facilitate teacher preparation and PD in which they take teachers' ideas seriously by both (1) elevating and maintaining a focus on teachers' physics ideas and (2) collaboratively (with teachers) subjecting these ideas to the kinds of tests to which physicists subject our own ideas. We argued that it is important to give teachers authentic experiences of having their own ideas taken seriously as they learn science, given our field's adage that "most teachers tend to teach as they were taught".[11] Further, we argued that the specialized way of taking teachers' ideas seriously—including both (1) and (2) above—answers to the nuanced vision of NGSS in which the pursuit of students' ideas is not a free-for-all but is disciplined, emergent, and generative, as it is in science.

We used examples from our local context, Focus on Energy PD for elementary teachers, to illustrate what this can look like. In particular, in the fan and convection episodes, PD instructors took teachers' ideas seriously by identifying experiments that answered participants' questions; constructing analogies that isolated relevant mechanisms; and drawing on additional experiments and concepts to check for consistency and coherence. We showed that these instructor moves were generative, both in supporting the intellectual progress of the teachers in the moment and, as reflected in interviews with Brian and Candy, in signifying to teachers *that* their ideas were worth pursuing.

We anticipate that our analysis and discussion will raise particular questions. For example, is subjecting teachers' ideas to hypothetical experiments, weighing their ideas against other concepts or evidence, etc., just another form of correcting these ideas? We think that the answer to this question depends on the context, including the relationship and interactional history of the actors involved. In the examples in this paper, our interpretation is that each of the instructional moves that we highlight was *in the service of* either (i) supporting teachers in making progress on a question *they* authored or (ii) maintaining and considering an idea proposed by a teacher. The aim of these moves does not seem to be to either redirect the teachers to a pre-determined path with an externally determined outcome or to reveal the canonical incorrectness of a particular idea. In fact, Isla lent credence to an incorrect mechanism for the popper scenario. Rather, it was to press teachers forward in their own pursuits, in a manner similar to the way physicists use toy models and gedanken experiments. In this sense, these instances of subjecting and weighing feel distinct from correcting.

Further, we anticipate questions about whether the *entirety* of the FoE PD was spent pursuing teachers' own ideas and questions. Our answer is two-fold, and in both cases no. First, structurally, the FoE PD course was organized around curricular units: in this case, units about motion, thermal, and electrical energy. Teachers' questions and ideas were elevated and pursued *within* this structure; they did not fully determine it. (For more on responsive *curricula*—in which the curriculum itself emerges from students' own ideas—see Ref. 70.) Second, even within the two episodes we analyze, teachers voice ideas that are not taken up, at least not in that episode. For example, the focus is more on Brian's and Will's ideas—and less on Mia's—in the fan episode, and teachers like Pam on the other side of the room are almost entirely peripheral. This selective attention[71,72] is a natural part of human interaction, and it also problematizes questions of *whose* ideas are made central.[73,74]

This paper also *addresses* a concern that is often voiced in conversations about elevating and taking seriously learners' ideas. That is, instructors are often concerned about how much time this kind of classroom work will take, especially in light of curricular constraints, and about what learners will take away.[68,75,76] Each of the fan and convection episodes were less than ten minutes in duration, and in both, we argue that learners made significant intellectual progress.[77] In both cases, learners articulated plausible, coherent, mechanistic accounts of complex real-world phenomena, a central goal of the NGSS and of scientific endeavors more broadly.[78–83]

Finally, all of our rhetoric in this paper has been about the role of physics faculty in preparing *teachers* and about the importance of taking *teachers'* ideas seriously. But we suggest that many—if not most—of our arguments also apply to students in pre-college and university physics courses, especially if we want to create learning environments in which *students* are free to pursue their ideas and curiosity in the same way physicists are.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the contributions of all our FoE research partners, in particular, Sara Lacy and Sally Crissman (TERC) and Kara Gray and Lezlie DeWater (SPU). The authors feel particularly indebted to the teacher participants in our PD for their intellectual partnership, both in doing physics together and in supporting the development and refinement of the Focus on Energy curricular materials. This work was supported in part by NSF-1418211.

[1]NGSS Lead States, *Next Generation Science Standards: For States, By States* (The National Academies Press, Washington, DC, 2013).
[2]"Phenomena," 2016; accessed 24 January 2018, <www.nextgenscience.org/resources/phenomena>.
[3]"Next Gen PET," 2015; accessed 24 January 2018, <http://nextgenpet.sdsu.edu/index_old.html>.
[4]W. R. Penuel and P. Bell, "Qualities of a good anchor phenomenon for a coherent sequence of science lessons," 2016; accessed 24 January 2018, <http://stemteachingtools.org/brief/28>.
[5]W. R. Penuel, K. Van Horne, and P. Bell, "Steps to designing a three dimensional assessment," 2016; accessed 24 January 2018, <http://stemteachingtools.org/assets/landscapes/STEM-Teaching-Tool-29-Steps-to-Designing-3D-Assessments.pdf>.
[6]E. Furtak, M. Pasquale, and R. Aazzerah, "How teachers can develop formative assessments that fit a three-dimensional view of science learning," 2016, accessed 24 January 2018, <http://stemteachingtools.org/brief/18>.
[7]"Next generation science assessment: Developing NGSS-aligned assessments and curricula for the next generation of K-12 students;" accessed 24 January 2018, <http://nextgenscienceassessment.org/>.
[8]M. Windschitl, J. Thompson, and M. Braaten, *Ambitious Science Teaching* (Harvard Education Press, Cambridge, MA, 2018).
[9]M. E. Loverude, B. L. Gonzalez, and R. Nanes, "Inquiry-based course in physics and chemistry for preservice K-8 teachers," Phys. Rev. Spec. Top.-Phys. Educ. Res. **7**, 010106-1–18 (2011).
[10]D. L. Messina, L. S. DeWater, and M. R. Stetzer, "Helping preservice teachers implement and assess research-based instruction in K-12 classrooms," in *Proceedings of the 2004 Physics Education Research Conference* (2004).
[11]L. C. McDermott, "Millikan Lecture 1990: What we teach and what is learned—Closing the gap," Am. J. Phys. **59**(4), 301–315 (1991).
[12]F. Goldberg and S. Bendall, "Making the invisible visible: A teaching/learning environment that builds on a new view of the physics learner," Am. J. Phys. **63**(11), 978–991 (1995).
[13]D. Hestenes *et al.*, "A graduate program for high school physics and physical science teachers," Am. J. Phys. **79**(9), 971–979 (2011).
[14]L. C. McDermott, "Teacher education and the implementation of elementary science curricula," Am. J. Phys. **44**(5), 434–441 (1976).
[15]L. C. McDermott, "A perspective on teacher preparation in physics and other sciences: The need for special science courses for teachers," Am. J. Phys. **58**(8), 734–742 (1990).
[16]L. C. McDermott *et al.*, "Improving the preparation of K-12 teachers through physics education research," Am. J. Phys. **74**(9), 763–767 (2006).
[17]L. C. McDermott, "Preparing K-12 teachers in physics: Insights from history, experience, and research," Am. J. Phys. **74**, 758–762 (2006).
[18]D. E. Meltzer and V. K. Otero, "Transforming the preparation of physics teachers," Am. J. Phys. **82**, 633–637 (2014).
[19]E. Etkina, "Pedagogical content knowledge and preparation of high school physics teachers," Phys. Rev. Spec. Top.-Phys. Educ. Res. **6**, 020110 (2010).
[20]J. R. Thompson, W. M. Christensen, and M. C. Wittmann, "Preparing future teachers to anticipate student difficulties in physics in a graduate-level course in physics, pedagogy, and action research," Phys. Rev. Spec. Top.-Phys. Educ. Res. **7**, 010108 (2011).
[21]C. Fracchiolla and N. S. Rebello, "Assessing future elementary teachers' pedagogical content knowledge in a physics class," in *Proceedings of the 2014 Physics Education Research Conference*, edited by P. Engelhardt, A. D. Churukian, and D. L. Jones (2015), pp. 87–90.
[22]Z. Hrepic *et al.*, "Developing an inquiry-based physical science course for preservice elementary teachers," in *Proceedings of the 2005 Physics Education Research Conference*, edited by P. Heron, L. McCullough, and J. Marx (AIP Press, Melville, NY, 2006), pp. 121–124.
[23]N. S. Rebello and D. A. Zollman, "Assessing pedagogical content knowledge of future elementary teachers," in *Proceedings of the 2013 Physics Education Research Conference*, edited by P. Engelhardt, A. D. Churukian, and D. L. Jones (2014), pp. 297–300.
[24]M. Plisch, "The physics teacher education coalition," in *Recruiting and Educating Future Physics Teachers: Case Studies and Effective Practices*, edited by C. Sandifer and E. Brewe (American Physical Society, College Park, MD, 2015), pp. 21–25.
[25]H. Sadaghiani, "Scientific reasoning for pre-service elementary teachers," in *Proceedings of the 2010 Physics Education Research Conference* (2010).
[26]C. Fazio, B. Di Paola, and I. Guastella, "Prospective elementary teachers' perceptions of the processes of modeling: A case study," Phys. Rev. Phys. Educ. Res. **8**(1), 010110-1–18 (2012).

[27]P. G. Ashcraft, "Modeling aspects of nature of science to preservice elementary teachers," in *Proceedings of the 2006 Physics Education Research Conference* (2006).
[28]V. K. Otero and M. Nathan, "'After I gave students their prior knowledge.': Pre-service teachers' conceptions of student prior knowledge," in *Proceedings of the 2003 Physics Education Research Conference* (2003).
[29]M. Milner-Bolotin, D. Egersdorfer, and M. Vinayagam, "Investigating the effect of physics teacher candidates' pedagogical content knowledge," Phys. Rev. Phys. Educ. Res. **12**(2), 020128-1–16 (2016).
[30]R. Steinberg and S. Cormier, "Understanding and affecting science teacher candidates' scientific reasoning in introductory astrophysics," Phys. Rev. Phys. Educ. Res. **9**(2), 020111-1–10 (2013).
[31]E. Etkina, "Millikan award lecture: Students of physics—Listeners, observers, or collaborative participants in physics scientific practices?," Am. J. Phys. **83**(8), 669–679 (2015).
[32]V. Otero, S. Pollock, and N. Finkelstein, "A physics department's role in preparing physics teachers: The Colorado learning assistant model," Am. J. Phys. **78**(11), 1218–1224 (2010).
[33]N. Papadouris, S. Vokos, and C. P. Constantinou, "The pursuit of a 'better' explanation as an organizing framework for science teaching and learning," Sci. Educ. **102**(2), 219–237 (2018).
[34]C. Sandifer and E. Brewe, *Recruiting and Educating Future Physics Teachers: Case Studies and Effective Practices* (American Physical Society, College Park, MD, 2015).
[35]D. E. Meltzer and P. S. Shaffer, *Teacher Education in Physics* (American Physical Society, College Park, MD, 2011).
[36]D. E. Meltzer and V. K. Otero, "A brief history of physics education in the United States," Am. J. Phys. **83**(5), 447–458 (2015).
[37]D. H. Gitomer and C. A. Bell, "Evaluating teaching and teachers," in *APA Handbook of Testing and Assessment in Psychology*, edited by K. F. Geisinger (American Psychological Association: Washington, DC, 2013), pp. 415–444.
[38]M. M. Keller, K. Neumann, and H. E. Fischer, "The impact of physics teachers' pedagogical content knowledge and motivation on students' achievement and interest," J. Res. Sci. Teach. **54**(5), 586–614 (2017).
[39]J. Baumert *et al.*, "Teachers' mathematical knowledge, cognitive activation in the classroom, and student progress," Am. Educ. Res. J. **47**(1), 133–180 (2010).
[40]S. B. Empson and V. R. Jacobs, "Learning to listen to children's mathematics," in *Tools and Processes in Mathematics Teacher Education*, edited by D. Tirosh and T. Wood (Sense Publishers, The Netherlands, 2008), pp. 257–281.
[41]A. D. Robertson, R. E. Scherr, and D. Hammer, *Responsive Teaching in Science and Mathematics* (Routledge, New York, NY, 2016).
[42]E. Ochs, P. Gonzales, and S. Jacoby, "When I come down I'm in a domain state: Talk, gesture, and graphic representation in the interpretive activity of physicists," in *Interaction and Grammar*, edited by E. Ochs, E. Schlegoff, and S. Thompson (Cambridge U. P., Cambridge, UK, 1996), pp. 328–369.
[43]A. C. Maskiewicz, "Navigating the challenges of teaching responsively: An insider's perspective," in *Responsive Teaching in Science and Mathematics*, edited by A. D. Robertson, R. E. Scherr, and D. Hammer (Routledge, New York, NY, 2016), pp. 105–125.
[44]L. P. Project, "Responsive teaching in science," 2011; accessed 19 January 2012, <http://cipstrends.sdsu.edu/modules/modules/teacher.html>.
[45]A. R. Daane, S. Vokos, and R. E. Scherr, "Goals for teacher learning about energy degradation and usefulness," Phys. Rev. Spec. Top.-Phys. Educ. Res. **10**, 020111-1–16 (2014).
[46]A. R. Daane *et al.*, "Energy conservation in dissipative processes: Teacher expectations and strategies associated with imperceptible thermal energy," Phys. Rev. Spec. Top.-Phys. Educ. Res. **11**, 010109-1–15 (2015).
[47]R. E. Scherr and A. D. Robertson, "The productivity of 'collisions generate heat' for reconciling an energy model with mechanistic reasoning: A case study," Phys. Rev. Spec. Top.-Phys. Educ. Res. **11**, 010111-1–16 (2015).
[48]R. E. Scherr *et al.*, "Representing energy. I. Representing a substance ontology for energy," Phys. Rev. Spec. Top.-Phys. Educ. Res. **8**(2), 020114 (2012).
[49]R. E. Scherr *et al.*, "Representing energy. II. Energy tracking representations," Phys. Rev. Spec. Top.-Phys. Educ. Res. **8**(2), 020115 (2012).
[50]R. E. Scherr *et al.*, "Negotiating energy dynamics through embodied action in a materially structured environment," Phys. Rev. Spec. Top.-Phys. Educ. Res. **9**(2), 020105 (2013).
[51]J. L. Pierson, *The Relationship Between Patterns of Classroom Discourse and Mathematics Learning* (University of Texas at Austin, Austin, TX, 2008), p. 161.
[52]M. Lau, "Understanding the dynamics of teacher attention: Examples of how high school physics and physical science teachers attend to student ideas," Ph.D. thesis (University of Maryland, College Park, MD, 2010).
[53]D. M. Levin, "What secondary science teachers pay attention to in the classroom: Situating teaching in institutional and social systems," Ph.D. thesis (University of Maryland, College Park, MD, 2008).
[54]K. Brodie, "Working with learners' mathematical thinking: Towards a language of description for changing pedagogy," Teach. Teacher Educ. **27**, 174–186 (2011).
[55]J. Richards, "Exploring what stabilizes teachers' attention and responsiveness to the substance of students' scientific thinking in the classroom," Ph.D. thesis (University of Maryland at College Park, 2013).
[56]A. D. Robertson *et al.*, "What is responsive teaching?," in *Responsive Teaching in Science and Mathematics*, edited by A. D. Robertson, R. E. Scherr, and D. Hammer (Routledge, New York, NY, 2016), pp. 1–35.
[57]D. M. Levin *et al.*, *Becoming a Responsive Science Teacher: Focusing on Student Thinking in Secondary Science* (National Science Teachers Association Press, Arlington, VA, 2012).
[58]D. Hammer, F. Goldberg, and S. Fargason, "Responsive teaching and the beginnings of energy in a third grade classroom," Rev. Sci., Math., ICT Educ. **6**(1), 51–72 (2012).
[59]B. Jordan and A. Henderson, "Interaction analysis: Foundations and practice," J. Learn. Sci. **4**(1), 39–103 (1995).
[60]F. Erickson, *Qualitative Methods in Research on Teaching*, edited by M. C. Wittrock (Macmillan, New York, NY, 1986), pp. 119–161.
[61]J. A. Maxwell, "Using qualitative methods for causal explanation," Field Methods **16**(3), 243–264 (2004).
[62]S. Crissman *et al.*, "Looking through the energy lens," Sci. Child. **52**, 26–31 (2015).
[63]R. E. Scherr *et al.*, "Energy tracking diagrams," Phys. Teach. **54**, 96–102 (2016).
[64]A. R. Daane, L. Wells, and R. E. Scherr, "Energy theater," Phys. Teach. **52**, 291–294 (2014).
[65]M. C. O'Connor and S. Michaels, "Aligning academic task and participation status through revoicing: Analysis of a classroom discourse strategy," Anthropol. Educ. Q. **24**(4), 318–335 (1993).
[66]D. Hammer and E. van Zee, *Seeing the Science in Children's Thinking: Case Studies of Student Inquiry in Physical Science* (Heinemann, Portsmouth, NH, 2006).
[67]D. Hammer, "Discovery learning and discovery teaching," Cognit. Instr. **15**(4), 485–529 (1997).
[68]A. D. Robertson and J. Richards, "Teacher sense-making about being responsive to students' science ideas: A case study," Eur. J. Sci. Math. Educ. **5**(4), 314–342 (2017).
[69]D. Hawkins, "Messing about in science," in *The Informed Vision, Essays on Learning and Human Nature*, edited by D. Hawkins (Agathon Press, New York, 1974).
[70]L. J. Atkins and B. W. Frank, "Examining the products of responsive inquiry," in *Responsive Teaching in Science and Mathematics*, edited by A. D. Robertson, R. E. Scherr, and D. Hammer (Routledge, New York, NY, 2016), pp. 56–84.
[71]C. Chabris and D. Simons, *The Invisible Gorilla: How Our Intuitions Deceive Us* (Random House, New York, NY, 2011).
[72]K. F. Miller, "Situation awareness in teaching: What educators can learn from video-based research in other fields," in *Mathematics Teacher Noticing: Seeing Through Teachers' Eyes*, edited by M. G. Sherin, V. R. Jacobs, and R. A. Philipp (Routledge, New York, NY, 2011), pp. 51–65.
[73]R. A. Engle, J. M. Langer-Osuna, and M. M. de Royston, "Toward a model of differential influence in persuasive discussions: Negotitating quality, authority, privilege, and access within a student-led argument," J. Learn. Sci. **23**(2), 245–268 (2014).
[74]B. Warren *et al.*, "Rethinking diversity in learning science: The logic of everyday sense-making," J. Res. Sci. Teach. **38**(5), 529–552 (2001).
[75]C. J. Rop, "The meaning of student inquiry questions: A teacher's beliefs and responses," Int. J. Sci. Educ. **24**(7), 717–736 (2002).
[76]D. Chazan and M. Schnepp, "Methods, goals, beliefs, commitments, and manner in teaching: Dialogue against a calculus backdrop," Social Constructivist Teach. **9**, 171–195 (2002).
[77]R. A. Engle and F. R. Conant, "Guiding principles for fostering productive disciplinary engagement: Explaining an emergent argument in a

community of learners classroom," Cognit. Instr. **20**(4), 399–483 (2002).
[78]R. S. Russ *et al.*, "Recognizing mechanistic reasoning in student scientific inquiry: A framework for discourse analysis developed from philosophy of science," Sci. Educ. **92**(3), 499–525 (2008).
[79]R. S. Russ *et al.*, "Making classroom assessment more accountable to scientific reasoning: A case for attending to mechanistic thinking," Sci. Educ. **93**(5), 875–891 (2009).
[80]P. Machamer, D. Darden, and C. F. Craver, "Thinking about mechanisms," Philos. Sci. **67**, 1–25 (2000).
[81]P. Machamer, "Activities and causation: The metaphysics and epistemology of mechanisms," Int. Stud. Philos. Sci. **18**(1), 27–39 (2004).
[82]L. Darden and C. F. Craver, "Strategies in the interfield discovery of the mechanism of protein synthesis," Stud. History Philos. Biol. Biomed. Sci. **33**, 1–28 (2002).
[83]L. Darden, "Strategies for discovering mechanisms: Schema instantiation, modular subassembly, forward/backward chaining," Philos. Sci. **69**, S354–S365 (2002).
[84]All teacher and PD instructor names are pseudonyms.
[85]We are able to speak to what Isaac wants because he is a co-author on this paper (LS). We gave him a pseudonym in the paper—a name that starts with "I," to set instructors apart from participants.
[86]To watch a video of this scenario, go to: https://focusonenergy.terc.edu/resources/classroom/stopper.html).
[87]Full transcript and audio of the episode can be found here: goo.gl/zWXxBW.
[88]Because we cannot see Brian's or Pam's faces, it is difficult to draw conclusions about why Brian says this. Our guess is that Pam says something inaudible just before, or that her facial expression has communicated something to him that he interpreted as her questioning his support.

Tangent Galvanometer

I don't think that I have ever visited an apparatus collection that did not have a tangent galvanometer. Thus, I was not surprised to find this small and rather neat tangent galvanometer when I went to Baldwin Wallace University near Cleveland in early 2016 to give a talk. This one was made in Chicago in the early years of the 20th century. If you have ever tried to use a tangent galvanometer you will join me in wondering why these are so common. The key operating principle is that the compass needle points along the vector sum of the magnetic field produced by current passing through the coils and the horizontal component of the magnetic field of the earth. And there lies the rub, for modern physics buildings are just full of iron and steel, starting with the lab or demonstration bench on which the instrument is placed. This serves to change both the direction and strength of the earth's magnetic field; I have seen one example in which the field has been turned 45 degrees to its expected direction. (Picture and text by Thomas B. Greenslade, Jr., Kenyon College)