



## Teacher sense-making about being responsive to students' science ideas: A case study

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### Abstract

Being responsive to the substance of students' disciplinary thinking is central to current visions of reformed science teaching. Studies of classroom practice, however, show that this kind of teaching is relatively rare. In this paper, we use data from one cohort of university physics Learning Assistants (LAs) to illustrate what it looks like for teachers to sense-make about being responsive to student thinking. We draw on the theoretical lens of sense-making – including Spillane et al.'s (2002) notion that teachers need opportunities to sense-make not only about the substance of new instructional approaches but also their own relationship to these approaches – to unpack the central questions that LAs asked about being responsive. We give evidence from course assignments that these LAs' extended sense-making was productive both (1) for their attention to the substance of student thinking and (2) to their identification with responsiveness as a central facet of good instruction. Our case study highlights the tensions that teachers may experience as they enter this instructional space and what "resolution" of such tensions can look like.

**Keywords:** responsiveness to students' ideas, sense-making, university physics.

### Introduction

The following written reflection depicts a physics Learning Assistant (LA) grappling with a classroom interaction she had just facilitated in a university physics course, as her students "negotiate[d] what [they] mean by 'gravity'":

"... this was a case in which [students] have a lot of experience with gravity and have heard all about it, but their ideas are not fully developed and they could see they weren't all talking about the same thing. A lot of seeds came up in a discussion I had with one table group. They mentioned that there had to be something the same about gravity [in all contexts] (seed of canon) but there was also something different because it pulls bigger things more (seed of canon/connection). Then one student mentioned that gravity on earth is always 9.8, but it is less on the moon... During the whole discussion, I kept noticing these seeds, but I struggled with how to pull them out and develop them without feeding the students my own ideas or changing their ideas. What I want to do is notice these seeds and artfully pull them out so that the students feel validated and are able to see the process of their own ideas becoming a fully formed scientific idea."

Several weeks later, in a final project for her pedagogy course, the same LA wrote:

"It is my goal to be faithful to the discipline of physics while at the same time being responsive to individual students and the ideas they have. I find that teaching is just as much

a process of discovery and sense-making as learning is. In teaching, I discover what ideas students have that might be productive for learning or what ideas they have that are keeping them from fully understanding a concept. Teaching requires creativity, because one must find a way to weave students' ideas into a canonically accepted and coherent idea...The integration of student ideas and canonical thinking is the most exciting part of teaching in my mind, but also the most challenging."

In both of these reflections, we see this LA – in her role as an advanced undergraduate providing instructional support in introductory physics courses – discussing central aspects of what it means to teach in ways that are responsive to the substance of students' disciplinary thinking (e.g., Ball, 1993; Hammer, Goldberg, & Fargason, 2012; Jacobs, Lamb, & Philipp, 2010; Pierson, 2008; Robertson, Scherr, & Hammer, 2016). For instance, in her first reflection, the LA attended to students' ideas about gravity and framed them as "seeds" to build on, connecting to a growing emphasis in teacher education on building on existing resources within student thinking (Campbell, Schwarz, & Windschitl, 2016; Hammer et al., 2012; Rosebery, Warren, & Tucker-Raymond, 2015). She also identified an area in which she would like to grow (first reflection) and one that presents an exciting challenge to her (second reflection), that of supporting students in developing *their own* ideas – an area known to be central to student learning and the development of epistemic agency (Scardamalia, 2002; Stroupe, 2014), yet challenging to enact (Harris, Phillips, & Penuel, 2012).

For the reasons described above and more, teachers' close attention and responsiveness to the sense that students are making, and to disciplinary connections within, is a cornerstone of current visions of reformed teaching (e.g., Lampert et al., 2013; NGACBP and CCSSO, 2010; NGSS Lead States, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012). Previous studies have shown that instruction focused on understanding and building on students' ideas promotes enhanced conceptual understanding (Carpenter, Fennema, Peterson, Chiang, & Loef, 1989; Pierson, 2008) and can transform classrooms into places where students are empowered participants in scientific and mathematical practices, in ways that recognize their ideas as sensible and important (e.g., Cornelius & Herrenkohl, 2004; Engle & Conant, 2002). Researchers and teacher educators care deeply about these outcomes and have worked to provide teachers with experiences that would prepare them to teach responsively. However, we know that even with support, responsiveness to student thinking is both rare and challenging for teachers to enact (Banilower, Smith, Weiss, & Pasley, 2006; Horizon Research International, 2003; Levin, Hammer, & Coffey, 2009; Roth & Garnier, 2007; Sykes, Bird, & Kennedy, 2010), in part due to the multitude of constraints and demands that teachers face in their local settings.

We hypothesize that responsiveness to student thinking often gets "lost in translation" between teacher education and classroom instruction in part because, in order to successfully implement any instructional approach, teachers need opportunities to *sense-make* about both the approach itself, and about their relationship to it (Spillane, Reiser, & Reimer, 2002). In particular, literature on sense-making points out that new educational approaches often trigger ambiguity and uncertainty for teachers, who receive many conflicting messages about teaching from stakeholders and from their own educational experience (Allen & Penuel, 2015; Coburn, 2005; Ketelaar, Beijaard, Boshuizen, & den Brok, 2012; Weick, 1995; Weick, Sutcliffe, & Obstfeld, 2005). The process of sense-making – especially with others (Coburn, 2001; März & Kelchtermans, 2013; Spillane et al., 2002) – helps to resolve these ambiguities and support implementation (Allen & Penuel, 2015; Coburn, 2001; März & Kelchtermans, 2013; Weick, 1995).

While many existing approaches to supporting teachers' responsiveness offer opportunities for sense-making about student thinking, the discipline, and/or particular instructional moves, to our knowledge the literature does not document what it looks like for teachers to sense-make *about*

responsiveness itself. Additionally, depictions of programs to support responsiveness (see the literature review) do not highlight opportunities for teachers to negotiate how a responsive approach interacts with their current ideas and contexts. While such opportunities may occur, cases show teachers doing this kind of sense-making in their workplaces (rather than in teacher education contexts), and often on their own (e.g., Levin, 2008).

In this paper, we contribute a case of LA sense-making about being responsive to students' disciplinary thinking. LAs, as briefly depicted above (and described in more detail below), are relationally competent undergraduate students who act as instructional assistants in introductory physics courses (Otero, Finkelstein, McCray, & Pollock, 2006; Otero, Pollock, & Finkelstein, 2010). While actively in their teaching placements, LAs take a university pedagogy course that focuses on educational theory and best practices. Here, we take up the following questions, using data from one cohort of Seattle Pacific University physics LAs:

1. **What does it look like to “sense-make” about being responsive to students’ ideas?** In our case, LAs’ sense-making took the form of negotiating a small number of key questions over time (e.g., whether it was “okay” to take up students’ canonically incorrect ideas, or how they might build on students’ ideas). LAs’ consideration of these questions evolved in two ways – in which questions were most salient, and in the specific forms the questions took at varied points.
2. **In what ways is such sense-making productive for LAs’ development as responsive practitioners?** We suggest that LAs’ sense-making had two particular affordances. First, as LAs made sense of what they could attend to and build on in student thinking, their noticings of disciplinary connections within students’ responses in their teaching placements took up the language of their sense-making, suggesting that this sense-making was entangled with their noticing and responsiveness in practice. Second, we argue that LAs’ sense-making played a role in their identification with responsiveness as a central tenet of teaching.

We see these two questions as speaking to the overlap between the sense-making and responsiveness literatures – the sense-making literature poses this process as central to the take-up of instructional approaches, but we do not have examples of what this looks like (or means) in the context of responsiveness to students’ disciplinary thinking. In offering this case study, our aim is to foster teacher educators’ awareness of opportunities to capitalize on teachers’ sense-making in their own contexts, by showing what it can look like and in what ways it may be consequential for teacher thinking and practice.

## Literature Review

*What does it mean to be “responsive” to the substance of students’ disciplinary thinking?* Responsiveness to students’ disciplinary thinking, as construed here and elsewhere, is grounded in several foundational assumptions: that students come to classrooms with a wealth of productive knowledge and experience; that this wealth is too rich and diverse for teachers and/or curricula to know fully in advance; and that the ideas students are bringing to bear are *sensible* in some way (Hammer, 2000, 2004; Hammer & Elby, 2000; Hammer, Elby, Scherr, & Redish, 2005). From these assumptions comes the stance that teaching begins with listening and seeking to understand.

For these reasons, responsive instruction *foregrounds the substance of students’ ideas* (Ball, 1993; Carpenter et al., 2000; Coffey, Hammer, Levin, & Grant, 2011; Duckworth, 2006; Hammer, 1997; Hammer et al., 2012; Jacobs et al., 2010; Levin et al., 2012; Levin et al., 2009; Schifter, 2011; Sherin et al., 2011); teachers attend to the meaning that students are making of their disciplinary experiences, assuming a stance of seeking to understand rather than quickly evaluating. Responsive instruction

also *seeks out disciplinary connections within students' ideas* (Ball, 1993; Hammer, 1997; Hammer et al., 2012; Jacobs et al., 2010; Levin et al., 2012; Russ, Coffey, Hammer, & Hutchison, 2009; Schifter, 2011; Sherin & van Es, 2005), assuming that there is inherent sensibility and “disciplinary progenitors” (Harrer, Flood, & Wittmann, 2013, p. 4) within student ideas. These disciplinary progenitors – or “seeds” of science (Hammer, 1997, p. 511) – may be, for example, the beginnings of canonical understanding, the instantiation of specific scientific practices, or affective experiences that promote feelings of pleasure in doing science. As teachers are responsive to students' ideas, they “consider the [discipline] in relation to the [students] and the [students] in relation to the [discipline]” (Ball, 1993, p. 394). Being responsive to student thinking also means *adapting or building instruction on the basis of students' ideas* (Ball, 1993; Empson & Jacobs, 2008; Fennema et al., 1996; Hammer, 1997; Hammer et al., 2012; Jacobs et al., 2010; Levin et al., 2012; Maskiewicz & Winters, 2012; Russ et al., 2009; Schifter, 2011; Sherin & van Es, 2005), in ways that both preserve the essence of student thinking and make progress along disciplinary dimensions. In this sense, responsive instruction is *emergent* (at least in part), on short- and longer-term scales. Hammer, Goldberg, and Fargason (2012) write:

A responsive approach... is to adapt and discover instructional objectives responsively to student thinking. The first part of a lesson elicits students' generative engagement around some provocative task or situation (or, perhaps, by discovering its spontaneous emergence). From there, the teacher's role is to support that engagement and attend to it – watch and listen to the students' thinking, form a sense of what they are doing, and in this way identify productive beginnings of scientific thinking. In this way, the teacher may select and pursue a more specific target, in a way that recognizes and builds on what students have begun (p. 55).

Being responsive to the disciplinary substance of students' ideas coheres with conceptualizations of formative assessment (Black and Wiliam, 1998; Clinchot et al., 2017; Coffey et al., 2011); both involve paying attention and responding to students. However, responsiveness takes a particular orientation toward student thinking – one that seeks out the disciplinary productivity and potential within students' ideas.

*Why should we seek to promote responsiveness to student thinking in science teacher education?* The literature identifies a number of benefits of responsive instruction. Central among them is the sense that being responsive to students' ideas supports students in building knowledge in ways that are consistent with the practices of science (Ball, 1993; Coffey et al., 2011; Hammer et al., 2012; Hutchison & Hammer, 2010; Kelly, Brown, & Crawford, 2000; Richards, 2013; Schifter, 2011; Siry & Max, 2013). Experiments, argumentation, model-building, and other practices are inspired by and in the service of pressing into students' own ideas. For instance, when Sean – a third grade student in Ball's mathematics classroom – proposes that six is both even and odd (Ball, 1993), Ball sees an opportunity for her students to explore the role of mathematical definitions and their “nature and purpose in mathematical activity and discourse” (p. 387). Throughout the “Sean numbers” episode, Ball invites students to evaluate one another's thinking and to try on their peers' definitions of even and odd numbers. By distributing authority for the construction and assessment of ideas and by elevating nascent scientific and mathematical practices that emerge in the flow of classroom activity, instruction that is responsive to student thinking brings students closer to the heart of what it means to *do* science or mathematics.

Building instruction around students' disciplinary ideas has also been shown to improve students' conceptual understanding, more so than more traditional approaches (Carpenter et al., 1989; Empson & Jacobs, 2008; Fennema et al., 1996; Fennema, Franke, et al., 1993; Hiebert & Wearne, 1993; Kersting, Givvin, Sotelo, & Stigler, 2010; Pierson, 2008; Radoff, Robertson, Fargason, & Goldberg, in press; Saxe, Gearhart, & Seltzer, 1999). In fact, Fennema et al. (1996) found that gains in students'

mathematics achievement co-occurred with shifts in teachers' responsiveness to their students' mathematical thinking.

We – and others – additionally argue that responsiveness is important for reasons of equity and agency. Framing students' intuitive ideas as misconceptions may systematically disadvantage students from diverse cultural, linguistic, and socioeconomic communities:

“...children most particularly disadvantaged by approaches based in a dichotomous view [e.g., focusing on the correctness vs. incorrectness of student thinking] are those whose everyday ways of knowing and talking are seen as being the furthest from those traditionally valued in school science or even in national standards” (Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001, p. 531).

On the other hand, framing student ideas as productive beginnings of disciplinary thinking has the potential to broaden participation among historically underserved groups (Empson, 2003; Hudicourt-Barnes, 2003; Michaels, 2005; Rosebery, Ogonowski, DiSchino, & Warren, 2010; Rosebery et al., 2015; Warren et al., 2001). Shifting the emphasis away from teacher as knowledge provider – and toward students as agents of their own learning and knowledge construction – can dismantle systems of privilege within STEM classrooms (Freire, 2000; Levin, Tudela, & Lau, 2016).

*What are existing approaches to preparing teachers to be responsive to their students' thinking?* There are a number of different teacher preparation and professional development (PD) efforts that focus on supporting teachers in attending and responding to students' scientific or mathematical thinking. Though not a comprehensive list, these efforts include approaches that center on engaging teachers in doing science, video clubs, practice-oriented approaches, and approaches oriented toward teacher learning about frameworks for student thinking. We briefly discuss each of these in turn.

One approach to inducting teachers into responsive instructional practices engages teachers in responsively-facilitated scientific inquiry: teacher educators facilitate *teacher* learning about science in ways that take up and pursue *teachers'* own ideas and questions about the phenomena under investigation (Dorph & Chi, 2013; Hammer et al., 2012; Jaber & Hammer, 2016; Lineback, 2015; Maskiewicz, 2016; Maskiewicz & Winters, 2012; Radoff & Hammer, 2016; Sikorski, 2016). In such contexts, teachers are asked to take seriously the various ideas that emerge in their own discourse (Lineback, 2015; Maskiewicz & Winters, 2012), and they experience what it feels like for their instructors (the PD facilitators) to take those ideas seriously as well. The overarching aim is for teachers to learn what it means to engage in authentic, integrated scientific inquiry – inquiry in which *ideas* are at the center of the class' discourse and practices – and thus to learn how to identify the *beginnings* of such inquiry among their students. Maskiewicz (2016) writes that:

“[t]he overarching PD goal was that over the course of three years, as the teachers participated in discourse with others to make connections, provide support, question, clarify, generalize, and refine explanations, they would discover that science *is* inquiry. We hoped these experiences would help them approach their own science instruction in the same way” (p. 108).

Teachers in inquiry-oriented professional development also watch video that foregrounds students' thinking. Facilitators encourage teachers to focus on what students are saying and doing in the video, “identifying and interpreting the students' ideas... and proposing possible ways a teacher might respond in order to build on the students' reasoning” (Maskiewicz & Winters, 2012, p. 434).

Video clubs are a second approach to supporting teachers in becoming attentive and responsive to students' thinking (Hammer & van Zee, 2006; Levin et al., 2012; Luna & Sherin, under review; Sherin & Han, 2004; Sherin & van Es, 2005; van Es, 2011; van Es & Sherin, 2008, 2010). In these contexts, teacher educators select a classroom episode that showcases students' mathematical or scientific thinking, watch the episode with teachers, and invite teachers to describe what they noticed. The goal is to shift teachers' attention toward students' *mathematical* or *scientific thinking* (as opposed to, for example, their on- or off-task behavior) and to promote *interpretation* (rather than evaluation or mere description) of student thinking.

Other teacher preparation and professional development efforts focus on developing a set of high leverage or ambitious teaching practices, including noticing and responding to student ideas (e.g., Ball & Forzani, 2009; Ghouseini, Beasley, & Lord, 2015; Grossman, Hammerness, & McDonald, 2009; Lampert, Beasley, Ghouseini, Kazemi, & Franke, 2010; Lampert et al., 2013; McDonald, Kazemi, & Kavanagh, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012). These efforts are tied to a recent move in teacher education toward focusing on the *practices* inherent in skilled teaching (as opposed to, say, the *knowledge* that teachers draw on in teaching). Researchers in this tradition have deconstructed the work of teaching, identifying the practices that are most central to the profession and most consequential for student learning, and engage teachers in rehearsing, enacting, and inquiring into these practices.

Still other efforts center on teacher learning about frameworks for student thinking that then become tools for deciding how to build on students' ideas during instruction (Carpenter, Fennema, & Franke, 1996; Carpenter et al., 2000; Carpenter et al., 1989; Fennema, Carpenter, Franke, & Carey, 1993; Fennema et al., 1996; Fennema, Franke, et al., 1993; Franke & Kazemi, 2001; Furtak, 2009; Furtak et al., 2016). For example, the Cognitively Guided Instruction (CGI) project aims to help teachers respond to the substance of students' mathematical thinking during instruction by providing "an organized set of [research-based] frameworks that delineated the key problems in the domain of mathematics and the strategies children would use to solve them" (Franke & Kazemi, 2001, p. 103), with the goal of informing (though not determining) how teachers interpret students' strategies and decide on instructional next steps. In particular, the frameworks map students' problem-solving strategies as more or less sophisticated based on the underlying mathematical ideas students are using, such that teachers can identify which strategy students are using and what scaffolds they might need to make progress.

Though these efforts include opportunities to sense-make – about a scientific phenomenon, about one another's ideas, about *students'* ideas, and about how research on students' ideas applies to a given student in a given moment – sense-making *about* responsive instruction and/or how it fits into teachers' current thinking or institutional systems is not the focus, nor is this latter kind of sense-making documented in the research literature. It is against this background that we articulate our own teacher education context in the "Study context and research methods" section. Importantly, the first author, who taught the pedagogy course, took a *responsive* approach to her LAs' ideas about and reactions to readings and classroom video that depicted teachers being responsive to their students' ideas. This responsive approach to the pedagogy course – and the pedagogy course curriculum that emerged from it – provided a number of opportunities for LAs to sense-make about what it means to be responsive to students' ideas and whether they had the capacity to do so in their local university setting; this sense-making is the focus of our analysis (below). First, though, we briefly articulate our theoretical framework for sense-making.

### Theoretical framework: Teacher learning as situated sense-making

We conceptualize teacher learning – including LA learning – as a constructive and situated sense-making process (Allen and Penuel, 2015; Coburn, 2001; März and Kelchtermans, 2013; Spillane et al., 2002; Weick et al., 2005), where teachers actively develop their understanding of different forms of teaching and learning in relation to (1) their existing knowledge, goals, and experiences and (2) the varied contexts in which they are embedded. This coheres with conceptualizations of sense-making in organizational studies – as a process that individuals or groups engage in when faced with novel situations (Weick, 1995). As we allude to above, Spillane et al. (2002) argue that to implement a particular instructional approach –*i.e.*, to *learn* how to teach in a particular way -- teachers need to make sense both of the approach itself and how the approach fits with their current ideas and contexts. This requires active meaning making and the coordination of ideas with action.

Throughout this paper, we use *sense-making* as the central construct for describing and analyzing what LAs are doing and thinking in relation to responsive instructional practices. We identify sense-making in artifacts from LAs' university pedagogy course (described below), where they read articles, watched classroom video, and discussed how to attend and respond to the substance of student thinking. In analyzing these artifacts for evidence of sense-making, we used key features that recur across descriptions of sense-making in the literature (Allen & Penuel, 2015; Coburn, 2001; Ketelaar et al., 2012; März & Kelchtermans, 2013; Spillane et al., 2002; Weick et al., 2005):

- *Sense-making occurs in response to ambiguity or uncertainty, and aims toward some kind of resolution.* Resolution need not be a definitive or final stance on an issue; it may be more of a feeling of clarity or a step in the “continued redrafting of an emerging story” (Weick et al., 2005, p. 415).
- *Sense-making is an active process of meaning construction.* It involves noticing and selecting relevant features of a situation to attend to, and interpreting and creating meaning from these in interaction with existing ideas, prior experiences, etc.
- *Sense-making is situated in nature.* Several authors describe how sense-making is distributed across situations (Spillane et al., 2002) or “deeply situated in teachers’ embedded contexts” (Coburn, 2001, p. 147). These descriptions demarcate sense-making as something that happens not in the abstract, but in relation to and interplay with localized contexts and actions.
- *Sense-making is social.* Coburn depicts the sense-making process as “collective in the sense that it is rooted in social interaction and negotiation” (p. 147); as Allen and Penuel indicate, this interaction may be with real or imagined others.
- *Sense-making involves affect and identity.* Multiple studies demonstrate that sense-making is not a purely cognitive process. As Weick et al. discuss, “When people face an unsettling difference, that difference often translates into questions such as who are we, what are we doing, what matters, and why does it matter? These are not trivial questions” (p. 416). Instructional approaches are tied to values and notions of legitimacy as a teacher (März & Kelchtermans, 2013; Spillane et al., 2002), indicating that sense-making in this landscape may be especially emotionally-charged.

In the following section, we describe our research context and analytical approach in more detail, giving examples of how we used this framework to identify sense-making in LA coursework.

### Study context and research methods

*Teacher education context.* The data for this paper come from a weekly university pedagogy course for physics Learning Assistants at Seattle Pacific University, (SPU) a small private university in the Pacific Northwest United States. Learning Assistants (LAs) (Otero, Finkelstein, McCray, & Pollock, 2006; Otero, Pollock, & Finkelstein, 2010) are relationally and intellectually competent undergraduate students who provide instructional support in undergraduate introductory physics courses. LA Programs are meant to serve as both a (1) teacher recruitment mechanism for students with strong

disciplinary grounding by providing them with early teaching experiences and (2) specialized teacher preparation opportunity for already-committed pre-service teachers. As such, many LAs intend – or eventually decide – to become K-12 science teachers.

The content and structure of the LA Program at SPU provides LAs with experiences comparable to those of pre-service teachers in science methods courses that include field placements: LAs take a pedagogy course that focuses on educational theory and best practices, in conjunction with ongoing instructional placements in introductory physics courses. In their placements, LAs facilitate collaborative dialogue among groups of students who are completing worksheets designed to build conceptual understanding and address common misunderstandings in introductory physics [*i.e.*, misunderstandings that have been widely documented among K-12 as well as university students (Driver, Guesne, & Tiberghien, 1985; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Duit, 2009)].

In the 2013-2014 academic year, the first author worked with a total of twelve LAs; Table 1 indicates which LAs participated in which quarters of the program (*i.e.*, their participation in a given quarter was voluntary). The remainder of the paper focuses on discussions and assignments from the Winter and Spring 2014 pedagogy courses; these discussions more centrally focused on attending and responding to students' science ideas. During these two quarters, LAs met with the first author for approximately 20 hours of pedagogy instruction, distributed across 20 weeks (one hour per week).

**Table 1.** LAs' participation in the LA Program in the 2013-2014 academic year

| Pseudonym | Fall 2013 | Winter 2014 | Spring 2014 |
|-----------|-----------|-------------|-------------|
| Charlie   | •         | •           |             |
| Eddie     | •         | •           | •           |
| Ellie     | •         | •           | •           |
| Jane      | •         | •           |             |
| Katie     | •         | •           | •           |
| Lizzie    | •         | •           |             |
| Martin    |           |             | •           |
| Maya      |           | •           |             |
| Rose      | •         | •           | •           |
| Rusty     | •         | •           |             |
| Victoria  | •         | •           | •           |
| Will      |           |             | •           |

Throughout the course, the first author took an explicitly responsive stance toward LAs' ideas, treating these ideas as worthy of consideration and collective reflection. LAs' questions, concerns, and ideas drove the substance of class discussions, and subsequent assignments were often based on LAs' developing interests and ideas. LAs themselves also took an empathetic, curious stance toward one another's ideas; they chose "pursuing one another's ideas" as an explicit class goal and even asked the first author to write that phrase on the board for the first several weeks of the Winter quarter. Assignments often included questions like the one below:

This week in class, Charlie posed the question, "Is it right for the teacher to pursue these [mathematical "seeds"], or is it just going to confuse students?" (We started to answer this question, but I think there's more discussion to be had!) What do you think would be Ball's answer to this question?



LAs were regularly asked to say where they were in relationship to particular ideas (e.g., those discussed in a paper) or why their peers' ideas made sense to them, even if they disagreed.

Further, LAs' developing ideas were situated in their practice (Borko & Putnam, 1996; Putnam & Borko, 2000); through their writing of teaching reflections, LAs considered responsive instruction *in relationship* to their instructional context and interactions with students. This course structure and framing provided LAs with multiple opportunities to sense-make about being responsive to students' ideas, and it provided the first author with opportunities to understand LAs' thinking and design further instruction in response.

The focus on responsiveness to students' ideas in the Winter and Spring quarters built from LAs' consideration of theories of learning in the Fall [constructivism (Driver & Bell, 1986; von Glasersfeld, 1983), misconceptions and pieces (Scherr, 2007; Smith III, diSessa, & Roschelle, 1993), and acquisition and participation metaphors (Sfard, 1998)] and from their consideration of possible foci of assessment in science classrooms in early Winter. The first example of responsive instruction they interacted with as a class was *Discovery Learning and Discovery Teaching* (Hammer, 1997); this manuscript was framed in part as an example of a teacher "choosing among multiple, competing foci of attention" (assignment, 1/21/14). The remainder of the course assignments were designed in response to the questions LAs raised about case studies and videos of responsive instruction.

*Selection of case for analysis.* Our selection of the 2013-2014 cohort of LAs as a relevant case (Erickson, 1986; Yin, 2003) for understanding sense-making about responsiveness to students' disciplinary thinking was informed by a number of criteria. The first was our sense that the instructional context (the physics LA pedagogy course at SPU) is appropriate for informing teacher education – the pedagogy course structure and content are similar to science and math methods courses at some institutions. Further, the *LA Program* itself is a relevant context for studying sense-making because LAs' learning about teaching is situated in their ongoing instruction. LAs are expected to "try on," in their instructional practice, the theories and approaches they discuss in their pedagogy course. Likewise, they are expected to refine their understanding of educational theory and strategies on the basis of what they learn from interacting with students. This "conversation" between (1) LAs' instructional context and (2) educational theory and approaches (including attending and responding to students' ideas) –*i.e.*, the situated nature of their learning – offers opportunities to understand how LAs are sense-making about instruction. Finally, we selected the 2013-2014 *cohort* of LAs (a) because of their sustained focus on responsive instructional practice over the course of 20 weeks, which allowed us to track their evolving thinking over time through course artifacts and assignments, and (b) because we had evidence that many of the LAs began to *enact* responsive instruction, providing authentic opportunities to iterate their thinking about and enactment of this tenet of teaching.

We argue that this case shows what is possible (Eisenhart, 2009): as Spillane et al (2002) call for, these LAs are sense-making about responsiveness to students' thinking and about its relationship to their existing ideas and contexts, even as novice teachers considering this approach for the first time. This case also highlights sense-making as a powerful construct for understanding the take-up of reform-oriented teaching and gives examples of how sense-making can be deeply entangled with LAs' epistemologies and identities. Though in many ways the specific points of sense-making we lay out are tied to the first author's local context and to this group of LAs, we believe that the questions these teachers ask (over and over again) are central to the essence of being responsive to student thinking; in this sense, our case could broaden other teacher educators' awareness (Donmoyer, 1990; Eisenhart, 2009; Erickson, 2011; Maxwell, 1992; Wehlage, 1981) of the possibilities for sense-making in their contexts.

*Data sources.* We collected all artifacts that LAs produced or contributed to across the Winter and Spring quarters of the pedagogy course. (Sample assignments can be found in the supplementary materials online.) These artifacts include:

- *Photos of notes taken on the whiteboard during class discussions.* The first author often scribed key ideas while the class was discussing classroom cases or questions that came to mind in response to readings or teaching experiences. LAs regularly edited the notes to ensure they matched what they intended to communicate. Figure 1 shows an example of a white board photo.
- *Reading reflections.* LAs regularly read journal articles about instruction and submitted individual reflections on targeted questions and implications for their own teaching.
- *Discussion reflections.* At times, rather than engaging with new readings, the weekly assignment was to synthesize and reflect on in-class discussions that had occurred.
- *Teaching journals.* LAs also kept journals where they reflected in detail on significant instructional interactions each week. Prompts for journal reflections were more targeted at the beginning of the course sequence, asking LAs to attend to specific features of their interactions with students, but they changed to be more open-ended so that LAs could reflect on what stood out to them any given week. (This shift was suggested by one of the LAs, Rose; we describe this interaction in our findings.)
- *Final projects and essays.* Finally, LAs completed a project each quarter in which they analyzed video of their interactions with students. LAs selected a five-minute clip from one of several filmed class periods, transcribed it, and wrote a 1500-word reflection about the extent to which they saw the themes of the pedagogy course at work in their interactions. The focus of these assignments in both quarters was what LAs noticed about student thinking and their responses to it, both in the moment and upon reflection. In the spring quarter, LAs also wrote an essay on their current theories of learning as informed by literature, discussions, and teaching and learning experiences.

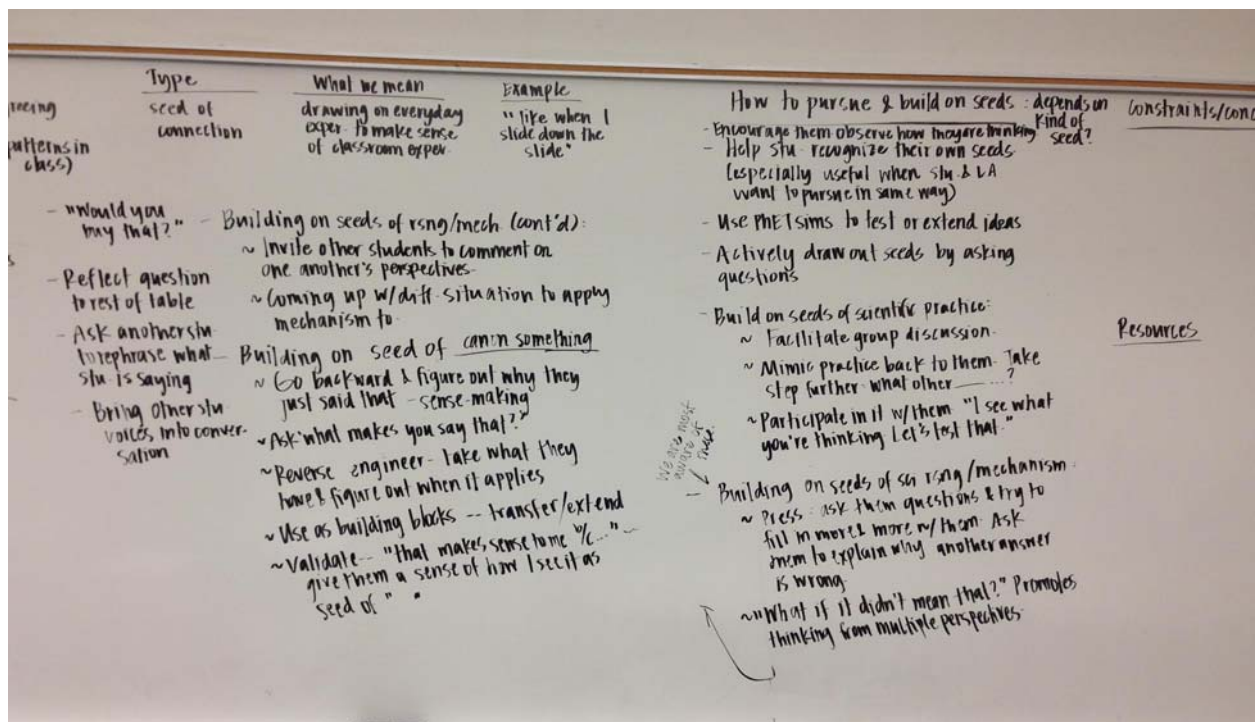


Figure 1. Example pedagogy whiteboard photo

In total, we collected 36 whiteboard photos, 231 weekly reflections (on readings, discussions, or teaching), and 23 final projects and essays. In the rest of this section, we describe how we analyzed the data for themes in LAs' sense-making about attending and responding to students' science ideas.

*Analytical approach.* We drew on the characteristics of sense-making described in our theoretical framework to identify instances of LA sense-making about responsive instruction, as evidenced in records of pedagogy course discussions and assignments. Specifically, we attended to instances in which LAs did one or more of the following: raised a question or concern about attending to and building on students' ideas (evidence of ambiguity/uncertainty), explicitly articulated the meaning they were making of some aspect of responsive instruction (evidence of meaning construction), considered responsiveness in relation to their own contexts (evidence of situated nature), negotiated something about responsiveness with real or imagined others (evidence of social nature), and/or displayed an affective or identity-laden response to responsive instruction (evidence of affect/identity). For instance, consider the following reading reflection on *Discovery Learning and Discovery Teaching* (Hammer, 1997):

Victoria: "This view requires that teachers are flexible, perceptive, and use their best judgment in discerning which paths to explore with students and how to move on from certain topics/discoveries... David states that this type of teaching is neither all inquiry based nor is it completely traditional based—it is a balance between the two with a greater focus on inquiry. In this sense, I think I tend to lean towards a traditional view of teaching and curriculum. This is not due to the fact that I despise inquiry, but rather that the majority of my learning has been in a traditional setting. Also, as an LA, I don't feel confident enough in the physics content where I would feel comfortable exploring students' inquiries in the way described by David." (Reading reflection, winter quarter, week 3)

Here, in reflecting on Hammer's article (which the first author selected as an example of responsive instruction), Victoria articulated her sense that this type of teaching requires teachers to be "flexible, perceptive," and "discerning" in which paths to follow (evidence of meaning construction). She distinguished this from her own more traditional learning experiences (evidence of situated nature) and identified a particular affective concern with respect to being responsive to students' ideas – a discomfort with exploring these ideas because of perceived limitations in her understanding of physics content (evidence of affect/identity). These kinds of evidentiary warrants mark this entry as an instance of sense-making about responsiveness. In identifying instances, we did not distinguish between instances when (1) LAs were asked to engage in sense-making versus when (2) they spontaneously engaged in sense-making about being responsive to student thinking; rather, our aim was to understand the *substance* of the sense-making they did in either case.

We then looked across entries of LAs' sense-making about responsiveness for recurrent themes in their content. We began by inductively analyzing moments from different sources of data separately – the first author took the first pass at synthesizing themes from the reading and discussion reflections, and the second author worked with the teaching journals. When we compared our analyses, we noticed several coherences in LAs' sense-making about responsive instruction across these data sources and across time. These coherences became our primary findings (documented in the following section) – points that were raised again and again by multiple LAs, and that evolved in substance over time. We then looked for additional evidence of these points of sense-making across the remainder of the data corpus and traced the story of each point across time. Our findings depict these intertwined stories of sense-making about responsive instruction.

## Sense-making about being responsive to students' thinking

In this section, we illustrate what it looked like for one cohort of LAs to sense-make about being responsive to the substance of students' thinking. To do so, we document four central points of sense-making that came up for the cohort of LAs as they considered responsive instruction. We frame these points in terms of the primary questions LAs were seeking to answer for themselves, and we present the questions in the order in which they emerged, though many of the questions coexisted and influenced each other. We show that the substance of each question evolved over time, as did the salience of particular questions.

*Is this okay?* One of the first questions that emerged for LAs as they considered responsive instruction, and which persisted over time in various iterations, was the question of whether this kind of teaching is "okay." In many cases, this question was associated with tensions LAs felt around a particular implication of being responsive to students' ideas—namely, the notion that pursuing students' ideas at times means pursuing ideas that are not canonically correct, or leaving students with the "wrong" answer at the end of a class session. This consideration represented a substantial source of uncertainty for LAs, and their comments were often affectively-charged as they tried to determine how they and their students would perceive the matter.

Emergence. In reading and discussing a paper about attending to mechanistic reasoning, over and above the correct answer (Russ et al., 2009), LAs questioned whether it was okay to leave students with the wrong answer. Several LAs directly discussed or raised questions about the importance of canonical correctness in their reading and teaching reflections. For example:

Charlie: "I make sure th[at] students g[e]t to the correct answer. This is still an important piece of it all for me, and I always do (and probably always will...) hold this in the highest regard, as I maintain that it is not fair for me to ignore that piece, focusing instead on understanding, and leaving them to fight for themselves on quizzes and exams." (Teaching reflection, winter quarter, week 2)

Katie: "The first and most noticeable thing is that this seems to mean leaving students with an incorrect answer at times. While I think that there are cases that this would be fine and the discrepancy would be resolved on its own, the students expect me to correct them when their answer is "wrong" and there would probably be a lot of backlash." (Reading reflection, winter quarter, week 2)

Lizzie: "How often is this okay to do? I feel like it could be unhealthy if students leave a classroom often not feeling satisfied with the work they just did and still don't understand." (Reading reflection, winter quarter, week 2)

Initially, for many (but not all) LAs, students knowing the right answer was a critical consideration, and they questioned whether responsive instruction would accomplish this goal. This consideration was deeply social for them, as they regularly considered students' perspectives on being left with the wrong answer.

Evolution. LAs continued to grapple with whether responsive instruction— and in particular, leaving students with "wrong" answers – was okay throughout the winter quarter. A related concern that arose midway through winter quarter was whether students would become attached to misconceptions if they were not addressed quickly. Some LAs eventually started wondering about a flip question – if and when direct instruction was okay. For instance, in a teaching reflection (winter quarter, week 7), Katie raised a question about the direct approach she took:

“I saw that one student was on this question and I kind of took charge and did the problem out loud with them rather than trying to get the students to work through it on their own. I questioned whether this was the appropriate move or whether I should have asked more inquiry-based questions, though.”

LAs’ ambiguity around direct instruction became more prevalent in the spring quarter. LAs raised questions about the utility of leading questions and explaining ideas to students. Additionally, beyond asking whether various instructional approaches are okay *writ large*, LAs started digging into whether particular aspects of responsive teaching are okay. For instance, they considered whether focusing on mechanistic reasoning is okay, asking if doing so devalues other cultural discourses.

By the end of spring quarter, LAs continued to report varied perspectives on whether responsiveness to student thinking is okay, considering the question from multiple angles. In week 8, the first author asked LAs to explicitly reflect on where they stand with respect to the question of leaving students with the wrong answer. Excerpts from several LAs’ responses (in reading reflections) are included below:

Ellie: “I am still on the never leave a student with the wrong answer on purpose... In the society we currently live in the right answer is important and I feel constrained by that. I also feel like you might lose the students trust if they find out that you let them leave with the wrong answer...”

Rose: “I think that it is beautiful to leave a student with a seed of an idea that they’ve had. And it’s good to cultivate the seed and help it to grow, but I think that sometimes that takes time.”

Victoria: “I think that leaving students with the wrong answer gives them the power to learn things themselves, which seems to be more important than just giving out answers.”

Katie: “I would not have said this at the beginning of the year, but I do think there are some particular instances where it is acceptable to leave students with the wrong answer. I’m still really interested in my students knowing the ‘right’ answer, so I think that I am only willing to leave students with the wrong answer if I am confident we will either revisit the idea in class or they will figure it out in some other way... My main purpose in doing so is to foster disciplinary affect and practice. I think that being left hanging, or with the wrong answer, can be a good way to encourage students to be passionate about answering questions and to be comfortable with not knowing the answer.”

These excerpts demonstrate that the right answer is still important to LAs, but balanced for some with other considerations – e.g., it takes time to process ideas, it is a powerful experience for students to see themselves as able to figure things out.

*Can I do this?* The question of whether or not LAs themselves *could* engage in responsive instruction also emerged early on. Instantiations of this question focused on LAs’ perceptions of whether they have the skills to notice and respond productively to students’ disciplinary ideas (uncertainty with respect to their capabilities), or whether it is possible for them to teach responsively given the constraints of their instructional context. Questions about what teachers need in order to be responsive to their students’ ideas – and conditions that afford or constrain doing so – are part of the national discourse on teacher noticing and responsiveness (e.g., Robertson, Scherr, and Hammer, 2016; Sherin et al., 2011), and as such represent an important point of sense-making about responsive instruction by LAs.

**Emergence.** Much of the early sense-making around the question “Can I do this?” was about whether or not LAs had the skills to engage productively with students’ ideas. They expressed different ideas about whether they had the knowledge to pursue unanticipated lines of inquiry, with most LAs indicating that they needed to know certain content to productively support students:

Victoria: “I don’t feel confident enough in the physics content where I would feel comfortable exploring students’ inquiries in the way described by David [in Discovery Learning and Discovery Teaching].” (Reading reflection, winter quarter, week 3)

Eddie: “Times of tension usually arise from me not having enough of an understanding on a topic. When I understand a topic, and am able to figure out where the student is at with their thinking, I am very excited and feel joy when I can either continue their thinking to wherever it may lead, or suggest approaching the idea from a different angle.” (Teaching reflection, winter quarter, week 5)

Ellie: “This was a hard day for me because I didn’t feel confident in my knowledge of what the step by step situation was supposed to be. I felt like it was hard for me to determine what was a seed because I didn’t really know the worksheet.” (Teaching reflection, winter quarter, week 8)

In these reflections, LAs reported both instances in which they felt content knowledge *supported* their identification of productive lines of inquiry (e.g., when Eddie understands a topic, he feels more able to build on student thinking in various ways) and in which they felt a lack of content knowledge *constrained* their interactions with students (e.g., when Ellie did not understand the worksheet, she feels she cannot identify productive beginnings in students’ ideas). These experiences were described in affect-laden terms, including excitement and “joy” as well as not “feel[ing] confident.” However, not all LAs felt constrained by a perceived lack of content knowledge:

Rusty: “So the first time I went through this the guy asked me why or what happens...and because I had no idea I said let’s try it out! We tested it (I was surprised) and then we both reasoned through the problem of explaining it. It was fun because I was discovering with the student! I wonder if I can do this with more subjects even though I may be re-discovering, again, and again!” (Teaching reflection, winter quarter, week 3)

**Evolution.** As winter quarter proceeded, the first author specifically asked LAs to reflect on what they perceived as constraints with respect to building on students’ ideas. LAs raised varied situated and social considerations about mandated curricula, time constraints, and students’ expectations:

Rusty: “We as LAs do not choose the material. It is chosen for us.” (Reading reflection, winter quarter, week 7)

Jane: “I am concerned that without ample time to explore everything and have a wrap up at the end of every class there will be confusion. I can easily imagine students from the Sean number video being confused about odd and even numbers if there was not a wrap-up. I can also imagine frustration on a physics idea if no one brings up the canonical idea and there is a rich discussion but at the end they do not have the right answer for the test.” (Reading reflection, winter quarter, week 7)

Ellie: “I think one thing that will constrain us is the student’s ideas of what we are there to do. Some of them think we are there to give answers so pursuing the seeds won’t be important to them.” (Reading reflection, winter quarter, week 7)

LAs also continued to discuss the skills needed to be responsive to students’ ideas, though the substance of LAs’ reflections became more about how to choose among productive “seeds” or ideas students raised and less about the content knowledge needed to follow up on emergent ideas. For example:

Katie: [Lingering concerns about building on “seeds of science”:] “Time to follow seeds, and when multiple seeds come up at once I can’t usually pursue both.” (Reading reflection, winter quarter, week 7)

Eventually, LAs began to foreground instances in which not knowing the answer had been *fun* for them, in that they were free to learn with students. This reflected a shift for some LAs, including Eddie who had initially framed not understanding as a tense experience:

Eddie: “One of the interesting [parts of our conversation about “problems of practice”] was the idea of not knowing an answer. I would like to emphasize how not knowing can be part of the fun of being a learning assistant. Some people are really upset if you aren’t able to quickly lead them to the correct answer, but I also know how much more myself and a student feel accomplished and happy with an answer when we both contribute towards finding the answer.” (Reading reflection, spring quarter, week 1)

Rose: “I never did the prop[a]gation of periodic waves tutorial when I was in physics... As a consequence, I never really acquired the model of deep vs shallow water for the prop[a]gation of waves. But, one of my students was doing the “Interpretation of Ray Diagrams” homework, and on it, I saw him apply the lines representing crests and troughs/wavelength from the prop[a]gation of periodic waves into different mediums. I really liked that it showed an understanding of connecting those two models for light – waves and rays– as it moves from a faster to a slower medium and vice versa... It was really awesome to see a student connecting concepts in a way that I never had. :) They teach me so much!” (Teaching reflection, spring quarter, week 5)

In sum, the question of whether or not LAs felt *they* could enact responsive teaching – with respect to their sense of the skills needed to do so and other situated/social factors – came up early and often in their engagement with this kind of instruction. Their specific considerations moved from concerns about whether this was something they felt they could do, to questions about specific parts of doing so (*e.g.*, choosing among multiple productive lines of inquiry from students), to celebrations of moments in which they discovered ideas alongside students.

*What is a “seed of science”?* Throughout both winter and spring quarters, LAs continuously grappled with a question central to the underpinnings of noticing and responding to students’ disciplinary thinking – what constitutes a “seed” of science in student thinking that could be taken up and refined instructionally? In class, the first author and the LAs co-constructed shared meanings of the *nature* of seeds and the *kinds* of seeds that represent scientific beginnings. As such, this area of sense-making brought LAs into close contact with their own (perhaps tacit) definitions of science, as they negotiated their senses of what “counts” as science.

Emergence. The idea of a beginning or “seed” of science first came up in a paper the class read in the third week of winter quarter (Hammer, 1997). In the paper, Hammer framed the student ideas he

elevated as “seeds” of physicists’ concepts or practices (p. 511), and the first author asked LAs to articulate for themselves what they saw as the seeds of disciplinary thinking/practices in one of the episodes in the paper. In doing so, LAs started to define for themselves what makes something a “seed”:

Charlie: “The students are discussing the [e]ffect a charged rod has on a hanging pith ball. They see the ball first attracted to the rod, and then repelled. They use an explanation that mimics magnetism, saying that the pith ball has fixed poles, and when the rod was brought closer, the pith ball rotated, and thus exposed the opposite ‘pole’ to the rod, which repelled it... this was the one that most seemed like a ‘seed’ of physicists’ concepts, as it showed a very basic understanding of another concept (magnetism), and applied it to another topic. That at least fulfills my understanding of a ‘seed,’ as they showed a basic beginning to a more complex idea.” (Reading reflection, winter quarter, week 3)

The ideas that seeds (a) have scientific potential but (b) are underdeveloped were common among LAs’ reflections, and these ideas helped LAs frame their instructional role, in part, as identifying and nourishing such seeds. Over the next few class sessions, they watched classroom video together and practiced noticing seeds of scientific ideas and practices, and in the fifth week of the quarter an LA (Rose) proposed that they focus their teaching reflections on seeds they notice in student thinking.

Evolution. Though LAs quickly oriented – early on – to what they considered to be productive student ideas, the first author noticed that they were not necessarily specifying *what* was productive about those ideas nor necessarily attending to ideas that could be considered “beginnings” (as compared to fully fleshed-out understandings). In the seventh week of winter quarter, she asked LAs to brainstorm different kinds of “seeds of science.” The two whiteboard photos below show the first iteration of a table co-constructed in class:

| Type of seed   | what we mean  | Example   | Type      |
|--|---|---|-----------|
| seed of sci practice   | echoes what scientists do, the way scientists do things   | scientific discussion: giving reasons, always hypothesize & test; making connections b/w diff. experiences; noticing anomalies, patterns; questioning others' ideas | seed      |
| seed of sci reasoning  | reasonable, mechanistic, causal, sensible   | taking into acct negligible grav. forces  | intuit    |
| seed of mechanism  |   | "where does this hit?"  |           |
| seed of canonical thinking/rightness/correctness/Kernal of truth | Something that is correct in certain contexts but not properly applied or not fully developed anything that's canon correct | "mass doesn't matter"   | Character |

Figure 2. First iteration of LAs’ definitions for “seeds” of science



| Type   | What we mean  | Example  |
|--|---|--|
| Seed of<br>- resource<br>- application<br>- reality<br>- life<br>(connection)<br>intuition | Drawing on everyday<br>experiences to make<br>sense of classroom/<br>sci-exper. | "Like when I slide<br>down the slide"<br>Canonical<br>thinkg |

Figure 3. First iteration of LAs' definitions for "seeds" of science (cont'd.)

As seen in the table, LAs initially named four kinds of seeds of science, though there was much negotiation around their meanings and boundaries: seeds of scientific practice, seeds of scientific reasoning/mechanism, seeds of canonical thinking/rightness/correctness/kernels of truth, and seeds of intuition. The ambiguity and multiplicity of terms for some categories illustrate that they were actively under construction, and LAs continued debating and refining the categories in class and in their individual reading and teaching reflections.

One point of ongoing sense-making was whether all four categories of seeds were necessary. Some LAs felt that the entire typology could be collapsed. This question was the subject of a series of affectively-charged conversations in class and was reflected in some LAs' written syntheses of the "seeds" discussion at the end of winter quarter. For example, Jane wrote:

"Some of us, myself included, believed that every seed could be absolved into the category 'seed of scientific practice,' but we wanted to separate them out because we agreed they were valuable enough to identify separately."

Other LAs felt that ideas and practices should remain separate in the typology (*i.e.*, that seeds of scientific practice and seeds of canonical thinking should be independent categories) but that seeds of scientific reasoning and intuition fell under scientific practice. Others felt strongly that all four categories of seeds were important and would contribute to their practice in distinct ways. Later, another kind of seed was also added, in interaction with an early draft of Jaber and Hammer's paper on disciplinary affect (Jaber & Hammer, 2016), and LAs continued to construct their senses of how the kinds of seeds fit together:

Rose: "I think that disciplinary affect is a seed that we can seek out and use as a starting point for a discussion with students. I think that it goes under 'seeds of scientific practice' because I think that disciplinary affect is 'an echo of what scientists do/the way that they do things.'  
\*\*\*Note, this has not been proposed in [our pedagogy] classroom and I sort of saw parallels last week in the discussion. I'm interested in hearing what the other [LAs] have to say about this idea.\*\*\*" (Reading reflection, spring quarter, week 7)

Note in both Jane's and Rose's reflections the clear sense that LAs were negotiating the meaning of seeds with each other—this was a highly social sense-making endeavor.

As part of LAs' sense-making around the question of what should be included in a list of "beginnings of science," they examined their own sense of *what science is*. In their reflections, we see increasing openness to science as being about more than the correct answer, as they began to connect science to certain forms of reasoning, activity, and affect:

Maya: “The biggest distinction I can make between the ‘seeds’ and the ‘kernels of truth,’ which [we discussed] last year [see Lovegren and Robertson (2013) for a description of the previous year’s course], is that the ‘seeds of science’ recognize a wider range of acts as worthy of affirming. The ‘kernels of truth’ affirmed reasoning and intuitive canonical correctness, but the seeds of science also affirm debate, experimenting and application to situation[s] outside of the curriculum.” (winter quarter synthesis assignment)

Katie: “I have realized that there is much more to learning science than just the facts. Science is fueled by people who are so passionate about answering questions that they cannot sit still or let a problem go until it has been solved... Science exists in a place that straddles the barrier between the known and unknown, and scientists find this exciting and intriguing rather than overwhelming.” (spring quarter theory of learning essay)

Victoria: “As our conversation about ‘seeds’ has developed and as I have practice identifying seeds in the classroom, I have realized that I do not recognize the seed of canonical thinking as a seed. Personally, I value scientific reasoning or mechanism over the right answer.” (spring quarter final project)

As illustrated above, LAs started describing science as encompassing “a wider range of acts” and orienting to seeds other than canonical thinking as central. This represents a substantial shift from their initial response to the idea of responsive teaching (see “Is this okay?”), in which many of the LAs framed the right answer as the most important aim.

The question of what counts as a seed of science is one that recurred and evolved for LAs – collectively as they negotiated their typology in class over time, and independently as they interacted with examples of their own and others’ teaching. In order to do so, LAs needed to negotiate their own senses of disciplinary productivity and how to recognize different variants thereof in their interactions with students.

*How can I respond to and build on the “seeds of science” within students’ ideas?* Finally, the question of how to respond to and build on students’ ideas was also central to LAs’ work. This question was less central in early conversations when LAs were grappling with the idea and possibilities of being responsive to students’ ideas more generally, but it became the explicit (and primary) focus in the spring quarter. Further, the question (and LAs’ responses to it) became increasingly specific over time – from how can we value students’ ideas; to how do we respond to specific “seeds of science” in what students are saying and doing; to how do we respond to *this* seed in *this* moment, as instantiated by *this* student? The question of how to respond in ways that build on or develop students’ ideas has been documented as particularly challenging (Harris et al., 2012).

**Emergence.** In the fall quarter, LAs read about and discussed theories of knowledge and/or learning. Though there was significant diversity among LAs’ understanding and take-up of these theories, as a group they highlighted how focusing on students’ ideas played a central role in student learning, engagement, and agency. Thus, one of their questions became how to value and build on students’ ideas in the classroom, launching the work of the winter and spring quarters.

**Evolution.** The question of how to build on students’ ideas quickly became “How can I respond to and build on the ‘seeds of science’ within students’ ideas?,” as the question “What is a ‘seed’ of science?” emerged and evolved. The question started to take this more specific form in week 3 of winter quarter, when LAs asked how they could apply ideas from Hammer (1997) in their teaching. They came up with a preliminary list in class:

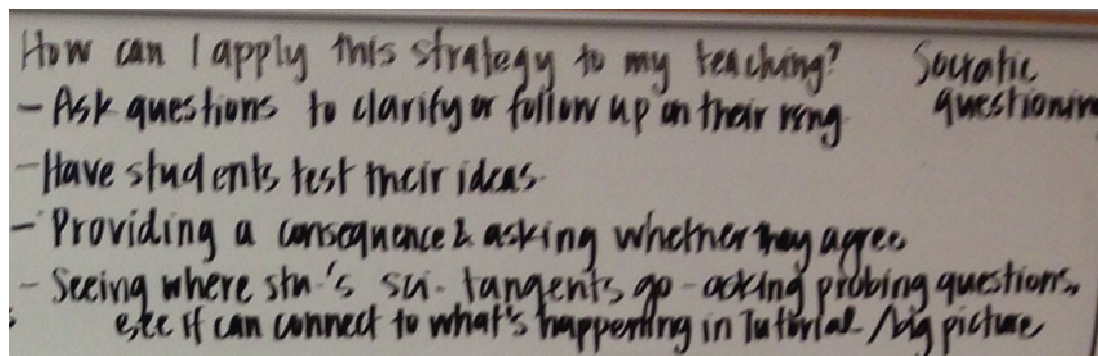


Figure 4. Preliminary list of applications from Hammer (1997)

LAs then tried to emulate this in their teaching the following week, and they practiced noticing and identifying seeds of scientific practice and seeds of scientific reasoning by watching videos in class.

As the “seeds” discussion evolved, so did LAs’ ideas about how to pursue and build on various seeds. Table 2 reflects a class brainstorm in weeks 7 and 9 of the winter quarter, where LAs initially described some general moves but then wondered if different kinds of seeds might require different kinds of responses. They articulated a number of separate responses for different kinds of seeds:

Table 2. LAs’ initial ideas about responses to “seeds”

| Type of seed                           | Brainstormed list of “how to pursue and build on seeds”   |
|--|---|
| Seed of scientific practice            | <ul style="list-style-type: none"> <li>• Facilitate group discussion.</li> <li>• Mimic practice back to them, and take [one] step further [sic].</li> <li>• Participate in [the practice] with them. [Say,] “I see what you’re thinking. Let’s test that.”</li> </ul>   |
| Seed of scientific reasoning/mechanism | <ul style="list-style-type: none"> <li>• Press: Ask them questions and try to fill in more and more with them. Ask them to explain why another answer is wrong.</li> <li>• [Ask them,] “What if it didn’t mean that?”</li> <li>• Invite other students to comment on one another’s perspectives.</li> <li>• Com[e] up with different situations to apply mechanism to.</li> </ul>   |
| Seed of canonical thinking             | <ul style="list-style-type: none"> <li>• Go backward and figure out why they just said that.</li> <li>• Ask, “What makes you say that?”</li> <li>• Reverse-engineer: Take what they have and figure out when it applies.</li> <li>• Use as building-blocks – transfer [and] extend [their thinking].</li> <li>• Validate [their ideas, saying,] “That makes sense to me because...” Give them a sense of how I see it as a seed of ____.</li> </ul> |

Although LAs brainstormed responses that drew on the substance of particular seeds, the first author noticed that when it came to bringing this lens to the videos they watched in class, LAs’ sense of how the teachers in these episodes were responding to student ideas was still fairly general. They focused on moves like “asking a clarifying question,” “asking [other students] what they think,” “letting the other students ask questions,” etc. While these moves may have been motivated by attention to specific aspects of student ideas, the moves did not highlight nor capitalize on the disciplinary potential of particular student ideas. In response to this, the first author began to press LAs to

articulate or identify *specific* responses to *specific* seeds. LAs in turn began to negotiate what particular responses looked like in more situated ways, both in classroom videos and their own teaching:

Eddie: “The third seed... in this brief interaction is seen when Ofala, a third student, brings up another point, that we can also view odd numbers as groups of 2 plus one. With this thought, Ball provides the class with a working definition that is directly related to the idea Ofala presented... I thought this is a great way to affirm student thought, by relating it to, and showing how it is symbiotic with canonical concepts or definitions.” (Reading reflection, spring quarter, week 3)

Katie: “The students report that charge will transfer from one thing that is aluminum to another thing that is aluminum (a seed of canonical thinking), to which [the teacher] responds by asking what they think would happen if the plate and ball were plastic instead. This both clarifies the students thinking (both for teacher and students) and leads them to an important canonical distinction between conductors and nonconductors.” (Reading reflection, spring quarter, week 3)

Victoria: “I was working with a table group on Friday that was working on the Circuits 1 homework. I remembered doing this homework somewhat as a student last year but I wasn't quite sure about the correct answers. There was a question that asked about a specific circuit and what would happen to the bulbs in the brightness when a wire was added... In the moment I was really excited about the students' discussion about the topic. Two students had differing ideas about what would happen, while I suggested another idea. I made sure to point out that each idea made sense and that it was cool that we were all looking at the circuit from a different perspective.” (Teaching reflection, spring quarter, week 7)

In these and other reflections, LAs demonstrated that they were noticing particular productive seeds in situated examples of student thinking and were identifying (or seeking to identify) productive responses.

*Summary.* In sum, as LAs considered attending and responding to students' disciplinary thinking through examples and their own situated attempts, they engaged in several points of sense-making central to doing so—determining how it fit with their own commitments, whether they felt able to engage in it, and further constructing what responsive teaching really looks like in terms of specifying disciplinary beginnings in student thinking and responses that build on those beginnings. In the next section, we highlight how this extensive sense-making about responsiveness supported LAs in (1) noticing and responding to disciplinary connections within students' ideas in practice and (2) developing personal relationships with responsiveness to student thinking as a central facet of instruction.

### **Sense-making as generative for LAs' development as responsive practitioners**

Throughout this paper, we repeatedly reference Spillane et al.'s (2002) suggestion that to successfully enact instructional reforms, teachers need opportunities to sense-make both about (a) the reform itself and (b) their relationship to it. The previous section showed that LAs engaged in sense-making of both types, centered on four questions. In this section, we show that this sense-making was entangled with LAs' practical and personal development as responsive practitioners in two evident ways. First, we saw that LAs' noticing of and responsiveness to specific disciplinary connections within their students' ideas drew on the language of their “seed” typology, suggesting that this particular aspect of sense-making was productive for their own instructional and reflective practice. Second, some LAs came to identify with responsiveness to students' ideas as a central tenet of teaching, as evidenced in

the identity-laden language they used to discuss their engagement in and valuing of responsiveness. We frame such identification as a potentially unique affordance of participating in sustained sense-making, supported by the responsive approach to the pedagogy course.

*LAs' sense-making about "seeds" of science shaped their noticing and responsiveness in practice.* As LAs sense made about ways in which students' ideas could be "seeds" to build on, their teaching reflections (and thus what they noticed while teaching) took up the ideas and language from their discussions with one another. In fact, mid-Winter-quarter, an LA, Rose, *asked* to focus their teaching reflections on the seeds they noticed; all LAs agreed, and their ensuing reflections demonstrated a range of noticings and responses to specific seeds in student thinking.

In one example, Victoria framed her students' efforts to reconcile two equations – (1) the equation for the gravitational energy of an object at a height  $h$  above the Earth ( $mgh$ ) and (2) the equation for the gravitational force between two masses ( $m$  and  $M$ ) separated by a distance  $r$  – in terms of "seeds":

Victoria: "Yesterday, we were discussing when and how to use the  $mgh$  equation and the  $(GMm)/r^2$  equation. I honestly didn't know exactly how the two equations would relate. I decided to just check in on some tables to gauge their thinking on the problem. I stopped at one table and asked them to tell me what they were thinking. They were trying to plug [and] chug but each equation was yielding a different answer. Then, one student suggested that we should explore the energy story in both situations (seed)! I think this was a seed because they used skills they already knew to help figure out a new physics problem. On their own they started assigning the initial and final kinetic energies and potential energies. I just thought it was cool that they were working towards the answer on their own and with what they had been learning about the different stories (energy, velocity, acceleration, momentum, etc.). Go physics students!" (teaching reflection, winter quarter, week 8)

Here, Victoria highlighted a "seed" in her students' thinking: when trying to reconcile these two mathematical descriptions involving gravity, students drew on their existing understandings of energy. Victoria not only attended to her students' thinking in detail, she oriented toward it as productive (and not only in terms of its correctness), and with enthusiasm. Though she doesn't explicitly identify the seed as one within LAs' evolving typology, we see the substance of her noticing as tied to LAs' discussion of "seeds of connection" (or "intuition"), which LAs identified as instances when students make connections across concepts, or between what they are learning in class and their everyday lives.

In another example, Ellie described a specific "seed of reasoning" she noticed in her students' conversation about sinking and floating:

Ellie: "Today I heard a seed of reasoning. [The course instructor] had asked the group a question about a boat with a rock in it. The boat had displaced a certain amount of water. If you took the rock out and let it sink to the bottom of the pool would the water level increase, decrease, or remain the same? This group is more math minded so they took the problem to the extreme. They asked what if the rock weighed 1000N and the boat 15N[;] if you were to take the rock out it is now only going to displace a little water compared to when the rock was in the boat.

I think they saw a question and found that there might be a proportionality issue and were trying to find a way to try and think about it. They did this by going to the extreme to see what would happen and that helped them figure out the right answer. ... I asked a few

clarifying questions ... and I nodded my head a lot, but they were the ones coming up with the awesome idea." (Teaching reflection, winter quarter, week 10)

Like Victoria, Ellie described her students' ideas in detail. What stuck out to her about this interaction was the reasoning strategy the students used to answer a question posed by their instructor: they invented a similar scenario that "took the problem to the extreme." She called this an "awesome idea," and described her role as primarily asking clarifying questions during the course of their reasoning.

In a third example, Rose described participating in an emergent set of experiments with a group of students:

Rose: "I had a really cool experience with a table while working on the 'Magnetic Interactions' tutorial. The students were given a set of random objects and were supposed to come up with three classes of magnets. But the students realized that they weren't given anything non-metallic like wood or rubber. So, I handed them some random objects that were around their table (a hot wheels track and a gray colored pencil). I figured neither of them would respond to a magnet... However, one [student] realized that the gray colored pencil was attracted to the strongest magnet at their table... So, we talked about why the pencil did this. One student suggested we get another colored pencil from the same brand and another from a different brand. It turned out that the pencils from that one brand stuck to the magnet, and the others were indifferent to it... The table then tested to see if it was attracted to the tip/colored bit of the pencils and it wasn't. One student suggested that there must have been something metallic in the paints used to coat the pencils of that one brand... That seemed like the best hypothesis of the situation to me, so that remains my current theory." (Teaching reflection, spring quarter, week 10)

Here, Rose adapted the instructional set-up in response to students' observations that they did not have anything "non-metallic," and she pursued the surprising result that the colored pencil was attracted to the magnet with the table of students. She described the factors that students considered for why this happened. While Rose's reflection does not draw on the language of seeds, her response aligns with one of the ways that LAs discussed building on "seeds of scientific practice" [*i.e.*, participating in emergent inquiry with students and test their ideas (see second row of Table 2)].

Throughout these examples, LAs noticed and documented the seeds within students' ideas, articulated their productivity from a disciplinary standpoint, and described how they responded – all in ways that connected to their sense-making conversations in the pedagogy course. As seen throughout this paper, many examples of LAs attending and responding to the substance of students' ideas took up the language, insights, or questions that LAs were negotiating in their sense-making together. For instance, LAs regularly identified students' ideas as "seeds of reasoning," "seeds of scientific practices," "seeds of canonical thinking," or "seeds of affect." At times, LAs included questions about how to respond to specific ideas in their reflections on their practice (*e.g.*, "Any thoughts on what would be a good course of action or what I can do with these in the future?"). We take these linguistic and conceptual connections as evidence that LAs' sense-making about noticing and building on seeds was productively entangled with their practice.

*Some LAs came to see responsiveness as part of their instructional identity.* At the end of the course sequence, LAs were asked to articulate their theory of learning, philosophy of teaching, and "how the two are connected." In some ways, these essays represent where LAs "landed" with respect to their notions of good teaching, and they illustrate coherent, grounded visions tied to the sense-making we have described in this paper. For example, Rose reflects on her role as an LA, writing:

Rose: "As an LA, I take on a role. What that role looks like to me is listening to [students'] ideas and responding to them. I want to help the student make their own sense of a concept. Sometimes, what makes sense to them is not something that I had thought about before. As a teacher, I need to be ready to understand and respond to what they're saying. What I'm trying to say is that my experiences with my students shape my interpretation of the world. As an LA/teacher, I am not immune to constructivism. I am a part of it. And so are my students. In that sense, we are equals who share in the learning process."

Here we see Rose treating learning as sense-making, with fruitful but unanticipated lines of inquiry emerging from this process. Her sense that she "can do this" is tied to her reframing of her role as a co-learner (rather than as a guide) and of teaching as a constructive process; as her students share their understandings of the world with her, she reconstructs her own understandings.

Like Rose, Katie frames teaching as a process of discovery:

Katie: "When I teach physics as a Learning Assistant, I hope to help students develop consistent reasoning behind the concepts of physics by refining and building upon their own experiences and intuitions. It is my goal to be faithful to the discipline of physics while at the same time being responsive to individual students and the ideas they have. I find that teaching is just as much a process of discovery and sense-making as learning is. In teaching, I discover what ideas students have that might be productive for learning or what ideas they have that are keeping them from fully understanding a concept. Teaching requires creativity, because one must find a way to weave students' ideas into a canonically accepted and coherent idea. This process was exemplified for me in "With an Eye on the Mathematical Horizon" and in the video we watched of Deborah Ball and the Sean Numbers episode. The integration of student ideas and canonical thinking is the most exciting part of teaching in my mind, but also the most challenging."

In this snippet (which is excerpted in the Introduction to this paper), we see that Katie is framing students' ideas as continuous with the discipline, and her role as refining and weaving their ideas together to reflect the concepts and reasoning of physics. She frames her role as a discoverer as both challenging and exciting, and central to her conceptualization of teaching.

A third LA, Victoria, reflects on how her thinking about teaching has changed, toward recognizing that students are "capable of figuring things out for themselves":

Victoria: "Throughout the year, my philosophy of teaching has changed dramatically. In the beginning, I was very concerned with directing students to the canonical answer. I held on tightly to the tutorial, and was afraid of deviating from it. I listened for specific buzzwords from students, and when I heard those words, I pursued them to the canonical answer. Personally, I think that this stemmed from my lack of confidence in my ability to answer students' specific questions. As we wrestled through the question, 'Is it okay to leave students with the wrong answer?' in pedagogy, I wrestled with my philosophy of teaching. I began to realize that students are capable of figuring things out for themselves and that I wasn't required to know everything or leave them with the right answer. When I started to realize this, it felt like a huge weight was lifted off of my shoulders. I felt freer in my teaching, and I began to take on the role as 'expert learner' instead of 'expert answer giver.' Instead of guiding students to a certain answer, I began to value their ideas and really care about what those ideas were. It made me excited to see all that students could do and it reinforced my teaching as 'expert learner.'"

Here, Victoria depicts a liberating shift in her orientation toward students' ideas as she grew in her capacity to sit with and value students' own ideas, over and above their correctness or incorrectness. Like Rose and Katie, she reframes her role as a learner alongside students.

In these essays – and in similar essays written by their peers – LAs articulate orientations toward teaching and learning that are deeply consistent with foundational orientations of responsive teaching (Ball, 1993; Hammer, 1997; Hammer et al., 2012; Robertson, Scherr, and Hammer, 2016). Importantly, Rose, Katie, and Victoria (and others) claim these for themselves. We notice their engagement in identity work (Carlone, Webb, Archer, & Taylor, 2015) through language like “what this looks like to me,” “I want,” “I am,” “I hope,” “it is my goal,” etc. Their senses of self and stances with respect to responsiveness contrast with their early questions and, we suggest, reflect their engagement in extended, authentic sense-making – they have tried on being responsive to student thinking *for themselves*, and taken the time to reach a sense of resolution and knowing.

## Discussion

In this paper, we have illustrated what sense-making about responsiveness looked like for one cohort of university physics LAs, and we suggested that this sustained, deep sense-making was productive for LAs' practice of and identification with responsive teaching. In particular, we have shown that in the first author's responsive university pedagogy course, LAs grappled with questions about whether or not being responsive to students' ideas was okay (and/or fit with their existing ideas about good teaching), whether or not they had the skills or flexibility to engage in this kind of instruction, what counts as a “seed” of science, and how they might respond to or build on the “seeds” of science in students' ideas.

Our work has a number of implications for teacher education and research. First, our documentation of teachers' questions about being responsive to student thinking may support other teacher educators in providing opportunities for their teacher participants to sense-make about responsiveness, offering teacher educators a kind of PCK (Ball, Thames, & Phelps, 2008; Shulman, 1987) and/or adding to their professional vision (Goodwin, 1994). Certainly we do not anticipate that all teachers who are considering what it means to attend to and build on students' disciplinary thinking would have the same questions as did our LAs. In fact, we anticipate that teachers embedded in a K-12 setting – or, more broadly, teachers with different institutional constraints or lived experiences – will sense-make differently, since their thinking about responsiveness may be in relation to very different existing ideas or considerations. However, we hope that our work can point teacher educators toward the *kinds* of questions that teachers may have, and more generally broaden their awareness of – and thus attentiveness to (Wehlage, 1981) – opportunities for sense-making about this instructional approach that emerge within teacher preparation and professional development contexts.

Second, the connections we highlight between (1) LAs' sense-making about responsiveness and (2) their enactments of and identification with responsiveness illustrate what a *responsive approach* to teacher education can afford. In particular, we suggest that the first author's responsive approach afforded rich LA sense-making, both about responsive instruction and LAs' own relationship to it; in turn, this sense-making afforded LAs' development as responsive practitioners in ways described in the previous section. We suggest that the first affordance we name – noticing of and responsiveness to specific disciplinary connections within their students' ideas – is not unique to teacher engagement in extended sense-making; many other responsiveness-oriented teacher education efforts have documented success along this dimension (Dorph & Chi, 2013; Fennema et al., 1996; Fennema, Franke, et al., 1993; Philipp et al., 2002; Sherin & van Es, 2009; van Es, 2011). However, the second – teacher *identification with* responsiveness – may be unique to approaches that invite sense-making about responsive instruction, since such identification requires deep consideration of one's



relationship with an instructional approach. Through assignments, class discussions, and course projects that regularly asked LAs to articulate their own position with respect to responsiveness, and through framing claims from articles or class discussions as ideas to try on in their teaching (rather than as voices of authority about teaching and learning), LAs had ongoing opportunities to develop their own senses of self in relation to responsiveness.

Third, LAs' sense-making processes show that one form of resolving ambiguity – a central aim of sense-making as depicted in the literature (e.g., Allen & Penuel, 2015; Coburn, 2001; Ketelaar et al., 2012; März & Kelchtermans, 2013; Spillane et al., 2002; Weick et al., 2005) – can be learning to *sit with* tensions and questions. Many LAs felt they had not “answered” the question of whether or not responsiveness to students' own ideas was “okay,” *writ large*, even as they regularly engaged in and identified with responsive forms of instruction. They spoke of their shift toward responsiveness as a relinquishing of the need to always have the right answer. The excerpt from Katie's philosophy of teaching, featured in the previous section and in the Introduction, highlights an ongoing question of how to teach in ways that are *both* responsive to students *and* responsible to the discipline. Here and in her teaching reflections, we get the sense that she is still grappling with questions about the extent to which these may be in tension with one another in any given moment. Thus, the product of extended, deep sense-making may not be an enhanced sense of certainty about a given approach or teaching interaction, but instead a deepened capacity for uncertainty and *holding* the tensions that are inherent to the complex act of teaching (e.g., Ball, 1993; Hammer, 1997; Lampert, 1990).

Finally, our work highlights and illustrates how sense-making about instructional reform can be entangled with epistemology and identity (Luehmann, 2007; März & Kelchtermans, 2013; Spillane et al., 2002; Weick et al., 2005). For example, in sense-making about what counts as a seed of science, LAs needed to consider *what science is* and what it means to *know* in science. And deeply considering whether or not one *can* or *should* enact a particular instructional approach – and then how to do it in ways that are faithful to the discipline and to students' ideas (Ball, 1993) – necessarily involves questions about one's values, integrity, and identity. If this is true, taking teachers' own questions seriously – and providing opportunities for them to sense-make – means that we as teacher educators must make room for the doubt and uncertainty that accompanies this kind of work. Being present to this doubt and uncertainty can be difficult; being responsive to it involves intellectually (and in some cases emotionally) empathizing with teachers who are deeply questioning the legitimacy of responsive teaching or their capacity to participate. Just as we ask our teachers to sit with the “instructional tension” (Chazan & Schnepf, 2002; Levin, 2008; Levin et al., 2009; Maskiewicz, 2016) at the heart of teaching *science* responsively, we suggest that we should be asking ourselves how we (teacher educators) can sit with the tensions at the heart of inviting others into this endeavor.

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