Rigor and Responsiveness in Classroom Activity

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Background/Context: *There are few examples from classrooms or the literature that provide a clear vision of teaching that simultaneously promotes rigorous disciplinary activity and is responsive to all students. Maintaining rigorous and equitable classroom discourse is a worthy goal, yet there is no clear consensus of how this actually works in a classroom.*

Focus of Study: *What does highly rigorous and responsive talk sound like and how is this dialogue embedded in the social practices and activities of classrooms? Our aim was to examine student and teacher interactions in classroom episodes (warm-ups, small-group*

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conversations, whole-group conversation, etc.) and contribute to a growing body of research that specifies equity in classroom practice.

Research Design: *This mixed-method study examines differences in discourse within and across classroom episodes (warm-ups, small-group conversations, whole-group conversation, etc.) that elevated, or failed to elevate, students' explanatory rigor in equitable ways. Data include 222 secondary science lessons (1,174 episodes) from 37 novice teachers. Lessons were videotaped and analyzed for the depth of students' explanatory talk and the quality of responsive dialogue.*

Findings: *The findings support three statistical claims. First, high levels of rigor cannot be attained in classrooms where teachers are unresponsive to students' ideas or puzzlements. Second, the architecture of a lesson matters. Teachers and students engaging in highly rigorous and responsive lessons turned potentially trivial episodes (such as warm-ups) of science activity into robust learning experiences, connected to other episodes in the same lesson. Third, episodes featuring one or more forms of responsive talk elevated rigor. There were three forms of responsive talk observed in classrooms: building on students' science ideas, attending to students' participation in the learning community, and folding in students' lived experiences. Small but strategic moves within these forms were consequential for supporting rigor.*

Conclusions/Recommendations: *This paper challenges the notion that rigor and responsiveness are attributes of curricula or individual teachers. Rigorous curriculum is necessary but not sufficient for ambitious and equitable science learning experiences; the interactions within the classroom are essential for sustaining the highest quality of scientific practice and sense-making. The data supported the development of a framework that articulates incremental differences in supporting students' explanatory rigor and three dimensions of responsiveness. We describe implications for using this framework in the design of teacher programs and professional development models.*

INTRODUCTION

There are few examples from classrooms or the literature that provide a clear vision of teaching that simultaneously promotes rigorous disciplinary activity and is responsive to all students. In one of the few large-scale studies that examined similar constructs, researchers found only 13% of the K–12 math and science lessons observed were highly respectful of students' ideas while also encouraging serious learning (Horizon Research International, 2003). Examples from the literature suggest that classrooms can be responsive, yet lack rigor; students can have meaningful conversations but not build substantive scientific understandings. Alternatively, classrooms can aim solely for scientifically rigorous standards, ostensibly holding students accountable for canonical vocabulary and knowledge, yet be insensitive to students' ideas. Students might sound like scientists, but there is little room for them to fit these understandings into the contexts of their own lives.

This paper addresses the conceptual and practical challenges of merging ideas about rigorous and responsive instruction. One of the first challenges is developing integrated definitions of rigorous and responsive instruction. Bodies of research on the development of scientific ideas often do not include responsive teaching with rigorous teaching, offering few examples of how students productively make sense of ideas tailored to their local learning environments (see Rosebery & Warren, 2008, for exceptions). This is particularly true for secondary classrooms. Likewise, research focusing on responsive instruction often lacks attention to the development of substantive disciplinary ideas (Coffey, Hammer, Levin, & Grant, 2011). Yet understanding the interaction between student experiences and disciplinary ideas is particularly relevant in recent research that points to the importance of teachers learning to notice, assess, and respond to students' ideas (Levin, Hammer, & Coffey, 2009; Michaels, O'Connor, & Resnick, 2008; Rosebery & Warren, 2008; Sherin & van Es, 2009).

The second challenge of merging rigorous and responsive instruction can be framed in terms of practice; teachers must decide when to work with and on students' ideas and when to focus on canonical science ideas. In daily moment-to-moment interactions, teachers feel tension between helping students arrive at right answers and construct understandings. While these foci may appear diametrically opposed, we agree with Coffey, Hammer, Levin, & Grant (2011) that such a framing is a false dichotomy because learning the content and practices of science requires that students make progress on their ideas as they develop canonical understandings. While naming the tension is helpful, there is a clear need to provide frameworks to help teachers navigate these in-the-moment decisions in order to support the integration of students' ideas and science ideas in equitable ways.

We address the intertwined nature of these conceptual and practical challenges by examining how teachers and students advance both rigorous and responsive classroom instruction. Our research questions are:

1. What do instructionally rigorous and responsive discourses sound like in practice? How frequently do they occur in classrooms?
2. How are teachers using episodes within lessons to press for highly rigorous and responsive talk?
3. What forms of responsive talk occur? And how do they each support students' explanatory rigor?

THEORETICAL FRAMEWORK

CONCEPTUALIZING RIGOR AND RESPONSIVENESS AS MAKING PROGRESS ON IDEAS

Our theory of action for rigorous and responsive teaching in classrooms rests on the assumption that teaching is fundamentally about setting intellectually meaningful learning goals and then creating opportunities for students to learn through mediated action (Cohen, 2011; Lampert, 2010). In this paper we focus on scaffolded, sense-making discussions because they are prime opportunities (or missed opportunities) to deepen understanding of complex concepts over time (Cobb, Gravemeijer, Yackel, McClain, & Whitenack, 1997; Herrenkohl & Guerra, 1998; M. O'Connor & Garnier, 1996). The pedagogical task for teachers, then, is not to have students memorize information, follow procedures, or reproduce textbook explanations, but to build upon students' initial ideas, partial understandings, and everyday experiences to support construction of ongoing, evidence-based, and generalizable explanatory accounts of natural phenomena (Lehrer, Schauble, & Lucas, 2008; Thompson, Windschitl, & Braaten, 2013; Windschitl, Thompson, Braaten, & Stroupe, 2012). These instructional explanations (Leinhardt & Steele, 2005) balance various accountability goals to students' lived experiences, the classroom community, and expectations for legitimate participation in disciplinary work (Michaels et al., 2008).

Inherent in this vision of teaching is a commitment to merging ideas about rigor and responsiveness under the general umbrella of reasoning with phenomena and constructing explanations in a way that values the *progress of students' ideas* as a disciplinary norm (Bereiter, 1994). Bereiter (1994) challenged the notion that classroom discourse should be static and objective; he argued that classroom talk needs to better reflect the process of constructing knowledge in science, not reproduce final-form products from the discipline (such as the scientific method):

> Classroom discourse can be progressive in the same sense that science as a whole is progressive. Scientific progress is not one homogeneous flow; it contains innumerable local discourses that are progressive by the standard of the people participating. (p. 9)

Our view of rigorous and responsive teaching focuses on planning, enacting, and reflecting on the varied paths students take to make progress on substantive science ideas, rather than an emphasis on arriving at a right answer or finished knowledge (Cohen, 2011).

CONCEPTUALIZING RIGOR AND RESPONSIVENESS AS EQUITY-IN-PRACTICE

Engaging in these forms of discourse requires teaching that is uncompromisingly responsive to the development of students' ideas. In this sense we draw on the term *responsiveness* from multicultural education in general and *culturally responsive teaching* (Gay, 2000) specifically. Our intention in using the term is not merely to suggest that teaching is relational and that classrooms are spaces where teachers and students purposefully react to one another's utterances. Rather, we draw on two core principles of culturally responsive teaching: (1) it assumes a non-deficit perspective on students' capabilities and their lived experiences, and (2) it takes a critical perspective on the structural ways knowledge is reproduced in and through classroom interactions.

In doing so we contribute to a growing body of research focused on *specifying equity-in-practice* (Boaler & Staples, 2008; Esmonde, 2009; Horn & Kane, 2012; Jackson, Garrison, Wilson, Gibbons, & Shahan, 2013; Rosebery & Warren, 1995). These lines of research make visible the ways in which learning communities (with teachers *and* students) support equitable participation in rigorous disciplinary activity. More than just describing teaching moves that provide equal opportunities for students to gain access to knowledge, these lines of research focus on how: (1) students are positioned and scaffolded competently to learn from one another as they engage in disciplinary talk and tool use, and (2) classroom exchanges are part of larger sets of social and institutional discourses (Gee, 2001; Gutiérrez, Rymes, & Larson, 1995). This second point is methodologically challenging. Students and teachers often use multiple linguistic registers when participating in science classrooms. For example, a student may rely more on everyday language associated with cooking rather than isolated molecules to describe chemical and physical changes in a chemistry course. Incorporating students' language into classroom discourse pulls more students from more backgrounds into the conversation, calling on their experiences inside and outside school walls. Our aim is to advance the ways teachers use resources from students' multiple discourse communities (Gee, 2001; Moje, Collazo, Carrillo, & Marx, 2001) to make progress on student ideas at the level of turns-of-talk in classroom activity.

RIGOR AND RESPONSIVENESS FRAMEWORK

We used the constructs of *equity-in-practice* and *making progress on ideas* as conceptual anchors to build out a framework for describing interactions in classrooms. The framework represents our working model for attending to rigor and to three forms of responsiveness from a socially situated discourse perspective.

DEFINING RIGOR AS SENSE-MAKING WITH SCIENTIFIC PHENOMENA

We view rigor as an emergent property of discursive classroom interactions, rather than a predetermined quality of instructional activities. Scholars examining classroom interactions have characterized similar emergent qualities of discourse as accountable talk (e.g., Michaels et al., 2008; C. O'Connor & Michaels, 2007), productive talk (e.g., Engle & Conant, 2002; Herrenkohl, Palincsar, DeWater, & Kawasaki, 1999), responsive talk (e.g., Harris, Phillips, & Penuel, 2012; Levin et al., 2009), or dialogic talk (e.g., Alozie, Moje, & Krajcik, 2010; Mortimer & Scott, 2003; C. O'Connor & Michaels, 2007). As shown through these projects, when classroom discourse publicizes students' ideas, questions, and reasoning while staying grounded in central disciplinary practices and concepts, it elevates the rigor of the learning experience.

In these classroom practices rigorous talk can take many forms; in our work we focus on the substantive ways students collaboratively construct scientific explanations, or *explanatory rigor*. We selected explanatory rigor as an object of study because constructing and modifying evidence-based explanations is a central practice in scientific fields. In science disciplines, engaging in complex/rigorous reasoning about scientific phenomena means not just describing observable patterns, but also positing hypotheses using existing theories, marshaling and weighing evidence, and ultimately holding one another accountable to standards for making knowledge claims (Duschl, 2008; Kelly & Brazerman, 2003). For example, when investigating why two earthquakes of the same magnitude have different levels of destruction, scientists (and students engaging in similar forms of explanatory discourse) break down features of scientific phenomena (such as the movement of the boundary plates, the type of soil, the amount of friction, the distance from the epicenter, etc.) and examine why a phenomenon happens using scientific theories, models, and laws that go beyond simple cause-and-effect relationships.

The tricky part in classroom dialogue is differentiating pseudo-rigorous conversations—in which students and teachers use short responses and heavily lean on facts and vocabulary terms—from rigorous conversations that might not yet have the accuracy of commonly accepted scientific terminology (Lemke, 1990). Rigorous sense-making discourse, then, is more about helping students make progress on ideas by juxtaposing first-hand experiences with known scientific ideas and concepts (Palincsar & Magnusson, 2001). In this interplay students develop language that not only helps students take ownership of ideas, but also helps them see science as a social, humanized activity that they can better relate to (Lemke, 1990; Newmann, Wehlage, & Lamborn, 1992).

Classrooms can provide strategic opportunities for students to reason with puzzling scientific phenomena relevant to students' lives and develop explanatory models and arguments that extend prior knowledge and experiences (Palincsar & Magnusson, 2001). In preparing the novice teachers we focus on three pedagogical practices: (1) selecting scientifically important "big ideas" and models to teach that are also important to the lives of young learners (Windschitl & Thompson, 2006); (2) pressing students to develop evidence-based scientific explanations and arguments (Duschl, 2008; Sandoval, 2009; Windschitl et al., 2012); and (3) explicitly teaching the epistemic features of models, explanations, and arguments (Kuhn, 2010; Lehrer et al., 2008; McNeill, Lizotte, Krajcik, & Marx, 2006; Osborne, Erduran, & Simon, 2004). These practices provide powerful sense-making opportunities because they support students in generalizing across multiple phenomena, and they appear to support forms of reasoning central to other subject matter domains (as indicated by the emphasis on developing explanations in math, literacy, and social studies described in Common Core standards).

Such learning opportunities are associated with more coherent understanding of ideas (Smith, Maclin, Houghton, & Hennessey, 2000), the spontaneous use of explanatory models in related contexts (Brown & Kane, 1988), and, over time, students becoming more adept at referencing evidence and using it to support explanatory claims (Lehrer et al., 2008). We propose that, unlike typical American science classrooms (Banilower, Smith, Weiss, & Pasley, 2006; Horizon Research International, 2003; Roth & Garnier, 2007; Sykes, Bird, & Kennedy, 2010), teachers enacting rigorous practices make intentional, specific, and responsive discursive moves that allow students to engage in complex reasoning about puzzling and relevant scientific phenomena.

RESPONSIVENESS TO STUDENTS' INDIVIDUAL AND COLLECTIVE KNOWLEDGE CONSTRUCTION

Like *rigor*, defining and understanding *responsiveness* in teaching is difficult. We attend to three dimensions of responsiveness that appear in the literature and also emerged from our analysis of responsiveness in classrooms. These dimensions are: (1) building on students' scientific ideas, (2) encouraging participation and building classroom community, and (3) leveraging students' lived experiences and building scientific stories. Although these dimensions of responsiveness have roots in the literature on teaching and learning, they are not typically considered or analyzed together as features of classroom discourse. Following is a brief review of the literature about each of the three dimensions.

Responsiveness to Building on Students' Scientific Ideas

In classroom research on disciplinary teaching and learning, responsive teaching is often conceptualized as evaluating students' ideas (Cohen, 2011). Research has focused on sets of pedagogical moves that teachers use in the moments of teaching to work on the disciplinary ideas students publically share (Leinhardt & Steele, 2005; Mercer, 2008; Michaels & O'Connor, 2012). Many types of teacher talk moves acknowledge students' contributions, including *revoicing*, *recapping*, and *invitations to say more*, *add on*, or *agree/disagree*. These moves provide students with opportunities to express and clarify their ideas, and teachers with opportunities to support students in elaborating ideas, deepening their reasoning, and building norms for classroom talk so that students can routinely engage in these complex forms of social reasoning. Looking beyond a teacher's talk moves, Michaels et al. (2008) argue for three forms of accountability in constructing ideas in classrooms: (1) accountability to the learning community in which students build ideas together; (2) accountability to accepted standards of reasoning in which local and logical connections among ideas are made; and (3) accountability to knowledge, or the texts and ideas housed in a local context such as a classroom. Thus, as teachers and students hold each other accountable to shared forms of knowledge production, they develop a discursive culture in which each person "take[s] one another seriously, take[s] risks and build[s] complex arguments together" (Michaels & O'Connor, 2012, p. 1). This culture raises awareness of *how* language is used for collective reasoning (Mercer, 2008).

In the daily realities of classroom life, being accountable to these forms of classroom talk (Michaels et al., 2008) requires that teachers design high cognitive tasks and maintain the level of imagined rigor in conversations.

For example, Pierson (2008) found that responsive instruction (defined as teachers encouraging students to respond to targeted mathematical ideas, and then putting student logic and reasoning on display) in combination with cognitively demanding tasks supported student learning and moderated the impact of students' prior content knowledge, thus leveling the playing field for students' intellectual participation. Two recent studies have traced the fate of the intellectual demand of tasks and have documented that highly rigorous and responsive beginnings of lessons matter for maintaining the rigor in sense-making conversations for the remainder of the lesson (see Jackson et al., 2013, and Kang, Windschitl, & Thompson, under review).

Responsiveness to Participation and Building Classroom Community

In addition to *responding to students' scientific ideas*, one of the functions of classroom talk is connection building, in which a community of speakers jointly makes meaning as they link ideas together (Mortimer & Scott, 2003). We recognize that linking ideas can occur haphazardly or intentionally; thus, having participation structures in place for students to listen and respond to one another's ideas provides opportunities for the entire classroom community to engage in difficult intellectual work together. We can imagine how teachers might structure their classroom community to provide students with opportunities to engage in a whole-class debate (with more than five of the most frequent participators) about a puzzling phenomenon. Teachers and students might explain why a lake can be toxic for animals late in the summer. In that community, teachers and students would attend to the content of one another's ideas about eutrophication and interconnectedness of biotic and abiotic factors, promoting disciplinary ways of thinking (such as using a structure of Claims-Evidence-Reasoning), and inviting and providing opportunities for each of the 34 students in the class to discuss and develop socio-scientific norms (i.e., for how the class is improving on critiquing scientific ideas). Herrenkohl and Guerra (1998) described how the development of audience participation roles with sentence stems supported students in coordinating evidence and explanations in whole-class conversations. These norms for participating shape in-the-moment interactions, or the dynamic aspect of the talk (Mercer, 2008), and make explicit tacit cultural scripts for participation. Moreover, strategically positioning individual students competently in role assignment can help address status differences among students. Research on small-group interactions has shown that students of high status (perceived academic ability and popularity) have greater access to material resources and discourse; with more opportunities to develop fluency, these students do better on tests at the end of a unit of instruction (Bianchini, 1997).

Taken together, these lines of research suggest that the development of equitable and rigorous classroom learning communities demands that teachers and students actively set up structures for participation, monitor them, and provide feedback on them for both the class and for individuals.

Responsiveness to Students' Lived Experiences

There is overwhelming consensus that building on students' lived experiences is meaningful for students as it provides a focus on authentic learning contexts and new opportunities for identifying with science (Barton & Tan, 2009; Ladson-Billings, 1995; Moje et al., 2004; Paris, 2012). However, there are few examples that specify how teachers and students can engage in science instructional activities that substantively connect learners with diverse, culturally based experiences. Students enter the classroom with prior knowledge and experiences that should be used as resources for learning during sense-making talk; however, the degree to which teachers allow students to learn from a familiar cultural base and to connect new knowledge to their own narratives varies (Bergeron, 2008; Menchaca, 2001). Typically, being responsive to the development of collective and individual identities across multiple contexts becomes serendipitous and is not necessarily due to the teacher's frameworks for supporting sense-making talk in their classroom.

Some studies have shown that when students' lives are intentionally used as a way to contextualize science, knowledge-authority roles are reversed, students' stories are revealed, and students' incoming science ideas are leveraged and linked to lived experiences, all resulting in an increase in students' participation in school science (Barton & Tan, 2009; Moje et al., 2001). Research has also shown that students' utterances shape and are shaped by participation in multiple discourse communities in and across social contexts such as one's home, school, and workplace (Dreier, 2003, p. 21). Yet challenges exist for teachers to fully see the role of students' lived experiences and their participation in multiple communities in shaping science understanding. Studies that look into the merging of students' stories with science stories discuss the difficulty in doing this daily in connection with rigorous science (Barton & Tan, 2009; Moje et al., 2001). Moje et al. (2004) discuss the challenges in connecting students' lives to science when the curriculum does not support such connections clearly and students do not voluntarily offer experiences from their everyday lives. Our hope is that this study will help chip away at this theory-to-practice translation problem and identify how practices of working with students' lived experiences are supported by the other dimensions of rigorous and responsive classroom activities.

METHODOLOGY

This study employs a mixed-method approach (Creswell & Plano Clark, 2011; Croninger, Buese, & Larson, 2012) to examine differences in the structure of the interactions within lesson episodes that supported, or failed to support, students' explanatory rigor in responsive ways. Quantitative analysis data examines the statistical relationship between rigor and responsiveness, which helped us systematically identify instances of their co-occurrence. Qualitative analysis provided an in-depth look at the structure of talk in activity.

PARTICIPANTS AND CLASSROOM OBSERVATIONS

The participants of this study were 37 secondary science teachers involved in a two-year preparation and induction program at a public university in the northwestern United States. The teachers participated in a teacher education program built around a core set of teaching practices with tools to support ambitious and equitable science teaching.

Teachers' classroom instruction was observed at least five times during their practicum and their first year of teaching. We videotaped lessons and took field notes during the lesson. A total of 222 science lessons from 37 participating teachers were observed between the 2010 and 2012 academic years. We were interested in studying interactions that elevated students' explanatory rigor in responsive ways. Thus, we opted to focus on lessons that supported students in making sense of investigations or activities, as opposed to lessons at the beginning of a unit where students have not yet learned much content or lessons in which students were only conducting material activities. Specifically, we chose windows of two to three weeks for observations, and asked participants to select days within the window when students were discussing evidence-based explanations following a science activity or laboratory investigation. Researchers in our team observed each lesson, focusing on capturing classroom conversation and the interactions between teachers and students in their field notes (Clandinin & Connelly, 2000; Hammersley & Atkinson, 1995). After each lesson, we typically typed 10 single-spaced pages of dialogue from our field notes and watched videos to fill gaps in our notes. We also recorded notes about the nature of the task and the tools with specific attention to (a) the ways in which teachers framed discussion tasks for students and (b) the ways in which teachers drew attention to models, explanations, evidence, and observable and unobservable data. We photographed and took notes of the inscriptions on classroom walls, collected copies of handouts given to students, and took photographs of student work. Following each observed lesson, we debriefed with teachers as part of our larger study and asked teachers about the purpose of the lesson and why they chose to ask certain questions, select particular tasks, and use particular tools (Mortimer & Scott, 2003).

SOURCES OF DATA AND MEASURES

Identifying Teaching Episodes

Our data indicated that the larger grain size of a lesson was not adequate for describing the variation in teacher and student levels of rigor and responsiveness. Moreover, it was not useful for detailing how talk was embedded in classroom activities. We began to notice how some classrooms would make the most of warm-ups, small-group conversations, and whole-class conversations, while in other classrooms talk did not vary greatly across these episodes. We thus opted to examine teaching episodes, or "small, socially shared scripted pieces of behavior" recognizable across most classrooms (Leinhardt & Steele, 2005). In total, we coded 1,174 episodes within the 222 lessons. On average each lesson contained five episodes. Table 1 describes how we developed and distinguished episodes by the actors involved, participant roles, temporal attributes, and goals/purposes of the episode.

Measuring Rigor

For this study levels of rigor were based on the depth of scientific thinking and talking in the classroom. Specifically, we looked at how students and teachers negotiated understandings about why phenomena occurred, how students reasoned with both observable and unobservable components of models, and the role of scientific theoretical components in students' explanatory talk (see Table 2). We paid particular attention to how students and teachers co-constructed science talk along a continuum of conceptual and epistemic goals for the development of scientific explanations and explanatory models. We looked for episodes of classroom interactions and activity in which students and teachers were building ideas together and, more rarely, negotiating what counts as a scientific explanation through a process of norm-building and critique. Using episodes as the unit of analysis, the level of student rigor was coded on a scale of 0 to 4, with 4 representing highly rigorous explanatory science talk (0 = no talk and/or no rigor, 1 = definitions, 2 = descriptions, 3 = under-theorized explanations, 4 = fully theorized explanations).

Table 1. Episodes of Classroom Activity

Episode	Who? Actors/Participants	When? Temporal Attribute	Why? Purpose(s)
Warm-Up	Teacher initiates a task or question. Students respond to the task or question.	Beginning of some activity or at the transition to a new activity.	To get students focused and organized into a routine.
Instructions	Teacher gives instructions for a task. Students may ask clarifying questions.	At the beginning of a task or activity.	To define a task.
Table Talk	Teacher enters and leaves student conversations. Small groups of students engaging in activities.	Within a task or activity. Generally follows an "Instructions" episode.	To engage students in defined intellectual or material activity through social interaction.
Whole-Class Discussion	Teacher directed or initiated whole-class talk. Teachers may orchestrate cross-talk between students. Students respond to teacher and may participate in cross-talk between students.	Follows a period of activity and may follow another episode like "Content Injection."	To discuss ideas and questions that are now part of the public domain. May serve sense-making, summarizing, or other purposes.
Sharing Out	Teachers "call on" or choreograph the order of student speakers. Not all students are involved as speakers— only a small selection. Students share individual or group ideas but there is no larger discussion or commentary.	Follows a small-group or individual activity.	To share ideas in order to make individual or small-group ideas part of the public domain.
Gallery Walk	Teacher organizes roles for students as presenters and active audience members. Teachers often provide extensive scaffolding for student–student talk. Students present their work/ideas for part of the episode and then serve as active (discursive) audience members interacting with other students for part of the episode.	Usually after some small-group work such as a jigsaw or an investigation. Might, therefore, come after Table Talk.	To have students share ideas with other students who are positioned to be active discussants.

Table 1. Episodes of Classroom Activity (continued)

Episode	Who? Actors/Participants	When? Temporal Attribute	Why? Purpose(s)
Seat Work	Teacher monitors students while they work. Teacher is a passive participant. Students work individually on a task, activity, or question.	Anytime following a “Warm-Up” episode.	To respond to questions, practice a task/skill, or read silently.
Content Injection	Teacher directs or initiates presentation of science content. Teachers may pose fill-in-the-blank questions or simple recall questions. Students listen and may respond to teacher’s questions. Students may pose clarifying questions.	Anytime.	To authoritatively convey science information or ideas.
Closing	Teacher marks the end of class and probably dominates the talk. Students are often listening but not talking.	At the end of the class period or at the end of an activity before transitioning to another episode.	To end the class or end a segment of activity.

Table 2. Forms of Explanatory Rigorous Talk

1 **Definitions without epistemic features**	**2** →	**3**	**4** **Fully theorized science explanations**
Explicating definitions. Talk is about facts, procedures, equipment. Emphasis is on static entities (i.e. defining forces, evolution, etc.).	Offering descriptions or observations of a phenomenon – “what” you can see happening. OR talking about recording data about a phenomenon – what could be measured or recorded. When describing a correlation between variables – the emphasis is on “what” happens to X when Y is changed. Talk about unobservable ideas is in the form of vocabulary and is not specifically linked to the phenomenon under investigation.	Explaining “how” a phenomenon “works”—in one of 3 ways: 1) Talking about “how” a phenomenon is part of a larger process, 2) Talking about simple cause-effect relationships between two observable features of a phenomenon – simple correlation/ causation, or 3) Talking about what is happening on an unobservable (i.e. molecular) level but this is only tangentially linked to observable events.	Explaining theoretical underpinnings for “why” a phenomenon happens in the form of talking about scientific theories, models, laws [either standard ones or student-generated ones] that go beyond simple cause-and-effect relationships. Observable features of the phenomenon are broken down and underlying unobservable processes or entities are used as evidence for the theory or model.

Measuring Responsiveness

Turns of talk by the teacher and the students within episodes were coded using a 0 to 3 scale (0 = no responsiveness, 1 = responsive to utterances, 2 = responsive to answers, 3 = responsive to ideas). Zero coding levels included times when students were not involved in the classroom discourse, when the teacher was the only one talking, or when the students were doing silent work during an episode. Observers first coded three dimensions of responsiveness: (a) responding to and building on students' scientific ideas (BSI), (b) responding to participation structures and the building of a community (PART), and (c) responding to students' lived experiences and building scientific stories (STORY). This coding framework was iteratively developed between observation and analysis. The final versions are described in detail in the findings section.

The dimensions of responsiveness were discussed at weekly research meetings and continuously modified until all the members of our research team reached consensus. To rate episodes we used a 75% rule: If 75% or more of the talk in a lesson was at a higher level, we coded the lesson higher. To ensure inter-rater reliability we cross-coded the first 25 transcribed lessons, compared codes with each other, and discussed any differences in coding until we reached agreement. We continued to discuss discrepancies, such as encountering a new instance of classroom talk and borderline cases.

DATA ANALYSIS

Statistical Patterns of Rigor and Responsiveness in 222 Lessons

We ran descriptive analysis on the level of rigor and responsiveness across episodes and lessons to understand overall patterns. Pearson's correlation coefficient between students' explanatory rigor (RIGOR) and three different types of responsiveness (BSI, PART, and STORY) indicated the strong correlations among the four variables. To further understand the relation between rigor and responsiveness, we ran hierarchical multiple regression analyses using students' explanatory rigor as a dependent variable. For this analysis we used the 1,174 episodes in the 222 lessons observed. Episodes were nested in individual teachers; teacher variables were controlled using dummy variables. The results of this regression analysis showed that all three responsiveness variables significantly accounted for the variance in students' explanatory rigor.

Selecting and Analyzing Comparative Lessons and Episodes

We conducted in-depth qualitative discourse analyses using a subset of data to further understand how rigorous and responsive conversations were constructed. We first selected a subset of lessons with moderate or above moderate levels of rigor (average rigor > 2) and responsiveness (average responsiveness > 1). A total of 14 lessons were selected using these parameters. Shifting the grain size of analysis from lesson to episodes, we then examined the level of rigor and responsiveness within and across episodes for each of the 14 selected lessons, both quantitatively and qualitatively. By using the episode as the analytical unit, we were able to look into the ways rigor and responsiveness wax and wane as the different episodes within the lesson unfold.

FINDINGS

We organize the findings around three assertions that articulate how rigor interacts with responsiveness in classroom activity. All three are based on the assumption that students' rigorous elaborations of scientific ideas require teachers and students to develop a shared expectation that their daily interactions involve collaborative engagement. The findings challenge the notion that rigor and responsiveness are attributes of curricula or individual teachers. Rather, they are socially negotiated constructs constituted by students, teachers, tools, structures within and across lessons, and broader purposes for participating in school.

ASSERTION 1: HIGH LEVELS OF RIGOR CANNOT BE ATTAINED IN CLASSROOMS WHERE TEACHERS AND STUDENTS ARE UNRESPONSIVE TO STUDENTS' IDEAS OR PUZZLEMENTS.

We found that high levels of explanatory rigor did not emerge in classrooms where teachers and students were unresponsive to publically voiced ideas or puzzlements. One might expect that the absence of student voices would result in low-rigor classrooms. Very few lessons, however—only 0.5%—had no evidence of attending to scientific explanations in responsive ways (see Table 3). The majority of the 222 lessons we observed (74.3%) were attempts to be responsive to students' ideas, but remained low in rigor and responsiveness. Only about 6% of the observed lessons were high in both rigor and responsiveness. These lessons helped define what was possible when students took ownership of their own and others' learning. Responsiveness appeared to be strongly associated with the generation of classroom talk that is high rigor. To illustrate, we begin with a case from the 6.3% of the lessons that exemplified the co-occurrence of rigorous and responsive talk in classroom activity.

Table 3. Percent of Lessons with Low and High Levels of Rigor and Responsiveness

		Teacher and Student Responsiveness: Building on students' ideas, supporting participation structures, building on students' lived experiences		
		High	**Low**	**No**
Student Rigor: Selecting scientifically important big ideas and models, pressing students to develop evidence-based scientific explanations, and emphasizing epistemic features of models and explanations	**High**	6.3%	6.8%	0%
	Low	6.7%	74.3%	5.4%
	No	0%	0%	0.5%

High rigor: > 2; low rigor: 0–2 (on a 5-point scale)

High responsiveness: > 1; low responsiveness: 0–1 (on a 4-point scale)

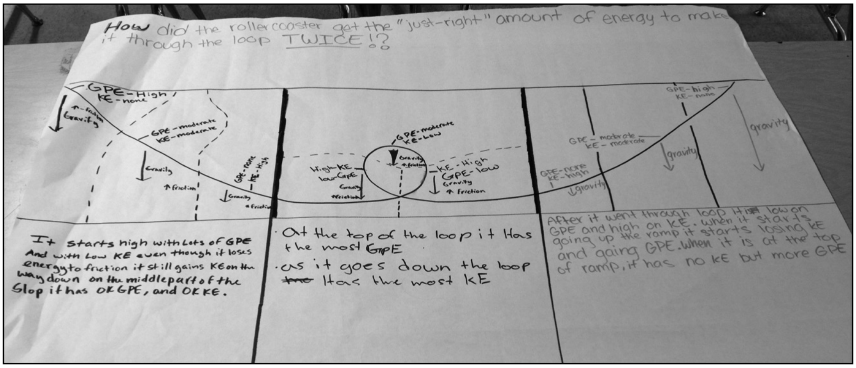
A Case of a Highly Rigorous and Responsive Unit of Instruction

Our case is from an eighth-grade class studying forces and energy. Rather than complete a series of activities found in her curriculum, the teacher (who we call "Rinat") framed the unit by selecting a puzzling phenomenon about a roller coaster that goes through the same loop twice (once forward and once backward) with ramps on either side. Rinat drew a diagram of a rollercoaster with a high ramp leading into a tall loop to serve as a focal point for class discussion. In an activity with tubing and marbles, students initially attempted to reconstruct the phenomenon represented in Rinat's drawn model but quickly noticed that the marble frequently fell from the top of the loop.

Given their observations, Rinat and her students read materials and continued experimenting to try and explain how and why energy in systems keeps objects moving forward. In the classroom talk, students did not merely restate facts about gravitational and kinetic energy; they used definitions to theorize about why the teacher's model of the puzzling scientific phenomenon did not align with their testing of roller coaster models. We rated this lesson a 4 on the rigor scale because the lesson clearly aimed at theory-building activities.

The classroom learning community was responsive to students' evolving scientific ideas, both within and across multiple lessons. For nine days of instruction, Rinat's drawing was the unquestioned scientific model. However, on the 10th day students started to question the model and

Figure 1. Student model explaining the amount of energy needed for a rollercoaster to make it through a loop twice—once forward, and once backward



It starts high with Lots of GPE And with Low KE even though it loses energy to friction it still gains KE on the way down on the middle part of the Slop it has OK GPE, and OK KE.

- At the top of the loop it Has the most GPE
- as it goes down the loop ~~the~~ Has the most KE

After it went through loop it is low on GPE and high on KE. when it starts going up the ramp it starts losing KE and gaing GPE. when it is at the top of ramp, it has no KE but more GPE

Rinat took this as an opportunity to highlight the importance of critiquing models and explanations. For a warm-up she asked students to draw their own roller coaster loop and describe where the marble needed to start from to make it through the loop.

The following excerpt shows a brief exchange that was part of a larger conversation, with students making suggestions for how to revise the teacher's model. In terms of rigor, note how the teacher prompts students to think about energy in their proposed changes to a model. In terms of responsiveness, note how she references multiple students' ideas and positions them competently with respect to the content.

> Teacher: So we're suggesting different ways to change it [response to multiple students' suggestions]. So why is that so important? Why does the starting point need to be so high above the loop? And when you answer, I want you to try and use the word "energy."
>
> Una: Because as the roller coaster is going up [moves hand up in the air], it means that the car will have a lot of potential energy. So when it goes down [drops hand down quickly], the gravitational potential energy (GPE) drops to almost none, and it gains kinetic energy. The kinetic energy then, just like, moves it through the loop [moves hand in a loop] and then back up the next hill where it gains more potential energy.
>
> Teacher: OK. We're pausing because we're letting that sink in. [silence in class for 5 seconds]. That was a lot of science talk. That was good science talk. So here's my question. So Una was

> just talking about pulling it up to give it lots of GPE. It goes down and turns most of that into kinetic energy. Now I want someone other than Una to connect that to why making the loop smaller as James suggested, or starting higher, with more GPE, would make it easier for the roller coaster to get through that loop. So pick one of those choices—pick making the starting point higher or making the loop smaller.

These conversations were supported by structured ways of listening and responding to other students. For example, later in this lesson Rinat created a structure for students to work together to weigh forms of evidence that supported or refuted different models. Students used red stickers to mean they "red lighted" or disagreed with someone else's evidence and green stickers to agree. During the lesson she ended up creating a third category of yellow lights for uncertainties, which she then highlighted in a whole-class conversation. These structures helped students publically theorize about *why* Rinat's model was incorrect with evidence from their experiments.

In summary, Rinat was intentional about responding to students' scientific ideas and creating structures for students to reason with one another. On the social plane of classroom talk, students pressed one another and the teacher for deeper levels of explanatory rigor.

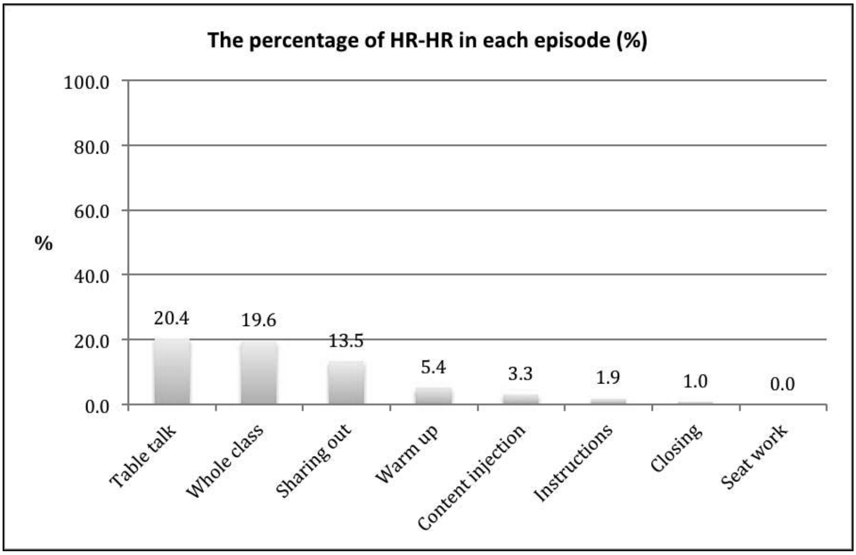
While Rinat's unit supported highly rigorous and responsive talk, most lessons from the larger data set did not. Some lessons had high rigor but low responsiveness (6.8%). These lessons had rich explanations; however, it was the *teachers*, not the students, who did much of the intellectual heavy lifting to piece together the explanation. Other lessons had low rigor but high responsiveness (6.7%, Table 3); our best way to characterize these classrooms was as "bird walks," where students chipped in to the discussion in a way that did not amount to building up substantive parts of the larger scientific explanation. In this paper, we opted not to describe instances of student bird walks and teachers shoveling information, but to focus on comparing episodes of high rigor and high responsiveness (6.3%, Table 3) with less successful attempts (the 74.3% of the low responsiveness and low rigor lessons, Table 3).

ASSERTION 2: TEACHERS FOCUSING ON RIGOROUS AND RESPONSIVE TALK USED DISCUSSIONS TO TURN POTENTIALLY TRIVIAL EPISODES INTO MEANINGFUL AND CONNECTED LEARNING EXPERIENCES.

We found qualitatively different patterns of rigor and responsiveness in classroom *episodes*. We observed that curricular (topics), structural (design of activity), and temporal (allocation of time) dimensions of episodes helped define—and confine—opportunities for rigorous and responsive talk.

For example, in Rinat's classroom the warm-up episode was tightly connected conceptually and discursively to other episodes in the same lesson (whole-class and small-group conversations about evidence for and against various models). The episodes within lessons had less clear distinctions, or breaking points, as the class moved from a warm-up to instructions to table talk. In highly rated lessons, rigorous and responsive talk was most likely to occur in two types of episode: table talk and whole-class conversations (Figure 2 shows the frequency of highly rigorous/highly responsive talk by episode). Importantly, teachers who pressed for highly rigorous and responsive talk in episodes such as whole-class conversations and table talk also transformed less likely episodes—those typically associated with managerial tasks and low-cognitive tasks such as warm-ups and instructions—into opportunities for rich intellectual work. This spillover effect required intentional repurposing of the episode activity into a time for expansive thinking.

Figure 2. The percentage of high rigor/high responsiveness by episode



In our data set, most warm-ups asked students to engage in low-level cognitive tasks such as defining relevant vocabulary as teachers sought to accomplish managerial tasks of taking roll and checking completed homework. In the highly rigorous and responsive lessons, however, teachers added a press for a science explanation that sought to connect student-generated explanations from one day to the next. For example, in a unit centered on the problem of how potted plants can accumulate mass if the amount of soil in the pot remains the same, students were asked in a warm-up to describe the difference between a what-level explanation and a how and why-level explanation. This lesson was toward the end of the unit, and the teacher wanted to help students reason about how energy was important in photosynthesis.

> T: OK. So you just told us three kinds of things it needs. Now what's your *how*?
>
> S: Yeah. Trees grow from the vitamins carried by the water and that react with the sun.
>
> T: React with the sun. OK. What did you write for your *why*?
>
> S: That tree grows by reacting with the sun in a process called photosynthesis to make food and also by the vitamins from the soil that are carried to the roots by water to create fibers and growth.
>
> T: OK. I'm going to push you to add a little bit more. I'm going to say that what you wrote right now for your *why* is probably still at a *how*. So I want you [addressing whole class] to look at what is needed in a *why* and see what you can add to that. And just also something to be careful about is under *why* we say "energy," but so if I ask you, "why does a tree grow?" and you just say . . . "Energy," what kind of answer is that? On those three levels what kind of answer would it be?
>
> S: It's a *what*.
>
> S: A *what*.
>
> T: It'd probably just be a *what*. You're just telling me a vocabulary word that you've heard us say. So you really want to think about what the purpose of the energy is. What is it doing? And something that we've connected to energy a lot is stability. So you maybe want to think about what's more or less stable? Or why does it need energy in order to react? Those kinds of questions. So make sure you're not just stopping at the word "energy." And I noticed some people wrote "photosynthesis" for their "what

> explanation." That is definitely just a *what.* "Photosynthesis is how it gets its mass," because that's just a vocab and a definition. It doesn't really tell me the story at all. So if you want to really tell me, describe photosynthesis and all its pieces then maybe we're getting into more of a *why.*

These dual-purposed warm-ups often led into highly rigorous whole-class discussions. Statistically, we found the lessons that began with high rigor/high responsive warm-ups were *twice* as likely as lessons with low rigor/low responsiveness warm-ups to have subsequent high rigor/high responsiveness episodes. This finding also implies that rigorous and responsive talk can serve a carry-over function for linking episodes, rather than lessons having conceptually isolated episodes where students' ideas do not accumulate.

The remainder of this paper features examples from individual episodes rather than looking across a unit. We recognize there are trade-offs to focusing on episodes within rather than across lessons. On one hand, this level of analysis reveals small yet consequential moves teachers and students make in the moments of teaching, yet it masks ways in which teachers may be responsive to students' ideas, participation structures, and students' lived experiences over time (see Stroupe, 2014, for a research study attending to the latter).

ASSERTION 3: THERE ARE THREE FORMS OF RESPONSIVE TALK THAT CO-OCCUR WITH HIGH RIGOR. SMALL BUT STRATEGIC MOVES IN THESE FORMS OF RESPONSIVE TALK HAVE BIG CONSEQUENCES FOR SUPPORTING RIGOROUS THINKING AND WORK BY STUDENTS.

Last and most importantly, we used classroom observations to articulate the three dimensions of responsiveness that discursively structured episodes: building on students' science ideas (BSI), attending to participation in the learning community (PART), and developing students' lived experiences (STORY). These linguistic building blocks distinguished highly rigorous and responsive episodes and lessons.

Each of the three forms of responsiveness was positively and uniquely related to student rigor, even considering the fact that each teacher/classroom could vary significantly across lessons (see Table 4). The regression analysis indicated unique effects of all three responsiveness variables that accounted for the significant variance in the students' level of rigor in classroom conversations (see Table 4). First of all, there was a significant, unique effect of responsiveness to BSI, holding all other predictors constant ([b = .73, SE = .04], t[1134] = 18.79, p < .001). In other words, with the increase of one standard deviation of responsiveness to student ideas, there was an estimated mean increase of .73 points on the level of rigor for classroom talk, holding all other predictors constant. There was also a significant unique effect of responsiveness to both STORY and PART on rigor. Specifically, there was an estimated mean increase of .21 and .17 points on the level of rigor in classroom talk with the increases of STORY and PART respectively, holding all other predictors constant. Across forms of responsiveness, it appears that BSI is three times more powerful for supporting rigor in the classroom than the other two kinds of responsiveness.

We now unpack each of the responsiveness dimensions and use examples from the data set to show how slight differences in talk and episode activity can have large consequences for rigorous dialogue.

Responding to and Building on Students' Ideas (BSI)

Across the 1,174 episodes examined for this project, there were significant differences in how teachers *worked on students' ideas.* On one end of the spectrum, teachers responded to student utterances, evaluating and extending students' incomplete thoughts; on the other, teachers posed additional questions, prompting students to use more descriptive language and asked *students* to pull together the set of ideas on the table.

Table 4. Hierarchical Multiple Regression Analyses for the Impact of Three Types of Responsiveness on Rigor of Student Explanation

	B	*SE*	b	*T*
First Block				
37 teachers				
F (36, 1137) = 3.24, $p < .001$, $adj.R^2 = .06$				
Second Block				
Building on student ideas (R1-BSI)	.73	.04	.56	18.79***
Participation structures and the building of a community (R2-PART)	.17	.04	.12	4.14***
Students' lived experiences and building scientific stories (R3-STORY)	.21	.05	.11	4.07***
Fchange (3, 1134) = 300.48, $p < .001$, $R^2_{\text{change}} = .40$				
The Overall Model: F (39, 1134) = 28.48, $p < .001$, $adj.R^2 = .48$				

Notes. A total of 37 dummy variables for 37 teachers were entered. The coefficients for 37 teachers are not reported in this table for its brevity.

*** $p < .001$

Teachers and students in high BSI episodes were able to substantively build ideas in small-group and whole-group conversations.

In this section we contrast patterns of high rigor/high BSI responsiveness with low rigor/low BSI responsiveness in table-talk episodes. Using our first 25 classroom observations, we differentiated features of teacher and student construction of science ideas in classroom talk. We created a framework based on specific teacher–student and student–student discourse. Reading across the framework, we describe three different positional frames for responsive teaching. Each frame considers both the construction of knowledge and the intersection of the teacher, student, and subject matter (Ball & Cohen, 1999): (1) responding to students' utterances, (2) responding to multiple students' answers, and (3) responding to multiple ideas in the community. When teachers respond to individual's contributions as utterances, teachers position students as siloed learners whose isolated talk contains possible answers to questions that seek canonically accepted answers. When teachers respond to multiple students' answers, they continue to position themselves as the primary knowledge authority; although the teacher recognizes that the classroom should be a place in which students share ideas, the teacher continues to direct the collective group's thinking to "correct" science answers. Lastly, when responding to multiple ideas in the classroom community, the teacher and students use each other's ideas as resources as they co-construct progressively more sophisticated science explanations over time (Cohen, 2011).

We also describe four discursive sub-dimensions for the varied ways teachers and students build on students' ideas: re-voicing ideas, responding to content, highlighting concepts, and reflecting on scientific practices. We represent these ideas in a 4-by-3 matrix in Table 5. Below we briefly describe how these discursive moves and positional frames worked in concert with one another to differentiate purposes in classroom activity. For example, in episodes where the teacher responded to an utterance (column 1), the teacher would often publically re-voice a student's idea to elevate the importance of a particular canonical idea while adding to the student's utterance. In this frame, teachers would subtly re-craft and amplify students' ideas for the purpose of identifying a correct scientific interpretation in students' utterances. Others have described a similar type of responsive activity as recaps or summaries of what teachers find to be most salient in students words; some recaps are reconstructive, meaning the teacher rewrites history presenting a modified narrative that fits with the teacher's content storyline (Edwards & Mercer, 1987; Mercer, 1995). In these cases, the teacher was the primary actor operating on (rather than with) students' individual utterances (rather than ideas).

Table 5. Dimension of Responsiveness: Responding to and Building on Students' Scientific Ideas

	Features of Scientific Thinking/Talking in Classroom Discourse		
	Responding to individual's utterances (1.x)	**Responding to multiple students' answers (2.x)**	**Responding to multiple ideas in the community (3.x)**
Re-voicing ideas (x.1)	Teacher responds or re-voices students' science ideas, recognizing the students' contributions and providing feedback on students' ideas (1 student or multiple students) VERSION B: T. asks students to clarify their idea before doing the above moves (1.1b)	Teacher adopts a student word/idea as a part of the ongoing classroom discourse to build towards a scientific word/idea. Teacher might also show student work to the rest of the class.	Teacher and students re-voice ideas or use other students' ways of talking about science ideas.
Responding to content (x.2)	Teacher collects multiple students' ideas and stitches students' ideas together	Teacher encourages students to respond to one another's science ideas (i.e. juxtaposing or weaving students' ideas by clarifying which ideas need to be added to). T. adds "filler" (such as, "and", "because") words to support students in building on one another's ideas. Students do not just state ideas independently. Students use additive language in which they make arguments for claims that become more sophisticated over time, raise new questions, recognize a confusion, or made a new connection among ideas.	Teacher and students respond to partial understandings of others and both build on and critique the ideas.

Features of Scientific Thinking/Talking in Classroom Discourse			
	Responding to individual's utterances (1.x)	**Responding to multiple students' answers (2.x)**	**Responding to multiple ideas in the community (3.x)**
Highlighting concepts (x.3)	Teacher highlights important contributions students make OR T. tacks on new pertinent content to s. idea toward the construction of an ideal/ normative scientific explanation	Teacher tracks and recounts to students their ideas that can be used to co-construct a scientific explanation (in small groups teacher tells students which of their ideas they need to stitch together, in whole class teacher tracks piece by piece students' contributions or draws attention to a part of an explanation students are struggling with).	Teacher tracks how students are formulating scientific ideas. Teacher encourages students to explore and build their own scientific ideas (explanatory flexibility). Non-normative forms of science talk are worked with on a public plane to elaborate and challenge known science ideas.
Reflecting on scientific practices (x.4)	Teacher tells students about conventional ways scientists represent ideas.	Teacher helps students distinguish characteristics of good scientific explanations and arguments from forms of talk in every-day language.	Students discuss what counts as good explanations and argumentation and distinguish from everyday talk. Students create hybrids between naturalistic ways of talking and following discursive norms in science.

In other episodes, students' ideas did not end with the teacher re-voicing or summarizing, but rather with the teacher encouraging multiple forms of elaboration that turned the intellectual work over to the students. Re-voicing, for example, was used for the purpose of creating sides of an argument that students could take up (C. O'Connor & Michaels, 2007). Students were asked to construct arguments for claims, raise new questions, recognize confusion, or make a new connection among ideas (Engle & Conant, 2002). In other episodes, teacher and students positioned each other as co-learners and honed scientific ideas. Talk was purposefully aimed at elaborating, questioning, and reorganizing ideas, but the progress of ideas was clearly visible, rooted in students' thinking and language, and was co-generated by teacher and students.

In most lessons, teachers struggled to move beyond asking questions that directed students toward normative scientific "right answers." The result was that a majority of episodes (74.3%) were analyzed as having low rigor and low responsiveness to students' building scientific ideas. Combinations of 1.1 and 1.2 in Table 5 were most typical of the low/low episodes. In the following examples, we contrast two episodes from different high school biology classrooms that were each working with the concept of osmosis to demonstrate key differences between low rigor/low responsiveness and high rigor/high responsiveness talk.

Low rigor/low R1 responsiveness to building on students' ideas (BSI). The first example comes from a unit about osmosis. The teacher provided students with opportunities to share science ideas; however, she placed great emphasis on their answering questions "correctly." In the following lesson, students watched a video of a plant cell shrinking in water, and then worked in small groups to review facts stated in the film. Students were asked to reason about the phenomenon of a plant cell losing water, but there were no explicit connections to an overarching puzzling phenomenon (e.g., Why do vegetables become floppy if they sit out on the kitchen counter?). Students had a list of factual questions to support group conversations. The teacher walked around to each table, and remained until a student produced the correct answer. When a student recited the answer, she indicated the answer was correct and then left the table. However, if a student had difficulty, she funneled the student's thinking to correct answers. For example:

Line #	Table-talk Episode, Rigor Level 1	Responsiveness Coding (BSI)
1	T: What is hypertonic?	
2	S1: Low concentration.	1.3 Highlighting
3	T: Of what?	concepts
4	S1: Whatever.	1.2 Responding to
5	T: Hypertonic is more solutes outside the cell than	content
6	inside. When we added salt water, we made it hyper-	
7	tonic. What do you need to add to the outside of	
8	your drawing?	
9	S1: Water molecules.	
10	T: More or less?	
11	S1: More.	
12	T: OK, but still show the salt in your drawing. What	
13	happens to the water?	
14	S2: Don't know.	
15	T: When you add salt here, there is less room for the water. More salt equals less water. So put that together.	
	S1: If there is a low concentration of water outside the cell and more salt there, the water will go outside.	
	T: Good. Write that down.	

There are two striking pieces to this set of verbal exchanges. First, the teacher worked one-on-one with students despite the fact that multiple students were facing one another; this reduced opportunities to generate student-built ideas (this is also an example of low responsiveness to participation structures, described in the next section). Second, she worked to fill in gaps in student thinking when the students responded to her questions with sentence fragments. The teacher tacked on new pertinent content (BSI 1.3) and did the work of stitching individual student's ideas together (BSI 1.2). During the class period, the teacher's emphasis on funneling toward correct answers limited her opportunities to hear students' scientific reasoning, resulting in a low-rigor, fact-based, discourse episode. By line 15 the student stated what the teacher considered an accurate definition for a hypertonic solution. Explicating definitions, however, is not the same as explaining the phenomenon. Students did not have substantive opportunities to elaborate, question, and reorganize their ideas.

High rigor/high R1 responsiveness to building on students' ideas (BSI). Episodes that substantively supported students in making progress on their ideas were embedded in units of instruction conceptually anchored in puzzling phenomena. The following example comes from a high school lesson that was partly about osmosis, but also about the impact of producers dying from a lack of osmotic regulation on a food web in the Great Salt Lake.

For two weeks the biology students investigated differences between the north and south arms of the lake, which is divided by a causeway. They did a series of investigations varying the amount of salt for halobacterium (a producer and extremophile with a high internal concentration of salt) and brine shrimp larvae (a first-order consumer). The focus of conversation was to determine what might happen to halobacterium as the salinity of water increased in the lake's north arm. Note that the teacher did not participate in the following table-talk episode. Students assumed the role of asking one another to elaborate, reconciling alternative explanations, and together they focused and reorganized their ideas. They were given a diagram of the Great Lake and possible food webs for each of its arms. Student 1 began by sharing his hypothesis that halobacterium was dying because of "too much salt," which affected the rest of the food web. Students 2 and 3 asked for clarification about whether the salt (versus water) caused cell death ("popping") and if the lake had a higher concentration of salt than the inside of halobacterium. They recognized that they were reasoning with two different parts of the model: the halobacterium as an extremophile (with an internally high salt concentration) and the external concentration of the salt water.

Line #	Table-talk Episode, Rigor Level 4	Responsiveness Coding (BSI)
1 2 3 4 5 6	S1: When it gets too much salt it will start to expand, expand, expand and it pops. So it ends up dying off. So when that happens these two I think are the only ones [pointing to the other producers] left to feed the brine shrimp. So when that happens . . . the brine shrimp, that feeds that American Avocet [a bird], it would only pretty much have like half of what it eats, because the brine shrimp wouldn't have all that it needs. You understand?	
7 8	S2: So in the lab [referencing lab with brine shrimp] you mentioned like . . . you're sure it was salt going in?	3.3 Highlighting concepts
9	S3: I thought it was water.	
10	S1: No, that's salt, bro.	
11	S3: Salt goes—water goes with salt. Through osmosis.	
12 13 14 15 16 17	S1: Alright. How are you going to tell me . . . ? [laughs] That's what she [referencing teacher] said, bro. I'm just saying this is what happens. Look. I'll draw you—I'll draw a picture for you, alright? Look. So you have . . . the Halo, right? You've got salt, you've got salt in here. [Draws a model of halobacteria in a high salt concentration and represents salt as dots and water as arrows flowing in and out of the organism.]	3.2 Responding to content
18	S3: I'm right though. Just make sure.	

Line #	Table-talk Episode, Rigor Level 4	Responsiveness Coding (BSI)
19	S1: You're not; you're not right at all.	
20	S2: I'll let you guys have a little discussion, OK?	
21 22	S1: Then there's—look, like salt right here, salt, and there's hecka salt on the outside, right? There's hecka salt on the outside, right?	3.2 Responding to content 3.3 Highlighting concepts
23	S3: I guess so.	
24 25 26	S1: This goes into this because it, like, attracts more salt. Because it wants salt. It needs—like it loves salt. So this is all going in and then from that it pops. It pops, alright?	
27	S3: I believe you.	
28 29	S1: It pops. From when it pops it's dead. [laughter] It's dead. It's gone. There is no more, there is no life. There's no nothing, it's done. No more Halo.	
30	S3: And how does this work?	
31 32	S2: Well um . . . how about you explain your side with what you know about osmosis.	2.2 Responding to content
33 34	S3: So . . . but I don't know. I know water goes with salt. So it goes in here and it makes it get fat or whatever, and then it pops.	
35	S2: So well, to support either you guys' things . . .	
36 37	S1: Actually we're obviously both right because it's salt water. So the thing about it . . .	3.1 Re-voicing ideas
38 39	S2: So sort of parallel this with either of the arms of the lake. So in the north arm we know there's halobacteria, right?	3.2 Responding to content
40	S1: Uh huh.	
41 42 43	S2: And we know, like, after everything we learned is it salt water in the north end. So based on this, I don't know, like if there's just saltwater where the halobacteria is why isn't the salt killing the bacteria?	3.2 Responding to content 3.3 Highlighting concepts
44	S3: Not too salty.	
45	S1: Exactly. So like we also figured out that in a certain . . .	3.2 Responding to content
46	S3: It's not salty enough.	
47	S1: Exactly. So in a certain medium the halobacteria will not die.	
48 49 50 51 52	S2: In that case I think you're both right. So there is a threshold, basically, of saltiness, right? So you can't go too far with salt, but lacking salt entirely would kill it. So here [pointing to the north arm] all the water will be attracted to the salt inside halo and would travel in, to the point where it pops. That's why.	
53 54	S1: Yeah. So like instead of the water going outwards and popping it would go inwards.	
55		

In this table-talk episode the three boys elaborated on one another's ideas by leveraging and responding to concepts from classroom investigations as well as with the phenomenon at hand (lines 7–11, 21–26, 42–44, rigor 3); they identified and addressed alternative explanations by drawing models and asking for clarification on how osmosis occurs (lines 14–17, 21, rigor 3); and they reorganized their ideas and converged on a shared understanding about how water flows across a cell membrane. They also agreed that a more pertinent question to focus on was why halobacteria could survive in the north arm (lines 39–44, 49–53, rigor 4). They devised a "threshold theory" (lines 49–53, rigor 4) based on the observable features of the phenomenon and the underlying unobservable processes for why halobacteria might survive or die in the salty environment. In this way they were not highlighting one another's answers but unearthed and publicized substantive ideas not yet defined by the community. One caveat about this episode was that it occurred in April, after the students and teachers had time to build norms for talking with one another. Regardless, what is clear is that the students elevated the explanatory rigor by using and challenging models and by positioning one another as competent learners. Not only were the boys respectful of one another, but they were also responsive to the way they made progress on ideas.

Participation Structures and the Building of a Community (PART)

While the first form responsiveness (BSI) described how students were situated with respect to the content, this second form highlights discursive ways teachers and students provided structural opportunities to participate in the classroom community. Our analysis showed that this form of responsiveness co-occurred with the first (BSI) and that the two forms together made it more likely for students to engage in deeper levels of explanatory rigor. There were slight but significant ways teachers and students solicited the participation of others, animated and reinforced participation norms, used status treatments to increase participation, and labeled the collective purpose of classroom participation. These actions structurally positioned learners with respect to one another in substantively different ways. In the development of the coding framework, we described the first cluster as positioning students as individual contributors, the second as listeners and learners, and the third as learners operating competently with respect to others and to opportunities to engage in legitimate scientific practices. The framework for responsiveness to students' participation structures (PART) is represented in a matrix with the four sub-dimensions in the rows in Table 6 and the same three frames of references as BSI (as columns in Table 6). We contrast two ninth-grade lessons that engaged students in studying the electromagnetic spectrum and the brightness of stars.

Low rigor/low R2 responsiveness to participation in the learning community (PART). Examples of low responsiveness to participation structures tended to be limited to singular utterances. Common teacher examples included: “Let’s share our ideas.” “Does anyone have something to add?” These bids were important for helping students put their ideas on a social platform, but there were no substantive structures to support students in continuing to share ideas. These bids fell especially flat in lessons that emphasized the naming of terms; the rigor remained low throughout the lesson. The example below shows a teacher inviting students to participate in a discussion about light waves from stars, with no structures that encourage students to talk to one another and with the emphasis on naming correlations. The task asked students to make sense of the inverse square relationship between luminosity and apparent brightness for the purpose of building a checklist of wave properties. Students looked at secondhand data from a luminosity and apparent brightness investigation, but there were few opportunities to explore causal explanations about the role of electromagnetic energy in light waves. The conversation began with the teacher asking students to consider which items were most important to studying star evolution. After just a few turns of talk, however, the conversation turned to naming terms (initiated by a student) and to naming a correlation (initiated by the teacher) rather than exploring an underlying causal explanation.

Table 6. Dimension of Responsiveness: Responding Participation Structures and the Building of a Community

Features of Scientific Thinking/Talking in Classroom Discourse			
	Responding to individual's utterances (1.x)	**Responding to multiple students' answers (2.x)**	**Responding to multiple ideas in the community (3.x)**
Soliciting student participation (x.5)	Teacher encourages student participation (teacher asks to hear multiple students' ideas, and asks students to listen to one another)	Teacher encourages students to respond to other students' ideas (generally, not science specific). Teacher (verbally or nonverbally) asks *each* student to contribute a thought or response to another student. Students make bids for other students to participate.	Students invite participation from classmates and refer to one another without intervention from the teacher (reversing authority).
Animating and reinforcing norms for participation (x.6)	Noticing the need for classroom participation norms	Teacher reflects with students on how classroom norms are being enacted in classroom conversations OR T. consistently reminds students of his/her high expectations for student participation ("I am expecting great things from this table").	Teacher and students reflect on how norms are supporting conversations.
Using status treatments for equitable participation (x.7)	Teacher attempting a status treatment (for example assigning participation roles, or using popsicle sticks to call on individual students for answers).	2.7 Teacher uses status treatments to invite more students to share/ hear ideas with one another (i.e. jig-saw activities that position students as knowledgeable when sharing information with classmates).	Teacher employs status treatments that change how dominating/not dominating students interact with one another by increasing the number of participants and the range of ideas up for discussion (i.e. structured turn-and-talks that elaborate students' causal hypotheses).

Features of Scientific Thinking/Talking in Classroom Discourse			
	Responding to individual's utterances (1.x)	**Responding to multiple students' answers (2.x)**	**Responding to multiple ideas in the community (3.x)**
Labeling the purpose of participation as building a classroom and/or scientific community (x.8)	Teacher makes statements about being a good participant, listener.	2.8 Teacher draws parallels between classroom & places where scientists work; students are "like" scientists.	3.8 Students are recognized for legitimate participation in authentic science conversations or debates, critiquing one another's ideas and legitimized science ideas. Students' ideas and forms of participation are marked as contributions to science.

Line #	Table-talk Episode, Rigor Level 2	Responsiveness Coding (BSI, PART)
1 2	T: OK, what's the relationship with these guys? Why are these important when studying stars?	
3	S2: [Mumbling] Without matter light will not travel.	
4	T: The light won't travel through matter? What do you mean by that?	1.1b Re-voicing ideas
5 6	S2: It won't travel as far no matter how much energy the star has. And I just put that . . .	
7	T: OK, Alicia what do you think? Do you have a check list goin'?	
8	S1: Yeah, um. I said the medium affects the wave.	
9	T: So you think that's pretty important?	1.5 Soliciting student participation
10 11	S1: Yeah and the strength of the star in that medium. And I said the star in at-a-glance stellar parallax lab was very important.	
12	T: Why?	
13 14	S1: It told us that closer stars have a bigger shift while farther stars have a smaller shift.	
15 16 17	T: OK, so if you know, if you know that. If you make that measurement, and you have a distance. And then let's say you know apparent brightness based on a light meter. What can you determine?	1.3 Highlighting concepts
18	S1: You can figure out . . . How much energy the star has?	
19 20	T: Were you guessing? That was a really good guess. [Teacher turning to next student] Henry, so you got anything?	1.5 Soliciting student participation
21	S3: What?	
22	T: What is going on with your checklist? What would be important?	
23	S3: Closer star equal brighter, farther star [fades away]	
24	T: Good, keep going.	
25 26	[Teacher walks to next group. The group of students then work silently on making checklists.]	

In this table-talk episode, the teacher highlighted important contributions students made, specifically by asking students to clarify their own ideas and inviting other students to share their ideas (BSI 1.1b and PART 1.5). However, there were no attempts to bring together Student 1 and Student 2's ideas about light traveling in different media and what that means about the energy of stars. Instead of attending to the expressed student idea, the teacher tacked on new information to Student 1's idea, "let's say you know apparent brightness on a light meter. What can you determine?" to lead the student to thinking about the normative scientific relationship between luminosity, apparent brightness, and distance (lines 15-17). Student 1 responds to this question with a question "you can figure out . . . How much energy the star has?" (line 18). This answer was confirmed by the teacher with "that was a really good guess" (line 19) followed by the teacher turning to another table-talk member. The lesson ends with students adding to the checklist of wave properties. Items added included: "all lights travel with the same speed, but with different amounts of energy," "apparent brightness is affected by distance and luminosity," and "color is energy." Students generated a list of right answers without deep engagement in the ideas or with one another.

High rigor/high R2 responsiveness to participation in the learning community (PART). We contrast this lesson with another ninth-grade classroom from one of the highest-poverty schools in our region. Students were learning about light waves and stars by focusing on a phenomenon about a "death star" (a large star that would soon release a massive amount of photons when it ran out of gasses fueling fusion in the core; the photon beam would be intense enough to destroy Earth). For this lesson students were given five color images of stars from different phases of their life cycle and were asked to arrange them in the order of their cycle, and then focus on a particular phase of the cycle to describe why it was changing. They moved from interacting in small groups to episodes where students shared life cycles they had specialized in. We include conversations from each type of episode and describe the participation structures in place—and in play—for this lesson.

Groups of students were given a worksheet that asked them to differentiate three types of explanations for (1) what the star looked like at a particular phase (color, brightness), (2) how it was changing, and (3) why it was changing. Each section included word/phrase banks to focus students on explanatory ideas, with prompts about forces, friction, and energy. The students had not yet learned about fusion as an energy source but had learned about forces. In the episode below the teacher has just helped a group of students think about what is happening as a nebula forms. She leaves the group with a message about group work and about focusing on why the phenomenon occurred. Students invite one another to participate, just as their teacher had modeled, and they use ideas from the idea bank to push their thinking. Students 1 and 2 took turns recording ideas for the group, and all students took turns passing around the sheet to check to make sure their ideas are recorded.

Line #	Table-talk Episode, Rigor Level 4	Responsiveness Coding (BSI, PART)
1 2 3 4 5 6 7	T: And the next time I see you we are going to start really talking more about *why* this is happening. But start your ideas about why. So think about what you see and what you think is happening and then use these words [pointing to idea banks] and start to think about "the why" as much as you can. You guys have some nice ideas. As a team you're working as a group. OK, so talk, I wanna have you guys talking. [Teacher leaves group]	2.4 Reflecting on scientific practices 2.6 Animating and reinforcing norms 3.8 Labeling the purpose 3.1 Re-voicing ideas
8 9 10	S2: Why is it happening is because of gravity, it's pulling on it, it's pushing together the gases making it solid. [Pictures of stars in middle of table. Worksheet between S2 and S3.]	3.5 Soliciting student participation 3.4 Reflecting on scientific practices
11 12	S1: Gravity is pulling all the particles and elements? [Pointing to picture]	3.8 Labeling the purpose of participation
13	S2: Yeah, gases hydrogen, oxygen, helium, all that, all the gases together to make a new star.	
14 15 16 17	S1: It's spinning. Just kinda try to bring all the ideas together and if you get stuck just let us know [referring to S3 who is writing on worksheet]. Um, and eventually it just like a concentrated amount of energy in the center.	3.4 Reflecting on scientific practices 3.8 Labeling the purpose
18	S2: Into its core.	3.2 Responding to content
19	S3: It has energy in the middle?	
20 21 22	S2: Are you saying why in that box? I thought you were supposed to put why right there [pulling worksheet over and referring to why section]. WHY IS IT HAPPENING. Yeah, it says why is it happening.	3.4 Reflecting on scientific practices
23 24	S1: Is how and why kinda like the same question in this situation? [Pointing to worksheet how and why prompts]	
25 26	S3: Oh, how is it happening, it's swirling. And why is because the gravity is pulling all the particles.	
27 28	S1: And you could put "how" there. [Pulling worksheet over and pointing to how section]	
29	S2: No, this is "what" we see [pointing to writing in what section].	3.3 Highlighting concepts
30 31	S3: What we see and how. This is how [pointing to worksheet], swirling.	
32	S1: Swirling, oh darn. So we are pretty much done, ah. [Pushes worksheet in middle of table]	
33 34	S2: Um, is there anything on . . . [Pulls worksheet over, students looking on idea checklist]	3.2 Responding to content
35 36	S1: Yeah, friction, friction, pressure when it's swirling it has more friction in there. [Leaning in to read idea checklist]	3.5 Soliciting student participation
37 38	S2: But doesn't friction make it slow down? To make a star form you need tons of speed to make a star form as it	

Line #	Table-talk Episode, Rigor Level 4	Responsiveness Coding (BSI, PART)
38	grows and as it spins it grows because of gravity is um pulling	3.8 Labeling the purpose of participation
39	on the gases that can combine together because it's	
40	growing. But a little bit of friction into it but not a lot.	
	S1: It's all lumpy. So, it's all swirling around each other.	3.5 Soliciting student participation
41	S2: But as it turns it's not so lumpy.	
42	S1: It's kinda smooth.	3.3 Highlighting concepts
43	S3: Is it pressure that pushes down?	
44	S1: Pressure pushes particles into center.	3.4 Reflecting on scientific practices
45	S3: Can you read this? [Pushes worksheet out for others	
46	to see and read] The gravity of pressure is pulling and	
47	pushing the molecules. . . .	
48	S1: Anything else? We see a star forming. We still see a	
49	glowing orange, yellow circle in the middle. We still see	
50	reminisce of the nebula swirling around this glowing center	
51	and that's how. The why is the gravity and pressure is	
52	pulling and pushing all the particles and elements together	
	to make a new star. There is a concentrated amount of	
	energy in the middle and that's why it is glowing. When	
	it's swirling it has a little bit of friction. It's good.	

In this table-talk episode, students complete one another's sentences and come to a new understanding that reflects a stitching together of their ideas (lines 7–17, 33–43, 46–52). We categorized this as rigor level 4 because students use unobservable processes as justification for their observations about the amount and color of light and the "lumpiness" of material in the picture of a star being formed (lines 35–43). It is a good example of students working together to build an explanation, while challenging their understanding of differences between "what," "how," and "why" explanations in science (BSI, Reflecting on Scientific Practices, lines 18–28).

The teacher used this table-talk episode to prime students for their presentations, a "sharing out" episode. We include this outtake to demonstrate the other dimensions of responsiveness to participation structures and the building of community in combination with high rigor and high responsiveness. Of interest is the way in which the teacher encourages a shift in the purpose of the activity from being a "reporting out and recording information" activity to a debate about ideas. She intersperses whole-class discussion episodes between the sharing-out episodes in response to the group's ideas. In the following whole-class discussion episode, the teacher returned to norms the students set at the beginning of the year and engaged students in a debate using evidence. The nebula group featured above just finished sharing out to the whole class their explanation for how and why stars form.

Line #	Whole-Class Episode, Rigor Level 3	Responsiveness Coding (BSI, PART)
1	T: Let’s visit norms. Norms for you guys is respect. So, please	2.6 Animating and
2	be respectful. That’s the most important norm. Yu Du, I don’t	reinforcing norms
3	feel like you are being very respectful right now. Because I	
4	am telling you about norms and I see you goofing around.	
5	That makes me feel like you don’t value me. And I think it’s	
6	worth your time to listen to each group presenting up here	
7	because they have spent a lot of time thinking about a part	
8	of the star’s life that you haven’t been focusing on. You may	
9	not agree with them exactly but listening to what they’ve been	
10	thinking about can give you some ideas about how you want	
	to explain that same period of the star’s life when you are do-	
	ing your full explanation.	
	[second and third presentations]	2.5 & 3.5
11	S9: How do you know it’s running out of fuel, or gas?	Soliciting student
12	S10: Did you go to that star and check? [laughter]	participation
13	T: Well, guys, guys, guys. Let’s be serious, let’s talk about	
14	evidence. What might be evidence that the star is running out	
	of fuel?	
15	S6: Because it’s getting older	3.1 Re-voicing ideas
16	S9: Because it’s red	
17	T: So, it’s getting old. Why do you think it’s getting bigger?	3.3 Highlighting
18	Does it have to do with running out of fuel? OK, he has a	concepts
19	question and Vincent wanted to share something.	3.7 Using status
20	S2 (Vincent): (Same S2 from previous table-talk episode.)	treatments
21	The star is running out of its hydrogen. It’s using most of its	3.2 Responding to
22	hydrogen inside and it’s supplying it from its core. That’s why	content
23	it’s expanding. As it expands it will explode sooner or later	
	because it needs hydrogen.	2.5 & 3.5
24	T: Egbert, do you want to share any ideas?	Soliciting student
25	S8: Why does it turn red? Why doesn’t it stay blue and then	participation
	blow up?	
26	T: One at a time, one at a time.	3.6 Animating and
27	S4: I dunno, why don’t you tell us teacher?	reinforcing norms
28	T: No you guys come on. I am not, not the . . . My job isn’t to	(3.6)
29	teach you the facts of the life cycle of the star. We are teaching	3.2 Responding to
30	you how to figure it out, what’s causing the whole process. It’s	content
31	a complicated thing to learn, it takes a while . . .	
32	S10: It’s because blue means hot.	
33	S8: OK, yeah but why doesn’t it stay blue and then blow up?	
34	Class: [lots of mumbling comments]	2.6 Animating and
35	T: One at a time, one at a time. I know Mr. Robinson [a stu-	reinforcing norms
36	dent] wanted to share something.	3.2 Responding to
37	S11: Um, because when it’s blue it doesn’t explode because it	content
38	has like a lot of energy so you can’t explode.	
39	S4: So the red one doesn’t have enough energy to blow up.	2.5 Soliciting stu-
40	T: I heard you say something about gases. Can you tell me	dent participation
	more?	
41	S5: [Inaudible]	

Line #	Whole-Class Episode, Rigor Level 3	Responsiveness Coding (BSI, PART)
42	T: Can you tell me if I hear you right? You're saying when it	3.1 Re-voicing
43	loses its gases, when it runs out; it's turning red because it's	
44	getting less hot.	
45	S5: Yeah.	2.3 Highlighting
46	T: Good, so you guys all have really good ideas and this is	concepts
47	helping us make a story about the super gamma ray star, that	
48	death star. We have evidence that tells you that this star is	
49	changing and you know it's cooling down because it's turning	
	. . .	
	Class: Red	

During the first two presentations students sat quietly and most filled out a worksheet with information about the other phases of their stars' life cycle. But following the third presentation students began asking questions. The teacher took a question (line 12, framed as a joke) about evidence posed by a student and opened up the activity for questions that linked evidence of star color and energy with the evolution of stars (starting at line 13). This in-the-moment structural change, reinforcement of norms for participation (PART-animating and reinforcing norms 2.6 & 3.6, lines 1–10, 13), and continuous solicitation of student participation (PART 2.5 & 3.5) opened up opportunities for other groups to contribute ideas and change the range of ideas up for discussion (BSI, Responding to Content, 3.2). For example, it was during this conversation that Student 2, from the previous table-talk episode excerpt (lines 20–23), folded in his group's ideas about the source of energy. This building of ideas between presentations continued and ultimately afforded students the opportunity to describe the cyclic nature of star evolution.

In other episodes that were similarly high in rigor and responsiveness, we observed not just students inviting other students to participate, but students inviting teachers to participate in conversations, as well as students completing the teacher's ideas (PART 3.5). We also noted that several of these lessons made explicit references to students participating as scientists in authentic experiences (PART 3.8, labeling the purpose of participation as building a classroom and/or scientific community). In another sharing-out episode, a chemistry teacher designed an authentic science task for students to share their explanations for why fake gold oxidizes in saltwater. Students participated in a poster carousel and explicitly likened their work to scientists presenting ideas at conferences. As a part of this lesson, the teacher also clarified presentation and audience roles (PART 3.7, using status treatments for equitable participation) that would help students clarify why-level explanations. One student in each group had the explicit role of "being a younger sibling who always asks why five times." Each group was required to drive down to explanations with intramolecular and intermolecular forces. Students, in turn, held one another accountable to the roles and to the press for why-level explanations.

Responding to Students' Lived Experiences

We found the third dimension of responsiveness—to students' stories of interacting with the world outside of the classroom—to be uniquely predictive of student rigor. Other lines of research have similarly described teachers being responsive to students' funds of knowledge, or knowledge from multiple and varied experiences that stretch beyond the school walls. Similar to these studies, we found that teachers typically were unable to capitalize on students' lived experiences beyond making nominal, hypothetical approximations to students' lives (Barton & Tan, 2009; Levin et al., 2009; Moje et al., 2004). In only a few cases (38% of total episodes, with 35% being low rigor/low STORY responsiveness and 3% being high rigor/high STORY responsiveness) were teachers able to use conversations about students' lived experiences to alter the course of the scientific ideas being developed. Noticeably, being responsive to students' lived experiences was more likely to occur in table-talk and whole-class episodes, and almost never occurred in other activity structures.

In analyzing lessons, we noted three types of talk associated with responsiveness to students' lived experiences. Each has temporal dimensions. The first was the way in which teachers asked students to *share stories* and how they *inquired into students' stories during classroom interactions.* The second was what they did with these stories: did they trivially or meaningfully *link students' lived experiences to the scientific story at hand?* Finally, some of the responsive work was built into the curriculum so there were *multiple opportunities to revisit students' lived experiences across lessons and across episodes.* Similarly to the other dimensions of responsiveness (BSI and PART), we placed these forms of talk in a 3-by-3 matrix with a continuum of being responsive to students' utterances, answers, and multiple ideas (see Table 7).

Low rigor/low responsiveness to students' lived experiences (STORY). Of the few lessons in which teachers attempted to be responsive to students' lived experiences, most were coded low in responsiveness and rigor. Students' stories were nominally recognized and were not used as a resource to build on scientific ideas. Ultimately, students' stories were left behind and not reanimated throughout or across episodes or lessons. We provide two examples of low rigor and low STORY responsiveness from two types of episodes: a sharing-out episode and a whole-class conversation. In the first example, eighth-grade students shared information about beneficial and harmful properties of microbes.

Table 7. Dimension of Responsiveness: Responding to Students' Lived Experiences and Building Scientific Stories

	Features of Scientific Thinking/Talking in Classroom Discourse		
	Responding to individual's utterances (1.x)	**Responding to multiple students' answers (2.x)**	**Responding to multiple ideas in the community (3.x)**
Sharing culturally and linguistically diverse stories (x.9)	Teacher asks students to contribute questions, ideas or stories from lived experiences	Teacher encourages students to share lived experiences. Teacher encourages students to express and work with their ideas about a science story in familiar terms or in a primary language. Students offer examples from their experiences that connect to a science story.	Teacher encourages expression of multiple facets of students' stories for the purpose of building related scientific stories over time. Students share more than examples but rather meaningful stories and how these stories are rooted in their multiple cultural practices. Students take intellectual risks when transitioning back and forth between primary & secondary languages.
Linking everyday stories to canonical science (during instruction) (x.10)	1.10 Teacher acknowledges that students' examples are from a lived experience.	Teacher uses parts of students' stories to build a scientific story.	Students use stories and questions from their lived experiences to add to a scientific story. Teacher helps students work with their stories to understand science story.
Using lived experiences to create responsive curriculum (x.11)	1.11 Teacher approximates (makes a best guess about) relevant examples that connect science to kids' experiences. For example teacher uses an analogy he/she believes most students will be able to relate to.	Teacher constantly revisits relevant analogies.	Teacher uses students' stories to organize lessons or units.

Line #	Sharing-Out Episode, Rigor Level 1	Responsiveness Coding (BSI, PART, STORY)
1	T: Thank you table 2. Table 3? What did you find that was beneficial?	1.5 Soliciting student participation
2	S1: They (microbes) eat other bacteria or protists.	1.1 Revoicing ideas
3	T: They eat other bacteria or protists, anything else?	
4	S1: They are in our food, like ice cream, and in toothpaste.	2.9 Sharing culturally and linguistically diverse stories
5	S2: What is beneficial about them being in ice cream?	
6 7 8 9 10 11	T: Beneficial means positive, that they help us. They make it, ice cream, congeal together, like the agar we used on Thursday, made of protists. We can eat them or make products with them. Raise your hand if you've eaten sushi or nori. [Pause, many students raise hands] Then you've eaten protists. [Students respond with noise representing surprise] Shhhh . . . all right, anything that is harmful, table 3?	1.11 Using lived experiences to create responsive curriculum
12	S3: They can give you diarrhea.	
13 14	T: They can give you diarrhea, they can make you sick. One protist, called giardia, can give you diarrhea. Table 5 . . .	

In this example, the teacher moderates how students share facts about microbes from readings. The teacher attempts to connect to students' lived experiences by generally referencing a relevant example that could potentially connect entities (microbes) to students' lives. The rigor in this episode remained at a low, fact-based level (rigor 1). There were missed opportunities to expand on students' lived experiences, not just with microbes but the connection to *processes* of how microbes cause illness. Both scientific explanations and students' lived experiences remained static.

Although it was typical of episodes low in responsiveness to students' lived experiences (STORY) to also be low in rigor, in a few lessons we observed teachers using students' experiences to build students' scientific content. One such example of in-the-moment responsiveness to students' lived experiences came from a high school chemistry lesson on physical and chemical changes. The teacher decided, in the moment, to help students reason not just with the phenomenon he proposed (a burning log) but an idea a student proposed (cooking an egg).

Line #	Whole-Class Conversation, Rigor Level 2	Responsiveness Coding (BSI, PART, STORY)
1	S1: Would ash [from a log] be considered a physical	
2	change? Like an egg?	
3	T: So what did we just have in the back of the class?	3.5 Soliciting student
4	S3: We thought also that it was physical changes even	participation
5	though it comes after melting and boiling.	2.9 Sharing cultur-
6	S4: I don't agree with that because even though there	ally and linguistically
7	was a color change CO_2 was emitted so the identity of	diverse stories
8	the log would have to change.	
9	T: Does anyone have something to add to this? . . . So	2.5 Soliciting student
10	this is chemistry. Let's think about this at an atomic	participation
11	level. What makes up an egg?	3.2 Responding to
12	S5: Elements	content
13	S6: Potassium	
14	T: Be specific.	2.5 Soliciting student
15	S7: Proteins, and when we cook proteins the proteins	participation
	change.	3.3 Highlighting
16	T: What does it look like? What happens when it cooks?	concepts
17	[Teacher draws on board and shows a tightly bound	2.10 Linking everyday
18	protein and an unwound protein.]	stories to canonical
19	S7: So it is breaking and forming bonds.	science
20	S8: It expanded because of heat. When it heated they	3.2 Responding to
21	[bonds] move apart rather than together.	content

In this whole-class episode, the teacher was able to use part of his students' stories, a seemingly shared story of cooking eggs, to support students in questioning the dichotomy of physical and chemical changes occurring when an egg is cooked (line 4). He used student language and experiences to press the talk to a molecular level (line11).

High rigor/high responsiveness to students' lived experiences (STORY). Our data set did not contain many cases of high rigor and high responsiveness to students' lived experiences—only 2.7% of all episodes. The 2.7% were marked by intentional efforts by teachers to ground entire units of instruction in students' cultural backgrounds and everyday lived experiences. There were a few examples of teachers specifically attempting to include students' cultures and/or open doors for English learners. One teacher adapted her curriculum to focus evolutionary concepts on the fennec fox and privileged her African immigrants' stories of living in the African desert. Another teacher taught climate change in the context of water levels rising in the Samoan Islands. Her Samoan students had new opportunities to share their experiences and had a place in the curriculum to share stories of living on the shores of the islands. These were non-trivial efforts on the teacher's behalf but they were reflected more in the curriculum than in instruction and moment-to-moment conversations. In practice, students rarely had more than one opportunity to author substantive stories. And yet the data suggest that even modest connections to students' lives (level 2, *responding to multiple students' answers*) co-occurred with rigorous forms of talk.

While teachers were less successful at using *multiple students'* narratives around race, community, and culture, some were successful using individual stories to adapt the course of a unit of instruction. For example, in an eighth-grade classroom studying dog evolution, the teacher (Janna) invited students to share stories about how dogs evolved. Students brought pictures of family dogs and posted them on Janna's bulletin board. They reasoned about how "ankle-biters" (a student's term for Chihuahuas) and other small breeds evolved over time. Another group of students tried to understand Curtis's story of his dog that was part wolf. Janna moved these conversations from table-talk episodes to whole-class conversations. We share how Janna elevated Curtis's story:

Line #	**Whole-Class Conversation, Rigor Level 3**	**Responsiveness Coding (BSI, PART, STORY)**
1	Janna: Now we need to hear Curtis's story	3.9 Sharing culturally and linguistically diverse stories
2	because it will help us as we continue talking about this topic. Curtis?	1.5 Soliciting student participation
3	Curtis: My family and I had a dog. A few years	
4	ago it got sick and we had to take it to the	3.10 Linking everyday stories to canonical science (during instruction)
5	vet. They did some blood tests and found out it was 15–20 percent wolf.	
6	Janna: And what happened?	3.3 Highlighting concepts
7	Curtis: They had to put it down.	3.10 Linking everyday stories to canonical science (during instruction)
8	Janna: OK, so there are two things here we	
9	need to think about during this unit. The	
10	first is, what does it mean to be 15–20% wolf?	3.11 Using lived experiences to create responsive curriculum
11	The second is, why would that make a dog too dangerous and need to be put down?	

Curtis's story became a shared problem that the class community worked on for three weeks. During the unit, students developed a more complete science explanation for the genetic variation among dogs. They frequently returned to the 15%–20% wolf story as a context for learning more content. In this example, the teacher used students' stories to organize a unit of instruction.

In the full data set we were surprised by how little talk space there was for students to expand science-themed, out-of-school narratives over the course of a unit. We were unable to find substantive examples of codes 3.9 and 3.10—teachers encouraging expression of multiple facets of students' stories for the purpose of building related scientific stories over time and students sharing meaningful stories rooted in their multiple cultural practices. For us, these talk moves remain hypothetical in the context of the development of rigorous scientific explanations.

DISCUSSION

We began this study with what appeared to be simple questions: What does highly rigorous and responsive talk sound like and how is this dialogue embedded in the social practices and activities of classrooms? In the small fraction of lessons we coded as highly rigorous and responsive, students authored and owned scientific explanations while carefully listening and building on the ideas of others. Both teachers and students regularly engaged with in-the-moment sense-making and focused on synthesizing knowledge. Multiple students' ideas were framed as legitimate resources that helped the whole class make progress on canonical science understandings, even as the science was localized in students' experiences. Scientific knowledge was treated as partial and under constant revision. This allowed for a hybrid form of epistemic authority that combined canonical science knowledge with students' locally authored science ideas. The result was shared scientific understandings that were made public, challenged, and revised until well-warranted (Duschl, 2008; Ford, 2012). Additionally these lessons had a unique architecture with substantive talk being the organizing feature of activity—within and across episodes, including warm-ups, and small-group and whole-class discussions. This thread of substantive talk seen in the elusive high rigor/ high responsiveness lessons served as an essential binding for meaning-making within and between episodes that otherwise stood alone as fragmented, often disposable, components of science classroom interaction.

In the Findings section we made three empirically based assertions about the discourse and structure of these lessons relative to the full data set. We now unpack the meaning and implication of these by revisiting the constructs of rigor and responsiveness as *equity-in-practice* and as *making progress on ideas.*

RIGOR AND RESPONSIVENESS ARE INTERTWINED IN SUBSTANCE, PRACTICE, AND IN-THE-MOMENT DILEMMAS

Our first assertion was that high levels of rigor cannot be attained in classrooms where teachers and students are unresponsive to students' ideas or puzzlements. We were curious as to why this co-occurrence was rare. All classrooms had interactions among teachers and students, but there were qualitative differences in the substance of the conversations. In looking at the differences between the first and third columns in Tables 5, 6, and

7 describing characteristic discursive moves, we conjecture that different classrooms must be differentially negotiating four in-the-moment dilemmas: (1) how much to value canonical scientific knowledge, (2) how much to build on ideas from previous lessons, (3) the "right" number of students participating in discussions, and (4) how to legitimately use students' lived experiences and language to shape instruction. How teachers and students navigated these in-the-moment dilemmas—or not—helps explain the full range of more and less successful intertwining of rigor and responsiveness in our data set. We unpack these four areas of tension below.

First was the dilemma of whose knowledge was valued and to what end. At times the canon of science and the words of the students did not align. In most classrooms, teachers felt tensions about how to unify students' ideas with textbook knowledge, while still maintaining some sense of responsiveness. As Sohmer, Michaels, O'Conner, and Resnick (2009) reported, we found that the cognitive demand of tasks decreased over the course of a lesson as teachers reverted to Initiate-Response-Evaluate (IRE) discourse to help the students and to "keep the conversation moving and more socially comfortable" (p. 112). The present study indicated, however, that in highly rigorous and responsive classrooms, teachers and students moved through this dilemma using their emerging understanding of canonical knowledge. Both the teachers and students made progress on ideas and seeded conversations that afforded opportunities to draw on prior knowledge and help define the trajectory of the lesson.

Second was the dilemma of time, which often surfaced for teachers as a question about prioritizing connections to students' ideas in the past versus focusing on ideas in the present. Classrooms that emphasized the correctness of ideas and did not resolve the first tension about which knowledge to promote—canonical versus students' ideas—tended to bifurcate discussions about students' activities done in the *past* and about their *present* accumulation of ideas. In highly rigorous and responsive classrooms, however, representations of ideas that had unfolded over the course of days were publically displayed. In this way, students' ideas were inscribed in artifacts (such as poster paper) and could travel over time to reemerge when needed. Thus, the history of students' ideas played a crucial role in determining the direction of the lesson. Highly rigorous and responsive classrooms, therefore, honored and used the community's idea history to revise current explanations of phenomena.

Third was the dilemma of how many students should share ideas before moving on to other ideas or topics. In most classrooms, teachers weighed how much they needed to hear from individual students to assess overall student learning and make determinations on how to respond. Such teachers also struggled with how much airtime to give students' ideas before layering on the "correct" information. Highly rigorous and responsive classrooms redefined this dilemma by focusing on how individual contributions advanced the collective community's ideas. Teachers, for example, made meta-comments about the strength of students' synthesized explanations through collaborative activity (PART 3.6). While teachers initially framed this dilemma as an issue around *equality* in participation, teachers and students focused on the *quality of ideas generated by the collective* and the ways in which members of the learning community held themselves accountable to one another, to science ideas, and to forms of engaging in disciplinary talk (Ford, 2012; Michaels et al., 2008). Thus, equity-in-practice was marked in the quality and careful scaffolding of the discourse.

Fourth, but related to the previous three, was the dilemma of integrating and emphasizing students' everyday experiences in out-of-school communities. This well-documented dilemma (e.g., Gutiérrez & Vossoughi, 2010) presented the most difficult challenge for learning communities. Only 2.7% of the highly rigorous and responsive lessons we observed co-developed students' stories and science stories (level 3 in Table 7). Nearly 75% of the lessons we observed failed to capitalize on or even attempt to incorporate students' rich experiences outside of school. In most cases—if and when teachers elicited student stories of everyday experiences—teachers borrowed language from those stories to integrate into teacher-centered explanations. Assimilation of students' ideas, language, and experiences into the teacher's version of science presented two equity problems. First, teachers engaged in the intellectual heavy lifting during the lesson. While they presented coherent theoretical ideas *to* students, opportunities for students to make sense of such information remained scarce. This denies students the opportunity to engage in intellectual work and see themselves as knowledge producers (Banks, 1997). Second, teachers extracted and re-appropriated fragments of students' language from their lived experiences. Rather than acting as an anchor for community-building and science, students' language and experiences became trivialized and served the teacher's needs. By co-opting students' language and experiences in this manner, teachers preserved their own storyline for science and marginalized student contributions by treating them as tokens.

Highly rigorous and responsive lessons, on the other hand, elevated students' experiences and discourse from outside of school, keeping them alive during public discussions. Rosebery and Warren (1995) describe a similar concept of equity-in-practice as *equity in the future tense*, meaning that students' discourse and lived experiences are the foundation from which science should emerge. Rather than dismiss students' lives outside of school as incompatible with canonical science, highly rated classroom environments purposefully and publically placed student stories as equal to stories found in textbooks and curriculum. Thus, the rigorous and responsive classrooms became places where students' lives framed the community's science work.

Learning communities that engaged with each of these four in-the-moment dilemmas by negotiating hybrid practices or finding nuanced, complex resolutions for tensions were able to avoid common pitfalls that result when dilemmas are framed as either/or choices. As they foregrounded the progress of students' ideas over time—by creating ongoing records of student thinking and by tailoring learning goals to particular groups of students—teachers and students better intertwined rigorous and responsive activity in substance and in practice.

THE SOCIAL AND STRUCTURAL ORGANIZATION OF THE CLASSROOM

Our second assertion was that teachers focusing on rigorous and responsive talk turned potentially unproductive parts of a lesson structure into meaningful episodes of intellectual work. Classrooms that best supported the development of students' ideas in equitable ways had deliberate and purposeful episodes and sequences of episodes. Episodes were not isolated containers of ideas; they were engineered to support the unfolding of ideas across a lesson. This finding suggests that teachers found structural ways to work on the dilemmas—particularly the second dilemma of working with past and present ideas. Linking episodes with purposeful talk was the organizing feature for their classroom activity. Ironically, this finding challenges our coding framework for examining episodes—in particular the purposes component in Table 1. While there remained different temporal attributes, there were larger discursive purposes (such as making progress on students' ideas) that functioned to organize the structure of entire lessons.

THE BAKED-IN LANGUAGE OF SCHOOLING: AUTHORITY AND AUTHORSHIP

Our third assertion based on our regression analysis was that all three forms of responsive talk—building ideas, participation structures, students' lived experiences—uniquely relate to high explanatory rigor. We conjecture that each dimension of responsiveness not only supported the rigor of the lesson but also had unique contributions to supporting students in authoring ideas and becoming intellectual authorities. Authorship and authority come from the same Latin root word *auctor* (meaning author or originator), but often in practice students are not asked to be authors and local authorities on a set of science ideas. Not only are these teaching practices subject to the various in-the-moment dilemmas and the challenges in lesson structures described earlier, but they also stand in opposition to the baked-in language and practices of traditional schooling. These traditional discourses carry assumptions that teachers are "the" knowledge authority and that instruction is about controlling the classroom and covering curriculum (Kennedy, 1999).

Sharing intellectual authority is challenging. It requires teachers to deeply understand disciplinary content and students' ideas well enough to move students forward in their thinking through a combination of social, cultural, and epistemic practices that challenge and refine thinking over time (Duschl, 2008; Ford, 2012). In our data set we found that a large portion of teachers—74.3%—elicited students' ideas, opening up a range of possible ideas for consideration, but then narrowed the set of possible ideas to the correct science ideas by the end of the class period, doing little to support subsequent sense-making. These lessons were typified by limited technical skill—teachers with only a narrow range of discourse moves. They superficially addressed the first dilemma by tacking students' ideas onto canonical science ideas, but did not navigate the following three dilemmas. Thus, the teachers struggled to make connections with the evolution of ideas over time, worried about an optimum number of student participants, and grappled to meaningfully incorporate students' stories and lived experiences into science lessons.

We speculate that the larger contextual discourses of control and coverage common in schools may function as a "sink stopper" to the flow of ideas in classrooms. Yet, in highly rigorous and responsive classrooms, teachers and students used a diverse set of discourse moves, navigating around many of the stoppages and negotiating dilemmas. Importantly, these repertoires contained moves that explicitly confronted the traditional approach to school science by redefining the purpose of classroom discourse as participation in legitimate scientific activity (see Table 6 examples of PART 3.6, 3.7, and 3.8). This created fundamentally different spaces for students to develop ideas about themselves as authors and intellectual authorities.

CONCLUSION

Classrooms have the potential to be highly rigorous and responsive learning environments that produce capable, competent learners. This paper describes some of the preconditions and forms of talk that engage students and teachers in productive and progressive conversations—an important step to creating rigorous and equitable learning opportunities. Below we raise two cautionary tales for practitioners, teacher educators, and educational researchers.

First, this study challenges the notion that rigor is an inherent quality of curriculum that can stand alone or exist separately from the interactive work of teaching and learning. Our data suggest that curriculum prompting students to work on complex, authentic science questions and explanations—including teacher-developed instructional materials and teacher-modified commercially available instructional materials—was more likely to support teachers and students in working with theoretical ideas and coordinating evidence with puzzling phenomena. Yet it was the actors—the teachers and students—who layered rigor and responsiveness onto the science topics embedded in the curriculum. Because of these findings, we now view the notion of rigorous curriculum as necessary but not sufficient for ambitious and equitable science learning experiences; the interactions within the classroom are essential for sustaining the highest quality of scientific practice and sense-making.

Second, simply handing teachers segments of discourse or frameworks, or presenting the dilemmas described by this study, will not be sufficient to develop practice. A central challenge is that educators have few images of students working with canonical ideas, and as the demand for discursive classrooms increases, so will the demand for more frameworks representing the complex work of supporting students in taking intellectual leadership in classrooms (Resnick, 2010). But exemplars and frameworks alone are not enough to support shifts in teaching practice.

Teachers and teacher educators will need to focus on developing not just the vision for what is possible in classroom activity, but also principles for how and why these practices support student learning. This will require the articulation of what it means to work on the gap between idealized and realized pedagogy (Michaels et al., 2008). We believe the incremental differences described in the proposed rigor and responsiveness framework can be used in teacher preparation programs and professional development models to support teachers, teacher educators, and researchers in collaboratively interrogating into productive variations on practice. To support teacher learning and the improvement of teaching, the specified practices should not be viewed as "best practices" in a static state (Lefstein & Snell, 2014). Educational communities need to ask critical questions about the practices: Who does the practice work for? Under what conditions? To surface tacit principles undergirding the practices, the four dilemmas should also be objects of interrogation.

Studying the development of practice in such communities will require a more expansive view of teacher learning. Rather than investigating the ways in which teachers are disposed to respond to students' ideas, our findings suggest that further research needs to focus on how *communities of teachers and students* learn to negotiate in-the-moment dilemmas and how organizational structures support progressive and equitable learning experiences.

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