Opening up curricula to redistribute epistemic agency: A framework for supporting science teaching

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Abstract
This study proposes a strategic framework to guide teachers’ curriculum adaptation, planning, and enactment as a lever for redistributing epistemic agency. This framework intends to position teachers as strategic decision-makers around when and how to open up aspects of their curriculum. We argue that seeing the aspects of Next Generation Science Standards-aligned curricula—the methods of investigation, the anchoring phenomena, and the explanatory models students construct—as entry points for redistributing epistemic agency may help teachers make inroads to shifting their classroom practice towards more responsive instruction. Importantly, our tool acknowledges that there are different “levels” at which teachers might strategically decide to open up space for student decision-making. These decisions may have a differential impact on students’ subsequent participation in science practices. In this paper, we will use three cases to highlight the specific and incremental ways that teachers can open up aspects of the curriculum and how those openings redistributed epistemic agency in their classroom. We argue that this framework may be used as a tool for engaging teachers in conversation about how they can begin to position students as partners in the epistemic decisions that drive classroom activity.

KEYWORDS
curriculum adaptation, epistemic agency, professional development, science education, teacher education
1 | INTRODUCTION

Taking the “practice turn” (Ford & Forman, 2006) in K-12 science classrooms is often described in terms of shifting students from learning about science knowledge to figuring out key science ideas through participation in practices. We take the stance that participation in these practices requires that students develop both explanatory science ideas and practical forms of the epistemologies undergirding science practices (Berland et al., 2016; Duschl, 2008; Lehrer & Schauble, 2006; Windschitl, Thompson, & Braaten, 2008). We also argue that the practice turn necessarily involves students in making judgments about the state of their knowledge and in making decisions about their knowledge-building processes. In this paper, we focus on students’ enacted ownership in making those judgments and decisions as a central component of epistemic agency (Damşa, Kirschner, Andriessen, Erkens, & Sins, 2010; Stroupe, 2014). The epistemic agency is often cited as a key factor in shifting from “rote” to more meaningful forms of participation in science (Berland et al., 2016; Calabrese Barton & Tan, 2010; Schwarz, Passmore, & Reiser, 2017). In this paper, we are interested in ways that teachers might support students in enacting epistemic agency as they engage in scientific practices. However, there is often a felt tension between teaching in ways that support students’ epistemic agency and using standards-based curriculum materials that have been developed with specific learning targets in mind (Hammer, 1995; Hammer, 1997). We are particularly interested in supporting teachers in navigating this tension in ways that ultimately lead to science teaching that promotes students’ epistemic agency.

Two central questions guiding this paper are: how can we support teachers in opening up aspects of their curriculum to involve students in making judgments and decisions about their knowledge-building work? And how does opening up the curriculum influence students’ participation in that work?

In this paper, we present a framework that we position as a tool for supporting teaching that promotes students’ enactments of epistemic agency. This framework is derived from a synthesis of literature on epistemologies in science, teacher practice, and curriculum theory and is refined through case study examination of video of science classrooms. This paper motivates and presents the framework and uses it to interpret three cases of how teachers opened up aspects of their curricular activities and invited students to partner in the epistemic decisions driving classroom activity. In each of the three cases, what teachers opened up had different implications in terms of the resulting impact of the decisions that students made. We conclude with a discussion about the implications, challenges, and affordances of using this framework to support science teaching.

2 | LITERATURE REVIEW

2.1 | The state of science education reform in the U.S.: practices, discourse, and intellectual ownership

Research in science education has long prioritized understanding how learners co-construct knowledge about the natural world, advocating for learning environments that support students’ deep sensemaking around core disciplinary content (Brown & Campione, 1996; Lehrer & Schauble, 2006). This emphasis is drawn from conceptualizations of science as practice (e.g., Pickering, 2010) and of learning as rooted in situated, collaborative social activity (Greeno, 2006; Rogoff, 1993). Current reforms in science education aim to support students’ deep sensemaking through their participation in science knowledge-building practices (National Research Council, 2012; NGSS Lead States, 2013).

One of the key goals of these reforms is supporting learners’ participation in building explanatory model-based accounts of natural phenomena (Lehrer & Schauble, 2006; Passmore & Svoboda, 2012). As embodied by this goal, students should be involved in both making judgments about the state of their knowledge so far and in making...
decisions about how their investigations should proceed accordingly (Duschl, 2008; Ford, 2015; Stroupe, 2014). This specification of what participation involves is important; while the original use of “participation” as a way of characterizing learning (Lave & Wenger, 1991) captured a broad range of goal-directed activity as meaningful participation (e.g., refilling pipette trays and restocking buffers is a meaningful role in a biochemistry lab), the emphasis on participation in knowledge-building practices focuses in on particular types of participation. This specification is supported by turning over varying degrees of knowledge-building responsibility to students (e.g., Calabrese Barton & Tan, 2010; Engle & Conant, 2002; Forman & Ford, 2014; Kelly & Licona, 2018; Scardamalia, 2002). As well, many scholars agree that supporting students’ epistemic agency (as we define it here) is a key goal underlying these reforms and that involving students in this way is a distinguishing factor between “rote” versions of doing science in school and more meaningful forms of participation in science practices (Berland et al., 2016; Calabrese Barton & Tan, 2010; Duschl, 2008; Stroupe, 2014; Svoboda & Passmore, 2013; Windschitl et al., 2008). In this way, the kind of participation intended by these reform goals are those forms in which students take on roles as epistemic agents for their science knowledge building.

Making the shift to teaching science by involving students as epistemic agents in science practices is challenging, as it is a “radical departure” from the kind of teaching and learning that has typified K-12 science education in the United States (Banilower et al., 2013; Corcoran & Gerry, 2011). In particular, making the shift requires learning goals that focus on core science ideas in depth rather than covering a breadth of content; and developing these core ideas incrementally through participation in science practices in which students apply and revise these ideas to explain phenomena (Reiser, Novak, & McGill, 2017). Supporting this new kind of learning requires (for many teachers) new kinds of interaction in classrooms, and new kinds of pedagogical practices to support those interactions (Wilson, 2013). Often, these interactions and practices increase instructional uncertainty for teachers: they are less able to anticipate how a lesson may play out, and they often need to respond, in real time, to the strengths and needs that can vary widely between multiple students or groups in a way that somehow maintains a semblance of coherence and a sense of progress towards learning goals (Hammer, 1997; Manz & Suárez, 2018; Richards, Levin, Atkins, & Robertson, 2015). Undoubtedly, shifting instruction in ways that support students’ epistemic agency is challenging.

2.2 | Defining epistemic agency

Before we discuss how teachers might shift instruction in ways that support students’ epistemic agency in their classrooms, we first discuss more precisely what epistemic agency is and how we use it in this manuscript. We highlight here a few key features of epistemic agency drawn from existing literature that are central to our definition. From research on collaboration amongst small groups of students, Damşa et al. (2010) theorize that epistemic agency is an emergent characteristic of a group that allows the group to make progress on a shared knowledge object, rather than as a trait of an individual. This characteristic is visible in participants’ joint negotiations in interactions that are consequential to the collaborative construction of a shared knowledge object. For example, a small group who routinely checks in on goals and their progress towards them, and subsequently makes progress in constructing a final group paper, demonstrates epistemic agency. It is the dynamic interaction between the individuals, rather than traits or characteristics of any given individual, that indicate epistemic agency.

Work inside science classrooms also suggests that structures within schools convey different expectations about the roles that teachers and students play in deciding what knowledge is valuable and how to go about constructing that knowledge (Miller, Manz, Russ, Stroupe, & Berland, 2018; Stroupe, 2014). That is, the power structures present in schooling inherently assign epistemic agency and authority to teachers rather than students (Apple, 2013; Carlone, Johnson, & Scott, 2015; Varelas, Settlage, & Mensah, 2015). And yet, when teachers retain this agency and authority, there is little opportunity for students to become collaborators in co-constructing knowledge. Positioning students as epistemic agents requires an intentional redistribution of power. Work outside of science education has described this redistribution being accomplished through a teacher intentionally opening
up dialogic space in classroom interactions (e.g., Hand, 2012), allowing for students to be part of these knowledge-building decisions, including when that participation involves forms of resistance.

Based on these characterizations, throughout the remainder of this paper, we will use the phrase "redistributing epistemic agency" to describe our vision for science classrooms. Synthesizing the aforementioned literatures, we view the epistemic agency as a dynamic and multidimensional construct negotiated through interaction, rather than as a binary property that one either has or does not. More specifically, we view student agency in classrooms as "the way in which [a student] acts, or refrains from acting, and the way in which her or his action contributes to the joint action of the group in which he or she is participating" (Gresalfi, Martin, Hand, & Greeno, 2009, p. 53; emphasis added). We add the modifier of "epistemic" because we are focused on the actions (or refrains from action) that are consequential to the collaborative construction of a shared knowledge object: an explanatory account of a natural phenomenon. Finally, we use the verb "redistributing" to capture how the power structures present in schooling make necessary teachers' intentional efforts to open up dialogic space that allows for dynamic negotiation in interactions with students around the joint action of the classroom community and the development of their shared knowledge object (e.g., Colley & Windschitl, 2016; Manz & Suárez, 2018; Stroupe, Caballero, & White, 2018). Put simply, "redistribution" of epistemic agency means more dynamic negotiations, such that students are increasingly involved in guiding the construction of knowledge in their classrooms.

2.3 | Depictions of the goal of epistemic agency in the science education literature

The current reforms in science education in the United States, including the Next Generation Science Standards (NGSS; National Research Council, 2012; NGSS Lead States, 2013) depict science as a complex constellation of practices, which work towards the development of scientific ideas with greater explanatory power (Ford, 2015). The articulation of science as practice is grounded both in a large swath of literature in science studies (Gooding, 1990; Latour & Woolgar, 2013; Pickering, 2010), as well as in sociocultural views of learning (Gutierrez & Rogoff, 2003; Lave & Wenger, 1991; Wenger, 1998) in which knowledge-building processes rely on active, social, contextually situated interactions between members of a learning community (Brown & Campione, 1996; Scardamalia & Bereiter, 2007). In addition, the NGSS also specify learning performances (LPs) that can be used as targets of long-term instruction and assessment, which can help guide both teachers and students in formative and summative assessments of the practices (Gane, Zaidi, & Pellegrino, 2018; Harris, Krajcik, Pellegrino, & McElhaney, 2016; Heredia, Furtak, Morrison, & Renga, 2016). Both the description of the practices and associated LPs reflect the underlying premise that having students participate in scientific practices necessitates that they are involved in developing a set of criteria, methods, and approaches that define their learning communities (Chinn & Buckland, 2012; Manz, 2012; Ryu & Sandoval, 2012). In other words, the theoretical underpinnings of these reforms make students’ epistemic agency a necessary feature of their participation in science practices.

Importantly, building learning environments, in which students participate as epistemic agents, goes beyond telling students about the epistemic criteria or practices used by professional scientists, without first developing a felt need for them within students' own inquiry (Ford & Forman, 2006). That is, we want students to be developing "epistemologies for," rather than "epistemologies of," science: epistemic criteria and reliable processes for their own knowledge building because these criteria and processes are productive for them for building and refining knowledge (Russ, 2014). Thus, students are part of shaping the practices of the community to which their ideas are accountable, and their criteria and processes are meaningful because they are useful and productive to that community.

Recent scholarship has also begun to argue that, in addition to playing a central role in negotiating epistemic criteria and reliable processes, students should be taking increasing responsibility in navigating their own inquiry: making decisions about next steps to be taken and new areas to investigate (e.g., Keifert, Krist, Scipio, & Phillips, 2018; Manz, 2015; Melville, Kerr, Verma, & Campbell, 2018; Reiser et al., 2017; Stroupe et al., 2018). In other words, when students are positioned by teachers as epistemic agents, they not only have a hand in shaping the
knowledge production and practices of their community, but they also play a key role, with support from their teacher, in making key decisions about their arc of the inquiry: for example, deciding what variables to test, why they might matter, the methods by which to test them, and ways to clarify or strengthen their conjectures through subsequent empirical and theoretical testing. These navigational decisions are dynamic interactions that are constantly negotiated, shaped, and embedded within the social context, and subject to change as students encounter new phenomena, generate new inquiry questions, and face uncertainty and challenges in developing explanatory accounts for real-world phenomena.

So how does one ever manage to teach in this way? In the next section, we explicate the theory of action guiding the framework for teaching that we present in this paper: what teaching is, what the work of teaching for epistemic agency involves, and why it’s challenging, and how our framework can help support it.

2.4 Teaching for epistemic agency: our theory of action

Our work is grounded in a view of teaching that situates it as practice, in practice (Ball & Bass, 2000; Cohen, Raudenbush, & Ball, 2003). Teaching involves setting intellectually meaningful learning goals, then helping students learn for themselves: cultivating opportunities for students to interact with each other, with the teacher, and with the material world that allow them to make progress towards those learning goals (Cohen, 2011; Forzani, 2014; Lampert, 2010; Thompson, Hagenah, Kang, Stroupe, & Braaten, 2016). This view of teaching acknowledges it as inherently uncertain work (Ball & Bass, 2000; Hammer, 1997; McDonald, 1992), filled with instructional tensions that teachers must embrace, rather than avoid, in their reflective practice (Ball, 1993; Hammer, 1995, 1996).

More specifically, the moment-to-moment work of teaching requires responsiveness to student ideas in that these opportunities for learning include tasks that surface students’ knowledge resources and help develop them into conceptions (Colley & Windschitl, 2016; Hammer, Elby, Scherr, & Redish, 2005; Russ & Luna, 2013). Responsiveness requires deciding on a repertoire of moves to create opportunities for meaning-making (Richards et al., 2015; Rosebery, Warren, & Tucker-Raymond, 2016); engaging students in tasks that have them represent and inspect each other’s ideas (Colley & Windschitl, 2016); and providing epistemological scaffolding for how to make decisions and judgements about those ideas (Elby, 2001; Hammer, 1994). This work requires a broader pedagogical stance of a teacher as one who is constantly reflective, engaged in practical inquiry, and improvisation in response to students’ ideas, interests, and extant understandings (Cochran-Smith & Lytle, 1993; Forzani, 2014; Richardson, 1994).

Although surfacing students’ initial ideas is relatively easy, helping them to coordinate and develop them into disciplinary ideas can be challenging (Harris, Phillips, & Penuel, 2012; Michaels, O’Connor, & Resnick, 2008; Richards & Robertson, 2015). Doing so depends not only on teachers’ deep conceptual content knowledge, but also their perceptions and judgements about how to make decisions in real time about responding to students’ ideas (Ball, 1993; Hammer & van Zee, 2006; Maskiewicz & Winters, 2012; Russ, Coffey, Hammer, & Hutchison, 2009). These judgments directly influence how and to whom a teacher responds, and determine whether students’ ideas become elevated or overlooked. Examining the nature of teachers’ perceptions and actions is especially critical because students’ contributions may not necessarily sound like intellectually generative science ideas or be communicated in ways that are immediately sensible to the teacher or other students (Colley & Windschitl, 2016; McDermott, 1990; Rosebery et al., 2016; Wallach & Even, 2005). This is especially true for students from nondominant backgrounds who may leverage repertoires of communicative practices that differ from practices that are typically recognized in formal schooling (Calabrese Barton & Tan, 2010; Gutiérrez, Baquedano-López, & Tejeda, 1999; Rosebery, Ogonowski, DiSchino, & Warren, 2010). To effectively advance and deepen student understandings, teachers must navigate the “emergent curriculum” (Hammer, 1997), by considering how these contributions relate to rich disciplinary understandings (Leinhardt & Greeno, 1986).

The work of teaching for epistemic agency adds another layer that needs to be attended and responded to. Teachers will also need to make moment-to-moment decisions about how to respond to students’ ideas about
where to go next. This stance adds to the contingent nature of teaching (Forzani, 2014): rather than the teacher considering the kinds of next activities that might best contribute to students’ intellectual growth in response to their ideas (Fennema et al., 1996; Fennema, Franke, Carpenter, & Carey, 1993), it requires considering when and how to involve students in those decisions (Russ & Luna, 2013). Just like their initial science ideas, students’ ideas about next steps might be partial and self-contradictory.

From this perspective, the goals of teaching also include supporting students in developing disciplinary epistemic considerations guiding their practices (Berland et al., 2016; Ryu & Sandoval, 2012; Sikorski, 2016), taking up students’ initial intuitions and figuring out how to respond in ways that support their epistemic growth. Thus, teaching for epistemic agency asks that teachers also understand the emergent epistemic curriculum: which student intuitions are seeds of productive (and/or disciplinary) criteria, and how to leverage and support those seeds over time, concurrently with supporting the development of students’ conceptual understanding (Elby, 2001; Elby, Macrander, & Hammer, 2016; Redish & Hammer, 2009; Sandoval & Reiser, 2004). As a field, we know very little about what such emergent epistemic curricula might look like, and even less about the kind of work from teachers that might be required to develop and support them.

We also want to recognize that the challenges associated with such increased instructional uncertainty do not simply stem from a lack of knowledge, ability, capacity, or familiarity of practice on the part of individual teachers. Responsive teaching goes “against the cultural grain” (Hammer, 1997, p. 520; see also Forzani, 2014). Teaching that redistributes epistemic agency pushes even more firmly against that grain. Instruction that engages students in developing disciplinary ideas and making decisions about how to incrementally proceed ultimately redistributes how epistemic agency is typically allocated in classrooms and schools. Giving students this latitude requires taking steps away from models of schooling where teachers (or curriculum materials, or administrators) hold the ultimate authority in determining what ideas are valued, how the lesson ought to proceed, and the scope of the disciplinary content that is the focus of instruction (Apple, 2013; Carlone et al., 2015; Hammer, 1997; Varelas et al., 2015). Put simply, shifting epistemic agency requires shifting power. Shifting power opens potentially uncomfortable spaces in educational systems designed with implicit assumptions of certainty and predictability (in measurements of student knowledge, in how a lesson or unit will proceed, in the outcomes of particular interventions, etc.; McDonald, 1992; Rodriguez & Berryman, 2002).

Thus, we view the work of shifting instruction to redistribute epistemic agency as requiring teachers to consider when and how to apply new images of practice to their own instruction (Ball & Cohen, 1999; Lampert, 2010), coupled with explicit recognition of and reflection on the particular tensions and discomforts that may arise for both teachers and students as a result of shifting power (Boaler, 2004; Rodriguez & Berryman, 2002). To support students’ epistemic agency, teachers must develop responsive instruction, as a baseline. In addition, they must develop practices that scaffold students’ epistemic learning while at the same time managing the contingent, uncertain nature of instruction.

Perhaps paradoxically, we also contend that well-designed curriculum materials can help support teachers in redistributing epistemic agency. We explore this contention next and propose a framework as an epistemic tool to be used in conjunction with curriculum materials to support this redistribution.

### 2.5 Use of curriculum materials in teaching for epistemic agency

We focus on curriculum materials as a productive leverage point for teachers in considering how their instruction may begin to shift to redistribute epistemic agency in their classrooms. Curriculum materials are a powerful mechanism for shaping instruction because they specify the set of activities or phenomena that cohere to a set of learning objectives or student performances. In particular, curricular features that support science as practice include a focus on investigating and generating explanations for complex phenomena, the use of discourse to construct and evaluate candidate ideas, and a recursive development and refinement of explanatory accounts through empirical investigations (Krajcik, McNeill, & Reiser, 2008; Manz, 2015; McNeill & Krajcik, 2009; Michaels &
O’Connor, 2012). Rather than seeing “good teachers” as the ones who do not use curriculum or textbooks, we now recognize the importance and value of well-designed curriculum materials in supporting the complex forms of learning that we expect to take place in science classrooms (Ball & Cohen, 1996; Fishman & Krajcik, 2003).

However, the use of exemplar curricula brings a key tension into sharp relief: how can thoughtfully-designed, standards-based curriculum materials that are developed with specific learning targets in mind create a context that supports students’ epistemic agency in terms of their ideas, questions, and plans for doing science?

To answer this question, we focus on curriculum enactment, rather than only the concrete features of the materials themselves. Curriculum enactment is a function of the social interaction between teachers and students, embedded in specific questions or phenomena, and influenced by how schools and districts support and assess teachers and students (Remillard & Heck, 2014). As such, enactment involves the constant work of adaptation and improvisation of curriculum materials (Ball & Cohen, 1999; Ben-Peretz, 1990; Brown, 2009; Brown & Edelson, 2003; Remillard, 2005). Instruction that supports students as epistemic agents requires this kind of responsive adaptation and improvisation, including in the midst of instruction (Drake, 2002; Heaton, 2000; Lampert, 1986). We know that there is great variation in terms of the number and kinds of adaptations that teachers make (Ball & Cohen, 1996; Choppin, 2011; Drake & Sherin, 2002; Remillard, 2000). These decisions can directly influence the epistemic goals and knowledge-building processes that students engage in (Kang, Windschitl, Stroupe, & Thompson, 2016) and the roles that students and teachers take on as part of those processes (Drake & Sherin, 2006). As such, we propose that if the teacher is able to recognize specific curricular components as opportunities for reconsidering their own and students’ roles, curriculum materials can become a supportive tool for redistributing students’ epistemic agency.

A number of recent papers have begun to articulate and explore the tension between supporting students as epistemic agents while enacting carefully designed curricula with prespecified learning targets in responsive ways. For example, Stroupe et al. (2018) articulated this general tension with more specificity. How much uncertainty do we allow in terms of the direction of students’ questions and investigations? When and how should we involve students in laying out the objectives for engaging in practice? And when there are discrepancies between the prespecified goals and students’ interests, which of these is privileged and why? Their depictions of instructors navigating these tensions in practice highlight that there is not necessarily a “right answer,” and how a particular teacher answers them may shift depending on the context, requiring principled design and instructional decisions. Zivic et al. (2018) and Manz and Suárez (2018) each articulate some of the principled design and instructional decisions that need to go into navigating these tensions. Zivic et al. (2018) showed that when teachers enacted curricula that solicited and built from students’ ideas at the inception of their design, the majority of students’ questions were addressed by working toward the learning objectives specified in the materials, emphasizing the inclusion of students’ interests, and careful examination of student thinking as part of the curriculum design process (whether it was designed by teachers or developers). When enacting such curriculum materials, Manz and Suárez (2018) demonstrated how supporting shifts in epistemic agency required that teachers develop the capacity to both design for and manage uncertainty in students’ investigations.

We want to emphasize that in the aforementioned studies, it was not that the curriculum or curriculum materials were in tension with epistemic agency; but rather that epistemic agency needed to be an explicit target of the instructional design work that teachers regularly do. From this perspective, curriculum materials are a resource that teachers can draw on, adapt, and improvise from as they are designing instruction that centers redistributing epistemic agency as a key instructional goal. At the same time, a responsive adaptation of curriculum materials that redistributes epistemic agency creates varying degrees of uncertainty in how science learning unfolds in the classroom. This uncertainty pushes back on the very purpose of clear and tractable learning objectives and outcomes that shape curriculum materials and that teachers are accustomed to designing their instruction around. We argue that navigating this uncertainty requires that teachers develop a new lens when planning, using and adapting curriculum materials. They need to map students’ nascent ideas onto the conceptual space of their science lesson and recognize and support students’ intuitions that are seeds of productive epistemic criteria for
knowledge-building. Thus, in alignment with Manz and Suárez (2018), we argue that teachers need to develop a lens for reading and enacting curriculum materials with an eye towards opportunities for redistributing epistemic agency in the midst of substantive scientific work.

2.6 | Presentation of the framework and design rationale

We present a framework as an epistemic tool for supporting teachers’ planning and reflection on their teaching through such a lens, leveraging their existing curriculum adaptation practices around NGSS-aligned materials. Grounded in our theoretical perspectives of student learning as meaningful shifts in practice (Gutierrez & Rogoff, 2003; Lave & Wenger, 1991; Wenger, 1998) and of the work of teaching as constructing learning-goal-directed experiences for students and responding in real time to the ideas and forms of participation that then emerge through enactment (Ball, 1993; Cohen, 2011; Forzani, 2014; Hammer, 1995; Lampert, 2010; Thompson et al., 2016), we intend this framework to be an object that teachers might use to guide their responsive enactment of curriculum materials in ways that explicitly aim to redistribute epistemic agency. However, we do not intend for this framework to become a static checklist or prescriptive device for instruction. Instead, we present this framework as a “thinking tool” — a living, evolving guide for teachers’ ongoing interpretation and reflection. Second, we emphasize the utility of the framework for researchers. We intend for this framework to help sensitize researchers to “seeing” opportunities to promote students’ epistemic agency in the midst of local practice and to facilitate reflective conversations with teachers about it. Thus, this framework exists as a mediational object between researchers and teachers (Star, 2010), providing an adaptable organizing structure for teachers’ interpretations of their concrete curriculum enactment in a way that makes salient the abstract, theory-driven instructional goal of redistributing students’ epistemic agency. In this sense, the framework lives at the junction of theory and practice, serving as an epistemic tool for supporting both enactment and analysis.

This framework has two primary affordances supporting its function as an epistemic tool: (a) it provides a way of visualizing the epistemic arc of curricular units, potentially helping to support teachers’ sense of the space within which an epistemic curriculum may emerge; and (b) it provides a platform for thinking about opening up space for redistributing epistemic agency at multiple levels, aiming to support teachers’ flexible, principled decision-making in a way that supports their incremental growth in teaching that redistributes epistemic agency.

This framework (Figure 1) is built around a way of visualizing the core epistemic elements of NGSS-aligned curriculum materials: a driving or anchoring phenomenon that sets the goal or problem space for instruction (e.g. Krajcik & Mamlok-Naaman, 2006; Krajcik & Sutherland, 2010; Windschitl & Calabrese-Barton, 2016); a central model or explanatory account that is incrementally revised over time to explain the problem space (Schwarz et al., 2009; Windschitl et al., 2008); the purposeful use of investigation (broadly construed) to incrementally build and refine this model-based account (Ford, 2015; Lehrer, Schauble, & Lucas, 2008; Pierson, Clark, & Sherard, 2017); and the use of discourse, evidence, and argumentation to generate claims and supporting evidence to build and refine aspects of the explanatory account (Berland & Reiser, 2009; Kelly, 2007; Warren, Ballenger, Ogonowski, Rosebery, & Hudicourt-Barnes, 2001). While these components might play out in slightly different ways across curriculum materials, they are broadly taken as consensus by the field as the core features of materials that support “3-dimensional” teaching and learning (see Achieve & National Science Teachers Association NSTA, 2014).

We focus in this paper on the different levels within a set of curriculum materials at which teachers might strategically decide to open up space for student decision-making. Prior work has typically considered epistemic agency at two very different levels: (a) opening up space at the level of classroom dialog: making room for students’ ideas, perspectives and cultural practices to be part of a conversation (e.g., Bang, Warren, Rosebery, & Medin, 2012; Hand, 2012; Warren et al., 2001); and 2) opening up space at the systems level of education (Barton, Tan, & Rivet, 2008; Carlone, Scott, & Lowder, 2014; Hand, 2012; Nasir, Hand, & Taylor, 2008), which invites reflection on who gets to be counted as scientific/mathematical. The two 2018 studies described above (Manz & Suárez, 2018; Stroupe et al., 2018) are notable exceptions that explore gradations of opening up space in between these two
levels to explore how to support teachers in taking incremental steps to shift their practice while designing and enacting curricular lessons units. We see our framework as contributing to this trajectory of explicating gradations of opening up space.

When we use the term “levels” within our framework, we are referring to something like the structural and temporal “levels” at which different components of the curriculum materials exist in relation to the scope and design of the unit (as indicated by the spatial arrangement of these components in Figure 1). For example, the Driving Question or Phenomenon is intended to drive the entire unit. Thus, the Driving Question or Phenomenon is at a high level. In contrast, a specific claim based on one investigation or a related set of investigations is at a lower “level” in that it feeds into an explanatory model, but it may not directly influence an investigation that occurs three weeks later. In terms of epistemic agency, the decisions that students are involved in making about the driving question of the unit will ideally influence, to some extent, all subsequent models, investigations, and claims. At the very least, students’ sense that they were involved in making that decision will be carried throughout, if the curriculum materials are coherently designed to answer that driving question. In contrast, the decisions that students are involved in terms of, for example, how to best measure the speed of a car may only “feel” relevant to subsequent lessons in which they are measuring (or analyzing and interpreting data about) car speed. As soon as they move to investigations of the nature of particular types of materials, there is a new set of decisions that could be opened up for students to be involved in.

We describe the magnitude of influence on subsequent lessons as the “reach” of a decision to open up space. Here, we are only focused on the potential “reach” as afforded by the design of the curriculum materials and the impact of the specific outcome of decisions students are involved in making—which perhaps better described as the conceptual reach, rather than the epistemic one, of that decision. We recognize that there may be important epistemic messages (Russ, 2018) that these decisions convey that would ideally “reach” beyond a specific activity or

**FIGURE 1** Opening up science curricula to redistribute epistemic agency. The impact, or different levels of reach, of opening up these elements can be realized within a single lesson, across multiple lessons, or across an entire unit [Color figure can be viewed at wileyonlinelibrary.com]
unit. For example, decisions about how to measure cars may convey some underlying principles about justification and evidence that could be brought up and reapplied in a new setting (e.g., Ryu & Sandoval, 2012). Even more broadly, the epistemic messages may be contributing to negotiating the epistemic framing of what it means to “do science here” in terms of how students are allowed and expected to participate (Hutchison & Hammer, 2010). Due to empirical and space limitations, we do not address this version of “reach” in this manuscript. We encourage continued empirical work that aims to track and characterize these processes of epistemological development.

The goal of this paper is to demonstrate this framework’s utility in identifying variations in when and how teachers might open up space for redistributing epistemic agency at different levels, and the conceptual reach of these decisions for students’ subsequent participation. We do this by conducting secondary analyses of video of expert teachers’ practice. Within the context of these three rich case studies, we examine the opportunities and challenges raised by opening up space at different levels and discuss the implications, challenges, and affordances of using this framework to support science teaching.

3 | METHODS

To show this framework’s utility in identifying variations in opening up space for redistributing epistemic agency at different levels, we present three case studies that illustrate three potential variations and what using this framework as a lens allows us as researchers to “see” in those data. These cases are drawn from a large corpus of video data collected from middle school science classrooms. All of these classrooms were using a curriculum designed to support students’ participation in science knowledge-building practices (Krajcik et al., 2008). In the following section, we describe the video corpus; the curriculum context; our method and criteria for case selection; and our analysis of the cases.

3.1 | Video corpus

The corpus of video from which we are drawing is a collection of recordings of middle school science classrooms. These classrooms were part of a related series of research projects focused on understanding how students learned to participate in science practices over time. The same schools (n = 5) and science teachers (n = 24) participated in both projects. As a result, this video corpus consists of multiple recordings of the same science teachers in several different years. All students in all of the participating teachers’ classrooms were informed about the study by a member of the research team each year. Parental consent and student assent were obtained to participate in multiple aspects of the research projects. Identifiable images of or vocalizations from students who did not assent or did not have parental consent to participate in the video recording were excised from the data.

Both authors participated in data collection efforts as part of this project: Ko (2014) collected data in 6th-grade classrooms in three of the schools in 2009–2010 and 2010–2011, and Krist (2016, 2018) collected data in all five schools, observing 6th-grade classrooms in 2012–2013, 7th grade classrooms in 2013–2014, and 8th grade classrooms in 2014–2015. Both authors also generated field notes and wrote analytic memos from the classrooms they observed, which fed into other analyses (Ko, 2014, 2013; Krist, 2016; under review). Because of our familiarity with these videos, we chose to only re-examine video that we had used as part of these prior analyses. This involved 73 class periods and approximately 49 hr of video footage. For Krist, this involved 89 class periods and approximately 59 hr of video footage.

3.2 | Curriculum context

The classrooms we observed were all using the Investigating and Questioning our World through Science and Technology (IQWST) curriculum (Krajcik, Reiser, Sutherland, & Fortus, 2013). This curriculum was designed to
engage students meaningfully in scientific practices organized around a driving question and sets of related phenomena (Krajcik & Mamlok-Naaman, 2006; Krajcik & Sutherland, 2010; Windschitl & Calabrese-Barton, 2016). Each IQWST unit begins with a puzzling phenomenon (typically introduced through a demonstration), which provides the context for introducing a driving question (DQ) for the unit. Through whole-group discussions, teachers and students devise a Driving Question Board (DQB) that documents their initial wonderings and questions about the observed phenomenon in relation to the anchoring DQ that shapes the arc of inquiry for the entire unit. The DQ and DQB are designed to support students in monitoring their progress as they interface increasingly complex phenomena and collect additional data through each new investigation to construct, revise, and update their explanatory models.

For example, one IQWST unit centered around the DQ “Can I believe my eyes?” uses an optical illusion as an opening phenomenon to spark discussions about what students see and why. This is used to motivate subsequent investigations of light waves and their interaction with matter. Each class develops a DQB, drawing on students’ inquiry around light and its behavior, which serves as a benchmark for students as they progress through the unit. As well, students generate a preliminary model to explain how objects are seen through their eyes and iteratively refine this model using empirical data as evidence to support each revision. In total, the IQWST curriculum consists of a physical science unit, a chemistry unit, a life science unit, and an earth science unit for each middle school grade level (6th–8th). These units have a spiral design: the principles that are developed in the 6th-grade units are leveraged as building blocks for developing deeper conceptual ideas in the 7th and 8th-grade units.

These materials are explicitly intended to redistribute epistemic agency in the sense that they are designed around the use of students’ ideas and interpretations of data as the substance that drives classroom activity through students’ participation in science practices. However, they do not explicitly support students’ involvement in decision-making about when and how to proceed next. There are notes in the teacher materials, such as suggested questions and prompts, that may potentially promote the redistribution of epistemic agency. But as found in mathematics curriculum materials (Drake et al., 2015), these opportunities for opening up space in the materials are often relegated to the periphery. Thus, these materials require intentional work on the part of teachers to more fully open up space for redistributing epistemic agency.

### 3.3 Case selection

The goal of this paper is to present paradigmatic cases that reveal key elements or dimensions of our phenomenon of interest (Mills, Durepos, & Wiebe, 2010)—here, how teachers open up aspects of the curriculum materials for redistributing epistemic agency in science classrooms at various levels within our framework. In addition, in identifying cases at various levels, we took a diverse cases approach, aiming to highlight the differences (and similarities) between these levels (Seawright & Gerring, 2008) rather than looking for typicality or representativeness.

We first bounded our data set by looking at days of instruction (class periods) that were the beginning of something at each level: the beginning of a new unit, a transition to a new lesson set that was beginning to investigate a new aspect of the phenomenon, or the beginning of a new empirical investigation or experiment. While we recognize that teachers may adjust mid-instruction by choosing to open up space in response to how a lesson is proceeding, we chose to focus in this initial survey on episodes of “opening up” that were likely intentional or planned on the part of the teacher. We then reviewed our prior content logs and field notes from each of these class periods and identified candidates examples of instruction that opened up space for redistributing epistemic agency. Operationally, we looked for instances in which:

1. The teacher did something that diverged from the curriculum materials as written (e.g., modifying or extending an activity, adding a new question for discussion); and
2. Their adaptation increased uncertainty around knowledge and/or procedures that were intended to be taken-for-granted (e.g., presenting ideas or next steps as open to negotiation, emphasizing extreme cases that problematized an otherwise settled idea, regularly expressing their own confusion, skepticism, or disbelief).

We interpret the presence of these conditions as indicators of the teacher working to open up dialogic and epistemic space in their classroom.

In addition, we looked to see whether students took up the invitation to engage in dialog around that opened-up idea. Specifically, we looked to see whether students were generating multiple possibilities for claims or procedures and providing rationales for those possibilities. The presence of this kind of student discourse indicated that students (implicitly) recognized and took up the teachers’ work as opening up a dialogic knowledge-building space.

Our initial scan identified five potential lesson cases; each lesson case consisted of between three and six sequential class periods. We analyzed these five lesson cases as described in the section below, comparing between them to identify the unique aspects of our framework that were opened up and used to redistribute epistemic agency. The three cases presented in this paper each focus on a key moment during one of the class periods in each lesson case. We selected these three moments because they reflect the greatest diversity between these five cases.

3.4 | Case analysis

For each case, we rewatched the video and reread the transcripts to create an additional analytic log with notes and key excerpts about the following questions:

1. What is being opened up to uncertainty (by whom and for whom)?
2. How is this opening up deviating from the curriculum materials?
3. What is the conceptual reach, or impact on students’ trajectory of inquiry, as compared with what is described in the curriculum materials? What are the challenges and opportunities this creates for the classroom teacher?

Because of our paradigmatic, diverse cases approach, we sought to develop rich descriptions of each case along each of these dimensions rather than generate a discrete coding scheme. At the same time, there were indicators that we drew on in developing these descriptions that sensitized us to each dimension. These indicators are described in more detail in the Appendix. We also note that, for this manuscript, our discussion of conceptual reach and the related challenges and opportunities is theoretically driven, based on our framework (Figure 1). Ideally, empirical analysis of this construct would trace epistemic impacts beyond the theorized scope (e.g., throughout an entire content-area unit, or even across units) and would more carefully document teachers’ perspectives on challenges and opportunities.

Both our case selection and analysis processes are driven by our underlying theory of action: when teachers open up aspects of the curriculum materials to student decision making, they provide opportunities for students to take intellectual ownership over their engagement in scientific practices, and in turn, opportunities to redistribute epistemic agency. We discuss each of the paradigmatic cases in detail below, drawn from the classrooms of Ms. K (6th grade), Ms. B (6th grade), and Mr. M (8th grade).

4 | FINDINGS

The three cases presented below reflect diverse variation in levels of what was being opened up to redistribution of epistemic agency. Based on our framework (Figure 1), the cases illustrate three levels of “opening up”, including (a) making uncertain the methods for investigation; (b) generating alternative claims
which, in turn, motivates model revision; and (c) expanding the explanatory goals of the unit. In presenting each case, we first describe the lesson as presented in the curriculum materials. We then provide a brief narrative account of how the lesson played out, both in terms of what the teacher “opened up” and how students responded. Finally, we present an interpretive commentary on the account that addresses the relationship between the aspect that was opened up, the nature of students’ resulting participation in terms of epistemic agency, and the challenges and opportunities for the classroom teacher.

4.1 Case 1: opening up space for developing methods for investigation (Ms. K)

4.1.1 Case context and lesson as written

This lesson took place in the spring semester of the 6th-grade IQWST chemistry unit centered on the driving question, “How can I smell things from a distance?” The unit is intended to span multiple weeks and explore the molecular nature of matter. Rather than starting by introducing students to the particle nature of matter, the unit begins by having students explore a variety of phenomena to develop a model of how people smell odors. This model is then used to explain the behaviors of solids, liquids, and gases. The model that is generated and revised throughout this unit reflects the understanding that matter is made of particles that are in constant motion.

The focal lesson for this case occurs about one-third of the way into the unit, as students begin to consider how their initial model of gases might need to be modified to account for the behavior of liquids. As specified in the curriculum materials, the lesson asks the teacher to begin with a demonstration that involves two unlabeled flasks of clear liquids. Students are asked to generate observations that can potentially differentiate between the two liquids, and the materials state that students “should recognize that further investigation is needed” (Sangari Active Science, 2013a, p. 121). The teacher is then asked to demonstrate how an indicator paper, like other detectors explored in lessons prior, detects the presence of different materials by changing colors. The teacher would then carry out a demonstration that shows that the two liquids are different by placing the indicator paper into the two flasks. Because one flask contains ammonia and the other acetic acid, the indicator paper will turn blue and red, respectively. Thus, the indicator paper provides observable evidence that the flasks contain different liquids. The indicator paper is also used to motivate model revision: teachers are asked to place the indicator paper inside each flask by attaching it to the end of a stopper to show that the vapors from the liquids also cause a color change. Students are then asked to “create a model that can be used to explain what made the indicator paper change color without being submerged into the liquid” (Sangari Active Science, 2013a, p. 122). Although the curriculum materials imply that students’ initial observations should be used to motivate the need for further investigation and model revision, providing students with the agency to suggest or explore methods is not written in the materials.

4.1.2 Lesson enactment: what was opened up?

In alignment with the instructions outlined above, Ms. K began the lesson by showing students the two unlabeled containers of clear liquids. She then asked her students, “...how can we tell the difference between these two sources of odor? Who can tell me? What’s different? Let's put a list on the board here of what's different between these sources of odor.” After the students identified their similarities (e.g. both liquids were clear) and differences (e.g. one seemed “foamier” than the other), Larry conjectured that the two flasks might contain different liquids. Ms. K then asked how they might Test Larry’s claim, saying, “They might be different types of liquids. How can we figure that out? How could we tell?” Rather than jumping in and using the indicator paper to show that the liquids were different, Ms. K’s invitation after Larry’s claim opened up the opportunity for students to be involved in deciding on the method for investigating whether the two were different.
Students took up Ms. K’s invitation by proposing a variety of ideas for investigation, such as smelling, shaking, freezing, weighing, and tasting the liquids (to which Ms. K responded that this was not allowed in the science lab) to determine whether they were the same or different. One student proposed combining each liquid with another chemical to see how they react or weighing the two flasks to detect differences in density. Finally, Steven suggested a method of investigation that mirrored how the indicator paper was intended to be used:

Steven: So you could get a turkey baster or a syringe or something, and then put [it] in there, take some of the liquid, and put it on a paper and do the same thing with the other one. And then if something different happens, then you’ll know the difference between what it is.

It is important to note that Steven not only suggested the materials that could be used (turkey baster, syringe, paper) and how they might be used but also what the results of that investigation would tell them about those two liquids. Inviting students into this study had important epistemological implications because students were invited into making decisions about how they might go about investigating the difference between the two liquids, which would then impact the type of data that might be used as evidence to support alternative claims.

Ms. K responded to Steven’s suggestion by saying, “Oh, you made me think of something.” She retrieved litmus paper from a cabinet, telling students that she had a “detector paper.” After describing how the paper worked to students, they agreed that it could be a good way to test whether the liquids were different. She then proceeded with the demonstration as written in the curriculum materials, showing how one paper turned red while the other turned blue. Ms. K then placed the indicator inside each flask, and students observed a similar color change when the indicator paper was hanging above (but not touching) the clear liquids inside the two flasks. Ms. K then used these observations to motivate a closer examination of the mechanism underlying this change, saying, “Take a look, okay, because something happened. Even though the paper is not touching the liquid, how is that possible? How is that possible?” Ms. K then had the students turn to their worksheets to begin constructing a model, building off of their consensus model of gases, that could account for these observations.

The open, co-constructed nature of their investigation thus far came to a halt as they turned to the worksheets to begin drafting their models. Betty read the worksheet’s directions for model construction out loud: “In class you observed the indicator paper changing color without dipping it into the liquids in the flask...” She then paused and exclaimed, “Wait, that was all planned?!” The mention of the indicator paper was startling because up to that point, the decision to use the indicator paper had felt like a collective, in-the-moment, decision that relied entirely on the student input, as opposed to something that was predetermined and scripted by the curriculum materials. In response, Ms. K went on to reassure the students of the value of their input, saying, “You know what, though? I tell you what. It is planned, but if you guys had not come up with that plan, we would not have done it.”

Opportunities and challenges

In this lesson, Ms. K opened up the methods for investigating the differences in two unknown substances. She positioned students’ initial conjectures that the two liquids were different as in need of further inquiry (“they might be different...”) and then collectively engaged the class in brainstorming tools and methods for inquiry (“how can we figure this out?”). The students, in turn, proposed multiple possible methods for carrying out an investigation. Involving students in the work of planning the investigation and generating the alternative hypotheses also enabled them to elaborate on the implications for the results they would obtain from the investigation. Ms. K’s adaptation of this lesson enabled students to identify a need to investigate whether the two liquids were, in fact, different and to determine the appropriate methods and tools for collecting evidence for their hypotheses. The conceptual reach
of Ms. K’s decision (Figure 1) resides within a single lesson because it directly influenced students’ participation in the immediate investigation within the lesson.

Opening up the methods for investigation introduced some level of uncertainty to Ms. K’s plans for instruction. The similarities between Steven's proposal and the indicator paper specified by the curriculum minimized the adaptations that were needed in order for the class to continue toward the predetermined goals of the lesson and unit. However, in light of the students’ numerous proposals, Ms. K focused their efforts on carrying out the method most closely aligned with the one specified by the curriculum materials, minimizing the need to engage in on-the-fly adaptation of the goals and instructions for the remainder of the lesson. Ms. K’s fluid movement between students’ ideas and the written lesson also had important implications for the degree of redistributed agency felt by the students. Betty felt “tricked” when she realized that their collective efforts were in fact planned all along, even though Ms. K reassured them otherwise. Betty’s response indicates that while the discussion may have felt genuinely open-ended in honor of students’ proposals, Ms. K’s decision to enact the curriculum as designed may have felt disingenuous to Ss’ ideas, causing students to question whether or not they had “true” ownership over the process.

4.2 | Case 2: opening up space for generating alternative claims and motivating model revision (Ms. B)

4.2.1 | Case context and lesson as written

This lesson comes early in the 6th-grade physical sciences unit centered on the driving question “Can I believe my eyes?” (Sangari Active Science, 2013c). The unit begins by introducing a set of optical illusions that seed uncertainty about what students really see. The first set of lessons explores the behavior and properties of white light as it "interacts" with various objects and progresses to explorations of how light moves, how light is detected by the eye, and how light is perceived. This lesson set results in an initial model for how light allows us to see (Figure 2). Over the course of the remainder of the unit, students co-construct and refine this model to account for different types of objects and different colors of light. Notably, this unit is used in the Fall semester, and it is students’ first introduction to the science practices that are emphasized in the curriculum, including modeling. Thus, there are a number of lessons dedicated to discussing what counts as a scientific model and to explorations of how to depict ideas and relationships in model form, as well as the various types of models that count as a scientific model.

**FIGURE 2** Ideal consensus model at the end of the first lesson set for how light allows us to see by traveling from a source, bouncing off an object, and entering the eye. Reprinted from Sangari Active Science (2013c)
The focal lesson for this case is the first lesson of the second lesson set after the class has settled on the above consensus model. (This would be represented by the beginning of the Box B in Figure 1). The lesson as written has the objective of generating evidence about the difference between the ways light bounces off a mirror and off paper. It begins with a demonstration of shining a flashlight on a piece of paper and on a mirror. After students generate observations about the differences, the lesson then moves into an investigation using a light meter to determine the amount of light that is reflected at various angles off a mirror versus off paper. The goal of these data is to show that the angle at which light hits the mirror’s surface is identical to the angle at which it is reflected (also known as the Law of Reflection), whereas for paper, light bounces off at various angles (it scatters). From these data, and a few other investigations, students refine their model to show that light reflects off smooth surfaces like mirrors and scatters off rough surfaces like paper (Figure 3).

4.2.2 | Lesson enactment: what was opened up?

In line with the written curriculum, Ms. B began the lesson with a demonstration. She turned off all the lights in her classroom and closed the blinds and aimed a flashlight at a piece of white paper taped to the whiteboard, and asked students to explain why they were able to see the paper. She then directed the beam of light at a handheld mirror, rotating the mirror so that it reflected the light around the room, and (to the students’ dismay), directly at some students’ eyes. They made some observations about what they saw and jokingly asked her to direct the light at specific students.

Then, instead of moving directly to the activity involving light meters as written in the curriculum materials, Ms. B engaged her students in a whole-class discussion that spanned half of the class period. During that discussion, she explicitly used the differences in how light was behaving with a mirror and a piece of paper to problematize their current model by persistently pressing students for how and why it was behaving differently. For instance, when Ms. B directed the beam of light toward the students, who reacted by laughing, grimacing, and talking over one another, Ms. B called out this discrepancy, saying, “When I [aimed the light at the] paper you were not yelling.” Students responded by saying it was bouncing off the mirror, using language from their consensus model. Ms. B. continued to push, calling out their use of the same term to describe both interactions:

Ms. B: ...I mean, you said the light was bouncing off paper and going into your eyes...

Illana: When you use paper, it’s just shining (inaudible) but when it hits the mirror it’s bouncing...

Ms. B: So why does it do it for a mirror and not for a paper?

(Many hands raised in the front of the room)

Illana: Cause the mirror is like, if we look you can see your reflection...

Ms. B: ((to Illana, who seems stumped)) Why? ... Anne?

FIGURE 3 Ideal revised model at the end of the second lesson set. Reprinted from Sangari Active Science
Anne: Because that's the mirror and... (inaudible) its cuz the light... (inaudible) light anymore because some light (inaudible)

Ms. B: So is the light hitting different objects differently?

Students: ((in unison)) Yes

....

Ms. B: But how does light know that? How does light know... to act differently when it hits this ((pointing the flashlight at the paper)) and react differently when it hits this ((pointing the flashlight at the mirror))?2

Ms. B used this demonstration and the discussion that followed to point out the insufficiency in their existing model, opening up their "settled" knowledge for further exploration. She did this by pointing out the gap between what they saw (light behaving differently with different materials) and their model thus far (which did not distinguish between materials). Through this discussion, she eventually got students in agreement on what they needed to explain: how and why the light was bouncing differently. In turn, this opened up space for students to begin to refine their model by generating potential claims and candidate investigations.

4.3 | Students’ participation: how did students take up epistemic space?

Students responded to Ms. B’s invitation by proposing candidate explanations. First, students began generating some conjectures about factors that could influence the different ways of bouncing:

Ms. B: Why do you think it's different...[referring to mirror versus paper]

Alden: Uh I think it's different cuz when it hits the paper its carrying a - there’s kind of photographic message ...

Alex: I was going to say that you could see the flashlight on the mirror is brighter because that's what glass is made out of...

....

Georgie: Because um the mirror is MADE to do that, the paper is made for only... (inaudible)

After students generated several candidate explanations, Ms. B said, "Ok, a couple more ideas and then we’re going to try to—should we get some data, collect some more information about this? Try to figure this out?", positioning their upcoming investigations as a way of generating evidence for this new problem with their model.

Students responded to this proposal by generating some additional questions about light. Nina said, “Well, I just have a question. When you’re looking at something straight in the mirror when there's light behind you, would it still bother your eyes?” Ms. B. had Nina write her question on a sticky note and add it to the DQB. While she was doing so, Anne tried to address Nina’s question:

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2Transcription key: (()) indicate nonverbal behaviors. Ellipses [...] indicate excluded transcript.
Anne: Cause you--you put the light in the mirror, it might not go into your eye, but if you put it in the right direction, it would go to your eye, like (inaudible).

This idea about the directionality of light coming off of a mirror is the key idea that the next planned investigation aimed to address, and Ms. B picked up Anne's idea:

Ms. B: So should we try this and put a light to the mirror and see where it goes (Ss: Yeah) and then we can identify it? (S: Yeah, we should do it). Ok. So let's do it.

They then began the next investigation, as planned in the curriculum materials.

4.3.1 | Opportunities and challenges

Ms. B's continued press for how and why encouraged students to propose alternative claims about what might be causing the observed differences in how light behaved with a mirror and with paper. Her questions also worked to highlight how the opening demonstration directly challenged their existing model and emphasized that their current model was unable to account for this difference. Notably, the curriculum materials specify that this demonstration should be used to help students see that light behaves differently when it interacts with these two objects, but it does not specify that these observations could be used as data to motivate a need to modify their existing model. Opening up their model to uncertainty in this lesson had a conceptual reach that could be felt in subsequent lessons: by encouraging students to generate candidate claims about why light might be behaving differently with these two types of objects, and Ms. B positioned their subsequent empirical activities (the next investigation, and all subsequent investigations in the lesson set) as opportunities to generate evidence to refine that model (see Figure 1). Thus, the conceptual reach of inviting students to propose alternative claims could be felt across multiple lessons within the unit.

Inviting students to contribute alternative explanations also required that the teacher be able to navigate and, if possible, anticipate those alternatives and their relationships to the arc of inquiry in the written curriculum materials. There was also the possibility that students would not offer up suggestions that could lead to advances in their model construction, in which case the teacher must decide how to proceed. Navigating the landscape of possible trajectories requires a deep familiarity with curriculum and trajectory and how each investigation advances students toward the target explanatory account, as well as the ability to predict some degree of the landscape of possible responses that students might generate. Finally, teachers face the challenge of honoring each students' contributions in light of the teacher's and the curriculum's goals.

4.4 | Case 3: opening up space for expanding the explanatory goals (Mr. M)

4.4.1 | Case context and lesson as written

This case took place during the first few days of an 8th-grade biology unit on genetics and inheritance (Sangari Active Science, 2013b). The unit is organized around the driving question, “Why do organisms look the way they do?” Over the course of the unit, students work to build a Mendelian model of genetic inheritance.

As written, the first lesson in the curriculum begins with a few exploratory activities that lead up to the building of a DQB for the unit. The first activity has students look at photos of fish, birds, and plants, speculate about the functions of their different traits, and discuss variations of traits. The second activity has students brainstorm different human traits, identify variations in those traits, and survey the class for frequencies of the human traits of hitchhiker's thumb, attached versus detached earlobes, widow's peak, and right versus left thumb overlapping with folded hands. As part of this conversation, the materials suggest that students might discuss whether these traits were inherited or acquired. Then, students would ask questions and build a DQB. The curriculum materials suggest that the DQB might look like the diagram in Figure 4, and that all of these activities would likely take 2–3 class periods.
4.4.2 Lesson enactment: What was opened up?

Mr. M knew from experience that the traits of fish, birds, and plants were not very compelling, and while he did show the photographs, he planned to move very quickly to the conversation about human traits. He also planned that instead of having students only collect data on the four traits specified in the materials, he would have students select an observable human trait of interest to them and select a population amongst whom to observe it (e.g., their family members, patrons of Burger King, the first 100 results of a Google image search for “celebrities,” etc.).

As he had planned, Mr. M moved quickly through the pictures of birds and fish to human traits. The idea of inherited versus acquired traits came up very quickly in this context, and it was very contentious. A debate about it lasted for two class periods and continued throughout the next three days as they discussed the data from their trait observations. Centering the conversation around human traits of interest to students led to a spontaneous decision on the part of the teacher to reorient the unit around a set of family cases, as we will see in the following section. Overall, Mr. M made a series of decisions that opened up the anchoring phenomenon for the unit, which led to a student-driven shift in the driving question for the unit. This shift then required a series of downstream decisions about the format and necessity of upcoming activities.

4.4.3 Students’ participation: How did students take up epistemic space?

As mentioned, the discussion about inherited versus acquired human traits became very contentious. One key debate began about whether height was inherited or acquired. A student said that he thought height was inherited: if your parents are tall, you are likely to be tall, and if they are short, you are likely to be short as well. Several students immediately responded to this claim with counterexamples from their own families: a sibling who was very tall even though their parents were short, or a mother who was short but an aunt who was tall like them. In addition, a few students brought up ideas about nutrition, such as that they should not drink coffee because it would stunt their growth, or that they should drink milk because it would make them grow tall and strong, leading

![Diagram](figure4.png)

**FIGURE 4** Suggested driving question board arrangement and sample questions, as printed in the curriculum materials. Reprinted from Sangari Active Science (2013b)
them to argue that height was (at least partially) acquired. Still, other students argued that it was totally random: height was unpredictable based on either your parents or grandparents or from your nutritional choices.

Mr. M allowed this discussion about height to continue for nearly the entire 40-min class period. Towards the end of class, he made a move to transition the class into the planned data collection activity (Activity 1.2) while still leaving open the possibility of continuing the discussion:

Mr. M: I'm not going to resolve this but I'm feeling like, if this is becoming a compelling question, ... if we're going to figure out if something is random, I feel like we should collect some data. So uh. Let's take a couple more comments and if we're kind of moving towards that "what's the pattern" question, then I want to move to [Activity] 1.2. If not, if we've just got, if we're generating some questions, cool, let's do it now. So um. ((points to Carmen)) Did you have--?

In response, Carmen brought up how her hair was very similar to her aunt's but not to either of her parents' and she asked if inheritance could work that way rather than only through parents and grandparents:

Carmen: I actually wanted to make a counterargument—like you said not aunts and uncles, but like I have really wavy and like sometimes curly hair, but like my mom and my sister and my dad all have like the straightest hair, but like my aunt has really curly hair like me, so like, can not like that be a thing too?

Mr. M: So are you saying you got it from your aunt? Or what about that? (points to the word "ancestor" on the board)

Carmen: I don’t know if it was from an ancestor, but I'm my aunt's daughter. Like I look like my aunt.

Mr. M: But...that's not the case though, right?

Carmen: No ((laughs))

Carmen's input was a direct interruption to Mr. M's bid to "move on" to the next planned activity, and to Mr. M's insistence earlier in the conversation that students stick to "direct" lines of inheritance (parents and grandparents), as indicated on the suggested DQB from the curriculum materials. In response to Carmen's push-back, Mr. M pointed out it sounded like there was a pattern that a lot of people were noticing: they had traits that did not come directly from parents or grandparents. Mr. M then explicitly acknowledged the push-back they had been giving him and allowed the four students who still had their hands up to share their ideas:

Mr. M: Let's, here, so, I've been trying to pull us in a certain direction, I like where you guys are pulling us though, I like that you're wanting to stick with examples from our own families. In our last four I want us to make sure that you're turning to our speakers ..., so I want us to face this way and let's go to Elena.

The bell rang after Elena shared. Before they left, Mr. M spontaneously decided to give each student an index card and asked them to record the patterns from their families that they thought were important "clues" to helping them understand inheritance. When students returned the next day with their index cards with family patterns, they made a second driving question board with those "family cases." As they were constructing this driving question board, the discussion about whether each trait mentioned was inherited or acquired continued, including conversations about traits, such as athleticism, spoken language, and race. After another entire class period of this discussion, Mr. M asked students to pick one of these traits to observe and to pick a population in which to observe it, over the course of the weekend (his modified version of Activity 1.2, as he had initially planned). They spent two
more class periods discussing the data from these observations and continuing to build the DQB and the family case board. In total, “Lesson 1” took five class periods, or about twice as long as suggested by the curriculum materials.

Mr. M’s decision to allow the classroom conversational space to be opened to students’ persistent interest in the patterns in their own families, and his in-the-moment response to create a second driving question board, broadened and made more complex the anchoring phenomena that students were trying to explain. In addition, his doing so allowed students to decide, through co-construction in the conversation, what kind of explanation they were going to be working to build over the course of the unit. This was no longer a unit about different traits in different species or differences between humans in obscure traits like hitchhiker’s thumbs. Instead, it was a unit about complex patterns of inheritance within their own families—the thing that was both interesting and bothersome to them. It set the expectation that whatever models they were developing should be able to at least partially explain these complex patterns, and that whatever their models could not explain should drive their future investigations. In other words, the conceptual reach of Mr. M’s decision could influence the entirety of the unit. And that was the case: students continued to draw on family-based examples throughout the unit, even while discussing the genetics of plants and moths.

4.4.4 | Opportunities and challenges

By opening up the explanatory goals of the unit, Mr. M was able to cultivate a sense that students’ interests and/or concerns could be the focus of their work in class. This likely contributed to increased student buy-in to the unit. In addition, allowing for additional complexity around the driving phenomena made it more scientifically authentic, as not every genetic pattern follows simple Mendelian inheritance. Centering that complexity around family cases also created opportunities for conversations about race, cultural heritage, and ethics, which are often missing from biology education (Donovan, 2015). Finally, this case reflects what we might consider a “strong case” for redistributed epistemic agency in that we can see the power dynamics at play in students’ talk: they explicitly pushed back on where Mr. M was trying to pull them, and Mr. M explicitly acknowledged their push-back.

At the same time, opening up the explanatory goals of the unit created challenges. We have presented a (fairly) “clean” narrative of what happened in class. The full transcript is incredibly messy and difficult to follow, with jumps of topics across speakers and even across class periods, claims and questions left hanging, and sidebar conversations that inexplicably became lengthy tangents that were then dropped. Mr. M was engaged in (and arguably, contributing to) this messiness, primarily by asking clarifying questions and monitoring turn-taking. From the nature of his questions and his explicit meta-talk, it was often quite clear that he was struggling in the moment to figure out (a) what exactly students were wanting to talk about and why it mattered to them; (b) whether and how their ideas and interests were related to the rest of the unit as planned; and (c) how to respond to students’ ideas and suggestions in a way that honored and genuinely built on what they were talking about so that the rest of the unit would not feel artificial—an attempt to avoid, among other things, the sense of feeling “tricked” that Ms. K’s students experienced. While Mr. M was quite comfortable with—and often seemingly invigorated by—this messiness and tension, other teachers may be fearful of wading through such complexity or feel anxious about their ability to navigate a substantive pathway through it.

In addition, the extent of the conceptual reach, in this case, is daunting. Because opening up the driving question of the unit has implications for the entire unit (Figure 1), it meant that Mr. M set himself up for constant re-evaluation of lessons and activities to ensure that they still contributed to the goal of explaining patterns of family inheritance. In addition, he set himself up for possibly needing to supplement with some lessons to address some nuances or additional aspects of these more complex cases.

At the same time, Mr. M’s “opening up” was incredibly strategic, informed by his deep knowledge of the curriculum content and goals. He knew that the model of inheritance they were aiming to develop could be used to explain patterns of inheritance in families in a way that would be satisfying for 8th graders, even if it could not
explain the full complexities of the genetic basis of eye color or hair texture. In addition, he himself seeded this focus by expanding the opening phenomena and adding a more open-ended data collection activity. Thus, students’ push-back in this case was a request to continue moving in a direction that he had already set up for them. They were interested in going further in that direction than he anticipated, but the direction itself was not unexpected or unproductive. This kind of strategic opening up, done in conjunction with deep knowledge of the curriculum materials, likely alleviated the daunting sense of instructional open-endedness and uncertainty that can accompany teachers’ work to redistribute epistemic agency.

4.4.5 | Summary of cases

In each of the three cases, what teachers opened up had different implications in terms of their conceptual reach: the potential impact of the decisions that students were involved making (Table 1). Ms. K opened up the methods for investigation in Case 1, creating the opportunity for students to shape how they conducted the investigation and the claims they could draw from it. In Case 2, Ms. B problematized their existing model of light, which opened up space for students to make alternative claims. These decisions framed their subsequent investigations for the next few days, leading to revisions to an aspect of their light model. Finally, in Case 3, Mr. M opened up the opportunity to expand the phenomenon that anchored the entire unit. The reach of this decision was long-ranging: even though his students completed most of the activities in that unit as written, they were framed by, and constantly connected to, a need to explain the puzzling patterns of inheritance that students observed in their families. Although none of these cases were instances where students did the “opening up” spontaneously or intentionally (cf. Calabrese Barton et al., 2013; Engle & Conant, 2002), these cases illustrate how teachers can open up space within the constraints and boundaries of the curriculum (Figure 1) to create opportunities for incrementally redistributing epistemic agency.

5 | DISCUSSION

We began this paper with two guiding questions: how can we support teachers in opening up aspects of their curriculum to involve students in making judgments and decisions about their knowledge-building work? And how does opening up the curriculum influence students’ participation in that work? The cases we presented reflected variations in what it might look like to involve students in making judgments and decisions about how their scientific work should proceed. We discuss the implications of these variations next. We also discuss some of the affordances and limitations of the framework we presented, and the implications for how we might think about using it with teachers as an epistemic tool for supporting teaching.

5.1 | Implications for redistributing epistemic agency in science classrooms

The variations highlighted in these cases make salient the tensions and trade-offs that teachers encounter when opening up space for redistributing epistemic agency. These tensions are, perhaps, a reframing of the felt tension between teaching for epistemic agency and teaching using standards-based materials. Rather than viewing these forms of teaching as mutually exclusive, we see this tension as an integral part of the interpretive decision-making work that teachers regularly do. In other words, this tension should not be avoided or chosen between, but rather embraced. Our framework embraces this tension by centering intentional consideration and reflection on decisions about redistributing epistemic agency as part and parcel of teaching science. The cases presented here vary in when and how these redistribution decisions were enacted and indicate the multiplicity of such decisions while teaching.
At the same time, there were some common themes in the tensions across all three cases. Teachers all ran into, in some form or another, the need to ensure that students felt like their decision-making was actually consequential, even if activities were planned. These teachers were running up against a version of what Miller et al. (2018) described as pseudoagency: students were given space to make decisions about constructing knowledge products, but only to the extent that the science knowledge that they built was expected or canonical (p. 18). We might add also: to the extent that the science knowledge was expected such that its alignment with future plans was clearly evident to the teacher. Where this line is drawn—what “counts” as pseudoagency versus what is thoughtful, responsive teaching—is often fuzzy and unclear. Navigating this line is perhaps the best reflection of the teaching tension to be embraced in opening up space for redistributing epistemic agency.

The impacts of navigating this decision might be seen here in students’ affective responses: in Ms. K’s class, for example, she picked up on and amplified the suggestion for a method that was expected. As a result, her students felt like they had genuinely decided on a method to use; when they saw that it had been expected all along, they were surprised. This likely called into question the extent to which they had really made a decision, perhaps undermining their sense of ownership. Without student interview data, it is hard to know exactly the nature of students’ reactions. But it is clear that there was an effective component at play. This case suggests that, in addition to the potential for excitement, challenge, and pride that comes with knowledge-building work (Jaber & Hammer, 2016), decision-making about how to proceed is also effectively laden. Determining “what counts” as pseudoagency versus not (if this is even the right question to be pursuing) should be based on close empirical examinations of students’ affective experiences in these kinds of science classrooms.

We point out, also, what we did not see in these cases in terms of redistributing epistemic agency. We did not see students doing the “opening up” spontaneously or intentionally, such as how Engle and Conant (2002) described students’ long-standing debate about orca whales or the explicit kinds of identity work that Calabrese Barton et al. (2010) identified as students actively sought to “make space” for themselves in science. Our cases also did not demonstrate epistemic agency that made an impact on the world in the way that socio-political stances towards science education argue for (Calabrese Barton & Tan, 2010; Miller et al., 2018; Roth & Lee, 2004). In part, this is due to the fact that the classroom contexts examined here were not explicitly designed to invoke this kind of student participation. For this manuscript, this was intentional, as we were selecting cases to see the possibilities for incremental steps in opening up spaces for redistributing epistemic agency that teachers can take. But we do not want to lose a broader, more expansive and justice-focused vision for what redistribution of epistemic agency can look like.

### Table 1: Overview of cases

<table>
<thead>
<tr>
<th>Case</th>
<th>What aspect is the teacher opening up?</th>
<th>How do students participate?</th>
<th>Reach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>The methods for investigation</td>
<td>Students brainstorm candidate methods &amp; tools that will generate evidence to help distinguish two unknown liquids</td>
<td>Within the investigation in a single lesson</td>
</tr>
<tr>
<td>Case 2</td>
<td>Their current explanatory model for light</td>
<td>Students propose alternative claims for the observed phenomenon. This leads to a new phase of evidence collection and subsequent model revision in later lessons</td>
<td>Investigations and model revision within days of a single unit</td>
</tr>
<tr>
<td>Case 3</td>
<td>Anchoring phenomenon that motivates explanatory goal</td>
<td>Students continued to bring up puzzling patterns of trait inheritance in their own families, which eventually become part of the anchoring phenomenon.</td>
<td>Influences explanatory goals (and models, investigations, and claims) for the entire unit</td>
</tr>
</tbody>
</table>
5.2 Affordances and limitations of the framework and implications for it as an epistemic tool

By applying this framework to analyze video cases of expert teachers’ practice, we demonstrated its utility in identifying variations in when and how teachers opened up space for redistributing epistemic agency. Based on these cases, we discuss the affordances, limitations, and the next steps for utilizing this framework in support of students’ epistemic agency.

5.2.1 Affordances

We argued that one of the “needs” for teachers to be teaching in this way was to have a mental “mapping” of the epistemic dimension of the curriculum, in addition to a map of the conceptual space. The diagrammatic representation of this framework provides a way of beginning to visualize some of that dimension. It provides a way of thinking about curriculum materials in terms of how knowledge elements are built up and related to each other in a concise and generalizable way: it can be used across multiple sets of curriculum materials. This snapshot also allows teachers to consider epistemic “opening up” in relation to other factors they consider anyway (students, beliefs, their knowledge of how curricular elements fit together, their own capacity, etc.), tying them in as a legitimate rationale for a decision with respect to redistributing epistemic agency. We are excited about the possibility of using this framework to broaden the definition of educative curricula (Davis & Krajcik, 2005) to include supports for teachers in identifying decision points within the curricular arc to shift students’ participation and ownership in the intellectual work at various levels. In this context, the framework can help provide a vision for growth, making visible how teachers can think about making incremental change.

5.2.2 Limitations

However, there also are challenges that may come with using this representation. Is it truly generalizable? We have used it only in classrooms using the IQWST curriculum. Although the framework reflects agreed-upon features for NGSS-aligned curriculum design, there may be bugs that come with attempting to map specific curriculum materials to it. In addition, there are ways in which it may be too general. For example, it does not specify specific epistemic criteria or aims (e.g., Berland et al., 2016; Pluta, Chinn, & Duncan, 2011) or related decisions that might be important for students to make, such as deciding on a “fair test” during an investigation (e.g., Ryu & Sandoval, 2012) or figuring out the “sweet spot” of an interesting and investigable problem space or set of questions in response to a driving phenomenon. In addition, it is currently agnostic about the particulars of the content that is opened up. It does not explicitly indicate or provide a support for careful consideration of which lessons to open up in terms of their centrality to DCI (i.e., we would ideally want teachers to decide to “open up” a model that serves as a more central fulcrum for the unit rather than one, i.e., less central or more of an extension). Although a framework with this degree of flexibility and generality may be in alignment with arguments that capturing a grasp of the big picture of science inquiry is more effective than focusing on each individual component of it (e.g., Lehrer, Schauble, & Petrosino, 2001), empirical studies looking at the use of this framework in a PD context with teachers are needed to refine the generality or specificity of these features such that they are useful.

Along these lines, the framework does not provide specific strategies or guidelines for how to consider opening up space for redistributing epistemic agency. Again, this was, in part, intentional: we did not want to prescribe strategies without the empirical and practical backing of their effectiveness. It is also important to maintain the nuance that more is not always better: opening up more space, at more levels, for redistributing epistemic agency may not always be an effective approach. In many cases, “more space at more levels” is probably a recipe for
disaster. There are likely some heuristics, or rules of thumb, that teachers might use as decision-making guides in practice. These questions should be explored through empirical work with teachers.

5.2.3 | Consequences of opening up curricula: Problems of practice

Additional problems of practice may arise for teachers who use this framework to identify opportunities for opening up their enacted curriculum. For example, teachers will need to be open to adapting their pacing, intended coverage, and/or amount of time spent on the unit overall as they attend to the range of student responses that emerge as teachers open up different components of their lessons or units. We see these potential adaptations, and the associated stresses and challenges, as a necessary tradeoff to disrupt the typical power dynamics that pervade science classrooms. We hope that the framework is a helpful tool as teachers navigate this learning curve.

Furthermore, opening up curricula is a necessary but (on its own) insufficient practice for redistributing epistemic agency. If teachers open up space and continue to look for canonical or "expected" responses, this will thwart the goal of using this framework for shifting the power dynamics within the classroom. In other words, if teachers do not take seriously the complexity and range of student responses that emerge in that opened space, attending to the epistemic dimensions of their curriculum does not directly impact teachers' interpretive power (Rosebery et al., 2016). We hope that teachers use this framework as a starting point: to see how their curricular decisions impact students' participation in the knowledge-building processes of science and to facilitate reflection on future decision-making.

5.2.4 | Next steps: Further exploration of “reach”

The analyses presented here also minimize the consideration of "reach" as a component of the framework. Here, we are only focused on the conceptual reach as afforded by the design of the curriculum materials and the impact of the specific outcome of decisions students are involved in making, rather than the epistemic reach. We recognize that there may be important epistemic messages (Russ, 2018) that these decisions convey that could (and ideally would) reach beyond a specific activity or even unit. For example, messages about mechanistic accounts or about norms of measurement would ideally persist throughout every investigation, even in new science contexts (Krist, Schwarz, & Reiser, 2018; Manz, 2012). Even more broadly, messages about the epistemic framing or sense of how students are allowed and expected to participate would ideally carry over and continue to influence all subsequent activity in a space that was framed similarly (Hutchison & Hammer, 2010; Rosenberg, Hammer, & Phelan, 2006). This sense of reach is crucial for fully considering the scope of the epistemic curriculum and students' epistemic development. We encourage empirical work that aims to track and characterize these processes of epistemological development.

6 | CONCLUSION

The shift to NGSS requires significant effort from teachers. We have situated the epistemic agency as a key goal of enacting these reforms in ways that support students' participation in knowledge-building work themselves. Although we have a rich body of literature visualizing and conceptualizing how the work of students needs to shift, there are few images of what the work of teaching involves that facilitates students' activity. This framework and the accompanying cases presented in this paper contribute to this arena, adding a conceptualization of the work of teaching required for supporting students' epistemic agency and the subsequent impact of these instructional decisions. We propose that this conceptualization can be used to help us think about teacher learning: how teachers gradually and incrementally make this shift, through practice, over time, and to develop a heuristics for identifying and taking up opportunities to increase students' ownership and participation.
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### APPENDIX

#### TABLE A1 Indicators for case analysis coding questions/dimensions

<table>
<thead>
<tr>
<th>Questions/dimensions</th>
<th>How is this opening up deviating from the curriculum materials?</th>
<th>What is the conceptual reach, or impact on students' trajectory of inquiry, as compared to what is described in the curriculum materials? What are the challenges and opportunities this creates for the classroom teacher?</th>
</tr>
</thead>
<tbody>
<tr>
<td>What is being opened up to uncertainty (by whom and for whom)?</td>
<td>Indicators that something has deviated:</td>
<td>Indicators of challenges or opportunities related to reach:</td>
</tr>
<tr>
<td></td>
<td>• Teacher asks an open-ended (rather than known-answer) question to initiate activity</td>
<td>• Look to teachers’ explicit meta-commentary throughout the enactment of the lesson in terms of the goals/purposes of activities, or their plans for the lesson</td>
</tr>
<tr>
<td></td>
<td>• Teacher continues to press for new idea generation</td>
<td>• Look for repetitions of questions as either a sign of a challenge to get to a &quot;good&quot; place or as a sign of intentionally pressing for deeper student thinking/idea generation</td>
</tr>
<tr>
<td></td>
<td>• Students generate multiple possibilities</td>
<td>• Describe, qualitatively, the nature of students’ participation after the &quot;opening up&quot;; aim to characterize it in relation to other characterizations of student participation (e.g., IRE discourse patterns; students’ participation in science practices; collaborative learning scripts)</td>
</tr>
<tr>
<td></td>
<td>• Students continue to generate possibilities beyond the teacher’s prompting or do so without the teacher’s prompting</td>
<td>• Look for students’ affective responses: are they excited? Invested? Frustrated? Disengaged? Confused?</td>
</tr>
<tr>
<td></td>
<td>• Teacher or students problematize something upon which they had consensus</td>
<td>• Look for student uptake of teachers’ framings, both implicitly and explicitly. Do students’ responses suggest that they buy that this is a new problem, a method worth agreeing upon, a question worth discussing, etc.?</td>
</tr>
<tr>
<td></td>
<td>• Teacher frames upcoming activities in relation to new problematization</td>
<td></td>
</tr>
</tbody>
</table>