Designing NGSS-Aligned Curriculum Materials

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The Need for New Curriculum Materials for the NGSS

The *Framework for K-12 Science Education* outlines a bold new vision for K-12 science education (National Research Council, 2012) that has guided the development of the Next Generation Science Standards (NGSS Lead States, 2013) and other new Framework-derived state standards. As of November 2017, 19 states had formally adopted the NGSS, accounting for 36% of all U.S. children in public schools (NSTA, 2018). At the heart of these reforms is the Framework's definition of science education in terms of three dimensions: science and engineering practices, disciplinary core ideas, and crosscutting concepts. The Framework proposes integrating these dimensions to make science and engineering more meaningful to students by engaging them in science and engineering practices to develop and apply the target science ideas (Schwarz, Passmore, & Reiser, 2017).

Realizing the vision of the *Framework* and NGSS will require making substantive shifts in curriculum materials to support teachers and students in the necessary instructional shifts (National Research Council, 2015). For example, the *Framework* calls out the need for curriculum developers to address all three dimensions in lessons and units. This integration requires more than simply including these dimensions as separate areas of attention — engagement in science and engineering practices requires that students' participation in these practices is directly motivated by their goals of making sense of phenomena or solving problems they have identified (National Research Council, 2012; Reiser, Novak, & McGill, 2017). At the same time, the *Framework* left open questions about which practices, crosscutting concepts, and core ideas to feature in lessons and units, in order to ensure that all receive sufficient attention. In addition, while the *Framework* and others (Fortus & Krajcik, 2012; Fortus, Sutherland Adams, Krajcik, & Reiser, 2015) have called for curriculum developers to consider materials that help students to develop increasingly sophisticated understandings from kindergarten to twelfth grade, it does not offer a completely specified path for doing so. Similarly, while the *Framework* calls for curriculum that addresses science as a human endeavor that is shaped by and informs historical, cultural, social, and ethical issues, it asks curriculum developers to take up questions of how.

At present, curriculum materials that meet these criteria are only beginning to emerge. As of December 2017, Achieve, Inc.'s Science Peer Review Panel[1] had published reviews of just seven units across K-12 submitted by teams for review according to the EQuIP rubric (Achieve, 2016), a framework for analyzing materials for alignment to the NGSS. Still, there are a number of units and materials that have been developed and investigated as part of the research on science learning included in the *Framework* and

[1] https://www.nextgenscience.org/peer-review-panel/peer-review-panel-science

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prior research synthesis that can inform guidance as to the needed features of new materials and that teams of teachers, local leaders, and researchers can adapt and supplement while new materials are being developed (National Research Council, 2007, 2015).

In this paper, we argue for the characteristics of curriculum materials needed that reflect the vision of the *Framework*, can develop students' three-dimensional science proficiency, connect to their interests, identities, and experiences, and support teachers in making the necessary shifts in their own practice. We describe the kinds of artifacts students would produce as part of experiencing these new curricula. To illustrate these design features, we describe how these features are embodied in a unit that our team developed and that has been reviewed by Achieve, Inc. Then, we present evidence from studies of materials that partly reflect the new vision because they embody some important aspect of the vision and its core assumptions (*Framework*, Chapter 2), such as the importance of integrating knowledge and practices, building understanding over time, and promoting equity. Finally, we describe gaps in the evidence base about important curricular features, needed resources for development and implementation, and the kinds of capacities we can build upon but must also develop, in order for all students to experience curriculum materials that reflect the vision of the *Framework.*

Key Features of Materials that Reflect the Vision of the Framework

Below, we review key features of curriculum materials that reflect the key assumptions of the *Framework for K-12 Science Education.* We are able to identify these, because the *Framework*'s vision grew out of decades of research on children's science learning. At the same time, there are some major changes required for curriculum materials to reflect that vision that address our growing understanding of what it takes to support meaningful science learning among students from different cultural communities and linguistic backgrounds. Table 1 summarizes the design features we argue reflect the central design approaches needed in curriculum materials necessary to support the Framework and NGSS. These ideas build on arguments for supporting effective learning with reform-based curriculum materials (e.g., Ball & Cohen, 1996; Krajcik, McNeill, & Reiser, 2008; Roseman & Koppal, 2008; Roseman, Stern, & Koppal, 2010), and prior analyses of the needs of curriculum materials for the Framework and NGSS context (BSCS, 2017; National Research Council, 2015). We review each of these principles in the following sections.

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Table 1. Key Features in Curriculum Materials that Support the Framework and NGSS

	Principles of Instructional Materials to Support the Framework and NGSS	**Instructional Strategies Common in Prior Instructional Materials**
1	Three-dimensional learning: Science and engineering practices build and use disciplinary core ideas and crosscutting concepts	Separate treatment of content and process goals; Curriculum and teachers explain and students apply ideas
2	Central role for phenomena and design challenges	Phenomena as examples to illustrate ideas that have already been taught
3	Designed for incremental sensemaking	Modular lessons and units; individual lessons mapped to standards
4	Coherent from the students' perspective	Logic of instructional sequence clear to curriculum writers and teachers but not students
5	Support for equitable participation	Few supports beyond extension activities for students, little that addresses the need for connecting to students' experiences and identities or for ensuring equitable participation in classroom discussion
6	Multiple opportunities for teachers to elicit and interpret student thinking	Supports include common "misconceptions" of students but not how to build on student ideas as resources
7	Support for teacher learning	Text-based supports; thought to be separate from, but not integrated with curriculum materials

1. Three-Dimensional learning

A central shift in the Framework and NGSS is bringing together science and engineering practices with science ideas in the definition of science literacy, rather than treating "content" and "process" as separate learning goals. Every learning goal is articulated as a performance expectation defined as the use of a science and engineering practice with science ideas (disciplinary core ideas and crosscutting concepts). This move reflects an evolution of earlier reforms in science education to bring the doing of science, articulated as inquiry, into classrooms as a key component of what and how students learn about science (Deboer, 2006). The key step taken in the *Framework* and NGSS is going beyond viewing the methods of building knowledge in science as another topic to be learned in a parallel fashion to learning science content. Instead, the recognition is that the science disciplines are social and intellectual *practices*, and learning science thus means learning to engage in the practices of the disciplines (Lehrer & Schauble, 2006; National Research Council, 2007; Osborne, 2014). Rather than viewing the methods of science as skills of inquiry, such as designing experiments or analyzing data, the *Framework* identifies how the practices of science work together as part of a meaningful effort to help a community develop, test, and refine knowledge:

> Seeing science as a set of practices shows that theory development, reasoning, and testing are components of a larger ensemble of activities that includes networks of participants and institutions [10, 11], specialized ways of talking and writing [12], the development of models to represent systems or phenomena [13-15], the making of predictive inferences, construction of appropriate instrumentation, and testing of hypotheses by experiment or observation [16]. (National Research Council, 2012, p. 47)

Critical to the notion of three-dimensional learning is that practices and ideas are not intended as *independent* learning targets, to be developed and assessed as separate domains of knowledge and skill. Instead, learning science is defined as learning to *use* science, engaging in practices to develop and apply these scientific ideas.

> …[S]tudents cannot fully understand scientific and engineering ideas without engaging in the practices of inquiry and the discourses by which such ideas are developed and refined [1-3]. At the same time, they cannot learn or show competence in practices except in the context of specific content… Thus standards and performance expectations must be designed to gather evidence of students' ability to apply the practices and their understanding of the crosscutting concepts in the contexts of specific applications in multiple disciplinary areas. (National Research Council, 2012, p. 218).

This requires a fundamental shift from many traditional approaches to curriculum materials and the way they are enacted. For example EQuIP Criterion I of "NGSS 3D Design" states "The lesson/unit is designed so students make sense of phenomena and/or design solutions to problems by engaging in student performances that integrate the three dimensions of the NGSS" (Achieve, 2016, p. 2). The Framework talks about this integration of practices both as a means to develop the science ideas and to use those ideas in context:

> Science is not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge. Both elements—knowledge and practice—are essential. (National Research Council, 2012, p. 27).

Thus, the traditional paradigm of having textbooks or curriculum materials simply present the central parts of disciplinary core ideas, and having students then explain them back or use them to solve problems fails to reflect this three-dimensional nature of lessons. While obtaining information such as reading results of others' scientific investigations is one of the science and engineering practices, this should be a part of a larger meaningful “ensemble of activity” in which students engage in practices such as argumentation from evidence or constructing explanations to put the pieces together and develop an explanation or model, rather than simply taking in a full-blown articulation of the explanation. At the other end of the spectrum, inquiry activities in which students empirically explore relationships between variables, but do not end up explaining why those relationships hold, also reflect only a partial view of three-dimensional learning, since this leaves out the knowledge-building focus of the practices. Similarly, while science practices such as designing and conducting investigations may require instrumental skills, such as using a microscope or making a graph, simply learning these skills, isolated from an effort to make progress on disciplinary core ideas, would not reflect the integration of the three dimensions. While a range of different pedagogical approaches may be possible to achieve three-dimensional learning, what is clear is that certain pedagogical approaches leave little room for meaningful integration of the three dimensions.

2. The Central Role of Phenomena and Design Challenges

A key consequence of the integration of practices and science ideas is that true three-dimensional learning requires a *meaningful purpose* for using science and engineering practices to work with science ideas. The *Framework* defines these purposes: “Science begins with a question about a phenomenon… and seeks to develop theories that can provide explanatory answers to such questions.” Analogously, “Engineering begins with a problem, need, or desire that suggests an engineering problem that needs to be solved” (National Research Council, 2012, p. 50, Box 3-2). Thus, integration of the Framework’s three dimensions means more than simply focusing students’ attention at some point in a lesson on each of the three dimensions in separate parts of the work. This view of drawing on these dimensions together to address questions or problems is reflected in criterion I.C of the EQuIP rubric on Integrating the Three Dimensions in NGSS lessons — “Student sense-making of phenomena and/or designing of solutions requires student performances that integrate elements of the science and engineering practices, crosscutting concepts, and disciplinary core ideas” (Achieve, 2016, p. 2). Thus, phenomena and design challenges are central in NGSS-designed curriculum materials.

Phenomena and design play a key role in making students’ work purposeful and meaningful. This requires more than simply teaching students what steps to take, as that can lead to rote performance and “doing school” rather than engaging in meaningful work to build knowledge (Chinn & Malhotra, 2002; Jiménez-Aleixandre, Rodríguez, & Duschl, 2000; Windschitl, Thompson, & Braaten, 2008). Phenomena and problems thereby provide an anchor that can guide a coherent sequence of lessons, as students develop, evaluate, and revise explanatory models of phenomena and solutions to problems (Blumenfeld et al., 1991; Windschitl et al., 2008). In units so anchored, student questions arising from phenomena and problems posed to them help to motivate students’ building and using disciplinary and crosscutting ideas over time (National Research Council, 2015, p. 53). These questions or problems that drive the work are more than motivation, however; they provide a context in which students can apply, test, and extend their developing ideas. Thus, anchoring units in this way can facilitate students making deeper connections among ideas and developing a better grasp of science and engineering practices (Edelson, 2001).

The use of phenomena to anchor three-dimensional instruction differs from ways that phenomena are sometimes used in instruction today. In some cases, phenomena are chosen and used with the intent to challenge student preconceptions, by presenting so-called discrepant events to them (Chiappetta & Koballa, 2014). Although these might make for good anchoring events in a lesson, they may not be good choices for anchors for units, because most cannot sustain students' interest over multiple days of instruction. Second, sometimes teachers introduce a new topic by presenting them with a phenomenon that can engage them in the topic but then drop the phenomenon from discussion after the first day. This approach may fail to help students see how science can help them make sense of their everyday world, because their subsequent learning does not relate back to the phenomenon presented. A third and very common use of phenomena is to provide examples that illustrate or provide opportunities to students to reinforce science ideas teachers have already taught, rather than opportunities to build those ideas themselves (Banilower et al., 2013).

Phenomena and design challenges must meet three key criteria for them to embody the vision of the *Framework for K-12 Science Education* and support science learning for all. First, explaining the phenomenon or solving the problem must require developing or applying key elements of disciplinary core ideas and crosscutting concepts. A phenomenon that can be explained *without* reference to targeted core ideas or crosscutting concepts will not provide an adequate context for three-dimensional learning (Achieve, 2016). Similarly, a phenomenon that could be explained, in principle, by disciplinary ideas, but does not enable students to interact with it and *figure out* these ideas from investigable elements would not provide a phenomenon useful for instruction. For example, a teacher could show a second-grade classroom dry ice turning to gaseous carbon dioxide (which technically illustrates a phase change, the process of sublimation), but it is difficult to see how investigating this phenomenon will help second grade students develop the target ideas of the nature of matter about solids and liquids for the K-2 grade band. To support three-dimensional learning, the phenomenon should provide a context in which students can explore and build the relevant science ideas, not simply a context for teachers or instructional materials to demonstrate those ideas or explain them to students.

Second, the phenomenon or design challenge must address a sufficient number of performance expectations so as to be worthy of investing extended classroom time and help students see connections among different science ideas. Units anchored in phenomena or design challenges build student understanding incrementally, so that students see how ideas relate to one another. Thus, to adequately address the standards, units that bundle performance expectations that work together are necessary (Krajcik, Codere, Dahsah, Bayer, & Mun, 2014). Third, anchors for units should connect to students' interests and everyday experiences. Interest is a key catalyst for science learning in both the short- and long-term (Bathgate & Schunn, 2017; Bricker & Bell, 2014; Crowley, Barron, Knutson, & Martin, 2015). Problematizing everyday phenomena for students—that is, inducing in students "perplexity, confusion, or doubt" (Dewey, 1910, p. 12) in relationship to those phenomena—is one strategy for sparking and sustaining interest (Engle, 2012), and to push students to go deeper and develop explanations for phenomena they may take for granted (Reiser, 2004; Reiser, Novak, et al., 2017; Watkins, Hammer, Radoff, Jaber, & Phillips, 2018, in press). Although phenomena that are already familiar to students are not necessary, all phenomena should allow students to make ready connections to everyday experiences and captivate their attention. To address the diversity of student interests and experiences, multiple phenomena will be needed. Evidence related to the interest and personal relevance of phenomena can be used to select phenomena and design challenges, so as to facilitate broad student engagement (Penuel et al., 2017).

Thus, how phenomena and problems are treated in NGSS classrooms requires key instructional shift in both curriculum materials and teaching. Phenomena and problems need to shift from illustrations or applications of science ideas students have already been taught to contexts that raise questions or challenges in which students develop, reason through, and utilize these ideas to explain phenomena or solve problems.

3. Designed for Incremental Sensemaking

A key shift in the *Framework* is a change in the aim of science education away from simply knowing science to *using* science and engineering ideas and practices to make sense of the world or solve problems. This requires working with students' initial resources for sensemaking as valuable starting points, even though they may be piecemeal and contextualized in everyday experiences rather than coherent, generalized theories (diSessa & Minstrell, 1998; Hammer & Elby, 2003; Minstrell, 1992). Therefore, curriculum materials need to be organized to help students build on their prior understandings, incrementally extending and revising these understandings as they use practices in meaningful ways to explore phenomena and design challenges. Furthermore, the target disciplinary core ideas are more than collections of facts, but are complex coherent understandings of mechanisms, such as how matter can be rearranged or how living things get the energy and matter they need. Constructing these ideas is not like simply providing a series of answers to particular questions or testing a series of hypotheses about different variables. Instead, this knowledge building is incremental. The Framework argues that learning should be viewed as a progression "designed to help children continually build on and revise their knowledge and abilities, starting from their curiosity about what they see around them and their initial conceptions about how the world works" (National Research Council, 2012, p. 11). Thus, curriculum materials need to support students' building initial models, and continuously extending them as they encounter new phenomena, connecting to prior explanations, deepening mechanisms to improve their explanatory power, and revising them as they uncover limitations in these models (Berland et al., 2016; Windschitl et al., 2008; Windschitl, Thompson, Braaten, & Stroupe, 2012).

Curriculum materials that develop student understanding over time must provide extensive supports for continuous sensemaking and incremental model building. Students do not simply engage in investigations for the sake of providing them with hands-on experiences. Rather, investigations provide a means for students to answer questions the class has decided are important to answer. In addition, materials that support sensemaking provide guidance to teachers about how to support students in making connections between their investigations and the questions they are trying to answer. They provide tools and routines that students can use to keep track of their questions and the progress they are making to answer them, to help assemble evidence they have gathered into coherent science explanations, and to help students come to consensus as to key components and interactions to represent in explanatory models of phenomena and criteria for solutions to problems (Windschitl & Thompson, 2013; Windschitl et al., 2012). Importantly, these tools and routines are introduced "just in time" rather than "just in case" students need them. They are not "front loaded" at the beginning of the school year or a unit, as has been customary in science textbooks that begin with a first chapter on the scientific method (Osborne & Quinn, 2017; Windschitl et al., 2008).

This differs from common instructional practices in several key ways. A key motivation for the *Framework* and NGSS was the "growing national consensus around the need for greater coherence—that is, a sense of unity—in K-12 science education. Too often, standards are long lists of detailed and disconnected facts, reinforcing the criticism that science curricula in the United States tend to be 'a mile wide and an inch deep' (Schmidt, McKnight, & Raizen, 1997)." The goal of the Framework is to organize standards so they reflect sensible learning sequences that would support students in systematically building and connecting ideas across time. Analyses of standards and curriculum materials reveal that traditional materials jump from topic to topic, without helping students build ideas piece by piece, putting them together over time, and making connections to other relevant ideas, and to their own experiences (BSCS, 2017; Kesidou & Roseman, 2002; Roseman et al., 2010; Schmidt, Wang, & McKnight, 2005; Stern & Roseman, 2004). Indeed it is common today for teachers to adopt the strategy of assembling individual lessons on a topic from colleagues or downloading individual lesson plans from social networking sites (Greene, 2016; Hunter & Hall, 2017). While sharing instructional materials could be a valuable resource to support professional learning, the types of individual lesson plans found in these venues may not reflect high quality independently evaluated instructional resources. Furthermore, cobbling together individual lesson plans is unlikely to result in supporting students in incrementally developing, extending, and refining their explanatory models.

4. Coherence from the Student Perspective

We have already indicated the stated importance of "coherence" as a goal of the Framework. There are a number of different ways to interpret coherence when exploring how curriculum materials and teaching can support more effective approaches to science teaching and learning. The Framework articulates three approaches for supporting coherence:

> The framework endeavors to move science education toward a more coherent vision in three ways. First, it is built on the notion of learning as *a developmental progression*. It is designed to help children continually build on and revise their knowledge and abilities, starting from their curiosity about what they see around them and their initial conceptions about how the world works…
>
> Second, the framework focuses on a *limited number of core ideas* in science and engineering both within and across the disciplines. …to allow more time for teachers and students to explore each idea in *greater depth*.

> Third, the framework emphasizes that learning about science and engineering involves *integration of the knowledge of scientific explanations* (i.e., content knowledge) *and the practices* needed to engage in scientific inquiry and engineering design... (National Research Council, 2012, pp. 10-11, emphasis added).

As this description shows, there are multiple aspects of trying to move science learning from a large number of disconnected facts to a more coherent approach. The shifts of greater depth and integration of explanation and practices are reflected in the first two principles of 3D learning and the focus on explaining phenomena and solving problems discussed earlier. The principle of incremental sensemaking is one implication of the *Framework's* first strategy of "a developmental progression." The notion of "developmental progression" could be taken in part to reflect a logical sequence based the structure of the discipline as disciplinary experts see it, as Bruner (1960) argued. This approach of disciplinary coherence, for example as reflected in the *Atlas* work of AAAS (2001, 2007), would be a major advance over many existing curriculum materials which do not pay adequate attention to connecting ideas and helping students build complex ideas from more simple ones (Roseman et al., 2010). However, it would not necessarily provide students with meaningful encounters with how scientific activity unfolds in practice. The logic of walking through an already-worked out explanation (with 20-20 hindsight) is quite different from what may make sense for students to question and work on, step by step. Reiser, Novak, and McGill (2017) argue that supporting meaningful engagement in three-dimensional learning requires developing and enacting curriculum materials that are coherent *from the students' perspective*. They argue that the notion of a social practice suggests that it is insufficient for curriculum materials or teachers to present in a top-down fashion what questions or problems students should work on and what practices they should engage in:

> We contrast coherence from the *students'* perspective with coherence considerations from a purely *disciplinary* or expert perspective, in which the reason to work on particular topics or undertake new investigations follows a learning progression outlining a sequence of building ideas that exclusively reflect the logic of the science ideas. …The reason the class is moving from one topic to another may be apparent to curriculum designers, scientists, and teachers, and may make sense in hindsight, once one already understands the target ideas. Yet the logic may not be apparent, convincing, or compelling for students. (Reiser, Novak, et al., 2017, p. 1)

Instead, Reiser et al. argue that authentically engaging in science and engineering practices should help students address questions or problems they have identified and committed to address. They build on earlier arguments for project-based learning (Blumenfeld & Krajcik, 2006; Blumenfeld et al., 1991) and learning-for-use (Edelson, 2001; Kanter, 2010) to argue that achieving the *Framework*'s vision means that students should be partners, along with curriculum materials and teachers, in figuring out what to work on next in order to make progress on questions or problems.

In units that are designed to be coherent from the student point of view, students build new ideas that start from their own questions and initial ideas about phenomena

(Reiser, Brody, Novak, Tipton, & Sutherland Adams, 2017; Reiser, Fumagalli, Novak, & Shelton, 2016; Severance, Penuel, Sumner, & Leary, 2016). The flow of lessons is intended to help students build new ideas systematically and incrementally through their investigations of their questions. The lessons build toward disciplinary understandings, but the order of lessons reflects students' evolving sense in which these ideas emerged as their questions led to partial explanations, and then to new questions, rather than the order that a disciplinary expert might impose. If the order of lessons were to be organized around the logic of the discipline, engaging in practices to figure out key ideas may not make sense to students. Thus, in a unit that is coherent from the student point of view, students are engaged in science and engineering practices because of a felt need to make progress in addressing questions or problems they have identified.

To see the contrast between coherence from the disciplinary and student perspectives, consider the following example. Osmosis is an important biological process, because it explains how materials (such as food) can get into cells, and how waste can be removed. Thus addressing this process can be justified as addressing questions raised about cell structure and function (National Research Council, 2012, pp. 144-145, LS1.A). Yet from a student's perspective, until their class has established that cells need to take in food and get rid of waste, there is no motivation to figure out what could get through the barrier of a cell. Establishing that cells are increasing in mass over time or getting energy *then* raises the question about what could get into or out of a cell, and motivates investigating what can get through a membrane.

The importance of judging unit coherence from the student point of view reflects the shift from inquiry as isolated skills to the emphasis on science and engineering as meaningful practices in the *Framework*. The purpose of classroom activity shifts away from teachers making sure that students can formulate experimental questions, plan fair tests, and interpret graphs as skills devoid of content. Rather, students engage in work in the classroom as part of a meaningful and purposeful attempt to build knowledge together. The practices are part of a coherent system of activity guided by common goals, expectations, and norms for the discipline (Berland et al., 2016; Ford & Forman, 2006).

Of course, it is not possible to replicate professional scientific practice in classrooms, but it is viable to engage students directly in negotiating and adapting science practices and relate these to professional practice (Berland, 2011; Gouvea & Passmore, 2017; Kelly, 2008; Manz, 2015a; Passmore, Gouvea, & Giere, 2014). Doing so requires curriculum materials that support teachers in both eliciting and developing students' questions related to phenomena and problems. It requires also activity structures in which students are guided to co-construct with the teacher and their peers ways to investigate those questions. It further requires tools for helping students think about how the results of their investigations can be used to develop explanatory models for how and why a phenomenon occurs and how multiple investigations, taken together, can help a class reach consensus on an explanatory model (Passmore & Svoboda, 2012; Schwarz et al., 2009). This is a different approach than is typical in most curriculum materials today, in which the sequence of investigation questions and the means for answering them are prescribed and may follow an opaque rationale. It requires designing units around phenomena and problems in which curriculum developers anticipate student questions that will arise and sequence exploration of those questions so as to help students build and test explanatory models or design and test solutions progressively over time.

It is important to point out that attention to coherence from the students' perspective does not imply that teachers should follow students wherever their questions, prior conceptions, and interests take them (Krajcik et al., 2008; Reiser, Brody, et al., 2017; Reiser, Novak, et al., 2017). The goal is to help students develop the target disciplinary core ideas and turning over complete control to students could take the investigations too far afield. But rather than ensuring treatment of the target ideas by simply presenting the important questions to address, the goal of coherence is to use phenomena and guiding questions from the teacher or curriculum materials to negotiate and *co-construct* questions with students so that they are partners in figuring out what to work on and how to proceed (Manz & Renga, 2017; Reiser, Brody, et al., 2017). Thus, students see how engaging in the science and engineering practices will help them make progress on phenomena they are trying to explain or engineering problems they are trying to address, even if developing the questions and plans for investigation included important contributions from the teacher.

Taking coherence from the student point of view seriously demands careful consideration of inter-unit coherence as well. The *Framework* emphasizes the need to organize learning of core ideas around developmental progressions that students explore across multiple years. It is not possible to support such learning through disconnected units; curriculum developers must integrate coordinated supports among units to build student understanding over time (Fortus & Krajcik, 2012). Hypothetical learning progressions are critical tools for building inter-unit coherence. Learning progressions are testable, empirically supported hypotheses about how student understanding develops toward specific disciplinary goals for learning (Corcoran, Mosher, & Rogat, 2009; National Research Council, 2007). These provide guides for possible routes for organizing student learning opportunities across different units. Inter-unit coherence does not entail covering the same territory over and over, however. Across units, students encounter the different dimensions of a core idea within different science and engineering practices, and they encounter crosscutting concepts across investigations of different core ideas. Over time, moreover, students' understanding of core ideas and crosscutting concepts develops so that they can be presented with more complex phenomena and design challenges, and their increasing grasp of practice supports their ability to engage with these phenomena and challenges. Importantly, in this endeavor the primary orientation is to focus on using students' ideas as resources and "stepping-stones" for developing more sophisticated understandings, rather than as misconceptions to be debugged (Campbell, Schwarz, & Windschitl, 2016; J. P. Smith, III, disessa, & Roschelle, 1993/1994).

The audiences for the products students construct begin with the classroom and extend outward. Students are first accountable to making sense of ideas for themselves, publically and to make those ideas available for others to work on and with (Engle, 2012). The classroom learning community itself is also a key audience for products, that is, an audience of peers in a community that adheres to norms for how to hold one another accountable for supporting ideas with evidence, for listening to others and building ideas together, and for critiquing and asking questions about one's own and other's ideas (Berland & Reiser, 2011; Berland et al., 2016). For design challenges, the audience may be the wider community, especially when those challenges connect students to ongoing endeavors in the community that are applying science and engineering practices to solving problems (Birmingham et al., 2017; Calabrese Barton & Tan, 2010; Penuel, 2016).

5. Integrated Supports for Equitable Participation

A challenge for teaching units anchored in explaining phenomena and solving problems is ensuring that *all* students can engage with activities and learn from their participation. One condition that is necessary is that schools allocate sufficient regular time to teach science, especially at the elementary level (National Research Council, 2013). On average, students receive just under three hours of instruction in science at the third grade level, as compared to ten hours of reading and six hours of math instruction (Hoyer & Sparks, 2017). Another necessary condition for broad participation is having sufficient materials available for students to directly engage in the full range of science and engineering practices (National Research Council, 2015; Oakes, 1990). In fact, classes with lower prior achievement of students and with higher percentages of students from nondominant groups have less access to material resources such as calculators, probes, and microscopes (P. S. Smith, Trygstad, & Banilower, 2016). Equipment needed to plan and carry out investigations, as well as physical materials or computer technology for making use of simulations to make sense of phenomena or test solutions to problems, are key and are difficult for some schools to obtain. In addition, non-science specific materials like chart paper for recording students' questions and copies of student activity sheets are important and can also be difficult for some teachers with limited paper budgets to obtain for all their students.

Access to equipment and supplies is not sufficient to ensure equitable participation in classroom activities. A key dimension of creating equitable classrooms involves building a particular culture in which students' ideas are not only welcomed but also expected from all students. Teachers need to be able to support students "as they explicate their ideas, make their thinking public and accessible to the group, use evidence, coordinate claims and evidence, and build on and critique one another's ideas" (Michaels & O'Connor, 2012). Group norms of participation, respect for others, a willingness to revise one's ideas and equity are all critical, and the norms of the classroom need to align with those of the best forms of collaborative scientific practice (Berland & Reiser, 2011; Bricker & Bell, 2008; Calabrese Barton & Tan, 2009; Duschl & Osborne, 2002; Osborne, Erduran, & Simon, 2004; Radinsky, Oliva, & Alamar, 2010).

Curriculum materials need to provide differentiated supports to ensure equity. The science and engineering practices require students to engage in intensive forms of language use for both communication and learning (Lee, Quinn, & Valdés, 2013). Leveraging the communicative resources students bring to class and enabling them to express understanding using different modalities is critical in both instructional and assessment tasks (B. A. Brown & Spang, 2008; Buxton et al., 2013). Materials that follow principles of Universal Design for Learning (UDL; Rose & Meyer, 2002) can ensure that a variety of entry points and modalities are integrated by design. For specific populations of students, curriculum that reflects principles of contextualization derived from ethnographic research in students' communities can support students linking everyday ways of making sense of the world and scientific practices (Sánchez Tapia, Krajcik, & Reiser, in press). In addition, focusing on helping students navigate between these different ways of knowing—rather than expecting students to give up their

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everyday ways of knowing—is critical for promoting respect for different cultural worldviews and epistemologies (Aikenhead, 2001; Bang & Medin, 2010). As Lee and colleagues (2013) write, across different student populations, to promote equitable participation

> …the emphasis should be on making meaning, on hearing and understanding the contributions of others, and on communicating their own ideas in a common effort to build understanding of the phenomenon or to design solutions of the system being investigated and discussed. (p. 225)

Given the gaps between current practice and those shifts, those teachers will need access to well-designed professional development and ongoing opportunities to work with colleagues' to reflect on their practice teach equitably (National Academies of Sciences Engineering and Medicine, 2015). It is likely that this will require increased allocation to teacher professional development, especially at the elementary grades where in 2013, 65 percent of teachers reported they had received less than six hours of professional development in science in the previous three (Banilower et al., 2013) years. Additional attention to the professional development needs of teachers in schools with high percentages of low-achieving students may also be needed, as a lower percentage of teachers report receiving professional development on student-centered teaching than teachers in schools with higher achieving students (Banilower et al., 2013).

6. Multiple Opportunities for Teachers to Elicit and Interpret Student Thinking

Curriculum materials must integrate a variety of assessment activities to help teachers elicit student thinking, to help them and their students reflect together on their learning, and guide instructional decision making. Research suggests that support for each of these different processes of formative assessment is critical. Successful assessment interventions not only provide rich questions for teachers to ask students; they also provide formats for engaging students in self- and peer-assessment, frameworks for interpreting student ideas, and strategies for teachers to employ when student thinking reveals problematic ideas after instruction (Penuel & Shepard, 2016). In science curriculum materials, planned assessment activities, moreover, should follow the "contours of practices," that is, reflect how scientists and engineers assess and evaluate one another's questions, investigations, models, explanations, and arguments (Ford, 2008; Ford & Forman, 2006). In that way, assessment activities provide occasions for teachers and students to both gain a sense of and improve their grasp of practice. They will, moreover, need to be more than just written tests, because many scientific activities are collaborative and thus require more interactive forms of assessment.

A key challenge will be developing assessments that both elicit three-dimensional science learning and that also provide evidence of students' interest and engagement with curriculum materials. It is still true that few assessments exist today that adequately reflect the vision of the *Framework* (cf., Pellegrino, 2013). Moreover, no single assessment can provide sufficient evidence to guide instructional decision making or help teachers understand fully what their students know and can do. Only a system of assessments centered on the classroom can provide such evidence (National Research Council, 2014). Such a system needs to include ways to assess students' explanatory models of phenomena and solutions to design challenges, as well as tasks that elicit students' ability to apply their understanding to reason about novel phenomena and problems (Ruiz-Primo, Shavelson, Hamilton, & Klein, 2002). Such tasks need to include scoring guides that help teachers interpret students' responses in light of the overall goal for unit learning, not just discrete elements of disciplinary core ideas, science and engineering practices, and crosscutting concepts. Finally, the tasks will need to include supports for "what to do next," depending on students' responses to tasks, so that they can be used to support learning (Debarger et al., 2017).

7. Supports for Teacher Learning

To be effective, curriculum materials need to be bundled with professional development for teachers, along with assessment activities, into an integrated "curricular activity system" (Roschelle, Knudsen, & Hegedus, 2010). Of particular importance is professional development that helps teachers to discern underlying purposes and structures of the curriculum, so that when they adapt materials, they do so with integrity to the coherence of the materials (Davis & Varma, 2008). In addition, professional development should be closely tied to what teachers will be expected to do to support students' productive disciplinary engagement with activities that are part of the materials: focused on the content of the unit, its underlying theory of how to develop student understanding, and pedagogical strategies hypothesized to support learning in the unit (Ball & Cohen, 1999). The professional development, moreover, needs to be sustained over time and connected to the goals of teachers' schools, districts, and states (Garet, Porter, Desimone, Birman, & Yoon, 2001; National Academies of Sciences Engineering and Medicine, 2015; Penuel, Fishman, Yamaguchi, & Gallagher, 2007; Supovitz & Turner, 2000). Because the gap between teachers' current approaches to using materials and uses that can support three dimensional learning is large, innovative approaches will be needed that can provide extended opportunities to learn at scale (Reiser, 2013; Wilson, 2013).

Some supports for teacher learning should be integrated into materials themselves. Curriculum materials, as concrete reflections of the way instructional shifts can play out in teacher moves and in student work, are a key component of helping teachers shift their practice (Ball & Cohen, 1996; Remillard & Heck, 2014). Curriculum materials that incorporate resources to support teacher learning are called *educative curriculum materials* (Davis & Krajcik, 2005). Their purpose is to help guide teachers in making instructional decisions—such as how to respond to different student ideas—when using the materials. They may be targeted toward developing teachers' subject matter knowledge, their pedagogical content knowledge with respect to particular core ideas, practices, or crosscutting concepts, and their knowledge of typical student patterns of student thinking and problem solving.

Consideration of the challenges involved in NGSS suggests several areas in which educative curriculum materials and associated professional learning opportunities could productively focus. As we argued above, a central shift in NGSS is the shift from treating science ideas and inquiry skills as separate learning targets and supporting the central role of science and engineering practices as both a means to build science ideas and as a way to use those ideas to make sense of the world. Thus, helping teachers incorporate science and engineering practices into their lessons needs to be a central focus in the support within educative materials and professional learning (Reiser, 2013; Reiser, Michaels, et al., 2017). Consistent with this view, Davis, Janssen, and van Driel (2016) argue that a key challenge facing NGSS is that teachers tend to reduce the cognitive demand of tasks when working with reform-based instructional materials, which could result in struggles with the science and engineering practices. The related shifts of incremental sensemaking and coherence from the students' perspective are also key places that educative aspects of instructional materials will have to support. Teachers will need examples of how to work with students' questions and help them participate in identifying what to work on and how to investigate it, while at the same time making progress on building the disciplinary core ideas. Educative features such as specific prompts and general strategies for discussion and student work from classroom enactments could help teachers support the classroom discourse needed. Curriculum materials will also have to explore ways to represent the trajectory of a coherent investigation and how the disciplinary core ideas are built across lessons to help make these instructional shifts concrete and accessible for teachers (Reiser, Novak, et al., 2017).

An Example Unit: Why Don't Antibiotics Work Like They Used To?

To illustrate how the key characteristics of curriculum materials described above can be integrated to create a coherent experience from the student point of view, we describe a unit that our two research groups co-designed with a team of teachers (Next Generation Science Storylines, 2017). The unit, *Why Don't Antibiotics Work Like They Used To?*, focuses on the core ideas of evolution as represented in the *Framework* for high school life sciences (LS4) and incorporates connected ideas from genetics (LS3). The unit builds on students' understanding of ecosystems developed as part of a unit that opens a year-long sequence of phenomenon-based units. There are two primary anchoring phenomena for the unit, the increase in antibiotic resistance over the past few decades, and the apparent change in a behavioral trait—boldness—in a species of bird, *Junco hyemalis* (Dark-Eyed Junco). The unit culminates in a design challenge, in which students produce an infographic for a health clinic that communicates a scientific rationale for guidelines that the Centers for Disease Control has issued regarding the use of antibiotics. Importantly, as a strategy for promoting equity, the anchors for this unit were chosen through a systematic process that included soliciting students' interest in a subset of phenomena the research team and teachers had identified as candidates for the evolution unit. As part of our design process, these data are disaggregated by race, gender, and home language and used—alongside other criteria—to select the anchoring phenomenon.

Our description of the unit in this section traces the *artifacts* that students generate as individuals, in small groups, and as a class. Artifacts are important, because a key aspect of making scientific practices central is establishing accountability to others in the classroom and to disciplinary norms for knowledge building (Engle, 2012; Engle & Conant, 2002; Michaels, O'Connor, & Resnick, 2008). Students have to be able to give an account to themselves, to peers, and ultimately to standards outside the classroom for warranting their claims. By giving a public account—rendered in a variety of artifacts, such as drawings, written explanations, diagrams, and lists— of what they have figured out and why their ideas make sense, students have the chance to build ideas over time and create the conditions for others to contribute to the development of the community's knowledge (Berland et al., 2016; Windschitl et al., 2008; Windschitl et al., 2012). These representations enable the classroom as a learning community to monitor and direct its knowledge building toward answering its initial questions, as well as ones that emerge from investigations (Manz, 2012, 2015a; Schwarz et al., 2017). Because units anchored in phenomena and design challenges typically unfold over many weeks, moreover, shared public representations serve as a way to keep track of what the class has concluded or learned that helps them to build, incrementally, a model that accounts for evidence from a number of investigations and core ideas they are developing through the activities of the unit.

The unit opens with a presentation of a short video of a girl, Addie, who has been hospitalized and who has multiple bacterial infections that are resistant to antibiotic treatment. As part of this gripping opening, students generate and prioritize as a class a list of questions that they need to answer to explain what is going on with Addie. In the initial lesson, students write questions individually and in small groups, and they identify experiences they have had that might help them understand what is going on. As a class, they build a timeline of the events that they see in the video. Then, students in small groups draw an initial model to explain what they think is going on. This leads students to generate questions about parts they can't explain. The class together assembles these questions and organizes them into major categories, recording them on an artifact called the Driving Question Board (Blumenfeld et al., 1991; Weizman, Shwartz, & Fortus, 2010). Table 2 illustrates the types of organizing questions classes construct from their original questions. Figure 1 shows a sample driving question board from one classroom.

Table 2. The Organization of Questions Co-constructed by the Class

Organizing Question Constructed by the Class	Example student questions
Why isn't MRSA way more common?	• Why doesn't everyone have MRSA? • Where did MRSA come from?
Where do we find bacteria?	• Is MRSA more common in third world countries? • How long does MRSA live outside in a public community area without people? • Can animals get MRSA? Can they give it to people?
How do I make sure I don't pick up MRSA?	• Does everything you handle have MRSA? • What keeps us from getting MRSA and getting very sick if you can get it so easily?
How do we fight off MRSA?	• Why are some people more sensitive than others? • Do the things we use to clean wounds like alcohol/peroxide kill MRSA?
How does antibiotic resistance form?	• How does different types of staph form? • Does being around antibiotics make it easier to form?
How does bacteria get from the inside to the outside?	• How does it enter the body to cause an infection? If it's already on your skin where does it get in? • Do you have to have a cut or scab to get MRSA? If not how does it get inside someone's body?

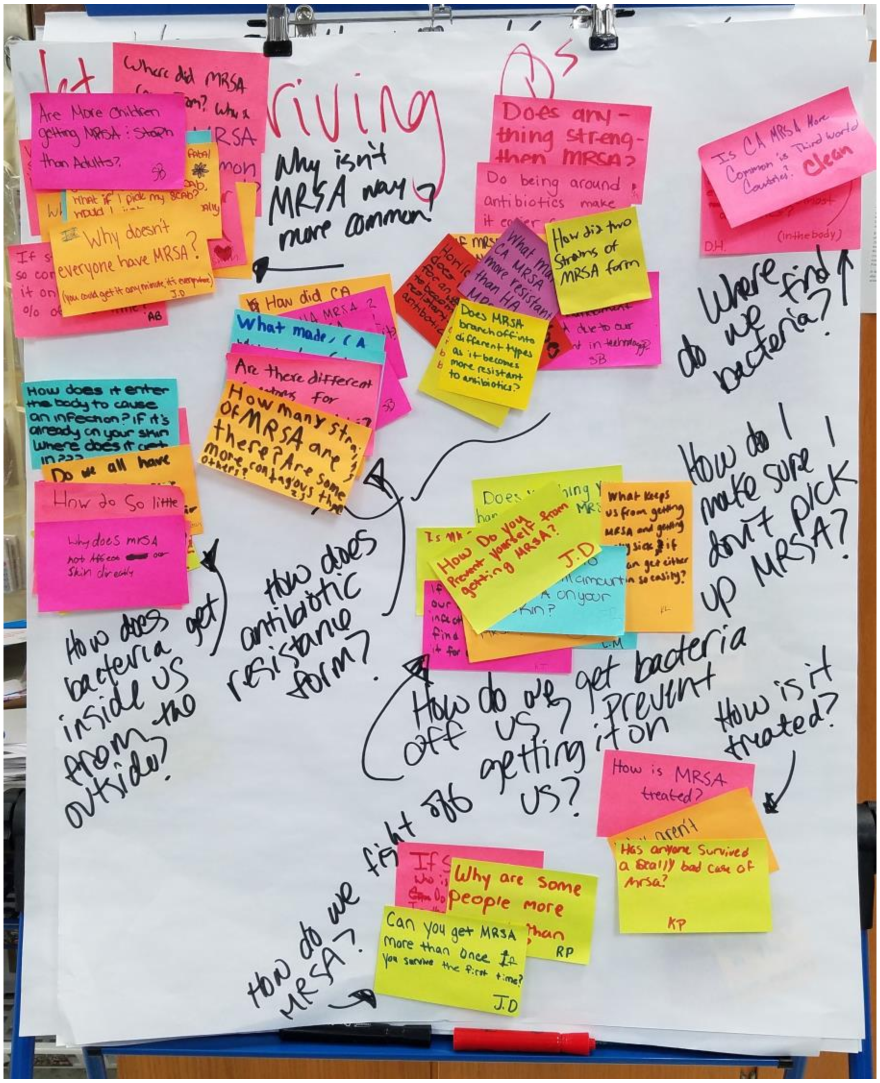

Figure 1. A driving question board of questions from students from one classroom

This public representation acts as a reference point for the classroom community's collective purpose, though individuals and small groups may pursue their own questions along the way. For each of the class questions, the class brainstorms an initial list of investigations they might conduct in class to help them answer these questions. These are just placeholders at this point, intended to position students as capable of answering the questions they have posed with the material resources available to them as a class.

In this unit, the phenomenon of the sick girl is used as a context to explore how a population of bacteria can change over time through the process of natural selection. This exemplifies Principle 2 of using phenomena or design challenges as contexts to build and use the science ideas. It also reflects Principle 5, supporting equitable participation by choosing an anchor for which there is evidence of a connection to student interests. Contrast this with a unit that starts by telling students they are going to learn about natural selection, and introduces the theory first and uses the case only to illustrate it.

As students explore more about the anchoring phenomenon, they are confronted with an alarming finding — the frequency of antibiotic resistance is increasing. The

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introduction of this complexity triggers new questions from students that they record on the board, and follow with a new cycle of model building. At this point, few if any students may bring an understanding of the concepts of adaptation and natural selection to make sense of this phenomenon, although that is where this twist in the storyline will lead them. The point of inviting model building here is to create the need for developing these ideas through cycles of investigation. Asking students to model at this point helps them realize what they cannot explain and raises further questions. In addition, the twist parallels real challenges scientists face as they pursue investigations, new complexities that complicate their efforts to make sense of the natural world (Manz, 2015b).

Next students begin growing their own bacteria in class to try to figure out some of their questions about out where bacteria come from, how they grow, and how they can be killed. But unlike traditional curriculum materials—even those that are “inquiry-based”—the procedures are not fully provided to students. Instead, students are involved in co-constructing the questions that lead to these investigations, and co-constructing how to act on their questions. Although the key milestones are laid out in advance in the storyline, to help students build the important components of the key ideas, using the prompts in the curriculum materials the teacher is able to involve the students in working through the logic of how to make progress on their questions. Students sometimes lack the technical knowledge needed to figure out exactly how to investigate some of their ideas. But because they came up with the motivation for the question, and a general idea of what they would need to see, the teachers’ guidance can easily become part of the co-construction. For example, students identified the question of exactly how bacteria grow and what kills them (see Table 2), so the teacher could then provide guidance about how scientists test such questions, e.g., swab bacteria from possible sources, put them on agar plates, seal them, measure growth, etc.

Students develop their larger questions into more focused investigations of bacteria growth that help them add to their models of what is going on with Addie, and begin to explain why there are an increasing number of cases of people who are infected with resistant strains of bacteria. The artifacts they produce as part of these investigations are not traditional laboratory reports, but rather plans and protocols for data collection, sketches and diagrams showing what happens to bacteria under different conditions over time, and elaborated descriptions of how patterns they observed in data support particular claims or “answers” to their questions. Occasionally, those plans and protocols are subject to peer review within the unit, as students develop increasingly sophisticated understandings of the focus of investigations and construct explanations of how the bacteria population could change, laying the groundwork for a more general model of adaptation and natural selection.

This reflects several of the principles stated above. In the entire sequence described so far, notice that the need for the investigations about how bacteria grow, how they can be killed, and how some can survive emerged from attempting to explain phenomena, making progress, and realizing new questions. This is the essence of coherence from the students’ perspective. In addition, the students are building the core ideas about biological population change piece by piece, using the science practices and crosscutting concepts (equilibrium and change), thus reflecting the integration of the three dimensions (principles 1 and 3).

At the conclusion of each lesson, students are invited to reflect publicly on what they've figured out related to one or more of the questions on the Driving Questions Board. That reflection may take the form of an electronic exit ticket that teachers can review overnight to decide what might ideas need further discussion and development (principle 6), as well as to analyze student perceptions of the lesson's personal relevance (principle 5) (Penuel, Van Horne, Severance, Quigley, & Sumner, 2016). It might take the form of a group discussion that produces a list of hypotheses or conjectures about what's going on that the class is considering at the moment, but about which there is not yet agreement. That discussion might help to clarify for the class precisely what the class agrees on so far, as well as where there are disagreements. In this way, rather than being introduced as a standalone practice, argumentation and the need to update their explanations *emerges from* the ongoing activity of the class to make sense of the overarching phenomena, as well as the investigations they conduct to help them answer their questions (Manz, 2015a; Passmore & Svoboda, 2012), again reflecting the coherence from the students' perspective.

Every few lessons, the class takes stock of the knowledge they have developed together in a "putting-pieces-together" routine. In this routine, students work in small groups and as a class to synthesize evidence, generate claims, and build a public representation of their current understanding of the phenomenon. One of these key moments occurs after students have had a chance to explore a simulation that depicts different types of bacteria with different traits. The traits in this case relate specifically to antibiotic resistance, and the simulation provides a first insight for students as to *why* resistant bacteria might proliferate in the environment of a human body. Students work in groups to create their models and, then, using a Gallery Walk participant structure (Kolodner, Crismond, Gray, Holbrook, & Puntambekar, 1998), students review and critique one another's models. The ultimate aim of the activity is to develop a class-wide consensus model for the phenomenon so far. This frequent stock taking and revision reflects incremental sensemaking (principle 3), and reveals the multiple opportunities for teachers to elicit and interpret students' thinking (principle 6).

At this point in the unit, students have an emerging but incomplete understanding of key mechanisms of evolution. They have figured out that all bacteria of the same type (e.g., staph) are *not* the same, and that variations between induvial bacteria in a population can affect how they survive in the case of challenges in the environment, such as administration of antibiotics (poisonous chemicals for the bacteria). The survivors who are less affected by the antibiotics survive and reproduce, creating more like them that can resist the antibiotic. Over multiple generations, the number of resistant bacteria increase, and their proportion in the overall population increase. This accounts for many aspects of the Addie story students were trying to figure out – why she started to get better and then get worse, why there are more antibiotic resistant bacteria in the environment (and in hospitals) now than in previous decades, and why these bacteria are so hard to kill. An example of a small group's final model for this segment of the unit is shown in Figure 2.

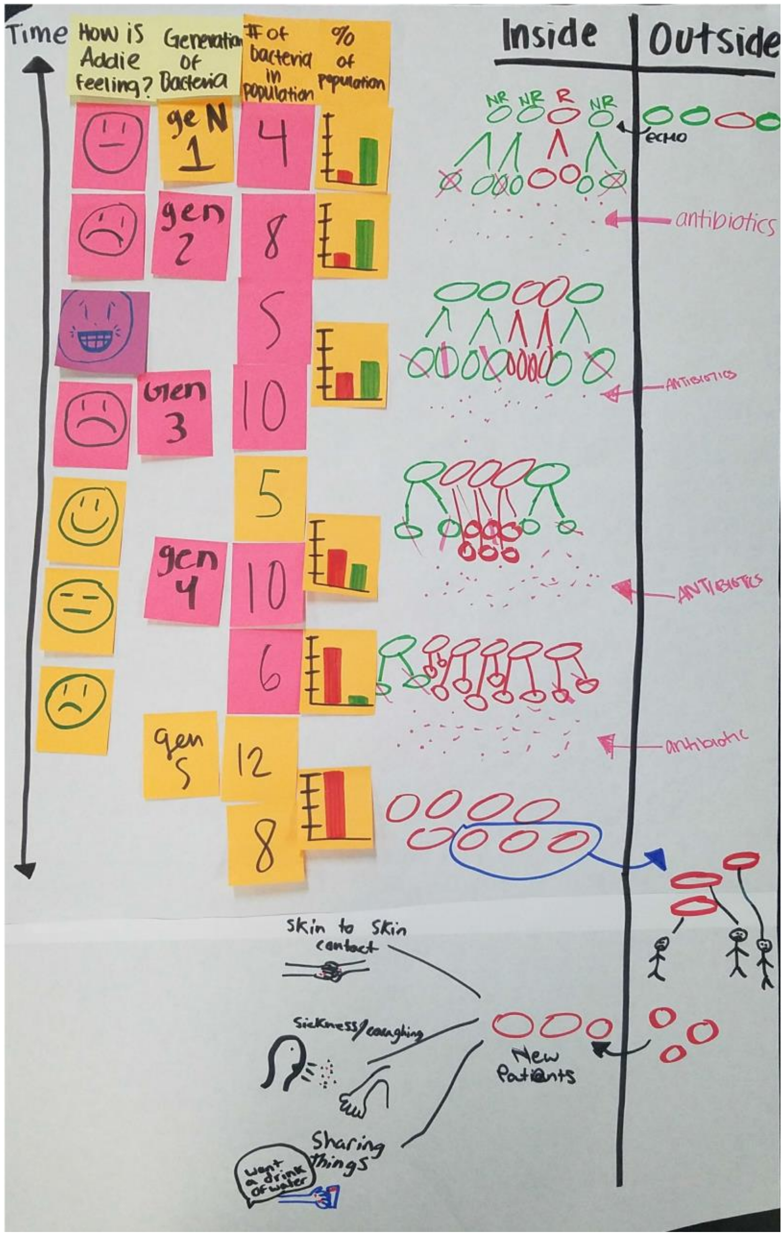

Figure 2. A small group’s revised model to explain how Addie’s condition changed as the bacteria changed within her. The model is organized into how Addie is feeling, the generation of bacteria, size of the resistant (R) and non-resistant (NR) bacteria population, and what is happening inside Addie’s body and outside her body.

Having figured out part of the explanation, the class also is prompted to consider whether other populations of organisms could change like the bacteria have changed. The teacher uses the resources in the curriculum materials to introduce a new phenomenon with features that can help develop their understanding further, the microevolution of the Dark-Eyed junco. This new phenomenon has the advantage of having multiple datasets the students can investigate and capturing their attention by focusing investigation on a behavioral trait—boldness—common to many animals that adapt to life alongside humans in cities. It also will provide an opening to explore speciation through simulating what might happen over many generations to the birds they are studying.

One of the representations that is key in supporting students' making sense of how this new phenomenon can support the overall model they are developing is the building of a side-by-side chart of key features that they studied related to antibiotic resistance and what they learn from a short video introduction to the Dark-Eyed junco. After identifying the parallels, students individually consider whether the explanation they have built for antibiotic resistant bacteria could help them explain the changes in the population they are seeing in the junco case (see Table 3).

Table 3. A Student's Analysis of Whether the Antibiotic Resistant Bacteria Model Could Help Explain the Changes in the Junco Population

Does the junco case have the characteristics we need to help the sort of questions we developed for this key interaction in the previous lesson? If it appears it does, explain how. If it appears it does not, explain what's missing.
A. Is it a heritable trait? *Yes. The juncos on campus have certain traits distinguishable from the mountain juncos, like more white on tails and shorter wings. These traits are heritable and can be passed on to offspring.*
B. Did something change in the environment of the population? *Yes. The juncos on the UCSD campus are exposed to humans and therefore have more interactions with them. Their wild food sources are limited, so they must interact with people to eat food scraps.*
C. Did the environmental change put pressure on the population? *Yes. The increase of human interaction needed allows for bold birds who are willing to go up to humans to survive more easily, giving them a competitive advantage over timid birds.*
D. Will offspring of the organism retain the same trait variation? *Yes. Those who are bolder and more willing to interact with humans survive and reproduce, which passes this personality trait on to their offspring.*
We used these key interactions in our model to explain how bacteria became more resistant. Do you think we will be able to use these same interactions to explain how one population of juncos came to look like and behave differently than the other? Do you think the model will need to be revised or no? Explain. *I think we will be able to use a similar model, but some adjustments must be made if it is going to be able to fit the juncos. The bacteria model showed how a population is able to better survive and environmental stressor when the weakest individuals are killed off and the strongest survive and reproduce. I think the same kind of interaction will be able to be used, yet we will have to alter some aspects, such as the reproduction process. For instance, bacteria reproduce asexually, while the juncos reproduce sexually. We will have to make this process into account in our model and we may have to represent it different than in our bacteria model.*

The advantage of introducing a second phenomenon to explore addresses a common challenge to case- and problem-based learning, namely generalization. When students encounter big ideas through particular cases, it is critical that they be able to abstract those ideas from the case. Typically multiple cases are necessary, in order to facilitate reasoning from cases to develop generalized ideas (Kolodner, 1993; Kolodner et al., 2003). This becomes a central challenge in organizing NGSS curriculum materials around phenomena. While the phenomenon or design challenge provides a context for developing and applying the important science ideas, it is necessary to investigate the scope of those ideas, and multiple cases become the vehicle to do this. For example, after building a preliminary model of how individual variation in bacteria enabled some with certain traits to increase in numbers, it was important to ask whether populations of more complex organisms (like birds or mammals) could exhibit the same pattern of change across multiple generations. Continuously challenging successful models to see how far they can be pushed and continue to explain a range of phenomena is thus a key part of the modeling, argumentation, and explanation practices in NGSS (Berland et al., 2016; Gouvea & Passmore, 2017; Passmore et al., 2014; Schwarz et al., 2009). Purposefully chosen contrasting cases can support students more generalized explanations, by helping students notice similarities and differences between cases (Schwartz & Bransford, 1998; Schwartz, Chase, Oppezzo, & Chin, 2011). This need for revising and generalizing the model again reflects the incremental sensemaking inherent in NGSS (principle 3). In addition, we see the importance of phenomena in creating a need to extend students' models (leading to coherence for students), rather than the curriculum materials or teacher telling students where their ideas are incomplete and where they should focus.

The unit also includes a multi-lesson design challenge, focused on developing an infographic or video as a type of public service announcement to warn people about the dangers of not taking complete doses of antibiotics (see Figure 3), thus connecting the science to an everyday concern in their communities (principle 5). Infographics and videos such as public service announcements are an authentic tool for communicating scientific information to the public and engage students in the practice of communicating scientific information (e.g., Lamb, Polman, Newman, & Smith, 2014; Polman & Gebre, 2015). The intent behind the design challenge is also in this case to support students in developing a grasp of key engineering practices. As part of the challenge, students have to define the communication problem they are to solve, and they have to conduct investigations focused on understanding the needs and constraints that must be met as part of their solution. They develop and provide feedback on one another's drafts, and they review them for scientific accuracy. A staff member of a local health clinic (sometimes in the students' own school) reviews and selects some of the infographics to be posted, which provides motivation for students to attend carefully to their particular needs and constraints.

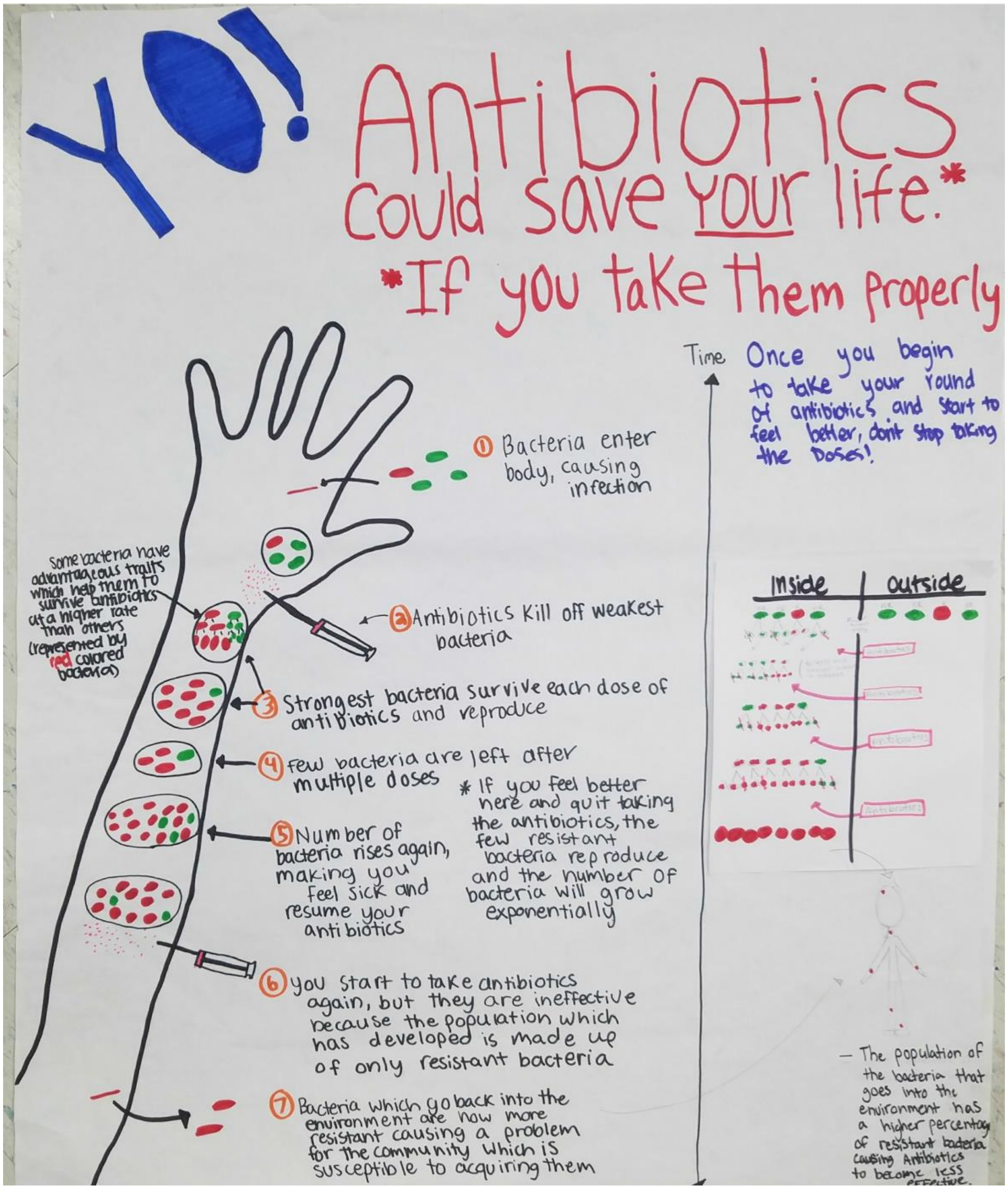

Figure 3. A group's infographic about the dangers of not taking the full dose of antibiotics

Following the investigation of phenomena with a project such as this one provides an additional way for students to integrate their learning. This pattern of following up problem-based learning with project-based opportunities has strong support from learning sciences research. As Barron and colleagues (1998) write,

> By following the problem with a project, students are likely to develop more flexible levels of skills and understanding. In addition, if students know they will be completing real projects in their community, they are

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> motivated to learn. Students view the problem-based learning as preparing them for “the real thing.” (p. 278)

As with our scaffolded assessments of student models, scaffolds for supporting specific aspects of the infographics design challenge are critical. Students do not just produce infographics as part of their lessons; they also provide justifications for design choices that teachers can use to evaluate student understanding.

As a further way to assess student understanding, the unit includes multicomponent tasks (see National Research Council, 2014) that can be used to test students’ understanding of the targeted performance expectations using new phenomena presented to students. These tasks present students with sufficient data and prompts to elicit understanding of relevant core ideas and crosscutting concepts, using science practices to explain the new phenomenon. An example from the evolution unit is a task that requires students to build an explanation for the evolution of wing length in swallows living under highway overpasses (see Appendix A). The task draws on real datasets that are presented to students, but it is students who have to recognize the task as an opportunity to apply their understanding of concepts of evolution to explain the patterns on the data they observe. The assessments include a set of prompts that scaffold parts of students’ reasoning, some of which are derived from a set of tools we and members of another research team at the University of Washington have developed to support the design of three-dimensional assessment tasks. The prompts are not generic, but tailored to explaining the phenomenon at hand.

In telling the story of this unit, we have focused on how students experience it, and so we have not yet called out the embedded teacher supports that would illustrate principle 7. Embedded through these materials are several kinds of supports. An important support is for discussion, including prompts to start discussion, examples of possible student ideas that might emerge, and a taxonomy of types of discussion (e.g., brainstorming, building explanatory consensus modes). Other supports include explicit guidance about the storyline — embedding conversations that help students reflect on where they left off and what questions today’s lesson should be addressing, and wrapping up lessons with reflection about what they figured out, and where they need to go next.

Evidence of Student Learning for Grades 6-12

Evidence for fully worked examples of NGSS-designed curriculum materials is not yet available, because these units are only now beginning to emerge. However, there is rich program of research providing evidence for the benefits of the principles in Table 1 that underlie the design of NGSS units. In this section, we review some of these findings relevant to the design principles we have proposed.

Principles 1 and 2: Evidence for learning from units that combine practices and science ideas, organized around phenomena and design challenges

In this review, we combine the first two principles of 3D learning and a focus on phenomena and problems, because these two principles rely so heavily on one another. The evidence addresses the underlying thrust of principle 1, using science and engineering practices to build and use science ideas. However, a limitation of the evidence so far is that these studies typically focus on science and engineering practices with disciplinary ideas, and few have looked explicitly at the crosscutting concepts.

The pedagogical approach most studied for integrating practices with science ideas is project-based learning. Initial evidence for the effectiveness of this approach emerged from studies of student learning in an urban systemic reform project in Detroit Public Schools (Geier et al., 2008; Marx et al., 2004). Participating schools used project-based learning curriculum materials that integrated science and engineering practices with science ideas and provided connected professional development for their teachers. Geier et al. (2008) compared students from participating classrooms with peers in the district and found higher scores in "science content understanding and process skills" and higher pass rates on the high-stakes state test for participating students than their peers.

More recent evidence for the effectiveness of project based learning in science comes from a recent study of two units from the Project-Based Inquiry Science (PBIS) curriculum (Kolodner, Krajcik, Edelson, Reiser, & Starr, 2010). The study is significant, both because teachers in the study received professional development in the *Framework* and because the outcome measures were tests that incorporated three-dimensional assessment tasks (DeBarger, Penuel, Harris, & Kennedy, 2015). In the study (DeBarger et al., 2015), 42 schools in a large urban school district were randomly assigned to either a treatment (PBIS) condition or a comparison (regular curriculum) condition. A total of 94 teachers and 757 students participated in the study. The researchers found that the students in the PBIS classrooms outperformed those in the comparison classrooms on both unit tests, with average effect sizes of +0.22 and +0.25. The results were similar across all three background characteristics of students analyzed: main treatment effect did not vary significantly by gender, ethnicity, or parent education.

Research on instructional sequences that are anchored in problems supports the claim that students retain knowledge longer and are better prepared to solve future, related problems than when introduced to these ideas first and then given the chance to apply them (Bransford & Schwartz, 1999; Cognition and Technology Group at Vanderbilt, 1992; Schwartz & Bransford, 1998). Phenomena or problems can provide the context to help students build connections with existing knowledge (Manz, 2015b, 2016; Manz & Renga, 2017) and explore these ideas more deeply than when the ideas are presented without a context that illustrates how they can be applied (Kanter, 2010; Rivet & Krajcik, 2008).

Another aspect of evidence for these principles comes from studies of the efficacy of curriculum materials that use phenomena or design challenges that connect to students' everyday experiences and interests. A number of studies have explored when science learning helps to support the development of "practice-linked" identities, that is, a sense among students that they are participants in and contributors to disciplinary practices (Nasir & Cooks, 2009; Nasir & Hand, 2006). This is important, because research suggests that wanting to participate in science is influenced partly by whether students identify themselves as people who can or cannot do science (Brickhouse, Lowery, & Schultz, 2000). Seeing others productively struggle to generate questions, plan investigations, and figure out science ideas in a supportive environment also likely contributed to an increased sense that science instruction was meaningful to them, a finding reported by Luehmann (2009).

A study by Tzou and Bell (2010) provides evidence that curriculum materials that explicitly draw on students' everyday experiences can support both their learning and identification with science. In their *Micros and Me* curriculum unit (Tzou, Bricker, & Bell, 2007), students develop an understanding of microorganisms and health through a series of investigations, some of which are focused on their own practices for maintaining health and avoiding getting sick. In the unit, students take photographs of these practices, bring them into class, and construct their own questions in collaboration with their teacher to investigate. Students in the fifth-grade classroom who participated showed an increase in their understanding of factors that contribute to the growth of microorganisms and a stronger grasp of the practice of planning and carrying out investigations, and they identified more strongly with science.

Principle 3: Evidence for benefits of supporting incremental sensemaking and model building

There is a rich series of studies that reveal the failures of much of traditional science instruction to engage with learners' prior ideas, and the way this can lead to "inert knowledge" or decontextualized knowledge that can fail to connect with students' prior conceptions (e.g., Chi, 2005; Hammer, 1996; J. P. Smith, III et al., 1993/1994). There is increasing recognition that eliciting students' prior ideas and helping them revise and extend these ideas is a key component of effective support for science learning (see National Research Council, 2007 for a review). A key part of helping students engage and develop their intuitive ideas into more sophisticated science conceptions are the strategies to support incremental sensemaking in curriculum materials — helping students articulate their intuitive ideas that arise when trying to explain a puzzling phenomenon (like Addie), describe relevant experiences, and articulate questions, and then using these questions to guide investigations and subsequent knowledge building. This requires a coherent instructional approach focused on supporting a learning community in articulating explanations and models, uncovering gaps, planning investigations, and revising their ideas.

Particular studies have highlighted the importance elements of such a system. For example, argumentation plays a key role in supporting developing and revising ideas, resulting in more effective development and refinement of explanations and models (Berland, 2011; Berland & Reiser, 2009, 2011; Gouvea & Passmore, 2017; Passmore & Svoboda, 2012). The need for principled argumentation emerges from identifying where explanations are in conflict, and a genuine commitment to figuring out as a community and reaching consensus (Berland, 2011; Berland & Hammer, 2012; Berland & Reiser, 2009, 2011; Manz, 2015a). Of course, classroom discourse plays a key role in doing this knowledge building work. Strategies to support teachers in drawing out students' ideas and helping them attend to one another's ideas to collectively evaluate and revise them support knowledge building in science and mathematics (O'Connor, Michaels, & Chapin, 2015; Resnick, Michaels, & O'Connor, 2010).

The importance of the incremental nature of the knowledge building arises most clearly in studies supporting students in the practice of modeling. Providing an opportunity and motivation to revisit and refine earlier ideas plays a key role in helping students develop more sophisticated explanations of scientific phenomena (Baek & Schwarz, 2015; Manz, 2012; Schwarz & White, 2005; Wilkerson-Jerde, Gravel, &

Macrander, 2015). These studies reveal the advantages of having students articulate their ideas as initial models and revise them incrementally, helping students build on their ideas, rather than attempting to guide students into a complete and fully correct model from the start.

Principle 4: Coherence

As described earlier, the principle of a coherent learning sequence draws on the strategies of the first three principles – incremental 3D knowledge building. In addition to looking at the incremental nature of knowledge building and the role of practices, some studies have looked specifically at the way the progression of questions and ideas are organized. Units organized around learning progressions have shown some promise, though primarily within studies using single-group designs. For example, Songer, Kelsey, and Gotwals (2009) used a dose-response design in which they found a link between higher levels of implementation of a unit focused on biodiversity, BioKids, as measured on teacher's log and students' complex science learning. The Carbon TIME curriculum materials are based on a learning progression related to transformations of energy and matter (Mohan, Chen, & Anderson, 2009). Single-group studies conducted of the project have shown growth from pre-test to post-test on the assessments used to measure the growth of students' explanations of carbon-transforming phenomena (Anderson, 2017). As with BioKids, researchers have found associations between teachers' support for student sensemaking through discussion and larger gains in student learning assessments (Jin, Johnson, Shin, & Anderson, 2017).

There is some evidence, too, that inter-unit coherence can facilitate student learning and development over multiple units and years. The Inquiry Project was designed to support children's learning along a hypothetical learning progression based on prior research about how children's understanding of the particulate nature of matter develops (C. L. Smith, Wiser, Anderson, & Krajcik, 2006) and on syntheses of research about quantitative reasoning, especially regarding ratio and proportion (Schliemann & Carraher, 1992). A comparison group study of the effects of the curriculum units in the Inquiry Project provide some evidentiary support for the claim that organizing units around a multi-year progression grounded in research on children's learning can facilitate learning of more complex concepts related to matter. Researchers found that by Grade 5, students in experimental classrooms were significantly more likely than were students in comparison classrooms to have developed an explicit concept of matter and to realize that even tiny things have weight (Doubler, Carraher, Tobin, & Asbell-Clarke, 2011; Wiser, Smith, & Doubler, 2012).

A recent study of the IQWST curriculum materials explored whether students built on understandings of the crosscutting concept of energy developed in early units in subsequent units (Fortus et al., 2015). Using a set of curriculum-aligned tests, researchers examined student responses to multiple-choice questions related to energy (the items were not three-dimensional). The students had been participants in a field test of the materials. The analysis showed a strong predictive relationship between performance on earlier energy items and subsequent items associated with later units, providing supportive evidence of the value of inter-unit coherence.

Principle 5: Evidence for integrating supports for equitable participation.

One strategy for promoting more equitable participation in science classrooms is to focus on phenomena and design problems that connect to students' everyday lives. Curricula that build on students' own funds of knowledge, everyday experiences, and cultural practices in families and communities evidence great potential for supporting students from nondominant communities' active participation in science class (Calabrese Barton, Koch, Contento, & Hagiwara, 2005; Hudicourt-Barnes, 2003; Rosebery, Ogonowski, DiSchino, & Warren, 2010). A challenge to ensure that curriculum connects to all students in a classroom is that any "standardized" science curriculum that is designed for broad implementation will require significant adaptations and modifications by teachers (Lee & Buxton, 2008; Suriel & Atwater, 2012). Professional development to support teachers in learning about students' cultural practices at home and making adaptations to curriculum that strengthen connections between science practices and those practices may be one strategy for supporting the process (Tzou & Bell, 2009).

Other research on promoting equitable participation has focused on how best to support student participation in discussion, particularly within the practice of argumentation. This includes research on teachers' use of educative features of materials to support discussion, such as research by Cervetti and colleagues (Cervetti, Kulikowich, & Bravo, 2016) as reported above and by Arias and colleagues (Arias et al., 2015) on supports intended to facilitate productive discussion of texts in science class. While Cervetti and colleagues' research points to an overall positive effect of uptake of these kinds of supports for English learners, Arias and colleagues report wide variability among four teachers they studied intensively with respect to their uptake of embedded supports for discussing science texts, and none led to regular discussions to support deeper student understanding of the focal core ideas within the curriculum materials.

Still other research has focused specifically on how curricular sequences might better support participation of students from nondominant groups in science in the context of technology-based instruction. For example, in a study of an online Knowledge Integration Environment (Linn, 2000), Hsi and Hoadley (1997) found girls to participate much more actively in an online discussion forum than in classroom discussions, generating explanations, revising ideas of others, and asking questions at rates greater than boys in the online forum. They attributed the differences to the fact that the environment provided anonymity that made them feel safe expressing their ideas.

There is a larger body of research that is descriptive in nature and that focuses on equity of participation within science classrooms, even though it does not describe curricular or professional development supports that are associated with more equitable participation. The research does point to conditions for equity that could be considered in designing curricular supports for more equitable participation in classrooms. They include the need for teachers to pay attention to and recognize students' diverse sense-making repertoires as intellectually generative in science learning and teaching (Rosebery & Warren, 2008; Warren & Rosbery, 2011); the need to broaden students' conceptions of who scientists are and "desettle" preconceptions of what scientists do (Bang, Warren, Rosebery, & Medin, 2012; Bianchini, Johnston, Oram, & Cavazos, 2003; Carlone, Haun-Frank, & Webb, 2011); the need to draw on and incorporate students' home language and linguistic resources in instruction, in written curriculum materials, and assessments

(Buxton et al., 2013); and the need to anticipate the way students will engage with curriculum differently, depending on their own purposes for participation in discussion and their social identities in the classroom (Carlone, 2004; Lynch, Kuipers, Pyke, & Szesze, 2005).

Principle 6: Evidence for value of providing multiple opportunities for teachers to elicit and interpret student thinking

Evidence for the value of providing integrated supports for classroom assessment comes from a study of the Contingent Pedagogies project (Debarger et al., 2017). In that project, a set of formative assessment tasks was integrated into two investigation-based units in middle school Earth science. Teachers received professional development in how to use these tasks to elicit students' initial ideas prior to investigation and to check their understandings at the conclusion of investigations. The assessment materials included a set of questions for teachers to ask that drew on identified problematic facets of student understanding, clicker technology for collecting student responses, and a set of talk moves to use to support student argumentation about their responses. The materials also included a set of "teaching routines" (DeBarger, Penuel, Harris, & Schank, 2010) for enacting the full cycle of formative assessment that included a set of activities teachers could use if students were having particular difficulties with understanding the focal ideas of an investigation. A quasi-experimental study of the materials that compared students in classrooms with the assessment-enhanced curriculum materials to students with the original units found students in the treatment condition outperformed students on tests of Earth science knowledge for both units. The study also found that teachers were able to use the materials to foster norms of supporting claims with evidence, which mediated student learning outcomes.

Principle 7: Supporting teacher learning

Perhaps the strongest evidence for the efficacy of integrating professional development with comes from the Science Teachers Learning from Lesson Analysis (STeLLA) project. STeLLA engages teachers both in analysis of their own practice from the standpoint of its coherence and in the analysis of student thinking. It is aimed at improving teacher and student learning at the upper elementary grades in science. The program of professional development includes curriculum materials (a brief unit), as well as materials that support teachers in eliciting student ideas and predictions, engaging students in reasoning about and interpreting data, and observations, engaging students in using and applying new ideas in varied contexts, and engaging students in making connections among ideas. Several studies (Roth et al., 2011; Taylor, Roth, Wilson, Stuhlsatz, & Tipton, 2017) —including ones involving random assignment—have shown that teachers who participate in the program have increased their content knowledge, as well as their pedagogical content knowledge about student thinking. The studies have also documented a positive impact on student learning.

Another study focused by Penuel, Gallagher, and Moorthy (2011) examined the efficacy of approaches to supporting teachers' principled adaptation of curriculum. In that study, researchers randomly assigned teachers to one of four conditions: (1) a curriculum design condition, in which teachers learned how to develop their own units of instruction according to principles of understanding by design (Wiggins & McTighe, 1998) as applied to science teaching; (2) a curriculum implementation condition, in which teachers were expected to implement an inquiry-based science unit with fidelity; (3) a principled adaptation condition, in which teachers applied the principles of unit design to adapt materials from the unit; and (4) a comparison condition. The researchers found that teachers in the principled adaptation condition were able to plan more coherent, rigorous sequences of instruction and engage students in activities that were meaningful to students (Penuel & Gallagher, 2009; Penuel et al., 2009). Students whose teachers were assigned to that condition also learned more than those in the curriculum design and comparison conditions (Penuel et al., 2011).

Davis and Krajcik (2005) argue that curriculum materials can embed a range of supports to support teacher learning. They proposed nine heuristics to support design of these supports into educative curriculum materials related to teachers' content knowledge, as well as their pedagogical content knowledge for engaging students productively with science ideas and practices. Since that time, they and other teams (e.g., Cervetti et al., 2016; Loper, McNeill, & González-Howard, 2017) have undertaken a number of empirical studies of how teachers take up educative features of curriculum materials and examine their effects on teaching and learning. Taken together, these studies show that teachers can and do take up some designed features intended to support their learning in ways that shape their instruction, but impacts on student outcomes are mixed.

One line of research by Davis and colleagues focused on kit-based elementary units with integrated educative features. Their research found that teachers used these features variably and for different purposes, such as for identifying different ways to teach the lesson and identifying main ideas (Davis, Palincsar, Smith, Arias, & Kademian, 2017). Those that were preferred most were ones closely connected to practice, two studies showed (Arias, Bismack, Davis, & Palincsar, 2016; Bismack, Arias, Davis, & Palincsar, 2014). The researchers also found that educative features supported student engagement in science and engineering practices that were not evident in classrooms where teachers did not make use of the enhanced materials (Arias et al., 2016; Bismack, Arias, Davis, & Palincsar, 2015). At the same time, educative features supported engagement of students in some science practices better than others (Arias, Smith, Davis, Marino, & Palincsar, 2017; Bismack et al., 2015). Use of materials to support teacher content learning and use of scientific text in the classroom varied widely (Arias et al., 2016).

The results of comparison group studies that examined effects on teaching and learning outcomes that the group conducted were mixed. On the one hand, they observed positive effects on teacher content learning and on students' justifications of predictions, an aspect of scientific practice (Davis et al., 2017). But a test of students' content understanding did not show any effects (Arias et al., 2017; P. S. Smith & Smith, 2014). This assessment did not assess three-dimensional learning outcomes, and so it is unclear whether results might have been different for such an assessment.

Another study by Cervetti, Kulikowich, and Bravo (2016) examined the use and effects of educative curriculum features designed to support emerging bilinguals (English learners') in fourth and fifth grade science classrooms. The study found no main effects on science content knowledge for the test of space science, but the researchers did find greater use of the strategies promoted for supporting emerging bilinguals' engagement in

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science classrooms in the treatment classrooms. They also reported a positive association between the use of the strategies and student learning outcomes. The strategies promoted in the study included encouraging teachers to give additional time for reading and writing responses, connecting to students' prior experiences, and allowing students to use different modalities for expressing their ideas.

One study that examined on teachers' use of educative curriculum materials for high school genetics focused on the role of professional development in explaining differences in student learning. In a quasi-experimental study, Schuchardt and colleagues (2017) examined student learning gains on a two-dimensional assessment that focused on students' use of mathematics and understanding of genetics to make qualitative and quantitative predictions about the possible genetic makeup of offspring. They compared learning gains of teachers who received 23 hours of professional development, 8 hours of professional development, and no hours of professional development. Those students teachers who received 23 hours did gain significantly more than the students in the other two sets of classrooms for items focused on quantitative predictions, but gains were similar across conditions for qualitative predictions. They concluded from their findings that the impact of professional development with educative materials depends on the content focus.

Addressing Gaps in Our Knowledge, Resources, and Capacity

There are few curriculum materials today that adequately meet the needs for supporting the instructional shifts outlined in the *Framework*, and fewer still that have been studied. In addition, once materials are developed—or as part of development—appropriate proximal and distal assessments must be designed or selected, in order to evaluate materials' potential for supporting students' three-dimensional science proficiency (DeBarger et al., 2015; Ruiz-Primo et al., 2002). Districts, schools, and classrooms will need to be selected that reflect the cultural, racial, and linguistic diversity of the United States, so that questions about what works when, where, and for whom can be adequately addressed. The path to developing knowledge related to new curriculum materials will take more than a few years to develop. Intense political pressure on advocates of the new standards is, therefore, likely unavoidable given the belief of many stakeholders that such research and development can happen quickly. It will also require significant resources and new capacities for educators, curriculum developers, and researchers, as we detail below.

New Knowledge Needed

We have described the type of instructional shifts in classroom teaching and learning needed to realize the vision of the *Framework* and NGSS. This raises important questions about how curriculum materials and professional learning opportunities that draw on them can best support the type of teacher learning and shifts in practice that are needed. For example, how can curriculum materials best support teachers in engaging their students in science and engineering practices? While it is clear that examples from classroom interaction are central, how should the examples be selected? How should rich examples from classrooms be represented in educative curriculum materials? What kinds of professional learning opportunities will be most effective in helping teachers analyze and draw important lessons from these cases, and how can these opportunities be provided prior to and during their enactment? How can teachers' engagement with examples of practice be best framed, so that they draw valuable inferences from the cases but do not see the cases as practice to emulate, but rather examples to adapt to fit their own context? How can these types of examples be best represented in materials? And perhaps most important, the type of teaching that involves co-construction by teachers and students requires careful negotiation between students' ideas and questions and the trajectory teachers and materials have planned to incrementally assemble the science ideas. This type of teaching cannot be scripted. How can materials reflect the balance between drawing out and building on students' ideas to motivate questions and ideas for investigation, while ensuring that the trajectory succeeds in meeting the learning milestones needed?

Design-based research (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; The Design-Based Research Collective, 2003) and Design-Based Implementation Research (DBIR; Fishman, Penuel, Allen, Cheng, & Sabelli, 2013) are two ideal approaches to developing such knowledge. Both approaches in the early stages focus on careful observation of how teachers and students make use of materials in classrooms in order to test how and when specific design features support learning (Sandoval, 2004, 2014). DBIR approaches this task with a focus on the professional development and other supports that will be necessary for helping a broad range of teachers working in varied organization conditions to implement them well (e.g., Penuel & Yarnall, 2005).

Adoption of emerging approaches to collaborative design and development can accelerate both the design of new materials and the development of knowledge related to their usability and value in a broad range of settings. Agile design and development is one such approach, used widely today in application development to support rapid design and testing through a sequence of design "sprints," release of working prototypes, followed by iteration based on customer feedback from prototypes (Cockburn & Highsmith, 2001; Martin, 2003). Co-design methodologies for DBIR are another way to organize curriculum development in a way that develops usable materials, while also fostering teacher agency and ownership (Bell et al., 2016; Severance et al., 2016). Co-design is a highly facilitated process—timed to the cycle of the school year—that engages educators as full partners in the design process (Penuel, Roschelle, & Shechtman, 2007). Some models of curricular co-design also include significant roles for family members, youth, and community members (e.g., Bang, Medin, Washinawatok, & Chapman, 2010; Pinkard, Erete, Martin, & McKinney de Royston, 2017).

Resources Needed to Develop and Test New Materials

Significant, but targeted, resources are needed to support both the design process and research on curriculum implementation and outcomes. Particularly beneficial would be an investment in helping design teams from across the country to identify a wide range of potential phenomena and design problems for students to solve that address the breadth of performance expectations of the Next Generation Science Standards and that are potentially engaging to students. As part of the process, teams would need to bundle and analyze performance expectations, identify candidate phenomena, and gather evidence regarding their potential for engaging students and connecting with their everyday lives. Such an up-front investment would help build awareness and capacity among educators and educational leaders about the central role of explaining phenomena and solving problem, as well as the challenge of identifying viable anchors for units. It could provide design teams with useful starting points for the design of curricular units that reflect the criteria we have identified above.

Second, resources are needed to build a network to support design teams that are distributed across the country in building coherent, relevant materials from carefully chosen unit anchors. Such a network could advise curriculum developers, researchers, and local educators on how to form teams with relevant expertise in science, student and teacher learning, and local communities to build materials that are accurate, effective, and linked to the lives of students from different cultural and linguistic backgrounds. The network could also provide guidance regarding tools and routines for supporting curriculum development, as well as set up peer feedback mechanisms to review other teams' work. Finally, this network could serve as a vehicle for focused testing of particular curricular strategies, using processes from agile development or from improvement science (Bryk, Gomez, Grunow, & LeMahieu, 2015). We propose this networked approach, rather than a centralized approach, both because of the need for curriculum materials to be tailored to local policy contexts and because of the need for curriculum materials to connect meaningfully to phenomena and problems that students might encounter in their communities and broader region.

Additional resources will be needed for both the network as a whole and for members of design teams to invest time in the development of the materials. The networked approach would make it easier to garner such resources because of strong leadership. Funding from local foundations and districts could supplement funding from national foundations and public agencies at the state and federal level. Key to successful implementation of the approach would be compensation for educator involvement in the process, as well as creating a cycle of design, development, and testing that is timed to fit within the constraints of teachers' availability to participate in design.

Another use of such networks would be to gather resources from classrooms that could be effective in supporting teacher learning. Professional learning supports anchored in curriculum enactment are sorely needed. There are two parts to addressing the teacher learning challenges. First, teachers need support in developing the knowledge, beliefs, and practices needed to support their students' three-dimensional learning in general. Second, they need to see how to implement these approaches in particular phenomena and design challenges contexts working with particular curriculum materials. These two challenges should not be tackled independently (Harris et al., 2015; Reiser, 2013; Severance et al., 2016). Attempting to provide professional learning without contextualizing the instructional shifts in specific examples of curriculum materials, task design, and student work will not be effective; nor will providing new curriculum materials intended to help teacher change their practice without also supporting teachers learning about instructional shifts before and while they are enacting the materials (National Academies of Sciences Engineering and Medicine, 2015; National Research Council, 2015). To support these professional learning curriculum-embedded opportunities, the field will need a rich collection of video cases of three-dimensional learning in action, with the task design, curriculum materials, and example student work that are artifacts from these cases (Reiser, Michaels, et al., 2017; Roth et al., 2011; Taylor et al., 2017).

New Field Capacities Needed

For local education leaders to facilitate the kinds of processes we have outlined and for educators, scientists, curriculum developers, education researchers, and community members to participate in them, it will require us as a field to develop new kinds of individual and social capacities. For educators, a commitment to iterative experimentation and capacity to engage in deep, collective inquiry will be needed. For scientists and curriculum developers, a willingness to work closely with one another to identify engaging phenomena and problems that prepare young people to engage with contemporary science ideas and issues is necessary. For education researchers, it will require the adoption of new strategies for more agile data collection and interpretation, such as collaborative, improvement-oriented learning analytics (Krumm, Means, & Bienkowski, 2018), to work at a speed that is required for fast-moving research and development. And for facilitators of design teams—whether they come from the community or are scientists, researchers, curriculum developers, or education leaders—capacities for organizing inclusive iterative design processes will be needed.

This list of capacities is, we acknowledge daunting, given where we sit now as a field and because of the complex and turbulent environments of education. Yet, they are necessary if this endeavor is to succeed, namely broad and equitable implementation of the vision of the *Framework for K-12 Science Education.* And, this approach is one in which we imagine positive feedback loops or virtuous circles are possible: through participation in the activities of creating new materials together, we develop the very capacities that are needed to succeed at the effort, even as we learn from what will surely be many mistakes. If we build a broad, national network of multidisciplinary, inclusive teams capable of creating and testing powerful curriculum materials, we can co-create the very system of science education we hope to bring about.

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Appendix A: Sample Transfer Task for the Unit Why Don't Antibiotics Work Like They Used to?

The data in this task are drawn from Brown and Brown (2013). The transfer task addresses the NGSS performance expectation HS-LS4-3:

HS-LS4-3. Apply concepts of statistics and probability to support explanations that organisms with an advantageous heritable trait tend to increase in proportion to organisms lacking this trait.

Task:

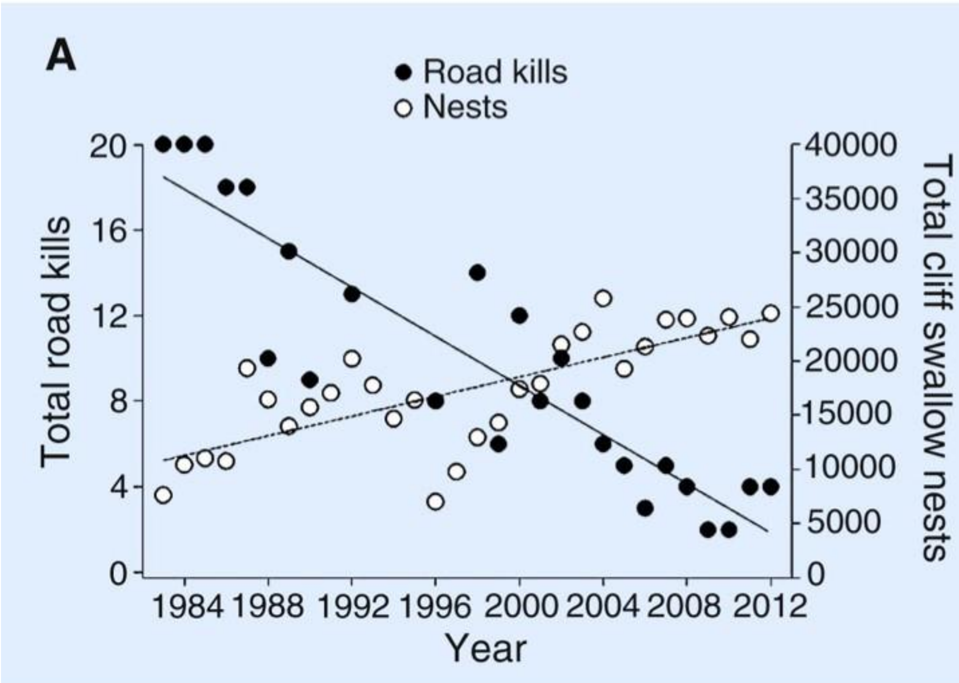
Scientists observed roadkill over a period of 45 years in Keith County, Nebraska. Scientists started studying roadkill there, because after I-80 (an interstate highway) was completed in 1967, people noticed a large number dead cliff swallows on the highway.

Cliff swallows now commonly nest underneath highway bridges, overpasses. The nests are grey or brown with openings at one end. The picture on the left shows several nests underneath a highway structure. The picture on the right shows two birds in their nests.


Image source:
http://www.cell.com/cms/attachment/2021743115/2041577164/gr1_lrg.jpg

Q1. What do you think are some of the challenges of cliff swallows living in this environment? What are some advantages of the habitat to the cliff swallows?

Question 2. The graph below shows changes in road kill and number of nests in the population of cliff swallows in the area over time. What do you think is happening to the size of the population of swallows between 1984 and 2012? What patterns in the road kill and nest data make you think that?



Q3: What do you think might be causing the change in population of swallows?

Q4. Cliff swallows now commonly nest underneath highway bridges, overpasses (see pictures above). Use this information and the pattern of data in Chart C below to help explain what is happening in the cliff swallow population over the time period scientists observed them? Be sure to include in your explanation: (1) the advantage of shorter versus longer wings; (2) your ideas about the likely pressures of the environment; (3) the data on wing length for swallows that survived; and (4) the mechanism that drives the changes in the data you see. Note: Wing length is a heritable trait.

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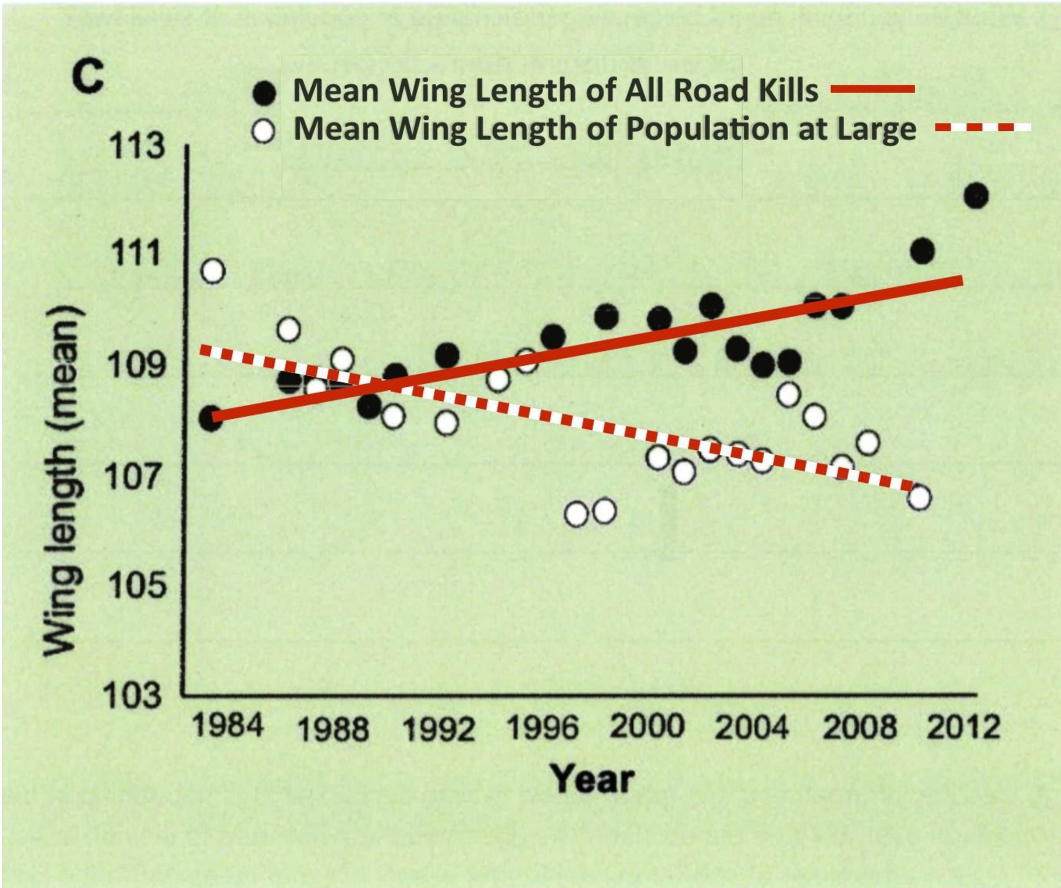

Draw a dot on the chart below to indicate what you predict the average wing length of the population will be in 2020. How did you estimate where to place the dot? Be sure to say what assumptions about the environment you made to create your estimate.