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# Connecting student interests and questions with science learning goals through project-based storylines

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## Abstract

In this conceptual paper, we describe the approach in storylines that builds on principles of project-based learning and focuses on supports for making science learning coherent from the students' perspective. In storylines, students see their science work as addressing questions and problems their class has identified. We present design principles that guide the teaching and enactment of storyline units and explore the connections of these principles to ideas of project-based science. We illustrate how these design strategies are reflected in a high school biology unit co-developed by teachers and researchers. We present student artifacts that document the agency students take on in this work. We then summarize results from earlier studies examining students' learning and perceptions of coherence of their learning experiences.

**Keywords:** Coherence, Project-based learning, Storylines, Interest, Epistemic agency, Science and engineering practices, Next Generation Science Standards

## Introduction

Reforms in science education emerging internationally identify the need for important shifts in teaching, curriculum materials, and assessment. Central among these shifts is the commitment to more meaningful science learning by involving students in the work of building, revising, and applying science ideas to their world. In the U.S., this is articulated in *A Framework for K-12 Science Education* (National Research Council, 2012) and in the standards it has guided, including the *Next Generation Science Standards* (NGSS Lead States, 2013), by integrating science ideas with science and engineering practices that reflect the goals, norms, discourse, and knowledge-building work of science and engineering disciplines. Erduran and colleagues have argued that engaging in practices is a key element of understanding the

nature of science and making sense of ideas such as data, models, and explanations (Dagher & Erduran, 2016; Erduran et al., 2018). Engaging in practices entails not simply taking steps to *do science* by following directions, but rather to build and use science knowledge in a way that reflects the disciplinary practice of investigating meaningful questions and applying that knowledge.

One approach to making science more about the meaningful building and use of science ideas is to contextualize and situate the science that learners build in its application to real-world problems, rather than viewing learning “the basics” as a precursor to “application.” These arguments for *project-based learning* (e.g., Condliffe, 2017) and related arguments for *context-based learning* in science (e.g., Sevan et al., 2018), draw on the need to connect the science students learn with real world phenomena and problems to build interest and motivation, support connections and elaborations for richer knowledge, and to avoid problems of “inert knowledge” of isolated facts one cannot apply in appropriate

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settings. Miller and Krajcik (2019) presented an argument for *project-based science* that builds on four basic principles of project-based learning: active construction, situated learning, social interactions, and cognitive tools, combined with the recommendations of the *Framework* and the Next Generation Science Standards for three-dimensional learning. They explore how the recommendations in the *Framework* and NGSS for engaging students in science and engineering practices to investigate questions and design solutions for problems in everyday phenomena can be realized through the project-based learning approach of active construction that is situated in real world problems. They argued that collaborative engagement in practices, using tools, provides a mechanism for the social interactions and use of cognitive tools that are central in project-based learning.

The focus on science practices builds on but also extends the emphasis given to inquiry both in the United States and in countries around the world. The *Programme for International Student Assessment* (PISA: OECD, 2019), for example, names a core competency in science as being able to evaluate and design science inquiry, and many countries explicitly encourage the use of inquiry-based methods of teaching (see Oliver et al., 2021, for examples). In inquiry-based approaches, emphasis is given to practices that directly support student investigations, such as planning and carrying out investigations and drawing conclusions from data generated from those investigations. In the shift from inquiry to practices in *A Framework for K-12 Science Education*, greater emphasis is given to the science disciplinary practices that build generalizable knowledge from investigations—particularly model-building, explanation, and argumentation—that were not emphasized in earlier U.S. standards and in guidance regarding inquiry (Furtak & Penuel, 2019). The field of science studies has identified each of these as key to knowledge building in science (e.g., Dunbar, 1995; Latour & Woolgar, 1986). Project-based learning supports a science-as-practice approach, because it provides a focal point—phenomena or problems that anchor sequences of learning—for knowledge building using science and engineering practices, particularly those that are not typically emphasized within inquiry-based approaches to teaching.

Reiser, Novak, McGill, and Penuel (2021) build on ideas in project-based learning and explore the implications of the *Framework* for coherent and meaningful progression of learning that builds by engaging students in practices. Framing this knowledge-building work as a practice, rather than as simple skills-building, entails that the work not only reflects the discipline, but is meaningful for students. Rather than simply engaging in the work because “that is what scientists do” or “because it will help you learn,” students should be engaging in the

process of knowledge building because it helps them figure out and solve problems their classroom community has adopted. We refer to this as *coherence from the student’s point of view* (Penuel & Reiser, 2018; Reiser, Novak, et al., 2017; Reiser et al., 2021). We refer to the instructional strategies that support this approach to coherence as *storylines that are coherent from the students’ point of view* (Reiser, Novak, et al., 2017; Reiser et al., 2021). The design strategies used in these storylines build on principles of project-based learning and focus on supports for making science learning meaningful both to the classroom community and to the disciplines of science (Berland et al., 2016).

In this conceptual paper, we describe the design strategies for storylines that are developed to be coherent from the students’ point of view, rather than based solely on a logic apparent to disciplinary experts (Penuel & Reiser, 2018; Reiser, Novak, et al., 2017; Reiser et al., 2021). We present design principles that draw on the ideas of project-based science to guide the teaching and enactment of storyline units. We illustrate how these design strategies are reflected in a high school biology unit and present student artifacts that document the agency students take on in this work. We briefly summarize results of previous studies of students’ learning and their perceptions of their role as learners.

### The quest for coherence in science curriculum materials

Since the Sputnik era, science curriculum reforms have sought ever greater coherence in curricula by organizing them around the key ideas of the discipline. Bruner (1960) argued that science curricula should be organized around the structure of the discipline and that students could be introduced—with appropriate supports—to key ideas at an early age, developing more sophisticated understandings through subsequent re-encounters with those ideas. The ideal of coherence as reflected through the lens of key ideas of the discipline was applied in the late 1990s to evaluate curriculum as part of Project 2061. In this work, Roseman and colleagues defined coherence as the “desired set of connections among scientific ideas that students need as they progress through school” (Roseman et al., 2008, p. 13). Such connections might include that matter as made of particles too small to see as an idea to be established prior to figuring out how matter rearranges and is conserved in a chemical reaction (AAAS, 2001).

More recently, the field has embraced the ideal of *developmental* coherence in both standards and curricula. When standards and curricula are developmentally coherent, they organize the ideas that are most important to teach according to conjectures about how students’ ideas might be expected to develop in a given domain

(National Research Council, 2012). Sometimes, both the ideas and progressions are articulated through the consensus of subject matter experts. Other times, they are grounded in research on learning progressions that have identified both productive entry points for learning specific ideas, as well as steppingstones in their development toward canonical understandings of science ideas (Duncan & Rivet, 2013; National Research Council, 2007). The NGSS includes a blend of both: experts' best conjectures about hypothetical progressions in particular domains, as well as empirical research in some well-studied areas, such as how students develop an understanding of the particle nature of matter (Smith et al., 2006).

Contemporary project-based learning materials development for the NGSS aims to achieve the vision of developmental coherence—both with their emphasis on a few core ideas and on helping students build from their own resources and experiences. These efforts build on earlier work to articulate different levels of coherence to which designers must attend—intra-unit coherence, interunit coherence, and across-years coherence (Fortus et al., 2015; Krajcik et al., 2008; Miller & Krajcik, 2019). These different forms of coherence support learning by engaging students with ideas so that they can leverage prior understandings to build more sophisticated knowledge (Miller & Krajcik, 2019). Most commonly, developmental coherence is supported, too, by organizing instruction around an anchor, like a phenomenon, that can provide a common focal point for instruction.

In a critique of the notion of curricular coherence, Sikorski and Hammer (2017) argue that even developmental approaches to coherence leave out consideration of the active role of students in making their thinking and reasoning “hang together” (p. 930). They argue that coherence cannot inhere in curriculum, nor can it be expected that the development of student thinking will necessarily mirror the sequences of lessons in a curriculum. Further, they argue that even though NGSS enjoins curriculum developers to embrace a notion of science-as-practice, “curriculum development continues to be guided by the notion of coherence as a relationship between concepts, rather than as part of the scientific pursuit” (p. 935). They argue that curriculum developers should attend to students' actual experience of the curriculum as coherent, and that curriculum materials should leave room for students to try to explain phenomena, to make their thinking visible and evaluate one another's ideas and evidence for consistency, develop shared criteria for science knowledge, and experience finding gaps in ideas and pursuing investigations to address those gaps (Jaber & Hammer, 2016; Sikorski & Hammer, 2017). Consistent with this concern, we have argued that even when project-based curricula targeting

having real-world questions and problems create a reason to learn the science, that reason may be apparent to teachers and designers but not to students who may not see or be persuaded how a given day's lesson will help address the questions their class has identified (Reiser et al., 2021).

Our notion of coherence from the student point of view builds on aspects of coherence emphasized in the design of project-based learning materials and with key assumptions articulated in Sikorski and Hammer's (2017) critique of these designs. On one hand, we agree with the idea that curricula should be organized around the development of a few key ideas in science and in anchoring curricula in meaningful phenomena. However, we recognize that by taking students' questions seriously, their questions may not follow a logical or hypothesized developmental sequence of activities. Like Sikorski and Hammer (2017), we argue for designing for student experience—in particular, for the opportunity to grapple with uncertainty, with decisions about how to proceed, and hence gain a grasp of scientific practice through their collective knowledge building.

We view *coherence from the students' perspective* as when a classroom community engages in meaningful investigations in which students work together as collaborators with the teacher in managing the trajectory and substance of their knowledge building. Establishing a project with a meaningful anchor is part of the strategy. But we emphasize the additional role of involving students in evaluating progress and figuring out where to go next. When learning is coherent from their perspective, students see each step in their science work as in service of trying to figure out answers to questions or design solutions to problems their class has committed to address, and not simply in terms of accomplishing the demands of the teacher or textbook. The knowledge building is incremental in a way that makes sense *to students*. Students develop ideas over time, where each step is motivated by new questions or problems that emerge from their work so far, and the science ideas they develop are seen as tools to help them address these questions (Edelson, 2001; Kanter, 2010; Odden & Russ, 2019). To develop toward science ideas targeted in standards, unit designers aim to anticipate student questions and ideas that arise from phenomena, rather than establish a flow based simply on a logical progression of ideas.

### **A storylines approach to instructional materials and teaching**

Achieving these goals of coherence requires shifts in how teachers frame the goals of the science work and the epistemic roles that students take on. This requires shifts in instructional materials that lay out trajectories

of learning activities to support students' meaningful engagement in science, the strategies teachers use to support students in this work, and in the classroom norms that support students' increased epistemic agency (Reiser et al., 2021).

We refer to our design as a *storylines approach* because we argue students should experience lessons as connecting together to help students form a coherent and developing story. Researchers have used the term "storyline" to refer to a variety of approaches that emphasize how the lessons should fit together. Some scholars have advocated that science can be presented as a narrative organized around major advances in sciences (Egan, 1989; Isabelle, 2007). Other scholars have explored units where multiple threads of stories are purposefully woven throughout the unit to come together only at the end (e.g., McDonald et al., 2008). The NGSS refers to "grade-level storylines" specifying how disciplinary ideas are allocated in each grade or grade band, i.e., the proposed developmental progression across years. Similarly, Roth et al. (2011), in their STeLLA project, have developed "science content storylines" as supports for teacher learning that articulate how ideas in a lesson or unit are sequenced and connected to one another. These content storylines take the viewpoint of the subject matter expert as the backbone providing coherence. Our approach to coherence in storylines shares a commitment with these approaches to a logical and incremental building of a story across time. Our approach differs in emphasizing how that work must involve students as agents in engaging in conversations about the management of the work, so that they anticipate and make sense of each decision. For example, in disciplinary-based storylines, the logic of why the class is conducting a particular investigation or examining a particular phenomenon may be apparent to the teacher but not the students. While it may make sense to the students at the end of the unit, from their perspective, they are being asked to "trust" the teacher or curriculum, rather than being involved as collaborators in how to make progress on their questions. We agree with Nordine and colleagues who add to this story-building notion the idea that coherence should not only include connections between lessons, but also needs to establish a "need to know" that drives students' work (Nordine et al., 2019; Nordine et al., 2021).

Next we summarize four design principles that guide our storyline design work (Penuel & Reiser, 2018; Penuel et al., 2021, in press; Reiser, Novak, et al., 2017; Reiser et al., 2021; Severance et al., 2016) and empirical investigations of classroom enactments (Krumm et al., 2020; Penuel, Van Horne, et al., 2018; Penuel et al., 2016; Zivic et al., 2018). These principles articulate shifts in epistemic agency for students and the collective nature of

the work in which students engage (Alzen et al., 2020). We build on Miller and Krajcik's (2019) design principles that incorporate project-based learning with the goals of three-dimensional learning and add a focus on coherence from the students' perspective. Next, we describe these principles and explore how they are reflected in a high school biology storyline unit.

#### **Principle 1: anchor knowledge building in questions and problems students identify from engaging in phenomena connected to their interests and experiences**

A key consequence of the commitment to supporting learners' engagement in the work of science knowledge building as a practice is that practices require a *meaningful purpose* for their use. This requires more than simply instructing 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 et al., 2000; Windschitl et al., 2008). Engaging in a practice means participants pursue shared goals with shared ways of making progress (Ford, 2008; Manz, 2015; Osborne & Quinn, 2017). The *Framework* defines these purposes as central: "Science begins with a question about a phenomenon ... and seeks to develop theories that can provide explanatory answers to such questions" (National Research Council, 2012, p. 50). Analogously, "Engineering begins with a problem, need, or desire that suggests an engineering problem that needs to be solved." Thus, our first principle starts with Miller and Krajcik's principle for anchoring units "with a driving question about a phenomenon and engineering problem, a problem to be solved or experience to be explained" (Miller & Krajcik, 2019, p. 6).

We argue, however, that truly addressing the *Framework* vision of meaningful science and engineering practice requires considering what is entailed in the terms "questions," "problems," and "need." It requires not simply "providing" a goal through an anchor but also cultivating interest and buy-in to that goal on the part of the classroom community. In a practice, problems and needs are not simply "assigned." The community has agency in recognizing the need and committing to address the questions or problems. Thus, problems and phenomena provide a context in which to establish the *need* for the target science ideas, situating that need in real-world situations (Edelson, 2001). This provides a reason to build the target ideas and provides a way for students to monitor how useful the knowledge that they are developing is for those goals. This approach to developing knowledge in the context of its use places a central focus on the project-based learning goal of situated learning – students develop the knowledge in contexts in which it is both motivated and useful, rather than learning



abstractions that may result in inert knowledge (Krajcik & Shin, 2014). It is knowledge-in-use.

However, to be meaningful for students, phenomena and design challenges must 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 et al., 2015). Swirski, Baram-Tsabari and Yarden (2018) argued that connecting to students' interests through their questions is essential for context-based learning. Of course, not all phenomena and design challenges that are potentially interesting may be suitable for anchoring units. 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. Similarly, a phenomenon that could be explained, in principle, by target disciplinary ideas, but does not enable students to interact with it and figure out these ideas through investigation would not provide a phenomenon useful for instruction. Thus, phenomena and design challenges must connect to student interests and experiences, while simultaneously creating a need and a feasible pathway for students to develop the targeted science ideas and practices.

Our design process attends to this goal in several ways. First, as other project-based curriculum design efforts do, we begin with an "unpacking" or analysis of a group of standards that are to be targeted in the unit (Krajcik et al., 2014). Second, a team of educators and researchers brainstorm candidate phenomena and develop explanations of those phenomena that we would expect students to be able to construct by the conclusion of the unit. This ensures that explaining the phenomena will require the use of the key ideas in the standards. Third, we conduct a broad survey of students from different racial, ethnic, and linguistic backgrounds and of all genders, to assess which candidate phenomena would most interest them and which problems or design challenges address issues important to them and their communities. The unpacking, explanations, and survey results disaggregated by student group all serve as resources for deliberation among a co-design team when choosing an anchor (Edelson et al., 2021).

Another component of supporting interest in anchors is our use of an anchoring phenomenon routine to cultivate deeper interest and engagement in the phenomenon (Reiser et al., 2021). We draw on the idea of a routine as pedagogical patterns in that they reflect the important intellectual and social work accomplished in the elements of a lesson, which can be realized by a variety of particular activity structures (DeBarger et al., 2010). Cultivating interest may involve problematizing everyday phenomena for students, eliciting "perplexity, confusion, or doubt" in students in relationship to those

phenomena (Dewey, 1910, p. 12), to spark and sustain interest (Engle, 2012), and to push students to go deeper and develop explanations for phenomena they may take for granted (Manz & Suárez, 2018; Reiser, 2004; Reiser, Novak, et al., 2017; Watkins et al., 2018). Thus, the anchoring phenomenon routine involves several elements that go beyond presenting the phenomenon itself. Students are asked to try to develop a model to explain the phenomenon, drawing on their prior knowledge. In the discussion, teachers prompt to push students for a mechanism, helping them see the gaps in their intuitive explanations. Students are asked to bring in their own experiences that might be related to the phenomenon. This helps generalize beyond the specifics of the anchor, and can raise further questions. They brainstorm ways they might gather evidence to further their explanations. Indeed, productive science investigations may require helping students see that everyday occurrences they do not take notice of are actually confusing, when they are pushed to try to systematically explain how they occur. For example, everyday phenomena we take for granted, such as that rapping on a door makes sound or that iced drinks eventually warm up, can be productive contexts that effectively motivate clusters of scientific questions for students, when they are pushed to try to explain these and related everyday occurrences students bring into the conversation (Reiser, Brody, et al., 2017; Reiser et al., 2021; Zivic et al., 2018).

## **Principle 2: support students' incremental building of science ideas and practices**

Our second principle expands on the notion that students "engage in shared knowledge building" to develop "solutions to the driving question" proposed by Miller and Krajcik (2019, p. 6), articulating the step-by-step coherence from the students' own perspective in this knowledge-building work. Supporting students in using science and engineering ideas and practices to make sense of the world or solve problems 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 (Campbell et al., 2016; Hammer & Elby, 2003). Therefore, curriculum materials need to help students draw on their intuitive ideas to build initial models to explain phenomena, support students' building initial models, and continuously challenge them to extending those models as students encounter new phenomena, deepening mechanisms to improve their explanatory power, and revising them as they uncover limitations in these models (Berland et al., 2016; Passmore et al., 2014; Schwarz et al., 2009; Windschitl et al., 2012).

Curriculum materials that develop student understanding over time must provide supports for continuous sensemaking and incremental model building. They must provide guidance to teachers about how to support students in making connections between their investigations and the questions they are trying to answer (Gouvea & Passmore, 2017; Guy-Gaytán et al., 2019; Singer et al., 2000). They must provide tools and routines that students can use to keep track of their questions and the progress they are making, to assemble evidence into coherent science explanations, and to debate and come to consensus on key components and interactions in explanatory models of phenomena and 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).

Attention to coherence from the students’ perspective adds an important element to this project-based science approach. In storylines that are coherent from the students’ perspective, the impetus for revising models should come from students’ own recognition that more work is needed, rather than from the teacher simply asserting that there is more to learn. This can arise in several ways. First, as we shall see in the example in the next section, students’ initial questions can often be used to prompt students to undertake additional investigations that will extend their model to address unanswered questions. Second, the storyline may include plans for a problematizing lesson, in which phenomena are introduced or revisited to help students identify gaps in their current model. For example, in a middle school unit on sound (Reiser et al., 2021), students figure out through several lesson investigations how instruments make sound. They develop a model in which something pushes or strikes an object (e.g., finger plucking a guitar string), the object vibrates back and forth, and makes sound while it is vibrating. Their model is successful in explaining how a range of instruments (drum, guitar, xylophone) make sound. The next planned lesson encourages the teacher to bring back some of the examples students mentioned in the anchoring phenomenon on sounds that involved solid objects rather than instruments, such as banging on a table or footsteps down a hallway. (While each class brings up different specific examples of sound phenomena, all classes bring up phenomena that work for this purpose.) The teacher asks students whether their model of instrument parts vibrating can explain these sounds – “does the floor vibrate when I walk on it?” Across many classrooms,

disagreement typically emerges in the discussion that follows, with some students conjecturing that the floor must vibrate in ways not visible to the naked eye, while others arguing that something different must be happening with solid objects like floors, walls, and tables. At that point, the class realizes, with teacher prompting as needed, that they don’t agree on this new situation, and that they need to do further investigation to figure it out. Thus, while the strategic decision to problematize student models was suggested by the curriculum materials and enacted by the teacher, students were part of the conversation in identifying the need (that their models were incomplete) and the question (do all objects vibrate when they make sound?), and they talked through what investigations would help them make progress to resolve the ambiguity.

### **Principle 3: support students as collaborators in managing the trajectory of investigations**

The third principle addresses how this knowledge-building work is managed. This principle articulates the need for involving students in the “regulative” elements of epistemic agency (Damşa et al., 2010) – being involved in identifying questions and problems, making decisions about how to make progress, evaluating progress, and determining next steps. This principle is not typically explicit in models of project-based learning – it is central in what differentiates storylines that are coherent from the student perspective from other units that may be organized according to how experts construct connections among big ideas in science.

The flow of lessons indicated by the storyline is intended to help students build new ideas systematically and incrementally through their investigations of their questions and identified problems. The lessons are laid out in advance to build toward disciplinary understandings articulated in standards, but this trajectory is designed to fit a coherent sequence of incremental ideas, based on what we empirically determine to be the questions most salient to students, rather than the order that a disciplinary expert might impose. The task for designers is to anticipate many of the questions that students are likely to generate related to problems and phenomena they encounter, and then to iterate on the lesson flow based on an analysis of actual student questions (Reiser et al., 2021). In lieu of a “science content storyline” (Roth et al., 2011) that guides the development of the unit, designers rely on testing the anchoring phenomena routine with pilot classrooms to explore the questions and ideas that emerge. These provide the basis for drafting an initial flow for a unit grounded in the kinds of questions students may pose.

Supporting students in the practices of building knowledge entails bringing students in as collaborators in the

decision making on what to investigate and how to go about it. In the first design principle, we discussed how students can be part of identifying what questions and problems they need to pursue. This third principle concerns developing the steps that pursue those goals. Each of these steps requires deliberation. Of the questions established about the phenomena, which aspects should the class pursue first? How could they go about pursuing that investigation? This requires the ongoing work of evaluating progress, figuring out what questions are most important to pursue next, and debating alternative ways to proceed. We refer to this work as *navigation*, where new work begins as students collaborate with teachers to identify necessary next steps and consider how to pursue them (Reiser et al., 2021). As the class makes progress, students collaborate with teachers to evaluate what they have figured out, where the important gaps are, and what next steps could be helpful. Being involved in this work helps students build richer understanding that includes not only their explanatory models for the phenomena, but also how they figured out that model and how they rejected competing ideas.

Thus, designing materials that are coherent from the point of view requires particular supports. It requires supports for both eliciting and developing students' questions related to phenomena and problems (Harris et al., 2012). It requires activity structures in which students are guided to co-construct with the teacher and their peers ways to investigate those questions while still addressing core ideas and practices targeted in the unit (Miller et al., 2018; Reiser, Brody, et al., 2017). The example storyline in the next section illustrates how planned storylines can involve students in participating in figuring out what next steps are needed.

#### **Principle 4: curriculum should support teachers in creating an inclusive classroom community**

In supporting students to figure out core ideas, curriculum must support teachers in developing an inclusive community where all students' voices matter when it comes to explaining ideas, making thinking public and accessible to others, using evidence, and building on and critiquing one another's ideas (Windschitl & Calabrese Barton, 2016). Of course, this principle is not unique to storylines coherent from the students' perspective. We include it because it plays a central role in this approach – all student voices need to be on the table so that all students are involved in the negotiation of what questions to investigate and how to proceed.

Simply attempting to create space through redesign of instructional materials and teaching strategies that invite participation will not succeed without also cultivating a classroom climate that creates a safe space for students to participate. Support is needed to create a sense of

belonging and commitment to the intellectual community of the classroom, including among students for whom school has been an unwelcome space. Promoting equitable engagement with science practices requires actively countering limiting images of what it means to do science, as well as challenging classroom norms that could contribute to potential identity threats for some students (Carlone et al., 2011). Furthermore, as part of countering these challenges, norms must engender a group sense of responsibility and ownership for the knowledge building, so that students expect to listen to their peers' ideas, build on them, and see reaching consensus as an essential part of the knowledge building (Michaels & O'Connor, 2017; Michaels et al., 2008; Park et al., 2017). This includes respect for others and a willingness to revise one's ideas, aligning with ideals of collaborative scientific practice (Berland & Reiser, 2011; Bricker & Bell, 2008; Calabrese Barton & Tan, 2009; Krist & Suárez, 2018; Osborne et al., 2004; Radinsky et al., 2010). Finally, it is critical that materials provide guidance for teachers to respond to student goals and contributions that do not follow a given curricular storyline in such a way as not to reinforce race- and gender-based conceptions about whose contributions are valuable (Miller et al., 2018).

As Miller and Krajcik (2019, p. 6) argued, supporting productive engagement in this knowledge-building work requires scaffolding with discourse tools that invite and help students participate. We have explored a system of professional learning supports for teachers' development of these discourse approaches essential to supporting students' agency in storylines. We include educative supports (Davis & Krajcik, 2005) embedded in instructional materials for talk moves that help teachers elicit student thinking and support students in respectfully building on and critiquing one another's ideas (Michaels & O'Connor, 2012). These supports include discourse prompts, discussion planning tools, and example scenarios of ideas students might bring in and how teachers might respond (Edelson et al., 2021). Our professional learning workshops provide teachers with opportunities to experience these moves as learners, and to practice them through teaching rehearsals (Lampert et al., 2013) to help them develop confidence in the use of these moves and support the development of new inclusive classroom norms (Debarger et al., 2017; Reiser, Michaels, et al., 2017). It is also possible to integrate supports for monitoring patterns in which students' contributions are being solicited and taken up (Berson et al., 2018; Penuel & Watkins, 2019).

These four principles work together to guide both the design and enactment of storylines that are coherent from the students' perspective, so that students take on a role in identifying questions and problems from

phenomena and collaborate with teachers to manage the knowledge-building work. Ideally, at each point students should see their science work as addressing their own questions and problems rather than as work they are undertaking simply because that is the assigned lesson of the day.

### **An example storyline unit: Why Don't Antibiotics Work Like They Used To?**

To illustrate how these design principles can be integrated to create a coherent experience from the student point of view, we describe a high school unit that our research groups co-designed with a team of teachers. The unit focuses on the core ideas of evolution as represented in the *Framework* for high school life sciences (*Core Idea LS4: Biological Evolution: Unity and Diversity*) and incorporates connected ideas from genetics (*Core Idea LS3: Heredity: Inheritance and Variation of Traits*). There are two anchoring phenomena for the unit, the increase in antibiotic resistance over the past few decades (the anchor for the first half of the unit), and the apparent change in a behavioral trait (boldness) in a species of bird, *Junco hyemalis* (Dark-Eyed Junco) (the anchor for the second half of the unit). 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, reflecting a concern for the threat to public health posed by antibiotic resistance in bacteria.

In the description below, we embed examples of student work collected from early pilots. The classroom artifacts are drawn from two teachers in the same school (Ms. H, Mr. W) just outside a large midwestern city. (The district student population identifies as 75% Black, 15% white, 6% two or more races, and 4% Latinx, with 64% students classified as economically disadvantaged.)

#### **The anchoring phenomena**

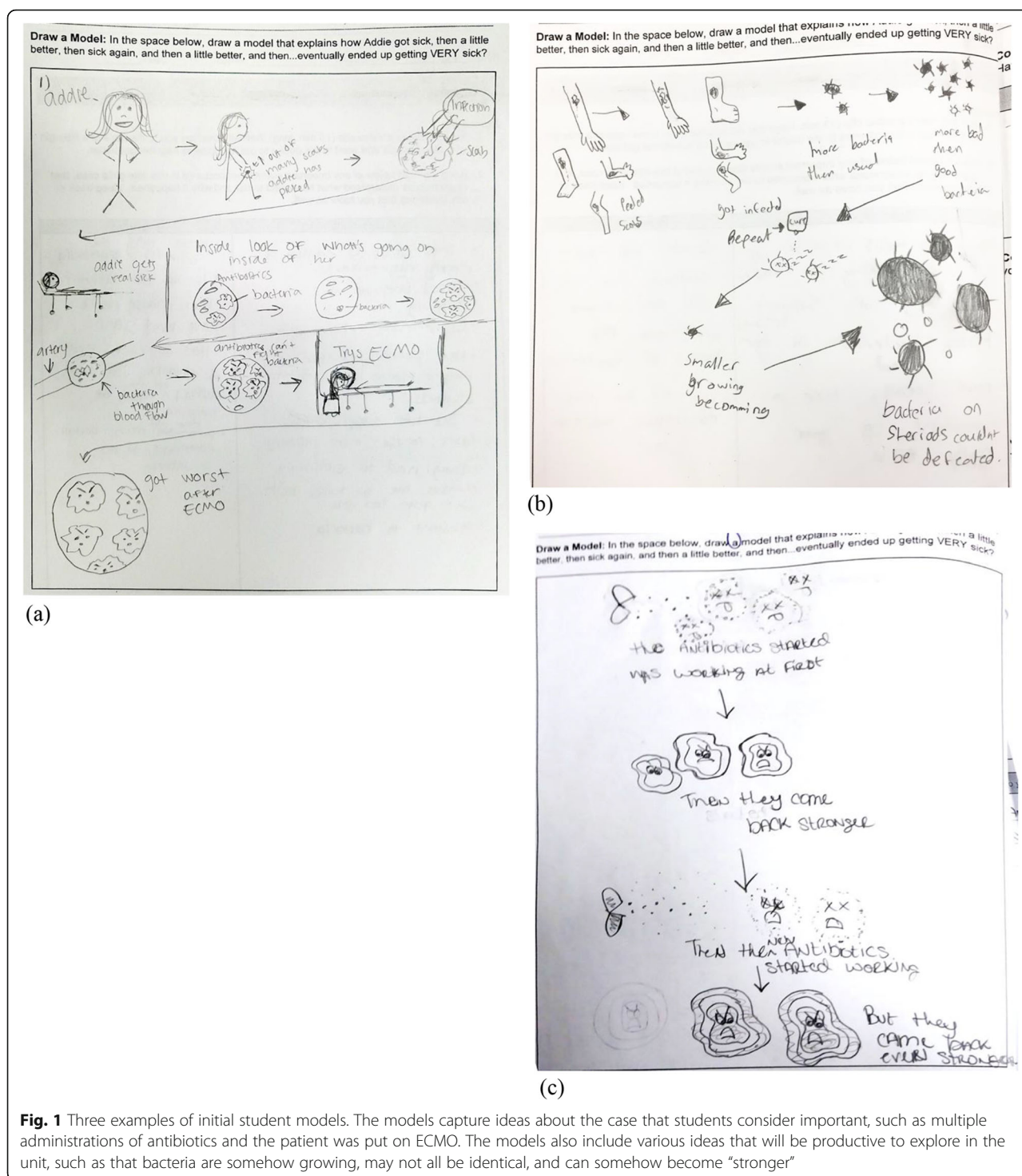
As mentioned above, we develop anchors through a systematic process that includes soliciting students' interest in a subset of candidate phenomena for the learning goals. While each of the candidate phenomena is vetted first for its potential to motivate student questions that can support the development of target ideas, none of these is presumed ahead of time to connect to young peoples' interests. Thus, as part of our anchor for this unit, we collected and analyzed data on student interest, disaggregated by race, gender, and home language (Penuel et al., 2021, in pres). We selected a version of the anchoring phenomena that received the highest rating among students surveyed, concerning the risk of "superbugs."

This 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 begin to generate questions that they need to answer to explain what is going on with Addie. Students identify their own relevant experiences with getting sick and recovering, and brainstorm related phenomena that may help them make sense of the anchor. Then, students in small groups construct an initial model to explain "how Addie got sick, then a little better, then sick again, and then a little better, and then ... eventually ended up getting VERY sick." Fig. 1 shows three typical examples of student models. These initial models help capture the findings and record features of the case students suspect are significant, such as when Addie was put on an ECMO machine for heart and lung support and the fact that she was administered several different antibiotics at different times.

At this point, students are not expected to 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 eventually lead them several weeks later. Inviting model building as part of the anchoring phenomena routine is included to create the need for developing these ideas through cycles of investigation. Asking students to model at this point leads students to generate questions about parts they can't explain, and helps them realize gaps in their knowledge, such as how germs make us sick, why it can take a few days before the sickness develops, what happens inside our bodies to fight disease, and what could be going wrong in Addie's case. Indeed, students bring in several ideas in these initial models that will be productive to explore. Model (a) includes ideas that bacteria are flowing through the blood and some ideas about how the bacteria may have entered Addie's body. Model (b) includes the idea that not all bacteria are the same ("good" bacteria and "bad" bacteria) and that bacteria grow. Model (c) includes the idea that bacteria somehow can become stronger. These will be productive ideas to explore as the unit proceeds, and indeed map to investigations planned in the storyline.

As students explore more about the anchoring phenomenon, they are confronted with an alarming finding — the frequency of antibiotic resistance in the population is increasing over time. The introduction of this complexity triggers many new questions from students. There are now two phenomena in the anchor — what is going on with Addie that explains how the antibiotics are not working, and why are cases like hers rising over the last few decades? Challenged with what they would need to figure out to explain this puzzling scenario, the class together assembles their questions and organizes





them into major categories, recording them on a Driving Question Board. Table 1 depicts a sample of typical questions and organizing themes emerging from field test classrooms. Figure 2 shows a sample Driving Question Board from one classroom.

This public representation acts as a reference point for the classroom community's collectively negotiated

purpose. The class brainstorms an initial list of investigations they might conduct in class to help them answer these questions. While we do not expect students to have all the background knowledge necessary to envision how to investigate their questions, pushing students to brainstorm possible investigations starts them thinking about what kinds of contrasts might be helpful to

**Table 1** A Sample of Question Themes and Questions from High School Classrooms

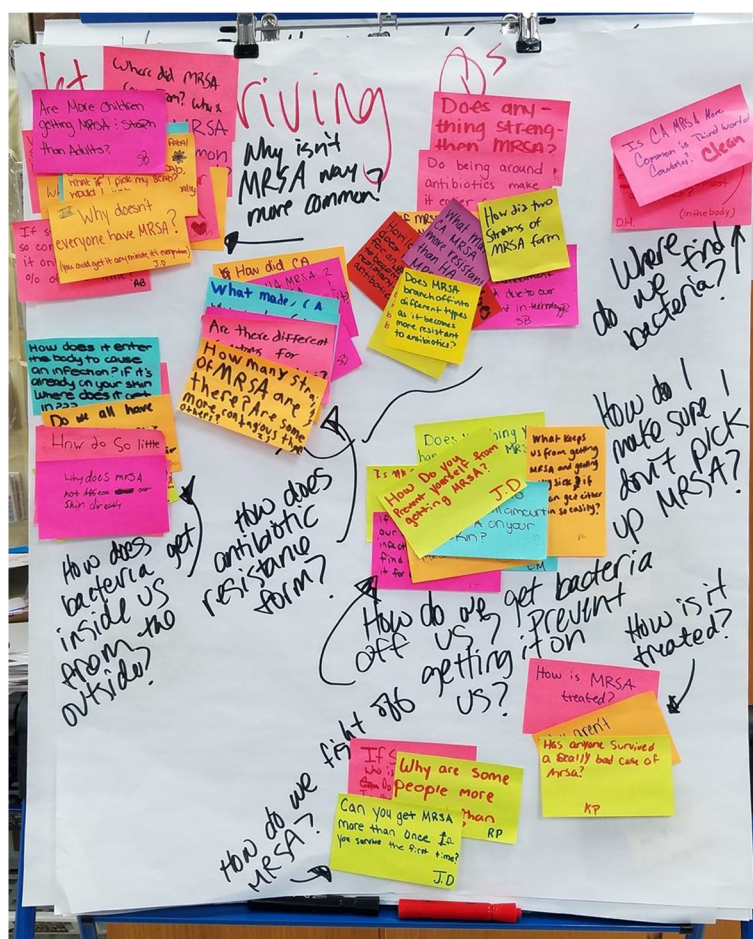
Organizing Question Constructed by the Class	Example student questions
A. <i>How do bacteria grow and become resistant?</i>	<ul style="list-style-type: none"><li>• How do bacteria grow so fast?</li><li>• How do bacteria become resistant?</li><li>• How does different types of staph form?</li><li>• Does being around antibiotics make it easier to form?</li><li>• How long does it take for bacteria to become resistant to antibiotics?</li></ul>
B. <i>Where do we find bacteria?</i>	<ul style="list-style-type: none"><li>• How long does MRSA live outside in a public community area without people?</li><li>• Can animals get MRSA? Can they give it to people?</li><li>• Is MRSA more common in third world countries?</li></ul>
C. <i>How does bacteria get inside us from outside?</i>	<ul style="list-style-type: none"><li>• How do bacteria spread?</li><li>• How does it enter the body to cause an infection? If it's already on your skin where does it get in?</li><li>• Do you have to have a cut or scab to get MRSA? If not how does it get inside someone's body?</li><li>• Why is it easy to get MRSA from hospitals?</li></ul>
D. <i>How do antibiotics work?</i>	<ul style="list-style-type: none"><li>• How do antibiotics kill bacteria?</li><li>• What happens when anti</li></ul>
E. <i>How do I make sure I don't pick up MRSA?</i>	<ul style="list-style-type: none"><li>• Does everything you handle have MRSA?</li><li>• What keeps us from getting MRSA and getting very sick if you can get it so easily?</li></ul>
F. <i>Why isn't MRSA way more common?</i>	<ul style="list-style-type: none"><li>• Why doesn't everyone with a scratch get MRSA?</li><li>• What keeps some people from getting MRSA?</li><li>• Where did MRSA come from?</li></ul>
G. <i>How do we fight off MRSA?</i>	<ul style="list-style-type: none"><li>• Why are some people more sensitive than others?</li><li>• Do the things we use to clean wounds like alcohol/peroxide kill MRSA?</li><li>• Are our bodies stronger than the bacteria that is trying to spread?</li></ul>

explore and what kinds of evidence would help further their explanations. Indeed, in this anchoring phenomenon lesson, students typically identify several needed investigations, including studying bacteria growth over time, exploring what can kill them, and looking for which bacteria survive treatment rather than are killed. Figure 3 shows student ideas for investigations from the other teacher’s classroom in the same school (Mr. W.). In this classroom, students’ ideas include “changing temperature with bacteria - see what happens,” “try different ways to kill bacteria,” compare places to explore “how much bacteria” is tied to “how often cleaned” and “how many people go to a place,” “look at bacteria with microscope” and see “how bacteria respond to antibiotics” and give “different doses of antibiotics.”

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 1 of using phenomena and design challenges as contexts to build and use the target science ideas. It also reflects this principle in that

there is evidence—obtained through analysis of our survey results—of a strong connection to students’ interests.

The anchoring phenomena routine involves more than simply presenting a phenomenon. It is important to sufficiently explore the phenomena to realize there is something interesting that needs to be explained or a problem to be solved. Asking students to attempt to make sense of the phenomena by explaining or modeling it draws out productive ideas students may be able to use and ensures that what students figure out is connected to their prior ideas. Pushing students to explain can problematize the phenomena, helping students identify gaps in their knowledge and question something they may take for granted, such as how germs make us sick and it can take a few days after being infected for the germs to affect us. Storyline units typically include four elements in engaging with the anchor – explore the phenomena, attempt to make sense, identifying related phenomena, and brainstorm ideas for investigations (Reiser et al., 2021).



**Fig. 2** A driving question board of questions from students from Ms. H's classroom. Each individual sticky note is a student's question. Students organized them into clusters as they shared them, and the teacher scribed a description for an emerging theme for a cluster as students identified them. Clusters for this class included "How does bacteria get inside us from the outside," "How do we get bacteria off us / prevent getting it on us," and "How is it [MRSA] treated?" Themes and example questions are shown in Table 1

### Connecting planned investigations to students' questions through the navigation routine

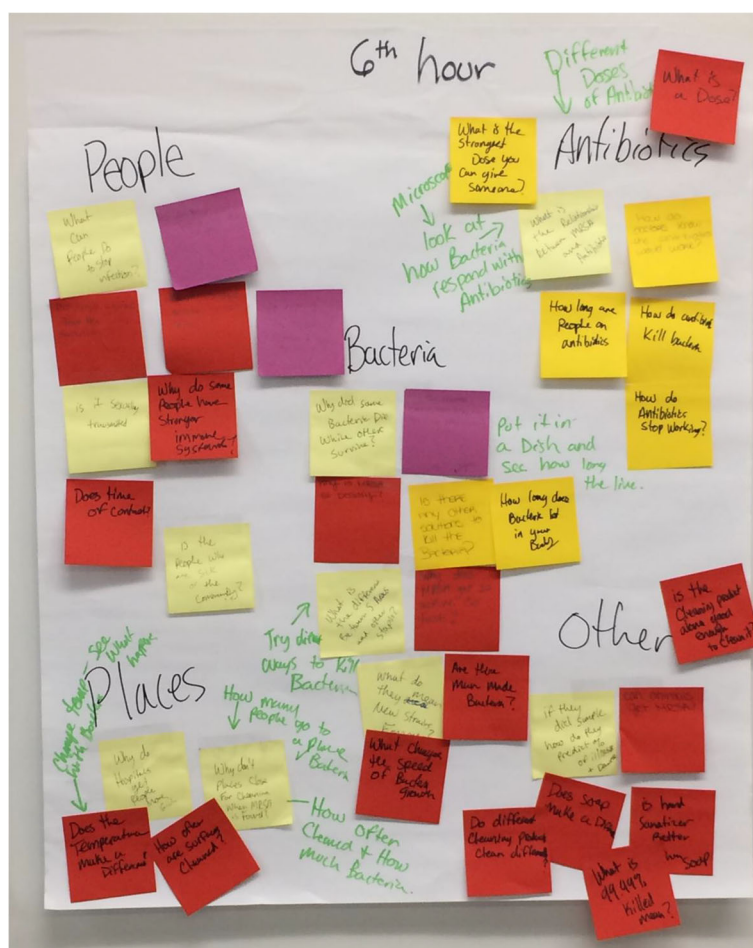
At the conclusion of the anchoring phenomena routine (Lessons 1–2), students have identified a problem (increasing antibiotic resistance), shared initial ideas about what might be causing it (articulated in their models), and together assembled a collection of questions and ideas for investigation. These provide the initial resources that teachers use in enacting the storyline to support student coherence – students' commitment to exploring these issues and their perception that the investigations the class takes up are responsive to the questions and problems they identified.

In what way are the next investigations responses to *their* questions? The storyline is a planned trajectory. But if the storyline and its lesson guides already exist, how can teachers involve students in working out where to go next? The essence of enacting storylines coherent from the students' perspective are the routines that

involve students in reflection and planning discussions to collaborate on where to go next (Principle 3). These navigation discussions implement the ongoing joint decision making about how to proceed in their investigations.

Table 2 shows the trajectory of questions reflected in the first part of the storyline, and indicates for each one the strategies supported in the materials for establishing the lesson question. The set of questions and ideas for investigation established in the anchoring phenomena routine (Lessons 1–2) provide a rich foundation that aligns with many of the targeted directions in the storyline. For example, students had many questions about how bacteria spread in the environment and how they get into people (Table 1, B, C). The ideas of collecting bacteria and watching bacteria grow were ideas for investigations students proposed. In the navigation from the anchor to their first investigation (Lesson 3), the teacher suggested the class start by exploring their





**Fig. 3** Students' ideas for investigation from one classroom

questions about bacteria, referencing these ideas from their Driving Question Board and investigation ideas, and suggested a methodology that could accomplish this (swab locations for bacteria, observe their growth on a Petri dish). While the teacher played a strong guiding role, students were true collaborators in the work. The students had generated questions about where bacteria grow, whether they were in their own school environment, how they grow in number, and how fast this occurs. The teacher, drawing on the lesson guides, suggested these questions as a good place to start. In discussion of these questions, students articulated the needs – a way to collect bacteria from the environment, a way to allow it to grow, and to contain it safely while it does. The teacher suggested various tools such as the equipment (Petri dishes, microscopes, gloves) and lab techniques (plating bacteria) to enable them to address these needs. Many of the key elements of the investigation, such as growing bacteria, killing bacteria, using antibiotics, were able to be linked directly to students' questions in this way (See Table 2). This collaboration is

the essence of involving students in managing the trajectory of their investigations.

To support teachers in these discussions, the instructional materials and professional learning supports include guidance to help teachers enact a *navigation routine* to conduct these conversations (Reiser et al., 2021). The navigation discussion includes both looking back and looking forward. At the conclusion of each investigation, students discuss what they have figured out from their data. For example, they figured out from their bacteria growth investigations that there are bacteria in many common places, that they grow by multiplying in numbers, and that a single application of antiseptic does not kill all the bacteria on the surface where it is applied. They tie this back to the question they were asking and consider what parts of the question the class can answer, and what parts are still open. In addition to reaching consensus where the class agrees, this discussion may surface that there are findings for which students disagree on the explanations. In this way, rather than being introduced as a standalone practice, argumentation and



**Table 2** Supports in the Storyline for Navigation Discussions

Lesson Question from Storyline	Navigation from ...	How does the lesson question emerge from students' questions so far?
L1: How did this little girl (Addie) get so sick? L2: How common is this problem? Can this happen to me?	Anchor	The anchoring phenomena lesson begins the unit and raises new questions
L3: Where are the bacteria around us?	DQB questions	The DQB includes questions about how bacteria spread and get to people from the environment. The idea of watching bacteria grow was an Idea for Investigation. In a discussion of these questions and next steps, the teacher suggests a methodology that can accomplish this (swab, Petri dish).
L4: How are we using our antibiotics?	DQB questions	The navigation discussion leverages students' questions from the anchor about why in some cases antibiotics don't work. The teacher revisits these questions and suggests first figuring out how antibiotics should work, what the recommendations are for using them, and if something could be wrong with how people are using them.
L5: How do bacteria grow?	L3 findings	In L3, findings revealed visible bacteria colonies growing from non-visible swabs of material on the plate. This led to questions about how bacteria can grow so quickly and whether they got bigger and/or increased in numbers. The navigation discussion revisits this questions and suggests using time lapse videos under a microscope to investigate the growth.
L6: How do bacteria grow in a simulated environment?	L5 findings and questions	L5 findings revealed bacteria grow by dividing, and mathematical modeling showed how quickly the numbers increase by that process. The lesson ended with wondering what in the environment might stop or limit bacteria from growing. The navigation discussion suggests using a simulation to track how environmental factors affect the pattern of growth.
L7: How do bacteria get killed?	L6 findings	L6 findings revealed how quickly bacteria populations can increase, and how limited resources limit growth. The navigation discussion asks students to consider what happens if a drug kills most but not all of bacteria population and suggests using mathematical modeling to make predictions of various scenarios.
L8: How do antibiotics affect bacteria when they are put together?	L7 findings	L7 math modeling findings revealed how quickly populations could spring back, and the importance of hitting populations with multiple doses to kill all the bacteria. The navigation discussion asks students to apply those ideas to real bacteria and antibiotics, and suggests a methodology to investigate this safely with antibiotic discs and Petri dishes.
L9: What's happening inside Addie?	L2-L7 findings	The navigation discussion suggests putting together what students have figured out in Lessons 1–7 to apply to explain Addie's case. (This lesson occurs in parallel with waiting for L8 results)
L10: How does a bacterial population change in a simulated infection?	Questions from L9	The navigation discussion identifies questions emerging from comparing students findings from three systems (Addie, Petri dish, computer model) and suggests using a new simulation that incorporates antibiotics and variations of bacteria to explore these questions.
L11: How does moving bacteria that survive antibiotic doses from one environment to another affect the population over time?	L8 findings L10 findings and questions	L10 findings showed changing population sizes of resistant and non-resistant bacteria when antibiotics were applied in low enough doses so that not all bacteria died. The navigation discussion asks students to transfer what they figured out to consider what might happen in human patients.
L12: How did the bacteria population become more resistant in Addie and in our community?	L11 model findings, DQB questions	The navigation discussion draws on the model developed in L11 and asks students to revisit the Addie case and attempt to explain her case, and how populations of bacteria moving through a community might change over time.
L13: What questions can we answer about bacteria and Addie's Situation?	L1-L12 findings	The navigation discussion asks students to put their findings together into a general model and attempt to explain all remaining DQB questions.
Part 2 of the unit L14	L13 findings	The navigation discussion asks students to evaluate the whether their model could work for other organisms.

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, 2015; Passmore & Svoboda, 2012). This argumentation then leads to a new question for the class to pursue to compare their competing explanations.

Not all questions needed to motivate lessons emerge in the initial anchoring phenomena discussions. A second important navigation strategy involves identifying new questions from the findings of the current lesson. This may involve identifying gaps in students' explanations. For example, in Lesson 3 students figured out there were bacteria all over their school environment, particularly in places not cleaned very often. They found visible growth on the plates over time even though the initial swab on the plate was not visible. This led to questions about what the visible splotches on the plates actually consist of – are there more individual bacteria or just larger bacteria? And how did the bacteria grow or reproduce to do this? This question became the motivation for a later lesson, examining time lapse videos of growth of a bacteria colony (Table 2, Lesson 5). Here again the need came from the students, anticipated by the storyline and guided by the teacher, and the teacher provided resources to pursue it (time-lapse microscope videos). Students figured out that bacteria grow by dividing, and were able to model that process mathematically, explaining the very rapid rate of growth. Additional questions emerged from Lesson 5 about whether a colony would grow forever or what might stop its growth, leading to the investigation in lesson 6 in which students used a simulation to explore factors that might limit population growth.

The navigation discussions at the beginning and end of each lesson are critical in helping students be part of constructing the logic of the unfolding story. In the navigation discussion the teacher guides students to reach consensus on what they figured out, evaluate how it addresses their questions, identify what questions remain and what new questions they have, and then debate where they could go next to make progress. Students may 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.

Figure 4 shows a portion of the designed storyline for this unit. Each row shows another step in the logic of students' investigations, from the questions that led to engaging in practices around phenomena and problems, leading to what students figured out in that lesson. The navigation to the next lesson is shown as an arrow from

the “what we figured out” end of a step to the question of the next lesson. Each investigation arises from a question from the anchor or a previous lesson, and what students figure out leads to a subsequent lesson.

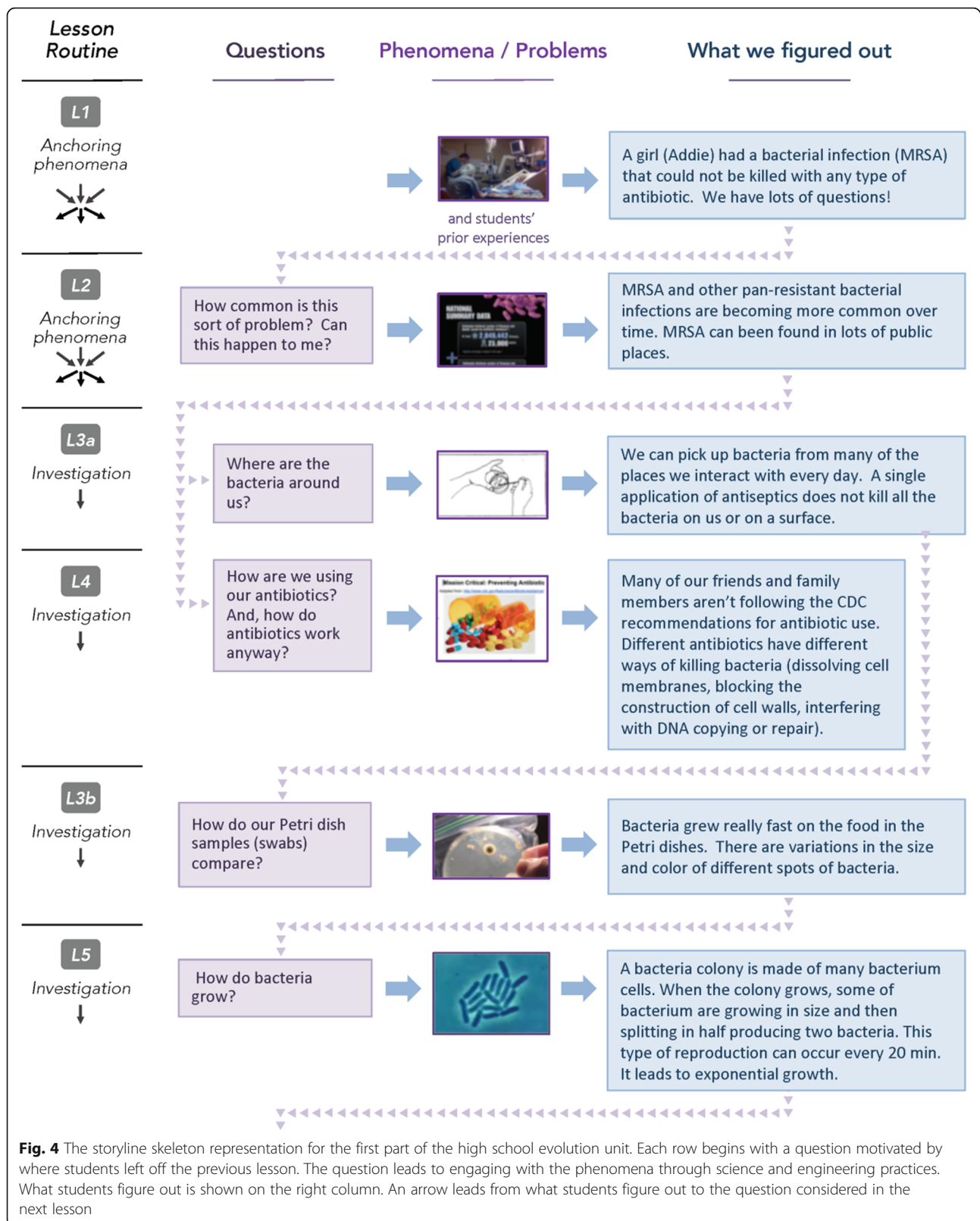
### Supporting reflection

Ongoing reflection is essential to support coherence from the students' perspective. Ongoing conversations help students keep track not only of what their question is for today, but *why* they need to figure out this question. Ideally, at any point, students are able to tell the unfolding story of what the class was trying to figure out, what pieces of the puzzle they have figured out so far, where they are trying to go today, and how concretely what they are working on today will help accomplish that. Public artifacts play a key role in helping the classroom track the history of their knowledge building so far. The Driving Question Board organizes the class questions, serving as a place to record new questions as they emerge during the unit, and to mark questions as the class decides they can address them. Consensus models, investigation ideas, key results, and other artifacts serve as public representations to record the class progress (Blumenfeld et al., 1991; Miller & Krajcik, 2019; Windschitl et al., 2018; Windschitl et al., 2012). In addition, individual artifacts help students track where they have been and where they are going in their own words and diagrams. In key lessons where the class makes progress, students summarize the trajectory in a progress tracker (OpenSciEd, 2019). Typically, students record the question their class has been working on, what they figured out (in words and diagrams), and how they figured it out (their evidence). Students can refer to this tracker as they revise their models, explanations, or designs and use the tracker to compare their thinking with others. Figure 5 shows an example of an individual student's progress tracker entry.

Another reflection tool useful both for students and for teachers to track students' thinking are individual exit tickets. In exit tickets, students reflect on questions such as whether they understood how today's activity helped the class make progress on their questions, where they expected to go next, and what new questions they have (see Table 3).

### Incrementally revising models

At key points, the class takes stock of the knowledge they have developed together in a “putting-pieces-together” routine (Reiser et al., 2021). 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 explanation of the phenomenon. One of these key moments occurs after students have had a chance to explore a simulation that depicts



Lesson & Date	What did we figure out that we should include in a model that can help answer our question?	How did we decide to represent this in our model?										
9/14	Should change over time key components - Bacteria (more than 1 kind) - Antibiotics (different kinds) - Addie (keep ideas in mind) ways to get antibiotics into Addie interaction between all components	Our models need components, interactions, and mechanisms.										
	<div>Var.</div> <table><tr><th colspan="2">Kinds</th></tr><tr><td>Staph</td><td>Steno</td></tr><tr><td>resistant</td><td>MRSA yes</td></tr><tr><td>non-resistant</td><td>?</td></tr><tr><td></td><td>yes</td></tr></table>	Kinds		Staph	Steno	resistant	MRSA yes	non-resistant	?		yes	
Kinds												
Staph	Steno											
resistant	MRSA yes											
non-resistant	?											
	yes											

Lesson	What did we figure out that we should include in a model that can help answer our question?	How did we decide to represent this in our model?
2 9/19/17	- Addie was not the only one (case) - we can use her case to help explain - explaining this case may help learn how to address the issue - show environments inside/outside Addie's body	
4 10/4/17	- A lot of people don't use antibiotics how they are supposed to - Different antibiotics and how they work; they work w/ bacteria one at a time	use different shapes; Ovals, circles, etc.
3a 10/11/17	- Bacteria is everywhere - Needs to get inside body to be a threat	Petri Dish and growing the bacteria on the Agar.

**Fig. 5** Excerpt of a student's progress tracker page. The left column includes important things that the student figured out in each lesson. In this classroom, the class used the right column to keep track of important evidence

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 et al., 2003), students review and critique one another's models. The 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 2).

In the first half of the unit (lessons 1–13), students develop 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 individual bacteria in a population can affect how they survive in the case of changes and threats presented by 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 increases. This accounts for many aspects of the Addie story students were trying to figure out – why she started to get better

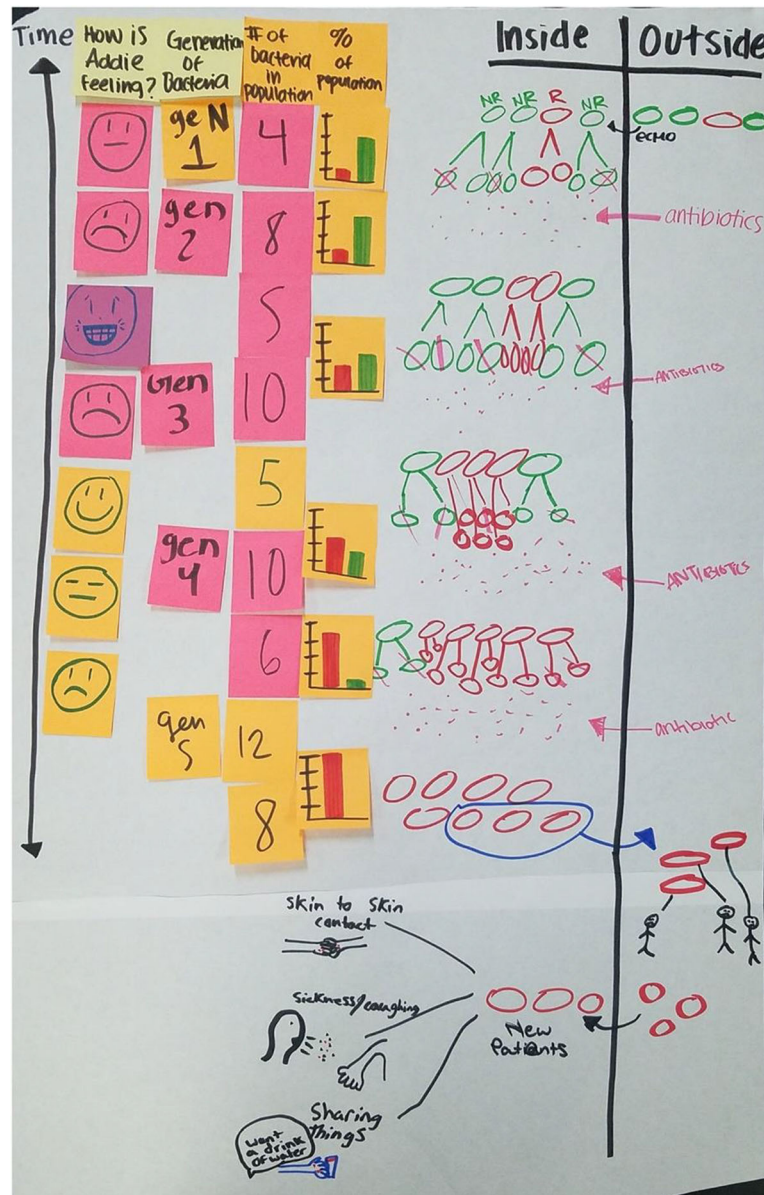


**Table 3** The student exit ticket

Category	Question	Responses
Coherence	Name	[constructed response]
	What lesson did you do today in class?	[constructed response]
	Our class used the driving question board to guide what we did today.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	We used the Progress Tracker to record what we learned today.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	I understand how what we've done so far is helping us answer the big question.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	I know what questions to investigate next.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	One question we could answer next is ...	[constructed response]
	What is something you are going to remember from today's class	[constructed response]
	What we did or learned about in class today matters to me because: [select the option that BEST describes your feelings]	<ul style="list-style-type: none"> <li>• It is interesting</li> <li>• It will be useful to me in the future</li> <li>• It is important for my everyday life / people I care about</li> <li>• It will help me get a good grade</li> <li>• It doesn't matter to me</li> </ul>
	What we learned about in class today matters to people in my city or town because	<ul style="list-style-type: none"> <li>• This material is important and people should know about it.</li> <li>• This material could improve the lives of people in my city / town.</li> <li>• What we did doesn't matter to people in my city/town.</li> </ul>
Relevance	What we figured out today is interesting to me	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> </ul>
	What we figured out might be useful to me at some point.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> </ul>
	What we figured out today is like what scientists do.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> </ul>
	What we figured out today will help me get a good grade.	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> </ul>
	Did you share your ideas today?	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	Did your ideas influence the class or help others?	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>
	Did other students share ideas today?	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>

**Table 3** The student exit ticket (Continued)

Category	Question	Responses
	<i>I was able to build off of someone else's idea.</i>	<ul style="list-style-type: none"> <li>• Yes</li> <li>• No</li> <li>• Not sure</li> </ul>



**Fig. 6** A small group's revised model to explain how Addie's condition changed as the bacteria changed within her. The first column in the model shows how Addie is feeling as time elapses. The next column marks the generation of bacteria. The numbers in the next column indicate the relative size of the bacteria population as a whole, followed by a graph of the proportion of the resistant bacteria (labeled R in the diagram, the red bar in the graph) and non-resistant bacteria (labeled NR in the diagram, represented by the green bar in the graph) in the population. The graph and numbers reflect the step-by-step model that students drew out mapping the bacteria inside Addie's body. An X on the bacterium means the antibiotic killed the bacterium. A branch means the bacterium divided. Of course only surviving bacteria reproduced. The number in the next generation is the number of bacteria minus the ones that died after the survivors reproduced

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 Fig. 6.

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 anchoring phenomenon with features that can help develop their understanding further, the microevolution of the Dark-Eyed Junco. Not only does this phenomenon allow students to explore adaptation in an organism that reproduces sexually, it also is a case in which sexual selection shapes adaptation. This new phenomenon has the advantage of having multiple datasets the students can investigate to triangulate their model. Furthermore, it is designed to capture 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.

The advantage of introducing a second anchoring phenomenon addresses a common challenge to the inductive model building students do with 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 to facilitate reasoning from cases to develop generalized ideas (Kolodner, 1997). 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. 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 (Berland et al., 2016; Reiser, Brody, et al., 2017). Purposefully chosen contrasting cases can support students more generalized explanations by helping students notice similarities and differences between cases (Bransford & Schwartz, 1999). This need for revising and generalizing the model again reflects the incremental sensemaking needed for developing students'

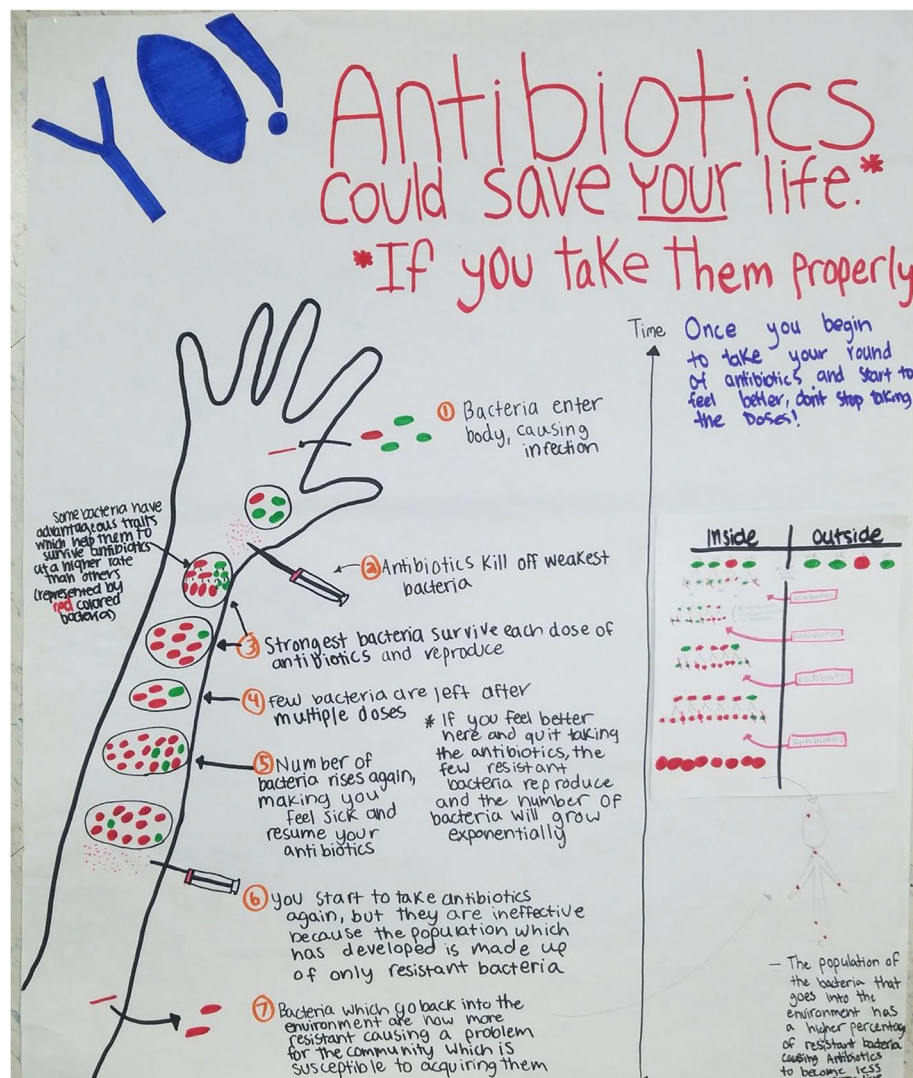
integrated understanding of core ideas, practices, and crosscutting concepts (Principle 2). In addition, we see the importance of phenomena in creating a need to extend students' models (leading to coherence for students), rather than the curriculum materials or teacher telling students where their ideas are incomplete and where they should focus.

### **Design challenges as contexts to create a need for the science**

The unit also includes a multi-lesson design challenge to connect the science to an everyday concern in students' communities (Principle 1) in ways that engage them in engineering practices. The design challenge is to develop 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 Fig. 7). Infographics and public service announcements can be an authentic tool for communicating scientific information to the public and engage students in the practice of communicating scientific information (e.g., Lamb et al., 2014; Polman & Gebre, 2015). The design challenge also supports students in developing a grasp of key engineering practices. As part of the challenge, students must define the communication problem they are to solve, and conduct investigations focused on understanding the needs and constraints that must be met as part of their solution, both of which are aspects of the engineering practice of defining problems. They develop and provide feedback on one another's drafts, and 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. In design practices involving communication, these are examples of "tests" of a design. Notably 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. The design challenge itself represents an occasion to help students see how science and engineering can be relevant to their everyday lives (Principle 1), and the student justifications provide another occasion to make visible students' evolving sensemaking (Principle 2).

### **Evidence of coherence, engagement, and student learning from prior studies**

In prior studies, we explored the feasibility of storylines coherent from the students' perspective in multiple design research studies in elementary, middle school, high school biology and chemistry classrooms. In this section, we summarize some of our questions and findings that have helped us refine the storylines approach. Critical to



**Fig. 7** A group's infographic about the dangers of not taking the full dose of antibiotics

the goals of coherence from students' own perspective is that students see *why* they are doing what they are doing in science class, and see their work connected to the questions and problems their class has identified. Thus, an important question to address is: How well have designers anticipated student questions in developing units? As suggested in Figs. 1-2 and Tables 1-2, we typically find good alignment between the questions, related phenomena, and ideas for investigations students generate with the target ideas of the planned storyline (see Reiser et al., 2021 for other examples). We have observed teachers working with storyline materials use anchoring phenomena to elicit student questions and ideas for investigation, work with student questions and ideas through navigation to motivate investigations, help problematize areas for further investigation, and support students in putting ideas together to reach consensus

across multiple investigations in units in multiple grades. As in the examples here, we find alignment between student questions, experiences and ideas for investigation with the planned storyline across biology, physics, chemistry, and earth science focused units in middle school (Edelson et al., 2021; Krajcik & Reiser, 2021; Reiser et al., 2021). Similarly in a 2nd grade storyline unit on plant growth (National Academies of Sciences Engineering and Medicine, 2017, Chapter 1), a 4th grade unit on waves (McGill et al., 2021), and 5th grade units on ecosystems and Earth systems (Brinza et al., 2019), we see teachers successfully using phenomena to elicit questions they can use to drive the investigations in which students build the target science ideas and practices.

Of course, not all questions are anticipated, particularly in early versions of units. One of our studies, for example, found that 62% of student questions on the



Driving Question Board had been anticipated by unit designers (Zivic et al., 2018). While this figure represents a majority of students' questions, more than a third of students' questions were not addressed. To improve the likelihood that students' questions related to the science ideas targeted in the unit will be addressed in the unit, developers use the actual questions from multiple classrooms' Driving Question Boards to revise the storyline for the unit. In addition, they also use responses to questions on student exit tickets that students have at the conclusion of a lesson to refine the storyline. Teachers can also use these responses to inform their efforts to navigate between lessons.

Another important question is whether students see the connections that writers do between lessons; that is, are lessons actually perceived to be coherent from students' own point of view? We have explored students' perceptions of coherence in several studies through students' responses on exit tickets (see Table 3). In a study of this high school unit (Penuel et al., 2017) we analyzed 562 observations from students of five teachers whose students completed multiple exit tickets over the course of the unit. Remarkably, 85% said that on that day's lesson, they understood how today's lesson fit with their class' questions, suggesting the unit as enacted was in fact coherent from their point of view. The study of the storylines middle school unit described above (Zivic et al., 2018) focused on five teachers with a total of 1119 exit ticket observations of 373 students (students filled out exit tickets once per week during the unit). They found that in most cases (90% of responses), students reported knowing why they did what they did in class. Similarly in most cases (88% of responses), students expected their class would figure out at least part of their questions. Thus although students' questions on the Driving Question Board included a number of questions not directly answered in the unit, students felt they were making progress on their questions, and were able to see how what they were working on was related to their questions. Importantly, students were more likely to report feeling happy, excited, or confident in class if they reported they knew where class was going or if they made progress on the Driving Question Board. This suggests the perception of coherence was indeed important to students. Similarly, the study suggests students' perception of agency was also important to their experience -- students' report of agency (a rating scale from *The teacher told us everything we need to know to We figured everything out as a class, with the teacher helping but not telling us the answer*) was positively correlated with students answering *What we did or learned about in class today matters to me*. Together these results support the importance of students' agency and feelings of coherence.

Finally, an important set of questions pertains to what students learn from engaging with storyline units. Investigating three-dimensional learning requires new kinds of assessments than ones that test content or skills in isolation (Pellegrino, 2013). Our team has been working to develop and validate three-dimensional assessments of student learning. We have explored the promise of this high-school unit for supporting students' three-dimensional science learning. In a recent study of 583 students in 11 different urban classrooms (Penuel et al., 2019), we gave students assessments that measured whether students could apply the core science ideas learned in the unit to two science phenomena they had never seen. The sample for this study of student was comprised of high schoolers, in which 55.5% were Hispanic, 23.2% were white, 13.4% were Black, 4% were other, 3.2% were Asian, and 0.6% were American Indian. Over two-thirds (68.5%) of the students received free or reduced-price lunch, and over one-third (36.8%) were English Learners. Although the study found that gains depended on the transfer tasks given to students, on average student scores increased by 0.48 standard deviation units. These findings suggest the unit showed promise, but further work is needed to refine assessments for the units so that they were equivalent in difficulty.

## Discussion and conclusion

We began with the argument that building on the promise of project-based and context-based learning in the era of the Framework and NGSS requires that we explore how to support science learning that is coherent from the students' perspective. To truly involve students in practices as they build, use, and refine science ideas means establishing a real need for the science work in the classroom community. We presented four design principles that aim to negotiate the demands of accountability to address target science ideas and practices with supporting students' epistemic agency, as they become part of identifying and managing the progress of their science work. In this section, we consider the potential for and the challenges facing this storylines approach.

### Contributions of the storyline approach to project-based learning

The storyline approach provides one compelling way to support coherence from the student point of view. Coherence from the student's point of view shares with earlier conceptions of coherence in project-based curriculum that emphasize a focus on a few core ideas, building knowledge incrementally, and anchoring units in phenomena. But it departs from approaches to curriculum design that emphasize the ordering of lessons according to a hypothetical progression of ideas as

defined by the subject-matter expert. Rather, storylines support developing units that advance from student ideas about phenomena and problems they are exploring, building toward science understandings that are motivated by questions they pose. Such units require ongoing discussion and collaboration with students so that they are not passively following along to perform the next investigation, but instead actively engage in deliberations about how to proceed.

The storyline design principles attempt to address what makes a “project” meaningful and therefore a context for situating learning in engagement in the social practices of science and engineering – a context for context-based learning (Sevian et al., 2018). This involves negotiating two competing demands – accountability and agency. On the one hand, the commitment is to address target science ideas. On the other hand, doing so in ways that involve meaningful practice means cultivating contexts that students come to care about and seek to take action to figure out or solve problems. While this balance can be tricky, the examples presented in this paper illustrate the promise of the approach and raise some important questions about how best to achieve the goals.

### **Meaningful contexts**

Storyline enactments illustrate the promise of situating science in meaningful contexts, consistent with earlier work on project-based science that demonstrated that meaningful projects can be effective contexts for students to engage deeply with and develop sophistication in science ideas (Geier et al., 2008; Harris et al., 2015; Marx et al., 2004; Singer et al., 2000). Yet there are real challenges for design and teachers’ enactment in effectively using a project as an effective context throughout the unit to situate the students’ day-to-day science work, rather than be merely as an initial motivator that is then abandoned (Rivet & Krajcik, 2008; Schneider & Krajcik, 2002). The storyline approach explores strategies for leveraging the project context through the day-to-day navigation conversations that involve students in the management of the work. We suggest this attention to coherence from students’ own perspective may help teachers and students connect more easily and consistently with the project context, supporting the ongoing use of the knowledge as students develop it. In the evolution storyline, rather than an abstract study of population dynamics, student explored factors affecting death and reproduction of bacteria to try to figure out the puzzling aspects of the case, such as how the drug initially helped the patient, who then became even sicker. Our classroom studies suggest that there are relationships between students seeing these connections and continued interest and engagement. It will be important in further

work to explore how predictive initial interest surveys can be, how best to empirically explore the potential interest of different project contexts, and how to sustain student interest in phenomena for the duration of an extended project.

### **Coherence**

A central element of this approach involves supporting student coherence. These examples illustrate how storyline units can be designed to elicit questions from students that are productive to investigate and help the classroom establish a path toward figuring out the target science ideas. Through iterative testing and refinement of the unit, storyline units come to reliably anticipate many of the questions students are likely to pose. Teachers’ enactment of the evolution unit was effective in eliciting questions that were productive to investigate and were addressed by the planned unit. Students had ideas about how to investigate these questions that were productive starting points for teachers to introduce specialized methodologies (culturing bacteria, using antibiotic discs) that addressed the directions students had identified. In the classroom data summarized here, students generally felt that their science work was making progress on their questions and felt like they knew why they worked on what they did in class.

### **Working as a learning community**

The example highlights how working together to advance learning of the classroom community can be an important part of the context for pursuing this work. Students’ individual models, such as the initial models in Fig. 1, are important for helping students explore the space and uncover productive ideas. Small group modeling work, such as the model in Fig. 6, enables students to collaborate, find gaps in their thinking, practice questioning explanatory models, and synthesize ideas to assemble a new model. These group models become the basis for conversation to reach consensus as a whole class, and uncover what work remains to be done to address new questions and controversies.

### **Challenges for the storyline approach**

#### ***The enacted curriculum is central***

The storyline materials lay out a sequence of questions, activities, and discussions designed to support a progression that can build the target ideas. But supporting these shifts in agency and coherence for students depends critically on the way teachers enact these materials. Teachers can draw on these resources, but teachers must adapt them for their local context, leveraging specific ideas students bring up, calibrating when and how much to push and guide. Navigation and sensemaking discussions need to build dynamically on student ideas

and questions in enactment (Berland et al., 2020). Teachers need to establish a classroom climate with norms that are supportive of these shifts in agency, where students expect to take on responsibilities in the knowledge building and expect to build on one another's ideas to reach consensus as a community (Park et al., 2017; Windschitl & Calabrese Barton, 2016). Enacting these types of instructional approaches presents challenges for many teachers. In addition, teachers may be successful in creating conditions in classrooms where many students contribute, but where not all students feel their ideas are heard or taken seriously (Krumm et al., 2020). While materials can be designed to be educative as part of a system of support, professional learning support for teachers to learn in and from their practice is essential (Lampert, 2010; National Academies of Sciences Engineering and Medicine, 2015).

### ***The tension between learning goals and student agency***

A central challenge emerges from the tension that motivated the storyline approach – the need to address targeted learning goals while also trying to support student agency. Teachers are accountable for addressing state standards, and so they cannot simply follow students' interests and ideas wherever it might take the particular class. Teachers need to address state standards in their teaching, and for those in tested grades, ensure their students can meet those standards. Our storylines work is motivated by the assumption that within these broader constraints of ensuring that students learn target ideas (such as evolution), designers and teachers can work to situate that learning in contexts that are meaningful. The goal is to help teachers orchestrate the classroom work so that students take on increased agency in the knowledge building, so that students' science work is more meaningful and learning more effective.

A central challenge emerging from this tension is that selecting and cultivating contexts that situate the target science is not a simple task, and there are many ways designs can fail. As we have explored developing anchoring phenomena across elementary, middle, and high school contexts, we have seen many ways that anchoring phenomena can fail to succeed. As mentioned above, phenomena can be engaging, but then lead students to pose questions that don't succeed in helping address the target science ideas. In some cases, redesign can help provide more focus that succeeds in problematizing the important science ideas. But in some cases, design teams find it is more feasible to shift gears and focus on other phenomena. In other cases, while initially engaging, phenomena do not turn out to be generative enough to maintain students' interest across the several weeks it may take to help students develop the target science ideas.

Another aspect of this challenge is where the needs of proceeding in particular directions to meet target learning goals emerges in tension with honoring students' ideas and their agency in setting direction. While the approach we advocate involves eliciting intuitive ideas and working with these ideas, the need to make progress within the limited time allocated can create pressure to cut off certain lines of inquiry, and push against fully empowering students to pursue their questions and be coauthors in developing knowledge (Sikorski & Hammer, 2017). Furthermore, managing multiple ideas from different students that may lead in different directions can complicate this navigation. Miller et al. (2018) warn against the potential to create a situation of “pseudoagency” in which students see teachers' attempts to open scientific sensemaking as disingenuous, where teachers ask for students' ideas, but then fail to fully honor them when standards and accountability pressures require proceeding in other directions.

In conclusion, we see these tensions as central to address in exploring how to support knowledge building as a practice while also ensuring accountability to specific science target learning goals. The storyline methodology is offered as an approach to productively manage these tensions, and support students' agency in seeing their science work as more than simply following directions and doing particular science activities because they are assigned as the task of the day. While acknowledging that it is a classroom community within a school system and not a scientific community, we suggest storylines can be an effective approach to aspire toward a productive integration of science and classroom communities.

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### **Authors' contributions**

WRP, BJR, MN, and TAWM contributed to the storylines instructional model presented in this paper, and contributed to the design of the instructional materials presented in this paper. AO contributed to the design of the instructional materials and field tested these materials in her classroom. KVH provided project leadership in instructional materials development. WRP and BJR led the writing of the manuscript with contributions from the other authors. All authors read and approved the final manuscript.

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### **Availability of data and materials**

Due to IRB restrictions, the raw dataset of student artifacts is not public. Deidentified data is available from the author.

## Declarations

### Competing interests

The authors declare that they have no competing interests.

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