

Supporting Inservice Teachers' Skills for Implementing Phenomenon-Based Science Using Instructional Routines That Prioritize Student Sense-making

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Abstract

Widespread implementation of phenomenon-based science instruction aligned with the Next Generation Science Standards (NGSS) remains low. One reason for the disparity between teachers' instructional practice and NGSS adoption is the lack of comprehensive, high-quality curriculum materials that are educative for teachers. To counter this, we configured a set of instructional routines that prioritize student sensemaking and then modeled these routines with grades 6–12 inservice science teachers during a 3-hour professional learning workshop that included reflection and planning time for teachers. These instructional routines included: (1) engaging students in asking questions and making observations of a phenomenon, (2) using a driving question board to document students' questions and key concepts learned from the lesson, (3) prompting students to develop initial models of the phenomenon to elicit their background knowledge, (4) coherent sequencing of student-led investigations related to the phenomenon, (5) using a summary table as a tool for students to track their learning over time, and (6) constructing a class consensus model and scientific explanation of the phenomenon. This workshop was part of a larger professional learning partnership aimed at improving secondary science teachers' knowledge and skills for planning and implementing phenomenon-based science. We found that sequencing these instructional routines as a scalable model of instruction was helpful for teachers because it could be replicated by any secondary science teacher during lesson planning. Teachers were able to work collaboratively with their grade- or course-level colleagues to develop lessons that incorporated these instructional routines and made phenomenon-based science learning more central in classrooms.

Introduction

The *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) outline ambitious targets for student learning in science based on goals described in the *Framework for K-12 Science Education* (National Research Council [NRC], 2012). Both the NGSS and the *Framework for K-12 Science Education* present a vision of science education in which students continuously revise their knowledge and skills through investigations of relevant phenomena and real-world problems using three interrelated dimensions: science and engineering practices, disciplinary core ideas, and crosscutting concepts. To reach these goals, K–12 science requires significant shifts in terms of how curriculum is developed, how

teachers support student learning over time, and how student proficiency is measured. Forty-four states have adopted the NGSS wholesale or developed standards based on the *Framework for K-12 Science Education* (National Science Teaching Association, 2020). With large-scale adoption of these standards, there is a concomitant need for inservice teacher professional learning and support.

A recent report by Smith (2020) indicates that widespread implementation of instructional models that engage students in relevant, authentic, natural phenomena or engineering problems remains low. Reasons abound for the disparity between the relatively widespread adoption of the NGSS and teachers' actual classroom practice. For instance, there are few comprehensive, high-quality instructional materials aligned with the NGSS (Achieve, Inc., 2018; EdReports.org, 2020; Smith, 2020) that are educative for teachers (Pringle et al., 2017). The majority of teachers in states that have adopted the NGSS or NGSS-like standards report having curriculum and instructional resources that were published prior to 2009, and they still use these materials to guide the structure and content of their lessons and units (Smith, 2020). In addition, a lack of contextualized, job-embedded, professional learning that meets the particular needs of teachers in their course or grade-level assignments leaves them with few opportunities to enhance or improve their classroom practice (Penuel, Fishman, Gallagher, et al., 2009; Penuel, Fishman, Yamaguchi, et al., 2007; Windschitl & Stroupe, 2017). In some cases, school policies and priorities can undermine NGSS-aligned teaching, such as when teachers are required to frontload vocabulary or provide students with low-level learning objectives that focus mainly on factual recall (Allen & Penuel, 2015; Penuel, Fishman, Gallagher, et al., 2009, Windschitl & Stroupe, 2017). These factors point to a need for ongoing professional learning that supports science teachers' knowledge and skills for planning and implementing phenomenon-based instruction.

The purpose of this article is to describe a set of instructional routines that we have used during several professional learning workshops with secondary science teachers. In the workshop that we describe here, we presented all six of the instructional routines together for the first time to teachers through a model lesson on dead zones in estuaries. These instructional routines were intended to support their knowledge and skills for implementing phenomenon-based science lessons. The goals of the partnership were to: (1) improve middle and high school science teachers' knowledge of instructional routines that support student sensemaking of phenomena and (2) support teachers in planning lessons that incorporate these instructional routines into their lesson plans.

Professional Learning and the Instructional Model

Context

The professional learning took place in a mid-Atlantic, urban, public school district that serves nearly 10,000 students from pre-kindergarten through 12th grade in a state that was an early adopter of the NGSS. During the 2019–2020 academic year, the student body was approximately 3% Asian American, 45% African American, 21% Latino, 4% Multi-racial, and 27% White. More than a third of students came from low-SES backgrounds.

In Colonial School District, as in all districts in Delaware, teachers are responsible for developing their own lesson plans as well as formative and summative assessments. Although there is a state-adopted curriculum for grades 6–10, the curricula in each of these grades are not fully aligned with the NGSS. In most cases, these curricula lack a productive anchor or lesson phenomena that can be used to coherently sequence lessons to guide students toward an increasingly sophisticated understanding of those phenomena. As a result, the lack of alignment requires teachers to substantively revise or enhance the state-mandated curricula. In grades 11 and 12, there are no state-adopted curricula for science courses; thus, teachers are responsible for all aspects of curriculum development, lesson planning, and formative and summative assessments. The collaboration between Colonial School District and the University of Delaware was intended to help teachers develop the knowledge and skills for writing new or enhancing existing curricula to be more fully aligned with the NGSS using phenomena as the anchor to drive teaching and learning.

For the last 5 years, the Colonial School District partnered with the University of Delaware to develop and implement a long-term, research-based, professional learning series for its classroom teachers (21 middle school science teachers and 18 high school science teachers). Middle school teachers were responsible for teaching a mix of disciplinary content at each grade level. For example, eighth-grade teachers facilitated three instructional units per year: weather and climate, ecosystems, and energy across physical systems. High school teachers were responsible for one or more disciplinary courses designated as 11th- or 12th-grade science electives: Integrated Science I (ninth grade, $n = 6$), Biology (10th grade, $n = 5$), and Chemistry ($n = 2$), Physics ($n = 2$), Environmental Science ($n = 1$), Integrated Science III ($n = 3$), AP Biology ($n = 1$), AP Chemistry ($n = 1$), or AP Physics ($n = 1$). (Some high school teachers have more than one course assignment). Although there was some limited staff turnover during the 5 years, the majority of teachers who participated in this professional learning workshop had been part of the long-term professional learning partnership.

Over these 5 years, Colonial School District and the University of Delaware worked collaboratively to support science teachers' knowledge of the structure and content of the NGSS, enhance their knowledge of models for phenomenon-based science teaching, and support them in developing three-dimensional curricula and classroom assessments. Instructionally productive phenomena are relatable, authentic, observable events that occur in the natural and designed (human-built) world; they are sufficiently complex so that students must use a range of scientific ideas (i.e., disciplinary core ideas), science and engineering practices, and crosscutting concepts to predict or explain using evidence from

multiple, related investigations (Penuel & Bell, 2016). Phenomenon-based science teaching anchors instruction in these observable events and sequences student investigations coherently to support students in developing an increasingly sophisticated understanding of scientific ideas.

Previous professional learning workshops during the 5-year partnership focused on understanding the content and structure of the NGSS, differentiating between science topics and instructionally productive phenomena, and supporting student sensemaking through classroom discourse about their questions, ideas, and evidence supporting those ideas. Although co-planning lessons and units with grade-level teaching teams took place during common planning time and professional learning community (PLC) meetings during the academic year, we did not have consistent access to these planning sessions and PLC meetings. Therefore, they are not part of the professional learning workshop outlined in this article, which took place during the 2019–2020 academic year.

During prior years of the collaboration, Colonial School District administration and the first author critically reviewed district-mandated instructional priorities that served as barriers to phenomenon-based science teaching. In particular, the district's use of the Learning-Focused Schools model (Learning-Focused.com, 2019; Pate & Gibson, 2005) ran contrary to instructional and pedagogical strategies needed to engage students in making sense of and explaining how or why natural phenomena occur. The strategies from the Learning-Focused model shown in Table 1, all of which had been previously mandated by the district, were placed on hold during this partnership.

Table 1
Learning-Focused Strategies That Were Being Used by Teachers Prior to the Professional Learning Partnership

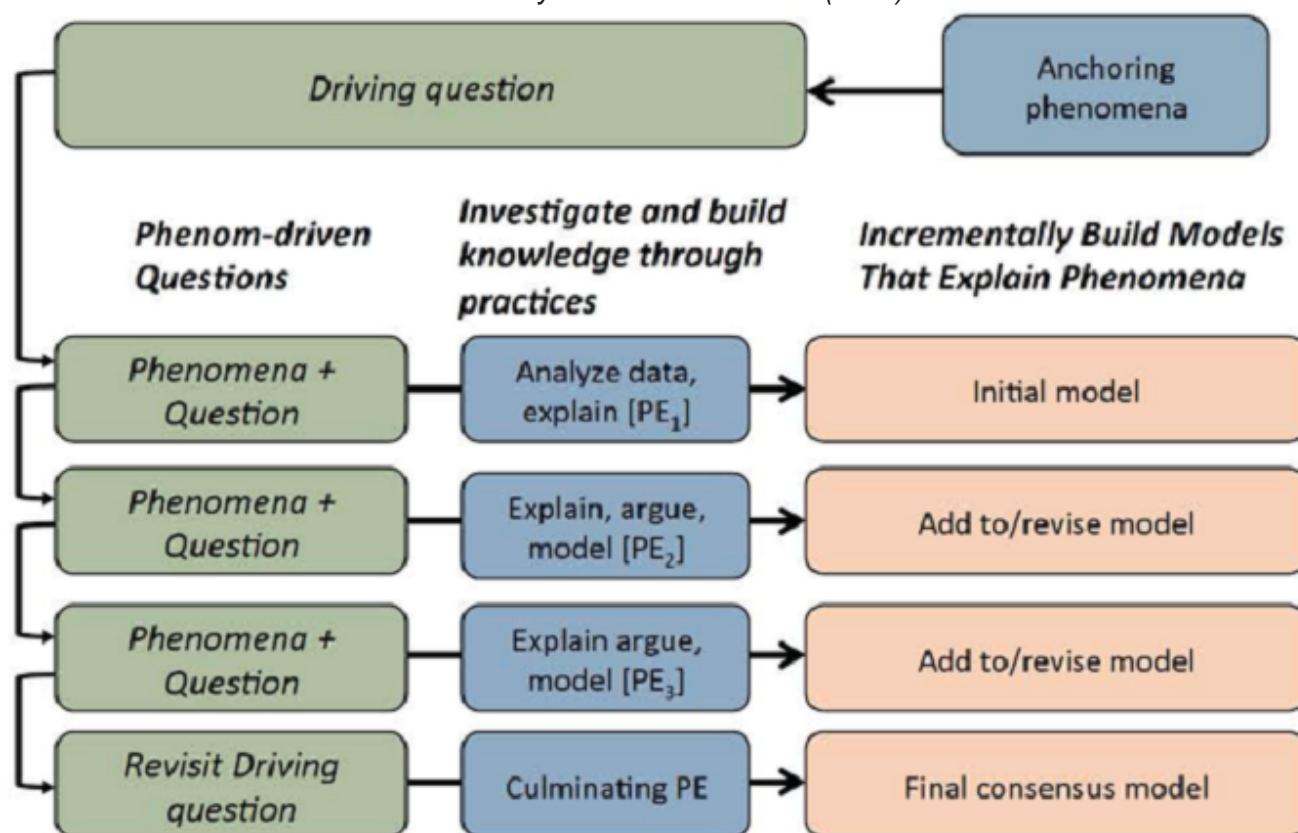
Learning-Focused strategy	How it was being implemented by science teachers
Unit and lesson essential questions	Guiding questions intended to drive learning but too often focused on acquisition of declarative knowledge.
Student learning maps	Students copied rote information from the teacher such as lists of vocabulary words students were expected to memorize during a unit of study. An example student learning map, which shows evidence of topic-based teaching, can be found in Supplemental Document 1.
Distributed guided practice	Intended to be embedded opportunities for students to practice skills, but often operationalized by teachers as plug-and-chug or algorithmic problem-solving.
Previewing vocabulary	Rather than providing students with a first encounter with important terms and concepts, teachers often simply frontloaded vocabulary terms through lecture.

Although we collectively made progress in helping teachers identify productive phenomena to plan their own science lessons and units, we found several ongoing tensions in teachers' efforts to initiate and sustain phenomenon-based science instruction. First, we found that some teachers conflated the use of phenomena as the context for learning and doing science in a lesson or unit with simply presenting discrepant events or flashy demonstrations when launching a lesson or unit. Although discrepant events can be useful for driving student interest and engagement in a science topic, generally, they are not robust enough to engage students in sustained investigation of phenomena or result in scientific models or explanations that describe how or why phenomena occur (Furtak & Penuel, 2018). A second tension in our partnership arose around instructional coherence. Many teachers had been prepared under an educational paradigm in which teachers had been expected to cover concepts or topics (e.g., density, convection, photosynthesis, and food webs) at the expense of engaging students as epistemic agents in knowledge building (Sherwood, 2020); in other words, building scientific knowledge through doing science in a coherent sequence of learning events. Traditional topic teaching in which teachers traverse from one concept to another in their course without some relevant or connected purpose for learning does not meet the goals set forth in the *Framework for K-12 Science Education* (NRC, 2012). In an effort to support teachers in overcoming these barriers to coherent phenomenon-based science teaching, we developed a set of instructional routines that draw on prior research on science teacher professional learning in the era of NGSS. In this article, we explain the instructional routines and the professional development workshop in which we introduced and modeled the instructional routines for secondary science teachers in the district. Then, we provide evidence of teachers' learning from their instructional planning documents and some limited instructional artifacts provided to us by teachers after the workshop.

Instructional Routines

Although others have used a storyline tool to scaffold teachers' work in curriculum development (e.g., Reiser, 2014; Severance et al., 2016), we have found the storyline tool (see Figure 1) too ambiguous in structure and too large in focus for our teachers. "A storyline is a coherent sequence of lessons" that is anchored by a phenomenon and "driven by students' questions" about that phenomenon (Next Generation Science Storylines, n.d.; see also Reiser, 2014; Reiser, Fumagalli, et al., 2016; Severance et al., 2016). It has been difficult for teachers in our partnership to develop full instructional units centered on a single anchor phenomenon and include the construction of multiple lesson phenomena and explanatory models intended to span multiple weeks (about 6–9 weeks) of instruction.

Figure 1
BlankStoryline Tool From Reiser (2014)



Note. PE = NGSS performance expectation.

Based on our work with teachers in this district and throughout the state, we have found that many teachers interpret the time or number of lessons between instances of constructing and revising models to be equal (e.g., at the end of every lesson), even when the nature of the lesson or its intended outcomes did not lend itself to this practice. We believe that this is an artifact of teachers' nascent understanding of structure of NGSS-aligned storylines and their underdeveloped knowledge of scientific models and modeling. To counter these difficulties, we formulated a compact instructional model (i.e., smaller in focus) that encompassed a lesson of a few days to up to 2 weeks of instruction rather than 6–9 weeks of instruction, which is typical for an instructional unit. In this compact instructional model, we reconfigured some of the high-leverage practices outlined in Windschitl and colleagues' *Ambitious Science Teaching* model (Windschitl, Thompson, & Braaten, 2018; Windschitl, Thompson, Braaten, & Stroupe, 2012) and the coherent sequencing of investigations and scientific modeling (i.e., storyline framework) outlined by Reiser and colleagues (Next Generation Science Storylines, n.d.; Reiser, 2014; Reiser, Brody, et al., 2017; Reiser, Fumagalli, et al., 2016) into repeatable instructional routines to privilege student sensemaking through scientific discourse during learning. We sequenced these instructional routines within a compact instructional model to help teachers make sense of how and when to use the various NGSS-aligned strategies they had encountered during previous professional learning.

Our intention was not to test the efficacy of this reconfigured model of instruction but to synthesize professional knowledge into a coherent instructional framework that teachers could use for planning and classroom implementation. We combined and reconfigured Windschitl, Thompson, and Braaten's (2018) high-leverage practices with Reiser and colleagues' (Next Generation Science Storylines, n.d.; Reiser, 2014; Reiser, Fumagalli, et al., 2016) storyline framework into a repeatable sequence of instructional routines with the goal of streamlining phenomenon-based science teaching by highlighting pedagogical practices that encourage students to talk about science ideas, support claims with evidence, and formulate how or why explanations of phenomena. In other words, this sequence of instructional routines was intended to be a digestible model that encouraged teachers to plan for and implement strategies for student sensemaking. The instructional routines are outlined below and in Table 2.

- **IR 1: Introduce a phenomenon** to students at the beginning of a lesson sequence to provide a relevant, central context for learning and to elicit students' background knowledge.
- **IR 2: Use a driving question board**, posted publicly in the classroom, to capture students' observations, background knowledge, and questions about the phenomenon and to document changes to thinking and answers to questions during the lesson sequence. The driving question board should be revisited after each investigation and include concepts and ideas upon which students agree (Reiser, Brody, et al., 2017; Reiser, Fumagalli, et al., 2016; Windschitl, Thompson, Braaten, & Stroupe, 2012).
- **IR 3: Engage students in developing an initial explanatory model of the phenomenon.** The purpose of this initial model is two-fold: to elicit students' background knowledge and to provide a context for students to reflect on their understanding during the lesson. Students should revise or add to their initial models at the end of investigations.
- **IR 4: Coherently sequence investigations directly related to the phenomenon.** Investigations can take many forms, including gathering information from science texts, using simulations, and collecting firsthand data with scientific tools and materials. In all cases, these investigations require students to use one or more science and engineering practices to build understanding of related disciplinary core ideas and crosscutting concepts. The investigations are sequenced to allow students to develop a more sophisticated and complex understanding of core ideas and crosscutting concepts over time.
- **IR 5: Prompt students to track their learning in a summary table** (see Table 3) at the end of each investigation. The summary table includes space for students to explain what they learned and how it relates to the phenomenon. The summary table can be used in conjunction with the driving question board to facilitate whole-class discussion about the phenomenon. The primary purpose of the summary table is to help students keep track of their ideas and what they learned as it relates to the lesson phenomenon.

- **IR 6: Develop a class consensus model and an explanation for the phenomenon** that includes whole-class discussion facilitated by the teacher. This consensus model leverages disciplinary core ideas and crosscutting concepts to explain how or why the phenomenon occurs.

Modeling the Instructional Routines in a Professional Learning Workshop

In order to support teacher learning about the instructional routines, we modeled a modified lesson on dead zones in marine systems based on estuary education resources from the National Oceanic and Atmospheric Administration (NOAA) Office for Coastal Management (2020). We engaged teachers as learners in the modified lesson during a 3-hour professional learning workshop, which took place during a scheduled professional development day during the academic year. After the model lesson, teachers were divided among grade- or course-level teams to plan an upcoming lesson using the instructional routines in our exemplar model of instruction. The purpose of the modified lesson on marine dead zones was not curriculum training; instead, it was intended to be the vehicle for teachers' learning about the instructional routines. Although teachers could have used this particular lesson in their own classroom, the focus was to guide them through an example as learners before creating their own lessons.

To begin the model lesson, we introduced the phenomenon (IR 1) by showing pictures of finned fish and crustaceans washed up on a beach in Mobile Bay, Alabama. This phenomenon is called a fish jubilee because the people who live along these shores collect and consume the fish. Teachers were prompted to make observations and ask questions, which we documented on a driving question board (IR 2)—in this case, large pieces of chart paper hung in the front of the room for public viewing (15 min). To elicit background knowledge, we asked teachers to work in small groups of three to five teachers to discuss how and why so many fish had washed up on the beach. Each group was asked to draw and label an initial model and write a causal explanation (IR 3) on a sheet of large chart paper (10 min). Then, we asked each group to share their initial model and explanation with the whole group. As new questions arose, we documented them on the driving question board hung at the front of the room (15 min).

After introducing the phenomenon and eliciting teachers' background knowledge through the construction of initial models, we engaged teachers in a series of investigations (IR 4) carefully sequenced to provide teachers with increasingly detailed information about the phenomenon (about 60 min). In this workshop, the investigations were abridged to fit within the 3-hour session; however, the content of the original NOAA lesson plan included investigations of water density based on salinity and temperature. In the professional learning workshop, we skipped the density investigations from the original NOAA lesson plan; however, we did use the news report, a set of abbreviated reports from scientists, an

online simulation that showed how dead zones formed in estuaries, and graphs of physical conditions (i.e., high/low tides, wind direction, dissolved oxygen, and ambient temperature) on four different days in Mobile Bay. The original series of investigations would encompass several class periods if implemented with students. After reading the scientific reports and engaging in the simulation (Investigations 2 and 3, respectively, see Table 2), teachers were asked to revise their initial model with their team (5–7 min each time). We also modeled how to facilitate discussion to complete the summary table (see Table 3) after each investigation (IR 5) in order to keep track of ideas they had learned through the investigations. After each investigation, we returned to the driving question board to determine which, if any, questions we had answered through the investigation and then summarized what we had learned about the phenomenon (5 min).

Table 2

Description of Instructional Routines (IRs) With Reflection Prompts for Teachers During Professional Learning (PL)

IRs	Description	Reflection questions for teachers during PL workshop
1. Introduce the phenomenon ¹	A relatable, authentic, observable occurrence in the world that is too complex to be answered in a single lesson and would require students to use practices, core ideas, and crosscutting concepts in multiple investigations to figure out. Phenomenon is introduced at the beginning of the lesson or unit through video, text, pictures, or illustrations. It drives sequencing of investigations and is revisited after each lesson. (See summary table.)	- What strategies have we used thus far that allowed you to make sense of the phenomenon? - How do these strategies encourage all learners to engage in the phenomenon?
2. Driving question board (DQB)	Our DQB is a three-column chart: (1) what do we observe about the phenomenon? (2) What questions do we have about the phenomenon? and (3) What have we figured out? We revisited the DQB each time we engaged in an investigation to model how the DQB is a living document to publicly show changes to thinking over time.	- What is the purpose of the driving question board? - How does the DQB encourage all learners to engage in the phenomenon?
3. Develop an initial model	Drawing, sketch, concept map, flow chart, graph, or written representation that explains how or why, or predicts when the phenomenon occurs. The goal here is to elicit students' background knowledge and to begin to compare ideas among the community of learners.	- What is the purpose of asking students to devise an initial model before any learning activities have occurred? - How might group discussion of the initial model support student learning?
4. Investigations of phenomena	Engage learners in a related set of investigations that range from gathering and analyzing firsthand data with scientific tools to gathering information from texts, and using simulations to understand the relationships among variables, etc. Investigations are carefully sequenced to support students in building on increasingly complex understanding of disciplinary core ideas and crosscutting concepts related to the phenomenon.	- What science and engineering practices did you use to make sense of the phenomenon? - How do the investigations (activities) help students answer questions on the driving question board?
5. Summary table	This instructional routine is used as a discursive tool for students to talk about what they learned and how it relates to the phenomenon. Teachers are expected to hold a whole class discussion at the end of each investigation to help students add to their summary tables (see Table 2).	- What purpose might the summary table serve in supporting student learning? - How does the summary table support student sensemaking?
6. Consensus model and explanation	Using information and data from previous investigations, a class consensus model is constructed along with a causal or predictive written explanation for how or why the phenomenon occurs.	- What is the purpose of developing a class consensus model at the end of a lesson? - What is the purpose of revisiting the DQB at this point?

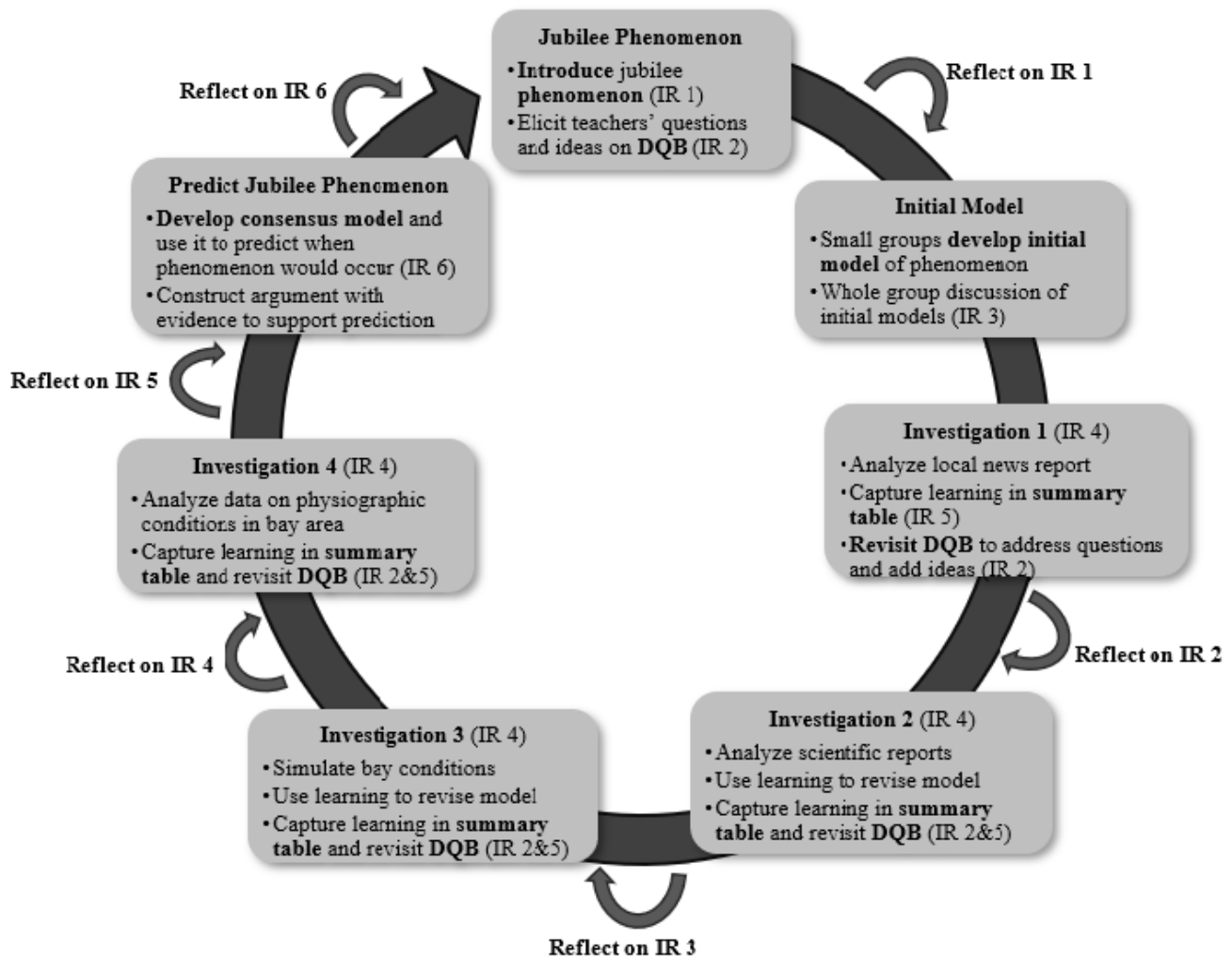
After the fourth investigation, we prompted teachers to revise their model (5–7 min). During the whole-group discussion, we looked for similarities in the models and documented them on a class consensus model (20 min). We also prompted teachers to explain the relationships among factors such as nutrient pollution, runoff, weather conditions, tide,

dissolved oxygen, and rates of respiration and photosynthesis among aquatic organisms. After we worked as a group to develop a consensus model, we asked the teachers to work in small groups to predict when a fish kill would occur (IR 6; 20 min).

We embedded several reflection questions for teachers to consider as we modeled each instructional routine. An illustration of the repeated cycles of investigation, scientific modeling, and teacher reflection used during the workshop can be found in Figure 2. We provided each teacher with a copy of these reflection questions at the beginning of the professional learning workshop so that they could capture their thoughts in real time during the session (see Table 2). After we modeled each instructional routine in the lesson, we stopped and debriefed with the teachers as a whole group to discuss these reflection questions. This reflection time was invaluable for understanding how teachers understanding the routines in relation to their own practice, answering questions they might have, identifying potential affordances, and discussing potential solutions to challenges in using these routines in their own classrooms.

Figure 2

Repeated Cycles of Investigation, Modeling, and Teacher Reflection on Instructional Routines in the Fish Jubilee Model Lesson



Note. An explanation of the instructional routines (IRs) and reflection questions can be found in Table 2.

Teacher Implementation of Professional Learning

At the end of the model lesson on the fish jubilee in Mobile Bay (see Table 3 for an explanation of the phenomenon) and in subsequent PLC meetings in the weeks following the workshop, teachers assembled in grade- or course-level teams to plan a phenomenon-based lesson using the instructional routines. We were not present at all subsequent PLC meetings for each grade- or course-level team, so making the most of planning time during the 3-hour workshop was vitally important to supporting teachers in planning a phenomenon-based lesson that included instructional routines.

Table 3

Sample Summary Table From Professional Learning With Middle and High School Teachers

Phenomenon: There are many finned fish and crustaceans washed up on the beach or in the shallow water of the shoreline in Mobile Bay, AL			
Driving question: Why are there so many fish washed up on the beach in Mobile Bay?			
	What did we observe?	What did we learn? (related DCIs)	How does it relate to the phenomenon?
Investigation 1: Analyze local news article on fish jubilee	Dissolved oxygen (D.O.) in Mobile Bay was extremely low for 5 days in August 2011	Dissolved oxygen (D.O.) <4 ppm can be harmful or lethal to fish D.O. level related to wind, tides, temperature, amount of decaying organic matter	Low D.O. could be one reason why so many fish were washed up onto the beach
Investigation 2 Analyze reports from scientists	Manmade pollution comes to Mobile Bay from rivers Pollution causes algal blooms, algae die and then consumed by bacterial decomposers Lack of wind = low water turnover	Eutrophication caused by nutrient pollution runoff from land causes low D.O. Water stratification caused by temperature, lack of wind and differences in salinity in water column	When there is a dead zone, fish tend to stay at the top of the water column where D.O. is higher. Dead zone grows at night as oxygen consumed via respiration (no photosynthesis)
Investigation 3: Simulation of diurnal conditions in Mobile Bay	Wind direction: during day from ocean, at night from shore Tides: rising tide pushes dead zone closer to shore, falling tide takes dead zone out towards open ocean	High and low tide can affect location of dead zone in relation to shore Wind direction and speed affects how much water is turned over in the water column, which affects D.O.	Fish are more likely to wash up on the beach at night or early morning) and when the wind is blowing from the eastern shore and tide is rising towards shore
Investigation 4: Analysis of conditions data	Number of days in summers which physical conditions are ideal for dead zones is increasing	Combination of rising tide, wind direction from shore, and high temperature just before sunrise leads to fish kill	Increases in the amount of manmade pollution and increase in average temperature means future increase in number of summer fish kills
Consensus model and explanation: We developed a consensus model to explain why a fish kill would occur (using information from investigations) and then used physical data from different dates to predict when it would occur.			

To help teachers begin lesson planning, we provided them with a brainstorming tool to help them choose a lesson phenomenon and anticipate students' ideas, questions, background knowledge, and what students would include in their scientific models and explanations. Figure 3 shows an exemplar of the brainstorming tool based on the model lesson from the professional learning workshop. Note that the teacher brainstorming tool (Figure 3) is not the same as the student summary table (IR 5). The teacher brainstorming tool is intended to help teachers choose an appropriate lesson phenomenon, anticipate students' questions and observations, and begin planning the lesson; however, the student summary table (IR 5) is intended to help students keep track of their ideas during learning.

Figure 3

*Planning Tool Completed With Information From the Model Lesson on Fish Kills Modified From NOAA
Office for Coastal Management (2020)*

The phenomenon or design problem: (describe, provide link to video, upload pictures or other resources)		
Fish jubilee in Mobile Bay, AL Jubilees occur in summer when large numbers of fish and crustaceans wash up onto the beach or into shallows due to hypoxic or anoxic water conditions that result from a combination of high temperature, low wind, and low oxygen conditions. Low oxygen is generally the result of eutrophication followed by rapid decomposition (aerobic respiration).    		
Anticipated phenomenon/design question(s): (students will address this in their final model, argument/explanation)		
What is causing fish and crustaceans to wash up onto the beach? How can we predict when this will occur?		
Anticipate what students will share: (What questions will students likely ask about the phenomenon? What background knowledge or ideas will they probably share?)		
Anticipated student questions		Anticipated student ideas/observations
- Are the fish and crabs alive? Are they dead? - Are the fish and crabs in mating season? - What is causing them to end up on the beach? - Was there a big storm or hurricane before these pictures were taken? - How long have they been there? - When did this happen? - Is <u>it</u> low tide or high tide?		- Beach area, along coast - There are fish and crabs (maybe eels) on the beach. - Several different types of ocean organisms on the beach <u>All of</u> the pictures seem to be during daytime
Constructing a scientific model: (what will <u>you</u> prompt students to include in each revision?)		
Initial Model	First Revision	Second Revision
Students can draw any plausible reason for the dead <u>fish</u> , <u>but</u> should be prompted to think about how the physical or biological conditions may have contributed to what they observed. For instance, asking them to consider: - What might be the conditions in the ocean water, weather, or on land that contributed to fish on the beach? - What interactions with other living things might have contributed to fish on the beach?	Students should add to/revise their models to include: - low dissolved oxygen - decaying organic matter (or aerobic respirations) - freshwater layer on top of saltwater (different densities) preventing surface overturn - migration of ocean organisms from low oxygen areas towards shore	Students should add to/revise their models with: - sources of nutrients from land runoff and effect on algae growth - influence of hot summer temperatures on decomposition - low tidal action and low wind result in low surface turnover (cause of low oxygen) - most decomposition of algae occurs on seafloor/benthos - migration of ocean organisms to shallow areas at night - wind coming from east side of Bay (from land) - tide rising, pushing dead zone towards shore
NGSS PEs aligned to this phenomenon:		
HS-LS2-2. Use mathematical representations to support and revise explanations based on evidence about factors affecting biodiversity and populations in ecosystems of different scales.		
HS-LS2-6. Evaluate the claims, evidence, and reasoning that the complex interactions in ecosystems maintain relatively consistent numbers and types of organisms in stable <u>conditions</u> , <u>but</u> changing conditions may result in a new ecosystem.		

Figures 4 and 5 show what the chemistry and integrated science teachers devised in the brainstorming tool. The chemistry team chose a lesson phenomenon related to the Statue of Liberty, and the integrated science team chose a phenomenon related to weather. Both phenomena were appropriate in that they were observable to students and sufficiently complex so as to require students to use multiple interrelated ideas to explain how or why the phenomenon occurred. The chemistry team (see Figure 4) anticipated potential questions that students might ask and how students' models would change after each revision based on new learning. The teachers anticipated that students would use their knowledge of different reaction types to, at least partially, explain the changes to the Statue of Liberty (see Figure 4). Supplemental Document 2 provides an example of student work from this redesigned lesson. The integrated science team (Figure 5) also anticipated students' questions about the polar vortex of 2019 (the phenomenon) and their expectations for students to develop models related to the phenomenon. In Figure 5, teachers included key concepts related to weather but not about climate change, which is key to explaining the increasing frequency and duration of polar vortexes in the last decade. It is unclear why teachers did not make the connection between climate change and the models they expected students to produce (see Figure 5). Perhaps this was included in a later lesson set after students learned about variables that influence weather.

Figure 4

Planning Document Completed by Teachers on the High School Chemistry Team

The phenomenon		
Statue of Liberty changing from brown to green over time https://www.dailymail.co.uk/sciencetech/article-4652254/The-Statue-Liberty-RED-turned-green.html		
 Image from: https://www.reddit.com/r/civ/comments/h893el/concept_saw_this_image_of_the_statue_of_libertys/		
Anticipated phenomenon question		
What caused the Statue of Liberty to change color over time? How do you know a chemical reaction has occurred?		
Anticipated student questions	Anticipated student ideas/observations	
- When was it put up? - When did it change colors? - How long did it take to change color? - Why did it change colors? - Can we reverse it? - Is it related to pollution? - Is it related to its location? - Where did the copper go/is it still copper? - Why is it still green after all this time? - Other uses for copper (copper roofing, etc.)	- Pollution - answers why - Weather patterns - Scraping off the green - More stable	
Devise a model for why the Statue of Liberty turned from brown to green.		
Initial Model	First Revision	Second Revision
- Before → After with emphasis on weather or pollution - Atomic-level vocab	- Identify that a chemical reaction occurred - Copper reacted with the oxygen in the air and the water. - Pollution had an impact.	Students identify specific chemical reaction(s) $\text{Cu} + \text{H}_2\text{SO}_4$ $\text{Cu} + \text{HCO}_3$ $\text{Cu} + \text{HNO}_3$ $\text{Cu} + \text{HCl}$
NGSS PEs aligned with this phenomenon:		
HS-PS1-2: Construct and revise an explanation for the outcome of a simple chemical reaction based on the outermost electron states of atoms, trends in the periodic table, and knowledge of the patterns of chemical properties HS-PS1-3: Plan and conduct an investigation to gather evidence to compare the structure of substances at the bulk scale to infer the strength of electrical forces between particles		

Figure 5

Planning Document Completed by Teachers on the High School Integrated Science Team

The phenomenon		
Extreme Weather Event: Polar Vortex occurring during winter 2019, which resulted in extreme cold, power outages, and deaths. Extreme weather events result from uneven heating of Earth's surface, Earth's rotation, and moving air masses. https://www.cbsnews.com/news/polar-vortex-what-is-the-2019-polar-vortex-weather-event-and-is-global-warming-to-blame/		
Anticipated phenomenon/design question:		
What caused the polar vortex of 2019 and will extreme cold events continue to occur?		
Anticipated student questions		Anticipated student ideas/observations
• What is causing the extreme cold? • Where is the extreme cold coming from? • What is the trend that is occurring with the weather? • How does/or does global warming relate to the polar vortex? • How does this weather event affect me and my community? • How to protect themselves from the weather event?		• Cold air coming from the north pole. • Being outside is not safe for long periods of time for anyone.
Scientific model		
Initial Model	First Revision	Second Revision
Uneven heating of Earth's surface by the sun: • Cold comes from the north • Earth is tilted • Hot in the south	Include factors affecting polar vortex: • Air masses move • Temps result from air masses • Warm air expands-less dense • Cool air sinks- • air circulation	• Include factors that affect students and community. • Preventative measures against extreme weather events.
NGSS PEs aligned to this phenomenon:		
HS-ESS2-2. Analyze geoscience data to make a claim that one change to the Earth's surface can create feedbacks that cause changes to other Earth systems. HS-ESS2-4. Use a model to describe how variations in the flow of energy into and out of Earth's systems result in changes in climate.		

In the survey we distributed at the end of the professional learning workshop, several teachers provided us with positive feedback about the instructional routines. This feedback emphasized teachers' growing knowledge of how the instructional routines worked together to support student sensemaking. A high school teacher indicated,

I'm beginning to understand how phenomenon should be driving the lesson, not the lessons or demonstrations I've used in the past. I'm ready to update my lessons using the [brainstorming] tool provided by [facilitators], but I have to admit I'm nervous about how it will work in my classroom. This workshop was a good step.

A middle school teacher noted that they understood how the student summary table could be helpful for keeping track of ideas:

After this workshop, I'm finally beginning to understand how a student summary table could help students stay organized and think about how each day's lesson connects to previous lessons. I've been frustrated by the fact that students don't seem to remember what they learn from day to day. I think this summary table will help them remember how everything's connected.

After the professional learning workshop, teachers provided direct evidence of their use of the instructional routines. For example, an eighth-grade teacher shared with us her lesson plan on thermal energy, which was embedded in a larger instructional unit on energy across physical systems (see Supplemental Document 3). In this document, she provided a list of ideas that she expected students to understand based on previous learning (see Prompt 1) and some examples of initial models drawn by students (see Prompt 2). In an earlier lesson in this unit on energy across systems, the teacher provided us with an example of a summary table filled out by a student (see Supplemental Document 4). During PLC meetings, middle grades teachers created their own teacher version of the summary table to plan upcoming lessons embedded within larger units of instruction. The sixth-grade team, for instance, outlined their lesson on the revolution of the Earth to help them ensure coherence in student-led investigations (see Supplemental Document 5). These teacher summary tables were used by grade-level teachers across all three middle schools in the district to plan for curriculum implementation within their individual classrooms. The teachers acknowledged during the workshop that filling out a teacher version of the summary table helped them anticipate and facilitate students' learning as they completed the student version of the summary table. We believe that this shows evidence that teachers took up the instructional routines we had presented in the professional learning workshop and were finding ways to embed those routines into their professional practice.

Lessons Learned

Providing teachers with professional learning about the structure and content of the NGSS is a necessary antecedent but is alone insufficient for driving real and lasting change to teachers' classroom practice. Sustained change will only occur through modeling phenomenon-based instructional practices during professional learning, giving teachers time for collaborative lesson planning, offering constructive feedback on those plans, and providing in-classroom support during implementation (Severance et al., 2016; van Driel, et al., 2012). Teachers need ongoing opportunities to plan for high-leverage practices in their teaching; this includes common planning time among course- or grade-level teams and focused professional learning communities that allow teachers to share their successes and challenges and engage in collaborative problem-solving (NRC, 2015; Penuel, Fishman, Yamaguchi, et al., 2007).

One benefit of the sequence of instructional routines is that it catalyzed conversations about using old confirmatory and hands-on activities as investigations in the instructional sequence. Especially for experienced teachers, it is difficult to set aside activities that have been a longstanding part of their instructional repertoire. We have found that many teachers begin the shift to NGSS-aligned teaching with the belief that hands-on activities automatically equate to phenomenon-based investigations (Furtak & Penuel, 2018, Sherwood, 2020). However, with feedback and reflection on purposes and outcomes, we have been able to push teachers to think critically about how, when, or why an activity is appropriate for driving students' understanding of a lesson phenomenon. Using the structure of the brainstorming tool (see Table 3 and Figures 3 and 4) helped teachers center their lesson on a phenomenon and then begin to plan for investigations that would lead students toward understanding the science concepts necessary to explain how or why the phenomenon occurs, using scientific models and explanations to show their thinking.

That is not to say we experienced complete success. In follow-up coaching, we have found that some teachers reverted to prior practices, such as frontloading vocabulary, lecturing on content, and then providing students with a confirmatory lab activity. Why this reversion to prior, more traditional practice occurred is an important question that influences the day-to-day implementation of phenomenon-based science instruction and potentially impacts student achievement in science. We have some anecdotal evidence for this based on our observations in classrooms and from planning meetings with teachers, but we contend that this issue requires comprehensive investigation through an empirical research study. During this partnership and in ongoing work across the state, we found that systematically engaging students in developing and using scientific models has been difficult for our teachers to sustain over time and in all lesson sequences. We posit that the reasons for this are multifarious. We suspect that teachers in our partnership haven't yet developed a comprehensive knowledge of scientific models and modeling, and they don't fully understand the role of developing and using models in supporting student learning. Some teachers have taken out the initial model instructional routine because they deem it inappropriate or too hard for their students.

Suggestions for Implementation

Collectively, our observations of teachers reinforce the notion that phenomenon-based science teaching is complex. Sophisticated pedagogical skills are needed to support student learning through phenomena. Thus, NGSS-aligned teaching requires sustained professional support and substantial feedback as well as ongoing opportunities to enhance content knowledge and skills by teachers.

In order for other teacher educators to use these instructional routines with teachers during professional learning, a necessary prerequisite would be for those teachers to have a basic understanding of the goals of the *Framework for K-12 Science Education* (NRC, 2012) and the structure and content of the NGSS (NGSS Lead States, 2013). Teachers need background knowledge about how the NGSS differs from previous content standards and the ways in which students are expected to engage in science as investigators of natural phenomena. Also, prior to professional learning on instructionally productive phenomena (Penuel & Bell, 2016), it is necessary to help ensure that teachers have some common understanding of the difference between a science topic and a phenomenon.

Because the instructional routines require teachers to frequently facilitate classroom discussion, anticipate that teachers will need follow-up classroom support, including real-time feedback or coteaching during implementation. Relinquishing control over the conversation in the classroom can be difficult for our secondary teachers because they often believe students can't or won't participate (Trauth-Nare, 2012; Trauth-Nare, et al., 2016). However, we have found this to be roundly untrue. Students will engage deliberately and deeply in discussions about science ideas if structures are in place for them to do so. Thus, our follow-up support for teachers often focuses on promoting a collaborative culture of inquiry in the classroom, establishing norms for discussion, and holding students (and the teacher) accountable for listening and responding to others' ideas.

When possible, we recommend that professional learning is tailored to the particular content teachers are expected to cover in their grade level or course. However, we recognize that this is not always the reality in district-based professional learning. We rarely have the opportunity to work with small groups of teachers at a single grade level; however, we have always engaged teachers in professional learning that is embedded in relevant secondary science content, and we attempt to model through our facilitation the same pedagogical strategies that we expect teachers to employ in their classrooms. We have found that keeping professional learning as close to classroom practice as possible makes it easier for teachers to envision how it would play out with their students.

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