Coherence from the Students' Perspective: Why the Vision of the Framework for K-12 Science Requires More than Simply "Combining" Three Dimensions of Science Learning[1]

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The Need for Coherence

The *Framework for K-12 Science* defines science learning as the combination of the three dimensions of disciplinary core ideas, crosscutting concepts, and science and engineering practices (National Research Council, 2012). The Next Generation Science Standards (NGSS) implement the Framework by articulating performance expectations, which are defined by assembling elements of these three dimensions (NGSS Lead States, 2013). We argue that achieving the vision of the Framework and NGSS in classrooms requires important shifts in teaching approaches and instructional materials to support *coherence from the students' perspective*.

One explicit goal stated in the argument for the Framework for K-12 Science is attention to a lack of coherence in U.S. K-12 education.

> The framework is motivated in part by a growing national consensus around the need for greater coherence—that is, a sense of unity—in K-12 science education. Too often, standards are long lists of detailed and disconnected facts, reinforcing the criticism that science curricula in the United States tend to be "a mile wide and an inch deep" (Schmidt, McKnight, & Raizen, 1997). (National Research Council, 2012, p. 10)

The Framework identifies three strategies for supporting coherence: (a) organizing learning goals around a "developmental progression …designed to help children continually build on and revise their knowledge and abilities, starting from their curiosity about what they see around them and their initial conceptions about how the world works"; (b) focusing on a "limited number of core ideas"; and (c) integrating knowledge and practices (National Research Council, 2012, p. 11). Our argument for coherence from the students' perspective builds on criteria (a) and (c) — organizing learning so that students can build new ideas systematically and incrementally starting from their curiosity and initial conceptions, and supporting students in authentically engaging in science and engineering practices because of a genuine need to make progress on addressing questions or problems they have identified.

We contrast coherence from the *students'* perspective with coherence considerations from a purely *disciplinary* or expert perspective, in which the reason to work on particular topics or undertake new investigations follows a learning progression outlining a sequence of building ideas that exclusively reflect the logic of the science ideas. We will argue that such coherence is

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not sufficient for the Framework's vision of learning that combines the three dimensions of practices, disciplinary core idea, and crosscutting concepts (often called *three-dimensional learning*). The reason the class is moving from one topic to another may be apparent to curriculum designers, scientists, and teachers, and may make sense in hindsight, once one already understands the target ideas. Yet the logic may not be apparent, convincing, or compelling for students. For example, consider the treatment of sound in the middle school grade band. NGSS includes these two performance expectations:

- MS-PS4-1. Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.
- MS-PS4-2. Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.

These performance expectations draw on the middle school articulation of the target disciplinary knowledge about waves in the Framework:

> A simple wave has a repeating pattern with a specific wavelength, frequency, and amplitude. A sound wave needs a medium through which it is transmitted. (PS4, National Research Council, 2012, p. 132)

Consider a well-designed middle school unit on sound that is organized to be coherent from a disciplinary perspective. It begins with the idea that sound is a wave that travels through a medium, and then poses investigations to explore the properties of wavelength, frequency, and amplitude. We could assemble lessons in which students are engaging in science and engineering practices, such as modeling and using mathematical thinking to work with these disciplinary ideas. For example, a lesson might have students observe that rice placed on a speaker bounces around when the speaker is making sound. The teacher could put a ringing timer in a bell jar, remove the air, and students would discover that they can't hear the ringing without the air. These experiments are clearly motivated for someone who already knows how sound works — because they know that sound is a compression wave and it needs a medium. When a speaker produces sound the surface moves back and forth to move air, sending a series of compressions and decompressions that make the rice bounce. When the air from the bell jar is removed the sound stops because there are not enough particles to push on the jar and transmit the energy from the ringing timer to our ears. Each of these lessons may technically appear to be three-dimensional lessons that combine practices, disciplinary ideas, and crosscutting concepts.

But consider the experience of the lesson from the students' perspective. Why are we putting rice on a speaker or putting a ringing object inside a bell jar and removing air? These activities themselves might be great to use, but to involve the deliberate sensemaking that reflects science and engineering practices, they need to make sense from the students' perspective. The students need to be involved in the group conversation and decision making about what makes sense to pursue next. While there is a phenomenon to be explored, and perhaps even a general question, such as "what will happen?" that motivate the experiment, the experiment is not motivated by the ongoing attempt to explain phenomena students have already tried to make sense of. Nothing in the prior conversation motivated, for the student, the selection of these phenomena. Furthermore, while the teacher could preface the experiment with the assertion that the experiment will help them see how sound can involve air, the framing of the experiment is essentially the teacher saying "trust me, this will be helpful, you'll see why later." That may work given many people's expectations about how school works, but it does not reflect engaging in a meaningful practice that builds knowledge.

Creating learning environments that reflect the shift toward three-dimensional learning will require that teachers or instructional materials do more than simply *combine* all three dimensions into a lesson so that they merely co-exist. We argue that it requires that teachers partner with students in developing and managing the trajectory of their investigations, and the process of building knowledge from these investigations. In the next section, we present a précis of this argument, and then briefly describe a framework that addresses this goal of coherence.

The Argument for Coherence from the Students' Perspective

We view coherence from the student perspective as when a classroom community engages in meaningful investigations in which students are partners in managing the trajectory of their knowledge building. They develop ideas over time, motivated by questions about phenomena, where each step is an attempt to address a question or gap in the current explanations and models. They are engaged in deliberate sensemaking, in which engaging in practices and building science ideas become ways of making progress on the questions they are trying to figure out or the problems they are trying to solve (Edelson, 2001; Kanter, 2010).

It is important to note that this does not entail simply following wherever students wish to go. It requires cultivating phenomena-based questions and working with students to *co-construct* ways to investigate them. It will certainly require teachers' guidance to help focus students on productive directions that can lead to the target disciplinary core ideas. Our key assertion here is that students can be partners in this negotiation, being brought along to work through these ideas, rather than simply presented with the productive next steps by the curriculum materials or teacher. This shift in classrooms requires reframing how teachers and students develop ideas over time, shifting the epistemic and power structures in the classroom. Our argument draws on three related issues: the nature of disciplinary practices, epistemic agency, and the particular nature of knowledge building in science.

Science as practice

The first argument concerns characterizing practices as meaningful disciplinary work. Framing scientific work as "practices" in the Framework rather than as "science skills" or "process goals" was quite deliberate (Osborne, 2014). This reflects the attempt to re-envision students' science work as a meaningful, purposeful attempt to build knowledge. A practice reflects a coherent system of activity, developing and using science knowledge to explain phenomena in the natural world or engineer solution to problems, that is guided by common goals, expectations, and norms for the discipline (Ford & Forman, 2006). Simply following instructions does not reflect engaging in a practice, nor does providing students choice of variables to investigate guarantee that these investigations serve a sensemaking goal that students have articulated and understand why they are pursuing.

This notion of meaningful practice has important implications for engaging in science. Science is fundamentally about building explanatory models and theories, supported by empirical evidence and argument (Giere, 1988; Passmore, Gouvea, & Giere, 2014). Questions arise from engaging with and trying to make sense of phenomena, which raises questions or problems that motivate investigations. If students are manipulating variables or designing experiments without an overarching question they helped articulate that reflects trying to understand some phenomena or solve a problem, they cannot be said to be truly engaging in science and engineering practices. Simply making a model or analyzing patterns in data because that is the task of the day, rather than being *driven* by their questions about phenomena, is simply going through the motions of "school science" rather than engaging in a knowledge-building practice (Jiménez-Aleixandre, Rodríguez, & Duschl, 2000; Lehrer & Schauble, 2006). Giving students freedom to manipulate variables or design an investigation, without motivating these investigations with phenomena that cannot be explained from students' prior knowledge, does not position students as "figuring out" how and why phenomena occur (Manz, 2014; Schwarz, Passmore, & Reiser, 2017). In fact, often instructional materials that aspire to be "inquiry activities" do not involve students in first negotiating what questions need to be investigated prior to giving them freedom to explore and manipulate variables.

Epistemic Agency

A second argument concerns *epistemic agency* (Stroupe, 2014). Committing to scientific knowledge building as meaningful practice has clear implications for participants' agency in making decisions about the work. If students are participants in a classroom community engaged in meaningful practice, they need to be partners in the knowledge-building work. Knowledge building is more than simply designing experiments when provided a collection of variables to manipulate or making sense of empirical results from an experiment that is provided. Engaging in knowledge building involves being part of the decision making in the ongoing process of identifying puzzles or problems that are important to pursue, refining those into researchable questions or design challenges, conceptualizing how to investigate the questions or solve the problems, conducting the investigations, making sense of the findings, and identifying next steps for the knowledge building work. Shared epistemic agency positions teachers and students as negotiating the decision making and management of the knowledge-creation process (Damşa, Kirschner, Andriessen, Erkens, & Sins, 2010).

In the K-12 science context, while teachers may guide and scaffold this work, engaging in knowledge-building as a practice means students need to take on part of the intellectual responsibility in developing and managing the work, and not simply follow steps dictated by the teacher (Berland et al., 2016; Ford, 2008; Manz, 2012). Students need to become partners with the teacher in identifying what the class needs to work on (questions, ideas for investigations, and next steps) in order to make progress, and in deciding what they have figured out and what questions or gaps in the explanation need to be resolved.

The Role of Questions and Phenomena in Scientific Knowledge Building

The third part of the argument builds on the idea of agency and draws on the nature of the explanatory knowledge teachers and students are building. Building explanatory knowledge requires deliberate attempts to test, generalize, and refine explanatory models (Passmore et al., 2014). This requires more than finding patterns in data and determining relationships between variables – it requires conceptualizing a question about a phenomenon, figuring out what manipulations of the phenomenon will inform an explanation of how and why it occurs, and evaluating evidence gathered so far to reach consensus and identify gaps (Schwarz et al., 2009). The practice of developing scientific models needs to begin with an explanatory question that arises from phenomena (Gouvea & Passmore, 2017). It requires uncovering what is difficult to explain or problematic about the phenomenon, and focusing what needs to be explained through scientific questions (Reiser, Brody, Novak, Tipton, & Sutherland Adams, 2017). Thus, developing explanations and models does not start with a scientific topic, such as asking students to "explain photosynthesis" or "explain chemical reactions." Explanation and model-building starts with raising questions about phenomena, such as noticing that plants get bigger and asking where the extra mass in the plant comes from. If the identification of questions to guide the knowledge building is simply presented to the students, without involving them in the work of identifying what needs to be explained and connecting to what they know already, they are not truly engaging in the knowledge building process. Thus, this requires the type of co-participation in developing and managing the trajectory of investigation reflective of coherence from the students' perspective.

Elements of Coherence in Storylines

In this section, we overview a framework for supporting coherence from the students' perspective that we are developing in instructional materials designed for NGSS. We have explored this framework in storylines, coherent units in which engagement in science practices is driven by questions arising from phenomena, and teachers and students work as partners in constructing and managing the trajectory of the resulting investigations and sensemaking[2] (Reiser, Fumagalli, Novak, & Shelton, 2016).

We see storylines as supporting a classroom culture that can be characterized by three norms governing the classroom community's engagement in knowledge building:

- We figure out the science ideas.
- We figure out where we are going at each step.
- We figure out how to put the ideas together over time.

In our studies of classrooms, we have identified five key issues that need to be addressed in the design of curriculum materials and in teachers' enactments in order to support students taking on the role of partners in managing investigations. For each of these key issues, we have identified a type of teaching routine or pedagogical pattern that reflects important intellectual and social work in developing and managing investigations (DeBarger, Penuel, Harris, & Schank, 2010). We view these as pedagogical patterns, in that they reflect the important intellectual and social work done during elements of a lesson, but may be realized by a variety of particular activity structures. For example, what is important pedagogically across the routines is that student questions become public and the classroom community periodically reviews them and evaluates which ones they have made progress on, and which questions still need to be addressed. This may be done with a variety of different pedagogical approaches, such as a driving question board (Weizman, Shwartz, & Fortus, 2010), KWL charts, notice and wonder charts, or other types of public representations of student ideas (Windschitl, Thompson, & Braaten, 2008).

1. How do we kick off investigations in a unit?

Investigations begin by engaging with a phenomenon that can raise questions that are worth investigating or problems that need to be solved. An anchoring phenomenon can provide a context for raising questions that can start off a sequence of related investigations for a unit

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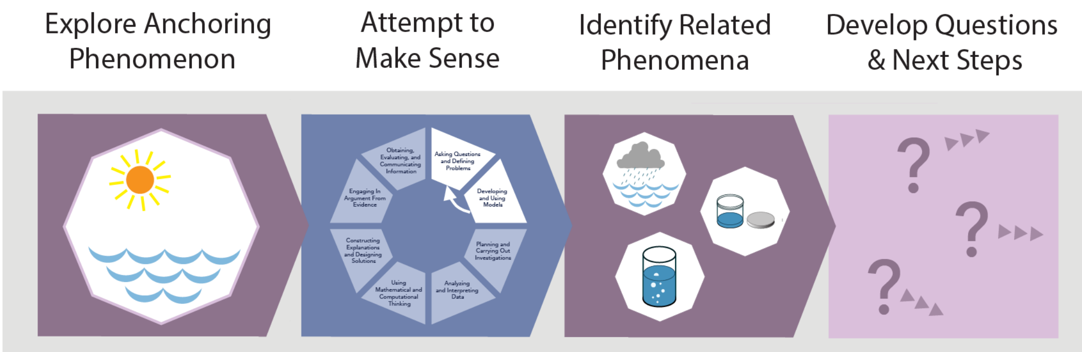
[2] For more information on storylines and to see full unit examples of curriculum materials, see http://www.nextgenstorylines.org/

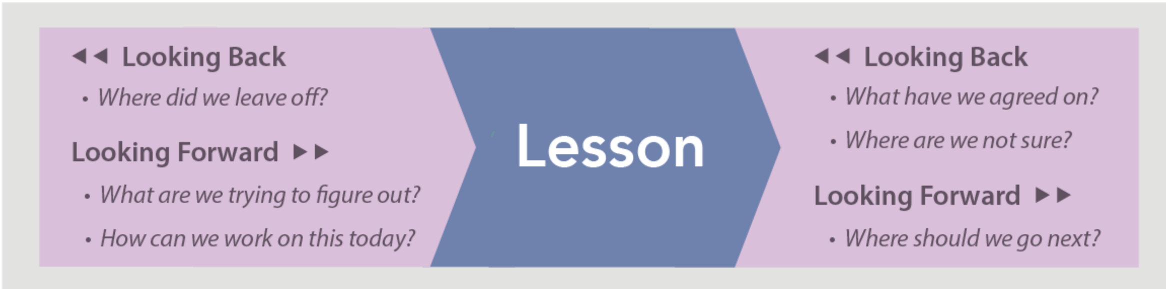
(Thompson et al., 2016; Windschitl et al., 2008). Yet more is needed than simply providing an exciting phenomenon. Other elements of a pedagogical pattern are needed to help students focus on what needs to be explained, often pushing students to get them to realize they cannot actually explain something they take for granted (such as that sound travels from a starting point to one's ears). Thus, pushing students to try to explain the anchoring phenomenon is a key step in helping focus questions. Furthermore, helping students connect the phenomenon to other experiences they have had helps broaden the range of phenomena students consider, and helps connect what they are going to investigate to their own prior experiences. Finally, it is important to have students articulate questions and ideas they have that may help the classroom community to make progress. The following schematic identifies four elements we see as key in curriculum materials and teaching approaches that initiate coherent investigations:



Key Elements of the Anchoring Phenomenon Routine

2. How do we work with students to motivate the next step in an investigation?

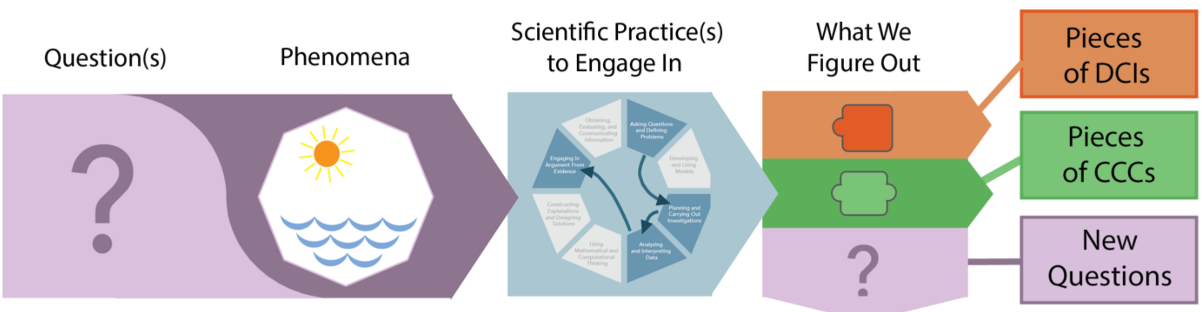
Figuring out next steps is a key element of coherence that reflects student epistemic agency, yet is one that is least likely to occur in many classrooms. Managing the knowledge building involves an ongoing process of figuring out where the classroom community is in its progress, and figuring out where they need to go next. We conceptualize this as an ongoing process of looking forward and looking back. The class looks back to figure out where they left off in the knowledge building, what pending questions exist or what obstacles or disagreements have arisen. Then they look forward to figure out given their progress, what they should work on in today's lesson. At the end of the lesson the class needs to look back and figure out what they have accomplished, and what new issues have emerged, and look forward to where they should go in the next lesson. This ongoing navigation work provides the thread that makes the classrooms' progress a process of building an ongoing "story" rather than going through a series of lessons connected only by a general theme ("we are doing a bunch of experiments about sound").



Key Elements of the Navigation Routine

3. How do we help students use practices to figure out pieces of the science ideas?

Within a lesson, the attention to student coherence relies on linking the practices the classroom community is engaged in to the classroom's identification of "What are we trying to figure out?" Students should be able to see how the practices they engage in will help them make progress on the questions they have identified. Analyzing what they figure out should lead to pieces of the target science ideas (disciplinary core ideas and/or crosscutting concepts) and may also lead to new questions. Coherence is evident when students can say what question they are trying to answer by engaging in the practices, and can tie back the punch lines of the lesson to the work they did using practices to engage with phenomena. We see these elements as key in situating investigations as knowledge building practice:

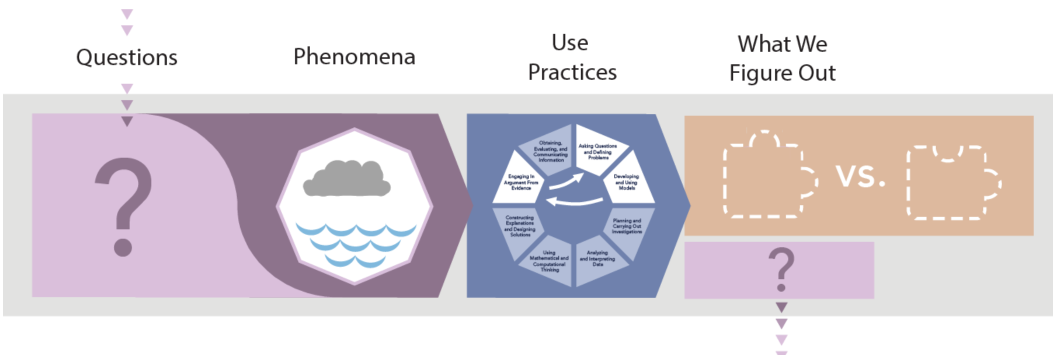


Key Elements of the Investigation Routine

4. How do we push students to go deeper and revise the science ideas we have built together so far?

Progress in knowledge building is not always a steady stream of steps forward. At key points in a unit, after students have made some progress in putting pieces together, the teacher may need to push students to go deeper. A key way to do this may involve problematizing (Reiser, 2004), in which the teacher foregrounds an issue that reveals problems or gaps in the classroom's current understanding. This may occur by cultivating and capitalizing on an emerging disagreement or by bringing in a challenging new phenomenon.

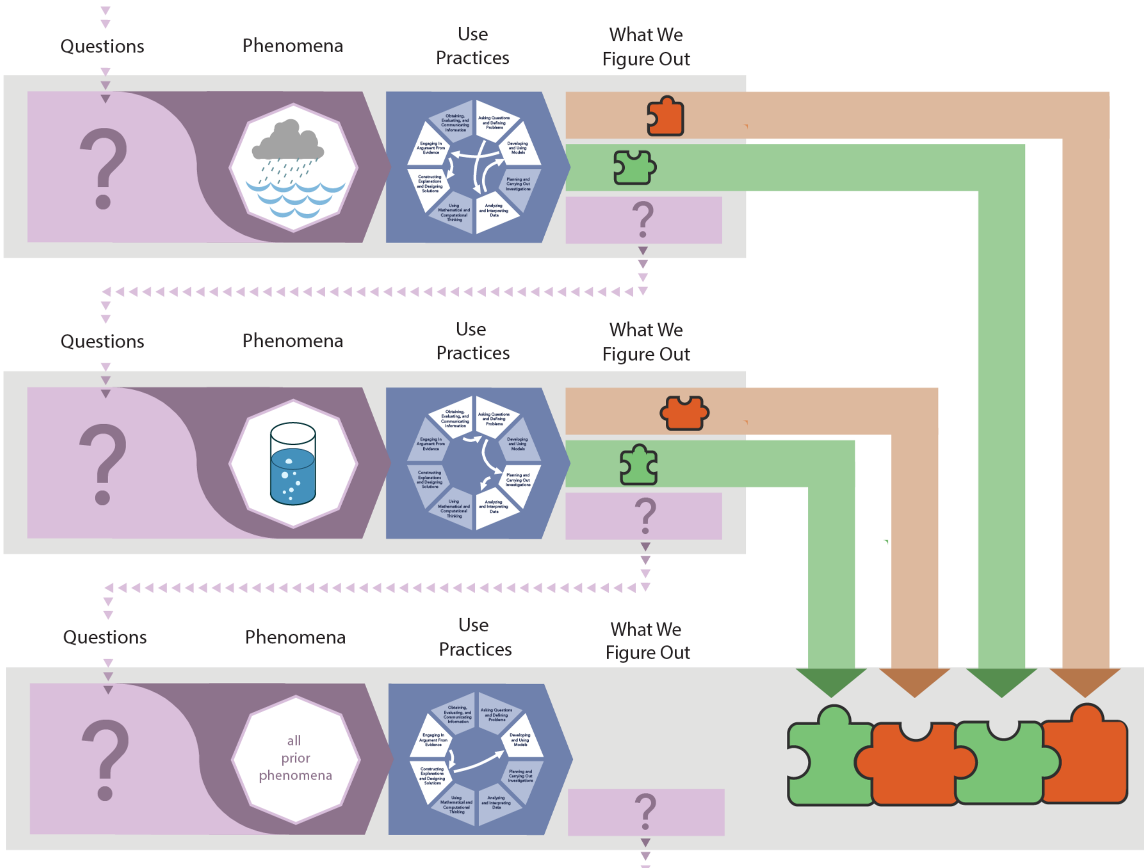
This process may help students then focus on an important question that could refine or extend their model. For example, it may be important to push students to generalize their model beyond the cases they have considered so far. Attempting to push the model to new situations may raise questions. For example, in a middle school sound unit, students explore what can cause sound, and begin that investigation by analyzing the behavior of parts of instruments involved in making sound. They formulate a model that involves applying a force to solid material (such as a drum head, guitar string, or the tine of a tuning fork), which then deforms, bounces back, overshooting its original position, and then again bouncing back, repeating the pattern until it dies out over time. At that point, the teacher either pushes students to think about whether that model can apply to *all* things that make sound when force is applied, such as banging on a table or footsteps down a hallway. This leads students to question and argue about whether all solid objects deform and spring back when they make a sound. Rather than resolve this disagreement, or reassure students that their model will work, the teacher cultivates this disagreement, to get students to think through the alternatives and realize the consequences for their explanatory model, before then guiding them into investigations that help resolve this issue. This type of problematizing may be needed to push students to question and evaluate the adequacy of their current ideas. The key elements are shown here:



Key Elements of the Problematizing Routine

5. How do we help students put together pieces of the disciplinary core ideas and crosscutting concepts?

A key feature of coherence in NGSS is that science ideas need to be built piece by piece. Each new investigation yields another piece of the puzzle, and raises more questions. At key points, students need to be prompted and guided to put the pieces together they have figured out so far. In this type of work, students take the pieces of ideas they have developed across multiple lessons and figure out how to they can be connected together to account for the phenomenon they have been working on. Again this may take a variety of forms, drawing on different pedagogical approaches for helping students keep track of their ideas — science notebooks, public summary charts, etc. The activity might be organized as developing a summary explanation, a consensus model, or a design for a problem. The key is that students pull together the punch lines across lessons, and attempt to collaboratively develop a product (model, explanation, design) that works for the range of phenomena they have encountered so far. A schematic of this routine is shown below.



Key Elements of the Putting Pieces Together Routine

Summary

We have contrasted coherence with simply designing an experiment or analyzing data because this was given as day's goal— that is, "doing school" rather than "doing science" (Jiménez-Aleixandre et al., 2000). We have presented five key questions we suggest are productive for curriculum materials developers to grapple with in order to support coherence from the students' perspective. The particular routines we have suggested are illustrative of approaches we have seen to supporting students as partners in navigating scientific sensemaking. While variations are certainly possible, we have attempted to identify some key elements that need to be addressed by the particular activity structures or pedagogical approaches employed.

References

Berland, L. K., Schwarz, C. V., Krist, C., Kenyon, L., Lo, A. S., & Reiser, B. J. (2016). Epistemologies in practice: Making scientific practices meaningful for students. *Journal of Research in Science Teaching, 53*(7), 1082-1112. doi: 10.1002/tea.21257

Damşa, C. I., Kirschner, P. A., Andriessen, J. E. B., Erkens, G., & Sins, P. H. M. (2010). Shared epistemic agency: An empirical study of an emergent construct. *Journal of the Learning Sciences, 19*(2), 143-186.

DeBarger, A. H., Penuel, W. R., Harris, C. J., & Schank, P. (2010). Teaching routines to enhance collaboration using classroom network technology. In F. Pozzi & D. Persico (Eds.), *Techniques for fostering collaboration in online learning communities: Theoretical and practical perspectives* (pp. 224-244). Hershey, PA: Information Science Reference.

Edelson, D. C. (2001). Learning-for-use: A framework for integrating content and process learning in the design of inquiry activities. *Journal of Research in Science Teaching, 38*(3), 355-385.

Ford, M. J. (2008). Disciplinary authority and accountability in scientific practice and learning. *Science Education, 92*(3), 404-423. doi: 10.1002/sce.20263

Ford, M. J., & Forman, E. A. (2006). Redefining disciplinary learning in classroom contexts. *Review of Research in Education, 30*, 1-32.

Giere, R. N. (1988). *Explaining science: A cognitive approach*. Chicago: Univ. of Chicago Press.

Gouvea, J. S., & Passmore, C. M. (2017). 'Models of' versus 'models for'. *Science and Education, 26*(1-2), 49-63. doi: 10.1007/s11191-017-9884-4

Jiménez-Aleixandre, M. P., Rodríguez, A. B., & Duschl, R. A. (2000). "Doing the lesson" or "doing science": Argument in high school genetics. *Science Education, 84*(3), 757–792.

Kanter, D. E. (2010). Doing the project and learning the content: Designing project-based science curricula for meaningful understanding. *Science Education, 94*(3), 525-551.

Lehrer, R., & Schauble, L. (2006). Scientific thinking and science literacy: Supporting development in learning in contexts. In W. Damon, R. M. Lerner, K. A. Renninger & I. E. Sigel (Eds.), *Handbook of child psychology, 6th ed.* (Vol. 4, pp. 153-196). Hoboken, NJ: John Wiley and Sons.

Manz, E. (2012). Understanding the codevelopment of modeling practice and ecological knowledge. *Science Education, 96*(6), 1071-1105. doi: 10.1002/sce.21030

Manz, E. (2014). Representing student argumentation as functionally emergent from scientific activity. *Review of Educational Research*. doi: 10.3102/0034654314558490

National Research Council. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. Washington, DC: National Academies Press.

NGSS Lead States. (2013). *Next Generation Science Standards: For states, by states*. Washington, DC: The National Academies Press.

Osborne, J. F. (2014). Teaching scientific practices: Meeting the challenge of change. *Journal of Science Teacher Education, 25*(2), 177–196. doi: 10.1007/s10972-014-9384-1

Passmore, C. M., Gouvea, J. S., & Giere, R. (2014). Models in science and in learning science: Focusing scientific practice on sense-making. In M. R. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 1171-1202): Springer Netherlands.

Reiser, B. J. (2004). Scaffolding complex learning: The mechanisms of structuring and problematizing student work. *The Journal of the Learning Sciences, 13*(3), 273-304.

Reiser, B. J., Brody, L., Novak, M., Tipton, K., & Sutherland Adams, L. M. (2017). Asking questions. In C. V. Schwarz, C. M. Passmore & B. J. Reiser (Eds.), *Helping students make sense of the world through next generation science and engineering practices* (pp. 87-134). Arlington, VA: NSTA Press.

Reiser, B. J., Fumagalli, M., Novak, M., & Shelton, T. (2016). *Using storylines to design or adapt curriculum and instruction to make it three-dimensional*. Paper presented at the NSTA National Conference On Science Education, Nashville, TN. https://www.academia.edu/24083676/Using_Storylines_to_Design_or_Adapt_Curriculum_and_Instruction_to_Make_It_Three-Dimensional see also http://www.nextgenstorylines.org/

Schmidt, W. H., McKnight, C. C., & Raizen, S. A. (Eds.). (1997). *A splintered vision: An investigation of U.S. Science and mathematics education*. Bostson: Kluwer.

Schwarz, C. V., Passmore, C. M., & Reiser, B. J. (2017). Moving beyond "knowing" science to making sense of the world. In C. V. Schwarz, C. M. Passmore & B. J. Reiser (Eds.), *Helping students make sense of the world through next generation science and engineering practices* (pp. 3-21). Arlington, VA: NSTA Press.

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Acher, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. S. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632-654. doi: 10.1002/tea.20311

Stroupe, D. (2014). Examining classroom science practice communities: How teachers and students negotiate epistemic agency and learn science-as-practice. *Science Education, 98*(3), 487-516. doi: 10.1002/sce.21112

Thompson, J., Hagnah, S., Kang, H., Stroupe, D., Braaten, M., Colley, C., & Windschitl, M. (2016). Rigor and responsiveness in classroom activity. *The Teachers College Record*, 1-29.

Weizman, A., Shwartz, Y., & Fortus, D. (2010). Developing students' sense of purpose with a driving question board. In R. E. Yager (Ed.), *Exemplary science for resolving societal challenges* (pp. 110-130). Arlington, VA: NSTA Press.

Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education, 92*(5), 941-967. doi: 10.1002/sce.20259