This is the accepted version of

Sikorski, T.R. & Hammer, D. (2017). Looking for coherence in science curriculum. *Science Education*. 101, 929-943.

The published version is available at https://onlinelibrary.wiley.com/doi/10.1002/sce.21299

Looking for Coherence in Science Curriculum

Tiffany-Rose Sikorski
Department of Curriculum and Pedagogy, The George Washington University, 2134 G Street, Washington, DC 20052, USA

David Hammer
Departments of Education and Physics & Astronomy, Tufts University, Medford, MA 02155, USA

Abstract

Despite myriad attempts over the years to design curricula with logical ordering and connections, concerns persist that students view science as a body of prescribed information to memorize. In this essay, we argue that attempts to build coherence into the curriculum reflect fundamental and enduring misconceptions about the nature of coherence itself. Using examples of prominent curriculum projects over the past decade, we argue that *premeditated coherence*, the kind of coherence that is planned and designed for students, may inhibit students' learning to seek coherence for themselves. We conclude with an approach to curriculum and assessment that emphasizes students' epistemic agency in seeking coherence.

Introduction

Reacting to reports that mainstream instruction leaves students viewing science as an assortment of disconnected facts (Lerner, 2000; Budiansky, 2001; Gulyaev & Stonyer, 2002; Liu, Lee, & Linn, 2010), authors of *A Framework for K-12 Science Education* (NRC, 2012) and *Next Generation Science Standards* (NGSS Lead States, 2013) outlined a vision for coherence in US science education. That vision includes standards that explicitly link concepts, practices, and crosscutting concepts; storylines and progressions that describe how students get better at doing science over time; and guidelines for aligning science curriculum, professional development, and assessments. Though signs of positive change exist, much K-12 science instruction still consists of reviewing facts and explanations (National Academies of Sciences, Engineering, and Medicine, 2015). Two years post release of NGSS, only 24% of US 4th grade teachers and 21% of 8th grade teachers report emphasizing scientific investigation in at least half of their lessons (Martin, Mullis, Foy, & Hooper, 2016). Instead, students label the parts of the cell, draw the types of geologic faults, calculate energy required for phase changes, and so on.

The NGSS and associated documents present *curricular coherence* as the solution to fragmentation in science instruction. The argument for curricular coherence is as follows: for students to construct deep, interconnected understandings of natural phenomena and see a "sense of unity" in science, the curriculum must be carefully sequenced to make those connections clear to students (NRC, 2012, p. 10). Curriculum writers aim to pre-establish coherence, so that concepts, activities, and assessments are organized in a way "that holds together, that makes sense as a whole; and its parts, whatever they are, are unified and connected by that sense of the whole" (Beane, 1995, p. 3). There are a variety of unifying structures for curriculum, including essential questions, problems or projects, big ideas, and content storylines; each approach contains its own rationale for how the various pieces fit together into a coherent whole. Most centrally, designers attend to the sequences of and connections between concepts and topics.

Yet, attempts to achieve cognitive coherence through curricular coherence have demonstrated only limited success (Shwartz, Weizman, Fortus, Krajcik, & Reiser, 2008). Perhaps counterintuitively, the carefully constructed instructional sequences designed by education and science experts do not appear to help students see science as something that makes sense (Finkelstein & Pollock, 2005). And in some instances, even the most carefully designed, research-informed sequences appear to make things worse, leaving students with even less sophisticated attitudes and views about science then when they started (Adams, Perkins, Podolefsy, Dubson, Finklestein & Wieman, 2006; Redish, Steinberg & Saul, 1998). It might be that designers have failed to create optimal sequences; perhaps the problem is in teachers' low-fidelity implementation.

In what follows, we contend that the core problem is the field's conceptualization of coherence as a premeditated property of the curriculum. We present two related lines of argument. First, we argue that treating coherence as a feature of the curriculum obscures and may inhibit students' development of epistemic aims and values of the discipline (Chinn, Buckland, & Samarapugnavan, 2011). Second, we argue that studies which claim to empirically verify the importance of coherence in curriculum have conflated coherence with correctness.

We then offer an alternative conceptualization of coherence as a feature of learners' sense-making. In part, it means to shift attention to how students' ideas and reasoning hang together, particularly when those connections differ from the intended curriculum. More, however, it is to emphasize attention — instructional objectives and pedagogical assessment — toward students' seeking coherence. By this alternative conceptualization, fostering coherence in the science classroom will require opening up space in the curriculum for students' epistemic agency, as well as supporting educators to distinguish coherence from correctness in assessments of student learning. We begin with a brief account of coherence in science curriculum projects, starting with the immediate post-Sputnik era.[1] Then, we introduce two critiques of this line of work.

Approaches to Coherence in Science Curriculum

The use of coherence as a descriptor of curriculum appears at least as early as Abraham Flexner's (1908) critique of higher education. Within science education, many notable curriculum projects from the 1960s onward treat coherence as a property of the curriculum. The Physical Science Study Committee designed for coherence using fundamental principles of science (Finlay, 1960). Harvard Project Physics designed for coherence using a historical storyline of scientific development (Holton, 1969). In the late 1980s and early 1990s, curricular coherence motivated Physics First (Bardeen & Lederman, 2001), the Project 2061 Middle Grades Textbook Evaluation (AAAS, 2002), and the Third International Mathematics and Science Study (TIMSS) Videotape Classroom Study (Stigler, Gonzales, Kawanaka, Knoll & Serrano, 1999). More recently, interest in coherence resurged in the context of developing learning progressions and content storylines for NGSS. Though definitions of coherence have shifted over time, informed in part by deeper appreciation of student ideas and how they can inform instruction, the treatment of coherence as a descriptor of curriculum continues to dominate thinking in science education.

Coherence Rooted in Disciplinary Structure

In *A History of Ideas in Science Education,* DeBoer (1991) characterizes the post-Sputnik era of the 1960s and 1970s marked a shift in science curriculum development. While earlier courses emphasized science as a tool for improving students' everyday lives, post-Sputnik era science courses "focused on the logical structure of the disciplines and on the processes of science" (DeBoer, 1991, p. 160). In Schwab's (1962) view, science underwent an important transition from simply "seeking facts of nature and accurately reporting them" to the development of "conceptual structures which could be revised when necessary, in directions dictated by large complexes of theory, diverse bodies of data, and numerous criteria of progress in science" (p. 197-198). Instruction, Schwab argued, should engage students in the conceptual and syntactic structure of science, so that students can appreciate the coherence of scientific knowledge. Jerome Bruner also advocated for a disciplinary structure approach. According to Bruner, "Grasping the structure of a subject is understanding it in a way that permits many other things to be related to it meaningfully. To learn structure, in short, is to learn how things are related" (Bruner, 1960, p. 7 as cited in DeBoer, 1991, p. 160).

Two major curriculum projects of the era—The Physical Science Curriculum Study (PSSC) and the Biological Sciences Curriculum Study (BSCS)—interpreted the idea of disciplinary structure to mean that coherence must be built into curriculum via carefully sequenced topics and activities. According to DeBoer (1991), members of the Biological Sciences Curriculum Study (BSCS) were concerned that "biology was not being presented as a coherent, integrated conceptual whole but rather as unconnected fragments, bits and pieces that could be learned without developing a sense of the relationships between groups of concepts" (p. 150). The committee developed sequences investigations designed to introduced concepts, and relationships between those concepts, in a predefined logical order. Likewise, the PSSC physics course, which comprised a series of laboratories focused on particular concepts, aimed first and foremost "to present physics as a coherent set of related concepts as they had developed over the years" (p. 148).

Coherence and Conceptual Change Research

The emphasis on the structure of the discipline in the post-Sputnik era of curriculum reform led to further examination of how students learn scientific concepts. From the 1960s to the early 1990s, researchers documented discrepancies between students' and experts' conceptions (e.g. Chi, Feltovich, & Glaser, 1981; Driver, 1985), proposed various models for how students advance from initial to more expert-like understanding of concepts (e.g. Posner, Strike, Hewson, & Gertzog, 1982; Carey, 1986; Ranney & Thagard, 1988; Gelman & Wellman, 1991) and created curriculum and instructional approaches to bring students toward "coherent" mental models and explanations of phenomena (e.g. Smith, Blakeslee, Anderson, 1993). Thus, in the context of conceptual change research, coherence was treated simultaneously as inherent property of scientific knowledge, a desired property of students' knowledge, and a feature of well-designed curriculum.

Of particular relevance for the present discussion of coherence, conceptual change research explicitly investigated causal links between the organization of a curriculum and the organization of students' ideas, i.e. linking curricular coherence to conceptual coherence. DeBoer (1991) describes competing modes of thought on the issue:

> A distinction could be drawn between those who felt that the best way to develop conceptual understanding was by means of carefully organizing instruction that was presented directly to students and those who felt that students acquired a mastery of science content, at least in part, through direct and independent interaction with the materials of science themselves. (p. 201)

In refining the notion of curriculum coherence, the central question for science education research was whether optimal sequences should consist primarily of carefully organized lectures about concepts in science, or a series of investigations and laboratories through which these concepts could be deduced. In refining the notion of conceptual coherence, debates centered on whether it was appropriate to treat learner knowledge and reasoning as coherent. Both sides of the well-known "intuitive theory" vs. "knowledge-in-pieces" debate used coherence in describing the structure of student knowledge (for review, see DiSessa, Gillespie, & Esterly, 2004). Proponents of the intuitive theory of knowledge held that "children's intuitive knowledge can be conceptualized as consisting of a *coherent* and systematic set of ideas which deserve to be called a theory" (Vosniadou & Brewer, 1992, p. 537; *emphasis added*). Knowledge-in-pieces models, on the other hand, theorized that knowledge consists of small bits (p-prims, resources, etc.). Learners create explanations for phenomena dynamically through "locally *coherent* activations of resources" (Hammer, Elby, Scherr, & Redish, 2005, p. 94; *emphasis added*). Both views acknowledge that students must play an active role in their learning, i.e. students must *seek coherence*. But, implications for curriculum design differ:

> …the 'fragmented' view suggests extended collection and organization of elements along the path to expertise, and it has much more room for individual variation. In contrast, the "coherent" view suggests that debate and rational argument among a few alternatives might be effective. (DiSessa, Gillespie, & Esterly, 2004, p. 846)

Historically, proponents of intuitive theory-like models of student thinking emphasize coherence as a static property of curriculum, whereas proponents of knowledge-in-pieces models emphasize coherence as a dynamic property of student sense-making.

Curriculum Mapping and Textbook Analysis

The late 1990s and early 2000s popularized the treatment of coherence as a characteristic of curriculum materials and course sequences. In their 2001 article *Coherence in Science Education*, Margaret Bardeen and Leon Lederman advocated for large-scale restructuring of high school science course sequence under what became known as the Physics First movement. At the time, the typical course sequence for high school began with biology, followed by chemistry, and finally physics. Bardeen and Lederman argued that the sequence ought to be reversed to better represent the "rational order" of science, to begin with physics, the most fundamental science, followed by chemistry and finally the complex world of biology. The Physics First sequence, according to Bardeen and Lederman, would "ensure that a scientific way of thinking is instilled in all high school students" (p. 179). Their argument presumes that coherence lives in the sequences of topics in a curriculum, and, that student thinking mirrors the logical sequence of the curriculum (or lack thereof).

Meanwhile, from 1995 to 1998, Project 2061's analyses showed that science textbooks contained too many topics, two few connections between these topics, and many irrelevant activities. Textbooks reviewed in the study scored especially low on the criterion of coherence, defined in the study as connections "(1) among the key ideas, (2) between the key ideas and their prerequisites, and (3) between the key ideas and other, related ideas" (AAAS, 2002). For example, the coherence assessment of the text *Prentice Hall Exploring Physical Science* notes:

> The material makes some conceptual connections among ideas; however, the connections are often implicit, brief, and difficult to locate. For example, on page 215s, an opportunity is missed to connect chemical reactions explicitly to the constant motion of molecules. Later, though, the idea that increased temperature means increased molecular motion is connected explicitly (and adequately) to the fact that an increase in temperature generally increases the rate of reaction (AAAS, 2002, p. 217s).

Like Physics First, Project 2061 began with the notion that coherence is a feature of curriculum, but Project 2061 went a step further to operationalize and quantify that notion for a single science course. Moving to an even finer grain size, the 1999 TIMSS study explored the coherence of individual science lessons from eighth grade classrooms around the world. The analysis operationalized coherence to mean:

> (1) whether the pattern of content development focused on making connections or acquiring facts, definitions, and algorithms, (2) whether strong conceptual links were made among science ideas in the lesson, and (3) whether goal and summary statements were used to clarify the content organization of the lesson. (Roth et al., 2006, p. 64)

Teachers in the U.S. showed skill in creating engaging lesson activities, according to TIMSS findings, but they "did not typically use these various activities to support the development of content ideas in ways that were coherent and challenging for students." Instead, US science lessons were commonly organized "as a collection of discrete facts, definitions, and algorithms rather than as a connected set of ideas" (Roth & Garnier, 2006/2007, p. 20).

In suggesting a new "path to coherence" for science education, the National Academy of Education Working Group on Science and Mathematics Education recommended the design of new curriculum, assessments, and teacher development that provide "intellectually coherent instructional sequences in each field" (Kilpatrick & Quinn, 2009, p. 4). Curriculum developers went in search of optimal "storylines" (Roth & Garnier, 2006/2007) for various science topics, informed by *Project 2061's Atlas of Science Literacy* (AAAS, 2001/2007), research on student "misconceptions" and conceptual change, and their own perceptions of the organization of scientific knowledge.

Learning Progressions and Content Storylines in the NGSS Era

More recently, the treatment of coherence as a feature of curriculum has re-emerged in the context of research and curriculum development in the context of NGSS. Pre-NGSS, curriculum maps were designed to reflect the mappers' understanding of how concepts in a discipline build on one another and/or confront students "misconceptions." While these methods were not altogether abandoned, learning progressions developers aimed to use research on how students ideas evolve in response to instruction to create "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time" (NRC, 2007, p. 214). Rather than treat coherence strictly as a matter of concepts and the relationships between them, learning progressions treat coherence as dependent on students' prior knowledge and experience – what is coherent to students may be different from what is coherent to scientists. Thus, curriculum designers must consider when and how students' understandings progress (NRC, 2012).

NGSS attempts to establish coherence in at least three ways: (1) through the crosscutting concepts, (2) through the integration of the three dimensions of the standards—disciplinary core ideas, science and engineering practices, and crosscutting concepts—into performance expectations, and (3) through the organization of disciplinary core ideas into content storylines. Unlike the disciplinary storylines of the immediate post-Sputnik era, NGSS-aligned content storylines chart students' expected progress toward accepted scientific ideas *while taking into consideration* the ideas students bring to the sequence from their everyday and prior schooling. Yet, coherence continues to be treated as a feature of the curriculum. According to Pruitt (2014):

> For the NGSS to be successfully implemented, instruction must be designed as a full instructional plan as opposed to a series of lessons. Attempting to teach the NGSS from day to day will negate coherence. A set of PEs [performance expectations] that provide students with coherent connections among the concepts represented within and across disciplines should be the beginning point of the instructional plan. This set of standards is referred to as a bundle. There are several methods for bundling standards. (p. 150-151)

One of the best examples of NGSS-aligned curricula is the 6th-8th grade IQWST[2] curriculum (Krajcik, Reiser, Sutherland, & Fortus, 2012). In two independent reviews, IQWST scored higher than comparable curriculum on the EQUiP rubric, a tool used to measure alignment with NGSS (Roseman, Fortus, Krajcik, & Reiser, 2015). IQWST consists of 12 units, during which students revisit the concept in physical, earth, and biological science contexts, with coherence as a design principle within and across units:

> IQWST addresses the challenges of building coherent curriculum by carefully analyzing learning goals, selecting relevant and motivating contexts for learning these ideas, engaging students in a variety of practices in a manner that becomes progressively more demanding and less scaffolded, and sequences ideas across units and disciplines. (Shwartz, Weizman, Fortus, Krajcik, & Reiser, 2008, p. 201)

IQWST aims for students to "build coherent understanding of both science content and practices in an inquiry-driven context" (p. 201). For example, the 7th grade energy unit begins with a driving question and anchoring activity, followed by a series of investigations to encourage students' conceptions of energy to "become more integrated and organized around the idea of transformation" (Nordine, Krajcik, & Fortus, 2010, p. 675). In contrast to course sequences based on hierarchical analysis of the topic, the IQWST energy unit takes into account common student ideas about energy, and it assumes conceptual restructuring model of learning, in which students' ideas are expected to evolve non-linearly as students try to incorporate new ideas into their intuitive understandings. The treatment of coherence as a design feature of curriculum is a key reason why the IQWST curriculum scores so highly on the EQUiP rubric. According to the rubric, unit coherence means "i. Each lesson links to previous lessons and provides a need to engage in the current lesson" and "ii. The lessons help students develop proficiency on a targeted set of performance expectations" (EQUiP, 2016).

As evidenced by language in the EQUiP rubric and IQWST curriculum, the notion that coherence lives in the curriculum continues to drive curriculum development in the era of NGSS. The goal is to find optimal storylines to design into curricula, now guided by research on learning as well as analysis of the structure of the discipline. The strategy for developing learning progressions continues to be designing sequences of activities and investigations that introduce concepts in a particular order, to move students through a series of stepping stones to the "upper anchor" or target performance expectation. It was in the context of our own work on developing learning progressions for inquiry in the context of energy[3] that we began to articulate two lines of argument against the treatment of coherence as living in the sequence of activities and topics of these storylines.

The first argument, the *disciplinary aims and practices of science* argument, holds that in trying to build curricular sequences that unfold coherently *for* students, we risk undermining students' active role in seeking coherence, and thus their substantive engagement in the discipline. The second argument is the *evidence* argument. Valid assessments of coherence are elusive, as researchers struggle to account for the perspective-dependent and scale-dependent nature of coherence. Further, coherence is routinely conflated with canonical correctness, casting doubt upon the oft-cited claim that curricular coherence is "the most dominant predictive factor of student performance" (Fortus & Krajcik, 2012, p. 783). We illustrate these arguments in the context of NGSS curriculum development and assessment.

The Disciplinary Aims and Practices Argument

Historians and philosophers of science debate the role of coherence within the scientific enterprise. Yet, there is agreement that coherence is an important criterion in scientific justification and explanation (Thagard, 2007). In that vein, we distinguish *coherence,* used as a descriptor of an explanation, argument, or body of knowledge, from *coherence seeking*, the ongoing process of "trying to build meaningful, mutually consistent relationships between information" (Sikorski, 2012, p. 153).

In the former and more familiar sense, coherence refers to the interconnectedness and consistency of the principles, theories, explanations, and evidence in science, i.e. explanatory coherence (Thagard, 1989). Used in this way, coherence describes the conceptual content that students are to learn, and applies at multiple scales. At one scale, educators may be concerned with how students reconcile Newton's Third Law with their everyday experiences (Ranney & Thagard, 1988), how students make sense of the shape of the earth given contradictory observations (Vosniadou & Brewer, 1993), or how students integrate natural selection into their explanations of species variation (Sandoval, 2003). On a larger scale, the *Framework* identifies seven crosscutting concepts that, from the committee's perspective, provide an "organizational framework for connecting knowledge from the various disciplines into a *coherent* and scientifically based view of the world" (NRC, 2012, p. 83; *emphasis added*). For example, the principle of conservation of energy brings coherence to scientific knowledge because it can be applied across domains. It is this familiar treatment of coherence as the interconnectedness of scientific knowledge that influences much of the work on curriculum coherence, whereby the curriculum possesses a sort of narrative coherence, "an unfolding story" that helps children "connect the bits and pieces to larger concepts" (Tyson, 1997 as cited in AAAS, 2001, p. 238).

In the latter and perhaps less familiar sense, coherence is an epistemic criterion that guides the ongoing process of sense-making in science, i.e. scientists *seek coherence*. According to the *Framework:*

> …the aim of science is to *find* a single coherent and comprehensive theory[4] for a range of related phenomena. Multiple competing explanations are regarded as unsatisfactory and, if possible, the contradictions they contain must be resolved through more data, which enable either the selection of the best available explanation or the development of a new and more comprehensive theory for the phenomena in question. (NRC, 2012, p. 48, *emphasis added*)

Seeking coherence can involve checking for consistency and non-contradiction (Meheus, 2002), addressing anomalies (Chinn & Brewer, 1993), evaluating the scope of an explanation (Brody, 1993), building various kinds of connections and relationships between ideas (Gentner & Jeziorski, 1989; Machamer, Darden, & Craver, 2000), identifying gaps in knowledge and explanations, deepening mechanism (Thagard, 2007), and more. The search for coherence occurs within all of the disciplinary practices of science identified in NGSS, but perhaps most explicitly within *constructing explanations* and *engaging in argument from evidence* (Sandoval, 2003).

A strength of the NGSS is that conceptual content and practices are explicitly linked. But, curriculum development continues to be guided by the notion of coherence as a relationship between concepts, rather than as part of the scientific pursuit. In the revised IQWST energy unit, for example, the teacher's guide contains a section called "building coherence" for each lesson which describes the logic behind the sequencing of activities. The Lesson 3 building coherence section states:

> Students revisit the falling cans (Lesson 2) and a pendulum (Lesson 1) to learn about gravitational energy. This lesson introduces the concept of energy conversation (energy can be converted from one type to another) and a new type of model that will be used throughout the unit (energy conversion diagram). This lesson is key to the Driving Question's subquestion, "What determines how fast or how high an object will go?" (Fortus et al., 2012, p. 37)

In this description, coherence is treated as existing in the sequence of topics and concepts that are introduced to students. Examples of gravitational energy come first, followed by examples of conservation of energy, followed by a tool for keeping track of energy conversions. Missing in this "building coherence" is any discussion of students' coherence seeking.

To be clear, the IQWST developers and the broader science education research community recognize that coherence is something to be sought and established *by students*. The IQWST designers acknowledge "in order for students to activate, reorganize, and make links to their existing ideas, they must think analytically about familiar phenomena…" (Nordine, Krajcik, & Fortus, 2010, p. 675). However, the community, including the IQWST group, persists in talking about curriculum as the agent that makes connections:

> To build integrated understandings, instruction must be built from coherent curriculum. To be coherent, curriculum must align with learning goals based on a set of core scientific ideas while avoiding nonessential information, make connections between new ideas and prior knowledge explicit, connect evidence to scientific ideas, and connect the ideas of science to the natural world. (Nordine, Krajcik, & Fortus, 2010, p. 675)

The distinction between who (or what) makes connections is not merely semantic. We examined four prominent examples of sequences for energy—Conceptual Physics (Hewitt, 2015), FOSS (Lawrence Hall of Science, 1998-2016), Project 2061, and IQWST—and each refer to their curriculum as "making" connections. Curriculum can present certain inconsistencies for students to resolve, or it can draw students' attention to particular connections between ideas. Curriculum could also, we propose, support students' inclination to search for meaningful, mutually consistent relationships between information—to help students see science as the pursuit of such relationships. But in no case can curriculum make connections for students.

Moving beyond semantics, curriculum can support, or inhibit, students' coherence seeking. We have discussed the possibility of "narrative seduction", namely that in the midst of pre-scripted curriculum, students will "find the storyline so compelling that they do not check it themselves for plausibility or consistency" (Hammer & Sikorski, 2015, p. 428). This sort of undermining of students' coherence seeking happens quietly and could be hard to detect, a point we discuss in the next section. A more violent undermining of students' coherence seeking can occur when the connections students are trying to make fall outside the pre-scripted sequence. The IQWST designers allude to this real classroom challenge:

> A major design tension arises from the need to coherently organize pre-specified learning goals and in parallel remain faithful to the content and contextualization dictated by the driving question…Real-world problems can easily branch out and lead students to seek knowledge that is not included in the learning goals. (Shwartz et al., 2008, p. 12)

Sequences that attempt to guide students through a series of investigations to arrive at the canonically accepted (and "coherent") explanation may do so at the risk of students' own agency in deciding what coherences to seek next. In related work, IQWST developers have made the case that learning the practices means learning when and how to engage in these practices and for what purposes. Schwarz et al. (2009) note:

> Scientists create a model to help their own thinking and share their ideas with peers to test whether they are convincing in the professional community. In the case of our classroom materials, students are typically told when to create models, and their utility, if apparent, needs to emerge as they are used in their subsequent work…While students saw the point of making partial answers more complete or more correct, as with constructing models, the class was always told to revise their models. This effectively took the decisions about when their models were sufficient and when they need to be revised out of the students' hands. (p. 652)

The IQWST is notable in that students' models for scientific phenomena become more aligned with the canonically accepted models as a result of instruction. But, without careful cultivation of the disciplinary aims of modeling, students will be left treating modelling as just another "science answer." Schwartz et al. suggest building moments of need and choice into the sequence, whereby students must choose between competing models or decide how to address gaps in their models. While such activities may seem superfluous, tangential, or even incoherent from a disciplinary structure perspective, they are aligned with the real challenges scientists face as they weigh competing models in search of coherent explanations.

Any form of curriculum faces the challenge of how to respond to students' myriad and sometimes unexpected ideas and lines of inquiry. Our concern here is the disciplinary substance that guides decisions for how to respond to those ideas. That design tension Shwartz et al. (2008) will recur as tension for teachers, when they will have to choose between taking up students' spontaneous seeking of connections and searches for consistency, i.e. their substantive disciplinary engagement, or keeping class in line with the curriculum. That developers and school systems explicitly value "high fidelity" implementation makes it all the more difficult for teachers to follow students' coherence seeking.

The Evidence Argument

Our second argument against viewing coherence as existing in the relationships between topics and activities in a curriculum grows from the weak evidence that such an approach positively impacts student learning. Evidence is weak in part because of the science education community's failure to clarify what it means to "view science as more than disconnected facts." Further, the studies that claim to show that curricular coherence matters for student learning utilize assessments that conflate correctness with coherence.

Calls for curricular coherence stem from the desire to help students see science as more than just "disconnected facts." Such a general statement contains at least three distinct goals for student learning. The first goal is conceptual—to help students integrate their scientific knowledge into conceptually coherent frameworks. A second goal is metacognitive and epistemological—to help students see meaning, value, and a "sense of unity" in their science learning experiences (NRC, 2012, p. 10). The C-LASS, for example, asks students to rank their agreement with statements like "I think about the physics I experience in everyday life" and "Knowledge in physics consists of many disconnected topics" (Adams et al., 2006). These questions do not gauge the coherence of students' knowledge, but do ask students how they feel about science and science learning. A third goal is dispositional—to help students develop the "inclination" to seek connections between information (Roseman, Linn, & Koppal, 2008, p. 13).

Evidence for the success of coherent curriculum overwhelmingly relies on evidence from the first category, conceptual understanding. For example, claims that IQWST's inter-unit coherence supports students' learning arises in part from students' responses to questions such as the following: "A table is made from wood. The wood comes from a tree. Where did the tree originally get the *energy* to make the wood? (1) From sunlight (2) From water (3) From carbon dioxide (4) From soil." [5] The question assesses vocabulary understanding and, to a degree, conceptual understanding. It is a check for alignment with the canon, not coherence. Nor, certainly, can the question assess students' inclination or ways of seeking connections between ideas.

The IQWST team also conducted clinical interviews and gathered written feedback from students. In one interview, a student is shown an image of an electric heater and responds:

> It has electrical energy, chemical energy, heat energy, light energy, uh, because it starts with chemical energy in the power source and that changes into electrical energy which then goes to the heater and is transformed into heat energy and light energy. (Nordine, Krajcik, & Fortus, 2010, p. 682)

The excerpt is presented as evidence that the student identifies and relates the different types of energy involved in the operation of the electric heater, and further that the student "has the ability to connect between ideas and to make sense of everyday scenarios" (p. 682). But the student's response could easily be a script; evidence lacks that the student is seeking anything other than the correct terms to apply to the situation. Another interview with a battery, bulb, and switch prompt is similar:

> Allen: The electrical and I suppose some of the chemical energy in the filament is transferred over to the same amount of energy in light and heat.
>
> Interviewer: You mention "the same amount of energy." Why is that the same amount?
>
> Allen: Energy is never created or destroyed, it is only reassembled, I guess, in the equation. It's an equation, it's equal, like, that's the definition. It also works to a certain extent with mass. (p. 686)

Allen's interviews are presented as evidence of the positive impact of the IQWST curriculum on student learning. Based on the data provided, students who participate in IWQST are better able to talk about everyday phenomena using language of the canon. But these interviews provide mixed signals when it comes to how students are approaching science. When probed to explain why the energy is the same, Allen begins with what sounds like a recitation, "energy is never created or destroyed," and then refers — with a hedge "I guess" — to "the equation" and "that's the definition." He adds that "it also works to a certain extent with mass," probably a reference to the conservation of mass, including another hedge, "to a certain extent" he does not elaborate.

Likewise, Schmidt, Wang, and McKnight (2005) used findings from the 1995 TIMSS to determine the correlation between the coherence of content standards and student learning. The team defined "content standards, in the aggregate, to be coherent if they are articulated over time as a sequence of topics and performances consistent with the logical and, if appropriate, hierarchical nature of the disciplinary content from which the subject-matter derives" (p. 528). Countries in the TIMSS study were assigned a grade based on the perceived coherence of their district, state, and national science content standards. These grades correlated with TIMSS scores, leading to the oft-cited claim "that coherence is one of the most critical, if not the single most important, defining elements of high-quality standards" (Schmidt, Wang, & McKnight, 2005, p. 554; Schmidt & Houang, 2012).

Other work has critiqued the validity of the TIMSS for assessing students' scientific understandings (see for example Harlow & Jones, 2004). Here, we restrict our analysis to the extent to which TIMSS assesses the goals that science educators claim to value when they build coherence into the curricula. For example, one released TIMSS 1999 Grade 8 energy item asks students:

> Chemical energy ➔ Heat energy ➔ Mechanical Energy (with wasted heat)
>
> The sequence of energy changes shown in the diagram explains which event?
>
> A. A flashlight is on.
>
> B. A candle burns.
>
> C. Gasoline burns to power a car.
>
> D. Electric current runs a refrigerator.[6]

Students' ability to answer this question may indicate their ability to apply the definitions they have learned about each kind of energy and map it to an everyday scenario. However, the question does not provide any evidence in the way of the three goals stated at the outset of this section: deep conceptual understanding, the inclination and to seek connections between information, to see meaning, value, and a "sense of unity", in their science learning experiences (NRC, 2012, p. 10).

The open-ended TIMSS questions, which include samples of student responses, raise further concerns. One question asks, "When a nail is pulled out of a wooden board, the nail becomes warm. Explain why." Two sample student responses have been released publicly, "The nail becomes warm because of the energy that was in it as it was pulled out" (labelled correct) and "Because the inside of the board is warmer than it is on the outside" (labelled incorrect).[7] The first student's answer applies the word *energy* to the phenomenon, but nothing more that could be called "correct." It is, indeed, difficult to follow the reasoning: How does the energy come to be in the nail? The response exemplifies Feynman's concern about energy instruction:

> Look at it this way. That's only the definition of energy. It should be reversed. We might say when something can move that it has energy in it, but not "what makes it move is energy." This is a very subtle difference…I finally figured out a way to test whether you have taught an idea or you have only taught a definition. Test it this way: You say, "Without using the new word which you have just learned, try to rephrase what you have just learned in your own language." (Feynman, 1969)

The incorrect answer does use everyday language, and it expresses reasoning we can follow, that the nail is warm because the wood is warm.

If the student responses presented here are representative, there are serious reasons to question the persistent use TIMSS scores in making the case for curricular coherence. The conflation of coherence with correctness is also evident in the *Framework* and *NGSS* supporting documents, for example:

> To capture the vision in the Framework, students should be assessed on the extent to which they have achieved a coherent scientific worldview by recognizing similarities among core ideas in science or engineering that may at first seem very different, but are united through crosscutting concepts. (Achieve, 2013, p. 3)

Yet, there is some progress worth noting regarding the third sub-goal: students experiencing a sense of unity in science. The team interviewed students, asking them to compare their experience in the IQWST units to other units they had experienced before. The question is useful because coherence is perspective-dependent, and just because the unit seemed coherent to the designers does not mean the students experienced it that way. Students made statements like: "It was more serious, not jumping between subjects, understanding better" and "In other science units we didn't do experiments and got less homework. We didn't talk so much in class. I feel I understand better, because it explains more than in other units" (Shwartz et al., 2008, p. 207).

These comments are helpful because they reveal something about the student's experience in the curriculum, and also tell us about students' expectations for their science learning. Additional data along these lines, partnered with samples of students' in the moment sense-making, would lead to a more robust case for the impact of curricular sequencing on students' coherence seeking.

Alternative: Treat Coherence as a Dynamic Feature of Learner Sensemaking

If we take seriously the goal of helping students' come to see science as more than disconnected facts, and to see science as about searching for connections and consistency between ideas, then we need to begin treating coherence as something that lives in learner sense-making, sense-making that is undoubtedly shaped by the curriculum but not isomorphic to it. If we want to students to experience a coherent science education — the conceptual interconnectedness of science, the affective sense of unity, and the epistemic inclination to look for new connections and reconcile inconsistencies — then perhaps we need to find ways to open up our storylines so that students can play more active roles in seeking coherence.

Some of the most compelling connections students make are completely unexpected. In an example previously reported (Hammer & Sikorski, 2015), a third grade student worked to defend his idea that balls roll more quickly down shallow ramps by making an analogy to snowballs. On a shallow ramp, he reasoned, the ball “has more time to gather up energy,” just like a snowball. There are multiple reasons to value the analogy to the snowball, not the least of which that in making the analogy, Zachary is exhibiting that inclination to seek connections between ideas, to try to use things he already knows in the world to explain the movement of balls down ramps. In designing a storyline for our energy unit, we would not have thought to include a lesson about comparing balls rolling down ramps to snowballs rolling down hills! But because we designed the unit to be flexible, the teacher had the opportunity to deviate from her anticipated storyline and make room for Zachary’s unexpected and productive ideas.

A curriculum truly supportive of coherence would cultivate students’ own seeking. It would urge students to try to explain phenomena, to share and inspect each other’s ideas for consistency, to develop shared criteria for coherence, and experience the tensions and excitement of finding gaps in ideas and trying to resolve them (Jaber & Hammer, 2016). Rather than move efficiently from concept to concept, investigation to investigation, greater emphasis would be placed on the disciplinary activity of working to identify, articulate, and motivate problems that need solving (Phillips, Watkins, & Hammer, 2016), and in deciding which science practices to bring to bear in working on those problems. For example, the IQWST team has suggested “engineering” moments for students must make choices about how to use the practices:

> …one possibility for helping students understand what aspects of models are important to evaluate would be to engineer situations in which students are working with candidate models from others and having more trouble understanding one model than another. In addition, students might try to use someone else’s model (or their own) to explain an unknown phenomenon, and then unexpectedly uncover limitations in the model. Students might try to use different models to make predictions or develop explanations, and observe tradeoffs in the models’ utility, noticing that one model is more useful in one situation than another. (Schwarz et al., 2009, p. 652)

Surely, we see value in teachers anticipating or even seeding these scenarios. But, in our experience, if students are given generative questions and space to talk about them, they will challenge each other’s models and struggle to understand each other’s ideas. These moments occur spontaneously and do not have to be engineered. The challenge is in recognizing these moments and responding to them in ways that deepen students’ engagement in science. That engagement requires, at least temporarily, deprioritizing the goal of leading students through a sequence of concepts to arrive at a particular model (Manz, 2015). It also requires ongoing attention to what kinds of connections students are *trying* to make.

We work from the assumption that students are always seeking some sort of coherence. Rather than check *if* students are seeking coherence, we ask: What kinds of coherences do students seek? In what ways? To what end(s)? We have observed students seeking linguistic, narrative, and conceptual coherence while trying to explain what makes a bulb light and what happens to puddles that seem to disappear on a hot day. We have also observed teachers using prompts such as “How did we get from talking about Topic A to talking about Topic B?” to gauge how the unit hangs together (or not) from the student’s point of view. Rather than ask students to follow a storyline of a curriculum, they participate in its construction (Sikorski 2015).

If curriculum is viewed as a resource for coherence seeking, rather than the source of coherence itself, then teachers need to be willing, able, and encouraged to deviate from storylines to follow student thinking. To be clear, we are not recommending complete abandonment of storylines. We have good reason to question the quality of learning that occurs in classrooms where biology is about labelling parts of the eye and parts of the cell, where physics is a set of hands on activities followed by some loosely connected problem solving, or where science is reduced to following students' whims unguided. When teachers design storylines for planning purposes, they seek coherence as they make sense of connections between topics, activities, and potential student lines of inquiry (Algren & Kesidou, 1995; Hanuscin et al., 2016). But what we can learn from existing curriculum design movements is that the order of the sequences may not be nearly as important as the teachers' willingness and flexibility to cue and build upon the sense that students are seeking in the moment. The added flexibility for teachers to follow student thinking also eliminates the inherent fragility of carefully sequenced curriculum, which requires that topics be taught in just right order within a unit, an academic year, and across grades for desired learning to occur.

Concluding Remarks

> Too many continue merely to "Stir the Pot" with new efforts to produce teacher-proof curricula and new pathways to achieve the old goals and prescribed curricula. We need more who can practice the visions, logic, and features of science teaching; i.e., science [as] a way of exemplifying science itself." (Yager, 2011, p. 14)

We want students to experience science as a body of knowledge that makes sense, as well how to intentionally search for that kind of sense for themselves. We try to meet these goals by showing students the important connections in science, the way science makes sense to us. Often, these coherences are things that we have the benefit of recognizing after years of instruction and reflection on our teaching. When we present sequences of instruction that will be coherent in these ways, we forget that despite our best efforts, curriculum cannot do the work of sense-making for students. But, if we are not careful, curriculum can send the message to students that science is a set of storylines to follow and memorize.

The perspective on coherence put forth in this paper is not to suggest that the order of activities in a curriculum is meaningless, or that teachers need not put thought into how they order activities. Rather, we argue that the process by which teachers and curriculum designers make those decisions must be reconsidered, so that students, rather than curriculum, are recognized as the agents of coherence seeking, and that their search for coherence is as central a goal for science education as their coming to learn the particular connections that scientists have found important in explaining the natural world.

While conceptual understanding matters, it is not a very good proxy for the sense of coherence and inclination to seek connections. Zachary's snowball analogy for energy seems to challenge the script that as an object rolls downhill, PE transforms to KE with the total energy remaining constant. But, he is seeing the analogy as an appropriate tool for sense-making in science, and he is using the analogy in a way that is consistent with his argument that objects roll faster down shallower ramps. If the designers of highly sequenced instruction wish to argue empirically that their curriculum helps students see science as more than a collection of disconnected facts, they must begin to look closely at students' pursuit of connections—their coherence seeking—rather than focusing solely on students' attainment of particular connections outlined by the sequence and the canon.

Acknowledgements
We thank two anonymous reviewers, Andy Elby, Carla Finkelstein, Mike Hull, Lama Jaber, Eric Kuo, Colleen Nyeggen, Curtis Pyke, Jennifer Richards, Minjung Ryu, Mary E. Short, Jason Yip, the Physics Education Research Group at Florida International University, and members of the Tufts Center for Engineering Education and Outreach for very helpful feedback on the arguments presented in this paper. An early version of this essay was presented at the March 2012 Annual Meeting of the National Association for Research in Science Teaching in Indianapolis, IN. This work was supported in part by a grant from the National Science Foundation, Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy, DRL 0732233. The views expressed are those of the author and not necessarily shared by the Foundation.

Footnotes

[1] A complete history of philosophies, theories, and perspectives on coherence that have influenced science education (e.g. Hume, 1738; Lakoff & Johnson, 1980; Thagard, 1989; Bohm, 1990) is beyond the scope of this work.

[2] See http://create4stem.msu.edu/project/iqwst

[3] National Science Foundation DRL 0732233, Learning Progressions for Scientific Inquiry: A Model Implementation in the Context of Energy.

[4] Some readers may question whether finding "a single coherent and comprehensive theory" really characterizes the aims of modern science. Indeed, scientists respond to inconsistency and contradiction in a variety of ways, including accommodation or even acceptance (Feyerabend, 1975; Chinn & Brewer, 1993; Meheus, 2002). Mitchell (2009) anticipates that the search for single, unified explanations in biological science must give way to integrative pluralism, or the search for multiple explanations to capture the complex and contingent nature of biological phenomena. Coherence seeking, as defined here, does not require that the search always aim toward or result in a single unified explanation.

[5] This problem appears on page 8 of Fortus, Adams, Krajcik, & Reiser (2015).

[6] TIMSS 1999 Assessment. Copyright © 2001 International Association for the Evaluation of Educational Achievement (IEA). Publisher: TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, Chestnut Hill, MA and International Association for the Evaluation of Educational Achievement (IEA), IEA Secretariat, Amsterdam, the Netherlands.

[7] TIMSS 2003 Assessment. Copyright © 2005 International Association for the Evaluation of Educational Achievement (IEA). Publisher: TIMSS & PIRLS International Study Center, Lynch School of Education, Boston College, Chestnut Hill, MA and International Association for the Evaluation of Educational Achievement (IEA), IEA Secretariat, Amsterdam, the Netherlands.

References

(AAAS) American Association for the Advancement of Science. (2001). *Designs for science literacy*. New York, NY: Oxford University Press.

(AAAS) American Academy for the Advancement of Science. (2002). *Middle grades science textbooks: A benchmarks-based evaluation*. Retrieved from http://www.project2061.org/publications/textbook/mgsci/report/content.htm

(AAAS) American Academy for the Advancement of Science. (2001/2007). *Atlas of Science Literacy*. Washington, DC.

Achieve. (2013, April). Appendix G—Crosscutting Concepts. Available from http://www.nextgenscience.org/get-to-know.

Adams, W., Perkins, K., Podolefsky, N., Dubson, M., Finkelstein, N., & Wieman, C. (2006). New instrument for measuring student beliefs about physics and learning physics: The Colorado Learning Attitudes about Science Survey. *Phys. Rev. ST Phys. Educ. Res. 2*, 010101.

Ahlgren, A. & Kesidou, S. (1995). Attempting curriculum coherence in Project 2061. In J. Beane (Ed.), *Toward a Coherent Curriculum* (pp. 44-54). Alexandria, VA: ASCD.

Bardeen, M, & Lederman, L. (1998). Coherence in science education. *Science, 2*, 178-179.

Beane, J. (1995). Introduction: What is a coherent curriculum? In J. Beane (Ed.), *Toward a Coherent Curriculum* (pp. 1-14). Alexandria, VA: ASCD.

Bohm, D. (1990). A new theory of the relationship of mind and matter. *Philosophical Psychology, 3*(2-3), 271-286.

Brody, T. (1993). *The philosophy behind physics*. L. de la Peña & P.E. Hodgson (Eds.). New York, NY: Springer-Verlag.

Budiansky, S. (2001, February). The trouble with textbooks. *Prism*, 24-27.

Carey, S. (1986). Cognitive science and science education. *American Psychologist, 41*(10), 1123.

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive science, 5*(2), 121-152.

Chinn, C. A., & Brewer, W. F. (1993). The role of anomalous data in knowledge acquisition: A theoretical framework and implications for science instruction. *Review of Educational Research, 63*(1), 1-49.

Chinn, C.A., Buckland, L.A., & Samarapungavan, A.L.A. (2011). Expanding the dimensions of epistemic cognition: Arguments from philosophy and psychology. *Educational Psychologist, 46*(3), 141-167.

DeBoer, G. E. (1991). *A history of ideas in science education: Implications for practice*. New York, NY: Teachers College Press.

Driver, R. (1985). *Children's ideas in science.* UK: McGraw-Hill Education.

DiSessa, A., Gillespie, N. M., & Esterly, J. B. (2004). Coherence versus fragmentation in the development of the concept of force. *Cognitive Science, 28*(6), 843-900.

EQUiP. (2016). EQuIP Rubric for Lessons & Units: Science, Version 3.0.

Feynman, R.P. (1969). What is science? *The Physics Teacher, 7*, 313-320. Obtained from http://cw.routledge.com/textbooks/9780415965286/

Finlay, G. C. (1960). Secondary School Physics: The Physical Science Study Committee. *American Journal of Physics, 28*(3), 286-293.

Finkelstein, N. & Pollock, S. J. (2005). Replicating and understanding successful innovations: Implementing tutorials in introductory physics. *Phys. Rev. ST Phys. Educ. Res. 1*, 010101.

Flexner, A. (1908). *The American college: a criticism.* New York, NY: The Century Company.

Fortus, D., Abdel-Kareem, H., Chen, J., Forsyth, B., Grueber, D. J., Nordine, J., & Weizman, A. (2012). Why do some things stop while others keep going? In J. S. Krajcik, B. J. Reiser, L. M. Sutherland, & D. Fortus, (Eds.), *Investigating and questioning our world through science and technology (IQWST).* New York: Sangari Active Science.

Fortus, D. & Krajcik, J. (2012). Curriculum coherence and learning progressions. In B. Fraser, C. McRobbie, & K. Tobin (Eds.), *Second International Handbook of Science Education* (pp. 783-798). Dordrecht: Springer Verlag.

Fortus, D., Sutherland Adams, L. M., Krajcik, J., & Reiser, B. (2015). Assessing the role of curriculum coherence in student learning about energy. *Journal of Research in Science Teaching, 52*(10), 1408-1425.

Gelman, S. A., & Wellman, H. M. (1991). Insides and essences: Early understandings of the non-obvious. *Cognition, 38*(3), 213-244.

Gentner, D., & Jeziorski, M. (1993). The shift from metaphor to analogy in Western science. In A. Ortony (Ed.), *Metaphor and Thought (2nd ed.)* (pp. 447-480). Cambridge, England: Cambridge University Press.

Gulyaev, S.A. & Stonyer, H.R. (2002). Making a map of science: General systems theory as a conceptual framework for tertiary science education. *International Journal of Science Education, 24*(7), 753-769.

Hammer, D., Elby, A., Scherr, R. E., & Redish, E. G. (2005). Resources, framing, and transfer. In J. Mestre (Ed.), *Transfer of Learning from a Modern Multidisciplinary Perspective* (pp. 89-120). Greenwich, CT: Information Age Publishing.

Hammer, D. and Sikorski, T. (2015) Implications of complexity for research on learning progressions. *Science Education, 99*(3) 424-431.

Hanuscin, D., Lipsitz, K., Cisterna-Alburquerque, D., Arnone, K. A., van Garderen, D., de Araujo, Z., & Lee, E. J. (2016). Developing coherent conceptual storylines: Two elementary challenges. *Journal of Science Teacher Education, 27*(4), 393-414.

Harlow, A. & Jones, A. (2004). Why students answer TIMSS science test items the way they do. *Research in Science Education, 34*(2), 221-238.

Hewitt, P. (2015). *Conceptual Physics, 12th Edition*. Pearson Education.

Holton, G. (1969). Harvard Project Physics: A report on its aims and current status. *Physics Education, 4*(1), 19-25.

Hume, D. (1738/2001). *A treatise of human nature*. D. F. Norton & M. J. Norton (Eds.), Oxford: Oxford University Press.

Jaber, L. & Hammer, D. (2016). Engaging in science: A feeling for the discipline. *Journal of the Learning Sciences, 25*(2), 156-202.

Kilpatrick, J., & Quinn, H. (2009). *Science and Mathematics Education. Education Policy White Paper*. Washington, DC: National Academy of Education.

Krajcik, J. S., Reiser, B. J., Sutherland, L.M., & Fortus, D. (Eds.). (2012). *Investigating and questioning our world through science and technology (IQWST).* Greenwich, CT: Sangari Global Education/Active Science.

Lakoff, G., & Johnson, M. (1980). The metaphorical structure of the human conceptual system. *Cognitive Science, 4*(2), 195-208.

Lawrence Hall of Science. (1998-2016). Full-Option Science System (FOSS). Nashua, NH: Delta Education.

Lerner, L. (2000). Good and bad science in US schools. *Nature, 407*, 287-290.

Liu, O.L., Lee, H.S., & Linn, M.S. (2010). Multifaceted assessment of inquiry-based science learning. *Educational Assessment, 15*(2), 69-86.

Machamer, P., Darden, L., & Craver, C. F. (2000). Thinking about mechanisms. *Philosophy of Science*, *67*(1), 1-25.

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

Martin, M. O., Mullis, I. V. S., Foy, P., & Hooper, M. (2016). *TIMSS 2015 International Results in Science: Teachers emphasize scientific investigation.* Retrieved from Boston College, TIMSS & PIRLS International Study Center website: http://timssandpirls.bc.edu/timss2015/international-results/

Meheus, J. (Ed.) (2002). *Inconsistency in science* (Vol. 2). Netherlands: Springer.

Mitchell, S. D. (2009). *Unsimple truths: Science, complexity, and policy*. Chicago, IL: University of Chicago Press.

National Academies of Sciences, Engineering, and Medicine. (2015). Science Teachers' Learning: Enhancing Opportunities, Creating Supportive Contexts. Washington, DC: The National Academies Press.

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

Nordine, J., Krajcik, J., & Fortus, D. (2010). Transforming energy instruction in middle school to support integrated understanding and future learning. *Science Education, 95*(4), 670-699.

(NRC). National Research Council. (2007). *Taking Science to School: Learning and Teaching Science in Grades K-8*. Washington, DC: The National Academies Press.

(NRC) National Research Council. (2012). *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*. Washington, DC: The National Academies Press.

Phillips, A., Watkins, J., & Hammer, D. (2016, July). *Articulating problems*. Symposium talk presented at the Physics Education Research Conference, Sacramento, CA.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211-227.

Pruitt, S. (2014). The Next Generation Science Standards: The features and challenges. *Journal of Science Teacher Education, 25*(2), 145-156.

Ranney, M., & Thagard, P. (1988). Explanatory coherence and belief revision in naive physics (No. UPITT/LRDC/ONR/APS-17). Pittsburg, PA: University of Pittsburg Learning and Research Development Center.

Redish, E. F., Steinberg, R. N., & Saul, J.M. (1998). Student expectations in introductory physics, *Am. J. Phys. 66*(3), 212-224.

Roseman, J.E., Fortus, D., Krajcik, J., & Reiser, B. (2015). Curriculum Materials for *Next Generation Science Standards:* What the Science Education Research Community Can Do. Paper presented at the 2015 NARST Annual International Conference, Chicago, IL.

Roseman, J.E., Linn, M, & Koppal, M. (2008). Characterizing curriculum coherence. In Y. Kali, M. Linn, & J.E. Roseman (Eds.), *Designing Coherent Science Education* (pp. 13-36). New York, NY: Teachers College Press.

Roth, K.J., Druker, S.L., Garnier, H.E., Lemmens, M., Chen, C., Kawanaka, T., Rasmussen, D., Trubacova, S., Warvi, D., Okamoto, Y., Gonzales, P., Stigler, J., and Gallimore, R. (2006). *Teaching Science in Five Countries: Results From the TIMSS 1999 Video Study*

(NCES 2006-011). U.S. Department of Education, National Center for Education Statistics. Washington, DC: U.S. Government Printing Office.
Roth, K. & Garnier, H. (2006/2007). What science teaching looks like: An international perspective. *Educational Leadership, 64*(4), 16-23.
Sandoval, W. A. (2003). Conceptual and epistemic aspects of students' scientific explanations. *The Journal of the Learning Sciences, 12*(1), 5-51.
Schmidt, W.H., & Houang, R.T. (2012). Curricular coherence and the Common Core State Standards for Mathematics. *Educational Researcher, 41*(8), 294-308.
Schmidt, W.H., Wang, H.C., & McKnight, C.C. (2005). Curriculum coherence: An examination of U.S. mathematics and science content standards from an international perspective. *Journal of Curriculum Studies, 37*(5), 525-559.
Schwab, J. J. (1962). The concept of the structure of a discipline. *Educational Record, 43*(3), 197-205.
Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (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.
Shwartz, Y., Weizman, A., Fortus, D., Krajcik, J. & Reiser, B. (2008). The IQWST experience: Using coherence as a design principle for a middle school science curriculum. *Elementary School Journal, 109(*2), 199-219.
Sikorski, T. (2012). *Developing an alternative perspective on coherence seeking in science classrooms* (Unpublished doctoral dissertation). University of Maryland, College Park, MD.
Sikorski, T. (2015). Understanding responsive curriculum from the students' perspective. In A. Robertson, R. Scherr, & D. Hammer (Eds.), *Responsive teaching in mathematics and science (pp. 85-104)*. New York, NY: Routledge.
Smith, E. L., Blakeslee, T. D., & Anderson, C. W. (1993). Teaching strategies associated with conceptual change learning in science. *Journal of Research in Science Teaching, 30*(2), 111-126.
Stigler, J.W., Gonzales, P., Kawanaka, T. Knoll, S. & Serrano, A. (1999). *The TIMSS Videotape Classroom Study: Methods and Findings from an Exploratory Research Project on Eighth-Grade Mathematics Instruction in Germany, Japan, and the United States*. Department of Education, National Center for Education Statistics (NCES 99-074). Washington, DC: US Government Printing Office.
Thagard, P. (1989). Explanatory coherence. *Behavioral and brain sciences, 12*(03), 435-467.
Thagard, P. (2007). Coherence, truth, and the development of scientific knowledge. *Philosophy of Science, 74*(1), 28-47.
Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: A study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535-585.
Yager, R. E. (2011). *Real Reform in Science Education Takes More than "Stirring the Pot".* The Iowa Academy of Education Occasional Research Paper #8. Science Education Center, The University of Iowa.