

Summit for Examining the Potential for Crosscutting Concepts to Support Three-Dimensional Learning Conference Proceedings

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University of Virginia – Darden Sands Family Grounds
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The Need for a Summit for Examining the Potential for Crosscutting Concepts to Support Three-Dimensional Science Learning

Sarah J. Fick, Jeffrey Nordine, and Kevin W. McElhaney

The *Framework for K-12 Science Education* (National Research Council, 2012) and the Next Generation Science Standards (NGSS Lead States, 2013) represent a major effort to re-imagine school science instruction in a way that aligns with research into student learning, provides students with a window into how science is done, and prepares a new generation of scientifically literate citizens. These documents outline a vision for science learning that include three interdependent dimensions: disciplinary core ideas (DCIs), science and engineering practices (SEPs), and crosscutting concepts (CCCs) that work together so students can make sense of phenomena and solve problems. These three dimensions of science learning form the foundation of “knowledge in use,” that is, scientific knowledge that prepares students to make sense of their world and function successfully in an increasingly scientific and technological society. The vision of three-dimensional science learning represents a substantial departure from traditional science teaching, and teachers need support in adapting their instruction. Existing research can offer substantial guidance for integrating DCIs and SEPs in science instruction and how these ideas can be built over time, but there is a pressing need to advance research into the roles that the CCCs play when integrated into science instruction focused on supporting students’ ability to make sense of phenomena. In existing work, researchers have found that difficulties in applying CCCs may contribute to students’ development of misconceptions (e.g., Chi, Roscoe, Slotta, Roy, & Chase, 2012) and struggles to correctly apply scientific ideas (e.g., Lindsey, Heron, & Shaffer, 2012). There is a pressing need to better understand the role that CCCs play in supporting students’ science learning and in investigating how ideas about CCCs can be built over time. To address this need, the summit convened a group of science education researchers, science teachers, and scientists to:

- 1) develop shared understandings among the community of stakeholders regarding the role of CCCs in science teaching and learning, and
- 2) identify central issues and questions that can guide future research in order to prioritize these topics for future lines of research, and initiate productive collaborations among participants to pursue these questions.

The CCCs hold great potential for supporting student learning in science. The *Framework* describes this potential by arguing that the CCCs “help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world” (National Research Council, 2012, p. 83). CCCs are used across all scientific disciplines. They hold the promise of helping students establish connections between scientific ideas and to make sense of phenomena, strengthening their science knowledge and making it more broadly applicable, more durable, and more generalizable. The *Framework* identifies seven CCCs in science: (1) patterns, (2) cause and effect: mechanism and explanation, (3) scale, proportion, and quantity, (4) systems and system models, (5) energy and matter: flows, cycles, and conservation, (6) structure and function, and (7) stability and change. These CCCs highlight different aspects of a scientific phenomenon and how it works, creating a fuller picture for how and why phenomena occur. For example, students can consider the role of energy & matter within a watershed, and this may provide insight into how the movement of water is driven by energy from the sun and the force of gravity. Similarly, considering the watershed

from a systems perspective may lead to insights into how to identify the origin of a point source pollutant in a stream or river.

The CCCs included within the *Framework* are not entirely new; most have appeared in a similar form in previous iterations of standards documents (Duschl, 2012), but past standards documents have not as explicitly integrated these CCCs with SEPs and DCIs. A core component of the vision of the *Framework* is the recognition that the scientific ideas only become useful when they are integrated with scientific practices and CCCs. Thus, the CCCs play a new role in the standards, and accordingly, there does not yet exist a robust research base with respect to how students learn about CCCs or the role they play in supporting students' science learning and ability to integrate science ideas reliably across a range of contexts. Even the premise that the CCCs can provide connections across the science disciplines is largely untested in educational contexts. The need for additional research into how the CCCs might be used to support student learning is driven by the powerful, yet unproven, role that they may play in helping students to make sense of SEPs and DCIs more effectively. As they are envisioned within the *Framework*, the CCCs hold promise for supporting students to transfer science ideas and concepts across disciplines, something that education researchers and teachers have struggled to support.

There is a pressing need for the research community to develop a shared understanding of the role of CCCs in supporting student understanding, how students develop their understanding of CCCs over time and across disciplines, and how to integrate CCCs into instruction. To address these needs, it is necessary to convene a group of science education researchers, teachers, and scientists who have been working to understand the role of CCCs in the various science disciplines and their role in supporting science learning and instruction. The summit was organized to produce two key outcomes:

- the development of shared understandings about the roles for the CCCs in supporting teaching and learning in science and engineering, and
- articulating key issues and questions that can guide future research examining the CCCs.

Although the research community has not reached consensus about the roles that CCCs play in student learning, or how to develop students' understanding of the CCCs as lenses on phenomena over time, existing research can provide a clearer message about what roles the CCCs might play and how students can be supported to achieve that knowledge. There is a critical need to enhance research into the teaching and learning of CCCs, and a coordinated effort to summarize and examine what research exists would make it possible to more clearly identify strengths and gaps in the existing research and to identify promising issues and questions to advance promising future research. This summit was focused on addressing a clear need in order to fulfill the vision of the *Framework* and NGSS, and also setting the stage for potentially transformative research into the role of CCCs in supporting student learning and their ability to reliably connect ideas across disciplinary boundaries.

Existing Research Related to NGSS Crosscutting Concepts

The explicit integration of CCCs into the NGSS represents one of the most ambitious aspects of the new standards and reflects a critical aspect of preparing 21st century scientists and citizens. Yet, very little coordinated knowledge exists about the role of CCCs in supporting students' science learning or how students build ideas about CCCs over time. The CCCs are described in the *Framework* and NGSS as lenses that can be applied in similar ways across science

disciplines; one challenge to such a claim is that while the transfer of learning across topics is a central goal of education (e.g. Bransford & Schwartz, 1999; Bransford et al., 2000), evidence of transfer has traditionally been difficult to find (Detterman & Sternberg, 1993). However, research into the conditions that promote transfer has revealed the importance of coordinating memory and cognitive processes, and helping students to recognize the deep structure that underlie related contexts (Day & Goldstone, 2012; Schwartz & Goldstone, 2016). One possibility for promoting such coordination and supporting transfer is through the use of consistent language across contexts (Bransford et al., 2000). Another approach put forward by Goldstone and Wilensky (2008) is to ground the students' learning of a CCC in a particular example with opportunities to build their understanding of that concept through interacting with it through models and to provide students with language that allows them to transfer the idea to a new circumstance. This creates a situation for students that is both "perceptually grounded yet also idealized in many respects" (Goldstone & Wilensky, 2008, p. 503). Through a combination of consistent language grounded in concrete opportunities to build understanding of the concept, it is possible that students might be able to independently use the CCCs to make sense of DCIs and SEPs across science disciplines (Fick, 2018; Goldstone & Wilensky, 2008).

In contrast to the CCCs, an extensive body of research has been dedicated to how students learn DCIs, as students' understanding of particular scientific concepts has been a central focus of science education research for decades (e.g., Allen, 2010; Chen et al., 2014; Driver, Squires, Rushworth, & Wood-Robinson, 1994; Hestenes, Wells, & Swackhamer, 1992). Similarly, a robust and growing literature base also exists with respect to how students learn to engage in SEPs throughout K-12 (e.g., Berland & McNeill, 2010; McNeill, Lizotte, Krajcik, & Marx, 2006; Osborne, 2014; Schwarz et al., 2009; Schwichow, Croker, Zimmerman, Höffler, & Härtig, 2016; von Aufschnaiter, Erduran, Osborne, & Simon, 2008). Further, a significant body of research has been conducted to advance understanding of how DCIs and SEPs can be integrated to support students' science learning (e.g. Songer, 2006; McNeill, Lizotte, Krajcik, & Marx, 2006; Lehrer & Schauble, 2006). In this work, researchers have also used a learning progression perspective to examine the kinds of support that students need at various grade levels in order to develop science content knowledge through the use of authentic practices of the discipline. As a result, frameworks exist for supporting students in building science knowledge through engagement in science practices such as experimentation (Emden & Sumfleth, 2016; Schwichow et al., 2016), explanations (McNeill & Krajcik, 2012; Zembal-Saul, McNeill, & Hershberger, 2013), argumentation (Chen, Wang, Lu, Lin, & Hong, 2016; Sampson, Enderle, Grooms, & Witte, 2013; von Aufschnaiter et al., 2008), and modeling (Cheng & Brown, 2015; Manz, 2012). A similarly robust empirical literature base exploring how concepts are built and connected over time within the context of learning science does not exist for CCCs. While some researchers have examined students' learning of individual CCCs, little research has systematically focused on how those understandings can be supported over time, as in a learning progression, or examined the potential for the CCCs to support student learning both within and across science disciplines.

There is existing work focused on components of individual CCCs. For example, systems and system models, one of the CCCs in the NGSS, has been the focus of several different lines of research. Researchers have studied students' system thinking skills in the context of earth science (e.g., Ben-Zvi-Assaraf & Orion, 2005), chemistry (Vachliotis, Salta, & Tzougraki, 2014), life science (e.g., Riess & Mischo, 2010), physics (Lindsey et al., 2012), and engineering (Gero & Zach, 2014). Further, researchers have addressed systems thinking by arguing for the importance

of systems-thinking as an explicit learning goal in education (Jacobson & Wilensky, 2006), comparing novice and expert understanding of systems (Hmelo-Silver & Pfeffer, 2004), and describing methods for assessing systems-thinking in science (Brandstädter, Harms, & Großschedl, 2012), but little research has focused on supporting students to understand systems, as opposed to having them use systems concepts without awareness of their purpose. While there are existing lines of research that align with the described components of the CCCs, much of this work focuses on the CCCs alone without attending to the interactions with the DCIs and SEPs to support three-dimensional learning.

Challenges in synthesizing crosscutting concept research.

We find four challenges to synthesizing research (listed in Table 1). These challenges make it difficult to find and synthesize the existing literature referencing the CCCs as a foundation for teaching and learning. The first challenge is that the definitions for the CCCs in existing research do not necessarily align with the *Framework* or NGSS definitions. Within the literature focused on CCCs, there is a lot of variation in the language that has been used to define the CCCs. For example, in Hmelo-Silver & Pfeffer's (2004) contribution to the systems literature, their language focused on examining the structure, behavior, and function of systems does not exactly appear within the description of the NGSS CCC. Some of the existing research within each of the themes requires translation to be able to fit with the NGSS definition. Or, in another example, Goldstone and Wilensky (2008) focus on students' understanding of a mechanism of positive feedback, which does not have an NGSS corollary. The NGSS description of systems and system models does describe flows of energy, matter, and information, but does not address positive and negative feedback (NGSS Lead States, 2013). A second challenge is that there are likely many articles and studies that describe CCCs and their impacts on teaching and learning but do not use the terminology of the NGSS. For example, many of the curriculum materials that pre-date the NGSS included aspects of the CCCs (e.g. Songer, 2006; McNeill et al., 2006), to help students make sense of the concepts. These articles are much harder to find since they do not necessarily use any of the keywords or phrases that would be associated with the CCCs. A third challenge is sorting through a class of work that is self-described to be three-dimensional. Within these papers we need to determine which papers have useful recommendations for how the CCCs might be implicitly incorporated into three-dimensional instruction (e.g. Krajcik et al., 2014), and research in which the CCC is superficially included without real suggestions or implications for teaching and learning. A fourth challenge is a body of research that appears to be theoretically based, without a clear reference to empirically studied applications. While some of the theoretical papers contribute new understandings based on the ways that the CCCs have been described (e.g. Rivet et al., 2016), others posit theoretical ideas about how they might be used in teaching and learning without a clear research base to support those suppositions, because guidance is needed and clear research is slim (e.g. Bybee, 2012). These four challenges highlight the clear need for researchers and other stakeholders to come together and work to build common understandings of what research exists, what has been tested, and what questions remain.

Table 1. Challenges in Synthesizing Crosscutting Concept Research

Challenge	Description	Example
Discrepancy between NGSS CCC definitions and existing research	Research that defines a CCC differently than the NGSS definition.	Hmelo-Silver & Pfeffer's (2004); Goldstone and Wilensky (2008)
Implied Implicit Inclusion of the CCCs	Research that may implicitly include a CCC, and therefore have insights, but was not named using the NGSS terminology.	Songer, 2006; McNeill et al., 2006
Self-Described Three-Dimensional	Research that includes the three dimensions, within which some papers have suggestions for the implicit inclusion of the CCCs, while others include a superficial reference to the CCCs.	Krajcik, Codere, Dahsah, Bayer, & Mun, 2014
Theoretical papers without a clear empirical grounding	Papers that are theoretically based, but without reference to empirical research	Bybee, 2012

Research into the roles of crosscutting concepts to support student learning.

While research into student learning of CCCs as a dimension of science learning is not yet robust, some theoretical work has been done to clarify the intended role of CCCs in learning and instruction. Rivet and colleagues (2016) analyzed the NGSS (NGSS Lead States, 2013) and selected relevant documents and articles to describe how the CCCs were discussed. Their analysis identified four metaphorical perspectives used within these documents for thinking about the role of CCCs in learning and instruction: a) lenses, supporting students to deepen their own understanding about a topic through the application of various CCC lenses to examine a phenomenon from multiple perspectives, b) bridges, supporting students to make connections across science topics to deepen their understanding of new concepts, c) tools, serving as a tool that students can use to clarify confusion and leverage existing understanding to build new explanations and ideas, and d) rules of a game, which specify common practices and language within a community. While some initial work has been done to clarify how instruction can explicitly emphasize CCCs, much of this work addresses only the potential role of CCCs in instruction without providing empirically-grounded guidance about how to incorporate CCCs in support of teaching and learning. Summarizing their work to support teachers and developers in designing and implementing three-dimensional instruction, Rivet and colleagues (2016) report that “we have found the CCCs to be the most difficult dimension to discuss and develop shared understanding” (p. 970). A major goal of this summit was to support researchers in developing shared understandings that will aid in pushing the field forward.

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The Summit for Examining the Potential of Crosscutting Concepts to Support Three-Dimensional Learning

University of Virginia – Sands Family Grounds
Arlington, VA
December 6th – 8th, 2018

Summit Agenda

Thursday, December 6th, 2018

1:00pm-2:00pm – Welcome, Logistics, Introductions

2:00pm-3:45pm – Base Working Group Model Generation

Objective: Participants conduct a synthesizing discussion about position papers submitted by group members and, based on this, brainstorm a model to represent how CCCs support student learning in science.

3:45pm-4:15pm – Break

4:15pm-5:30pm – Base Working Group Presentations

Objective: Groups develop a presentation to share their thinking regarding the model developed in the previous session to the whole group and receive feedback. Presentations occur on Friday.

5:30pm – Closing reflection and wrap up

Friday, December 7th, 2018

*8:00am-8:45am – Breakfast at UVA Darden Sands Family Grounds & Prepare for Presentations
(Working Breakfast)*

8:45am-10:00am – Base Working Group Model presentation refinement and preparation

10:00am -10:10am – transition and break

10:10am-10:30am – Logistics and introduction to presentation format and feedback groups

10:30am-11:30am – Base Working Group model presentation (Session 1) – 1 group presents

Objective: Summit participants consider and provide feedback for a variety of different models representing how CCCs support student science learning.

11:30pm-12:30pm – Lunch

12:30pm-1:30pm – Base Working Group model presentations (Session 2) – 1 group presents

1:30pm-1:45pm – Break

1:45pm-3:45pm – Base Working Group model presentations (Session 3) – 2 groups present

3:45pm-4:00pm – Break

4:00pm-5:00pm – Base Working Group model presentations (Session 4) – 1 group presents

5:00pm-5:15pm – Closing remarks

Saturday, December 8th, 2018

8:00am-8:45am – Breakfast at UVA Darden Sands Family Grounds

8:45 am-10:15 – Base working Group Revising/Writing Time – Model revision, reflection, and paper writing

Objective: Base Working Groups incorporate feedback from group presentations to revise and refine their initial models and consider areas of convergence and divergence that are emerging in discussions thus far. By the end of the day, groups should have an outline and a plan for writing their summit paper. (There is also time in the afternoon for this.)

10:15-10:30 am – Coffee break

10:30 am - 10:40 am - Introducing the format for the research agenda session

10:45am - 12:15pm – Setting a research agenda World Cafe discussion (2 rounds)

Objective: Develop a research agenda focused on the role of CCCs in science.

12:15 pm-1:00 pm – Lunch

1:00pm - 1:30pm – Debrief the Research Agenda Discussion

1:30pm - 2:30pm – Assigning Follow-up Writing Tasks – Base Working Group Writing Time – Model revision, reflection, and paper writing

2:30pm-3:00pm – Wrap-Up and Future Planning

3:00pm-4:00pm – Informal Conversations

Crosscutting Concept Summit Attendees

Organizing Committee Members

Sarah Fick, PI	University of Virginia
Kevin McElhaney, co-PI	SRI International
Jeffrey Nordine, co-PI	IPN Institute for Math and Science Education, Germany
Cindy Hmelo-Silver	Indiana University
Joe Krajcik	Michigan State University
Lindsey Mohan	BSCS Science Learning

Summit Attendees

Andy Anderson	Michigan State University
Aneesha Badrinarayan	Achieve Inc
Lauren Barth-Cohen	University of Utah
Jason Y. Buell	University of Colorado – Boulder
Melanie Cooper	Michigan State University
Christine Cunningham	Pennsylvania State University
Cesar Delgado	North Carolina State University
Brian Gane	University of Illinois at Chicago
Okhee Lee	New York University
Lauren Levites	Chicago Public Schools
Kristin Mayer	Kentwood High School
Thomas "TJ" McKenna	Boston University
Joi Merritt	James Madison University
Brett Moulding	Utah Partnership for Effective Science Teaching and Learning
Ann Novak	Greenhills School
Jonathan Osborne	Stanford University
Abeera P. Rehmat	Indiana University
Ann Rivet	Columbia University – Teachers College
Nancy Ruzycki	University of Florida
Cary Sneider	Portland State University
Art Sussman	WestEd
Tina Vo	University of Nevada – Las Vegas
Ted Willard	National Science Teachers Association
Susan Yoon	University of Pennsylvania

Supporting Students' Learning of Science Content and Practices Through the Intentional Incorporation and Scaffolding of Crosscutting Concepts

*Sarah J Fick, Lauren Barth-Cohen, Ann Rivet,
Melanie Cooper, Jason Buell, and Aneesh Badrinarayan*

Foundational to our model is a recognition that CCCs are valuable, important and worthy of focus in science teaching and learning. Pragmatically we focused on what CCCs *do* as part of three-dimensional learning, but this emphasis has the potential to overlook the fundamental assumption about the value of CCCs. We moved to unpack these assumptions, and clearly state the reasons why we felt that CCCs were valuable and productive. This led to the focus of our model on two key questions: a) why do crosscutting concepts (CCCs) matter for student learning? And b), what would we lose if they were not present?

Our subsequent discussions around these two questions lead to a two-part model of the role of CCCs in three-dimensional learning. The first is a Venn diagram (Figure 1) that represents the critical connective role that we felt CCCs had in bridging the classic divide between science content and practice, between the knowing that and knowing how, that have plagued science education reform efforts for the past 50 years (National Research Council, 2007). While we have made progress in addressing this divide in the research community, these efforts have not widely been taken up at the same rate in classrooms, and thus the divide persists (e.g., Abd-El-Khalick et al, 2004; Czerniak & Lumpe, 1996; Pea & Collins, 2008). Yet this Venn diagram representation was insufficient - it did not represent our views on how CCCs support science learning or the mechanisms that connect CCCs to the other two dimensions. Thus the second part of our model was our attempt to represent the key role that CCCs play in the learning process by identifying the inputs that students bring to science learning, the ways that CCCs operate in science learning, the interim learning shifts that happen because of engagement with the CCCs, and the relationship of these shifts to the “big goal” of three-dimensional science learning. In the discussion below we elaborate on each aspect of our two-part model. While we also attempted to represent connections and relationships between parts of our model using arrows, we recognize that those relationships are currently under-developed (under-theorized) and in need of further research by the field.

Historically, in the development of recommendations for science teaching, the content that is being taught and the practices of science have been addressed as separate aspect of learning (e.g. National Research Council, 1996). In some documents, there was even the inclusion of an often ignored third component the themes of science. The third aspect of science knowledge, what was once referred to as the unifying concepts of science (NRC, 1996), the crosscutting concepts are another important aspect of how this knowledge is generated. We see the crosscutting concepts as an important part of both the traditional knowledge and practice of science, where it is important to know how they work and how to use them in order to develop scientific understandings (Figure 1). Furthermore, crosscutting concepts have the potential to bridge the persistent content (knowing)-skills (doing) divide.

Similar to how science practices were once approached as an independent dimension, how to use the crosscutting concepts has often been taught separate from the science content and practices (e.g., Goldstone & Wilensky, 2008) or implicitly through learning activities (e.g., Ben-Zvi Assaraf & Orion, 2005), if it was taught at all. While they are often undervalued or dismissed (Osborne et al., 2018), others have theorized that it is the misuse of crosscutting concepts that

leads to sticky misunderstandings about the mechanisms for science processes (Chi et al., 2012). We see the lack of explicit instruction about how and why to use the crosscutting concepts as an important motivator. Previously CCCs have inadvertently contributed to unequal learning opportunities with some students implicitly picking up their use, while others are left behind. This is similar from how science practices were once discussed (McNeill & Krajcik, 2008).

One of the major problems that the crosscutting concepts face, however, is that unlike the practices they are often vaguely defined, their usefulness is not universally understood, and they lack a strong evidentiary basis. In the following sections, we describe our vision for how the crosscutting concepts can support science knowledge and science learning.

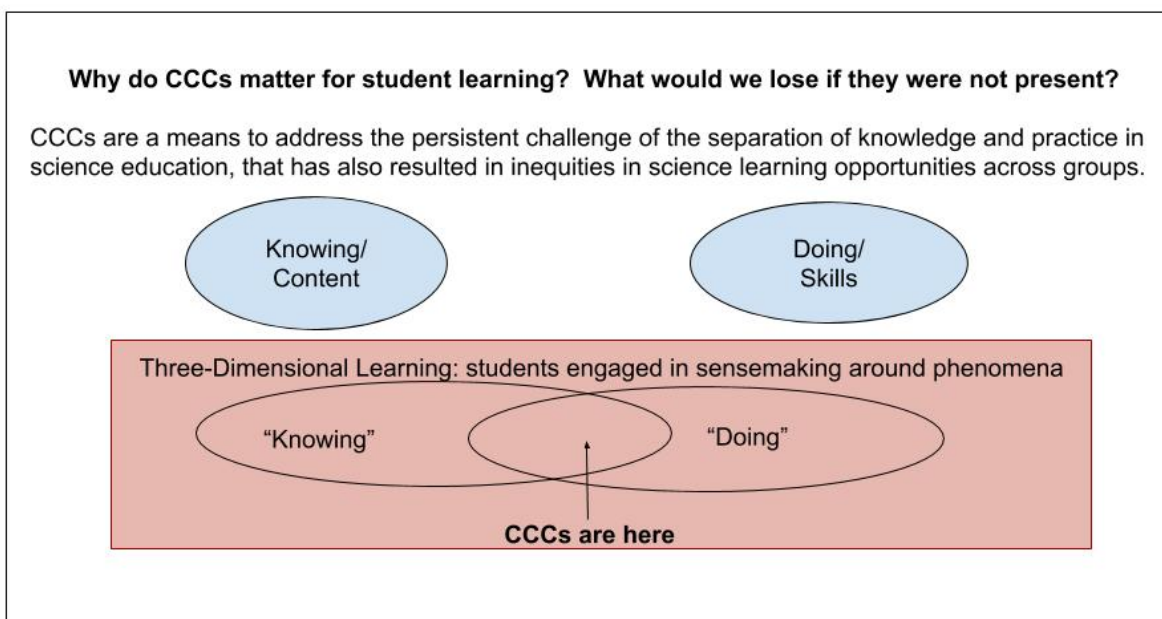


Figure 1. The intersection of CCCs with Knowing and Doing, and its relationship to traditional approaches to science.

Description of the Model

Students come to learning experiences with a wide range of prior knowledge and experiences, and resources that can be brought to bear on sensemaking around phenomena. Accordingly, the CCCs can operate in various ways as students learn, not only acting as lenses to focus on a particular aspect, but also a way to support students agency and identity as science learners. As CCCs are operationalized we propose various interim learning shifts will come into play, in which ideas may shift from background to foreground, and operate with increasing sophistication over time and across different phenomena and disciplines. The model also predicts that different combinations of CCCs and DCIs will allow different aspects of a phenomenon to be highlighted. Not least, CCC reasoning will bring culturally related reasoning strengths to science learning. All of these learning shifts should move us to toward the dual goals of rich and meaningful science learning in an environment that recognizes and rewards culturally and linguistically diverse learners.

Outcome of the Model – Big Goal

This model is focused on how students interact with the CCCs, therefore the ultimate goal considers what we imagine students to be doing with them to support learning and understanding. With this in mind, we imagine that the NGSS vision of science learning involves students using CCCs as connectors to cross both DCIs and SEPs for the purpose of sensemaking about science phenomena and the development of engineering design solutions that will address human needs. This process should specifically focus on supporting students from culturally and linguistically diverse backgrounds to have interest, capacity, motivation, and confidence to pursue STEM workforce opportunities, and to use their science knowledge and practices (where CCCs are seen as a part of both) to solve everyday problems. Furthermore, when engaged in this process, we expect students to draw from a variety of prior knowledge and experiences related to sensemaking around the science phenomena and the development of engineering design solutions that in turn influence how CCCs operate in science learning, impact DCIs, support transfer, and function over time.

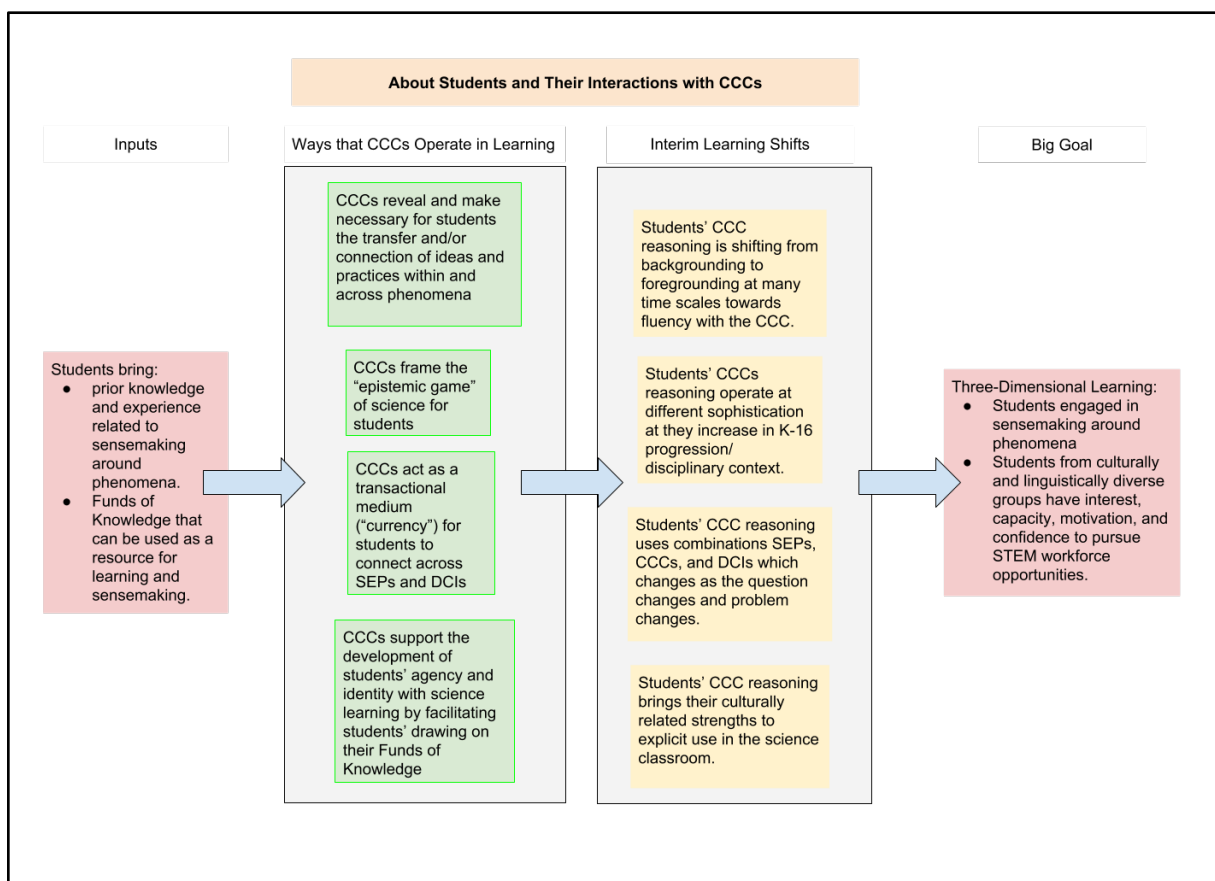


Figure 2. Our model of students and their interactions with the crosscutting concepts that support three-dimensional science learning aligned with the vision of the Next Generation Science Standards.

Inputs

When engaged in this process where they interacting with CCCs, we expect students to draw from a variety of prior knowledge and experiences related to sensemaking around the science phenomena and the development of engineering design solutions. This may include a variety of mainly cognitive resources, such as intuitions, mental models, and conceptual understandings

about the phenomena, disciplinary core ideas, and possibly also about the CCCs themselves (Chi et al., 1994; diSessa, 1993; Gentner & Stevens, 1983; Vosniadou & Brewer, 1992). There also might be epistemological beliefs about knowledge and learning related to CCCs (Hammer & Elby, 2002) and other beliefs related to one's intersecting school and everyday identities, experiences, and background that could impact how CCCs operate in learning. Finally, students also bring relevant and diverse funds of knowledge from their everyday and out of school lives that can mediate their discourse with CCCs (Moll et al., 1992).

Ways that CCCs Operate in Learning

We recognize that there are a variety of ways that CCCs can operate in learning. CCCs can exhibit many functions that connect the relevant inputs with resulting outputs. Aligned with these different functions, there are many ways the CCCs can support three-dimensional learning.

Reveal and make necessary. When a variety of CCCs are applied to the same DCI, the intersection of each CCC with the DCI has a tendency to highlight different aspects of the DCI than another CCC might illuminate (Fick, Arias, & Baek, 2018). For example, Water in Earth's Surface Processes (DCI) from an energy and matter perspective might focus on the evaporation, condensation, precipitation, and movement of water on the surface (the water cycle). While from a systems perspective, one might examine the inputs, outputs, boundary, interactions, and nested systems of the water, leading to think about the movement of water on the surface of the Earth and its collection in larger bodies of water (watersheds). While from a scale perspective, one might consider how the micro-level absorption of water leads to and drives the landscape level water flows on the surface. These three lenses help to reveal and make necessary different parts of the bigger DCI. Scientists apply lenses to help them ask questions, answer questions, and develop investigations, as well as when they model phenomena. Research has shown that these same practices for revealing what we do and do not understand about a phenomena might be useful for supporting students' science learning (Fick, 2018).

CCCs might also be able to be used to support students to represent ideas across science practices. If one uses a CCC to highlight the important aspects of how a phenomenon works, it could make it easier to represent those same aspects in different forms (i.e. modeling or explanation) or even to help figure out what questions to ask. For example, using a systems perspective to examine watersheds might make it easier to know what questions to ask to determine the source of pollution in a water body, knowing where the watershed boundaries are and from where the water originated will help to determine the source of the pollution.

Epistemic games. Another perspective on how CCCs operate in science learning is to view them as a kind of "rules of the game" (Rivet et al, 2016). We do not intend to trivialize science by referring to it as a game, or confuse it with the genre of digital-based "epistemic games" as described by Shaffer and others (e.g., Shaffer, 2005; Rupp et al, 2010). Rather, we expand on the perspective of epistemic games as described by Collins and Ferguson (1993) and Perkins (1997) to consider science as a shared organized activity that is governed by a set of rules and norms of engagement. This perspective foregrounds the notion of science as a disciplinary practice of knowledge creation and development (Ford, 2008). In a scientific community, ideas and explanations for phenomena or designs are debated and weighed against evidence from the natural world. Explanations evaluated by the community to effectively account for the evidence in productive ways are valued as authoritative ideas of science. This process of engaging in

disciplinary practice is governed by implicit rules and norms shared by the community. We postulate that CCCs operate as one category of these rules, in that they provide structures and metrics to formulate and debate the merits of new ideas and explanations (Ford, 2005). The guidance provided by CCCs supports community members in communicating and expressing relationships between core concepts and phenomena through evidence.

For example, a cause and effect relationship has specific features and structures that distinguish it from a correlational relationship. Learners can use the features and structures of this CCC to both develop and propose an explanation, and as a form to critique and evaluate explanations from their peers. Additionally, learners can use multiple CCCs to develop and evaluate explanations of a single phenomenon, considering it from different perspectives (e.g., components of a system, behavior at different scales, and relationships of structure and function). In this way, they use the CCCs to learn and effectively play the epistemic game of science.

Currency. One option for how CCCs can support transfer of ideas is by functioning as currency. That is, a CCC could be used as a common medium for exchange across contexts. A CCC can be used to exchange information from one context to another such that information that otherwise might be impenetrable in one context becomes transparent. For example, a pattern such as a correlation might be readily apparent in one context but nebulous in another context. Using that CCC across contexts might help one recognize that pattern across contexts. As another example, if one is reasoning about Stability and Change in one context they might focus on rates of input and output and find that emphasis to be productive. Then, at a later point in time, in a new context, when encountering difficulties, they might attempt to use that information, about rates of input and output to reason through a new phenomenon where they otherwise might be stymied. From this perspective, there needs to be a root idea that can be translated across contexts and disciplines. The currency of CCCs could also support someone to make connections across science practices by using a CCCs to highlight key components of a core science idea (DCI), holding those key components constant as the representation of the knowledge (SEP) changes. Or, highlighting similar key components (CCC) in a representation (SEP) across core science ideas (DCIs).

Funds of knowledge. We know that students bring prior knowledge and experience to their learning, and traditionally there was a small set of experiences that “counted” as useful prior knowledge. Often these related to prior out of school experiences or in classroom learning that was directly relevant to the current learning situation. With the implementation of the Framework and NGSS, there has been an emphasis on ensuring that all students have equal access to science learning opportunities and that approaches to instruction are inclusive and motivating to a diverse student population.

Examining science learning through the perspective of the crosscutting concepts reveals an entire additional set of knowledge and experiences that students can use as resources for building on in classroom learning, and to support others’ learning. Students’ funds of knowledge from their lived experiences in their home communities can be resources for both the knowing and doing of science (Gonzalez & Moll, 2002). For example, students from other countries might be familiar with the metric system that is useful for supporting a sense of scale (Delgado, 2013) or students with a cultural background that prioritizes systems thinking and cause and effect as ways of understanding the natural world (Bang & Medin, 2010). Positioning the classroom around

valuing these experiences and ways of knowing will provide all students with the opportunity to see the natural world from the perspective of a different lens on science.

Knowing that learning can be a social process, CCCs can serve two important purposes as a mechanism for connecting students existing competences and knowledge with their school experiences. First, CCCs can provide a concrete and explicit mechanism for students to access and connect their previous experiences (in school and out-of-school experiences) to new learning environment--when students are faced with unfamiliar situations, facility with the CCCs can provide a way for students to leverage their prior experiences as a way to begin exploring and explaining new phenomena and problems. Second, facility with the CCCs can elevate for students the value of their prior experiences for making sense of the world around and them, and help build student confidence to explore new work. Rosebery, Warren, and Conant (1992) report on how language minority students appropriate scientific ways of knowing and reasoning through participation in a collaborative inquiry about water quality in their home and school communities. Over the course of an academic year students shift towards more sophisticated uses of cause and effect in their reasoning and on a final transfer task they put forward more testable hypotheses and were no longer invoking anonymous agents.

Interim Learning Shifts

Given the previously described inputs, along with the potential ways that CCCs operate in learning (mechanisms), there are a variety of short term or intermediate outcomes. These outcomes include different ways CCCs interact individually and as a group over time, which in turn impact three-dimensional learning. All of these interim learning shifts can be related to any of the ways that CCCs operate in learning. We are not claiming any particular correlations, which is why the arrows are connected on the broadest scale possible. Connections between individual elements are what we later propose might be the subject of additional research, examining which connections have more weight for student learning.

Backgrounding and foregrounding CCCs. When reasoning about a scientific phenomenon involving CCCs, often there are multiple CCCs at play and those CCCs may have different roles and functions at different points in time. That is, one CCC might be momentarily foregrounded while others are backgrounded and this would change over time (Bybee, 2013) as individual CCCs operate different ways in learning. This idea builds on Bybee's (2013) notion of backgrounding and foregrounding of CCCs in particular lessons and units to say that it might be a shift within a lesson or making sense of a phenomenon occurring from moment to moment that drives the change. For example, in an empirical study described in Barth-Cohen and Wittmann (2017), a group of 9th grade students were generating and discussing models for the steady state energy of the earth. The modeling environment and the phenomenon being discussed touched upon many CCCs, Energy flow, Systems and system models, and Stability and change, which encompasses equilibrium and steady state. During the discussion students asked questions about their peers' models and often the questions momentarily centered on one of the CCCs while backgrounding the others. For instance, in response to a model about more energy entering the earth than leaving it, one student asked "How come there is only one thing leaving, but three [units of energy] coming in? I think the earth would like, explode eventually." The essence of this question for grounded Stability and Change (a lack of equilibrium) with Systems and system models being backgrounded. But, at other points in time other questions foregrounded System models or Energy Flow while backgrounded Stability and change. The ability to foreground or

background different CCCs is an important intermediate result that is potentially derived from different ways that CCCs can operate in learning.

Increasing sophistication in use of the CCCs. As students become more proficient with using CCCs a lens or tool to think about particular phenomena, we might also expect them to be able to extend these ideas not only across phenomena but also across disciplines. Over time, as students' understanding increases in sophistication, and in particular as they move from high school to college, students will become able to reason about both the similarities and the differences that a particular CCC may bring to reasoning across disciplines. For example, college students who were co-enrolled in introductory chemistry and biology courses were asked to reason about phenomena using the CCC structure-function, which had been introduced in both courses separately (Kohn, Underwood, & Cooper, 2018). What was interesting and encouraging was that when asked to think across chemistry and biology, a majority of the students were able to construct a connection that had not been made explicit in either course: that is, structure determines properties that influence functions. They understood that in chemistry the emphasis is on structure–property relationships, while in biology it is on structure–cellular or organismic (system) function, but they also recognized that in biology the connection between structure and function often omits a consideration of the specific mechanism of action, that is, the way molecular structure facilitates the function. By interposing the idea of structure-properties into this relationship students believed that they would be better able to understand the mechanisms by which biological molecules carry out their function, and not coincidentally also brings in the CCC cause and effect (mechanism and explanation). This synthesis across disciplines by the students themselves highlights the ongoing importance of the CCCs as students move into higher education (Cooper et al., 2015).

Dynamic combinations. Following up on the prior example of dynamically backgrounding and foregrounding CCCs, in those circumstances, multiple CCCs were present in dynamic ways. For instance, in the previously mentioned discussion in which 9th grade earth science students were reasoning about the steady state energy of the earth, at different moments during the discussion certain CCC were foregrounded in being the essence of the discussion question. In those questions, certain CCCs were present, but not functioning as that same level as the other CCCs. This raises a question about to what extent the backgrounded CCCs are allowing or enabling the essential question. In these cases with backgrounded and foregrounded CCCs, it is possible the relationship between them is dynamic in the sense that they play off of and support each other in ways that change through learning and instruction. Possibly a question that foregrounds one CCC while backgrounding another is relying on an explicit or implicit understanding of the relationship between the two. Knowledge or understanding of one CCC might cue a question about another.

As students are learning to foreground CCCs, they may also learn to use a foregrounded CCC in combination with specific SEPs or DCI. These combinations are dynamic in that students can learn to spontaneously pair specific CCCs and SEPs or DCI based on their learning and scientific goals. It may also be the case that there are specific combinations of CCCs and SEPs or DCIs that have high leverage for supporting learning and scientific goals. In one ongoing research project (Furtak & Briggs, 2018), researchers, in partnership with a local school district, have chosen to focus on the SEP of developing and using models and the CCC of energy flows. Energy can be used in many discipline and classroom-specific ways as an analytic tool. By

teaching the CCC with modeling, students learn specific ways to use energy to analyze a phenomenon. This combination of SEP and CCC may have high leverage because there are aspects of modeling that afford deeper learning of energy flows and, likewise, there are aspects of understanding energy flows that make particular practices of modeling more salient. For example, when learning about energy flows, modeling at multiple scales supports students in understanding how macroscopic phenomena are produced or emerge from micro- and nanoscopic mechanisms. When modeling energy, students must clearly define the system and the surroundings. For learning energy this is critical for ultimately understanding the conservation and dissipation of energy and for the modeling it makes explicit how one must define system boundaries. Whether these two dimensions in combination do provide leverage for additional learning is an empirical question currently under investigation. It may be that all combinations of SEPs, DCIs, and CCCs can provide similar leverage or that certain combinations are particularly powerful. We suspect that the latter is the case and that initial research can be done in developing and testing possible criteria regarding the selection of high leverage combinations.

When learning about the movement of water on and through the Earth's surface (DCI) to predict the impacts of an oil spill on land on the surrounding environment (phenomenon), there are many CCCs that have explanatory power for helping to predict what will happen. Initially, one might ask about why water is absorbed by the surface, requiring a smaller scale (CCC: Scale) examination of the materials and their properties, then zooming out to the larger scale one might examine the role of gravity (CCC: Energy and Matter) in pulling the water downhill towards areas of lower elevation, in thinking about where the water is coming from and where it is going one might invoke the notion of systems (CCC: Systems and System Models) to consider the inputs and outputs, or a conservation of matter (CCC: Energy and Matter) perspective to consider where is all the water going. These dynamic combinations of CCC and DCIs, as well as SEPs help students to make sense of the phenomenon.

Culturally related strengths. Recent literature focused on supporting students' learning about crosscutting concepts, specifically scale, has examined the culturally different ways of knowing that students approach science (Chesnutt et al., 2018; Cheek, 2017). These differences are sometimes related to different ways that individuals and groups understand the CCCs based on the ways that societies function. For example, Cheek found that Indonesian students seemed to use their experience with powers of ten with their currency, where currently 1 USD=14240 IDR, were able to transfer that understanding to the scientific concept of geologic time. Bang and Marin's (2015) research examines the ways that indigenous people bring different values to understanding nature, for example a holistic focus on the long term impacts (CCC: Cause and Effect) on various other aspects of the environment (CCC: Systems), and some of those values could be related to a culturally developed emphasis on systems and the cause and effect of interactions with the environment. These different ways of knowing can be seen as strengths in students' ability to use crosscutting concepts to understand the world around them. Applying these ways of knowing with science and engineering practices might lead to diverse problem solving and understanding.

Examples of this Model in Practice

This model for how the CCCs support learning is based on several assumptions, (1) that traditionally science learning has not focused on making how and why to use the CCCs apparent to students, (2) that making the purposes of using the CCCs apparent to students will support

students to develop a deeper understanding of science concepts. These assumptions are supported by research that shows that the CCCs are a component of a more thorough understanding of the science (e.g. Jin & Anderson, 2012), and that when students fail to use the CCCs they do not incorporate the more complex aspects of a science concept (e.g. Fick et al., 2019). In the research of Fick and colleagues, we see an example of students who were not taught to use the CCCs showing their understanding of how rainfall becomes runoff, and the interactions with surface materials that increase and decrease the amount of runoff because of absorption. The students' conceptual models of the process generally included inputs (rainfall) and outputs (runoff and absorption), but the findings show that students often didn't include outputs that were less key to the process and that students often failed to show a conservation of matter within their models (equal inputs and outputs) which led to a challenge in interpreting the proportion of water that was absorbed or running off in the scenario, the key take-away from the unit. Without attending to this cross-cutting aspect of the process, the students showed that there was a relationship between rainfall, runoff, and absorption, but failed to show what that relationship is.

Supporting students to use the CCCs means that students will be more likely to attend to the proportions in the above example of runoff, but this kind of learning requires a shift in thinking about how we value students' prior knowledge and experience in the classroom, and how we support students to use the lenses of science (CCCs) to make sense of science ideas and phenomena. This shift is in part related to how we value students' prior knowledge, in part about how we think about building on students' prior learning from other disciplines, and also about how we value and foster students' independent thinking and questioning related to their learning. Using the CCCs as a tool to support students' learning involves valuing culturally different ways of knowing that students may bring to the learning experience, and providing those different ways of knowing with space to be shared and valued for the perspective they bring to the learning experience. As students in the classroom begin to learn how and why to use the CCCs to interrogate science ideas and the processes that drive them, students will need support to know which particular CCCs to use to explain phenomena (Chi et al., 2012). Providing students with opportunities to practice using the CCCs to question their own understanding and to develop additional science knowledge will support them to see how and why to use them in other contexts and disciplines. Use of the crosscutting concepts in different contexts is integral to understanding what aspects can be used to make sense of phenomena and develop science ideas in different disciplines. This transportable currency helps students realize what they know and do not know about how things work and the processes that drive them. CCCs can also help students to ensure that they represent the key aspects of a science idea or how a phenomenon works by using the CCCs as lenses to ensure that the key aspects are represented.

Conclusion

In summary, the model proposed here not only provides an approach to thinking about CCCs as tools or lenses to approach sensemaking around particular phenomena, but also provides a theoretical approach to how CCCs can be integrated into teaching and learning. This model focuses primarily on students, their learning and their interactions with the CCCs, rather than on teachers, curriculum, instruction, or assessment. We are also not implying that the CCCs should exist in science learning without DCIs or SEPs. We do think that it is through highlighting the CCCs that students will start to learn how and why to apply them in the future.

The model structure allows us to identify a range of future research questions, including:

- What are the connections between the ways that CCCs operate in learning and interim learning shifts? What are the varying strengths of ties between the different components?
- On a more fine grain, how are the elements of the model connected? Which arrows in the model are weighted more and which operate at different time scales?
- Do outcomes look different when emphasizing different DCIs or SEPs?

In conclusion, this model provides us with ways to think about CCCs, ways to operationalize them, and ideas for future research on how CCCs can impact student learning.

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Using the Crosscutting Concepts to Integrate Science and Engineering

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Introduction

A Framework for K-12 Science Education (NRC, 2012), and subsequently, the Next Generation Science Standards (NGSS Lead States, 2013) includes engineering concepts and practices that are placed on equal footing with scientific concepts and practices. In contrast to prior standards that included just three science disciplines, the Framework and NGSS identify four: physical sciences; life sciences; Earth and space science; and engineering, technology and applications of science. Understanding the intersections across these four disciplines, and especially between the natural sciences and engineering is central to the vision of the NGSS.

In order to support NGSS-aligned student learning in science and engineering, three-dimensional learning—practices, crosscutting concepts (CCCs), and disciplinary core ideas—must occur in order for students to understand that the professional practices of science and engineering are tightly integrated. Common in the real world, uncommon in classrooms, this idea of three-dimensional science and engineering working side-by-side to solve problems represents a key part of the vision of the *Framework* and NGSS.

In this paper, we examine the particular role that CCCs can play in promoting the integrated nature of science and engineering in K-12 science instruction. We first provide some background on the conceptual and linguistic connections between the disciplines of science and engineering. We then describe an analogy illustrating how CCCs can serve as bridges to help learners connect science and engineering. This analogy informs a model that illustrates the central position of CCCs in the integration of science and engineering, leading to meaningful student learning outcomes. Finally, we present two illustrative examples of how CCCs are used as bridges between science and engineering in well-established curriculum materials.

Science and engineering are integrally linked. The understanding of phenomena developed through scientific inquiry informs the development of improved technologies through engineering design. These improved technologies in turn allow for further exploration of additional observations and phenomena. This relationship is an important foundation in the development of the *Framework*:

New insights from science often catalyze the emergence of new technologies and their applications, which are developed using engineering design. In turn, new technologies open opportunities for new scientific investigations. Together, advances in science, engineering, and technology can have--and indeed have had--profound effects on human society, in such areas as agriculture, transportation, health care, and communication, and on the natural environment (*A Framework for K-12 Science Education*, page 210).

The perspective that we offer in this chapter is one vision of the special role that CCCs can play in helping students weave together their growing understanding and ability in science and engineering to meet the challenges that they will be faced with as they leave our classrooms. As described in the *Framework* (pages 11-12):

The rationale for this increased emphasis on engineering and technology rests on two positions taken in *A Framework for K–12 Science Education* (NRC 2011). One position is aspirational, the other practical.

From an aspirational standpoint, the *Framework* points out that science and engineering are needed to address major world challenges such as generating sufficient clean energy, preventing and treating diseases, maintaining supplies of food and clean water, and solving the problems of global environmental change that confront society today. These important challenges will motivate many students to continue or initiate their study of science and engineering.

From a practical standpoint, the *Framework* notes that engineering and technology provide opportunities for students to deepen their understanding of science by applying their developing scientific knowledge to the solution of practical problems. Both positions converge on the powerful idea that by integrating technology and engineering into the science curriculum, teachers can empower their students to use what they learn in their everyday lives.

In this paper, we argue that the CCCs have a unique role in promoting students’ understanding of this important relationship between science and engineering.

The CCCs also have an important linguistic role in bridging science and engineering. One in four children in the United States speaks a language other than English at home (Mather, 2009), with this number projected to increase to one in three by 2060 (U.S. Census Bureau, 2012). English learners (ELs) are students “whose native language is a language other than English, and whose difficulties in speaking, reading, writing, or understanding the English language may be sufficient to deny the individual to meet the state academic standards” (U.S. Department of Education, 2016, p. 43). They face a unique challenge in school because they are learning English alongside learning content and developing literacy skills; thus, doing double the work (Short & Fitzsimmons, 2007). Given the realities of contemporary classrooms, teachers at all levels must be ready to address the needs of students from diverse linguistic and cultural backgrounds.

Stage, Asturias, Cheuk, Dara & Hampton (2013) found common skill development, such as obtaining evidence and synthesis of research across the NGSS and the Common Core State Standards Initiative (CCSSI, 2010). Research also indicates that ELs are able to read rigorous texts, engage in inquiry-based instruction, and participate in high quality dialogue about texts when provided high quality instruction from teachers trained to address language literacy, and content needs (Brooks, 2016; Lee & Anderson, 2009). The use of crosscutting concepts as bridges between science and engineering provides an opportunity for ELs to develop necessary language literacy and content knowledge by engaging in learning of both disciplines.

Teachers of ELs are required to provide language objectives, which promote student language development through reading, writing, speaking and listening. In addition, language objectives specify ways in which students will use language within the content. Furthermore, content-language objectives support language development of ELs in science (Jimenez-Silva, Merritt, Rillero and Kelley, 2016). These objectives explicitly state the ways in which language is used (e.g., explain, predict, compare and contrast), in relationship to the integrated science knowledge being learned and the supports needed (e.g., graphic organizers, working in pairs, small group discussion) to help them develop engineering and science proficiency. These content-language

objectives could be used to implicitly and explicitly support students in navigating between the disciplines using the CCCs. Thus, when bridging between content areas, language objectives could be used to identify what bridge students should be using, as well as how they will use the bridge to make sense of the content.

An analogy: CCCs as “bridges” between science and engineering

The NGSS is not intended necessarily to prepare all students to become scientists and engineers; rather, science and engineering provide opportunities to develop knowledge and skills that will allow students to participate productively in society as citizens. Science and engineering disciplinary core ideas, practices, and CCCs comprise knowledge and skills students need to solve everyday problems and succeed in a wide range of fields beyond science and engineering. When applied to the development of instructional materials and professional development of teachers, the vision of CCCs as bridges has the potential to accomplish two especially important outcomes: helping students fluidly integrate science and engineering as they encounter problems in daily life; and developing language literacy in the context of science and engineering.

In practice, scientists and engineers incorporate the three-dimensions into their content specific work. While engineering and science have their own specific disciplinary languages and practices, the CCCs weave throughout and across disciplines in connecting ways. Scientific inquiry and engineering design constitute distinct domains, each with their own language and customs. In this paper, we will describe how the CCCs can serve as bridges that connect the two domains—enabling the exchange of information in a way that is understood by each. While the CCCs defined by NGSS are often implemented as stand alone content, this paper posits that in actual practice, CCCs are bridging ideas between and within disciplines which serve to bring together core ideas and practices in three dimensions to produce scientific knowledge or a new idea.

A practical example of this is the development of a new battery for long term energy storage. One could envision diverse science and engineering professionals (e.g., chemists and physicists, electrical engineers, chemical engineers, materials engineers) exchanging information through conferences, publications, and personal communication. Within each discipline there exists language unique to the discipline, yet each discipline informs the others through a common language that incorporates CCCs such as energy and matter, structure and function, or scale, proportion, and quantity. While each discipline has its own language and way of working, CCCs can provide a common language framework for disciplines to inform and share information through this shared language and concepts. For example, a physicist may have an atomic perspective on battery storage and be concerned primarily with the ways in which electrons are stored within the atomic lattice, while an engineer may be interested in the bulk properties of the material the physicist is using in order to build a device. Through the language and bridging nature of CCCs such as *cause and effect* of material behavior, or language that specifies the *scales* at which these phenomena occur (atomic or bulk), the engineer is able to understand and apply the work of the physicist on a bulk material level. Although both have a different perspective on their common problem, the crosscutting concept of energy and matter help them bridge the gap.

Figure 1 illustrates the CCCs-as-bridges analogy. In Figure 1, the bridges represent the multiple pathways (the CCCs) that transverse science and engineering, any one of which is a potential exchange pathway for information, ideas, and technology development. Where multiple

scientists and engineers are working toward engineering solutions based on scientific principles, the pathway provides a common language for the exchange of information. While a physicist may be studying energy storage at the atomic level, an engineer can understand the “scale and proportion” or the “energy flow” embodied in this physics disciplinary work and apply the atomic level concepts to their own macroscale work. Similarly, K-12 teachers across disciplines can utilize the CCCs to support students’ understanding about how the disciplines connect and build upon each other. In the example of the solar oven later in the paper, physics concepts that describe atomic interactions of materials with heat and light are used to choose an insulating material for use in an engineering application for a solar oven. CCCs enable students to see the common thread between the disciplines and apply the information using the CCC. For example, the CCC of energy and matter helps students understand why insulating materials work the way they do, through bridging back to physics to understand conductivity and diffusivity of materials at the atomic level. Energy and matter also provides a lens through which students can make a design decision about what material to use by becoming part of a design criterion. By making the CCCs explicit, teachers can support students in understanding the link between science and engineering and model the role of CCCs in this understanding.

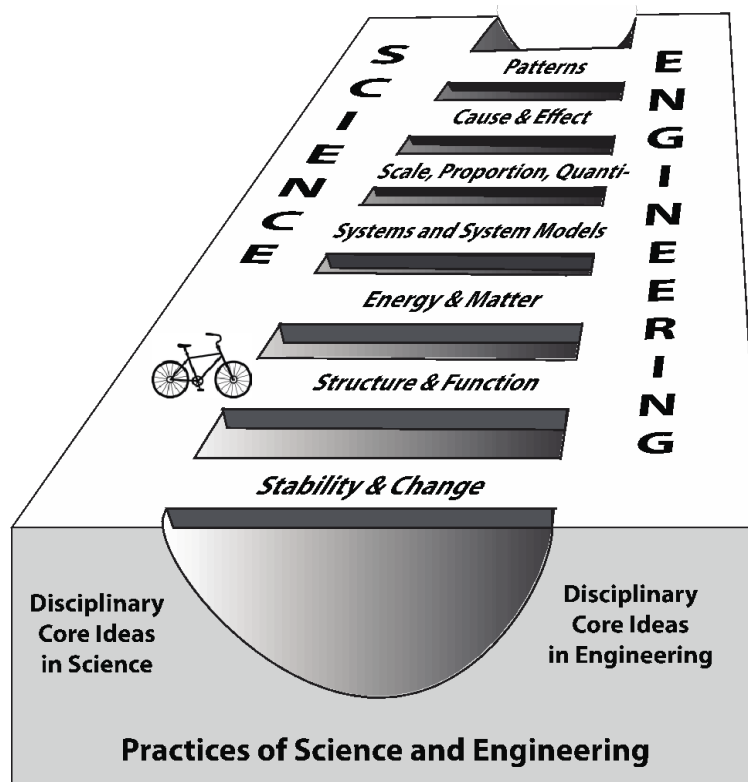


Figure 1. Analogy for CCCs as bridges between the distinct domains of science inquiry and engineering design

Fluidly Integrating Science and Engineering

Often in classrooms, without well-designed curriculum and supports, engineering projects lack connections with content and problem solving and become a craft project. Instead, engineering projects should make science consequential to understanding and solving a meaningful problem. CCCs can be used as a bridge to link engineering design

with scientific inquiry. Prompting students explicitly and thoughtfully to use the CCCs enables them to recognize the skills they are using to better understand and solve the problem, increasing the likelihood that they will apply these skills when encountering future problems.

For example, in many design challenges, students must choose materials with appropriate physical properties in order to achieve their design goal. CCCs can highlight the relationship between investigating the properties of different materials (science) and the decision about which material would be most likely to perform best for a particular purpose (engineering). For example, at the high school level students might apply *structure and function* to examine the molecular structure of alternative materials to predict which might be a good fit (such as for the NGSS PE HS-PS2-6: *Communicate scientific and technical information about why the molecular-level structure is important in the functioning of designed materials*). Students might subsequently use *systems and system models* to simulate the designed artifact in order to identify the best materials (such as for the NGSS PE HS-ETS1-4: *Use a computer simulation to model the impact of proposed solutions to a complex real-world problem with numerous criteria and constraints on interactions within and between systems relevant to the problem*).

Although students might not be explicitly aware of each CCC during the activity, reflection on how these CCCs helped them navigate between science and engineering to accomplish a goal would be a valuable lesson supporting the application of the process to future situations. Each of these examples provide a different aspect/dimension to the instructional experience and provides new information to inform the instruction. Whereas structure and function may tie back to physics core content at the lattice structure level to explore conductivity and diffusivity, systems and systems models provides a macroscopic viewpoint to inform decision making. The choice of CCC determines the type of information flow across/between disciplines.

There are myriad ways that thinking of CCCs as bridges between science and engineering can inform curriculum activities, scaffolds, assessments, and teaching moves. CCCs can help students (and teachers) move seamlessly between an engineering design problem and the science principles underlying that problem (Fick, 2018; Fick and Baek, 2017; Fick, et al., 2017). CCCs provide pathways that can help learners appreciate the interrelatedness of disciplines science and engineering. Promoting movement between science and engineering also helps to promote iteration between the disciplines--an important aspect of engaging in engineering problems that are anchored in one or more science disciplines. As students have opportunities to apply the same crosscutting concepts in many different situations, then can begin to see the common thread between the disciplines on their own, allowing them to consider new ways of thinking about the problem they endeavor to solve.

We envision that the choice of which CCC best bridge particular engineering design and science inquiry activities would initially be made by curriculum designers, teachers, and ultimately by students. Curriculum scaffolds in carefully designed instructional materials would guide students toward one or two specific CCCs that would be particularly appropriate for bridging an aspect of engineering design with an underlying aspect of science inquiry. Teachers could also learn to use CCCs as part of their teaching moves to support students in crossing back and forth between engineering and science in appropriate ways. Over time (perhaps years), through repeated interactions with the CCCs, a student might be able to move from scaffolded intentional (explicit) interactions towards autonomous use of appropriate CCCs to fluidly integrate

engineering and science toward the solution of new problems that they encounter in everyday life. Later in this paper we discuss examples of how this approach could be implemented.

An instructional model for promoting student learning

Figure 2 illustrates a model for how instruction can promote student outcomes of interest. The model places the view of CCCs as a bridge in the context of other model components. Here we describe each component of the model and its key interactions with other components.

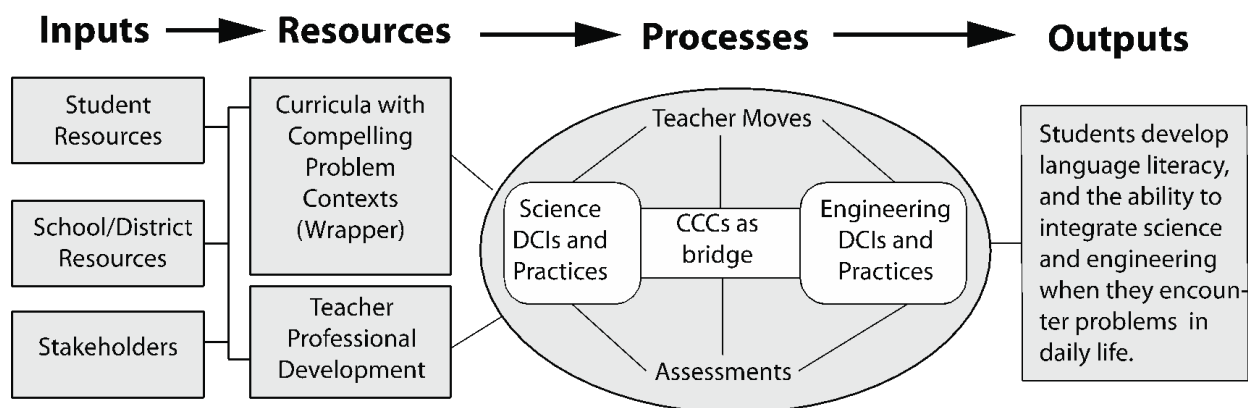


Figure 2. Model illustrating the central position of CCCs in the integration of science and engineering, leading to meaningful student learning outcomes

Student resources. Students bring a range of cultural and linguistic resources and experiences to classroom settings. We describe the ways CCCs in particular can leverage students' linguistic resources to bridge the disciplines of science and engineering. These resources and experiences should underlie determinations of what problems students find "compelling" in addition to teacher PD that helps teachers consider and leverage the resources and experiences students bring to the classroom.

School/district resources. How curriculum materials are implemented with students depends on school and district resources that are available to teachers.

Stakeholders such as parents/local communities, schools/districts, states, curriculum and assessment developers, and education researchers are all in a position to shape NGSS-aligned instruction.

Curriculum Materials with Compelling Problem Contexts address the intersections between engineering and science. Analogous to an authentic "driving question" in science that culminates in a scientific explanation of a compelling phenomenon, engineering units should be "wrapped" in an authentic problem context that compels the students to engage iteratively in engineering design and science inquiry to arrive at a solution (e.g., Fortus et al., 2005). These problem contexts can be centered around a particular technology, which can also help drive iteration across engineering and science. "New insights from science often catalyze the emergence of new technologies and their applications, which are developed using engineering design. In turn, new technologies open opportunities for new scientific investigations." (Framework, p. 210) These materials (many of which already exist) include student instructional activities, guidance for

teachers, and both embedded formative and summative assessments. Especially relevant for this model is that they feature CCCs as bridges between the disciplines, as described above.

Teacher Professional Development informs the successful classroom implementation of curriculum materials. NGSS-aligned teacher PD should help teachers understand the relationships between science and engineering, the nature of the three NGSS dimensions and, in particular, the potential role of CCCs to help students integrate these disciplines.

Processes occurring in classrooms to promote student learning include student instructional activities, guidance for teachers, and assessments. Activities integrating science and engineering could feature CCCs in appropriate ways to help bridge the disciplines, as described above. Embedded assessments could be designed to measure students' ability to integrate science and engineering by way of a specific bridging CCCs. Guidance for teachers can suggest teaching moves that can best highlight the most appropriate bridging CCCs for specific engineering and science contexts. Teacher guidance can also help teachers use responses from instructionally-supportive assessments to guide students toward integrated understanding of science and engineering.

Learning outcome: Following the *Framework*, we identify as a meaningful student learning outcome that students are able to participate in ways of thinking that are consistent with epistemic practices of engineering and science and specifically the two goals described above: language literacy in science and engineering, and the ability to fluidly integrate these fields to solve problems in everyday life.

Curricular examples

We close the paper with two examples of how CCCs are used as bridges between science and engineering in well-established engineering curriculum materials: *Engineering is Elementary* and *Engineering the Future*. These examples illustrate how different parts of the model can be implemented toward the development and implementation of three-dimensional curriculum materials that integrate science and engineering.

Example 1: Designing a solar oven

The *Engineering is Elementary Now You're Cooking: Designing Solar Ovens* curricular unit (Engineering is Elementary, 2011) interweaves CCCs with disciplinary core ideas related to energy. It is well aligned with NGSS Performance Expectation 4-PS3-4: *Apply scientific ideas to design, test, and refine a device that converts energy from one form to another*. Students are introduced to the engineering problem with a storybook. It features a girl, Lerato, from Botswana who is responsible for many chores. A fellow villager studying green engineering at college, gives Lerato a solar oven, which could eliminate the task of collecting firewood. But Lerato needs to improve the oven so it works. Students in the class also tackle this problem. This unit takes an unconventional approach to solar oven design. Instead of asking students to design the external parts of the oven (box and window), students are challenged to think about how they might engineer insulation for the oven system that helps it retain heat. Because the unit focuses on the field of green engineering, students' designs are also assessed based on how environmentally friendly their solution is.



Figure 3. Students design insulation for their solar oven. (Image courtesy of EiE, Museum of Science, Boston.)

As students engage in the open-ended design of a solar oven, they apply their knowledge of heat transfer, energy, and insulators to an authentic, concrete context. The unit’s design reinforces science concepts that include:

- Some materials transfer heat energy more readily than other materials (there are thermal insulators and conductors)
- Heat transfer constitutes an engineering design variable for the construction of a solar oven
- Energy can be transferred from one object or material to another
- Heat energy always moves from warmer locations to cooler locations (Engineering is Elementary, 2011, p. 78)

Thus, the CCC related to *energy and matter flows, cycles, conservation* is a central focus of the unit. Concepts related to *structure and function* and *patterns* also become important in the design and evaluation of their solar oven.

To encourage students to adopt a knowledge-based approach to the design of their solar oven insulation, prior to tackling the full challenge students engage in hand-on lessons that develop their understandings of how solar ovens work and the properties of the materials that will have available to use as insulation. Students are prompted to consider *structure and function* of a solar oven--students must articulate the relationships among purpose, its parts, and why it’s designed in the way it is. By design, the conversation elicits concepts related to *energy flows* as students must explain that what the oven technology needs to do is trap light and heat energy from the sun and transfer it to the food.

Before students begin to design their insulation solution, they also conduct some controlled tests to determine how well the available materials perform as thermal insulators. Students test five materials—foam sheets, felt, aluminum foil, newspaper, and plastic—in two forms—flat and shredded—and compare it to a control. They predict which materials will work best and why, and record temperatures over time when each is used as an insulator.



Figure 4. Student conduct tests of materials' performance as thermal insulators.(Image courtesy of EiE, Museum of Science, Boston.)

Once they have collected all the data, the student groups calculate the change in temperature. In their groups and as a class they analyze these data on how the materials and treatment performed. In so doing, they identify a number of specific kinds of *patterns*—in the shape of the temperature graph, in the performance of a materials across groups, and in the properties and *structures* of a materials that determine how well it works as an insulator. Throughout, students are prompted to explain their results in terms of *energy flow and conservation*.

The focus on green engineering also invites a second type of *energy flow and conservation* analysis. In the final step of the materials exploration lesson, students discuss the environmental impact of the available materials. They think about how energy is used in the production and use of the various materials: whether it is natural or processed, how much they need, whether it has previously used, and/or whether then can recycle it. From these conversations, students create an environmental impact scale that ranks the materials. Such dialogue encourages students to talk amongst themselves to identify *patterns* in their results that inform the development of a class-wide impact scale. Throughout, they are thinking at a broad level about the *flow of energy* with respect to materials choices and the impact these have on the environment.

Having developed some insights into the materials they will use, students are better prepared to make informed decisions as they tackle the design challenge of creating insulation for their oven. They revisit the data from their previous experiments as they make design choices. Which materials should they use? How much of each? In what configuration inside the oven? Here they apply their understandings of performance *patterns*, *structure and function*, and *energy flow and conservation*. The students are authentically using the concepts because they are motivated to design a high-performing oven. They create their initial design and test it, gathering data about how quickly the oven heats up and how well it retains heat when removed from the heat source. They also assess the environmental impact of the materials they selected. Student groups analyze their data, then share their designs with classmates and look for *patterns* across designs that could inform subsequent revisions as they reflect upon what has worked, what has not, and why.

As students participate in the activities, they develop knowledge that is relevant to the problem at hand. Finally the authentic context invites students to engage continually and in meaningful ways with CCCs with respect to both science inquiry and the engineering design of an artifact for

which the science inquiry is consequential to the outcome. Students think about their experiments and data and generate *patterns* that they use to inform their next steps or design choices and explanations. They consider the *structure* of the materials they used, and the structure of how they arranged them in the oven as they sought to optimize the *function*, or performance, of their oven. And throughout the unit, both as they chose environmentally responsible materials that *conserved energy* and as they designed a technology that relied on *energy flow and conservation*, students think about how energy moved through the system as they worked to maximize its conservation within the oven. In these ways, students “cross the bridge” from materials science to engineering design by considering the crosscutting concepts of patterns, structure and function, an energy flow and conservation. within the oven. Each of these crosscutting concepts provides a different way of seeing the connection between scientific thinking (such as the energy properties of different materials) and engineering design (the way those materials are used to build an efficient solar oven.)

Creating a classroom environment that encourages students to move back and forth between science and engineering knowledge, practices, and CCCs can be challenging. A variety of types of professional development--face-to-face, online, video resource etc.--can support teachers as they consider how to introduce such new types of activities. Teachers value opportunities to experience the lessons as learners and as educators. They engage in the activity and then step back to think about how facilitation can encourage students to traverse the disciplines and the dimensions that are present throughout the activity. It will be important for the teacher to help the students explicitly apply crosscutting concepts by asking pertinent questions, such as: “What pattern do you see in your graphs of temperature over time? Are there some features that are the same in the graphs from different teams? Which different structures of reflecting materials worked best to focus the sun’s energy? Which structures of insulating materials worked best to keep heat from escaping from the oven? How did the energy flow through your oven? Where did it come from? Where did it go?”

The solar oven curricular example details several aspects of our instructional model Figure 2. (1) Students bring many **conceptual and linguistic resources** to activities on energy. Colloquial use of the terms energy and heat different in specific ways from their use in science and engineering. Instruction should address these distinctions head-on. (2) **School resources** required to enact these activities are minimal, as they employ common materials and equipment. Access to refined and tested curricula such as Engineering is Elementary also constitutes a key school and district resource. (3) The solar oven unit comprises a **compelling engineering design context** anchored to an authentic scenario taking place in Botswana. (4) Teacher professional development provides guidance to teachers on how to scaffold students’ understanding so that they can accomplish creative engineering tasks. (5) Energy and matter, patterns, and structure and function comprise the **central CCCs that bridge** students engagement with scientific investigation about the thermal properties of materials and the performance of these materials for the purposes of engineering design the solar oven. In the solar oven unit, the activity sequences and explanation prompts are carefully designed to elicit the use of these CCCs to explain materials properties and justify engineering design decisions.

Example 2: Designing a battery

We draw a second example of how CCCs can bridge between engineering and science from a ninth grade engineering curriculum, *Engineering the Future: Science, Technology, and the*

Design Process, 2nd Edition (Bunn et al., 2018). Each of the four major projects of the course begins with an engineering design challenge—a meaningful task, we refer to as a “wrapper” that motivates students’ scientific investigations and engineering design activities throughout the unit. One of these challenges is to design a battery that can be constructed in case of emergencies from common household materials. The battery has to have sufficient voltage to light an LED with enough current to generate useful light.

Earlier in the unit, the students learned about various types of circuits, and designed and built battery holders and “LED gadgets” to accomplish goals of their own choosing. In the earlier activities the battery was a “black box.” That is, they used batteries but didn’t know how they functioned. The purpose of this activity is for students to learn not only how batteries work, but also how they are designed to maximize electrical power in a small space.

The activity begins with the common lemon battery, using coins and washers for two different metals. Students join several fruit cells together to generate a higher voltage, using a digital multimeter (DMM) to measure voltage. These are essentially “maker” activities, intended to give students practice using the technology. In order to determine how to engineer a better battery they need to conduct a scientific investigation to determine what materials they can use to structure the battery so it functions more efficiently.



Figure 5. Fruit battery. Image courtesy of Cary Sneider

Teams begin a scientific investigation to test various combinations of electrodes (pairs of different metals) and electrolytes (liquids in which the electrodes are immersed.) The only way for them to make sense of the data from their investigation is to vary the materials systematically and use a common testing protocol and DMM to quantify the results. Once they discover which materials produce the most power (defined as voltage times current) they design their batteries, considering what they can expect to find around the house in case of emergencies. Students are often surprised to see how much light they can produce—and how long their battery will last—with just a few common materials.

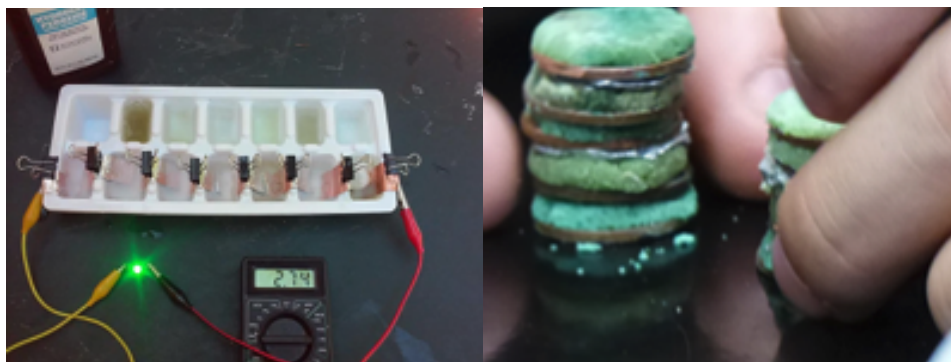


Figure 6. Examples of students' final designs. Images courtesy of Cary Sneider and Mihir K. Ravel

Professional development workshops that we've conducted on how to use the curriculum have emphasized essential teacher moves that are common to all four units: start with a meaningful challenge that will motivate your students for several weeks. Engage them in a hands-on activity on the first day, and continue with hands-on activities throughout the unit in which they cycle back and forth between science and engineering to develop the science and practices that they need to meet the challenge. Use maker activities to enable students to develop facility with the technology, then transition to creative engineering activities once they've learned enough to meet the challenge. At various stages along the way, have the students reflect on their work, using CCCs to connect the various activities within and across the four units (as described below). The CCCs that the students apply multiple times as they move from engineering to science and back again include:

Cause and effect. Once the students are clear on the effect they want to achieve—light the LED as brightly as possible—they apply cause and effect to the investigation of lemon battery technology and as well as to final engineered designs. Cause and effect guides the interpretation of the investigations of specific materials, and consequently the causal relationship between the engineering materials in the battery and the battery's performance. In other words, cause and effect provides a bridge from their scientific understanding to their ability to design a functioning battery.

Energy and matter. Students refine their mental models of how energy is conserved as chemical energy is converted to electrical energy, and finally to light energy. A critical question in design is how to reduce the amount of energy that is “lost” to the environment at each step—the CCC frames the discussion about the impact of this lost energy on the performance of the battery. This is perhaps the clearest case where understanding of the science is essential in asking the right question needed to make the device more efficient. Since some energy becomes less useful (not actually “lost”) during transformations, students are directed to points in their design where energy is transformed from chemical energy to electrical energy, and from chemical to light energy, as well as connections where energy is transferred from one component to another.

Structure and function. During their science activities, students investigate the structure of individual cells, varying the distance between the electrodes and the amount of metallic surface that is exposed to the chemical reactions. This investigation reveals the relationships between the physical structure of their battery and its performance. They then apply their findings to engineering batteries that produce maximum power for the

longest time. The data from the science experiments can be thought of as the bridge helping students connect their scientific investigations with the design of their batteries. Again, the teacher's role in calling attention to these ideas by asking the right questions at appropriate times, and calling on students to reflect on their use of the CCCs is essential in helping them learn to use the CCCs as invaluable ways to bridge between their understanding of science, to solving realistic problems through engineering.

The battery curricular example details several aspects of our instructional model in Figure 2. (1) Students bring many **conceptual and linguistic resources** to their understanding of electricity. Students' everyday understanding of electricity tends to be vague and often does not distinguish between specific scientific concepts such as current, voltage, and electrical power. The battery unit recognizes these conceptions and prompts students to distinguish the concepts. (2) **School resources** required to enact these activities include common household items, making them easy to implement in the classroom. (3) The battery unit comprises a **compelling engineering design context** around building a battery in the event of an emergency, with the tangible and practical goal of producing a useful amount of light. (4) **Teacher professional development** emphasizes teacher moves that are common to activities integrating science and engineering and use the CCCs to bridge the two disciplines. 5) Energy and matter, cause and effect, and structure and function comprise the **central CCCs that bridge** students engagement with scientific investigation about electrodes and electrolytes and the performance of these materials for how the battery should be designed.

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The Integration of Cross-Cutting Concepts in Three-Dimensional Learning

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Introduction

The Framework for K-12 Science Education (Framework; NRC, 2012) and the Next Generation of Science Standards (NGSS Lead States, 2013) present a new vision of science teaching and learning. The Framework advances three dimensions of scientific learning that include disciplinary core ideas (DCIs), crosscutting concepts (CCCs), and scientific and engineering practices (SEPs) that work together to support learners in “scientific inquiry and engineering design” (NRC, 2012, p. 2). The three dimensions appeared in earlier standards documents, as “content standards”, “unifying concepts and processes”, and “science as inquiry” (NRC, 1996), but their relationship was not fully elucidated. A major contribution of the Framework is describing how the dimensions work together to support student learning, through experiences in which students “actively engage in scientific and engineering practices and apply crosscutting concepts to deepen their understanding of the core ideas in these fields” (NRC, 2012, pp. 8-9).

DCIs are powerful in that they are a foundation for future learning. DCIs have some or all of the following characteristics: they are important in various disciplines of science or are a “key organizing principle” in one discipline; they “provide a key tool for understanding or investigating more complex ideas and solving problems”; they are relevant to societal problems and/or students’ lives; and they are broad enough to support teaching and learning over several years (NRC 2012, p. 31). The deep coverage of a small set of fundamental ideas is aimed at developing learners who can continue to learn, assess the reliability of sources of information, and continue their development as scientists. This kind of learning stands in contrast to the wide but shallow coverage of disconnected facts that result in fragile, fragmented knowledge (p. 31). SEPs consist of the multiple ways in which scientists and engineers explore and understand the natural and the designed world.

The Framework also requires learners to develop CCCs that are major ideas that traverse and are important to all the science disciplines (Duschl, 2012). The seven CCCs identified in the Framework are: Patterns; Cause and Effect; Scale Proportion and Quantity; Systems and System Models; Energy and Matter; Structure and Function; and Stability and Change. CCCs are posited to “help provide students with an organizational framework for connecting knowledge from the various disciplines into a coherent and scientifically based view of the world” (NRC, 2012, p. 83). The Framework notes that there is limited research on teaching and learning CCCs. This gap has posed an obstacle to the implementation of the vision of the NGSS. In this paper, we set forth a model for systematic development of both teachers’ and students’ understanding of how CCCs integrate with DCIs and SEPs

Theoretical Framing

In this section, we articulate the theoretical considerations that underpin our model that includes: 1) Exposure to and adaptation of high quality curriculum and assessment tools; 2) Working with stakeholders in the educational ecosystem that includes researchers, expert teachers, and curriculum developers in communities of practice that builds both human and social capital; 3)

Commitment to addressing the one-size does not fit all constraints of real world classrooms through iterative design to support the integration of CCCs in all learning contexts.

Exposure to and adaptation of high-quality curriculum and assessment tools

High-quality curriculum and assessment tools can only be built following a well-specified, theoretically driven, design process. One approach is the construct-centered design (CCD) process (Pellegrino et al., 2008; Shin et al., 2010). This approach builds on learning-goals-driven design (Krajcik et al., 2008) and evidence-centered design (Mislevy et al., 2003), and is consistent with current thinking in instructional and assessment design (e.g., Pellegrino et al., 2001; Wilson, 2005). The steps in CCD are to clearly define and "unpack" the construct; specify claims that describe what we wish students to be able to do with their knowledge of the construct; define what we will take as evidence that the student has met the claim (mastered the knowledge); and develop tasks that will produce the evidence (Pellegrino et al., 2008). These tasks can lead to an assessment instrument, and also can serve to suggest learning activities aimed at producing understanding keyed to those tasks. Unpacking a construct includes defining and breaking apart the concepts, identifying prerequisite knowledge, making implicit understandings explicit, identifying illustrative phenomena and then – relying on extant or new research - determining likely student prior knowledge and challenges (Krajcik et al., 2008; Stevens et al., 2010).

Working with stakeholders in the educational ecosystem in communities of practice

Penuel and colleagues (2011) discuss major challenges in determining what collection of activities will be effective across a variety of learning environments and impact the greatest number of students and teachers. They suggest that such innovations require coordination in local contexts. Successful implementation is contingent on the ability of the teachers, school leaders, and principals to adapt tools and support to local contexts. Penuel et al. describe a design-based implementation research (DBIR) framework that illustrates the necessary design elements for innovations to take hold at a larger scale: (a) the formation of teams of multiple stakeholders focused on persistent problems of practice; (b) a commitment to iterative collaborative design, in which teams focus on designing, learning from, and redesigning project activities; (c) a focus on developing theories about how people learn in particular contexts; and (d) developing capacity for sustaining change within systems through intentional efforts to develop infrastructures.

Growth models of teacher practice are often based on the acquisition of skills and knowledge, overlooking the importance of contextualized training (Rice & Dawley, 2009) and learning within a community of practice (Lieberman & Mace, 2010). A review of the literature suggests that PD is most effective when it (a) is embedded in subject matter, (b) involves active sensemaking and problem solving, and (c) is connected to issues of teachers' own practice (Garet et al., 2001). Moreover, research on teacher learning highlights the following important characteristics to consider in the design of PD: (d) treating teachers as knowers and agents of change, (e) fostering social relationships focused on knowledge sharing about problems of practice, and (f) creating networked teacher communities that are based on a foundation of trust (Baker- Doyle, 2011; Cochran-Smith & Lytle, 1999; Hatch et al., 2006; Lieberman & Mace, 2010; Yoon, 2018). We assume from the outset that teacher training will include a focus on the

development of human capital (e.g., teacher’s understanding of crosscutting concepts); and the development of social capital (e.g., sharing and acquiring knowledge of how to implement the crosscutting concepts from others).

Commitment to iterative design

We take the approach aligned with Cobb et al. (2003) and Sandoval (2004) that the design of learning environments is a theoretical activity and that “learning environments intrinsically embody hypotheses about how learning happens in some context and how to support it” (Sandoval, 2014; p. 20). We adopted the use of conjecture maps, a method proposed by Sandoval (2014) as a tool within the DBR paradigm to systematically scrutinize our theoretical ideas about CCC curricular development and implementation.

Sandoval (2014) explains that “[w]hatever the context, learning environment designs begin with some high-level conjecture(s) about how to support the kind of learning we are interested in supporting in that context” (p. 21). The conjectures are then instantiated in the particular embodiments that the design team believes will lead to desired outcomes in a particular context. This includes the embodiments of the *design* (tools and materials, task structures, participant structures, and discourse practices); *mediating processes* (what we can observe and measure); and *outcomes* (e.g., content learning or participation). Conjecture maps organize what we attend to as researchers for improving the design of interventions. By following conjectures, as designers of research, we can locate how and in what ways our embodiments lead to the desired outcomes with the goal of iterating toward improvement.

Description of the Model

Figure 1 illustrates our conjecture map that shows the elements of our model for integrating CCCs into three-dimensional learning.

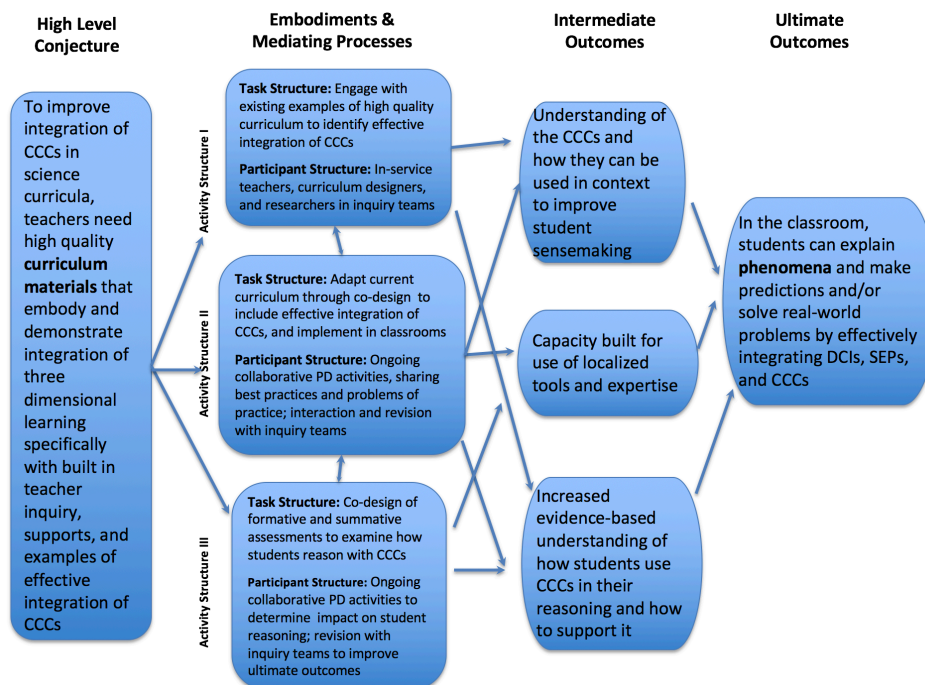


Figure 1. Conjecture map of CCC integration in three-dimensional learning.

We modify the original conjecture map structure in Sandoval (2014) to both simplify embodiments and mediating processes and to include teachers and students in learning and participation outcomes. We assume that tools, e.g., simulations or models that help to support systems understanding, are included in high quality curriculum. We also assume that discourse practices are included in both task structures (e.g., student's collaboratively solving problems) and participant structures (e.g., teacher's negotiating problems of practice). For mediating processes, we assume that embodiments will be evaluated with and by relevant stakeholders (e.g., teachers through action research; researchers through observations and interviews). Furthermore, our model includes intermediate outcomes that are related to teachers and instructional capacities, as well as, ultimate outcomes that describe what we expect students to learn and do through three-dimensional science learning.

To instantiate our high-level conjecture, we offer two activity structures that encompass the embodiments we offer in our model. These are described in more detail below.

Activity Structure I

This activity structure begins with examining existing high-quality curricula to identify effective use of CCCs. Researchers can provide initial curricula that have already been developed to support three-dimensional learning and tested or assessed with evidence of successful learning outcomes with students (see examples below). Researchers will work with in-service teachers to investigate what specific CCCs look like in practice, the value-added nature of CCCs and how they have been used in particular content domains to interact with SEPs and DCIs to improve student sense-making. The intermediate outcomes will include teachers learning about CCCs and how they can be used in practice in addition to understanding how students reason with CCCs to make sense of the phenomenon.

Activity Structure II

This activity structure focuses on working with in-service teachers as co-designers and adapters of high-quality curricula and investigating implementation in local school contexts. As teachers implement, they are asked to assess the characteristics in their environment that afford and constrain their ability to effectively use CCCs in their instruction. Teachers along the novice-expert continuum work with researchers together in professional development to share best practices and problems of practice to support each other in developing their understanding of CCCs, how they are used in practice, and how students are reasoning with them. An added intermediate outcome in this activity structure has to do with the building of local capacities both in tool use (e.g., computer models) and pedagogical content knowledge, such that expertise is distributed across educational systems

Activity Structure III

This activity structure works concurrently with the first two activity structures to support the development of formative and summative assessment tools that examine how students are reasoning with the curriculum and through the CCCs. Similar to the other activity structures, teachers will work with researchers in inquiry teams to integrate these assessment tools in their curricula. Assessment tools can take many forms including transfer of knowledge to different content, ability to apply knowledge and problem solve in real world contexts, ability to effectively use tools to gather information in CCC categories to make sense of phenomena (e.g.,

collecting data from simulations to show how whether patterns change in climate systems). The intermediate outcomes for teachers will be the development of assessments as tools for understanding student reasoning.

Examples of the Model

In this section, we provide two examples of particular activity structures that illustrate how we envision the model operating to better integrate CCCs in three-dimensional learning.

The BioGraph Project and Learning About Systems

This first example illustrates Activity Structure II: Working with in-service teachers as co-designers and adapters of high-quality curricula and investigating implementation in local school contexts. BioGraph project was an NSF-funded project aimed at improving high school Biology instruction through a central focus on the CCC of systems and system models (for more details see Yoon et al. 2016; 2017). This professional development design and development study was conducted between August 2012 and June 2014. We worked with the same teachers over the course of the study, who themselves worked with separate cohorts of students in the 2012–2013 and 2013–2014 academic years. Teachers participated in two week-long summer PD workshops (one workshop per summer, 30 hours each) and follow-up Saturday workshops during the school year (approximately two workshops per semester for 10 hours per year). PD activities included hands-on training in five biology units on the topics of Genetics (DCI-LS1B, Evolution (DCI-LS4B), Ecology (DCI-LS2A), the Human Body (DCI-LS1A), and Animal Systems (DCI-LS3). The units entail working with a systems modeling tool called StarLogo Nova that uses graphical blocks-based programming. Figure 2 shows a screen shot of the simulation used in the unit entitled, “Modeling a Pond Ecosystem.”

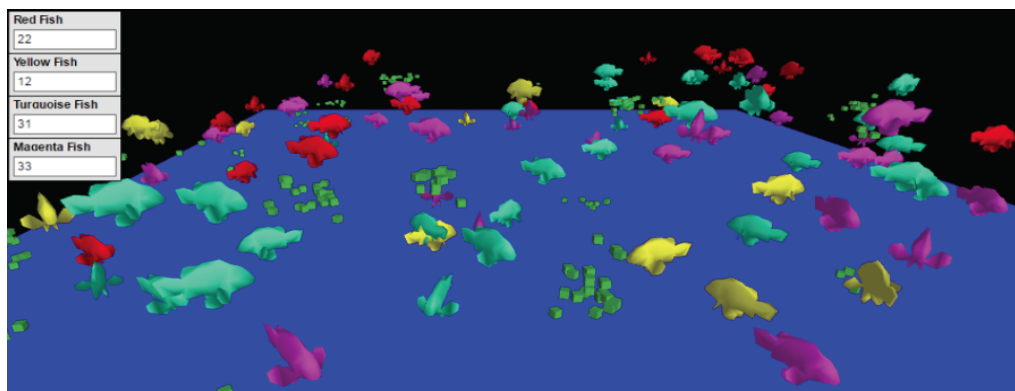
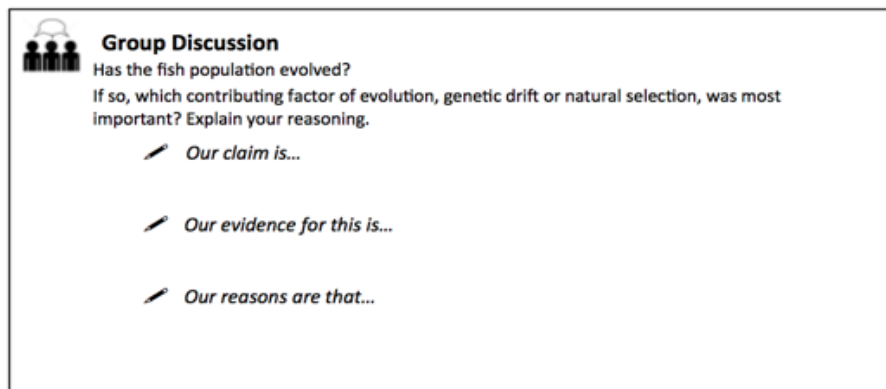


Figure 2. StarLogo Nova translates blocks of computer code into a virtual 3D ecosystem of fish, grasses and algae.

Students are asked to build an ecosystem made up of interacting and interdependent parts and learn that biotic (living) and abiotic (non-living) variables are constantly interacting with and changing each other. They learn about the concepts of random motion, competition, reproduction rates, and energy, in an effort to support student understanding of how healthy ecosystems operate.

All the units include working through experiments that provide experiences in core NGSS SEPs, such as analyzing and interpreting data, engaging in argument from evidence, and obtaining, evaluating and communicating information (see Figure 3 for a curricular argumentation prompt).

Students normally work in groups of 2 or 3 to complete the units. There is no set sequence for the units; instead, teachers can implement them in the order that suits their school curriculum. The explicit focus on learning about systems are instantiated in curricular materials for each unit that take 2–3 days to complete and include popular and academic literature about systems as well as short movies, PowerPoint presentations, and teacher and student activity guides.



Group Discussion

Has the fish population evolved?
If so, which contributing factor of evolution, genetic drift or natural selection, was most important? Explain your reasoning.

Our claim is...

Our evidence for this is...

Our reasons are that...

Figure 3. Curricular example of scaffolding the scientific argumentation process with the simulation activity.

PD activities in the summer included training in core systems structures, behaviors, and functions, such as feedback, interdependence, self-organization, emergence, and scale. Other activities required teachers to complete all the units in partners to learn about what their students would experience, extended reflection with each other and the research team on how the units could be improved, pedagogical issues they foresaw in terms of implementing the units in class, e.g., how to make connections to the regular biology curriculum, and how to conduct inquiry-based experiments, argumentation, and explaining systems concepts to their students. Teachers also spent time planning how the units would fit into the scope and sequence of their courses, and brainstormed ways that the curricula could be modified to meet their student population needs, e.g., learning how to program.

During the school year, teachers implemented the units in their biology classes. Approximately twice a semester, teachers assembled in Saturday morning workshops to share their best practices and problems of practice and to participate in further training based on feedback from implementation efforts. Teachers understood from the beginning of the project that they were co-testers and collaborators, and that their feedback about any classroom issues was critical to redesigning resources for optimal learning. We then collected a series of data sources to understand what was working and what was not working in the first year. Teachers moved fully into co-designer roles after the first year of implementation. During the second summer workshop, several teachers led workshop sessions and shared additional curricular supports they created during the year. Teachers also worked in teams to develop assessments, create differentiated opportunities for second-language learners, and locate additional topics in the school biology curricula for which systems could be highlighted.

We present here a model of an activity structure that enabled teachers and researchers to jointly adapt curriculum to meet the needs of their specific teaching and learning contexts that was driven by a central focus on the CCC of systems and system models. Through ongoing collaborative PD activities, teachers and students developed instructional and content expertise through integrated three-dimensional learning (Yoon et al., 2015; 2016; 2017).

How can Nanotechnology Keep me From Getting Sick?

The second example describes an existing high-quality curriculum focused on the crosscutting concept of scale, proportion, and quantity, and traces potential next steps that illustrate all three activity structures in our model. The 12-hour middle school curriculum unit was developed as part of the National Center for Learning and Teaching in Nanoscale Science and Engineering with funding from the National Science Foundation. The curriculum focused on the “unifying theme” of scale as described in the AAAS *Benchmarks* (1993). The unit was project-based and framed by the driving question, “How can nanotechnology keep me from getting sick?” (Delgado et al., 2015). The unit was developed following a construct-centered design process, and implemented in a free, two-week summer camp with 32 middle school students from a low SES, high-minority public school district. Activities included use of physical and computer models, investigations of bacteria on various surfaces through incubation, microscope investigations of cells using the students’ own hair as a boundary object between the macroscopic and microscopic worlds, and the critical analysis of one nanotech product’s claims of being so smooth it would not harbor germs. Community involvement included presentations by scientists and student groups presented their work at a final event that included parents. This curriculum resulted in statistically significant, high effect-size learning gains that closed the gap between the public school students and their private middle school peers in a near-by city; the campers’ level of knowledge was descriptively higher than their high school peers in the same public school district after the unit (Delgado et al., 2015).

The summer camp setting provided significant leeway in designing the unit. Learning goals were developed based on concepts of scale, with no explicit consideration of district or national standards. Furthermore, the unit was developed prior to the publication of the Framework and NGSS. Thus, the scaling up of this promising unit will require modifications in order to be suitable and feasible for middle school science classes and aligned with the current standards. We envision a process starting with Activity Structure I, in which teachers would experience the unit as learners, trace specific features to DCIs, CCCs, and SEPs, and proposing ways to adapt the unit to their existing contexts and constraints. The research around this unit provides rich descriptions of how students reason with CCCs to make sense of phenomena.

Activity Structure II would be implemented next, involving in-service teachers as co-designers and adapters of the unit for their own context. For instance, the original unit is framed around the then-newsworthy issue of antibiotic-resistant bacteria; more current issues could be recruited to make the unit more relevant to students’ interests. The adaptation process would thus proceed among multiple parallel tracks, affording an excellent opportunity for teachers and researchers to collaboratively assess the characteristics in their environment that afford and constrain their ability to effectively use CCCs in their instruction. For instance, some teachers might *add* DCI and SEP foci to the existing unit, while other might *draw from* the unit a subset of activities to support the CCC of scale, proportion, and quantity in their DCI + SEP-focused units. An enhanced understanding of how students are reasoning with CCCs in general, and scale in particular, would be expected to emerge. An inductive analysis could lead to a nascent understanding for what PCK for CCCs consists of, and how it might develop.

Activity Structure III would involve the creation of assessments that test all three dimensions of learning, but that also evaluate whether students’ growing understanding of the focus CCC does in fact yield more connected and organized knowledge. For instance, do students better distinguish between cells and molecules (Arnold, 1983) or cells and atoms (Flores, 2003;

Harrison & Treagust, 1996)? Do they better understand the connection and relationship among these entities? Do they use scale concepts in arguments about weather and climate in the context of global climate change?

In sum, the three activity structures in the model presented here would support the adaptation, implementation, and evaluation of a promising curriculum implemented in a summer camp environment to the packed and pressured context of teachers' classrooms.

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CCCs as epistemic heuristics to guide student sense-making of phenomena

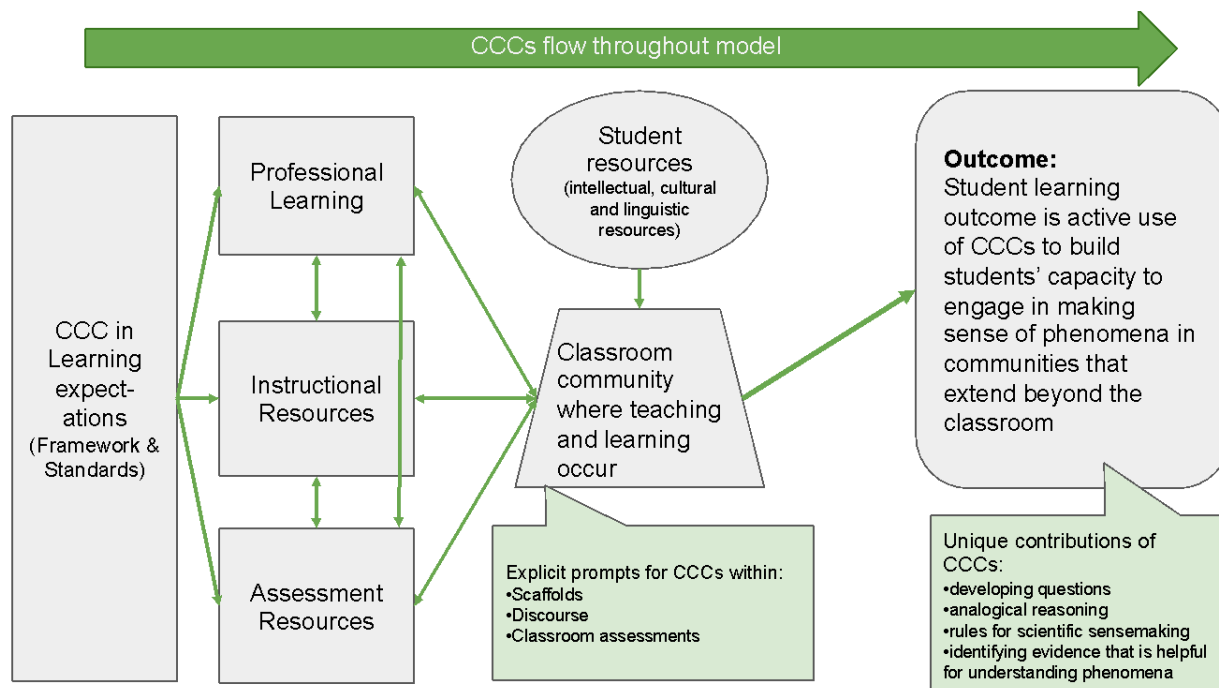
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Theoretical Framing and Introduction of the Model

In developing the model of crosscutting concepts (CCC's) and their relation to learning and instruction, we took a backwards design approach that began with a consideration of what outcomes were important and what it would take to achieve them (Wiggins & McTighe, 1998). In elaborating the CCC's and generating the model, we focused on highlighting the CCCs but we caution that CCC's should never be learned or assessed in isolation without appropriate DCI's and SEP's.

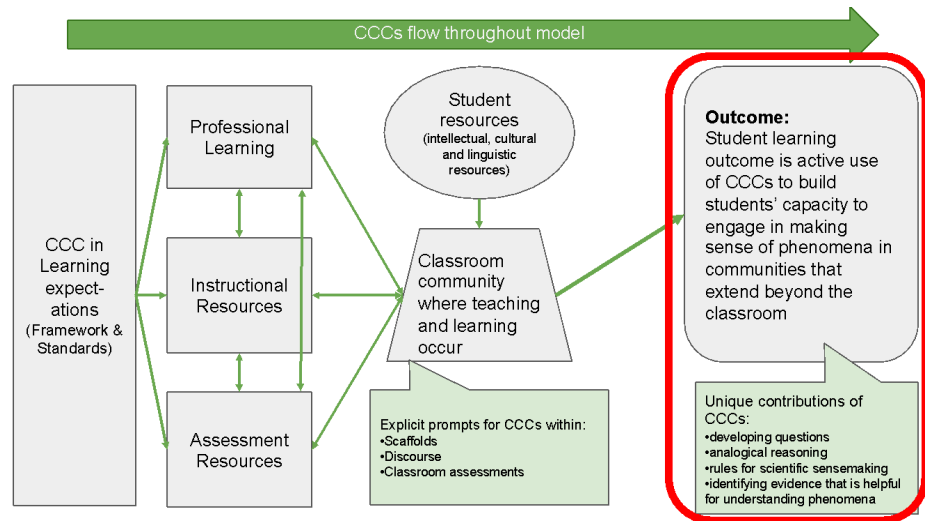
The model presented in Figure 1 takes the sociocultural context into account and the broader issues related to creating a classroom community that supports and enables students' capacity to transfer what they have learned (Danish & Gresalfi, 2018). Such a perspective considers learning and activity to be inextricable from contexts, communities, and practices, (Engeström, 1999; Lave & Wenger, 1991). From this perspective learning is mediated by both material and conceptual tools, including disciplinary and discursive practices (Kozulin, 1998). Scaffolding is important in helping learners accomplish tasks that they could not do without support as well as allowing learning to fully engage in meaningful activity while learning (Hmelo-Silver, Duncan, & Chinn, 2006). Our model represents these tools in terms of the range of resources that students and teachers bring to the learning situation, the role of the community, scaffolds, and what learners bring to the community beyond the classroom.



Components of the Model: Descriptions and Examples

Outcome of the Model

We begin our discussion of outcomes with the idea that children go to school to prepare for life outside of school. How will understanding CCCs help students to be informed and productive participants in their homes, neighborhoods, and work?



Defining our outcome

Our brief answer is in the Outcome box of our model: *CCCs can build students' capacity to engage in making sense of phenomena in communities that extend beyond the classroom.* Let's parse the two key phrases in this sentence.

Building capacity to make sense of phenomena: In this paper we will use *phenomena* in a broad sense, to encompass not only systems and events in the material world, but also design challenges and socio-scientific issues. In school classrooms there is only time for students to engage a few phenomena, and those phenomena are usually carefully curated—chosen for their importance, social relevance or educational usefulness. Outside of classrooms, though, we encounter *uncurated phenomena*—whatever the world throws at us. This requires what has traditionally been called “transfer,” or what Bransford and Schwartz (1999) refer to as *preparation for future learning*: Students will need to use what they learned in school to engage productively with new phenomena that they encounter outside of school.

Communities that extend beyond the classroom: As many scholars have pointed out (e.g., Gee, 1991; Lave & Wenger, 1991) we live our lives in *communities of practice*. So our outcome focuses on what we prepare students to do in communities that extend beyond the classroom. What do students take to other communities of practice--their families, work, neighborhoods, etc.--that will enable them to contribute productively? Communities of practice are also *discourse communities*: they share what Gee (1991) calls “discourses” or Bakhtin (1981) calls “social languages”—ways of talking and writing that enable them to fulfill their purposes. Given our focus, we next elaborate on the ways that CCCs contribute to engagement with phenomena and participation in communities of practice.

An example: compost bin. Let's consider a hypothetical example that we will revisit throughout this paper: A high school student has studied animal metabolism and combustion of organic materials, but not decay. At some point in her life (perhaps on the weekends while she is

in high school, perhaps years later) she has a plot in a community garden. She decides to enrich the soil by composting garden waste and table scraps. Her compost bin is an example of what we would call an uncultured phenomenon: She encounters it in her life even though she never explicitly studied it in school. It poses a variety of sense-making and design challenges. For example:

- A sense-making challenge: What is happening to plant stems and leaves as they are transformed into compost?
- A design challenge: What are the essential qualities of a compost bin that make good compost?
- A socio-scientific issue: Is making compost more environmentally responsible than buying fertilizer? Why?

Unique contributions of CCCs.

Our desired outcomes are three-dimensional performances, so what can we say about the particular contributions that CCCs make to those performances? Note that these challenges address DCIs related to plants and SEPs related to design along with the CCCs related to energy and matter as well as systems and systems models. We focus here on how CCCs (a) identify key linguistic features of scientific discourse and (b) serve as a basis for epistemic heuristics that guide our model.

CCCs identify key linguistic features of scientific discourse. There is an important difference between the “ideas” described in disciplinary core ideas (DCIs) and the “concepts” described in CCCs. The DCIs are empirically based: they describe models and patterns in data that are supported by arguments from observable evidence. In contrast (with the exception of energy and matter conservation laws) CCCs tend not empirically based. Rather than being the products of arguments from evidence, CCCs point to key features of the language that scientists use when they make their arguments from evidence. Thus CCCs identify key syntactic and semantic features of scientific discourse.

CCCs thus often describe the “rules of grammar” controlling what kinds of statements are acceptable. These rules often operate unnoticed in the background until they are broken. For example, we typically do not consciously notice that “She is eight years old” is grammatically correct, but we notice immediately that “She am eight years old” is incorrect. Similarly, scientifically literate people will immediately notice that “Humans get energy by sleeping at night” is a perfectly reasonable claim in colloquial discourse, but is not consistent with the specialized definition of “energy” that prevails in scientific discourse.

CCCs serve as a basis for epistemic heuristics. Krist, Schwarz, and Reiser (2018) describe “epistemic heuristics” that students use in constructing mechanistic explanations. We suggest that epistemic heuristics are generally useful when we engage in science and engineering practices—particularly making sense of new phenomena—and that CCCs can serve as a productive basis for those practices. The callout on our model identifies four key characteristics of epistemic heuristics based on CCCs. We illustrate each characteristic with an example related to the compost bin context introduced above

- *CCCs help to identify productive questions and goals for sensemaking.* CCCs suggest questions—about energy and matter, systems and system models, cause and effect, etc.—that are likely to serve as productive questions and goals for inquiry.

- *CCCs can support analogical reasoning.* A key strategy for making sense of new phenomena involves reasoning about how they are alike, and different from, others that we already understand in a three-dimensional way. CCCs can help identify those similarities and differences, and therefore what models and principles apply to the new phenomena.
- *CCCs provide rules for scientific sensemaking.* As described in the “rules of grammar” analogy, CCCs identify rules or principles that constrain scientific explanations and arguments from evidence.
- *CCCs can help to identify essential evidence.* Figuring out a new phenomenon always requires context-specific evidence about that phenomenon. CCCs can help guide a search for that evidence.

Using CCCs for the compost bin. In the compost bin example, let’s consider how a student might leverage her three-dimensional understanding of animal metabolism and combustion to engage in sense-making around the question of what is happening to the garden and food waste in her compost bin. All of the CCCs generate potentially useful epistemic heuristics. For the sake of parsimony, we concentrate on two CCCs in this example: (a) energy and matter, and (b) systems and system models.

- *Identifying productive questions and goals for sensemaking.* The Energy and Matter CCC suggests that tracing energy and matter is often a productive way of understanding what’s happening in a system, so the student might ask: “How are energy and matter being transformed in my compost bin? How is my compost bin exchanging energy and matter with the outside world?” Similarly, she might use the Systems and System Models CCC to ask: “What are the components of my compost bin system, including subsystems down to the atomic-molecular scale? How are those components interacting with each other?”
- *Supporting analogical reasoning.* Our student understands some related phenomena, including physical changes like rusting and metabolic changes like animals digesting food. How could these be productive analogies? If our student learns that her compost bin contains decomposing bacteria and fungi, and that those bacteria and fungi require oxygen, she can identify the animals as a potentially useful analogy.
- *Providing rules for scientific sensemaking.* Our student learns that the compost bin loses mass, so the principle of conservation of matter tells her that matter **MUST** be leaving the system. The molecules in the system can be broken down, but physical and chemical changes in the system cannot create or destroy atoms, or convert atoms to energy.
- *Identifying essential evidence.* Our student knows some empirical patterns she must figure out, through her reading or observation, in order to understand the compost bin system. But she needs to learn whether the compost contains living organisms, whether they need oxygen, what is happening to the mass of the system, etc. She might connect evidence related to how different design features of the compost bin affect how energy and matter flow through the compost bin system, perhaps creating models of the systems embodied in those models.

So CCCs can play an essential role in the student’s productive sense-making, guiding a process where she learns by observing and reading, following practices and using epistemic heuristics that she learned while studying other related systems.

Student Resources

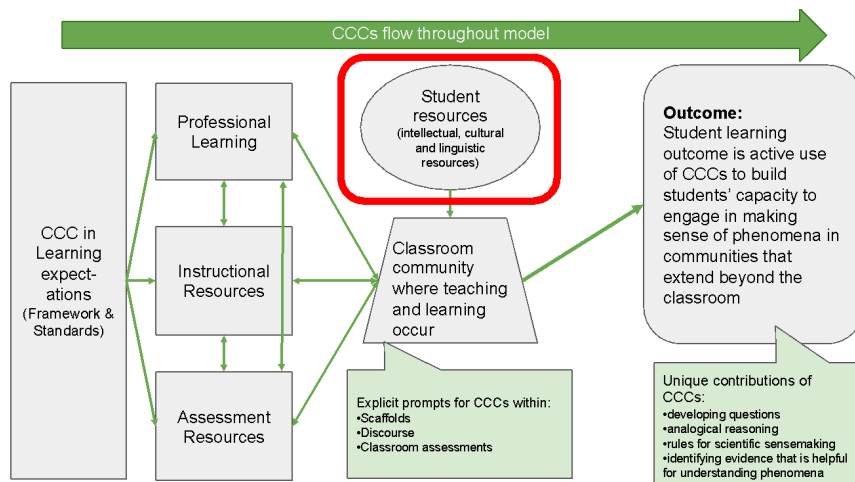
Students can achieve the outcome described above only if classroom communities acknowledge and build on the intellectual, cultural, and linguistic resources that children bring with them to school. We cannot review the huge literature on children's resources here (e.g., NRC, 2007, Chapter 3). In keeping with our emphasis

on CCCs, we focus on one aspect of those resources: what Gee (1991) describes as children's *primary discourses*: the ways of speaking that they master in their homes and childhood communities. In contrast, scientific communities rely on a *secondary discourse* that students must learn in school or through engagement with scientifically literate people.

So it can be useful to think about analogies between three-dimensional science learning and second-language learning. When we learn a second language we don't forget our primary language, and we still use it when appropriate. Similarly, students who master the secondary discourse of science can still use their primary discourses and use them when they are appropriate. Developmental research (e.g., NRC, 2007, Chapter 3), sociocultural research (e.g., Moje, et al., 2004), and learning progression research (e.g., Jin & Anderson, 2012; NRC, 2007, Chapter 8) all provide insights into students' primary discourses. We focus on one particular aspect of this rich body of knowledge, having to do with the epistemic heuristics implicit in most students' primary discourses. Pinker (2007), following Talmy (1988), argues that the syntax and semantics of all European and Asian languages is built around force-dynamic reasoning:

Force-dynamic reasoning explains events in terms of four elements: actors, enablers, purposes and results. For example, force-dynamic reasoning explains the growth of a tree by identifying the actor (the living tree), its purpose (to grow), its needs or enablers (sunlight, water, air, and soil), and the result (the tree grows bigger and bigger): The living tree always wants to grow and maintain life; with the help from its enablers, it grows bigger and bigger. Thus force-dynamic reasoning entails tracing *sequences of cause and effect*. What endures in a force-dynamic account of a process is the actor. The enablers (including materials and forms of energy) are used by the actor and then disappear from the narrative. The results emerge when the actor achieves its purposes. (Jin & Anderson, 2012, p. 1155)

So in force-dynamic reasoning energy is like the vitality or "life force" of living things that enables them to grow and survive. When they die, they lose that vitality, and thus are no longer able to resist the inevitable process of decay. Thus our student's compost pile, rather than being a system where matter and energy are conserved and transformed, is interpreted as a place where the process of decay completes the "circle of life," making the bits of energy that remain in the dead plants available to new growing plants as soil nutrients.



There is nothing inherently wrong with this force-dynamic account, but many high school students today are “scientifically monolingual”—this is the only account that is meaningful to them. A key goal for science education is to help them become “scientifically bilingual”—also able to figure out what is happening in the compost pile using the resources of scientific discourse, including CCC-based heuristics.

Classroom Communities

Curated phenomena that students investigate in school can serve as resources that are accessible to students when they engage in other communities of practice outside of school.

However, building classroom communities in ways that account

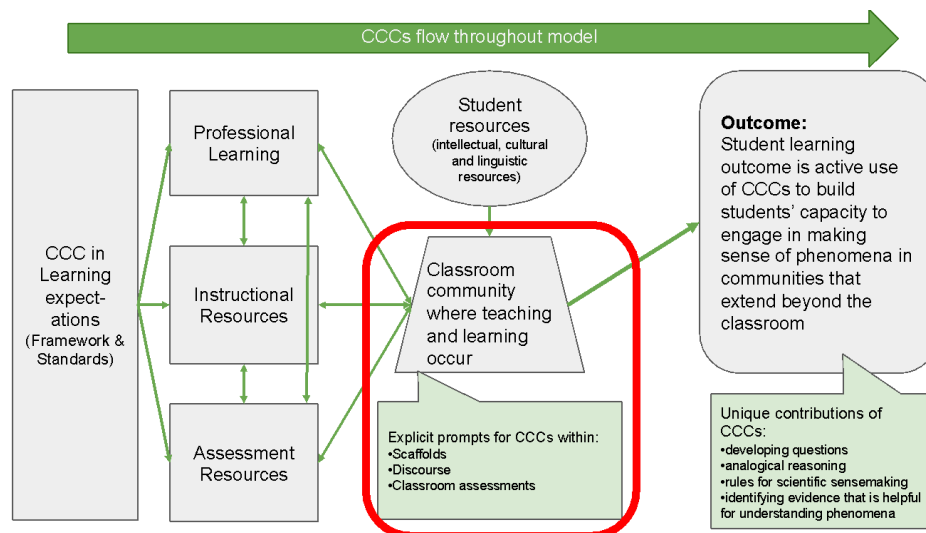
for student resources, attend to three-dimensional learning, and support transfer beyond the classroom is challenging. While there is no panacea for this, CCC’s can be as epistemic heuristics for developing these robust classroom communities. Consider the example ‘Using CCCs for the compost bin.’ It is this type of deep thinking classroom communities we should be supporting for students. By using CCC’s as lenses to think about curated phenomena we are able to build students’ capacity and potential for applying ideas outside of the classroom (e.g., home gardens, 4H, city landfills).

When engaging with three-dimensional performance in classroom communities, supporting students to engage with any of the three dimensions (DCIs, SEPs, or CCCs) will require explicit instruction, providing purposefully constructed opportunities that draw students’ attention to identifying key linguistic features of scientific discourse and the development of epistemic heuristics.

When considering high-leverage practices (Grossman, Hammerness, & McDonald, 2009; Windschitl, Thompson, Braaten, & Stroupe, 2012) our model emphasizes that classroom communities should (a) explicitly scaffold students’ experiences with CCCs to cultivate them as epistemic heuristics, (b) have explicit discourse about CCCs, and eventually (c) leverage student resources to support instruction and shift three-dimensional thinking outside the classroom. We next illustrate what these kinds of supports might look like in such a classroom community.

Explicitly using CCCs to scaffold sense-making.

As students make sense of what is going on inside a compost bin they might be guided to create scientific explanations and to identify essential evidence they should consider. One way to scaffold CCCs would be the use of guiding focus questions.



To illustrate this, a teacher could guide students by providing the statement: “We know matter is conserved in a biological process. With that rule in mind, can you develop an explanation about what is happening to the matter in the compost bin?” This approach acknowledges the significance of energy and matter: flows, cycles, and conservation and begins shaping the linguistic discourse needed to ask productive questions about both the DCI and CCC.

Explicit discourse about CCCs.

Classroom communities should have explicit engagement with the CCCs to help identify and employ linguistic features that are tacit characteristics of science discourse (AAAS, 1994). Further, leveraging student resources in concert with CCCs would provide a sounder foundation for sense-making.

For instance, having students create analogies for a curated phenomenon is commonplace, and can easily be focused on CCCs to produce opportunities for discourse. “Think about the different cause and effects going on in a compost bin. What else has similar mechanisms? Explain why you think these things are alike.” This prompt asks students to reflect on their own experiences, thinking explicitly about cause and effect. Being able to draw relationships and explaining those connections lay the groundwork for scientific discourse. Through consistent practice and support, classroom communities could encourage students to advance their heuristics past the need for formal scaffolds beyond the classroom.

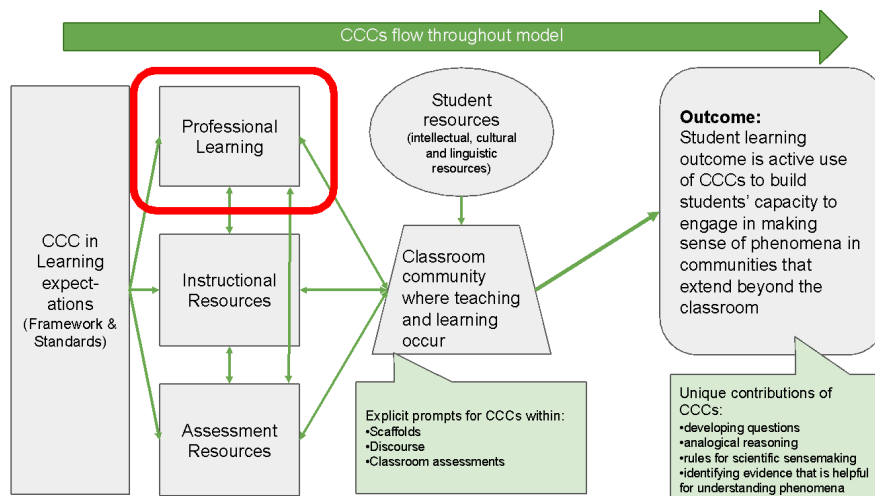
Shifting three-dimensional thinking beyond classroom communities.

CCCs can act as a vehicle for transfer between classroom communities and communities beyond school. The ability to identify patterns, investigate and discuss systems and systems models, and recognize the importance of structure and function are functions of science literacy, essential for sense-making and dealing with socio-scientific issues. The epistemic heuristics students develop allow for dynamic engagement with uncured phenomena, and access to meaningful discourse. We acknowledge however the challenges in measuring this learning outside of school settings.

Professional Learning

Teacher professional learning begins with undergraduate teacher education and continues through an educator’s career. Professional learning experiences support instructional practices consistent with the vision for teaching and learning presented in the *Framework for K-12 Science Education*.

Effective professional learning experiences should: 1) engage teachers in science performances which rely on using the crosscutting concepts within the professional development; 2) provide



teachers with resources and strategies to use in classroom instruction; and 3) be coherent and sustained in duration and learning experiences (CSSS, 2018).

Effective professional development (PD) models the instruction we hope our teachers use to engage students in using crosscutting concepts in three-dimensional science performances. High quality professional learning experiences are critical for preparing teachers to engage students in using the CCCs in science investigations and classroom discourse. If an educator has never engaged in using the crosscutting concepts to make sense of science phenomenon, we can't expect them to engage students in using crosscutting concepts in three-dimensional performances. Therefore, teachers need PD opportunities during which they observe and engage in using CCCs to structure investigations to develop the confidence, content knowledge, and pedagogical knowledge needed to engage student in effective three-dimensional science learning.

Effective PD provides participants with resources and specific strategies to use CCCs in their classrooms. The materials provided in the professional development need to be consistent with the grade-level of instruction and contain scaffolded support for the teacher and students. These resources should include formative assessments that utilize CCCs to prompt student performance (NRC, 2014).

Example of **using CCC to direct student performances** and/or prompt formative assessment.

Phenomenon: The center of an old pile of grass clippings is warm, even on a cold day.

Students prompt: Develop a model to show how changes in the matter in the grass pile causes the transfer of energy among the components ecosystem to make it feel warm.

Example of **using CCC to engage in teacher performances in PD** and model assessment..

Phenomenon: Running up stairs causes you to feel warmer than walking on flat ground.

Develop a model to show how changes in matter cause energy to be transferred among systems that cause you to feel warmer when you run up and down stairs.

The teachers engage in the second performance and reflect on how the crosscutting concepts are used to make sense of the two analogous phenomena. Teachers reflect on ways to use the crosscutting concepts to focus students on specific aspects of a phenomenon and/or to assess student three-dimensional science learning.

When CCCs are used as familiar touchstones throughout professional learning experiences, teachers are more proficient at using them as familiar touchstones within instruction. PD should engage teachers in science performances consistent with how students learn science, (e.g., using the crosscutting concepts of systems, causal relationships, and patterns to provide evidence for the causes of phenomena).

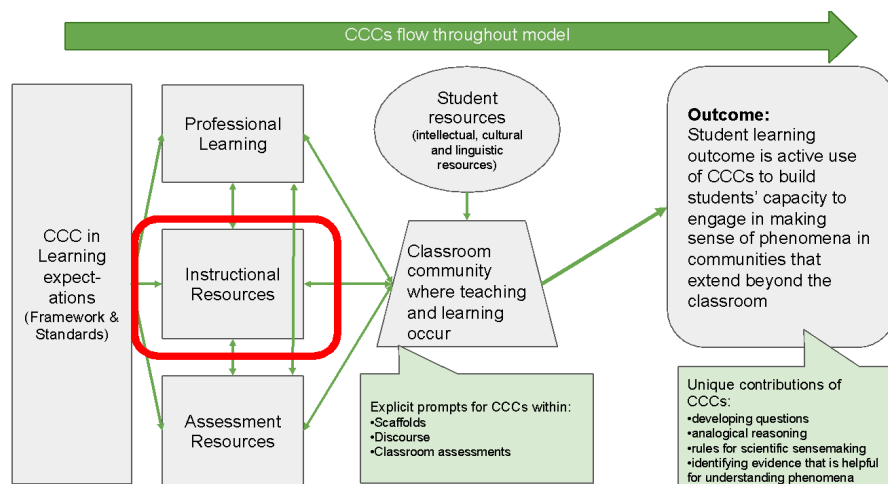
Sustained PD of sufficient duration is associated with changes to educators' science instruction (Penuel & Gallagher, 2009) and provides teachers with time to implement new instructional strategies and reflect on the effectiveness of new approaches to teaching and learning. Lasting instructional change including the effective use of CCCs is made possible by PD that models the instructional strategies for three-dimensional science learning, which provides coherence for the underlying theories of action in the design of the learning experiences.

Instructional Resources

Instructional resources are a second component that bridges the learning expectations set for students and schools and the classroom communities in which students work.

Instructional resources include the materials teachers use to guide their planning and instruction (e.g.,

curriculum maps, lesson plans) as well as the materials students interact with during class time (e.g., handouts, digital notebooks). The number of instructional resources available to teachers has grown exponentially with online access, but even given this wealth of resources, the current availability of ones that would support students in achieving the outcome we describe is limited. We next discuss how instructional resources can support building a classroom community necessary to achieve those outcomes.



Instructional resources that use CCCs to scaffold student sense-making and discourse.

Our model proposes a goal for students to transition from highly scaffolded experiences with CCCs applied to curated phenomena to limited scaffolding with uncurated phenomena. Instructional resources can support this transition by providing explicit support for CCCs at moments early in an instructional sequence and removing those supports over time as students become more autonomous in their use of CCCs. If CCC-based epistemic heuristics are like grammatical rules of language, then students cannot simply learn to apply heuristics by being told that CCCs are principles to follow; they must also appropriate epistemic heuristics through personal experience, discussion, and practice in developing scientific explanations. Instructional materials and other resources should be designed with this goal in mind, specifically to support teachers and students in building the classroom community we have described. Below are a few examples of how instructional resources can support student learning and sense-making:

- *Support students' use of CCCs to ask productive questions about phenomena.* Students tend to struggle in their generation of productive questions. Students also get 'stuck', not knowing what kinds of questions they should ask. Tools, such as the questions sets described below, can be used by students to help identify productive kinds of questions they could ask about phenomena. Suggestions for how to use CCCs to help students generate productive questions should be included in instructional resources for teachers.
- *Provide principles and heuristics to guide model building and explanation.* When students are asked to develop a model for explaining a phenomenon, the task can be daunting to many students. Instructional resources can guide students to apply one or two CCCs to their model building and explanation practice, cueing students into accounting for key elements they may otherwise ignore. Prompts and checklists provided in the

materials that students interact with are one approach to scaffold students during these moments in instruction and to provide opportunities for reflection.

- *Sequence students' experiences of related phenomena in ways that engage students in analogical reasoning.* As students encounter new, but related phenomena, CCCs are a way to make sense of the new phenomena even if students are unfamiliar with science ideas necessary to explain it completely. Thus, instructional resources should be strategic in how students' experience phenomena across an instructional sequence and include dedicated moments in which analogical reasoning between phenomena is supported.

Example: Question prompts (Joyce Parkers' question prompts; STEM Teaching Tool #41)

Systems and Systems Models

- What are the key components of the system?
- Are there key components that are invisible?
- How are the components related?
- How do the parts of the system work together?
- What would happen in the system if you increased X component?

Structure and Function

- What unique structures does this object/living thing have?
- What function do the structures have?
- How does the structure facilitate the function?
- How does the shape of _____ help it function (or behave)?

Question prompts and sentence stems are examples of instructional tools that support students as they actively learn the purposes and rules of scientific discourse. Two additional examples of instructional resources that particularly support students discourse include STEM Teaching Tool #41 (<http://stemteachingtools.org/>), *Prompts for integrating crosscutting concepts into assessment and instruction* and the BSCS *Communicating in Scientific Ways* sentence stems. These resources provide guidance to teachers about the kinds of questions to ask their students, as well as prompts that students can use to support their own developing scientific discourse. Over time, one can imagine a classroom community co-constructing their own repertoire of sentence stems and question prompts they find useful when using CCCs.

The use of CCCs as described will require teachers to have strong skills in facilitating productive discourse —skills that are likely to be both new and challenging for teachers. Resources like sentence stems and frames and question prompts, can make explicit the science discourse norms important for students to appropriate. These tools can also help students see the distinctly different foci of talk and writing that occur when applying CCCs to the phenomenon, and how discourse shifts with different CCCs. Instructional resources are an important “go-to” support for both teachers and students, particularly during highly scaffolded learning experiences in which CCCs have a central role. These resources can be critical to building teachers' confidence in using CCCs in their classrooms, and in strategically sequencing the experiences students have with CCCs and phenomena over time.

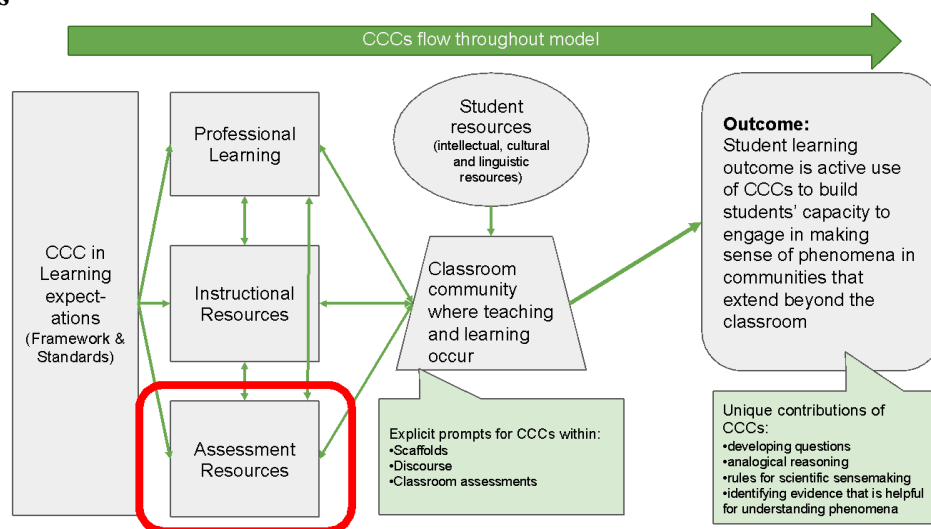
Instructional resources to support professional learning.

Instructional resources should be educative for teachers, providing teachers with rationale for the affordances certain CCCs bring in particular contexts. Though we know that embedding these kinds of supports in instructional resources, like teacher guides, may not be sufficient without additional professional learning (e.g., McNeill, 2009), we also know that educative resources are one avenue for professional learning and can “serve as cognitive tools to help teachers add new ideas to their repertoires (Davis & Krajcik, 2005, p. 7).” It is important that instructional resources communicate clearly to teachers that CCC-focused tools are not intended to be used didactically. Rather, these tools are scaffolds to support students use of CCCs and ultimately intended to fade.

Assessment Resources

As with instructional resources, assessment resources need to be explicitly designed to include CCCs and to capitalize on their discursive features when writing assessment prompts and interpreting student responses. In this section we present several

principles that can be used to guide the development of assessment resources that can be used in the classroom to effectively measure and promote student learning, explain how pilot testing can specifically provide support for CCC reasoning, and end with an example assessment task that reveals students’ use of CCCs.



Principles for development of assessment resources that effectively use CCCs.

Assessments need to be integrated in a way that enables three-dimensional science performances, such as making sense of phenomena or solving applied problems (National Research Council, 2014; Science SCASS States, 2018). Our model proposes students move from being able to make sense of and reason about curated phenomenon to eventually being able to do the same with uncurated phenomenon. In assessment tasks, one is defining the situation in which a student is asked to enact some performance, therefore the phenomenon are always curated. Selecting an appropriate phenomenon to which the CCCs can be used in sensemaking is critical when developing assessment tasks that can provide evidence for students’ use of CCCs. The CCCs can be used to constrain and guide students’ sensemaking of the phenomenon by acting as cognitive and/or linguistic structures that students use to reason about the causes of, the system involved in, and the patterns revealed by the phenomena (Science SCASS States, 2018).

As with instructional resources, not only does one need to select an appropriate phenomenon, but one also has to consider if and how to scaffold the curated phenomenon. Both heavily scaffolded

and minimally scaffolded assessment tasks need to be explicitly and consistently designed in ways that guarantee that students who understand how to use the targeted CCC can actually use that CCC productively to make sense of the phenomenon and to engage in scientific discourse around the phenomenon. For heavily scaffolded tasks this means they must be designed to elicit student thinking about the CCCs, using specific language that connects to students' learning experiences (see <http://stemteachingtools.org/brief/41> for examples of CCC prompts for use in assessment tasks; also see the example assessment task below). If this explicit use of CCC prompts does not occur, then a student's answer that lacks sufficient CCC reasoning will constrain the inference one can make: Did students not know how to use the CCC? Or, did they just not realize the use of the CCC was necessary in this assessment task?

Although it is one aspect of performance for students to learn to use the CCCs to structure their thinking and explanations, it is a different aspect of performance for students to recognize (on their own) when using a CCC will be helpful (e.g., Fick et al., 2017). Doing so would suggest that students are able to naturally, and without prompting, use the CCCs to guide their thinking and discourse. To test whether students can use the CCCs in this manner, scaffolding that is initially present should eventually be removed to assess whether students can bring the CCCs to bear on a curated phenomenon without any aid.

Finally, rubrics need to be designed to reveal students' use of CCCs. Just as the assessment tasks can explicitly reference CCCs for the aid of students, assessment rubrics should explicitly guide teachers to features of students' responses that can indicate their use of the CCCs as an analogical bridge or as rules of grammar.

Processes for developing assessment resources that effectively use the CCCs.

In order to keep track of the various aspects and design decisions when developing three-dimensional assessments, one should use a principled design process, such as construct mapping or evidence-centered design (National Research Council, 2014). Following a principled design process should also entail iterative development, based on pilot testing with students and feedback from teachers. Pilot testing should include looking for evidence that the tasks have elicited students' use of the CCCs. In the compost pile example, we know that students often write explanations that fail to include atmospheric gases in the system (systems and system models) or fail to trace all the mass of the decomposing materials (matter conservation). Pilot testing can identify whether scaffolds need to be added to structure students' use of the CCCs. Pilot testing can involve think-aloud protocols or cognitive labs, where students' verbalize their reasoning and answer questions about their reasoning. This is particularly important for using CCCs as there exist multiple views of how CCCs might be used as cognitive tools and so these cognitive labs have the potential to also answer multiple research questions. For instance, when the context for an assessment task differs from the instructional context, can students use the CCCs to support their analogical reasoning and to bridge connections to prior learning? Do students' use of CCCs serve as epistemic heuristics to, for instance, guide their sensemaking or questioning around the phenomenon?

Example of using CCCs in assessment tasks

Consider how we might use an assessment task to probe students' understanding of the CCCs in a classroom studying decomposition. The following example from the *Carbon TIME* project (<http://carbontime.bsccs.org/>) uses both a selected-response and a constructed-response format.

A loaf of bread was left alone for 2 weeks. Three different kinds of mold grew on it. Assuming the bread did not dry out, which of the following is a reasonable prediction of the mass of the bread and mold after the 2-week period?

a) The mass is going to:

- a. *increase*, because the mold has grown.
- b. *remain the same* because the mold converts bread into biomass.
- c. *decrease* as the growing mold converts bread into energy.
- d. *decrease* as the mold converts bread into biomass and gases.

b) Explain your reasoning. Why does the mass of the bread and mold change in the way you selected above?

The bread mold phenomenon affords students the opportunity to reason with the Systems & System Models CCC and Energy & Matter CCC. The Energy & Matter CCC is perhaps the simpler of the two to collect evidence for whether students are using it or not. For instance, a student that has a strong understanding of the Energy & Matter CCC would not choose (C) because it violates conservation of mass. In addition to the Energy and Matter CCC, there is space for the Systems and System Models CCC to be used. Students' answers to both the prediction of what will happen to the mass, and their explanation for their reasoning are coded using scoring rubrics that distinguish responses that rely on force-dynamic epistemic heuristics vs. responses that rely on scientific understanding of systems and system models. In this example the use of the CCC is explicitly designed into the item, with a phenomenon that affords using the targeted CCCs, one of the CCCs is heavily scaffolded, and the scoring rubrics identify responses that differentially use the CCC.

Scope and Limitations of our Model

Our model encompasses formal K-12 schooling with a goal of students being able to transfer their knowledge into their world beyond school. With an explicitly socio-cultural perspective, it focuses on supporting and using the CCCs as conceptual tools (specifically language and discourse). This model focuses on the CCCs as tools for constructing explanations of scientific phenomena. One limitation of the model is that we didn't foreground how this might apply to engineering design although we can see its applicability. Finally, we want to reiterate that CCCs don't stand alone. Although they are a unique dimension of student learning, they cannot be learned in isolation from SEPs and DCIs.

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Modeling the Role of Crosscutting Concepts for Strengthening Science Learning of All Students

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Recent reform efforts in the United States have led to the development of *A Framework for K-12 Science Education* (National Research Council [NRC], 2012; shortened to the *Framework* hereafter) and the Next Generation Science Standards (NGSS; NGSS Lead States, 2013). The *Framework* defines the foundational knowledge and abilities in science and engineering that students should develop by the end of 12th grade. The vision in the *Framework* and the NGSS expects students to engage in three-dimensional learning by blending *science and engineering practices* (SEPs), *crosscutting concepts* (CCCs), and *disciplinary core ideas* (DCIs).

The *Framework* argues that CCCs unify the study of science and engineering through their common application across disciplines (NRC, 2012). CCCs are seen as critical for learning science and engineering for several reasons. First, CCCs connect SEPs and DCIs. Second, CCCs represent “science knowledge and science as a way of knowing” (Duschl, 2012) and are designed to foster students’ understanding of the sciences. Third, CCCs are intended to help students develop a coherent and scientifically grounded view of the world. Finally, as emphasized in this chapter, CCCs serve as a conceptual lens to make sense of phenomena.

Despite their important role in learning science, CCCs have been historically ignored in curriculum and instruction. Given that students come to school with intuitive ideas about CCCs, it is important that science instruction should leverage these intuitive ideas and begin to use CCCs to make sense of phenomena. There should be explicit instruction about CCCs that support formalization of their intuitive ideas. As these ideas grow in sophistication, students should be able to reuse these ideas when making sense of a range of phenomena. Therefore, exploring the value of each CCC and inter-relationships among CCCs is important for science teaching and learning.

The purpose of this paper is to develop a theoretical perspective regarding how CCCs may support students in engaging in SEPs and DCIs to make sense of phenomena. Toward this end, we present two models. The first model describes inter-relationships between individual CCCs in order to unpack how they build upon, and connect to, each other (see Figure 1). The order of CCCs presented in this model can be a way for students to build on sophistication pertaining to CCCs. The second model describes theory of action that illustrates how explicitly engaging students in learning about CCCs supports them in making connections between SEPs, CCCs, and DCIs to explain and predict phenomena (see Figure 2). A key component of this model of theory of action is students’ intuitive ideas about CCCs based on their funds of knowledge in their homes and community.

Model of CCCs as First- and Second-Order Crosscutting Concepts

We view CCCs as an interconnected set of ideas. Perhaps the most foundational idea among CCCs is the notion of a “system” (*CCC systems*); it is what forms or frames what is under investigation. Scientists first have to identify the system under consideration, as represented by the dotted boundary line in Figure 1. Within the boundary of a system, there are two first-order *CCCs patterns* and *cause and effect: mechanism and explanation* (hereafter *cause and effect*).

The search for, and identification of, patterns can “guide organization and classification and prompt questions about relationships and causes underlying them” (NGSS Lead States, 2013, p. 15). Categorization and classification are types of pattern analysis, which are basic to all sciences and enable scientists to answer the first fundamental question of “what exists” in the natural and designed world. Answering the question of what causes these patterns to exist involves CCC cause and effect. “Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science and engineering” (NGSS Lead States, 2013, p. 15), and searching for causal relationships enables scientists to answer the second fundamental question: “why does it happen?” Thus, both patterns and cause and effect are first-order CCCs.

Both patterns and cause and effect are supported by second-order CCCs that support the identification of patterns or explanation of cause and effect. Hence, as one way of identifying patterns in a phenomenon, “it is critical to recognize what is relevant at different size, time, and energy scales, and to recognize proportional relationships between different quantities as scales change,” based on *CCC scale, quantity, and proportion* (NGSS Lead States, 2013, p. 16). Likewise, systems are both stable and changing, thus *CCC stability and change*. This is particularly true of ecosystems, for instance. Identifying what is stable and what changes helps the identification of patterns and what needs to be explained.

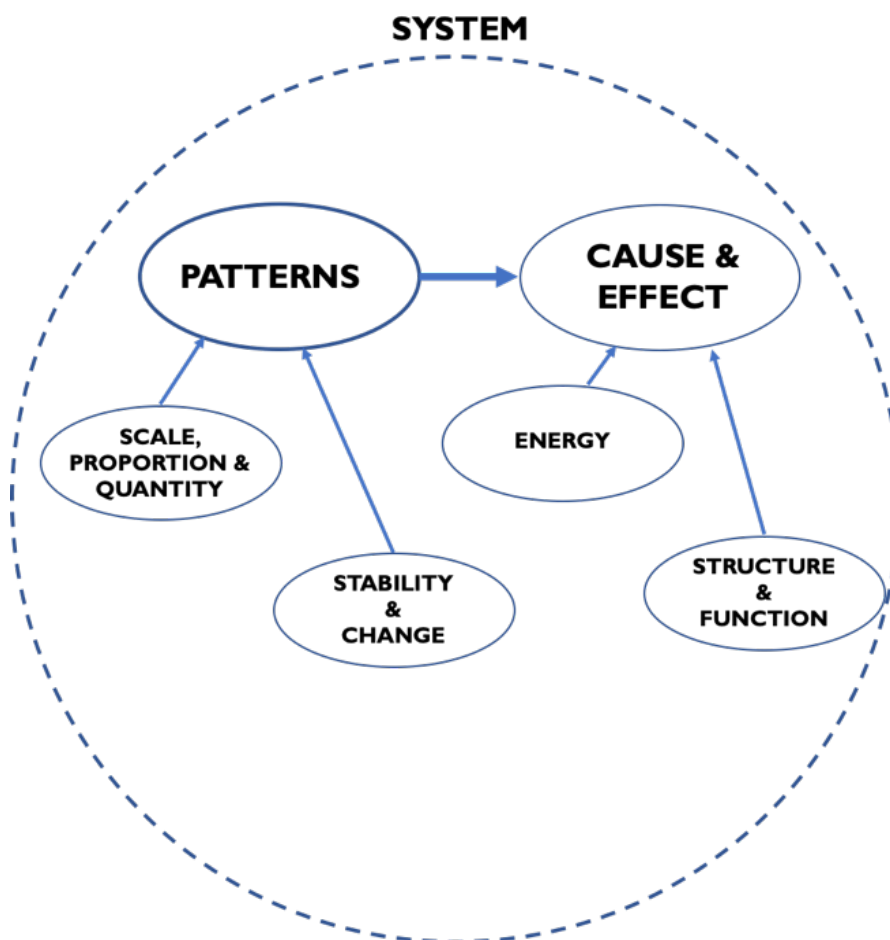


Figure 1. The crosscutting concepts and their inter-relationships.

When it comes to constructing explanations for the CCC *cause and effect: mechanism and explanation*, CCC *energy and matter: flows, cycles, and conservation* and CCC *structure and function* are invaluable. The flow and transfer of energy in any system is an important element to identify in explaining why a phenomenon happens. For instance, the fact that the surroundings heat up when a candle burns is evidence that energy is transferred from the burning candle to the surroundings, and this is a critical step to uncovering a particle-level mechanism that explains why burning causes a temperature increase. To establish causality, such a mechanism must also correspond to an energy decrease in the system of reactants and products during burning. Likewise, structure and function are key to explaining cause and effect: why do certain finches only exist on certain Galapagos islands? A full causal explanation includes the relationship between the structure of their beaks and their associated function for eating specific foods available on the island.

The model of inter-relationships among CCCs, as presented in Figure 1, provides an overarching unity that is missing in *A Framework for K-12 Science Education*. First, it shows how CCCs are interrelated. Second, it shows that within the boundary of a system, patterns and cause and effect are of prime importance of answering two of the three fundamental questions of science: (1) “what exists?”, (2) “why does it happen?”, and (3) “how do we know?” (Osborne, Rafanelli & Kind, 2018). In this way, Figure 1 goes beyond CCC organizational scheme given in NGSS Appendix G that groups CCCs according to Patterns, Causality, and Systems.

Model of Theory of Action

The overarching unity presented in Figure 1 has guided our model of theory of action, which highlights the central role of the science learning environment to promote student learning, as presented in Figure 2. In this learning environment the input is students’ intuitive ideas and experiences they bring with them to this learning environment. As students begin to actively engage in CCCs to make sense of phenomena, their understanding of CCCs evolves, leading to intentional use of CCCs in conjunction with SEPs and DCIs to explain and predict phenomena.

The science learning environment might be a classroom but could can also be an after-school program or a visit to an informal science institution. Students enter that environment with intuitive ideas based on their prior experiences that are related to CCCs. For example, they have noticed patterns in the world around them or have seen that some objects tip over easily (are less stable) than others.

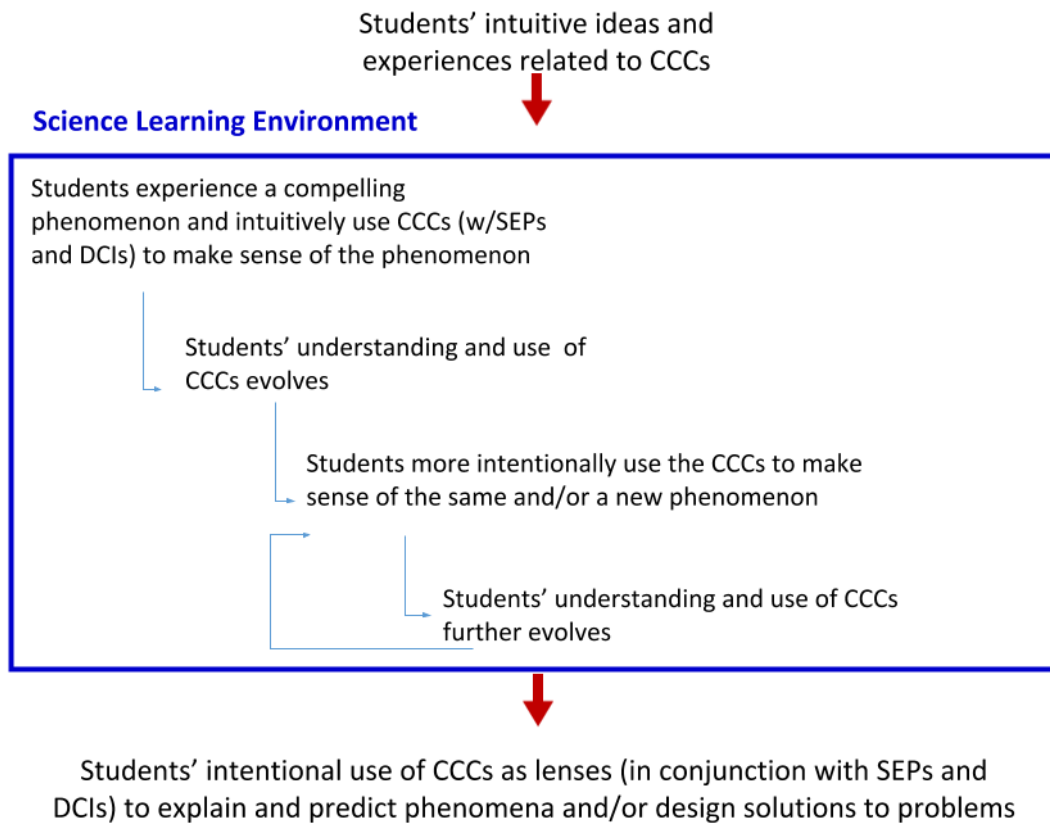


Figure 2. Model of theory of action representing key inputs, processes, and outcomes related to how CCCs support students in making sense of phenomena and designing solutions to problems.

Within the science learning environment, students encounter a compelling phenomenon. In collaboration with students, an educator selects the phenomenon for its instructional effectiveness in meeting learning goals and instructional efficiency in terms of instructional time and supplies. The educator then guides students in their sense-making and helps them develop a deeper understanding of CCCs. With this deeper understanding of CCCs in place, students can use CCCs more intentionally to examine the same phenomenon or a new phenomenon. And whenever students use CCCs to make sense of phenomena, they have the opportunity to further develop their understanding of CCCs.

This whole process is iterative, as evident in Figure 2. Within the whole process, there are multiple mini cyclical processes that play a role to help students formalize their understanding of CCCs. This cyclical process fosters a sophisticated understanding of CCCs, which are likely to become intentional over time. For this process to progress effectively, (1) phenomena need to be compelling to students based on their funds of knowledge from their homes and communities and (2) science instruction needs to make explicit to students how they use CCCs to make sense of phenomena. Each of these two issues is discussed next.

Capitalizing on Students' Funds of Knowledge to Select Compelling Phenomena

Broadening access to science is a central theme of the *Framework* and the NGSS, hence “all standards, all students” (NGSS Lead States, 2013). Traditionally, it has been expected that students come to the science classroom to learn canonical science knowledge. Moreover, it has traditionally been assumed that students, especially from nondominant backgrounds, bring little or limited prior canonical science knowledge. However, as the NGSS emphasize “all standards, all students,” it is imperative that science be made real and relevant to students, capitalizing on the funds of knowledge that all students bring to the science classroom from their homes and communities.

In their everyday lives, students use various resources to make sense of the world. In the NGSS classroom, students use CCCs to make sense of phenomena or design solutions to problems as scientists or engineers do in their work. CCCs can be thought of as resources that students use in their everyday lives to make sense of the world and bring to the science classroom to help make sense of phenomena.

This perspective on CCCs as resources that all students bring to the science classroom to make sense of phenomena is particularly important for students who do not see science as relevant to their lives or future careers. This perspective on CCCs creates relevance by capitalizing on students’ funds of knowledge from their homes and communities (González, Moll, & Amanti, 2005). This perspective on CCCs also allows students to communicate their ideas using all of their meaning-making resources, including everyday language, home language, and multimodality (Lee, Quinn, & Valdés, 2013). Finally, this perspective on CCCs promotes participation of all students by offering access to science and inclusion in the science classroom.

If students are expected to use their understanding of CCCs to explain and predict phenomena or design solutions to problems, science learning environments need to provide them with compelling phenomena involving the use of CCCs. They are motivated to figure out the phenomena that are real and relevant to them, their families, and their community. In figuring out the phenomena, students bring their funds of knowledge from their homes and community.

One such phenomenon is the health of a freshwater system for supporting aquatic organisms. To make sense of the phenomenon, students investigate, “*How healthy is the stream for freshwater organisms and how do our actions on land potentially impact the stream and the organisms that live in it?*” (Novak & Krajcik, 2019; Novak & Treagust, 2018). Whether one lives in an urban, suburban, or rural environment, or a water rich or water scarce area, all students have experiences with water. All students also live in a watershed that directs the flow of rainwater or snowmelt along with potential pollutants—products people use outside on the land—into nearby lakes, rivers, and streams. Each student, therefore, brings valuable personal experiences to a unit on water. This makes a water quality unit naturally engaging to all students. The teacher can further motivate students to learn by personalizing and situating a water unit to their community (<http://create4stem.msu.edu/curric/water> or <https://drive.google.com/drive/folders/1--l-qtDfhdkEkNO7lngVZoq6cIhl35xrk>). The teacher can set a context with a local waterway or local issues in the community or have students research to find out if there are local water issues. There may be water issues right in the local community, a nearby community, or somewhere in the state.

In addition to SEPS and DCIs, integration of CCCs is essential for students to make sense of the stream phenomenon. They need to understand that a freshwater stream is a complex system (CCC systems) that is comprised of freshwater and freshwater organisms and is also part of a

watershed. Complex relationships exist between what people do on the land and the impact on the water's quality from run-off and on the aquatic organisms (CCC cause and effect), and that a change to one part of the system can have a tremendous impact on another part of the system (CCC stability and change). Crucial to students' sense-making is looking for patterns and trends (CCC patterns) as they work to figure out what their water quality data means.

Making CCCs Explicit to Students

Given that students come to school with intuitive ideas about CCCs, science instruction should leverage these intuitive ideas. CCCs that students utilize to figure out a phenomenon should not remain implicit to students. Instead, through instruction, CCCs need to be made explicit to students. This necessitates that the teacher develops strategies to support students in using CCCs when investigating phenomena. For example, when a student asks a question that involves a pattern, the teacher describes how the question involves looking at a pattern. When the class engages in a task that involves a pattern, the teacher points out how the task involves looking at a pattern. Through multiple opportunities to use CCC patterns, students develop an understanding of how they can use CCC patterns to figure out phenomena.

As science instruction makes CCCs explicit to students, they become more familiar with CCCs and build more sophisticated understanding of CCCs. Moreover, as students' understanding and use of CCCs evolves over time, they use CCCs more intentionally, especially when they are presented with complex or uncertain phenomena. For example, students look at a phenomenon using multiple CCCs and then decide on a particular CCC that can address the phenomenon. As they figure out the phenomenon, they look at different aspects of the phenomenon using particular CCCs.

The CCCs that contribute to students' ability to figure out and explain a phenomenon, like the overall health of a stream to support organisms described above, should not remain implicit to students. Through instruction, CCCs should be made explicit for students. Therefore, the teacher needs to develop strategies to scaffold students in ways that assist them to utilize the CCCs when investigating this phenomenon. One strategy is to focus their attention on responding to questions like, "Why did we get our results?" and "What do our results mean?" Such questions guide students to think of causes (why?) and effects (what do they mean?), which helps them to see relationships and identify patterns. This can be done through scaffolded guide sheets that prompt students, and through discourse in small group work or in a class discussion. Because a stream phenomenon is a complex system with many components, one challenge is to help students to engage in systems thinking rather than seeing the stream as separate, unconnected water quality measures. How to assist students in understanding systems thinking is one area that can be addressed by the research community.

Conclusion

CCCs apply across science disciplines. They are integral for science teaching and learning as they provide conceptual tools, which educators and students can use in conjunction with the SEPs and DCIs to explore the world around them. All students bring to the science classroom their intuitive ideas and experiences from their homes and communities. The science learning environment plays an important role in students' understanding and formalization of CCCs. This environment should make CCCs explicit to students, so that they utilize CCCs as conceptual tools to explain and predict phenomena and design solutions to problems. The consistent use of

CCCs in science learning can lead to students' intentional use of CCCs and sophistication in their understanding of CCCs. Ultimately, if K-12 science instruction has been effective, students are prepared to use CCCs in conjunction with SEPs and DCIs to explain and predict phenomena and to design solutions to problems.

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Looking Forward: Setting an Agenda for Research into the Crosscutting Concepts

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The NGSS are the most recent set of science education standards that have been developed based on decades of theoretical discussion and empirical research into how students learn science. However, the empirical research base undergirding the NGSS is uneven. Unlike the disciplinary core ideas (DCIs) and the science and engineering practices (SEPs) that appear within the Next Generation Science Standards (NGSS), the crosscutting concepts (CCCs) were not based on a robust body of research ([Osborne, Rafanelli, & Kind, 2018; Saleh et al., 2019](#)), a fact readily acknowledge by the *Framework for K-12 Science Education*, which noted:

The research base on learning and teaching the crosscutting concepts is limited. For this reason, the progressions we describe should be treated as hypotheses that require further empirical investigation. ([National Research Council, 2012, p. 84](#))

Thus, the CCC-related learning progressions described within the NGSS reflect a set of “best guesses” about how students may learn and use the CCCs over time, but these progressions are not well-grounded in empirical research. This is not an ideal situation for a set of standards that have been widely adopted and are currently guiding instructional decisions affecting millions of students. This lack of an empirical foundation that guides statements about how students should learn and use the CCCs is both noteworthy and concerning. A major impetus, therefore, for the *Summit for Examining the Potential of Crosscutting Concepts to Support Three-Dimensional Learning* was to identify a research agenda that can inform our understanding of how students learn about the CCCs and to establish an empirical base regarding the conceptual utility of the CCCs for student learning in science. In this chapter, we describe the process by which summit participants began to outline a CCC-focused research agenda and we identify key questions and topics that may guide future research.

Our process for discussing a research agenda

Identifying focal areas. To begin to clarify a research agenda, summit participants (who represented a range of backgrounds in science research, science education research, K-12 science teaching, and policy-making) identified four areas within science teaching and learning to focus their discussions. These areas included:

- Curriculum and instruction
- Teacher learning
- Assessment
- Nature of the crosscutting concepts

The four focal areas were identified by a two step process in which suggestions for focal areas were solicited from the large group and recorded. Then, the whole group discussed the merits of each proposed area and voted on which areas should be further elaborated.

Structured discussions. Once focal areas were identified, we engaged in a structured discussion of the CCC-related research priorities within each area. These discussions took place

using an adaptation of the “World Cafe” format ([Brown & Isaacs, 2005](#)) for engaging in generative discussion. In such a conversation format, a room is arranged with a set of tables, each focused on a particular topic or guiding question. In our case, we organized four tables, each focused on one of our focal areas. Participants were invited to join a table of their choosing, and engaged in an open conversation for 45-minutes that was guided by this guiding question:

Based on the summit models and discussions so far, what are the implications for research in this area?

Additionally, participants were encouraged to consider these subquestions:

- What might be research questions?
- What constitutes evidence?
- What might a progression through the research agenda look like?

During the 45-minute open discussion, a Table Host (who also participated in the conversation) took notes and helped to ensure that the conversation did not stray too far from the guiding question. Additionally, tables were covered with paper “tablecloths” as well as note cards on which participants were encouraged to record key thoughts and comments. At the end of the 45-minute discussion participants took a short break and were asked to join a new table (which reflected a new focal area), while the Table Host remained in place. To begin the second round of discussion, participants were given time to look at the comments and graphics written on the paper tablecloths and notecards by the previous discussants, and the Table Host provided a brief overview of the discussion that took place in the first round of discussion. In this way, the Table Host helped to ensure that the second round of discussion built on the first, but also included new ideas and pathways of reasoning. After the conclusion of the second 45-minute round of discussion, the structured discussions came to a close. The tablecloths at each table were photographed and the note cards were gathered, and the Table Host uploaded their notes to a central electronic folder. These artifacts documented key areas of overlap (as well as divergent thinking) among summit participants regarding priorities in CCC-focused research. After the CCC summit, the Table Host reviewed their notes and the generated artifacts and synthesized key outcomes from the conversations. In the following sections, we report on this synthesis.

It is important to note that the World Cafe format is designed for a diverse group of stakeholders to engage in generative discussion regarding a shared issue/problem of concern. While this format may identify some areas of consensus, it is equally common (and desirable) to recognize a need to know more and to ask new questions. Thus, the research questions and recommendations reported below have been minimally edited in an effort to illustrate the range of views that emerged in these generative discussions.

Key outcomes from research agenda conversations

Curriculum and instruction. The curriculum and instruction table focused on issues relating to the teaching and learning of the CCCs in both formal and informal settings.

Round 1 Participants:

TJ McKenna (Table Host), Boston University
Andy Anderson, Michigan State University

Jason Buell, University of Colorado - Boulder
Christine Cunningham, Museum of Science - Boston
Joi Merritt, James Madison University
Lindsey Mohan, BSCS
Abeera Rehmat, Indiana University
Cary Sneider, Portland State University

Round 2 Participants:

TJ McKenna (Table Host), Boston University
Sarah Fick, University of Virginia
Cindy Hmelo-Silver, Indiana University
Joe Krajcik, Michigan State University
Lauren Levites, Chicago Public Schools
Brett Moulding, Utah Partnership for Effective Science Teaching and Learning
Nancy Ruzycki, University of Florida
Susan Yoon, University of Pennsylvania

The Round 1 discussion identified three major areas for research. The first area focused on the extent to which there is a progression of learning connected to the crosscutting concepts. Key questions that might guide subsequent research are:

- Is learning improved with intentional foregrounding & sequencing across the year?
- How do we know where students are starting (with respect to the crosscutting concepts) and build off of that?
- How do we use CCCs to keep students engaged over longer time periods?

The second area focused on the how resources can be embedded within curriculum and instructional materials to support learning connected to the crosscutting concepts. Key questions are:

- How do we help teachers understand what are the non-negotiable elements of curriculum - and how can we clearly articulate our rationale?
- How can the research on crosscutting concepts look across multiple units, multiple grades?
- At the classroom level - there is an issue between what do you tell and what do you let students figure out
- At the curriculum level - what needs to be included to make teaching and learning robust?

The third area focused on the nature and design of scaffolding to support students as they develop their understanding of the crosscutting concepts. Questions include:

- What is the optimal balance between explicit coaching versus telling (and how is this coaching build into curriculum and instructional materials?)
- How much coaching is right for students to take-up and use the crosscutting concepts?
- How long does it take for students to begin to use certain crosscutting concepts?
- How much coaching is required for students to internalize the performance?

- What are educative components of instructional materials that can help teachers effectively use the crosscutting concepts?

The Round 2 discussion at the curriculum and instruction table identified four major areas for research. The first area focused on decisions that curriculum designers make in designing instructional materials so that teachers can support students in using the CCCs. Key questions include:

- How do we support teacher development around crosscutting concepts in culturally responsive ways?
- How do researchers work with teachers as partners to understand the curriculum and instruction needed to enact the crosscutting concepts?
- It's not just the teachers who do not know - it is the field who does not have a framework for how to enact these - do teachers and researchers have a common understanding?

The second area focused on building complexity of the crosscutting concepts across grade bands and time, and group members emphasized that curriculum is designed to provide scaffolds for building complexity over time. Notably, this focus acknowledges the critical relationship between instruction and assessment. Key questions include:

- How do students use crosscutting concepts in their reasoning, and how can this be measured?
- How might one measure the metacognition of students making informed choices about specific (and productive) crosscutting concepts in their reasoning?

The third area involves the design and implementation of exemplary curricular materials that include and appropriate emphasis on the crosscutting concepts.

- How do we design flexible curriculum to address a variety of learners to use CCCs flexibly along with DCIs & SEPs to make sense of phenomena and real-world problem solving?
- How are crosscutting concepts an implicit component of how we make sense of science? At what times is it useful to make this explicit?
- Do we believe it is true that we learn science implicitly through the crosscutting concepts? Research in systems and systems modeling says you cannot see the system...
 - How do we shift this to all learners?
 - How do we differentiate the use of the crosscutting concepts?
- What are contenders of high quality curriculum of NGSS and how are the crosscutting concepts built into them?
 - What can exemplars tell us about the use of crosscutting concepts?
 - How do we ensure appropriate use of the crosscutting concepts in curriculum and instruction?
 - What are crosscutting concepts (fundamentally) and what are the relationships?
- How can we use curriculum and instructional materials to show teachers that the crosscutting concepts have value while also building in opportunities for them to see how students apply their use over time?

Teacher learning. The teacher learning table discussion focused on the professional knowledge teachers need in order to successfully incorporate crosscutting concepts into their instruction and how this knowledge can be developed through professional learning opportunities linked to practice.

Round 1 Participants:

Tina Vo (Table Host), University of Nevada - Los Vegas
Cindy Hmelo-Silver, Indiana University
Lauren Levites, Chicago Public Schools
Brett Moulding, Utah Partnership for Effective Science Teaching and Learning
Jeffrey Nordine, IPN-Kiel
Nancy Ruzycki, University of Florida
Ted Willard, National Science Teachers Association
Susan Yoon, University of Pennsylvania

Round 2 Participants:

Tina Vo (Table Host), University of Nevada - Los Vegas
Andy Anderson, Michigan State University
Okhee Lee, New York University
Kristin Mayer, Kentwood High School
Joi Merritt, James Madison University
Lindsey Mohan, BSCS

The teacher learning table focused their discussion on two central ideas:

1. What is the purpose of a research-focused agenda on CCCs in Teacher Learning
2. What are the implications of CCC focused research on this area? (e.g., study design)

From these ideas, a myriad of discussions around teacher learning occurred. The conversation often turned towards the larger issues around the NGSS and the state of education, the group felt because of CCCs supportive nature this wasn't problematic. The conversation also addressed specific issues related to the CCCS. For example, the second round group established a consensus that CCCs would/should typically be taught in conjunction with a DCI (e.g., Energy & Matter in physical science), and/or a SEP (e.g., Cause and Effect with Modeling and Using Models). Further agreeing, a standalone unit on CCCs (or SEPs or DCI's for that matter) would not be as strong. Overall, the discussions of this group can be broken down into four categories:

- Baseline questions about CCCs the field should address to inform intervention
- CCCs impact on professional learning opportunities for teachers
- Teachers' use of CCCs to improve science learning environment and student learning
- Appropriate study designs to provide strong evidence of CCCs

First, when addressing baseline questions about CCCs the field should address to inform intervention the following ideas were discussed:

- A literature review should be conducted looking into how CCCs are discussed in science education. Another literature review might be undertaken to see how CCCs are

considered in other contexts: developmental literature, complex systems works, learning sciences, teachers' understanding of inquiry, analysis of coherence curriculum materials,

- A cross-sectional look at how experts in science and science education use the CCCs presented in the NGSS (e.g., are they tied to SEP or DCI more closely)
- To what extent have teachers adopted/invested classroom time into the CCCs
- What does 3D thinking look like without the CCCs, and is student 3D thinking reliant on teachers' use of the CCCs?
- Are there Clusters of CCCs that occur naturally together in science (within and across DCI's)?
- If a CCC does not span across multiple DCI's, but across multiple phenomena does that count?
- What is the current understanding of CCCs within stakeholders (e.g., teachers, students, administration, science professionals)?
- Given the model: Prior Knowledge → Professional Learning → Teacher learning → Student learning
 - How do CCCs get measured in each of those arrows?
 - What CCCs current state in each of those constructs?

Second, CCCs impact on professional learning opportunities for teachers was expressed as an area of concern for the table. To further clarify, this idea focuses on increasing teacher knowledge about CCCs. While there are still some very foundational questions that need to be answered, this section is focused on teachers' professional learning around CCCs and the roles they play in the classroom and in the lab/field.

- Are there differing understandings of CCCs among elementary and secondary teachers?
- How, if at all are teachers using CCCs in the classroom currently?
- What value, if any, do teachers place on the CCCs versus SEPs and DCIs?

Further, in this section, some productive talk was focused on the challenges that interfered with teachers' professional learning:

- Teachers' who already believe they are doing 3D teaching by rehashing old lessons
- Teacher attrition (why would teachers be interested in learning about, adopting, and integrating CCCs when they are soon leaving the field)
- The group noted a lack of experiences or examples of CCCs in actual science experiences.
- What should professional development, webinars, educative curriculum convey about the CCCs?
- The group noted a lack of professional learning communities. What kind of pushback would teachers have to implement the CCCs (and how would those be different than SEPs and DCI's)?
 - One group had a lengthy discussion around their administration and teacher evaluation issues. While everyone wants teachers to use the standards, understanding practical applications is challenging. A related research question might be: what happens to classroom instruction when neither teachers nor principles have a clear vision for what teaching using the CCCs look like?

The group identified tools that may help teachers to engage with CCCs more productively:

- Videos, books, workshops series; choosing 1 DCI and highlighting all the related CCCs, then do the same for other DCIs.
- Curriculum using CCCs as a lens to understand a topic or phenomenon (e.g., water) with educative curriculum materials
- Webinars that provide examples of CCCs in action
- Access to professional learning communities through NSTA and projects
- Professional development that focuses on three-dimensional learning should pay special attention to highlighting the CCCs.

Third, when considering teachers' use of CCCs to improve science learning environment and student learning the group was interested in:

- What do teachers think students' know about the CCCs?
- Is there a way to leverage students' implicit knowledge of some CCCs (patterns/cause & effect) to teach science?
- Little evidence that a change to incorporate CCCs would lead to better experiences for their students would make teachers hesitant to include. What kind of evidence would be just as valuable to teachers as researchers (see study design section)
- What is the relative importance of each of the CCCs within and across grade level? Are some more developmentally appropriate to introduce later or sooner?
- Would some CCCs be more impactful to students presented in connection to specific SEPs, DCIs or other CCCs?
- What is currently in curriculum about CCCs that teachers might already be using?
- There should be scaffolds developed to support the use of CCCs within each DCI, what might these look like?

Fourth, intertwined within all of the previous topics, an ongoing discussion about appropriate study designs to provide strong evidence of CCCs occurred. While these suggests were often tied to a specific idea, it was the general agreement of the table that tools themselves could serve multiple purposes. These included:

- Clinical Interviews focused on assessing teachers' current knowledge and understandings of the CCCs and if teachers saw natural grade alignment or clustering, and other foundational topics
- Assessment of CCCs could (but should they?) be developed to measure understanding and transfer
- Development of a learning progression around different CCCs with examples from multiple DCIs
- Empirical studies focused on individual CCCs (which may or may not be paired with a specific SEP/DCI) to provide evidence of teacher enactment
- Teacher reflection pieces concentrate on their ideas an understanding before and after engaging with CCCs
- Studies of teacher learning in the context of professional development

The table host noted relatively little time was spent discussing preservice teachers' knowledge and learning of the CCCs. This population could be uniquely supported by CCCs, particularly within elementary contexts where a more holistic approach to science occurs.

Assessment. The assessment table focused on issues relating to the design of assessments that can measure students' understanding and use of the crosscutting concepts and the interpretation of data gathered from these assessments. Discussions at this table focused on three central challenges:

1. What does it look like when students use the crosscutting concepts effectively?
2. Is it necessary that students know that they are using crosscutting concepts when they use them?
3. How can research better illuminate how students are reasoning with the crosscutting concepts?

Round 1 Participants:

Brian Gane (Table Host), University of Illinois - Chicago
Aneesha Badrinarayan, Achieve Inc.
Ann Novak, Greenhills School
Joe Krajcik, Michigan State University
Kevin McElhaney, SRI International
Sarah Fick, University of Virginia

Round 2 Participants:

Brian Gane (Table Host), University of Illinois - Chicago
Jason Buell, University of Colorado
Melanie Cooper, Michigan State University
Jeffrey Nordine, IPN-Kiel
Ann Rivet, Teachers College, Columbia University

Table participants identified a pressing demand for research that advances the assessment of crosscutting concepts. Key questions include:

- Is there empirical support for a CCC construct through students' responses to the assessment task?
 - What constitutes observable evidence that students are proficiently using CCCs?
 - Do students need to know that they are using a CCC? Given the emphasis on explicit instruction about CCCs in the NGSS, to what extent should students' metacognition about CCCs be a target of assessment?
- How can assessments illuminate the learning trajectories taken by students as they develop more sophisticated understanding and uses of the CCCs?
 - Group members noted that there is some existing research, for example in the case of Systems and System Modeling and Energy and Matter: Flows, Cycles, and Conservation, but very little of this research has been conducted in the context of three-dimensional teaching and learning.
- How can pedagogical content knowledge (PCK) of the CCCs be defined and measured? What are common alternative conceptions and canonical representations, and how can these be identified through assessment?

Table participants also identified that issues related to CCC assessment are embedded in a larger issue relating to assessing three-dimensional learning. Within this conversation, participants

identified that teachers play a critical role in developing and interpreting assessment data, and that professional learning experience for both teachers and assessment designers is critical for the development of new three-dimensional assessments that truly incorporate and elicit the CCCs.

Table participants recognized a tension between the requirements and assumptions of existing psychometric models and the demands and affordances of three-dimensional learning assessment. Key questions related to this tension are:

- Can, and should, assessments be able to measure CCCs, DCIs, and SEPs as different dimensions? To what extent is “pure” measurement of each dimension appropriate and achievable?
- To what extent are “1-dimensional” (e.g., focusing on familiarity with DCIs) and “2-dimensional” assessments useful in a formative, small-scale setting when helping students achieve the broader aims of three-dimensional learning?
 - When considering the value of “1-D” and “2-D” assessments, participants made an analogy to doing drills in sports training, e.g., practicing free-throws and dribbling to learn to play basketball in a game situation.
 - To what extent does the value of “1D” or “2D” assessments depend on the specific dimensions that are selected?
- What counts as evidence of validity when developing and using three-dimensional assessments?
 - Table participants noted that such evidence may be provided through psychometric (model-based) evidence, but validity also depends upon the instructional utility of assessments, e.g., how teachers can use tasks to support students’ three-dimensional learning.

Table participants noted that there are significant design and development challenges that need to be overcome in order to produce assessments that appropriately incorporate the CCCs and can be used to inform instruction. Key questions include:

- What’s a design process to make sure that CCC is integrated to make sure it has to be used in addition to SEP and DCI?
- How can assessments be designed that ensure that all students are given the opportunity to develop and engage with the CCCs?
- What are tools that teachers and designers can use to develop three-dimensional assessments and associated rubrics?
- How can educative resources be designed and embedded (e.g., in tasks and rubrics) for teachers to support three-dimensional assessment practices (including the interpretation of assessment results)?
- What type(s) of student feedback is needed so that assessments can best support student learning of the CCCs?

With respect to these questions, table participants noted a need for exemplary models of assessment items in which CCCs must be used in both the design of tasks and scoring rubrics. These examples could be balanced with counter-examples in which CCCs are not needed.

Finally, table participants discussed the importance of identifying research and development methods for advancing the use of CCCs in assessment. These methods include:

Cognitive labs. In this method, a primary emphasis is on conducting cognitive interviews with students which focus on identifying which CCC(s) students used to respond to an item and to evaluate the nature and extent of their metacognition regarding the use of CCCs.

Classroom-based research. The emphasis here is on teachers' use of assessment tasks to support students in their use of, and learning about, the crosscutting concepts.

Design-based research. Here, the focus is on identifying methods for integrating CCCs into assessment tasks that effectively elicit students' use of the CCCs. A key outcome would include the development of task design procedures and templates that can be shared with the larger community. Key foci of this research method includes the types of professional learning experiences that teacher and developers need so that they can design three-dimensional assessments, and the design of educative resources that support such professional learning.

Nature of the crosscutting concepts. This table focused on foundational issues relating to the crosscutting concepts themselves, such as their historical and philosophical basis, metaphors for understanding crosscutting concepts, and their ontological status.

Round 1 Participants:

Lauren Barth-Cohen (Table Host), University of Utah
Kristin Mayer, Kentwood High School
Okhee Lee, New York University
Ann Rivet, Teachers College, Columbia University
Jonathan Osborne, Stanford University
Melanie Cooper, Michigan State University

Round 2 Participants:

Lauren Barth-Cohen (Table Host), University of Utah
Kevin McElhaney, SRI International
Ted Willard, National Science Teachers Association
Aneesha Badrinarayan, Achieve, Inc.
Ann Novak, Greenhills School

Through their discussions, table participants noted a major concern regarding the lack of any historical or philosophical basis for the crosscutting concepts themselves, and further identified that this was also an issue in *Science for All Americans* ([American Association for the Advancement of Science, 1990](#)). Yet, participants did note that two CCCs - Patterns and Cause and Effect: Mechanism and Explanation - do have a philosophical basis. Key questions that emerged from these discussions include:

- Is there a literature basis for the CCCs that is not cited within the *Framework for K-12 Science Education*?
- What do disciplinary scientists and engineers think about the CCCs? Do they view CCCs as important to their work? How are CCCs used in professional science?

A second discussion thread related to the use of metaphors in making sense of crosscutting concepts. Such metaphors include: lenses, bridges, tools, heuristics, and game rules. The group identified a set of questions for guiding related research:

- How do metaphors for CCCs support students, teachers, and/or instruction?

- What are the affordances and limitations of metaphors for understanding and using the CCCs?
- How well do metaphors (which participants note are rooted in George Lakoff's work in linguistics rather than science) apply to the CCCs, and where do they break down?
- Which metaphors are most helpful for achieving what ends (e.g., three-dimensional learning, understanding the CCCs themselves)?
- Are CCCs the grammar of science? (Note: to address this question, we need studies comparing the linguistics in learning spaces with and without the inclusion of CCCs). What are the differences? This direction might help us figure out which metaphors (in what context) help students engage with CCCs.
- How do various metaphors/perspectives on the CCCs impact outcomes for student learning, teaching, and instruction?
 - Are students more likely to use certain perspectives on CCCs?
 - Does instruction implicitly include certain perspectives on CCCs?
 - Are there certain contexts where certain perspectives on CCCs are more or less useful?

Table participants also noted the importance of investigating how teachers understand the crosscutting concepts. Such research would need to consider the teachers science content background, as this may mediate their thinking. Participants noted that there has been some work done to date that investigated teachers and district personnel's views on the NGSS. A core challenge of research in this area is that teachers don't seem to perceive CCCs as hanging together as a coherent class of elements, yet, teachers have also reported the power of CCCs in their own classrooms. Related questions emerging from this line of discussion are:

- How are teachers making sense of crosscutting concepts?
- How do teachers utilize crosscutting concepts in their instruction?

Many questions emerged from discussions regarding the nature of the crosscutting concepts themselves and the value of their inclusion in the NGSS. While some of these questions may be addressed with empirical investigations, others require research that clarifies the theoretical foundations and justification for the crosscutting concepts. These include:

- How are CCCs manifested differently in various disciplines?
- What kinds of learning, outcomes, and ways of engaging do we see in teaching and instruction that includes CCCs beyond teaching and instruction that does not include CCCs? Furthermore, what new challenges and difficulties arise when CCCs are included in teaching and instruction beyond when they are not included?
- What do CCC as a unit (not individually) offer beyond using just SEPs and DCIs?
- Can the other six CCCs be learned within the context of a focus on systems thinking? Can the other six CCCs be learned without system thinking?
- How are CCCs different from DCIs? What is the ontological (or epistemological) difference between CCCs and DCIs? Possibly DCIs and CCCs have the same form because they are both "knowledge statements," which mean that both are things that are known/facts (noun) and not actions (verbs). How are the CCCs articulated differently from the DCIs in the framework?
- Looking across many studies of the same CCCs (or many classrooms using the same CCCs), what are the commonalities? Or, what is missing without CCCs?

- Are CCCs “concepts” according to existing theories of concepts within conceptual change?

In addition to identifying a set of questions to guide future research, table participants made several suggestions for the conduct of future research in this area, which include:

- Researchers communicating and writing about CCCs should begin by stating what they think the CCCs are and their associated assumptions about CCCs.
- Future research may conduct a retrospective analysis examining prior research on CCCs (even implicitly) and see how prior work communicates about CCCs (what perspectives are used when communicating about CCCs). For example, such research may involve coding prior research studies for what perspective they use on CCCs (e.g. lens, bridge, concept, Epistemic tools, etc.) One could also do this with prior research studies that focus on only one of the CCCs (e.g. patterns).
- It would be helpful to have studies looking at the same DCIs taught with two different CCCs. For example, what is different when the water cycle is taught with emphasis on Energy and Matter: Flows, Cycles, and Conservation as compared to when the water cycle is taught with emphasis on Systems and System Modeling or Cause and Effect: Mechanism and Explanation?
 - Another version of this research would be to implement studies with various scaffolds that emphasize different CCCs or even different metaphors for the same CCC.

Summary

A primary outcome of the *Summit for Examining the Potential of Crosscutting Concepts to Support Three-Dimensional Learning* was to identify key areas of need for future research into the teaching and learning of the crosscutting concepts. Through these discussions, the summit participants identified a wide range of new research directions and questions that may help to clarify the nature and value of the crosscutting concepts in supporting and strengthening students’ science learning. While the NGSS acknowledge that the inclusion of the CCCs was not based on a strong foundation of research, their explicit inclusion as a dimension of science learning has both begun a conversation and issued new challenges for the science education research community. While the research priorities identified in this section are certainly not exhaustive, they represent a range of new directions for science education research that will help to better understand how the crosscutting concepts may be more explicitly taught in school science and to lend empirical evidence to whether and how the crosscutting concepts support student thinking and learning in science and engineering.

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