What Are Crosscutting Concepts in Science? Four Metaphorical Perspectives

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Abstract: To think more productively about the role of crosscutting concepts (CCCs) and how they influence students' three-dimensional science understandings of phenomena, we took a hermeneutic approach to examine the literature and language of the *Next Generation Science Standards* and its supporting documents. Using the perspective of Lakoff and Johnson (2003)'s conceptual metaphors, our analysis identified a set of four metaphorical perspectives – CCCs AS LENSES, CCCs AS BRIDGES, CCCs AS TOOLS, and CCCs AS RULES – that the texts use to describe the role of CCCs in three-dimensional science learning. We discuss the affordances and limitations of each perspective, their implications for instruction and assessment design, and directions for future research.

Introduction

Traditional science instruction has primarily consisted of a series of teaching activities focused around a single core idea. Current reforms in science education are changing that perspective to emphasize three-dimensional understanding of core conceptual ideas in combination, interaction and progression with science practices and crosscutting concepts, in ways that bridge ideas from multiple disciplines across phenomena (Pellegrino, Wilson, Koenig & Beatty, 2014; Roseman, Fortus, Krajcik, & Reiser, 2015). The seven crosscutting concepts (CCCs) in the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013a) play a particularly important role in this new perspective on learning. In *A Framework for K-12 Science Education* (referred to as the *Framework*), the National Research Council [NRC] (2012) emphasizes these concepts as particularly important and necessary, in that they "help provide students with an organizational framework for connecting knowledge from various disciplines into a coherent and scientifically-based view of the world" (p. 83).

In our efforts to support teachers and developers with designing instruction for three-dimensional learning, however, we have found the CCCs to be the most difficult dimension to discuss and develop shared understanding. The language used to describe the CCC dimension and how it relates to the other two dimensions in the *Framework*, the NGSS, and other supporting documents is generally sparse, ambiguous, and inconsistent. The lack of consistency and details in explaining the CCCs is a contributing factor that has limited our ability to consider ways to effectively support understandings of this important dimension in terms of instruction and curriculum materials. To address this problem, we conducted a hermeneutic analysis of the texts describing CCCs from the *Framework*, NGSS and its appendices, and other supporting and foundational documents. Through this process, we identified four different metaphors used to describe the nature of CCCs. Rather than representations of what the CCCs actually are, we found that these metaphors served a more abstract purpose, in that they are used to describe four different conceptual frameworks for thinking about the role CCCs play in three-dimensional understandings of science.

This paper presents the results of this analysis, describing the affordances and limitations of these four metaphorical perspectives on CCCs. We consider how these different perspectives may help the field better conceptualize and utilize CCCs productively, particularly with respect to instruction and assessment design.

Theoretical framework and methodology

Lakoff & Johnson (2003) define conceptual metaphors as linguistic representations of complex phenomena that make use of language associated with more relatable experiences. For example, one often describes the concept of time using words that we might more readily apply to money: that meeting *wasted* my time; this shortcut will *save* you hours; traffic on the highway *cost* me three hours (Lakoff & Johnson, 2003). These idioms reflect a coherent metaphor, *TIME IS MONEY*, which allows us to think productively about how time is a valued resource with the language usually applied to money, a more tangible resource that people value. In our hermeneutic analysis we focused on how the language around CCCs in the *Framework*, the NGSS appendices (NGSS Lead States, 2013a; 2013b) and other supporting documents reflect different conceptual metaphors.

Our analysis began by examining theses texts for instances where they describe the nature and use of crosscutting concepts through comparison to more tangible phenomena. These instances were flagged and clustered into nine potentially productive conceptual metaphorical categories. We compared, scrutinized and re-clustered the evidence in this initial categorization scheme against foundational and supplementary documents to further support how the metaphors provided meaningful insights on the CCCs and the interrelation between CCCs, SEPs, and DCIs. This process resulted in a set of four conceptual metaphors for CCCs that operated in ways akin to that of the *TIME IS MONEY* metaphor (Lakoff & Johnson, 2003).

Four metaphorical perspectives for thinking about cross cutting concepts

Metaphor 1: CCCs AS LENSES

Most commonly, the language of the NGSS and related documents conveys the crosscutting concepts through the metaphor of a set of lenses, particularly describing them as a means of observing and seeing salient features of phenomena. For example, the language of the NGSS (NGSS Lead States, 2013b) notes that *Patterns* (one of the seven CCCs) must be "observed" or "noticed." Another crosscutting concept, *Scale, Proportion and Quantity* allows students to see things that are "too small, too large, too fast, or too slow to observe directly." A third, *Cause and Effect,* helps students to "see events" in terms of the internal causal phenomena (NRC, 2012). Sight is an understandably useful experience to ground metaphorical understanding (Lakoff & Johnson, 2003), as many of the goals of science are described as attempting to see the previously unseen (Duschl et al., 2007). We refer to this conceptual metaphor as *CCCs AS LENSES*. This metaphor has a number of affordances for scientific reasoning. When students engage with the CCCs via the *CCCs AS LENSES* metaphor, they consider features of a phenomenon or problem that they may have previously found insignificant. The different CCCs allow analyses of a situation or problem in distinct ways, all of which can be considered legitimate approaches to reasoning about that phenomenon. For example, a problem involving force and motion can be addressed by taking an *Energy and Matter* lens (i.e. focusing on the transfer of energy in the system), or it might also be examined from a *Cause and Effect* lens (i.e. focusing on what forces will cause changes in motion). These perspectives could also be combined to consider both the causal relationship and the transfer of energy within the interaction. Taken together, considering *CCCs AS LENSES* results in students' robust three-dimensional understandings of the relationship between force and motion.

However, real lenses are engineered for a limited set of purposes; one would not expect a pair of glasses to help them observe the structure of a cell nor a microscope to help them read the newspaper. Similarly, *CCCs AS LENSES* suffers from a lack of well-defined transferability amongst disciplines. While several lenses may be useful to solve a particular problem in a discipline, it may not be obvious that the lens has utility in a new context. The *CCCs AS LENSES* metaphor is a productive way of thinking, but understanding the CCCs also requires the ability to see how the same concept is used across several scientific knowledge domains.

Metaphor 2: CCCs AS BRIDGES

To develop sophisticated scientific understanding, it is important for students to recognize the application and transfer of content knowledge between interconnected domains and phenomena. The NGSS and supporting documents use the language of "connections" and "directions" to convey this role of crosscutting concepts in three-dimensional science learning. We labeled the use of this language as reflecting a second metaphor for CCCs, that of *CCCs AS BRIDGES*. For instance, the NGSS states that the crosscutting concept *Cause and Effect* serves to help students understand phenomena A and B in terms of "interactions which connect" the two (NGSS Lead States, 2013b). Similarly, the CCC progression for *Systems and Systems Models* includes that in high school, "students can…simulate the flow of energy, matter, and interactions within and between systems." (NGSS Lead States, 2013b). An example of the utility of understanding the crosscutting concept *Structure and Function* from the *Framework* (NRC, 2012) describes how an engineer's understanding of the role of density in structural design can "lead in turn to an examination of atomic-scale structure" in designing a new bike (NRC, 2012, p. 97). The language of connectivity, transfer, and movement is emblematic of this linguistic image of *CCCs AS BRIDGES*. In this metaphor, students use CCCs to recognize conceptual relationships between phenomena, and as a means for explaining the complexity of a macrosystem in terms of its constituent parts.

However, considering *CCCs AS BRIDGES* is potentially limited in its ability to support understanding relationships between concepts in the ways that scientists do. Given the plethora of potential connections that could exist between phenomena – and without clear criteria for evaluating the efficacy of one connection over another – connections that scientists make may not be seen as productive by students. It is also the nature of "connection" to emphasize similarities over differences. Students using *CCCs AS BRIDGES* may find correspondences between concepts more prominent than non-correspondences, when both are required for developing sophisticated understanding. This metaphor is a powerful means to develop a sense of the transferability and connectivity between concepts, but understanding CCCs also requires one to recognize which connections are productive in explaining and predicting the natural world.

Metaphor 3: CCCs AS TOOLS

Within the *Framework* (NRC, 2012), we identified a third metaphor for understanding the role of CCCs: *CCCs AS TOOLS*. The authors of the *Framework* frequently emphasize a mechanistic approach in which consideration of a CCC helps students leverage existing understanding to produce more sophisticated knowledge. "Crosscutting concepts have value because they provide students with connections and intellectual tools that are related across the differing areas of disciplinary content and can enrich their application of practices and their understanding of core ideas" (NRC, 2012, p. 218). This underscores the value of CCCs in helping students to engage with science and engineering practices in a more meaningful and effective ways. We also found evidence for this third metaphor in the language of the NGSS. For instance, within the description of the CCC *Patterns*, "students progressively build upon this innate ability [to identify patterns] throughout their school experiences" (NGSS Lead States, 2013b). In one performance expectation (HS-PS2-1), students are expected to use their understanding of the CCC *Cause and Effect* to generate the evidence needed to "support an argument that the gravitational force exerted by Earth on objects is directed down." (NGSS Lead States, 2013a). The language of tools, building, and construction is evidence for the mechanistic *CCCs AS TOOLS* metaphor. Just as levers and pulleys provide mechanical advantage in doing physical work, through this metaphor, students gain advantage in using their existing understandings to construct complex explanations and resolve practical problems. In this sense students' understandings of different CCCs operate as cognitive tools (Brown, Collins & Duguid, 1989) that develop meanings through their applied use in different contexts.

While the perspective of *CCCs AS TOOLS* conveys the useful and practical aspects of developing understandings of CCCs, this view does not imply that subsequent use CCCs will be inherently transferable or generalizable. Rather, students' situated expertise with CCCs develops over time, and requires explicit reflection on when, how, and for what kinds of phenomena and problems consideration of the different CCCs are most productive. Additionally, considering *CCCs AS TOOLS* specifically emphasizes the ways that these perspectives leverage students' prior knowledge and understandings to explain phenomena or address problems. However, it is important to keep in mind that students' prior knowledge varies across groups and contexts. This in turn impacts the ways in which different students may be able to use the *CCCs AS TOOLS* and the depth to which they engage with the CCCs in their learning, thus further influencing the extent to which they develop robust three-dimensional science understanding as called for in the NGSS.

Metaphor 4: CCCs AS RULES of the Game

In the NGSS and supporting documents, the process of developing robust three-dimensional understanding of science is at times portrayed as a form of playing an epistemic game (Collins & Ferguson, 1993) which has both goals (Krajcik, Codere, Dahsah, Bayer, & Mun, 2014) and rules of engagement (Collins & Ferguson, 1993). From this perspective the CCCs play the role of *CCCs AS RULES* for this epistemic game. In this sense, understanding and using different CCCs to learn science can provide order and structure to students' potential understandings of a complex (and often chaotic) world. For example, applying the CCC *Patterns* can make "order…emerge from chaos" (NGSS Lead States, 2013b) by creatively organizing students' thoughts about phenomena (NRC, 2012). Likewise, when describing CCCs such as *Structure and Function*, the NGSS states that understanding how CCCs serve rule-like functions helps constrain investigations "in order to know what properties [and aspects]…are relevant" (NGSS Lead States, 2013b). Rules help to establish a shared language to communicate acceptable behavior within a game (Walton, 1990); CCCs are able to serve a similar purpose from this point of view. An early step in developing sophistication for understanding the CCC *Scale, Proportion, and Quantity* is for students to recognize that there exists "standard units" of measurement agreed upon by the scientific community (NGSS Lead States, 2013b). The existence of rules helps to justify representational systems (Walton, 1990), including scientific investigations (Duschl, et al., 2007), to ensure that outcome of the game leads to understandings (Collins & Ferguson, 1993) of the natural world as aimed for in the NGSS.

In describing the three dimensional learning framework, Duschl (2008) points out how students must develop epistemic understanding of "[the] specialized ways of talking, writing, and representing phenomena" (p. 275) in the sciences. Considering *CCCs AS RULES* enables students to use CCCs as a way to organize their learning in light of these epistemic practices of science (NRC, 2012). The epistemic focus of this metaphor is a strength but also a challenge. In science classrooms, students often develop epistemologies of their practices that are distinct from what scientists do, often with unproductive results (Sandoval, 2005). Likewise, students using *CCCs AS RULES* may consider the CCCs as rules for the classroom, but not necessarily for the scientific community. Ideally, students' understanding of the CCCs should enable them to develop formal and practical epistemologies about their science knowledge similar to those of practicing scientists (Duschl et al., 2007; NRC, 2012; Sandoval, 2005).

Implications for teaching and assessment

Our discussion of these four metaphorical perspectives on CCCs identified from the framing documents of the NGSS illustrates how students' understanding of the role of CCCs as part of three-dimensional learning can vary, and the implications that these different understandings of CCCs may have on their resulting science understanding. We believe these metaphorical perspectives will be helpful for teachers and curriculum designers who are using the NGSS and supporting documents to craft instruction. For example, teachers can direct students to the *CCCs AS LENSES* metaphor to suggest novel ways of looking at situations using several different CCCs, and help students recognize that each lens results in a different way of considering the problem. When bundling several NGSS performance expectations (Krajcik, et al., 2014) into a coherent unit, designers may utilize the *CCCs AS BRIDGES* metaphor as a way to assist both students and teachers to connect content ideas that address different parts of a bigger problem or context. Alternatively, teachers may use the *CCCs AS TOOLS* perspective to leverage students' understandings of simple systems to construct more complex explanations that are useful for a greater set of problems or contexts. Teachers may consider the *CCCs AS RULES* metaphor as a way to foster the idea that science is socially constructed, as rules of games are often socially negotiated (Walton, 1990), or as criteria to limit the scope of an investigation (Collins & Ferguson, 1993) in ways that are most productive for answering particular questions.

Each of these metaphorical perspectives conveys a different story about the CCCs. The story that students develop about CCCs will frame their views of how the crosscutting concepts fit within their three dimensional understanding of phenomena. Like any other representation, the set of four linguistic representations of CCC understanding have both affordances and constraints. No single representation is as useful in isolation as they are together. Thus the aim is for students, like scientists, to not draw distinctions between the different ways of understanding CCCs. Instead, these combined perspectives on CCCs are one aspect of more encompassing gestalt system that is greater than the sum of its parts.

The NGSS challenges not only existing curriculum materials (Roseman, et al., 2015), but also the nature, role, and features of existing assessments (Pellegrino, et al., 2014). These metaphorical perspectives on CCCs in three-dimensional learning can also provide guidance for considering the design of assessments. They provide a means for conceptualizing how evidence of the role of CCCs can be made visible in student activities and products, and may be used to inform understanding of learning progressions and instructional decision-making. Our future research and design efforts will focus on these goals.

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