# Learning About Crosscutting Concepts as Concepts

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**Abstract:** Despite a growing interest in examining the learning processes involved in three-dimensional science learning, crosscutting concepts are an understudied dimension. We view crosscutting concepts as a type of *concept*. We argue that crosscutting concepts can be viewed as a kind of concept called a coordination class. We document two types of learning about crosscutting concepts. The first is focused on intuitions that provide a causal explanation, while the second focuses on coherent conceptual systems that are refined over time. In both cases there is an intertwined relationship between multiple crosscutting concepts, with some foregrounded or backgrounded. The results provide a new perspective on three-dimensional science learning that incorporates crosscutting concepts and relevant learning mechanisms.

## Background and future of crosscutting concepts

There is a growing interest in learning and teaching about crosscutting concepts, yet there are disagreements about their relative importance and ontological status (Osborne, Rafanelli, & Kind, 2018). The *Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012) called for a novel approach to science learning that equally emphasizes three-dimensions: science content knowledge, the practices of what scientists do, and the *crosscutting concepts* that are used as reasoning tools to support connecting knowledge across disciplines into a coherent view of the world. There are the seven crosscutting concepts: patterns; cause and effect; mechanism and explanation; scale, proportion, and quantity; systems and system models; energy and matter: flows, cycles, and conservation; structure and function; and stability and change. Researchers and teachers have argued for the potential of crosscutting concepts to support science learning (e.g. Fick, 2018), but moving forward requires unpacking the nature of these concepts. Further, we have a limited understanding of the relevant types of learning with and about crosscutting concepts. There are also different perspectives on the essence and ontological status of crosscutting concepts. One can view crosscutting concepts as metaphors that function as lenses, bridges, tools, or roles of a game (Rivet et al., 2016). Our perspective is to take seriously the intention suggested by their name and to view crosscutting concepts as *concepts*.

## Theoretical background: Coordination classes

We use a definition of a concept known as a *coordination class* which arises out of a theory of conceptual change called Knowledge in Pieces (KiP). KiP assumes that learners have a complex knowledge system consisting of many pieces that operate at various grain size across contexts (diSessa, 1993). Learners may have many types of knowledge structures that may arise or diminish over time as connections strengthen or weaken. The continual reorganization of knowledge across contexts is taken to be an underlying mechanism for learning (Wittmann, 2006). Research on coordination classes has focused on characterizing knowledge systems, the system components, their function, structure, dynamics, and long-term development. Many studies have focused on one knowledge element, *p-prims*. P-prims are small intuitions that are used to explain how the physical world works. One prototypical p-prim is Ohm's p-prim, which is a physical intuition that more effort leads to more results, "more is more." A p-prim can be applied in many contexts, leading to reasoning difficulties or successes. The term "primitive" describes how p-prims are typically seen as "that's just how things are," that is, they operate by being recognized. Existing research has documented dozens of p-prims that are applicable across topics (Barth-Cohen, 2018; diSessa, 1993). Explanations composed of p-prims are commonly seen when learners have less coherent knowledge systems and are working to assemble a seemingly sensible explanation based on their existing intuitions (Kapon & diSessa, 2012). To describe changes to knowledge structures over time, researchers have used a cognitive model of learning known as coordination class (diSessa & Sherin, 1998). Experts with a highly developed coordination class are able to consistently read out essential properties of that concept across contexts. In contrast, learners may struggle to read out the essentials of a concept across contexts. Incorporation and displacement of knowledge is the key learning mechanism relevant to changes in one's coordination class.

We make two hypotheses: (1) crosscutting concepts can contain p-prims, and (2) crosscutting concepts can be coordination classes. Past studies suggest the value of both hypotheses, as they have involved learners reasoning about notions that are crosscutting concepts, without having been labeled as such. diSessa (2014) examined stability and change, energy flow, and patterns. Similarly, Barth-Cohen and Wittmann (2017) examined energy flow and systems and system models. In this paper, we reanalyze two existing empirical studies to address the following research questions: 1) What is the relationship between crosscutting concepts? 2) What kinds of knowledge systems were evident in learning about crosscutting concepts?

## Methods: Re-Analysis of existing results

Responding to the push for transparency and openness in education research (AERA, 2017; Cook et al., 2019), we use shared data and materials to present a re-analysis of two existing empirical studies by diSessa (2014; 2017) and Barth-Cohen and Wittmann (2017). These two studies were chosen because they are situated within the same theoretical framework and involve the same crosscutting concept, which allows for ease in comparisons. We present existing empirical results through narrative vignettes that highlight the existing analyses and results, followed by new questions, considerations, and results. While this approach is limited by issues of data collection and initial analysis techniques, its allows for increased access and communication between studies.

## Case 1: Invoking p-prims when generating an explanation for temperature equilibrium

In this case, presented in diSessa (2014; 2017), a group of high school students used their intuitive conceptions to develop an explanation for thermal equilibration. The instructional goal was for the students to understand that temperature difference drives the rate of temperature change (based on Newton's law of heating). Student explanations used a variety of p-pirms and crosscutting concepts. When initially discussing a cold glass of milk placed at room temperature, a student introduced the word "equilibrium." Another student, W, used anthropomorphic agency when describing the room and the milk as a "battle to reach dynamic equilibrium," where the milk gets "beaten by the room," and eventually they will "exist in harmony." In this explanation, there are dual agencies with the room and the milk competing. Possibly, he was invoking the *dynamic balance* p-prim, a common intuitive physics notion in which opposing forces cancel out (diSessa, 1993). The students then explored many graphs (*e.g.*, overshoot equilibrium, a slowing to equilibrium, and the normative graph) and discussed key features, including the gradual slowing of temperature change over time. The correct model for Newton's law of heating had not yet been introduced. From the perspective of crosscutting concepts, a pattern arose in the sense of an observed regularity in change over time (fast then slow) over multiple experiments. One student generated an explanation of why the temperature verses time graph starts out steeply and then becomes less steep:

1. I think that the liquids like to be in an equilibrium.
2. So, when one is way off, they sort of freak out
3. and work harder to reach equilibrium.
4. And when it is closer to equilibrium, they're more calm,
5. so they sort of drift slowly toward equilibrium.
6. So maybe that's why it moves fast at first, because it is like freaking out.
7. But then it just calms down as it approaches the right temperature. (diSessa, 2014; p. 813)

The student first invokes the *abstract balance* p-prim, using anthropomorphic language to assert that liquids like to be in equilibrium. The second line phrase "freak out" evokes an active agentive state that is dichotomous when compared to a "normal" state. The phrase, "when one is way off," implies a parameter that causes the freaking out, which may be invoking agency where there is none and connecting it to temperature differences. Line 3 connects the effort of the agent with the difference in temperatures, suggesting the invocation of *Ohm's p-prim* where the effort of an agent is the control parameter for the result. This modifies the earlier dichotomous phrasing of a transition point ("when one is way off") into a continuous parameter. Lines 4 and 5 extend this causal chain to when two temperatures are closer to equilibrium and the liquids have less activation, which is linked to a lower rate of temperature change. In lines 6 and 7, the student contrasts the agentive temperature difference and the causal result of moving faster with the lower temperature difference and the slower result. The crosscutting concept of *cause and effect* is present in the sense of a causal anthropomorphic agency that accounts for why the temperature changes first quickly and then slower. Subsequently, other students and the teacher affirmed W's freaking out explanation. A different student mentioned that the difference between water and room temperatures impact the relative steepness of the graph. W explained that being farther away from room temperature led to a "bigger freak out." He was thus using the same pattern of regularity in change over time across multiple graphs, thereby applying key feature of the explanation to a new context.

Students then began to mathematize the crosscutting concept of pattern by mentioning a numerical difference ("If you had a number line with negative and positives"…"The hot temperature [H] is farther away from room temperature [R] than the cold temperature [C] is"). This involved an implicit use of the crosscutting concept of scale, proportion and quantity. Twice, later, students mentioned the same pattern of regularity in temperature change. First, a student, C, asked "Would it have to do with W's number line thing?" Two days later, when discussing graph steepness, C explained "Because the hot one started farther away than the cold one." In sum, these students engaged in an extended reasoning process. The initial explanation accounted for a slowing to equilibrium using dramatic anthropomorphic causality. This language became socially shared, applied to several contexts, but the students expanded these ideas towards mathematization. By the end, students eliminated the dramatic anthropomorphic causality and utilized the crosscutting concept of stability and change.

### Analysis of crosscutting concepts, p-prims, and three-dimensional learning

Throughout these explanations, multiple crosscutting concepts were present in different ways. Stability and change framed the instruction and sensemaking of temperature change. Patterns were seen in the graphical trend in temperature change, early on involving anthropomorphic agency and then mathematized. The proposed number line was a quantitative version of the pattern and involved a relative scale with proportionality, which is the scale, proportion and quantity crosscutting concept. Finally, cause and effect was present early, but was limited, given no atomic level. Over time, there was a diminishing role of p-prims, first being invoked to justify temperature changed and later being invoked less often as students became more conversant with the explanation across contexts. This may have been a shift from a less coherent knowledge system to either fewer p-prims or a diminished role of this p-prims as the explanation evolved, and could also relate to the learning mechanism of shifts in contextuality and the composition of elements. While the results show that an explanation composed of p-prims can also invoke crosscutting concepts, this is new domain for p-prims and worthy of theoretical extension. Student learning centered on the crosscutting concepts. The changes in knowledge systems involved the composition of elements centered on stability and change (equilibrium) and patterns. There were no changes in the DCIs of Energy and Matter or the scientific practice of generating explanations.

## Case 2: Conceptual learning about the steady state energy of the earth

The second case (from Barth-Cohen and Wittmann, 2017), describes conceptual difficulties encountered and ways a classroom of students made progress in learning about how the steady state (equilibrium) energy of the earth was represented in a series of embodied models. Steady state is similar to dynamic equilibrium and highlighted within the stability and change crosscutting concept (NRC, 2012). The data comes from a classroom of ninth grade earth science students using Energy Theater (ET), a pedagogical activity where students collectively use their bodies to model energy flows and transformations (Scherr et al., 2013). In ET each person represents a unit of energy (though it can have different forms). During two 45-minute classes team-taught by two teachers, students engaged in modeling the steady state energy of the earth. The students first generated an ET model in their own classes. Then the two teachers' classes came together and each class presented their model to the other, followed by questions and discussion. Finally, the two classes created a joint consensus model.

When creating class models, one group generated a model with an uneven amount of energy entering and leaving the earth. Three people at a time walked from the sun to the earth, representing UV, IR, and visible light, and one person representing IR light left the earth. Then an observing student asked, "How come there is only one thing leaving but three coming in? I think the earth would like, explode." In response, several students recognized that there was an uneven energy flow ("Not enough [energy] leaving the earth;" "I don't know if they already explained it, but how many different rays were hitting the earth, and only one coming out. Isn't there supposed to be equal coming in and the same out?"). The presenting students thought that the individuals entering and leaving were worth different amounts of energy ("[The one person leaving the earth] was worth all three of us. Cause we were just representing the three different kinds of energy that were going through the earth. And he was the one kind of energy come out of the earth.") Their model violated the ET rule in which each person is a single unit of energy. To the observing students, their representation violated expectations of how energy flows. Then, the presenting students appeared to understand the difficulty caused by representing steady state energy flow differently than expected. Later, the two groups of students created a joint model with equal numbers of individuals entering and leaving, representing consistent flow. The presenting group had to displace prior knowledge about types of light entering and leaving the earth along with knowledge about unequal amounts. The students, reasoning about the intertwined crosscutting concepts of energy flow and stability and change, learned to represent steady state rather than types of energy during the process of energy flow.

### Analysis of crosscutting concepts, knowledge, and three-dimensional learning

Multiple crosscutting concepts were present in different ways. Instruction highlighted the crosscutting concept of stability and change, which was central to students learning. Systems and system models and energy flow were present as the basis for questions and discussion. This suggests an inter-relationship with different crosscutting concepts serving different functions. We assumed that different groups and individuals had their own knowledge systems. Their questions often centered on implicit juxtapositions of their knowledge systems as the students encountered difficulties aligning their prior understanding with their peer's understanding of the same concept (e.g. people being worth different amounts of energy). These difficulties were resolved through discussion, resulting in changes to the model, or changes in their understanding of the concept through the mechanisms of incorporation or displacement. Here the learning (incorporation of new knowledge) centered on the crosscutting concept. There were no observable changes in the DCI of Energy or the scientific practice of modeling.

## Discussion: Learning of crosscutting concepts as *concepts*

We documented two cases of learning about crosscutting concepts, one focused on intuitions that provide a causal explanation, the other focused on coherent conceptual systems that are refined. In both cases, multiple crosscutting concepts were intertwined. These results show first that learners have existing knowledge systems based on p-prims related to crosscutting concepts, as suggested in our first hypothesis. Second, previously documented learning mechanisms, such as the incorporation, displacement, reorganization, and composition of elements apply to the learning of crosscutting concepts. These results suggest that crosscutting concepts as concepts can be thought of as coordination classes (diSessa & Sherin, 1998). Possibly certain crosscutting concepts are more aligned with intuitions and others more aligned with coherent knowledge systems (coordination classes). In both cases, we found that learning centered on the crosscutting concepts, while the DCIs and practices played a foundational but service role. These results may be related to the specifics of the instruction, data, and analysis. Still, we wonder, is learning centered on one dimension sufficient for the intentions of the Framework? How likely is learning that simultaneously involves changes to knowledge systems and practices pertaining to all three dimensions? Perhaps three-dimensional learning occurs in a piece-meal fashion. Addressing these questions requires future studies observing changes in knowledge systems pertaining to all three dimensions.

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