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The Crosscutting Concepts: Critical Component or “Third Wheel” of Three-Dimensional Learning?

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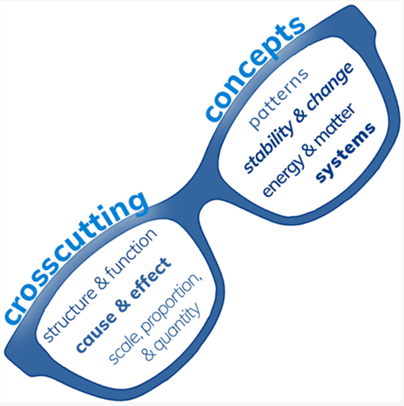
ABSTRACT: Three-dimensional learning is the name given to the vision for science education described in the National Academies consensus report *A Framework for K−12 Science Education*. Of the three dimensions described in the Framework, the Disciplinary Core Ideas and the Science and Engineering Practices have been enthusiastically adopted by many in the science education community. However, the third dimension, Crosscutting Concepts (CCCs), has received less attention. Indeed, some researchers have begun to question both the necessity and the theoretical rationale for the CCCs. That being said, emerging work both supports the use of the CCCs and provides practitioners with approaches to their use that not only hold potential for supporting students’ construction of deeper and more useful knowledge but also may provide an approach to learning that is more equitable. In this paper, examples highlight the use of CCCs as lenses, tools, bridges, or “rules of the game” (epistemic heuristics), that can support sensemaking about chemical phenomena in the context of three-dimensional learning.



KEYWORDS: *High School/Introductory Chemistry, First-Year Undergraduate/General, Second-Year Undergraduate, Learning Theories*

■ INTRODUCTION: WHAT ARE THE CROSSCUTTING CONCEPTS AND WHERE DID THEY COME FROM?

In 2012 the National Academies of Science Engineering and Medicine (NASEM) published a consensus report *A Framework for K−12 Science Education* (the *Framework*)[1] that subsequently became the basis for the Next Generation Science Standards (NGSS).[2] This report synthesized the extant research on how we learn science and provided a vision that represents a major effort to reimagine the teaching and learning of science. The *Framework* presents three interdependent dimensions, (i) the science and engineering practices (SEPs); (ii) the disciplinary core ideas (DCIs); and (iii) the crosscutting concepts (CCCs), that are intended to be blended together in what has become known as three-dimensional learning (3DL). This approach provides a way to structure knowledge-in-use that aligns with what we know about how students learn science, and that provides support for curriculum developers, assessment developers, and instructors as they design materials. While the focus of the *Framework* was at the precollege level, much of its scope is also applicable to higher education, certainly for the gateway STEM courses since there is effectively little difference between a high school senior and a first-year college student.[3] There is now an emerging body of work in higher education that is explicitly guided by the *Framework* as more instructors and researchers find value in the ways that it can help structure how students not only construct knowledge, but also are able to use that knowledge in fruitful ways.[4−6]

Of the three dimensions specified by the *Framework*, both the DCIs and the SEPs and their integration are supported by significant bodies of work. Indeed, it has now been widely accepted in higher education that individual pieces of knowledge should be connected to larger ideas of the discipline. For example, the ACS examinations institute specifies “Anchoring Concepts”,[7] while the advanced placement (AP) reinvention project uses a similar approach to specify “Big Ideas”.[8] In biology, the Vision and Change report also identifies “Core Concepts”.[9] The principle that knowledge should be organized and connected to larger concepts is one that is relatively self-explanatory and is also supported by theory, research, and evidence.[10,11] Similarly, the SEPs are also gaining traction as the “engine” by which we can help college students put their knowledge to use. There is increasing acceptance of the idea that students should construct and use models to predict and explain phenomena,[12,13] should be able to analyze and interpret data,[14] and should construct an evidence-based argument.[15−20] When taken together, the eight SEPs are well-described characterizations of the things that scientists and engineers do, and as such are recognizable as something we might also want students to do. In the past some of these practices may have come under the

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Table 1. Examples of Questions That Might Be Associated with a Particular Crosscutting Concept

Crosscutting Concept	Questions We Might Ask	Use of CCC
Patterns	What patterns can we see in these data?	Tool for analyzing data
	Are there ways to treat the data that allow us to see the patterns?	
Cause and Effect (Mechanism and Explanation)	How and why does this phenomenon occur?	Lens to focus on the mechanism of a phenomenon
	What are the underlying entities (at a scalar level below the phenomenon)?	
Scale Proportion and Quantity	What happens when we move from one scale to another?	Lens to focus on how scale and proportions affects outcomes
	What happens if we increase the amount of this material?	
	Do we have to change amounts in proportional ways?	
Systems and System Models	What are the components of subsystems of this system and how might they interact?	Tool for analyzing systems
	How can we model this system?	
Energy and Matter (Transfer and Conservation)	How does energy and or matter transfer within (or among) systems?	Lens to focus on a particular aspect of systems
	What transformations of energy are occurring?	
Structure and Function	How does the structure of this material affect the way it behaves?	Lens to focus on how structure affects function
	How does the structure of this material affect its purpose?	
Stability and Change	Why is this system stable?	Both a Lens and a Tool
	What happens if we make a particular change to the system?	
	Under what conditions does the system operate?	

banner of "inquiry". However, because inquiry is such an amorphous term, with no generally accepted meaning, there is a growing recognition that the better articulated SEPs are more useful. Certainly, it is not possible to assess what is not well-defined in the first place, and the SEPs provide extensive guidance about what the components of the scientific enterprise are.

In contrast, the crosscutting concepts have received much less attention than DCIs and SEPs both in the research literature, and in the ways that they are enacted. While most of the CCCs are not new (they have appeared in some form or other in other standards documents[21]), their purpose and use are less obvious, and in those earlier documents they were not explicitly connected to the concepts and practices of science but were often considered separately.[22]

Problems with Conceptualizing the CCCs

There are several reasons why the CCCs may have received less attention. The first has to do with a misunderstanding of why they are grouped together. While the DCIs and SEPs are recognizable sets of entities that clearly have commonalities, the CCCs, at first sight, may appear as a collection of rather disparate "things". For example, it is not immediately obvious that "patterns", "cause and effect", and "proportion and quantity" belong in the same group. This has led to confusion about what the CCCs are "for" and how they could be incorporated into learning.

The second problem lies both in the designation as "crosscutting" and in their descriptions that together seem to emphasize the idea that the CCCs are intended to support cross-disciplinary connections. For example, in the *Framework* the CCCs are introduced by this quote from the American Association for the Advancement of Sciences in *Science for All Americans*[23] (quoted in ref 1, p 83):

> *Some important themes pervade science, mathematics, and technology and appear over and over again, whether we are looking at an ancient civilization, the human body, or a comet. They are ideas that transcend disciplinary boundaries and prove fruitful in explanation, in theory, in observation, and in design.*

The *Framework* goes on to say that the CCCs are "concepts that bridge disciplinary boundaries, having explanatory value throughout much of science and engineering". This emphasis on the idea that the CCCs are ways to connect across disciplines has led not only to confusion, but also to criticism from leading education researchers. For example, Osborne et al. have indicated that there is little justification or theoretical basis for concepts being applied in the same way (i.e., crosscutting) across disciplines.[24] These authors note not only that "[T]he crosscutting concepts have no scholarly basis for what the sciences have in common" but also that (ref 24 p 4)

> *[T]here has been an increasing recognition in the past 15 years of their (the sciences) methodological, epistemic, and ontic diversity within the sciences—a view which challenges the contrasting and dominant account that there is some form of methodological unity consisting of "the scientific method".*

The authors point out that physics, chemistry, and biology value and emphasize different approaches and different kinds of reasoning. For example, physics takes a reductionist, deterministic approach to understanding and explaining the world, the quintessential scientific method, while such an approach in biology is inadequate: For example, no single organism can represent all organisms of that class. While physics is governed by laws, living entities are subject to stochastic events and how they interact with the environment. In chemistry, the periodic table allows us to make extensive predictions, but these predictions are not laws, and a huge amount of underlying understanding and theory is required to make sense of them. They propose that distinct disciplinary cultures and ways of thinking do not align with the idea that some concepts may be applied in a similar manner across all disciplines.[24]

Furthermore, others have noted that (ref 25, p 5)

Table 2. Example of How the CCCs Can Be Used to Interrogate Different Aspects of the Same Phenomenon: The Decrease in Atomic Radius across a Row of the Periodic Table

CCC-Focused Question	Science Practice	Core Idea (Chemistry)
What patterns can we see in these data?	Analysis and interpretation of data	None
How might you represent the data to show the patterns and interpret them?		
What are the components of the atomic system that are interacting that affect the atomic radius?	Constructing and using models	Bonding and interactions
What is the mechanism by which the atomic radius changes?		
What causes the change in atomic radius?		
Why is the atomic radius of a given element relatively stable?	Models/explanations	Change and stability in chemical systems/bonding and interactions
What would make the atomic radius change?		
If the proportion of relative charges were changed, what would happen to the atomic radius?	Mathematical thinking	None
How do the potential and kinetic energy of the atomic system change as the radius increases or decreases?		Energy

> *[T]here 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.*

What Then Are Curriculum Developers, Researchers, and Practitioners to Make of the CCCs?

To address these concerns, a group of scholars were invited to participate in "The Summit for Examining the Potential of Crosscutting Concepts to Support Three-Dimensional Learning in Science and Engineering"[25] in Fall 2018. The discussions and conclusions from this summit are available, along with a number of white papers that lay out potential models to guide the use of the CCC.[25] Insights from this summit provided the impetus for this paper in which approaches to the use of the crosscutting concepts, with particular emphasis in chemistry, are discussed. The goal is not to critique the CCCs themselves but to provide instructors with approaches to their use that are consistent with the intent of the Framework, and that are supported by our current understanding of learning.

■ THE CCCS CAN SERVE DIFFERENT PURPOSES

There have been a number of reports in which authors grapple with the roles of the CCCs in 3DL.[25] Indeed, the proceedings of the Summit provide a wide range of ideas about how, when, and why CCCs can and should be incorporated into learning. Most of the suggestions in this paper build on the work of Rivet et al., who have proposed that the roles the CCCs play can be explained by four metaphors: namely[26]

- Tools
- Lenses
- Bridges
- "Rules of the game"

Each of these metaphors provides a way to think of the CCCs as they are used in different contexts. For example, a lens provides a way to focus on a specific aspect of a phenomenon which can require a student to think more deeply and explore that phenomenon in a specific way, a CCC used as a tool allows students to participate in an analysis that can make sense of the phenomenon, a bridge can connect phenomena both within and across disciplines, and the "rules of the game" can explicitly provide students with the ways of thinking that underpin how science in done. All of these metaphors can provide us with a framework for incorporating CCCs into our instruction to promote 3D learning.

CCCs as Tools or Lenses

The CCCs each provide a different, yet complementary, approach to thinking about chemical phenomena. Table 1 provides the kinds of questions that we might ask about a phenomenon using the approach of CCCs as tools or lenses to focus student thinking on a particular aspect. Many of these CCCs are already in use in various pedagogical approaches, and an extensive list of suggested questions for each CCC can be found as no. 41 on the STEM teaching tools website.[27]

In fact, others of the individual CCCs are also quite familiar in chemistry education, and there are growing bodies of literature addressing student thinking in the context of particular CCCs. For example, most POGIL worksheets begin with data that students analyze and use to identify *patterns* and construct meaning.[28] *Scale* obviously has a particular resonance for chemists, and there are several reports on student understanding of scale.[29,30] There have also been a number of reports that have investigated mechanistic reasoning across a range of phenomena,[31−33] which could certainly be encompassed under the CCC *cause and effect* (*mechanism and explanation*). However, the approaches and definitions about what constitutes mechanistic reasoning used by researchers have not been consistent with each other, and as we will see, this may be problematic if we want to think about how the CCCs could be integrated in a meaningful way in 3DL.

As to the other CCCs, the periodic table is the very embodiment of the ways that patterns are important in science, and there are obviously standard chemistry topics such as stoichiometry and thermodynamics that can (and should) be thought of both in terms of the CCC of *energy and matter conservation and flow* as well as *scale, proportion, and quantity*. Indeed, one can recast most chemistry topics in terms of CCCs (along with SEPs and Core Ideas), and as we will see, this may provide opportunities to deepen and strengthen student understanding of chemical phenomena.

An interesting prospect is opened up with regards to "systems thinking" which has recently emerged as a focus of interest in chemistry learning.[34−36] However, there is, as yet no broad consensus on what exactly systems thinking entails, which makes it rather difficult to make broad generalizations, or to develop appropriate assessment instruments. Systems thinking may well align with the CCC *Systems and System Models*, but it has also been suggested that the CCC as a whole may be a way to provide entrée into a systems thinking perspective.[25] Each CCC might be considered as a set of questions that focus student attention on one aspect of the system, and the whole suite of CCCs could be thought of as a way to interrogate systems as a whole.

CCCs as Tools or Lenses to Deepen Understanding of a Single Phenomenon

While individual CCCs can provide students with a specific insight into a phenomenon, using the CCCs in combination with each other to probe a particular phenomenon may be even more fruitful. The example provided in Table 2 shows how a selection of the CCCs could be used to probe different aspects of the rather puzzling phenomenon that the atomic radius of atoms decreases across a row of the periodic table. Each of these CCCs provides a different but complementary focus for students to engage with the phenomenon. Note that the complete exercise also incorporates the use of scientific practices and core ideas, making this a scaffolded three-dimensional instructional unit. While not all of the CCCs might lend themselves to every phenomenon, using them to spotlight particular aspects can help students understand phenomena in multiple ways. At the moment, we do not have strong evidence about which combinations of CCCs are most appropriate for a particular phenomenon, or in which order they might be most effective.

Several more examples of this approach aimed at different phenomena are provided in the Supporting Information.

CCCs as "Rules of the Game" or Epistemic Heuristics

Another metaphor of the CCCs is that they provide an entrée into the "rules of the game": that is, as a way to help students understand that there are (often implicit) scientific norms, or rules of engagement that are shared by the scientific community. It is these implicit norms that may act as barriers to entry by marginalized communities. As Ford says (ref 37, p 405)

> *Students need not recapitulate in the learning process what scientists have done to construct knowledge. But a grasp of scientific practice, its key reasoning patterns, and an awareness of the architecture of knowledge these produce can be crucial resources in learning novel scientific ideas with understanding.*

That is, the CCCs may act as more explicit ways for students to understand how scientific ideas are developed, critiqued, and structured.

One example of this idea comes from Krist et al., who have proposed a set of "epistemic heuristics" or "*ideas about how to direct one's intellectual work*" that can be used by students as they construct causal mechanisms to predict and explain phenomena (the CCC *cause and effect, mechanism and explanation*).[38] They suggest that as students construct a mechanism for a phenomenon, they must go down a scalar level, identify and unpack the entities at the lower scalar level that contribute to the phenomenon, and then connect the lower-level interactions and behaviors to the phenomenon being explained. As we will see, for CCCs to become useful across phenomena it is probable that such "epistemic heuristics" need to be developed and used consistently, initially to analyze single phenomena, then across multiple phenomena in a single discipline, and perhaps eventually across disciplines.

CCCs as Bridges: A Tantalizing Possibility for "Transfer"

By using CCCs to explicitly provide models for scientific thinking, it may be possible to address one of the most elusive goals of education, that of "transfer".[39] That is, how do we help students use understanding gained from one realm in another? If one narrowly defines transfer as the intact movement of knowledge or skills from one situation to another, then evidence for the construct is certainly elusive.[40] However, a more useful approach to the idea of transfer might be that proposed by Schwartz and Bransford: "preparation for future learning".[39] That is, if we provide students with experiences that prepare them to use their knowledge at a later date, we are more likely to see learning take place. The CCCs may provide a way to support students to make connections across phenomena, and perhaps across disciplines by providing a common framework for students to use. That is, once students understand the "rules of the game" for a particular CCC in a given phenomenon, it may function as a bridge to another phenomenon when that same CCC is used.

Crosscutting Concepts as Bridges across Phenomena (in the Same Discipline)

The CCC *cause and effect (mechanism and explanation)* is clearly applicable across numerous chemistry phenomena. The epistemic heuristic developed by Krist et al.[38] means that causal mechanistic explanations at the molecular level explicitly require us to move down a scalar level to explain how and why electrons move during chemical reactions. We have used this framework to support students as they construct explanations about acid–base reactions,[33,41] London dispersion forces,[42] and nucleophilic substitutions. Each of these phenomena can be approached using the core ideas of structure–property relationships and bonding and interactions, the scientific practices of constructing and using models, and constructing explanations, but all these dimensions are inextricably linked by the crosscutting concept of *cause and effect*. That is, *cause and effect* provides a way to connect different phenomena and helps students develop a more connected framework of chemistry concepts. For example, we have found that students who are able to provide a causal mechanistic explanation for how and why acid–base reactions occur are significantly more likely to construct appropriate electron-pushing mechanisms for such reactions than students who simply describe the reaction.[33,41]

Similarly, the CCCs *systems and system models*, together with *energy and matter (transfer and conservation)*, could provide a way for students to analyze and synthesize ideas about a wide range of different phenomena. Certainly, while phenomena associated with energy transfer have traditionally been taught using the systems approach (defining systems, surroundings, etc.), treating a broader range of chemical phenomena as systems may also provide students with approaches to analyzing, predicting, and explaining. For example, the relatively complex (for general chemistry) systems that require students to predict how systems at equilibrium are affected by changes could be made more accessible to students by being explicitly treated as interconnected systems that can be unpacked and analyzed. For example, the addition of common ions, addition of acid or base to a buffer system, and multiple reactions linked by common intermediates such as those in biochemical pathways all are accessible through analyses of the systems, their components, and the effects of the changes. These ideas are notoriously difficult for students, and the systems approach may support a more connected understanding. Indeed, there is great interest in "systems thinking", which encompasses much more complex systems affected by humans, geography, and other factors. If the goal is to understand such complex systems, it is highly likely that using the CCC systems and system models for simpler systems is a necessary precursor to understanding and modeling such complex ideas.

Crosscutting Concepts as Bridges across Disciplines

While connections across disciplines might on the surface be thought of as the primary role of the CCCs, there is currently scant evidence for this aspect at the college level. However, there are a few tantalizing reports in the literature about such cases. For example, students who were concurrently enrolled in college introductory biology and chemistry courses that both emphasized 3DL were interviewed about specific ideas to identify whether they had actually made any connections between the courses.[43] When asked about the CCC "*structure and function*", all of the students agreed that this idea had been emphasized strongly in the biology course, but that in chemistry it was the related idea of structure and properties that was stressed. On further discussion, the majority of the students interviewed were able to make a connection for themselves that had not been emphasized in either course: that the molecular structure determines the properties of the substance (which is a core idea in chemistry), and that it is these properties that determine the function. Not only did these students understand that in each course a similar (but not the same) idea was being taught, but also that in each course there was a missing element that did not allow them to understand the whole story. This finding aligns with Osborne and co-workers' assertion that disciplines use these ideas differently.[24] Nevertheless, these students were able to go beyond what they were taught to make meaningful connections.

However, these same students were mostly unable to make such meaningful connections between chemistry and biology when asked about energy transfer.[44] Indeed, some students explicitly stated that they knew how energy was to be treated differently in the two disciplines: In chemistry they were taught that bond breaking requires energy, but in biology, breaking bonds in ATP releases energy. Certainly this problematic idea is well-known,[45,46] but it may be that explicitly connecting the CCCs across the disciplines will provide an approach that is both appropriate and respectful of disciplinary differences.

■ FOREGROUNDING CCCS AS A WAY TO SUPPORT ALL STUDENTS

The *Framework* is intended to provide support for all students, to be inclusive and motivating for diverse groups. By explicitly foregrounding the CCCs, being explicit about the "rules of the game", and supporting reasoning both within and across phenomena, it may be possible to make science more accessible to students. Historically, in chemistry we have provided explicit numerical problem-solving strategies; indeed, large sections of traditional textbooks are devoted to such endeavors, including dimensional analysis and ICE (initial, change, equilibrium) tables for analyzing equilibrium systems. However, there seems to be some resistance to providing similar students with explicit approaches to the development of heuristics for the analysis of phenomena. Certainly, students who have strong backgrounds and have experienced rich learning environments may be able to intuit these strategies without such explicit instruction (although there is scant evidence for this). However, generally, even the best prepared students struggle with tasks that require them to use their knowledge and reasoning skills unless they are supported by instruction and practice. Explicitly foregrounding these different ways of thinking about a phenomenon may well support all students to develop more complex reasoning skills. Teaching students how to approach mechanistic thinking can provide students with cognitive resources that they may not have picked up without explicit instruction. This is particularly true if students have only ever been expected to regurgitate facts and do simple calculations without ever learning what connects these ideas, or why they might want to do these things in the first place. Even a simple restructuring of a task prompt can help students connect their cognitive resources to provide more sophisticated responses.[33] However, to do this we need to have a shared understanding of what exactly we mean by systems thinking (or mechanistic reasoning, structure−function, or energy transfer); otherwise, it is unlikely that students will be able to apply their resources appropriately in different situations.

■ CONCLUSIONS

The CCCs are an integral component of 3DL (yet have received less attention than the DCIs and the SEPs) both from a theoretical stance, and from the perspective of how they might be enacted. Here, we offer several approaches to thinking about how the CCCs might be fleshed out and their use made more explicit. The first approach relies on the idea that there are specific epistemic heuristics, or "rules of the game" that can support students in their learning. For example, students can learn how to gather their resources to provide mechanistic reasoning that can explain cause and effect, or analyze systems and system models so that the interaction of their components is made visible and clear. There is emerging evidence both within and across disciplines that students can marshal these resources to model, explain, and predict phenomena.[33,43] CCCs may also be considered as a lens or tool to investigate or explain a particular aspect of a phenomenon. When combinations of the CCCs are used together in this way, students can be provided with explicit opportunities to explore phenomena in different ways, which should give rise to a richer and deeper understanding.

These approaches, when used explicitly (and repeatedly), may provide students with the cognitive tools that are often implicit in experts but rarely made explicit in teaching and learning. By making the ways we want students to think about a particular idea clearer it may be that we can provide students of all backgrounds with a robust framework of connected and useful ideas instead of sets of fragmented ideas and skills.

■ ASSOCIATED CONTENT

SI Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.9b01134.

Examples of how different phenomena may be interrogated by combinations of CCCs (PDF, DOCX)

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Notes

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