Article

On the Nature and Utility of Crosscutting Concepts

Jeffrey Carl Nordine 1,* and Okhee Lee 2

1 Department of Teaching and Learning, College of Education, University of Iowa, Iowa City, IA 52242, USA
2 Department of Teaching and Learning, Steinhardt School of Culture, Education, and Human Development, New York University, New York, NY 10012, USA; olee@nyu.edu
* Correspondence: nordine@uiowa.edu

Abstract: The crosscutting concepts (CCCs) are a collection of ideas that span the science and engineering disciplines. While various standards documents have identified similar sets of ideas in the past, calls for their explicit inclusion into science and engineering instruction began in earnest only about a decade ago. When these calls began, the research base on the teaching and learning of the CCCs was limited; in the intervening years, educators have debated whether and how the CCCs are useful for supporting science and engineering learners. In this article, we summarize a recent scholarship that has clarified the role of CCCs in supporting science and engineering learning. Then, we highlight two exemplary curricular units (one elementary and one secondary) that showcase CCC-informed instruction. Based upon these research and development efforts, we identify three core messages: (1) CCCs provide learners with a set of complementary lenses on phenomena, (2) CCCs are powerful tools for broadening access to science and engineering, and (3) practitioner innovations play an especially important role in the time-sensitive work of establishing a more robust research base for how CCCs can strengthen science and engineering teaching and learning.

Keywords: crosscutting concepts; Next Generation Science Standards; three-dimensional science learning; phenomenon-based instruction; curriculum development

1. Introduction

As it is currently used, term “crosscutting concept” (CCC) is relatively new in science education, dating approximately to the publication of the US A Framework for K-12 Science Education [1] roughly a decade ago. This publication served as the foundational visioning document for the US Next Generation Science Standards (NGSS) [2], which specifies what students should know and be able to perform in science and engineering across K-12 grades. In the Framework, the term “crosscutting concept” refers to seven specific “concepts” that are used across all disciplines of science and engineering. They are:

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
7. Stability and change

Importantly, scientists and engineers do not use CCCs in isolation. Thus, the Framework stresses the idea that CCCs should be learned and used in conjunction with two other dimensions of science and engineering learning: science and engineering practices (SEPs) and disciplinary core ideas (DCIs). Accordingly, performance expectations in the NGSS explicitly include a particular SEP, DCI, and CCC. The Framework authors wrote that the explicit inclusion of CCCs into science and engineering instruction would “help provide students with an organizational framework for connecting knowledge from the various
disciplines into a coherent and scientifically based view of the world". [1] However, the Framework authors also acknowledged that “the research base on learning and teaching the crosscutting concepts is limited”. [1] This acknowledgement recognizes that science education research has largely focused on the learning and teaching of the other two dimensions of the Framework: SEPs (e.g., developing and using models, engaging in argument from evidence) and DCIs (e.g., matter and its interactions, Earth and human activity). Accordingly, despite the centrality of CCCs to doing and learning science and engineering, relatively little has been known about how students construct an understanding of CCCs over time and gain competence in using them to make sense of phenomena and solve problems.

Since the publication of the Framework, researchers have explored the theory and conceptual frameworks regarding how CCCs support science and engineering learning, and practitioners have developed promising instructional approaches that leverage CCCs to strengthen science and engineering learning. In this article, we use the benefit of a decade of hindsight and additional research to (1) elaborate upon the history and nature of CCCs, (2) clarify the role of CCCs in supporting science and engineering learning, and (3) illustrate two examples of how CCCs can strengthen science and engineering teaching and learning.

2. The History and Nature of CCCs

The Framework was certainly not the first document to attempt to identify commonalities among the science and engineering disciplines and to include them as a part of what students should learn. The US Benchmarks for Science Literacy [3] identified four “common themes” in science, which are: (1) systems, (2) models, (3) constancy and change, and (4) scale. Likewise, the National Science Education Standards [4] included the “unifying concepts and processes” of science, which are: (1) systems, order, and organization, (2) evidence, models, and explanation, (3) change, constancy, and measurement, (4) evolution and equilibrium, and (5) form and function. Building on these documents, the Framework added two CCCs: (1) “patterns”, which describes the foundational role of pattern recognition and description in science and engineering, and (2) “energy and matter: flows, cycles, and conservation”, which identifies that all scientists and engineers rely upon conserved quantities—of which matter and energy are the most widely used. The similarity of CCCs in the Framework to what came before them in previous standards documents reinforces that these CCCs were not simply invented by the Framework authors; rather, they were likely to emerge from a systematic consideration of what it means to do science and engineering.

Further evidence that CCCs describe universal science and engineering ideas can be found by considering non-US standards documents. One particularly illuminating comparison can be made with the German Bildungsstandards [5–7], which identifies a set of basic concepts [Basiskonzepte] that apply across a wide range of contexts in biology, chemistry, and physics. While the basic concepts are intended to apply within rather than across science and engineering disciplines, it is noteworthy that they include a significant overlap with CCCs, including systems, structure and function relationships, matter, energy, and change over time.

Comparing the German basic concepts (which were identified by looking within school science subjects) and the US CCCs (which were identified by looking across school science subjects) reveals a deeper structure of the relationships between individual CCCs—that is, one can identify a conceptual hierarchy to CCCs which may correspond to differences in how CCCs are utilized between disciplines. Rehmat et al. [8] described this hierarchy in terms of “first-order” and “second-order” CCCs (see Figure 1).
First-order CCCs include Patterns and Cause & Effect, and these are foundational to humans—survival depends upon humans’ ability to recognize patterns in nature and society as well as their ability to identify cause and effect relationships in their environment. Accordingly, first-order CCCs are also fundamental to all of science and engineering. Recognizing and describing patterns guides the exploration of what exists in the world around us and the process of systematically asking questions about underlying relationships. A key function of science and engineering is to explore why patterns in nature exist as they do, which involves the identification of causal relationships and the mechanisms that mediate them. Although identifying patterns and uncovering causal relationships are innate to humans, they also must be explicitly learned and used in evermore sophisticated ways in the context of practicing science and engineering.

Second-order CCCs support this more sophisticated use of patterns and causality. For example, thinking in terms of structure and function relationships can support causal thinking by explicitly considering how the shape and size of interrelated components lead to different structures and functions. Chemists use structure and function to support explanations of why water is a universal solvent, and biologists use structure and function relationships to help explain why certain animals occupy similar niches within different ecosystems. Perhaps the most foundational second-order CCC is the idea of systems, as this idea involves specifying what part of the universe is being investigated. Description of any system involves imagining an artificial boundary around small portions of the universe for the convenience of investigation [1].

Foundational, of course, does not mean simple—real systems smaller than the universe interact with other systems and can usually be further described in terms of layers of sub-systems that are composed of different components interacting in various ways. The identification of systems is closely connected with the construction of system models, which represent how the interacting components of systems and sub-systems are related to each other. Identifying and representing systems under consideration is a foundational step to looking for patterns and constructing causal explanations as well as delineating the range of applicability of explanatory accounts. In this way, systems could perhaps be considered a zeroth-order CCC.
An examination of the NGSS performance expectations supports the notion that CCCs can be reasonably ordered into a hierarchy, with systems classified as a zeroth-order CCC, patterns and cause and effect classified as first-order CCCs, and all remaining CCCs classified as second-order. Osborne et al. [9] tallied how often particular CCCs appeared in the NGSS performance expectations across each grade band and found that the first-order CCCs were represented consistently throughout the grade bands, whereas the second-order CCCs were almost completely absent from the early grade bands. Systems were included more commonly than any second-order CCCs, but less commonly than the first-order CCCs. These results indicate that the balance of representation of CCCs in the NGSS performance expectations aligns with the notion that first-order CCCs are generally more intuitive and accessible to use, whereas second-order CCCs require more explicit instruction before students are expected to use them.

3. The Role of CCCs in Supporting Science and Engineering Learning

CCCs are foundational ideas to science and engineering which have appeared in many documents attempting to clarify what it means to know and be able to do, in science and engineering. The CCCs identified in the Framework are built upon significant precedents from previous documents both in the US and internationally. What is new about CCCs is that they are, for the first time, explicitly integrated into the NGSS performance expectations. What is not new is that teachers and researchers struggle to clearly articulate the role that CCCs should play in science and engineering teaching and learning [10].

In one of the earlier efforts to clarify the role of CCCs in supporting science and engineering learning, Rivet et al. [11] reviewed the NGSS and related documents and identified four metaphorical perspectives regarding the role of CCCs in science and engineering teaching and learning: (1) lenses, (2) bridges, (3) tools, and (4) rules of the game. The lens metaphor describes CCCs as ways to view phenomena and problems—different lenses can emphasize different features of the phenomena and problems, and these different ways of viewing phenomena and problems can deepen understanding. The bridge metaphor describes CCCs as a support for students to connect across different phenomena and problems, potentially supporting the identification of similar underlying features across a range of phenomena and problems. The tools metaphor refers to how students might use their existing understanding of CCCs to build new and more sophisticated explanations and ideas about phenomena and problems. Finally, the “rules of the game” metaphor describes how CCCs identify common language and practices in the science and engineering community.

There is little doubt that CCCs are widely used by practicing scientists and engineers [12]; yet, there has been substantial debate about whether and how CCCs are useful for learners. Osborne et al. [9] construct a theoretically- and historically-based argument that CCCs are not optimal for supporting students in seeing coherence in the science and engineering curriculum. Instead, they point to the power of so-called “styles of reasoning” (e.g., hypothetical modeling, probabilistic reasoning) for supporting coherence within and across science and engineering disciplines. In a review of the existing literature, Fulmer et al. [13] note that CCCs are often excluded from consideration in the NGSS interpretation activities (e.g., instructional unit planning). One US state (Massachusetts), which was one of the NGSS Lead States, adapted the NGSS to explicitly exclude CCCs [14]. While the notion that scientists widely use CCCs is commonly accepted, whether and how explicit inclusion of CCCs in science and engineering instruction supports student learning has not been well established in the literature.

Fick and Arias [15] conducted the most comprehensive review of theoretical and empirical contributions to the CCC literature since the release of the Framework. They identify five major themes in publications between 2012 and 2019 that explicitly address the role of CCCs in science and engineering teaching and learning: (1) opportunities to learn about CCCs, (2) student funds of knowledge about CCCs, (3) utility of CCCs for understanding disciplinary core ideas (DCIs), (4) utility of CCCs for engaging in science and engineering practices (SEPs), and (5) how CCCs might support students in bridging across disciplines.
They note that, while much work has been conducted since the release of the Framework, there remains a long way to go toward consensus regarding what it means to explicitly and coherently teach CCCs.

To clarify how CCCs ought to be intentionally incorporated into instruction, clarity about the role of CCCs in supporting science and engineering learning is required. There is some level of emerging consensus regarding the value of CCCs in science learning, as evidenced by overlaps between Rivet et al.’s, metaphorical perspectives and Fick and Arias’ literature review themes (see Table 1). First, the most obvious overlap is the role of CCCs in bridging across disciplines, which appears on both lists. Second, Fick and Arias point to the role of CCCs in connecting to DCIs (theme 3) and SEPs (theme 4), which corresponds to the tools metaphor. The perspective that CCCs are a conceptual tool that support the use of DCIs and SEPs for making sense of phenomena and solving problems tracks strongly with what is meant by three-dimensional learning of science and engineering [16]. Third, there is an overlap between the student funds of knowledge theme (Theme 1) and the lens metaphor. Here, the emphasis is on students’ use of their existing ideas when confronting unfamiliar problems or phenomena. These existing ideas may come from the students’ in-school or out-of-school experiences, but the important feature is that CCCs provide students with multiple points of entry for meaningfully engaging with novel situations.

Table 1. Overlap between the CCC metaphors identified by Rivet, et al. and the CCC literature themes identified by Fick and Arias.

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>N/A</td>
<td>Opportunities to learn</td>
</tr>
<tr>
<td>Lenses</td>
<td>Funds of knowledge</td>
</tr>
<tr>
<td>Tools</td>
<td>Connection to DCI</td>
</tr>
<tr>
<td>Bridges</td>
<td>Connection to SEP</td>
</tr>
<tr>
<td></td>
<td>Bridges across disciplines</td>
</tr>
</tbody>
</table>

While there is some degree of emerging theoretical and empirical consensus about the role of CCCs in strengthening science and engineering learning, there remains a pressing need to illustrate what effective CCC-informed instruction looks like [13,15]. In the next section, we elaborate on two instructional units—one at the elementary level and one at the secondary level—that illustrate what CCC-informed instruction looks like in practice.

4. What Does CCC-Informed Science Instruction Look Like?

4.1. CCCs in Elementary Science Instruction

4.1.1. CCCs as Resources with Diverse Student Groups

Broadening access to science is a central theme of the Framework and the NGSS. 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 diverse backgrounds, bring little or limited prior canonical science knowledge. It is imperative that science be made real and relevant to all students. Utilizing CCCs as resources is one way to conduct this.

To address CCCs in relation to diverse student groups, teachers view CCCs as resources that students use in their everyday lives to make sense of the world and bring to the science classroom to make sense of phenomena. Then, teachers cultivate students’ “funds of knowledge” from their homes and communities [17], including their everyday experiences with CCCs. Thus, CCCs serve as resources that all students bring to the science classroom community of practice and that teachers build on and make visible across science disciplines and over the course of instruction. This perspective on CCCs has three key implications for teachers:
Implication 1: All students come to the science classroom with intuitive ideas about CCCs [18] based on their funds of knowledge from their homes and communities. Teachers need to leverage these intuitive ideas about CCCs and guide students in using CCCs to make sense of phenomena. Over time, teachers build on, and make visible, students’ intuitive ideas about CCCs so these ideas become shared resources in the classroom community. This perspective on CCCs calls for a shift in teacher disposition from a deficit perspective (i.e., students from diverse backgrounds come to the science classroom with limited sensemaking resources) to an asset perspective (i.e., students from diverse backgrounds come to the science classroom with intellectual resources).

Implication 2: Teachers provide opportunities for students to use CCCs across science contexts and disciplines. Meaningful use of CCCs in different disciplines allows all students to formalize their intuitive ideas about CCCs. Rather than associate a particular CCC with a specific discipline, students view CCCs as resources they can draw upon flexibly to make sense of phenomena in any discipline.

Implication 3: Teachers guide students in using CCCs intentionally when presented with unfamiliar phenomena so that their understanding and use of CCCs become more sophisticated across grade levels, grade bands, and K-12 education. For students to progress from an intuitive use of CCCs to one that is more intentional, teachers design coherent instructional sequences that help students recognize how and when CCCs are useful resources for sense making of phenomena.

4.1.2. The SAIL Garbage Unit

The Science and Integrated Language (SAIL) is a year-long, fifth-grade curriculum aligned to the NGSS and aimed at promoting both science and language learning for all students with a focus on multilingual learners [19]. The SAIL curriculum consists of four units:

- Unit 1: What happens to our garbage? (physical science)
- Unit 2: Why did the tiger salamanders disappear? (life science)
- Unit 3: Why does it matter if I drink tap water or bottled water? (Earth science with engineering embedded)
- Unit 4: Why do falling stars fall? (space science)

We provide one example from Unit 1 as a fifth-grade teacher leveraged students’ everyday experiences with the CCC patterns. On the first day of science instruction in the school year, fifth-grade students walked into their classroom and immediately saw something unusual: piles of garbage from their school cafeteria on tarps. The teacher divided the class into groups of four or five students with varying levels of English proficiency in each group and assigned each group to a pile of lunch garbage. In preparing the garbage materials, the teacher ensured that there was no hazardous material.

Wearing gloves and goggles and using tongs to move the garbage materials around, students made observations of the garbage materials. The teacher instructed students to sort their garbage pile into different groups or categories. When working with each group, the teacher asked probing questions about the similarities and differences in each sorted category and provided feedback to students as they continued to think about categorizing. Groups sorted the garbage materials based on how the materials looked or what they had been used for before being discarded. For example, one group sorted their materials by color and texture, while another group sorted their materials into three categories of utensils, bowls, and food, recognizing that different materials had different purposes before being thrown away. The teacher listened to the groups’ rationales for their garbage categories, looking for students’ use of the CCC patterns. While listening, the teacher recognized that the students were already using the CCC patterns by identifying similarities and differences in the garbage materials.
After talking with each group about similarities and differences in the garbage materials, the teacher brought the class together to discuss their observations. Each group shared their categories of school lunch garbage. In this discussion, the teacher made the students’ use of the CCC patterns explicit by telling the class how scientists look for and find patterns of similarity and difference in their observations, which can lead scientists to ask new questions or find new ways to organize their data. At the end of the lesson, the teacher commended the students for using patterns, as scientists do, to categorize the garbage materials. He also suggested that the class keep in mind this concept of patterns when investigating other phenomena in the future. For homework, students identified patterns of similarity and difference in their home garbage materials. Here, students were able to use their intuitive understanding of patterns more intentionally to make sense of the phenomenon.

In this classroom example, the teacher capitalized on the students’ everyday experiences with the CCC patterns as a resource to begin making sense of the phenomenon of garbage. The teacher listened to how groups decided on their categories (e.g., color, texture) and students were able to use their intuitive ideas about patterns based on their everyday experiences. After providing students with the opportunity to use patterns based on their everyday experiences, the teacher made the use and purpose of the CCC patterns visible to students. The teacher connected the students’ intuitive use of CCCs to the work of scientists and encouraged all students to see themselves as scientists from the very beginning of the school year (Implication 1).

This classroom example comes from the first day of instruction in the physical science unit. By starting the unit with the students’ intuitive ideas about the CCC patterns and by making the students’ use of the CCC patterns visible, the teacher is laying the foundation early in the year so that this CCC can be used to make sense of phenomena in other science disciplines (e.g., space science) in future instructional units (Implication 2).

Finally, the teacher guides the students to use the CCC patterns more intentionally through specific probing. The first probe (“How did your group decide which materials go together?”) is an open-ended question intended to elicit how students are intuitively using the CCC patterns. The second and third probes (“What is similar about the materials in this category?” and “What is different about the materials in each category?”) prompt students to identify similarities and differences in their observations, which is an important element of the CCC patterns in fifth grade. Finally, the fourth probe (“If you were given a new material, how would you know which category it belongs to?”) presents a hypothetical scenario to promote students’ more informed use of the CCC. By following this sequence of probes, the teacher is able to move students from a more intuitive to a more intentional use of the CCC (Implication 3).

The teacher’s perspective on CCCs as resources was especially beneficial to the multilingual learners who were able to use all their meaning-making resources to make sense of the phenomenon [19]. In this example, the opportunity to use everyday language in combination with gestures (e.g., “Put that one here!” while pointing to specific garbage materials) at the beginning of instruction before progressing to the more specialized language of the NGSS Performance Expectation (“distinguish materials by patterns in their observable properties”) enabled students to participate meaningfully from the outset. This perspective on CCCs departs from a more traditional approach of introducing specialized language (e.g., patterns) at the beginning of instruction before students have experienced and developed an understanding of science concepts. In the instruction, the teacher embraced the notion that language is a product of, not a precursor to, “doing” science by recognizing how the students’ everyday language related to the CCC patterns served as an entry point to science learning.

All students come to school with experiences from their homes and communities that they can use as resources to make sense of phenomena in the real world and the science classroom. This perspective on CCCs as resources promotes student participation and inclusion and allows students to see themselves as scientists.
4.2. CCCs in Middle School Science Instruction

4.2.1. Energy as a Crosscutting Idea

In order to make sense of how energy instruction can benefit from a CCC-informed perspective, it is first important to distinguish between energy as a physical science idea and energy as an idea that is useful across all science and engineering disciplines. Energy appears in the NGSS as both a DCI (in the physical sciences) and as part of a CCC (energy and matter: flows, cycles, and conservation).

Energy is named as a DCI in the physical sciences because energy ideas describe physical interactions and changes, no matter their size or scale, whether systems are living or nonliving, naturally occurring or human-designed, etc. All systems under study in science are fundamentally physical systems, therefore, energy ideas apply to all disciplines of science and engineering. This is not, however, why energy also appears as a crosscutting concept—after all, plenty of physical science ideas do not appear in the CCCs. Importantly, energy is only part of a CCC that focuses on the importance of conserved quantities across the sciences, of which matter and energy are the two most widely used.

Conservation only makes sense in the context of systems (which is a primary reason why energy can be classified as a second-order CCC). However, energy instruction in the physical sciences routinely treats the importance of systems implicitly rather than explicitly. For example, physics students will commonly be asked to predict the speed of a roller coaster at various points in its path by assuming that the sum of kinetic and (gravitational) potential energy remains constant, but they will not be asked to explicitly identify the system in which they are assuming that energy is constant. Perhaps unsurprisingly, physics students commonly have difficulty using energy and systems ideas together [20,21] to analyze the behavior of systems. In contrast to many physics classrooms, life science students are seldom asked to assume that energy is constant within the system of interest, whether it be single organisms or ecosystems, and are typically asked instead to track energy flows between organisms, trophic levels, etc. What makes energy a truly crosscutting concept in science is that it is transferred between interacting systems in such a way that the total energy in all interacting systems remains constant. A major problem in energy instruction is that students are typically introduced to energy ideas in the context of physical science, but by failing to explicitly address the foundational connection between energy and systems, students are not well-positioned to consistently use energy ideas across disciplinary boundaries in science and engineering. When introducing the CCC “Energy and Matter: Flows, Cycles, and Conservation” the Framework authors emphasized the inextricable link between conservation and systems ideas, writing, “One of the great achievements of science is the recognition that, in any system, certain conserved quantities can change only through transfers into or out of the system” [1]. Thus, CCC-informed energy instruction must emphasize the central role of transfers between systems.

4.2.2. The ELeVATE Energy Unit

As a part of a research project called Exploring Learning in Various Approaches to Teaching Energy (ELeVATE), researchers developed an approach to teaching energy in middle school which was heavily informed by the way energy is presented in the NGSS as both a DCI and part of a CCC. In this approach, called the systems-transfer approach [22], students learn to make sense of phenomena by constructing models of energy transfers that occur between interacting systems. A central design principle for the systems-transfer approach was to make the concepts of energy and systems inextricable as students learned to use energy ideas to interpret and explain phenomena. We contrast the systems-transfer approach with the more widespread “forms-based” approach, in which students learn to make sense of phenomena by tracking energy conversions between various energy forms (e.g., kinetic, chemical, elastic). While systems ideas are part of a forms-based approach, they are not as central and unavoidable compared to the systems-transfer approach.
Instruction in the EL-eVATE systems-transfer unit begins with students watching a video of a professionally-designed Rube Goldberg machine. After watching the video one time through, students are asked to pick an interesting event in the video (e.g., one rolling tire hitting another) and to focus on this event in a second viewing. In this second viewing, students are prompted to consider what is involved in the event (e.g., the two tires), what happens to them (e.g., an initially stationary tire starts moving and the tire that is slowing down), and how they interact (e.g., by bumping into each other). Students pick many different events in the video, which naturally leads to a discussion of how one event leads to another and how parts of the machine are all connected, but can be thought of as consisting of a set of sub-parts. Without introducing the term “system”, students are using their intuitive ideas to analyze the Rube Goldberg machine as a system composed of many interacting components that undergo various change processes as events in the system occur.

After using intuitive ideas about systems to describe the events in a Rube Goldberg machine, students are introduced to a Crooke’s radiometer, which begins spinning as a flashlight is shined on it. They begin to construct simple models of this phenomenon in which they represent the objects involved, what processes they undergo, and how they interact. Students share and discuss their initial models and, along with teacher facilitation, combine and simplify models into something like the one shown in Figure 2.

![Figure 2](image1)

**Figure 2.** Sample model showing the objects, processes, and interaction as a flashlight shines on a Crooke’s radiometer, making vanes of the radiometer spin.

In a subsequent lesson, students apply the same analytical framework to a simple Hero’s engine, in which a soda can with two tangentially-oriented holes that is partially filled with water begins turning as it is heated by a large candle. Students construct a model of this phenomenon like the one shown in Figure 3.

![Figure 3](image2)

**Figure 3.** Sample model showing the objects, processes, and interaction as a candle heats a soda can in a Hero’s engine, making the soda can spin.

It is not until after students have explored the Rube Goldberg machine (Lesson 1), the Crooke’s radiometer (Lesson 2), and the Hero’s engine (Lesson 3) that students are introduced to the term “energy”. Students have noticed and modeled that the Crooke’s radiometer began turning when light from the flashlight illuminated it, and the soda can began turning when it was heated by the candle—both the light from the flashlight and the heat from the candle transfer energy from the flashlight/candle to the radiometer/can. Energy is introduced as a concept that: (1) can help us to discuss different phenomena that work via different interaction mechanisms, and (2) is inextricably linked to systems.
After they begin to learn to model energy transfers between systems, students begin to investigate systems like colliding coins, hot/cold objects in thermal contact, and objects that stop due to friction. Through their explorations, they gather empirical evidence that any increase in the energy of one system must be coupled with a decrease in energy in at least one interacting system. By focusing on systems in which interacting objects change speed or temperature, students draw upon their experiences to readily accept that an object that speeds up or heats up has energy transferred to it (its energy increased) and that an object that slows down or cools down has energy transferred from it (its energy decreased).

At this point, students are ready to learn and use the more generalized “systems-transfer perspective”, which is that any time a phenomenon occurs, energy is transferred between interacting systems such that one undergoes a process that increases its energy, and another undergoes a process that decreases its energy. This perspective can be represented by the generalized “energy transfer model” (ETM) shown in Figure 4.

![Figure 4. Generalized energy transfer model (ETM) for representing the direction of energy transfer between two interacting systems and the associated processes that increase/decrease the energy of the systems.](image)

When students learn to make sense of phenomena by representing them using an ETM, they must always consider the system(s) under consideration as the phenomenon occurs. The energy and systems concepts are thus inseparable and are always used together when using energy ideas to interpret and explain phenomena. In addition to better aligning with how energy ideas are used across science disciplines, this perspective can be particularly generative for students in prompting them to gain insights into hidden systems or processes involved in everyday phenomena. For example, when students consider two carts with repelling magnets that are held together and released, representing this phenomenon with an ETM quickly leads students to discover that energy was transferred to both carts as they repel each other and that there is no obvious system from which energy was transferred. This puzzle leads students to recognize the critical role of fields in storing and transferring energy during phenomena. Applying the systems-transfer perspective to phenomena can help students to use energy analysis to recognize that they have not accounted for all the relevant systems in a phenomenon. Likewise, the systems-transfer perspective can help students to recognize a need to learn more about hidden processes. For example, when using the systems-transfer perspective to consider a car that heats up when the sun shines on it, middle school students quickly recognize that the relevant systems are the sun and the car and that energy is transferred from the sun to the car, increasing its energy as it heats up. Students are then typically puzzled at the implication that the energy of the sun must be decreasing. Though they rightly suspect that the temperature of the sun is not decreasing, they also know that the energy of the sun must be somehow decreasing. This leads to insights that the lifetime of the sun must be finite and that there must be other processes happening in the sun that result in an overall decrease in energy. This recognition is critical for future learning about the role of fusion processes in the sun. By inextricably linking the ideas of systems and energy, the systems-transfer perspective can support students in using the energy concept to generate new insights about how and why phenomena occur.
In the ELeVATE research project, a unit utilizing the systems-transfer approach was compared with a unit utilizing the forms-based approach. Both units investigated the same phenomena using the same curriculum design principles. Researchers found that systems-transfer students became more capable of using energy ideas to explain phenomena and solve problems [23], developed more parsimonious and well-integrated ideas about energy [23,24], and were less likely to violate the conservation principle when using energy ideas to interpret and explain phenomena [25].

5. Discussion

Since the Framework for K-12 Science Education introduced the term “crosscutting concept” in science and engineering education, continued research and practice have helped to clarify the nature of CCCs and their role in supporting science and engineering learning. We summarize the results of this continued research and practice in three core messages: (1) CCCs are a powerful set of complementary lenses, which when used in conjunction with SEPs and DCIs, help students to make sense of phenomena and solve problems, (2) CCCs hold great promise for broadening access to science and engineering by connecting with funds of knowledge that diverse student groups bring to the science classroom, and (3) there is a pressing need for research–practice partnerships that support and leverage practitioner innovations in order to establish a more robust research base regarding what high-quality CCC-informed instruction looks like. Each message is elaborated on next.

First, by providing students with a set of complementary lenses on phenomena, CCCs provide students with a set of conceptual tools that are useful as they ask questions, conduct investigations, and solve problems. While the CCC lenses are indeed widely used across science and engineering disciplines, their primary power lies in their ability to strengthen student learning as they focus on particular phenomena and problems. That is, while supporting students in making connections across disciplines may well be a benefit of CCC-informed instruction, their conceptual power is in no way diminished when they are used in the context of a single discipline. As the example of the ELeVATE energy unit shows, learning about energy in the context of a physical science unit can be enhanced by using CCCs to reframe the way that energy is commonly taught. Such a reframing may well support students in consistently using energy ideas across disciplinary boundaries, but even without such a cross-disciplinary focus, empirical investigation indicates that a CCC-informed approach strengthened students’ understanding of energy and their ability to use energy ideas to make sense of phenomena in the physical sciences. As a part of three-dimensional science and engineering learning, CCCs help to make explicit a set of conceptual tools that have always been a part of science but have traditionally been used implicitly.

Second, when CCCs remain implicit in science and engineering instruction, students miss opportunities to engage with phenomena and problems in meaningful ways. CCCs have the potential for broadening access to science and engineering by leveraging students’ everyday experiences in, for example, looking for patterns or considering what is relevant to a phenomenon or problem. In the SAIL garbage unit, students are merely asked to sort their garbage into different groups—a common task in everyday life whether one is sorting laundry, putting away dishes, or arranging a collection of action figures. Through their engagement with everyday tasks, students leverage funds of knowledge that support their ability to productively use CCCs in the science and engineering classroom. In this way, CCCs provide students with multiple points of entry to thinking about phenomena and problems. First-order CCCs may be particularly useful for students in the early grades as they begin to make sense of unfamiliar problems or think about familiar phenomena in new ways. As they grow and develop competency, students can draw upon an expanded set of lenses with the second-order CCCs. A commonality between the SAIL and ELeVATE examples is the importance of designing instruction such that students have rich opportunities to activate and use their existing ideas related to CCCs in order to make sense of phenomena and problems before being expected to use specific terminology or CCCs more intentionally.
Finally, there is a critical need for conducting research that explores the design, implementation, and effects of CCC-informed science and engineering curriculum. This is not the work of researchers or practitioners alone, but rather requires skills, expertise, and collaboration across both groups of stakeholders. The SAIL and ELLeVATE curricula serve as examples of how CCCs can strengthen student learning and broaden participation in science and engineering instruction. Both the SAIL and ELLeVATE units were co-development projects between researchers and practitioners, with practitioners playing a primary leadership role in developing and refining instructional strategies that leveraged the power of CCCs in classroom instruction. While such research–practice partnerships are always powerful approaches to investigating science learning, they are particularly important in the case of CCCs whose potential needs to be fully explored. Yet, formalized curriculum research and development is typically slow, taking many years to secure funding, develop and refine materials, and publish findings. With just over 10 years since the Framework introduced CCCs as an explicit dimension of science learning, the most active learning environments for innovation have been the science and engineering classrooms of practitioners who have not had the luxury of waiting for the limited CCC research base to be more extensive [19]. The field will not wait indefinitely for robust evidence regarding how CCCs can effectively be used to support student learning, so time is of the essence. There currently exists a wealth of practitioner knowledge base about how CCCs can be meaningfully utilized in science and engineering instruction, and it is up to both researchers and practitioners to sharpen and disseminate this knowledge base through partnerships that meaningfully connect research and practice.

Author Contributions: Conceptualization, J.C.N. and O.L.; writing—original draft preparation, J.C.N. and O.L.; writing—review and editing, J.C.N. and O.L.; funding acquisition, J.C.N. and O.L. All authors have read and agreed to the published version of the manuscript.

Funding: The SAIL units were funded by the US National Science Foundation (NSF DRL-1503330). The ELLeVATE unit was funded by the US National Science Foundation (NSF DUE-1431725).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Conflicts of Interest: The authors declare no conflicts of interest.

References
7. Sekretariat der Ständigen Konferenz der Kultusminister der Bundesrepublik Deutschland. Beschlüsse der Kultusministerkonferenz—Bildungsstandards im Fach Biologie für den Mittleren Schulabschluss (Jahrgangsstufe 10) [Report of the Cultural Ministry Conference—Education Standards in the Subject Biology for the Completion of Middle School (Grade 10)]; Luchterhand: Munich, Germany, 2005. Available online:


Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.