Crosscutting Concepts

Strengthening Science and Engineering Learning

Jeffrey Nordine and
Okhee Lee, Editors

nsta Press
National Science Teaching Association

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Dedication

Aaron Rogat initiated this book. His creative thinking and forethought provided a road map for the project and laid the foundation for the series of collaborations that ultimately led to the chapters that follow. A talented scientist and science educator, Aaron dedicated his career to improving science teaching and learning. Aaron left us too soon, but he had meaningful impact on those who had the privilege to work with him.

Rachel Ledbetter, Managing Editor
Andrea Silen, Associate Editor

Art and Design
Will Thomas Jr., Director

Printing and Production
Catherine Lorrain, Director

National Science Teaching Association
1840 Wilson Blvd., Arlington, VA 22201
www.nsta.org/store
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Preface

The Role of Crosscutting Concepts in Three-Dimensional Science Learning

Helen Quinn

This book is designed to enrich and expand your understanding and use of each of the crosscutting concepts defined by *A Framework for K–12 Science Education* (the *Framework).* That *Framework* introduces these concepts and defines them as one of the three dimensions of science learning. The premise of this book is that you, as a teacher, parent, or mentor, can better guide students' three-dimensional science learning, including learning to understand and use these concepts as you enrich your own understanding of them and see examples of their use in both real-world problem solving and classroom contexts.

I chaired the committee that developed *A Framework for K–12 Science Education*. When, in the course of that work, we formulated the idea of three-dimensional science learning, we were seeking a description of teaching and learning that would resonate in the field. We wanted a term that would remind everyone to attend to three important aspects of science learning in their instructional planning. The goal was to avoid some of the failures of previous attempts to encourage and support effective science teaching through the formulation of standards for science learning.

As we introduced the crosscutting concepts (CCCs), we knew that certain "big ideas" or "themes" (AAAS 1993) or "unifying concepts and processes" (NRC 1996) had been chosen and described as important in prior documents intended to guide science education. However, they were rarely taken up by curriculum developers, and their use in classrooms was limited at best. Our challenge was to describe them better and to come up with a formulation in which they could not be forgotten. We did this by calling the science and engineering practices (SEPs), crosscutting concepts, and disciplinary core ideas (DCIs) each a separate dimension of science learning and by stressing that learning should be three-dimensional. We hoped to achieve the goal of integrating the learning about and use of these practices and crosscutting concepts into science learning. The aim was to make them useful to students, not to simply add to the list of things students must learn and remember.

Looking at the situation now eight years later, I see that our success so far has been limited. Many states have adopted standards based on, or derived from, our *Framework*. A shift to two-dimensional learning is clearly underway. One state has even adopted a two-dimensional approach for their standards. Teachers across the country are beginning to see that students' science learning is deepened and enriched when students engage in the full cycle of science and engineering practices while simultaneously learning and applying the disciplinary core ideas to explain phenomena or develop designs. However, it seems to me that most teachers and curriculum designers still struggle to incorporate the dimension that we call crosscutting concepts. Disciplinary core ideas are seen as the usual "content," and the practices are seen as the doing of science or engineering, so why is this other set of concepts needed?

What are the crosscutting concepts (CCCs)? And why are they needed? I find that the description that resonates most for teachers is one that we did not use in the *Framework*. The CCCs are conceptual tools for examining unfamiliar situations and finding an approach that helps develop understanding. Each CCC is a lens for looking at a problem. Each lens highlights a particular perspective and thus leads its user to ask productive questions that arise from that perspective. Productive questions here mean questions that are useful and effective in guiding and expanding thinking and thus aid in sense-making and problem-solving efforts.

Scientists use these lenses all the time because we have somehow learned that they are effective. When I talk to scientists about the CCCs, they generally agree that they use all of them and that they are most useful when confronting an unfamiliar problem or situation. All too often, we expect students to discover these lenses for themselves, without ever explicitly discussing their use. Three-dimensional learning should provide students with experiences in using these concepts as they seek to build models and explain phenomena or design solutions to problems; time to reflect on the use of these concepts is also important. This experience of use and reflection makes the usefulness of the crosscutting concepts an explicit element of students' science learning.

Each lens is a tool to be taken up as needed and used to enrich the SEPs and DCIs as they are applied to develop designs to solve engineering problems or to explain phenomena. A tool is not useful if it is unfamiliar, so students must develop familiarity with these tools and need to be guided to use them in multiple contexts. Eventually with use, CCCs should, like the SEPs, become part of the toolkit that a student freely calls on and uses when confronted with any unfamiliar science phenomenon or engineering problem.

If these things are tools, why did we call them *concepts*? The answer is that they are *conceptual* tools. We could call them conceptual frames; the idea of a lens is that it helps us frame a problem in a particular way, directing our attention to aspects relevant to that framing. However, we don't start out by teaching students that a given concept is a lens; instead, we start by giving them experiences where the lens is useful, suggesting they use it, and then asking them to reflect on how it helped them approach the phenomenon or problem. Only as they become familiar with the lens do we begin to talk about it abstractly as a tool they might use again in other circumstances.

Being told to look for patterns is not useful unless the student has begun to develop the idea that the patterns they observe in any given system are something that their model for the system must reproduce and explain. This is learned not by talking about noticing patterns but by first doing activities that ask students to use patterns and find relationships between them. For example, a third-grade class might be looking at the native plants in their region and given photos of the plants and a map that shows where each type of plant is likely to be found. Then the students are asked how they could organize the plants into groups. Some teams of students decide to group the plants by the size of their leaves. Others may choose to group the plants by the locations where they are found. Each has found a pattern and used it to group the plants. (If the teacher sees a possible grouping that none of the students has chosen, he or she can suggest it as an alternative way to carry out the task.) Now the teacher can ask two groups of students who have used different strategies to discuss whether there is any relationship between their grouping methods. Imagine their excitement when they discover that the plants by the stream generally have larger leaves than those on the open hillside. Now they have found a pattern that begs for an explanation and also generates many interesting questions to explore: Why is it that these two completely different ways of grouping the plants actually were quite similar in their outcomes? What else is different about the hillside environment and the streamside one? What advantages and disadvantages are there to having big leaves? What could be the advantage for smaller leaves on the hillside? What do leaves do for the plant anyway?

There is a deep interplay between developing the crosscutting concepts as tools and engaging in the SEPs, always, of course, with the goal of explaining some phenomenon or designing a solution to a problem using science ideas. In some cases, a pairing between a particular concept and a particular practice is obvious and explicit: We cannot develop or use models effectively without having some concept of systems and system models, nor can we construct explanations or design solutions without calling on our understanding of the concept of cause and effect.

Four of the crosscutting concepts—patterns, relationships between structure and function, conditions for stability or change in a system, and conserved qualities (flows and cycles of matter and energy into, out of, and within a system)—provide the conceptual basis for asking productive questions about one's model and how well it represents these essential aspects of the system. These questions can help us refine our model and deepen our understanding of the system and the phenomena occurring within it.

Notice that in the discussion above, I have slightly renamed several of the crosscutting concepts in order to stress what is essential about them. For example, I renamed the CCC of cause and effect: mechanisms and explanation, labeling it instead as "mechanisms of cause and effect." I find that too many people lose track of what comes after the colon, which is in fact the essence of the CCC. The same is true for energy and matter: flows, cycles, and conservation. It is not the idea of energy or matter that is crosscutting here. Instead, what is crosscutting is the additional concept of conserved quantities, namely that something that cannot be produced or destroyed must be supplied and disposed of, and its availability—or lack of it—limits what can occur. Hence, it is very useful to understand how a system functions in order to track how the conserved quantity or substance flows into, out of, or within the system. For this reason, I renamed the CCC "tracking conserved quantities (flows and cycles of matter and energy into, out of, and within a system)." Likewise, with the CCC of stability and change, the question is not whether a system is stable or changing. Rather, the question is under what conditions or over what timescale is it stable, and what changes in conditions lead to what changes in the system. Therefore, I renamed this concept "conditions for stability or change."

I suggest the aforementioned name shifts based on my experiences working with teachers to help them use these concepts. The names we gave them in the *Framework* work once you know how to use the concepts, but I find renaming them helps point the way to begin using each concept.

The CCC of patterns invokes a particular type of observation: namely, looking for patterns in the form or behavior of the system. This concept, which we could likewise rename "recognizing and explaining patterns," can be useful in that it is connected to every practice. In particular, there are questions one can ask about the patterns in a phenomenon or system that link to every practice: What questions do I have about the patterns I have noticed? Does my model reproduce these patterns? What do I need to investigate about this system to understand this pattern better?

The CCC of scale, proportion, and quantity comes into play as one seeks to define any quantitative relationships in developing a model and to test and refine the model through the practices of (a) planning and carrying out investigations (which, of course, involves observations and measurements to be recorded) and (b) analyzing and interpreting data (which is often but not always quantitative). Note that this crosscutting concept cheats; it introduces not one concept but three, linked together by the fact that all involve quantitative thinking, as well as units of measurement.

Thinking about relationships of scale, proportion, and quantity in a system typically involves us in the practice of using mathematics and computational thinking. Measurement requires that students decide (a) on what scale to model the system, (b) what to measure about it, and (c) what units of measurement to use for those quantities. These are critical for developing models and planning investigations. Measurement also makes the mathematics of proportion in science something more than that of fractions in mathematics. This is because in science one can take ratios of quantities with different and incommensurate units and define entirely new quantities, as is the case with speed—a ratio of distance traveled to time elapsed. Students need support to see the critical role that the different types of units play; unlike feet and meters, which are both units of length and can be freely converted, distance units and time units bear no relationship to one another.

Many readers have interpreted the *Framework* and the *Next Generation Science Standards* as a call for an approach to the teaching of science that is integrated across all disciplines. There is, however, little agreement in the field about what it means for a curriculum to be "integrated." Does "three-dimensional" imply that the curriculum is integrated? Are units designed around explaining phenomena necessarily integrated science? Let me define a unit as "integrated" if its learning goals include core ideas from more than one disciplinary area and as "discipline-focused" if all the core ideas addressed are from the same discipline. Either way, it could be taught in the three-dimensional approach, where students are applying the DCIs they are learning and using the SEPs and the CCCs in order to explain an overarching phenomenon that provides the central core of the unit.

Certainly, both the SEPs and the CCCs highlight what is common across all areas of science. Beyond that, the sciences today are much more interconnected than they were when high school science was divided into three courses—biology, chemistry, and physics—and even the experts saw little connection between them. Today, even high school biology contains a large segment of biochemistry, and no serious biologist thinks there is a "life force" (*vis vitalis*) that is outside of physics and chemistry. Chemistry functions by the same quantum physics as materials science. And Earth systems science requires expertise from geology, meteorology, oceanography, as well as physics, chemistry, and biology to understand the complex interconnectedness of the geosphere, biosphere, atmosphere, and hydrosphere.

The *Framework* does stress that whatever the course structure, whether discipline-focused or cross-disciplinary, science overall needs to be taught in such a way that students are supported in building connected knowledge across the disciplines and use their knowledge from one discipline in the context of another when and where it is relevant.

Topics that play a role across all disciplines need to be discussed in such a way that students can connect what they learn in one disciplinary context with that in another. Consider the teaching of energy, for example. No matter the order in which their courses are offered, students should be supported in connecting their physics understanding about energy to what they are learning in chemistry, and they should be able to connect both chemical and physical ideas about energy to language about energy used in biology or Earth science courses or units. To apply the crosscutting concept of conservation of energy and matter, one needs a single approach to energy (and to matter) that begins to be developed in middle school and is applied similarly across all high school courses. This does not argue for any particular organization of courses or units, but it does argue for curriculum design and course planning that looks at more than a single course and its particular disciplinary goals.

I do not think you can integrate or apply ideas that you have not met. The core ideas of each discipline need attention and must be developed as such, even when this work occurs in an interdisciplinary context. Detailed physical science ideas may be relevant to a larger real-world problem, for example in Earth systems science. But if the ideas are to be first introduced in that context, the unit will also require some experiments and activities that look more like traditional discipline-based school science to develop the relevant core ideas effectively. Curriculum design around real-world problems requires careful planning to include the relevant smaller scale activities that support learning the disciplinary ideas well, and these activities must be introduced in a way that students see they are indeed connected to the larger question. A unit can be designed to introduce core ideas from more than one discipline, or from only one of them. What makes it three-dimensional is that the students are seeking to explain a phenomenon that is relevant and interesting to them by (a) using the science they are learning to develop models of the relevant system, (b) engaging in multiple science practices, and (c) using crosscutting concepts as they develop and refine those models to produce a model- and evidence-based explanation of the phenomenon. In fact, most often, the evidence is used to refine and then support the model, and then the model provides the reasoning that connects this evidence to the explanation.

So far, this discussion has viewed the crosscutting concepts from the perspective of how scientists use them and how they can be used in the classroom to enrich and inform student work to develop explanations of phenomena. They also play a role in developing engineering designs. As with the SEPs, the role of and language around the use of each CCC is somewhat different in the engineering context than in the science one. There is a chapter in this book that discusses engineering uses, so I will only give a couple of examples here. Engineers design systems, which may be objects, collections of objects, or processes. Clearly, the CCC of systems and system models is critical for system design. Engineered systems are governed by the same rules of physics, chemistry, and even biology; therefore, CCCs such as the tracking of conserved quantities or the conditions for stability and instability are equally applicable to designed systems as they are to natural phenomena. Their use in the design process most often is in asking questions like: the following: How can I improve my design? How can I make it function well under a broader range of conditions (conditions for stability)? How can I make it use less fuel to the do the same job (tracking flows of matter and energy)?

In this latter context, it is worth noting that engineers talk about inputs and outputs with a somewhat different meaning than the science concept of inflows and outflows to the system. In engineering, an input is something that must be provided (and hence paid for) in order for the system to operate, and an output is either a product or a task that the machine is intended to make or do. An inflow of oxygen from the air is rarely counted as an input, and outflows of waste products such as exhaust gases are not generally included in the term *output*, even though they are clearly both things that must be considered in machine design. It is helpful for students to experience and use the terms *input* and *output* and to become aware of both the overlaps and the differences with the terms *inflow* and *outflow* as they apply this concept.

To support three-dimensional learning, we need to consider how to elicit use of all three dimensions not only in instruction but also in assessment tasks, especially as we design formative assessment. Decisions about which CCC and SEP to highlight in a lesson or unit must be made during the design of the instructional sequence. Leaving this decision to be made only during classroom instruction runs the risk of allowing these important concepts to slip into the background. Therefore, the design of an instructional unit, or an extended curriculum plan that includes multiple units, should include the intentional and explicit use of particular crosscutting concepts, and related SEPs, within each unit. However, as students become familiar with these tools, they may call on others not specifically stressed in the curriculum plan.

With regard to assessment, this too should be a part of curriculum design—which outcomes are intended and how they will be measured should inform the content and approach of the unit. The crosscutting concepts are a particular challenge for external- or test-based assessment in that the use of the tool is not necessarily visible in the finished product or response on the test. I can pose a problem for which a particular crosscutting concept would be a powerful tool, yet not be able to tell with certainty from looking at the solution achieved whether or not the student called on that tool. For summative assessment, this may not matter much; a good solution to a problem is good however it was reached. If one does wish to know how students have used a particular crosscutting concept, then the test tasks must explicitly elicit that information. However, in formative assessment, one does need to know to what extent students are able to take up and use the appropriate tools. In particular, we need to know whether students are using the crosscutting concept that is being developed and used in a unit in order to make decisions about further instruction. As stated above, this is difficult to see from short assessment tasks. Planned and documented classroom observations of students at work on projects can provide some of the missing information, not necessarily for grading purposes but in a way that can guide further instructional choices. Formative assessments need not be designed to assign grades; they should be designed to inform subsequent instruction. This allows a wider range of methodologies than those for summative assessment where a grade is to be assigned.

In the chapters of this book, each crosscutting concept is explored in depth and its usefulness across the sciences is highlighted. Each chapter also seeks to illustrate how that concept might be used in the classroom. However, it is easy to lose sight of what is common about these concepts in exploring the richness of each one of them. Here is one commonality to keep in mind: The metaphor of the lens for viewing phenomena or problems and asking productive questions about them is a useful one that spans all of the crosscutting concepts and links them together as conceptual tools.

Another commonality is that the use of any of these concepts is not specific to any one discipline of science; they are all useful across all disciplines, and many of them apply well beyond the natural sciences and are useful in many problem-solving contexts. Hence, students who develop the ability and the disposition to use these tools are better positioned to apply their science knowledge to everyday situations. This ability develops, as do most, through practice and effort, with coaching and guided reflection on that effort. Students need multiple opportunities to use each of the crosscutting concepts in many different contexts, and they also need time and support to reflect on what they did and how it helped them understand the problem they were tackling. In other words, the crosscutting concepts are concepts students must learn to use appropriately, rather than concepts to be taught as abstractions.

The same can be said of the other two dimensions; students learn the practices by engaging in them and reflecting on that work, and they learn science concepts by using them to help explain phenomena. The three dimensions work together to build a "knowledge for use" of science and how it functions. The expectation is that students who experience such learning will be better able to apply their learning in new contexts than those who have just learned disciplinary ideas as things to remember.

This book will enrich your thinking about each of the crosscutting concepts and prompt you to think of many questions related to the perspective brought by each. My hope is that it also helps you see them each as a powerful tool for student learning and recognize them as a class of concepts with some similar uses, even though each of them is distinct. Use of these concepts as lenses interweaves with and supports student engagement in the practices and the application of their growing knowledge of disciplinary concepts. Learning and assessment tasks that ask students to use them in powerful ways can help students recognize their importance. The goal of three-dimensional science learning is that students will take this learning out of the classroom and into their lives, using and expanding it as they meet issues and opportunities or challenges where it can be helpful to them. Once a tool enters their conceptual toolkit, it becomes theirs, and they can use it whenever and wherever they choose.

Among your goals as a teacher, I expect that you want not just to "cover" the required material but also to provide your students with tools for life and lifelong learning. Both the science and engineering practices and the crosscutting concepts can be such tools, useful well beyond the science classroom. Providing students with the multiple experiences they need to master the use of these tools and add them to their personal toolkit requires well-designed three-dimensional curricula and teaching approaches over multiple years. This book can help you construct the experiences that deliver such learning.

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About the Editors

Jeffrey Nordine is the associate professor and deputy director of physics education at the Leibniz Institute for Science and Mathematics Education (IPN) in Kiel, Germany. His research focuses on the design, implementation, and effects of coherent science instruction. In particular, he studies how the energy concept might be taught in order to strengthen connections across science disciplines and to support future learning about energy-related contexts, both in and out of school. He was an award-winning physics teacher and dean of instruction for mathematics and science in San Antonio, Texas, and he was the chief scientist for the San Antonio Children's Museum (The DoSeum). Beginning in August 2021, he will be an associate professor of science education at the University of Iowa.

Okhee Lee is a professor in the Steinhardt School of Culture, Education, and Human Development at New York University. Her research involves integrating science, language, and computational thinking with a focus on English language learners. Her latest research addresses the COVID-19 pandemic and social justice. She was a member of the *Next Generation Science Standards* (*NGSS*) writing team and served as leader for the *NGSS* diversity and equity team. She was also a member of the steering committee for the Understanding Language Initiative at Stanford University. She became a fellow of the American Educational Research Association (AERA) in 2009, received the Distinguished Career Contribution Award from the AERA Scholars of Color in Education in 2003 and the Innovations in Research on Equity and Social Justice in Teacher Education Award from the AERA Division K Teaching and Teacher Education in 2019, and was recognized by the National Science Teaching Association (NSTA) Distinguished Service to Science Education Award in 2020.

Contributors

The following list contains the contact information for the book's contributors.

Preface

Helen Quinn, Stanford University, *quinn@slac.stanford.edu*

Chapter 1

Jeffrey Nordine, Leibniz Institute for Science and Mathematics Education (IPN); Kiel, Germany, *nordine@leibniz-ipn.de*

Okhee Lee, New York University, *olee@nyu.edu*

Chapter 2

Joseph Krajcik, CREATE for STEM, Michigan State University, *krajcik@msu.edu*

Brian J. Reiser, Northwestern University, *reiser@northwestern.edu*

Chapter 3

Marcelle Goggins, Research Improving People's Lives, *mgoggins@ripl.org*

Alison Haas, New York University, *ams728@nyu.edu*

Scott Grapin, University of Miami, *sgrapin@miami.edu*

Rita Januszyk, Gower District 62; Willowbrook, Illinois, *ritajanuszyk@gmail.com*

Lorena Llosa, New York University, *lorena.llosa@nyu.edu*

Okhee Lee, New York University, *olee@nyu.edu*

Chapter 4

Kristin L. Gunckel, University of Arizona, *kgunckel@arizona.edu*

Yael Wyner, The City College of New York, City University of New York, *ywyner@ccny.cuny.edu*

Garrett Love, North Carolina School of Science and Mathematics, *garrett.love@ncssm.edu*

Chapter 5

Tina Grotzer, Harvard Graduate School of Education, *tina_grotzer@harvard.edu*

Emily Gonzalez, Harvard Graduate School of Education, *emily_gonzalez@harvard.edu*

Elizabeth Schibuk, Conservatory Lab Charter School; Dorchester, Massachusetts, *eschibuk@conservatorylab.org*

Chapter 6

Cesar Delgado, North Carolina State University, *cesar_delgado@ncsu.edu*

Gail Jones, North Carolina State University, *mgjones3@ncsu.edu*

David Parker, The Outdoor Campus, South Dakota Game, Fish and Parks, *David.Parker@state.sd.us*

Chapter 7

Sarah J. Fick, Washington State University, *s.fick@wsu.edu*

Cindy E. Hmelo-Silver, Indiana University, *chmelosi@indiana.edu*

Lauren Barth-Cohen, University of Utah, *lauren.barthcohen@utah.edu*

Susan A. Yoon, University of Pennsylvania, *yoonsa@upenn.edu*

Jonathan Baek, Honey Creek Community School; Ann Arbor, Michigan, *jbaek@hc.wash.k12.mi.us*

Contributors

Chapter 8

Charles W. (Andy) Anderson, Michigan State University, *andya@msu.edu*

Jeffrey Nordine, Leibniz Institute for Science and Mathematics Education (IPN); Kiel, Germany, *nordine@leibniz-ipn.de*

MaryMargaret Welch, Seattle Public Schools; Seattle, Washington, *mmwelch@seattleschools.org*

Chapter 9

Bernadine Okoro, Ephesus Media; Washington, D.C., *bernadine.okoro75@gmail.com*

Jomae Sica, Beaverton School District; Beaverton, Oregon, *jomae_sica@beaverton.k12.or.us*

Cary Sneider, Portland State University, *carysneider@gmail.com*

Chapter 10

Brett Moulding, Partnership for Effective Science Teaching and Learning, *mouldingb@ogdensd.org*

Kenneth Huff, Williamsville Central School District; Williamsville, New York, *khuff@williamsvillek12.org*

Kevin McElhaney, Digital Promise, *kmcelhaney@digitalpromise.org*

Chapter 11

Joi Merritt, James Madison University, *merritjd@jmu.edu*

Kristin Mayer, Kentwood Public Schools; Kentwood, Michigan, *kristin.mayer@kentwoodps.org*

Chapter 12

Jo Ellen Roseman, American Association for the Advancement of Science (retired), *roseman.joellen@gmail.com*

Mary Koppal, American Association for the Advancement of Science (retired), *mrk1346@yahoo.com*

Cari Herrmann Abell, BSCS Science Learning, *cabell@bscs.org*

Sarah Pappalardo, Howard County Public Schools, *sarah_pappalardo@hcpss.org*

Erin Schiff, Howard County Public Schools, *erin_schiff@hcpss.org*

Chapter 13

Ann E. Rivet, Teachers College, Columbia University, *rivet@tc.columbia.edu*

Audrey Rabi Whitaker, Academy for Young Writers; Brooklyn, New York, *rabi@afyw.org*

Chapter 14

Christine M. Cunningham, Pennsylvania State University, *ccunningham@psu.edu*

Kristen B. Wendell, Tufts University, *kristen.wendell@tufts.edu*

Deirdre Bauer, State College Area School District; State College, Pennsylvania, *dmb13@scasd.org*

Chapter 15

Erin Marie Furtak, University of Colorado Boulder, *erin.furtak@colorado.edu*

Aneesha Badrinarayan, Learning Policy Institute, *abadrinarayan@learningpolicyinstitute.org*

William R. Penuel, University of Colorado Boulder, *william.penuel@colorado.edu*

Samantha Duwe, Aurora Public Schools; Aurora, Colorado, *srduwe@aurorak12.org*

Ryann Patrick-Stuart, Aurora Public Schools; Aurora, Colorado, *repatrick-stuart@aurorak12.org*

Chapter 16

Emily C. Miller, PBL Science Connections; University of Wisconsin-Madison, *emilycatherine329@gmail.com*

Tricia Shelton, National Science Teaching Association, *tshelton@nsta.org*

Chapter 17

Jeffrey Nordine, Leibniz Institute for Science and Mathematics Education (IPN); Kiel, Germany, *nordine@leibniz-ipn.de*

Okhee Lee, New York University, *olee@nyu.edu*

Ted Willard, Discovery Education, *twillard@discoveryed.com*

Chapter 3

Broadening Access to Science: Crosscutting Concepts as Resources in the *Next Generation Science Standards* Classroom

Marcelle Goggins, Alison Haas, Scott Grapin, Rita Januszyk, Lorena Llosa, and Okhee Lee

Although crosscutting concepts (CCCs) are not new ideas in science education, their inclusion in *A Framework for K–12 Science Education* (the *Framework*; NRC 2012) and the *Next Generation Science Standards* (*NGSS*; NGSS Lead States 2013a) has new implications for science instruction. All students come to school with experiences to make sense of the world around them that relate to CCCs in the *NGSS*. For example, in their everyday lives, students notice patterns, recognize how parts work together as a system, and try to figure out what causes things to happen. Given that students use CCCs in their everyday lives, these concepts can be thought of as resources that students bring to the *NGSS* classroom. Teachers can help students make their thinking explicit as they develop an understanding of CCCs as resources to make sense of phenomena.

A perspective on CCCs as resources is timely in the context of increasing cultural and linguistic diversity of the K–12 student population. In recent years, underrepresented groups in terms of race/ethnicity have become the majority in U.S. public schools, and students classified as English learners represent the fastest-growing subset of the student population. Traditionally, science education has not provided opportunities for students from underserved groups to see science as relevant to their lives or future careers. By viewing CCCs as resources that all students bring to the science classroom, teachers can integrate them into science instruction in ways that build on the students' everyday experiences in their homes and communities. This perspective on CCCs as *resources* makes science real and relevant to all students and allows them to see themselves as scientists from the moment they enter the science classroom.

In this chapter, we describe how a perspective on CCCs as resources is particularly powerful for achieving the *NGSS* vision of "all standards, all students" (NGSS Lead States 2013b). First, we frame CCCs as resources that all students bring to the science classroom. Second, we acknowledge how our perspective builds on and extends the emerging research literature on integrating CCCs into science instruction. Third, we provide classroom examples to illustrate how a perspective on CCCs as resources is enacted by two teachers in a yearlong, fifth-grade curriculum with a focus on English learners. Finally, we conclude with classroom strategies for implementing this perspective on CCCs.

Crosscutting Concepts 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 those from underserved groups, bring little or limited prior canonical science knowledge with them. It is imperative that science be made real and relevant to all students. Utilizing CCCs as resources is one way to do this.

CCCs have previously been thought of as "common themes" (AAAS 1989) and "unifying concepts and processes" (NRC 1996) that are present in different science disciplines; however, they were not emphasized in science standards, which was problematic from the perspectives of both science and equity. From the perspective of science, these "themes" and "concepts" became secondary to science content or inquiry in both the research literature and classroom implementation. As a result, CCCs did not figure prominently in science instruction, especially with student groups that were traditionally underserved in science education (NGSS Lead States 2013b).

In contrast to previous standards, the *NGSS* explicitly integrates seven CCCs into the standards, which is an advance from the perspectives of both science and equity. From the perspective of science, by including CCCs alongside science and engineering practices (SEPs) and disciplinary core ideas (DCIs) as part of three-dimensional learning, the *NGSS* elevates the status of CCCs. From the perspective of equity, the *NGSS* posits the importance of CCCs for all students. Specifically, the *NGSS* states that "explicit teaching of crosscutting concepts enables less privileged students, most from non-dominant groups, to make connections among big ideas that cut across science disciplines. This could result in leveling the playing field for students who otherwise might not have exposure to such opportunities" (NGSS Lead States 2013b, p. 6).

To address CCCs in relation to diverse student groups, we propose that teachers view them as resources that students use in their everyday lives to make sense of the world and that they bring to the science classroom to make sense of phenomena. By capitalizing on students' funds of knowledge from their homes and communities (González, Moll, and Amanti 2005), including their everyday experiences with CCCs, teachers demonstrate value for students' cultural and linguistic resources. With English learners in particular, we posit that a view of CCCs as resources invites these students to use all of their meaning-making resources, including everyday language, home language, and multiple modalities, in the science classroom (Lee et al. 2019b).

Emerging Literature on Crosscutting Concepts

The *Framework* defines CCCs as concepts "that unify the study of science and engineering through their common application across fields" (NRC 2012, p. 2). The research literature on CCCs has been limited (Osborne, Rafanelli, and Kind 2018) and is only beginning to emerge (e.g., Fick, Nordine, and McElhaney 2019). Our perspective on CCCs as resources builds on and extends this limited literature by considering CCCs from an equity perspective (Goggins et al. 2019). Specifically, our perspective is informed by the theoretical ideas of Lave and Wenger (1991), who conceived of learning as participation in communities of practice. In such communities of practice, all members are viewed as legitimate and recognized for bringing individual resources that contribute to the collective functioning of the community. Initially, these resources may be invisible[1], thus allowing for "smooth entry into practice" (Adler 2000, p. 214) as students use their everyday experiences for initial meaning-making. Over time, these resources are made visible so they can be more intentionally "used [to] extend practice" (Adler 2000, p. 214). The dual functions of invisibility and visibility allow all students' resources to be used as individual resources for meaning-making from the outset and to become collective resources of the classroom over time.

Based on this theoretical grounding, we propose viewing CCCs as resources that all students bring to the science classroom community of practice and that teachers can build on and make visible across science disciplines and over the course of instruction. This perspective on CCCs has three key strategies for teachers:

1. All students come to the science classroom with intuitive ideas about CCCs that can serve as resources that develop into knowledge they learn to use more intentionally (Fick, Arias, and Baek 2017). Thus, as teachers leverage these intuitive ideas about CCCs, they guide students in using CCCs to make sense of phenomena. Over time, teachers can build on and make visible students' intuitive ideas about CCCs. In the science classroom, all students bring their funds

1. Lave and Wenger's (1991, p. 103) use of the term *invisible* is not intended in a pejorative sense (e.g., to indicate "missing" or "absent") but rather to indicate "unproblematic interpretation and integration [of resources] into activity." In contrast, they use the term *visible* to indicate "extended access to information" about how and why a resource is used in a particular way.

of knowledge about CCCs from their homes and communities (see Chapter 8 in Fick, Nordine, and McElhaney 2019). This perspective on CCCs as resources calls for a shift in instruction from a deficit perspective (i.e., students from underserved groups come to the science classroom with limited sensemaking resources) to an asset perspective (i.e., students from underserved groups come to the science classroom with sensemaking resources).

> "This perspective on CCCs as resources calls for a shift in instruction from a deficit perspective (i.e., students from underserved groups come to the science classroom with limited sensemaking resources) to an asset perspective (i.e., students from underserved groups come to the science classroom with sensemaking resources)."

2. Teachers can 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 should view CCCs as resources they can flexibly draw on to make sense of phenomena in any discipline.
3. Teachers can guide students in using CCCs intentionally when presented with unfamiliar phenomena so their understanding and use of CCCs becomes 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 can design coherent instructional sequences that help students recognize how and when CCCs are useful resources for sensemaking of phenomena.

To summarize, building on CCCs as resources during instruction makes students' intuitive ideas about CCCs visible (Strategy 1), provides opportunities for students to apply CCCs across science disciplines (Strategy 2), and guides students in using CCCs intentionally over the course of instruction (Strategy 3). These strategies come together to support equity by viewing students' everyday and home experiences as sensemaking resources (Strategy 1), extending students' resources to other contexts in order to showcase their value for sensemaking (Strategy 2), and making the resources explicit for all students so the classroom community of learners use the resources collectively to make sense of phenomena (Strategy 3).

Classroom Examples

This section provides classroom examples from the implementation of Science and Integrated Language (SAIL), a yearlong, fifth-grade curriculum aligned to the *NGSS* with a focus on English learners. The SAIL curriculum bundles the 16 fifth-grade performance expectations in the *NGSS* into four units that address physical science, life science, Earth science with engineering embedded, and space science. Each unit in the curriculum focuses on a local phenomenon that is real and relevant to students (Lee 2020; Lee et al. 2019a).

- 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)
- Unit 4: Why do falling stars fall? (space science)

To develop the curriculum, we worked closely with teachers in an urban school district who field-tested the curriculum and provided feedback on how to improve the curriculum to better meet the needs of all students, particularly English learners. In this section, we provide examples from two classrooms where we field-tested our curriculum over three years. In one school, 25% of the student body were English learners, and 89% of students qualified for free or reduced-price lunch. In the other school, 24% of the student body were English learners, and 77% of students qualified for free or reduced-price lunch.

The following classroom examples each highlight the three strategies previously described. First, they illustrate how teachers capitalize on students' intuitive ideas about CCCs to make sense of phenomenon (Strategy 1). Second, they illustrate how a perspective on CCCs as resources applies across science disciplines (Strategy 2). Third, they illustrate students' learning progressions in using CCCs more intentionally from the first unit to the final unit of the school year (Strategy 3). For each of the classroom examples, we provide a description of the classroom instruction and then offer our commentary with a focus on these three key strategies for CCCs. In the examples, we include excerpts from the SAIL curriculum to illustrate how the curriculum is purposefully designed to promote the perspective on CCCs as resources.

Patterns in Garbage Materials

Description

The first classroom example shows how a teacher capitalized on students' everyday experiences with the CCC of patterns.

CLASSROOM SNAPSHOT 3.1

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 there were no hazardous materials included. (See Figure 3.1 for the safety measures the teacher took for this garbage sort.)

Figure 3.1. Safety measures taken for the garbage sort

Garbage Sort Safety Guidelines
• When assembling the piles of garbage for the activity, the teacher made sure not to include broken glass or sharp objects. • The teacher ensured the garbage had as little liquid as possible. • The teacher directed students to wear plastic gloves, plastic aprons, and protective goggles and to use tongs for handling the garbage. • The teacher directed students to wash their hands after handling the garbage. • If students had allergies (e.g., to nuts or mold), the teacher consulted the school nurse before proceeding with the garbage sort.

Wearing gloves, aprons, and goggles and using tongs to move the garbage materials around, students made observations of the materials. Then the teacher described their task, explaining that the groups of students would sort their garbage piles into smaller piles or categories. Since students had to agree with their group members about which sorting categories to use, the groups were communicating patterns they found in the garbage. The teacher guidance and prompting was minimal for groups making decisions about the categories. Teacher prompts such as "Why are you grouping these materials together?" allowed students to express the underlying reason for why they sorted the materials in a particular way. (See Figure 3.2 for possible teacher prompts related to the CCC of patterns.) 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 materials by color and texture, whereas another group sorted materials into the three categories of utensils, bowls, and food, recognizing that different materials had different purposes before being thrown away. The teacher listened to groups' rationales for their garbage categories, looking for students' use of the CCC of patterns. While listening, the teacher recognized that his students were

Continued

Classroom Snapshot 3.1 (*continued*)

already using the CCC of patterns by identifying similarities and differences in the garbage materials.

Figure 3.2. Possible teacher prompts to probe for students' intuitive use of patterns before making the CCC explicit

Possible Teacher Prompts Related to Patterns
1. How did your group decide which materials go together?
2. What is similar about the materials in each category?
3. What is different about the materials in each category?
4. If you were given a new material, how would you know which category it belonged to?

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 its categories of school lunch garbage. In this discussion, the teacher made students' use of the CCC of 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 garbage phenomenon.

Commentary

In this classroom example, the teacher capitalized on students' everyday experiences with the CCC of patterns as a resource to begin making sense of the phenomenon of garbage. He listened to how groups decided on their categories, 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 of patterns visible for students. The teacher connected 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 (Strategy 1).

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

Finally, the teacher guided students to use the CCC of patterns more intentionally through specific probing. As shown in Figure 3.2, the first probe ("How did your group decide which materials go together?") is an open-ended question intended to elicit how students intuitively used the CCC of patterns. The second and third probes ("What is similar about the materials in each category?" and "What is different about the materials in each category?") prompted students to identify similarities and differences in their observations, which is an important element of the CCC of patterns in fifth grade (NGSS Lead States 2013c, p. 4). Finally, the fourth probe ("If you were given a new material, how would you know which category it belonged to?") presented a hypothetical scenario to promote students' more informed use of the CCC. By following this sequence of probes, the teacher was able to move students from a more intuitive to a more intentional use of the CCC (Strategy 3).

The teacher's perspective on CCCs as resources was especially beneficial to the English learners who were able to use all of their meaning-making resources to make sense of the phenomenon (Lee et al. 2019b). In this example, the opportunity to use everyday language in combination with gestures (e.g., saying "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 (i.e., "Distinguish materials by patterns in their observable properties") enabled English learners 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 his instruction, the teacher embraced the notion that language is a product of, not a precursor to, "doing" science (Lee et al. 2019b) by recognizing how students' everyday language, related to the CCC of patterns, could serve as an entry point to science learning.

Systems of Garbage Disposal in the School, Home, and Community

Description

The second classroom example illustrates how the teacher capitalized on students' everyday experiences with a different CCC, systems and system models, to figure out how garbage was disposed of in their school, home, and community.

CLASSROOM SNAPSHOT 3.2

After sorting their school lunch garbage in the first lesson of the unit, students began to wonder where all of the garbage would go once it left the classroom. The teacher called on several students to share their initial ideas. Student responses included "the garbage can," "garbage trucks," and "landfills." The teacher wrote student responses on sticky notes and posted them on the board, asking students how the responses were related to one another. Student responses provided connections between the ideas listed on the sticky notes. For example, students said, "The janitor takes the garbage outside of the school" and "The garbage bin gets dumped into the garbage truck." The class connected the sticky notes with arrows to show how the different parts worked together to transport garbage from the classroom to the landfill.

Next, the teacher assigned groups to develop their own models of garbage disposal in either the home or community. Each group wrote the different parts on sticky notes (e.g., garbage can, dumpster, garbage truck) and used arrows between the sticky notes to show how the parts were related to one another. As the groups worked, the teacher asked probing questions and provided feedback on how the parts worked together. (See Figure 3.3 for possible teacher prompts related to the CCC of systems and system models.)

Figure 3.3. Possible teacher prompts to probe for students' use of systems and system models before making the CCC explicit

Possible Teacher Prompts Related to Systems and System Models
1. Where do you put your garbage at home?
2. Where in your neighborhood do you throw out garbage?
3. What would happen if a part, like the garbage truck, were missing?
4. How would the garbage end up in the landfill?

After circulating to each group, the teacher asked groups to place their models on the board in the front of the room. Students identified similarities and differences in the systems, which allowed the teacher to reinforce the CCC of patterns from the previous lesson, and students noticed that all of the garbage ended up in the landfill. In this discussion, the teacher described what the class developed as "models

Continued

Classroom Snapshot 3.2 (*continued*)

of several garbage disposal systems." He also explained to the class that scientists identify parts, or components, of systems and identify how those components work together, or interact. The interactions among the components enable the system to carry out functions that the individual components cannot. The teacher commended the students for using systems, as scientists do, to figure out where garbage goes when it is disposed. The teacher also suggested that the class keep in mind this concept of systems when investigating other phenomena in the future.

Commentary

In this classroom example, the teacher used students' everyday experiences with the CCC of systems and system models as resources to make sense of how garbage in the school, home, and community end up in a landfill. Similar to the first example, the teacher made students' intuitive ideas about the CCC of systems and system models visible by making the CCC explicit after students had experience using the CCC (Strategy 1). For English learners in particular, the opportunity to use all of their meaning-making resources (e.g., saying "This one comes first!" while rearranging the position of the sticky notes in their model) at the beginning of instruction before progressing to more specialized language (e.g., "Identify the components and interactions of the garbage disposal system.") provided access to science learning.

Using the CCC of systems and system models in the physical science unit exposed students to the CCC in a particular discipline. Students' classroom experiences with the CCC of systems and system models could then be extended in future units on different science disciplines. Furthermore, using this second CCC, in addition to the CCC of patterns, provides an example of how different CCCs may be used to make sense of one phenomenon in a particular discipline. This promotes a more flexible approach to using CCCs as resources for sensemaking, as multiple CCCs can be used to make sense of the same phenomenon (Strategy 2).

The teacher extended students' understanding of the CCC of systems and system models by probing their thinking on how the components of the system interact. As shown in Figure 3.3, the probes move from questions that ask students to name individual components of a system relevant to their everyday lives (e.g., "Where do you put your garbage at home?") to questions that probe students' thinking about how the components work together as a system (e.g., "What would happen if a part, like the garbage truck, were missing?"), which promotes more sophisticated use of the CCC over the course of instruction (Strategy 3).

Patterns and Systems in the Night Sky

Description

In the final unit of the year—the space science unit—students confronted the following driving question: Why do falling stars fall? They used the CCC of patterns to distinguish the properties of falling stars from stars such as the Sun. Students handled real falling stars (meteorites) and watched videos of falling stars at different times of the year. They wondered why they could see specific falling stars at certain times of the year. This final classroom example shows how students use their prior experiences with stars to help scaffold their understanding of falling stars before constructing physical models later in the unit.

CLASSROOM SNAPSHOT 3.3

The teacher began the first class of the unit by asking students if the sky looks the same every night of the year. Students shared out their experiences of seeing different objects in the night sky at different times of the year. The questioning valued students' intuitive ideas about finding the pattern of changing objects in the sky over the course of a year. The teacher passed out a data table listing the annual falling star showers (groups of falling stars), the constellations they are named after, and the dates for when the falling star showers occur. She prompted partners to talk about what the data table revealed about falling star showers. One English learner excitedly exclaimed that she and her partner already knew what to do: They were going to look for patterns in the data. The student demonstrated agency in learning science, as she recognized the power of patterns in the data to make sense of the phenomenon.

As partners talked, the teacher listened to how students made sense of the data. She recognized and shared with the class that partners found two different patterns. Some students looked for patterns within a single year, whereas others noticed patterns over multiple years. To make students' use of the CCC of patterns more intentional, the teacher asked students what each pattern could help them figure out. Through a class discussion, students concluded that patterns *within a single year* could help them figure out why they see different falling stars at different times of the year, whereas patterns *over multiple years* could help them figure out whether they would see the same falling stars at the same times next year.

Next, the teacher projected Stellarium, a free, open-source virtual planetarium program (*https://stellarium.org*), to show the night sky from the schoolyard over the course of the year. Working in groups, students made predictions about when they

Continued

Classroom Snapshot 3.3 (*continued*)

would see certain constellations. As they made observations of the night sky, they collected data about constellation positions during different months. As students shared their thinking about why they would see specific falling stars at certain times of the year, the teacher circulated to groups to prompt their use of the CCC of patterns. (See Figure 3.4 for possible teacher prompts related to patterns in space.)

Figure 3.4. Possible teacher prompts to probe for students' different use of patterns in space before making the CCC explicit

Possible Teacher Prompts Related to Patterns
1. What did you observe for each constellation over one year?
2. What did you observe for each constellation over multiple years?
3. What do these observations tell us about why we see different constellations at night during different times of the year?
4. What predictions can you make from these observations?

Finally, the teacher brought the class together for a discussion of students' observations. Groups shared their thinking about the patterns in the data they collected from Stellarium. Students noted that they only saw the constellations in some of the months each year (e.g., Leonids falling stars are visible in November but not May), but it was the same months every year (e.g., Leonids were visible in November over multiple years). To close the lesson, students used the patterns they had identified to write their predictions about which constellation and falling star shower they would see in November two years in the future and to record their initial ideas about *what caused* these patterns.

The teacher began the next class period by asking students to refer back to their initial ideas based on the Stellarium constellation data about why they only saw specific falling stars at certain times of the year. She then prompted students to think about how they could test these ideas using a physical model in the classroom. The teacher called on students to share what components they should include in their models, reminding them of the different systems they studied over the course of the year (e.g., the garbage disposal system). She wrote students' suggestions on the board. The class came to a consensus to include Earth, the Sun, and two different falling star showers: the June Bootids falling star shower and the November Leonids falling star shower. Then, the teacher presented students with supplies for developing a physical model to test their ideas: a polystyrene foam ball and a pencil to

Continued

Classroom Snapshot 3.3 (*continued*)

represent Earth, a toothpick in the Earth to represent the school's location, a light bulb in the center of the classroom to represent the Sun, and images of falling stars hanging from coat hangers to represent the two falling star showers.

The teacher directed students to share their ideas with their group members about why they would only see specific falling stars at certain times of the year. After passing out supplies for the physical model to each group, the teacher listened to students as they shared and tested their initial ideas. Students were eager to test out their ideas using the physical model, noticing that if they changed one component (e.g., how Earth moves around the Sun), the change resulted in different interactions (e.g., Earth interacted with different groups of falling stars at different times of the year). The teacher prompted groups to think about how changes to their system model related to their everyday and classroom observations of the night sky. (See Figure 3.5 for possible teacher prompts related to systems and system models in space.)

Figure 3.5. Possible teacher prompts to probe for students' use of the CCC of systems and system models in space

Possible Teacher Prompts Related to Systems and System Models
1. How are the components in your model interacting?
2. How do the interactions explain why we only see falling stars at certain times of the year?
3. How does knowing that Earth moves through the debris of the falling stars help us understand Earth's movements?
4. What does your model predict?

After observing each group, the teacher gathered the students together so the class could formulate an answer to the lesson question: "Why do we only see falling stars at certain times of the year?" In sharing their models, most groups noted that in order to see falling stars at different times of the year, Earth must move around, or orbit, the Sun. The teacher asked students about how the components of their models interacted. Groups showed different shapes of orbits, resulting in a discussion about how they might modify their system models to better support their ideas about Earth's orbit around the Sun. Some students added a new component, a third falling star shower, to better show how Earth passes different groups of falling stars at different times of the year.

Continued

Classroom Snapshot 3.3 (*continued*)

In the final section of the unit, students watched a video of a meteor falling to Earth, prompting them to ask what caused the meteor to fall. Students then obtained information about gravity's effect on objects and revised their models to explain that gravity pulls the falling stars toward Earth.

Commentary

This classroom example represents the three key strategies of implementing CCCs as resources. First, students used their everyday and classroom experiences with the CCC of patterns as a resource to answer the lesson question, "Why do we only see falling stars at certain times of the year?" (Strategy 1). Building on their experiences seeing different objects in the night sky at different times of the year, students analyzed and interpreted the data table about falling star showers and their observations of the night sky over multiple years in Stellarium.

Second, students used the CCCs of patterns and systems and system models in different science disciplines—from sorting garbage and developing the garbage disposal system in physical science to analyzing constellation data in space science (Strategy 2). This lesson came at the end of the school year after students had used patterns and systems and system models multiple times to make sense of phenomena in different science disciplines, which allowed students to move from more concrete observations (e.g., developing a system model of components they see every day) to more abstract observations (e.g., modifying a system consisting of components and interactions at a scale too big to see.)

Finally, the classroom example highlights students' progression with using the CCCs of patterns and systems and system models over the course of the school year—from using CCCs intuitively to build on their everyday experiences to using CCCs more intentionally as scientists do (Strategy 3). In this example, students intuitively used the CCC of patterns based on their everyday and classroom experiences *and* intentionally said they were going to use the CCC of patterns to make sense of their data. Whereas students' use of patterns in the first unit focused mainly on identifying similarities and differences in observations, their use of patterns in the final unit was much more sophisticated. Here, they considered how different patterns were useful for answering different questions about phenomena. Students also used the CCC of systems and system models in a more sophisticated manner in the final unit. Whereas students focused on naming system components in the first unit, they focused on changing the interactions of the system components in the final unit, which their teacher prompted with questions such as those in Figure 3.5. Additionally, students demonstrated a more sophisticated understanding of a system by including multiple interactions in their models, including Earth's daily rotation around its axis and Earth's orbit around the Sun and through falling star debris.

Students' intentional use of the CCCs suggests their understanding of how CCCs may be useful in science, building on intuitive use from their everyday and classroom experiences. Furthermore, students demonstrated a deep understanding of using CCCs as resources at the end of the school year when they used two CCCs to explain a single phenomenon. In the final classroom example, students used patterns to make sense of the constellation data, which in turn made students wonder what interactions of the system could be causing the observed patterns. This example contrasts with the first two examples in which students used the CCCs separately, and it represents a progression in students' use of CCCs as resources. Here, not only did students draw on such resources from their homes and communities and from previous experiences in the science classroom, but they also understood when and how to use these resources.

For the English learners in the examples, the progression from an intuitive understanding to an intentional use of the CCC of systems and system models also represents a progression in sophistication of language. As their understanding of when and how to use the CCC became more sophisticated, these English learners communicated their understanding in more sophisticated ways. The students moved from naming individual components of the garbage disposal system (e.g., "garbage truck") to explaining the interactions of the components in the space system (e.g., "How does knowing that Earth moves through the debris of the falling stars help us understand Earth's movements?"). Although this learning progression applies to all students, it is particularly important for English learners who are valuable members of the classroom community based on the merit of their ideas, even if using less-than-perfect English.

Summary

To carry out the perspective of CCCs as resources in the classroom, we recommend three key strategies for curriculum design and classroom implementation. First, we propose intentionally designing classroom investigations and activities that provide opportunities for students to use resources from their everyday experiences with CCCs. To do this, CCCs may be introduced in the context of local phenomena (e.g., garbage, falling stars) that students have experience with in their everyday lives (Lee et al. 2019a). In this way, the phenomena act as scaffolds for introducing CCCs at the beginning of the year and for extending students' use of CCCs over the course of instruction. The intentional design around local phenomena allows students to draw on CCCs as resources so local phenomena and CCCs are mutually supportive for making students' ideas visible.

Second, we recommend that teachers and curricula consider "look fors" that help teachers recognize students' intuitive use of CCCs regardless of how that use is communicated. For instance, in the first classroom example, the teacher knew to look for different ways in which students sorted their garbage (e.g., by color, use, or material type). Once teachers ensure students are using a given CCC, they can use targeted probes (Figures 3.2–3.5) to make students' ideas visible and make the CCC in use explicit (Grapin et al. 2019).

Finally, we suggest scaffolding students' use of CCCs over time. Some CCCs are more intuitive to students (e.g., patterns), especially at the elementary level, than others (e.g., energy and matter in terms of flows, cycles, and conservation). To promote all CCCs as resources, designing instruction around students' use of more intuitive CCCs at the beginning of the school year lays the foundation for students to better use all CCCs over time. By explicitly naming the CCCs students use intuitively at the beginning of the year, students are made aware of the resources they bring to the classroom and see themselves doing the work of scientists. In turn, students develop more intentional use of CCCs over time as they make sense of different disciplines and different phenomena. By explicitly building on students' intuitive ideas, CCCs can act to both broaden participation and strengthen science learning for all students.

"All students come to school with experiences from their homes and communities 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."

All students come to school with experiences from their homes and communities 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.

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Chapter 8

Energy and Matter: Flows, Cycles, and Conservation

Charles W. (Andy) Anderson, Jeffrey Nordine, and MaryMargaret Welch

Diamonds are forever. Or so James Bond and your local jeweler may want you to believe. But in fact, diamonds can burn. It's not easy to burn a diamond—you'd need to heat it in air to about 900°C (over 1600°F)—but at that temperature, diamonds will burn, leaving the world with one less diamond. When a diamond burns, where does it go? In the living world, small acorns grow into large oak trees without using up the soil they live in. Where did all that wood come from? The answers to these questions involve quantities that truly are forever: matter and energy.

One of the great achievements of science is the development of the matter and energy conservation laws. These laws state that during physical and chemical changes, certain quantities do not change, no matter what happens. A conserved quantity does not spontaneously appear or disappear, and this fact often provides a powerful starting point for understanding even the most mysterious and complex phenomena. When a diamond burns, the diamond is gone but its matter is not. Similarly, conservation laws require that the energy released during burning was not produced by burning but in fact already existed.

This is not obvious; our intuition tells us that when something burns, the matter goes away and energy is produced. When energy or matter seems to appear or disappear, the conservation laws insist that we ask questions such as, "Where did the matter go?" and "Where did the energy come from?" These questions help us gain deeper insight into how and why phenomena occur.

Matter and energy are unique in that they appear in *A Framework for K–12 Science Education* (the *Framework*; NRC 2012) and the *Next Generation Science Standards* (*NGSS*; NGSS Lead States 2013) both as disciplinary core ideas (DCIs) and as crosscutting concepts (CCCs). The primary difference, as we see it, is in the ways these important concepts are used. The DCIs focus primarily on *mechanisms* involving matter and energy—explaining change—whereas the CCC focuses primarily on *conservation* of matter and energy, tracing what stays the same. That is, even though different science disciplines focus on different mechanisms for changes in matter and energy (e.g., photosynthesis, boiling, water cycling), they all rely on the idea that matter and energy are conserved. The classical conservation laws, separating energy conservation from matter conservation, apply with great precision to phenomena involving physical and chemical changes from the atomic-molecular to the global scale.[1] The conservation laws enable us to "take a step back." They provide us with strategies for making sense of systems and phenomena even when we don't know all the details. In particular, the conservation laws are powerful for two purposes.

Conservation laws as rules. Scientific models, explanations, hypotheses, and engineering designs must conform to the conservation laws. The conservation laws function as rules that constrain the range of possibilities for how systems behave. These rules provide a basis for evaluating the viability of ideas. For example, there may be rich debate about the best diet for people to eat, but we can all agree that humans cannot produce their own energy or matter (we must get them from the food we eat) and that this matter and energy are not simply "used up" when we go about our daily activities—both must go somewhere.

Because the conservation laws are accepted across disciplines, they can serve as a sort of "scientific Rosetta Stone." Even though an astrophysicist may know very little about the biochemical mechanisms involved in photosynthesis, she would know that something is wrong with any explanation of photosynthesis that implies that matter or energy either go missing or appear out of nowhere.

Tracing matter and energy as heuristics. Heuristics are "rules of thumb" that people can use to get started on difficult problems. Tracing matter and energy is often a valuable heuristic. Matter and energy conservation are frequently a good place to start when little else is known. No matter how vexing the phenomenon or system under consideration, matter and energy conservation can suggest questions that lead to deeper insight about how phenomena occur and systems operate.

For example, several brands of wristwatches are advertised as never needing a battery and never needing to be wound. Conservation of energy prompts the question "How

1. In nuclear processes, the matter and energy conservation laws cannot be separated in the way we discuss them in this chapter. Conservation laws are critical to understanding nuclear changes, but applying mass-energy equivalence is beyond the scope of the *NGSS*.

is energy transferred to the watch from the surroundings?" Answering this question involves investigating what parts of the environment interact with the watch in ways that result in enough energy transfer to power the movements of the watch. Similarly, the fact that a nail gains mass while it rusts is a clue that there must be some interaction with the environment that transfers mass to the nail. By tracing matter and energy through systems as they interact and undergo changes, we can gain important insights into how the world works. Fully understanding the function of a watch or the rusting of a nail also requires specific disciplinary knowledge of things such as torque or the electronegativity of atoms, as well as knowledge of science and engineering practices (SEPs), such as Planning and Carrying Out Investigations and Analyzing and Interpreting Data. Although the CCC of energy and matter may help spur and frame an investigation, all three dimensions are necessary to fully investigate and explain phenomena.

Conservation laws are so powerful and pervasive that they are used by all scientists and by scientifically literate citizens; in this way, they cut across all scientific disciplines. Yet, scientists in different disciplines use different terms and representations as they apply the conservation of matter and energy. In this chapter, we identify common uses of the conservation laws in different disciplines and in people's practical actions. Then we discuss how students can build understanding of these laws across disciplines as they move through elementary, middle, and high school, and we illustrate instructional strategies that can help students use these powerful principles to interpret and explain phenomena.

How Do Scientifically Literate People Use the Conservation Laws?

Like other crosscutting concepts, the true utility of the energy and matter conservation laws emerges when they are blended with SEPs, DCIs, and even other CCCs to predict and explain how phenomena happen in the natural and designed world. People who are successful in using conservation laws as rules and heuristics engage in three strategies: (a) defining systems, (b) identifying matter and energy, and (c) connecting systems at different scales.

"Like other crosscutting concepts, the true utility of the energy and matter conservation laws emerges when they are blended with SEPs, DCIs, and even other CCCs to predict and explain how phenomena happen in the natural and designed world."

Defining Systems

The conservation laws are closely connected with the SEP of Developing and Using Models and the CCC of systems and system models. In fact, the conservation laws themselves are commonly stated in terms of systems. The law of conservation of matter states that the mass of a system can only change by the amount of mass transferred to it from some other system. The same is true for energy, as described by the *Framework*:

> *That there is a single quantity called energy is due to the remarkable fact that a system's total energy is conserved. Regardless of the quantities of energy transferred between subsystems and stored in various ways within the system, the total energy of a system changes only by the amount of energy transferred into and out of the system (NRC 2012, pp. 120–121).*

In order to use the conservation laws, it is important to specify the system(s) that are involved in the phenomenon or device (such as an appliance or a machine) under consideration. In the simplest terms, a system is the part of the universe we are interested in, and we can draw an imaginary boundary between what is in our system and what is outside of it (see Chapter 7 for more about systems and system models).

When we define a system such that no matter crosses this imaginary boundary, we call it a *closed system*. For example, Classroom Snapshot 8.1 (p. 177) focuses on a soda can. If we define our system boundaries as the walls of the can, we can say that a sealed can is a closed system because no matter leaves or enters. In an *open system*, mass can cross the system boundary. If you open the soda can and place it on a scale for a few days, the reading on the scale will decrease as the soda goes flat (i.e., dissolved carbon dioxide [CO_2] bubbles out of the soda) and water in the soda evaporates. After a few days, there is less mass in the soda can than there was before. In the context of the conservation of matter, systems are either closed or open. In a closed system, the total mass of the system remains the same; in an open system, the total mass of the system changes by the amount that enters or leaves the system.

In the context of conservation of energy, the concept of an *isolated* system is useful, even though isolated systems do not exist in the real world. An isolated system is one in which there is no energy transferred across the system boundary, but the systems we encounter are never truly isolated. Consider the sealed soda can once more. No matter crosses the system boundary, but we can easily heat or cool the can of soda, which is evidence that energy crosses the system boundary; therefore, the soda can system is closed but not isolated. Some containers are designed to reduce energy transfer, like ice chests or vacuum-insulated containers that can keep our drinks cold (or hot) for hours, but not forever. Energy transfer across a system boundary is impossible to prevent, since it involves stopping interactions like collisions between molecules (Nordine and Fortus 2016, pp. 62–63). As a result, energy conservation is exceptionally difficult to observe through experimentation. Hot drinks tend to cool down, motion tends to stop, and electric devices cease to operate.

The conservation laws really show their power when they are used as rules for constructing models of how open systems and devices behave. Conservation laws help put limits on what is possible and what is not, and they help recognize whether models have fully accounted for all relevant systems and interactions. If we observe that the energy in a system is decreasing over time, we know there must be some mechanism by which our system interacts with its surroundings such that more energy leaves the system than enters it. Related to this, if a device seems to continue operating indefinitely with no apparent energy input, we know our model must specify some energy input that is equal to the amount of energy transferred to the surroundings.

> "Conservation laws help put limits on what is possible and what is not, and they help recognize whether models have fully accounted for all relevant systems and interactions."

Identifying Matter and Energy

The CCC of energy and matter focuses on *matter and energy as conserved quantities.* Because they are conserved, we can use them for accounting purposes. Just as tracing money can play an important role in understanding our economy, tracing matter and energy can play an important role in understanding phenomena. In order to use matter and energy for accounting proposes, we need to make clear distinctions between matter and energy and other entities that are not matter or energy. There is extensive research that documents students' struggles to identify manifestations of matter and energy (Fortus and Nordine 2017; Jin and Anderson 2012; Mayer and Krajcik 2017; Mohan, Chen, and Anderson 2009; Smith et al. 2006). Many of these struggles are rooted in the multiple ways that *matter* and *energy* are used in everyday language and in science. Here are a few in-depth examples of the challenges:

Matter and energy in everyday language. *Matter* and *energy* are common words in our everyday language. People use these words all the time but in ways that don't correspond with their scientific meanings.

Matter as solid and liquid "stuff." As students learn to apply the matter conservation law and trace matter through systems, a key challenge is often *expanding their notions of matter.* In particular, young students have trouble accepting that gases can be as massive and substantial as solids and liquids. This notion is built into our everyday language. For example, *Thesaurus.com* identifies 20 synonyms for *matter* when used to mean "substance." Most of these synonyms (e.g., *material*, *thing*, *body*, *entity*, *stuff*, *substantiality*, *corporeity*) are associated with solids and liquids, but none are associated with gases.

Matter conservation is a useful rule only if we identify *all* the matter in a system and *all* the matter that crosses system boundaries—that's all the solids, liquids, and gases, including the ones that change state or become new substances through chemical changes. Tracing matter works as a strategy only if we recognize that *materials* can be created or destroyed, but not *matter.* A fire destroys wood (a material), but the matter that it is made of still exists, mostly as gases in the atmosphere.

Energy as causes and resources. In contrast to matter, a key challenge in applying conservation laws and tracing energy through systems is *restricting our notions of energy.* For example, *Thesaurus.com* lists 79 synonyms for *energy* in two broad categories: one associated with technology and the physical sciences (used in the sense of "generated power," with 25 synonyms), the other associated with living systems (used in the sense of "spirit or vigor," with 54 synonyms). Most of these synonyms suggest that energy *causes* events to happen or that energy is a *resource* that enables organisms and devices to do their work. For example, the stimulants in coffee or energy drinks give us "energy" that is consistent with many of *Thesaurus.com*'s synonyms (e.g., *spirit, stamina, vitality, animation*) but in scientific terms is not energy at all.

Many of *Thesaurus.com*'s synonyms that do have scientific meanings (e.g., *conductivity, current, force, friction, gravity, horsepower, kilowatts, pressure, voltage, wattage*) are causes or resources but NOT synonyms for energy in scientific terms. So, in our everyday language, all of us are accustomed to using *energy* in an expansive way that makes it difficult to use the energy conservation law effectively.

Matter and energy in science. Matter and energy can be hard to trace because they *appear* so different in different systems and phenomena. This was a problem, too, for 18th- and 19th-century scientists who developed different labels for the manifestations of matter and energy that they encountered in their disciplines. We live today with the legacy of this historical development; scientists still label manifestations of matter and energy differently in different disciplines. Thus, we all face the challenge of applying the conservation laws in systems where the concepts of matter and energy have a variety of scientific labels and the words *matter* and *energy* have additional colloquial meanings. Meeting this challenge requires connecting models of matter and energy in systems at different scales.

Connecting Systems and System Models at Different Scales

Constructing models that trace matter and energy can be very useful for making sense of systems. These models are typically constructed at different scales (i.e., macroscopic, atomic-molecular, and ecosystem or global scales), and different energy and matter representations are useful at each scale.

Macroscopic Scale

This scale is the "everyday" scale. Conservation of matter and energy is challenging at this scale because both appear in many different manifestations, and because both scientific and everyday language include many different labels for those manifestations (see the previous section Identifying Matter and Energy). Applying the conservation law of matter requires identifying substances and changes in substances and mass; applying the energy conservation law requires identifying the variety of different manifestations of energy.

Furthermore, the rules governing those manifestations can seem arbitrary: Why is air a form of matter but not sound? Why can people get energy from food but not from water or sleep? In order to see how those apparently arbitrary rules are based on underlying principles, students need to connect their macroscopic observations of phenomena with atomic-molecular models.

Atomic-Molecular Scale

Atomic-molecular models enable students to see the hidden continuity in manifestations of matter and energy that seem to appear or disappear when they observe phenomena at the macroscopic scale.

Matter: Identifying Continuity of Atoms and Molecules Through Changes

The solids, liquids, and gases in the world around us are mixtures of substances, or materials consisting of one kind of molecule. The DCI of Matter and Its Interactions focuses on how materials and substances change (Krajcik and Mayer 2017). The CCC of energy and matter, on the other hand, focuses on what *doesn't* change. Atomic-molecular models make it clear what doesn't change:

- Molecules stay the same during physical changes in matter. When water evaporates, for example, all the water molecules are still there, now moving freely as a gas.
- Atoms stay the same during chemical changes in matter; the atoms are rearranged into new molecules.

Chemical equations provide a concise way of keeping track of all the atoms involved in a chemical change. For example, the chemical equation for methane burning ($CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$) shows how one carbon atom, four hydrogen atoms, and four oxygen atoms are rearranged from one set of molecules (methane and oxygen) to another set of molecules (carbon dioxide and water). This rearrangement happens quintillions of times whenever we light a gas stove (HS-PS1-7).

Many students follow the procedure for balancing chemical equations without realizing that they are using conservation of matter as a rule. Since atoms are not created or destroyed in chemical changes, we know that the molecules of the products in a chemical reaction MUST have the same atoms as the molecules of the reactants. Chemical equation balancing is a way to check to make sure the numbers are correct.

Measuring Matter: Mass as Fundamental

In everyday life, we use a variety of measures for the "amount" of a material we have—mass, weight, volume, and apparent size are a few such measures. In order to use the matter conservation law, we must recognize that one of those measures—mass—is fundamental. Other measures, such as volume, can change without the amount of matter changing (e.g., through thermal expansion or a change of state). However, mass is different: *If the mass of a system changes, then matter MUST have moved into or out of that system.* Thus, we can always use mass changes to detect movements of matter and to know exactly how much matter has moved.

Atomic-molecular models make it clear why mass is the fundamental measure of matter: *The mass of a system is the total mass of all the atoms in the system.*Therefore, changes in a system that rearrange the atoms—like rolling a ball of clay into a sausage shape or the thermal expansion of a balloon—don't change the mass, but if atoms move into or out of the system then the mass must change (MS-PS1-5).

Energy in Fields and Particle Motions

The *Framework* and *NGSS* provide indications of how energy is manifested at the macroscopic and atomic-molecular scales:

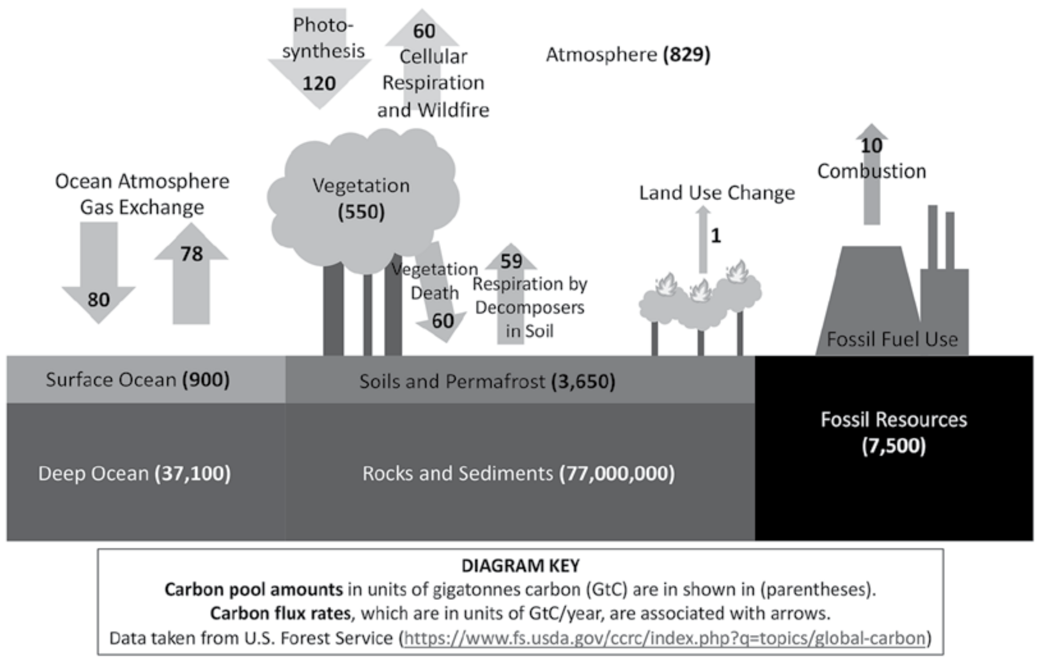
- At the macroscopic scale, energy manifests itself in multiple ways, such as in motion, sound, light, and thermal energy (NRC 2012, p. 121).
- These relationships are better understood at the microscopic scale, at which all of the different manifestations of energy can be modeled as either motions of particles or energy stored in fields (which mediate interactions between particles). This last concept includes radiation, a phenomenon in which energy stored in fields moves across space (HS-PS3-2).

At the atomic-molecular scale, the confusing welter of macroscopic forms of energy is radically simplified. Energy is manifest as the motion of atoms and molecules and in the fields that mediate their interactions (Nordine and Fortus 2016); so, when atoms rearrange in a chemical reaction, changing fields can change the speed of the atoms. As these faster or slower atoms interact with their surroundings, energy is transferred either to or from the environment.

Ecosystem and Global Scales

Scientists commonly use *pool-and-flux models* to trace matter and energy through large-scale systems such as ecosystems, weather systems, human agricultural and industrial systems, and global systems. Figure 8.1 is an example of this kind of model; it follows the conventions of using boxes or images to represent matter pools and using arrows to represent fluxes that move matter from one pool to another.

Figure 8.1. Quantitative global carbon cycling diagram



Source: U.S. Forest Service 2019.

Earth's global systems, represented in Figure 8.1, are virtually closed systems—the amount of matter entering or leaving global systems is negligible. In addition to carbon cycling, represented above, the *NGSS* mentions cycling of materials in Earth's interior, water cycling, and global atmospheric circulation. In all of these closed systems, the conservation laws lead to a basic pattern: *matter cycles; energy flows.* Energy from two sources—sunlight and radioactive decay in Earth's interior—drives movements of matter and changes in matter through convection, changes of state, and chemical changes. This energy ultimately leaves Earth systems as infrared radiation going into space. Within Earth systems, the same atoms are recycled over and over as they move and combine into different molecules.

Regional and local Earth systems, such as ecosystems, local weather systems, watersheds, and human agricultural and industrial systems, are open systems. Both matter and energy enter and leave these systems.

Quantitative Reasoning About Large-Scale Systems

The conservation laws provide important rules and heuristics for understanding all of these large-scale systems because they lead to an ironclad relationship between fluxes and pool sizes: *Changes in pool sizes are determined by the balance of fluxes into and out of the pools.* Scientifically literate people can learn to use this relationship to understand quantitative predictions of global environmental issues such as climate change (HS-ESS2-6).

How Students Can Learn to Use the Conservation Laws Over Time

The conservation laws can be stated simply, but as the previous discussion shows, that doesn't mean they can be applied simply. People who successfully use the conservation laws as rules and trace matter and energy as heuristics have mastered these three associated strategies for applying the conservation laws:

1. *Defining systems* and constructing models of the systems that illustrate the conservation of matter and/or energy
2. *Identifying matter and energy*, including the many forms of evidence and descriptive terms that scientists use to describe matter and energy and to trace matter and energy through systems
3. *Connecting scales,* or tracing manifestations of matter and energy through system models at different scales, from atomic-molecular to global

Building expertise in applying these strategies is a long and intellectually arduous process, taking all of children's K–12 years and beyond. Yet, K–12 students can make substantial progress down the road toward expertise. In this section, we describe some of the key milestones in this process during students' elementary, middle, and high school years.

"Building expertise in applying these strategies is a long and intellectually arduous process, taking all of children's K–12 years and beyond. Yet, K–12 students can make substantial progress down the road toward expertise."

Elementary School: Laying the Foundations for Conservation Rules and Heuristics

The *NGSS* do not advocate explicitly teaching the conservation laws to K–5 students. Although elementary students could learn to apply conservation laws to some phenomena, it is unlikely that this is the best way for them to spend their time. Elementary students can learn to recount, for example, that "energy is never created nor destroyed," but they generally do not have all the experiences they will need in order to use the conservation laws systematically. Elementary students can, however, make substantial progress as they become more proficient in these three strategies: defining systems, identifying matter and energy changes, and connecting scales.

Children's learning during the elementary school years is particularly focused on the second strategy—identifying matter and energy. As we will discuss momentarily, this involves a growing awareness of the manifestations of matter and energy in phenomena (i.e., recognizing more aspects of the systems involved), but formal definitions of systems are more appropriate for the middle and high school years. It's important to note that the vast majority of focus during the elementary years is on building ideas about matter, not energy. Energy ideas really only appear in earnest in fourth grade, and even then in limited scope. Similarly, the *NGSS* recommends that students' introduction to atomic-molecular models (which are more useful for applying conservation laws) wait until middle school.

Matter: Tracing Materials and Measuring Amount

Although it is generally not productive to teach elementary school children a formal definition of matter or formal rules for applying the matter conservation law, they can learn to trace matter through increasingly complex phenomena. In particular, this growing understanding involves developing their capacities for tracing materials and measuring amounts of matter.

Tracing Materials: In some circumstances, when there is observable continuity of matter for a phenomenon, young children learn to trace matter. For example, Piaget and his colleagues (Driver 1985; Piaget 1951) showed how young children come to understand that pouring water from a tall, narrow glass to a short, wide glass does not change the amount. These children are successfully recognizing the continuity of water as a material in the system of water and the two glasses.

However, tracing matter gets more difficult in more complex systems.

- It is nowhere near as clear to children that when water freezes there is still the same "amount" of ice as there was water before. Children in elementary school can study this system and see how water can change to ice and back again, as well as how the mass[2] and volume of water remain the same after these changes. These experiences can help them develop the argument from evidence that ice is another form of water and that freezing and melting do not change the amount of water.
- Tracing materials for changes of state involving gases—evaporation and condensation—is more challenging still, especially since it contradicts the notion in everyday language that matter is solid or liquid "stuff." When a puddle evaporates, why should children believe that the water is still there—in the air, invisible—and that it weighs just as much as the water did before it evaporated? To trace materials in this system, children need to see how water vapor, like ice, is another form of water and how they can trace water as it goes to and from the air. (The *NGSS* advocates waiting until middle school to teach children atomic-molecular explanations for these processes; see performance expectation 5-PS1-1.)

2. Elementary students should not be expected to distinguish between mass and weight, so students could equivalently monitor the "weight" of the water.

- In chemical changes, some materials cease to exist and new materials are created. Tracing matter through these changes is more productive when students learn to use atomic-molecular models in middle school.

Measuring Amounts of Matter: The question of "how much" of a material there is can be complicated, particularly if children are comparing different materials or different states of the same material. A balloon gets larger when it is moved from a cold to a warm place. Does that mean there is more air inside the balloon in the warm place? A liter of water forms more than a liter of ice when it freezes. Does that mean there is more ice than there was water? Children in elementary school can make substantial progress toward scientific answers to these questions.

Piaget's conservation tasks show a predictable progression in how children develop more sophisticated ideas about "amount." For example, Elkind (1961), replicating Piaget's earlier work, asked children of different ages about what happened when a ball of clay was rolled out into a sausage shape. For eight-year-old children:

- 72% said the "amount" of clay stayed the same after it was rolled out. The other children generally relied on perceptions (e.g., that the clay was longer or thinner) to make judgments about how the ball was different.
- 44% said the "weight" of clay stayed the same.
- 4% said the volume of clay stayed the same (agreeing that "They both take up the same amount of space," p. 221).

The important takeaway from results like these is not about specific ages at which students accomplish specific tasks. It is that judging or measuring "how much matter" is in a system is both conceptually and procedurally complicated, so children in elementary school need multiple opportunities to compare and measure amounts of materials.

The Piaget tasks did not involve measurement, but measurement and quantification play an essential role in arguments from evidence that involve conservation of matter. These can involve both qualitative comparisons like the Piaget tasks and quantitative comparisons in which children measure volume and mass/weight (not differentiated at the K–5 level; see NRC 2012, p. 96, p. 108). In addition to learning how to make these measurements accurately, children in grades K–5 can work toward the understanding that *mass is fundamental,* as discussed in the section on macroscopic conservation:

- If the volume of a system changes, then it is possible that materials in the system expanded or contracted.
- If the mass of a system changes, then matter *must* have moved into or out of the system.

Precise and inexpensive digital scales make it possible for teachers and children to measure and reason about even small changes in mass. Classroom Snapshot 8.1 illustrates how Ms. Ramirez uses these measurements to engage students in tracing matter through changes of state (addressed in *NGSS* PE 5-PS1-2).

CLASSROOM SNAPSHOT 8.1
Tracing Changes of State With a Soda Can

Ms. Ramirez's fifth-grade students have been observing different forms of matter and thinking about matter within a system. Today, Ms. Ramirez is engaging her students in sensemaking activities about what happens to matter when water condenses on a cold soda can.

Ms. Ramirez says, "Do you think I can change the weight of this cold soda can without opening the top to pour anything in or pour anything out? I mean, if I just let it sit here in the open, do you think I can get it to change weight?"

Her students turn and talk to their table partners to discuss how to change the mass of the can. Jack suggests they might add clay from the art bin to the can. Ms. Ramirez says, "Yes, you are correct that adding a solid like clay would change the can. But I mean, what if we didn't physically add anything? Do you think the can could change weight if we just let it sit here? Let's remember our discussion about a system. Do you think the clay is a part of the system? What should we consider our system?"

The students engage in a discussion and agree that the system they want to focus on is the can, the contents of the can, and the air surrounding the can. Ms. Ramirez says, "Now that we have defined our system, how do you think we could change the weight of the can in this system?" Ramona says, "Let's do an experiment to find out." Ms. Ramirez asks the student to help her design the experiment.

Students busily write their ideas on their whiteboards, and then the class does a gallery walk to share those ideas. Finally, they come to consensus about what to investigate. Tomorrow, they will take the cold soda can and weigh it immediately after it comes out of the refrigerator during their morning math lesson. Then they will let it sit out until they have science class in the afternoon and weigh it again.

The next day, Ms. Ramirez takes the can from the refrigerator, wipes off the outside of it, and then weighs the can. She records the mass of the full, closed can on the board. Then the children get to work on their lesson. Throughout the morning, though, they write down their observations of the can, including remarks about the moisture drops gathering on the outside of the can.

During science class, Ms. Ramirez calls for the students' attention once again and asks them to write down their observations independently. She asks students what

Continued

Classroom Snapshot 8.1 *(continued)*

they notice. Most students share that they notice water on the outside of the can. Ms. Ramirez says, "Where do you think the moisture on the outside of the can came from?" This starts a conversation among the students:

Samantha: "I think that it came from inside the can. Some of the water inside leaks out when it's cold."

Ahmad: "I think it came from the air. Water in the air got on the outside of the can."

Jenna: "But there isn't any water in the air in this room; if there was, it would feel like it is raining."

Manuel: "I think it's because the can was cold. Water forms on cold things when you leave them out. I remember this summer when it was hot outside, my mom had a glass of ice water and she left it on the table. The same thing happened. I don't know why, but I saw this happen before."

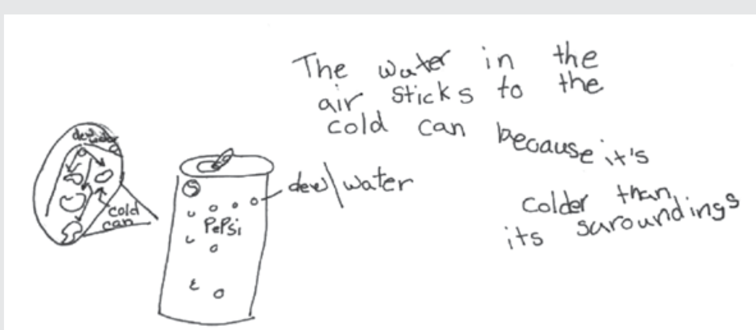
Ahmad: "I saw water on the grass in the morning even though it wasn't raining. Somehow water can get on things even when you don't see water in the air."

Isaac: "There is always water in the air, even when it isn't raining. I think that water in the air sticks to the can because the can is cold."

Ms. Ramirez: "We have several ideas about where the moisture came from. How could we collect evidence about these ideas? Talk with your partners and tell me your thoughts."

Student teams talk and share their ideas with the class. Some teams suggest weighing the can again. Ms. Ramirez weighs the can again and writes this mass on the board. Then she says, "Where did the extra weight come from? Using the drawing, explain what you think happened."

Isaac draws the following illustration and shows it to the class, which starts another conversation:



Continued

Classroom Snapshot 8.1 *(continued)*

Samantha: "I think that maybe Isaac is right; it came from somewhere outside the can. What happens if you wipe off the moisture and weigh the can again?"

Ms. Ramirez uses a towel to wipe the can dry and weighs it again. "It still weighs the same as it did when it came out of the refrigerator. What do you think that means?"

Samantha: "I think that means that there is no water seeping out of the can."

Ms. Ramirez: "Let's try one more consideration for our soda can. What if I open the can but do not pour out any of the soda? Just let it sit here. What do you think will happen to the weight? Draw your initial ideas."

Students write down their ideas and share at their tables. Ms. Ramirez pops the top of the can and lets it sit for 15 minutes. Then she says, "No liquid has been poured out of the can. We did not remove the pop top. Let's weigh the can and write down the mass. Will there be a change in mass? Why or why not?" Ms. Ramirez weighs the open can and writes this weight on the board. "Draw what you think is happening to the weight," she says. The students begin a discussion, to be continued later, of how the can could lose weight even if no liquid was poured out.

Recognizing Manifestations of Energy as a Basis for Energy Conservation

Children in elementary school should engage with many different phenomena, and all of those phenomena will involve energy, since all phenomena involve energy changes. As they encounter the phenomena in upper elementary, they have the opportunity to discuss energy and its various manifestations (the DCI). For example, students at the elementary level can begin to explore simple phenomena in which energy is transferred—such as colliding balls or putting a room-temperature rock into warm water—and to ask questions such as "What components are involved?" and "Where does energy come from?" and "Where does energy go?" (see Crissman et al. 2015). In such investigations, students begin to attach the idea of energy to its different manifestations and recognize that energy is transferred between objects as they interact. This is enough. In middle and high school, students will learn to use energy ideas more explicitly to make sense of an increasing variety of systems.

Middle School: Using Conservation Rules and Heuristics to Analyze Phenomena

Middle school students begin to coordinate all three strategies—defining systems, identifying energy and matter changes, and connecting scales—as they explain phenomena using conservation laws as rules and heuristics. While they begin to use matter conservation in a more quantitative way (e.g., measuring the mass of reactants and products in a chemical reaction), they use energy conservation qualitatively—meaning they recognize that energy is neither created nor destroyed, but they do not calculate amounts of energy.

Defining Systems: Defining System Boundaries and Distinguishing Changes in Matter From Changes in Energy

Middle school students study systems in which both energy and matter change, including living systems, Earth systems, and technological systems. Three-dimensional engagement with these systems requires students (a) to distinguish between changes in matter and changes in energy and (b) to define systems and system boundaries carefully.

Distinguishing Between Changes in Matter and Changes in Energy

Middle school students commonly believe that engines "consume" fuel or that humans "burn off" fat when they exercise or that those processes convert matter into energy. The idea that every atom of the fuel or fat is still present as invisible gases is much less intuitive. The example of growing plants shows a similar pattern:

- When asked about sources of matter, most middle and high school students correctly identify soil nutrients and water as sources of matter for growing plants, but they leave out a gas (carbon dioxide) that is a primary source of matter. Students often describe gas exchange separately from plant growth, saying that plants "breathe in" carbon dioxide and "breathe out" oxygen, exchanging one colorless, odorless gas for another.
- When they are asked about energy at the beginning of life science courses, most middle and high school students correctly identify sunlight as a source of energy for growing plants. However, before taking biology courses, 95% of students *incorrectly* identify soil nutrients as a source of energy, and 94% of students *also* identify water as a source of energy. (For students who have completed traditional high school biology courses, 84% identify soil nutrients as a source of energy, and 81% identify water as a source of energy.)[3]

These responses make perfect sense for students with restricted notions of matter and expansive notions of energy like those in *Thesaurus.com*. Students commonly think that soil nutrients and water are solids and liquids that provide materials for plant growth, whereas carbon dioxide is an ephemeral gas. Notions of energy as a cause or resource also make it natural to identify anything that contributes to the "spirit or vigor" of growing plants as an energy source, but these expansive notions make it impossible to trace energy through living systems with scientific accuracy.

So, instruction at the middle school level needs to help students expand their notions of matter and refine their notions of energy. Students who believe that fuels or fat are

3. These data come from assessments administered by the *Carbon TIME* project to 4,773 middle and high school students.

converted to energy can learn that substantial amounts of mass can end up in gases. They can begin to ask questions such as, "Where does the carbon in the CO_2 that plants 'breathe in' go?" and "Where does the carbon in the CO_2 that people breathe out come from?" Students can begin to recognize that many of the things that help people feel "energetic" (e.g., caffeine) or that help plants grow vigorously (e.g., soil nutrients) are not actually sources of energy, meaning that energy is more difficult to obtain than students might assume.

Defining Systems and System Boundaries

Helping middle school students trace matter and energy through systems also involves helping them analyze the boundaries of systems and the movements of matter and energy across system boundaries. This involves recognizing "invisible" forms of matter and energy that exist in systems and cross-system boundaries. In the examples above, many students assume that the gases in the air are too ephemeral to have much of an effect on the solids in plant and animal bodies. Instruction can help students understand that even materials that are not dense, like air, can still be massive; in fact, *a lot* of matter is exchanged between the atmosphere and the bodies of plants and animals.

Similarly, students see phenomena every day in which energy seems to be "used up" and disappear: Moving objects come to a stop; hot objects cool down; light is absorbed; engines run out of gas; animals die without food. What's happening to that energy? For students who think of energy as a cause or resource (see the Identifying Matter and Energy section on p. 185), it makes sense to say the energy is gone. It can no longer cause events to happen or serve as a resource for organisms. These students need to recognize "invisible" forms of energy that remain in the system (e.g., thermal energy—the kinetic energy of atoms and molecules) or that leave the system (e.g., infrared radiation from objects that are not hot). As we will discuss, atomic-molecular models can provide powerful tools for understanding these invisible forms of energy.

An important idea undergirding both matter and energy conservation is that both entities must always be *somewhere*. That is, they cannot be transferred *from* one system without being transferred *to* another, and vice versa. When matter is exchanged between two systems, the mass of one system increases and the other decreases by the same amount. The same is true for energy, though the evidence of increase or decrease in the energy of a system can look different, as energy can be manifest in different ways. Likewise, the systems involved in energy transfer can be difficult to identify, and students need support in learning to identify these systems and in recognizing how they change in the process. Classroom Snapshot 8.2 (p. 182) illustrates how middle school students can use a tool for identifying the systems involved in energy transfers even when they are not obvious.

CLASSROOM SNAPSHOT 8.2
Developing System Models to Trace Energy

At the beginning of the period in eighth-grade science, Mrs. Gladwell holds two repelling magnetic carts, one red and one blue, close together on a track and releases them from rest. Both carts start moving away from each other.

From the back of the room, Tom exclaims, "Neat!" with his characteristic dry humor, hardly impressed by a phenomenon he's long been familiar with.

Mrs. Gladwell, who has asked students to think about the phenomenon using an energy lens, asks, "What's our puzzle, class?" Silence. Recognizing a need for some more prompts, she continues. "Let's think about the energy transfers here. Think about the red cart. Is there energy transferred *to* the cart or *from* it?"

"To the cart," answers Sarah.

"How do you know?" Mrs. Gladwell further prompts Sarah.

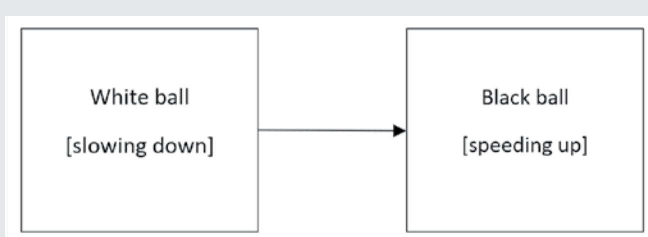
"Because it speeds up," Sarah says.

"And what about the blue cart? Is energy transferred *to* it or *from* it?" Mrs. Gladwell says.

Kim chimes in, "To it."

Mrs. Gladwell repeats her earlier question, "OK, what's our puzzle?"

For the past several weeks, Mrs. Gladwell's class has been studying energy by learning to construct models that represent energy transfers between systems as they interact during phenomena. They have learned that if an object speeds up, this is evidence of energy transfer to it; meanwhile, slowing down is evidence of energy transfer from the object. In a recent lesson, students constructed models of the energy transfers between colliding coins and billiard balls. By observing these interactions, students recognized that anytime one ball or coin sped up, the other one slowed down. To represent energy transfer in the collisions, they constructed models that they call energy transfer models, which look something like this:

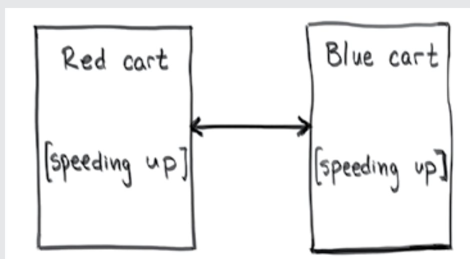


Continued

Classroom Snapshot 8.2 (*continued*)

Over time, and with practice across a range of phenomena, students have come to agree on some common features of their energy transfer models. A box represents a system or an object that is involved in the phenomenon being investigated, the arrow between the boxes represents energy transfer between systems/objects, and the brackets inside of the boxes describe the changes to the system/object that are associated with the energy transfer.

Mrs. Gladwell asks students to work together for a few minutes to think about how they might draw an energy transfer model for the repelling magnetic carts. She then asks students to come to the board and draw their ideas, even if they feel they are stuck. Two groups volunteer to draw their models. Amy and Beth's model looks like this:



"Will you tell us about your model?" asks Mrs. Gladwell.

"Well, we thought about what was involved, and we decided that the track and your hand weren't really involved since neither really makes the cart go faster. This leaves just the two carts. We know each has to have an arrow pointing toward it, since both speed up, so we made a double-headed arrow to represent this."

"But wait a second," Leo chimes in. "You can't have a double-headed arrow, can you?"

"Hmm … why not?" asks Mrs. Gladwell.

"Because we never do," Leo responds immediately.

"But why not?" Mrs. Gladwell pushes. "Who has an idea?"

After a few seconds of silence, Leo speaks up once more, "Well, the arrow represents energy transfer, right?"

"Right … " says Mrs. Gladwell, hoping for more.

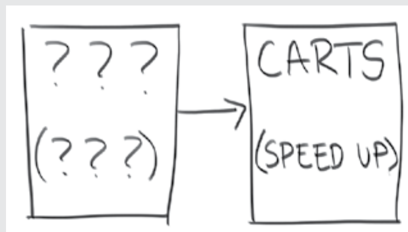
Leo continues, "And transfer means that it comes from one system and goes to another. But with a double-headed arrow, it means energy goes into both carts at once without coming from any other system."

Continued

Classroom Snapshot 8.2 (*continued*)

"Yeah," says Beth. "We thought about that and we weren't sure what to do. We knew energy had to be going to the carts but weren't sure where it was coming from."

"That was exactly our problem!" interjects David, who has drawn the second model on the board, which looks like this:



He continues, "We knew that energy was transferred to the carts and that this energy had to come from someplace, but we have no idea where. Hence all the question marks."

"Before we continue, tell us about your box labeled 'CARTS,'" Mrs. Gladwell says. "Amy and Beth had a box for each cart, whereas you had both carts in one box."

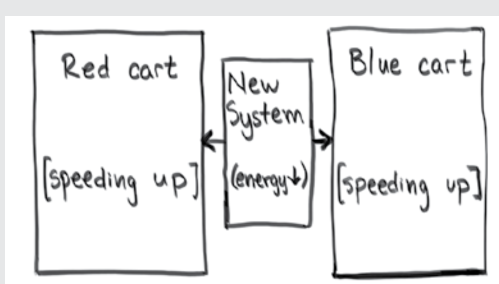
"Well, we just thought that would be the easiest way to draw it. We knew both carts did the same thing; and we knew that since they both speed up, they both have energy coming from someplace, and we figured that it must be the same place. So, we thought we could just draw them in the same system. Why, is that wrong?"

"Not wrong at all," responds Mrs. Gladwell. "Both models show energy transfer to both carts, and both identify the same process—speeding up—for the carts. Both models give the same information, even though you represented the cart systems differently. There is no one best way to make your models!"

"But our model is missing a box," says Beth.

"Where would you put it? Will you come show us?"

Beth goes to the board and erases the middle part of the arrow, barely squeezing a third box in between the existing ones.



Continued

Classroom Snapshot 8.2 (*continued*)

"Why did you add that?"

"Well, this way, we show that even though we don't know what it is, we know there must be some other system transferring energy to both carts at the same time."

"OK, so now we know our puzzle. Using our models and the idea that energy can only be transferred *from* one system *to* another, we have realized that there is something about this phenomenon we haven't included—something that is critical for fully explaining what is going on here. Today, we will begin exploring what that system is, how it transfers energy to the carts, and how it changes in the process. But before we get started, get into your lab groups and discuss these questions: (1) What do we already know about this new system? (2) What questions do you have about this new system?" The students go to their lab tables and get to work.

In Classroom Snapshot 8.2, students grapple with the idea that energy is transferred from one system to another without any loss of energy through a series of activities, which includes coming to consensus on how to represent energy transfer. Note the importance of marrying energy conservation with the CCC of systems and system models to give students boundaries to frame their ideas.

Identifying Matter and Energy: Working Toward Accurate and Principled Identification

Students' difficulties with tracing matter and energy separately through systems are closely connected with challenges in identifying changes in matter and energy. Middle school students should begin to identify and describe manifestations of matter and energy with more specificity. This means, in particular, recognizing that all solids, liquids, and gases are forms of matter and have mass. Energy transfers do not affect the mass of objects or everyday systems.

Foods and fuels are especially important examples of this distinction. Foods and fuels are important because almost all living systems, as well as human technologies that use fossil fuels or biofuels, rely on a single energy source—the oxidation of organic materials (i.e., materials with reduced carbon, indicated by C-C and C-H bonds). These organic materials all originated in photosynthesis. Chapter 12 covers this process in detail. Here, we will focus on the complementary oxidation processes.

Almost all middle school students can identify foods and fuels fairly accurately (with the exception of soil nutrients—see p. 180). They also recognize that living systems get energy from food and engines get energy from fuel. So far, so good. However, almost all middle school students rely on "force-dynamic" explanations of what organisms do with food and what engines do with fuel: They explain that the food and fuel are "used up" or converted into energy (Jin and Anderson 2012).

Instruction in middle school can help students see the value of the conservation laws as rules and heuristics. Matter conservation tells us that the matter in foods and fuels *must* still be matter—solids, liquids, or gases—after the foods and fuels are used and can guide students to learn more about gaseous products. Energy conservation tells us that the energy manifest as motion or heat existed before the food/fuel was oxidized and that it continues to exist afterward. It was not "created" in the process of using fuel and does not "run out" or "fade away" after the fuel is used. This energy can—and usually does—leave the system via heat transferred to the surrounding environment, but not as material waste such as carbon dioxide (see *NGSS* MS-LS1-7). High school students will learn to trace matter and energy through living systems in more precise ways.

Connecting Scales: Tracing Matter and Energy Using Atomic-Molecular and Large-Scale Models

Middle school students can use the conservation laws as rules and heuristics by tracing manifestations of matter and energy at the macroscopic scale. Atomic-molecular models can help them understand how and why the conservation rules make sense. Large-scale models can help them trace matter and energy through ecosystems and global systems.

Using Atomic-Molecular Models to Trace Matter and Energy Through Chemical and Physical Changes

When changes of matter involve invisible gases, it is difficult for students to observe that the matter is "still there." Atomic-molecular models provide some very simple rules to explain how the matter continues to exist:

- During physical changes in matter, molecules stay intact.
- During chemical changes in matter, atoms stay intact.

Instruction at the middle school level can help students master these rules and apply them consistently. For example, students learn to explain how the changes in mass when water condenses and evaporates on a soda can (see Classroom Snapshot 8.1 on p. 177) are caused by changes in the motion and arrangement of water molecules, and how those changes are associated with changes in the kinetic energy of the water molecules (MS-PS1-4). For the foods and fuels example, students learn to explain how the atoms in foods and fuels are rearranged into new molecules (but all the atoms are still there) and how these changes release energy to be used by engines and organisms (MS-PS1-4, MS-LS1-7).[4]

4. Sometimes, curriculum materials suggest that energy is released when chemical bonds in high-energy reactants are broken (e.g., glucose, gasoline, ATP). This is not true. Breaking the bonds of reactants ALWAYS requires energy, and forming the bonds of products ALWAYS releases energy. Therefore, the oxidation of foods and fuels releases energy when the bonds of product molecules are formed, not when the bonds of reactant molecules are broken (HS-PS1-4, HS-LS1-7).

Using Large-Scale Models to Trace Matter and Energy Through Ecosystems and Earth Systems

Instruction can help middle school students see how they can understand patterns in large-scale systems by tracing matter and energy. Middle school students can understand how water condenses and evaporates not only on soda cans but also on regional and global scales, with changes of state and cycling of water driven by energy from the Sun (MS-ESS2-4). Elementary students see the plants and animals in ecosystems as "actors" that depend on other organisms for the materials they need to survive; middle school students can study plants and animals as systems that transform matter and energy as the matter and energy move through food webs (MS-LS2-3; Mohan, Chen, and Anderson 2009).

High School: Principled Use of Conservation Rules and Strategies

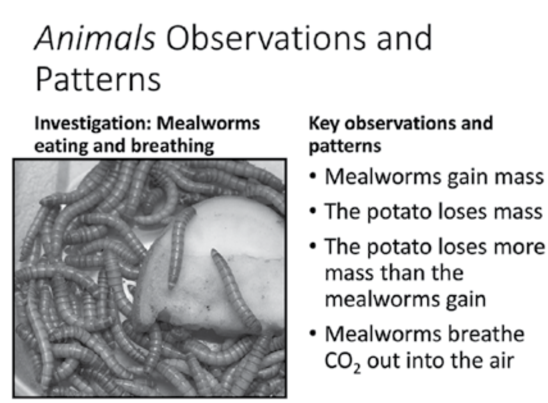
High school students continue their progression to principled use of matter and energy conservation as rules and heuristics.[5] The outcomes they achieve are described in the section How Do Scientifically Literate People Use Conservation Laws? (p. 167). This section builds on the previous sections by describing how instruction can help students achieve those outcomes.

Defining Systems: Learning to Be Strategic

Students can learn to be strategic in defining closed and open systems at all scales, defining system boundaries that make it easier to trace how matter and energy move into and out of systems and change inside the systems. Classroom Snapshot 8.2 (p. 182) illustrates this learning process, which continues through high school.

Strategic choices of system boundaries can support both conceptual clarity and quantitative reasoning. For example, in the mealworm investigation referenced in Classroom Snapshot 8.3 (p. 189), the mealworms gain mass as they grow while their food source (a slice of potato) loses mass (see Figure 8.2). No surprises there—just what students expect, and many high school students are happy to stop there, satisfied that they understand what is happening (see Dauer et al. 2014).

Figure 8.2. Observations during a mealworm investigation



However, using the conservation laws as a heuristic can lead to other questions: What about

5. The previous section on learning in middle school is, unfortunately, relevant to most high school students. Students of any age who experience a traditional "learning about" curriculum are unlikely to master middle school performance expectations (e.g., Jin and Anderson 2012).

a larger system, including the potato, the mealworms, and their waste? That system loses mass, so the conservation laws tell us there *must* be something going on here besides the mealworms eating and growing. Since no solids or liquids left the system, there *must* be gases leaving the system. By tracing the movement of matter across carefully defined system boundaries, high school students can construct arguments from evidence that support a deeper understanding of cellular respiration. (See Classroom Snapshot 8.3 for a continuation of this story.)

Identifying Matter and Energy: Learning to Be Principled

Students become more rigorous in recognizing manifestations of matter and energy at all scales and in distinguishing between scientific and colloquial language. In particular, they recognize how the many different forms of energy can be recognized as manifestations of fields and motions of particles and materials (see HS-PS3-2).

For example, instruction can help students connect changes in the speed or temperature of objects to changes in kinetic energy associated with the speed of particles. Similarly, students can recognize that phenomena such as the stretching of a spring, falling objects, or attracting magnets all involve energy manifest in fields between interacting particles, which is often referred to with the umbrella term *potential energy*. Students also recognize that waves across the electromagnetic spectrum all transfer energy through interactions between electrical and magnetic fields, which is often referred to as radiation (HS-PS4-4).

Connecting Scales: Learning to Use Quantitative Models

Students can learn to use quantitative models at all scales to make predictions, interpret and analyze data, and construct arguments from evidence. They recognize and use connections among conserving atoms in chemical changes in atomic-molecular systems, conserving mass in macroscopic systems, and analyzing how fluxes change pool sizes in large-scale systems (HS-PS1-7, HS-ESS2-6).

Matter conservation at the macroscopic and atomic-molecular scales is connected by a precise quantitative rule: *The mass of any system is the mass of all the atoms in that system.* Through instruction, students can appreciate the power of this rule and use it successfully. At the atomic-molecular scale, students can master algorithms for chemical equation balancing, but it is critical that they understand why those algorithms work. Chemical equations express matter conservation in mathematical terms; the algorithms assure that every atom in the reactants is accounted for in the products, and vice versa. Physical modeling, where students manipulate atomic-molecular models and follow what happens to each atom, can play an important role in helping students see the connections between chemical equations and tracing individual atoms through chemical changes (HS-PS1-7). Similarly, students can learn to relate the energy in chemical bonds (as field energy between particles) to the energy absorbed or released during chemical changes (HS-PS1-4). Classroom Snapshot 8.3 illustrates a teacher working with her students on an important chemical change: cellular respiration.

CLASSROOM SNAPSHOT 8.3
Explaining Cellular Respiration[6]

In her ninth-grade biology class, Ms. Callahan is working with her students to develop explanations of how matter moves and changes and how energy changes during cellular respiration in a cow's cells (connecting macroscopic observations with atomic-molecular models and using principles of conservation of matter and energy).

Establishing the Problem

Ms. Callahan begins with reminders about what the class has been working on (mealworm investigation data, molecular modeling kit) and asks if everyone is feeling confident. She says that at the end of the unit she wants students to be able to "say not only for school, but for life, [that] this is exactly what happens when the organism moves." She adds, "We're going to actually figure out what's going on in this cow's muscle cells. Get ready to explain."

Next, the class reviews the results of an earlier investigation: mealworms eating and breathing. Ms. Callahan highlights how the product of CO_2 might have something to do with the missing mass students found in their mealworm investigation evidence.

Private Writing

The students work on an Explanations Tool, which combines a graphic organizer for tracing matter and energy with a paragraph that students write giving an overall explanation of the process. Ms. Callahan assigns students to start their personal writing by saying, "All right, so now it's your turn to figure out some explanations for this. I want you to be specific. Use your evidence. Use your thoughts. Start putting all these things together." Students work for 10 minutes.

Partner Work to Share Ideas

The students work in pairs. Ms. Callahan instructs her students: "Don't just throw your paper at your partner and have them look at it. Talk to them. Communicate and work your way through it. Get out a different-colored pen or pencil. I want you

6. See HS-LS1-7; this Classroom Snapshot is based on Covitt et al. 2019.

Continued

Classroom Snapshot 8.3 (*continued*)

to circle any areas you have in common, and then if you want to add items in that's fine. You have a lot more in common but maybe still some differences, which could be interesting. So talk to each other. Use your words. Let's go. Four minutes."

Consensus-Seeking Discussion

The class comes together for a discussion. Sometimes, the discussion is very specific to the Explanations Tool; other times, it's related to the tool, delving into additional content students are curious about (e.g., tracing water through urine and milk in the body; reviewing functions of organs, including kidneys, gall bladder, and pancreas; discussing why urine is yellow; discussing ATP). Ms. Callahan uses talk moves (Michaels and O'Connor 2012) to scaffold students in figuring things out. Sometimes, she solicits short responses, but often she asks for extended explanations.

Ms. Callahan (after a student says that a cow's food is "grass"): "Grass and then where is it going? Someone raise your hand and tell me the next step. Emma."

Emma: "It's, like, chewed up. It gets started breaking down stuff."

Ms. Callahan: "OK. So, it gets started breaking down stuff. Add on to what Emma is saying. What does it mean to get started breaking down stuff? Logan."

Logan: "The saliva in the cow's mouth begins to break the grass down as it's chewing."

Ms. Callahan: "OK. Is it breaking down the glucose?"

Multiple students: "No. Not until you get into the digestive system."

Ms. Callahan: "So, Riley, tell me what happens next. We've got grass in the mouth. There's some saliva going on. It's breaking down the grass. What happens next?"

Reviewing Students' Written Explanations

The close of discussion scaffolds students in checking whether they have written good explanations. Ms. Callahan queries students about confidence and consensus.

Ms. Callahan: "Do you have an arrow showing oxygen or O_2 going into the cow's cells?"

Students: "Yes."

Ms. Callahan: "Is that pretty universally confident? You're good with that?"

Students: "Yes."

Ms. Callahan: "Excellent. All right. Coming out, do you have CO_2? Did you make it very clear that you're separating the ideas of matter and energy?"

Continued

Classroom Snapshot 8.3 *(continued)*

Students: "Yes."

Ms. Callahan: "At no point did you say glucose was converted into energy?"

Students: "No."

Ms. Callahan: "Good! I'm pretty excited about some of the common ground we have and that you're all in agreement on things that are going in and out after using your molecular modeling kits.[7] Which is great. So, we're good!"

7. Students used molecular model kits to illustrate how molecules are rearranged in a prior lesson.

Large-Scale Modeling

At the large scale, high school students build on their experiences with developing models for cycling materials such as water (MS-ESS2-4) to develop more complex models driven by chemical changes. In particular, they focus on the cycling of carbon through ecosystems and global systems (HS-LS2-5, HS ESS2-6) and on how carbon cycling affects flows of energy through Earth's atmosphere—climate change (HS-ESS2-6). This is a fitting final application of the energy and matter conservation laws, as students use them to study one of the most important socioscientific issues of their lives.

Summary

Energy and matter are unique in that they appear in the *Framework* and the *NGSS* both as DCIs and as a CCC. While the DCIs focus on mechanisms of change in matter and energy, the CCC focuses on *energy and matter as conserved entities.* For all phenomena involving physical or chemical changes, the amount of energy and the amount of matter must stay the same. The conservation laws are especially powerful for two purposes:

- As rules, our models and explanations of phenomena must always follow the conservation laws.
- As heuristics, tracing matter and energy generates good questions to ask about phenomena.

To be useful for making sense of phenomena, conservation rules and heuristics must be applied in conjunction with SEPs (e.g., modeling) and DCIs (e.g., chemical bonding). In order to successfully use conservation laws for three-dimensional sensemaking, students need to master three related strategies: (1) define boundaries and fluxes in closed and open systems that enable tracing matter and energy; (2) identify manifestations of matter and energy in phenomena; and (3) connect models of matter and energy at atomic-molecular, macroscopic, and global scales.

Matter and energy are discussed and represented differently in different disciplines, but conservation laws are applicable for a broad range of phenomena across disciplines. This is the power of this crosscutting concept.

Conservation rules and heuristics are not obvious and must be built over many years. Students' ideas about matter and energy are initially shaped by their everyday language and experience. Students in elementary school often think of matter as solid and liquid "stuff" (not including gases) and of energy as causes of phenomena or resources for living things. These are useful ideas, but matter and energy defined in these ways do not seem to be conserved. As they master more rigorous models and practices, students can initially trace matter and energy through macroscopic systems in local contexts, then build abilities to use matter and energy as conserved entities within and across systems at multiple scales.

Acknowledgments

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Crosscutting Concepts
Strengthening Science and Engineering Learning

Maybe you have a good grasp of disciplinary core ideas and science and engineering practices—critical parts of the *Next Generation Science Standards*—but you are looking for more resources about integrating crosscutting concepts (CCCs). Or maybe you understand CCCs but want to know more about how to make them part of your students' toolkit for exploring science phenomena or engineering problems, both now and in the future.

Regardless of your needs, *Crosscutting Concepts* is your guide. It shows how to design and implement three-dimensional instruction for all students by understanding the potential of CCCs to strengthen science and engineering teaching and learning. *Crosscutting Concepts* helps you do the following:

- **Grasp the foundational issues that undergird crosscutting concepts.** You'll find out how CCCs can change your instruction, engage your students, and broaden access and inclusion of all students into your science classroom.
- **Gain in-depth insights into individual crosscutting concepts.** You'll learn how to use each CCC across disciplines, understand the challenges students face in learning CCCs, and adopt exemplary teaching strategies.
- **Discover how CCCs can strengthen the way you teach key topics in science.** These topics include the nature of matter, plant growth, and weather and climate, as well as engineering design.
- **Understand related implications for science teaching.** These topics include student assessment and teacher professional collaboration.

Throughout *Crosscutting Concepts*, vignettes drawn from the authors' own classroom experiences will help you put theory into practice. Instructional Applications show how CCCs can strengthen your planning. Classroom Snapshots feature practical ways to use CCCs in discussions and lessons. Useful for teachers at all grade levels, this book will enrich your own understanding while showing you how to use CCCs for both classroom teaching and real-world problem solving.

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