Crosscutting Concepts as Epistemic Heuristics in Learning Progression Research and Curriculum Design

Charles W. (Andy) Anderson

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I am writing in this short paper about the work of the *Carbon TIME* project[1] (http://carbontime.bscs.org/), a design-based implementation research project teaching carbon cycling at multiple scales at the middle- and high-school level. *Carbon TIME*'s six units include investigations, explanations, and predictions from the atomic-molecular to the global scale. For the sake of parsimony this paper focuses specifically on students' explanation practices, and on four units (*Systems and Scale, Plants, Animals, Decomposers*) that focus on:

- Familiar phenomena observed at the macroscopic scale: burning organic fuels, plant and animal growth and movement, decay
- Model-based explanations of these phenomena that describe how metabolic processes transform matter and energy at the atomic-molecular scale: combustion, photosynthesis, cellular respiration, biosynthesis, digestion

How we address the three organizing questions for this summit in the *Carbon TIME* project is described below.

Roles of Crosscutting Concepts in Supporting Science Learning

The *Carbon TIME* project builds on a foundation of learning progression research. This empirical research has led us to a theoretical position on a productive interpretation of CCCs. For this paper we draw in particular on an article that we are currently revising for publication in *Science Education* (Miller, et al., accepted pending revision).

Rivet, et al. (2107) used a hermeneutic analysis of foundational and supplementary documents describing CCCs to develop "conceptual metaphors" for thinking about CCCs. We suggest that the CCCs themselves can be interpreted as a kind of hermeneutic analysis of scientific explanations, predictions, and arguments from evidence. Rather than conceptual metaphors, we find it useful to describe CCCs as what Krist, Schwarz, and Reiser (in press) describe as *epistemic heuristics* for the construction of scientific explanations.

Syntactic and semantic features of scientific language in the practice of explanation. CCCs identify syntactic as well as semantic features of scientific language: They expose the "rules of grammar" that define what kinds of statements are acceptable. These rules often operate unnoticed in the background until they are broken. We typically do not consciously notice that "She is eight years old" is grammatically correct, but we notice immediately that "She am eight years old" is incorrect.

In a similar way, the claim that "Sleep is an energy source for humans" is rejected by scientists in part because it violates the principle of conservation of energy, which serves as a rule—an epistemic heuristic—that governs our explanations of phenomena. For the phenomena that we focus on in this research—carbon-transforming processes in environmental systems—model-based explanations constrained by principles define the highest level in the learning progression framework.

Learning progression progress variables based on CCCs. The Miller, et al., paper provides a detailed analysis of students' three-dimensional performances in explaining the phenomena described above. The analysis identifies four key *progress variables*: the specific transitions that students must make to master model-based mechanistic explanations. For example, the progress variables describe the key features of a model-based explanation of how trees transform matter and energy as they grow:

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1. *Context-specific information about trees' structure and function.* Successful explanations are based on specific information about trees' structure and function. For example, trees have dual circulation systems, one carrying water and minerals from the roots to all parts of the tree, and the other carrying sugar from the leaves to all parts of the tree.
2. *Tracing matter and energy*. Successful explanations trace how matter and energy move and change through trees' systems and processes. For example, all of the chemical energy stored in trees' wood and leaves can be traced back to sunlight, while all the matter in trees' wood and leaves comes from atmospheric carbon dioxide, water, and soil minerals.
3. *Precision in language use*. Successful explanations use scientific vocabulary consistently and precisely. For example, "carbon" is an element while "carbon dioxide" is a gas. Similarly "sunlight" is a form of energy while "glucose" as a form of matter that has available chemical energy;
4. *Connecting systems at different scales*. Successful explanations connect macroscopic-scale observations with models at the cellular and atomic-molecular scales. For example, in colloquial discourse, it seems reasonable the trees would be able to convert one colorless, odorless gas—carbon dioxide—into another colorless, odorless gas—oxygen—while it seems absurd to claim that the mass of a mature tree comes mostly from carbon dioxide. Only by connecting macroscopic phenomena with atomic-molecular models can students explain how the latter claim is the one supported by scientific models and evidence.

We note that the second and fourth progress variables stem directly from CCCs: tracing matter and energy from CCC#5 (energy and matter) and connecting scales from CCC#3 (scale, proportion, and quantity) and CCC#4 (systems and system models). The other two progress variables are also connected with CCCs in more subtle ways. As noted above, the CCCs support successful explanations by functioning as epistemic heuristics that implicitly guide students' reasoning.

Classroom Implementation

Gee (1991) distinguishes between *acquisition* (developing knowledge through personal experience) and *learning* (developing knowledge through explicit study). CCC-based epistemic heuristics are like grammatical rules of language: Students cannot simply *learn* to apply heuristics after they are told that CCCs are principles to follow; they must also *acquire* epistemic heuristics through personal experience, discussion, and practice in developing scientific explanations. Our instructional challenge we face is to scaffold both learning and acquisition as students learn to construct scientific explanations of carbon-transforming processes.

All *Carbon TIME* unit are based on an instructional model in which students play the roles of questioners, investigators, and explainers, with each role focusing on different scientific practices. For some topics such as the study of watersheds described by Fick (2018), students can work in all three roles with minimal didactic instruction. They develop successively more sophisticated explanations through analysis of their experiences in the world and macroscopic-scale models.

Both our learning progression work and our practical experience in classrooms convince us that this is not the case for the explanations that we seek to scaffold—explanations that account for transformations of matter and energy in carbon-transforming processes. There are a number of reasons for this. Atoms and molecules are not directly observable, and they have properties that do not correspond with students' experiences. Similarly, scientific definitions of matter and energy are significantly different from the colloquial usages of those words that are familiar to students.

So we have concluded that our goals for students as explainers require explicit teaching of canonical scientific models and CCC-based heuristics. One key instructional resource that guides this teaching is the Three Questions, attached as an appendix at the end of this paper. The Three Questions define a good explanation of a carbon-transforming process (an explanation that answers the Three Questions). The second and third columns of the Three Questions table (Rules to Follow and Evidence We Can Observe) make explicit the CCC-based heuristics described above.

Note that the Three Questions *scaffold* rather than *replacing* consensus-seeking discussions and the process of figuring out phenomena. In traditional science teaching consensus-seeking discussions do not occur because the teacher tells the students explanations. In contrast, the Three Questions provide students with guidance as they figure out explanations.

The Three Questions and instructional tools based on them provide the basis for cognitive apprenticeship-based instructional sequences that support students' mastery of matter and energy-tracing explanations. We have assessment evidence that this approach is working at the scale of hundreds of classrooms (see Anderson, et al, 2018).

Challenges and Questions for Research

We have many questions related to this work that we hope to continue investigating. For example, we are also doing learning progression work on students inquiry practices and reasoning about systems at ecosystem and global scales. How can CCCs support other practices? What about other topics in the curriculum where matter and energy play less central roles, such as genetics and evolution? For the purposes of this conference, though, we would like to focus on two challenges that are especially salient:

- The instructional design challenge: When and how are explicit teaching of scientific models and CCC-based heuristics necessary, and when are more inquiry-based approaches appropriate? How can we make sure that students have experiences using CCCs and constructing explanations that support acquisition as well as learning?
- The teacher education challenge: How can we support the large-scale transformations in teaching practice that will be essential to enacting NGSS—to assessing and scaffolding students' three-dimensional engagement with phenomena, including their development of CCC-based epistemic heuristics?

We hope that the summit will provide opportunities for productive discussions of these salient issues.

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Appendix: The Three Questions

Answer each of the questions (numbered 1-4) below to explain how matter and energy move and change in a system. Note that matter movement is addressed at both the beginning (1) and end (4) of your explanation.

Matter Movement

Question

Where are molecules moving?

1 How do molecules move to the location of the chemical change?

4 How do molecules move away from the location of the chemical change?

Rules to Follow

All materials (solids, liquids, and gases) are made of atoms that are bonded together in molecules.

Scale: The matter movement question can be answered at the atomic-molecular, cellular, or macroscopic scale.

Evidence We Can Observe

Moving solids, liquids, and gases are made of moving molecules.

A change in mass shows that molecules are moving.

Matter Change

Question

2 How are atoms in molecules being rearranged into different molecules?

What molecules are carbon atoms in before and after the chemical change?

What other molecules are involved?

Rules to Follow

Atoms last forever in combustion and living systems.

Atoms can be rearranged to make new molecules, but not created or destroyed.

Carbon atoms are bound to other atoms in molecules.

Scale: The matter change question is always answered at the atomic-molecular scale.

Evidence We Can Observe

BTB can indicate CO_2 in the air.

Organic materials are made up of molecules containing carbon atoms:

- fuels
- foods
- living and dead plants and animals
- decomposers

Energy Change

Question

3 What is happening to energy?

What forms of energy are involved?

What energy transformations take place during the chemical change?

Rules to Follow

Energy lasts forever in combustion and living systems.

Energy can be transformed, but not created or destroyed.

C-C and C-H bonds have more stored chemical energy than C-O and H-O bonds.

Scale: The energy change question can be answered at the atomic-molecular, cellular, or macroscopic scales.

Evidence We Can Observe

We can observe indicators of different forms of energy before and after chemical changes:

- light energy
- chemical energy stored in organic materials
- motion energy
- heat energy