Summary of Research on Carbon Framework

Andy Anderson, January, 2010

This file is based on the review of our past work in the DRK12 proposal that we just submitted. I think that the five transitions around which it is organized can be useful to us across all three of the MSP strands. In carbon we have made substantial progress on the first 4 transitions, not so much on Transition 5—arguments from evidence and decision-making practices. Since our work on the first 4 transitions is well documented in other papers, I discuss them briefly below, while expanding on Transition 5.

We can summarize our prior work on carbon learning progressions in two broad stages. In the first stage we developed a learning progression, including a framework and assessment system, and validated it with culturally diverse students across a broad age range who were experiencing status quo teaching. The second stage of our work, currently in progress, focuses on teaching experiments designed to test our hypothesis that an alternate, more effective learning trajectory is possible for most students and can be achieved through manageable changes in our current science curriculum and teaching methods. Our results do date are summarized below.

Learning Progression Framework and Assessments

Our current learning progression framework and assessments have been developed through an iterative process beginning in 2004, including studies focusing on upper elementary through high school students (Mohan, Chen, and Anderson, 2009), at the college level (Wilson, et al., 2006; Hartley, et al., 2009), and comparing American and Chinese students (Chen, Anderson, & Jin, 2009; Jin, Zhan, & Anderson, 2009). During the course of this research we have administered and analyzed written assessments (available on the Environmental Literacy website at http://edr1.educ.msu.edu/EnvironmentalLit/publicsite/html/assess_cc_09-10.html) to over 5000 students and clinical interviews to almost 150 students.

We align our work with the NRC report *Taking Science to School* in defining learning progressions as "descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., six to eight years)" (Committee on Science Learning, 2007, Chapter 8). Through this research we have developed a framework that describes students' learning in terms for four Levels of Achievement. Our Lower Anchor—Level 1—describes the reasoning typical of upper elementary middle school students in our samples. Two intermediate levels—Levels 2 and 3—describe the reasoning we see in most current middle school and high school students. The Upper Anchor—Level 4—describes the reasoning we hope to see in environmentally literate high school graduates. In this section we first describe Level 4 reasoning, then address five key challenges or transitions that students must go through to achieve this Level.

Upper Anchor: Environmental Science Literacy for Informed Citizenship

Our work is based on the premise that a core function of schools is to prepare students to be informed citizens, so we define our upper anchor as *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems and to make informed decisions about appropriate actions and policies. A key idea for us is that *environmental science literacy gives people choices:* Level 1 reasoning is appropriate in some circumstances, but Level 1 students differ from Level 4 students in that they have no choice—they cannot use the resources of scientific reasoning even when the occasion calls for it.

We use a "Loop Diagram" (based on the LTER Network strategic plan, 2007) to describe an environmentally science literate understanding of carbon-transforming processes. Scientifically literate citizens need to be able to interpret the boxes and arrows of Figure 1 in terms of chemical models. The right-hand Environmental Systems box includes the familiar ecological carbon cycle, which students need to understand at multiple scales—as atomic-molecular, cellular, organismal, and ecological processes. This understanding is included in the current national standards documents (AAAS Project 2061, 1993;

NRC, 1996; NAGB, 2006). It highlights carbon-transforming processes in environmental systems, as well as the process of combustion that connects environmental systems to the needs and impact of human systems.

Environmental science literate students must learn to "see themselves in the Loop Diagram." That is, they must understand how their actions as consumers, voters, workers, and learners (the left-hand box) depend on and affect carbon-transforming processes in environmental system and affect those systems, including the effects of global climate change.

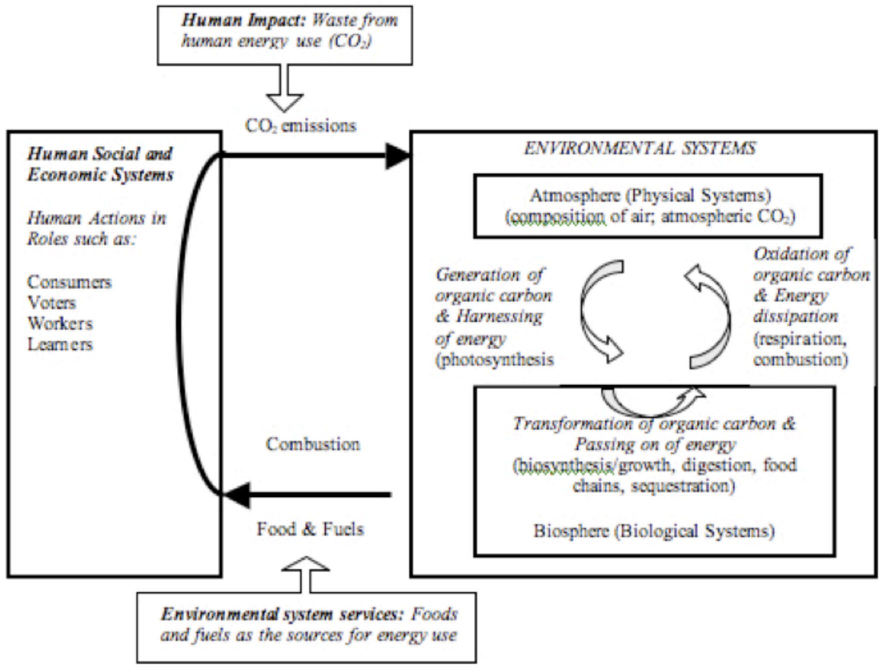


Figure 1: Carbon-transforming processes "loop diagram" (Mohan, et al., 2009)

As we have explored-carbon transforming processes in greater depth, we have come to believe that this topic is significant not only because of its inherent importance, but also because it can serve as a sort of *Drosophila* for core learning issues in the secondary science curriculum: Many of the challenges that students encounter in learning about carbon-transforming processes are deeply embedded throughout secondary science curriculum. In this section we use an organization from Anderson's (2009) recent invited presentation to the National Research Council's Board on Science Education to describe five key transitions that students must go through in mastering the practices of environmental science literacy.

Transition 1: Force-dynamic to scientific discourse

The first transition is both the most fundamental and the least understood by science educators. As Steven Pinker suggests:

> There is a theory of space and time embedded in the way we use words. There is a theory of matter and causality, too. … These conceptions… add up to a distinctively human model of reality, which differs in major ways from the objective understanding of reality eked out by our best science and logic. Though these ideas are woven into language, their roots are deeper than language itself. They lay out the ground rules for how we understand our surroundings. (Pinker, 2007, p. vii)

Following Talmy (1998; 2003), Pinker describes our common conceptions as *force-dynamic discourse* or reasoning. Force-dynamic reasoning construes the events of the world as caused by actors (including people, animals, plants, machines, and flames), each with its own purposes and abilities, or by natural tendencies of inanimate objects. In order to accomplish their purposes, the actors have needs or enablers that must be present. For example, force-dynamic reasoning explains the growth of a tree by identifying the actor (the tree), its purpose (to grow), and its needs (sunlight, water, air, and soil). Force-dynamic predictions involve identifying the most powerful actors and predicting that they will be able to overcome antagonists and achieve their purposes as long as their needs are met.

This approach to reasoning about carbon-transforming processes contrasts sharply with *principled scientific discourse*, which construes the world as consisting of hierarchically organized systems at different scales. Rather than identifying the most powerful actors, scientific reasoning sees systems as constrained by fundamental laws or principles which can be used to predict the course of events. The most fundamental of these principles—conservation of matter and energy—also turn out to be highly problematic for most students.

We feel that this transition in discourse is the most fundamental of the changes that students must go through, and the primary barrier to successful scientific reasoning for many students. Even college students routinely reason about carbon-transforming processes in ways that reflect force-dynamic assumptions and violate the principles of conservation of matter and energy, as we describe below.

Transitions 2, 3, and 4: Hierarchical reasoning about systems and processes at different spatial and temporal scales

We have found that students at all levels are familiar with carbon-transforming processes at the macroscopic scale, but differ greatly in how they explain those processes and in their ability to make robust connections across spatial and temporal scales. The transition from force-dynamic to scientific reasoning presents different challenges at each scale in the hierarchy.

Macroscopic scale: Observing and interpreting processes in principled ways. We have organized our learning progression framework and assessments around a set of macroscopic *linking processes,* italicized in Table 1, below. Students at all Levels of Achievement are familiar with these processes, but students at different levels construe them in quite different ways. For lower Level students, the processes involving living organisms—plant growth, animal growth, and animal movement—are closely related in that they have similar actors with similar needs and results associated with life. This is quite different from decay, which is something that happens when living actors die and lose their powers, and from combustion, where flames function as different kinds of actors.

Table 1: Contrasting ways of grouping carbon-transforming processes

<table>
<tr><td rowspan="2">Upper Anchor</td><td>Carbon-transforming process</td><td>Generating organic carbon</td><td colspan="3">Transforming organic carbon</td><td colspan="3">Oxidizing organic carbon</td></tr>
<tr><td>Scientific accounts</td><td>Photosynthesis</td><td>Biosyn-thesis</td><td>Digest-ion</td><td>Biosyn-thesis</td><td colspan="2">Cellular respiration</td><td>Combustion</td></tr>
<tr><td colspan="2">Macroscopic Events</td><td colspan="2">Plant growth</td><td colspan="2">Animal growth</td><td>Breathing, exercise, weight loss</td><td>Decay</td><td>Burning</td></tr>
<tr><td colspan="2">Lower Anchor: Informal accounts</td><td colspan="5">Plants and animals accomplishing their purposes, enabled by food, water, sunlight, air, and/or other resources</td><td>Natural process in dead things</td><td>Flame consuming fuel</td></tr>
</table>

This contrasts sharply with scientific explanations of these same events. Environmentally literate students can choose to construe these as chemical processes and trace transformations of matter and energy; this enables them to see the similarities among processes that appear very different, but all involve the oxidation of organic carbon. This leads students to perceive the events themselves differently. Gases such as oxygen and carbon dioxide, for example, become key repositories of matter rather than simply "needs" that enable a process to happen.

Atomic-molecular scale: Explaining with subsystem models. Students at intermediate Levels 2 and 3 know *facts* about cellular and atomic-molecular systems but are unable to use them as *models* with explanatory and predictive power. For example, students who can apply the principle of conservation of matter to atomic-molecular models recognize that chemical changes arrange atoms into new molecules but to not create or destroy atoms. This means that in all carbon-transforming processes *the carbon atoms have to go somewhere.* So plants don't just "breathe in" carbon dioxide and "breathe out" oxygen; they must incorporate the carbon atoms into their tissues. This "sense of necessity" is essential to seeing the basic patterns that make complex processes comprehensible.

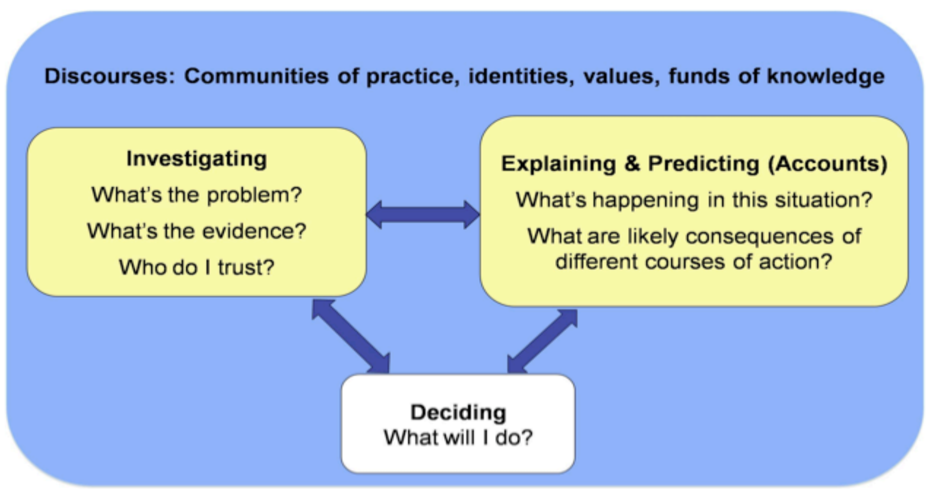
Large scale: Tracing matter and energy through systems. Environmentally literate students need to understand how smaller scale carbon-transforming processes, including those implicated in their own lifestyles, can have cumulative global effects. This involves tracing matter and energy through linked human and environmental systems, as depicted in Figure 1 (from Mohan, Chen, & Anderson, 2009). In contrast the reasoning in Figure 1, students at Levels 2 and 3 typically see two different cycles—(a) a nutrient cycle in which plant growth serves as a foundation for food webs and decay which recycles nutrients through the soil, and (b) the "oxygen-carbon dioxide cycle" in which animals breathe in oxygen and breathe out carbon dioxide while plants do the reverse. The implications of this conception for understanding ideas such as carbon sequestration are apparent.

Transition 5: Arguments from evidence and inquiry and decision-making practices

Our current national standards documents have separate chapters or sections on science content, inquiry, nature of science, and environmental and social implications of science, and there are extensive research literatures on these as separate practices. However, we have come to see these practices as deeply connected. We have been influenced by Metz (2004) and by Steering Committee member Leona Schauble (Lehrer & Schauble, in press; Lehrer, Schauble, & Lucas, 2009), as well as by our own investigations (Covitt, Tan, Tsurusaki, & Anderson, 2009).

We follow Neils Bohr (quoted in Hawkins, 1990, p. 100) in believing that "the task of science is both to extend our experience and reduce it to order," both for the practicing scientists that Bohr wrote about and for the science learners we work with. Learners at all levels extend their experience and reduce it to order by engaging in formal and informal investigations, either *first-hand investigations* that rely on learners' personal experience or *second-hand investigations* that rely on reports from other people or the media.

Transitions 1-4 all involve what we call *accounts*—the practices associated with explanation and prediction that are closely aligned with the "content" sections of standards documents. While we view the ability to produce and understand scientific accounts of carbon transforming processes as necessary for environmental science literacy, these practices are not sufficient. In particular, environmental science literacy involves two other types of practice (a) investigation and argumentation, and (b) decision making about environmental issues. Covitt, Tan, Tsurusaki, & Anderson (2009) report on our analyses of interviews with middle school and high school students focusing on these practices. Our comments here will focus on students' investigation and argumentation practices.



We emphasize again a point we made above: *Environmental science literacy gives people choices.* We all make most of our decisions on the basis of heuristics that involve little conscious thought. But what can we choose to do if the decision is a difficult one, such as where we should live or whether we should support a carbon tax? We found that students differed greatly in their ability to reach informed decisions—that is, decisions in which their deciding practices are supported by well-informed investigations and accounts. A core issue in students' environmental decision making is that students (and adults) often make decisions about lifestyle or policy without being able to predict the consequences of their actions. This is due in part to limitations in their accounts described above; it is also due in part to limitations in their understanding of the nature and limits of scientific inquiry. We focus here particularly on students' second-hand investigations, where they must rely on information from others or reports in the media.

Scientific standards for investigations. We follow Metz (2004) in taking the *reduction of uncertainty* as a key goal of scientific inquiry. We take a scientific stance toward uncertainty to begin from the premise that uncertainty is inevitable: We cannot know about the past, the present, or the future with complete precision and assurance. Our most powerful tools for reducing uncertainty in the knowledge claims we make about the material world come from our standards and methods for scientific inquiry, including the following:

- Giving priority to *arguments from evidence*: We judge knowledge claims on the basis of the evidence supporting them rather than the authority or the affiliation of the people making the claims.
- *Commitment to rigor in method*: We recognize standards of methodological rigor in data collection and data analysis and give priority to studies that meet standards of methodological rigor.
- *Collective validation*: We recognize that even the most conscientious individuals can be deceived, so we accept knowledge claims only if they can achieve consensus support from knowledgeable judges through peer review or other mechanisms.

Students' standards for investigations. Covitt, et al., found that most middle school and high school students had little knowledge and understanding of these standards. When confronted with conflicting claims about the possible effects of a well for bottled water on a trout stream, we often found students taking one or both of these positions:

Generalized distrust ("Everyone is biased"): Most students were quick to see indications of bias or self-interest in statements from different groups. For example, here is how one high school student evaluated position statements from different organizations on drilling a well near a northern Michigan trout stream (from Covitt, et al., 2009):

- … Nestle wants to build the factory so they're going to say any lie to you.
- …They [Nestle] might have to pay for the water, so the Department of Environmental Quality might be telling a little bit of fib because they might be getting a little money out of it and people might do a little for money.
- (Interviewer asked, "What about Trout Unlimited?") I think they're telling a fib because they don't want it to be built."

Like many of the other students we interviewed, this student showed some political sophistication in recognizing that most individuals and organizations make arguments that are influenced by bias and self interest. This sophistication becomes a kind of corrosive cynicism, though, if students have no way to see beyond evidence of bias. What many students were NOT able to do as well was to decide when some of those self-interested claims might in fact be trustworthy—that is, when the claims were backed by arguments from evidence that meets the scientific standards above.

This kind of corrosive cynicism can be seen in politically sophisticated adults as well as high school students. For example, here is what US Representative James Sensenbrenner (R-Wisconsin) had to say about E-mails revealing private discussions among scientists about evidence for global climate change: "These e-mails show a pattern of suppression, manipulation and secrecy that was inspired by ideology, condescension and profit." It is, of course, sometimes true that scientists are "inspired by ideology, condescension and profit," but again we would hope to give students the choice of evaluating arguments on the basis of the scientific standards above as well as evidence of bias or self-interest.

Unwarranted credulity ("Truth is easy if you know who to trust"): Many students were also quick to decide that some claims were trustworthy for a variety of reasons—agreeing with the positions the students had already taken, having the best interests of people in mind, having references, etc. For example, consider how Selena, a middle school student interviewed by Covitt, et al., decided who to trust:

Selena:	I think these [Trout Unlimited and Michigan Citizens for Water Conservation] are more trustworthy because they have the information that I was talking about mainly.

Interviewer: So they kind of match your own ideas?
Selena: Mhm.
Interviewer: So you think that makes them trustworthy?
Selena: Yes.

For Selena, trustworthy sources offered information that seemed reasonable or right to her based on her own experiences with the world.

Again, we see this kind of unwarranted credulity in adults as well as students. For example, here is how Kay Gross, director of the Kellogg Biological Station, responded to an E-mail message from a colleague who suggested that we had nothing to fear from creationists because their arguments were so obviously incredible:

> "I was at a painting class and the topic of Obama's citizenship came up. Everyone in the room felt that he was born in Kenya.. and raised in Malaysia.. and that the Obama administration had not provided anything to refute it. (What are they trying to hide???) I said he was born in Hawai'i and this had been repeatedly shown to be true.. they countered with the information that his grandmother was quoted as saying she had been at his birth in Kenya! So how do you argue with people that 'just know' things..." (Kay Gross, E-mail message, 11/18/09)

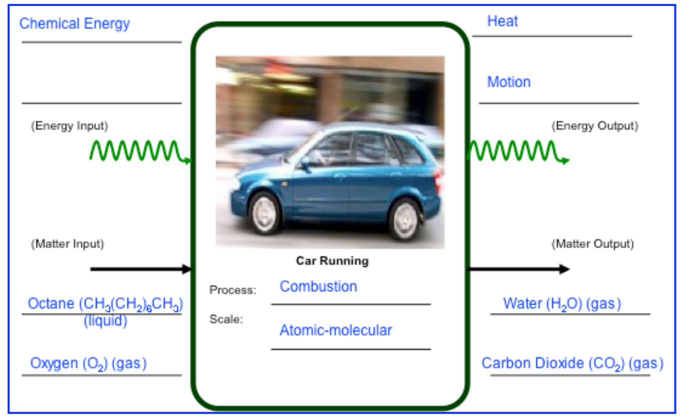
The danger we see in these naïve understandings of scientific inquiry lies in a pattern we see all too often in our political discourse, where collective action becomes impossible because different groups of citizens—the Prius drivers and the SUV drivers—construct their own alternative versions of reality supported by the authorities that they have decided to trust. However, earth systems do not understand out political arguments. In 50 years, we will know who is right and who is wrong about the environmental effects of our actions, and our children will live with the consequences. In the meantime, our best hope for informed collective action lies in public understanding of and commitment to scientific standards for judging and reducing uncertainty in our knowledge claims.

Teaching Experiments to Improve Student Learning

Our research to date does not provide an encouraging picture of student achievement: Mohan, et al. report that less than 10% of high school students achieved Level 4 reasoning in their sample, and much of our subsequent research indicates that even that number may be high (e.g., Chen, Jin, & Anderson, 2009). We have suggested a core problem responsible for this widespread failure: Status quo teaching exposes students to detailed models of carbon-transforming systems and processes without helping them to understand and use the fundamental principles that constrain those models, especially conservation of matter and energy and the hierarchy of systems at multiple scales. We are currently developing teaching materials using *Tools for Reasoning* (available on the Environmental Literacy website at http://edr1.educ.msu.edu/EnvironmentalLit/publicsite/html/cc_tm.html) and conducting teaching experiments to see whether an alternate learning trajectory leading to better student understanding is possible.

The alternate learning trajectories, teaching experiments, and Tools for Reasoning are described in papers presented at the NSF-supported Learning Progressions in Science (LeaPS) conference (Jin & Anderson, 2009; Mohan & Anderson, 2009). The *Structure-First trajectory* describes the trajectory documented by Mohan et al., (2009) using data from status-quo teaching contexts. In this trajectory we see progress for many students between Levels 1-3, but limited progress for students between levels 3 and 4. Students on this trajectory exhibit more advanced naming and labeling of systems and processes, but lag behind in their understanding and use of principles. The *Principle-First trajectory* describes an alternative to the status-quo (Gunckel et al., submitted), but one with promise of supporting progress to the Upper Anchor. This pathway describes students who show a commitment to explanations that use scientific principles even in instances when they do not have the chemical details and language to provide a full description.

A key part of our strategy is using *tools for reasoning* that make hidden scientific principles—matter, energy, and scale—visible to students. Our current tools for reasoning include (a) a *Powers of 10 Tool* that supports reasoning about relationships among models at different scales, (b) a *Matter and Energy Process Tool* (illustrated) that supports reasoning about conservation of matter and energy at multiple scales, and (c) *molecular models* that support reasoning about chemical change. We would also like to develop an *Arguments from Evidence Tool* that students can use to evaluate the quality of arguments from evidence associated with either first-hand or second-hand investigations



We are now analyzing data from our first teaching experiment, conducted in 14 classrooms during 2008-9. A second teaching experiment using improved teaching materials that incorporate Tools for Reasoning more systematically is now underway in 24 classrooms. The materials that we have developed for these experiments (available on the Environmental Literacy website) will be the basis for

Conclusion

Our children have a lot at stake with respect to public understanding in this domain. We face the necessity of collective action at a time when polls show that public skepticism about the science of global warming is on the rise (Brooks, 2010). We claim that, at a minimum, our society needs high school graduates who are capable of doing two things:

- "Putting themselves in the Loop Diagram"—understanding how carbon-transforming processes affect the earth's climate by altering the concentration of greenhouse gases in the atmosphere (Transitions 1-4 in our learning progression).
- Understanding and respecting scientific standards for arguments from evidence as our best approach to reducing in our knowledge of climate change (Transition 5).

Our research to date both documents the virtually complete failure of our science education system to achieve these goals and suggests promising directions for research and development, based on an empirically validated learning progression. Our work will (a) contribute to the science education knowledge base about learning progressions and climate change education, (b) develop flexible and adaptive tools based on work in culturally and geographically diverse sites that can be used for reforming standards, assessments, and curricula in this domain, and (c) develop an expanding network of sites that are contributing to this research and using our tools, starting with the core sites for this project and expanding through our through our partnerships with other LTER sites.

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