Learning Progressions for Environmental Science Literacy

Charles W. (Andy) Anderson, March, 2010

Contents

Learning Progressions for Environmental Science Literacy

Charles W. (Andy) Anderson, Michigan State University (andya@msu.edu)
Prepared for the NRC National Standards Framework Committee, March, 2010
Website: http://edr1.educ.msu.edu/EnvironmentalLit/index.htm[1]

This paper is mostly an amalgam of text and figures from other sources, organized to address three questions:

1) How did you identify your big ideas? That is, how did you decide what ideas to focus on?
2) How are you treating the relationship between content and practice?
3) What are the implications of learning progressions for writing standards?

Since 2004 we have been working to develop learning progressions in three interconnected content domains:

- *Carbon.* Carbon-transforming processes in socio-ecological systems at multiple scales, including cellular and organismal metabolism, ecosystem energetics and carbon cycling, carbon sequestration, and combustion of fossil fuels. These processes: (a) create organic carbon (photosynthesis), (b) transform organic carbon (biosynthesis, digestion, food webs, carbon sequestration), and (c) oxidize organic carbon (cellular respiration, combustion). The primary cause of global climate change is the current worldwide imbalance among these processes.
- *Water.* The role of water and substances carried by water in earth, living, and engineered systems, including the atmosphere, surface water and ice, ground water, human water systems, and water in living systems.
- *Biodiversity.* The diversity of living systems, including variability among individuals in population, evolutionary changes in populations, diversity in natural ecosystems and in human systems that produce food, fiber, and wood.

Since the work on the carbon learning progression is the most advanced, many of my examples will come from that work. That work has 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 water and biodiversity learning progressions are still in this stage. The second stage of the carbon 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. More detailed accounts of this work can be found on the Environmental Literacy website (URL above).

[1] This paper summarizes the work of many people. In particular, I acknowledge the contributions of:

- Hui Jin, Edna Tan, Jing Chen, Li Zhan, Josephine Zesaguli, Hsin-Yuan Chen, Brook Wilke, Hamin Baek, Kennedy Onyancha, Jonathon Schramm, Blakely Tsurusaki, and Courtney Schenk at Michigan State University
- Lindsey Mohan at National Geographic Education Programs
- Kristin Gunckel at the University of Arizona
- Beth Covitt at the University of Montana
- Laurel Hartley at the University of Colorado, Denver
- Blakely Tsurusaki at Washington State University, Pullman
- Rebecca Dudek at Holly, Michigan, High School
- Mark Wilson, Karen Draney, Jinnie Choi, and Yong-Sang Lee at the University of California, Berkeley.

This research is supported in part by grants from the National Science Foundation: Developing a Research-based Learning Progression for the Role of Carbon in Environmental Systems (REC 0529636), the Center for Curriculum Materials in Science (ESI-0227557), Learning Progression on Carbon-Transforming Processes in Socio-Ecological Systems (NSF 0815993), and Targeted Partnership: Culturally relevant ecology, learning progressions and environmental literacy (NSF-0832173). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

1) How did you identify your big ideas?

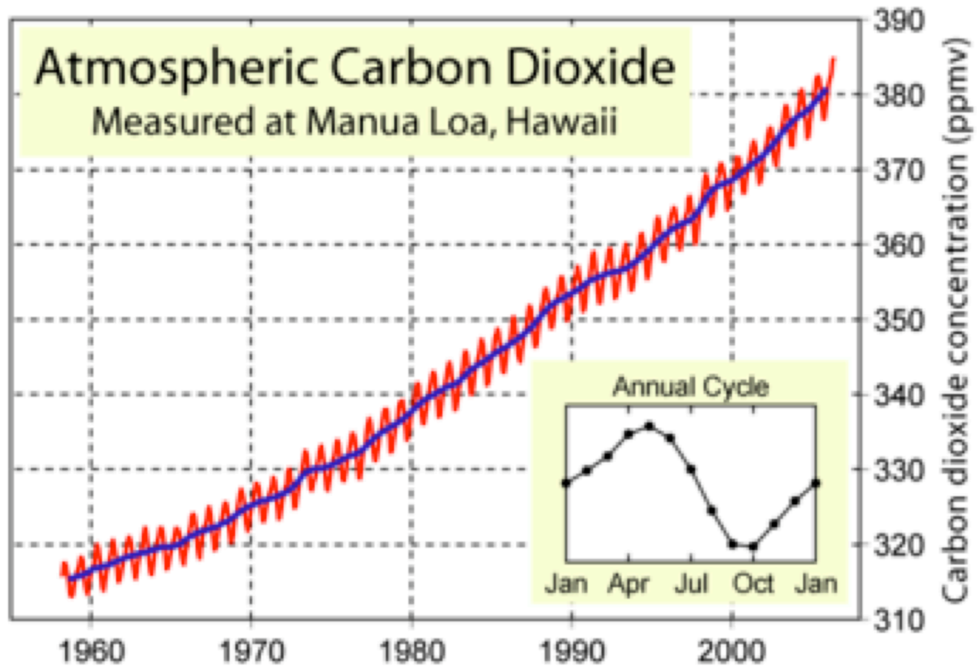
My work on environmental science literacy began with a meeting of science education researchers that I helped to organize for Project 2061 in 2001. The question before us was how to develop research-based curricula that addressed our current national standards. My conclusion from that meeting was that the current standards make large scale curriculum development a formidable challenge—we just cannot cover all the standards and teach for understanding in the time available for science teaching.

So I concluded that we need national standards that are *compact, coherent, and incomplete*. Furthermore, scientific importance does not work very well as a filter to decide what to leave out. Every topic in the current standards is there because it has a passionate constituency in the scientific and science education communities, backed by convincing arguments for its scientific importance.

So I turned to social utility: Will our nation suffer if ALL our citizens do not understand this? Two areas clearly pass this test for me: environmental and biomedical knowledge.

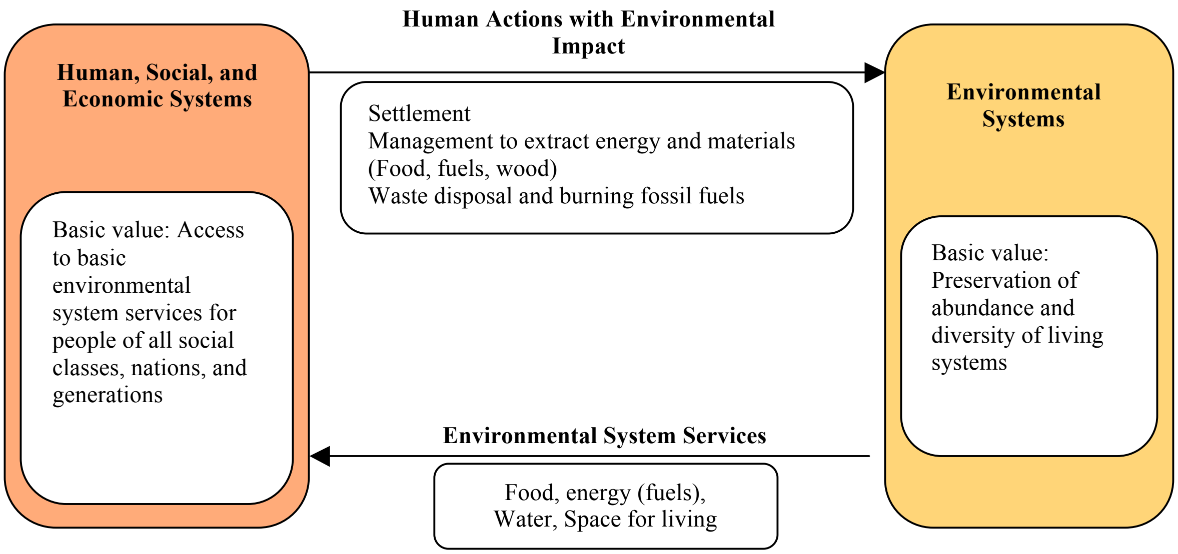
- Lack of biomedical knowledge hurts us both individually (when we make poor decisions regarding our own health) and collectively (when medical costs eat up more and more of our national productivity).
- Lack of environmental knowledge hurts us collectively—our children will live with the consequences of our environmental policies and actions.

Here's an example: The data on atmospheric carbon dioxide concentration from Mauna Loa, commonly known as the Keeling curve. We need informed citizens to understand that this is not a Democratic or Republican curve. This documents the atmosphere's responses to seasonal changes in living systems and humans' land use and life style choices. And the atmosphere does not consult the polls before deciding what to do. We can "bend the curve," but only through sustained collective action, and it is hard to imagine how we might summon the political and economic will for sustained collective action unless most citizens understand the curve better than they do now.



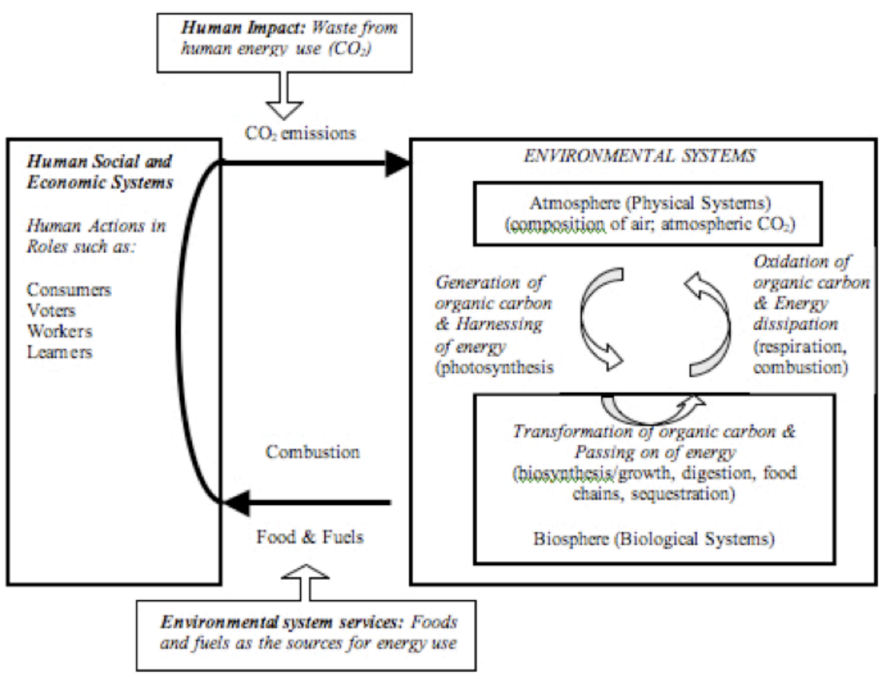
So what does it mean to "understand the Keeling curve?" More generally, what is the nature of the scientific understanding that people will need to be informed citizens with respect to environmental issues, such as those associated with carbon, water, and biodiversity?

Our general answer to this question lies in what we call the "Loop Diagram," a simplified version of the framework developed by the Long-Term Ecological Research (LTER) Network to describe their ongoing research agenda (LTER Planning Committee, 2007). The Loop Diagram suggests a way to understand the relationships between our societies and the environmental systems upon which we depend. It depicts the key relationships in terms of two boxes, representing human and environmental systems, and two arrows, representing the environmental impacts of our actions and essential environmental services.



Structures and Processes of Socio-ecological Systems (Loop Diagram)

We have developed topic-specific versions of the Loop Diagram for each of our three strands (carbon, water, and biodiversity). The carbon version (from Mohan, Chen, & Anderson, 2009) is below. 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), though different parts of it are spread across the sections on life, earth, and physical sciences.



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

We feel that environmental science literate students should be able to "see themselves in the Loop Diagram." That is, they should 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.

Note that the Loop Diagram is

organized around *carbon-transforming processes.* After a substantial amount of time exploring other aspects of systems (such as structure), we concluded that processes were keys to understanding. 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 science curriculum.

2) How are you treating the relationship between content and practice?

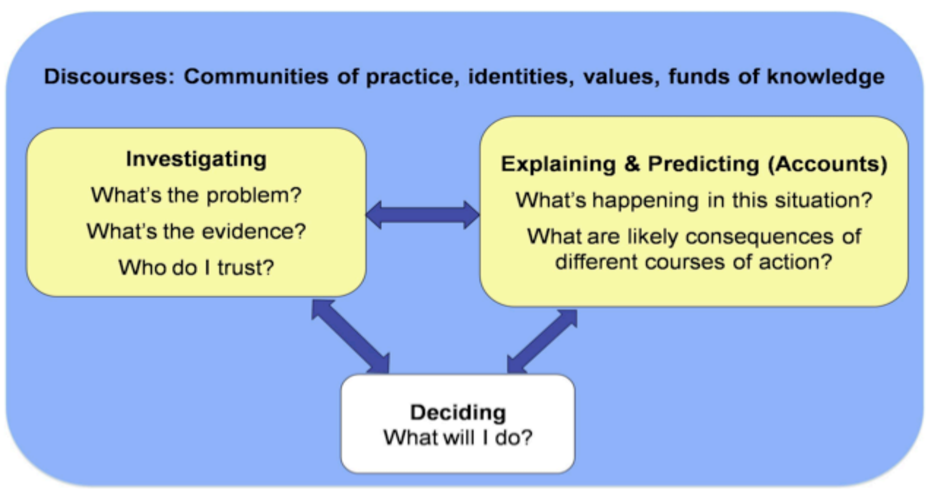
Along with most learning progressions researchers, we hold that knowledge (content) and practice are always connected. We learn content through practice, and we enact content in practice. So the unit of analysis in our learning progressions is the *learning performance:* some kind of content knowledge (such as the knowledge in the Loop Diagrams above) enacted in some form of practice. We have built our learning progressions around two key ideas relevant to this question. First, we focus on *practices of informed citizenship.* Second, our connections between knowledge and practice depend on distinguishing *observations, patterns, and models.*

Practices of informed citizenship: Investigating, accounts, and deciding

Our research has been guided by our ideas about *informed citizenship.* In both public roles (e.g., voter, advocate) and private roles (e.g., consumer, worker, learner) we want to prepare citizens who recognize how our actions affect the material world—the environmental systems on which we and our descendents depend—and can use scientific knowledge to assess the possible environmental consequences of our actions. For us that does not imply any particular political position, but it does mean two things. Citizens should be able to:

- understand and evaluate experts' arguments about environmental issues.
- choose policies and actions that are consistent with their environmental values.

When we investigated how students made decisions about environmental issues (Covitt, Tan, Tsurusaki, & Anderson, 2009), we saw their decisions as emerging from three interconnected practices: *investigating, accounts,* and *deciding,* as depicted in the figure below.[2]



- Investigating and argumentation involve both first-hand inquiry (learning from personal experience) and second-hand inquiry (learning from investigations of other through reports or the media). A key part of investigating involves evaluating arguments from evidence.

[2] We note that there is substantial overlap between these practices and the strands of scientific proficiency in *Taking Science to School:* Know, use, and interpret scientific explanations of the natural world; generate and evaluate scientific evidence and explanations; understand the nature and development of scientific knowledge; and participate productively in scientific practices and discourse. There is also overlap with the scientific practices in the *2009 NAEP Science Framework*: Identifying, using, inquiry, and technological design

- Much of our research so far has focused on what we call *accounts*—the practices associated with explanation and prediction that are closely aligned with the "content" sections of standards documents.
- Both investigations and accounts can contribute to citizens' decision-making practices. While there is a sense in which informed decision-making is the ultimate goal of our learning progressions, it has not been the main focus of our research. Deciding inevitably involves personal and social values that go beyond the realm of science—science does not tell us whether we should give priority to the survival or polar bears in Alaska or jobs in Michigan. So teaching students to make the "right" decisions is a practice that goes well beyond the science curriculum.

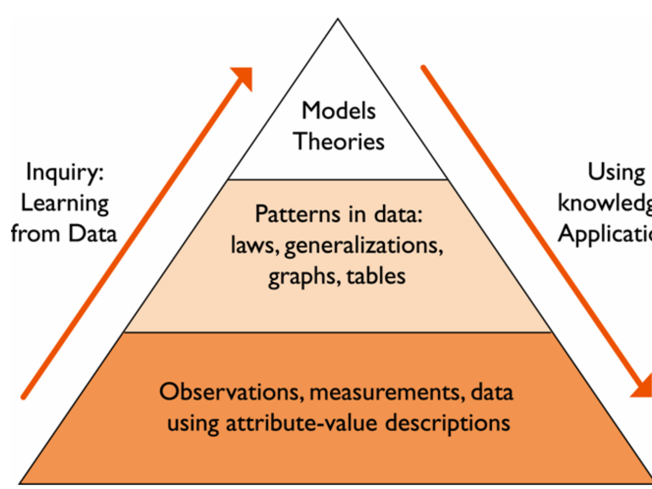
So our concerns have focused mostly on students investigating (i.e., inquiry) practices and their accounts (i.e., explaining and predicting practices). We wish to help students become informed citizens who are capable of using scientific knowledge and practices in support of their decisions.

This brings us to a key point: *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. That is, their inability to evaluate arguments from evidence and use them to explain and predict leaves them without the ability to choose informed decisions.

This observation about environmental science literacy is one that I would use to characterize learning progressions in general. Our goal is not generally to get student to abandon practices that they use when they are younger, even if those practices are non-canonical. It is to give them choices of alternative scientific practices and the ability to use those practices when appropriate.

Connecting content and practice through observations, patterns, and models

Another key idea informing our work concerns the nature of the connections between science content knowledge and practice. These connections depend on key epistemological distinctions among the kinds of knowledge claims that scientists make. In particular, we distinguish among *observations, patterns,* and *models,* as depicted in this figure from the Michigan High School Content Expectations (2006). The pyramid shape of the figure indicates the parsimony of scientific theories: Thousands or millions of observations are distilled into a few patterns, which are explained by even fewer scientific models or theories. We also note that scientists judge the quality of different kinds of knowledge claims according to different criteria: replicability and precision for observations, generality and signal-to noise ratio for patterns, and testability and connectedness for models.



These distinctions among types of knowledge claims make it possible to distinguish inquiry from accounts (application) in ways that connect content and practice. As I discuss below, they turn out to be difficult to make for students (and sometimes teachers) who regard all scientific knowledge as "facts."

3) What are the implications of learning progressions for writing standards?

I will try to answer this question at two levels. First, I will comment briefly on the general nature of learning progressions, then I will discuss results from our research that I think are directly relevant to developing standards.

Comments on the general nature of learning progressions

Learning progressions differ from traditional standards documents in two fundamental ways: (a) the approach to development and validation, and (b) the nature of the "developmental story" that they tell.

Approach to development and validation. It seems reasonable that developers of science education standards, curricula, and assessments should make use of insights from research on science learning. This has rarely happened, however, because developers and researchers work under *different design constraints*. Curricula and large-scale assessment programs need frameworks that describe learning in broad domains over long periods of time. Researchers, on the other hand, are required to develop knowledge claims that are theoretically coherent and empirically grounded. In general researchers have been able to achieve theoretical coherence and empirical grounding only for studies of learning over relatively short time spans (usually a year or less) in narrow subject-matter domains. Faced with a confusing welter of small-scale and short-term studies, developers have understandably based their frameworks primarily on logic and on the experience of the developers.

Recent research on learning progressions has been motivated by guarded optimism that we may be ready to bridge the gap—to develop larger-scale frameworks that meet research-based standards for theoretical and empirical validation. We will call the idea that this is possible the *learning progression hypothesis.*

The learning progression hypothesis suggests that although the development of scientific knowledge is culturally embedded and not developmentally inevitable, there are general patterns in the development of students' knowledge and practice that are both conceptually coherent and empirically verifiable. Through an iterative process of design-based research, moving back and forth between the development of frameworks and empirical studies of students' reasoning and learning, we can develop research-based resources that can describe those patterns in ways that are applicable to the tasks of improving standards, curricula, and assessments. This has two important consequences, which are discussed in more detail in Appendix A.

- *Inclusion of both frameworks and assessments.* At a minimum, learning progressions include both frameworks describing student learning as sequences of learning performances and assessments that measure student progress according to that framework.
- *Iterative development and validation process.* Learning progressions have to be developed through an iterative process in which early versions of frameworks generate hypotheses that can be tested through assessments and teaching experiments, which lead in turn to revisions of the frameworks.

Although we can envision a day when all standards are developed in this way, for now empirically validated learning progression results are limited to a few domains.

Nature of the "developmental story." Both traditional standards and learning progressions seek to place students inside a "story" of increasing scientific competence, but the "stories" that they tell are different. For traditional standards the story is one of the acquisition of scientific knowledge. Developers of a standards document seek to write standards that are all scientifically correct, but ordered from the simplest to the most difficult. Thus a student's scientific knowledge can be described in terms of which standards s/he has mastered, and which ones remain to be learned.

So rather than a story of acquisition of scientific knowledge, learning progressions tell a story that is more like a story of succession in a "conceptual ecology" (Posner, et al., 1982; Toulmin, 1972). Just as "pioneer species" in an ecosystem can create the conditions in which other organisms can flourish, non-canonical ideas and practices (learning performances) can represent important steps toward mature scientific understanding. Rather than focusing on the acquisition of increasingly difficult scientific knowledge, this story is about the evolution of students' conceptual ecologies from lower to higher levels of sophistication.

As described in more detail in Appendix A, this leads us to a general approach in which students' learning performances are organized into increasingly sophisticated *levels of achievement*—the rows of Table 1 in Appendix A—and aligned according to big ideas or *progress variables*—the columns of that table. I will elaborate on these ideas in the discussion of our research below.

Key Results of Our Learning Progression Research

Our current carbon 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. Our work on the water and biodiversity frameworks and assessments has also been substantial, though not as extensive as the work on carbon.

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. Level 4 reasoning is described above, as the knowledge and practices of environmental science literate citizens. In this section I describe three key transitions that students must go through as they progress from Level 1 to Level 4.

Transition 1: 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 based on 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 materials. 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. This transition involves learning to make both conceptual and epistemological distinctions.

Conceptual distinctions: From fungible "forces" to enduring entities. A key difference between force-dynamic and scientific discourse is that students go from seeing the world in terms of *fungible enablers and "forces"* that enable actions or "push and pull" actors and objects to *enduring entities* such as matter, energy, and genetic information. For example, here is a Level 1 student talking about sources of energy for a girl running (from Jin, 2010):

> Researcher: Do you think the girl's body uses the food for energy?
>
> Watson: Yes.
>
> Researcher: Do you know how?
>
> Watson: Because the food helps make energy for the girl so then she can like learn how to walk and crawl and stuff. And it will also help the baby so it will be happy, be not mean and stuff.
>
> Researcher: Yes, ok. Let's talk about the next one. You said sleep, right? So say a little bit about that. How is it related to growth?
>
> Watson: Because it will make it somehow so you'll grow. Because that way you will get more energy so you can like run and jump, and jump rope and walk and play. And that's it.
>
> Researcher: Does the baby's body need sleeping for energy?
>
> Watson: Yes. Because then it will be happy and it won't cry. And it will be able to play and make it so it will eat and stuff.
>
> Researcher: What do you think is energy? What energy is like?
>
> Watson: I think energy is like, it helps it grow and it helps it so it won't be crabby, like when you get mad.

It is pretty clear that "energy" has a much less specific meaning for this Watson than it does for scientists—or than it needs to have for students to understand energy flow in socio-ecological systems. That is, energy is fungible—it is available in a variety of different ways from exchangeable sources. Contrast this with a Level 4 student talking about the growth of a tree:

> Researcher: So how does a tree use air?
>
> Eric: The carbon dioxide in the air contains molecules, atoms, I mean specifically oxygen and carbon, which will store away and break apart to store it and use as food.
>
> Researcher: So do you think that the tree also uses water?
>
> Eric: Yes. The tree also needs water. All living things do. The water is used to help break apart food so that the tree can have energy. It's also used to combine parts of the water molecules together with parts of the carbon dioxide in photosynthesis and used as food.
>
> Researcher: So, you know, the tree, it begins as a very small plant. So over time, it will grow into a big tree and it will gain a lot of mass. Where does the increased mass come from?
>
> Eric: The mass comes from the food that the tree is producing during photosynthesis, which is mostly carbon and hydrogen pieces bonded together and that is then being stored away
>
> … …
>
> Researcher: So you also talk about energy, light energy. So where does light energy go?
>
> Eric: Light energy is, first it's absorbed through the leaves. It is then converted to a stored energy by combining the hydrogen and carbon atoms into various molecules.

Note that Eric has more specific meanings for the different enablers: air specifically provides carbon and oxygen; water specifically provides hydrogen; light specifically provides energy. And these entities are not the same. Note, too that for Watson energy occurs "in the moment;" he does not treat energy as an entity that endures over time, while that atoms and energy in Eric's account endure. Jin (2010) describes these contrasts in terms of *association*—the breadth and specificity of definitions—and *tracing*—the degree to which entities in the account are present before the event and endure after the event is over. Appendix B has Jin's descriptions of the four levels of achievement in terms of association and tracing.

Epistemological distinctions: From "facts" to observations, patterns, and explanations. Reasoning at the lower levels is also notable for its "epistemological flatness:" Students regard all scientific knowledge as "facts" rather than recognizing that science includes different kinds of knowledge claims that are validated and used in different ways. This has serious consequences for their approaches to both accounts and investigations, as described below.

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.

Transition 2: Accounts

We have found that students at all levels are familiar with socio-ecological 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 carbon 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.

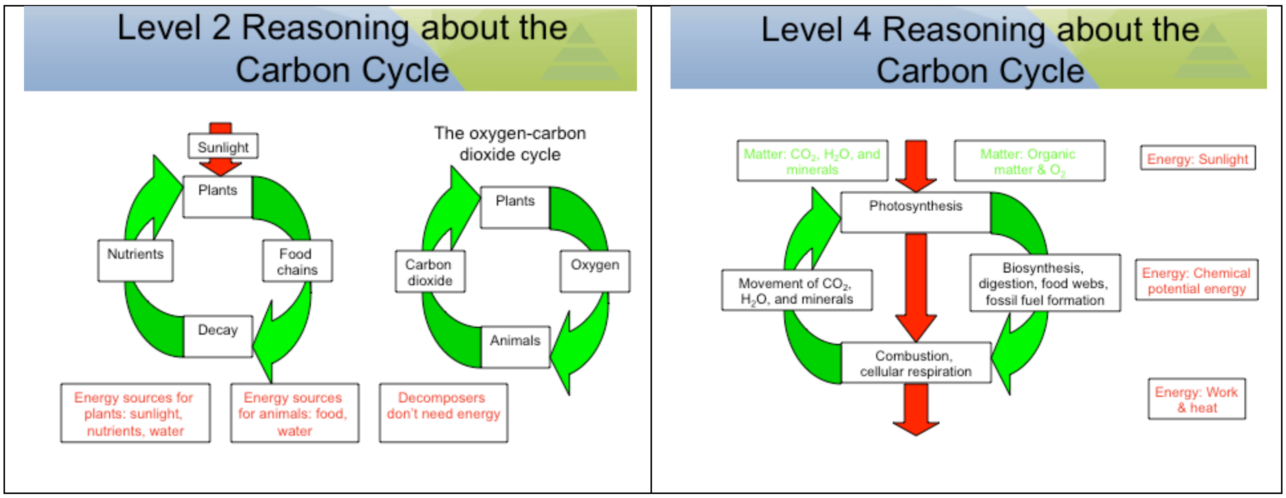
Table 1: Contrasting ways of grouping carbon-transforming processes

<table>
<tr><td rowspan="2">Upper Anchor: Scientific accounts</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 grouping and 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 if those atoms are going in and not coming out. 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 the Loop Diagram above. In contrast the reasoning in the loop diagram, 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.



Appendix C has summaries of the key transitions for all three of our current learning progressions, carbon, water, and biodiversity.

Transition 3: Arguments from evidence and inquiry 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.

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 scientific standards for arguments from evidence. 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

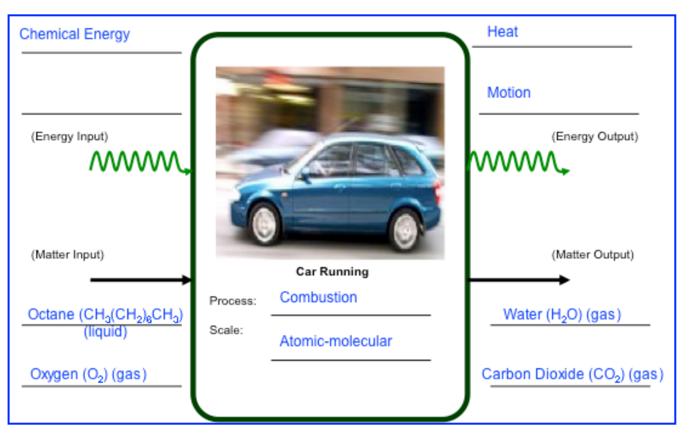
administration had not provided anything to refute it. (What are they trying to hide???) I said he was born in Hawai'i and this had been repeatedly shown to be true.. they countered with the information that his grandmother was quoted as saying she had been at his birth in Kenya! So how do you argue 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 and 2 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 3).

Our research to date both documents the virtually complete failure of our science education system to achieve these goals. Though this should give us pause as we develop new standards, our teaching experiments suggest that the goals are potentially reachable, and they are too important for us to abandon.

References

American Association for the Advancement of Science Project 2061 (1993). Benchmarks for science literacy. New York: Oxford University Press (http://project2061.aaas.org/tools/benchol/bolframe.html).

Anderson, C. W. (2009, December). Learning in high school: Learning progressions for environmental science literacy. Invited presentation to the National Research Council Board on Science Education, Beckman Center, Irvine, CA.

Chen, J., Anderson, C. W.. and Jin, X. (2009, April). American and Chinese students' written accounts of carbon cycling in socio-ecological systems. Presented at the annual meeting of the National Association for Research in Science Teaching, Garden Grove, CA.

Committee on Science Learning, Kindergarten through Eighth Grade. Richard A. Duschl, Heidi A. Schweingruber, and Andrew W. Shouse, editors. (2007). Taking science to school: Learning and teaching science in grades K-8. National Research Council, Board on Science Education, Center for Education, Division of Behavioral and Social Sciences and Education. Washington, DC: The National Academies Press.

Covitt, B. A., Tan, E., Tsurusaki, B. K., and Anderson, C. W. (2009, April). Students' Use of Scientific Knowledge and Practices When Making Decisions in Citizens' Roles. Presented at the annual meeting of the National Association of Research in Science Teaching, Garden Grove, CA.

Gunckel, K. L., Mohan, L., Covitt, B. A., & Anderson, C. W. (in preparation, 2009). Learning progressions in environmental science literacy: Shifts from primary to secondary discourse. To appear in A. Alonzo and A. W. Gotwals (eds.) Learning progressions in science.

Hartley, L., Wilke, B., Schramm, J., and Anderson, C. W. (2009, April). Are college students prepared to understand ecosystem carbon cycling? Why it's important and how principled reasoning can help. Presented at the annual meeting of the National Association for Research in Science Teaching, Garden Grove, CA.

Jin, H. (2010, February). Developing a learning progression for energy and causal reasoning in socio-ecological systems. Presentation to the Ohio State University faculty.

Jin, H., & Anderson, C. W. (submitted, 2009). Development and validation of assessments for a learning progression on carbon cycling in socio-ecological systems. To appear in A. Alonzo and A. W. Gotwals (eds.) Learning progressions in science.

Jin, H., Choi, J. & Anderson, C. W. (2009, June). Development and validation of assessments for a learning progression on carbon cycling in socio-ecological systems. Proceedings of the Learning Progressions in Science Conference, Iowa City, Iowa. http://www.education.uiowa.edu/projects/leaps/proceedings

Jin, H., Zhan, L., and Anderson, C. W. (2009, April). Interviews with American and Chinese students about carbon cycling in socio-ecological systems. Presented at the annual meeting of the National Association for Research in Science Teaching, Garden Grove, CA.

Long Term Ecological Research Network (2007). Integrative Science for Society and the Environment: A Plan for Research, Education, and Cyberinfrastructure in the U.S. Long-Term Ecological Research Network. Long Term Ecological Rsearch Network (http://www.lternet.edu/decadalplan/).

Metz, K. (2004). Children's understanding of scientific inquiry: Their conceptualization of uncertainty in investigations of their own design. Cognition and Instruction, 22(2), 219-290.

Michigan Department of Education (2006). Michigan Science High School Content Expectations. Lansing, MI: Michigan Department of Education.

Mohan, L., & Anderson, C. W. (2009, June). Teaching experiments and the carbon cycle learning progression. Proceedings of the Learning Progressions in Science Conference, Iowa City, Iowa. http://www.education.uiowa.edu/projects/leaps/proceedings

Mohan, L., Chen, J., and Anderson, C. W. (2009). Developing a multi-year learning progression for carbon cycling in socio-ecological systems. Journal of Research in Science Teaching, 46 (6), 675-698.

National Research Council (1996). National science education standards. Washington, DC: National Academies Press (http://www.nap.edu/readingroom/books/nses/html).

Pinker, S. (2007). The stuff of thought: Language as a window into human nature. New York: Viking Press

Posner, J., Strike, K., Hewson, P., & Gertzog, W. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*, 211-227.

Talmy, L. (1988). Force dynamics in language and cognition. Cognitive Science, 12, 49-100.

Talmy, L. (2003). Toward a cognitive semantics, Volume 1: Concept structuring systems (language, speech, and communication). Cambridge, MA: MIT Press

Toulmin, S. (1972). *Human understanding.* Princeton, NJ: Princeton University Press.

Wilson, C. D., Anderson, C. W., Heidemann, M., Merrill, J., Merritt, B. W., Richmond, G., Sibley, D. F., and Parker, J. M. (2006). Assessing Students' Ability to Trace Matter in Dynamic Systems in Cell Biology. CBE—Life Sciences Education, 5(4), 323–331.

Appendix A: General Framework and Validation of Learning Progressions

General Framework for Learning Progressions

Table 1 uses a learning progression that we are working on now, focusing on the development of environmental science literacy, to illustrate key features of a framework for learning progressions.[3] Most current research on learning progressions uses similar frameworks, though there is little consistency in vocabulary. The successive learning progression frameworks that we have developed have the same general structure, represented in Table 1. It identifies a unit of analysis: Learning Performances. It organizes students' Learning Performances according to (a) Progress Variables and (b) Levels of Achievement.

Table 1: Learning Progression Framework

<table>
<tr><th rowspan="2">Levels of Achievement</th><th colspan="5">Progress Variables (Carbon-transforming processes)</th></tr>
<tr><th>Photosynthesis</th><th>Digestion, biosynthesis</th><th>Cellular Respiration</th><th>Combustion</th><th>Large-scale processes</th></tr>
<tr><td>4: Qualitative model-based accounts</td><td colspan="5" rowspan="4">Learning performances for specific processes and Levels of Achievement:
Accounts of processes in socio-ecological systems</td></tr>
<tr><td>3: "School science" narratives</td></tr>
<tr><td>2: Events with hidden mechanisms</td></tr>
<tr><td>1: Force-dynamic narratives</td></tr>
</table>

Progress variables are our versions of what is sometimes referred to in the literature on learning progressions as "big ideas" (Catley, Lehrer, and Reiser, 2005; NRC, 2007, Chapter 8; Smith, et al., 2006). These are aspects of knowledge and practice that are present in some form at all Levels of Achievement, so that their development can be traced across Levels. The development of Progress Variables is an iterative process; they are derived partly from theories about how knowledge and practice are organized and partly from empirical research on assessment and student reasoning (Briggs, Alonzo, Schwab, & Wilson, 2004; Wilson, 2005, Draney & Wilson, 2007). In this learning progression, our progress variables are carbon-transforming processes in socio-ecological systems. Students have ways of accounting for these processes or their visible manifestations (e.g., plant growth for photosynthesis, animal growth for transformation of organic carbon, decay for cellular respiration) at all Levels of Achievement, so that their development can be traced across Levels.

Levels of Achievement are patterns in learners' knowledge and practice that extend across Progress Variables (see Mohan, Chen, & Anderson, 2009; Jin & Anderson, 2007). This is a key part of the learning progression hypothesis—that students' performances for different Progress Variables will be

[3] In this project we are developing a learning progression extending from upper elementary school through high school, focusing on key biogeochemical processes in socio-ecological systems at multiple scales, including cellular and organismal metabolism, ecosystem energetics and carbon cycling, carbon sequestration, and combustion of fossil fuels. These processes: (a) create organic carbon (photosynthesis), (b) transform organic carbon (biosynthesis, digestion, food webs, carbon sequestration), and (c) oxidize organic carbon (cellular respiration, combustion). All of these processes are included in current national standards. The primary cause of global climate change is the current worldwide imbalance among these processes.

aligned in predictable ways. As with Progress Variables, the development of Levels of Achievement is iterative; they are based partly on research about what constitutes higher and lower levels of performance and partly on data about students' actual performances. The five Levels of Achievement in this learning progression describe performances we have seen in students from upper elementary grades through high school.

Learning Performances are the contents of the individual cells of Table 1: the specific practices characteristic of students who are at a particular Level of Achievement and reasoning about a particular Progress Variable. Describing specific Learning Performances is at the core of the learning progressions hypothesis: The Learning Performances should be consistent with their position in Table 1, but they also provide specific predictions about student reasoning and student learning that can be tested empirically. Thus it is through Learning Performances that we can link the learning progression framework to empirical data from assessments and teaching experiments, enabling us to test the learning progression hypothesis.[4]

Standards and Processes for Validation

Here is my list of the qualities that we are trying to achieve in developing our learning progressions—our version of coherence, comprehensiveness and continuity.

- *Conceptual coherence:* a learning progression should "make sense," in that it tells a comprehensible and reasonable story of how initially naïve students can develop mastery in a domain.
- *Compatibility with current research:* a learning progression should build on findings or frameworks of the best current research about student learning. This research rarely provides precise guidance about what Learning Performances are appropriate for students at a particular grade level, but it does provide both domain-specific (i.e., focusing on specific subject matter) and domain-general (i.e., focusing on more general aspects of learning and reasoning) constraints on learning progressions.
- *Empirical validation:* The assertions we make about student learning should be grounded in empirical data about real students.

These criteria are applied to the key elements of the structure of learning progressions—Learning Performances, Levels of Achievement, and Progress Variables—in Table 2. The development and validation of learning progressions are iterative processes. We develop initial frameworks that reflect what we know from previous research and our experience, as well as our attempts to meet make the framework conceptually coherent. We use these frameworks to develop assessments and/or teaching experiments. We use the results of this empirical validation process to revise the frameworks. Then we start the process over again. With each new iteration we make progress toward meeting all of the criteria.

---

[4] For this learning progression we have identified a particular type of learning performance as the unit of analysis: *accounts of processes in socio-ecological systems.* The three parts of this phrase each have significance:

- Accounts: in focusing on accounts we are deciding to look at students' language, particularly accounts or stories about environmental events. This unit of analysis can hopefully allow us to make comparisons among accounts of the same or similar events for students of different ages and backgrounds.
- Processes: focusing on processes emphasizes the dynamism of the systems we are interested in. We want to see how students explain events, not just properties of the systems themselves.
- Socio-ecological systems: We are interested in the environmental systems box and the two arrows of the loop diagram (Figure 1), as well as the hierarchy of systems at different scales.

Table 2: Criteria for Validity of Learning Progressions

Characteristic of Learning Progressions	***Conceptual Coherence***	***Compatibility with Current Research***	***Empirical Validation***
Individual cells: Learning performances	• Learning performances are described in consistent ways, including (a) knowledge, (b) practice, and (c) context—real-world systems and phenomena.	• Learning performances are compatible with those described in the research literature.	• Learning performances describe actual observed performances by real students. • Students are consistent across different questions or modes of assessment (e.g., written assessments and clinical interviews) that assess the same learning performance
Rows: Levels of Achievement	• Levels are conceptually coherent: Different Learning Performances reflect some underlying consistency in reasoning or outlook	• Levels reflect consideration (explicit or implicit) of strands of scientific literacy (see above).	• Levels have predictive power: Students should show similar Levels of Achievement for Learning Performances associated with different Progress Variable.
Columns: Progress Variables	• Definition of Progress Variable captures important aspects of Learning Performances at all Levels of Achievement	• Progress from one Level to the next is consistent with research on students' learning, considering all strands of scientific literacy	• Progress from one Level to the next can be achieved through teaching strategies that directly address the differences between Learning Performances

Why Worry about Validation?

So this brings us back to a question: How important are *all* of the criteria in Table 2. How many of them should be met, and how well, in a learning progression? Dr. Heritage focuses primarily on the criteria in the first column: conceptual coherence. So what about the other two columns: Are compatibility with current research and empirical validation necessary for all learning progressions, or they luxuries that we all want, but can't afford while we get on with the important business of developing standards, curricula, and assessments?

There is no single answer to this question, of course; we need consider which criteria are important for which purposes. I want to make the argument, though, that the potential of learning progressions to transform standards, curricula, and assessments for the better lies largely in those research-based qualities: compatibility with current research and empirical validation. I would like to try making this case with a quote from Laurel Hartley, and ecologist who is participating in our learning progressions work.

> [We can make] parallels between a learning progression and an ecological model. The steps seem very much the same in that 1) you start with some initial information and you create a framework or model that you think is an accurate representation of how things really are, 2) then you make predictions based on your model and you "ground-truth" those predictions by seeing if what your model predicts is what happens in actuality, 3) then you use that new information about how well your model worked to further refine the parameters of your model, 4) then you ground-truth and adjust parameters again and again until your model becomes a satisfactory representation of reality. In ecology, you can use a good model to predict future events before they happen or to generate reliable approximations about a system without having to take a ton of expensive, time-consuming field measurements. In science education, a good model can help teachers predict the development of their students' understanding over time and it can help a

> curriculum writer or assessor to create developmentally appropriate material in a more efficient way. (Hartley, personal communication, 2/14/08)

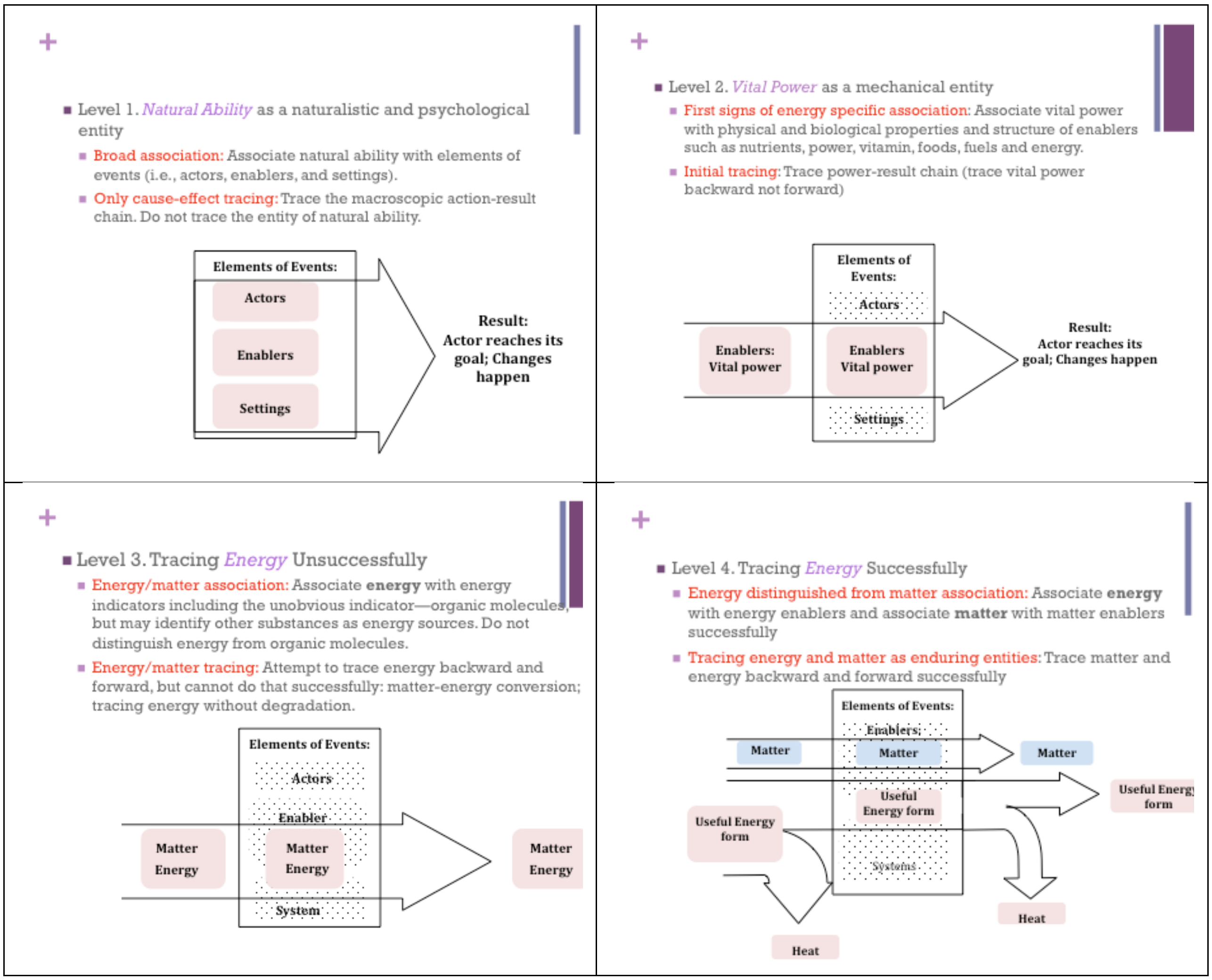
The learning progression hypothesis suggests that, as Dr. Hartley argues, a good model can be a powerful thing in education as well as in ecology. We can't create good models, though, just by developing conceptually coherent frameworks and using them. The model gains both power and validity through "ground-truthing"—the painstaking process of empirical validation.

I believe that this work suggests a worthwhile alternative to current procedures for developing standards and large-scale assessments. Standards and assessments are currently developed through a linear process: Standards are developed and finalized, then those standards are used as the basis for assessments and curricula. If assessment development suggests ways that the standards can be improved, it's too late; the standards will not be revised for at least several years. In contrast, learning progressions are developed through an iterative process of design-based research, where the results of the assessments are used to revise frameworks, and vice versa.

I think that our best opportunities for truly productive dialogue between researchers and developers can be found this process of empirical validation. A conceptually coherent framework is an important step as the first draft of a learning progression. If researchers and developers can use that framework to develop assessments and teaching experiments, *then use the results of those assessments and teaching experiments to revise the framework,* then we will be on our way to "ground-truthed" models that can guide practice in new and more powerful ways.

Appendix B: Levels of Reasoning about Energy in Carbon-transforming Processes

The figures and tables in this Appendix (from Jin, 2010) detail the levels of understanding in students' accounts of energy and its role in causation. Level 1 reasoning is force dynamic; students think of energy as primarily occurring "in the moment" of a an event (not tracing it as an enduring entity) and as being associated with many different aspects of the event (broad association). In contrast, Level 4 students trace energy through time, but give it a much more specific role in the event (narrow association). Levels 2 and 3 are intermediate stages.



	Association	**Tracing**
Level 4	Energy • Associate energy with energy indicators consistently; • Identify energy sources correctly • Energy clearly and consistently distinguished from matter and from other enablers such as conditions	Trace **energy** at atomic-molecular and global scales successfully • Trace energy with degradation and separately from matter in carbon-transforming processes across scales.
Level 3	Energy • Associate energy with energy indicators including unobvious indicators such as familiar organic molecules, but may identify other substances as energy sources or do not distinguish energy and organic molecules.	Trace **energy** at atomic-molecular and global scales unsuccessfully: • Trace energy without degradation in large-scale systems such as ecosystems (e.g., energy recycles). • Trace energy and matter but with confusion about labels (e.g., glucose is energy; ATP is energy) and or matter-energy conversions (e.g., fuel is converted to heat and light in flame) • Describe energy transformation correctly but cannot connect that to matter transformation in chemical reaction
Level 2	Vital power: • Recognize that actors cannot create vital power and that they must gain vital power from enablers • Recognize that enablers contain vital power (the notion of vital power is indicated in a list of words that students use such as energy, vitamin, nutrients, combustible, etc.) • Associate energy with obvious indicators, but also hold the idea that all enablers are energy sources	Trace the **power-result chain** in uphill and downhill events: • Trace power/energy backwards but not forwards • Actor gaining vital power/energy through hidden processes • Vital power triggers hidden processes • Actor losing vital power through hidden processes • Can trace "energy" through food chains
Level 1	Natural Ability: • Associate natural ability with elements of events such as actors, enablers, settings, aspects of processes, and so on.	Trace the macroscopic **action-result chain** in uphill and downhill events: • The actor uses its enablers to take action. As the result, it reaches its goals to keep alive, to grow, to keep burning, and so on. • When the actor loses its natural ability or loses enablers, it changes towards the downhill direction. • Do not trace any scientific entities behind the action-result chain. Actors and settings endure over time, but not materials (in chemical changes) or energy.

Appendix C: Transitions for Carbon, Water, and Biodiversity Learning Progressions

This table compares and contrasts informal reasoning (predominant in current high school students) and scientific reasoning (what we need for environmentally science literate citizens) in terms of five aspects:

Hierarchical reasoning: Understanding and connecting models of systems and processes at different spatial and temporal scales

1. *Observing and interpreting macroscopic systems and processes.* High school students tend not to be aware of critical aspects of systems around them that are required for scientific understanding. This lack of understanding of systems and processes, results in an inability to see important patterns, apply principles such as conservation of matter and energy, or make connections across scales of these systems.
    a. gaseous reactants and products and chemical potential energy for carbon-transforming processes;
    b. interconnections among surface water, ground water, and atmospheric water systems, and human engineered systems;
    c. (phylo)genetic and functional diversity in natural and managed biological communities.
2. *Explaining with subsystem models.* High school students have learned *facts* about microscopic and atomic-molecular subsystems, but they cannot use them as *tools* to explain macroscopic and landscape-scale phenomena, for example:
    a. models of chemical change in carbon-transforming processes,
    b. dissolved and suspended substances that affect water quality,
    c. genetic resources that constrain phenotypic plasticity in organisms.
3. *Large-scale systems and processes*. High school students tend to see humans as caretakers or managers who can shape landscape-scale and global environments, rather than seeing systems that operate predictably in accord with scientific principles:
    a. Energy flow and carbon reservoirs and fluxes
    b. Reservoirs and fluxes of water and materials carried by water
    c. Biological communities constrained by phylogeny (dispersal), environment, population dynamics, disturbance

Discourse and practice: Understanding core characteristics of scientific accounts, practices, and values

4. *Principled reasoning*. High school students tend to "learn science" by fitting scientific facts and definitions into narratives about the world and how it works that are at odds with scientific principles and models.
    a. High school students tend to reason about environmental systems in force-dynamic ways (Talmy, Pinker). Processes are caused by actors (humans, animals, plants, machines, flames) with different needs and powers, as well as some "natural" processes. What happens depends on the "balance of forces" exerted by different actors according to their powers.
    b. These students tend not to use scientific reasoning, which constructs models of systems that operate according to specific rules determined by natural laws or principles, including conservation of matter and energy and genetic continuity.
5. *Inquiry and scientific argument.* The core issue here is how people deal with uncertainty about the present state of socio-ecological systems and the effects of our actions on those systems.
    a. High school students often rely on social judgments about who is trustworthy and tend to believe either that the truth is absolutely knowable or that truth is relative—different for different people and cultures.
    b. Whereas, scientific literacy involves accepting that uncertainty can never be completely eliminated, but that it can be reduced by rigor in method and argument and by collective validation based on consensus (not just a majority) of scientific communities.

Comparing Informal and Scientific Reasoning at the High School Level

Issue	***Carbon***		***Water***		***Biodiversity***		***Inquiry***	
Level	***Informal***	***Scientific***	***Informal***	***Scientific***	***Informal***	***Scientific***	***Informal***	***Scientific***
Observing and Interpreting Macroscopic Systems and Processes	Actors (plants, animals, machines, flames) Needs Results	Processes in systems, including invisible gases and chemical potential energy	Water in the landscape, serving the needs of actors and manipulated by actors	Water systems, including surface, ground, atmospheric water, human-engineered systems	Undifferentiated landscapes, "stages" for charismatic macrofauna and a few identifiable plants, insects	Interactive biological communities of populations distinguished by phylogeny and function	Knowledge cannot dispel uncertainty (Your guess is as good as mine), OR Trust in: -authority (trust books and people who know) -community (trust sources your friends trust) -personal experience (seeing is believing) Trust based on social judgments about bias, self interest	World is fraught with uncertainty, but it can be reduced through rigor in method and argument: --precision and reliability in data generation --rigor in pattern finding --theoretical arguments from evidence —collective validation by consensus of scientific communities
Explaining with Subsystem Models	Organs, cells, molecules, atoms as "facts" about systems and processes	Atomic-molecular models of chemical change	Water quality as property of water itself	Water quality as dissolved or suspended materials in water	Heredity and environment as comparable "forces" shaping individual organisms	Phenotypic plasticity separate from genetic resources		
Large-scale Systems and Processes	Separate oxygen-CO_2 and nutrient (food webs, decomposition) cycles	Socio-ecological carbon reservoirs and fluxes Energy flow	Water moving around, polluted or purified by nature and humans	Fluxes and reservoirs of water and other substances in watersheds with human intervention	Landscapes shaped by nature or managed by humans	Biological communities constrained by phylogeny (dispersal), environment, population dynamics, disturbance		
Principled Reasoning	Actors accomplish their purposes if their needs are met	Processes constrained by conservation of matter, conservation and degradation of energy	Humans have the power to move, pollute, purify water in the landscape; no need to explain mechanism	Humans rely on ecosystem services or engineer processes that follow physical and chemical constraints	Individuals and communities are shaped by the most powerful "forces," including dominant organisms, human management, forces of nature	Communities rely on primary production, constrained by genetic resources, environment, community dynamics		