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Addressing Challenges in Developing Learning Progressions for Environmental Science Literacy

Kristin L. Gunckel, University of Arizona
Lindsey Mohan, Michigan State University
Beth A. Covitt, University of Montana
Charles W. Anderson, Michigan State University

In a world where human actions increasingly affect the natural systems on which all life depends, we need educated citizens who can participate in personal and public decisions about environmental issues. The effects of global warming have wide-reaching ramifications. No longer can policy decisions be made by a select few. For example, decisions about how to distribute water so that urban, agricultural, and natural ecosystems have adequate water supplies or about whether to tax carbon emissions require that citizens understand scientific arguments about the effects of our actions. Scientists and policy makers are presenting results of scientific research directly to the public–for example, 2007 Nobel Prize Winners Al Gore (2006) and the Intergovernmental Panel on Climate Change (2007). A question that confronts us as science educators is how we can help the public to respond to these reports and the debates around them: How can we prepare our citizens to engage directly in the collective human response to global climate change?

The purpose of the Environmental Literacy Project is to contribute to the preparation of citizens to participate in the necessary collective response to global and local environmental issues. We believe that citizens must have an understanding of underlying scientific models and principles in order to evaluate experts' arguments about environmental issues and recognize policies and actions that are consistent with their environmental values. Environmental science literacy requires understanding of many aspects of science, including chemical and physical change, carbon cycling, water cycling, biodiversity, and evolution by natural selection. These phenomena are currently addressed in many state and national standards documents and in school curricula, but typically they are addressed in disconnected ways—in different courses or in different units in the same course.

Research in the Environmental Literacy Project is divided into four strands. Research groups for three of these strands are working to develop and validate learning progressions leading toward connected and coherent understandings of three key aspects of socio-ecological systems: water (Covitt, Gunckel, & Anderson, 2009; Gunckel, Covitt, Dionise, Dudek, & Anderson, 2009), carbon (Jin & Anderson, this volume; Mohan, Chen, & Anderson, 2009), and biodiversity (Zesaguli, Wilke, Hartley, Tan, Schenk, & Anderson, 2009). A fourth research group has investigated students' decision-making practices in citizenship roles (Covitt, Tan, Tsurusaki, & Anderson, 2009). The work on citizenship practices is relevant to the other three research strands of the project because it explores students' developing capacities to use their understandings of water cycling, carbon cycling, and biodiversity to make informed and responsible decisions about socio-ecological issues.

The goal of developing an environmental science-literate citizenry defines the parameters of our learning progression frameworks. Three parameters are of particular importance. First, developing environmental science literacy involves both cognitive and sociocultural aspects of learning. Citizens must understand the conceptual scientific models related to important environmental issues and be able to draw on their understanding of models to participate in discussions and decision-making processes. These two aspects of learning mean that we must address such questions as: What cognitive models and types of reasoning are necessary for understanding environmental issues? What forms of participation are valued in a community, and how does one become an informed and engaged member of a community? We have chosen to develop frameworks that describe changes in students' knowledge and practices as they progress toward environmental science literacy.

Second, our learning progressions cover broad scientific content areas. Even within the domain of any single strand of our research (i.e., water or carbon), the content involves multiple conceptual models. Furthermore, environmental science literacy involves making interconnections among the three content domains. Therefore, our learning progression frameworks do not focus on any single conceptual model (e.g. atomic-molecular theory). Rather, we have chosen to focus our learning progression frameworks on the changes in knowledge and practices that are apparent as students develop scientific, model-based views of the world.

Third, our learning progressions are not tied to a specific curriculum or curriculum material because we want to describe the current progression of student thinking given the status quo curriculum and state of education. We seek to develop learning progressions for a large age range of students, from upper elementary through high school, in urban, suburban, rural, and international settings. Our frameworks have to account for diversity in student backgrounds and grade levels. Therefore, we have chosen to use a large-grain size in defining the steps in our learning progression in order to make evident the patterns in student thinking across this wide range of students.

In this chapter, we describe our responses to two challenges that these choices have presented to our work. One challenge we have faced is *defining what progresses in a learning progression* that spans a large grade range of diverse students across three conceptual domains. We have found that elementary students' accounts of phenomena rely on a different worldview and different word meanings from the scientific understandings we want students to develop by twelfth grade. This challenge has led us to use a Discourses framework for all of our learning progressions. We describe this framework in the context of the water cycle learning progression. Another challenge we have faced is *describing the role that instruction plays in defining a learning progression*. We have identified two possible pathways that students could take through our learning progressions and hypothesize that each pathway may be linked to different instructional approaches. We describe these pathways and approaches in the context of the carbon cycle learning progression.

Challenge 1: What Progresses in a Learning Progression?

Our approach to defining what progresses in our learning progressions has changed over time. During our initial rounds of framework development, we focused on determining what students did and did not understand about the big ideas in each domain. However, we soon discovered that we had difficulty connecting the responses that younger students gave us to the responses that older students provided and connecting both younger and older students' ideas to the scientific, model-based reasoning of environmental science literacy without taking a deficit perspective on younger students' responses and thinking. For example, when we asked students if the rain near the ocean would be salty, we received some responses from young students that included, "No, because the rain taste[s] the same," and "No because it's filtered by the sky." Older students' responses included "No because as it [the water] evaporates back into the clouds, the salt molecules are too heavy to evaporate as part of the water molecules." One interpretation could have been that the younger students had misconceptions about how water and substances cycle through the atmosphere and the older student had conceptions that were closer to correct. However, this interpretation only told us about what the students did not understand. It did not help us understand how the younger students' reasoning might change to be more like the older students' ideas.

We realized that students were reasoning about the problems we posed to them in very different ways from the ways that scientists would reason about the problems. We initially sought to make sense of the differences by contrasting informal narrative accounts with scientific model-based accounts of phenomena. However, we eventually realized that both informal and scientific accounts can take the form of narratives; they are merely different types of narratives. Informal narratives tell stories about actors that make things happen. Scientific accounts also tell stories about phenomena. However, scientific narratives are constructed using scientific laws and principles to constrain possible outcomes and explanations. Thus, when asked what happens to a puddle on the ground, a student who provides an informal narrative may say that the sun dried up the water, while a student using a scientific narrative will recognize that the water does not disappear but instead changes state by saying that the water in the puddle evaporated to become water vapor in the air.

Furthermore, our choice to focus on the sociocultural aspects of learning meant that we had to develop a framework that accounted not just for students' conceptions and reasoning, but also for how they participate in various communities. Members in different communities provide different types of accounts for phenomena, based upon the norms for talking and interacting within a community and the purposes for the account (Driver, Asoko, Leach, Mortimer, & Scott, 1994). Children talking with parents at home may use informal, everyday narratives of the world that would be insufficient and unacceptable among scientists grappling with scientific problems. To address these challenges, we turned to a Discourses-Practices-Knowledge framework to organize our learning progressions and track changes in student thinking.

Discourses-Practices-Knowledge Framework

In the Discourses-Practices-Knowledge framework, learning is conceptualized as the process of mastering a new Discourse (Cobb & Hodge, 2002; Wenger, 1998).

Discourses are the ways of talking, thinking, and acting that identify a socially meaningful group. Discourses are enacted in communities through the practices in which members of the community engage (Gee, 1991). Participating in the practices of a community, in turn, requires specific knowledge. Figure 1 shows the embedded relationship of knowledge in practices in Discourses. Tracking students' progress as they learn new Discourses requires tracing changes in student knowledge as students engage in new practices.

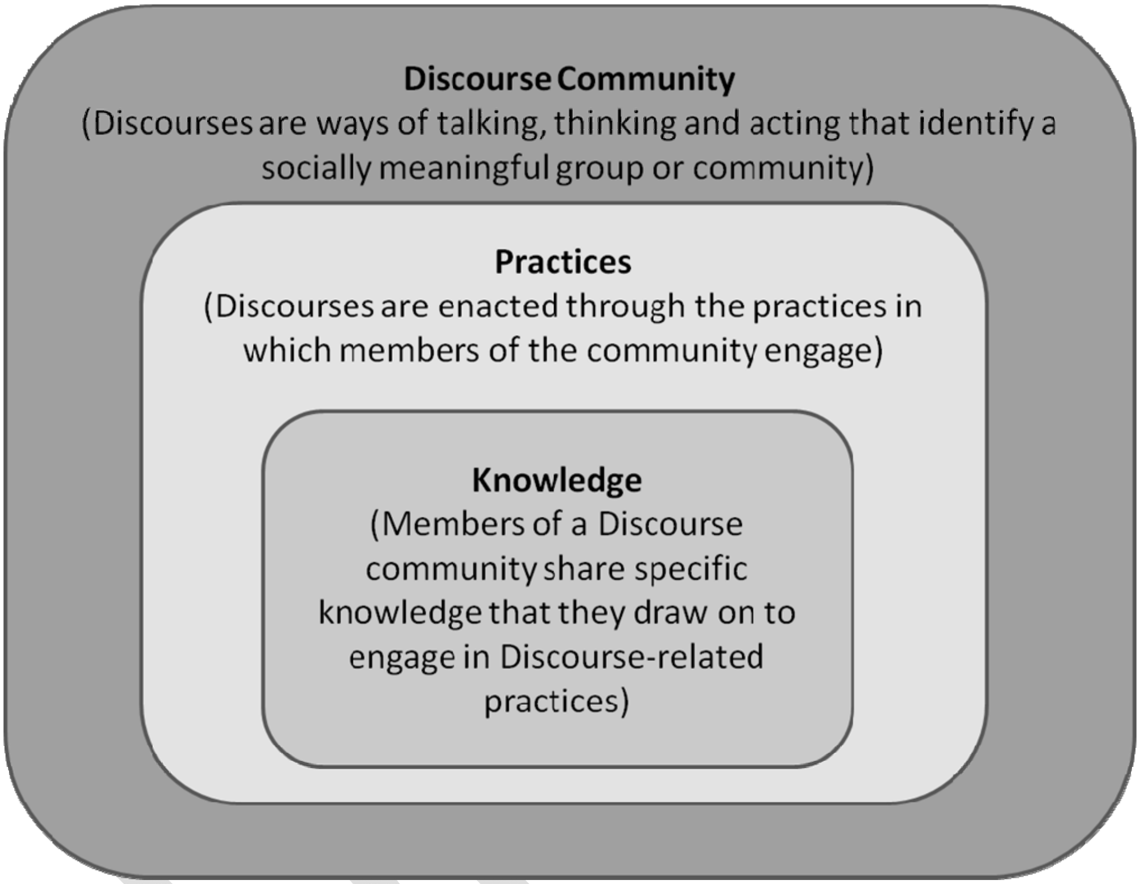

Figure 1. Embedded relationships among Discourses, practices, and knowledge.

Discourses. We describe the patterns of language use that define the perspectives, values, and identities that link people together in social networks as Discourses. These Discourses provide the lenses through which people see and make sense of their world.

People participate in many different communities during their lives and can thus draw on many Discourses. Everyone starts life with the primary Discourse of their home community. "All humans… get one form of discourse free, so to speak… This is our socioculturally determined way of using language in face-to-face communication with intimates…" (Gee, 1991, p. 7). As people expand their communities of participation, they learn new, or secondary, Discourses.

> Beyond the primary discourse, however, there are other discourses which crucially involve institutions beyond the family…. Let us refer to these institutions as secondary institutions (such as schools, workplaces, stores, government offices, businesses, or churches)….

> Thus we will refer to them as “secondary discourses.” (Gee, 1991, p. 8)

In our framework, students’ primary Discourses define the lower end of our learning progressions. The process of learning involves mastering the ways of talking, thinking, and acting of secondary Discourses. The target secondary Discourse for the Environmental Literacy Project learning progressions is the Discourse of environmentally-literate citizens capable of using science to inform their participation in the roles of democratic citizenship (Covitt, Gunckel, et al., 2009; Covitt, Tan, et al., 2009; Mohan, Chen, & Anderson, 2009). For example, with respect to the water cycle, environmentally literate citizens participate in the collective decision-making processes necessary to maintain and protect adequate fresh water quality and quantity for people and the natural ecosystems on which humans depend. Below we describe the primary and secondary Discourses that are relevant to our learning progressions.

Primary Discourse: Force-Dynamic Reasoning. Students’ primary Discourses provide insight into how students make sense of their world. Understanding students’ primary Discourses is about more than just determining what students do and do not know about the world; it also involves understanding how students view the world and their experiences in the world.

Although there are many different primary Discourses rooted in diverse sociocultural communities, one common feature that they share is a force-dynamic approach to explaining the events of the world. Linguist Stephen Pinker (2007) and developmental psychologist Leonard Talmy (1988) argue that there is a “theory of the world” built into the basic grammar of all languages. We must learn this theory in order to speak grammatical English, and this theory, in turn, shapes how we view and explain events. Talmy and Pinker label this theory of the world force-dynamic reasoning[1].

> 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).

Pinker notes that this structure is present in many other languages, not just English. Thus, characteristics of how students make sense of the world are rooted in the grammatical structure of the language of their primary home Discourse. Recognizing these characteristics in students’ primary Discourses allows us to use patterns in students’ language structures to look across students’ diverse social and

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[1] We recognize that there is a large literature on communities and discourse in education and science education, in particular, and on the differences between students’ home communities and school (Heath, 1983; Lee & Fradd, 1998; O'Connor & Michaels, 1993). We respect and have learned from this literature. In this chapter we are referring to specific characteristics of students’ language and the relationship between language and how they make sense of the world.

cultural home communities and find common patterns in their ways of thinking about the world.

Force-dynamic reasoning explains the events of the world in terms of cause and effect relationships between objects with "intrinsic tendencies and countervailing powers" (Pinker, 2007, p. 219). Characteristics of force dynamic reasoning include:

- *Actors and abilities*. The events of the world are largely caused by actors in accord with their abilities. Humans have the most abilities, followed by animals, then plants. Dead things have no abilities, so they are acted on by other actors. Non-living entities such machines can be actors with limited abilities. Depending on the situation, water can also be an actor, such as when a river carves a canyon.
- *Purposes and results.* Actors have goals or purposes, and the results of events are generally the fulfillment of the actors' purposes. Higher level actors can have many purposes, so animals grow, move, think, etc. Lower level actors have fewer purposes, so the main purpose of a tree is to grow. While inanimate materials such as water do not have purposes, they do have "natural tendencies" to move toward their appropriate places in the world. One such tendency of water, for example, is to flow downhill.
- *Needs or enablers.* In order to use their abilities and fulfill their purposes, actors have needs. For example, a tree needs soil, water, air, and sunlight to grow. Conversely, actors can also have inhibitors or antagonists that prevent them from fulfilling their purposes. Thus, a concrete sidewalk inhibits water from soaking into the ground. Water can also be an enabler or an inhibitor for another actor, such a person who needs clean water to drink.
- *Events or actions.* The events of the world take place when actors have all of their needs met or all the conditions are present. For example, water can go from one lake to another lake if there is a river connecting them.
- *Settings or scenes* for the action. Finally, there are settings or scenes for the action, including air, earth, stones, etc. These settings provide the background landscape or the stage for the actors to act and events to happen. Water is often the background landscape against which other events happen.

In force-dynamic reasoning, the ultimate outcome of an event, or an action on the part of an actor, is the result of an interplay of what can broadly be called "forces"—forces that support the action through enablers, and forces that hinder the action through antagonists.

Secondary Discourse – Scientific Reasoning. The secondary Discourse of environmentally-literate citizens that defines the upper end of our learning progressions embodies a different type of reasoning from the force-dynamic reasoning of students' primary Discourses. The Discourse of environmentally-literate citizens relies on scientific reasoning, which views all phenomena as taking place in connected and dynamic systems that operate at multiple scales and are constrained by fundamental principles. Scientific reasoning relies on models that are grounded in observations (data) and applied in consistent ways to explain the events of the world (Anderson, 2003; National Research Council, 2007; Sharma & Anderson, 2009). For example, model-based reasoning about water in socio-ecological systems involves recognizing that water and other substances are parts of connected systems (e.g. watersheds, groundwater, municipal water systems, etc.) and that the movement of water and other substances through these systems is constrained by natural laws and principles, such as the law of conservation of matter and the law of gravity.

Practices. Discourses are enacted through the practices of the communities in which people participate (Cobb & Hodge, 2002; Wenger, 1998). We define practice as a pattern in activity that is engaged in repeatedly. Discourses shape or mediate the activities in which members of a group participate (Cobb & Hodge, 2003; Wertsch, 1991).

We are interested in the practices that are essential for environmentally responsible citizenship: investigating, accounting (explaining and predicting), and deciding (Figure 2). These are the practices all citizens engage in when making decisions and acting in public and private roles:

- Public roles: voter, advocate, volunteer, elected official
- Private roles: consumer, owner, worker, learner

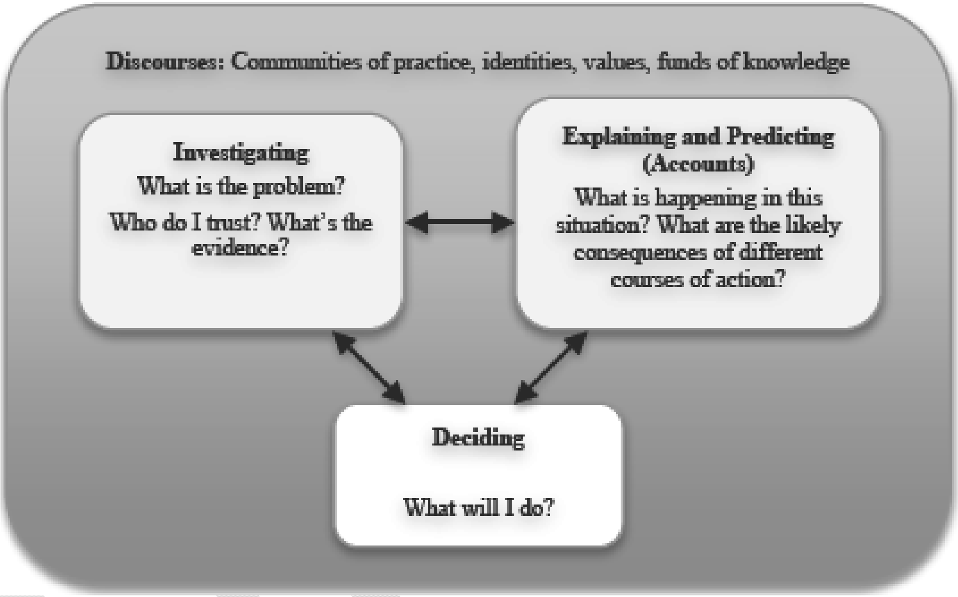


Figure 2. Citizenship practices (Covitt, Tan, et al., 2009)

How people in their various roles engage in these practices depends on the Discourses of the communities in which they are participating. People who participate in communities that use the secondary Discourse of scientific reasoning engage in these practices in ways that represent environmentally responsible citizenship. We would like students to become informed citizens who are aware of the possible environmental consequences of their actions and take those consequences into account.

Citizens' decisions and actions always can- and should- be based on considerations and values other than scientific knowledge and environmental consequences. Environmental science literacy is about giving people real choices – helping them to understand possible alternative actions and their consequences – rather than leaving them trapped by ignorance. The citizenship practices we are interested in are:

1. *Inquiry (Investigating):* Inquiry involves investigating issues and deciding whom to trust. Environmentally literate citizens learn from experience and use evidence to construct and evaluate explanations. They evaluate both sources of evidence and the evidence itself. For example, citizens must be able to learn about and understand the specifics of particular water quality and supply issues and situations. They must be able to identify and understand pertinent evidence and then analyze and evaluate the quality of evidence and arguments presented by multiple stakeholders. In contrast, people engaging in inquiry practices embedded in non-scientific Discourses may be limited to investigating issues by considering social rather than scientific information (Fleming, 1986). They may rely on immediate factual claims rather than considering those claims in conjunction with scientific theories and content knowledge learned in school (Kolstø, 2006). Furthermore, in deciding who and what to trust, people using non-scientific Discourses use strategies such as “thinking for themselves” and evaluating the motivations, interests and biases of different sources (Kolstø, 2001) without considering the relevance and validity of evidence presented by sources with perceived “suspect” interests. From a scientific perspective, one should not assume that just because evidence is, for example, presented by a large corporation that it is, by virtue of its source, automatically invalid.
2. *Accounts:* Accounts involve the practices of explaining and predicting outcomes of processes in socio-ecological systems.
    - *Explaining* processes in systems. Environmentally literate citizens must combine scientific and socio-scientific models and theories (i.e., general knowledge) with specific facts of the case (i.e., local knowledge) to explain what is happening to water in the socio-ecological systems in which they live and how these systems are affected by human actions. People using non-scientific Discourses explain processes using informal knowledge rooted in family experience, popular culture, and popular media. As such, their explanations often differ greatly from scientific explanations.
    - *Predicting* effects of disturbances or human policies and actions on processes in systems. When making informed decisions, citizens must use their understanding of socio-ecological systems to make predictions about the potential consequences of possible courses of action on the local water system. While predictions are always complicated by limited information and uncertainty, scientists use specific strategies (e.g., calculating confidence intervals) for dealing with uncertainty. In contrast, in their day-to-day lives, few people consciously engage in weighing uncertainties when making predictions (Arvai, Campbell, Baird, & Rivers, 2004). Instead, people generally rely on heuristic principles (i.e., intuitive judgments) (Tversky & Kahneman, 2000) when predicting likely outcomes of different actions. Nevertheless, with instructional support, children as young as second grade are capable of conceptualizing multiple types of uncertainty in scientific investigations (Metz, 2004).

3. *Deciding*: Decision-making involves conscious or unconscious choices about personal lifestyles or courses of action in private roles and people or policies to support in public roles. Decisions related to socio-scientific issues always depend not just on science, but also, and ultimately, on personal values (Kolstø, 2006). Thus, scientific values cannot determine our decisions, but our decisions can be informed by scientific knowledge and practice. Scientifically-informed decision-making involves using science as a tool to support all of the practices in Figure 2: investigating, explaining, predicting and deciding.

In the Environmental Literacy Project, we have done some work on students' inquiry and deciding practices (Covitt, Tan, Tsurusaki, & Anderson, 2009). Our primary focus, however, has been on students' accounting practices: explaining and predicting.

Knowledge. Citizenship practices for environmental science literacy require that citizens understand and use knowledge. Such knowledge ranges from understanding general principles, such as conservation of matter, to specific knowledge of local situations. Figure 3, adapted from the Loop Diagram from the Long Term Ecological Research Network (Long Term Ecological Research Planning Committee, 2007), shows the domain of general knowledge about water in socio-ecological systems necessary for environmentally literate citizens to engage in the practices described above. The boxes show the environmental systems and human social and economic systems that comprise a global, connected socio-ecological system. The arrows connecting the boxes highlight that the systems in neither box exist in isolation. Human social and economic systems depend on natural systems for freshwater; the decisions and actions that take place within the human social and economic systems have significant impacts on the quality and distribution of water in environmental systems.

The Loop Diagram represents the knowledge that we believe students should have upon graduation from high school. How students think about and understand the systems and processes through which water and substances in water move is the focus of our learning progressions research. The next section presents the learning progression framework that describes the knowledge and practices that students bring to learning about water in socio-ecological systems and how their knowledge and practices change through their experiences in school.

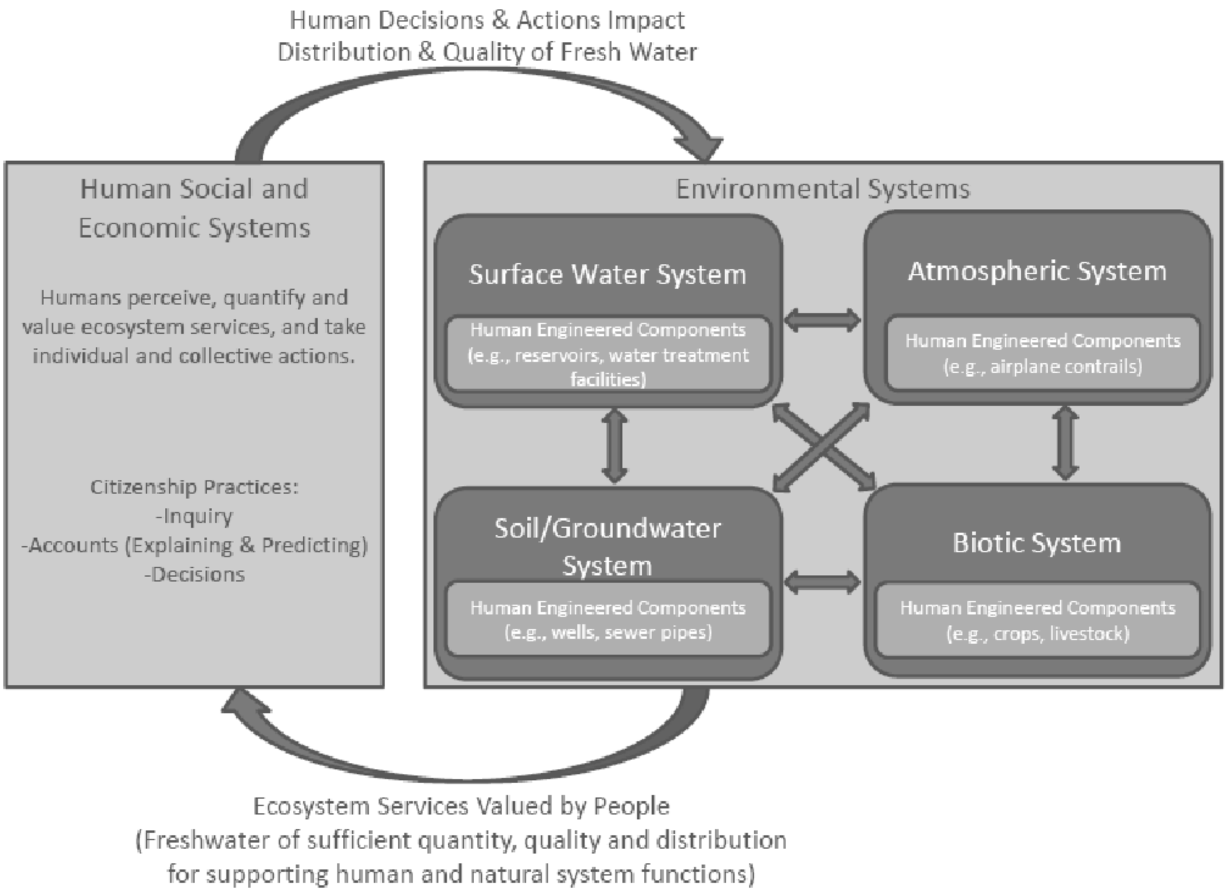


Figure 3. Loop diagram for water in socio ecological systems.

Using the Discourse-Practice-Knowledge Framework to Build Learning Progressions

The Discourse-Practice-Knowledge framework has been helpful in incorporating students' knowledge and practices into our learning progressions focusing on carbon, water, and biodiversity in socio-ecological systems. Our development work thus far has focused primarily on students' accounts: their approaches to explaining and predicting phenomena (see Figure 2 above). In this section, we explain how we used this framework to build and test our learning progressions. We begin by explaining our development methodology, then we provide an overview of the components of our learning progressions and a description of the learning progression for water in socio-ecological systems. We end with a description of some of the current challenges we face.

Methods

Our method for developing all three learning progressions has followed an iterative design research process (Barab & Squire, 2004; Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Design-Based Research Collective, 2003). For each strand of our research, we began by developing our Loop Diagrams and identifying the key conceptual understandings that environmentally literate citizens must have. We call these understandings the Upper Anchors of our learning progressions. We then developed initial assessment items to probe students' thinking about these ideas. Assessments were administered to students in grades 4-12. All students' responses to an assessment item were pooled, and then a sample of responses was ranked from least sophisticated to most sophisticated. We used our Upper Anchors as the standard against which we ranked responses.

This process involved many discussions among the researchers as we debated what constituted a more or less sophisticated answer. For example, if a student said that the water in a puddle "dried up," was the student describing evaporation? Did the student believe that the water disappeared forever? Was the student describing an observation (e.g., the puddle is gone) as opposed to describing a process (e.g., drying is a process of becoming unwet)? If a student said that the water from a puddle "soaked into the ground," was that evidence that the student was tracing water, or did the student believe that water that soaked into the ground was gone forever?

We realized that the challenge was understanding how students' language provided clues to their views of the world. We turned to the work of linguists such as Stephen Pinker and Leonard Talmy, who have studied the connection between language and cognition. Eventually, we were able to use the characteristics of force-dynamic and model-based reasoning as lenses through which we looked at the data. By searching for characteristics of force-dynamic and model-based reasoning we began to see patterns in the rank order and to identify groups of student responses with similar characteristics. We were then able to identify features in student responses that were changing from less to more sophisticated answers. We used these features to build an initial framework for the learning progression. Responses in the least sophisticated group were labeled the Lower Anchor and represent the ideas and accounting practices representative of the primary Discourse that students bring to learning about water, carbon, and biodiversity. Groups of responses that were more sophisticated than Lower Anchor answers and less sophisticated than the Upper Anchor were used to describe changes in student thinking across the initial learning progression. Once we had an initial framework, we continued to conduct successive rounds of assessment design, administration, and analysis to refine the learning progression. We followed this procedure for developing each of our learning progressions (i.e., water, carbon, and biodiversity).

Components of a Learning Progression

All of the learning progressions in the Environmental Literacy Project have the same general structure, similar to the one represented in Table 1 for the learning progression for water in socio-ecological systems (Anderson, 2009). This framework uses a learning performance as a unit of analysis. Learning performances are students' responses to assessment items. The learning progression framework organizes students' learning performances according to Progress Variables and Levels of Achievement. The next sections describe these features in terms of the learning progression for water in socio-ecological systems and connect these features to the Discourse-Practice-Knowledge framework described above.

Table 1

General Learning Progression Framework

Levels of Achievement	*Progress Variables*	
	Movement of Water	Movement of Substances
4: Qualitative model-based accounts		
3: “School science” narratives	Learning performances for specific Progress Variables and Levels of Achievement	
2: Force-dynamic with hidden mechanisms		
1: Force-dynamic narratives		

Progress Variables. Progress variables are aspects of accounts that are present in some form in all students’ accounts and can be used to track changes in student reasoning across levels. Determining what aspects of accounts to use as progress variables has been a challenge because our learning progressions involve complex domains. Progress variables are derived partly from theories about how knowledge and practice are organized and partly from our empirical research data (Briggs, Alonzo, Schwab, & Wilson, 2006; Draney, Wilson, Choi, & Lee, 2007; Wilson, 2005). Because knowledge and practices are organized differently for each of our learning progressions, progress variables of one learning progression framework do not necessarily map on to the progress variables of another learning progression framework. As a result, the progress variables identified for the water learning progression, described below, are different from the progress variables identified and described in the second half of this chapter for the carbon learning progression.

Accounts of water in socio-ecological systems explain and predict the movement of water and substances through multiple connected systems. In earlier versions of our learning progression, our progress variables distinguished between students’ understanding of the structure of connected systems and the processes that move water and substances through these systems. This organization, however, proved unproductive because we could not separate students’ understanding of structure from their understanding of processes. We moved to considering elements of a complete account as progress variables. A complete account for water in any of these systems (e.g. groundwater system) traces both water and substances in water. Therefore, for the water learning progression, we have chosen to examine student progress in tracing water and tracing substances in water as our progress variables.

1. Movement of Water – Describes how students identify and describe processes that move water across landscape-scale distances through connected systems. This progress variable includes whether or not students recognize and apply constraints on processes such as conservation of matter, gravitational control of water flow, and permeability of materials. It also includes students' understanding of the structure of the systems through which the water moves (e.g., groundwater system, surface water system).
2. Movement of Substances in Water – Describes students' conceptions of water quality and how students identify and describe processes that mix and move substances with water. It includes students' attention to the microscopic and atomic-molecular scales when describing substances in water and the processes that mix, move, and unmix substances. The progress variable describes whether or not students recognize and apply constraints on processes, including conservation of matter, gravity, and permeability of materials.

Levels of Achievement. Levels of achievement are patterns in learners' performances that extend across progress variables (Mohan, Chen, & Anderson, 2009). We have identified four levels of achievement that trace student accounts from a force-dynamic to a model-based view of the world. Levels 1 and 2 describe a force-dynamic Discourse. Level 2 represents a more fully-developed force-dynamic account of events of the world than Level 1. Levels 3 and 4 describe the transition to a scientific model-based view of the world, with Level 4 representing more fully developed model-based reasoning than Level 3. The next section describes these levels in detail.

A Learning Progression for Water in Socio-ecological Systems

The following description of the levels of achievement for the learning progression for accounts of water in socio-ecological systems was developed based on student written responses to 20 assessment items addressing different aspects of hydrologic systems. Student in grades 2-12, from rural, suburban, and urban schools, responded to these items. The descriptions provided below use examples of student responses from a subset of these 20 items.

Items focusing on movement of water

1. *Puddles*: After it rains you notice puddles in the middle of the soccer field. After a few days you notice that the puddles are gone. Where did the water go?
2. *Bathtub*: Could the water (from the puddles) get in your bathtub?
3. *Groundwater*: Draw a picture of what you think it looks like underground where there is water.
4. *Water in Rivers*: How does water get into a river?

Items focusing on movement of substances in water

1. *Water Pollution*: What are examples of water pollution?
2. *Salt Dissolving*: What happens to salt when it dissolves in water?
3. *Treatment*: Describe the different treatments that are used to make sure water is safe to drink.
4. *Ocean Water*: If you had to make ocean water drinkable, how would you go about doing it?
5. *Salty Rain*: If you live by an ocean, will your rain be salty? Why or why not?

Level 1: Force-Dynamic Narratives. Level 1 students explain and predict using the language of force-dynamic Discourse. Their accounts include the key characteristics of force-dynamic reasoning about the course of an event, including the setting, the actors and their abilities, purposes, and needs. Actors can achieve their purposes if they have all the necessary enablers and if there are no antagonists or opposing actors. If there are antagonists, then the outcome depends on which actor has greater powers.

Moving Water: Water in the Background Landscape. Level 1 responses describe water as part of the background landscape. Responses at this level do not account for what happens to visible water after it disappears from view. For example, Level 1 responses to the Puddles item included, "It got dried up by the sun." Similarly, a response to the Bathtub item was, "No. It already disappeared into the air." When asked to draw water in places they cannot see, such as underground, Level 1 students imagine water in locations they can see and translate those images to places they cannot see. For example, they draw pictures of groundwater as water in underground pipes or tanks.

Substances in Water: Accounts of Types or Qualities of Water. Level 1 students describe water quality in terms of types of water rather than describing other materials mixed with water. For example, one student's examples of water pollution included, "Lake water, ocean water, sea water, well water, pond water." Another student wrote, "black merkey [sic] water." Level 1 students focus on visible features and on human actors as agents. Thus, one response to the Water Pollution item focused on a human action rather than matter, "Some examples are throughing [sic] bottles and pop cans." When asked about materials in water that are not visible, Level 1 students tend to express that the materials have gone away. Answering the Salt Dissolving item, one student wrote, "…the water overpowers the salt by making it disappear." Level 1 students think of changes in water quality as something that changes water from one type to another and of water purification as something that humans do without describing a specific process. For example, in response to the Ocean Water item, one student wrote, "I would not be happy because I would have to drink uncleaned water." Another wrote, "Cleaning it and making sure it's clean."

Level 2: Force-Dynamic with Hidden Mechanisms. Level 2 students still explain and predict using force-dynamic reasoning but give more attention to hidden mechanisms in their accounts. They recognize that events have causes and often use simple mechanisms to explain or predict events. Students at Level 2 are beginning to trace water and substances, recognizing that water and substances that are no longer visible go someplace else.

Moving Water: Natural Tendencies with Conditions. At level 2, students still think about water as part of the background landscape, but their conception of the size of the background landscape is larger. Level 2 students think about the water in rivers as connected to water in other rivers and groundwater as layers of water underground. Level 2 students think about the movement of water as a natural tendency of water, and they identify possible enablers and antagonists to movement. For example, Level 2 responses to the Bathtub item included, "Yes. If it was a rainy day and if there were puddles saved from yesterday and you open the door it could go in to the bath tub then there would be puddles in the bathtub." And, "Yes. If you had a window in your bathroom like I do, if you happened to have it open it would condensate." These responses identify an action that a person must take to enable water to move from the puddle into the bathtub.

Substances in Water: Objects and Unspecified Stuff in Water. At Level 2, students recognize that water can mix with other materials. Water pollution is thought of as harmful things put in water, often by people. These harmful things may be objects (e.g., "garbage," "dead animals," "rotten food") or unspecified materials (e.g., "muck," "cemicals [sic]"). When materials are mixed with water, and the materials are no longer visible (e.g., salt dissolving in water), Level 2 students, like Level 1 students, may explain that the materials have disappeared. However, Level 2 students begin to provide novice explanations for tracing matter. Example responses to the Salt Dissolving item include explaining that the substances stay separated, "The salt will go to the bottom," or explaining that you will see a visible change, "The water changes color." Level 2 students also describe human actors as using simple, macroscopic scale mechanisms to mix or unmix water and other substances. For example, one student responded to the Treatment item by writing that a filter, "Takes the rocks and mud/dirt out of it." Level 2 students have difficulty tracing substances with water through invisible system boundaries. For example, some Level 2 students answered the Salty Rain item by suggesting that salty water evaporates and turns into salty rain. Another student suggested that salty water does not turn into salty rain because the water is "filtered by the sky."

Level 3: School Science Narratives*.* Level 3 accounts can be characterized as the re-telling of stories about water that are learned in school. Students recognize that water and substances in water are parts of connected systems, and their accounts include processes that move water and substances through systems. However, there are gaps in students' reasoning suggesting that students' stories are not connected into complete models that they use to explain and predict. Level 3 students do not consistently use principles to constrain processes. While they recognize that water and substances can exist at atomic-molecular scales, Level 3 students mostly identify processes (e.g. evaporation) without describing what happens to atoms and molecules.

Moving Water: Partially Connected Systems. At Level 3, students are beginning to trace water through connected systems. However, the nature of the connections among systems is not always clear to students. Hidden or invisible connections are most problematic. For example, a Level 3 responses to the Bathtub item stated "I think yes because of the fact where else would we get our water from? I know this because after it goes back into the water system it gets cleaned and then it goes to our wells and gets used in our bathtubs." This student left out essential steps in moving water from puddles into the engineered water system. An example Level 3 response to the Water in River item is, "through streams, tributaries, and run off." This response suggests that the student is tracing water along multiple pathways along the surface, but is not considering possible underground pathways to the river.

Substances in Water: Substances Mixed with Water. Students at Level 3 understand water quality in terms of identified substances mixed with water and sometimes use common chemical names (e.g., identifying "chlorine" as a possible water treatment). They also conserve matter through changes in water quality, including invisible changes such as salt dissolving in water. Students' accounts demonstrate awareness of smaller than visible scales (e.g., they use the word "molecule"), but they do not describe structures and processes at the atomic-molecular scale. For example, one student answered the Salt Dissolving item by writing, "The salt molecules spread out in the water." At this level, students' accounts trace water and substances across invisible boundaries, generally using descriptions that do not account for atoms and molecules. For example, one student answered the Salty Rain item, "No, because when water evaporates it only evaporated as water and leaves the salt behind."

Level 4: Qualitative Model-Based Reasoning. Level 4 students use scientific model-based accounts to explain and predict. Their predictions use data about particular situations along with principles to determine the movements of water and substances in water. Students who use scientific model-based thinking can trace water and substances in water along multiple pathways through connected systems. Furthermore, students at Level 4 can connect phenomena that happen at the macroscopic scale to landscape and atomic-molecular scales.

Moving Water: Connected Systems. At Level 4, students trace water through connected natural and engineered systems along multiple pathways. For example, Level 4 responses to the Puddle item trace water along multiple pathways. "Runoff into drainage system or seeped into groundwater supply or evaporated into air or combination of all of these." Level 4 responses to the Bathtub item show more detailed connections between the natural and human-engineered systems. "Yes: As the water returns to groundwater, it flows into an aquifer. This aquifer could possibly be the one tapped for city water. The water would be purified and delivered via pipes to my house." Furthermore, Level 4 responses apply principles to constrain processes at the landscape scale. For example, one Level 4 response to the Water in River item noted that water could get into a river through the aquifer by following the downhill underground flow and an impermeable layer underground. This response identified how topography and permeability constrain the flow of water in aquifers.

Substances in Water: Identified Substances Mixed with Water at Multiple Scales. Students at Level 4 consistently provide chemical identities for substances and consider relative amounts of substances to reason about water quality. Furthermore, identified chemical substances are connected to an understanding of structure at the atomic-molecular scale. For example, one student answered the Salt Dissolving item by writing, "When salt is dissolved into water the salt breaks up into its ions of NA^+ [sic] and CL^- [sic]." In the assessment data, there were some responses that reached Level 4 with respect to simple substances (e.g., salt). However, there were very few responses reaching Level 4 with respect to more complex substances (e.g., sewage). In addition, few students provided Level 4 accounts by tracing substances mixed with water across system boundaries (especially invisible boundaries) with atomic-molecular scale descriptions.

What is Progressing?

In our view, growth along a learning progression represents movement towards mastering a secondary Discourse. Students' primary Discourses include characteristics of force-dynamic reasoning. As students develop the model-based reasoning of the secondary scientific Discourse, force-dynamic thinking does not disappear. Students at lower levels of achievement have only their primary

Discourse to frame the way they view the world and participate in communities. As students gain mastery over secondary Discourses, they have more tools to use to account for their experiences and make sense of the world. The practices they engage in depend on the Discourses of the communities in which they are participating. Thus, students may be capable of providing a model-based account of water in environmental systems, but they may provide force-dynamic accounts if they judge that is what their listeners or readers are expecting. In fact, force-dynamic accounts can often be sufficient for explaining phenomena. It is not always necessary to explain evaporation in terms of molecules and energy if one just needs to communicate that the puddle in the field is no longer there and the team can now play soccer (“The field dried up; let’s go play”). Stating that the puddle is gone is all that is necessary in this situation. However, if one is participating in a community that is trying to figure out why the soccer field is always soggy (e.g., it was built in a place where the water table is close to the surface), one needs to use a model-based account of a scientific secondary Discourse. Students who control secondary Discourses can participate in more communities. Without access to the Discourses necessary for environmental science literacy, students cannot become active participants in evidence-based discussions about local and global environmental issues.

Remaining Issues

The Discourse-Practice-Knowledge framework has been productive in helping us describe and trace what progresses in learning progressions that must account for a wide range of students’ changing knowledge and practices. It has helped us to organize our data in ways that have allowed us to see important patterns in students’ reasoning. However, there are still some challenges that we are working to address.

One difficulty has been in describing the nature of Level 3. We are still trying to determine if students at Level 3 are developing beginning model-based reasoning or if their accounts are the result of layering on more details to their primary Discourse view of the world. This challenge is complicated because the process of developing a new Discourse is a process of adding a secondary Discourse and not replacing the primary Discourse. Thus characteristics of both primary and secondary Discourses are often present in Level 3 accounts. For example, a Level 3 student asked to explain how water gets into a river responded:

> Water gets into a river by a cycle called the water cycle. First, clouds fill up with water droplets and rain onto mountains. The water on the mountains builds up and slides down the mountains into the river. Some of this water evaporates and becomes more clouds.

This student seems to be tracing water from the atmosphere to the surface water system and back. However, the description includes force-dynamic elements, such as clouds filling up with water. Is this student developing a model-based view of the world, or is this student just incorporating school-based narratives about how water cycles into their force-dynamic views of the world? Plans to conduct more clinical interviews that probe students’ responses to assessment items may help us tease apart these details.

Another difficulty is writing assessment items that can be answered by students who are at different levels of achievement. We have had to learn how to write assessment prompts that can elicit responses across a range of Discourses. We have found that students who can use model-based reasoning may provide force-dynamic responses to assessment items if a model-based response is not specifically requested by the item prompt. For example, students who can use a model-based account to describe what happens when salt is mixed with water may not do so unless specifically requested to include descriptions of atoms and molecules in their answer. However, adding these clues to the prompts sometimes makes the prompt seem too difficult to students who have not developed a model-based view of the world. Sometimes, these students do not provide any response to the item, even though a force-dynamic response would have been possible. We continue to explore ways to write assessment prompts that can be productive for both force-dynamic and model-based reasoners (Jin & Anderson, this volume).

The Discourse-Practice-Knowledge framework has been productive in helping us meet the challenges that our choices for our learning progressions have introduced. We will continue to leverage the benefits that it provides and address the limitations that it presents as we move forward. In the next section, we describe another challenge that our goals for developing interconnected learning progressions for environmental science literacy have presented.

Challenge Two: Defining Pathways and Linking to Instruction

The research groups of the Environmental Literacy Project are at different stages in the learning progression design process. The water research group has developed two critical design products—the learning progression framework and associated assessments. The carbon cycle research group has also developed a third design product aimed at linking the learning progression framework to instruction. This third design product is a set of instructional resources that allow teachers to make use of learning progressions in their classrooms while allowing us, as researchers, to investigate how students learn the practices of environmental science literacy.

We recognize that progress through a learning progression is not developmentally inevitable, that instruction does influence progress, and that students may take more than one path through learning progression levels depending on the instruction they receive. While the majority of students we assessed over the past five years showed similar types of reasoning that were characteristic of levels 1-3 in our learning progressions (as described previously for the water learning progression), the carbon research group also collected evidence to suggest that some students exhibit notable differences in reasoning compared to their peers at the same grade level (Chen, Anderson, & Jin, 2009; Jin & Anderson, this volume; Jin, Zhan, & Anderson, 2009; Mohan, Chen, & Anderson, 2009). We interpreted these differences as indications of alternative pathways in the learning progression. Our project uses the term “pathway” to describe paths learners may take between the Lower and Upper Anchors. While pathways share anchor points, the intermediate levels vary, which makes the pathways distinguishable. The variation in these intermediate levels provides an opportunity to explore the role instruction plays in the learning progression.

The teaching experiments conducted as part of the carbon cycle research provide an example of how we approached the challenge of identifying and defining multiple pathways and the challenge of defining the link between instruction and the learning progression. In this section we will provide a brief overview of the carbon cycle learning progression framework. We will then introduce how we identified and defined alternative pathways in the learning progression, the approach we took to link these pathways to instruction, and limitations to our approach.

Overview of the Carbon Cycle Learning Progression Framework

The Upper Anchor of the carbon cycle learning progression identifies three groups of carbon-transforming processes that are necessary for mastering scientific Discourse. These include processes that *generate* organic carbon through photosynthesis, processes that *transform* organic carbon through biosynthesis and digestion, and processes that *oxidize* organic carbon through cellular respiration and combustion. We chose to organize the Upper Anchor around these processes because they are the means by which living and human systems acquire energy and the means by which environmental systems regulate levels of atmospheric CO_2; thus an understanding of these processes is central to environmental science literacy. Grouped in this way, these categories highlight important similarities and differences in how processes alter the flow of matter and energy at different scales.

Table 2 shows that progress from the Lower to Upper Anchor requires substantial reorganization of knowledge about these processes. The middle row—macroscopic events—is accessible by individuals using both Lower and Upper Anchor Discourses; thus, we can use these events to examine different Discourses (see Jin & Anderson, this volume). The bottom row shows how an individual using primary Discourse might organize and account for macroscopic events, while the top two rows show how an individual who has mastered scientific Discourse would account for the same set of events (i.e., the top carbon-transforming process row shows patterns in chemical reactions, while the second scientific accounts row shows specific chemical processes learned in school).

Table 2
Contrasting ways of grouping carbon-transforming processes

Upper Anchor	**Carbon-transforming process**	Generating organic carbon	Transforming organic carbon			Oxidizing organic carbon		
	Scientific accounts	Photosynthesis	Biosynthesis	Digestion	Biosynthesis	Cellular respiration		Combustion
Macroscopic events		Plant growth		Animal growth		Breathing Exercise Weight loss	Decay	Burning
Lower Anchor: Informal accounts		Natural processes in plants and animals, enabled by food, water, sunlight, air, and/or other things					Natural process in dead things	Flame consuming fuel

Students at the Lower Anchor view macroscopic events as characteristics of organisms and objects. These students organize their world based on actors—

plants, animals, objects—as opposed to processes. They pay particular attention to different needs and abilities of actors and to outcomes of events that involve actors struggling to fulfill their natural tendencies. Dead things have lost their capacity to be actors (students often say they "have no energy"), so they are prone to decay.

While individuals at the Upper Anchor observe the same macroscopic events, they are able to provide scientific accounts that reflect organization based on scientific principles. Mastering scientific Discourse includes recognition that every process obeys the following principles:

1. hierarchy of systems and scale (i.e., the world is organized into dynamic systems that have structures and processes that occur at multiple scales),
2. conservation and cycling of matter (i.e., laws of conservation of mass and atoms), and
3. conservation and degradation of energy (i.e., energy is like matter in that it is not created or destroyed, but it cannot be recycled).

The top row of Table 2 reflects how an individual at the Upper Anchor would use scientific principles—especially matter and energy principles—to construct explanations and organize processes in the world.

The carbon cycle learning progression framework uses both processes (i.e., generation, transformation, oxidation) and principles (i.e., scale, matter, and energy) as key dimensions. These dimensions have recognizable face validity in the science and science education communities. We used processes and principles to operationalize the knowledge and practice components of our learning progression framework. These dimensions guided the development of assessments and analyses of data. Both dimensions became especially important as we began to explore pathways in the learning progression and the relationship between pathways and instruction.

Limitations of the Carbon Cycle Framework

Before the 2008-9 academic year we focused on developing a learning progression framework that describes the current reality of how student reasoning changes, or evolves, without special instructional interventions from researchers. As in the learning progression for water, the development process for the carbon learning progression used an iterative approach, where framework development and empirical data from assessments informed each other. What emerged from several years of work was a learning progression that documented consistent patterns among student responses across different settings (Mohan, Chen, & Anderson, 2009). The initial design products of this research included a learning progression framework and assessments.

Processes and principles were central to the initial stages of our work. Both dimensions helped to define the knowledge and practice necessary for reasoning about carbon cycling, and both dimensions were useful for designing assessments. For example, assessment items were designed to tap into students' accounts about at least one process and at least one principle (e.g., the item, "where does the mass of a tree come from?" targets the process of photosynthesis and the principle of conservation of matter; "where does gasoline go when a car's fuel tank is empty?" targets the process of combustion and conservation of matter). For this reason, our initial work used processes and principles as progress variables in the carbon cycle learning progression. We used the macroscopic events from Table 2 to identify types of accounts. Most of our questions elicited student accounts of individual macroscopic processes (e.g., plant growth), while a few questions focused on comparisons among processes or connections between processes (e.g., how decomposition connects to plant growth). We used principles to identify elements of accounts. A complete account of any process would describe changes in matter and/or energy at different scales.

As we continued our development and validation work, however, we saw two limitations to the framework. The first limitation was a conceptual problem: although using the processes as progress variables to describe types of accounts was useful as a data analysis strategy, using principles proved problematic because these principles are not easily differentiated for many students. The second limitation concerned evidence of failure in our educational system: few students were achieving Level 4 reasoning, mostly because of their inability to consistently conserve both matter and energy.

Conceptual limitations: Matter and energy as progress variables. As we began to look more closely at alternative pathways, we initially hypothesized that alternative pathways within the learning progression would be related to students making different progress on processes and/or principles. We hypothesized that students may be able to reason at higher levels about particular processes (e.g. photosynthesis) or particular principles (e.g., conservation of matter) compared to other processes and principles. If we found this to be true, our learning progression framework would need to account for these differences. In fact, we would need to be especially attentive to these differences when designing instructional materials. For example, if students seemed to grasp matter principles more readily than energy principles, we would want to use this information to inform our instructional interventions.

In order to test these hypotheses, we designed assessments to elicit responses about both processes and principles. Our goal was to explore whether students tended to reason at higher levels about particular processes or principles. The assessments were comprised of open-response items about the five macroscopic events from Table 2. Within the context of these five events, the 29 assessments items we used asked students to account for what happens to matter and/or energy during the event. We scored student performance on individual items. While we used 29 items, we gave 45 scores to each student, meaning that some items were scored for more than one process or principle. For example, of the 29 items, 25 were scored for matter and 20 were scored for energy. It is important to point out that some items targeted either matter or energy, but student responses often included both, which prompted coders to score both principles. For example, when students were asked to explain what happens to matter during weight loss, many students used energy in their explanations, prompting coders to score for matter principles and energy principles.

After scoring individual items we conducted Multidimensional Item Response Theory (IRT) analyses, obtaining person ability estimates. The person ability estimates gave us the average performance of a single student on all items related to a process or principle. We examined whether performance on items about one type of process or principle correlated with performance on items about another process or principle (Mohan, Chen, Baek, Anderson, Choi, & Lee, 2009). In order to conduct our analyses, we used a sample of assessments from 771 students across

18 classrooms from grade 4-12. We found correlations between the processes were generally moderate to high (.542 or greater). Cellular respiration and growth/biosynthesis events appeared slightly more difficult for students compared to other processes, but in general students exhibited consistent levels of reasoning about the processes.

However, we encountered two significant difficulties when we examined principles—matter and energy–as progress variables in our coding and analyses. The first of these was conceptual: What do matter and energy mean to students reasoning at Levels 1 and 2? When we coded Level 3 and 4 accounts, we could generally identify elements that corresponded to the scientific concepts of matter and distinguish those from scientific concepts of energy. As we uncovered the force-dynamic reasoning of Level 1 and 2 accounts, trying to identify "matter" and "energy" in these accounts became increasingly problematic. In talking about growth of plants, for example, Level 1 and 2 students did not distinguish between needs that we would identify as forms of energy (sunlight), as forms of matter (air, water, soil), or as conditions, (warmth, care). Level 1 and 2 students frequently used the word "energy," but sometimes they used it to identify powers or abilities of actors (e.g., the girl can run because she has energy), and sometimes they used "energy" to refer to generalized needs or enablers (e.g., water, air, sunlight, and soil all supply plants with energy in different ways).

Our search for developmental precursors to scientific concepts of matter and energy proved intellectually fruitful. We were able to trace connections between younger students' ideas about enablers and results of macroscopic events and older students' ideas about matter and energy (Mohan, Chen, & Anderson, 2009). Similarly, we saw connections between younger students' ideas about cause and action and older students' ideas about energy sources and transformations of energy (Jin & Anderson, 2008). These connections, however, did not really solve our underlying conceptual difficulty. The intellectual precursors to scientific concepts of matter and energy were like tributaries to a stream: There were many of them, and it did not really make sense to privilege some and not others by labeling them as "matter" and "energy" elements in the accounts of students who really were not thinking about matter and energy.

A second limitation with matter and energy as distinct progress variables emerged from our data analyses. We found the correlation between matter and energy dimensions was high (0.959), indicating students had very similar scores for both matter and energy, a finding that reflects both the conceptual difficulty in separating the two principles and the limitation these two principles place on scoring. While this finding did not support our original hypothesis that students may come to understand one principle before the other, the results made sense given the characteristics of student accounts, especially at the lower levels. In our prior studies, students seemed to use energy as an expedient means for accounting for mass changes that should have been attributed to gases. Thus, students' developing knowledge about matter—especially gases—and energy were deeply intertwined, and trying to separate and code the two principles was forcing a distinction that was not present for most students.

Our project has retained matter and energy as progress variables because both are distinguishable at the Upper Anchor, and it is likely that students given targeted instruction on these principles may demonstrate pathways that show differences between these two principles. However, our initial use of matter and energy progress variables proved fruitless given the understanding of students experiencing status-quo instruction.

Practical limitations: Evidence of failure in our educational system. We did not aim especially high in our definition of the Upper Anchor (Level 4) of the carbon cycle learning progression. The key ideas are all included in current national standards (National Research Council, 1996) and in the curriculum standards of many states, including Michigan, where we collected much of our data (www.michigan.gov/mde). Our data showed, however, that few students were achieving these standards: Mohan, Chen, and Anderson (2009) found that 10% of high school students in our sample provided Level 4 accounts of processes and principles. These students were receiving similar instruction compared to their peers—instruction that mainly focused on delivering detail-oriented science information to students.

A detailed examination of our data showed that the core of students' difficulties with achieving Level 4 reasoning lay in their difficulty in understanding and applying our key principles. For example, Level 3 students had difficulty connecting macroscopic events with atomic-molecular models (scale), and they often converted matter to energy or vice versa in their accounts of processes with gaseous reactants or products (matter and energy).

So these findings left us with a dilemma. On the one hand, matter and energy principles did not work very well for us as progress variables. At the same time, though, the key difficulties of our students in achieving Level 4 reasoning lay in their failure to understand and apply those same principles. We also knew that the principles should play a critical role in developing our third design product—instructional resources—especially given the central role of principles in Upper Anchor reasoning. We organized our research during the 2008-9 academic year around this dilemma.

Alternative Pathways

As we struggled with this dilemma, we identified a potential solution based on research comparing data from Chinese and American students (Jin & Anderson, this volume). Interesting evidence emerged from our analyses of data from Chinese students that suggested we were missing an important dimension from our framework. Jin, et al. (2009) and Chen et al. (2009) gave written assessments and conducted interviews with middle and high school Chinese students. Results from their analyses showed that Chinese students could more readily use technical language that accurately identified appropriate processes, yet when Chinese students were probed to elaborate, they struggled to construct explanations that obeyed scientific principles. We reconsidered data from American students and recognized that many American students also showed an ability to give scientific "names" to systems and processes that exceeded their ability to construct an explanation using scientific principles.

With this new insight, we reexamined data from both Chinese and American students in terms of students' ability to provide "names" for systems and processes and students' ability to use scientific principles in their explanations. We labeled these "naming" and "explaining". The "naming" dimension was used to explore students' use of specific key words and phrases characteristic of particular levels of reasoning. The “explaining” dimension was used to examine the structure of explanations and how grounded these explanations were in terms of scientific principles (Jin & Anderson, this volume). In this way, scientific principles remained a centerpiece to our new explaining dimension.

In reexamining our data, we observed that the majority of students showed levels of naming that exceeded levels of explaining (e.g., Jin et al., 2009). This observation made sense given that most of the students in our sample were receiving traditional science instruction, or what we refer to as status-quo instruction. This type of instruction pays particular attention to communicating to students the technical language of science (e.g., Lemke, 1990), and to building up detailed narratives about specific processes. These narratives are constrained by scientific principles, but students often focus on the details of the narrative, rather than the more general principles. For example, students can memorize chemical equations such as, $C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2$ without recognizing that “balancing the equation” is a way of applying conservation of matter as a constraining principle—the process of cellular respiration does not create or destroy atoms. Similarly, students often fail to connect accounts of processes across scales. Students learn narratives about principles too, such as reciting conservation laws. The principles, however, remain largely invisible to students, and connections between process narratives and principle narratives is not made. For example, students may be able to describe conservation laws, but cannot use them as tools for reasoning in different contexts.

Our reexamination of the data also revealed that some students had similar levels of naming and explaining, while for others, levels of explaining exceeded levels of naming. For example, some students showed a strong commitment to principles, such as conserving matter or energy, without knowing the technical language and technical details of a chemical process. This additional pattern was an indication of the possibility of an alternative pathway in our learning progression. For this reason, naming and explaining dimensions became particularly useful for distinguishing between pathways students take through the learning progression levels. We labeled these pathways “structure-first” which focused on naming and “principle-first” which focused on explaining with principles. Figure 5 shows these pathways given shared Lower and Upper Anchor points.

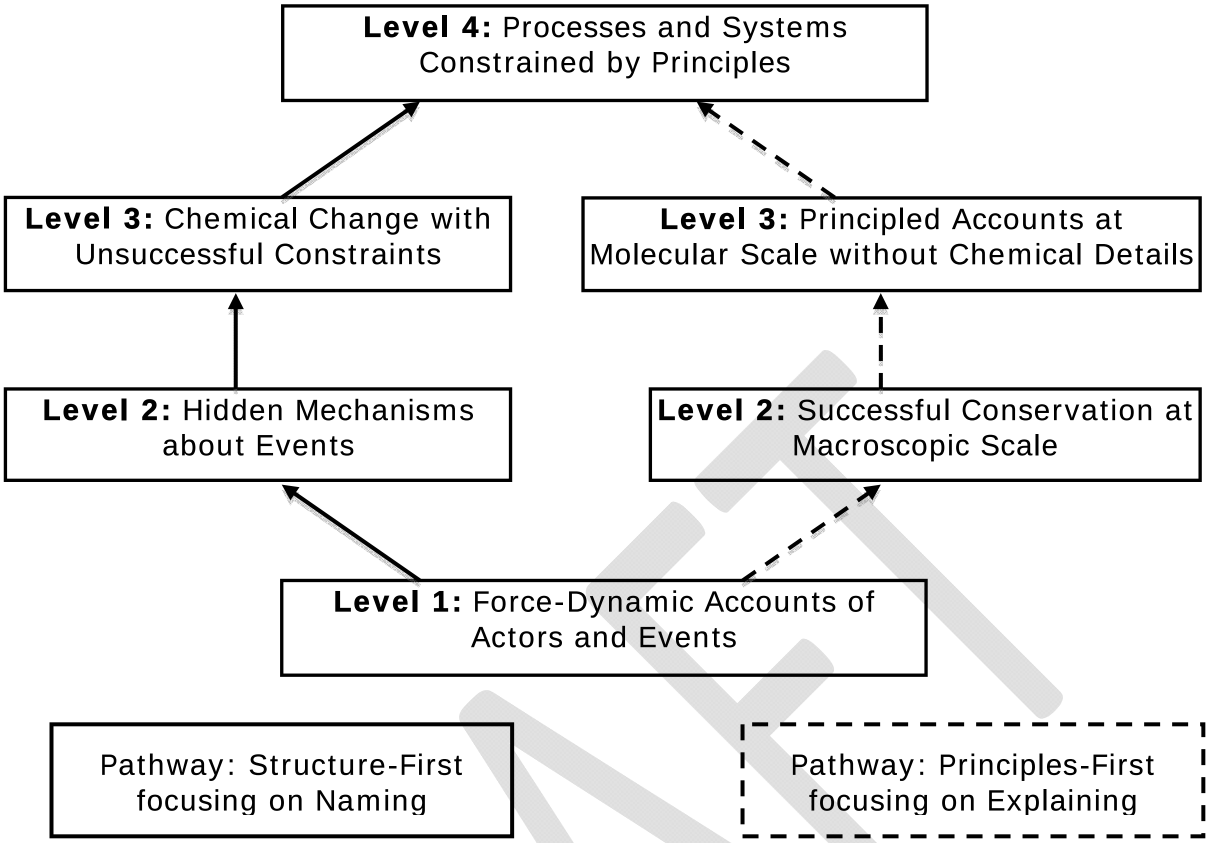


Figure 5. The learning progression shows that lower and upper anchor points are shared, but that students can make progress to the upper anchor on different pathways.

Structure-First Pathway and Naming. The current carbon cycle learning progression as described in Mohan, Chen, & Anderson (2009) and the description of water cycle levels provided earlier in this chapter are largely descriptions of the "structure-first" pathway (solid line in Figure 5). Students on this pathway acquire new scientific words and phrases but use them in explanations that retain significant force-dynamic characteristics (e.g., student may identify "photosynthesis" as a key process in plants but cannot explain how it changes matter or energy). Students may be able to recite conservation laws when prompted to do so on a test, but cannot use these laws to explain what happens to matter or energy during weight loss, combustion, or other carbon-transforming processes. Thus we expect students taking this pathway to have higher levels on the Naming progress variable than on the Explaining progress variable.

We interpret our data and other research on classroom teaching (e.g., TIMSS Video Study, Roth et al, 1999) to show (a) that the structure-first pathway is currently the norm in American classrooms and (b) that progress to the Upper Anchor through the structure-first pathway is limited to a small percentage of students. The transcript below illustrates one student on the structure-first pathway. This high school student, Dan, showed level 3 in terms of naming, but level 2 in terms of explaining.

Example 1: Structure-First Pathway

> INTERVIEWER: How does sunlight help photosynthesis?
>
> DAN: The, well like the vitamins and stuff in it, like that's what it uses.
>
> INTERVIEWER: And you also talked about a food...What do you mean by food?
>
> DAN: Like glucose that the tree uses to grow.
>
> INTERVIEWER: Okay. So where does glucose come from?
>
> DAN: The tree makes it from all the different things that it uses.
>
> INTERVIEWER: Could you talk a little bit about what are the different things?
>
> DAN: Like air, vitamins, the soil, nutrients, sun and water.
>
> ... ...
>
> DAN: Well, yeah I think that uses like all the same…after it makes its food it uses the glucose for energy.
>
> INTERVIEWER: Glucose is a type of energy?
>
> DAN: Yep.
>
> ... ...
>
> INTERVIEWER: Okay. Now, you know, the tree, when the tree grows it becomes heavier, right? It will put on more weight. So where does the mass come from?
>
> DAN: It comes from the, all like glucose that it makes, it like keeps building on and building on until it gets as big as it is.
>
> INTERVIEWER: So what are the energy sources for the tree?
>
> DAN: Well, the same as photosynthesis- vitamins, water, air, light, yeah.

Level 3 reasoning in the carbon cycle learning progression framework involves the incorporation of chemical processes into a students' account. Dan is able to provide scientific names for a chemical process (photosynthesis) and a chemical identity for an important material (glucose), which indicates he has acquired "names" consistent with level 3 reasoning. He also understands that plants make glucose from other components and that glucose contributes to the increase in mass. Yet, Dan cannot differentiate between key materials and energy resources in terms of scientific principles. In addition to light, he also lists vitamins, water, air as energy sources for photosynthesis..

As in the water learning progression framework, level 2 reasoning about the carbon cycle is characterized by force dynamic accounts including actors ("The tree makes it from all the different things that it uses.") and enablers ("vitamins, water, air, light"). While Level 2 students understand that actors accomplish their purposes through hidden mechanisms ("photosynthesis"), students at this level lump enablers into one group. To Dan, materials and "light" are lumped into a group of enablers required by the tree for growth. While he has acquired "glucose" as a new descriptive term, he appears to be confused about whether it is a form of matter or a form of energy, or he does not see the need to differentiate between the two.

Principles-First Pathway and Explaining. Figure 5 also shows a "principles-first" pathway focused on explaining (dashed line). 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. While we have examples of students who demonstrate explaining that is aligned with or exceeds their naming, this pattern is rare in our data. The transcript below shows an example of a middle school student, Ryan, who exhibits a pattern in which explaining is aligned with or exceeds naming. This student shows level 3 on explaining and instances of level 2 or 3 on naming.

Example 2: Principle-First Pathway

> INTERVIEWER: You said sunlight, can you tell me a little bit about sunlight, how does it supply the tree with energy, do you know how it happens?
> RYAN: It comes in, obviously as a form of light energy, and that being a form of energy, it then converts through photosynthesis, it converts that to a form of energy that the tree can use.
> INTERVIEWER: What form of energy is that?
> RYAN: Either kinetic or stored, I am not sure, probably more stored.
> INTERVIEWER: Keep going.
> RYAN: And it would use kinetic for whatever growing it does at the moment, but it would probably use more stored energy to store it away for another time to use.
> INTERVIEWER: Where does the tree store its energy?
> RYAN: It stores it mostly in the trunk, since that's the largest area, but in all of the branches of it, in the form of starch.
> INTERVIEWER: Do you think energy is stored in molecules?
> RYAN: No.
> INTERVIEWER: You mentioned a form of starch, do you think starch is a molecule and do you think energy is stored in that?
> RYAN: It is. I am not sure how it's stored in it. It might be with the molecule's vibrations or something. I am not positive.

Ryan has developed a story about energy transformations in plants that recognizes different forms of energy. He admits not knowing how starch stores energy, but does not default to the matter-energy conversions often observed among level 2 and 3 students on the structure-first pathway. Ryan shows a commitment to conservation of energy without fully understanding the chemical nature of molecules, and does not use scientific terms that exceed the explanation being provided.

As described earlier in the paper, our goals for environmental science literacy include the belief that model-based reasoning is necessary for students to master scientific Discourse and to participate as environmental-literate citizens. While the principle-first pathway appears to be the exception to the rule, it is our belief that this pathway has potential for supporting students in acquiring model-based reasoning. For this reason we have used our learning progression framework, especially the principle-first pathway, to help design our instructional resources.

Designing Instructional Interventions

Our approach to learning progression work and instructional interventions is notably different from other learning progression projects. Some learning progression researchers focus on defining a clear link between instruction and framework early in their design process and then develop instructional materials that have a very specific,and carefully laid out instructional sequence that is closely linked to progress from one level to the next (e.g., Schauble, 2009; Wiser & Smith, 2008; Wiser, Smith, Asbell-Clarke, & Doubler, 2009). These projects document what is possible for students given a specific instructional context and what students are capable of doing in those environments. Learning progressions developed within this perspective tend to focus on the boundaries of what could be, given the right set of curricula and support within a given context.

In contrast, our work began by documenting what is happening in the instructional context of our schools today. We focused on developing frameworks and assessments that could capture the current reality of schools. We designed an assessment system that could be used to elicit responses from students of diverse age, culture, and social backgrounds (Jin & Anderson, this volume), and we needed a framework and operationalized system for handling that diversity. We also devoted time to refining our framework based on what we learned from those assessments.

Our data suggested that status-quo teaching leads many students to achieve level 3 reasoning on the structure-first pathway with naming exceeding explaining. However, we believed an alternative to this instructional approach—one that emphasized principle-based reasoning—would support students on the principle-first pathway and this pathway would be more successful in helping students reach the Upper Anchor. We recognized the link between instruction and the learning progression framework was not tied to a specific instructional sequence, but rather reflected a teacher's general approach to conveying the importance of principle-based reasoning in a variety of contexts. Rather than using our teaching experiments to test the effectiveness of a sequenced set of activities, we chose to design a learning progression system and instructional intervention based on the following goals:

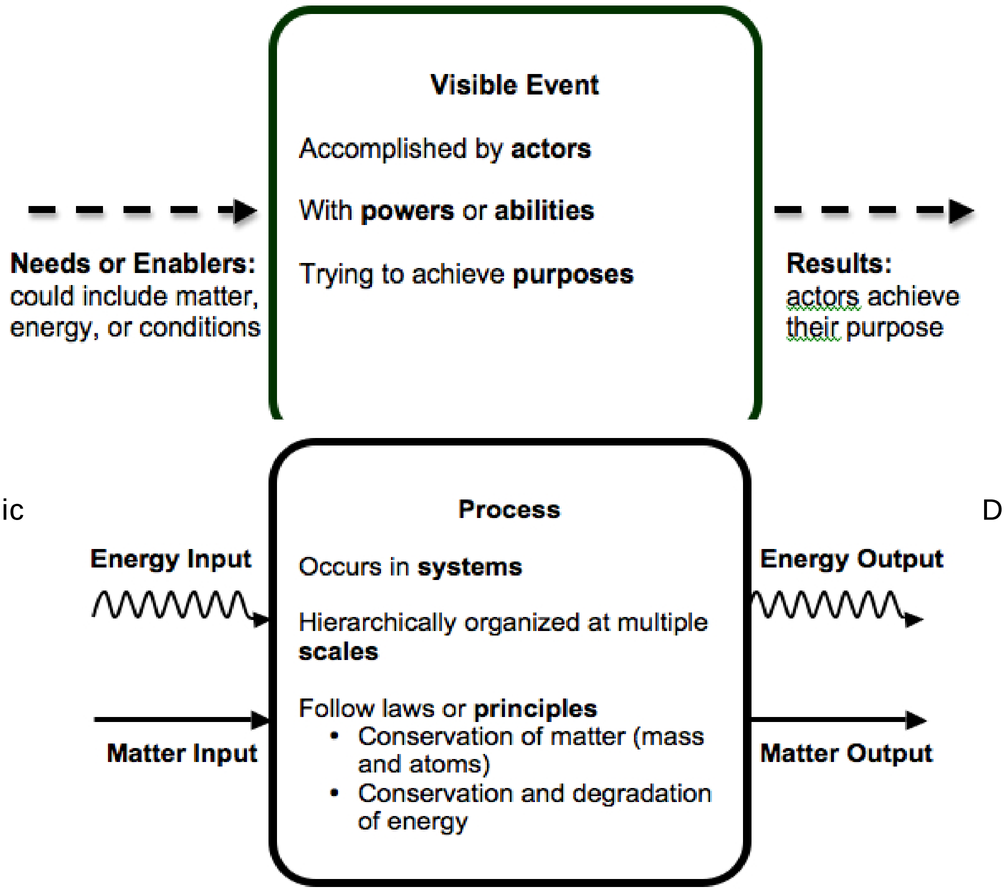
- We wanted to help teachers recognize that scientific Discourse involves careful attention to principle-based explanations, and provide suggestions for how to make these principles more visible to students.
- We wanted to make conservative changes to instruction that would improve student performance without whole scale changes in curricula.
- We wanted the instructional interventions to span a large age range and be of use to teachers and students in a variety of settings.
- We wanted the instructional interventions to be flexible so that teachers could use our resources within the curriculum adopted by their district.

Given these goals, we focused on designing Tools for Reasoning that were closely linked to the learning progression framework. These tools needed to capture important aspects of different processes, obey scientific principles, and ultimately help students construct explanations as opposed to focusing on names and school science narratives unconstrained by scientific principles. When working with a large age span of students from diverse settings, this also meant generating tools that had continuity across the ages and ones that could be used within different instructional and social contexts.

The matter and energy Process Tool is an example of a principle-based tool used in our instructional interventions (see Figures 6 and 7). It is designed to scaffold construction of scientific accounts of carbon-transforming processes. For students who have mastered scientific Discourse, the process tool can be used to track matter and energy inputs and outputs. For students who have not mastered scientific Discourse, their accounts for the same process will be very different. For example, Figure 6 shows a comparison account of a process for both primary and scientific Discourses. Students reasoning with their primary Discourse describe needs or enablers (which may include materials, forms of energy, or conditions) that actors must have to accomplish their purpose. The results are usually not in material forms; matter is simply allowed to appear or disappear without accounting for conserving the matter. Students using their primary Discourse describe the end purpose or results accomplished by actors when they obtain enablers they need. In contrast, a student using scientific Discourse, distinguishes inputs in terms of matter and energy for particular processes, and the results of events are matter and energy outputs. Thus, in the scientific Discourse, there is a storyline about how matter and energy transform during a particular process.

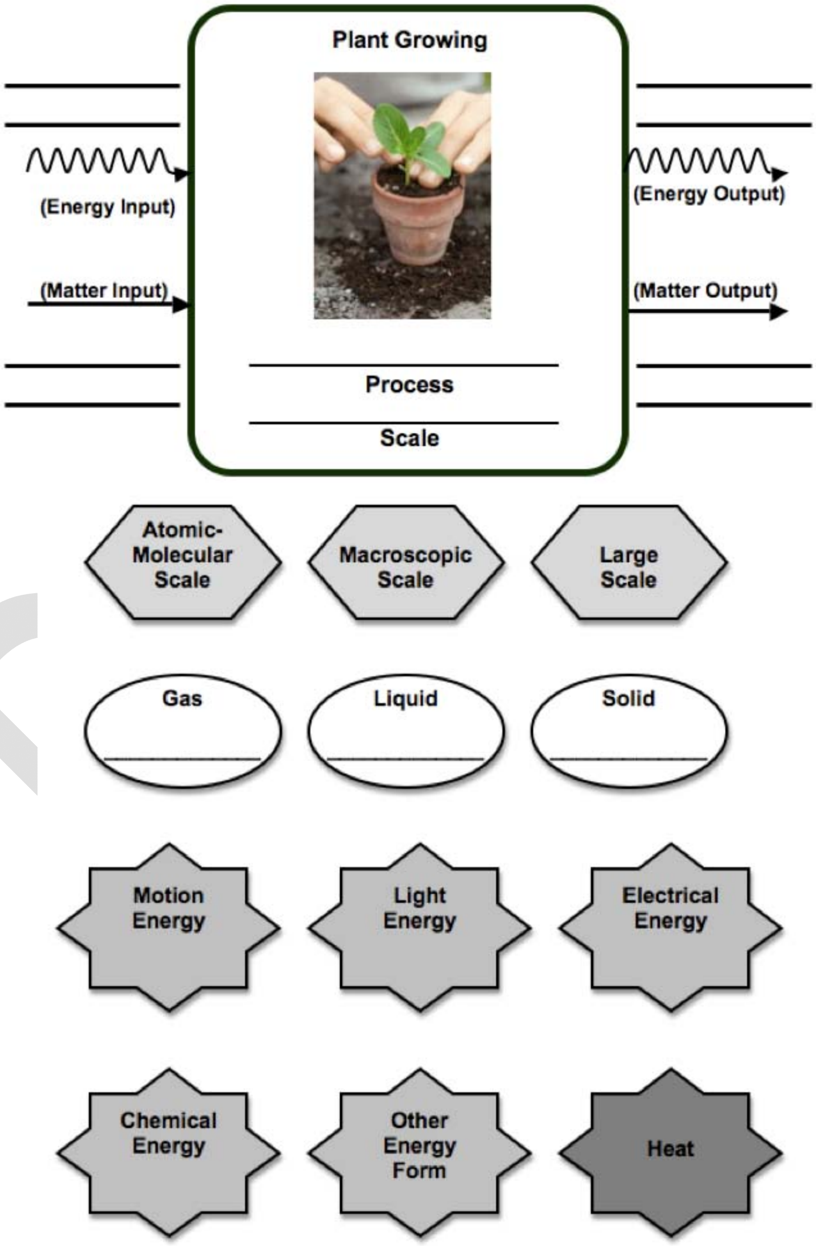
Figure 6. These diagrams show a comparison between the structure and content of the process tool for primary versus scientific discourse.

Primary Discourse



Scientific Discourse

For classroom use, we designed the Process Tool to help organize students' accounts around the structure of scientific Discourse shown in Figure 6. When using the Process Tool, students must choose from a given set of matter and energy inputs and outputs. Students are asked to identify the materials going into the system. Students are also asked to identify the energy going into the system. The students use labels to represent these matter and energy inputs. Like the inputs, students must choose from the same set of labels in order to identify matter and energy outputs. Figure 7 shows an example of what the process tool would look like for plant growth, with a set of labels that students would choose from. The matter labels shown in Figure 7 provide space for students to identify specific materials.



The Process Tool can be used to describe macroscopic events (e.g., match burning;

plant growing, etc), landscape-scale processes (e.g., primary production, food chains), and atomic-molecular scale chemical processes (e.g., combustion, photosynthesis). In elementary school the Process Tool can help students to begin tracing matter and energy through systems (focusing particularly on distinguishing between different types of enablers and becoming more aware of gases as a form of matter). We believe middle school students can learn how to use atomic molecular models to explain transformations of matter and energy with the Process Tool, though without much chemical detail. High school students can master additional chemical details.

The tool was designed to support students in using conservation of matter and conservation of energy to reason about events or processes. Students are given a limited number of forms of matter—solids, liquids, and gases—that they can use to label either material kinds (e.g., food) or chemical identities (e.g., glucose: $C_6H_{12}O_6$). The tool also uses a limited number of energy forms—light, motion, chemical energy, electrical energy, and heat. Students trace energy transformations between these forms to practice conservation of energy. In addition to conservation of energy, we wanted to provide teachers with an opportunity to highlight the principle of energy degradation, so “heat” uses slightly different labeling to indicate that it is a form of energy no longer usable to organisms or objects.

The design of the Process Tool allows for students to construct accounts of processes at different scales and discuss how the labeling of matter and energy inputs and outputs changes as a result of moving up and down scales (e.g., food at macroscopic scale may become carbohydrates, lipids, and proteins at atomic-molecular scale). The tool is used in the classroom in three forms: as a 3x4 poster with Velcro or magnetic tabs for matter and energy labels, in student activity pages, and in PowerPoints for the teacher to use during whole group instruction.

Limitations to Our Links to Instruction

The naming and explaining dimensions have been particularly helpful in distinguishing between a structure-first pathway and a principle-first pathway. These pathways share the same anchor points, but transitional levels vary in fundamental ways. The structure-first pathway describes transitional levels for individuals whose ability to name systems and processes exceeds their ability to explain. The principle-first pathway describes transitional levels in which naming and explaining are aligned, or explaining exceeds naming. Differences between these pathways have informed our design of instructional resources, which relies on the principle-first pathway—a pathway we believe will help students acquire model-based reasoning necessary for environmental literacy.

We are currently analyzing data from our pilot teaching experiments to explore whether use of Tools for Reasoning, such as the Matter and Energy Process Tool, appeared to influence student use of principle-based reasoning in their explanations. While we hope to see evidence of improved student learning, we are aware of important limitations in the materials that we are currently testing.

First, while our approach to instructional interventions includes what we refer to as “conservative” changes to instruction, we might argue that these changes represent substantial shifts in pedagogy—shifts that place more responsibility on classroom teachers. While we do provide teachers with some lesson plans and materials, our approach relies primarily on a set of tools—a learning progression framework, assessments, and Tools for Reasoning—with the expectation that teachers will determine how best to use these tools in their classroom. We still know little about the extent of professional development required to support teachers in being active users of the type of learning progression system proposed by our work.

Similarly, for our instructional interventions to achieve real change for students, teachers must also make decisions about when and how to integrate Tools for Reasoning and other instructional resources into their existing curricula. Yet, we still know little about the depth at which these tools must be integrated to achieve observable changes in student performance. Formative assessments would help teachers to track student progress and would help them make immediate instructional decisions using the learning progression to inform these decisions. We feel that formative assessments we have developed so far are limited and perhaps inadequate. Our proposed research plans seek to make formative assessments more central to our learning progression system.

Conclusions

In this chapter we have described our approaches to two core challenges that we have faced in defining learning progressions leading toward environmental science literacy: defining what progresses in a learning progression and defining alternate pathways that are linked to instruction. In addressing these challenges, we have developed a learning progression system that includes a coordinated framework, sets of validated assessments in several domains important to environmental literacy, and tools and instructional resources that can be flexibly used in the classroom.

An important feature of our learning progressions, assessments, and tools is our focus on language and language use. We have grounded our learning progressions in a Discourse framework that focuses on how language both shapes and represents student reasoning. Language shapes the way students view the world, and this language is also a clue to understanding how students reason about phenomena. This focus on language as both a shaper and a product of how students view the world has allowed us to develop learning progressions that account for the sociocultural as well as cognitive aspects of learning across a wide range of students and across broad scientific domains necessary for environmental science literacy.

Furthermore, paying attention to student language and practice helps us understand the pathways that students take through the learning progression from their primary Discourse to a secondary Discourse of scientific model-based reasoning. For the carbon learning progression we have recognized the key role the principles—the hierarchy of systems at different scales and conservation of matter and energy—play in scientific reasoning. We suggest on the basis of our research that these principles can be at the core of teaching that helps students take a “principles-first” pathway toward environmental science literacy that will be more effective than status-quo teaching. We are currently testing the effectiveness of instructional interventions that support this alternate pathway; we are looking forward to learning more about their effectiveness.

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