Developing a Learning Progression for Carbon Cycling in Environmental Systems

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[1] Andy Anderson, Lindsey Mohan, and Ajay Sharma wrote the words for this paper. The ideas, though, come from a much wider range of discussions. In particular, Ajay Sharma did much of the literature review work and developed the tests. Mark Olson's dissertation study was a source of many of the ideas about narrative and model-based accounts. Shinho Jang's dissertation study pointed out the central importance of process tracing to model-based reasoning. Mark Enfield's dissertation study points out the importance of projects for younger children. Many of the other ideas were developed in discussions of the Diagnostic Question cluster group (including Joyce Parker, John Merrill, Duncan Sibley, Merle Heidemann, Brett Merritt, and Chris Wilson), the Knowles and instructional teacher education groups (Gail Richmond, Ajay Sharma, Shinho Jang, In-Young Cho, Brett Merritt, and Steve Tuckey), the CCMS Environmental Literacy working group (John Lockhart, Aliah Carolan, Felicia Moore, Tim Parshall, Ajay Sharma, In-Young Cho, Beckie Forthoffer, Blakely Tsurusaki, Jim Gallagher), and others in the MSU science education community.

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Abstract

We synthesize published research and report findings from our own research on how learners account for phenomena associated with the ecological carbon cycle on a variety of scales, including (a) metabolic processes in cells, including cell growth, photosynthesis, and cellular respiration, (b) processes that are observable at a human scale including growth, death, and decay of plants and animals, metabolic processes such as eating, breathing, and digestion, and physical and chemical changes such as evaporation, convection, and burning, and (c) large-scale processes such as matter cycling and energy flow in ecosystems (including coupled human and natural systems), and changes in global carbon cycling.

We organize these results into a *learning progression:* a succession of children's performances, encompassing both knowledge and practice that leads to understanding of the material world. We use the word succession deliberately: We see learning progressions as describing changes in children's reasoning that are akin to ecological succession. There is no single defined sequence of events, but there are multiple pathways that connect children's naive ideas with the powerful insights of scientific theories.

We use accounts of phenomena as the unit of analysis around which the learning progression is organized. Children of all ages as well as adult scientists account for their observations of the world in a variety of ways, including stories, pictures, graphs, formulas, and formal conceptual models. Adult scientific accounts provide powerful insights into the nature of the material world and tools for predicting the likely results of our actions. Children's accounts can help us to understand how they reason about the world.

We have tentatively identified five properties of accounts that we expect to show successional trends: Developing a critical understanding of scientific accounts; connecting accounts of plants, animals, decomposers, and materials; connecting accounts of molecular, cellular, organismal, and environmental processes; gaining experience and precision in observations, and working flexibly with models at different levels of detail. Each of these trends is described and illustrated with examples of learners' accounts.

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This paper presents preliminary results from assessments that we have developed on how learners account for phenomena associated with the ecological carbon cycle on a variety of scales, including cellular, organismal, and ecosystem scales. We use these results, combined with results from other research to suggest a *learning progression:* a succession of children's performances, encompassing both knowledge and practice, that leads to understanding of the material world. We present our findings and the research synthesis in four sections:

1. The importance of carbon cycling in the science curriculum. In this section we explain why we feel that carbon cycling and related environmental processes deserve a central role in our required K-12 science curriculum.
2. Preliminary research methods and results. In this section we present preliminary results from pretests that we have administered to elementary, middle, and high school students.
3. Synthesizing research in a learning progression. In this section we suggest a synthesis of our work with other research to suggest a possible learning progression that would lead to a meaningful understanding of the role of carbon in environmental systems.
4. Conclusion and implications. In this section we suggest how learning progressions could be useful to guide research and practice.

1. The Importance of Carbon Cycling in the Science Curriculum

The topic of this research—transformations of matter and energy in biogeochemical systems—is currently recognized as a fundamental part of the K-12 science curriculum, and its importance is likely to grow in the future. Human populations draw sustenance—food, clothing, shelter, and the air we breathe—through these transformations of matter and energy. Many of the most important processes transforming matter and energy are included in the *ecological carbon cycle,* the focus of this project. As our populations grow and our technologies become more powerful, our responsibilities for maintaining the systems that sustain us will grow, too. We include in this topic systems and processes that transform carbon compounds on a variety of scales. For example:

- Chemical changes in carbon compounds, including combustion of organic materials and basic biochemistry
- Cellular metabolic processes, including cell growth, photosynthesis, and cellular respiration.
- Macroscopic and organismal processes including growth, death, and decay of plants and animals, organismal metabolic processes such as eating, breathing, and digestion, and physical and chemical changes such as evaporation, convection, and burning.
- Large-scale processes such as matter cycling and energy flow in ecosystems (including coupled human and natural systems such as cities and farms), and changes in global climate and carbon cycling caused by deforestation and the burning of fossil fuels.

Thus the content addressed in this paper goes well beyond the "carbon cycle" as it is currently presented in most school textbooks. A better label might be something like: *The Role of Carbon in Environmental Systems.* Much of this content can be found in current standards documents, textbooks, and science achievement tests, albeit in a somewhat fragmented form. We argue in this section that the processes listed above can and should be used to provide coherence to the science curriculum, and that as a country we need our citizens to understand these processes.

Changes in Science and in the Science Curriculum

Maintaining the environmental systems that sustain us is a shared responsibility of all citizens. Citizens take individual actions that affect biogeochemical systems when they decide what kinds of food to buy, how they will get to work, where they will live, or what kind of car to drive. Citizens can also influence social or governmental actions with environmental implications—land use planning, tax policies, spending on mass transit, or participation in international treaties. Thus our future depends on our collective understanding—on the ability of all citizens to understand evidence-based arguments about the environmental consequences of our actions.

The standards-based reform movement (AAAS, 1993; National Research Council, 1996) has the goal of providing the resources that teachers need to help students understand biogeochemical systems, but the effectiveness of the reform movement is limited by some qualities of the standards themselves. The standards documents were written a decade ago; both educational and scientific research have made substantial progress since that time. We need to recognize important advances in environmental science which are not emphasized in the current standards. In particular:

- Environmental science has become increasingly *interdisciplinary*. Current standards and textbooks treat ecology primarily as a field within the life sciences, and not closely connected with fields in the earth sciences such as meteorology, oceanography, and atmospheric science. It has become increasingly clear, however, that the systems studied by these fields are interconnected with one another and with the human populations that depend on them. Thus communication between scientists practicing different disciplines has increased and all of these disciplines have made increasing use of frameworks and models that cross traditional disciplinary boundaries. These changes are reflected in the organization of scientific societies. For example, the American Geophysical Union and the Ecological Society of America have recently started Biogeosciences sections.
- Environmental science has focused increasingly on *coupled human and natural systems*. For example, the summary report of the NSF Advisory Committee for Environmental Research and Education (AC-ERE, 2003) identifies three areas where research and public understanding will be especially important: coupled human and natural systems, coupled biological and physical systems, and people and technology. These emphases differ substantially from the emphases of the current national standards and most current biology textbooks, which focus more on pristine ecosystems than on the human-influenced systems that dominate our landscape, including mines, factories, cities, roads, suburbs, farms, and ranches.
- Environmental science has increasingly recognized that *ecosystems are dynamic and contingent.* In addition to recognizing the importance of coupled human and natural systems, environmental science has undergone a series of theoretical shifts that might be summarized as

“the end of the balance of nature.” For the last half century environmental science has been shifting away from the idea that ecosystems and other large earth systems are in steady states and kept relatively stable by a “balance of nature,” and toward a view of dynamic environmental systems whose conditions and processes are contingent on changes in climate, additions or deletions of organisms, natural disturbances such as fire or windstorms, and human impacts.

These changes in the natural sciences are driven in part by increasing awareness among scientists of how human populations are changing local and global environments. The “carbon cycle” is no longer a cycle, on either local or global scales. Most local environmental systems—especially those altered by humans—are net producers or net consumers of organic carbon. Similarly, humans have altered the global system so that there is now a net flow of carbon from forests and fossil fuels to atmospheric carbon dioxide. Thus understanding the role of carbon in environmental systems entails understanding the balance between processes that produce and processes that consume organic carbon.

We start with a discussion of why carbon is uniquely important in the school curriculum. We then go on to discuss evidence that American adults understand many carbon-transforming processes in ways make it difficult for many citizens to reconcile their values with their personal practices and policy positions, or to understand and participate in debates about environmental processes involving carbon.

Why carbon?

We have chosen our focus because carbon-transforming processes are uniquely important in the global environment, because understanding those processes is essential for citizens’ participation in environmental decision-making, and because carbon-transforming processes exemplify big ideas in the environmental sciences.

Carbon-transforming processes are uniquely important. All living things are made of carbon compounds; they grow and store food by transforming carbon compounds; they obtain and use energy by oxidizing carbon compounds. Carbon compounds are equally important to human societies; we depend on biomass and fossil fuels for most of our food, energy, transportation, and shelter. The primary product of our activities—carbon dioxide—regulates global temperatures, atmospheric circulation, and precipitation. Thus an understanding of the many processes that transform carbon compounds is central to understanding environmental processes and systems in general.

Understanding carbon-transforming processes is essential to citizens’ participation in environmental decision-making. As a society we face a wide range of environmental issues that involve how we use or regulate carbon-transforming processes: Global climate change, prices and uses of fossil fuels and alternative energy sources, deforestation, soil fertility, hypoxic conditions in lakes and oceans, and so forth. As a nation, we need citizens who can understand and respond to these issues. We argue below that citizens’ lack of understanding has a profound effect on our political culture. Most citizens lack the conceptual tools and practices that they need to reconcile their personal actions and the policies that they support with their environmental values, or to understand debates among experts.

Carbon-transforming processes and systems exemplify big ideas in the science curriculum. Understanding how carbon compounds are transformed in human and natural systems involves reasoning about many important scientific ideas in the physical science (e.g., transformation and conservation of matter and energy), life sciences (e.g., photosynthesis and cellular respiration, growth and decay in plants and animals, and earth sciences (e.g., weather and climate, matter-transforming processes in environmental systems). Thus this topic affords us opportunities investigate a conceptually coherent domain that includes key ideas and ways of reasoning from different disciplines—ideas and ways of reasoning that students can use in many ways during their daily lives.

Adults' Understanding of the Role of Carbon in Environmental Systems

The evidence is strong that most citizens do not understand biogeochemical systems in ways that will enable them to make well-informed decisions. A video widely circulated by the Private Universe project shows Harvard and MIT graduates failing to understand that the mass of a tree comes largely from carbon dioxide in the air. Andersson and Wallin (2000) found that many Swedish students confused global warming with ozone depletion. In our own research at the college level, we found that most prospective science teachers—senior biology majors—said that when people lose weight their fat is "burned up" or "used for energy"—even when we offered a better option (the mass leaves the body as carbon dioxide and water). Other studies (e.g., Anderson, Sheldon, & Dubay, 1990; Songer &, Mintzes, 1994; Zoller, 1990; Fisher, Kathleen M. et al., 1984) document troubling gaps in adults' understandings of carbon-transforming processes, but they do not address the implications for these limited understandings.

We discuss the implications of these studies by looking in some depth at a study that investigated the relationships between adults' environmental values, their scientific understanding, their practices as consumers, and the policies that they advocated as citizens. (Kempton, Boster, & Hartley, 1995). Kempton and his colleagues conducted in-depth interviews with a sample of American adults, ranging from members of Earth First! and the Sierra Club to Oregon loggers whose jobs were endangered by environmental regulations. A first key finding of their study was that virtually all the informants were deeply concerned about the environment and convinced that we should be doing more to preserve and protect it. They believed that we should be changing our lifestyles now to protect the environment, either for the sake of natural systems themselves or for the sake of future human generations, including their own children and grandchildren.

Kempton and his colleagues also found, however, that most informants engaged in practices as consumers or advocated policies that were inconsistent with their espoused values. Focusing on global warming as a key issue, they found two key reasons for these gaps between values and practices.

First, most of Kempton's informants did not understand key aspects of the science. A fair number of them confused global warming with ozone depletion or attributed global warming to chlorofluorocarbons or other pollutants. Planting more forests and pollution controls were both ranked higher by survey respondents than reducing carbon dioxide emissions as steps we could take to reduce global warming. Thus the sources of their confusion about the scientific debate included (a) difficulties with understanding *processes or mechanisms*—the processes that lead to global warming, (b) difficulties with understanding *substances*—the chemical nature of key greenhouse gases, and (c) difficulties with understanding *quantities*—for example, the relative amounts of carbon dioxide released by burning of fossil fuels and absorbed by growing forests.

To anticipate the language we will use in discussing the K-12 curriculum below, we would say that these informants had not mastered the *conceptual tools and practices* that they needed to reconcile their values with their practices.

Kempton, et al., explained the gaps between values and practices by saying that related questions invoked different and disconnected *cultural models*. For example, after a thorough briefing on the science designed to help informants understand that reducing carbon dioxide emissions is a key to reducing global warming, Kempton et al. asked informants to react to a proposal for a tax on energy produced by burning fossil fuels. The responses were interesting not so much for the positions that informants took as for the reasons they gave for their positions. Most responded with either concerns about the immediate effects on their budgets or concerns about how the government would spend the money it collected. Thus they treated the proposal as mostly being about money. None of the respondents invoked the primary issue debated among experts, which is whether the tax would promote more efficient systems for using fossil fuels.

Thus many adults have not mastered the conceptual tools and practices that would enable them to see the important connections between their environmental values, their practices as consumers, and their participation in debates about environmental policy. These conceptual tools and practices include scientific understanding of processes, substances, and quantities. Citizens' dependence on disconnected cultural models for discussions of human and natural systems could have a profound effect on our political culture and our collective future. In a democratic society the people decide which experts to listen to, so it is important for our citizens to have access to the expert debate.

In the next section we present preliminary results from a study that we are starting on K-12 students' reasoning about key carbon-transforming processes. We then synthesize these results with the work of other researchers to suggest a possible learning progression leading to high school graduates who are better prepared for their adult roles as responsible citizens and consumers.

2. Research Methods and Preliminary Results

In this section we present preliminary results from a study currently underway that focuses on the reasoning of K-12 students about carbon-transforming processes in environmental systems. At the moment, we feel comfortable in presenting only broad generalizations about students' reasoning. As we continue the study, though, we hope to develop more nuanced and quantitative accounts of how students' reasoning develops.

Data Sources

We assessed elementary, middle, and high school students' knowledge of the role of carbon in human and natural systems using paper-pencil tests that were developed in consultation with a group of practicing science teachers. Two tests were developed, one to assess elementary students' understanding and another to assess middle and high school students' understanding. Two elementary teachers, four middle school teachers, and one high school teacher administered the tests to their respective science classes. The tests contained questions about producers, consumers, and decomposers, with the items appearing in multiple-choice or open-ended format. Two working papers were developed that contained rubrics specific to each test, one to code responses from the elementary test and the other to code responses on the middle and high school test. With the help of codes, the results were analyzed to detect underlying patterns and arrive at a grounded understanding of students' conceptions. Copies of the tests can be found on the project website: http://scires.educ.msu.edu/EnvironmentalLiteracy/index.html.

Data Analysis

Analyses were guided by Working Papers with rubrics for coding students' responses. Both the tests and the Working Papers are available on the project website. The rubrics were designed to highlight aspects of the students' responses relevant to the general theme of environmental literacy and the specific trends in the succession of students' reasoning described below. Reliability of the rubrics was assessed by having a second coder independently code a sample of the tests. When there were discrepancies, the rubrics were revised. Additional revisions were based on discussions with other project staff members.

We chose *accounts of phenomena* as the unit of analysis for this study. Accounting for (i.e., predicting and explaining) the phenomena of the material world is a fundamental purpose of science. Children of all ages as well as adult scientists account for their observations of the world in a variety of ways, including stories, pictures, graphs, formulas, and formal conceptual models. Adult scientific accounts provide powerful insights into the nature of the material world and tools for predicting the likely results of our actions. Children's accounts are less sophisticated and powerful, but by studying children's accounts carefully we can understand how they reason about the world. A more detailed discussion of accounts of phenomena, with examples, can be found in the Appendix.

Preliminary Assessment Results

The findings presented below result from initial analyses of tests given to elementary, middle, and high school students. The analyses focus on students' conceptions of producers, consumers, and decomposers, with test questions primarily focused on students' development of model-based understanding of specific processes and students' abilities to connect accounts of processes.

General Findings

- *Students at all levels show limited use of model-based reasoning, most especially at the lower grade levels*. During middle school, some signs of model-based reasoning appear in the form of students using constraints to help them reason (e.g., conservation of mass). A limited number of high school students continue to use constraints, but typically it is intermittent, such that some students may conserve mass of solids or liquids, but do not conserve mass of gases.
- *Students at all levels show fragmented knowledge about processes*. When middle and high school students were asked, 'Do you see connections between eating and breathing?' the most common response from students at both grade levels was that they are both needed to live and survive. A fifth of middle school students responded that the two processes are completely unrelated. A fifth of high school students said that the body needed O_2 from breathing and glucose from eating to produce ATP. This question shows that only a limited number of high school students are connecting their accounts of different processes.

Producers

The middle and high school level test contained eight items that specifically asked what plants need to live, grow, and make food (e.g., A small acorn grows into a large oak tree. Where does most of the mass of the oak tree come from?). The elementary level test contained two items that asked about producers (e.g., List and explain all the things that plants need to live and grow). The preliminary analyses of these questions reveal that students have particular difficulties in two areas:

- *Distinguishing between what is food for plants and what plants need to make food.* When middle school students were asked, 'What portion of food do plants make?' relatively few students responded 'ALL'. Middle school students tended to respond that some food is made, some is absorbed through roots, and some is absorbed through the leaves. Analyses showed a similar trend in high school students' responses, however, more students answered that plants make all of their food. Interestingly, the high school students did not want to rule out that some food was absorbed by roots and leaves. When middle school students were asked, 'Which of the following is food for plants?' an overwhelming majority responded that water and sunlight are food and far less students answered that glucose is food for plants. Similarly, the majority of high school students also said that water and sunlight are food, however, more high school students also claimed that glucose was food for plants. In elementary, when students were asked, 'what plants need to live and grow?' the two most frequent responses were water and sunlight, followed by air and soil.
- *Understanding that gases contribute to the mass of plants.* Middle and high school students show limited understanding of where plant mass comes from. When middle school students were asked, 'where does the mass of an oak tree come from,?' most responded that the mass comes from water absorbed through the plant roots or from sunlight converted to food. Only a small group of students responded that the mass comes from CO_2 in the air and H_2O absorbed from the soil. When high school students were asked the same question, the majority of students responded that the mass comes from water absorbed through the roots, and still a limited number of students responded that the mass comes from CO_2 and H_2O.

Consumers

The middle and high school level test contained four items that focused on human processes (e.g., respiration, weight loss). The elementary level test contained four items that asked about human processes (e.g., respiration, human growth, digestion). The preliminary analyses of these questions reveal that students have particular difficulties in three areas:

- *Understanding and connecting processes at multiple levels.* Elementary, middle, and high school students can explain respiration to varying degrees at the organismic level, but almost all have limited knowledge of the molecules and processes involved in respiration at the cellular level. When elementary students were asked to explain, 'what happens to air in the body?' most students mentioned the words breathing or lungs, and some elaborated beyond the respiratory system to the heart, blood vessels, or brain. When middle school students were asked, 'where and how does O_2 in get used in the body?' the majority of students responded that O_2 is used during breathing in the lungs. When high school students were asked this same question the most common response was also that

O_2 is used by the lungs. However, some high school students mentioned that O_2 is used in the cells during cellular respiration.

- *Understanding matter and energy cycles.* Middle and high school students show difficulty understanding matter and energy cycles and made erroneous matter-energy conversions, especially when asked to explain food digestion or weight loss. When middle and high school students were asked, 'when a person loses weight, what happens to the fat,' the majority of students responded that the fat is converted to energy for exercising or for body functions. A small group of students responded that the fat is converted to CO_2 and H_20, but when asked to explain their answer, the students did not explain the conversion at the molecular level.
- *Tracing substances.* The two problem areas mentioned briefly above allude to the fact that students have difficulty tracing substances through processes in the body, such as tracing substances in human respiration, digestion, and the break down of fat. Specifically, when middle and high school students were asked, 'how is CO_2 produced in respiration?' the majority of middle school students left the question blank and less than a third of high school students mentioned or explained that CO_2 production occurs during cellular respiration. Additionally, middle and high school students' limited ability to explain the breakdown of fat that results in weight loss, indicates that students may not understand how to trace materials in the body.

Decomposers

The middle and high school level test contained two items that specifically asked about the process of decomposition (e.g., compost piles, decomposing leaves). The elementary level test contained one item with three parts that asked about the process of an apple rotting. The preliminary analyses of these questions reveal that students have particular difficulties in three areas:

- *Understanding that decomposition involves materials in one organism becoming parts of another organism.* There is limited understanding among students at all levels that decomposition is a process where materials from one organism (e.g., apple, leaves) are used by other organisms (e.g., microbes). When elementary students were asked to explain 'what happens to an apple as it rots? What happens to its weight?' a couple of students mentioned that bacteria caused the apple to rot. These students could not explain their answer, but they did realize that another organism was using the materials from the apple. When middle and high school students were asked, 'why does a compost pile give off heat?' almost all middle school students left the question blank and a few high school students mentioned that microbes were the cause of the heat. Again, the students had limited understanding of the process by which the heat was created.
- *Understanding conservation of decaying matter.* Students at all levels have difficulty accounting for the 'disappearing' mass of decaying materials. However, even students at the elementary level show signs of using constraints to explain 'disappearance' of materials. When elementary students were asked about the cause of the apple rotting, the majority of students mentioned external factors such as air, wind, or heat causing the decomposition. Elementary students also explained that the weight change was due to evaporation of juice in the apple. Middle and high school students also showed signs of reasoning using constraints. When middle school students were asked, 'when leaves

decay, they lose mass. What do you think happens to the mass of the leaves?' the two most common answers were that the mass disappears or that the mass turns into soil minerals. The latter response shows that students are trying to conserve mass and thus, reasoning using constraints. Differently, when high school students were asked the same question, the two most common responses were that the mass turns into soil minerals or that the mass turns into heat energy. Both responses show that the students are trying to conserve mass, however, the former shows that students are making erroneous matter-energy conversions. Fortunately, very few high school students responded to this question by saying that the mass disappears.

- *Understanding matter and energy flows*. The previous two problem areas are closely related to students' understanding of matter and energy flows and students' tendency to explain the 'disappearance' of matter as a conversion of matter to energy. When high school students responded to the question about decomposing leaves, over a third of students answered that the mass of the leaves is converted to energy. Similarly, when high school students were asked why a compost pile gives off heat, over a third of students mentioned that the breakdown of the compost is transformed to energy in the form of heat.

In summary, students showed some of the same difficulties as Kempton's adult informants. In particular, they focused primarily on solids and liquids in accounting for processes where gases were important inputs or products, including photosynthesis, cellular respiration, plant growth, weight loss, and decay. They reasoned mostly at the organismal level, and had difficulty using ideas about cellular process to explain the functions of multicellular organisms. The older students did only slightly better than the younger ones, indicating that they tended to reason about carbon-transforming processes using cultural models from their out-of-school experiences rather than theoretical models that they studied in school.

3. Synthesizing Research in a Learning Progression

In this section we suggest an alternative to the current unsuccessful pattern of achievement, based on a synthesis of the results above with the results of other research. We suggest a possible *learning progression:* a succession of performances in which students master increasingly powerful conceptual tools and practices, in the process making connections among domains of knowledge that are disconnected for young children. We first provide an overview of possible successional trends in children's learning. We then suggest more specific developmental strands.

Overview of Successional Trends in Children's Learning

We know that mastery of the conceptual tools and practices that connect separate cultural models or domains of knowledge is a difficult feat, requiring intelligent teaching and sustained effort by learners and their teachers. We present a speculative account of how this feat might be accomplished in this important domain. To paraphrase Neils Bohr, learners must "extend their experience and reduce it to order," learning to make use of new conceptual tools and practices. They can use these new tools to develop scientific accounts that analyze environmental systems in terms of pools of organic and inorganic carbon and processes that transform matter, moving carbon from one pool to another.

How could student understanding develop?

The general picture: Children learn to make connections among initially separate domains of knowledge. Our reading of current research and our classroom experiences convince us that elementary school students see little connection among the domains of knowledge that are united in a mature understanding of carbon-transforming processes in environmental systems. They develop knowledge of properties and changes in matter, of plants and animals, of food chains and webs, and of human transportation and energy-generating systems in separate and disconnected ways. Thus their knowledge in each area is associated with different cultural models or domains of knowledge. Successful learning involves mastering the conceptual tools and practices that enable scientifically literate people to connect these initially separate domains, and thus to reason empirically about environmental systems and issues. We wish to study both learners who successfully make these connections and learners who fail to connect the separate domains (currently most American students).

Mechanisms for learning: Children need to engage important questions and master conceptual tools and practices. Learning is a complex process, but we hypothesize that we can identify *key questions* that are interesting and accessible to students of different ages and that have potential for payoff in critical learning. For example, elementary school students are interested in mechanisms (How do plants and animals do what they do?) and in needs (Why do plants need light and animals need food?). Children who are engaged with these questions are ready to appreciate the value of key *conceptual tools and practices* (for instance, atomic-molecular models of matter). We wish to identify the questions and conceptual tools that will enable students to make the key connections among their separate domains of knowledge.

Hypothetical developmental sequence and mechanisms

We hypothesize that successful learning over time involves making connections among domains of knowledge that are largely disconnected for children in elementary school: plants and animals; materials and changes in materials; matter cycling in ecosystems; and human economic and technological systems. We further hypothesize that the key to helping children make those connections lies in the areas that were problematic for Kempton's informants: processes or mechanisms; substances; quantitative reasoning, and connecting human and natural systems.

In the remainder of this section we suggest important learning issues for children in elementary, middle, and high school. Figure 1, below, provides a graphic organizer for our discussion. The general succession in Figure 1 depicts initially separate domains of reasoning (or cultural models, in Kempton's terms), becoming connected as children master key linking ideas. Our reading of the research suggests that many children in elementary school currently attain the understandings indicated on the first row. We feel that the understandings indicated on the second and third rows could be achieved by children in middle and high school, respectively, with appropriate science teaching. Students could make these connections by engaging with *key questions* and by mastering important *conceptual tools and practices.* This is not the case today, and this is the dilemma we intend to explore in our future research.

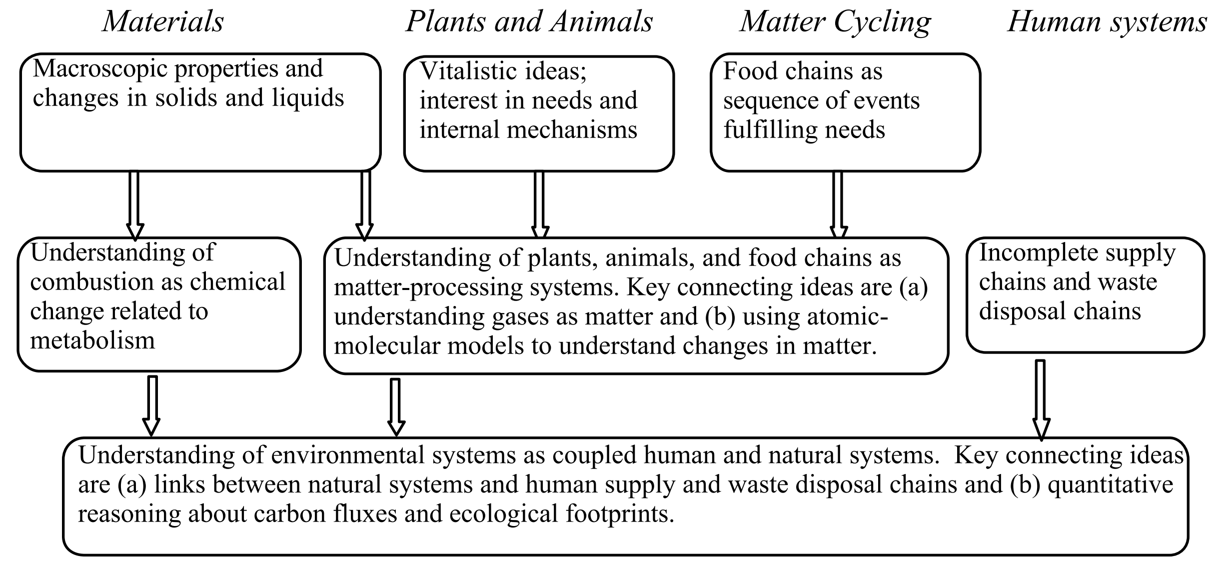


Figure 1: Suggested developmental progression for the role of carbon in environmental systems

Elementary and middle school story: Changes in matter as a conceptual bridge among (a) reasoning about materials, (b) reasoning about plants and animals, and (c) reasoning about food chains. Our preliminary story about the development of conceptual understanding in elementary and middle school children is well grounded in existing research for reasoning about materials (see Smith, et al., 2004) and reasonably well grounded with respect to plants and animals and food chains. We suggest that by middle school many children are ready to construct deeper links between their reasoning about plants and animals and food chains and their reasoning about materials.

Children entering elementary school are not ready to make those links. Young children's reasoning about *materials* focuses on objects and events. During the elementary and middle school years they come to distinguish objects from the materials of which they are made, and to recognize that materials come in different kinds. They learn to describe materials and material kinds in terms of their properties, and to wonder why different materials have different properties. They also come to recognize that many events involve changes in materials, and to label some events with names that recognize them as changes in materials (e.g., melting, evaporating, burning). Many (though by no means all) middle school children recognize that gases are materials like solids and liquids, and that events such as evaporation and condensation involve materials changing between liquid and gaseous states.

At the same time, children are learning about *plants and animals*. They observe (directly or vicariously) growth, death in decay in many plants and animals, including humans. Inagaki and Hatano (2002 Keil, 2003) make a case that children's thinking about plants and animals is characterized by vitalism (a belief that living things have unique vital properties) and teleology (a belief that living things are governed by purposes). Thus they see the functioning of plants and animals as quite different from properties and changes in materials. As they go through elementary school, they reason in increasingly sophisticated ways about the needs of plants and animals—for air, water, nutrients, and appropriate growing conditions—and about internal mechanisms for growth, movement, digestion, breathing, and circulation.

Children also study *food chains and webs* in elementary school and can construct links among plant, animal, and human populations (ref). On the basis of our work with older students, however, we suggest that they generally understand food chains and webs in narrative rather than model-based ways. That is, they see food chains and webs as sequences of events—mini-dramas in which, for example, the rabbit eats the grass and the wolf eats the rabbit. The recognize that the rabbit *needs* the grass and the wolf *needs* the rabbit to live and grow, but they are not familiar with the mechanisms by which the material in the grass becomes part of the rabbit, and the material in the rabbit becomes part of the wolf (Driver, et al, 1994; Smith & Anderson, 1986).

We suggest that around middle school many children are prepared to bring these three domains of reasoning together. To go through this successional change, children need extensive experiences with both living systems and with matter. In the elementary grades, these experiences can focus on visible changes—life cycles, death and decay, physical changes in solids and liquids. In middle school, the focus shifts to the nature of the invisible changes in matter that underlie visible changes in systems. Observable events are explained as transformations in atoms, molecules, and energy.

Two kinds of experiences are especially important for this transition. One focuses on *mass as a measure of matter.* Children need to make a transition from felt weight to measured mass as the key way of judging the "amount of stuff" in a system, to become more experienced and sophisticated in measuring mass, and to acquire a commitment to conservation of mass in all transformations of matter. The second kind of experience focuses on *gases as matter.* Children need to recognize that gases, along with solids and liquids, are states of matter. Thus gases have mass and are different from conditions or forms of energy that cause changes such as temperature, cold, heat, and light.

One example of how the learning progression might work is around the question of *what changes and what stays the same when animals grow.* Young children are likely to say that the weight changes but the animal stays the same. We would like older students to recognize that animals' bodies are stopping points for atoms that have generally stayed the same since the origin of the earth, so the animals' bodies change while the atoms of which they are composed stay the same.

Key insights that they need to achieve include:

- Plants and animals are made of materials; the needs of plants and animals are partly needs for materials (e.g., water, air, nutrients).
- The solids and liquids in plants and animals come from gases in the atmosphere and eventually are converted back into gases in the atmosphere.
- The mechanisms by which plants and animals grow, move, respond to their environments, or digest food involve changes in materials. Materials inside plants and animals change according to the same rules and processes as inanimate materials.
- Plants and animals are alike in many ways, but an important difference is how they produce or acquire food.
- Eating and decomposition involve materials in one organism becoming part of another organism.

Another key development that is possible in the middle school years, somewhat independent of their understanding of plants and animals, concerns their understanding of combustion. With appropriate instruction, middle school children can learn that when organic materials burn they react with an invisible gas (oxygen) and invisible gases (carbon dioxide and water) are the primary products. They can also recognize the similarities between the changes that take place in plant and animal metabolism (cellular respiration).

Children's achievement of these key insights needs to be driven by *key questions* and depends on their mastery of *conceptual tools and practices.* In the case of the transitions described above, we hypothesize that the some of the key questions may have to do with *needs* of plants and animals and with *mechanisms* that account for how plants and animals live and grow. With appropriate instruction, these questions can lead children to see the value of conceptual tools and practices that will make connected reasoning possible.

Thus children's knowledge and curiosity about changes in materials and the internal workings of plants and animals set the stage for new, deeper and more unified, insights into how plants and animals function as matter-transforming systems. Current survey research at the middle school and higher levels suggests that only a small minority of students achieve these insights. However, our previous teaching experiments also suggest that with appropriate instruction and teaching materials, far more students could achieve these insights (Blakeslee, Anderson & Smith, 1987; Anderson & Roth, 1989).

High school level: Using supply chains, waste disposal chains, and quantitative reasoning to connect natural and human systems. Since few students enter high school reasoning in model-based ways about materials, plants, animals, and food chains, the suggestions we make about what might be achieved in high school are more speculative. We wish to explore, however, what it might take for students who have learned to reason about natural systems in model-based ways to extend that reasoning to coupled human and natural systems—in other words, for future citizens to connect their values and their actions in ways that Kempton's informants could not.

We suggest that two kinds of additional conceptual tools are keys to this transition (see Figure 1 above). The first of these tools concerns how *supply chains and waste disposal chains* connect human and natural systems. In our current research we have been exploring how high school students account for the movement of carbon-containing substances (the beef in a hamburger and a paper cup) through supply and waste disposal chains. It appears that for these students, as for Kempton's informants, important steps that connect human and natural systems are essentially invisible. For example, feed lots are missing from virtually all of the hamburger supply chains. Similarly, students can trace the discarded paper cup to "the recycling center" (where presumably something good happens to it) or "the dump" (where presumably something bad happens to it), but cannot really suggest how or where the material in the cup is returned to the environment or new human supply chains.

The second key conceptual tool that students need to master includes *quantitative reasoning* about carbon-transforming processes in environmental systems. For example, we would like students to recognize the relative importance of recycling paper and transportation choices. (Driving 10,000 miles in car that gets 30 miles to the gallon emits about 3 tons of carbon dioxide.) Thus students' qualitative understanding of carbon cycling within ecosystems needs to become a quantitative understanding of carbon fluxes in coupled human and natural systems. The idea of *ecological footprints* may provide one accessible approach to quantifying the effects of human activities and technologies on environmental systems (see, for example http://www.ecofoot.org/). We also need to explore how students might make sense of quantitative models such as the global circulation models that predict possible environmental effects of global warming.

Specific Developmental Strands in Children's Accounts

A scientific understanding of the carbon cycle emerges from the blending of two kinds of stories that are initially separate for young children. These two kinds of stories focus on *living systems* and *matter.* In order to create accounts that blend these stories, children also need to learn a new kind of explanation—one that explains by tracing matter through systems rather than narratives of how conditions or circumstances cause events.

Based on our prior research and experience with this topic, we have tentatively identified five classes of *progress variables:* properties of accounts that we expect to show successional trends:

- developing a critical understanding of scientific accounts;
- developing specific accounts of plants, animals, decomposers, and materials;
- connecting accounts of molecular, cellular, organismic, and environmental processes;
- gaining experience and precision in observations, and
- working flexibly with models at different levels of precision and detail.

Each of these trends is briefly described below.

Critical understanding of scientific accounts: Narrative and model-based reasoning

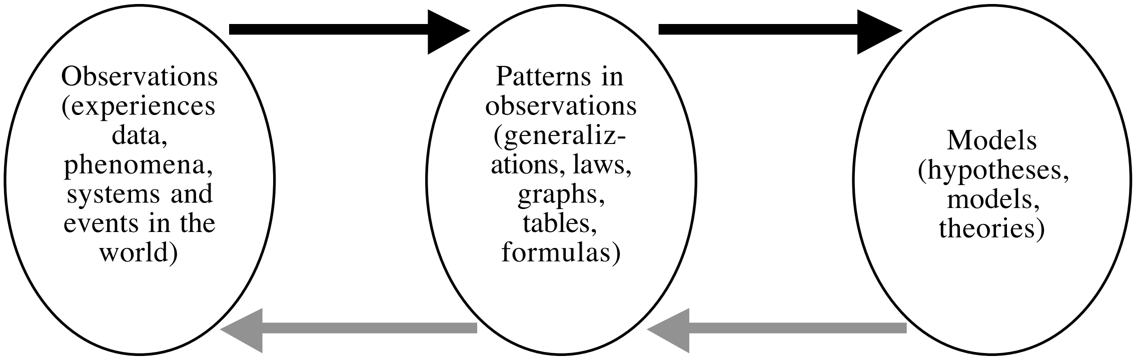
This is in some ways a "nature of science" variable in that it focuses on metacognitive or epistemological commitments that affect people's understanding of science. Rather than focusing on issues from the history of science or questions about how adult scientists reason, however, this trend focuses on epistemological commitments that are implicit in people's explanations and predictions about the world around them. Children and adults reveal in the form and content of their accounts how they think about the scientific enterprise and scientific reasoning.

We can contrast a model-based way of understanding phenomena as *processes in systems* with a narrative way of understanding as *events caused by actors in settings* (Anderson, 2003; Bruner, 1985; Olson, 2005). These two ways of understanding the world are complementary; a deep understanding of phenomena is BOTH narrative and model based. Most people, though, find narrative ways of understanding easier, so the challenge that most science curricula face is helping students to recognize and use model-based reasoning (Lehrer & Schauble, in press; Stewart, Cartier, and Passmore, 2005).

Scientific accounts involve coordinated reasoning about three basic kinds of knowledge claims, which we label observations, patterns, and models. Figure 2, below, suggests a variety of synonyms for these terms as well as relationships among them.

Our proposed learning progression will focus primarily on the practices associated with the right-to-left arrows in Figure 2. By investigating how children at different stages in their development describe and explain phenomena associated with the carbon cycle, we can gain insight into the patterns in their experience and the conceptual models they use to make sense of the world. We can also suggest the kinds of experiences and practices best suited to helping learners develop more powerful and sophisticated accounts.

Reasoning from evidence (Inquiry): Finding patterns in observations and constructing explanations for those patterns



Reasoning from models and patterns (Application): Using scientific patterns and models to describe, explain, predict, design

Figure 2: Scientific knowledge and practices (from Anderson, 2003)

Both narrative and model-based accounts of phenomena implicitly or explicitly assign a variety of properties to each example that they encounter. The table below is a first shot at enumerating and contrasting some of those properties.

Table 1: Contrasting Properties of Narrative and Model-based Accounts of Phenomena

Property	***Narrative Accounts***	***Model-based Accounts***
Nature of action	**Events**: Happenings that are located in time and space	**Processes**: Patterns that recur in time and space
Location and nature of actors	**Actors**: People, organisms, or objects that make events happen **Objects** that events happen to **Settings** where events happen	**Systems** whose subsystems interact through processes, and that interact with other systems through processes
Causes	Events are caused by **actors or triggering events**	Processes occur depending on the **state of the system`**
Connections among events/processes	Events are connected by **temporal sequence** or by **common actors**	**Hierarchies of processes and systems:** Higher level processes are emergent from processes in subsystems **Processes connected by inputs and outputs:** Products of one process are inputs to another
Connections to EPE (experiences, patterns, explanations)	Narratives are generally at one level of EPE **Experiential narratives:** Data-based stories about particular events **Theoretical narratives:** Generalized stories about patterns or models (e.g., steps in digestion or photosynthesis)	Accounts of processes generally connect different levels of EPE: **Inquiry** involves finding patterns in experiences and developing models to explain them **Application** involves using models to predict or explain experiences
Transfer: Accounting for related phenomena	**Reasoning by analogy:** Transfer occurs when a student notices similarities in actors, objects, or settings	**Reasoning by application of models:** Transfer occurs when students apply models to new systems and processes

Constraints on accounts	**Common-sense constraints:** Student decides whether the story makes sense or not	**Explicit theoretical constraints:** Principles and conservation laws provide tools that explicitly limit the nature of permissible accounts

Among the contrasts between narrative and model-based accounts of phenomena, two are especially important. One is best explained in terms of Figure 2 above. Narrative accounts stay “inside the ovals”: They typically are limited to one type of knowledge claim. Experiential narratives tell about sequences of specific events. Theoretical narratives tell about patterns or theories. Model-based accounts, however, typically “connect the ovals”: They connect specific observations or examples with patterns or models.

A second important contrast concerns the ability of model-based reasoners to use *constraints as tools.* Model-based reasoners understand that all processes associated with the carbon cycle are subject to constraints imposed by fundamental laws of nature, such as conservation of mass and energy and the fact that physical and chemical changes do not create or destroy atoms. Recognizing these constraints enables model-based reasoners to use *substance tracing* as a basic way of understanding processes at many different scales. At the molecular level, they may balance chemical equations as one way to keep track of all the atoms. At the macroscopic and environmental levels, they may try to trace mass changes or elements through a system as a way of checking their understanding—they know that they do not fully understand the system until they can account for all the mass and all the elements.

In contrast, narrative reasoners who see metabolic and environmental processes as sequences of events have no comparable set of constraints to help them choose among the many plausible narratives that might explain phenomena. Thus model-based reasoners can check their accounts against constraints in ways that are unavailable to narrative reasoners: “Have I accounted for all of the mass in the system? Have I accounted for all of the energy? Do any substances seem to appear or disappear in unexplained ways in my account?”

Current broad-scale assessments generally show that learners of all ages depend primarily on narrative reasoning. We hope to document in our teaching experiments that middle school and high school students can learn to use both narrative and model-based accounts in flexible and appropriate ways. Specific trends or progress variables and foci for assessment include:

- Developing accounts that connect or observations, patterns, and models
- Self-testing by checking patterns or applying models to new situations
- Commitment to constraints on analyses of processes
    - Tracing mass (or amount or weight): Misconceptions about gases and matter-energy conversions as special problems
    - Tracing substances or individual atoms: Recognizing chemical nature of organic substances as a special problem
    - Tracing energy: Misconceptions about matter-energy conversions and recognizing forms of energy as special problems

We suggest that students going through a successful learning progression will accomplish three levels of sophistication in scientific reasoning: Narrative (as in elementary students understanding of food chains as sequences of events), model-based qualitative (as in the understanding of plants and animals as matter-transforming systems), and model-based quantitative (as in the relative size of different carbon fluxes in environmental systems). Each of these levels of sophistication is associated with different ways of understanding the nature of scientific reasoning and the constraints (e.g., conservation of mass) on processes involving physical and chemical changes. Items associated with this progress variable will assess children's approaches to reasoning and their understanding of constraints on processes.

Developing accounts of specific processes: Materials, plants, animals, and decomposers

In children's learning progressions, model-based accounts of the carbon cycle emerge from the blending of two kinds of accounts that are initially separate for young children. These two kinds of accounts focus on *living systems* and *matter*. In fact, children's accounts are often more fragmented still, since they account for plants and animals in different ways, and may not see decomposition as being caused by living organisms at all. In order to create accounts that combine these stories, children need to learn a new kind of explanation—one that explains by tracing matter through systems rather than narratives of how conditions or circumstances cause events.

This is the successional trend that is best documented in the extensive body of conceptual change research on phenomena associated with the carbon cycle. This research is documented in Reinders Duit's extensive bibliography (Duit, 2005) and reviewed by Driver, et al. (1994). Smith, et al.(2004) have conducted a thorough review of the development of children's accounts of matter and changes in matter,. The research on learners' conceptions of metabolism and matter transformations in living systems is also extensive.

Some trends in this research are well established. For example, learners of all ages struggle to trace substances when asked questions that involve transformations between gases and solids or liquids (e.g., Where did the weight of a tree come from? What happens to the fat when a person loses weight? Where did the condensation on a cold cup come from?) Similarly, the concept of energy is more often confusing than helpful for learners of all ages, as when they say that "food is energy" or wood is "burned up to produce energy." There are still important gaps in our understanding of this class of progress variables, though, that need to be filled by additional research. Specific trends or progress variables and foci for assessment include:

- Properties of materials and changes in materials: Progress moves from macroscopic accounts of solids and liquids to atomic-molecular accounts of physical and chemical changes (including gases) to chemically detailed accounts of carbon fluxes in environmental systems.
    - Tracing substances and accounting for mass in common physical changes. Changes that involve gases (evaporation, condensation, boiling) as special problems
    - Tracing substances and accounting for mass in common chemical changes. Changes that involve gases (burning, oxidation) as special problems
    - Tracing energy through physical and chemical changes
    - Combustion: Progress moves from accounts of combustion as burning up or destroying materials to recognizing invisible gases as reactants and products to recognizing similarities between combustion of organic materials and cellular respiration.

- Plants and animals: Progress moves from vitalistic accounts with an interest in needs and mechanisms to accounting for growth and metabolism as changes in carbon-containing substances to plants and animals as subsystems in larger matter-transforming environmental systems.
    - Connecting conditions for growth with metabolic processes
        - Explaining why plants need light, water, soil minerals
        - Explaining how animals digest and use food for energy and growth
    - Accounting for weight gain and weight loss in plants and animals
        - Predicting weight gain and loss for plants in the light and dark
        - Explaining the role of light and gases in plant growth (Where did the mass of the log come from?)
        - Connecting gas exchange with food and cellular respiration (Where did the carbon in CO_2 come from?
        - Accounting for matter when people gain and lose weight
        - Accounting for mass loss in decomposition
- Matter cycling: Progress moves from narrative accounts of food chains to carbon cycling in ecosystems to carbon fluxes in coupled human and natural systems.
    - Distinguishing producers from consumers/decomposers in metabolic terms.
        - Comparing food production and use in plants and animals
        - Explaining how plants use light
        - Explaining decomposition as a metabolic process in decomposers
- Human supply and waste disposal chains: Progress moves from incomplete accounts of supply chains and waste disposal chains to accounts that qualitatively link human consumption with environmental systems to quantitative accounts that link human consumption to ecological footprints.

In general, students make progress on these variables as their accounts (a) focus more on changes in substances and less on events or vitalistic accounts of plants and animals, (b) make effective use of atomic molecular models, (c) connect systems and subsystems, and (d) recognize the important role of gases in many processes.

Connecting accounts of molecular, cellular, organismal, and environmental processes

Learners face two kinds of challenges in making connections: They need to account for connections among processes that occur at different scales within the hierarchy of environmental systems and subsystems, and they need to account for connections among processes that affect the same substances within a system. Each of these challenges is discussed in this section.

Connecting processes and systems at different scales: Molecular, cellular, organismic, and environmental. Scientists have constructed accounts of processes associated with the carbon cycle at a variety of scales, from the molecular to the global, and they understand those accounts to be linked through a hierarchy of systems and subsystems. Most of these systems are either too large or too small for us to see directly, so young children are not aware of their existence.

Older children are confronted by explanations and representations of these processes that take place at much smaller and much larger scales.

Coordinating those processes and representations is a major challenge. In our recent research at the college level, for example, we see that college science majors generally fail to connect what they have learned about cellular metabolic processes such as photosynthesis and cellular respiration with questions about weight gain and weight loss in plants and animals. Similarly, middle school students have trouble connecting their ideas about eating and growth in individual organisms with accounts of food chains in ecosystems (Smith & Anderson, 1986).

The research base on this strand is less extensive than the research base on the previous strand, so there are still lots of gaps to be filled in.

- Connecting representations (e.g., chemical equations, box-and-arrow diagrams) with events in real-world systems or with representations at a different scale
- Connecting processes at different levels
    - Connecting processes at the organismal level with processes at the ecosystem level (e.g., connecting food chains with digestion and growth in plants and animals)
    - Connecting processes at the cellular level with processes at the organismal level (e.g., explaining how cells work together to enable us to move, breathe, think, etc.)
    - Connecting processes at the cellular level with processes at the ecosystem level (e.g., connecting photosynthesis and cellular respiration with food chains, matter cycles, energy flow)
- Tracing energy through organic systems
    - Tracing energy through the bodies of plants and animals (e.g., connecting food and body heat)
    - Tracing energy through decomposition (e.g., explaining temperature of compost piles)
    - Tracing energy through ecological energy flow
    - Tracing energy through cellular metabolic processes
- Tracing effects of processes on other processes or on the size and composition of matter pools
    - Explaining buildup of carbon dioxide in the atmosphere
    - Predicting the effects of a change in one metabolic process on rates of other metabolic processes
    - Predicting the effects of disturbances on matter and energy flow in ecosystems

The focus for this progress variable is on students' ability to link processes and systems that occur at different scales. Possible levels of sophistication for this variable include (a) accounts that focus primarily on macroscopically observable processes and multicellular organisms, (b) accounts that link macroscopic with atomic-molecular and cellular processes and (c) accounts that link molecular processes with large-scale carbon fluxes.

Gaining experience and precision in observation/data collection

The two previous strands focused on successional trends on the right oval of Figure 2—how learners develop more sophisticated models to account for phenomena. This strand focuses on the left oval—learners' experiences with and observations of phenomena. In order to create sophisticated model-based accounts of the systems and processes of the carbon cycle, learners must extend their experiences, encountering a wide variety of different materials, systems, and processes, and they must learn to observe and describe those new experiences with increasing precision.

As children extend their experience and learn to describe experience with precision, they master new concepts, new skills, and the use of tools that enable them to overcome the limitations of their senses. For example, children learning about matter learn to measure important properties, a process that allows them to transcend more limited sensory definitions of those properties (e.g., weight as felt weight) as they construct an underlying mathematical model of the property in question (e.g., weight as additive physical magnitude that can be mapped to number and explicitly symbolized as the sum of equal-size units). Recognizing the advantages of measurement, they come to distinguish among properties that were initially confounded, and to sort out which are properties of objects (e.g., weight and volume) and which are properties of the materials they are made of (e.g., density).

Smith, et al. (2004) describe these successional trends in some detail for children's learning about matter. No comparable analysis is currently available for other important systems in the carbon cycle, such as plants, animals, cells, and ecosystems. Our planned research will enable us to describe those trends, and to assess which experiences are most useful for helping learners to develop more sophisticated models. Specific trends or progress variables and foci for assessment include:

- Observing wider variety of systems and processes
    - Observing more properties of more materials
    - Observing more physical and chemical changes in matter
    - Observing more organisms: plants, animals, microorganisms
    - Observing more processes in organisms and ecosystems
- Moving from personal impressions to scientific data (attribute-value descriptions, scientific classification
- Using tools to observe and measure
- Using archived data sets

This variable has several dimensions: Children extend their experience with carbon-transforming systems, learn to describe their experiences in more precise and reproducible ways, using scientific classification systems, learn to make effective use of data collected by others (which is only possible when those data are precise and reliable, and learn both to quantify their own experience using measuring tools and units of measure (Lehrer & Schauble, 2002).

Working flexibly with models at different levels of precision and detail

This is the most obvious form of learning. Children move from qualitative predications to quantitative problem solving. They learn specific steps in processes, they learn more detailed formulas and equations. These added details, however, make sense only if they are added to fundamentally sound accounts. Too often, this is not the case, and children memorize details that do not make sense to them. Our goal in developing a learning progression is to make the other essential dimensions of children's reasoning about the carbon cycle visible to teachers, curriculum developers, and assessment developers, so that learners can develop accounts that are powerful and meaningful to them, not merely detailed. Specific trends or progress variables and foci for assessment include:

- Moving from qualitative to quantitative accounts
- Developing more detailed descriptions of systems
- Developing more detailed descriptions of steps in processes

Sophisticated learners have access to a variety of different models that act at different levels of precision. They can select the appropriate model for an occasion and decide what level of precision is necessary for accounts based on those models. More sophisticated learners can produce more detailed accounts and hold themselves to higher standards in their accounts. Thus more sophisticated learners want to learn about hidden mechanisms, account for every atom in a chemical process, or make sure that quantitative carbon fluxes in a system obey matter conservation laws.

Summary table

Table 2 below takes a first shot at suggesting ages at which the developmental milestones in the previous section might be reasonable for most students.

Table 2: Possible Grade-specific Milestones

What Develops?	*Elementary*	*Middle*	*High*
Living systems Progression from focus on *individual plants and animals* to *integrated hierarchy of systems* and subsystems	Organisms: Plants and animals Make things happen to one another	Plants, animals, microscopic organisms Made of cells Connected in food chains and webs	Systems and subsystems: Ecosystems Organisms Cells Molecules & Atoms
Changes in living systems Progression from *events* in lives of plants and animals to *processes* in matter-transforming systems	Organisms grow, move, die, decay Changes are natural (growth, life cycles, decay) or caused by conditions or events (health, death)	Growth, movement, and decay all involve changes in matter Organisms exchange matter with one another and with their environments	Systems contain pools or reservoirs of organic and inorganic carbon Transformations or fluxes move matter among pools Energy drives changes in matter
Experiences with systems Progression from *life cycles* of plants and animals to *tracing matter* through systems	Observations of life cycles—growth, death, decay Systematic record keeping about changes in systems Essential role of food in growth and movement Weight as a way to measure growth	Light as condition for plant growth Careful measures of mass changes associated with growth, decay Observations of microorganisms, plant-based and detritus-based food webs	Gas exchange experiments in plants and animals Chemical analysis of organic compounds, living systems
Matter Progression from *gases as conditions* to *gases as matter,* tracing exchange of carbon between CO_2 gas and organic matter	Solids and liquids are matter Conditions and gases different Living things different?	Solids, liquids, gases are matter and have mass Conditions and forms of energy do not have mass Atoms and molecules Substances and mixtures	Matter is made of atoms and molecules Organic (high energy) carbon compounds are essential building blocks of life CO_2 in the atmosphere is

			a pool of inorganic carbon
Changes in matter Progression from changes as *macroscopic events* caused by conditions to *molecular processes,* tracing atoms and molecules through physical and chemical changes	Conditions or circumstances cause changes (e.g., heat causes ice to melt, water to boil, wood to burn)	Matter and mass are conserved when things change Conditions and energy cause changes	Physical changes: Appearances change, substances and molecules stay the same Chemical changes: Substances and molecules change, atoms stay the same Energy drives changes in matter
Experiences with matter Progression from *stories* of common changes to *analyses* of reactants and products of chemical changes	Observations of physical and chemical changes Learning to measure weight Weight does not change with melting, freezing, breaking, reshaping	Measured mass as essential measure of amount of matter Measuring mass of gases Conservation of mass in physical and chemical changes	Chemical changes involving organic compounds, oxidation
Nature of Explanations Progression from *stories about events* to analytical *accounts of processes* in matter-transforming systems	Stories: Plants and animals change in response to conditions Events have single causes Air is a condition for life	Tracing matter through changes in organisms: photosynthesis, respiration, growth, decay Conservation of mass Air is substances used by organisms	Tracing atoms and molecules through systems: matter pools, transformations, cycles Air is a part of the cycles Energy drives changes and is conserved

Conclusion for Learning Progression

In this section we have sketched out the key issues we wish to explore as we develop our ideas about learning progressions for carbon-transforming processes in environmental systems. The learning progression we describe does NOT represent current reality; it is hypothetical in two respects. First, many of the suggestions above represent extrapolations from existing research. The research base is strongest at the elementary school level, supported by suggestive teaching experiments at the middle school level, and largely speculative at the high school level. Second, as we noted above, the learning progression might better be described as "successional" rather than "longitudinal." We have constructed it by arranging results of short-term studies rather than following the development of individual students over long periods.

Progress variables focus on the conceptual tools and practices that students need to reason in connected ways about carbon-transforming processes. These conceptual tools and practices include (a) mastery of specific ideas and models, (b) ability to connect processes at different scales or in different parts of a system, (c) data acquisition and quantitative reasoning, and (d) meta-level understanding of model based reasoning and of the role of precision in using models.

We believe that the transitions suggested in Figure 1 can be achieved by most middle and high school students in appropriate instruction. We plan to test that belief through teaching experiments in which students have the opportunity to struggle with the key ideas described above, accompanied by careful assessment of their learning. We also believe that the issue connecting all the parts of Figure 1—the role of carbon in environmental systems—is too important to ignore. We need to figure out how to connect the reasoning of citizens to the debates among experts about this critical issue.

4. Discussion and Implications

We believe that learning progressions can help us trace the developmental pathways leading to powerful scientific knowledge. Teachers and curriculum developers must decide which learning experiences, and which conceptual tools and practices, are most appropriate for particular groups of students. We believe that this research can make those decisions clearer, more coherent, and better informed. We suggest that a learning progression is a useful organizational tool because it helps us to synthesize and draw on disparate studies, because it helps us use short-term studies to investigate long-term learning, and because it helps us to link research, policy, and practice.

We can draw on and synthesize disparate studies to study the development of big ideas. The available research is useful, but fragmented. Individual studies focus on students of different ages and cultures, different kinds of instruction, and different conceptual tools and practices. The framework for this study will enable us to make use of those studies in spite of their differences and use them as a starting point for our research. We will be able to investigate the interdependence of complex ideas and practices, successions or sequences of practices, and relationships among development, learning, and instruction. It is only through such synthetic work that we can study the development of complex and important Big Ideas in the natural sciences, including the role of carbon in environmental systems.

We can use short-term studies to investigate long-term learning. It is virtually impossible to conduct studies that follow the development of understanding in individual students over periods of years. We can, however, develop models describing the succession of children's ideas and reasoning strategies based on coordinated studies of diverse students of different ages.

Learning progressions can connect research, policy, and practice. Learning progressions organize and present research findings that make their applications to policy and practice clear. Phenomena associated with the carbon cycles 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. We argue that they can fit together as a coherent conceptual domain that all of our citizens need to understand. Furthermore, treating them as a coherent domain reflects current developments in the natural sciences and in our global environment.

A key characteristic of successful learning progressions is that they enhance learners' agency with respect to the material world. Learners going through the learning progression gain insights or skills that give them more control or a deeper understanding of the natural and technological systems and phenomena around them.

The draft Environmental Literacy Blueprint begins with a definition: *Environmental literacy is the capacity to understand evidence-based arguments concerning the interactions among human populations, technologies, and environmental systems and to participate knowledgeably in decisions based on those arguments.* This definition focuses on environmental literacy as informed action: We believe that schools should prepare citizens to participate in evidence-based reasoning about human actions and their environmental effects. The future of our environment (and of our children who will depend on that environment) depends on our collective understanding—on the ability of all citizens to understand evidence-based arguments about the environmental consequences of our actions.

Implicit in this definition is the idea that citizens need to reason in model-based ways about environmental issues. In order to anticipate the effects of our actions on environmental systems we must see our actions as *processes rather than events.* That is, we must recognize patterns in our actions and their environmental consequences and develop models that both explain the effects of past actions and predict the effects of future actions.

In this paper we suggest the feasibility of a style of research, and of writing about research, that connects a number of different elements:

- We try to construct a big picture of successional trends that is connected with specific studies of learners' reasoning.
- We suggest forms that the products of research can take that will connect research with standards, assessment, and curriculum development.
- We suggest a unit of analysis—accounts of phenomena—that can be used to connect children's reasoning about their experiences in the world with adult scientific reasoning.

At best, this attempt is incomplete. By focusing on accounts of phenomena, we ignore other scientific practices such as projects, investigations, and arguments. Because we ignore the practices most connected with learning, the learning progression that results is a series of snapshots rather than a dynamic account of learning. We acknowledge the importance of culture and history, but ignore them in this paper. There are many gaps where needed empirical research is missing (or just unknown to us). In spite of these limitations, though, we are excited about the potential of this approach and eager to explore it further.

Our experience and our reading of the available research have convinced us that scientific reasoning about the carbon cycle is a major intellectual achievement, requiring mastery of complex practices and a connected understanding of important ideas from the life, earth, and physical sciences. It is unlikely that most students will achieve this understanding without sustained, well-organized support from schools, yet the schools also need a supporting infrastructure that is currently lacking: Standards, assessments, curriculum materials, and professional development that are aligned with one another and that are effective in helping students develop the knowledge and practices that are essential to understanding.

References

AC-ERE: NSF Advisory Committee for Environmental Research and Education (2003, January). Complex Environmental Systems: Synthesis for Earth, Life, and Society in the 21st Century. Washington, DC: National Science Foundation.

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

Anderson, C. W. (2003). *Teaching science for motivation and understanding.* East Lansing, MI: Michigan State University (http://SciRes.educ.msu.edu/Science/Public/802Assignments.html).

Anderson, C. W., & Roth, K. J. (1989). Teaching for meaningful and self-regulated learning of science. In J. Brophy, Ed. *Advances in Research on Teaching, Volume 1.* Greenwich, CN: JAI Press, pp. 265-310.

Anderson, C. W., Sharma, A., Lockhart, J., Carolan, A., Moore, F., Parshall, T., and Gallagher, J. J. (2004, September). *Partial draft: Environmental literacy blueprint.* Center for Curriculumm Materials in Science, Michigan State University (http://scires.educ.msu.edu/EnvironmentalLiteracy/index.html).

Anderson, C. W., Sheldon, T. H., & Dubay, J. (1990). The effects of instruction on college non-majors' conceptions of respiration and photosynthesis. *Journal of Research in Science Teaching, 27 (8),* 761-776.

Andersson, B., and Wallin, A. (2000). Students' Understanding of the Greenhouse Effect, the Societal Consequences of Reducing CO2 Emissions and the Problem of Ozone Layer Depletion. *Journal of Research in Science Teaching, 37(10),* 1096-1111.

Bazerman, C. (1988). *Shaping written knowledge: The genre and activity of the experimental article in science.* Madison, WI: University of Wisconsin Press.

Berkowitz, A.R., M.E. Ford and C.A. Brewer. (in press). A framework for integrating ecological literacy, civics literacy and environmental citizenship in environmental education. In Johnson, E.A. and M.J. Mappin, editors: *Environmental education or advocacy: Perspectives of ecology and education in environmental education.* Cambridge University Press. New York.

Blakeslee, T. D., Anderson, C. W., & Smith, E. L. (1987, April). Teaching strategies associated with conceptual change learning in science. *Journal of Research in Science Teaching, 30(2)*, 111-126.

Bruner, J. (1985). Narrative and paradigmatic modes of thought. In E. Eisner (Ed.), *Learning and teaching: The ways of knowing.* Chicago: National Society for the Study of Education.

Diamond, J. (2005). *Collapse: How Societies Choose to Fail or Succeed.*

Driver, R., Squires, A., Rushworth, P., and Wood-Robinson, V. (1994). *Making sense of secondary science: Research into children's ideas.* New York: Routledge.

Duit, R. (2005). *Bibliography: Students' and teachers' conceptions and science education.* IPN: Univeristy of Kiel, Germany, http://www.ipn.uni-kiel.de/aktuell/stcse/download_stcse.html

Fisher, Kathleen M. et al. (1986, February). Student Misconceptions and Teacher Assumptions in College Biology. *Journal of College Science Teaching, 15(4),* 276-80

Hatano, G., and Inagaki, K. (1987, October). *Everyday biology and school biology: How do they interact?* The Quarterly Newsletter of the Laboratory of Comparitive Human Cognition, 9(4), 120-128.

Inagaki, K, and Hatano, G. (2002). *Young children's naive thinking about the biological world.* New York: Psychology Press

Keil, F. (2003). That's life: Coming to understand biology. *Human Development, 223*, 1-9.

Kempton, W., Boster, J. S., and Hartley, J. A. (1995). *Environmental values and American culture.* Cambridge, MA: MIT Press

Lehrer, R., and Schauble L. (Eds.) (2002). *Investigating real data in the classroom: Expanding children's understanding of math and science.* New York: Teachers College Press.

Lehrer, R., & Schauble, L. (2003). Origins and evolution of model-based reasoning in mathematics and science. In R. Lesh & H. M. Doerr (Eds.), *Beyond constructivism: A models and modeling perspective on mathematics problem-solving, learning, and teaching.* (pp. 59-70). Mahwah, NJ: Lawrence Erlbaum Associates.

Lehrer, R., & Schauble, L (in press). Developing modeling and argument in elementary grades. In T. A. Romberg, T.P. Carpenter, & F. Dremock (Eds.), *Understanding mathematics and science matters.* Mahwah, NJ: Lawrence Erlbaum Associates.

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

Olson, M. (2005). *Interns' narrative and paradigmatic ways of knowing science.* Unpublished doctoral dissertation, Michigan State University

Schauble, L., Klopfer, L. E., and Raghavan, K. (1991). Students' transition from an engineering model to a science model of experimentation. *Journal of Research in Science Teaching, 28 (9),* 859-882.

Smith, C., Wiser, M., Anderson, C. W., Krajcik, J., and Coppola, B. (2004, October). *Implications of research on children's learning for assessment: Matter and atomic molecular theory.* Paper commissioned by the Committee on Test Design for K-12 Science Achievement, Center for Education, National Research Council.

Smith, E. L., & Anderson, C. W. (1986, April). Middle school students' conceptions of matter cycling in ecosystems. Paper presented at the annual meeting of the National Association for Research in Science Teaching, San Francisco.

Songer, C. J., and Mintzes, J. J. (1994). Understanding cellular respiration: An analysis of conceptual change in college biology. *Journal of Research in Science Teaching 31(6),* 621-637.

Stewart, J., Cartier, J. L., and Passmore, C. M. (2005). Developing Understanding Through Model-Based Inquiry. In *How Students Learn: History, Mathematics, and Science in the Classroom.* Washington, DC: National Academies Press, pages 515-565

Wertsch, J. V. (1991). *Voices of the mind: A sociocultural approach to mediated action.* Cambridge, MA: Harvard University Press.

Zoller, U. (1990). Students' misunderstandings and misconceptions in college freshman chemistry (general and organic). *Journal of Research in Science Teaching 27(10),* 1053-1065.

Appendix: Model-based Reasoning and Units of Analysis

This Appendix includes thoughts about three issues that are relevant to the larger enterprise of helping learners to develop environmental literacy, but that fit awkwardly in the main argument about carbon-transforming processes and systems. The first part of the Appendix focuses on the question of units of analysis for research on students' reasoning about environmental systems. The second part provides several examples of contrasts between narrative and model-based reasoning for children of different ages. The final part suggests other systems for which a similar analysis might be possible.

Units of Analysis for Scientific Reasoning

We define a learning progression as a succession of children's performances, encompassing both knowledge and practice, that lead to the development of new insights about the material world. We use the word *succession* deliberately: We see learning progressions as describing changes in children's reasoning that are akin to ecological succession. There is no single defined sequence of events, but there are multiple pathways that connect children's naïve ideas with the powerful insights of scientific theories. Understanding a learning progression is kind of like understanding the science itself. We are trying to see the big picture AND the details AND the connections between them.

While the ecological succession metaphor is helpful, it does not answer one crucial question: *What is the appropriate unit of analysis?* In science in general, progress depends on our ability to define a unit of analysis and collect descriptions of multiple examples in an organized way, according to properties or variables whose meaning is understood by a community of practice. In ecology, the unit of analysis for descriptions of successional changes is often the population or species. What would the appropriate units be for describing how children's reasoning about science changes over time?

Wertsch (1991) has suggested that for analyses of human activity *individual(s) acting with mediational means* is an appropriate unit of analysis. He argued that this unit of analysis had several properties that made it more useful than the units of analysis traditionally used in science education, such as concepts or skills:

- It can be used to describe either the actions of a single individual or multiple individuals.
- It focuses on observable actions or acts, including speech and writing, (as opposed to unobservable mental states), though the focus may be on reasoning that a learner does silently.[2]
- It includes *mediational means*, which for Wertsch includes the full array of physical, cultural, and intellectual tools we use in our reasoning, of which language is the most important.
- It recognizes the importance of the sociocultural and historical contexts in which all of our actions occur.

These advantages are offset by the disadvantage that Wertsch's unit of analysis, which can be applied to all human activities, is too broad to be useful in science education. Out of the

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[2] Following Vygotsky, Wertsch argues that our silent reasoning arises from the internalization of social dialogues in which we have participates.

many actions we take in our lives, which ones should we label “scientific?” What are the particular properties that differentiate them from other actions? What makes these questions especially difficult is that we need a unit of analysis that will apply to not only adult scientific reasoning, but also its developmental precursors in elementary and middle school-aged children.

This section is very speculative, but we are intrigued by the idea that we could describe the development of children’s scientific reasoning by focusing on a relatively small number of practices or activities. Here are four nominations: Accounts of phenomena, projects, investigations, and arguments.

Accounts of phenomena. Accounting for (i.e., predicting and explaining) the phenomena of the material world is a fundamental purpose of science. Children of all ages as well as adult scientists account for their observations of the world in a variety of ways, including stories, pictures, graphs, formulas, and formal conceptual models. Adult scientific accounts provide powerful insights into the nature of the material world and tools for predicting the likely results of our actions. Children’s accounts are less sophisticated and powerful, but by studying children’s accounts carefully we can understand how they reason about the world.

Projects. A project is anything that people do that alters the world in a way that they desire. By this definition, projects can be big or small: an infant bouncing to make a mobile move, children flying kites, students designing and building Lego systems, and a construction crew building a dam are all engaged in projects. Projects are also like accounts in that they can occur in hierarchies of projects and subprojects, and in that they can be specified at different levels of detail.

Piaget and Bazerman (1988), among others, suggest that in many circumstances projects are developmentally prior to accounts. The first things we try to do in life are to develop the skills to make the world do what we want it to. When the world pushes back, resisting our attempts to manipulate it, we start developing accounts of phenomena—explanations of properties of the world that make it uncooperative. Schauble, Klopfer, and Raghavan (1991) made a similar point when they wrote about “Students' transition from an engineering model to a science model of experimentation.” Mark Enfield’s dissertation study suggested a similar conclusion: The activities that most engaged his second and third grade students tended to be projects—even when he as a teacher was trying to get them to develop accounts.

Investigations: learning from the material world. We are often confronted by phenomena that we cannot predict or explain on the basis of what we already know. In these cases, and investigation is necessary. We try to learn more about the world through our observations and analyses. Like accounts and projects, investigations can be very simple, as in Piaget’s descriptions of learning by young children, or very complex, as in the investigations of adult science.

Arguments: persuading and learning from others. Students also need to persuade others that their accounts or plans for projects are appropriate, or learn from others how to modify their accounts and projects to make them more successful or acceptable. We might use “arguments” as a broad term to encompass the wide variety of activities that involve mutual social learning.

Contrasting Accounts of Four Phenomena

In this section I will try to apply the contrasts in Table 1 to accounts of four different phenomena that differ greatly in complexity.

- Rolling a ball of clay into a "snake"
- A burning candle
- Part of a food chain: A rabbit eats grass and a wolf eats the rabbit
- Genocide in Rwanda

Rolling a ball of clay into a snake

This is a classic Piagetian conservation task. Very young children who watch a ball of clay rolled into a snake will say that there is more clay in the snake than in the ball. Slightly older children will be puzzled as to which has more, noticing that the snake is longer but the ball is thicker. At some point around kindergarten, most children make a transition to a different kind of account, saying that the amount has to be the same since no clay was added or taken away.

We can see this as a transition from a narrative to a very basic kind of model-based account of the process. The younger children see an event in which an actor (the interviewer or the child) does something to an object (the clay). The older children see a process that is constrained by a conservation rule—if nothing is added or taken away, then the amount has to stay the same.[3]

The preschooler who figures out that rolling the ball of clay into a snake doesn't change the amount of clay is using a very simple model: There are lots of facts she doesn't know about the clay, and her definition of "amount" is scientifically unsophisticated. Nevertheless, she has achieved a powerful insight that she can use on many materials other than clay. Furthermore, this insight is a necessary developmental precursor to many aspects of scientific measurement. Every time we measure the volume of a liquid by pouring it into a graduated cylinder, we rely on our own recognition that volume is conserved through this particular transformation.

Burning candle

High school students (or adults) accounting for a burning candle often give partially or completely narrative accounts. They describe the flame as an event that is caused by another event—the flame of the match that lit it—and that in turn causes other events—melting wax, burns on your fingers if you get them too close, etc. Unconstrained by conservation laws, they often respond in interesting ways to detailed questions. For instance, many identify the wick as the object that is burning, saying that the melting wax helps the wick to keep burning, but not noticing that the mass of wax is decreasing or trying to account for it. They may identify the flame as a product of a reaction. They usually recognize that the candle loses weight, but do not feel compelled to account for the lost weight, saying that the candle is burning up, or its mass is being converted to energy.

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[3] One interesting developmental trend has to do with children's developing gradually more sophisticated definitions of "amount." Young children come to realize that volume is a better measure of amount than linear dimensions like length and width. Older children come to realize that mass is a better measure than amount—but only after they can distinguish mass/weight from density.

These narrative accounts could be contrasted with model-based accounts that use different models and constraints. A *substance-tracing* account might work at the macroscopic level, recognizing that all the "stuff" of the candle still has to be around somewhere, and trying to account for where it has gone. Conservation of mass and energy play an important role. For example, the gaseous products of the burning must have the same mass as the gaseous and solid reactants. Chemists would try to develop a more detailed *atomic-molecular* account, identifying the molecules in the candle wax and explaining how they are oxidized, releasing chemical potential energy.

Food chain

Let's take a simple example of a food chain: Grass grows in the sunlight, a rabbit eats the grass, a wolf eats the rabbit. From a narrative perspective, these are facts to be put in the proper order and labeled appropriately: producer, first-order consumer, second-order consumer. Narrative reasoning does not involve distinctions among different kinds of facts. From a narrative perspective, becoming more knowledgeable about science involves adding details to the story: how the grass uses sunlight to grow, how the wolf stalks the rabbit, how the wolf digests the rabbit, etc.

In contrast, model-based reasoning starts with a fundamental distinction between types of knowledge: *observations or data* vs. *models or theories.* In model-based reasoning the fundamental task of science is to make connections between data and models, either through inquiry (developing models through data-based arguments) or through application (using models to predict or explain data). Thus from a model-based perspective the little sequence of events involving the grass, rabbit, and wolf becomes data that can be explained or interpreted using a variety of different models—about matter cycling and energy flow in ecosystems, evolution by natural selection, etc. As with narrative reasoning, many levels of detail are possible in model-based reasoning, but the expectations are always the same: Model-based reasoning requires explicit connections between features of the model and specific observations in the data.

The facts that narratives put in order are often interpreted as events that have single specific causes. Sometimes the cause is the preceding event, as when anaphase follows metaphase. At other times, the cause may be some other factor that triggers the event—the wolf was hungry because it hadn't eaten the previous day, or the rabbit ventured too far from the shelter of covering brush. In general, though, the causes are "triggers"—changes in conditions that cause the event to happen. Similarly events have effects—the wolf can survive and grow because it has found something to eat. It is possible, of course, to describe sequences of events in more or less detail.

In contrast, scientists account for processes in a very different way. Rather than looking for an event or condition that triggers a process, it typically is there as part of a system, and conditions are seen as regulating rates or some other aspects of the process. Furthermore, understanding processes requires tracing "entities" that are subject to conservation laws. Thus when the wolf eats the rabbit as a process, we can see it as a data point that we use to calculate the wolf's rate of food consumption. We can also see it as a step in the flow and transformation of matter and energy through the food web, or even a step in the flow and transformation of genetic information through generations of wolves. Again, it is possible to describe how process are regulated and transform matter, energy, or information at many levels of detail.

Consider the role of the wolf in the two accounts of the food chain. In the narrative account, the food chain is like a little drama with several scenes. The wolf is a protagonists one of those scenes, enabling its survival for another day by finding and eating food. (The protagonists in narrative accounts of science do not have to be organisms, they could also be the earth and sun, or enzymes, or clouds.) The non-living environment of the ecosystem is the setting in which this drama plays out. High school students know that the wolf has organs that are made of cells, but that information is part of another story, not directly connected with this one.

In the model-based account, the wolf is one system in a complex hierarchy of systems and subsystems. Model-based accounts don't really have "protagonists," but conserved "entities" such as matter, energy, and information play critical roles. The wolf is not so much a protagonist as a way-station for the matter, energy, and genomic information that flow through it. The account of the wolf is very much interconnected with accounts of its subsystems—cells and organs—and of the larger ecosystem within which it lives. Thus to "understand" the wolf we have to think about its role in a complex set of interconnected systems and processes.

Genocide in Rwanda

Jared Diamond's book *Collapse: How Societies Choose to Fail or Succeed* (2005) includes contrasting narrative and model-based explanations for the genocide in Rwanda. He first summarizes the standard narrative account, which emphasizes the role of opportunistic Hutu politicians in arming militias, assassinating the president, and stoking ethnic hatred and violence.

He then develops an alternative model-based account by focusing on one district, which also dissolved into violence even though the population was entirely Hutu. Diamond develops this account with data collected during an eight-year anthropological study that included the genocide. He depicts a period when population pressure was driving this district toward ecological collapse. Farmers forced onto increasingly tiny plots of land were skipping fallow periods and bringing marginal land into cultivation, leading to erosion and loss of soil fertility and a diminished capacity of the district for food production. Tensions within the society had been rising steadily and erupted at a time when many people saw their choices as being either murder or starvation.

An underlying theme in this account, and in all the accounts in Diamond's book, is that human populations live in integrated human and natural systems that are subject to the same basic constraints as other systems, including limits on the carrying capacity of ecosystems for animal (including human) populations. In Diamond's words, "population growth, environmental damage, and climate change provided the dynamite for which ethnic violence was the fuse." The narrative account describes the effects of lighting the fuse. The model-based account seeks to explain the dynamite.

Diamond's book is built around a diverse set of case studies from prehistory to the present, including both societies that have collapsed and societies that have successfully confronted environmental threats. Diamond interprets these case studies using an explicit model with three principal components:

- A list of 12 threats or ways that human populations put stress on environmental systems: deforestation and habitat destruction, soil problems (erosion, salinization, and soil fertility losses), overhunting, overfishing, effects of introduced species on native plants and animals, human population growth, increased per-capita impact of human populations, human-caused climate change, build-up of toxic chemicals in environmental systems, energy shortages, and full human utilization of the earth's photosynthetic capacity (introduced on pages 6-7).

- A list of 5 contributing factors that affect whether a society collapses or is able to respond productively to those environmental threats: extent of environmental damage, climate change, hostile neighbors, friendly trade partners, the society's response to environmental problems (introduced on page 11).
- A model of group decision-making that identifies 4 ways that social decision-making can go wrong: failure to anticipate a problem, failure to perceive it once it has arisen (due to rational bad behavior, irrational but deeply held values, or groupthink), failure to attempt to solve it once it has been perceived, and failure of attempts to solve it (introduced on page 421).

The model is complicated, as we would have to expect for a model that tries to explain a process as complex as the collapse of civilizations. In the course of over 500 pages of argument built around comparative case studies, though, Diamond assembles an impressive body of evidence to support the explanatory and predictive power of his model—he argues that we *can* understand our actions and their environmental consequences as processes rather than events.

We continue to feel that this is the most important single purpose of science education, both at the K-12 and at the college levels.

As an illustration of how difficult this challenge will be, we would point to the review of *Collapse* by Greg Easterbrook in the *New York Times Book Review.* On the one hand, it is significant that the *Times* found the book significant enough to give it a two-page review. On the other hand, it seems to us that Easterbrook managed to completely misread the book. He attributes the popularity of this book and of its predecessor *Guns, Germs, and Steel* to "pure political correctness," concluding that both books "come to conclusions that are probably wrong."

What is most significant to us is that Easterbrook does not seem to recognize the existence of Diamond's model, let alone try to refute it. He treats Diamond's cases as events rather than processes, suggests that Diamond's analyses give no role to human culture, and dismisses projections Diamond makes using his model: "If trends remain unchanged, the global economy is unsustainable. But the Fallacy of Uninterrupted Trends tells us that patterns won't remain unchanged."

Thus a sophisticated critic dismisses not just the particulars of Diamond's argument, but any attempt to bring scientific model-based reasoning to bear on problems that he sees as essentially social, economic, and political, and thus belonging to the realm of narrative reasoning (or at least reasoning in which the only applicable models come from the social sciences). We need to do everything in our power to educate the next generation to think differently.

Other Processes and Systems

As we hope the examples above indicate, we can use "accounts of phenomena" as a unit of analysis for accounts of many different systems and processes. Here is a list that comes from different projects that we have been working on.

- Physical and chemical changes in matter

- The water cycle: A system that circulates water through the oceans, atmosphere, surface water, and ground water.
- The rock cycle: A system that moves and transforms specific cations (Al, Ca, Na, K) and minerals (silica, feldspar, calcite, clay minerals, mica) through tectonic process driven by heat from the center of the earth and processes of weathering, erosion, and deposition driven by energy from the sun
- The geological carbon cycle: A system that moves carbon among pools in the atmosphere, oceans, carbonate rocks, and biosphere.
- The cell cycle: A system that preserves information—the structure and function of cells—during growth and reproduction. Important processes in the cell cycle include:
    - DNA replication
    - Protein synthesis
    - Mitosis and meiosis

Integrated human economies and environmental systems (e.g., global warming, environmental problems)