# Learning Progressions for Principled Accounts of Processes in Socio-ecological Systems

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# Contents

# Abstract

In this interactive poster symposium we describe and discuss the development of learning progressions from upper elementary through college focusing on preparing students to become environmentally informed citizens. The session is reports progress since a poster symposium presented at NARST last year. Posters describe students' learning progressions in four areas: carbon cycling, water cycling, biodiversity, and citizenship practices. The posters describe advances in five areas:

- We have developed ideas about the general dimensions of learning that change across our levels of achievement: *Discourse, practice, and knowledge*
- We have developed descriptions of the starting points (Level 1 accounts in our learning progressions) for most students as *force-dynamic reasoning.*
- We have developed descriptions of our goal of environmental science literacy (Level 4 accounts in our learning progressions) as *principled reasoning* about socio-ecological systems and processes
- We have developed ways of using *linking processes* to define intermediate levels in our learning progressions.
- We have developed hypotheses about *alternate learning trajectories,* including "principles-first" learning trajectories that we are testing as potentially more powerful than the "structure-first" learning trajectories that we see in our current data.

The work reported in this poster symposium both documents the current performance of our educational system and suggests ways in which that performance can be improved. We are looking forward to analyzing data from our carbon teaching experiments, since these data will provide a first test of our hypothesis that principles-first teaching can change both the nature and the extent of student learning. We believe that this work, and other work on learning progressions, has implications for research, for development of standards and curricula, and for science curriculum and instruction.

# Introduction

The posters in this symposium represent our current progress in an ongoing research program focusing on learning progressions leading toward environmental science literacy, covering students from Grade 4 to college age. We have significant progress to report since last year, and we have unanswered questions that we are still working on. In this overview paper we briefly present frameworks, methods, and results from our previous research, then describe what's new in the work that we are presenting this year. We have developed both new models and frameworks and new data and results since last year.

# Continuity in Goals, Frameworks, and Methods

There is continuity in the goals, frameworks, and methods of our project. In this section we briefly review ideas that are discussed in more detail in the overview paper from last year's NARST poster symposium (Anderson, 2008).[1]

## *Goals: Learning Progressions for Environmental Science Literacy*

This research program is built around two key ideas: *environmental science literacy* and *learning progressions.* We discuss the meaning of each below.

### Environmental science literacy

Global climate change and other environmental issues present a great challenge to our science education system. Our previous research and the work of others suggest that current levels of public understanding provide a perilously thin basis for the kinds of large-scale changes in lifestyle and political reasoning that will be required during the lifetimes of young people who are students today.

Responsible citizens must recognize that our actions affect the material world—the environmental systems on which we and our descendents depend—and find ways to use scientific knowledge to evaluate the probable environmental consequences of our actions as we engage in the various roles of citizens. For us that does not imply any particular political position, but it does mean two things. Citizens should be able to:

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

Thus the posters in this session present all share the goal of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of socio-ecological systems and to make informed decisions about appropriate actions and policies.[2] Environmental science literacy requires understanding of many aspects of science, including chemical and physical change, carbon cycling, water cycling, biodiversity and evolution by natural selection. These phenomena are currently addressed in many state and national standards

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[1] Papers and publications from the environmental literacy project are available on our website: http://edr1.educ.msu.edu/EnvironmentalLit/publicsite/html/paperp1.html.

[2] The term *socio-ecological systems* comes from the Strategic Research Plan of the Long Term Environmental Research Network (LTER Planning Committee, 2007). It reflects the understanding of these scientists that cutting-edge ecological research can no longer be conducted without considering the interactions between ecosystems and the human communities that occupy and manage them.

documents and in school curricula, but typically they are addressed in disconnected ways—in different courses or in different units in the same course.

Figure 1 is an adaptation of the "Loop Diagram" developed by the Long-Term Ecological Research (LTER) Network to describe their ongoing research agenda (LTER Planning Committee, 2007). The Loop Diagram suggests a way to understand the relationships between our societies and the environmental systems upon which we depend. Figure 1 depicts the key relationships in terms of two boxes, representing human and environmental systems, and two arrows, representing the environmental impacts of our actions and essential environmental services.

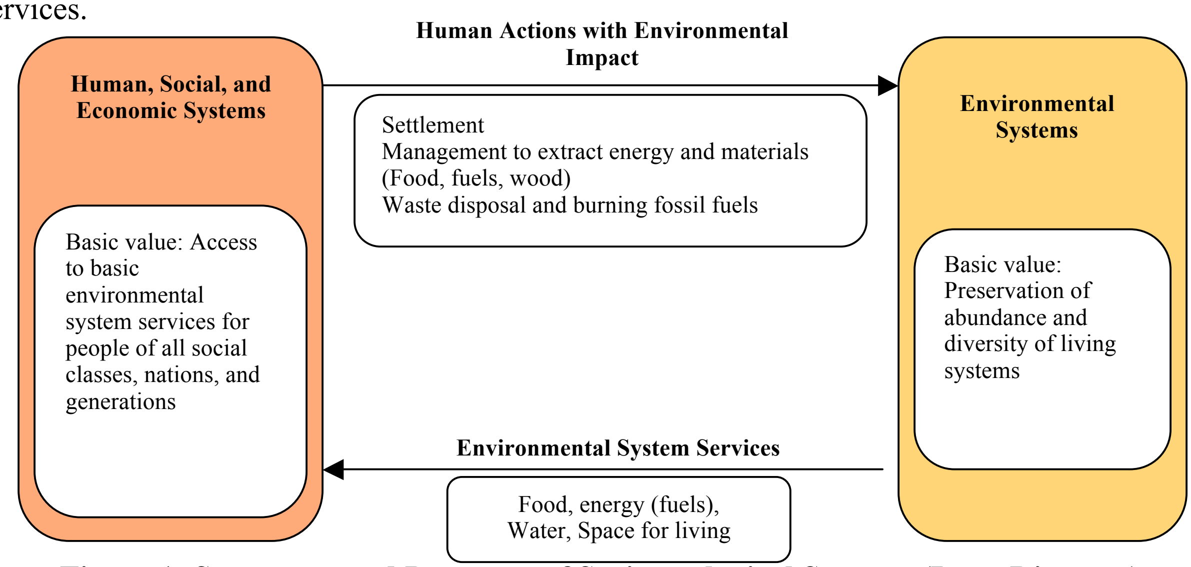


**Figure 1: Structures and Processes of Socio-ecological Systems (Loop Diagram)**

Thus understanding the loop diagram and applying that understanding to the practices of citizenship is important. Learners' and citizens' practices are always socially embedded. Practices are associated with identities-in-practice or social roles (Cobb & Hodge, 2006; Holland, Skinner, William, & Cain, 2001; Tan & Barton, 2006). We work with learners who will play multiple roles as citizens - as learners, consumers, voters, workers, volunteers, and advocates. In our work we focus specifically on the *scientific* knowledge and practices that citizens will need to play these roles.

## Learning Progressions

Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic (Committee on Science Learning, 2007). Well-grounded learning progressions can serve as a basis for dialogue among science education researchers, developers of standards documents, assessment developers, and curriculum developers. This approach is endorsed by both the National Research Council (Wilson & Bertenthal, 2005; Committee on Science Learning, 2007) and the National Assessment Governing Board in the framework for the 2009 NAEP science test (NAGB, 2006). Work has been published on the conceptual and methodological foundations for learning progressions (Briggs, Alonzo, Schwab, & Wilson, 2004; Smith, Wiser, Anderson, & Krajcik, 2007).

In these posters and papers we report on learning progressions in three interconnected content domains:

- *Carbon.* Carbon-transforming processes in socio-ecological systems at multiple scales, including cellular and organismal metabolism, ecosystem energetics and carbon cycling, carbon sequestration, and combustion of fossil fuels. These processes: (a) create organic carbon (photosynthesis), (b) transform organic carbon (biosynthesis, digestion, food webs, carbon sequestration), and (c) oxidize organic carbon (cellular respiration, combustion). The primary cause of global climate change is the current worldwide imbalance among these processes.

- *Water.* The role of water and substances carried by water in earth, living, and engineered systems, including the atmosphere, surface water and ice, ground water, human water systems, and water in living systems.
- *Biodiversity.* The diversity of living systems, including variability among individuals in population, evolutionary changes in populations, diversity in natural ecosystems and in human systems that produce food, fiber, and wood.

We have abundant evidence (including evidence from the posters in this session) that understanding in these domains is a difficult and hard-won accomplishment, currently not achieved by most high school and college students. This leads to the question of how that understanding can be achieved, and what roles researchers should play in developing educational systems supporting that understanding. Our answer to this question hinges on the development of learning progressions, as discussed in the next section.

## *General Framework for Learning Progressions*

The learning progression frameworks that we have developed for the carbon, water, and biodiversity strands have the same general structure, represented in Table 1. This framework identifies a unit of analysis: Learning performances. It organizes students' learning performances according to (a) practices, principles and processes and (b) Levels of Achievement.

**Table 1: Learning Progression Framework for Carbon, Water, Biodiversity Strands**

<table>
<tr><th rowspan="2">Levels of Achievement</th><th colspan="3">Practices, principles, and processes</th></tr>
<tr><td>Practices: Inquiry, accounts, decisions</td><td>Principles: Matter, energy, genetics, scale</td><td>Linking processes</td></tr>
<tr><td>4: Qualitative model-based accounts</td><td colspan="3" rowspan="4">Learning performances for specific processes<br>and Levels of Achievement:<br>Inquiry, accounts, citizenship decisions about processes in socio-ecological systems</td></tr>
<tr><td>3: "School science" narratives</td></tr>
<tr><td>2: Force-dynamic with hidden mechanisms</td></tr>
<tr><td>1: Force-dynamic narratives</td></tr>
</table>

**Practices, principles, and processes** are our versions of what is sometimes referred to in the literature on learning progressions as "big ideas" (Catley, Lehrer, and Reiser, 2005; Committee on Science Learning, 2007, Chapter 8; Smith, et al., 2006). These are aspects of knowledge and practice that are present in some form at all Levels of Achievement, so that their development can be traced across Levels. Our practices, principles and processes are derived partly from theories about how knowledge and practice are organized and partly from empirical research on assessment and student reasoning (Briggs, Alonzo, Schwab, & Wilson, 2004; Wilson, 2005, Draney & Wilson, 2007).

**Levels of Achievement** are patterns in learners' knowledge and practice that extend across practices, principles, and processes (see Mohan, Chen, & Anderson, in press). The four Levels of Achievement in our learning progressions describe performances we have seen in students from middle school through adult professionals (teachers).

**Learning Performances** are the contents of the individual cells of Table 1: the specific practices characteristic of students who are at a particular Level of Achievement and reasoning about a particular practice, process, and principle. The Learning Performances should be consistent with their position in Table 1, but they also provide specific predictions about student reasoning and student learning that can be used to develop assessment items and tested empirically.

## *Methods: Iterative Development and Validation*

The development and validation of learning progressions are iterative processes. We develop initial frameworks that reflect what we know from previous research and our experience, as well as our attempts to meet make the framework conceptually coherent. We use these frameworks to develop assessments and/or teaching experiments. We use the results of this empirical validation process to revise the frameworks. Then we start the process over again. With each new iteration we make progress toward meeting *standards for validation:* our list of qualities that learning progressions should have.

We seek to develop learning progressions that have three qualities:

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

These criteria are applied to the key elements of the structure of learning progressions—Learning Performances, Levels of Achievement, and Progress Variables—in Table 2.

**Table 2: Criteria for Validity of Learning Progressions**

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

# What's New in Our Models and Frameworks

We have made significant progress toward developing more powerful learning progression frameworks during the past year:

- We have developed ideas about the general dimensions of learning that change across our levels of achievement: *Discourse, practice, and knowledge*
- We have developed descriptions of the starting points (Level 1 accounts in our learning progressions) for most students as *force-dynamic reasoning.*
- We have developed descriptions of our goal of environmental science literacy (Level 4 accounts in our learning progressions) as *principled reasoning* about socio-ecological systems and processes
- We have developed ways of using *linking processes* to define intermediate levels in our learning progressions.
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## *Dimensions of Learning: Discourse, Practice, and Knowledge*

Learning progressions leading to environmental science literacy are difficult and complicated because students have to change their approaches to reasoning about processes in socio-ecological systems in three different dimensions. *Knowledge* is embedded in *practices,* which in turn are embedded in *discourses.*

**Discourse** is a term used by sociolinguists such as James Gee (1991) to denote general ways of thinking and manner of talking about the world. Specifically, Gee defines a discourse as "a socially accepted association among ways of using language, of thinking, and of acting that can be used to identify oneself as a member of a socially meaningful group" (Gee, 1991, p. 3)

We all participate in multiple discourses, including our primary discourse—the ways of thinking and talking that we acquire in our homes and families—and secondary discourses that we encounter in school, church, work, etc. Discourses are associated with *communities of practice*: groups of people who share common activities, values, and ways of talking and thinking. Discourses provide us with perspectives that we use to define issues and develop funds of knowledge, practices, values, and identities that we can use to decide our courses of action.

Gee further distinguishes between *primary discourses* that we acquire in our homes and *secondary discourses* that we learn in other social settings:

> All humans … get one form of discourse free, so to speak... This is our socio-culturally determined way of using language in face-to-face communication with intimates…
>
> Beyond the primary discourse, however, there are other discourses which crucially involve institutions beyond the family…. Let us refer to these institutions as secondary institutions (such as schools, workplaces, stores, government offices, businesses, or churches)…. Thus we will refer to them as "secondary discourses." (Gee, 1991, pp. 7-8)

Gee (1991, p. 8) defines literacy as "control of secondary uses of language (i.e., uses of language in secondary discourses)." Thus we can define the two ends of our learning progressions—levels 1 and 4—as primary and secondary discourses.

*Level 1 (force-dynamic) discourse.* Students acquire a "theory of the world" as they learn to speak grammatical English and experience everyday events. Although all students do not share the same primary discourse, linguists such as Stephen Pinker (2007) and developmental psychologists such as Leonard Talmy (1988, 2003) argue that there is a "theory of the world" built into the basic grammar of our language, so we all must learn that theory in order to speak grammatical English. Level 1 discourse, the way of talking about the world that is built into our everyday language, explains the events of the world in terms of actors and abilities, enablers, and purposes. We describe it in more detail below.

*Level 4 (scientific) discourse.* We are especially interested in one secondary discourse: scientific discourse, which has been developed in scientific communities of practice. Even though scientists may speak in English, scientific discourse has constructed an entirely different kind of world. Instead of actors in settings scientists see a hierarchy of dynamic systems at different scales. Instead of powers and purposes scientists see laws—fundamental principles that govern the working of the systems. We also describe level 4 discourse in more detail below.

**Practices.** We are interested in four practices that are essential for environmentally responsible citizenship, represented in Figure 2 below. Figure 2 represents citizens' decisions and actions in public and private roles:

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

We would like students to become *informed citizens* who are aware of the possible environmental consequences of their actions and take those consequences into account. Citizens' decisions and actions always can—and should—be based on considerations and values other than scientific knowledge and environmental consequences. Environmental science literacy is about giving people real choices—helping them to understand possible alternative actions and their consequences—rather than leaving them trapped by ignorance.

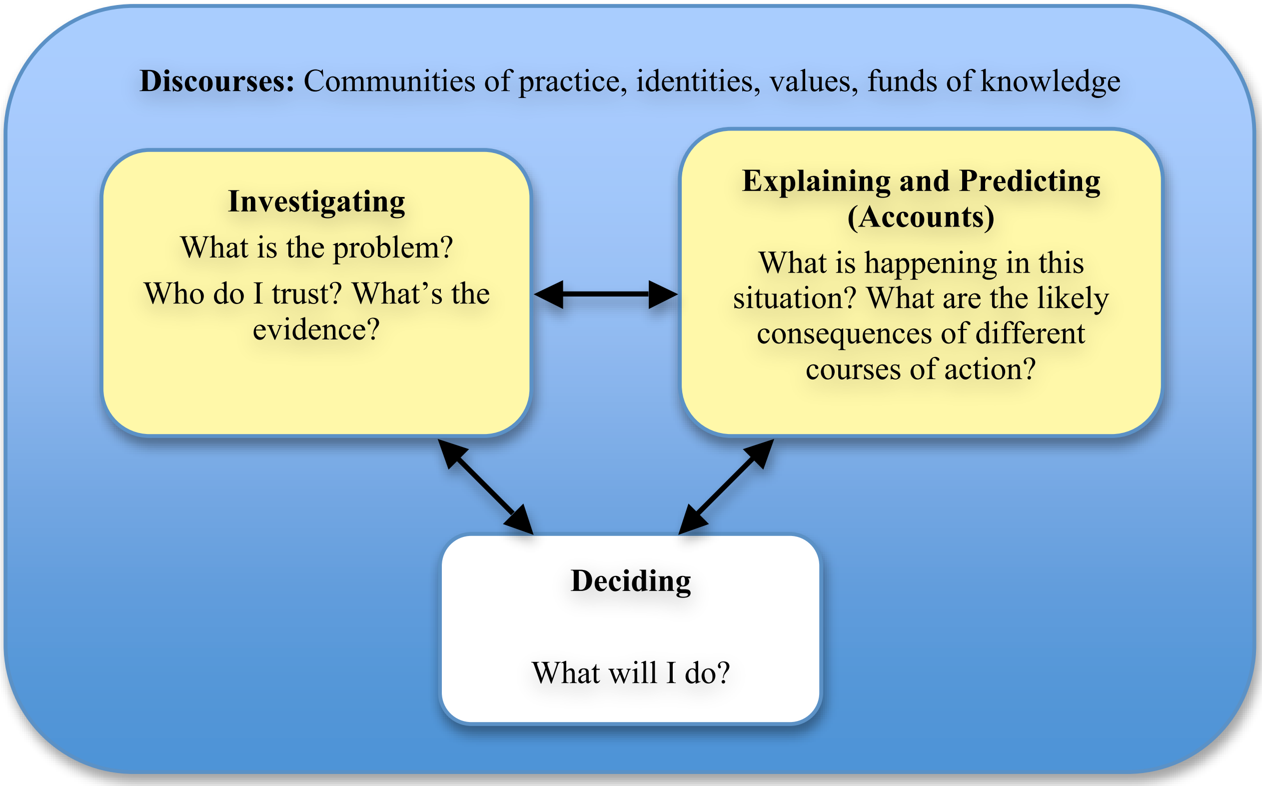


**Figure 2: Citizenship practices**

Figure 2 is our framework for citizenship practices. It suggests that the decisions we make in public and private citizens' roles involve four kinds of practices, two of which we have typically grouped together in our work:

- *Inquiry:* learning from experience, developing and evaluating arguments from evidence. Inquiry includes evaluating both sources of evidence and the evidence itself.
- *Accounts:* describing, explaining, and predicting outcomes of processes in socio-ecological systems.
    - *Explaining* processes in systems
    - *Predicting* effects of disturbances or human policies and actions on processes in systems
- *Deciding*: making choices (conscious or unconscious) about personal lifestyles or courses of action in private roles, people or policies to support in public roles.

One of our posters (Covitt, Tan, Tsurusaki, & Anderson) focuses on how students engage in decision-making in citizens' roles, so it includes data on all of the practices in Figure 1. The other posters focus primarily on the two practices we associate with scientific accounts, explaining and predicting.

**Knowledge** is embedded within discourses and practices, so students at different levels have very different ideas about what they need to know.

*Level 1 knowledge.* Level 1 students feel a need to know facts about the world, particularly about actors and their different needs and abilities, and about the outcomes of events in the world that involve actors struggling with antagonists or helping one another (by overcoming antagonists or providing enablers).

*Level 4 knowledge.* Scientific reasoning recognizes different kinds of knowledge claims that are warranted in different ways (see Figure 5 below). The goal of science is to build up coherent systems of observations, patterns, and models. These coherent systems are the basis for the scientific practices of inquiry and accounts (explanation and prediction). The loop diagram (Figure 1 above) summarizes some key characteristics of Level 4 knowledge. We discuss Level 4 knowledge in more detail in the section on Level 4 accounts, below.

## *Level 1 Accounts: Force-dynamic Reasoning*

Both our reading of the literature, including the work by Pinker and Talmy cited above, and our analyses of data have enabled us to develop a deeper understanding of level 1 accounts. In our previous work we tended to describe level 1 accounts as incomplete, vague, or fragmented. We now see them as more coherent—and more different from scientific accounts—than we had previously recognized.

As Pinker (2007) argues:

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

Thus Level 1 accounts are the everyday English predictions and explanations of events that students and adults rely on when they are not "reasoning scientifically." Level 1 accounts build their explanations for events in the world out of five basic elements.

- *Actors and abilities*. The events of the world are largely caused by actors in accord with their abilities. Humans have the most abilities, followed by animals, then plants. Dead things have no abilities, even to preserve themselves, so they decay away or are acted on by other actors. Non-living entities such as flames and machines can also be actors with limited abilities.
- *Needs or enablers.* In order to use their abilities and fulfill their purposes, actors have needs. For example, a tree needs soil, water, air, and sunlight to grow. A flame needs heat, fuel, and air to burn.
- *Purposes and results.* Actors have goals or purposes, and the results of events are are generally the fulfillment of the actors' purposes. Higher level actors can have many purposes, so animals grow, move, think, etc. Lower level actors have fewer purposes, so the main purpose of a tree is to grow; the main purpose of a flame is to burn.
- *Events or actions.* So the events of the world (such as trees growing, flames burning, people running, etc.) take place when actors have all their needs, so that they are able to achieve their purposes. Sometimes there are conflicts between different actors with different purposes (such as when the wolf wants to eat and the deer wants to live). In those cases, the more powerful actor prevails.
- *Settings or scenes* for the action. Finally, there are settings or scenes for the action, including air, earth, water, stones, etc. Unless the settings fulfill the needs of particular actors, they normally don't get a lot of attention in force dynamic accounts.

So the world as constructed by everyday English is dominated by actors (including people, animals, plants, flames, and machines), who fulfill their needs and accomplish their purposes. When actors come into conflict, the more powerful actor can control what happens.

Understanding the world means understanding the abilities, needs, and purposes of all the different actors.

This is a powerful way to make sense of human actors and actions. For example, the list above reconstructs Burke's dramatistic pentad, which was used by Wertsch, del Rio, and Alvarez (1995) to develop their own version of activity theory—an important scholarly approach to analyzing people's practices in social contexts. It does not always work as well, however, for analyzing events in which human purposes and actions are just part of the story.

So level 1 accounts explain processes in socio-ecological systems in terms somewhat like those of Figure 3 below.

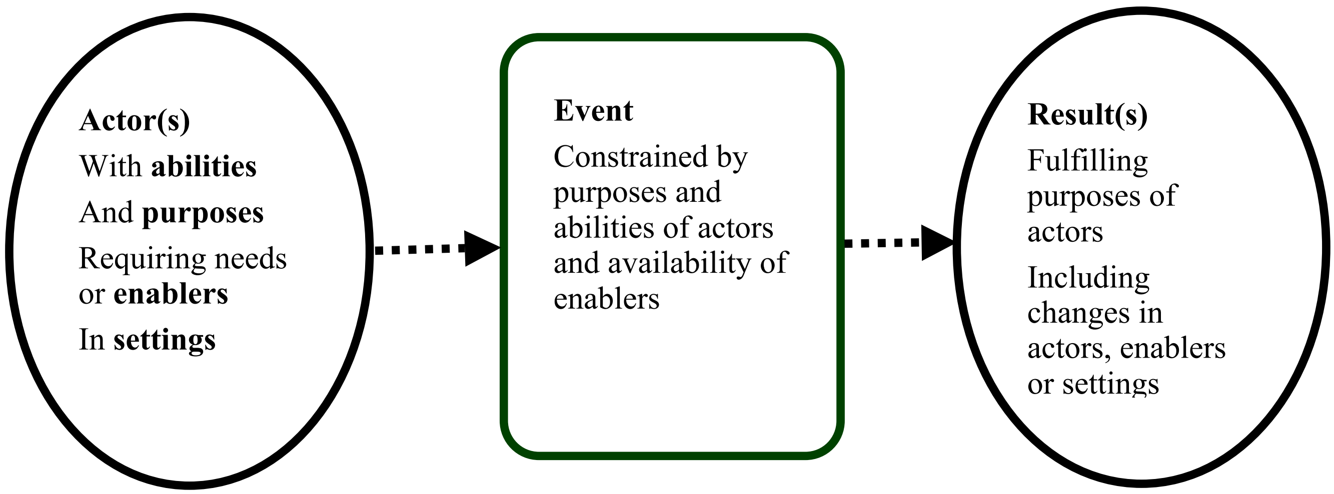


**Figure 3: Elements of level 1 accounts**

Level 1 accounts can also string events together, with the results of one event affecting the needs or enablers for others, as depicted in Figure 4.

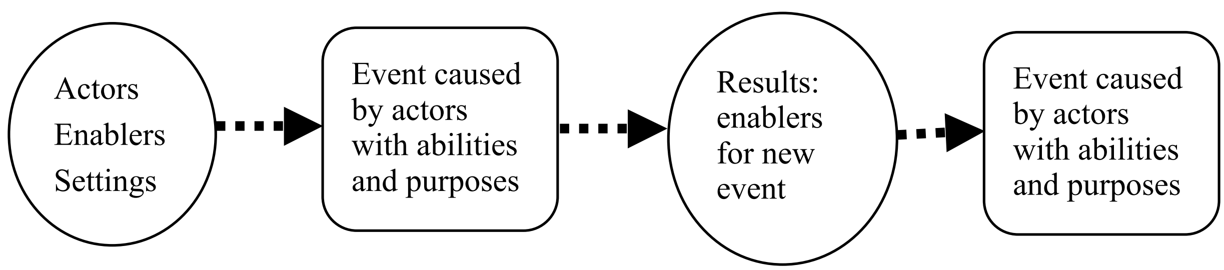


**Figure 4: Sequences of events in level 1 accounts**

*Level 1 explaining and predicting practices.* Level 1 students explain and predict using the language and theories of force dynamic discourse.

- A good explanation identifies the key elements that determine the course of an event: the actors and their abilities, the needs or enablers, and purposes or results. Aspects of settings (air, water, earth, etc.) are not important unless they satisfy needs of actors or prevent actors from achieving their purposes.
- A good prediction concerns whether actors achieve their purposes. They can achieve their purposes if they have all the necessary enablers and if there are no antagonists or opposing actors. If there are antagonists, then the outcome depends on which actor has greater powers.

Level 1 accounts provide a powerful approach to explaining and predicting the events of the world, especially the world of human events. As Pinker suggested in the quote above, we routinely rely on Level 1 reasoning when we use everyday English. Thus everyone, including scientists, relies on Level 1 reasoning much of the time. Thus it is not surprising, and not a problem, to discover that students often account for socio-ecological systems and processes in force-dynamic terms.

However, as Pinker suggests above, Level 1 accounts are not always sufficient, especially if we seek deeper explanations and more accurate predictions about the outcomes of socio-ecological processes. Thus the goals of our learning progressions are to *give students choices*, between Level 1 reasoning and more scientific approaches to reasoning, described below.

### *Level 4 Accounts: Using Scientific Models and Principles*

In describing level 4 reasoning, we aim to capture key elements of scientific discourse that are valuable to all citizens for inquiry, accounts, and decisions. Our descriptions of level 4 reasoning focus on accounts—the ways that environmental science literate learners explain and predict processes in socio-ecological systems.

Even though scientists may speak in English, scientific discourse has constructed an entirely different kind of world from force-dynamic discourse. Instead of actors in settings, scientists see a hierarchy of dynamic systems at different scales. Instead of powers and purposes, scientists see laws—fundamental principles that govern the working of the systems.

Scientific accounts of socio-ecological systems and processes begin with a basic fact: *The world is too complicated to understand completely.* Since the world is too complicated to understand completely, scientific communities have developed approaches to finding patterns in our experiences in the world and developing models to explain those patterns, as depicted in Figure 5 below. Figure 5 is discussed in more detail elsewhere (Anderson, 2007; Sharma & Anderson, 2007). We note briefly, however, (a) that Figure 5 distinguishes among types of scientific knowledge claims—observations, patterns, and models—and (b) that the arrows in Figure 5 represent scientific approaches to the practices in Figure 2: inquiry and accounts.

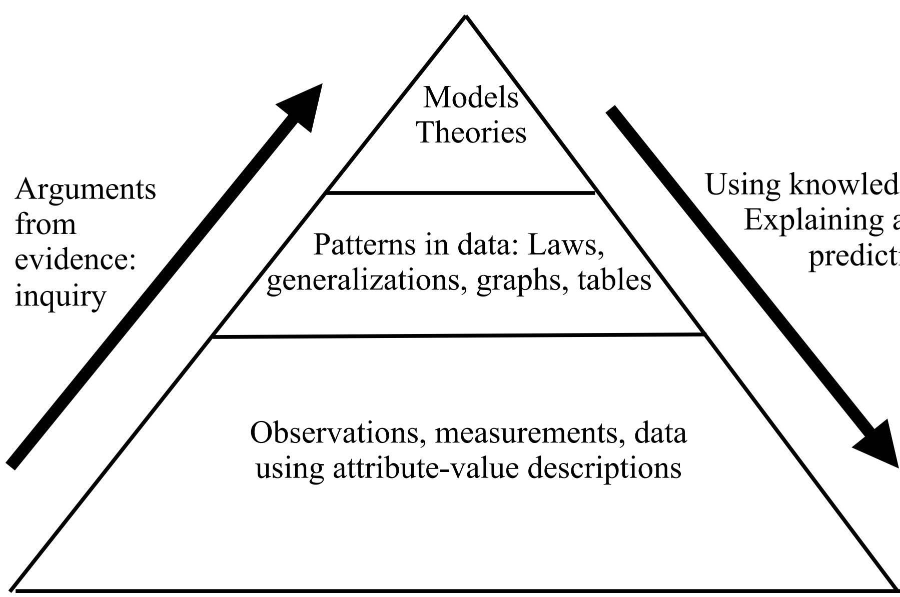


**Figure 5: Knowledge and practices of model-based reasoning**

Figure 5 is our representation of *model-based reasoning.* Scientifically literate people use arguments from evidence to create and validate scientific models, then use those models to explain and predict observations of phenomena in the world. Our descriptions of level 4 accounts emphasize that they rely on model-based reasoning. Level 4 accounts also exemplify *principled reasoning.* Some patterns in our observations are (such as conservation of matter and energy) so powerful and pervasive that we expect all models in a domain—and thus all explanations and predictions based on those models—to conform to them.

Level 4 reasoning in all three strands involves using models and principles to reason about *systems* and *processes,* particularly socio-ecological systems and processes that we depict using the loop diagram—Figure 1 above. We argue below that although scientific models of socio-ecological systems and processes can be extremely detailed and complex, the models are constrained by a few fundamental principles. These principles include conservation laws and other principles discussed below. So learners can see the power of scientific models if they understand and use appropriate constraining principles.

So level 4 accounts explain processes in socio-ecological systems in terms somewhat like those of Figure 6 below. The parallels to Figure 3 above are intentional; we want to set up points of comparison between model-based and force dynamic reasoning. There are important differences, though, between events caused by actors and processes constrained by principles, with each principle placing its own constraints on the process.

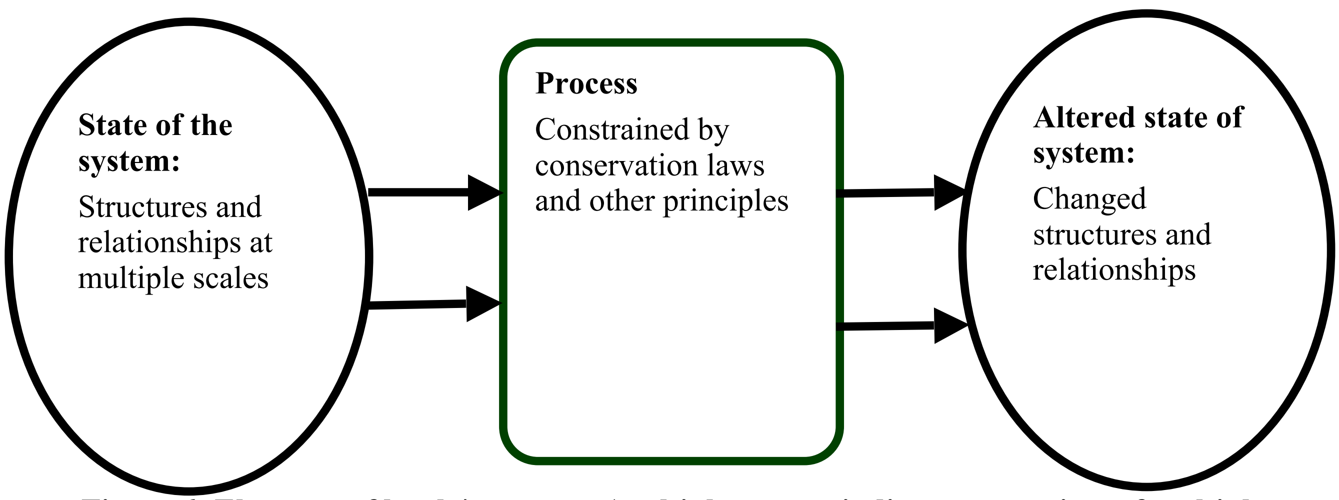


**Figure 6: Elements of level 4 accounts (multiple arrows indicate constraints of multiple principles)**

Level 4 accounts can also string processes together, with each process constrained by principles, as shown in Figure 7.

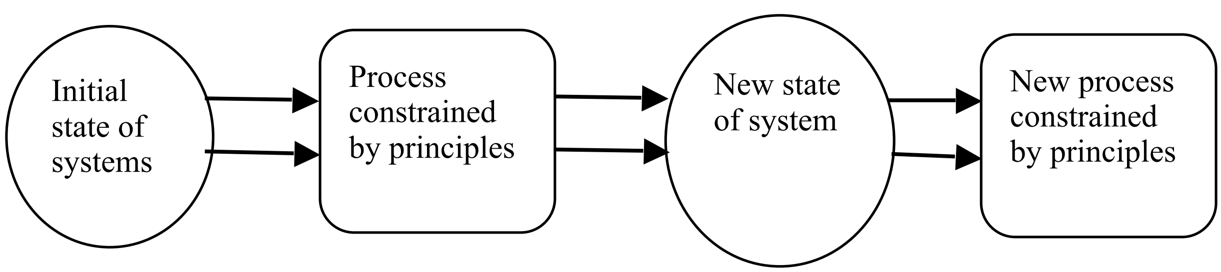


**Figure 7: Sequences of events in level 4 accounts**

*Level 4 explaining and predicting practices.* Level 4 students explain and predict using the language and theories of scientific discourse.

- A good explanation connects observations to patterns and models (see Figure 5 above) and uses appropriate models and principles. We are particularly interested in explanations that trace matter and energy through processes that transform carbon from organic to inorganic forms and back, using the key principles of matter, energy, and scale.
- A good prediction uses data about the particular situation with the laws of nature—models that follow principles—to determine the movement and transformations of matter and energy.

Table 3, below, suggests key principles for each strand. More detail about these principles can be found in the individual posters and papers.

**Table 3: Key Principles for Carbon Water, and Biodiversity Strands**

| | | ***Carbon Strand*** | ***Water Strand*** | ***Biodiversity Strand*** |
|---|---|---|---|---|
| ***Types of Accounts*** | | | | |
| ***Types of processes*** | | Processes that create, transform, oxidize organic carbon | Processes that move water across landscapes and processes that affect water quality | Disturbances to ecosystems leading to continuity and/or change |
| ***Characteristics of Each Account*** | | | | |
| ***Characteristics of systems*** | ***Structure and function*** | Inorganic substances: $CO_2$, $H_2O$, $O_2$<br>Organic substances: Monomers and polymers of biomolecules | Freshwater systems: watersheds, ground water, atmospheric water<br>Human water systems: pipes, treatment plants, etc. | Genetic characteristics: individual genotypes, population genetic variability, community species diversity<br>Phenotypic structure, function, relationships<br>Non-living environment |
| | ***Hierarchy of scales*** | Atomic-molecular, microscopic, macroscopic, large scales | Atomic-molecular, microscopic, macroscopic, watershed scales | Individual, population, community/ecosystem, landscape (multiple ecosystems) scales |
| ***Principles constraining processes*** | ***Principle 1*** | Conservation of matter:<br>-conservation of atoms<br>-conservation of mass<br>-fluxes and reservoirs of carbon-containing materials | Conservation of matter:<br>-conservation and movement of water through changes of state and landscapes<br>-conservation and movement of materials carried by water | Genetic continuity:<br>-organisms are descended from other organisms of the same kind<br>-disturbances affect size and genetic variability of populations with rules of inheritance |
| | ***Principle 2*** | Conservation and degradation of energy | Gravity and pressure: water runs downhill, constrained by impermeable materials | Ecological dynamics: Population size and variability are determined by environmental constraints, dispersal constraints, relationships among populations |

## *Linking Processes and Intermediate Levels of Achievement*

Level 1 and level 4 students see the world in very different, virtually incommensurable, terms. For level 1 students the events of the world are caused by actors (including people, animals, plants, flames, and machines) who use their abilities to make things happen. Level 4 students see processes that occur in systems at multiple scales.

But learning progressions are supposed to trace students' trajectories from level 1 to level 4, and we know that some students *do* get from level 1 to level 4. So how can we find the points of comparison that will enable us to trace students' learning trajectories?

This has proved to be a very difficult and challenging problem. It is not very helpful to focus on elements that are simply missing from level 1 students' accounts, such as atoms and molecules. Neither is it helpful to focus on elements of accounts that lose significance in scientific models, such as the abilities and purposes of actors. We need to identify types and elements of accounts that are meaningful at both level 1 and level 4, as well as intermediate levels.

We have settled (for now) on *linking processes* as the types of accounts that we can best use to trace learning trajectories. Linking processes are events that are visible at the macroscopic scale and that take place in time periods that are familiar to students across our age range—from a few seconds up to a year or so. Linking processes also need to be scientifically significant, so we choose visible manifestations of large-scale socio-ecological processes. The way we use linking processes to connect level 1 and level 4 accounts is illustrated for the carbon strand in Table 4 below (from Mohan, Chen, and Anderson, in press).

**Table 4: Linking processes for carbon strand learning progression**

<table>
<tr><td>Level 4 general processes</td><td>Generating organic carbon</td><td colspan="3">Transforming organic carbon</td><td colspan="3">Oxidizing organic carbon</td></tr>
<tr><td>Level 4 accounts</td><td>Photosynthesis</td><td>Biosynthesis</td><td>Digestion</td><td>Biosynthesis</td><td colspan="2">Cellular respiration</td><td>Combus-tion</td></tr>
<tr><td>Linking processes</td><td colspan="2">Plant growth</td><td colspan="2">Animal growth</td><td>Breathing, exercise</td><td>Decay</td><td>Burning</td></tr>
<tr><td>Level 1 accounts</td><td colspan="5">Plants and animals as actors, accomplishing their purposes in life, using their abilities, if their needs (food, water, sunlight, and/or air) are met</td><td>Natural process in dead things</td><td>Flame as actor consuming fuel</td></tr>
</table>

Note: Linking processes are in red.

Table 4 shows how the linking processes are familiar and significant to students who give both force-dynamic and scientific accounts, though students at the two ends of the learning progression interpret them in quite different ways. Level 1 students see plant growth, animal growth, and animal movement as all related expressions of the abilities and purposes of living things, while burning and decay are quite different. For level 4 students, animal movement, decay, and combustion are all related processes that oxidize organic carbon, while plant and animal growth are complex combinations of processes that generate and transform organic carbon.

We have also identified possible linking processes for the water and biodiversity strand. For water, those processes include visible processes in ground water, surface water and human water systems, such as rivers, wells, and water in showers. For biodiversity, those processes include changes or disturbances that affect natural landscapes (such as forests) and managed landscapes (such as farms). These processes include changes that we associated with continuity in the ecosystems, such as yearly cycles and life cycles, as well as disturbances leading to irreversible change, such as diseases or fires. For more on these processes, see the water and biodiversity posters and papers.

Linking processes are important because we can use them to describe intermediate levels—Levels 2 and 3 in our learning progressions. Strand specific descriptions of level 2 and level 3 accounts can be found on the individual posters and papers.

### *Alternate Learning Trajectories and Teaching Experiments*

Our current descriptions of level 2 and level 3 reasoning, based primarily on status quo teaching, show students learning facts about structure and function in systems but not learning how to use principles to constrain processes. In general, level 2 accounts add details to force dynamic reasoning. These details, such as internal movements of food inside of bodies and awareness of gas exchange in breathing, can provide the possible basis for principled reasoning in later grades.

It would make sense for level 3 accounts to show students making greater use of principles such as those described in Table 3, above, to constrain their reasoning about linking processes. However, that general is not the case. Currently, most of the level 3 accounts that we get from students include additional details about structure and function (the first row of Table 3) without much evidence that they are using principles to constrain their accounts (the remaining rows of Table 3). These findings lead us to hypothesize that alternate learning trajectories may be possible, as shown in Figure 8, below.

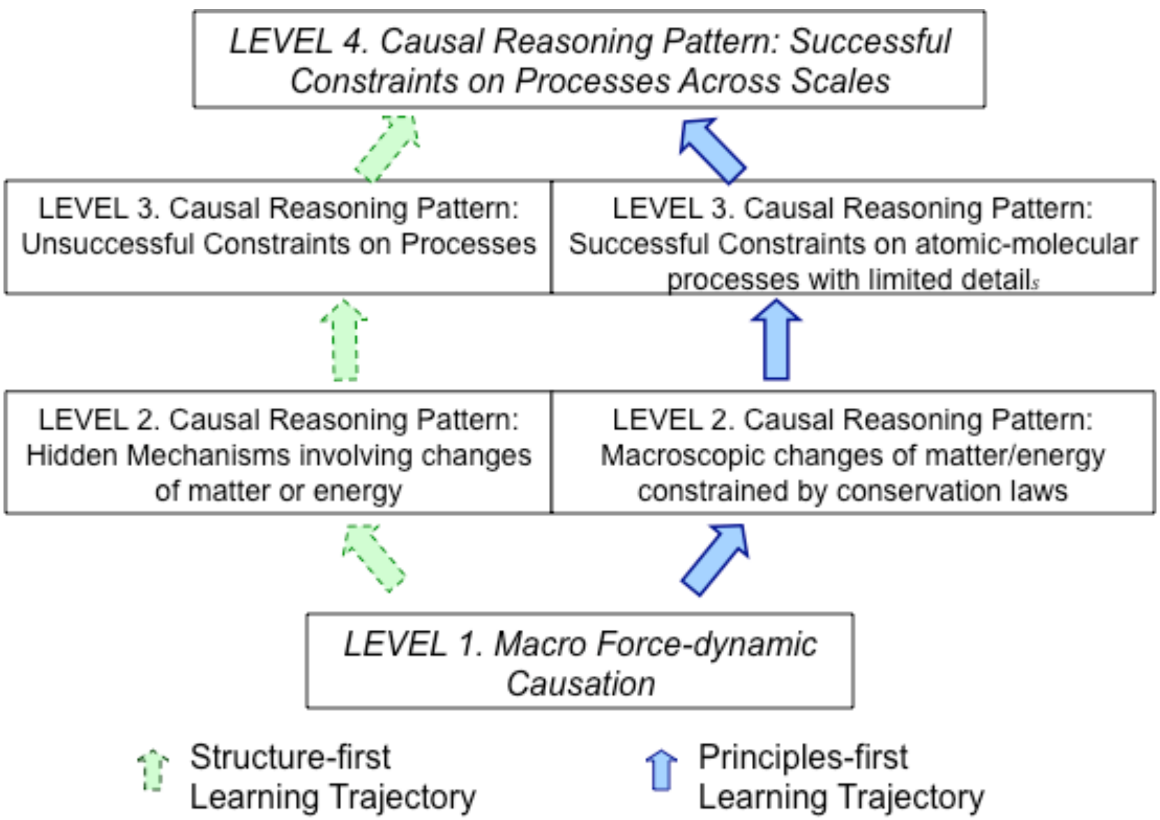


**Figure 8: Hypothesized alternate learning trajectories for carbon strand (from Jin, 2009)**

We are testing our hypotheses about possible alternate learning trajectories in the carbon strand teaching experiments that are currently in progress. The teaching materials that we have developed or adapted for these experiments are available on our website at http://edr1.educ.msu.edu/EnvironmentalLit/publicsite/html/cc_tm.html. These teaching experiments are built around a set of reasoning tools that embody the core principles—scale, matter, and energy—described in the carbon strand column of Table 4. They include:

- A video, wall chart, and PowerPoint slides that students can use to "zoom in and out" of different systems and processes, seeing representations from atomic-molecular to landscape scales.
- Atomic molecular models that students can use to model chemical changes such as photosynthesis, cellular respiration, and combustion of fossil fuels. These models embody the idea that chemical changes do not create or destroy atoms.
- The "Process Tool," available as PowerPoint slides, handouts, and a wall poster, that students can use to trace matter and energy through processes at different scales.

An excerpt from the introduction to our *Systems and Scale* unit (Mohan and Jin, 2009) that illustrates these tools is attached to this paper as Appendix B. The full unit is available at the URL cited above. Although our teaching experiments are still in progress, anecdotal reports from teachers make us optimistic about their effects. We hope that next year we will be able to report significant effects on the nature of students' learning, and significantly more students reaching levels 3 and 4.

# What's New in Our Data and Data Analyses

The improvements described above in our models and frameworks have been possible because they are based on new data and improved data analyses. These new data are reported in each individual poster and paper; they are also described briefly in the poster summaries in Appendix A. In this section we briefly mention a few of the notable additions to our data and analyses that are apparent on several different posters.

**Clinical interviews for citizenship, carbon, biodiversity.** Three posters report on results of clinical interviews with people ranging from elementary school students to adults, focusing mostly on middle school and high school students. These interviews have provided us with richer data and, we believe, deeper insights into the nature of students' accounts and the reasoning on which they are based.

**Statistical validation, calibration, and comparison.** Three posters report on statistical analyses that we have used to validate written assessment items, scoring rubrics, and frameworks, to compare American and Chinese high school students, and to compare pretest and posttest results for a limited sample of middle school and high school students.

**China-US comparisons.** Two posters describe comparisons between Chinese and American middle school and high school students, based on written assessments and clinical interviews. These studies show interesting qualitative differences in the nature of students' responses, suggesting that although the general progression from force dynamic to model-based reasoning (and the general failure of most students to achieve level 4 accounts) is similar in both countries, there are interesting differences that may be attributable to differences in culture and curricula.

**College level data.** Finally, one poster reports on data from college general biology and ecology classes. We anticipate that this will be a harbinger of work to be reported in the future, as we expand our learning progressions to include college students and adults, including science teachers.

# Conclusion: Implications for Research, Policy, and Practice

Work on learning progressions is important because learning progressions can bring science education research on student learning to bear on issues of science curriculum and large-scale assessment (Committee on Science Learning, 2007). This project is unique in that we have collected a large data set over a multi-year period and used those data to develop a set of learning progressions that span a large grade range (about grades 4-10) for significant scientific domains.

This work is also important because we develop a detailed argument about the future of the science curriculum that is grounded both in data and in arguments about the contributions of scientific knowledge to responsible citizenship. We suggest ways of reconciling important scientific standards of rigor, impartiality, and argument from evidence with the importance of preparing our children for the socio-ecological issues that they will face as future citizens.

The work reported in this poster symposium both documents the current performance of our educational system and suggests ways in which that performance can be improved. We are looking forward to analyzing data from our carbon teaching experiments, since these data will provide a first test of our hypothesis that principles-first teaching can change both the nature and the extent of student learning.

We believe that this work, and other work on learning progressions, has implications for research, for development of standards and curricula, and for science curriculum and instruction.

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# Appendix A: Descriptions of Posters

Descriptions of each poster and accompanying paper are included in this section, arranged according to the three strands for accounts described above—carbon, water, and biodiversity—and citizenship practices.

## *A Learning Progression for Carbon in Environmental Systems*

The symposium will include five posters and accompanying papers focusing on carbon and carbon cycling. Each poster is described below.

**1. Validation of a Multi-Year Carbon Cycle Learning Progression,** by Lindsey Mohan, Jing Chen, Hamin Baek, Jinnie Choi, Yong-Sang Lee, and Charles W. Anderson.

This paper reports on the empirical validation of a multi-year carbon cycle learning progression and specifically on the nuanced patterns within the learning progression, and statistical analyses of our assessments. The goal of this paper is to share results from both statistical and conceptual analyses aimed at understanding and improving the assessment instruments used in our learning progression work.

The two questions used to guide our work include (1) Are there patterns in the way students account for matter and energy? Do they tend to score the same, higher, or lower on one or the other dimension? (2) How consistent are students in terms of their accounts of processes? Are there patterns that indicate students understand some processes more or less than others? We conducted multidimensional IRT analyses using ConQuest software for empirical validation of the framework and assessments. The sample we analyzed includes 771 assessments (190 elementary, 288 middle, 294 high) and 25 assessment items; 45 item scores.

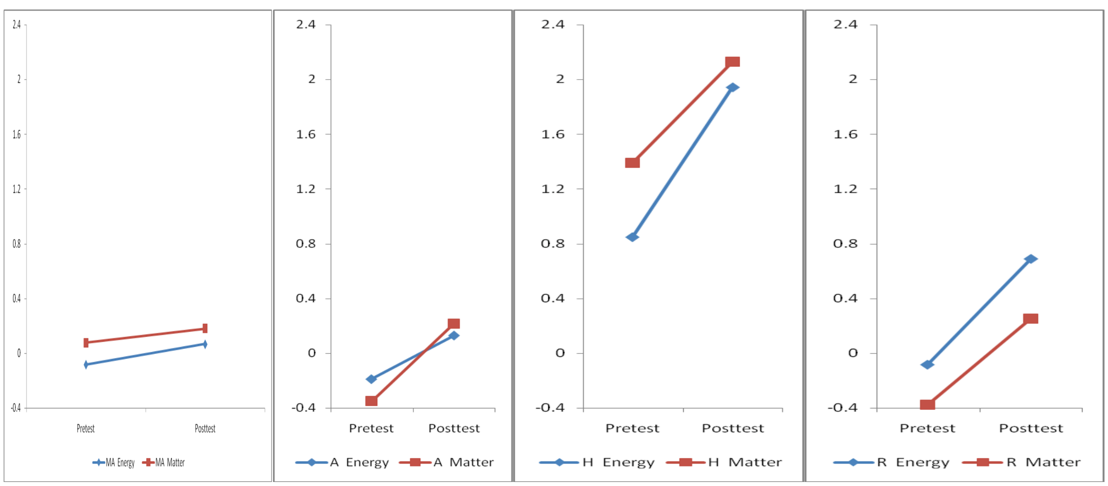
Our learning progression framework contains two important dimensions: *principles* (tracing matter, tracing energy) and *processes* (photosynthesis, digestion, biosynthesis, food chains, sequestration, cell respiration and decay, and combustion.). Within this framework, we have identified four levels of achievement. At Level 1 (Lower Anchor), students use force-dynamic reasoning to explain how enablers help actors fulfill their natural tendencies, paying attention to the interplay of forces—that support natural tendencies and the antagonists that prevent actors from fulfilling their goals. At Level 2, students attempt to explain processes using "hidden mechanisms" and begin to trace materials and energy forms that are visible or tangible (e.g., solids, liquids, heat, sunlight, motion, etc). At Level 3, students are aware of cellular processes and chemical reactions, and aware that materials are composed of different types of substances while they do not have a robust commitment to conservation of matter and energy, and often default to matter-energy conversions to account for mass change that should be attributed to gases. At Level 4 (Upper Anchor), students have a strong commitment to using scientific principles as constraints in their reasoning, attempting to conserve both matter and energy.

The analysis of the principles dimension shows a high correlation between matter and energy progress variables, indicating that a student scoring a particular level on one progress variable is likely to score similarly on the other. In addition, the analysis of process dimensions shows that most processes are correlated with one another indicating that students tended to score the same despite the process while the degrees of correlations vary. From these results we can conclude that students have a similar level of reasoning on matter as they do energy, and that level of reasoning about different processes is also similar. While there are unique patterns for each item, the overall trend does not suggest major differences in reasoning based on progress variable or process dimensions.

**2. Secondary Students' Accounts of Carbon-transforming Processes Before and After Instruction,** by Kennedy Onyancha, Karen Draney, Jinnie Choi, Yongsang Lee, and Charles W. Anderson.

The purpose of this study is to examine the extent to which more targeted instruction using designed instructional materials are helpful in eliciting student scientific explanations of 6 selected carbon-transforming processes. These were combustion, cross processes, decomposition, growth, photosynthesis, and respiration. Additionally, we examined these students' accounts regarding the corresponding principles of energy and matter. Students' accounts relating to these processes came from 4 secondary school teachers: Two of these teachers used designed instructional materials and two did not. We first used grounded theory to analyze these four teachers' students' responses to pre-posttests regarding the 6 processes. We then used matched-paired t-test to examine the effect of more targeted instruction.

We found two key patterns. First, there were overall significant pre-post gains in students' accounts in principles among teachers (H & R) who used more targeted instruction than those teachers (MA & A) who did not (see graph below). This was true even among teachers whose students' pretests were roughly similar (MA, A & R).




Graphical Pre-Post comparison of Principles by instruction (MA & A, no targeted instruction; H & R, targeted instruction)

Second, although there were overall more significant pre-post gains in students' accounts in processes among teachers who used more targeted instruction, there were no significant pre-post gains in these students' accounts in the process of growth at high school level irrespective of form of instruction. This suggests more future work, especially regarding this process. Our findings therefore suggest that more targeted instruction looks more promising than traditional forms of instruction

**3. American and Chinese Secondary Students' Written Accounts of Carbon Cycling in Socio-ecological Systems,** by Jing Chen, Xinhua Jin & Charles W. Anderson.

The United States and China currently account for 40% of the world's emissions. It is urgent for their citizens to be more environmentally literate. We investigate American and

Chinese students' learning progression of carbon cycle as a first step to find out ways to improve science education in these countries to help more students to be environmentally literate. In addition, we explore whether students in other countries under different science education systems and cultures still share similar patterns in their development of scientific knowledge and practice. This paper is guided by the following research questions:

1) How do American and Chinese students compare in terms of the accounts they give for carbon transforming processes and for fundamental matter/energy conservation principles?
2) How do general achievement levels compare for American students and Chinese students?
3) What are the implications for the validity of learning progression levels for the two groups? How do difficulties of a set of items developed by our research project compare for American and Chinese students?

600 American and Chinese students in total participated our written assessment, with 150 at the middle school level and 150 at the high school level from each country. We report our findings from the written assessment in terms of their understanding of carbon cycling in socio-ecological systems. Our results indicate that:

1) American and Chinese students share similar general trends associated with a learning progression from force-dynamic to scientific model-based reasoning.
2) Both groups have similar general distribution of responses at each level; only small percentages of students in both groups reached the highest achievement level—principled, model-based reasoning.
3) The order of item difficulties was different for American and Chinese students, suggesting that our framework describing four Levels of Achievement is less empirically valid for Chinese data than for American data. Thus Chinese students may have a different learning trajectory from American students.

The comparison between American and Chinese students' learning performances indicates that they perform differently in some related science content areas. American students perform better for photosynthesis items, digestion & biosynthesis items, and large-scale items, while Chinese students perform better for cellular respiration items and combustion items. Our results also show that Chinese students included chemical equations, named forms of energy, and mentioned the energy conservation principle more commonly than American students, though they often failed to use the principle as a tool to reason about carbon transforming processes. These differences may result from differences in various aspects of science education between these two countries.

**4. Interviews with Chinese and American Secondary Students about Carbon Cycling in Socio-ecological Systems,** by Hui Jin, Li Zhan, Charles W. Anderson.

In this research, we develop a four-level carbon cycling learning progression to describe how American and Chinese students understand carbon cycling as it relates to global warming. We designed interview protocols, which ask students to explain six key macroscopic environmental events of global warming: tree growth, baby girl growth, girl running, tree decaying, flame burning, and car running. Thirty-three American students and twenty-three Chinese students attended the research.

We found that students' explanations could be analyzed in terms of two aspects of performances—naming and explaining and that American students and Chinese students show similar patterns in each aspect. Naming refers to the performance of naming relevant knowledge including scientific facts, principles, and concepts learned from the science classrooms or other resources. Explaining refers to the performance of applying knowledge or intuitive ideas to explain events.

For each focal event, we developed two exemplar worksheets to describe achievement levels, one for the naming performances and the other for the explaining performances. We used the exemplar worksheets to code responses from both American and Chinese students. Our results indicate that naming performances and explaining performances for American students and Chinese students were aligned differently, as shown in Figures 1 and 2 below.

Figure 1. Alignment of Naming Performances and Explaining Performances for American Students

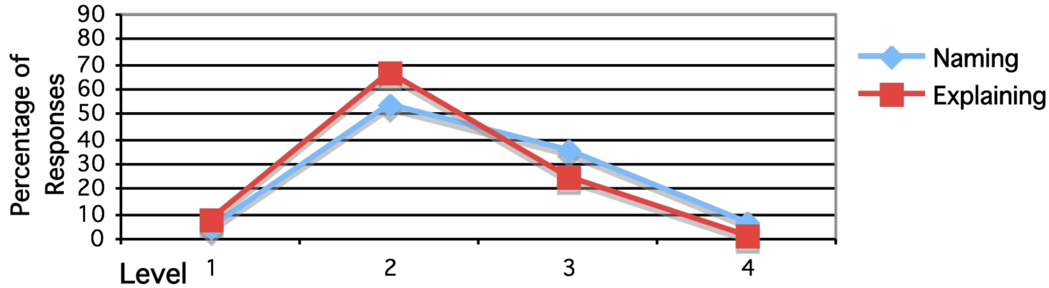
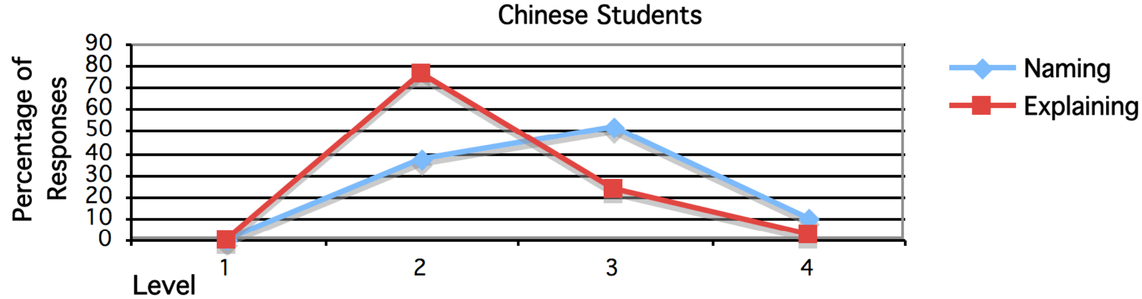



Figure 2. Alignment of Naming Performances and Explaining Performances for Chinese Students




These two figures show two patterns. First, American and Chinese students' explaining performances were very similar, with a majority of each group at level 2 – relying primarily on force-dynamic with hidden mechanism reasoning. This reasoning is implied and embedded in people's everyday experience with the material world and discourses. This indicates that the school science learning in both countries does not effectively help students to develop the ability of applying scientific knowledge (processes, concepts, and principles) to qualitatively explain environmental events. Hence, most secondary students still tend to rely on everyday reasoning to understand these events.

Second, naming performances were aligned differently for American and Chinese students. Students in both groups showed more Level 3 and 4 naming performances than explaining performances, but the difference was much larger for Chinese students. This indicates that although Chinese students learned to repeat more scientific facts and definitions, they still relied on level 2 hidden mechanisms reasoning to explain the events. This pattern is also confirmed by the qualitative data analysis when we were identifying the patterns of the explanations. For example, many Chinese students were able to correctly describe the formula of photosynthesis, but they also claimed that the increased mass of the tree came from materials the tree absorbed from the soil. Obviously, they could not link the formula of photosynthesis with the event of tree growth. The different alignments of naming and explaining performances show the two different learning trajectories for American students and Chinese students.

**5. College students' accounts of carbon transforming processes in socio-ecological systems,** by Laurel Hartley,[1] Brook Wilke,[2] Jonathon Schramm,[3] and Charles W. Anderson

[1]Dept. of Biology, University of Colorado, Denver [2]Crop and Soil Science, Michigan State University [3]Teacher Education, MSU

Reasoning about the intersection of social and ecological systems requires an understanding of the carbon cycle. Simultaneously, carbon-transforming processes are a prominent part of college-level biology curricula, but ideas are typically presented in disconnected ways. We believe that teaching students to explicitly and continuously apply the principles of conservation of matter and energy can lead to a deeper understanding of processes across multiple scales. This approach contrasts principled, scientific reasoning with informal or force-dynamic reasoning (see Figure 1 in poster). We maintained two primary objectives for this work: 1) look for patterns in student reasoning and generate hypotheses for further research and 2) examine the effects of instruction on student understanding of carbon related processes.

We investigated college students' ability to trace matter and energy through processes that generate, transform and oxidize organic carbon at multiple scales by developing and implementing diagnostic question clusters (DQCs) to investigate college students' reasoning about the carbon cycle. Faculty from eight institutions (research universities, liberal arts colleges, and community colleges) administered a total of four DQCs, two focused on carbon cycling and two on energy flow, to 267 students in biology and ecology courses. DQC's were used as both pre and post-tests. For further details about the DQCs and particular items, please see our web site at: http://demos.patrickgmj.net/griffithdemo/. Interviews were conducted at one university to further explore and validate student responses to written questions.

From this extensive data collection, we've identified several key results. First, most college student answers were a hybrid of scientific reasoning and informal accounts. Second, students demonstrated similar types of reasoning across the range of institutions. Third, despite that the type & frequency of active instructional interventions used by participating faculty varied, the majority of students saw significant learning gains pre- and post-instruction for both matter- and energy-focused questions (see Figure 3 in Poster). Finally, our results both corroborate patterns in student thinking identified in previous studies and lead to further hypotheses about student reasoning (see Table 1 in Poster). For example, most students believe that the majority of matter for plant growth comes from various materials the soil, rather than carbon dioxide from the atmosphere. This is an established pattern in student thinking, yet our results have led us to hypothesize about the reasons for this conception, including that a) students see overly simplified gas-gas and solid-solid cycles and b) students think atoms can become other atoms.

Despite the fact that the principles of matter and energy conservation across multiple scales are fundamental to understanding biology, and particularly ecology, this research indicates that students are not as well-grounded in those principles as faculty often assume. By helping to diagnose this "hidden curriculum" effect for faculty, DQCs can be an effective tool on which to base further instructional interventions.

## *Learning Progressions for Water, Biodiversity, and Citizenship*

**6. Developing a Learning Progression for Students' Understanding of Water in Environmental Systems,** by Kristin L. Gunckel, Beth A. Covitt, Tammy M. Dionise, and Charles W. Anderson.

This work, which is aimed at developing a learning progression for water in socio-ecological systems, conceptualizes learning as the process of mastering a new Discourse. Students enter school with their primary Discourses, or ways of understanding the world that are rooted in their family and community experiences and practices. Science education seeks to help students develop a second, science-based Discourse that is characterized by viewing the material world in terms of connected systems in which processes are constrained by principles such as conservation of matter. Students who have acquired a scientific Discourse are able to trace and characterize what happens to water and other substances as they move through connected human and natural systems.

The authors draw on analysis of elementary through high school student assessments to describe characteristics or levels of students' ways of thinking that span from primary, informal Discourses to secondary, scientific Discourse. Four levels of achievement, which are rooted in students' responses to the assessments, are described. Many young students' thinking may be characterized as force-dynamic in nature. As force-dynamic thinkers, students view the world as a stage where actors have abilities to make things happen. Water is a part of the background landscape of the stage. Force dynamic thinkers recognize water in visible, discrete locations, such as rivers, lakes or bathtubs. They also identify discrete types of water, such as "dirty water" or "salty water." In addition, they conceive of changes in water as a result of actions by actors without any stated mechanism.

Students at level 2 also use force-dynamic thinking, but they now view water as having natural tendencies that enable it to move and change. Students at Level 2 recognize that water can move from one place to another and that water can exist in places that they cannot see. However, the nature of those invisible places is not explicit and students often consider water in these places as gone or unavailable. In addition, students at level 2 often invoke actors or agents that enable or restrict movements of water or changes in water quality.

At Level 3, students view water as part of a connected system. Students recognize that water moves across invisible boundaries and understand that natural and engineered systems are connected. Furthermore, students at Level 3 understand that other materials can move with water and that these materials can be removed from the water by natural processes. However, students at Level 3 demonstrate errors in their thinking about the movement of water and materials, indicating that aspects of their models for water in environmental systems are incomplete. Furthermore, they tend to describe materials and processes at a macroscopic level.

By Level 4, students have complete or nearly complete qualitative models of water in socio-ecological systems. They can trace water and materials along multiple pathways across visible and invisible boundaries. They can describe substances in water with their chemical identities. Furthermore, they can describe the processes that move water and materials at both atomic-molecular and landscape scales and can apply scientific principles to reason through complex water situations (e.g., landfills polluting groundwater).

Through continuing work on this learning progression, the authors aim to inform a science curriculum that will help students develop model-based understanding about water in connected natural and human engineered systems.

**7. Developing a K-12 Learning Progression for Biodiversity in Environmental Systems,** by Josie Zesaguli, Brook Wilke, Edna Tan, Laurel Hartley, Courtney Schenck, Jonathon Schramm, and Charles W. Anderson

The loss of biodiversity is occurring at the fastest known rate in history, and is caused primarily by human activities. Daily, humans make decisions that impact biodiversity, and it is essential that citizens understand the implications of these decisions. Yet, biological systems are complex, with many details still being discovered. To simplify this complexity, we have identified several key principles below that are responsible for the complexity we see in ecosystems.

- Characteristics of Systems
    - Hierarchy of systems at different scales: Biodiversity exists in 3 distinct levels
    - Structure and Function: Population variability, species diversity, phenotypic structure, function, and relationships with the non-living environment
- Principles Constraining Processes
    - Genetic continuity: Every organism inherited its genes from parents of the same species
    - Ecological Dynamics: Populations have the potential to expand exponentially, but there are multiple ecological constraints preventing exponential increase, including 1) dispersal constraints, 2) environmental constraints and 3) internal dynamics (biotic interactions).

Using these principles as a guiding framework, we report specifically on clinical interviews conducted with ten Grade 5 to 12 students and three adults in Michigan. The interviews were a follow-up of the previously reported open-ended written responses from 475 students in grade four through high school. The interview protocol asked the respondents to assemble either a “natural” system (Michigan Forest) or a managed system (Michigan Farm), given pictures of samples of representative plants and animals and decomposers. The interview questions elicited students’ accounts, which enabled us to identify patterns in reasoning about structure and function as well as the processes that sustain and alter the biodiversity of local ecosystems. Analyses of the interview accounts led to substantial refinement of our guiding framework.

Levels of achievement for students and adults varied from force-dynamic (lower anchor) to model-based reasoning (upper anchor). Lower anchor students tended to explain landscapes as settings in which systems and processes are described in terms of actors with needs, powers and abilities, similar to anthropomorphizing stories such as “The Lion King”. To achieve their purposes, these actors use enablers and purposefully cooperate or compete with other actors.

Upper anchor accounts were provided more regularly by adults and occasionally by students of varying ages (see Table 1 in poster). These interviewees were concerned with the phylogenetic and ecological constraints placed on the organisms, and used these constraints to assemble their respective ecosystems. For example, upper anchor accounts included an explanation of how disturbances affect genetic, species and community diversity, and how these disturbances may lead to reversible or irreversible changes within the system.

Overall, a majority of the interviews tended to include a mixture of force-dynamic and model based reasoning. Very few interviewees provided accounts that were entirely constrained by scientific principles. Even adults that provided many upper anchor accounts often lacked appreciation for how genetic endowment is both a resource and a constraint for an individual organism in its environment. The findings of this ongoing study have implications for curriculum development, science instruction intended to facilitate students’ learning of concepts and principles of biodiversity, assessment, and for the revision of standards.

**8. Students’ Use of Scientific Knowledge and Practices When Making Decisions in Citizens’ Roles**, by Beth A. Covitt, Edna Tan, Blakely K. Tsurusaki, and Charles W. Anderson.

A fundamental challenge for science education in a democratic country is preparing its citizens to make informed socio-environmental decisions. The authors offer a framework for analyzing how students approach public and private environmental decisions. The research questions explored within the framework include:

1. When presented with a socio-environmental issue, how did students investigate and explain the issue and what consequences did they predict for their possible actions?
2. What decisions did the students make and how did they justify those decisions?
3. Given their understanding, what values and other resources did they draw on as they made their decisions?

The authors developed two interview scenarios to address the research questions, one about purchasing strawberries and one about a proposed water bottling business, and subsequently interviewed 22 elementary, middle and high school students.

Our framework emphasizes that decision-making is guided by students’ Discourses (Gee, 1990, 1991). Students come to school with primary Discourses that reflect their communities of practice, identities, values and funds of knowledge (e.g., Moje, et al., 2004; Wenger, 1998). In school and through other experiences, students may acquire secondary Discourses, such as scientific Discourse. Discourses influence how students engage with issues and make decisions. Students’ practices of investigating, explaining, predicting and deciding are embedded within their Discourses. The extent and ways in which students engage in these practices impacts how informed their decisions will be. While we would not advocate for a student to make one decision or another with regard to a socio-environmental issue, we do place a high value on using science as a tool to inform decisions. To the extent that science is relevant, we suggest that an informed decision makes use of scientific understanding.

The findings of this work show the prominent role that factors other than school science played in students’ decision-making practices. The students who had outside-of-school identities and practices, such as being a fisherman or an athlete, had an interest in the scenarios and usually drew on knowledge and values from these out-of-school resources more than school science. Overall, there was very limited use of school science in students’ decision-making practices. Water scenario students tended to invoke school science more than the strawberry-scenario students. This may be due partly to the way the two scenarios were structured and to the fact that compared with food supply chains, the water cycle is a more common topic in the K-12 science curriculum.

These interview results emphasize that decision-making is guided by students’ Discourses, and that students come to school with primary Discourses that reflect their communities of practice, identities, values and funds of knowledge. This work raises questions for science education instruction, prominently, how can school science be designed and implemented to help students connect their in and out of school experiences in order to become more informed and engaged socio-environmental decision-makers?

Moje, E., Ciechanowski, K. M., Kramer, K., Ellis, L., Carrillo, R., & Collazo, T. (2004). Working toward third space in content area literacy: An examination of everyday funds of knowledge and Discourse. *Reading Research Quarterly,* 39(1), 38-70.

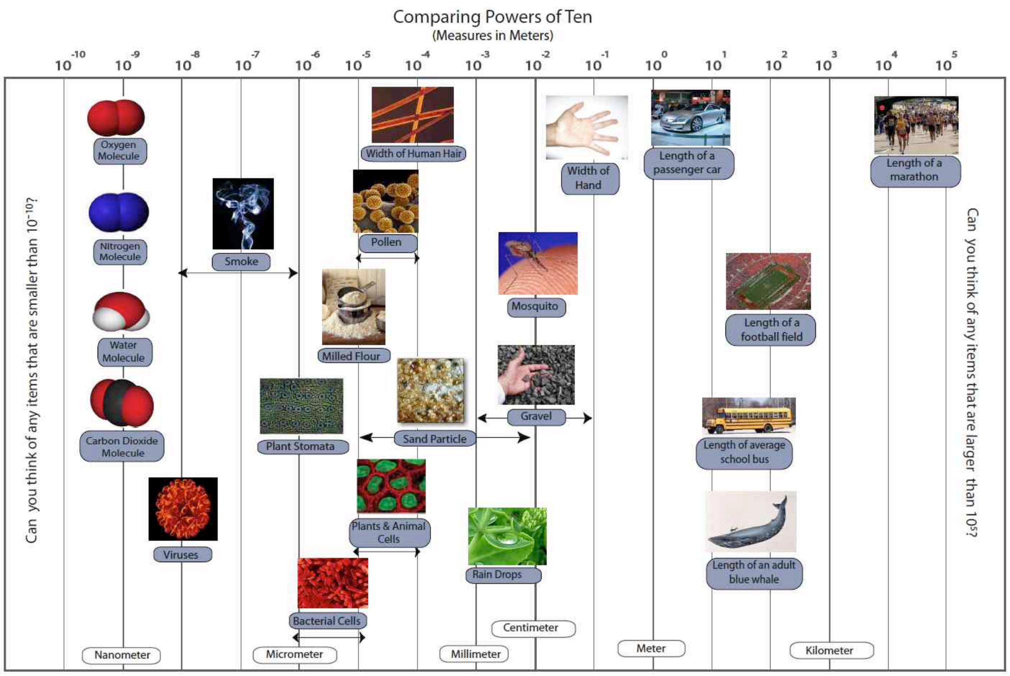
Wenger, E. (1998). *Communities of practice: Learning, meaning, and identity.* Cambridge: Cambridge University Press.

# Appendix B: Tools for Matter, Energy, and Scale

From *Systems and Scale* Middle School Teacher's guide, by Lindsey Mohan and Hui Jin, 2009

## *Scale*

### Powers of Ten Representation #1




### Powers of Ten Representation #2: PowerPoint slides

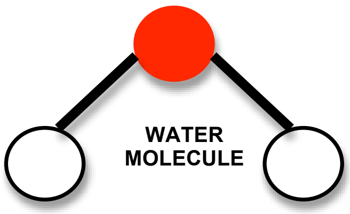
## The One-Meter Square

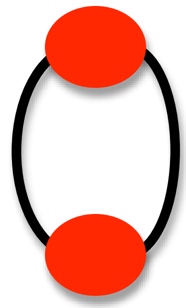
| $10^n$ | Prefix | Symbol | Decimal equivalent in SI writing style |
|---|---|---|---|
| $10^{24}$ | yotta- | Y | 1 000 000 000 000 000 000 000 000 |
| $10^{21}$ | zetta- | Z | 1 000 000 000 000 000 000 000 |
| $10^{18}$ | exa- | E | 1 000 000 000 000 000 000 |
| $10^{15}$ | peta- | P | 1 000 000 000 000 000 |
| $10^{12}$ | tera- | T | 1 000 000 000 000 |
| $10^{9}$ | giga- | G | 1 000 000 000 |
| $10^{6}$ | mega- | M | 1 000 000 |
| $10^{3}$ | kilo- | k | 1 000 |
| $10^{2}$ | hecto- | h | 100 |
| $10^{1}$ | deca- | da | 10 |
| $10^{0}$ | (none) | (none) | 1 |
| $10^{-1}$ | deci- | d | 0.1 |
| $10^{-2}$ | centi- | c | 0.01 |
| $10^{-3}$ | milli- | m | 0.001 |
| $10^{-6}$ | micro- | µ | 0.000 001 |
| $10^{-9}$ | nano- | n | 0.000 000 001 |
| $10^{-12}$ | pico- | p | 0.000 000 000 001 |
| $10^{-15}$ | femto- | f | 0.000 000 000 000 001 |
| $10^{-18}$ | atto- | a | 0.000 000 000 000 000 001 |
| $10^{-21}$ | zepto- | z | 0.000 000 000 000 000 000 001 |
| $10^{-24}$ | yocto- | y | 0.000 000 000 000 000 000 000 001 |


Scale: $10^0$ meters = 1 meter: Light takes about 3 nanoseconds to cross this picture

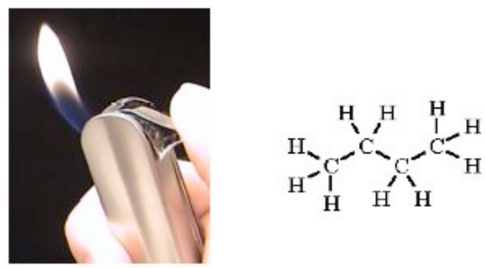
## *Matter and Energy*

### Molecular Model Kits



Propane ($C_3H_8$)



Butane ($C_4H_{10}$)

Ethanol ($C_2H_5OH$)

Methane ($CH_4$)

**Matter and Energy Process Tool**