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DEVELOPING ASSESSMENTS FOR A LEARNING PROGRESSION ON CARBON TRANSFORMING PROCESSES IN SOCIO-ECOLOGICAL SYSTEMS[1]

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Introduction

Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic (National Research Council [NRC], 2007). They provide promising frameworks for assessing students' understanding and learning. In our work to develop a learning progression for carbon-transforming processes, we involved participants from a wide age range (fourth grade through eleventh grade) and from two different countries (the United States (US) and China). We involved participants from a wide age range in order to develop a learning progression spanning from naïve reasoning to sophisticated scientific reasoning. In addition, studying how students progress under different cultural conditions will contribute to a better understanding of how students' learning is influenced by culture and schooling. The diversity of participants enabled us to collect extensive and detailed data for the development of the learning progression, but it also brings special assessment challenges. In this chapter, we describe these assessment challenges and our responses.

Our research involves an inquiry process of drawing inferences about what students know and how they progress, using evidence from students' performances. This process can be illustrated with the assessment triangle (Figure 1) that links three key elements: cognition, observation, and interpretation (NRC, 2001). Cognition refers to the models, theories, and beliefs about how students represent knowledge and develop competence in the subject domain; in the case of learning progression research, this is the learning progression framework. Observation contains the tasks or situations that allow researchers to elicit students' thinking. Interpretation comprises the methods and tools used to analyze the data and draw inferences, possibly leading to revision of the learning progression framework and assessment tasks.

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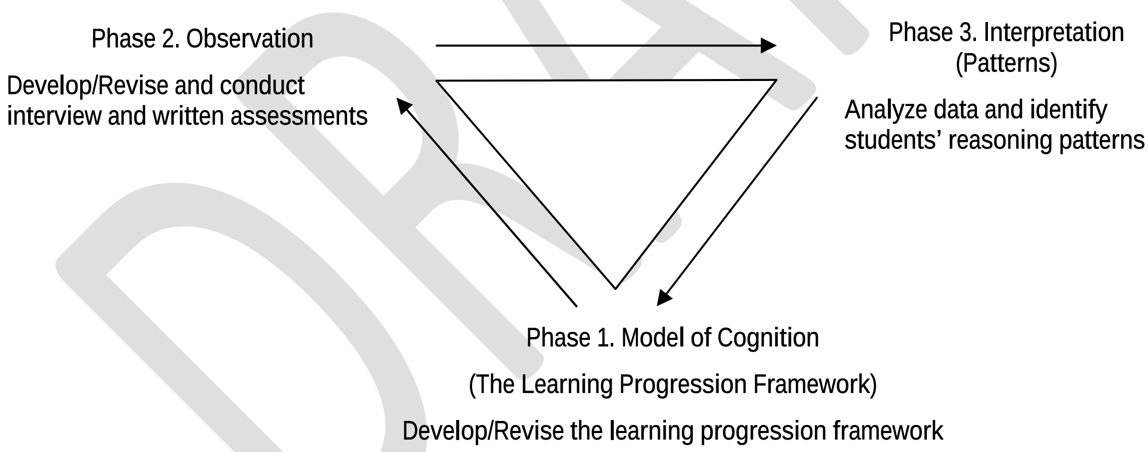
When we began this research in 2004, our learning progression framework and initial assessments were based on our experience and interpretation of assessment data from previous research (Anderson, Sheldon, & DuBay, 1990; Lee, Eichinger, Anderson, Berkheimer, & Blakeslee, 1993). In the process of eliciting students' understanding and interpreting students' responses to assessment questions, unexpected problems often emerged. We responded to these problems by revising or redesigning the assessments and the learning progression framework itself. Therefore, we adopted the approach of design-based research (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Edelson, 2002), which involves iterative cycles of assessment design and testing, using each testing cycle as an opportunity to collect data and inform subsequent assessment and framework design.

Our research goals include 1) developing a learning progression framework that describes students' increasingly sophisticated ways of reasoning about carbon-transforming processes and 2) developing associated assessments that are effective in eliciting a range of students' thinking about carbon-transforming processes. To reach these goals, our research framework, the iterative assessment triangle (Figure 1), is based on the work of the NRC (2001). The iterative assessment triangle represents the iterative cycles used to develop the learning progression framework and associated assessments.

Figure 1 Research Process: Iterative Assessment Triangle (Modified from the NRC's (2001) Assessment Triangle)



As indicated in Figure 1, our research process contains three phases: model of cognition (learning progression framework), observations, and interpretation.

- *Model of cognition* refers to the learning progression framework, which describes the progression of students' reasoning about carbon-transforming processes. It contains an Upper Anchor, the learning goal for high school graduates, and, below that, qualitatively different achievement levels that reflect students' ideas. In our initial learning progression framework (Jin & Anderson, 2008; Mohan, Chen, & Anderson, 2009), the Upper Anchor was developed based on literature from environmental science and national standards; hypotheses about lower achievement levels was based on our experience and reading of previous research. The learning progression framework is continuously revised and refined through the iterative cycles. We start each research cycle with the learning progression framework developed in the previous cycle. In each cycle, the learning progression framework guides our work in designing and revising assessments at the observation phase.

- *Observation* includes assessment design, assessment implementation, and data collection. We use both clinical interviews and written assessments to elicit students' ideas about carbon-transforming processes. The assessments are continuously revised and refined until they yield useful information for our understanding of students' ideas.
- At the *interpretation* phase, we develop coding rubrics to relate students' responses to the learning progression framework. Graduate students and post-doctoral fellows working in the research project apply the coding rubrics to interview and written data. Reliability checks for consistency of coding are performed during this process. The learning progression framework is continuously revised to resolve disagreements as well as other problems reported by the coders.

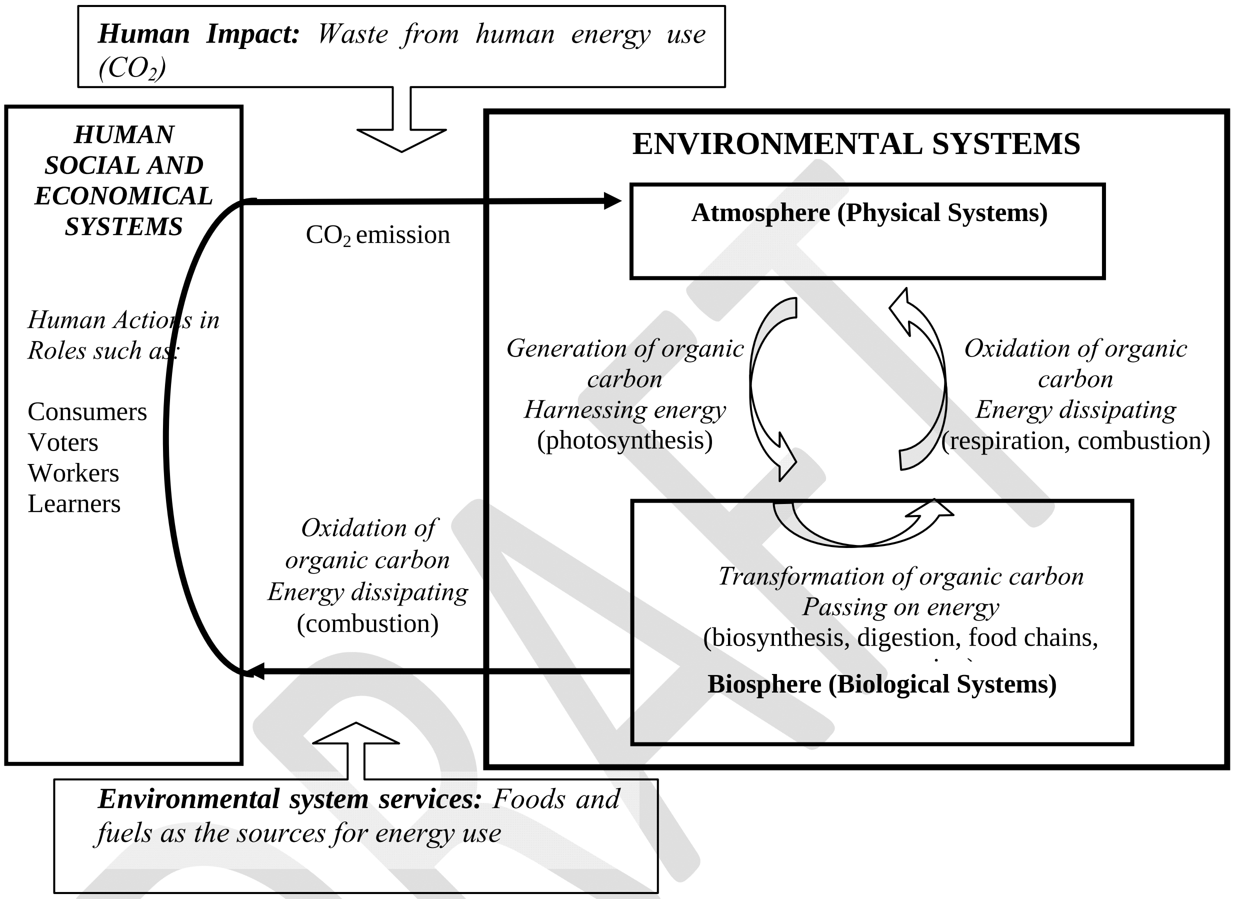
We have conducted five research cycles during the past six years of the project. In this chapter we focus on the 2008-9 cycle. We describe the preliminary model of cognition that we had at the beginning of the 2008-09 cycle. Then, we describe the assessment challenges we encountered and how we responded to the challenges at the subsequent observation, interpretation, and model of cognition phases of the assessment triangle.

Preliminary Model of Cognition

An important goal of school science learning is to develop model-based reasoning—using models and theories as conceptual tools to analyze natural phenomena (NRC, 2007). When students graduate from high school, they will take on responsibilities for making decisions about their personal lifestyles and public policy. As consumers, voters, workers, and learners in society, their activities and decisions collectively impact environmental systems. In particular, as global climate change is becoming an increasingly serious issue, it is important for every citizen to understand how human energy consumption activities contribute to climate change.

Therefore, our learning goal for high school graduates is the use of scientific model-based reasoning to explain how carbon-transforming processes contribute to global climate change. To elaborate this goal, we reviewed relevant literature from environmental science (Long Term Ecological Research Network [LTER], 2007) as well as national standards documents (American Association for the Advancement of Science [AAAS], 1993; NRC, 1996). One important focus of environmental science is the supply-feedback chain between human society and environmental systems (LTER, 2007). National standards documents emphasize understanding both carbon-transforming processes and fundamental principles (i.e., matter conservation, energy conservation, and energy degradation). We incorporated these two ideas to develop a Loop Diagram (Figure 2).

Figure 2 The Upper Anchor--Loop Diagram (Mohan, Chen, & Anderson, 2009)



We study students' accounts—narratives that explain processes at multiple scales. The Loop Diagram, which is the Upper Anchor of our learning progression framework, represents scientific *accounts* that explain carbon-transforming processes at multiple scales, from atomic-molecular to global, with matter and energy conservation as constraints. It is constructed around three scientific elements—scale, matter, and energy. It also highlights two learning performances:

- *Linking processes at multiple scales*

  Scientific models explain global fluxes of matter and energy as the cumulative effects of processes that take place at the atomic-molecular scale. There are three classes of carbon-transforming processes at the atomic-molecular scale: (a) organic carbon generation (photosynthesis), (b) organic carbon transformation (biosynthesis, digestion), and (c) organic carbon oxidation (cellular respiration, combustion). The cumulative effects of these atomic-molecular processes are the global carbon-transforming processes—carbon (matter) cycling and energy flow. Carbon recycles among the atmosphere, biosphere, and human socio-economical systems. That is, matter is transformed between the inorganic form—carbon dioxide—and the organic form—organic carbon-containing substances. Energy flows from sunlight to the biosphere and to socio-economical systems and finally dissipates outside of these systems as heat. These two global-scale processes of matter and energy explain humans' impact on environmental systems: humans gain energy from foods and fuels from the biosphere; as we use energy, we emit carbon dioxide (and other greenhouse gases) into the atmosphere. Imbalance among these processes causes global climate change over time.

- *Constraining processes with matter and energy principles*

  The carbon-transforming processes are constrained by matter and energy principles—matter conservation, energy conservation, and energy degradation. In particular, two points need to be noted. First, matter and energy are independently conserved in all physical and chemical changes. In other words, matter cannot be converted into energy and vice versa.[2] Second, whenever energy is transformed, heat is always released and cannot be recovered as usable energy.

The learning progression framework describes how students progress from their informal ways of reasoning towards the Upper Anchor. Each iteration of our learning progression framework describes students' progress using two parameters—*progress variables* and *levels of achievement* (Table 1). Progress variables are aspects of students' overall performance that differ for students at different levels of achievement. Students' learning performances relative to each progress variable can be ordered into different levels of achievement. Each revision in the iterative research cycles involves modifying one or both of these parameters.

We began the 2008-9 cycle with some confidence in our general definitions of the levels of achievement. These levels are described in more detail by Gunckel, Mohan, Covitt, and Anderson (this volume) and in other publications (Jin & Anderson, 2008; Mohan, Chen, & Anderson, 2009). We found that more advanced students were able to produce accounts in terms of matter and energy, while many elementary and middle school students tended to rely on *force-dynamic reasoning*—a reasoning pattern identified by cognitive linguists. Research in linguistics and cognitive development indicates that people construct specific ways of reasoning as they learn their native languages. Cognitive linguists studying English grammar (Pinker, 2007; Talmy, 2000) and Chinese grammar (Dai, 2005; Lai & Chiang, 2003) suggest that both languages have implicit theories of cause and action—force-dynamic reasoning, which explains events in terms of actors, enablers, and results.

- Actors: Actors have internal goals and abilities/tendencies to take certain actions. Living actors such as plants and animals have internal self-serving goals and the ability to act toward those goals—to grow, maintain health, and move. Machines and flames also have the ability to act—to move or keep burning, but they need humans to initiate the change

[2] Modern physical theories hold that this statement is not strictly true. We believe, however, that students need to learn to conserve matter and energy independently before addressing matter-energy conversions in nuclear reactions.

such as igniting the flame or driving the car. Dead plants and animals lose their ability to act and thus will change only by being acted on by actors or "running down"—decaying.

- Enablers: Although actors have the ability to take certain actions, they need enablers to make changes happen. Each actor needs particular enablers. For example, people need air, water, and food to stay alive. Without them, people will suffocate, dehydrate, or starve and finally die. Similarly, plants need sunlight, water, soil, and air; flames need fuel, heat, and air; and so forth.
- Results: The actor uses enablers for certain actions or changes towards its natural tendency. The actions, or changes in general, cause certain results—the living or moving actor fulfills its goal or the dead actor deteriorates.

Scientific accounts share this general framework, but with the meanings of each part substantially altered. Scientific accounts treat both actors and enablers as chemical entities, the composition and structure of which are explained in terms of matter and energy. The interactions between actors and enablers are not about actions and results, but about matter transformation and energy transformation at three scales—atomic-molecular, macroscopic, and global. In brief, scientific accounts are constructed around scientific elements—matter and energy at multiple scales. Students who have rich experience of school science learning may use matter and energy to construct accounts, but their accounts often indicate misconceptions. (This is Level 3 of our beginning learning progression framework, as shown in Table 1.)

The four levels of achievement are:

- Level 4 is defined as scientific accounts that are built upon model-based reasoning—tracing matter and energy within and across carbon-transforming processes at multiple scales. This model-based reasoning is illustrated in the Loop Diagram (Figure 2).
- Level 3 is defined as school-science accounts that involve atoms, molecules, and energy forms, but do not successfully conserve matter or energy.
- Level 2 is defined as force-dynamic accounts with hidden mechanisms that explain environmental events in terms of hidden processes and mechanisms, but still focus on actors, enablers, and results.
- Level 1 is defined as macroscopic force-dynamic accounts that describe the environmental events in terms of actors, enablers, and results.

We were less confident about the other parameter in our learning progression framework: progress variables, which we used to structure our detailed descriptions of the different levels of achievement. Students' understanding is usually reflected in multiple dimensions of their learning performances, all of which can be used as progress variables. For example, the loop diagram suggests two orthogonal types of progress variables:

- Carbon-transforming *processes* that generate (photosynthesis), transform (digestion & biosynthesis), and oxidize (cellular respiration and combustion) organic matter.
- Scientific *elements*—scale, matter, and energy.

We used these progress variables as the basis for the learning progression framework represented in Table 1. The learning progression framework organizes descriptions of each level of achievement first around the three carbon-transforming processes: organic carbon generation, organic carbon transformation, and organic carbon oxidation. Under each process, there are two subordinate progress variables: matter and energy. We found that students’ reasoning about scale is implicit in their reasoning about matter and energy, so we did not make scale a separate progress variable. More detailed versions of this table, with individual learning performances for each level, can be found in other project publications (Jin & Anderson, 2008; Mohan et al., 2009).

Table 1 Learning Progression Framework at the Beginning of the 2008-2009 Research Cycle

Levels of Achievement	Progress Variables					
	Organic Carbon Generation		Organic Carbon Transformation		Organic Carbon Oxidation	
	Matter	Energy	Matter	Energy	Matter	Energy
Level 4. Accounts based on model-based reasoning	Explain plant growth in terms of organic matter generation in photosynthesis	Explain plant growth in terms of energy transformation in photosynthesis	Explain human body growth in terms of organic matter transformation in digestion and biosynthesis	Explain human body growth in terms of energy transformation in digestion and biosynthesis	Explain burning, running, and decay in terms of organic matter oxidation in cellular respiration and combustion	Explain burning, running, and decay in terms of energy transformation in cellular respiration and combustion
Level 3. School Science Accounts	Explain plant growth in terms of changes involving glucose, sugar, or other familiar organic molecules May use matter-energy conversion for reasoning	Explain plant growth in terms of changes involving energy forms May use matter-energy conversion for reasoning	Explain human body growth in terms of changes involving glucose, sugar, or other familiar organic molecules May use matter-energy conversion for reasoning	Explain human body growth in terms of changes involving energy forms May use matter-energy conversion for reasoning	Explain burning, running, and decay in terms of changes involving oxygen and/or familiar organic molecules May use matter-energy conversion for reasoning	Explain burning, running, and decay in terms of changes involving energy forms May use matter-energy conversion for reasoning
Level 2. Force-dynamic Accounts with Hidden Mechanisms	Explain plant growth in terms of hidden processes (e.g., making food)	Explain plant growth in terms of triggering event (e.g., energy powers plant growth)	Explain human body growth in terms of hidden processes (e.g., food is broken down; useful stuff is extracted out of food)	Explain human body growth in terms of trigger event (e.g., energy powers human growth)	Explain burning and running in terms of hidden processes (e.g., food becomes sweat). Explain decay in terms of hidden processes (e.g., wood changes into dirt)	Explain burning and running in terms of triggering events (e.g., energy powers flame; energy powers running). Explain decay as a process of losing energy or power
Level 1. Macroscopic Force-dynamic Account	Explain plant growth in terms of macroscopic force-dynamic reasoning: plants use enablers such as air, water, soil, and sunlight to grow bigger Do not specify any invisible processes Do not recognize the role of matter or energy in plant growth		Explain human body growth in terms of macroscopic force-dynamic reasoning (e.g., animals/humans use enablers such as air, foods, and water to grow bigger) Do not specify any invisible processes Do not recognize the role of matter or energy in human body growth		Explain burning, running, and decay in terms of macroscopic force-dynamic reasoning (e.g., flame needs match to support it; dead things decay when getting old) Do not specify any invisible processes Do not recognize the role of matter or energy in burning, running, or decay	

Overview of the 2008-9 Research Cycle

We began the 2008-9 cycle with the learning progression framework described above. During the year, we went through each phase of the cycle:

- *Observation:* We conducted interviews and written tests in the US and China to elicit students' accounts of carbon-transforming processes. We gave interviews and tests both before and after an instructional intervention (described in Gunckel, et al., this volume) for the US students. We did not conduct an instructional intervention in China. In China, 24 students (8 students from each school level) participated in interviews and 300 students (100 students from each school level) responded to our written assessments. These students are from urban and rural schools located in Southeast China. In the US, 24 students (8 students from each school level) participated in the pre-interviews and post-interviews, 527 students participated in the pre-tests (91 elementary school students, 214 middle school students, and 222 high school students), and 543 students participated in the post-tests (125 elementary students, 211 middle school students, and 207 high school students). These students are from suburban and rural schools in a Midwest state. Since this chapter focuses on assessment development, we note only that the intervention added useful variability to our US sample.
- *Interpretation:* We developed approaches to coding students' accounts that revealed what we saw as significant patterns associated with differences in students' proficiency and culture.
- *Model of cognition:* We revised the learning progression framework in light of what we had learned.

During this research cycle, two assessment challenges became increasingly crucial. The first is a challenge for the observation phase: Our participants came from a wide range of ages (from fourth to 11th grade) and from US and Chinese cultures. Assessment questions that make sense to one age and cultural group may be understood quite differently—or not understood at all—by students from other age and cultural groups. How do we develop assessments that are effective in eliciting accounts from all students that best represent their ways of reasoning? In particular, how can we ask elementary students about the processes represented in the Loop Diagram when the key scientific elements of the model—matter, energy, and scale—are invisible to them?

The second challenge comes at the interpretation and model of cognition phases: Students' accounts differ in many ways, but which differences are really important? How can we define levels of achievement and progress variables that provide valid and parsimonious descriptions of students' understanding of carbon-transforming processes at different ages and in different cultures?

In the next two sections we discuss these assessment challenges in greater depth and describe how we responded to them during the 2008-9 research cycle.

Responding to the Assessment Challenge at the Observation Phase

In this section we first elaborate on the nature of the challenge that we faced. We then describe our response to the challenge, as well as continuing issues that we will need to deal with in the future.

The Challenge: Eliciting Accounts from All Students

In our earlier research cycles, we used questions focusing on matter and energy at multiple scales to elicit students' accounts. We found that although some middle and high school students were able to understand questions that asked about matter and energy at different scales, younger students were often confused by the questions and therefore provided irrelevant or "I don't know" type responses. Below is an example. Our intent was to find out how well students understood the roles of matter transformation (especially carbon dioxide and water to glucose and oxygen) and energy transformation (from sunlight to chemical potential energy) in plant growth.

> *Episode 1. Corn plants growing in sunlight*
>
> (An interview with a US seventh grader in our previous studies)
>
> Interviewer: What are the materials you identified in this event [corn plants growing in sunlight]?
>
> May: Water, soil, and sunlight.
>
> Interviewer: How do they change?
>
> May: They change by they… give their sources to the corns for them to grow, the water, soil, and sunlight. They give the corn water, and soil, and … that help the corn plants grow.
>
> Interviewer: Does this event change the air?
>
> May: I think it does change the air, because if there are more plants growing. It gives the air more… It refreshes the air. It makes the air smells like corn. And rain also refreshes the air. It washes everything away.
>
> Interviewer: What are the things in the air that do not change?
>
> May: The thing in the air that do not change is… (Silence) You mean with the corn plants grow or just in general?
>
> Interviewer: When the corn plants are growing, what does not change in the air?
>
> May: Oh. It does not change the color. It does not change the air by making it change color.

In the exchange above, the interviewer recognized that the student's account did not mention carbon dioxide or oxygen, so in keeping with the interview protocol he asked probing questions about the role of air: "Does this event change the air?" "What are the things in the air that do not change?" "When the corn plants are growing what does not change in the air?" However, the student did not recognize that air is required for the plant to grow. When asked to explain changes in air, the student's responses focused on changes in the quality of the air (refresh the air) and observable properties of the air such as color and smell. She may not share the interviewer's assumptions that air is a mix of gases and that the matter of air changes because the tree uses it. Rather than enabling the student to elaborate on her own ideas about how and why corn plants grow, the interview protocol diverted both interviewer and student to a "dead end"—a series of questions about air that the student did not connect with the initial question about how plants grow.

Although we learned a lot about students' reasoning from our interviews and written assessments, our data also showed us that questions designed to elicit students' ideas about scale, matter, and energy did not effectively elicit force-dynamic accounts from younger students. Thus the assessment challenge we faced was how to collect data on younger students' understanding that we could connect to our upper anchor—the Loop Diagram. In particular, what questions can elicit younger students' accounts that contain evidence of their informal reasoning? How can we construct interview protocols and written assessments that are effective in eliciting accounts from all students?

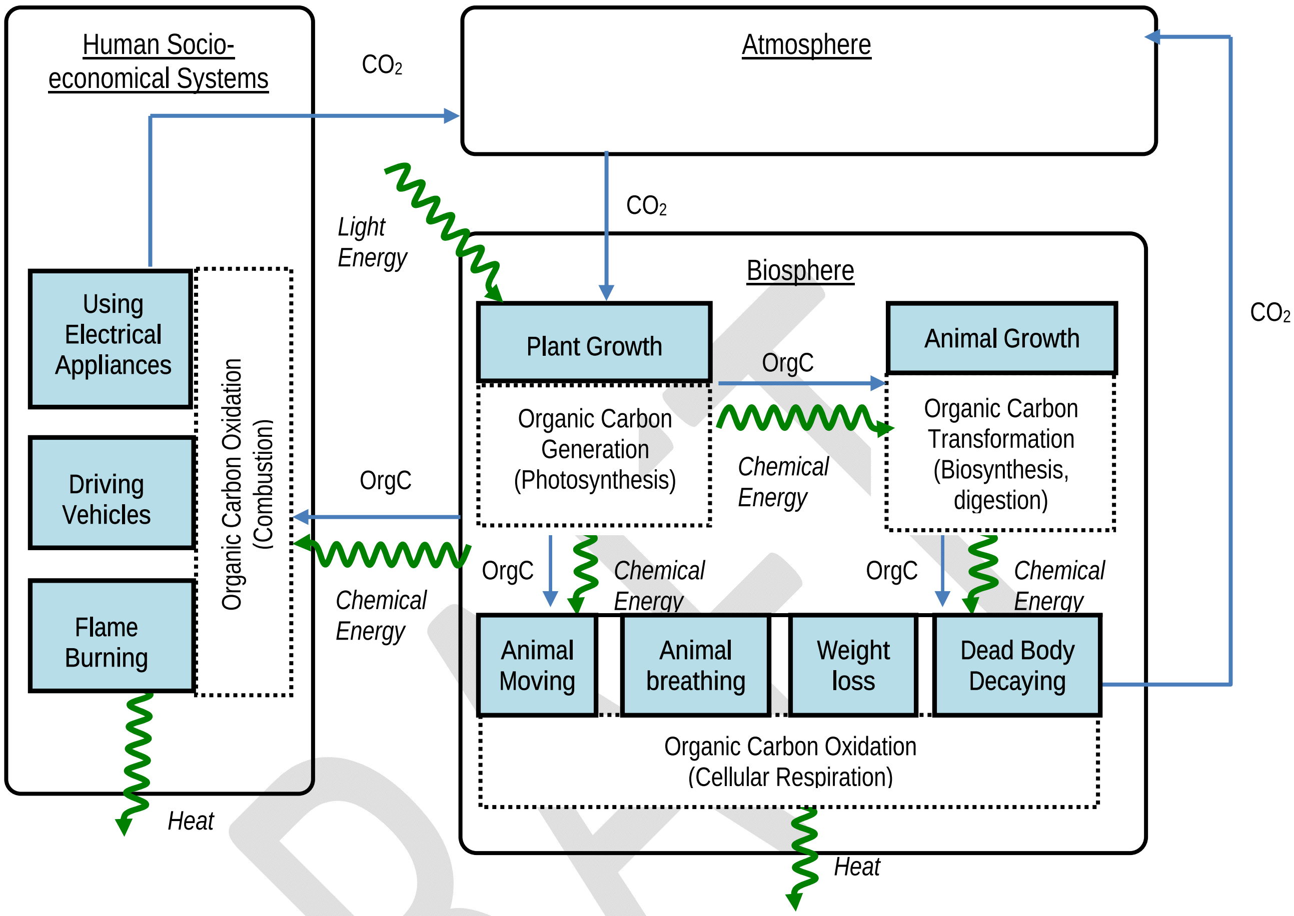
Responding to the Challenge: Linking Processes and Alternate Forms of Questions

We responded to this assessment challenge in two ways. First, we organized our interviews and tests around *linking processes* that were familiar to students of all ages. Second, we developed *alternate forms of questions* for students from different age groups.

Linking processes

We could not organize our interviews and written assessments around the atomic-molecular and global carbon-transforming processes in the Loop Diagram (Figure 2), since they are invisible to many students, especially younger students. Therefore, our first step in the revision process was to organize the assessments around macroscopic processes that are familiar to all students. Figure 3 shows our revised version of the Loop Diagram. It shows the same relationships among organic carbon generation, transformation, and oxidation as Figure 2, but it is organized around familiar macroscopic processes.

Figure 3 Linking Processes in the Loop Diagram



In Figure 3, processes at three scales—atomic-molecular, macro, and global—are linked together. The atomic-molecular processes in the dashed boxes—photosynthesis, digestion & biosynthesis, cellular respiration, and combustion—explain the macro-processes in the grey boxes—plant growth, animal growth, weight loss, using electrical appliances, driving vehicles, flame burning, etc. These processes are connected by matter transformation (straight arrows) and energy transformation (wavy arrows): in photosynthesis, organic carbon-containing substances are generated from carbon dioxide and water, and light energy transforms into chemical potential energy; organic carbon-containing substances transform, and chemical potential energy is passed on in biosynthesis and digestion; organic carbon-containing substances are oxidized into carbon dioxide and water, and chemical potential energy is released in cellular respiration and combustion. These atomic-molecular processes are embedded in two global scale processes: 1) carbon (matter) cycle—carbon moves from atmosphere to biosphere and human socio-economical systems, and then moves back to atmosphere—and 2) energy flow—energy moves from light to biosphere and then human socio-economic systems with heat dissipation.

Students across grade levels have rich experience with the macro-processes. Students may not understand photosynthesis, but they do know that plants grow and have special needs such as sunlight, water, and air. They may not understand combustion of fossil fuels as a chemical process, but they do have experience observing their parents refill cars with gasoline and burn propane for barbecues. They may not understand cellular respiration, but they are likely to have experienced that running causes sweating and fatigue. Hence, we organized both interviews and written assessments at all levels around the same set of macro-processes that are familiar to all the students in our research. By focusing on these *linking processes*, we were able to design assessments that elicited more detailed accounts from all students while enabling us to compare and contrast accounts at all levels of achievement.

Alternate forms of questions

While students from different age groups have rich experience with the macro-processes, their knowledge of processes at the atomic-molecular and global scales varies. Younger students learn very little about the atomic-molecular and global processes in school, but we do expect that middle and high school students have some knowledge of these processes. To ensure that the assessments are effective in eliciting accounts from all students, we designed alternate forms of questions for students at different school levels. In particular, we developed branching-structured interviews and designed item pairs for the written assessments.

Branching-structured interviews. Our revised interview protocols have segments for each of the macro-processes in Figure 3. For each macro-process, we start with a set of *general questions*—questions that use everyday language to ask about familiar phenomena. These general questions can be understood by younger students yet allow more advanced students to provide brief accounts about scale, matter, and energy. If students' responses to the general questions indicate some ideas about scale, matter, and energy, we ask follow-up questions that are designed to elicit more detailed higher-level accounts.

As elaborated earlier, lower-level students' accounts are constructed around force-dynamic reasoning, which contains three elements—actors, enablers, and results. Scientific accounts share this general framework, but treat actors and enablers as matter and energy and explain the events in terms of matter transformation and energy transformation at multiple scales. Hence, we constructed our general questions around this shared framework to elicit students' ideas that may include elements of both scientific and force-dynamic reasoning. Take tree growth as an example. The major general questions are:

- What does the tree need in order to grow?
- You said that the tree needs sunlight/water/air/soil to grow. Then how does sunlight/water/air/soil help the tree to grow?
- Where does the sunlight/water/air/soil go when it is used by the tree?
- Do you think that sunlight/water/air/soil will change into other things inside the tree's body? Why?
- The tree gets heavier as it grows. How does that happen?

Students can interpret these questions either as questions about transformations of matter and energy or as questions about an actor (the tree) and its enablers. Thus these questions allow students to provide both force-dynamic and scale-matter-energy accounts. If the students' responses to the general questions indicate more sophisticated understanding, we ask a set of higher-level questions to elicit more detailed accounts about matter, energy, and scale. Some examples of higher-level questions about tree growth are:

- Do you think the tree's body structure is made from things outside of the tree? If yes, what are those things? How do these things change into the tree's body structure?
- If the student mentions glucose/starch/cellulous/carbohydrates, ask: Do you think the molecules you mentioned contain carbon atoms? If yes, where do the carbon atoms come from? Where are the molecules in the tree's body?
- You said that the sunlight provides energy for the tree to grow. Where does that energy go when it is used by the tree? Do you think it is used up or becomes other things?
- If the student talks about CO_2—O_2 exchange, ask: You said that the tree needs carbon dioxide and breathes out oxygen. Where do the carbon atoms of CO_2 go?

These questions investigate how students link the macro-process to atomic-molecular and global processes. We use two examples to show how the branching-structured interview elicits both lower-level and higher-level accounts. Episode 2 is from an interview with a US fourth grader.

Episode2. Tree Growth: general questions and responses

(Pre-interview with a US fourth grader)

Interviewer: What does the tree need in order to grow?

Steve: Sun, water, soil, and that's it I think.

Interviewer: You said that a tree needs sunlight, water, do you think that these things help the tree to grow in the same way, in other words are they alike or different?

Steve: The water helps it grow bigger and the sunlight, it needs light just like us to grow, and the soil, that's where it originally lived.

Interviewer: What happens to the sunlight inside of the tree?

Steve: (silence)

Interviewer: How about water? What happens to the water inside the tree?

Steve: It sucks into the roots and then it goes up, so it can make the leaves and the branches grow.

The first several questions ask about the changes happening to the water/sunlight/soil inside the tree. The accounts Steve provides in response to these questions are basically force-dynamic in nature. For example, his explanation for how water helps the tree grow is: "It sucks into the roots and then it goes up, so it can make the leaves and the branches grow." In other words, as long as the water goes into the tree's body, it makes the leaves and branches grow. This explanation indicates that Steve does not recognize the change of matter—water changing into part of the tree's body structure in photosynthesis. Instead, he relies on force-dynamic reasoning and treats water as an enabler that allows the tree to achieve its destined result—growth in this case—through an unspecified mechanism. As is typical of force-dynamic accounts, Steve's accounts are vague about internal mechanisms; although he is sure that the tree needs sunlight, he doesn't know what the tree does with this enabler. The evidence above shows that Steve relies on macroscopic force-dynamic reasoning to explain the event of tree growth. His explanation of tree growth is about how the actor—the tree—uses enablers such as water, sunlight, and soil to accomplish its purpose—to grow.

The branching-structured interview is also effective for eliciting higher-level accounts. Episode 3 is from an interview with a US eighth grader, Sue.

Episode 3. Tree Growth: general questions and responses

(Pre-interview with a US eighth grader)

Interviewer: What does the tree need in order to grow?

Sue: Nutrients, water, sunlight, things to make it do photosynthesis.

Interviewer: So what do you mean by photosynthesis?

Sue: Like reproduce and get food and be able to produce carbon back or carbon or I mean oxygen. Sorry.

Interviewer: So you said the tree needs sunlight. So, how does the sunlight help the tree to grow?

Sue: The sunlight like gives it energy and things like nutrients and make it, so it grows.

Sue's responses to the general questions contain important elements of scientific accounts focusing on scale, matter, and energy, as she talked about the process of photosynthesis and related that to carbon However, her responses to these general questions do not provide enough information about her understanding of the atomic-molecular processes or matter and energy transformations. Episode 4 shows how the interviewer used higher-level questions to elicit Sue's understanding of matter.

Episode 4. Tree Growth: follow-up questions about matter and responses

(Pre-interview with a US eighth grader)

Sue: The carbon dioxide like makes it breathe. Like how we breathe in but they produce oxygen from the carbon dioxide.

Interviewer: How can carbon dioxide change into oxygen?

Sue: By the different like it's – it goes through like the system of like the tree or through the system of like a body.

Interviewer: So, if you compare carbon dioxide and oxygen, carbon dioxide has a carbon atom in it, right? Oxygen does not have that. So, how can't it have it?

> Sue: Because like the things in carbon dioxide, it gets like – like during the process, it gets used as energy or used as different things to make the tree grow and to make it produce oxygen.
>
> Interviewer: You mean the carbon atom of the carbon dioxide becomes the energy? Is that what you mean?
>
> Sue: Yes. And carbon gets used for other things like carbon can go back into a different cycle like air. And then back into another cycle.

The interviewer's probes focus on a key difference between Level 3 and Level 4 accounts: Does Sue conserve matter by recognizing that chemical changes like photosynthesis cannot create or destroy carbon atoms (Level 4), or does she have less scientific understanding about how materials can change into other materials, or perhaps into energy (Level 3)? Sue's responses indicate that she could not account for the processes at an atomic-molecular scale. She suggests that the carbon in carbon dioxide "gets used as energy," and confirms this idea in response to a probe from the interviewer. Although Sue attempted to use scale, matter, and energy to construct explanations of tree growth, the interview shows that she was reasoning at an intermediate level (Level 3) rather than the scientific Upper Anchor.

Compared with the initial interview protocol, this branching-structured interview protocol is more successful in eliciting accounts from students with diverse science backgrounds. The general questions allow younger students to provide their informal accounts about macro-processes and also provide more advanced students the opportunity to address scale, matter, and energy. By asking the general questions, the interviewer is able to find indicators of higher-level understanding and to decide whether it is necessary to ask follow-up higher-level questions to elicit more detailed accounts.

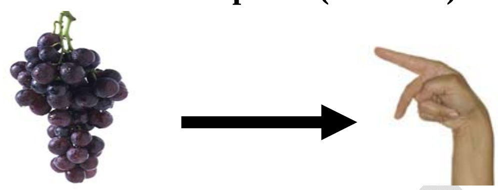
Item pairs in written assessments. During the earlier research cycles, we developed a set of open-ended items. These items have been continuously revised and refined with feedback from analysis of student responses. We have found it almost impossible, though, to design items that elicit good responses from both Level 1 and Level 4 students. Items worded to demand specific details about matter and energy transformations elicit guesses or "I don't know" from lower-level students; vaguely worded items elicit correct answers from upper level students that lack the detail necessary to judge whether the responses are at Level 3 or Level 4.

Our solution to this challenge is to design item pairs. Each item pair contains two items, which are about the same event or similar events, but use different ways to ask questions in order to elicit both force-dynamic accounts and matter-energy-scale accounts. Some of these item pairs are open-ended items. Others are two-tier multiple-choice items, which require the student to choose, and then explain.

For example, Figure 4 shows the grape and finger movement item. It is an open-ended item asking how a glucose molecule changes to help body movement. In the earlier research cycles, we asked this question to both middle and high school students. This item proved effective in diagnosing whether and how students conserve matter and energy in cellular respiration. Below are the responses from a US ninth grader. The student attempted to conserve matter and energy;

however, instead of conserving matter and energy separately, he used matter-energy conversion to explain how glucose helps the finger to move (characteristic of Level 3).

Figure 4: Grape and Finger Movement Item with Example of a US Ninth Grade Student's Response (Post-test)



The grape you eat can help you move your little finger.

a. Please describe how one glucose molecule from the grape provides energy to move your little finger. Tell as much as you can about any biological and chemical processes involved in this event.

The glucose molecule is converted to chemical energy in your body. Then your body uses that energy to make ATP, which is then used for cellular work, which allows you to move.

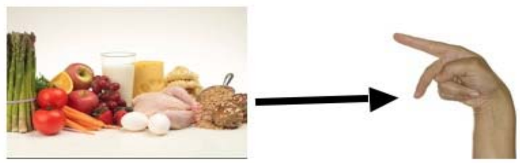
b. Do you think the SAME glucose molecule can also help you to maintain your body temperature, when it is used to provide energy to move your finger? Please explain your answer.

Yes, because in order to maintain your body temperature, your cells would need to work, and the cells get their working energy from ATP, which is converted by glucose.

Although the grape and finger movement item was effective in identifying and distinguishing between more sophisticated accounts, middle school students did not understand it. The major reason is that the two questions included in this item are posed at the atomic-molecular scale, which is usually invisible to younger students. When we used this item with middle school students, we received a lot of “I don’t know” type answers. Some students even doubted the meaningfulness of asking this kind of question. For example, a student replied: “Dude, I’m only 14 and I didn’t understand the ? [question].”

Hence, in the 2008-9 research cycle we developed a corresponding elementary/middle school item—food and finger movement (Figure 5). It was revised from the grape and finger movement item. Instead of asking about a specific food substance—glucose in the grape—the item asks about food in general. It uses informal language that can be understood by younger students.

Figure 5 Food and Finger Movement with an Example of a US Fourth Grader's Response (Pre-test)



How do you think the foods you eat can help you move your little finger?

I think the foods help move my finger because it gives off energy that help you move and communicate. When someone starts to starve, there [sic] body gets very tired and weak. This happens because there [sic] body is not getting the nutrients it needs from the food that you eat.

The student's response is constructed around the macroscopic actor (people), enablers (energy and/or nutrients of foods), and results (achievement of the goal of moving the finger). Thus, it indicates force-dynamic reasoning. Although the student used the word energy in her explanation, she did not distinguish between energy, nutrients, and foods in general.

We found that we could also use a complementary strategy to develop higher-level versions of items that initially were not specific enough for upper-level students. These items (such as the one in Figure 6) are open-ended questions that use everyday language and do not require students to link or constrain processes. We found that such questions are not effective in identifying and distinguishing between accounts at higher levels.

Figure 6 Light for Plants Item (Initial Version) with an Example of a US Ninth Grader's Responses (Pre-test)

Do you think plants need light to survive? Circle one: Yes No

If your answer is "yes", please explain why plants need light AND where the light energy goes after it is used by plants. If your answer is "no" please explain why plants can live without light.

Yes, because without light they can't perform photosynthesis and make food. With light energy they make food.

The high school student provided a correct explanation for why plants need light to survive. However, since the question did not require the student to explain how light energy is transformed in the process of photosynthesis, the student did not provide any details about that. As a result, the student's account does not provide enough information for us to tell whether she conserves energy in her account of photosynthesis. Her response could be either at Level 3—incorrect description of energy transformation—or Level 4—correct description of energy transformation.

In order to get more detailed accounts, we revised this item into a two-tier multiple-choice item pair. The first tier is a multiple-choice question while the second tier requires students to justify their choices. For the first tier, the options are characteristic accounts developed based on students' responses to the open-ended question that we had used previously. The elementary/middle school item contains foils that represent lower-level accounts, while foils in the high school item represent higher-level accounts about scale, matter, and energy. Our data indicate that these two-tier multiple-choice item pairs are more effective than the corresponding initial version in diagnosing and distinguishing between accounts at different levels. Figures 7 and 8 show how the revised versions of the "light for plants" item assess and distinguish between accounts at different levels.

Figure 7 Light for Plants Item (Elementary/Middle School Version) with an Example of a US Fourth Grader's Response (Pre-test)

Do you think plants need light to live? Please choose the best two answers from the list below.

a. Not all plants need light to live.
b. Light warms the plants.
c. Without light, plants will die in darkness.
d. Light helps plants to be healthy.
e. Light helps plants to make food.
f. Light helps plants breathe.

Please explain why you think these are the best two answers.

Choice: b. c.

Explanation: A plant needs light to live because when it is dark it's colder and they will get to [sic] cold and die.

The options of the first tier represent two levels of reasoning. Options a, b, c, d, and f are macroscopic force-dynamic accounts (Level 1). Choice a does not recognize that all plants need sunlight. Choices b, c, d, and f explain why plants need sunlight in terms of perceptions, including warmth, darkness, health, and breathing. These accounts do not mention any invisible processes. The student chose b and c. Both his choices and explanations indicate macroscopic force-dynamic reasoning. Option e is a more sophisticated account. It links the macro-process to the invisible process of "making food" and therefore indicates Level 2 reasoning. Although option e is more advanced than the other options, it does not address details about scale, matter, and energy. So, it is not effective in identifying the level of more sophisticated accounts. Therefore, a high school version of the item pair (Figure 8) was developed.

Figure 8 Light for Plants Item (High School Version) with an Example of a US Tenth Grader's Response (Post-test)

Sunlight helps plants to grow. Where does light energy go when it is used by plants? Please choose the ONE answer that you think is best.

a. The light energy is converted into glucose of the plants.
b. The light energy is converted into ATP in the plants.
c. The light energy is used up to power the process of photosynthesis.
d. The light energy becomes chemical bond energy.
e. The light energy does not go into the plants' body.

Please explain why you think that the answer you chose is better than the others (If you think some of the other answers are also partially right, please explain that, too.)

Choice: a.

Explanation: Because the plants take the light energy and convert into glucose. After that, glucose units combine to make starches that the plant can use to function. Starches are fatal [sic] for plant survival.

The item contains options describing how energy and matter change in the atomic-molecular process of photosynthesis. Options a and b use matter-energy conversion for reasoning. Option c treats light energy as the power that triggers the process of photosynthesis; this is correct, but the energy is not used up as this option suggests. Options a, b, and c represent the common misconceptions identified from previous research cycles. They are at Level 3. Option d is the scientific account that successfully traces energy in photosynthesis (Level 4). Option e does not recognize light energy as being related to any hidden process involved in tree growth. Students who chose this option reason at levels lower than Level 3–though this version of the item does not effectively distinguish between Level 1 and Level 2 accounts.

In the example response, both the student's choice and justification indicate an attempt to trace energy, but it is not clear that she distinguishes between chemical potential energy and matter that has chemical potential energy. Instead of conserving matter and energy separately, she explains the event in terms of matter-energy conversion—light energy is converted into molecules (glucose and starches). Therefore, her accounts are at Level 3.

We are not finished revising our interviews and written assessments, though. The general strategies of constructing branching interviews and item pairs are difficult to execute in practice, and they leave many aspects of students' accounts insufficiently explored, such as the basis for their beliefs and the connections that they make between accounts of different processes. We are continuing to learn and to revise our assessments, based on both the quality of students' responses and statistical indicators of item quality.

Responding to the Assessment Challenge at the Interpretation and Model of Cognition Phases

In this section, we describe the assessment challenge we encountered at the interpretation and model of cognition phases and our responses to that challenge. We also discuss the continuing issues that need to be addressed.

The Challenge: Describing and Comparing the Development of Students' Accounts in Meaningful Ways

Currently, most empirical studies of learning progressions are conducted within one country. In our research, we used a learning progression to compare students' understandings under different cultural and educational conditions. We believe that this investigation will enable us to better understand how culture impacts students' learning. In the 2008-9 research cycle, we involved students from two different countries (the US and China). These students use different languages for reasoning, have different science backgrounds, and are exposed to different educational approaches. Although the interview and written assessments effectively elicited accounts from both US and Chinese students, we encountered an assessment challenge as we were interpreting the data and revising the learning progression framework to include both US and Chinese students' accounts.

In our earlier research cycles, we constructed the learning progression framework around progress variables based upon scientific processes—organic carbon generation, organic carbon transformation, and organic carbon oxidation—and scientific elements—matter and energy (Table 1). Based on this framework, we developed detailed rubrics to code students' responses to written assessments. This process of coding led us to both conceptual and empirical difficulties.

Conceptually, the descriptions of Level 1 and 2 reasoning focused on what was <u>not</u> there (scientific concepts of matter and energy) rather than what <u>was</u> there (force-dynamic accounts of actors, enablers, and results). In other words, the progress variables—matter and energy—do not capture students' ways of informal reasoning at the lower levels. They are not valid progress variables that enable us to identify and describe younger students' characteristic ways of reasoning.

There were also empirical questions about the usefulness of coding matter and energy separately. The US written assessment data show that the correlation between students' achievement on the matter and energy progress variables was .96, indicating that our separate codes for matter and energy were largely redundant (Choi, Lee, & Draney, 2009; Mohan, Chen, Baek, Choi, & Lee, 2009). In other words, the matter and energy columns of Table 1 do not really describe separate progress variables.

At the same time, our US-China written assessments showed that rubrics based on the coding levels seemed to work better for US students than for Chinese students. For example, step thresholds—the level of proficiency at which a student has a 50% chance of being coded at one level in the learning progression vs. the level above—were generally consistent across items for US students. This was much less true for Chinese students. Many Chinese students received higher-level codes—Levels 3 and 4—on some items, but not on others. Thus the factors that made a response easy or difficult for Chinese students were different from those we recognized in the coding of learning-progression based levels in US responses.

There were no strong correlations between item difficulty and specific processes or the matter and energy progress variables (Chen, Anderson, & Jin, 2009). That is, the Chinese students did not consistently do better or worse than US students on matter items or energy items, or photosynthesis items or combustion items. The pattern of different difficulties seemed to be associated with characteristic(s) of the items that were not included in our 2008 progress variables.

Our US-China interview study (Jin, Zhan, & Anderson, 2009) suggested a possible explanation for the problems we encountered when analyzing the Chinese written data. In the interview study, we found that although some Chinese students were able to name scientific terms when explaining the events, they relied on relatively lower-level reasoning in their accounts, as illustrated in Episode 5. This type of performance was apparent only in the Chinese interviews.

Episode 5. Tree Growth

(Interview with a Chinese seventh grader)

Interviewer: You said that the tree inhales carbon dioxide and produces oxygen. Could you explain how carbon dioxide changes into oxygen?

Peng: Water.

Interviewer: How can water help the carbon dioxide to change into oxygen?

Peng: Chemical reaction.

Interviewer: Could you explain what this chemical reaction is?

Peng: Probably water plus carbon dioxide and become $C_6H_{12}O_6$. I don't know.

Interviewer: You mean sugar?

Peng: I don't know. How can the tree have sugar?

Interviewer: Do you think the tree contains sugar?

Peng: I don't think so.

Interviewer: Let's see this picture. The tree grew from a small plant into a big tree. Its mass increased a lot. Do you agree?

Peng: Yes.

Interviewer: So, where did the increased mass come from?

Peng: Water.

Interviewer: Is there anything else?

Peng: And nutrients from soil.

In Peng's first three responses, she appears to provide a sophisticated (Level 4) chemical explanation that traces matter through photosynthesis, but then in the remainder of her responses, she reverts to what seems to be a much less sophisticated (Level 2) explanation. How can we capture this kind of performance in our interpretations of students' accounts?

One hypothesis is that the scientific words the students used might influence the coders' decisions. In our previous study (Chen et al. 2009), Chinese students were rated at higher levels for some items, because these items were designed in ways that cued students to use scientific vocabulary. However, our 2008 framework, and codes based on that framework, did not make a distinction between scientific vocabulary and other aspects of students' accounts. As a result, many Chinese responses were rated at higher levels not because the students were able to reason at higher levels, but because they were able to recite scientific words. This led us to think about alternative progress variables that might be more effective in understanding and comparing US and Chinese students' accounts.

Responding to the Challenge: Explaining and Naming as Progress Variables

Rather than treating the highly correlated *scientific* elements of accounts—matter and energy—as progress variables, we began to explore progress variables focused on *performance* elements of accounts, which we labeled *explaining and naming.*

The explaining progress variable is about the nature of the accounts—the specific reasoning that students use to explain why and how the macro-processes happen. The explanations are always constructed around different types of causal reasoning. As elaborated above, younger students tend to rely on force-dynamic reasoning that explains the macro-processes in terms of actor, enabler, and result. More advanced students begin to pay attention to scale, matter, and energy and explain macro-processes in terms of changes of matter and energy in invisible processes. Thus we combined the separate matter and energy progress variables into a single explaining progress variable. At higher levels, it includes students' ideas about both matter and energy.

We used the 2008-9 interview data to construct a new progress variable that we called naming. This progress variable focuses specifically on the vocabulary students use— from words that describe actors and enablers in informal terms to more formal scientific names for substances, forms of energy, and carbon-transforming processes. The revised version of the learning progression framework using explaining and naming progress variables is represented in Table 2.

Table 2. Revised Learning progression

Explaining Progress Variable		Naming Progress Variable	
Level 4. Linking processes with matter and energy as constraints	Explain macro-processes by reasoning across scales: link carbon-transforming processes at atomic-molecular, macroscopic, and global scales with matter and energy as constraints	Level 4. Scientific statements	MATTER: scientifically appropriate names for both reactants and products; both gases and solids/liquids named as material reactants or products ENERGY: all forms of energy involved in the chemical change; heat as byproduct
Level 3. Changes of Molecules and Energy Forms with Unsuccessful Constraints	Explain macro-processes in terms of change of molecules and/or energy forms at atomic-molecular or global scale, but do not successfully conserve matter/energy	Level 3. Scientific words of organic molecules, energy forms, and chemical change	MATTER (organic molecules): glucose, $C_6H_{12}O_6$, monosaccharide, glycogen, lipid, ATP, ADP, carbohydrate, hydrocarbon, octane ENERGY (bonds, energy forms): C-C bond, C-H bond, light energy, *kinetic energy (US version)*, electrical energy, chemical energy, heat energy PROCESS (chemical reaction): *cellular respiration (US version), combustion (US version),* oxidation, light reaction, dark reaction
		Level 2.5. Easier scientific words with mixed meanings	MATTER: Fat, sugar, starch, organic matter, carbon, molecule, atom ENERGY: stored energy, motion energy, /动能 PROCESS: photosynthesis, decomposition/decomposer, chemical reaction/change, *燃烧 (Combustion/Burning in Chinese version), 呼吸作用 (Respiration/Breathing in Chinese version)* OTHERS: chloroplast
Level 2. Force-dynamic accounts with hidden mechanisms	Explain macro-processes in terms of unobservable mechanisms or hidden actors (e.g., decomposer), but the focus is on enablers, actors, and results rather than changes involving matter or energy.	Level 2. Hidden mechanism words	MATTER: carbon dioxide, oxygen, nutrients, gas (as in gas, liquid, and solid), ENERGY: calories, electricity PROCESS: digestion digest, digestive system, break down OHTERS: decomposer (e.g., bacteria, fungi, micro organisms), cell, power plants
Level 1. Macroscopic force-dynamic accounts	Explain macro-processes in terms of the action-result chain: the actor uses enablers to accomplish its goals; the interactions between the actor and its enablers are like macroscopic physical pushes-and-pulls that do not involve any change of matter/energy	Level 1.5. Easier hidden mechanism words	ACTOR: organs (e.g., lung, stomach, heart, etc.), machine parts (e.g., engine, cylinder, piston), material ENABLER: fuels (e.g., gasoline, diesel, oil, coal, petroleum), heat
		Level 1. Words about actors, enablers, and results	ACTOR: body parts (e.g., leaves, roots, leg, etc.) ENABLER: water, air, sunlight, food (e.g., food, milk, bread, etc.), bugs, wind, lighter, etc. RESULT: strong, healthy, grow, run, warm, etc.

The levels of the explaining progress variable are quite similar to the learning progression levels described above. They trace a line of development from force-dynamic to scientific reasoning as students learn to trace matter and energy through processes at multiple scales.The naming progress variable describes students' use of specific words and/or phrases in their accounts. Logically, accounts at different explaining levels are built upon different sets of words. For example, accounts at explaining level 1 are constructed using words about actors, enablers, and results, while accounts at explaining level 3 are built upon words about molecules and energy forms. Based on this idea, we first developed four groups of words that are aligned with the four explaining levels. However, some words may be more familiar to students than other words in the same group, simply because they are used as common words in everyday life. Hence, we added two adjusted levels—level 1.5 (easier hidden mechanism words) and level 2.5 (easier scientific words). Due to cultural differences, the US and Chinese versions of the naming levels are slightly different. One example relates to the word, "combustion". In English, "combustion" is the scientific term used to refer to the chemical change. In everyday life, people use "burning" to refer to the same process. In Chinese, there is only one word "燃烧", which is used in both everyday life and science. Hence, we put combustion at level 3 in the US version and put 燃烧 at level 2.5 in the Chinese version.

Although the naming and explaining levels are aligned in a logical way, students may construct accounts that indicate different naming and explaining levels. We found that some students were able to recite higher-level words, but relied on lower-level reasoning to make accounts; there are also students who adopted higher-level reasoning to make accounts, but lacked the necessary words to explain the specific processes.

Using the revised learning progression, we could identify Episode 5 as an example in which the student's naming level is ahead of her explaining level: Peng stated that carbon dioxide changed into oxygen through a chemical reaction in which water plus carbon dioxide become $C_6H_{12}O_6$. She named both reactants—carbon dioxide and water—and products—oxygen and $C_6H_{12}O_6$—of photosynthesis. Hence this account is at naming level 4. However, Peng's responses to the follow-up questions indicate that she used the scientific words without giving them scientific meanings. Although she was able to describe the chemical reaction of photosynthesis correctly, she still claimed that the increased mass of the tree came from water and nutrients from soil, indicating that she did not connect photosynthesis with tree growth. Peng's accounts indicate force-dynamic reasoning with hidden mechanisms—water and nutrients from soil somehow change into the tree's body structure, and the carbon dioxide the tree breathes in somehow becomes oxygen. Hence, this account is at explaining level 2.

As shown in Episode 6, there were also a few students who were able to use more sophisticated reasoning to explain the macro-processes, but lacked necessary knowledge about the specific contexts such as terms of specific molecules, processes and so on.

Episode 6. Flame Burning

(Post-interview with a US eighth grader)

Interviewer: Can you tell me about what is happening inside the [candle] flame as it burns?

Eric: Not specifically, all I know is that it is a chemical reaction and change and that's about all I know for sure, is to what's happening inside the flame itself.

Interviewer: Does this process require energy, the process of burning?

Eric: Yes it does, because it needs energy to perform the chemical changes and it takes the energy that is in the wick and uses that for energy a, to help take more energy out, and b, to send energy out in the form of heat and light.

Interviewer: The melting candle loses weight as they burn, how does this happen?

Eric: The wax of the candle will melt and then often it will pour over the side and spread onto the table or whatever its sitting on, or else it will slowly evaporate into the air.

Interviewer: You said it slowly evaporates into the air, what form is that?

Eric: I guess it would be wax vapor or something like that, and it basically the molecules of the wax spread apart and far enough from the heat, that because of the heat they become a gas and float into the air.

Interviewer: Are there chemical changes that are happening that the wax to what floats in the air, what is that that floats in the air from the wax?

Eric: It would be whatever chemicals the wax is made of, I am not sure what it is, the molecules of those chemicals will be transferred to the air.

Interviewer: You said that this process requires energy, what are the energy sources?

Eric: The energy source would be directly the wick, which got it from whatever the wick was made of, and it uses that stored energy for the energy of burning.

Interviewer: Do you think energy is released from this burning?

Eric: Yes.

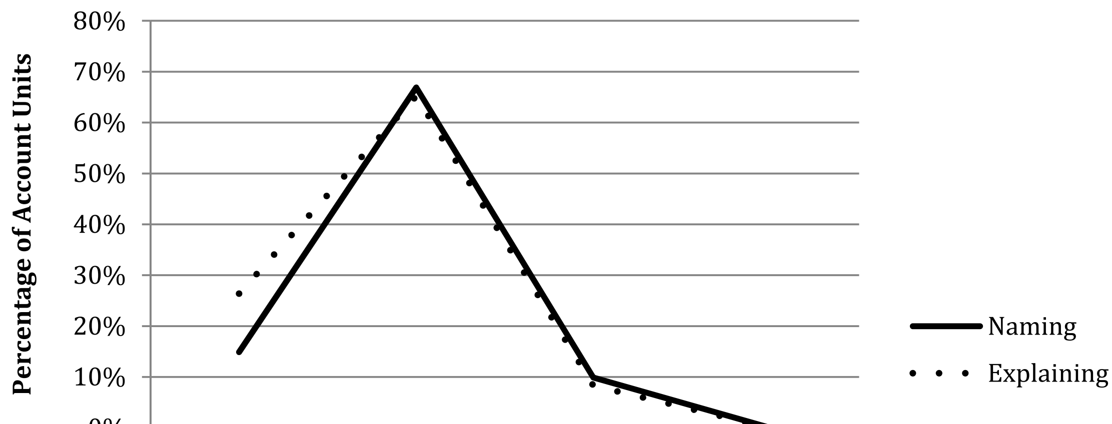
Interviewer: How is it released?

Eric: I am not sure, I believe it is just… the energy of it is changed from the stored energy into light energy or heat energy.

Eric identified a chemical reaction, although he was not sure what exactly the chemical reaction was: "Not specifically, all I know is that it is a chemical reaction and change and that's about all I know for sure, is to what's happening inside the flame itself." He made the common mistake of thinking that the wick, rather than the wax, was burning. Given this assumption, though, he was still able to construct an account that conserved both matter (the wax evaporates, but is still present in the air) and energy (the stored energy of the wick is converted to heat and light). The explaining level of Eric's account is 4, because he conserves matter and energy separately. The naming level is relatively lower, 2.5, because the most sophisticated terms in Eric's accounts are three level 2.5 terms—stored energy, chemical reaction, and molecule. Eric did not mention any specific molecules, nor did he name the chemical reaction as combustion.

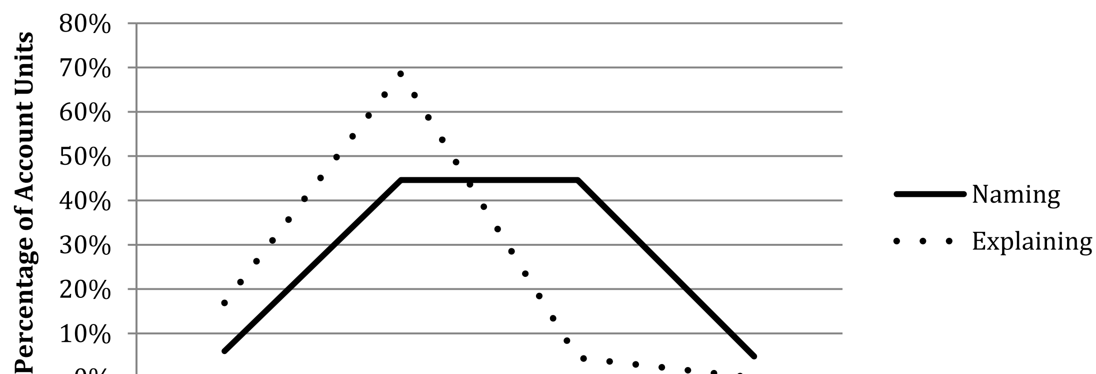
After we developed the final learning progression framework, we used it as guide to code students' interview responses. Our interview questions are structured around eight macro-processes. We developed naming-explaining coding rubrics for each macro-process based on the learning progression framework (Table 3). Student interviews were divided into eight account units (one for each macro-process), which were analyzed using the rubrics. We generated graphs that show the distribution of students' account units along the naming progress variable and the explaining progress variable. Figures 9 and 10 show the distribution of account units at different levels for US interviews and Chinese interviews[3].

Figure 9 Distribution Graphs for American Pre-Interviews
(16 Middle and High School Students)



	Level 1	Level 2	Level 3	Level 4
Naming	14.90%	66.90%	9.90%	0
Explaining	26.40%	65.20%	8.30%	0

Figure 10 Distribution Graphs for Chinese Interviews
(16 Middle and High School Students)



	Level 1	Level 2	Level 3	Level 4
Naming	6%	44.60%	44.60%	4.80%
Explaining	16.90%	68.70%	4.50%	0

[3] In our final coding results, account units coded as Naming level 1.5 were figured into the category of Naming Level 1 and account units coded as Naming Level 2.5 were figured into the category of Naming Level 2.

The naming-explaining distribution graphs indicate that both groups show higher levels for naming than for explaining, but the difference is much greater for the Chinese students. This indicates that although Chinese students used scientific terms, they sometimes did not understand the scientific meanings of these words and still relied on lower-level reasoning to make accounts. The naming and explaining performances show two different patterns of achievement for US students and Chinese students. This helps to explain why the coding rubrics we developed based on US student performances were less effective with Chinese data. Chinese students were sometimes coded at higher levels of achievement in previous studies, not because they reasoned at higher levels, but because they used vocabulary words that were reliably associated with high-level reasoning in US students.

Our analyses and revisions are still continuing. Although we have implemented both interviews and written assessments with students, we have not conducted systemic studies of the relationship between the interview data and written assessment data. In addition, the explaining progress variable describes students' performances in a very general way. We need to think about whether and how to make the progress variable specify more about the science content that we are interested in—carbon-transforming processes.

Conclusion

In this chapter we have described one research cycle using an iterative process that involves three phases: observation, interpretation, and cognitive model or learning progression framework (Figure 1). To develop a learning progression framework that captures major reasoning patterns of students and to better understand the nature of their learning, we involved participants from a wide age range and two countries. The diversity of participants has enabled us to collect rich data, but it also brought special assessment challenges. Our responses to the challenges are grounded in our data and in cognitive and linguistic theories about how students understand the world. To effectively elicit accounts from all students, we re-designed the interview protocol and written assessment items at the observation phase. At the interpretation and model building phases, our work focused on identifying progress variables – naming and explaining - that accurately describe students' learning performances and capture important differences between US accounts and Chinese accounts.

Our research is ongoing. As we continue with cycles of observation, interpretation, and model building, we continue to encounter assessment challenges. We close this chapter by noting five challenges that we are working on now.

1. Designing interview protocols. Our interviewers are often relatively inexperienced—teachers and graduate students—and may not be native speakers of English. Thus we need to develop protocols and training methods that both provide specific questions for interviewers to ask and support "on the spot" decisions about follow-up questions to further explore students' thinking. This is especially challenging when students give unexpected answers. Our interview data indicate that interviewers sometimes failed to probe incomplete responses, skipped questions incorrectly, or gave inappropriate clues to students.

2. Investigating students' accounts of large-scale systems. Our decision to focus on macroscopic linking processes means that we have not investigated students' understanding of large-scale systems. There are two important aspects of understanding large-scale systems: classification of macro-processes and connections among the macro-processes. In scientific accounts, the macro-processes are classified and connected in terms of matter transformation and energy transformation. However, students may use informal ways to classify and connect the macro-process, which often indicate their specific ways of reasoning. We developed some interview questions and written assessment items about classification and connections to explore these informal ways of reasoning, but most of the questions were not effective enough in eliciting students' ideas. Time is also a concern. In most of these interviews, the interviewers spent most of their time exploring students' ideas about the macro-processes and did not have enough time to ask about the classification of and connections between macro-processes.

3. Investigating students' arguments. Both interview and written assessment fail to explore students' reasons for their beliefs or how they would defend them. We did not investigate students' argumentation skills, although argumentation is an important component of environmental literacy. We are interested in exploring how students use data to defend their claims about each of the linking processes.

4. Cross-analysis of interview and assessment data. Although we implemented both interviews and written assessments with students, we have not conducted systemic analyses between the interview data and written assessment data. Clinical interviews enabled us to identify important patterns in students' informal ways of reasoning. However, due to the small sample size, findings based on interview data cannot be used for statistical generalizations. Compared with interviews, written assessment items are less effective in eliciting detailed accounts. This is especially true for younger students, whose responses can be very short and vague due to students' limited writing abilities. Therefore, we need to use interviews to validate our interpretations of the relatively brief and incomplete accounts that students give on written assessments. We used naming and explaining as progress variables to analyze interview data, but students' written responses usually only contain evidence of one progress variable, but not both. In such situations, how do we conduct the cross-analyses? One possible solution is to use item clusters. An item cluster contains items that ask different questions about the same macro-process. We expect that data from a cluster of items rather than one item would provide evidence of both naming and explaining.

5. Investigating the development of students' ideas about matter and energy. By focusing on general causal reasoning patterns, the explaining progress variable enabled us to avoid dealing with inconsistency between the two lower levels that are about force-dynamic reasoning and the two higher levels that are focused on matter and energy. Although younger students do not use matter and energy to account for the macro-processes, they develop intuitive ideas based on their everyday experiences, and some of those ideas are powerful precursors of matter and energy. Therefore, we need to identify progress variables that capture the common facets of both scientific performances of matter and energy and students' lower-level performances that are related to matter, energy, or their precursors. Such progress variables are both science-based and performance-based.

These are the challenges we are working on in our current research cycle. We look forward to tackling these, as well as additional challenges that will arise as we continue to develop a learning progression on carbon-transforming processes.

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