Developing a Long-term Learning Progression for Energy in Socio-Ecological Systems[1]

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Abstract

In this research, we report our work on developing a learning progression for energy in socio-ecological systems. We used both written assessments and interviews to elicit students' accounts about key macroscopic carbon-transforming processes: plant growth, animal growth, body movement, dead organism decaying, using electric appliances, driving vehicles, and burning fossil fuels. We conducted both written assessments and interviews with students from upper elementary to high schools. The research product is a learning progression framework with three progress variables. *Naming* progress variable refers to the performance of verbatim reproduction of vocabulary—the words students use to construct their accounts. *Explaining* progress variables describe the reasoning patterns implied in students' accounts. There are two Explaining progress variables—Association and Tracing. There are four levels of achievement of the Explaining (Association and Tracing) progress variables: Level 1. associates natural ability with elements of events and traces the action-result chain; Level 2. associates vital power with enablers and traces the power-result chain; Level 3. associates energy with energy enablers but traces energy unsuccessfully; Level 4. associates energy with energy indicators and traces energy successfully. We found that less than 10% written responses reach Level 4, indicating that most K-12 students are not able to use energy as a conceptual tool to successfully explain carbon-transforming processes.

Key Words: learning progressions; carbon-transforming processes; student reasoning

Introduction

Energy is a fundamental concept that spans the major science disciplines of physics, chemistry, and biology. In this research we intended to develop a learning progression for energy in socio-ecological systems. A learning progression is a sequence of successively more sophisticated ways of reasoning about a set of topics as students expand their experience in and out of school over time (National Research Council, 2007). We focused on K-12 students' understanding of energy as it relates to carbon-transforming processes. Carbon-transforming processes are important for students to understand, because they help students to understand how their everyday energy consumption activities are contributing to global warming. Global warming is the collective effect of a variety of socio-ecological events, including natural biological events (e.g., plant growth, animal growth, animal body movement) and human energy consumption activities (e.g., burning fossil fuels, driving cars, and using electric appliances). These events all involve carbon-transforming processes (i.e., photosynthesis, digestion and biosynthesis, cellular respiration, and combustion) that are constrained by energy principles—energy conservation and energy degradation. We studied both scientific explanations and students' intuitive explanations of these socio-ecological events. While scientific explanations of socio-ecological events are built upon energy principles, energy may not be an easy tool for students to construct accounts. Therefore, we designed a written assessment and a clinical interview to elicit students' accounts about socio-ecological events. We analyzed students' accounts and investigated the underlying reasoning patterns. Based on this work, we developed a learning progression for energy in socio-ecological systems.

This research is part of Environmental Literacy Research Project. This project focuses on developing learning progressions for matter and energy in socio-ecological systems. This paper reports on our work in developing a learning progression for energy. The learning progression for matter is reported in another paper about the project (Lindsey, Chen, Anderson, 2009).

Learning Progressions

Currently, different learning progressions have been developed in many content areas including evolution (Catley, Lehrer, & Reiser, 2005), matter (Liu & Lesniak, 2006; Mohan, Chen, & Anderson, 2009; Smith, Wiser, Anderson, & Krajcik, 2006), heredity (Roseman, Caldwell, Gogos, & Kurth, 2006), water cycle (Covitt, Gunckel, & Anderson, In Press), biodiversity (Wilson, Tsurusaki, Wilke, Zesaguli, & Anderson, 2007), energy (Liu & McKeough, 2005), and so on. Two of theses learning progressions—the learning progressions of energy and heredity (Liu & McKeough, 2005; Roseman et al., 2006)—are sequences of scientific concepts, principles, and theories ordered in terms of increasing complexity and levels of abstraction. The other learning progressions describe the development of students' learning performance with respect to the science topic addressed.

We see the ultimate goal of learning progression research as promoting science teaching and learning in schools. From a constructivist perspective, learning is a process in which students actively construct their ways of knowing as they expand their experience with the material world and with society (Cobb, 1994). It is not a process of knowledge acquisition. Accordingly, science teaching should focus on facilitating scientific ways of thinking, knowing, and reasoning, rather than transmission of scientific facts, concepts, and theories. Therefore, knowledge sequence learning progressions, with their neglect of students' thinking, would be misleading if were used as guidelines for science teaching. We suggest that learning progressions should address students' learning performance with focus on students' specific ways of thinking, knowing, and reasoning. In this research, we developed a learning progression describing increasingly sophisticated ways of reasoning about energy in socio-ecological systems.

Understanding Energy

Energy plays a key role in all branches of science, including biology, chemistry, and physics. Scientists working in different research areas use energy as a conceptual tool to understand the world. Energy is also consistently identified as a central concept in the science curriculum for K-12 schools. Energy is so important. Then, how well do we teach energy at K-12 levels?

Studies about Students' Understanding of Energy

Studies about K-12 students' understanding of energy focus on either or both of the following two aspects: the energy concept and energy principles (i.e., energy conservation and energy degradation). Studies about the energy concept investigate students' alternative views of energy. Studies focusing on energy principles investigate how students apply the two energy principles to physical and biological problems.

With respect to the energy concept, empirical research indicates that students usually have many intuitive ideas about what energy is and their ideas are usually inconsistent, fragmented, and situated in specific contexts. For example, students tend to associate energy only with living or moving things but not with situations when potential energy is involved (Gilbert & Pope, 1986; Gilbert & Watts, 1983; Watts, 1983; Watts & Gilbert, 1983). They may use different "frameworks" to describe energy: anthropocentric, depository, ingredient, activity, product, functional, and flow-transfer (Watts, 1983). They may treat energy differently in different situations—energy is sometimes treated as a type of semi-matter, sometimes as sensation, and sometimes as phenomena (Warren, 1983). When learning biology, students tend to see energy as a type of vital power or spirit that cause biological processes to happen (Barak, Gorodetsky, & Chipman, 1997). When learning physics, students often do not distinguish energy from two other physics concepts—force and power (Watts & Gilbert, 1983).

With respect to application of energy principles, empirical research indicates that students lack the ability to apply energy conservation and energy degradation to physical and biological problems. Although students may be able to solve quantitative physics problems using energy-related formula, their ability to use energy principles to construct qualitative explanations is very weak. Driver and Warrington (1985) found that students tend to rely on work definition (i.e., $W = Fd$), which is associated with more observable variables such as distance and force, and they seldom use energy conservation to solve problems—counting energy input and output. Duit (1984) found that students seldom use energy conservation to make predictions about mechanics problems. Solomon (1985) found that students tend to either neglect the role of energy degradation or treat it as contradictory to energy conservation. Students' ability to apply the two energy principles to biological contexts is even weaker. Barak and his colleagues found that students often construct ideas about energy that are contradictory to the energy principles: they tend to see energy as the vital power that is not conserved; they also tend to see heat as an available energy form for organisms (Barak et al., 1997). Lin et al. investigated the concept maps students developed to describe the food chain and found that students seldom use energy flow to describe food chain, although they are more capable in identifying matter transformation in the food chain (Lin & Hu, 2003). Similarly, Carlsson found that students generally do not have ideas about how photosynthesis and cellular respiration are connected in terms of energy (Carlsson, 2002a, 2002b).

In summary, studies of students' understanding of energy uncover many misconceptions about energy concept and energy principles, indicating that energy is not an easy tool for most students to construct their explanations about events. However, these studies do not provide enough information about what students are able to do. In other words, if energy is not a conceptual tool students use to construct explanations, what are the reasoning tools that students do use? Studies about students' intuitive ways of reasoning provide some general answers about this question.

Studies about Students' Intuitive Reasoning

Students construct their specific ways of informal reasoning through their interactions with the outside world.

In our everyday life, we interact with others and the media through language. The way we use everyday language largely influences our reasoning about the world. English grammar is built on force-dynamic reasoning (Pinker, 2007; Talmy, 2000). Force-dynamic reasoning understands the world in terms of the actor and its enablers: the actor has internal goals and abilities for taking certain direction or for resting, but they may need enablers. For example, a tree is an actor and has the internal goal and natural ability to grow and maintain life; it always needs enablers such as water, air, soil, and sunlight. This force-dynamic reasoning is very different from scientific reasoning, which treats both the actor and the enablers as being composed of matter and energy, and describes the interactions between the actor and the enablers in terms of matter transformation and energy transformation.

Through direct interactions with the material world, people construct intuitive ways of reasoning, which are useful tools for explaining one's observations and perceptions (Chi, 2005; diSessa, 1987; Grotzer, 2004; Pozo & Crespo, 2005). Intuitive everyday reasoning is usually linear and addresses observable and perceptual patterns. It is very different from scientific reasoning, which is usually complex and non-linear.

Empirical studies have found in various contexts that students tend to explain processes in terms of *hidden mechanisms* that describe invisible patterns isomorphic to the patterns observed at the phenomenon level. Some examples of hidden mechanism reasoning are as follows: Grotzer and her colleagues (Grotzer & Bell, 1999) found that students hold the idea that the battery and a light bulb connected by one wire instead of in a circuit would make the bulb light up; this explanation is built upon a consumer-source chain, which is isomorphic to a macroscopic pattern—batteries are the power sources and light bulbs are appliances consume the power. Chi (2005) found that, based on the observation that dyed water moving from high to low concentration, students constructed intuitive reasoning about diffusion—diffusion is caused by individual liquid molecules' intentional movement from high to low concentration. This reasoning about a hidden mechanism is different from scientific reasoning that explains diffusion as the result of random movement of individual molecules.

These ideas about students' intuitive ways of reasoning provide important information for us to develop a learning progression about energy. In particular, they provide interesting ideas for us to think about important issues of learning progression development: 1) Since many students, especially younger students who have less science background, do not use energy to explain events, what are the reasoning tools younger students use to make accounts? What are their intuitive reasoning patterns with respect to energy? 2) Do students develop precursors of energy at certain stages? How does the energy precursor differ from the scientific notion of energy?

Research Framework

Structure of the Learning Progression

Our goal was to develop a learning progression that describes the increasingly sophisticated ways of reasoning about energy in socio-ecological systems. We used the general structure of learning progressions that was developed in the Environmental Literacy Research Project (Table 1).

Table 1. Learning Progression Framework

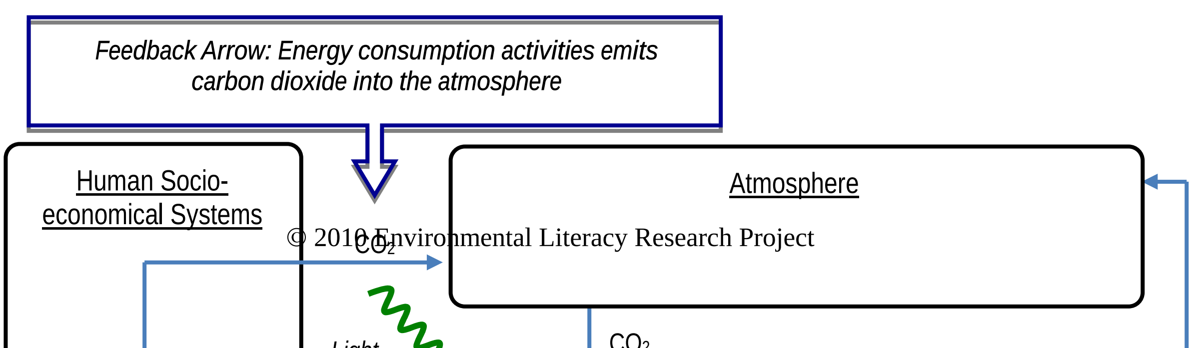
Levels of Achievement	Progress Variables		
	Variable 1	Variable 2	Variable 3
Upper Anchor	Learning performances		
Intermediate Levels			
Lower Anchor			

The learning progression contains two parameters—progress variables and levels of achievement. Progress variables are aspects of students overall performance that differ for students at different levels of achievement. Students' learning performance along each progress variable can be ordered into different levels in terms of the scientific proficiency. They are levels of achievement. They can be organized into three parts: the upper anchor, as the goal of science learning, describes scientific model-based reasoning about energy; the lower anchor is defined by younger students' informal reasoning and knowledge as they enter the age range that we focus on (upper elementary for the current study); the intermediate levels reflect the intersection of school science and students' informal reasoning and knowledge.

Upper Anchor of the Learning Progression

Based on ideas from environmental research and big ideas from disciplinary knowledge, we developed the upper anchor of the learning progression—scientific reasoning of carbon-transforming processes in socio-ecological systems. It is represented as the Loop Diagram (Figure 1).

Figure 1. Loop Diagram—Energy as constraints on carbon-transforming processes



The Loop Diagram highlights using energy conservation and degradation to constrain carbon-transforming processes across three scales—macroscopic, atomic-molecular, and global scales. In our everyday life, a variety of socio-ecological events are related to global warming. The events in the blue boxes are some examples. These events are explained in terms of three classes of biogeochemical processes at the atomic-molecular scales:

- *Harnessing Energy:* Photosynthesis explains the event of plant growth. In photosynthesis, light energy transforms into chemical potential energy, making energy available to biological and socio-economical systems on a global scale.
- *Passing on Energy:* Digestion and biosynthesis explain the event of animal growth. In these processes, organic compounds change from one form to another, losing some energy as heat but keeping most energy as chemical potential energy.
- *Energy dissipating*: Cellular respiration and combustion explain a variety of events related to energy consumption. These events include animal moving, animal breathing, weight loss, dead body decaying, using electric appliances, driving vehicles, and burning fossil fuels. In cellular respiration and combustion, the chemical potential energy contained in the organic compounds is released to do work and heat is also released as byproduct; finally all energy transforms into waste heat. At the same time, organic compounds are oxidized into carbon dioxide and water.

The atomic-molecular processes collectively lead to two global scale processes: carbon cycling among human socio-economical systems, the biosphere, and the atmosphere; energy flow from the biosphere to human socio-economical systems with heat dissipation. Human socio-economical activities largely rely on energy sources—foods and fuels—from biosphere. We constantly use the chemical energy stored in foods and fuels to do work and transform the chemical energy into waste heat. At the same time, carbon dioxide is emitted into the atmosphere, causing global climate change over time. Two points need to be noted about energy transformation: energy always conserves separately from matter; energy always conserves with degradation.

Therefore, the work of developing a learning progression framework for energy contains two tasks: identifying the progress variables that are effective in measuring students' understanding about energy and socio-ecological systems; developing the lower anchor and intermediate levels for each progress variable. We conducted both written assessments and interviews. We designed written assessments and an interview protocol to elicit students' accounts about socio-ecological events. We examined students' accounts and found patterns of the their learning performances, based on which, we identified progress variables and developed the lower anchor and intermediate levels of each progress variable.

Method

We adopted the principle of design research, which contains iterative cycles of design and implementation, using each implementation as an opportunity to collect data to inform subsequent design (Cobb, Confrey, diSessa, Lehrer, & Schauble, 2003; Collins, Joseph, & Bielaczyc, 2004; Edelson, 2002). Altogether, we conducted five cycles of research that lasted for six years. The findings reported in this paper are based on two sets of data: the written data from year 2007-08 and the interview data from 2008-09.

The research contained iterative cycles and each cycle contained three stages:

- *Design/re-design the assessment items and interview protocols:* We started with the initial written assessment items and interview protocols. As we were analyzing data and developing the learning progression, specific problems often emerged. These problems guided our work on revising and refining assessments, which were used in the following research cycle.
- *Implement assessments and collect data:* We implemented the assessments with students and collected data. In the last iterative cycle, a teaching experiment was conducted and pre-interviews and post-interviews were implemented before and after the teaching intervention.
- *Analyze data and develop the learning progression:* We examined students' responses from written assessments and interviews and identified possible progress variables. Then we grouped students' responses by the same characteristics and ordered the groups in terms of their underlying science value. Based on this work, we developed and revised the achievement levels of the learning progression.

Participants

Findings reported in this paper are based on written assessment data and interview data collected from the 2008-09 research cycle. We conducted teaching experiments. The participants were students from upper elementary to high schools located in suburban and rural areas. Interviews and written assessments were conducted before and after the teaching intervention. Altogether we collected 527 pre-assessments (91 elementary school assessments; 214 middle school assessments; and 222 high school assessments) and 543 post-test papers (125 elementary school assessments; 211 middle school assessments; 207 high school assessments). Among the participants, eight students from each school level also attended pre-interviews and post-interviews. To be noted is that our intention was not to evaluate the effectiveness of the teaching experiment, but to collect students' reasoning patterns, and as many as possible.

Assessments

As shown in the Loop Diagram, the learning goal for students is to use scientific reasoning about energy—use energy conservation and energy degradation to constrain processes at atomic-molecular, macroscopic, and global scales—to account for socio-ecological events. In the earlier research cycles, we used designed written assessments and clinical interviews to elicit students' understanding of energy as it relates to socio-ecological events. However, we encountered the assessment dilemma. In the earlier research cycles, we designed questions to investigate how students understand energy as it relates to the carbon-transforming processes. We found that although questions about energy and atomic-molecular/global scale processes worked well with high school students, they were not understood by younger students. Data from the earlier cycles of research indicate that younger students might rely on force-dynamic reasoning, which explains socio-ecological events in terms of actors, enablers, and result.

- 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 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 it own particular enablers. For example, people always 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. This action, or change in general, causes the 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. First, some "enablers" addressed in force-dynamic accounts are energy sources. For example, sunlight is the energy source for plant growth; food is the energy source for baby growth; gasoline is the energy source for car running. However, scientific accounts and force-dynamic accounts rely on totally different ways of reasoning to explain why the enablers or energy sources are needed and how they are used. Second, both force-dynamic accounts and scientific accounts explain changes happening to the actor and its enablers. While scientific accounts identify energy transformation in chemical processes at the atomic-molecular scale, force-dynamic accounts tend to focus on observable and perceptual changes. Third, both force-dynamic accounts and scientific accounts explain the connections among socio-ecological events. While scientific accounts explain the connections in terms of energy transformation at the global scale, force-dynamic accounts may only focus on obvious patterns or may not identify the connections.

In summary, scientific reasoning and force-dynamic reasoning share a general framework of reasoning, which contains three elements: identify enablers or energy source(s), explain individual macroscopic socio-ecological events, and explain the connections among the socio-ecological events. Hence, to solve the assessment dilemma, we constructed both interview and written assessment questions around this shared framework to elicit either the element of scientific reasoning—energy—or the elements of force-dynamic reasoning—actor, enablers, and results. We designed questions at different difficulty levels. To ask the questions, we used item pairs in the written assessment and the branching-structure interview.

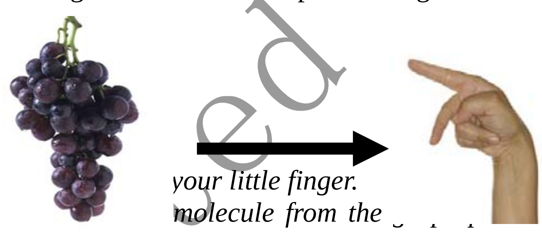
Written Assessment

The written assessment contains questions at two difficulty levels. The lower-level questions use everyday language to ask about actors, enablers, and macroscopic connections. They do not require students to reason about energy at either atomic-molecular scale or global scale. Students with little science background should be able to understand the lower-level questions and provide accounts that indicating their informal ways of reasoning. Although the lower-level questions allow more advanced students to reason about energy at atomic-molecular or global scale, they do not require students to provide detailed accounts. The higher-level questions examine to what extend students identify energy sources and to what extend students trace energy at the atomic-molecular or global scale.

In the written assessments, the elementary school assessments only contain lower-level items. High school assessments contain mostly higher-level items. Middle school assessments are the combination of both lower-level and higher-level items. During the earlier cycles of research, most assessment items were open-response items. These items have been continuously revised and refined with feedback from data analysis. The written assessments used in the final research cycle contain item pairs—both items in the pair ask about the same macroscopic event, but the elementary/middle school item uses everyday language to elicit lower-level accounts, while the high school item is designed to elicit accounts about scale, matter, and energy. Some of these item pairs are open-ended items. Others are two-tier multiple-choice items, where the student chooses, then explains.

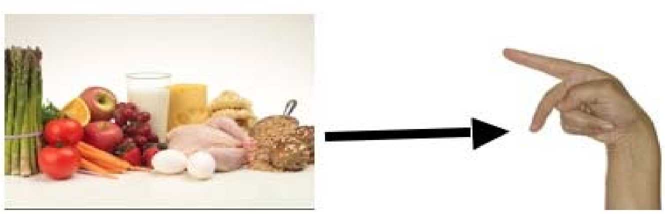
An example of open-ended item pair—"Grape/Food and finger movement"—is represented below. The higher-level item asks how a glucose molecule changes to help body movement and whether the same glucose molecule provides heat to keep body temperature. Sophisticated explanation should trace energy in cellular respiration. The lower-level item—food and finger movement—asks about a similar event, but uses informal language that can be understood by younger students.

Higher-level Item: Grape and Finger Movement



The grape you eat ca[…] your little finger.
a. Please describe h[…] molecule from the […] energy to move your little finger. Tell as much as you can about any biological and chemical processes involved in this event.
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.

Lower-level Item: Food and Finger Movement



How do you think

Clinical interview

The interview protocol contains questions at three difficulty levels—lower-level questions, transition questions, and higher-level questions. The questions are constructed around seven macroscopic socio-ecological events—tree growth, baby girl growth, girl running, dead tree decaying, flame burning, car running, lamp lighting. These events cover the key atomic-molecular carbon transforming processes (i.e., photosynthesis, biosynthesis & digestion, cellular respiration, and combustion). The interview begins with questions about each individual event and then asks about the connections among the individual events.

For each individual event, the interview begins with lower-level questions, then shifts to transition questions, and finally asks higher-level questions. The lower-level questions use everyday language to ask about actors, enablers, and results. Transition questions ask about changes happen to the energy or matter in general. Higher-level questions ask about energy transformation in chemical changes or at the global scale. When students' responses to the lower-level questions and transition questions indicate some understanding of energy, follow-up higher-level questions will be asked. The types of questions asked in interviews are listed in the table below.

Table 2 Types of Questions asked in interviews

	Questions at three difficulty levels
Identify enablers or energy sources	*Lower-level Questions* ask students to list enablers and compare the functions of the enablers. Examples: What does the tree need in order to grow? Do you think that they help the tree to grow in the same way or in different ways? Why? Can flame burn on sand? Why? *Transition Questions* ask students to distinguish energy enablers from other enablers in general. Examples: Does the flame use it for energy? Why? Do you think that flame can burn on sand? Why? Questions that ask students to identify energy sources at atomic-molecular scale. Examples: What are the energy sources for plant growth? Why?
Explain individual macroscopic events	*Lower-level Questions* ask about how the actor uses enablers and the results. Examples: How does sunlight help the tree to grow? The girl loses weight if she runs a lot. Where does the lost weight go? *Transition Questions* ask about changes happening to the actor and enablers. Examples: Do you think water will change when it is used by the tree (or, inside the tree's body)? Do you think the flame uses air for energy? Why? Where does the energy of car running come from? Where does the light energy go? Why? *Higher-level Questions* ask about matter transformation and energy transformation. Examples: Do you think heat is created in combustion or is it changed from other forms of energy in combustion?
Explain the connections among the individual macroscopic events	*Lower-level Questions* ask about the connection among the events in general. Examples: How are these events connected? *Higher-level Questions* ask students to explain the connection in terms of energy. Examples: How are these events connected in an ecosystem? Do you think that energy is also changing when carbon is moving?

Data Analysis

Data analysis contains two steps. At the first step, we used qualitative data analysis to develop the learning progression. We analyze the data by *account units*. The interview contains seven individual socio-ecological events and the connections of the events. Accordingly, we divided each student's interview into eight account units. For each unit, we grouped students' responses according to the characteristics of performance reflected in the responses. Then we ordered these reasoning patterns in terms of the sophistication and scientific values. In the written assessments, each item is one account unit. With respect to each item, we randomly chose 10 responses from each school level for data analysis. We used the same approach to group and order students' responses. Based on the analysis of written and interview data, we developed the levels of achievement of the learning progression.

At the second step, we used the learning progression framework as the guideline to develop detailed coding rubrics—the exemplar workbooks. The interview exemplar workbook contains eight exemplar worksheets (seven socio-ecological events and the connections among the events). The written exemplar worksheets contain exemplar worksheets for all written items. The exemplar worksheets have detailed level descriptions and exemplar responses selected from written assessment data. Nine coders from the project used the exemplar workbooks to code all interview and written assessment data. Reliability check was also conducted. We used the coding results to generate graphs that represent the distribution of students' responses along the learning progression.

Findings

In this part, we first report on the three stages of the research. Then, we represent the final learning progression for energy in socio-ecological systems. Finally, we report on the distribution graphs that represent students' development of Naming, Association, and Explaining performances.

Three Stages of Research

During the iterative research cycles, we continuously revised the learning progression framework according the problems identified in data analysis. Altogether, the learning progression framework underwent significant revisions at three stages of the research:

Stage 1 Science-based progress variable—energy

Stage 2 Performance-based progress variables—Naming and Explaining

Stage 3 Reconsider energy as progress variable

At stage one, we used the science element—energy—as the progress variable to analyze data. The data analysis focuses on students' understanding of energy. The learning progression framework at stage one is represented below. It was used as the guideline to develop detailed rubrics for coding interview and written assessment data.

Table 3 The Learning Progression Framework at Stage One

Levels of Achievement	Progress Variable: Energy
Upper Anchor	Level 4. Accounts that successfully explain energy transformation in carbon-transforming processes
Intermediate Levels	Level 3. Accounts about changes involving energy forms; Use energy principles unsuccessfully
	Level 2. Force-dynamic accounts with hidden mechanisms
Lower Anchor	Level 1. Macroscopic force-dynamic accounts that do not involve energy

However, this learning progression framework indicates both conceptual problem and empirical problem. Conceptually, the learning progression framework uses energy as progress variable to measure students' learning performances, but the lower levels (Level 1 and Level 2) are not about energy. They are about force-dynamic reasoning. In other words, the science-based progress variable—energy—is not effective in measuring lower-level reasoning. Empirically, the correlation between them was 0.96 (Choi, Lee, & Draney, 2009), indicating that the separate codes for matter and energy were largely redundant. These two problems were solved at stage 2 when we used the performance-based progress variables—Naming and Explaining—to develop the learning progression framework.

At stage 2, we conducted a cross-culture interview study in US and China. We found that although some students, especially Chinese students, may name scientific terms and recite scientific statements, they rely on relatively lower-level reasoning to make accounts. This finding led us to reconsider our progress variables. Rather than treating the highly correlated scientific elements of accounts—matter and energy—as progress variables, we began to explore rubrics that focused on performance elements of accounts, which we labeled Naming and Explaining (Jin, Zhan, & Anderson, Submitted). The Explaining progress variable describes the nature of the explanations students gave. It is about the specific ways of reasoning students use to make accounts. The Naming progress variable refers to the performance of verbatim reproduction of vocabulary—how students used both informal and scientific vocabulary in accounts.

However, both performance-based progress variables and science-based progress variables have advantages and disadvantages. On one hand, the performance-based progress variables—Naming and Explaining—have enabled us to find important patterns with respect to American and Chinese students' different performances, but they tend to describe performances in ways that lose track of science. In other words, the Naming and Explaining progress variables can be used to measure students' learning performances with respect to any science topic. They are not specific about energy. On the other hand, although energy is an important concept in physics and everyday life, it cannot be used as progress variable to measure younger students' informal reasoning. There is the dilemma of choosing between the performance-based progress variables and the science-based progress variables.

At stage three, our focus is to solve this progress variable dilemma. Instead of choosing between the science-based and performance-based progress variables, we tried to identify progress variables that are both science-based and performance-based. To identify the progress variables, we studied the historical development of the energy concept. The word energy derives from the Greek word "energeia". Aristotle first developed the word "energeia" to mean "being-at-work", the opposite of "being-at-end". In this reasoning, energy only exists in situations involving movement or activities. When objects or organisms are in the status of "being-at-end"—being dead or being at rest—energy disappears. This meaning of "being-at-work" has been built into our everyday informal reasoning. For example, we often say: "I have a lot of energy to start my work." "Fresh air gives me energy." "I'm so tired. I ran out all of my energy." In our everyday life, energy is something that powers the processes; it is used up and always needs to be replenished; we can either gain energy from enablers or create energy through eating, sleeping, breathing, etc.

This Aristotelian notion of energy is very different from the scientific meaning of energy described by Feynman. In his book *The Feynman Lectures on Physics,* Feynman explains what energy is (Feynman, Leighton, & Sands, 1989):

> The law is called the conservation of energy. It says that there is a certain quantity, which we call energy that does not change in the manifold changes which nature undergoes. That is a most abstract idea, because it is a mathematical principle; it says that there is a numerical quantity, which does not change when something happens. It is not a description of a mechanism, or anything concrete; it is just a strange fact that we can calculate some number and when we finish watching nature go through her tricks and calculate the number again, it is the same.

According to Feynman, energy is an important and useful concept, because we can trace energy through events of all kinds. Whenever changes happen, energy is always transformed from one form to other forms and the total amount of energy does not change. This is the content of the first law of thermodynamics—energy conservation. Another important aspect of energy is described as the second law of thermodynamics—energy degradation. According to energy degradation, whenever changes happen, the useful amount of energy decreases, part of the energy is always transformed into waste heat and dissipates into the environment. So, the total amount of energy keeps the same, but the useful energy decreases. In brief, in science, energy is an abstract quantity that is always conserved and degraded.

If we compare Aristotelian notion of energy, which represent our informal reasoning about energy, with the scientific meaning of energy, we can find that the differences exist in two aspects of learning performances. First, while Aristotle associated energy with many aspects of events such as activities, spirit, power, emotion, and so on, the scientific reasoning of energy is only associated with limited energy indicators such as motion, light, electricity, foods, fuels, warmth, and so on. Second, while Aristotelian energy only exists when things are "being at work" and disappears when things are "being-at-end" such as being dead or stopping moving, the scientific reasoning highlights tracing energy across processes—whenever changes happen, the total amount of energy conserves and the amount of useful energy decreases due to heat dissipation. Based on this analysis, we used Association and Tracing as Explaining progress variables to measure students' understanding.

In general, the learning progression framework underwent many revisions during the five-year iterative research process. At the beginning, we chose the science element—energy—as progress variable, but found that energy cannot be used as progress variable to measure younger students' understanding. Then we shifted to performance-based progress variables—Naming and Explaining, which enabled us to compare American students' accounts with Chinese students' accounts. However, the performance-based progress variables tend to describe learning performances in ways that lose track of science. In such situation, we reconsider energy as progress variable and identified Association and Tracing as progress variables that are both science-based and performance-based.

Final Learning Progression Framework

Therefore, the final learning progression for energy in socio-ecological systems contains three progress variables: one Naming progress variable and two Explaining progress variables (Association and Tracing). It is represented in the Table 4. *Naming progress variable* is about the performance of verbatim reproduction of vocabulary—the words students use to construct their accounts. *Explaining progress variables* describe the reasoning patterns students use to make accounts. We found that students' accounts at different sophistication levels were built on different "entities". While younger students' accounts are mostly built upon "natural ability" and "vital power", more advanced students are able to use "energy" to make accounts. With respect to each entity, students' accounts indicate patterns of two dimensions of learning performance—Association and Tracing. They are two Explaining progress variables:

- Association: Do students associate the entity (i.e., natural ability, vital power, or energy) with different things? What are those things?
- Tracing: Do students trace the entity backward and forward? How? If they do not trace the entity, do they trace anything else? What do they trace?

Table 4. The Learning Progression Framework for Energy and Causal Reasoning in Socio-ecological Systems

Explaining		
	Association	Tracing
Level 4	Energy Associate energy with energy indicators consistently; Identify energy sources consistently; Energy distinguished from matter and from other enablers such as conditions	Trace energy at atomic-molecular and global scales successfully Trace energy with degradation and separately from matter in carbon-transforming processes across scales.
Level 3	Energy Associate energy with energy indicators including unobvious indicators such as familiar organic molecules, but may identify other substances as energy sources or do not distinguish energy and organic molecules.	Trace energy at atomic-molecular and global scales unsuccessfully: Trace energy without degradation in large-scale systems (e.g., energy recycles). Trace energy and matter but with confusion about labels (e.g., ATP is energy) and or matter-energy conversions (e.g., glucose is converted into kinetic energy) Describe energy transformation correctly but cannot connect that to matter transformation in chemical reaction
Level 2	Vital power: Recognize that actors cannot create vital power and that they must gain vital power from enablers Recognize that enablers contain vital power (the notion of vital power is indicated in a list of words that students use such as energy, vitamin, nutrients, combustible, etc.) Associate energy with obvious indicators, but also hold the idea that all enablers are energy sources	Trace the power-result chain in uphill and downhill events: Trace power/energy backwards but not forwards Actor gaining vital power/energy through hidden processes Vital power triggers hidden processes Actor losing vital power through hidden processes Can trace "energy" through food chains

Naming	
Level 4	Scientific statements All forms of energy involved in the chemical change; heat as byproduct; configuration of atoms (C-C and C-H bonds) as high-energy bonds
Level 3	Scientific words of organic molecules, energy forms, and chemical change Organic molecules: glucose, C6H12O6, monosaccharide, glycogen, lipid, ATP, ADP, carbohydrate, hydrocarbon, octane; Energy forms: light energy, kinetic energy, electrical energy, chemical energy, heat energy Chemical reactions: cellular respiration, combustion, oxidation, light reaction, dark reaction
Level 2.5	Easier scientific words Organic materials: Fat, sugar, starch, organic matter, carbon, molecule, atom Energy: stored energy, motion energy Process: photosynthesis, decomposition/decomposer, chemical reaction/change Others: chloroplast
Level 2	Hidden mechanism words Materials: carbon dioxide, oxygen, nutrients, mineral, vitamin, chemicals. Energy: calories, electricity Process: digestion, digest, digestive system, break down Others: bacteria, fungi, micro organisms, cell, power plants
L	Easier hidden mechanism words

Level 1	Natural Ability: Associate natural ability with elements of events such as actors, enablers, settings, aspects of processes, and so on.	Trace the macroscopic action-result chain in uphill and downhill events: The actor uses its enablers to take action. As the result, it reaches its goals to keep alive, to grow, to keep burning, and so on. When the actor loses its natural ability or loses enablers, it changes towards the downhill direction. Do not trace any scientific entities behind the action-result chain. Actors and settings endure over time, but not materials (in chemical changes) or energy.		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.

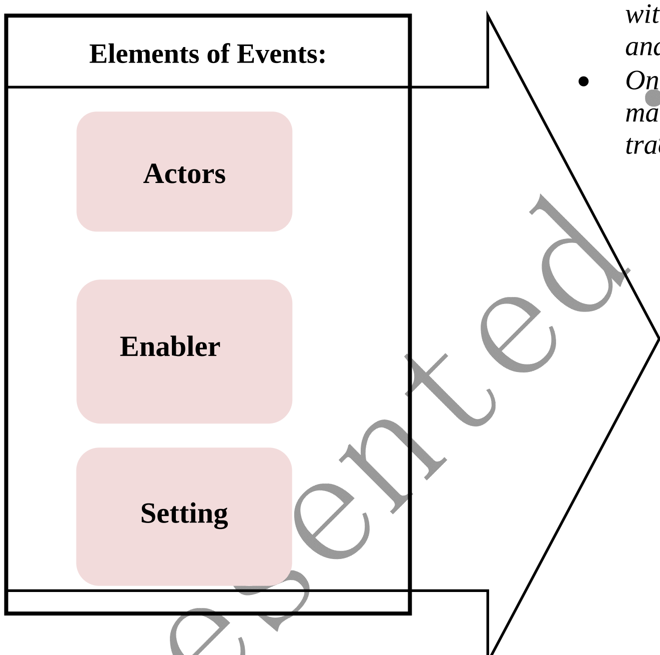
Overall, there are four achievement levels for the Explaining progress variables. The achievement levels are described as below.

Level 1. Natural Ability as naturalistic and psychological entity

At level 1, the socio-ecological events are treated as uphill and downhill events. Events involving growing, living, moving, and burning indicate changes toward the upward direction. They are treated as uphill events. For example, plant growth, people growth, people running, flame burning, and car running are all uphill events. Events such as apple rotting and tree decaying indicate changes toward downward direction and are treated as downhill events. Although the specific explanations about how and why the uphill events and downhill events happen are different, they are all built upon the same entity—natural ability. Natural ability is a naturalistic and psychological entity, which is loosely associated with elements of events such as actors, enablers, and setting. It is also a temporal entity that only appears as the elements of events present. The Level 1 reasoning is represented in the diagram below.

With respect to the performance of Association, Level 1 accounts indicate a broad association. They associate natural ability loosely with the elements and aspects of the event. The natural ability can be associated with the actor: the actor has the natural ability to change towards the uphill direction such as growing, moving, and burning. It can be associated with the enablers: the actor always needs to use certain enablers to make changes to happen; certain enablers are useful for the actor because they have certain natural abilities. It can be associated with the setting: the actor only lives in certain settings because naturally the setting can provide desirable conditions for the actor. It can also be associated with different aspects of the events such as activities, motions, emotions, feelings, and so on.

- *Broad association: Associate natural ability with elements of events (i.e., actors, enablers, and settings).*
- *Only cause-effect tracing: Trace the macroscopic action-result chain. Do not trace the entity of natural ability.*



Result:
Actor reaches its goal; Changes happen

Below is an excerpt from an interview with a 4th grader.

Pre-interview (4th grader)
Event: Baby Girl Growth

Interviewer: Do you think the girl's body uses the food for energy?
Watson: Yes.
Interviewer: Do you know how?
Watson: Because the food helps make energy for the girl so then she can like learn how to walk and

crawl and stuff. And it will also help the baby so it will be happy, be not mean and stuff.

Interviewer: Yes, ok. Let's talk about the next one. You said sleep, right? So say a little bit about that. How is it related to growth?

Watson: Because it will make it somehow so you'll grow. Because that way you will get more energy so you can like run and jump, and jump rope and walk and play. And that's it.

Interviewer: Does the baby's body need sleeping for energy?

Watson: Yes. Because then it will be happy and it won't cry. And it will be able to play and make it so it will eat and stuff.

Interviewer: What do you think is energy? What energy is like?

Watson: I think energy is like, it helps it grow and it helps it so it won't be crabby, like when you get mad.

In the interview, Watson used the word energy to answer questions. However, "energy" used in his accounts actually indicates a notion of "natural ability". "Energy" is associated with food, sleep, and emotion: Watson claimed that the girl gained energy from food and through sleep and explained that energy makes the baby girl "happy". When the researcher asked Watson to explain his understanding of energy, he said: "I think energy is like, it helps it grow and it helps it so it won't be crabby, like when you get mad".

With respect to Tracing, students relying on Level 1 reasoning do not trace where the natural ability comes from and where it goes. Instead, they trace the cause-effect relation, or, in other words, the action-result chain. Students relying on the "natural ability" reasoning provide similar explanations for uphill events, downhill events, and connection among events.

The interview excerpt with Watson is about baby girl growth, which is an uphill event. Watson's responses indicate that he is tracing a macroscopic action-result chain: The baby girl uses its enablers and takes certain actions—she eats food and has enough sleep—and the result of the tree's actions is growth.

According to the natural ability reasoning, the uphill events are caused by the actor's actions, while downhill events such as decay are caused by lack of actions. Tree decay and apple rotting are two examples of downhill events. In these events, decay is treated as the natural tendency that happens when the actor—the organism—gets old or dead and cannot take actions, or when the actor loses its enablers or living necessities. For example, some students explain that decay happens when the apple "loses moisture" or is not kept in the "cold fridges". Some Level 1 accounts also state that decay happens when the opponents (e.g., bugs, birds, bacteria, or fungi) "eat" or "overcome" the actors. Below is an interview excerpts about tree decay. Amy mentioned bacteria as one cause of decay, but her explanations of how bacteria cause decay—bacteria eat the dead body—indicate that bacteria are treated as the actor that utilizes the apple for living.

Pre-interview (4th grader)

Tree Decay

Interviewer: So what do you think is the cause of the decay?

Amy: Bacteria or like when you get old your body slows down and you don't have as much energy as you did before when you were a kid. So you just slow down and you can't really build that much muscle. Your heart is never really pumping and beating that it's supposed to be so. You just die.

Interviewer: So how does bacteria cause the decay?

Amy: Bacteria it eats at it kind of and tries to get all of the nutrients and stuff and it helps it die and decay.

With respect to the connections among events, Level 1 accounts generally focus on the macroscopic similarity, differences, or connections among events and do not trace any entity. For example, in the written assessments, we asked students how the following three things are related: a person plugs in an air conditioner in the US, trees grow in Amazon forest, and ice in the Arctic Ocean melts. Accounts at Level 1 usually identify the macroscopic similarities or relations among the events. For example, the two responses below explain that the three events all "give cool air" or "take time or money".

How are the three things related: a person plugs in an air conditioner in the US, trees grow in Amazon forest, and ice in the Arctic Ocean melts.

Response 1: They all give cool air or something like that.

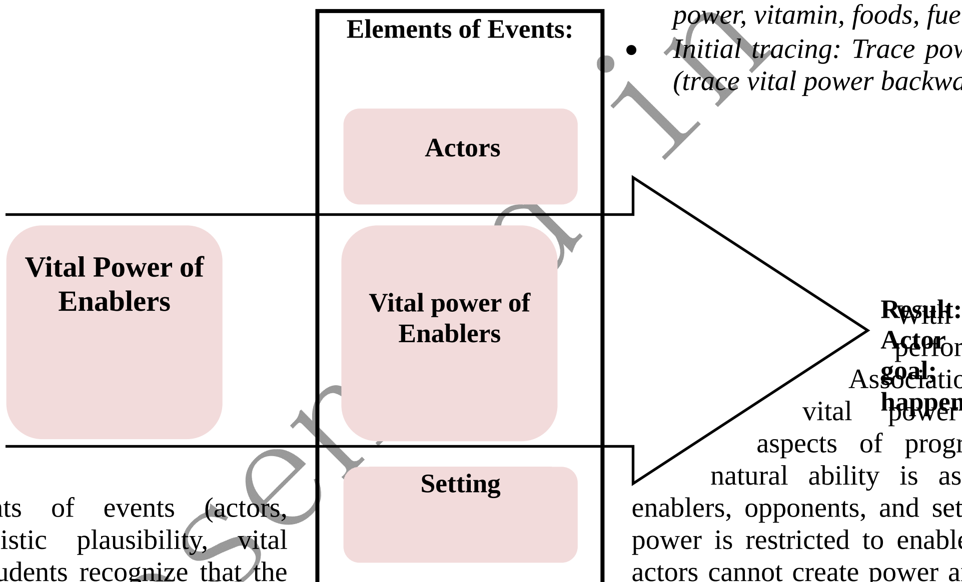
Response 2: They take time or money people don't use AC anymore they have it built in. Trees take years to grow, ice also takes time to melt.

In brief, accounts at Level 1 are constructed around the notion of natural ability. Natural ability is a naturalistic, psychological, and temporal entity. First, it indicates the naturalistic reasoning: actors, enablers, opponents, and settings have their natural abilities due to natural endowment. Since the abilities are naturally endowed, any inquiry about the invisible structure or properties of actors or enablers becomes unnecessary. Second, natural ability is also a psychological entity, since it is often associated with psychological state such as feelings, belief, and desire. Finally, natural ability is a temporal entity, since it only exists when actors, enablers, and setting present and does not endure after the events.

Level 2 Vital power as a mechanical entity

Accounts at Level 2 explain the uphill and downhill events in terms of *vital power*—the actor gains vital power from its enablers and the vital power triggers certain changes. Students rely on Level 2 reasoning use many words to mean vital power. Some examples are: “nutrients”, “energy”, “chemicals”, “vitamin”, and “calorie”. Unlike the naturalistic, psychological, and temporal notion of natural ability, vital power is a mechanical entity that is associated with mechanical properties or hidden structures of actors and enablers and exists before the events. However it although it does not endure when the events are over. The diagram below shows this reasoning pattern.

- *First signs of energy specific association: Associate vital power with physical and biological properties and structure of enablers such as nutrients, power, vitamin, foods, fuels and energy.*
- *Initial tracing: Trace power-result chain (trace vital power backward not forward)*



With respect to the performance of Association, the notion of vital power indicates two aspects of progress. First, while natural ability is associated with all elements of events (actors, enablers, opponents, and settings) in terms of naturalistic plausibility, vital power is restricted to enablers. This indicates that students recognize that the actors cannot create power and the power only comes from enablers. For example, while Level 1 accounts often claim that people can gain energy by sleeping and doing exercises, many Level 2 accounts claim that actions such as sleeping or doing exercises do not provide energy. Second, the notion of vital power also indicates that students begin to pay attention to hidden mechanisms. The notion of natural ability is associated with macroscopic perceptions, observations, desires, and feelings. Vital power is associated with “hidden characteristics” of the enablers such as the physical, mechanical, or biological structure or properties. For example, we asked students why people use gasoline instead of water to run cars. Level 2 accounts explain the reason as the following: gasoline contains or is made of “fuel”, “chemicals”, or “fumes”; gasoline is “flammable” but water is not. These responses indicate a mechanical notion of vital power—the gasoline can power the car because of its physical/chemical properties or composition.

However, the notion of vital power is still very different from the scientific concept of energy with respect to the performance of Association. First, the notion of vital power does not distinguish energy enablers from enablers that do not provide energy. Usually, everything the actor takes in is treated as the power source or energy source. For example, many accounts state that because people need food, water, and nutrients, these things are all energy sources for people. Second, the notion of vital power does not distinguish matter and energy in general. For example, in students' accounts, "nutrients", "vitamin", "water", "foods", and "gasoline" can all be energy.

Below is an interview excerpt with a 9th grader. Richard stated that the baby girl needed energy to grow and the energy comes from things the baby girl takes in—"nutrients, carbons, and other things that are consumed". He recognized that the baby girl's body did not create energy, but held the idea that everything the baby girl took in provided energy. Richard's accounts indicate the first sign of energy specific association—vital power is associated and restricted to enablers, although there is no distinction between energy enablers and other things.

Pre-interview (9th Grader)

Baby Girl Growth

Interviewer: Okay. The baby gets heavy as she grows. Right? How does that happen?

Richard: Well as with the tree, although it's quite a different process, *the nutrients, carbons and other things that are consumed slowly build up, and energy is created from them. [The energy] helps produce more cells and makes things expand and I guess I think that's it.*

Interviewer: Do you think baby growth requires energy?

Richard: It does require energy.

Interviewer: To grow?

Richard: Yes. *Energy is needed for anything to grow really for any living thing to grow because like as I said before, the energy is used to build up on cells.*

With respect to the Tracing performance, Level 2 accounts show initial tracing. They begin to trace the entity of vital power backward but not forward. Usually, the uphill events are described as the processes of the actor gaining vital power and using vital power to make changes to happen. Although Level 2 accounts do not trace vital power forward, they do trace things. Instead of tracing where the vital power goes, students relying on Level 2 reasoning trace a power-result chain—the vital power triggers certain hidden processes and causes certain results to happen. Some examples of students responses are: sunlight helps plants to grow by "triggering" the life processes such as "getting nutrients from soil"; Foods contain nutrients that "power the process of breathing"; Energy from food "powers running". According to this reasoning, as long as the vital power causes changes to happen, it is not necessary to worry about where it goes. Therefore, when being asked where the vital power (i.e., energy, nutrients, calorie, etc.) goes, many students did not have clear ideas and provided responses based on guessing. Some examples of responses are: when the car stopped, "the energy of gasoline went back and was stored in the engine or battery"; energy of foods is used to power running and after that the "energy goes into all parts of our body so that way we can think and walk and move our body".

Below is an interview excerpt, in which the student used Level 2 reasoning to account for the uphill event—tree growth. The interviewer asked Richard to explain what happens to oxygen when the girl's body uses it for running. Richard explained: "Oxygen is used as energy. So when energy is used up when running, the energy is lost and oxygen, on the other hand, becomes carbon dioxide or changes into it." Richard's explanation is constructed around the notion of vital power. He traced the vital power back to the enablers—energy comes from the enabler oxygen, but did not trace energy forward—energy is used up and oxygen becomes carbon dioxide when losing energy.

Pre-Interview (9th Grader)

Tree Growth

Interviewer: Basically, do you think that those things, the food, the water, and oxygen, are used up or changing into something else?

Richard: Well, oxygen is both used up and changed I think. Oxygen is not used up.

Interviewer: By used up, you mean it just disappears?

Richard: Oh it doesn't disappear.

Interviewer: It's consumed and disappears?

Richard: Well it doesn't disappear. The lungs, as they take in oxygen, oxygen is carried around the body. *Oxygen is used as energy. So when energy is used up when running, the energy is lost and oxygen, on the other hand, becomes carbon dioxide or changes into it.* So it's not … it doesn't vanish. It just changes into something else. The carbon dioxide becomes oxygen again once it enters a plant.

At Level 2, downhill events are treated as the result of the actor losing vital power (e.g., vital power evaporates into air or goes into soil, usually accompanied with matter) or the opponents gaining vital power from the dead body. In written assessments, we asked students to explain whether and how energy was involved in the events of tree decay and apple rotting. Below are some examples of responses: “for the tree to decay, it involves bacteria and decomposers, which use energy to decompose it and get energy from the tree itself”; “energy is used by other organisms to process decomposition. However, they receive energy in return from the nutrients gained in the process, so the benefit (energy gained) can cancel out the energy used”; “energy is involved in apple rotting, because the rotting apple is an energy for soil or micro-organisms”. In the interview excerpt below, the interviewer asked Dave to explain where the energy initially contained in the dead tree went. Dave explained: “it changes into something else like it will change into soil or yeah a different minerals and stuff”. According to Dave, the vital power goes into soil with the matter.

Pre-interview (9th grader)
Tree Decay

> Interviewer: What happens to the energy?
> Dave: Well I think like it changes into something else like it will change into soil or yeah a different minerals and stuff.
> Interviewer: Okay. So does that same thing go for the actual material in the wood? The matter that makes it up over time? Where is that going?
> Dave: It I think it turns into soil or it breaks down like into smaller pieces and it turns in to like nutrients in the soil.

With respect to connections among the events, Level 2 accounts trace the vital power at a global scale. One written assessment item asks students to explain whether the EcoSphere has energy exchange with the outside environment. Below is an example of Level 2 response. It traces the power backwards along the food chain—a chain that connects individual organisms by the feeding relations: The organisms are all located in the food chain; each organism provides the vital power for the next organism on the chain to stay alive.

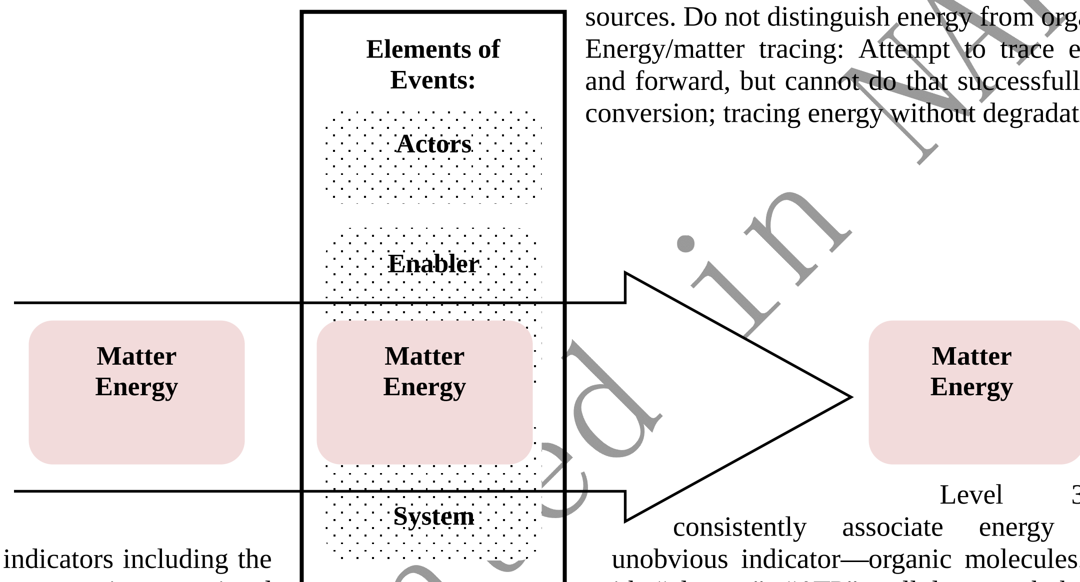
> *NASA scientists invented the EcoSphere – inside a sealed glass container, there are air, water, gravel, and three living things – algae, shrimps, and bacteria. Usually, these three living things can stay alive in the container for two or three years until the shrimps become too old to live. The picture above shows an EcoSphere and its inside part. The EcoSphere is a closed ecosystem and has no exchange of matter with the outside environment.*
> *a) Do you think the EcoSphere has energy exchange with the outside environment? If your answer is YES, please explain.*
> *b) If your answer is NO, why the living things can stay alive without energy exchange with the outside world?*
> Response: They rely on each other and each living organism is a contributing factor to the other organisms’ life, either by creating oxygen or being a food source.

In summary, at level 2, the naturalistic reasoning that the actor has the natural abilities to conduct certain actions still exists, but the biological and mechanical reasoning that explains why and how changes happen is developed and differentiated from the naturalistic and psychological reasoning. In particular, the notion of vital power is developed. Vital power is a mechanical and physical entity that is associated with the non-perceptual properties and hidden structures of enablers. Also, Level 2 accounts begin to trace the vital power backward, although not forward. The notion of vital power is thus a precursor of the scientific notion of energy. While energy is a physical entity that is associated with limited energy indicators and can be traced both backwards and forwards, vital power is a mechanical entity that loosely associated with almost all enablers and usually is traced backward but not forward.

Level 3. Trace energy unsuccessfully.

Level 3 accounts indicate a shift from reasoning about the actor and its enablers to matter and energy. Level 3 accounts associate energy with energy indicators including the unobvious indicator—organic carbon-containing molecules. On the other hand, Level 3 accounts do not sort events into uphill or downhill events. Instead, they treat all events as chemical changes and attempt to trace energy in chemical changes, although they usually cannot do that successfully. The diagram below depicts the Level 3 reasoning.

Energy/matter association: Associate **energy** with energy indicators including the unobvious indicator—organic molecules, but may identify other substances as energy sources. Do not distinguish energy from organic molecules.
Energy/matter tracing: Attempt to trace energy backward and forward, but cannot do that successfully: matter-energy conversion; tracing energy without degradation.



With respect to the performance of association, Level 3 accounts consistently associate energy with energy indicators including the unobvious indicator—organic molecules. For example, energy is associated with “glucose”, “ATP”, cellulous, carbohydrates, and so on. They also specify energy forms such as “kinetic energy”, “heat energy”, “chemical energy”, and so on. However, since students usually do not know that organic molecules contain chemical energy due to the configuration of atoms in the molecules (i.e., organic molecules contain C-C and C-H bonds), they may also identify other substances, which are usually input substances of the biochemical processes, as energy sources. For example, nutrients, which are also involved in biological processes, are identified as the energy source for plants; oxygen, the reactant of combustion, is identified as the energy source for burning. Some Level 3 accounts do not distinguish energy from organic molecules. For example, some responses claim that glucose and ATP are energy.

With respect to the performance of Tracing, Level 3 accounts attempt to trace energy not only backward but also forward in chemical changes or at the global scales. However, level 3 accounts usually cannot trace energy successfully. There are three patterns of this unsuccessful tracing energy.

The first pattern of this unsuccessful tracing performance is matter-energy conversion at the atomic-molecular scale. Although students recognize that both matter and energy are not created or destroyed, they did not trace matter and energy separately. Instead, they held the idea that organic molecules can be converted into energy and vice versa. For example, plant growth is explained in terms of the process of photosynthesis that “converts light energy into “sugar (glucose)”. Decay (decomposition) is treated as a process, in which “once living thing is breaking down, that energy is released in the form of carbon.” We asked students to explain how a glucose molecule of the grape can help people to move their fingers. Many high school students explained that the glucose molecules is converted into energy or a special energy form—ATP—in cellular respiration. Some examples of responses are:

> The glucose is consumed and is then brought to the mitochondria through the blood stream. Here, the cell does respiration and is made into ATP (energy).
>
> The glucose molecule goes into your body. Then, your body breaks down the glucose molecule through the Krebs cycle and another cycle. These cycles break down glucose and release carbon dioxide and change the carbon and energy in glucose into ATP, which can then be used as an energy form which the body uses to perform it's functions. Once the glucose is changed into ATP, it can be used in the body to make the muscles in your finger move, and is then released as a result of that.

Similarly, animal/people body growth is explained as a process in which “our body stores the glucose and converts it into energy when we need it”. The event of car running is explained as that “kinetic energy converts water or fuel particles into ATP for cars to use as energy”, or “energy of gasoline is converted into carbon dioxide”.

The second pattern is tracing energy without degradation. Students usually do not recognize that the total quantity of energy conserves, but the quality of energy—useful form of energy—always degrades. As the result, students may trace energy without recognizing that part of the energy dissipates as wasted heat. For example, students may claim that energy can be cycled in the ecosystem since energy conserves: “Energy is always reused in an ecosystem for the producers and consumers to use because it goes into the atmosphere and then is taken in by producers, which passes on to the next trophic levels”. One written assessment item asks students whether the same glucose molecule can also be used to maintain body temperature when it is used to move the little finger. Level 3 responses usually explain that since the glucose molecule has already been used to produce ATP in cellular respiration, it cannot be used to provide heat to keep body temperature. One example is: “No, because the glucose is apart of the ATP, but another glucose molecule can be used”. As shown in the response below, the student claims that EcoSphere only has energy input not energy output and justifies the claim in terms of a cycle that involve both changes of energy and matter: first plants use the energy of sunlight to produce oxygen and also “fuel” other organisms. In this cycle, energy is used again and again without degradation.

> *Do you think the EcoSphere has energy exchange with the outside environment?*
>
> The eco-sphere only takes in energy. It uses this to support the life that it has. For example, it uses the light to feed the plant. The plant provides oxygen, fueling the water to keep the shrimp healthy. Plus it fuels the algae, which the shrimp eat also, fueling the bacteria.

The third pattern is tracing energy without connection to chemical reactions. Some level 3 responses describe energy changing from one form to other forms, but do not correctly connect the process of energy transformation to relevant chemical reactions. Below is an interview excerpt:

Pre-interview (7^{th} Grader)

Girl Running

> Interviewer: How does each of the things, you mentioned food, water, and oxygen, help the child to run?
>
> Eric: Again I am not sure specifically, I believe it’s because it converts the energy that is in the food and sends it through either oxygen or water or the blood and it is through the body to use as energy for movement.

Eric explained girl running as the following: energy in the food was sent through oxygen, water, or the blood to use as energy of movement. He described the energy transformation—energy of food changes into energy of movement, but did not correctly explain how that change happens in the chemical reaction of cellular respiration. Instead, he treated oxygen and water, the two substances involved in cellular respiration, as the carrier of energy. The responses below are about tree decay. The student describes the process of energy transformation—potential energy is transferred into kinetic, moving energy, but s/he also states that the energy or ATP is used for decomposers to conduct cellular respiration.

> *Written Item: Is energy involved in the event of apple rotting?*
>
> Yes, potential energy is transferred from apple to decomposer, and it is then used to make ATP for the decomposers to perform cellular respiration, as well it is used by the decomposers to move and it is transferred into kinetic, moving energy.

To be noted is that at Level 3, students may provide conflicted accounts. They may still use the notion that the actor has ability to do things or the notion that energy "trigger" or "power" processes to explain the events, but the focus of their explanations is on tracing energy. For example, a student explained the event of baby girl growth as: "the child's body convert that stored energy into kinetic energy."

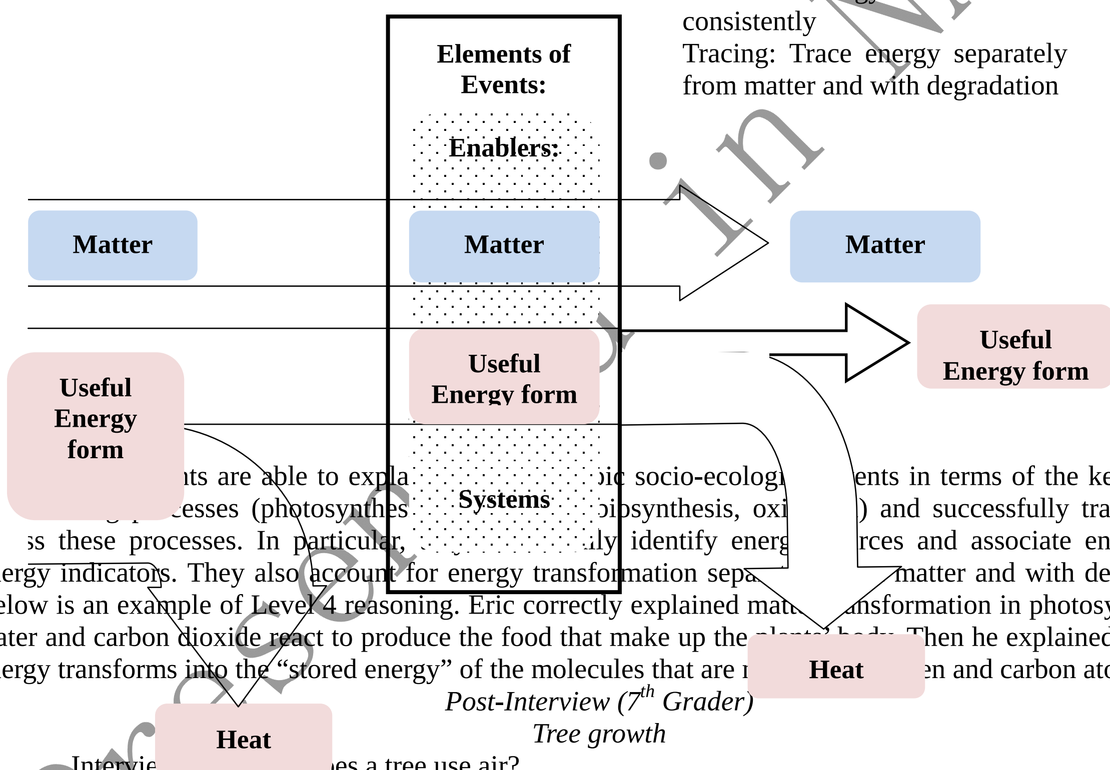
In summary, students relying on Level 3 reasoning develop the notion of energy and they begin to use energy as conceptual tool to analyze macroscopic events. They are able to associate energy with most energy indicators including organic carbon-containing molecules. However, since they usually do not recognize that energy is determined by the configuration of atoms in molecules, they often make some mistakes when identifying energy-rich materials. They attempt to trace energy backward and forward at the atomic-molecular and global scale. However, since they are usually not clear about the relation between energy transformation and matter transformation, they often cannot successfully trace energy.

Level 4. Trace energy successfully.

Level 4 is scientific reasoning of energy. It is represented in the Loop Diagram. The performances of Association and Tracing are represented in the diagram below.

Association: Associate energy with energy indicators consistently

Tracing: Trace energy separately from matter and with degradation



A[illegible]nts are able to expla[illegible]ic socio-ecologi[illegible]ents in terms of the key carbon-t[illegible]esses (photosynthes[illegible]iosynthesis, oxi[illegible]) and successfully trace energy a[illegible]ss these processes. In particular, [illegible]ly identify energ[illegible]rces and associate energy with energy indicators. They also account for energy transformation sepa[illegible]matter and with degradation. Below is an example of Level 4 reasoning. Eric correctly explained matt[illegible]ansformation in photosynthesis—water and carbon dioxide react to produce the food that make up the [illegible]. Then he explained that light energy transforms into the "stored energy" of the molecules that are [illegible]en and carbon atoms.

Post-Interview (7th Grader)
Tree growth

Intervie[illegible]es a tree use air?
Eric: The carbon dioxide in the air contains molecules, atoms. We mean specifically oxygen and carbon, which will store away and break apart to store it and use as food.
Interviewer: So do you think that the tree also uses water?
Eric: Yes. The tree also needs water. All living things do. The water is used to help break apart food so that the tree can have energy. *It's also used to combine parts of the water molecules together with parts of the carbon dioxide in photosynthesis and used as food*.
Interviewer: So, you know, the tree, it begins as a very small plant. So over time, it will grow into a big tree and it will gain a lot of mass. Where does the increased mass come from?
Eric: *The mass comes from the food that the tree is producing during photosynthesis, which is mostly carbon and hydrogen pieces bonded together and that is then being stored away*
… …

Interviewer: So you also talk about energy, light energy. So where does light energy go?
Eric: *Light energy is, first it's absorbed through the leaves. It is then converted to a stored energy by combining the hydrogen and carbon atoms into various molecules.*

The Naming progress variable describes students' performances of verbatim reproduction of vocabulary. Accounts at different Explaining levels are built upon different sets of words. For example, accounts at Level 1 are basically constructed by using words about actors, enablers, and results, while accounts at Level 3 are built upon words about atoms, molecules, and energy forms. Based on this idea, I first developed four groups of words that are aligned with the four Explaining levels. However, empirically, some words could be more familiar to students than other words in the same group, simply because they are used as common language words in everyday life. Hence, we made empirical adjustment to the four levels, which led to two intermediate levels—Naming Level 1.5 (easier hidden mechanism words) and Naming Level 2.5 (easier scientific words). More details about the Naming progress variable are discussed in another paper about the project (Jin, et. al., 2009).

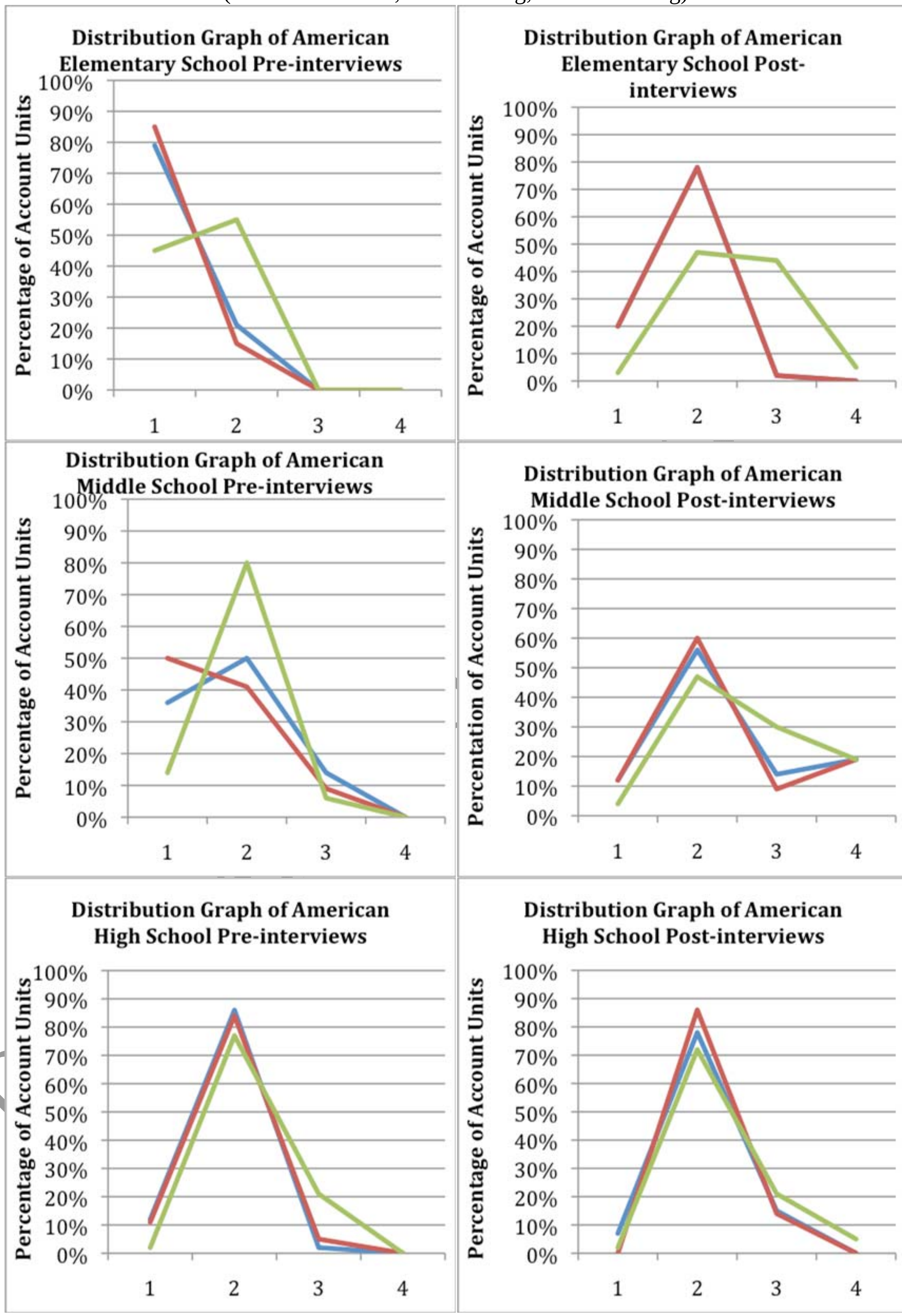
Development of Different Learning Performances

In the final learning progression framework, the three progress variables—Naming, Association, and Tracing—are three dimensions of learning performances. The Association progress variable and the Tracing progress variable each contains four levels of achievement. The Naming progress variable contains six levels of achievement. The levels of each progress variable are aligned in terms of the logic relations among them. However, in real situations, the same students may demonstrate different achievement levels for different progress variables.

We used the final version of the learning progression framework as the guideline to re-code all the interview data and written assessment data. The interviews and written assessments were divided into account units. Each account unit has three scores: the Naming Level, the Association Level, and the Tracing Level. We used the coding results to generate distribution graphs, which show the percentage of account units at each level of the Explaining (Association and Tracing) and Naming progress variables. The distribution graphs enabled us to identify patterns of student progress. In the paragraphs below, we use both qualitative examples and the distribution graphs to represent the patterns of students' development of different learning performances.

Below are the distribution graphs for pre-interviews and post-interviews at different school levels. The comparison between the distribution graphs shows three trends.

Figure 2. Distribution Graphs of American Pre-interviews and Post-interviews
(Blue: Association; Red: Tracing; Green: Naming)



The comparison among the distribution graphs indicates two trends. First, the development of Association performance is aligned with the development of Tracing performance for both pre-interviews and post-interviews. Altogether, 9.8% account units in pre-interviews (N=183), 5.6% account units (N=160) in post-interviews have different Association and Tracing Levels. In other words, students tend to rely on coherent reasoning to account for everyday socio-ecological events. There is debate about coherent or fragmented reasoning. Some researchers argue that students rely on coherent theories or framework to understand the world. Others believe that students tend to use fragmentary structures such as p-prims (diSessa, 1987). The finding of our research provides another example of the coherent theory.

Second, the comparison between the development of Explaining performance and the Naming performance indicates that the students' Naming performance is developed ahead of their Explaining performance. This pattern is shown at all school levels and in both pre-interviews and post-interviews. An important implication of this pattern is that teaching energy should focus on teaching the coherent reasoning about energy rather than focusing on transmitting scientific words to students.

Third, the graphs show improvement at elementary and middle school levels but not at the high school level. From pre-interviews to post-interviews, the distributions shifted toward higher-level responses for both Naming and Explaining at elementary and middle school levels. At the elementary level, the account units in pre-interviews tend towards Level 1 in Explaining and Level 2 in Naming, while the account units in post-interviews tend towards Level 2 in Explaining and Level 2 and 3 in Naming. This indicates that the teaching experiment is effective in helping the elementary participants to recognize the hidden mechanisms behind macroscopic events. At the middle school level, the post-interview distribution graphs show a significant increase in Level 3 and Level 4 accounts for both Explaining and Naming. However, this pattern of progress is not shown at high school level. The majority high school students still relied on Level reasoning to make accounts and they did not show significant improvement in using scientific vocabulary. One possible reason is that high school participant teachers did not use all the teaching modules we designed.

Implication

In science, energy is an abstract quantity that applies to many science topics. It is very difficult for students to understand, because we cannot see energy either through our naked eyes or any high technology. We can only "feel" it. Based on our everyday life experience, we know that light, heat, and motion indicate energy. Sometimes, we cannot even feel energy. Foods and fuels contain chemical energy, but we cannot feel it. When teaching energy, there is always the tension between the need of making energy "concrete" for students and the need to keep energy concept scientifically rigorous. This tension makes energy a disturbing topic in school science.

Current school science teaching does not successfully solve this dilemma. Some times, we try to keep the rigorousness of the concept, but neglect students' ways of knowing. For example, in physics, energy is defined as the ability to do work. This definition introduces the abstract concept of energy through another unfamiliar abstract concept—work. It does not provide students any useful information about what energy is and why it is an important concept to learn. Some times, we try to simplify the science content, but do not recognize that actually foster more confusions. For example, energy conservation is often expressed in science textbooks as that "energy is not created or destroyed". This statement is effective for rote learning. However, it is also misleading, because it does not clarify that energy cannot change into matter. Our data indicate that many students tended to use matter-energy conversion to make accounts.

Another problem with current school science teaching of energy is the lack of connection among different subject areas. In biology, energy is taught through a set of simplified biological narratives. These narratives are usually inferred conclusions about biological processes. They highlight the scientific facts but do not address the connection between the scientific facts and the energy principles. For example, energy pyramid is taught as the 10% rule—only about 10% energy is transferred to the next trophic level. This narrative does not explicitly address energy pyramid's connection to energy principles—the 90% energy lost at each trophic level is heat dissipating from the process of cellular respiration. A common science narrative about photosynthesis is that plants use light energy, carbon dioxide, and water to make food/glucose. Or, at the high school level, we often represent the formula of photosynthesis as: $CO_2 + H_2O$ + Light energy → Glucose + O_2. In theses narratives, energy is addressed at the reactants' side, but disappears at the products' side. Therefore, students may use their imagination to construct many misconceptions such as light energy powers photosynthesis or glucose is energy.

These are two common misconceptions we found in our data. We often describe energy transformation in ecosystems as "energy flow", but do not explicitly tell students that flow means the useful energy forms are decreasing due to heat dissipation. As the result, many students understand flow as recycle—energy can be used again and again.

Hence, we propose teaching energy through a coherent and reasoning-focused approach. It highlights two aspects of understanding: 1) a coherent reasoning about the two energy principles: energy conserves separately from matter; energy conserves with degradation. 2) a coherent reasoning that links processes at multiple scales—the atomic-molecular chemical reactions explain how and why the macroscopic events happen and the global processes of carbon cycling and energy flow explain the global effect of the macroscopic events.

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