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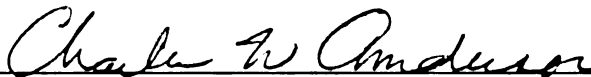
DEVELOPING A LEARNING PROGRESSION FOR ENERGY
AND CAUSAL REASONING IN SOCIO-ECOLOGICAL
SYSTEMS

presented by

HUI JIN

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**DEVELOPING A LEARNING PROGRESSION FOR ENERGY AND CAUSAL
REASONING IN SOCIO-ECOLOGICAL SYSTEMS**

By

Hui Jin

A DISSERTATION

**Submitted to
Michigan State University
in partial fulfillment of the requirement
for the degree of**

DOCTOR OF PHILOSOPHY

Curriculum, Instruction, and Teacher Education

2010

ABSTRACT

DEVELOPING A LEARNING PROGRESSION FOR ENERGY AND CAUSAL REASONING IN SOCIO-ECOLOGICAL SYSTEMS

By

Hui Jin

Global warming is one of the most serious environmental challenges we are facing today. Two science topics are important for students to understand how and why people's everyday energy consumption activities contribute to global warming. These two topics are: carbon-transforming processes and energy. They have been recognized as core content topics for many years in both science standards and curriculum. However, empirical research has uncovered that current school science learning was not successful in helping students to use knowledge of these two topics to explain how people's everyday energy consumption activities contribute to global climate change over time.

This study uses the approach of *learning progressions*—sequences of successively more sophisticated ways of reasoning about science topics (National Research Council, 2007)—to study K-12 students' understanding of energy as it relates to socio-ecological events that contribute to the global climate change. I develop a *learning progression framework* that describes increasingly sophisticated ways of reasoning students display in their explanations of socio-ecological events, use the learning progression framework to measure students' achievement in written assessments, and use the learning progression framework to investigate mechanisms of students' progress.

Students from 4th grade to 11th grade in suburban and rural schools of a Midwestern state participated the research. I used both interviews and written assessments to elicit students' accounts about energy and the socio-ecological events. I found that the differences between scientific explanations and students' intuitive explanations are reflected in two aspects of learning performances—Association and Tracing. I also found that, instead of using energy, students with less science background tended to use informal entities such as “natural ability” and “vital power” to make accounts. Based on these two findings, I developed the learning progression framework:

1. Natural ability: to associate natural ability loosely with various aspects of the events and trace the macroscopic action-result chain;
2. Vital power: to associate vital power with enablers and trace the power-result chain;
3. Energy: to associate energy with energy indicators and trace energy unsuccessfully;
4. Energy: to associate energy with energy indicators and trace energy across scales successfully.

I used the learning progression framework to measure students' achievement and found that most students did not achieve Level 3, at which the reasoning based on energy conservation began to develop. I also used the learning progression framework to investigate mechanisms of students' progress. I found that students tended to rely on relatively cohesive and consistent reasoning to account for events. They often construct coherent synthetic reasoning by using strategies to reconcile features of scientific knowledge learned from school with their existing force-dynamic reasoning. The results of this study contribute to the emerging theoretical understanding and empirical basis of learning progression research.

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To my husband Renlong Ding and my son Richard Ding.

ACKNOWLEDGEMENT

This study could not have been completed without support from many people.

Dr. Charles Anderson provided mentorship for my academic development. I would like to gratefully thank him for his guidance, understanding, and patience during my studies in Michigan State University. For five years, he had advisor meeting with me every week, helping me with my study and research. He always pushed me to accomplish more than I had ever thought possible. He is the kind of scholar I would some day hope to be.

I would like to thank my committee members, Dr. Jack Smith, Dr. Gail Richmond, Dr. Avner Segall, and Dr. Lynn Paine, for their support and guidance in my intellectual growth. In particular, I would like to especially thank Dr. Jack Smith, who provided critical and thoughtful comments for my dissertation and course papers. I would also like to thank Gail Richmond, for her help and support particularly in my beginning years of graduate study.

I would like to thank my colleagues, Li Zhan, Jonathon Schramm, Jing Chen, Hamin Baek, Kennedy Onyancha, Lindsey Mohen, Karen Draney, Jennie Choi, and Yongsang Lee, for their help with coding and calibration. I am also grateful for their helpful comments and suggestions for my dissertation study.

I would like to thank the participant teachers, Marie Toburen, Susan Zygodlo, Marcia Angle, Russ Stolberg, Cheryl Hach, Liz Ratashak, for their assistance and support in data collection. I would also like to thank their students, who participated in this study. I really enjoyed talking with them in the interviews.

I am grateful for the financial support from National Science Foundation. There are also other people who played important roles in my dissertation and academic development, even if they may not be aware of that. They are: Alicia Alonzon, Amelia Gotwals, Angela Barton, and Christina Schwarz.

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CHAPTER 1 INTRODUCTION

Energy is a fundamental concept that spans major science disciplines including physics, chemistry, and biology. It is a powerful conceptual tool scientists use to understand how socio-ecological events contribute to the global climate change. In particular, 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 socio-ecological events are explained in terms of a set of atomic-molecular carbon-transforming processes, which include photosynthesis, digestion and biosynthesis, cellular respiration, and combustion. Carbon transforming processes are constrained by two energy principles—energy conservation and energy degradation. Although energy and carbon-transforming processes have been highlighted as core topics in science standards and curriculum for many years, empirical research indicates that students hold many informal ideas and misconceptions related to these topics. In my dissertation study, I investigate K-12 students' accounts about the socio-ecological events and develop a learning progression for energy and causal reasoning to describe the increasingly sophisticated ways of reasoning that students display across school years.

RATIONALE FOR THE RESEARCH

I adopt the research approach of *learning progression* to investigate students' progress with respect to two science topics: energy and carbon-transforming processes. This study has three foci: energy, carbon-transforming processes, and causal reasoning.

Why Energy?

I chose energy as the focus of my study, because energy is a fundamental concept in science and science education, and it is also a very confusing concept for students. Energy plays a key role in all branches of science including biology, chemistry, and physics. It has also been consistently identified as a central concept in K-12 science curriculum. Why is energy so important? Feynman points out that energy is a useful concept, because it is a quantity that is always conserved; scientists can understand various changes, be they physical, chemical, or biological, by tracing energy (Feynman, Leighton, & Sands, 1989). Energy is so important. Then, how well do we teach it at K-12 level? Empirical studies have uncovered that students held many misconceptions of energy. Students' ability to apply the two energy principles to environmental issues could be even weaker. According to the National Environmental Education and Training Foundation's (NEETF) ten-year report (Coyle, 2005), only 12% of Americans passed a basic quiz on awareness of energy topics, and Americans' knowledge of energy issues lagged far behind their knowledge of other environmental issues. As NEETF claims, there is a serious problem of American's low energy intelligence.

Why Carbon-transforming Processes?

Carbon-transforming processes include photosynthesis, digestion & biosynthesis, cellular respiration, and combustion. They have been recognized as core topics of science curriculum for many years. Recently, they are receiving even more attention from science educators. The reason is that students need to understand carbon-transforming processes in order to achieve both scientific literacy and environmental literacy.

On one hand, understanding carbon-transforming processes is important to promote scientific literacy, because carbon-transforming processes manifest fundamental knowledge of major disciplines taught in K-12 schools. This knowledge includes the following: three physics principles that constrain carbon-transforming processes (i.e., energy conservation, energy degradation, and matter conservation), chemical reactions and chemical properties of materials, and biological processes (i.e., photosynthesis, digestion, biosynthesis, and cellular respiration).

On the other hand, understanding carbon-transforming processes is a major component of environmental literacy. Global warming is one of the most serious environmental problems that every country has to face and deal with. Carbon transforming processes explain the variety of socio-ecological events that contribute to global climate change. These socio-ecological events include various human energy consumption activities (burning fossil fuels, using electric appliances, etc.) and natural biological processes (plant growth, animal growth and body movement, decomposition, etc.). Among these events, plant growth is the only event that removes carbon dioxide from atmosphere. The underlying process that explains this phenomenon is photosynthesis. Humans consume foods and fuels from environmental systems and at the same time emit carbon dioxide into the atmosphere. This phenomenon is explained in terms of three processes—digestion & biosynthesis, cellular respiration, and combustion. When the carbon dioxide emitted into the atmosphere exceeds the carbon dioxide removed from the atmosphere, the concentration of carbon dioxide in atmosphere will increase, causing global climate change over time. This scientific understanding is becoming more and more important in recent years, because, as global warming is

becoming a bigger thread, students are expected to use their knowledge about carbon-transforming processes to understand how their everyday activities contribute to global climate change. Without this understanding, it is very difficult for people to recognize the necessity of changing their life styles.

Why Causal Reasoning?

I chose casual reasoning as the third focus. First of all, what is causal reasoning? Why is it important for science learning? Causal reasoning is at the core of explanations. An explanation answers why and how things happen. It identifies the cause of an event and explains how the cause produces certain effect. At the core of any explanation is the causal reasoning, or causation. Without it, the explanations do not have explanatory power.

To construct sophisticated explanations of socio-ecological events, students need to understand fundamental matter and energy principles (matter conservation, energy conservation, energy degradation) and key chemical reactions (photosynthesis, cellular respiration, and combustion). Although these topics have been recognized as the core content in national science standards and school curriculum for many years, empirical research indicates that students' ability to apply relevant knowledge to construct qualitative explanations is very weak.

One way to understand this problem is to think about how scientific knowledge has been constructed. The scientific knowledge, including scientific facts, concepts, principles, and theories, has been constructed and generated by a community of practitioners—scientists, over a long period of time. It always conveys the specific ways

of reasoning shared by the members within the science community. In science, the facts, concepts, principles, and theories are not fragmented knowledge pieces. They are coherently organized around scientific reasoning. In particular, the scientific explanations of the socio-ecological events are formulated and supported by discipline-specific causal reasoning, which can be characterized as “principles (energy conservation, energy degradation, matter conservation) constraining processes (photosynthesis, cellular respiration, combustion, digestion & biosynthesis)”. It is impossible to construct scientific explanations without a deep understanding of this underlying causal reasoning. Students usually have rich experience outside of the science classroom. Their life experience imparts various ways of informal causal reasoning, which are usually not identical with scientific causal reasoning. When scientific knowledge is transmitted without articulating the underlying scientific reasoning and when students’ informal reasoning left un-tackled, various misconceptions and confusions emerge.

This argument is also supported by empirical findings. In my previous studies on learning progression for energy, I found that although middle and high school students had learned about energy in their science classrooms, they tended to understand energy concepts based on their intuitive reasoning. While scientific reasoning about energy emphasizes a notion of constraints—energy principles constrain chemical processes, students tend to treat energy as power that can be used up to make things happen. If the scientific knowledge, energy concepts and principles in this case, is taught without emphasizing the underlying scientific reasoning, students will construct many intuitive meanings of energy based on their everyday reasoning. Hence, studying causal reasoning

will generate a deeper understanding of students' intuitive energy conceptions and provide informed suggestions for standards, instruction, and curriculum.

Why Learning Progressions?

I adopt the approach of learning progressions to study the development of students' understanding of energy and carbon-transforming processes. Learning progressions are sequences 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). They provide a new way for us to rethink the science standards. The current science standards are a set of content expectations for students at different grade levels. From a constructivist perspective, learning is a process in which students actively construct knowledge. Students' intuitive ideas play a key role in this process of knowledge construction (Cobb, 1994). Therefore, current science standards, with its neglect of students' thinking, would be misleading if were used as guideline for science teaching.

Unlike science standards, learning progressions are about students' ideas. They are sequences of increasingly sophisticated ways of thinking and reasoning students use to understand the real world. Therefore, learning progressions will be more effective in guiding meaningful science teaching and learning in schools. With respect to assessments, learning progression research often uses innovative assessment approaches such as diagnostic assessments and clinical interviews. Such approaches are more effective in eliciting students' understanding. Finally, in learning progression research, curriculum and instructions are often developed based on empirical findings about

students' understanding and therefore will be more effective in facilitating students' learning.

RESEARCH QUESTIONS

This study investigates students' reasoning with respect to energy in socio-ecological systems—how students account for socio-ecological events and whether and how they use knowledge of energy and carbon-transforming processes to make accounts. I intend to develop a *learning progression framework* that describes increasingly sophisticated ways of reasoning students commonly display in their explanations of the socio-ecological events, and use the learning progression framework to measure students' achievement and investigate mechanisms of their progress. Accordingly, the specific research questions are:

1. Development of the Learning Progression Framework:

- What are the causal reasoning patterns students use to account for the socio-ecological events?
- What are students' naïve ideas about energy as it relates to the socio-ecological events?
- How can students' intuitive causal reasoning patterns and naïve ideas about energy be ordered into increasingly sophisticated achievement levels?

2. Students' achievement:

- How can the learning progression framework be used to measure individual students' achievement?
- What are the general patterns of students' achievement?

3. Coherence and consistency of students' accounts:

- Do individual students reason at single achievement level or multiple achievement levels?
- If students rely on multiple achievement levels to make accounts,
 - 1) to what extent is their reasoning about each individual socio-ecological event coherent?
 - 2) to what extent is their reasoning consistent across different socio-ecological events?

Based on findings of these questions, I also suggest teaching approaches that are effective in facilitating students' progress towards scientific reasoning about energy in socio-ecological systems.

DISSERTATION OVERVIEW

This introductory chapter begins by pointing out the importance of energy and carbon-transforming processes as core topics in science and science education, and causal reasoning as the fundamental basis for conceptual understanding. I propose to use the approach of learning progression to study students' progress with respect to energy in the socio-ecological systems. Based on this discussion, I lay out three sets of research problems. They are problems about learning progression framework development, students' achievement, and mechanisms of students' progress.

In chapter 2, I review literature from four research strands: learning progression research, misconception research about energy, causal reasoning research, and conceptual change research. The literature provides useful but incomplete answers to my research

problems. First, empirical studies of learning progressions provide promising findings as well as challenging problems to be considered in designing the research. In particular, there are two critical issues to be considered: how to systemically integrate assessments, standards, curriculum, and instructions, and how to link students' naïve ideas to science in meaningful ways. Second, causal reasoning research and misconception research of energy uncovered many intuitive ideas from students. They provide useful information to understand students' thinking and reasoning. Finally, conceptual change research provides ideas about how to investigate mechanisms of students' progress.

In Chapter 3, I describe how I developed the conceptual framework based on the critical issues identified in Chapter 2 and how the conceptual framework is useful to solve the research problems. First, the conceptual framework aligns three research elements—learning progression framework, associated assessments, and suggested teaching approaches—around the core ideas of causal reasoning and energy conceptions. In particular, the learning progression framework describes students' progress in terms of two parameters—*progress variables* and *achievement levels*. In this chapter, I also reviewed two previous studies, based on which I identified two research dilemmas to be solved in developing the learning progression framework. The two dilemmas are: the dilemma between science-based progress variables and performance-based progress variables and the dilemma between lower achievement levels and the higher achievement levels. Then I discuss why and how the learning progression framework can be used to measure students' achievement and investigate the mechanisms of their progress.

In Chapter 4, I describe the research participants, the methodology, and research background. Interview and written assessments were conducted twice as the students were learning relevant knowledge. In this chapter, I elaborate how I designed interview protocol and written assessment items that elicit students' accounts about the socio-ecological events, and how I analyze data.

In Chapter 5, I first present the research findings and products. The learning progression framework has two progress variables—Association and Tracing—and address three increasingly more sophisticated entities—natural ability, vital power, and energy—that students use to understand the socio-ecological events. Then, I report the results of using the learning progression framework to measure students' achievement in written assessments. Finally, I describe the findings with respect to the mechanisms of students' progress. I found that students tended to rely on relatively cohesive and consistent reasoning to make accounts; they also tended to use strategies to reconcile new knowledge into their existing reasoning framework rather than restructuring their existing reasoning framework.

In Chapter 6, I summarize the findings of this study and discuss the implications for both research and practice. I focus on two major findings of this study: Tracing and Association as progress variables, and patterns of the cohesion and consistency of students' reasoning. With respect to research, I describe how this study fits in a broader research area and how the two major findings contribute to our understanding of students' understanding of energy. With respect to teaching practice, I make suggestions for teaching approaches based on the two major findings. Finally, I also discuss the

limitations and unsolved problems of this research, based on which I discuss my plan for future research.

CHAPTER 2 LITERATURE REVIEW

This study adopts the approach of learning progression to investigate students' achievement and progress with respect to energy in socio-ecological systems. I used an iterative research process, which lasted for five years. During the five years, my understanding of students' understanding about energy in socio-ecological systems underwent considerable development. The literature I drew on also changes a lot. The major contributors to my current research are ideas and studies from the following four research strands.

- *Learning progression research*

Previous learning progression studies conducted by other researchers have shown both promising findings and challenging problems, which informed the design of this research.

- *Misconception research about energy*

Empirical studies about students' misconceptions of energy uncover many intuitive energy conceptions of students. A better understanding of students' intuitive ideas about energy helps me to design assessments and develop the learning progression framework.

- *Causal reasoning research*

Causal reasoning research indicates that students may rely on intuitive ways of causal reasoning such as force-dynamic reasoning and hidden mechanism reasoning to explain their observations. These ideas help me to design more effective assessments and develop the learning progression framework.

- *Conceptual change research*

This study investigates students' progress with respect to their understanding of energy. Traditionally, such topics are studied within the conceptual change research. Recent conceptual change studies investigate the mechanisms of conceptual change through examining the cohesion and consistency of students' ideas. I used this approach to investigate the mechanisms of students' progress.

LEARNING PROGRESSION RESEARCH

A variety of different approaches to representing students' learning over time have been labeled "learning progressions". Most learning progressions have been developed based on empirical research. However, not everyone who writes about learning progressions agrees that empirical grounding is essential. For example, Heritage (2008) describes learning progressions as attempts to develop descriptions of expected student learning based on science content knowledge. Roseman et al. (2006) used concept maps to represent the learning progression for heredity, which describes the logical relations and orders of the scientific concepts and theories. However, if the ultimate goal of learning progressions is to promote science teaching and learning in real classrooms, they should be grounded in empirical data about real students' learning, thinking, and reasoning. This is the *empirical validation* of the learning progression research.

Empirical studies have developed learning progressions in a variety of science topics. Some learning progressions describe a sequence of science concepts, principles, or facts ordered from concrete to abstract and simple to complex. The assumption is that the understanding of any new knowledge relies on the mastery of previous more basic

knowledge. Although some of these learning progressions are developed based on assessments of students' performances, the primary concern is to find out which concepts and theories are easier and which are more difficult to students. For example, Liu and his colleagues used the TIMMS database to explore the developmental progression of matter and energy in K-12 students (Liu & Lesniak, 2006; Liu & McKeough, 2005). Lee and Liu (2009) conducted a similar research on energy concepts. These studies compare the difficulty levels of items about different concepts and theories. The final learning progression is a linear sequence of concepts and theories ordered in terms of the difficulty level. Although such learning progressions are developed based on empirical data, they do not address students' thinking. From this sense, these learning progressions are not empirically validated.

Many researchers have been engaged in the development and empirical validation of learning progressions. Usually, they represent learning progressions as sequences of students' performances (Alonzo & Steedle, 2008; Mohan, Chen, & Anderson, 2009; Schwarz et al., 2009; Smith, Wiser, Anderson, & Krajcik, 2006; Songer, Kelcey, & Gotwals, 2009). Among these efforts, diverse theoretical and methodological approaches are adopted. I conducted an analytical review to examine how different studies use learning progressions to address students' conceptual development.

Two of the above learning progressions address students' domain-general thinking. Songer et al. (2009) argue that learning progressions should address not only content knowledge but also students' "inquiry reasoning skills". The final learning progression they developed consists of a content progression and an inquiry reasoning

progression. The content learning progression is a sequence of science content topics ordered in terms of the difficulty levels identified based on assessment data. The inquiry reasoning progression is a sequence of meta-conceptual skills students used to construct scientific explanations. Students at one level of the inquiry reasoning progression could end up at all the different levels of the content progression. One advantage of this study is that, it recognizes that, as students are constructing explanations, their meta-conceptual awareness and strategies contribute to their conceptual development of content knowledge. However, the content progression they developed is still a sequence of science topics that address nothing about students' intuitive ideas related to those science topics. In this sense, this learning progression still lacks the empirical validation, at least to certain degree.

Schwarz et al. (2009) developed a learning progression for scientific modeling. Their research focuses on one specific meta-conceptual skill—modeling. The final learning progression is a sequence of students' performances of modeling from model as duplicate of phenomena to model as explanatory tools. They also studied how students make the “shifts” from a lower level to higher levels. The advantage of the learning progression for modeling is that the levels of the learning progression are not about the desirable modeling skills student should master, but are about what students did in real situations. However, their attempt to separate modeling skills from understanding of content is problematic. In particular, the “shifts” students made could be resulted from the development in understanding of the content knowledge rather than improvement of modeling skills.

Three studies address students' domain-specific thinking (Alonzo & Steedle, 2008; Mohan et al., 2009; Smith et al., 2006). They describe students' intuitive ideas with respect to the science topics. For example, the learning progression for force and motion address a sequence of ideas from the most naïve idea that force is push-and-pull to scientific understanding that connects force with motion by acceleration. The learning progression for carbon-cycling explicitly addresses students' specific ways of reasoning behind their learning performances, although, as will be discussed later, the lower-levels of this learning progression are not convincing enough. Smith and her colleagues (2006) used findings from empirical studies to develop a learning progression that addresses students' causal reasoning and epistemological beliefs. The implication of these three studies is that empirically validated learning progressions should have domain-specific cognitive basis. That is, learning progressions should address the development of students' thinking and reasoning in terms of cognitive constructs such as causal reasoning and epistemological beliefs.

In summary, one advantage of learning progression research comes from its integrative nature. Learning progressions can integrate assessments, standards, curriculum, and instruction in meaningful ways. In particular, two studies (Schwarz et al., 2009; Songer et al., 2009) include not only assessments but also teaching experiment. For learning progression to provide informed suggestions for classroom teachers, it should show the desirable learning trajectory of students, which only happen as students are exposed to effective teaching approaches. Another advantage of learning progressions comes from the empirical validation—the learning progressions are grounded on empirical data about students' real ideas. In particular, learning progressions are not

sequences of content expectations. They should address students' domain-specific reasoning as it relates to the science topics.

MISCONCEPTION RESEARCH ABOUT ENERGY

Empirical studies of K-12 students' understanding of energy focus on either or both of the following two aspects: energy concepts (energy definition, forms of energy, and energy sources) and energy principles (energy conservation and energy degradation). Studies of energy concepts investigate students' alternative views of energy. Studies focusing on energy principles investigate how students apply energy principles to physical and biological problems.

With respect to energy concepts, empirical research indicates that students usually have many intuitive ideas about what energy is and their ideas are apparently 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 energy principles, empirical research indicates that students lack the ability to use energy principles to construct qualitative explanations of problems in physical and biological contexts. Driver and her colleague found that students tended to rely on the definition of work (i.e., $W = Fd$), which was associated with more observable variables such as distance and force, and they seldom used energy conservation to solve problems—counting energy input and output (Driver & Warrington, 1985). Similarly, Duit (1984) found that students seldom used energy conservation to make predictions about mechanics problems. Solomon (1985) found that students tended 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 problems is even weaker. Barak et al. (1997) found that students often constructed ideas about energy that are contradictory to the energy principles: they tended to see energy as the vital power that is not conserved; they also tended to see heat as available energy form for organisms. Lin and Hu (2003) investigated the concept maps students developed to describe food chain and found that students seldom used energy flow to describe food chain, although they were more capable in identifying matter transformation in food chain. Similarly, Carlsson (2002) found that students generally do not have ideas about how photosynthesis and cellular respiration are connected in terms of energy principles.

As shown in the literature, the two content topics—energy concepts and energy principles—have been recognized as core topics in science education for many years and they are challenging topics for students. Therefore, it is important for the learning progression for energy to address these two content topics. Empirical studies of students' misconceptions about energy also uncover that energy is not a useful tool for most

students to construct their explanations. However, these studies do not provide enough information about what students are able to do. In other words, if energy is not a tool that students use to reason about events and solve problems, what could be the reasoning tools that students use? Literature about intuitive ways of causal reasoning provides some ideas to answer these questions.

RESEARCH ON CASUAL REASONING

Explanations tell about how and why things happen. At the core of explanations is the causal reasoning. However, when being asked to explain events, people may provide non-causal statements. Non-causal statements may be circular, subsumption, irrelevant, or covariation-based. Circular or repetitive statements do not provide any information beyond the information contained in the question (Keil, 2006). Subsumption statements are claims using lawful regularity or class inclusion. They do not address any causal processes or mechanisms behind the cause-effect relations (Brewer, Chinn, & Samarapungavan, 1998). Irrelevant explanations are totally irrelevant to the question asked. Covariation-based statements provide correlation information without entailing any causal processes or mechanisms behind the cause-effect relations (Ahn & Kalish, 2000; Ahn, Kalish, Medin, & Gelman, 1995; Salmon, 1984); Correlation does not imply causation. It is possible that the correlation between the two processes is not causal at all. Rigorously speaking, these non-causal statements are not explanations, because they do not explain how the cause produces certain effect.

Unlike non-causal statements, explanations stress causal reasoning. That is, they address the causal mechanisms behind the cause-effect relations—how the cause

produces the effect. There are different types of causal mechanisms. Gopnik and Wellman suggest that causal mechanisms are usually constructed around abstract theoretical constructs such as entities, processes, and principles (Gopnik & Wellman, 1994). A *teleological explanation* (Ahn & Kalish, 2000; Salmon, 1984) assumes that things occur for certain purpose. For example, people have hearts because hearts is required to circulate the blood. There is extensive evidence revealing young children's preference for teleological explanations across various contexts (Inagaki & Hatano, 1999; Kelemen, 1999, 2003; Lombrozo, 2006; Lombrozo & Carey, 2006). An *intentional explanation* considers beliefs and desires as the cause of processes (Carey, 1985). For example, people need to eat food because they feel hungry. If we use Gopnik and Wellman's theory to analyze teleological explanations and intentional explanations, we can find that these two types of explanations are constructed around the intuitive entity of "purpose" or "intention". A *mechanistic explanation* (Inagaki & Hatano, 1999) explains the cause-effect relations by means of mediating mechanisms. Scientific explanations are mechanistic. Although our everyday informal explanations could also be mechanistic, they rely on theoretical constructs different from those of the scientific explanations. For example, the scientific explanation of plant growth is built on a scientific model that has three theoretical constructs. These theoretical constructs are entities/concepts—matter and energy, process—photosynthesis, and principles—matter conservation, energy conservation, and energy degradation. The informal mechanistic explanations about plant growth may be constructed based on informal model that also have theoretical constructs. The theoretical constructs of the informal model can include informal entities such as leaves, roots, air, soil, and water, processes such as fresh air changing into waste gas and

nutrients in soil turning into the body structure, and principles such as body structure changing from solid and/or liquid materials.

Then, what are some characteristics of students' causal reasoning? Students construct their specific ways of causal reasoning through their interactions with the material world and the human society. Causal reasoning research has generated important findings about students' causal reasoning by investigating how students interact with the outside world.

First, students interact with the human society via language. The way they use their everyday language largely influences the construction of causal reasoning. There is increasing agreement in linguistic cognition that people construct specific ways of reasoning as they are learning and using their native languages. Cognitive linguists studying English grammar (Pinker, 2007; Talmy, 2000) suggest that English has implicit theories of cause and action—force-dynamic reasoning. According to the force-dynamic reasoning, there are two entities, each exerts a force on the other. The agonist has force tendency towards manifesting itself, while the antagonist exerts the opposite force. According to their relative strengths, the opposing forces yield a resultant, which is either action or inaction. This force-dynamic reasoning can be used to explain the socio-ecological events. For example, the tree is the actor (agonist). It has the internal goal and ability to grow, but it also needs help from enablers such as soil, water, air, and sunlight. When the tree dies, its opponents (antagonists) such as bugs and bacteria will overcome it and make it decay. This force-dynamic reasoning is very different from scientific reasoning that treats actors, enablers, and opponents as being composed of matter and

energy and describes the interactions among them in terms of matter transformation and energy transformation.

Second, through the direct interactions with the material world, people construct intuitive ways of reasoning, which are useful tools for them to explain their observations and perceptions. The 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 examples in various contexts that students tend to explain processes in terms of *hidden mechanisms*. Hidden mechanisms are usually invisible or non-perceptual patterns that are isomorphic to the obvious patterns observed at the phenomenon scale. Some examples of hidden mechanism reasoning are as follows: Grotzer (2000) found that students hold the idea that the battery and a light bulb connected by one wire instead of a circuit would make the bulb light up. This explanation is built upon a consumer-source chain, which is isomorphic to the macroscopic pattern—the batteries are the power sources and light bulbs are the appliances that 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. They tend to think that diffusion is caused by individual liquid molecules' intentional movement from high to low concentration. This reasoning of hidden mechanism is different from scientific reasoning that explains diffusion as the result of random movement of individual molecules.

The literature about students' intuitive causal reasoning indicates that students use intuitive ways of reasoning such as force-dynamic reasoning and hidden mechanism

reasoning to understand the world. These causal reasoning patterns are very different from scientific reasoning about energy and carbon-transforming processes. So, do students rely on these informal ways of causal reasoning to account for socio-ecological events and how? If they do, how are these informal ways of reasoning related to their understanding of energy? All these are important problems need to be investigated in this study.

CONCEPTUAL CHANGE RESEARCH

The learning progression framework describes students' progress in terms of a sequence of increasingly sophisticated ways of reasoning. In this study, we are concerned about students' progress that indicates conceptual development. Traditionally, students' conceptual development is studied in conceptual change research. New ideas from conceptual change studies also inspired my study.

Recent studies investigate the mechanisms of students' conceptual change by examining the cohesion and consistency of students' ideas. There are two major theories: the theory theory and the "knowledge-in-pieces" theory. Researchers from these two perspectives hold different ideas about the nature of students' knowledge, mechanisms of conceptual change, and desirable teaching approaches.

Theory Theory versus Knowledge-in-pieces Theory

There is a lively controversy within conceptual change research as to whether students' ideas are theory-like or fragmented. Theory theorists argue that students rely on a few coherent domain-specific theories to explain the phenomena they encounter in their

everyday life (Carey, 1985; M. T. H. Chi, 2005; Gelman, 1990; Gopnik & Wellman, 1994; Ioannides & Vosniadou, 2002). Knowledge-in-pieces theorists, on the other side, describe students' knowledge as p-prims (Andrea diSessa, 1993) or facets (Minstrell & Stimpson, 1996), which lack core characteristics of scientific theories.

To compare these two theories, we first need to know what theories are. Scientists use theories to interpret and explain observations and make predictions. In everyday usage, the word "theory" is used to denote a broad variety of conceptual understandings, from vague speculations such as guess, hunch, and conjecture, to testable hypothesis. So, what counts as a theory? What are the cores of a theory? What are some criteria that can be used to justify whether students' ideas are theory-like or fragmented?

Gopnik and Wellman (1994) discuss the nature of theory. They distinguish two concepts: empirical typologies/generalizations and theories. Empirical typologies and generalizations are "orderings, partitioning, and glosses of evidence and experience". They are at the level no deeper than that of evidence and "share the same basic vocabulary as the evidence itself". In this sense, empirical typologies and generalizations are mostly descriptive. They do not have explanatory power. Many of our everyday speculations share the key characteristics of empirical typologies and generalizations. For example, explaining why organisms need different things to live and grow by saying that because organisms are either animals or plants and animals and plants have different needs, is generalization and lack explanatory depth.

Unlike empirical generalizations, theories are tools people use to explain the world and make predictions. They have explanatory power. While empirical typologies

and generalizations only describe the evidential cause-effect relations, theories tell about the causal mechanisms behind the cause-effect relations. To manifest the causal mechanisms, theories have to be abstract and coherent. Gopnik and Wellman propose to define theories as systems of abstract constructs such as entities, processes, and principles. Theoretical constructs are abstract in the sense that they are proposed at a level deeper than that of the superficial evidence and therefore must be phrased in a vocabulary that is quite different from the evidential vocabulary. That is why and how theoretical constructs can be used to address causal mechanisms behind the evidential cause-effect relations. Theoretical constructs are also coherently connected, so that the explanations built upon them will make sense and provide interpretation. For example, the movement of planets can be explained in terms of the theory of gravitational force. This theory contains abstract constructs. It has three entities—force, mass, distance, which are abstracted from the superficial phenomena. It also has a principle— $F = GMm/r^2$, which describes the inter-relationships among the entities.

In general, the above discussion on the nature of theory suggests a way to understand and compare the theory theory and knowledge-in-pieces. Theory theory suggest that students' naïve ideas are built upon abstract and systemically connected theoretical constructs, while knowledge-in-pieces argue that students' ideas are basically empirical generalizations and lack theoretical depth.

Theory theorists argue that children develop domain-specific theories such as naïve theories of physics, psychology, and biology at very young age. A naïve physics theory about object interaction and movements—Theory of Body Mechanisms (ToBy)—

appear at very early stage of life such as infancy (Alan M. Leslie, 1994; Alan M. Leslie, 1995). This naïve physics theory can be analyzed in terms of Gopnik and Wellman's theory about theory. Movement of physical objects is explained in terms of theoretical constructs including entities, processes, and principles. The entities are "FORCE"—a type of primitive and generative power—and Agents—objects that have FORCE. The processes are mechanical interactions and movements of objects. The principles are: 1) when objects move, they possess or bear FORCE, and 2) when objects contact other objects, they transmit, receive, or resist FORCE. Naïve psychology is also developed at very early stage. For example, as young as three years old, children are able to understand that psychological entities such as thoughts and dreams are mental and immaterial. They are able to distinguish psychological entities from physical objects and entities (Wellman & Estes, 1982). Naïve biology is differentiated from naïve psychology later when children are at about ten years old. This naïve biology theory is characterized by different researchers as "living kind" theory (Carey, 1985), vitalistic theory (Inagaki & Hatano, 2004), or container theory (Crider, 1981). All these theories are developed based on biological entities such as organs, biological processes such as blood circulation, and principles such as organs functioning to maintain life and foods providing vital power to maintain life.

On the other side, knowledge-in-pieces theorists argue that even at high school level students' intuitive ideas can still be fragmented and lack theoretical depth. For example, students have constructed hundreds of relatively independent ideas (e.g., heavier things move faster) to explain movement of objects (Hunt & Minstrell, 1994). Students' understanding of physics is composed of hundreds of or thousands of p-prims

(phenomenological primitives), which are abstracted from life situations and are spontaneously and unconsciously activated when explaining different phenomena (Andrea diSessa, 1993). According to Gopnik and Wellman's theory about theory, the p-prims and facets are basically empirical generalizations not theories.

The debate between theory theory and knowledge-in-piece theory focuses on the cohesion and consistency of students' reasoning—whether students' intuitive ideas are cohesively constructed around theoretical constructs and how consistent do they use the reasoning to account for different events. These two different perspectives explain the mechanisms of students' conceptual development as different types of processes.

Knowledge-in-pieces theorists argue that conceptual change is a process of knowledge integration, in which new elements of knowledge is added, and, at the same time, connections among initially separated elements are developed (Andrea diSessa, 2002; Linn, Clark, & Slotta, 2003). However, this approach does have empirical difficulty. It is possible that students' repertoire of intuitive ideas are fragmented from scientists' perspective but are actually embedded in hidden causal reasoning frameworks from students' eyes.

Within theory theorists, both agreements and controversies exist with respect to the specific process and mechanisms of conceptual change. Most theory theorists distinguish conceptual development at two levels (M. Chi & Roscoe, 2002; Johnson & Carey, 1998; Vosniadou, 1994). At the level of knowledge enrichment, new information is added to an existing conceptual system. In this process, some peripheral ideas and concepts are also corrected. Unlike the process of knowledge enrichment, conceptual

change is a type of radical change. It involves the restructuring of the basic conceptual system or transformation of fundamental principles of the existing conceptual system. In this research, I focus on conceptual change, since the development of scientific reasoning about energy requires radical transformation of students' existing reasoning frameworks.

Carey (2009) defines conceptual change as a process in which a new incommensurate conceptual system is transformed from an existing one. Incommensurability means that the two conceptual systems share no common set of primitives. She further describes three major forms of conceptual change: conceptual differentiation, conceptual coalescence, and reanalysis of a concept's basic structure. In conceptual differentiation, the descendant new concepts are developed and differentiated from parent concept, and the undifferentiated parent concept from the existing conceptual system no longer plays any role in the new conceptual system. Two examples of conceptual differentiation are: the differentiation of weight and density from the parent concept of 'feel weight' and the differentiation of heat from temperature. In conceptual coalescence, fundamentally distinct concepts in the existing conceptual system are subsumed under a single concept in the new conceptual system. Two examples of conceptual coalescence are: Galileo's abandonment of Aristotle's distinction between natural and artificial motion and the coalescence of liquids, solids, and gases into a single concept of matter. The third form of conceptual change is reanalysis of a concept's basic structure. One example is Newton's reanalysis of weight from a property of objects to a relationship between objects.

Chi points out that Carey's theory about conceptual change largely relies on analysis of history of science and does not manifest how the new concepts and the existing concepts are incommensurate in students' understanding (Chi & Roscoe, 2002). Chi's research focuses on the ontological basis for conceptual change. She and her colleagues conducted a set of studies to investigate conceptual change of different science concepts and found that some naïve conceptions responded easily to instruction, while others were robust and resist change. Their conclusion is that some naïve conceptions are robust, because they often require shifting ontological categories. The ontological shift poses specific challenge to students, since students usually do not have meta-conceptual awareness of their own understanding and they often lack the ontological category for the new concepts or theories. For example, students encounter tremendous difficulty in understanding some science concepts such as heat, electrical current, light, natural selection, and diffusion. The reason is that students often categorize these concepts as a kind of substance or event, when in fact all of these concepts belong to the ontological category of equilibration processes (or, emergent processes). The equilibration processes consist of two levels of behaviors: the observational level and the constitutional level. The macroscopic phenomena we observe and perceive are explained in terms of the behaviors and movements of entities at the constitutional level. The behaviors and patterns at the constitutional level are very different from those at the macroscopic observational level.

Vosniadou studies students' understanding of physics concepts. She points out that students hold a naïve framework theory of physics. The naïve framework theory consist of framework theories—fundamental ontological and epistemological

suppositions and theories that describe the core structure of the conceptual domain—and specific theories—theories that describe various properties and behaviors of physical objects (Vosniadou, 1994, 2002). It is relatively easier to change the specific theories than the framework theories. Specific theories can be changed without revision of the framework theory. Conceptual change happens when the fundamental framework theory changes. In particular the conceptual change consists of three stages. First, students form the naïve framework theory based on their life experience. As students go to school, they are exposed to science instruction that is inconsistent with their existing framework theory. They try to assimilate new knowledge with the existing framework theory, which results in a set of incoherent and unstable synthetic meanings. Finally, the internal inconsistency is resolved and conceptual change is fulfilled. In the process of conceptual change, the cohesion and consistency of students' reasoning first breaks down and then re-established as new reasoning framework is fully developed.

In general, knowledge-in-pieces theorists claim that students' understanding is a repertoire of relatively independent knowledge pieces. Therefore, conceptual change is a process of knowledge integration: adding new science concepts and principles to the existing repertoire, correcting mistaken knowledge pieces in the existing repertoire, and gradually making appropriate connections among the knowledge pieces. Theory theorists argue that students rely on domain-specific theories to interpret their observations and make predictions. Students' naïve theories share some core characteristics of scientific theories. Both of them have abstract and coherent theoretical constructs such as entities (concepts), processes, and principles. Conceptual development usually happens at two different levels. Conceptual enrichment adds new information to the existing conceptual

system without restructuring it. Conceptual change happens when the fundamental conceptual system is radically restructured. This change takes several forms such as conceptual differentiation, conceptual coalescence, re-analysis of the basic structure, shift of ontological category, and synthesis and resolving inconsistency.

On one hand, it is very difficult to make the judgment with respect to which theory is correct. Especially, it is possible that students' ideas are theory-like within a certain context and are fragmented in a larger context. On the other hand, it is important to investigate the cohesion and consistency of students' reasoning, since the investigation of this aspect helps us to better understand mechanisms of students' progress and further provides informed suggestions for teaching approaches. In this study, students who reach the upper anchor of the learning progression framework should be able to use the scientific reasoning of energy to explain the socio-ecological events. In particular, their reasoning should be coherent within each individual event and consistent across different events. Therefore, the cohesion and consistency of students' reasoning constitute an important aspect of students' achievement. Investigation of this aspect will bring implications for us to better understand students' progress.

SUMMARY

In this chapter, I review literature from four research strands: learning progression research, misconception research about energy, causal reasoning research, and conceptual change research. The literature provides useful but incomplete answers to my research problems.

With respect to learning progression research in general, two important issues should be considered. First, many learning progression studies propose to integrate assessments, standards, curriculum, and instruction together, but there is no study systemically integrate these elements together. Second, although many learning progression studies take into account the empirical validity—grounded the learning progressions on empirical data from students, most of them do not link students' naïve ideas with science in meaningful ways.

With respect to the development of learning progression framework, misconception research and causal reasoning research provide plenty of useful information. In this research, I intend to develop a learning progression framework that begins with students' most naïve ideas and ends with scientific big ideas about energy and carbon-transforming processes. Two energy related topics—energy concepts and energy principles—should be involved in scientific big ideas, because misconception research of energy shows that these two topics are the most important topics for understand energy yet they are also the most confusing topics to students. With respect to students' naïve ideas, causal reasoning research indicates that students tend to reason based on intuitive ways of causal reasoning such as force-dynamic reasoning and hidden mechanism reasoning, and misconception research uncover many naïve energy conceptions of students.

Finally, conceptual change research suggests that the investigation of the cohesion and consistency of students' ideas would provide useful information to better understand the processes and mechanisms of students' progress. In this study, I investigated the

cohesion and consistency of students' reasoning and discuss how they help us to better understand the challenges students encounter as they progress towards the upper anchor—the scientific reasoning of energy in socio-ecological systems.

CHAPTER 3 CONCEPTUAL FRAMEWORK

In this study, I intend to 1) develop a *learning progression framework* that describes increasingly sophisticated ways of reasoning students commonly display as they are learning relevant science content, 2) use the learning progression framework to measure students' achievement, and 3) use the learning progression framework to investigate the mechanisms of students' progress.

In this chapter, I first describe how I developed the conceptual framework for the research based on ideas from literature. The conceptual framework contains three elements—learning progression framework, associated assessments, and suggested teaching approaches. My dissertation focuses on the element of learning progression framework. Details of assessment development are discussed in a book chapter (Jin & Anderson, 2010). I also report some data from a pilot teaching experiment in this dissertation.

Then, I discuss how I designed research to develop the learning progression framework and use the learning progression framework to measure students' achievement and investigate mechanisms of students' progress.

CONCEPTUAL FRAMEWORK OF THE LEARNING PROGRESSION RESEARCH

Based on the analysis of recent learning progression studies, I suggest two important characteristics of learning progression research. First, learning progression research should have an integrative nature—the learning progressions align assessments, standards, curriculum, and instruction together. Second, it should have empirical

validity—addressing the development of students’ domain-specific reasoning as it relates to certain science topics. These two characteristics are embodied in the general conceptual framework of learning progression research, which is represented in Figure 1.

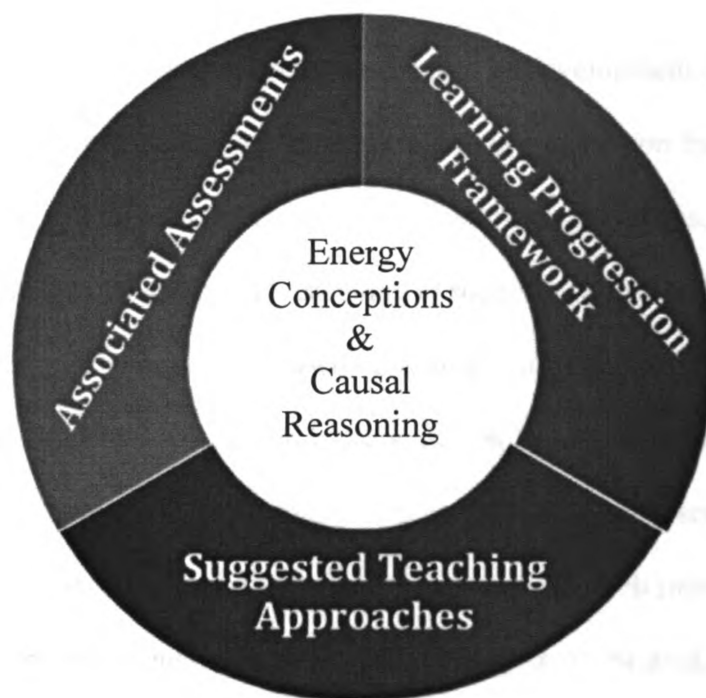


Figure 1 A General Conceptual Framework for Learning Progression Research

The general conceptual framework has three elements: learning progression framework, associated assessments, and suggested teaching approaches. The learning progression framework is a sequence of increasingly sophisticated reasoning patterns students normally display as they are explaining socio-ecological events. It can be used to measure individual students’ achievement and progress. The associated assessments include clinical interviews and diagnostic written assessments. They are designed to effectively elicit students’ ideas related to energy and socio-ecological events (carbon-

transforming processes). The teaching approaches are developed based on the learning progression framework, with the intention to facilitate students' transition from their intuitive ideas towards the scientific understanding of energy in socio-ecological systems.

The three elements of the conceptual framework are aligned together around the center of energy conceptions and causal reasoning. The development of one element is depended on the other two elements. First, the learning progression framework should capture a full range of ideas about energy in socio-ecological systems, from the most naïve energy conceptions and causal reasoning to sophisticated scientific causal reasoning of energy. It is developed based on students' intuitive ideas identified from assessment data. Students' ideas could be very different under different teaching approaches. If a successful teaching experiment is conducted, the researcher could collect data that show how students make successful transition from their naïve ideas towards scientific reasoning about energy in socio-ecological systems. Second, the assessments should be designed in ways that effectively elicit students' energy conceptions and intuitive ways of causal reasoning. Therefore, the learning progression framework can be used as guideline for assessment development. The assessment data could vary when students are exposed to different teaching approaches. Finally, teaching approaches are designed to facilitate students' transitions toward scientific reasoning of energy. The learning progression framework, which tells about how students' intuitive energy conceptions and informal ways of causal reasoning are different from scientific reasoning of energy, can be used as guideline for the development of teaching approaches. The effectiveness of the teaching approaches is then evaluated by assessments.

In this research I focus on one element of the general conceptual framework, the learning progression framework. The assessments have been designed and continuously revised during iterative cycles. They were effective in eliciting students' intuitive ideas about energy in socio-ecological systems. Details about the design of the assessments are reported in another paper of the project (Jin & Anderson, 2010). Teaching experiment was conducted in this research, but it was not successful for two major reasons. First, the teaching materials were designed based on previous learning progression frameworks developed in the project. Therefore, they do not address some important findings of students' understanding, which are critical for developing effective curriculum. Second, due to the pressure to complete school curricula, unfamiliarity to the teaching materials, and other reasons, the participant teachers did not use the teaching materials systemically. They only picked some activities to teach. Therefore, although I conducted interview and written tests both before and after the teaching intervention, the data does not allow me to investigate whether and how students make transitions under effective teaching approaches.

In this study, I first developed the learning progression framework and then used the learning progression framework to measure students' achievement and investigate the mechanisms of progress. Details are addresses as following.

DEVELOPMENT OF THE LEARNING PROGRESSION FRAMEWORK

The learning progression framework is anchored at one end of students' most naïve causal reasoning and energy conceptions and on the other end of the learning goal—scientific causal reasoning about energy in socio-ecological systems. These two

anchors are linked by a set of intermediate levels. The general structure of the learning progression framework is represented in Table 1. The research team of Environmental Literacy Research Project developed it.

Table 1 Learning Progression Framework

Achievement Levels	Progress Variables		
	Variable 1	Variable 2	Variable 3
Upper Anchor			
Intermediate Levels	Learning performances		
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’ conceptual development is usually reflected in multiple dimensions of learning performances. All these dimensions can be used as progress variables to describe students’ conceptual development. For example, students’ accounts are about different type of bio-chemical processes including photosynthesis, digestion & biosynthesis, cellular respiration, and combustion. So, the different bio-chemical processes can be used as progress variables to measure students’ conceptual development. A complete account of any process should address matter, energy, and/or scale. So, matter, energy, and scale can also be used as progress variables. It is crucial to identify progress variables that describe the differences between students’ intuitive reasoning with scientific reasoning in ways that uncover their different epistemic practices. Only by this way, we would be able to understand why some scientific concept

like energy is so difficult and confusing for students and why students' intuitive ideas resist change even after teaching intervention.

Students' learning performances with respect to each progress variable can be ordered into different levels in terms of scientific proficiency. They are achievement levels. Achievement levels contain lower anchor, intermediate levels, and upper anchor. Lower anchor is defined by the most naïve reasoning that students hold as they enter schools. Upper anchor is the scientific reasoning of energy that we expect high school graduates to master. Intermediate levels are reasoning patterns that students construct as their intuitive reasoning encounter school science learning. Theoretically, the levels along different progress variable can be aligned in terms of the logical relations among them, but, in real situations, the same student may achieve different levels for different progress variables. For each progress variable, students could also rely on reasoning patterns at different achievement levels.

Upper Anchor

Based on ideas from environmental research and big ideas from disciplinary knowledge, I developed the upper anchor of the learning progression. It is represented as the Loop Diagram (Figure 2). It highlights the notion of tracing energy with degradation across carbon-transforming processes at multiple scales—macroscopic, atomic-molecular, and global scales.

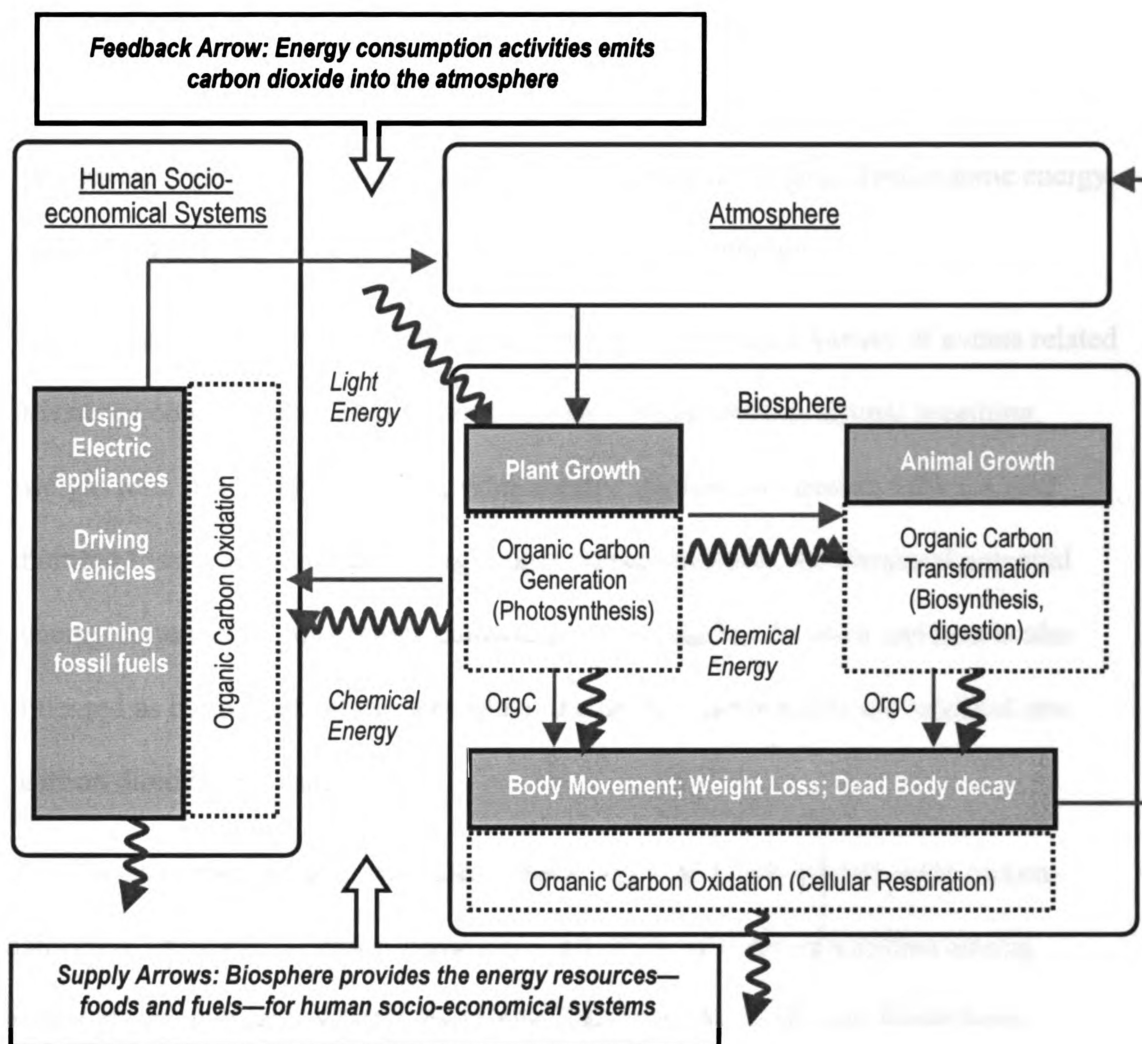


Figure 2 Loop Diagram: the Upper Anchor of the Learning Progression Framework

In our everyday life, a variety of macroscopic socio-ecological events are related to global warming. These events all involve carbon-transforming processes. The events in the blue boxes are some examples. These macroscopic 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 the biological and socio-economical systems on a global scale.

- *Passing on Energy*: Digestion and biosynthesis explain the event of animal growth. Fossil fuel formation explains how foods (plants and animals) become fuels. In these processes, organic compounds change from one form to another, losing some energy as heat but keeping most energy as chemical potential energy.
- *Using Energy*: 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. At the same time, the organic compounds are oxidized into carbon dioxide and water.

The atomic-molecular processes collectively lead to two global-scale carbon-transforming processes—carbon cycling and energy flow. Carbon is cycled among human socio-economical systems, biosphere, and atmosphere. Energy flows from biosphere to the human socio-economical systems with heat dissipation. Human socio-economical activities largely rely on the 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 atmosphere, causing global climate change over time. Two points need to be noted about energy transformation are: energy is always conserved separately from matter, and energy is always conserved with degradation.

Two Previous Studies

I have been working with the Environmental Literacy Research Project for five years. In the project, we conducted research in iterative cycles. This study was conducted in 2008-09 academic year. Before it, four research cycles have been completed. In particular, two previous learning progression studies (Study 1 and Study 2) informed my dissertation study.

Study 1. Energy as the Progress Variable

In Study 1, I used energy as the progress variable to analyze data. The data analysis focuses on students' understanding of energy. The learning progression framework is represented below.

Table 2 Energy as Progress Variable

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

This learning progression framework has both conceptual problems and empirical problems. 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 and hidden mechanism reasoning. In other words, the science-based progress variable—energy—is not effective in measuring students' understanding at lower levels. In the project, my colleagues developed a learning progression framework to describe students' conceptual development of matter concept. The correlation between matter progress variable and energy progress variable was 0.96 (Choi, Lee, & Draney, 2009), indicating the empirical problem that the separate codes for matter and energy were largely redundant.

Study 2. Naming and Explaining as the Progress Variables

The other study that informs my dissertation research is a cross-cultural study. I collaborated with my colleagues and conducted a cross-culture interview study in US and China (Jin, Zhan, & Anderson, Submitted). We found that although some students, especially Chinese students, were able to mention scientific terms in their explanation, they still relied on relatively lower-level reasoning to make accounts. Therefore, we used Naming and Explaining as progress variables to describe the differences of the learning performances American and Chinese students demonstrate.

The Explaining Progress Variable describes the nature of the explanations students gave. It is the combination of the previous matter progress variable and energy progress variable.

The Naming Progress Variable refers to the performance of verbatim reproduction of vocabulary. That is, how students used both informal and scientific vocabulary in accounts. Accounts at different Explaining Levels are built upon different sets of words.

For example, accounts at Naming Level 1 are basically constructed by using words about actors, enablers, and results, while accounts at Level 3 are using words about atoms, molecules, and energy forms. Therefore, we 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). The detailed Naming levels are represented as below:

- *Level 1 Words about actors, enablers, and results*

Words at Level 1 are words used to construct force-dynamic accounts. These words include observable parts of the actors, names of the enablers, and the observable and perceptual results such as strong, warm, grow, etc.

- *Level 1.5 Easier hidden mechanism words*

Level 1.5 contains words about internal organs of living actors, internal parts of machines, different types of fuels, and everyday words with mixed meanings such as material and heat. The word material can be used to refer to either matter or object. Similarly, heat can be used to refer to either energy or warmth. Due to the ambiguous nature of these words, we put them as Level 1.5, between Level 1 and Level 2.

- *Level 2 Hidden mechanism words*

Level 2 accounts use words about hidden structure of actors and enablers (e.g., carbon dioxide, oxygen, nutrients, gas), hidden properties associated with energy (e.g., electricity, calories), or invisible hidden processes (e.g., digestion, break down).

- *Level 2.5 Easier scientific words*

Level 2.5 accounts contain general scientific terms (i.e., atom, molecule, and chemical change/reaction) and words that can be used to mean specific organic molecules, energy forms, chemical reactions, but are also common language words used in everyday life or easier scientific words normally used in elementary science classrooms. Sugar and starch are organic molecules involved in carbon-transforming processes. However, these words are also common language words. If you go to supermarket, you can buy sugar, starch, or organic milk. Photosynthesis and decomposition are names of the atomic-molecular carbon-transforming processes; they are also included in elementary curriculum and are therefore very familiar to many elementary students. Hence, we put these words as Level 2.5, between Level 2 and 3.

- *Level 3 Scientific words describing organic molecules, energy forms, and chemical changes*

Level 3 accounts contain words naming specific organic molecules, energy forms, or chemical reactions. These words are normally introduced at middle or high school level.

- *Level 4. Complete list of reactants and products or all energy forms*

Level 4 accounts provide either a complete list of reactants and products of the chemical reaction or a complete list of energy forms involved in the chemical reaction.

When using the Naming and Explaining Progress Variables to code the interview data, we found that there was *discrepancy of development* between Naming and Explaining Performances. Many students' Naming Performance is developed ahead of their Explaining Performance. These students tend to name scientific words without understanding.

Below is an excerpt from the interview with a 4th grader, Sherry. It is about the event of car running.

Mid-interview (4th Grader)

Car Running

Interviewer: How does the gasoline change when it is used by the car?

Sherry: Well, when it burns, it's a liquid and then it turns into gas.

Interviewer: What gas?

Sherry: The exhaust that comes out of the car, that's gasoline that is like just left over and doesn't need to be used.

Interviewer: Do you think the exhaust is still gasoline or does it become something else?

Sherry: It might be ... I think it becomes smoke because it's not the part that the car needs anymore. It just lets it out and it just goes into the air.

Interviewer: Do you think it's still the same material?

Sherry: Sort of yes and sort of no, because it's letting out gasoline. So it sort of has to be gasoline, but yet it's smoke. It's kind of both.

... ..

Interviewer: Let's talk a little bit about energy. Do you think gasoline has energy?

Sherry: *Oh yeah, because the gasoline is sort of like food for the car. It's a chemical energy because it helps the car run like us. We have our food that helps us go for the day.*

Interviewer: Where does that chemical energy go?

Sherry: *We burn energy. We burn the food and it goes in the places that we need it for nutrition.* The car again with exhaust, it lets it out and the car needs parts of the gasoline ... it's sort of like nutrition for us.

Interviewer: You mean energy or gasoline?

Sherry: Yeah.

Interviewer: You mean energy or do you mean gasoline? Which one?

Sherry: *The gasoline it's the food. It turns into the energy of the car.*

Interviewer: When you are saying the energy of the car, you mean the energy of the car running. Right?

Sherry: Um hum.

Interviewer: Okay. So when the car stops, it is not running. Where does that energy go?

Sherry: Well, the engine is sort of still running, but it's not moving. *So the energy just sort of like stops and then when the car goes again, it starts flowing through.*

Sherry used a Level 3 phrase, chemical energy, in her responses. She said: "The gasoline is sort of like food for the car. It's a chemical energy because it helps the car run like us." However, Sherry was not able to associate chemical energy with any specific organic molecules. Instead, her responses indicate that food, chemical energy, and nutrients mean the same thing for her. On the other hand, Sherry's explanation about how gasoline helps the car to run indicates that she relied on Level 2 reasoning to make accounts: The gasoline, or energy, powers the car, so the car runs; after the gasoline is used, it becomes exhaust, which is basically smoke, and goes to the air; when the car

runs, the energy, or gasoline, flows and when car stops, it stops flowing. Therefore, Sherry's accounts about car running were rated as Explaining Level 2 and Naming Level 3. Although Sherry used the Level 3 scientific phrase chemical energy to explain the event, she did not understand chemical energy as a type of energy form associated with organic molecules. Instead, she treated chemical energy as another name of food and still relied on a lower level reasoning to make accounts.

Although the Naming and Explaining Progress Variables have enabled us to find the different patterns of progress that American and Chinese students display, 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.

Dilemmas in Developing the Learning Progression Framework

The two previous studies bring promising findings as well as challenges. In particular, there are two dilemmas with respect to the development of the learning progression framework.

The first dilemma is between science-based progress variables and performance-based progress variables. Study 1 used the science-based progress variable, energy. Study 2 used the performance-based progress variables—Naming and Explaining. Which kind of progress variables is more effective in measuring students' achievement and progress? 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 compare American and Chinese students'

learning performances, but they tend to describe performances in ways that lose track of science. On the other hand, due to the importance of energy in science and science education, it is important to use it as progress variable to measure students' understanding. However, younger students do not use energy to account for events, indicating energy progress variable cannot be used to measure and describe younger students' reasoning. One way to resolve this dilemma is to identify progress variables that are not only performance-based but also science-based. That is, the progress variables should manifest specific learning performances that both scientists and students exhibit.

The other dilemma is uncovered in Study 1. It is the dilemma between lower achievement levels and higher achievement levels. While higher levels (Level 3 and 4) describe students' performances related to an entity (i.e., energy), the two lower levels (Level 1 and 2) describe causal reasoning (i.e., force-dynamic reasoning and hidden mechanism reasoning). How do we make the levels descriptions consistent across levels? Theory theorists argue that young children explain the world in terms of domain-specific naïve theories and, their theories are abstract, coherent, and systemic to certain degree. Therefore, the two intuitive ways of causal reasoning, force-dynamic reasoning and hidden mechanism reasoning, could also be built around some intuitive entities. On the other hand, as uncovered by misconception research, students do hold intuitive image of energy such as effort, ingredient, power, activity, etc. If we can identify these intuitive entities and figure out how they are related to students' intuitive energy conceptions, we will be able to make the level description consistent.

INVESTIGATION OF STUDENTS' ACHIEVEMENT AND PROGRESS

When developing the learning progression framework, I first identify patterns of students' reasoning or other learning performances by examining their explanations of the socio-ecological events. Then I order the reasoning patterns and characteristic performances in terms of the sophistication and scientific value. Based on this work, I develop the achievement levels of the learning progression framework. Obviously, the learning progression framework developed in this way only contains disconnected achievement levels. It does not address students' progress—how students make the transitions towards the upper anchor. So, how can I study mechanisms of students' progress?

I used the learning progression framework to investigate mechanisms of students' progress. Since the teaching experiment was not successfully conducted, it is impossible to study how individual students' progress during the teaching intervention. Conceptual change research suggests another way to study mechanisms of students' progress. Here, we only concern students' progress as it particularly relates to conceptual development. In the process of conceptual development, the cohesion and consistency of students' ideas change. Knowledge-in-piece theory describes conceptual development as a process, in which students gradually add new elements to their existing repertoire of ideas and make appropriate connection among the ideas to achieve more and more cohesive thinking. Theory theory describes conceptual development as a process of conceptual framework transformation, which begins with assimilating new knowledge with existing theoretical framework, constructing ideas that are inconsistent, and finally reach a

cohesive new framework. Both theories describe mechanisms of students' progress in terms of the cohesion and consistency of students' thinking and reasoning. In this study, I adopted the same approach. I investigate students' progress by examining the cohesion and consistency of students' reasoning indicated in their explanations of the socio-ecological events.

By consistency, I mean the cohesion of individual students' reasoning across different socio-ecological events. By cohesion, I mean the cohesion of students' reasoning within each socio-ecological event. Student may rely on reasoning patterns at two or more levels to account for events. In such situations, students' accounts should contain features of different achievement levels (Figure 3). Some of these features are compatible, while other could be incompatible. It is important to identify incompatible features and examine whether and how students use them in their accounts.

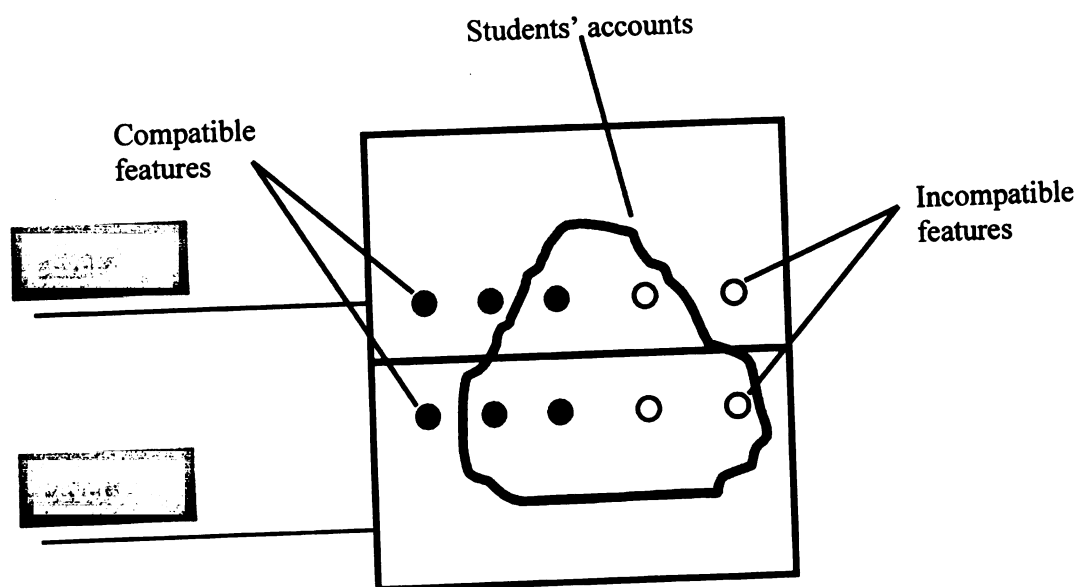


Figure 3 Cohesion of Students' Reasoning

Presumably, students in the sample could be at different stage of conceptual change. Some of them may mostly rely on their informal reasoning to make accounts. Some are at the midst of conceptual change and may rely on reasoning patterns at two achievement levels. Some accomplish conceptual change and reach Level 4. For students at different stages, the cohesion and consistency of their reasoning could have similar or different patterns. These patterns depict the mechanisms of students' progress.

SUMMARY

This chapter begins with the description of how I designed the conceptual framework based on the issues and ideas emerged from the literature review. The conceptual framework contains three elements: learning progression framework, associated assessments, and teaching approaches. This study focuses on the development of the learning progression framework and using it to measure students' achievement and investigate mechanisms of students' progress.

I first developed the upper anchor based on ideas from science. Then, I analyzed two previous learning progression studies and identified two dilemmas to be handled in developing the learning progression framework. The first dilemma is between science-based progress variables and performance-based progress variable. To solve this dilemma, it is important to identify progress variables that are both science-based and performance-based. The second dilemma is between lower and higher achievement levels—the level descriptions are not consistent. The solution to this dilemma requires identifying informal entities, which on the one hand are used to build students' informal

ways of causal reasoning and on the other hand implicate students' intuitive energy conceptions. In other words, these informal entities should reflect how students' naïve theories and intuitive energy conceptions are conflated.

I also discuss why and how students' achievement and progress can be studied. Students' achievement can be measured by using learning progression framework to code written assessment data. Mechanisms of students' progress can be investigated in terms of cohesion and consistency of students' reasoning in interview data.

CHAPTER 4 RESEARCH METHODS

In this chapter, I describe the research participants, assessment instruments including clinical interview and diagnostic written assessments, and data analysis.

RESEARCH PARTICIPANTS

The participants are students from 4th grade to 11th grade. They came from classrooms of two elementary school teachers, two middle school teachers, and two high school teachers. The schools are located in suburban and rural areas of a Midwest state. One high school is a math and science center in the State. Students from different schools in the nearby districts go to the math and science center to take AP courses. Most of these students go to college after they graduate from high schools. All other schools are regular public schools.

Initially, I was planning to conduct teaching experiment in this research. I worked with my colleagues and developed teaching materials. Written assessments and interviews were conducted before and after the teaching experiment, which lasted for two to four weeks. However, due to pressures from schools, the participant teachers only picked several activities to teach. During most time of the teaching experiment, they used their school teaching materials. None of the participant teachers used our teaching materials systemically with their students. Therefore, the assessment data only allow me to develop the learning progression framework and measure students' achievement. They do not allow me to assess students' progress under effective teaching approaches or evaluate the effectiveness of the teaching approaches we designed.

All participant students attended written assessments. Among these students, we randomly chose eight students from each school level (four students from each teacher's classroom) to attend the clinical interviews. The written assessments and interviews were conducted twice. The data sources are represented in the table below.

Table 3 Participants at the Three Stages of Research

Assessments	Elementary School	Middle School	High School
First Test	91	214	222
Second Test	125	211	207
First Interview	8	8	8
Second Interview	8	8	8

ASSESSMENTS

In this research, I adopted two assessment instruments: clinical interview and diagnostic written assessments. Clinical interview is effective in eliciting detailed accounts from students. It provides important information for me to understand students' energy conceptions and informal causal reasoning. However, due to the relative small sample size, the findings from the interview data cannot be generalized to the institutional level. Therefore, I also used written assessments to collect a large sample of data. In this study, I developed the learning progression based on both interview and written assessment data. I then used the learning progression framework to measure students' achievement in written assessment. Finally, I investigated mechanisms of students' progress based on interview data.

In order to develop the learning progression framework, I collected data from a wide age range of students (from 4th to 11th grades), which brings the assessment challenge—how to develop interview and written assessment questions that make sense to students with diverse science backgrounds? High school students, who have learned relevant knowledge about energy and carbon-transforming processes, are able to understand questions about chemical changes and energy transformation. However, these questions usually do not make sense to younger students. In particular, the carbon-transforming processes at the atomic-molecular (photosynthesis, digestion & biosynthesis, cellular respiration, and combustion) and global scales (energy flow) are usually invisible to younger students. Therefore, I have constructed the questions around a set of macroscopic socio-ecological events that are familiar to all participants.

I also designed the questions at different difficulty levels to fit students' differing abilities. As uncovered by relevant literature, younger students may construct accounts relying on force-dynamic reasoning, which explains events in terms of actors, enablers, and results. Therefore, the lower-level questions ask about 1) the needs of the actors, 2) changes happening to the actors and enablers, and 3) connections among macroscopic events. Misconception research indicates that students construct many intuitive ideas about energy concepts and principles and they apply these intuitive ideas to explain events. Therefore, higher-level questions focus on eliciting students' understanding of energy concepts and principles. In particular, they investigate students' understanding of the following aspects: 1) Identifying forms of energy and energy sources; 2) Applying the two energy principles (energy conservation and energy degradation) to explain individual macroscopic socio-ecological events; 3) Applying the two energy principles to explain

how different macroscopic socio-ecological events are connected. In order to ask questions at different difficulty levels, I used the branching-structure interview and written assessment item pairs.

Interview Protocol

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 happening to energy or matter in general. Higher-level questions ask about energy transformation in chemical changes or energy transformation 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 4 Types of Questions asked in interviews

	Questions at three difficulty levels
Identify enablers or energy forms and energy sources	<i>Lower-level Questions</i> 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? <i>Transition Questions</i> 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	<i>Lower-level Questions</i> 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? <i>Transition Questions</i> 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? <i>Higher-level Questions</i> 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	<i>Lower-level Questions</i> ask about the connection among the events in general. Examples: How are these events connected? <i>Higher-level Questions</i> 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?

Written Assessment Items

The written assessment items are about similar socio-ecological events. These events are plant growth, animal growth, animal body movement, animal maintaining body temperature, weight loss, flame burning, car running, using electric appliances, etc. Altogether, there are 17 written assessment items. Two of these item—grape and finger movement and weight loss—were revised from items initially developed in the DQC project (Diagnostic Question Cluster Project, 2009). One item was revised from the item initially designed in the Modeling Instruction Project (Swackhammer, 2005).

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 indicate 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 extent students identify energy sources and to what extent students trace energy at the atomic-molecular or global scale. The types of questions used in written assessment are elaborated in the table below.

Table 5 Types of Questions Used in Written Assessments

	Lower-level Questions	Higher-level Questions
Identify enablers or Energy sources	Questions that ask students to make distinctions among energy enablers and other things	Questions that ask students to identify the energy sources
Explain individual macroscopic events	Questions that ask students to explain changes happening to energy enablers such as light, foods, and fuels	Questions ask about energy transformation in chemical reactions
Explain connections among the macroscopic events	Questions that ask students to explain connections among the macroscopic socio-ecological events	Questions ask about energy flow at the 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 combinations of both lower-level items and higher-level items.

Some of the written assessment items are in pairs—the *item pair* asks about the same macro-process, 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, which require the student to chooses and then explain.

Below is an example of open-ended item pair. The item for high school students, the grape and finger movement item, asks how a glucose molecule changes to help body movement. It was proved effective in diagnosing whether and how students conserve energy in cellular respiration.

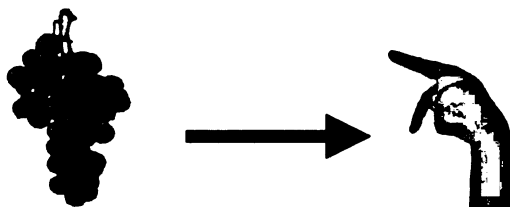


Figure 4 Item: Grape and Finger Movement Item

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.

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.

Although the grape and finger movement item was effective in identifying and distinguishing the level of more sophisticated accounts, it was not understood by younger students. Hence, I developed the elementary/middle school item—food and finger movement. It asks about the same process, but uses informal language that make sense to younger students. The item is shown as below:

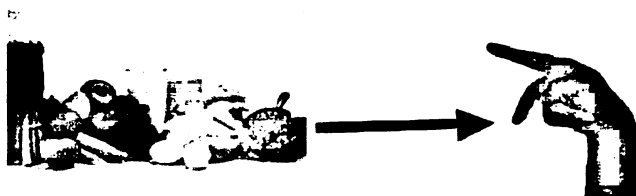


Figure 5 Food and Finger Movement Item

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

Some of the written assessment items are two-tier multiple-choice item pairs. They were revised from initial open-ended items. Both items of the item pair have two

tiers. 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 the students' responses to the open-ended question used previously. The elementary/middle school item contains distractors that are lower-level accounts about actors and enablers. Distractors in the high school item are higher-level accounts about energy and carbon-transforming processes at atomic-molecular or global scales. The data indicate that the two-tier multiple-choice item pair is effective in diagnosing and distinguishing the levels of students' accounts. Below is an example of the item pair—sunlight for plants.

The elementary/middle school item is shown below.

Elementary/middle school item:

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.

The options of the first tier represent two levels of reasoning. Options a, b, c, d, and f are macroscopic force-dynamic accounts. Choice a does not recognize that all plants need sunlight. Choice b, c, d, and f explain why plants need sunlight in terms of perceptions. They use terms about perceptions including warm, darkness, healthy, and

breathe. These accounts do not mention any invisible processes. So, they implicate the force-dynamic reasoning at the macroscopic scale. Option e is more sophisticated than other options. It links the macro-process to the invisible process of “making food”. The item also asks students to explain their choices, giving students the opportunity to write more details about their ideas.

The high school item is shown below.

High school item

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.)

The item contains options about how energy and matter change in the atomic-molecular process of photosynthesis. Both option a and option 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 option c suggests. These options are the common misconceptions identified from previous research cycles. Option d is the scientific account that successfully traces energy in photosynthesis. Option e does not recognize light energy as being related to any hidden

process involved in tree growth. It represents the reasoning level lower than the other options.

DATA ANALYSIS

In this study, I conducted three analyses:

- Analyze both interview and written assessment data to develop the learning progression framework
- Use learning progression framework to measure students' achievement in written assessments
- Use learning progression framework to investigate the cohesion and consistency of students' reasoning in interviews.

Development of the Learning Progression Framework

The first step is to develop the learning progression framework that has two parameters—progress variables and achievement levels along each progress variable. In particular, this work includes:

- Identify progress variables that are not only science-based but also performance-based.
- Identify informal entities that implicate both students' naïve energy conceptions and informal causal reasoning such as force-dynamic reasoning and hidden mechanism reasoning.
- Develop the achievement levels along each progress variable.

The unit of analysis is *account unit*. I divided each interview into eight account units. Each account unit is about one individual socio-ecological event (i.e., tree growth, baby girl growth, girl running, tree decay, flame burning, car running, lamp lighting) or the connections among the events. For each account unit, I grouped students' responses according to the characteristic reasoning reflected in the responses, and then ordered the groups in terms of the sophistication and scientific values. In the written assessments, accounts about each written item constitute one account unit. For each account unit, I randomly chose 10 responses from each school level (elementary school, middle school, and high school) for data analysis. I used the same approach to group and order students' responses. Then I closely examined these groups of interview accounts and written assessment responses in order to identify effective progress variables and informal entities students used to construction explanations. Based on this work, I developed the learning progression framework.

Measuring Students' Achievement

I used the learning progression framework to measure students' achievement in written assessments. I worked with my colleagues in data analysis. We used the learning progression framework as the guideline to develop rubrics for coding written assessment data. Nine graduate students in the project used the coding rubrics to code all written assessment data. Reliability check was also conducted. The agreement of coding for each written assessment item is above 80%. Based on the coding results, I generated a set of distribution graphs, which show the distribution of students' account units at each

achievement level. These distribution graphs indicate some general patterns of students' achievement.

Investigating Mechanisms of Students' Progress

The mechanisms of students' progress are investigated through examining the cohesion and consistency of students' reasoning. To study the consistency of students' reasoning, I work with my colleagues and used the learning progression framework to code all interview data. Each student's interview was divided into eight account units. Each account unit is about one event. We used the learning progression framework as guideline to code each account unit. Reliability was also conducted. 20% of the account units were coded by two coders. The agreement between different coders is above 90%. Based on the coding results, I constructed tables to show the consistency of each student's reasoning across events.

To study the cohesion of students' reasoning, I analyzed students' accounts of six individual events. These events are tree growth, baby girl growth, girl running, and tree decaying, flame burning, and car running. I did not include the two global-scale events, because the full interview usually lasted for one hour. In many cases, we did not have enough time to ask all interview questions about the two global-scale events. I first identified compatible and incompatible features based on the interview data. Based on this work, I developed the coding rubric to analyzing the cohesion of students' reasoning. I used the coding rubric to code all interview data. Reliability check is also conducted. One graduate student in the project coded 20% of the account units. The agreement of our

coding results reached 87%. The coding results show to what extent the students' reasoning is coherent.

SUMMARY

This chapter describes research participants and methodological issues. With respect to methodology, I discuss how I designed the interview protocol and written assessment items and analyze data in order to develop the learning progression framework, use the learning progression framework to assess students' achievement and progress, and evaluate the effectiveness of the teaching experiment. In order to develop the learning progression framework, I collected data from a wide age range of students (from 4th to 11th grades), which brings the assessment challenge—how to develop interview and written assessment questions that make sense to students with diverse science background? My solutions include constructing the questions around a set of macroscopic socio-ecological events and asking questions at different difficult levels.

Data analysis contains two steps. The first step is to develop the learning progression framework based on qualitative data analysis. At the second step, I used the learning progression framework to measure students' achievement in the written assessments and to investigate the cohesion and consistency of individual students' reasoning in interviews.

CHAPTER 5 FINDINGS

This research studies three aspects of students' conceptual development with respect to energy and causal reasoning in socio-ecological systems. The research problems are represented below:

1. Development of the Learning Progression Framework:

- What are the causal reasoning patterns students use to account for the socio-ecological events?
- What are students' naïve ideas about energy as it relates to the socio-ecological events?
- How can students' intuitive causal reasoning patterns and naïve ideas about energy be ordered into increasingly sophisticated achievement levels?

2. Students' Achievement:

- How can the learning progression framework be used to measure individual students' achievement?
- What are the general patterns of students' achievement?

3. Mechanisms of Students' Progress:

- Do individual students reason at single achievement level or multiple achievement levels?
- If students rely on multiple achievement levels to make accounts,
1) to what extent is their reasoning about each individual socio-ecological event coherent?

2) to what extent is their reasoning consistent across different socio-ecological events?

In this chapter, I first represent the learning progression framework that describes increasingly sophisticated ways of reasoning that students display as they are explaining the socio-ecological events. The learning progression framework was then used to measure students' achievement in written assessments and investigate the cohesion and consistency of students' reasoning in interviews.

LEARNING PROGRESSION FRAMEWORK

I developed a learning progression framework, which is a sequence of increasingly sophisticated ways of reasoning. As elaborated in chapter 3, two dilemmas need to be solved in order to develop the learning progression framework: the dilemma between science-based and performance-based progress variables, and the dilemma between lower and higher achievement levels. Based on the solutions to these two problems, I developed the learning progression framework.

Identification of the Progress Variables

The first dilemma is between science-based progress variables and performance-based progress variables. Although energy, as an important science concept, should be used as science-based progress variable to measure students' conceptual development, it is not effective in measuring younger students' understanding of the socio-ecological events. Naming and Explaining, as performance-based progress variables, enabled us to find important patterns of the development of students' performances, however, they tend

to measure and describe development in ways that lose track of science. The solution to this dilemma is to identify progress variables that are not only performance-based but also science-based.

I studied the historical development of energy concepts, since historical ideas usually reflect people's common ways of thinking. My intention was to discover, historically, what are some different meanings of the concept of energy and what specific epistemic performances scientists demonstrate as they developed and used the concept of energy. That is, why did people develop the concept of energy and how did they use the energy concept to understand the world.

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 the objects or organisms are in a states 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", and "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*:

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 (Feynman et al., 1989).

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, because part of the energy is always transformed into waste heat and dissipates into the environment. So, the total amount of energy stays the same, but the useful energy decreases. In science, energy is an abstract quantity that is always conserved yet it always degrades.

If we compare the Aristotelian notion of energy, which represents our informal reasoning about energy, with the scientific meaning of energy, we can find that the differences exist in two aspects of epistemic 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 a limited number of energy indicators such as motion, light, electricity, foods, fuels, warmth, etc. Second, Aristotelian energy only exists when things are 'being-at-work'. The energy and disappears when things are 'being-at-end' such as being dead or stopping moving. The scientific reasoning highlights tracing energy across processes. That is, whenever changes happen, the total amount of energy is conserved and the amount of useful energy decreases due to heat dissipation. Based on this analysis, I found that Association and Tracing are two epistemic performances that are implied in both informal (Aristotelian) and scientific reasoning. Therefore, they can be used as two Explaining Progress Variables to measure students' understanding of energy.

Identification of Informal Entities

The second dilemma of the previous studies is between energy conceptions and causal reasoning. While higher levels of the learning progression framework are about energy, the lower levels are about informal causal reasoning that does not involve energy. The solution to this dilemma is to find out whether students' naïve energy conceptions and informal ways of causal reasoning become inflated at certain point and how. Many studies indicate that students may use intuitive theories to explain the world and their theories usually have theoretical constructs such as entities, processes, and principles. Misconception research also indicates that students have constructed many intuitive energy frameworks. These intuitive energy frameworks are actually informal images about what energy is and how it behaves in events. They are in fact intuitive entities that

are very different from the scientific entity of energy. Therefore, if students make accounts by using certain informal entities, these informal entities may indicate both students' intuitive energy conception and informal causal reasoning.

In this study, I 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. The two informal entities, natural ability and vital power, implicate both informal causal reasoning and naïve energy conceptions.

Natural ability implicates both force-dynamic reasoning and naïve energy conceptions. Force-dynamic reasoning explains why events happen in terms of natural ability: actors use enablers to make things happen because both actors and enablers have certain naturally endowed abilities. Actors have the abilities, because that is how the natural world works or because the actors are made to have those functions. For example, plants have the natural ability to grow bigger; people and animals have the natural abilities to walk, run, eat, sleep, think, cry, etc.; flame has the ability to keep burning; cars are made to run. Enablers also have specific natural abilities. For example, wood can burn; water can make our body hydrated; foods can help our body to grow bigger and stronger.

Natural ability is also related to students' energy conceptions. Before the energy concept exists, the entity of natural ability takes its place to build explanations, but they implicate different ways of reasoning. With respect to the tracing performance, energy endures as the events are over. Energy must come from somewhere and go somewhere.

On the contrary, natural ability is naturally endowed and therefore it is not necessary to reason where it comes from and where it goes. With respect to the association performance, energy is a mechanistic entity that is associated with physical, biological, and chemical evidence, while natural ability is often associated with psychological attributes such as feelings and perceptions (e.g., being energetic, excited, warm, healthy, etc.).

Similarly, vital power also implicates informal causal reasoning and naïve energy conceptions. Vital power is the power contained in enablers such as sunlight, foods, fuels, soil, water, air, etc. The actors always need certain vital power from enablers. The vital power is often used up to make changes happen and always needs to be replenished. Vital power implicates force-dynamic reasoning, since it is the power that triggers changes. It also implicates hidden mechanism reasoning, since it is a type of invisible entity that associated with non-perceptual and invisible properties or compositions of enablers.

Vital power is a more advanced entity than natural ability, because it indicates that the mechanistic reasoning is differentiated from psychological reasoning. Although the psychological and naturalistic reasoning that actors have natural abilities still exists, the mechanical reasoning that explains events in terms of power triggering processes is developed and differentiated from the psychological reasoning. With respect to the association performance, vital power is an entity determined by the mechanical and biological properties of enabler rather than any psychological conditions of the actor. With respect to the tracing performance, since vital power is not naturally endowed, it

must come from somewhere. In this sense the entity of vital power is the first sign that students begin to trace things.

The entity of vital power shares some characteristics with the scientific notion of energy, because vital power has the implication that the actors cannot create energy, and that energy must come from certain sources, the enablers. In this sense, vital power can be treated as energy precursor. However, vital power is still very different from scientific concept of energy in that 1) vital power does not distinguish energy enablers such as sunlight, foods, and fuels from enablers that do not provide energy and 2) vital power does not endure as the events are over.

The Final Learning Progression Framework

The final learning progression framework for energy and causal reasoning in socio-ecological systems is represented in the table below.

Table 6 Final Learning Progression Framework

Explaining Progress Variables		
	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
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.

The learning progression framework is developed based on the integration of two ideas: 1) Association and Tracing as progress variables that are both science-based and

performance-based and 2) natural ability and vital power as informal entities that reflect both students' naïve energy conceptions and intuitive ways of causal reasoning. A complete learning progression framework should contain contains three progress variables. A Naming Progress Variable measures the performance of verbatim reproduction of vocabulary. Two Explaining Progress Variables—Association and Tracing—describe the nature of the accounts. This research focuses on the nature of students' accounts. Therefore, the table above does not show the Naming Progress Variable. Using Naming Progress Variable to measure students' development is discussed in another paper of the project (Jin et al., Submitted).

The Association Progress Variable and Tracing Progress Variable both have four achievement levels. From the lower anchor to the upper anchor, students construct their explanations based on different entities, from natural ability, via vital power, to energy. With respect to each entity, students' accounts indicates different Association and Tracing Performances:

- Association: Students associate different entities with different things. Natural ability is associated with actors, enablers, emotions, conditions, and so on. Vital power is associated with mechanistic properties or compositions of enablers. Energy is associated with energy indicators such as foods, fuels, light, warmth and so on.
- Tracing: Students demonstrate different Tracing Performances with respect to different entities. They do not trace natural ability. They trace vital power backward but not forward. They trace energy both backward and forward, although they may not always do that successfully.

Overall, there are four achievement levels for Association and Tracing Progress Variables. The achievement levels are described below.

Level 1. Natural ability as psychological, naturalistic, and temporal 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. They are downhill events. Although the specific explanations about 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 many aspects and elements of events such as actors, enablers, settings, motions, emotions, etc. It is also a temporal entity that does not endure when the events are over. The Level 1 reasoning is represented in the diagram below.

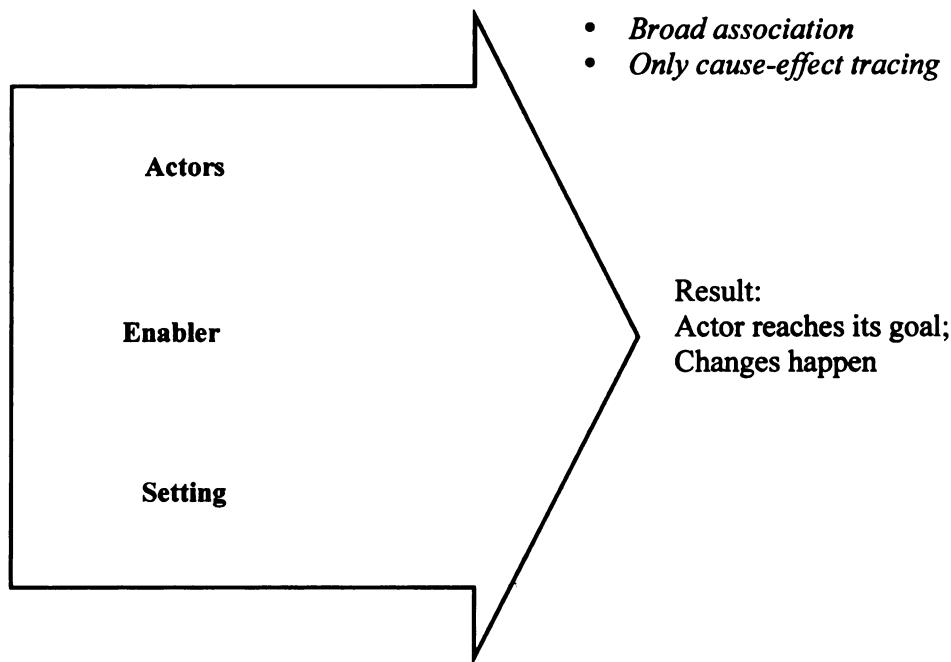


Figure 6 Level 1: Natural Ability as Naturalistic, Psychological, & Temporal Entity

With respect to Association Performances, Level 1 accounts indicate a broad association. They associate natural ability loosely with the elements and aspects of the event. Natural ability is associated with the actor: the actor has the natural ability to change towards the uphill direction such as growing, moving, and burning. Natural ability is associated with the enablers: the actor always needs to use certain enablers to make changes to happen, and certain enablers are useful for the actor because they have certain natural abilities. Natural ability is also associated with other aspects of the events such as activities, motions, emotions, feelings, and so on.

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

First 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, the word energy used in his accounts actually has the meaning of natural ability. Watson claimed that the girl gained energy from food and through sleep. He also 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 [the baby] grow and it helps it [the baby], so it [the baby] won't be crabby, like when you get mad". Obviously,

Watson associated energy with multiple aspects of the event including food, sleep, and emotion.

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 usually provide similar explanations for uphill events, downhill events, and connection among events. In the following paragraphs, I use examples of students' responses to explain the Level 1 Tracing Performances reflected in students' accounts about uphill events, downhill events, and connections among the events.

Accounts at Level 1 explain uphill events by tracing an action-result chain. The above 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; it takes certain actions such as eating foods and having enough sleep; as the result of the baby's actions, the baby's body grows bigger in size.

While uphill events are caused by the actor's actions, downhill events happen due to the lack of actions. Tree decaying and apple rotting are two examples of downhill events. In these events, decaying is treated as the natural tendency that happens when the actor—the organism—loses its ability to take actions as it is getting old or dead, or when the actor loses its enablers or living necessities. For example, some Level 1 accounts explain that the apple decays, when it “loses moisture”, or is not kept in the “cold fridges”. Some Level 1 accounts state that the tree decays, when the opponents such as bugs, birds, bacteria, or fungi “eat” or “overcome” the actors. Below is an interview

excerpt about tree decay. Amy mentioned that bacteria caused decaying, but she further explained that bacteria eat the dead body, indicating that bacteria were treated as the actor that utilized the apple for living.

First 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.

We also asked students to explain 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 does not endure after the events. As a naturalistic, psychological, and temporal entity, natural ability implicates two performances: a broad association and only cause-effect tracing.

Level 2 Vital power as a mechanical entity

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

- *First signs of energy specific association*
- *Initial tracing*

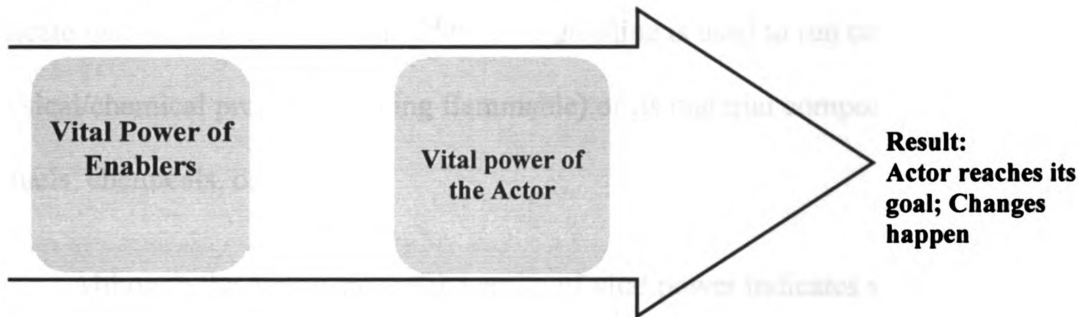


Figure 7 Level 2. Vital Power as Mechanical Entity

With respect to the performance of Association, the notion of vital power indicates progress in two aspects. First, while natural ability is associated with almost every aspect or element of events (actors, enablers, opponents, settings, motion, emotion, etc.) in terms of naturalistic plausibility, vital power is restricted to enablers. This indicates that students begin to recognize that 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 actors' actions such as sleeping or doing exercises do not create energy. Second, the notion of vital power also indicates that students begin to pay attention to hidden mechanisms. While, the notion of natural ability is associated with macroscopic perceptions, observations, desires, and feelings, vital power is associated with some '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. Some examples of Level 2 accounts are: gasoline contains “fuel”, “chemicals”, “oil”, or “fumes”; gasoline is “flammable” but water is not. These responses indicate that the students recognized that the gasoline is used to run cars because of its physical/chemical properties (being flammable) or its material composition (being made of fuels, chemicals, or fumes).

Although the emergence of the entity of vital power indicates some improvements in Association Performances, it is still very different from Association Performances implied in scientific reasoning about energy. First, 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, 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.

The interview excerpt below is an example that shows Level 2 Association Performance. The interview was conducted with a 9th grader. Richard stated that the baby girl needed energy to grow and the energy came from things the baby girl took in such as “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 with and restricted to enablers, although there is no distinction between energy enablers and things that do not provide energy.

First 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 in terms of a triggering process: The actors gain power from the environment and uses the power to trigger certain changes such as growth, bodily functions, movement, burning, and so on. 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. In the following paragraphs, I use examples to describe the tracing performances reflected in Level 2 accounts for uphill events, downhill events, and connections among the events.

Some examples of students explanations of uphill events 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”; the food we eat powers the action of growth; Energy from food “powers running”. According to this reasoning, as long as the vital power causes certain results, it is not necessary to worry about where the vital power goes. When being asked where the vital power (e.g., 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 an uphill event, tree growth. The interviewer asked Richard to explain what happened to oxygen when the girl’s body used 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. However, he did not trace energy forward—energy is used up and oxygen becomes carbon dioxide when losing energy.

First 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. For example, the energy/nutrients of the dead tree "evaporates" and goes into the air, or goes into the ground with the wood. 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 tree lost vital power and vital power goes into soil with the matter.

First 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.

Sometime, the downhill events are also explained as opponents gaining vital power from the dead bodies. For example, we asked students to explain whether and how energy was involved in the events of tree decaying and apple rotting in the written assessments. 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”.

In brief, the above examples indicate that accounts at Level 2 explain downhill events as a process of losing vital power. Students usually do not think about where the vital power goes. When being asked to explain, they often say that vital power goes with matter into air or soil. Some accounts explain decaying as an uphill event, in which opponents (bugs, bacteria, etc.) consume their own vital power to break the dead bodies and they can get more power by doing from the dead bodies.

Level 2 accounts about the connections among the events indicate that students begin to trace vital power at a global scale. For example, vital power is moving in food chains and food webs. As the vital power is passed on in food chains or food webs, some hidden processes may happen at the same time. 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. The student traced the power backwards along the food chain. He treated food chain as a chain that connected individual organisms by the feeding relations: the organisms were all located in the food

chain; each organism provided the vital power for the next organism on the chain to stay alive.

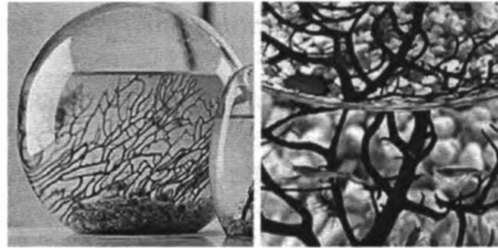


Figure 8 EcoSphere

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

mechanical/biological properties or 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 should be traced both backwards and forwards, vital power is a mechanical entity that loosely associated with almost all enablers and is usually 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. At Level 3, students begin to build their accounts upon the entity of energy. They begin to associate energy with energy indicators including the unobvious indicator—organic carbon-containing molecules. Instead of reason about uphill and downhill events, students recognize that all events are about changes of matter and/or energy. They also begin to trace energy both backward and forward, although they usually do not do that successfully. The graph below represents this reasoning.

- Energy/matter association
- Energy/matter tracing

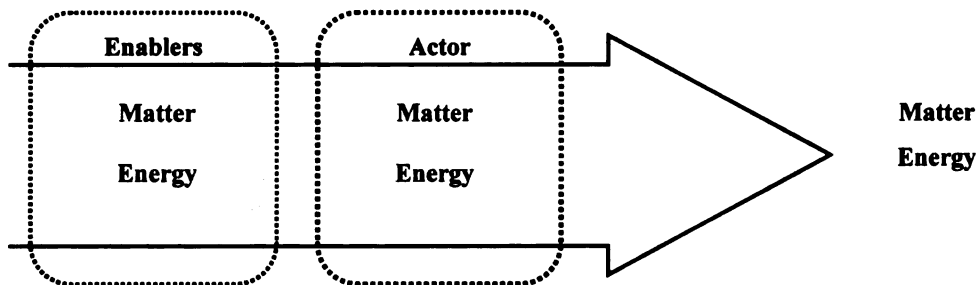


Figure 9 Level 3. Unsuccessful Tracing Energy

With respect to Association Performance, 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 often 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 Tracing Performances, Level 3 accounts attempt to trace energy not only backward but also forward in atomic-molecular processes or at the global scales. However, level 3 accounts usually cannot trace energy successfully. There are three patterns of this unsuccessful tracing.

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 do not trace matter and energy separately. Instead, they hold the idea that organic molecules can be converted into energy and vice versa. For example, plant growth is explained as that “photosynthesis that converts light energy into sugar (glucose)”. Decay is explained as that “once living thing is breaking down that energy is released in the form of carbon.” 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”. 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 molecule was converted into energy or into a special energy form—ATP—in cellular respiration. Below are two examples:

Response 1. 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).

Response 2. 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 its 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.

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 heat dissipation (degradation). In written assessments, we asked students whether energy is recycled in ecosystems. One response is: “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”. As shown in the example, the student claimed that energy could be recycled in the ecosystem, because energy is conserved. One written assessment item asks students whether the same glucose molecule used for finger movement can also be used to maintain body temperature. Many Level 3 responses explain that since the glucose molecule had already been used to produce ATP in cellular respiration, it could not 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”. The EcoSphere item asks students to explain the energy exchange between the ecosystem inside the EcoSphere and the outside environment. As shown in the response below, the student claimed that EcoSphere only had energy input not energy output and justified the claim in terms of a cycle that involve both changes of energy and matter: first plants used the energy of sunlight to produce oxygen and “fuel” other organisms. In this cycle, energy was 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 of the unsuccessful tracing is tracing energy without correct connection between energy transformation and 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:

First Interview (7th 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 described the energy transformation—energy of food changes into energy of movement, but did not correctly explain how that change happened in cellular respiration. Instead, he treated oxygen and water, the two substances involved in cellular respiration, as the carriers of energy.

In summary, at Level 3, the notion of energy is developed and is used as conceptual tool to analyze macroscopic events. Students 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 trace energy not separated from matter or trace energy without degradation.

Level 4. Trace energy successfully. Level 4 is scientific reasoning of energy—tracing energy across scales. How this scientific reasoning of energy explains and connects all socio-ecological events is represented in the Loop Diagram. The figure below represents Association Performances and Tracing Performances at Level 4.

- Associate energy with energy indicators consistently
- Trace energy separately from matter and with degradation

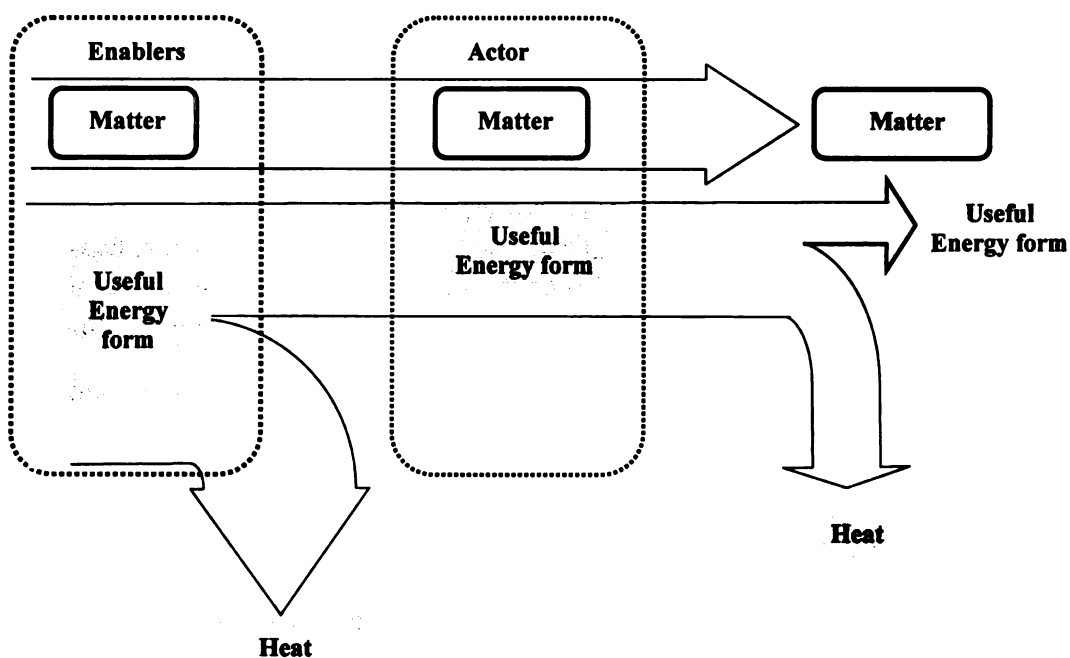


Figure 10 Level 4. Successful Tracing Energy Across Scales

At Level 4, students are able to explain the macroscopic socio-ecological events in terms of the key carbon-transforming processes (photosynthesis, digestion & biosynthesis, cellular respiration, and combustion) and successfully trace energy across these processes. In particular, they successfully associate different forms of energy with energy indicators. They also account for energy transformation separately from matter and with degradation. Below is an example of Level 4 reasoning.

Second Interview (7th Grader)

Tree growth

Interviewer: So how does 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.

Eric correctly explained matter transformation in photosynthesis—water and carbon dioxide react to produce the food that make up the plants' body. Then he explained that light energy transforms into the “stored energy” of the molecules that are made of hydrogen and carbon atoms.

The learning progression framework describes students' developmental stages. In general, students build their accounts upon different entities, from the most naïve entity of natural ability, via the mechanistic entity of vital power, to the scientific entity of energy. Students exhibit two performances as they use the entities to construct explanations. These two performances are the two progress variables—Association and Tracing. Each progress variable consists of four achievement levels: 1. Natural ability: to associate natural ability loosely with various aspects of the events and trace the macroscopic action-result chain; 2. Vital power: to associate vital power with enablers and trace the power-result chain; 3. Energy: to associate energy with energy indicators and trace energy unsuccessfully; 4. Energy: to associate energy with energy indicators and trace energy across scales successfully.

Alignment between the Association and Tracing Progress Variables

In the final learning progression framework, each progress variable (Association, and Tracing) has four achievement levels. The achievement levels along the Association Progress Variable are aligned with the achievement levels along the Tracing Progress

Variable in terms of the logical relations. For example, the Level 1 Association Performances and Level 1 Tracing Performances are both related to the entity of natural ability. However, in real situations, one student may achieve different achievement levels for different progress variables. Below is an example.

Second Interview (8th Grader)

Baby Girl Growth

Interviewer: So, what change will happen to the food when it is – when it goes to the girl's body?

Sam: It'll go through the digestive system. And then once it's in the digestive system then it goes through many processes to get into other nutrients like different things to make it grow.

Interviewer: So you see the baby growing into a big girl, right?

Sam: Um-hum.

Interviewer: She gains a lot of weight. So where does the increased material come from?

Sam: The mass just comes from like the tree, the nutrients and the things that it needs to grow. And then over time it'll just get bigger.

... ..

Interviewer: Okay. So, let's talk about energy. Do you think that the baby girl needs energy in order to grow?

Sam: Yeah because if you don't have energy, you can't do the things that make you grow like running or getting exercise.

Interviewer: So where does the energy come from?

Sam: The energy comes from the food and from water. It keeps it hydrated, and from a good night's sleep and from different things like that.

The excerpt is from an interview with a middle school student, Sam. With respect to Tracing Performance, Sam relied on Level 2 reasoning. He explained how food helped the baby girl's body to grow in terms of vital power. His explanation is that the food went

through some invisible processes, and the nutrients of food came out to power the process of growth. With respect to Association Performance, Sam replied: “energy comes from the food and from water. It keeps it hydrated, and from a good night’s sleep and from different things like that.” He associated energy with food, water, and also sleep. Since he stated that energy could be created through sleep, the Association Level for this account unit is Level 1.

The learning progression framework was used to assess students’ achievement and progress. First, it was used as guideline to code the interview data. The data were analyzed in terms of account units. Therefore, each account unit has two scores: one score for Association Performance and one score for Tracing Performance.

Our coding results show that 9.8% of the account units in First Interviews (N=183), 6.9% of the account units (N=160) in Second Interviews have different Association and Tracing Levels. In general, most students’ Association performance is aligned with their tracing performance, indicating that students’ reasoning within each event is coherent.

STUDENTS’ ACHIEVEMENT

I used the learning progression framework to measure students’ achievement in written assessments. I worked with my colleagues and used the learning progression framework to code all written assessment data. Then, I used the coding results to generate a set of distribution graphs, which represent the percentage of account units at different achievement levels of each progress variable. These distribution graphs indicate general patterns of students’ progress from elementary to high school.

The written assessment data analysis was conducted before the idea of Association and Tracing was developed. We used Explaining Progress Variable to code written assessment data. There are both conceptual and empirical reasons for that. Conceptually, the Explaining Progress Variable is the combination of Association and Tracing Progress Variables. Each achievement level of the Explaining Progress Variable describes reasoning patterns that can be categorized as either Association or Tracing performances. On the other hand, the interview data analysis also indicates that, in real situations, students' learning performances on Association and Tracing are highly aligned. Empirically, it is very difficult to use Association Progress Variable and Tracing Progress Variable to code written responses, since students' responses are usually very short and simple. They usually do not provide enough evidence for both Association and Tracing performances. Therefore, Explaining Progress Variable is more effective than Association and Tracing Progress Variables in coding written assessment data.

I used the coding results of written assessments to generate a set of distribution graphs. These distribution graphs show the achievement of students at different school levels. In the distribution graphs, the x-axis represents the achievement level. The y-axis specifies the percentage of account units at each achievement level. The total numbers of account units are listed in the table below.

Table 7 Number of Account Units in Written Tests

Grade Level	Number of Account Units	
	First Test	Second Test
Elementary	218	391
Middle School	793	921
High School	950	630

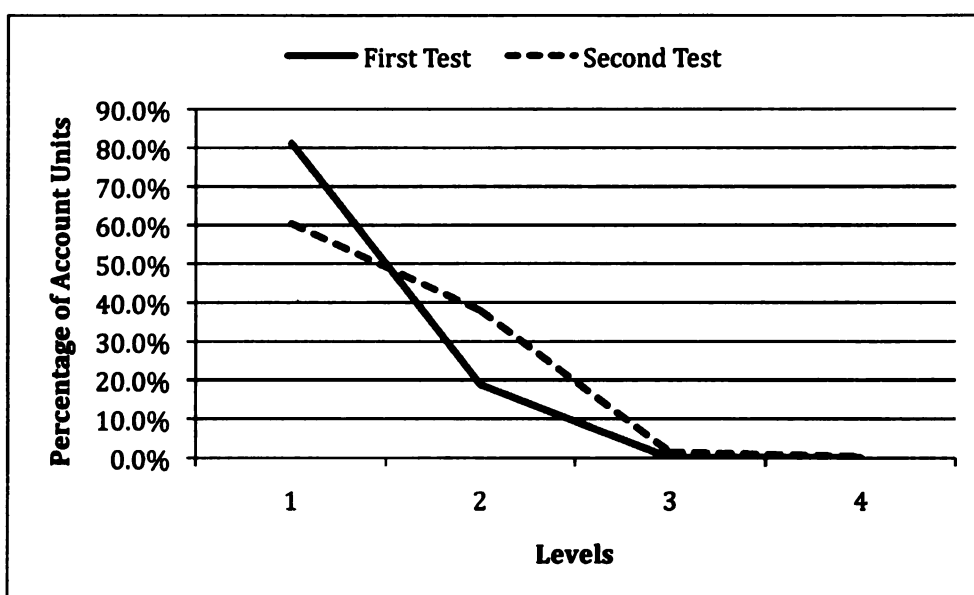


Figure 11 Distribution Graph of Elementary Tests

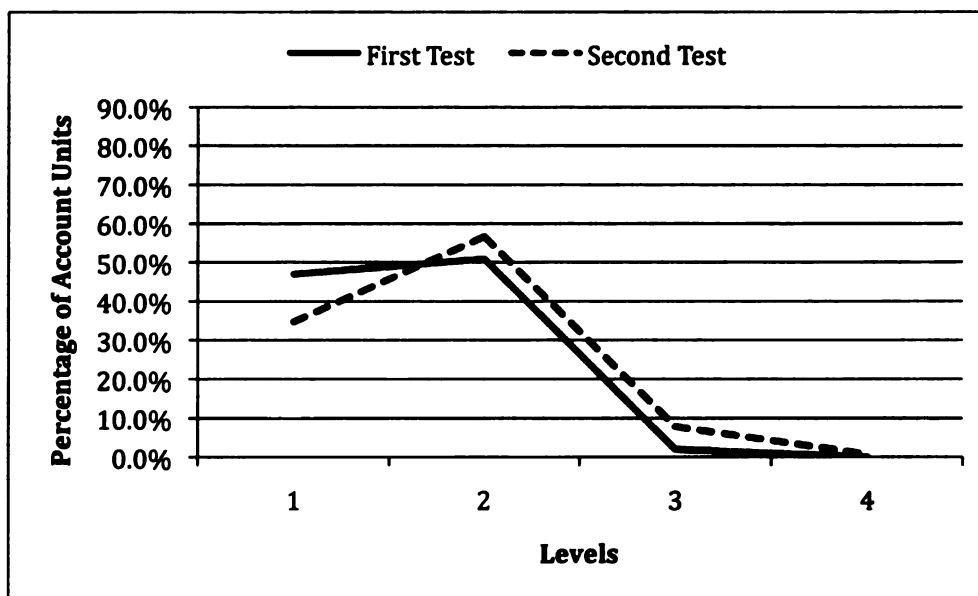


Figure 12 Distribution Graph of Middle School Tests

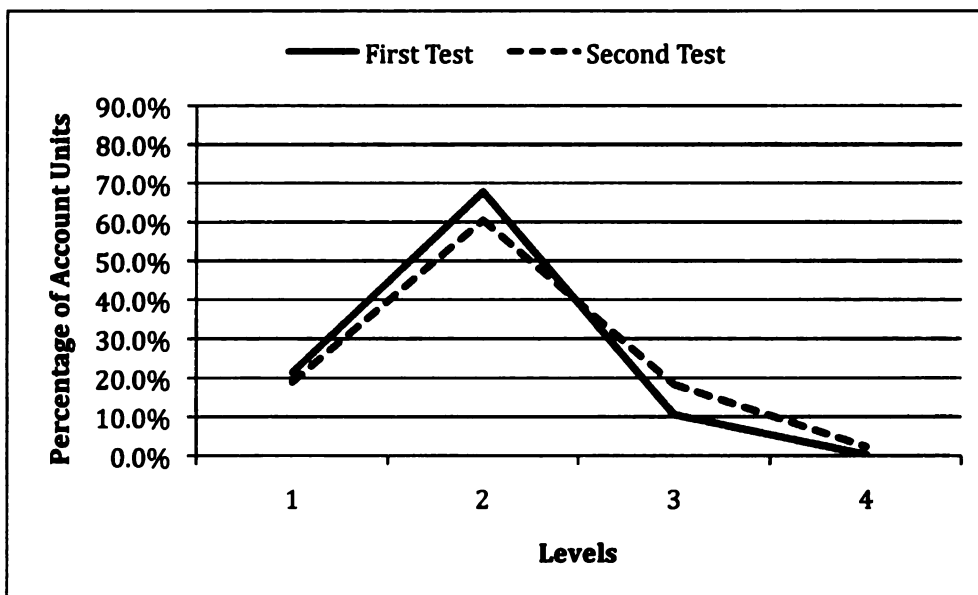


Figure 13 Distribution Graph of High School Tests

The distribution graphs show that, across school levels, the peak of the graph shifts from Level 1 to Level 2: elementary students mostly rely on Level 1 reasoning, middle school students mostly rely on Level 1 reasoning and Level 2 reasoning, and high school students mostly rely on Level 2 reasoning. Across school levels, the percentage of

account units that achieve Level 3 is very low: 0% at elementary school level, lower than 10% at middle school level, and lower than 21% at high school level. In brief, achieving Level 3 reasoning, reasoning about changes of energy, is very challenging for students. The results indicate that, although energy is emphasized as important concept at middle and high school level, the majority middle and high school students do not use energy as a conceptual entity to account for socio-ecological events.

COHESION AND CONSISTENCY OF STUDENTS' REASONING

The mechanism of students' progress is investigated in terms of the cohesion in students' accounts of individual carbon-transforming processes and consistency of students' reasoning across processes.

Cohesion of Students' Accounts for Individual Carbon-transforming Processes

To study the cohesion of students' reasoning, I analyzed students' accounts for six events: tree growth, baby girl growth, girl running, and tree decaying, flame burning, and car running. I first examined students' interviews and identified compatible and incompatible features. The learning progression framework represents major features of reasoning patterns at different achievement levels. Features at one achievement level could be either compatible or incompatible with the features at the next level. The compatibility between features at different levels is determined based on empirical data and reflect students' perspective. I found two patterns of how students make features at different levels compatible.

First, features at Level 1—macroscopic changes/perceptions—and features at Level 2—hidden mechanism—are often connected in reasonable ways. Below is an example. As a whole, Sue’s account unit has both Level 1 and Level 2 features. When explaining how sunlight helps the tree to grow, she explained two processes. She first stated that sunlight was energy that triggered the process of tree growth. This explanation has a Level 2 feature—it indicates certain hidden mechanism. Later, Sue explained that sunlight makes the tree warm, so that the tree keeps living and colorful. This indicates a Level 1 feature, since it addresses macroscopic changes and perceptions. From Sue’s perspective, these two types of processes are not incompatible, since sunlight has both functions.

First Interview (4th Grader)

Tree Growth

Interviewer: And you also talk about the tree needs sunlight, right? So, how does sunlight help the tree to grow?

Sue: Well, the leaves take in the sunlight, and I’m pretty sure they don’t release anything else. But, when they take it in, it goes through the tree as energy, which helps it grow.

Interviewer: Do you think that energy is used up, or do you think it gets released somewhere in the trees body?

Sue: Well, I think they use the sunlight and - well, nothing really comes out until the tree dies and all the energy goes into the ground when it’s decayed.

Interviewer: Mm-hmm. So, when the tree uses sunlight - you said sunlight provides energy for the tree, right? So how does that energy help the tree to grow bigger and bigger.

Sue: *Well, it keeps it warm. Like in the winter, it’s colder, so the tree dies and then it comes back alive in the spring and summer and it’s green and in fall the leaves change color and then the tree dies for winter.*

Second, features seem incompatible from scientific perspective could be compatible from students' perspectives. One important finding is that students may use strategies to make seemingly incompatible features compatible. Force-dynamic reasoning and matter/energy reasoning explain events in terms of different types of processes. At level two, students explain events in terms of force-dynamic processes at microscopic scale—vital power (e.g., vitamin, nutrients, sunlight, etc.) triggers hidden processes (e.g., plants making food, wood breaking down, etc.) or hidden processes happening due to losing vital power. At Level 3, students explain events in terms of matter/energy processes—processes involving changes of energy forms and molecules. These two types of processes seem incompatible, but the interview data indicate that students may use strategies to make them compatible.

The first strategy that the students used is to organize the force-dynamic processes and matter/energy processes into a time sequence. For example, in the example below, Douglas explained the event of tree growth in terms of cell growth, which contained three sequential processes. In the first process, the tree uses air, vitamins, soil nutrients, sun, and water to make food—glucose. Then, glucose is converted into energy. Finally, the energy is used to power cell growth and multiplication, causing tree growth. The first two processes are matter/energy processes, which are mostly about how molecules and energy change. In particular, the second process is matter-energy conversion at atomic-molecular scale. Therefore, these two processes indicate Level 3 reasoning. The third process is a force-dynamic process—energy is treated as vital power that triggers growth, indicating Level 2 reasoning. By arranging the matter/energy processes and the force-dynamic

process into a time sequence, Douglas successfully reconciled the Level 2 and Level 3 features.

Second Interview: Tree Growth
(9th Grader)

Interviewer: What do you mean by food?

Douglas: Like glucose that the tree uses to grow.

Interviewer: Okay. So where does glucose come from?

Douglas: The tree makes it from all the different things that it uses.

Interviewer: Could you talk a little bit about what are the different things?

Douglas: Like air, vitamins, the soil, nutrients, sun and water.

... ..

Interviewer: Okay. So do you think the tree uses any of these things you mentioned as energy?

Douglas: Well, yeah I think that uses like all the same take other after it makes its food it uses the glucose for energy.

Interviewer: Glucose is a type of energy?

Douglas: Yep.

Interviewer: Okay.

Douglas: The sugar.

...

Interviewer: And you also talk about glucose. So do you think there are some relationship between the cells and the glucose?

Douglas: Yeah, I think the glucose powers the cells.

Interviewer: The glucose powers the cells?

Douglas: Yep.

Interviewer: How about energy, energy for?

Douglas: Yeah, I think, yeah like the glucose is converted into energy, which powers the cells.

Interviewer: Powers the cells. Why does the cell need energy?

Douglas: To grow and reproduce.

Interviewer: So what kind of change, what happen to the cells when the tree is growing?

Douglas: They're getting more and more of the cells and some are dying and more are being reproduced.

The second strategy students used is to describe different types of processes as multiple causes of one result. That is, the force-dynamic processes and matter/energy processes happen at the same time and are different ways that cause the same result. For example, in the example below, Jack explained growth as a process, in which the tree is building on more mass. He explained different ways of building on mass: carbon dioxide provides carbon atoms for the tree's body; the energy from sunlight powers growth; the energy of carbon-hydrogen bonds is released and then used to power growth. The second process Jack explained has Level 2 feature: energy powers growth. The other two processes have Level 3 features, because they are about changes between molecules and energy. These three processes are compatible, because they are different ways that cause the same result of burning on mass.

Second Interview: Tree Growth

(9th Grader)

Interviewer: Do you think that the tree needs carbon dioxide to grow?

Jack: Yes.

Interviewer: Could you say a little bit more about that? So how does that help the tree grow?

Jack: Carbon dioxide helps the tree grow by the carbon is used in the cycle to add carbon into it I guess and that's pretty much the big one.

Interviewer: Can you say a little bit about that and how does the carbon change?

Jack: Carbon dioxide comes into it, and then it gets broken down into individual carbon and oxygen atoms, and the carbon will be added to certain chemicals, and then oxygen will be used where it's needed too.

... ..

Interviewer: The tree gets heavier right as it grows?

Jack: Yeah.

Interviewer: So how does that happen?

Jack: Since you bring it in more chemicals and it's getting larger, there's more mass so it gets heavier.

Interviewer: Okay. So you mentioned chemicals, where does the chemical come from?

Jack: From outside like the minerals it brings in.

Interviewer: Do you think the tree can naturally produce more and more mass?

Jack: Yes.

Interviewer: How?

Jack: It can, like the same question before.

Interviewer: Okay. Does the tree growth require energy?

Jack: Yes.

Interviewer: Okay. How?

Jack: It takes energy to produce more of itself.

Interviewer: Okay. So where do you think the tree gets the energy from?

Jack: Sunlight and the breaking down of chemicals.

Interviewer: Okay. Could you say a little bit more about the second part, not sunlight? So why do you think the things you just mentioned have energy?

Jack: Most of the energy made is from breaking down high energy bonds like carbon and hydrogen and then there are some other ones. And it breaks those bonds, which releases heat and energy and it uses energy to grow.

Interviewer: Thank you very much. Okay. Two more questions, where does the energy of sunlight go? It is used up or does it go somewhere? What happens to the energy?

Jack: I think the energy is used up.

When studying the cohesion of students' reasoning, I first examined students' accounts and identify both compatible and incompatible features. Based on this work, I developed the coding rubric that contained both compatible and incompatible features between levels (Table 8, 9, and 10).

Table 8 Compatible and Incompatible Features between Level 1 and Level 2 Accounts

Association	Tracing
<i>Compatible features:</i> • Level 1 accounts treat energy as a type of perception—energy appears as people are feeling happy/energetic/healthy and disappears as people are feeling tired. • Level 2 accounts treat energy as a type of vital power or semi-matter contained in enablers such as sunlight, vitamin, nutrients, etc. • Level 1 accounts explain why enablers can be used to help actors in terms of functions or natural tendency of enablers. • Level 2: accounts recognize that the properties or hidden structure of enablers determines the specific functions of enablers. <i>Incompatible Features</i> • Level 1 accounts may claim that energy can be created through actors' actions such as sleeping, rest, etc. • Level 2 accounts may claim that energy cannot be created by actors' actions and energy only comes from enablers.	<i>Compatible features:</i> • Level 1 accounts explain events in terms of cause-effect chain between enablers and the actor and therefore do not trace any entity. (In the cause-effect chain, the relations between the actor and its enablers are like physical interactions that do not involve any hidden processes. For example, sunlight warms the tree). • Level 2 accounts explain events in terms of power-result chain behind the cause-effect relation, and therefore trace power backwards but not forwards. (Vital power from enablers triggers hidden processes such as life processes, burning, movement, etc.) • Level 1 accounts explain the causes of decay in terms of natural tendency. (The actors lose life necessities/enablers or the actors lose their natural abilities. For example, the tree dies or getting old) • Level 2 accounts identify hidden actors as cause of decay. (Hidden actors are decomposers such as microorganisms, bacteria, fungi, etc.) • Level 1 accounts do not make connections among events or connect the events as series of events. • Level 2 accounts connect events in terms of feeding relations. <i>Incompatible Features:</i> • Level 1 accounts may describe changes happened to enablers as physical movement of enablers inside the actor's body (e.g., water moving in the tree to make the tree grow; gasoline move in the car to make it run.) • Level 2 accounts describe changes happened to enablers as hidden processes that involve changes of material kinds and energy (e.g., nutrients change into the tree's body.)

Table 9 Compatible and Incompatible Features between Level 2 and Level 3 Accounts

Association	Tracing
<i>Compatible Features</i> • Level 2 accounts do not identify organic molecules. • Level 3 accounts identify organic molecules as energy sources. • Level 2 accounts explain why actors use enablers in terms of properties or hidden structure of enablers • Level 3 accounts explain why actors use enablers in terms of organic molecules and/or bonding. <i>Incompatible Features</i> • Level 2 accounts do not distinguish energy enablers from other enablers—vital power is treated as a type of semi-matter contained in all enablers. • Level 3 accounts begin to make distinction between enablers in terms of substances involved in chemical reactions, chemical bonds, carbon atoms, and/or organic molecules.	<i>Compatible Features</i> • Level 2 accounts connect events in terms of series of triggering events. • Level 3 accounts connect events in terms of energy cycle. • Level 2 accounts explain events in terms of power-result chain and therefore trace energy/power backwards not forwards. • Level 3 accounts explain events in terms of changes of energy forms and molecules (e.g., matter-energy conversion at atomic-molecular scale). <i>Incompatible Features</i> • Level 2 accounts claim that energy is used up to trigger hidden processes. • Level 3 accounts recognize that energy cannot be used up and energy must go somewhere, but use atomic-molecular matter-energy conversion for reasoning.

Table 10 Compatible and Incompatible Features between Level 3 and Level 4 Accounts

Difference between Level 3 Accounts and Level 4 Accounts	
Association	Tracing
<i>Article I. Compatible Features:</i> • Level 3 accounts associate energy or chemical energy with familiar organic molecules, carbon atoms, or all chemical bonds. • Level 4 accounts associate chemical energy with C-C and C-H bonds of organic molecules. <i>Incompatible Features:</i> • Level 3 accounts identify organic molecules as energy sources, but do not distinguish between energy forms and organic molecules. • Level 4 accounts identify organic molecules as energy sources and distinguish them from energy.	<i>Incompatible Features:</i> • Level 3 accounts explain the events by tracing energy without degradation or not separately from matter (atoms and molecules). • Level 4 accounts explain the events by tracing energy with degradation and separately from matter. • Level 3 accounts connect events in terms of energy cycle. • Level 4 accounts connect events in terms of energy flow—energy passing on food chain with heat dissipation. • Level 3 accounts explain the events in terms of matter-energy conversion at atomic-molecular scale. • Level 4 accounts explain the events by tracing energy separately from matter. • Level 3 accounts do not connect energy transformation with chemical changes correctly. • Level 4 accounts connect energy transformation with chemical changes correctly.

I then used this rubric to code interview data. I found that students' account units could be divided into three groups. The first group contains account units that have features from single level. Account units in this group indicate cohesive reasoning. The second group contains account units that have compatible features at two levels. These account units could also contain one of the pair of incompatible features, but not both. Account units in this group indicate a synthetic reasoning that has features of two levels, but the features are not incompatible from the student's view. Therefore, the synthetic reasoning is cohesive. The third group contains account units that have incompatible

features from two levels. These account units indicate a fragmented reasoning. In the paragraphs below, I use examples from students' interviews to explain the three groups of account units.

The first group of account units indicates coherent reasoning at single level. Below is an example. In her first interview, Sue answered different questions about the event of tree growth. The account unit about tree growth has four level 1 features: describe the physical interactions between sunlight and the tree; describe the physical interaction between soil and the tree; describe the physical interactions between sunlight and the tree; describe the physical interactions between air and the tree.

First-interview: Tree Growth

(4th Grader)

Interviewer: What happens to sunlight inside the tree.

Sue: [silence].

Interviewer: How does the tree use sunlight for energy?

Sue: I'm pretty sure with the leaves. The leaves attract the sunlight and its like food to them. So that's how they grow. And I think it's the same with the tree.

→ Level 1 feature: describe the physical interactions between sunlight and the tree.

Interviewer: How about soil, do you think a tree uses soil for energy?

Sue: It has the nutrients in it, and it uses that to grow and stay alive.

Interviewer: How does that happen? [0:05:02.0]

Sue: The roots stay there and they take all of the nutrients and that's how it helps the tree grow.

→ Level 1 feature: describe the physical interaction between soil and the tree.

Interviewer: Is sunlight always necessary for tree growth, do you think?

Sue: Can you repeat that again?

Interviewer: Is sunlight always necessary for tree growth?

Sue: Yes because if it's always dark with the tree, then the leaves aren't always going to be colorful and it might die and shrivel up.

Interviewer: Why do you think the leaves become colorful and die, without sunlight?

Sue: Because it needs to be, the seasons change and sun in the summer makes the leaves green, and in the fall they turn a different color and then they go and fall off, and then at winter, you don't have any leaves on the trees, because it's cold. [0:06:18.5]

→ Level 1 feature: describe the physical interactions between sunlight and the tree.

Interviewer: Some students say that air is necessary for plant growth; do you think that air is necessary for plant growth?

Sue: Yes because the air is food too, and they need to breathe just like us, they filter the air.

Interviewer: How does that work, do you know how the plant uses air?

Sue: No I don't know that.

Interviewer: Do plants use air for energy?

Sue: Just like us, we need to breath and trees and plants cant move anywhere, except for the air moves them, like the leaves and sometimes little trees.

→ Level 1 feature: describe the physical interactions between air and the tree.

The second group of account units indicates synthetic reasoning that has compatible features from two different levels. Below is an example. The account unit in Sue's second interview has both Level 1 features and Level 2 features. Level 1 features are: describing functions of enablers, associating energy with perceptions, describing the physical interactions between sunlight and the tree. Level 2 features are: associating energy with sunlight and treating energy as power that triggers life process. The Level 1 and Level 2 features are not incompatible, since sunlight both provide the tree energy and

make the tree warm. This evidence indicates that Sue has constructed a cohesive synthetic reasoning that has features from Level 1 and Level 2.

Second Interview: Tree Growth

(4th Grader)

Interviewer: How does sunlight help the tree to grow?

Sue: Well, the leaves take in the sunlight, and I'm pretty sure they don't release anything else. But, when they take it in, it goes through the tree as energy, which helps it grow.

→ Level 2 features: associate energy with sunlight; treat energy as power that triggers life process.

Interviewer: So how does that energy help the tree to grow bigger and bigger.

Sue: Well, it keeps it warm. Like in the winter, it's colder, so the tree dies and then it comes back alive in the spring and summer and it's green and in fall the leaves change color and then the tree dies for winter.

→ Level 1 feature: describe functions of enablers; associate energy with perceptions; describe the physical interactions between sunlight and the tree.

The third group of account units has incompatible features from two levels and therefore indicates fragmented reasoning. Below is an example. Richard first explained why food has energy in terms of C-C and C-H bonds, which is Level 4 feature. However, when the interviewer asked him to explain why water is energy source, he could not use the same reasoning to answer the question.

Second Interview: Baby Girl Growth

(9th Grader)

Interviewer: Okay. So, do you think the girl needs energy in order to grow?

Richard: Yeah.

Interviewer: So where does the energy come from?

Richard: All the bonds that are in the food.

Interviewer: What are those bonds?

Richard: They are kind carbon-to-carbon, carbon to hydrogen, high-energy bonds.

Level 4 feature: identify food as energy source and explain that in terms of high-energy bonds.

Interviewer: Okay. So you also talk about the baby girl needs water in order to grow, right? So do you think water is also an energy source for the baby?

Richard: Yeah.

Interviewer: Why?

Richard: Because – [silence, indicating that he did not know.]

Level 2 feature: identify water (enabler) as energy source, but cannot explain in terms of bonds.

The percentage of account units in each group is represented in the figure below.

As the figure shown, students tend to rely on cohesive reasoning. They use either reasoning at single level or synthetic reasoning that reconcile features of two levels to make accounts.

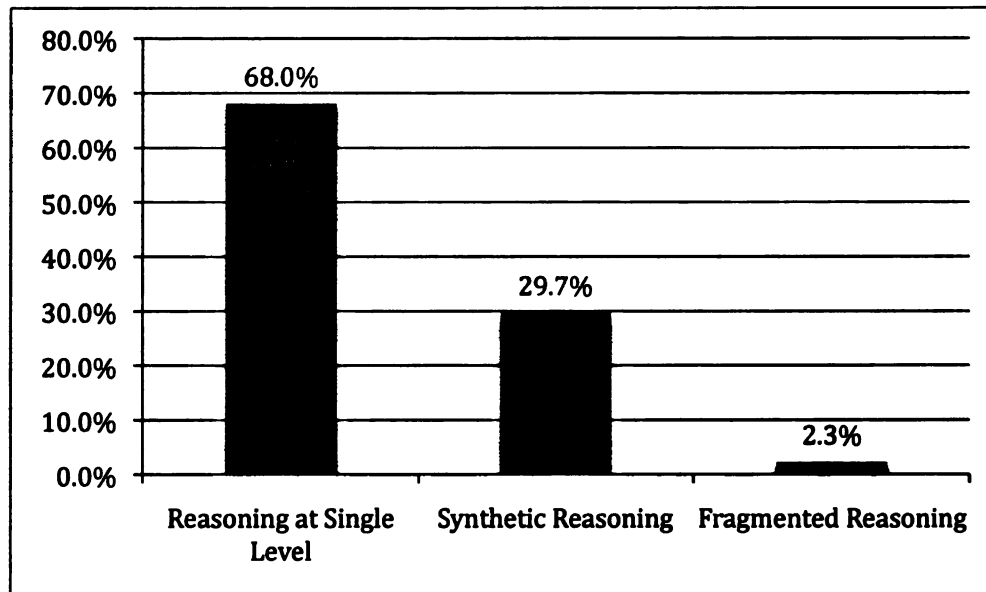


Figure 14 Cohesion of Students' Reasoning within Account Units

Consistency of Students' Accounts Across Carbon-transforming Processes

I also investigated the consistency of students' reasoning in interviews. That is, within each individual student, how consistent are the accounts of different carbon-transforming processes? I generated tables to show the consistency of students' reasoning. Each student's interview has codes for eight account units. I first identified the most frequent code—the level of the account unit that appears most frequently in the students' interview transcript—as the baseline. Then, each account unit that has the most frequent code is assigned "0". If the account unit has a code different from the most frequent code, a number that indicates the difference is assigned to that account unit. For example, if the most frequent level is level 2 and an account unit has level 3 for Association and Tracing Progress Variables, the account unit is then coded as 1. Similarly, if the most frequent level is level 2 and an account unit has level 1 for Association and Tracing Progress Variables, the account unit is then coded as -1. If the

account unit has different Association and Tracing codes, the average of the two codes will be used for comparison. The table below shows the consistency of individual student's reasoning across different socio-ecological events (N/A: missing data).

Table 11 Consistency of Students' Reasoning in First Interviews

	TG	BG	GR	TD	FB	CR	LL	XP
Sue	0	0	0	0	0	0	1	0
Amy	0	0	0	0	0	0	0	0
Nick	0	0.5	0.5	0	0	0	1	0
Dave	0	0	0	0	0	0.5	0	0
Kate	0	0	0	0	0	0	0	0
Isaac	0	-1	0	-1	0	-0.5	-1	0
Watson	1	1	0	0	0	0.5	1	N/A
Carolyn	0	0	0	0	0.5	0	0.5	N/A
Richard	0	0	0	0	-1	0	0	0
Steve	0	0	0	0	0.5	1	0	0
Tony	0	0	0	0	0	0	0	0
Alan	0	0	0	0	0.5	1	1	0
Eric	0	0	0	-1	0	0	-0.5	0
Bob	0	0.5	0.5	0	0	0	0	-1
Newman	0	0	0	-0.5	0	0	-0.5	0
Sara	0	0	0	0	-0.5	0	0	0
Jean	0	-1	0	-1	-1	0	0	0
Rose	0	0	-0.5	0	0	0	0	0
Jack	0.5	0	0	0	0	0	0	0
Alice	0	0	0	0	0	0.5	1	0
Arch	0	0	0	0	0	0	0	0
Susan	0	0	0	0	0	0	0	0
Sam	0	0	0	1	N/A	N/A	N/A	N/A
Douglas	0	0	0	0	0	N/A	N/A	N/A

Table 12 Consistency of Students' Reasoning in Second Interviews

	TG	BG	GR	TD	FB	CR	LL	XP
Sue	-0.5	-0.5	0	0	0	0	0	0
Amy	0	0	0	0	0	0	1	0
Nick	0	0	0	0	0	0	0	0
Dave	0	0	0	N/A	N/A	N/A	N/A	N/A
Kate	0	0	1	0	0	1	0	0
Isaac	0	0	0	0	0	0	0	0
Watson	-1	0	0	0	0	0	0	0
Carolyn	0	0	0	-1	0	0	0	0
Richard	0	0	-1	0	0.5	0.5	0	0
Steve	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Tony	0	0	0	-1	-1	-1	0	0
Alan	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Eric	0	0	0	0	0	0	0	0
Bob	N/A	N/A	N/A	-1	0	0	-1	N/A
Newman	0	0	0	-1	-0.5	0	0	N/A
Sara	0	-0.5	0	0	0	1	1	1
Jean	0	0	0	0	0	0	0	0
Rose	1	0	0	0	1	0	0	N/A
Jack	0	0	0	-1	-1	0	-1	-1
Alice	0	0	0	0	0	-0.5	-0.5	0
Arch	0	-0.5	-0.5	0	0	0	0	0
Susan	0	0	0	N/A	N/A	N/A	N/A	N/A
Sam	1	0	0	0	0	0	0	0
Douglas	0	0	0	-1	-1	-1	0	-1

The table below shows the percentage of account units at levels different from baseline. Altogether, 18% account units in the first interview and 21% account units in the second interview have levels different from the baseline level, indicating that the majority students tend to rely on consistent reasoning to account for different socio-ecological events.

Table 13 Level Difference

Level Difference	-1	-0.5	0.5	1	Total
First Interview	4%	3%	5%	6%	18%
Second Interview	11%	5%	4%	1%	21%

Summary: Cohesion and Consistency of Students' Accounts

The different patterns of the cohesion and consistency in students' reasoning indicate the mechanisms of students' progress. The results indicate that the participant students relied on reasoning at different achievement levels to account for the socio-ecological events. There are three patterns of the cohesion of their reasoning within each individual event. They could rely on reasoning at single level to make accounts. In such situation, their reasoning is cohesive. They could also explain events in terms of synthetic reasoning, which has features of two adjacent levels. In this case, they usually use compatible features from different levels of achievement in their accounts or use strategies to make seemingly incompatible features compatible and therefore maintain the cohesion in their reasoning. A few students relied on fragmented reasoning, which has incompatible features from different levels. Altogether, more than 90% account units show the first two patterns, indicating that students tended to rely on cohesive reasoning to make accounts. With respect to consistency, the results indicate that students' reasoning tend to be consistent across events.

SUMMARY

This chapter describes the findings of the study. First, I describe how I developed the learning progression framework. Students with diverse science backgrounds build their explanations upon different entities, from the most naïve psychological entity natural ability, via the informal mechanistic entity vital power, to the scientific entity energy. Students' reasoning with respect to different entities can be measure by two

progress variables—Association and Tracing. In particular, the achievement levels along the Association Progress Variable and Tracing Progress Variable are:

- Level 1 Natural ability as Psychological, Naturalistic, and Temporal Entity: to associate natural ability loosely with various aspects of the events and trace the macroscopic action-result chain
- Level 2 Vital power as Mechanistic Entity: to associate vital power with enablers and trace the power-result chain
- Level 3 Unsuccessful Tracing Energy: to associate energy with energy indicators and trace energy unsuccessfully
- Level 4 Successful Tracing Energy: to associate energy with energy indicators and trace energy across scales successfully

From the level description, we can see that the four levels of Association Progress Variable are aligned with the four levels of Tracing Progress Variable in terms of the logical relations. In real situations, students may reach different levels for different progress variables. The data indicate that less than 10% of the account units have different levels for Association and Tracing Performances.

After I developed the learning progression framework, I used it to measure students' achievement in the written assessments. The coding results indicate that the majority students relied on Level 1 and Level 2 reasoning to make accounts and only a very small percentage of account units reach Level 3 and Level 4, indicating that most students did not use energy to account for the socio-ecological events.

I then investigated the mechanisms of students' progress by examining the cohesion and consistency of students' reasoning in interviews. I found that the participant students tended to rely on cohesive and consistent reasoning to account for the socio-ecological events. They often used strategies to reconcile ideas learned from science classrooms with their existing force-dynamic reasoning framework.

CHAPTER 6 DISCUSSION

Energy has long been recognized as a core topic in both science and science education. It is an important concept in our explanations of how human activities and natural events collectively lead to global climate change. Causal reasoning, as foundation of conceptual understanding, is emphasized in both research and instructions. This study developed a learning progression for energy and causal reasoning in socio-ecological systems.

SUMMARY OF THE RESULTS

I first developed the learning progression framework that describes increasingly sophisticated ways of reasoning that students display when explaining socio-ecological events. Then the learning progression framework was used to measure students' achievement in written assessments. Finally, I used the learning progression framework to investigate mechanisms of students' progress.

When developing the learning progression framework, I first identified progress variables that effectively compared students' intuitive reasoning with scientific reasoning. The differences between scientific explanations and students' intuitive explanations can be described in terms of two aspects of learning performances—Association and Tracing. I also found that students with less science background tended to use informal entities such as “natural ability” and “vital power” rather than the scientific entity—energy—to account for the socio-ecological events. Based on these two findings, I developed the learning progression framework:

- Level 1 Natural ability as Psychological, Naturalistic, and Temporal Entity: to associate natural ability loosely with various aspects of the events and trace the macroscopic action-result chain;
- Level 2 Vital power as Mechanistic Entity: to associate vital power with enablers and trace the power-result chain
- Level 3 Unsuccessful Tracing Energy: to associate energy with energy indicators and trace energy unsuccessfully
- Level 4 Successful Tracing Energy: to associate energy with energy indicators and trace energy across scales successfully

In this learning progression framework, the achievement levels along the Association Progress Variable are aligned with the achievement levels along the Tracing Progress Variable in terms of the logical relations. For example, Level 1 Association Performance and Tracing Performance both indicate the entity of natural ability. In real situations, student may exhibit different achievement levels for Association and Tracing Progress Variables. The coding results indicate that less than 10% of the account units have different achievement levels for Association and Tracing Progress Variables.

Then, I used the learning progression framework to measure students' achievement in written assessments. The coding results show that the majority of students rely on Level 1 and Level 2 reasoning—force-dynamic reasoning—to account for the socio-ecological events and the percentage of account units reaching Level 3—reasoning about matter/energy—is very low. This evidence indicates that current school science

teaching does not effectively enable students to use energy to reason about socio-ecological events.

I also investigated mechanisms of students' progress by examining the cohesion of students' reasoning about individual carbon-transforming processes and the consistency of students' reasoning across processes. The results indicate that, in general, students tend to rely on cohesive and consistent reasoning to make accounts. One important finding is that students tend to use strategies to reconcile the new knowledge learned from science class with their existing force-dynamic reasoning, which leads to synthetic reasoning. In science, carbon-transforming processes are processes that change energy forms and molecules. Force-dynamic reasoning explains the socio-ecological events in terms of triggering processes—the power triggers hidden processes. To reconcile the new knowledge with existing force-dynamic reasoning, students may organize the two different types of processes in to a time sequence. They may also think that these two types of processes are happening at the same time, but are different ways that lead to the same result.

IMPLICATIONS

I discuss the implication of this study for both research and teaching practice.

Implications for Research

This study contributes learning progression-based research on students' conceptual development through its development of Association and Tracing as progress variables and through its findings about cohesion and consistency in students' reasoning.

Association and Tracing as progress variables. Using Tracing and Association as progress variables provides a more effective way to understand students' misconceptions about energy and to compare those misconceptions with scientific energy conceptions. Previous conceptual change research has focused on two important energy-related topics: energy concept and energy principles. Conceptual change research on energy concepts indicates that students hold many intuitive images of energy such as effort, force, power, ingredient, product, motion, vital power, semi-matter, sensation, and phenomena (Barak et al., 1997; Driver & Warrington, 1985; Warren, 1983; Watts, 1983; Watts & Gilbert, 1983). Although these studies uncover a list of intuitive images of energy, they do not tell the causes behind the list. That is, why do students hold those intuitive images of energy? What do those images have in common? How are those images similar to and different from scientific energy conception?

Similarly, conceptual change research on energy principles indicates that students seldom use energy principles to account for biological events (Barak et al., 1997; Carlsson, 2002a, 2002b; Leach, Driver, Scott, & Wood-Robinson, 1996), and that they usually do not see the connection between the two energy principles and tend to treat energy conservation and energy degradation as contradictory principles (Pinto, Couso, & Gutierrez, 2005). Although these studies uncover students' inability to use energy principles, they do not tell about what students can do. In other words, do students use any informal principles or theories to construct their accounts? In summary, conceptual change research has documented a list of students' misconceptions and confusions about energy, but does not tell about why students hold various energy misconceptions and how students understand the world.

In this study, the learning progression for energy and causal reasoning brings order to the previous confusing results about students' intuitive energy conceptions and helps us to see lines of development we did not see before. In science, energy is an abstract quantity associated with a variety of energy indicators and endures through physical and chemical changes. However, students usually do not appreciate the scientific meanings of energy. Instead of using energy, they often use two intuitive entities—natural ability and vital power—to construct explanations. These intuitive entities are precursors of scientific conceptions of energy but their meanings are different. The learning progression uses Tracing and Association as two progress variables to connect students' intuitive energy conceptions to the scientific energy conception.

The development of Association Performance can be described as increasingly restricted association. Natural ability indicates a broad association: it is not only associated with mechanical attributes of events (e.g., motion), but also associated with psychological and perceptual attributes of events (e.g., happiness, strength, etc.). Vital power represents more restricted association: vital power only comes from enablers and cannot be created by the actor; it is a mechanical entity that is only associated with mechanical properties and/or hidden structure (e.g., being combustible, containing power, etc.). The entity of energy indicates further restriction: it is associated with a limited list of energy indicators such as light, foods, fuels, motion, etc.

The development of Tracing Performance can be described as increasingly completed tracing: Natural ability is naturally endowed. Therefore, it is not necessary to reason where it comes from and where it goes. Vital power only comes from enablers and

cannot be created by the actor. Therefore, it indicates the first sign of energy specific tracing—tracing the vital power backward. Using energy to reason about events requires complete tracing—trace energy backward and forward; trace energy separately from matter and with degradation.

In brief, Association and Tracing are two progress variables that help us to better understand students' intuitive ways of reasoning and compare them with the scientific energy conception. Students' conceptual development with respect to energy can be described as the development of restricted Association Performance and the development of complete Tracing Performance. Association and Tracing also reflect human's general ways of reasoning. In this sense, they can also be used as progress variables to analyze students' understanding of other science concepts such as matter, biological processes, etc.

Cohesion and consistency in students' reasoning. Second, this study shows that students tend to rely on cohesive and consistent ways of reasoning to make accounts. I investigated the cohesion of students' reasoning within each individual event and the consistency of their reasoning across different events. The results show that students generally tend to rely on cohesive and consistent reasoning to account for events. When features of new knowledge are incompatible with their existing force-dynamic reasoning, students tend to use strategies to reconcile the incompatible features and therefore construct a relatively cohesive synthetic reasoning framework. In particular, even students do not see the connections among different socio-ecological events they do use cohesive and consistent ways of reasoning to make accounts.

Since students' reasoning tends to be cohesive and consistent, the levels of the learning progression are more likely to represent connected ways of reasoning about different socio-ecological events, rather than mere collections of elements that tend to be characteristic of students at a certain age. In this sense, the Levels of Achievement describe important patterns in students' conceptual development.

Implications for Teaching Practice

This study also brings implications for teaching practice. A major problem of our current approaches to energy is that we tend to teach students energy-related concepts and principles without targeting students' incorrect association and tracing performances. With respect to the Association Performance, instruction often focuses on broad association of energy. We often teach students that energy is everywhere and is associated with everything, which is correct but does not help students to understand how energy has restricted meaning—energy is associated with many phenomena but in limited ways. For example, when students say that energy is motion, energy is glucose, or energy makes you feel energetic, we often do not correct them. We seldom point out that motion is condition that associated with kinetic energy, that glucose is molecule (matter) that contains chemical energy, and that the building blocks of human body, organic molecules, contain chemical energy. As a result, students do not develop the ability to associate energy with limited energy indicators and they often confuse energy with matter and conditions.

With respect to the Tracing Performance, instruction does not emphasize the restricted and complete tracing performance—tracing energy should be separated from

tracing matter or tracing cause-effect sequences; tracing energy should include energy degradation. At elementary and middle school level, we often teach students that energy makes things happen, which actually implies tracing the energy-effect chain rather than tracing energy separately from cause-effect relations. In the learning progression, the performance of tracing energy-effect chain is at Level 2, which is different from scientific tracing performance. The middle and high school version of energy conservation is that energy cannot be created or destroyed. This simplified statement does not emphasize that energy cannot change into or from other things. Neither does it highlight energy degradation. As shown in this study, many students use matter-energy conversion for reasoning or trace energy without degradation. Such Tracing Performances are at Level 3. They are different from the scientific Tracing Performances at Level 4.

If we expect students to develop scientific Association and Tracing Performances consistently, our teaching approaches should keep consistent across major disciplines such as physics, chemistry, and biology. That is, instruction should focus on helping students to develop scientific Association and Tracing Performances across different content areas. Here, I suggest using two *tools of reasoning* that help students with Association and Tracing Performances.

The *Forms of Energy List* helps students to develop the ability to associate energy with energy indicators such as heat, electricity, foods, fuels, and so on (Appendix D). The Forms of Energy List covers the most important forms of energy involved in carbon-transforming processes, and explains how to identify and distinguish different energy forms based on perceptual and visible “energy indicators”. For example, the indicator of

light energy is light, the indicator of kinetic energy is movement, and the indicator for chemical energy is foods, fuels, and body parts. The Forms of Energy List also clarifies some of students' common confusions about energy forms. In both media and science textbooks, various forms of energy are introduced, but the distinction and relations among these energy forms are not explicitly addressed. For example, wind energy, sound energy, and kinetic energy may all be addressed at the same time, but the connection among them is not explained. The Forms of Energy List explains that, both wind energy and sound energy are kinetic energy, because they are related to the movement of air molecules.

The *Matter and Energy Process Tool* helps students to develop the ability to trace energy separately from matter and with degradation across scales. An example of using the Process Tool to analyze macro-processes is represented in Figure 15.

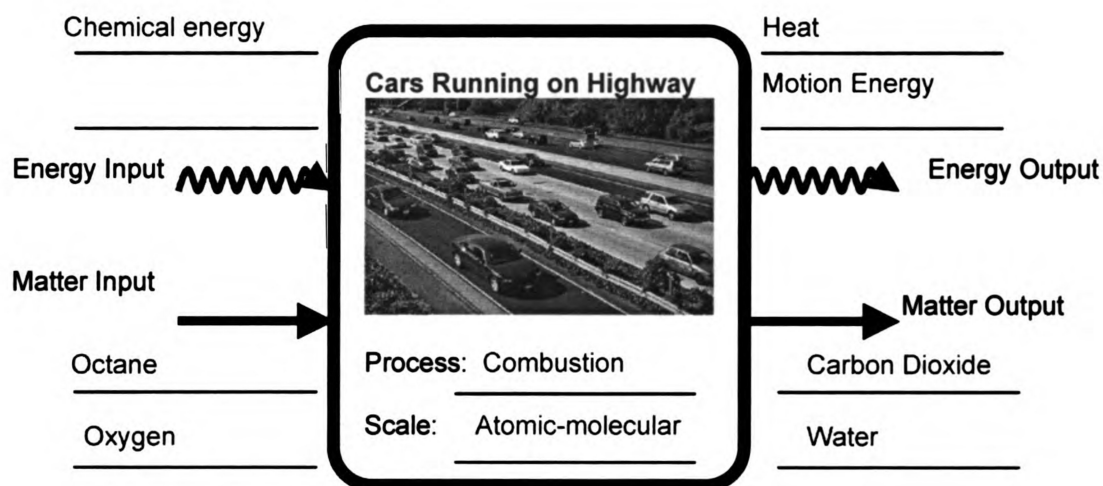


Figure 15 Process Tool

In this study, I found that students usually did not separate energy transformation from matter transformation and they traced energy without degradation. Therefore, the Process Tool uses wavy arrows to represent energy and uses straight arrows to represent matter. The wavy arrows and straight arrows are not exchangeable, indicating that energy and matter are not convertible. Three principles of matter and energy are represented in the Process Tool as follows: For matter conservation, whenever there is matter input (the incoming straight arrow), there is always matter output (the outgoing straight arrow); For energy conservation, whenever there is energy input (the incoming wavy arrow), there is always energy output (the outgoing wavy arrow); For energy degradation, at the energy output side, heat (red) is always released.

In this study, I also investigated mechanisms of students' progress and found that students tended to use strategies to reconcile what they learned from science classes with their existing reasoning framework and maintain the primitives of their existing reasoning framework. In particular, they tend to describe socio-ecological events as matter/energy processes and force-dynamic processes happening at different times or different locations. I suggest science teachers to pay special attention to this pattern and explicitly address that in class.

LIMITATIONS

The limitations of this study come from two aspects: teaching experiment and methods. First, I planned to conduct a teaching experiment, but participant teachers did not use the teaching materials systemically. Therefore, ideas about teaching approaches

have not been evaluated in real classrooms. Future research needs to be conducted to study the effectiveness of the teaching approaches I suggested above.

Second, there are limitations in methods. The findings of this study primarily come from analysis of interview data with 24 students in rural Michigan schools. Thus this sample is not nationally representative of American students. Although I used written assessment data in developing the learning progression framework, systemic validation between interview and written data analysis was not conducted. The reason is that students' written responses are usually very short and with limited details, and they do not provide enough information to be compared with the students' interview data.

FUTURE RESEARCH

Discussion of the implications and limitations of the study raised important questions that need further research. My plan for future research is elaborated as the following:

Conducting systemically validated interview and written assessment study.

To solve the above problems of generalization and validity, it is important to implement both clinical interview and large-scale written assessments and to conduct systemic validation between interview and written data analysis. In particular, I plan to use *item clusters* in written assessments. Each item cluster could be about one socio-ecological event. For example, all items about cellular respiration, including weight loss, eating food, etc., can be grouped together into one item cluster. Students' responses to all these cellular respiration items, when analyzed together, will provide rich information about

students' understanding of cellular respiration and ensure us to conduct validation between written assessment data analysis and interview data analysis.

Using Tracing and Association as progress variables to develop learning progressions for other content topics. Tracing and Association, as general ways of reasoning, can be used as progress variables to develop learning progressions about other content topics such as matter and biochemical processes.

Developing a more inclusive learning progression for energy. This study focuses on students' understanding of energy in socio-ecological systems. Can Association and Tracing be used as progress variables to measure students' understanding of energy in physical contexts and at large-scale? The answers to this question will enable me to develop a more inclusive learning progression for energy.

APPENDIX A ASSESSMENT DILEMMA AND SOLUTIONS

As shown in the Loop Diagram, the learning goal for students is to use the scientific reasoning about energy—tracing energy with degradation across processes at atomic-molecular, macroscopic, and global scales—to make accounts. This scientific reasoning is elaborated in the Loop Diagram. However, in the earlier research cycles, I encountered the assessment dilemma. The participants involved in my research came from a wide range of ages (from fourth graders to 11th graders). The questions used in the earlier research cycles are not effective in eliciting accounts from all students.

In the earlier research cycles, I designed questions to investigate how students understand energy as it relates to the carbon-transforming processes. I 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. In the interview excerpt below, the researcher asked three questions about energy with respect to the event of dead tree decaying. Mark's responses are "I don't know" or descriptions of changes happened to matter—"Bugs eat it, so it breaks down into the soil".

6th grader. (Tree decay)

Interviewer: Does this event involve energy?

Mark: Yeah, Yeah, Hmmm. Actually, I don't, I don't know.

Interviewer: Do you think the dead tree contains energy?

Mark: Yeah. It... Emmh, I don't know.

Interviewer: What happens to the energy of the tree?

Mark: Bugs eat it, so it breaks down into the soil.

In another example, we asked middle school students how the glucose molecule in the grape helps the finger to move. 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, one student replied: “Dude, I’m only 14 and I didn’t understand the ? [question].”

In the earlier research cycles, I also designed some general questions. These questions use everyday language ask about macroscopic events. Although they make sense to younger students, they are not effective in eliciting detailed responses from students with more advanced knowledge of science. Below is the “light for plants” item with a high school student’s response.

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.

Answer: 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 response about why plants needed light to survive. However, since the question did not require the student to explain how light energy changed in the process of photosynthesis, the student did not provide any details about that. As the result, the student’s account does not provide enough information for us to tell whether s/he conserves energy in photosynthesis.

From the examples of students’ responses, we can see that the assessment dilemma was caused because of students’ differing abilities. In the earlier research cycles,

my focus is on how students use energy concept to reason about carbon-transforming processes at three scales—atomic-molecular scale, macroscopic scale, and global scale. However, the data showed that energy was not a useful tool for younger students to make accounts and that carbon-transforming processes at the atomic-molecular scale and global scale were usually invisible to younger students. Students, especially younger students, tend to make accounts based on their specific ways of everyday reasoning, which are very different from scientific reasoning. Effective assessments should target students' informal reasoning. So, what could be younger students' specific ways of informal reasoning?

Data from the earlier cycles of research indicate that younger students might rely on *force-dynamic reasoning* to understand the macro-processes. I based this hypothesis on research in linguistics and cognitive development suggesting that people construct specific ways of reasoning as they learn their native languages. Cognitive linguists studying English grammar (Pinker, 2007; Talmy, 2000) suggest that both languages have implicit theories of cause and action—force-dynamic reasoning—that explain the world in terms of an action-result chain containing three elements—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 its 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. Scientific accounts focus on the energy transformation (or matter transformation) in atomic-molecular carbon-transforming processes behind the macroscopic interactions between the actors and its enablers. In particular, scientific accounts are constructed around the following three elements:

- **Energy sources for the socio-ecological events.** In science, energy cannot be created. It must come from energy sources. Light is the energy source for photosynthesis (e.g., tree growth); organic carbon-containing compounds are the energy sources for cellular respiration (e.g., girl running, weight loss, and tree decay), combustion (e.g., flame burning, car running, and lamp lighting), and digestion and biosynthesis (e.g., baby girl growth).

- Energy transformation in chemical processes at the atomic-molecular scale.

Scientific accounts explain the macroscopic socio-ecological events in terms of energy transformation in chemical processes. For example, tree growth is explained as that light energy transforms into chemical potential energy of organic carbon-containing compounds in photosynthesis.

- Energy transformation at the global scale. Scientific accounts explain the connections among various socio-ecological events in terms of energy transformation. For example, using electrical appliances will cause carbon emission, because most of our electricity is from burning coal. When coal is burning, the chemical potential energy of hydrocarbons transforms into electrical energy and at the same time carbon dioxide is released. When people are using electricity, electrical energy transforms into other forms of energy (e.g., light energy and heat).

If we compare force-dynamic accounts and scientific accounts, we can find that both of them are based on very similar framework. First, the energy sources are often identified as “enablers” in force-dynamic accounts, although force-dynamic accounts rely on totally different reasoning to explain why the enablers 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 the 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.

Hence, to solve the assessment dilemma, I 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. The shared framework contains three elements: identify enablers or energy source(s), explain individual macroscopic socio-ecological events, and explain the connections among the socio-ecological events. To ask questions at different difficulty levels, I used the branching-structure interview and item pairs in the written assessment. In the following paragraphs, I use examples of students' responses to show how the branching-structure interview and item pairs effectively elicit students' understanding.

Branching-structure Interview

Below is an excerpt from an interview with a forth grader, who rely on force-dynamic reasoning to account for the event of flame burning. The lower-level questions are in italic. The transition questions are underlined. The lower-level questions and transition questions effectively elicited Wilson's understanding of flame burning:

Wood/Match or wick helps flame to keep burning by supporting the flame and air helps the flame to breathe. When the interviewer asked the transition question—do you think the flame uses the wax or wood for energy, Wilson replied yes. However, his justification of that answer focuses on how the enablers—wood, wax, and wick—support the flame or provide a container for the flame: “it will help it so it stays in”; “the wax will probably help it so it stays inside the thing and the wick will make it so it will just keep burning

down". Since Wilson's responses indicate that he primarily relied force-dynamic reasoning and did not use energy to reason about the event, the interviewer did not ask higher-level questions.

First Interview (4th Grader)

Flame Burning

Interviewer: *What does the flame need in order to keep burning?*

Wilson: It will need wood. And so you can hold the match and then let go and then it will burn up. And then the candle will just need the wick.

Interviewer: Wick.

Wilson: So it will, that is where the fire will go. And then the wax will start melting and then soon you will have no candle.

... ..

Interviewer: Ok, let's talk about each of these. Ok, *what happens to wood of match, or wax of candle, what is going to happen to them when it is burning?*

Wilson: The wax will melt into the floor or the table. But for the match, it will keep burning right down to either to the end or the wood.

... ..

Interviewer: Ok. So do you think the flame uses the wax or wood for energy?

Wilson: Yes. Because it will help it so it keeps either burning whatever you want it to burn or it will help it so it stays in, the wax will probably help it so it stays inside the thing and the wick will make it so it will just keep burning down. And for the burning match it will either, you put it out at the end or it will keep burning the wood.

... ..

Interviewer: Ok, good. *Other students talked about air. They said air is needed. Can you guess why air is needed?*

Wilson: Air might be needed because it will help it give it energy so it keeps burning. And also it will need some air into like a fire so it won't like burn off a bunch of smoke and it will keep burning. And have you heard of people saying that fire will like, so it keeps being able to breathe?

The episode below is from the interview with a 4th grader. It is about the event of car running. The interview began with a lower-level question that asked about a macroscopic phenomenon (in italic): After the car runs for a while, if you touch the front part of the car, touch the engine part of the car, it's very hot. Why? Amy mentioned heat in her response to the question. The interviewer then asked a couple of follow-up transition questions (underlined): What do you mean by heat? Do you have any ideas about what heat is? Amy replied that heat is a form of energy, indicating that she might be able to use scientific reasoning of energy to explain the event. To investigate to what extent Amy trace energy, the interviewer asked two higher-level questions (in bold): Where does heat energy come from? You mean heat can be created or do you think the heat is changing from other things? Amy's responses indicate that she did not trace where heat energy came from.

Second Interview (4th Grader)

Car Running

Interviewer: *After the car runs for a while, if you touch the front part of the car, touch the engine part of the car, it's very hot. Why?*

Amy: Because stuff is getting burned inside of it, so it gets hot on top because when the **heat** starts to rise then it goes through the hood and through the motor and everything and so when you put your hand on it then it's hot.

Interviewer: So talking about the heat, what do you mean by heat? Do you have any idea about what heat is?

Amy: It's a form of energy.

Interviewer: **So where does heat energy come from?**

Amy: When something is burned it's the way to get hot. When you burn something then heat just comes from it.

Interviewer: You mean heat can be created or do you think the heat is changing from other things?

Amy: I think it changes from when oxygen and whatever is getting burned mix then it creates heat.

After the car runs for a while, if you touch the front part of the car, touch the engine part of the car, it's very hot. Why?

Item Pairs

In the following paragraphs, I use examples of students' responses to explain how item pairs elicit accounts from students from diverse age groups and how they help to identify and distinguish the levels of the accounts. One example is grape/food and finger movement item pair, which is an open-ended item. The other is a two-tier multiple-choice item pair—light for plants, which was revised from the initial open-ended item.

The grape and finger movement item asks how a glucose molecule changes to help body movement. It is proved effective in diagnosing whether and how students conserve energy in cellular respiration. Below are responses from a high school student. 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.

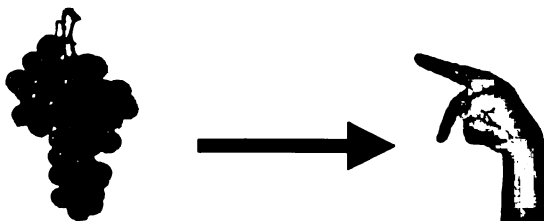


Figure 16 Grape and Finger Movement Item

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 the level of more sophisticated accounts, it was not understood by younger students. Hence, I developed the elementary/middle school item—food and finger movement. It asks about the same process, but uses informal language that can be understood by younger students. The item and an example of students' responses is shown as below:

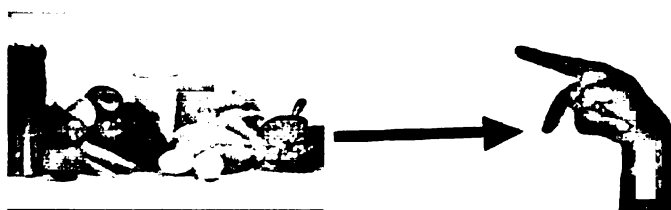


Figure 17 Food and Finger Movement Item

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 [their]

body gets very tired and weak. This happens because there [their] 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 (foods,) and results (achievement of the goal to move the finger). It indicates a force-dynamic reasoning. Although the student used the word energy for explanation, she did not distinguish energy, nutrients, and foods in general. She stated that energy helped people with communication, indicating that the word energy is used as a common language word.

The “light for plants” item, as elaborated before in this section, shows that general questions do not work well with more advanced students. In order to get more detailed accounts, I 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 the students' responses to the open-ended question used previously. In the item pair, the elementary/middle school item contains distractors that are lower-level accounts, while distractors in the high school item are higher-level accounts about scale, matter, and energy. The data indicate that the two-tier multiple-choice item pair is effective in diagnosing and distinguishing the levels of students' accounts. Below are the examples that show how the revised version of the “light for plants” item assesses and distinguishes the levels of accounts.

The elementary/middle school item with a student's response is shown as below:

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 [too] cold and die.

The options of the first tier represent two levels of reasoning. Options a, b, c, d, f are macroscopic force-dynamic accounts. Choice a does not recognize that all plants need sunlight. Choice b, c, d, and f explain why plants need sunlight in terms of perceptions. They use terms about perceptions including warm, darkness, healthy, and breathe. These accounts do not mention any invisible processes. Option e is a more sophisticated account. It links the macro-process to the invisible process of “making food”. The item also asks students to explain their choices, giving students the opportunity to write more details about their ideas.

The student chose b and c. Both his choices and explanations indicate macroscopic force-dynamic reasoning. Although option e is more advanced than other options, it does not address details about scale, matter, and energy. So, it is not effective in distinguish the level of more sophisticated accounts.

The high school item of the item pair is shown below:

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 it into glucose. After that, glucose units combine to make starches that the plant can use to function. Starches are fatal [vital?] for plant survival.

The item contains options about how energy and matter change in the atomic-molecular process of photosynthesis. Both option a and option 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 option c suggests. These options are the common misconceptions identified from previous research cycles. Option d is the scientific account that successfully traces energy in photosynthesis. Option e does not recognize light energy as being related to any hidden process involved in tree growth. It represents the reasoning level lower than the other options.

In the example, both the student's choice and justification indicate that although the student attempted to trace energy, 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 explained the event in terms of matter-energy conversion—light energy is converted into molecules (glucose and starches).

APPENDIX B INTERVIEW PROTOCOL

(Lower-level Questions are in *italic*; Transition Questions are underlined;
Higher-level Questions are in **bold**)

--- PLANT GROWTH ---

Tree Growing	
	
A small tree was planted in a meadow	After 20 years it has grown into a big tree, weighing 500 lb more than when it was planted.

Actor: tree

Enablers: sunlight, water, soil, and air

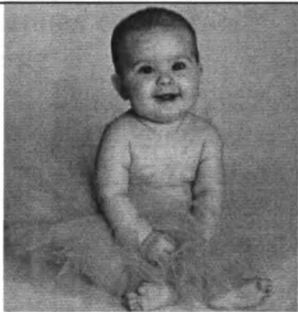
1. *What does the tree need in order to grow?*
2. *You said that the tree needs [sunlight, water, soil, air]. Do you think that these things help the tree to grow in the same way? How are they alike or different?*
3. *Follow up probes about each enabler [sunlight, water, soil, air]:*
 - a. How does [the enabler] helps the tree to grow?*
 - b. How does the tree uses [the enabler] to grow?*
 - c. What happens to [the enabler] inside the tree?*
 - d. Is [the enabler] used up to make the tree grow? Does it change into other things inside the tree's body? Or, do you think it will not change inside the tree's body?*
 - e. Does the tree use [the enabler] for energy? How does that work?*
4. *Follow-up probes on enablers not mentioned*
 - a. Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the tree growth?*
 - b. [If yes, use same probes as for other enablers.]*
 - c. [If no] Why not?*
5. **Scale**
 - a. Can you tell me about what's happening inside the tree as it grows?*
 - b. Do you think that the tree is made of cells?*
 - c. **Do you think that the tree's body is also made of molecules?***
 - d. **You said that the tree's body is made of both cells and molecules. What's the relationship between cells and molecules?***
6. **Matter**
 - a. The tree gets heavier as it grows. How does that happen?*

- b. *Where does the increased weight come from?*
- c. *Do you think the tree can naturally produce more and more mass?*
- d. If the students says no, ask: Do you think the tree's body structure is changed from things outside of the tree?
- e. If yes, how do these things change into the tree's body structure?
- f. **If the student mentions glucose/starch/cellulous/carbohydrates, ask: Do you think it contains carbon atoms? If yes, where does the carbon atoms come from?**
- g. Does the growing tree change the air? How does that happen?
- h. **If the student talk about CO₂—O₂ exchange, ask: You said that the tree needs Carbon dioxide and breath out oxygen. Where does the carbon atom of CO₂ go?**

7. Energy

- a. Does the process of tree growth require energy?
- b. If yes, where does the energy come from?
- c. Why do you think the things you mentioned have energy?
- d. **If the student associate energy with sunlight, ask: Where does the energy of sunlight go? Is it used up? Does it change into other materials? Or, is it still energy? Where is it?**
- e. **Do you think the tree stores energy inside its body? If yes, where does the tree store energy? In cells? In molecules? Where does that energy come from?**

--- BABY GIRL GROWTH ---

A Baby Girl Growing	
	
The baby weighed 22 lb when she was 5 months old.	The baby has grown into a big girl, weighing 50 lb.

Actor: Girl's body

Enablers: food, water, air, exercises, sleep

1. What does the baby need in order to grow?
2. You said that the baby needs [food, water, air, exercises, sleep]. Do you think that these things help the baby grow in the same way? How are they alike or different?
3. Follow up probes about each enabler [food, water, air, exercises, sleep].
 - a. How does [the enabler] helps the baby to grow?
 - b. How does the baby uses [the enabler] to grow?
 - c. What happens to [the enabler] inside the baby's body?
 - d. Is [the enabler] used up to help the girl to grow? Does it change into other things inside the girl's body? Or, do you think it will not change inside the girl's body?
 - e. Does the baby use [the enabler] for energy? How does that work?
4. Follow-up probes on enablers not mentioned
 - a. Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the baby growth?
 - b. [If yes, use same probes as for other enablers.]
 - c. [If no] Why not?
5. Scale
 - a. Can you tell me about what's happening inside the baby's body as she grows?
 - b. Do you think that the baby is made of cells?
 - c. **Do you think the baby's body is also made of molecules?**
 - d. **You said that the baby's body is made of cells and molecules. What is the relationship between cells and molecules?**
6. Matter
 - a. The baby gets heavier as she grows. How does that happen?
 - b. Do you think the girl's body can naturally produce more and more mass? Why?
 - c. If the students says no, ask: Do you think the girl's body structure is changed from things outside of the girl's body?
 - d. If yes, how do these things change into the tree's body structure?

e. If the student mentions glucose/starch/cellulose/carbohydrates, ask: Do you think it contains carbon atoms? If yes, where does the carbon atoms come from?

7. Energy

a. Does the process of baby growth require energy?

b. If yes, where does the energy come from?

c. Why do you think the things you mentioned have energy?

d. If the student associates energy with food, ask: Where does the energy of food go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?

e. Do you think the baby stores energy inside her body? If yes, where does the baby store energy? In cells? In molecules? Where does that energy come from?

--- GIRL RUNNING ---

A Girl Running



Actor: Girl

Enablers: food, air, water

1. What does the girl need in order to run?
2. You said that the girl needs [food, water, air, sleep]. Do you think that these things help the girl run in the same way? How are they alike or different?
3. Follow up probes about each enabler [food, water, air, sleep].
 - a. How does [the enabler] helps the girl to run?
 - b. How does the girl uses [the enabler] to run?
 - c. What happens to [the enabler] inside the girl's body?
 - d. Is [the enabler] used up? Does it change into other things? Or, do you think it does not change?
 - e. Does the girl use [the enabler] for energy? How does that work?
4. Follow-up probes on enablers not mentioned
 - a. Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the girl growth?
 - b. [If yes, use same probes as for other enablers.]
 - c. [If no] Why not?
5. Breathing:
 - a. Do you think breathing helps the girl to run? Why?
 - b. Do you think moving and breathing are related events? Why?
6. Warmth:
 - a. Why can people keep warm, but a stone cannot?
 - b. The girl will get hot when she runs. How could that happen?
 - c. You mentioned about heat. Do you think heat is energy? Where does heat come from?
7. Scale
 - a. Can you tell me about what's happening inside the girl's body as she runs?
 - b. Do you think that the girl's body is made of cells?
 - c. Do you think the girl's body is made of molecules?

d. You said that the girl's body is made of cells and molecules. What is the relationship between cells and molecules?

8. Matter

a. The girl will lose weight if she runs a lot. How does that happen?

b. Where does the lost mass go? Is it used up? Does it change into other things? Why?

c. Does the event of girl running change the air? How does that happen?

d. If the student mentions carbon dioxide from breathing, ask: Do you think it contains carbon atoms? If yes, where does the carbon atoms come from?

9. Energy

a. Does the process of girl running require energy?

b. If yes, where does the energy come from?

c. Why do you think the things you mentioned have energy?

d. If the student associate energy with food or body structure, ask: Where does the energy of food/body go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?

--- DEAD TREE DECAY ---

Tree Decaying



A tree falls in the forest. After many years, the tree will appear as a long, soft lump barely distinguishable from the surrounding forest floor.

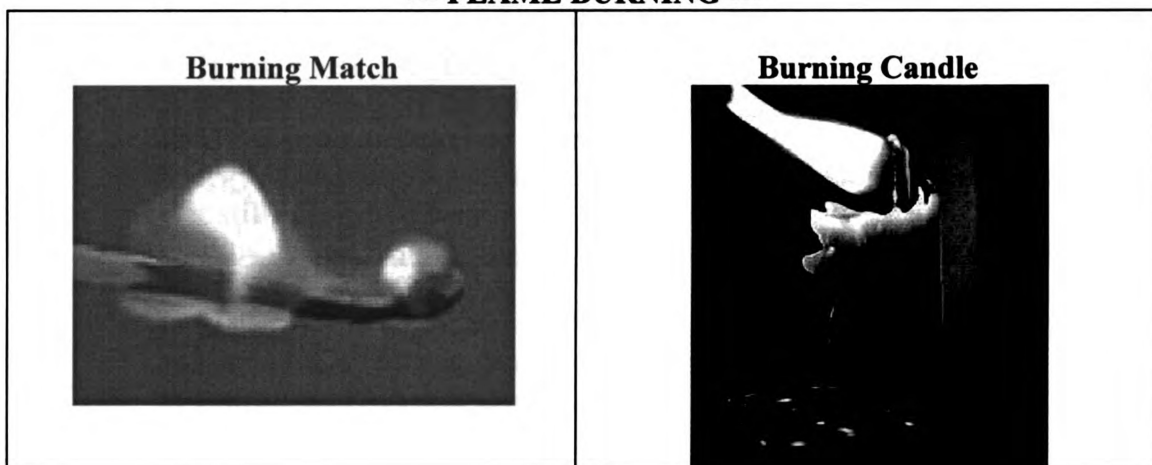
Actor: Dead Tree

No enablers such as tree decay due to becoming old

Enablers: rain, wind, sun, bugs

1. *Why do dead plants and animals decay but not living plants and animals?*
2. *What causes the changes in the wood?*
3. *If the student mentions decomposers/microbes/bugs/fungi, ask: Do you think the tree will decay if there is no decomposers/microbes/bugs/fungi?*
4. *How does each of the things you have mentioned cause that change?*
5. Scale
 - a. Can you tell me about what's happening inside the dead tree's body as it decays?
6. Matter
 - a. The tree lost a lot of materials over a long time. Where do you think the lost materials have gone?
 - b. What happens to the matter of the wood? Where does the matter that is no longer in the lump has gone? In what form (solid, gas, liquid)?
 - c. **Do you think chemical changes are happening to wood of the tree? If yes, what are those chemical changes? Could you use molecules to explain your answers?**
 - d. **Do you think the dead tree's body contains carbon atoms? If yes, where does the carbon atoms go when the tree is decaying?**
7. Energy
 - a. Do you think energy is somehow involved in the event of decay? How?
 - b. Do you think that the tree contains energy when it was living? Why?
 - c. Do you think that the tree contains energy when it dies? Why?
 - d. When the tree dies, what will happen to its energy? Do you think it will go somewhere?
 - e. **(If yes) Does that energy still exist somewhere? If yes, where is it? In what form? How does that happen?**

--- FLAME BURNING ---



Actor: flame

Enablers: fuels (wax, wick, wood), air

1. *What does the flame need in order to keep burning?*
2. *You said that flame needs [wax, wick, air, wood, ...]. Do you think that these things help the flame to burn in the same way? How are they alike or different?*
3. *Follow up probes about each enabler [wax, wick, air, wood, ...].*
 - a. *How does [the enabler] helps the flame to burn?*
 - b. *How does the flame uses [the enabler] to burn?*
 - c. *What happens to [the enabler] inside the flame?*
 - d. *Is [the enabler] used up? Does it change into other things? Or, do you think it does not change?*
 - e. *Does the flame use [the enabler] for energy? How does that work?*
4. *Follow-up probes on enablers not mentioned*
 - a. *Some other students have mentioned [other enabler]. Do you think [the other enabler] is necessary for the flame growth?*
 - b. *[If yes, use same probes as for other enablers.]*
 - c. *[If no] Why not?*
5. *Scale*
 - a. *Can you tell me about what's happening inside the flame, as it burns?*
 - b. *Do you think that the flame is made of materials?*
 - c. **If yes, do you think the flame is made of molecules and atoms? Please explain.**
6. *Matter*
 - a. *What change will happen to the match?*
 - b. *Do you think the match will lose weight? If yes, where does it go? Is it used up? Does it change into other things? Why?*
 - c. *What change will happen to the wax of the candle?*
 - d. *Do you think the candle will lose weight? If yes, where does it go? Is it used up? Does it change into other things? Why?*
 - e. *Does the event of flame running change the air? How does that happen?*
 - f. **Do you think wax/wood contain carbon atoms? If yes, where does the carbon atoms go when the flame is burning?**

7. Energy

- a. Does the process of flame running require energy?
- b. If yes, where does the energy come from?
- c. Why do you think the things you mentioned have energy?
- d. **If the student associate energy with wood or wax, ask: Where does the energy of wood/wax go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?**
- e. Why do you feel warmth, when the flame is burning? Do you think heat is released from burning?
- f. **If yes, how is heat released? Do you think heat is created in combustion, or do you think heat is changed from other forms of energy in combustion? Please explain.**

--- CAR RUNNING ---

Car Running



Tom's family went to Chicago on vacation. When they came back, Tom's dad found that their car consumed 50 gallons of gasoline for the trip.

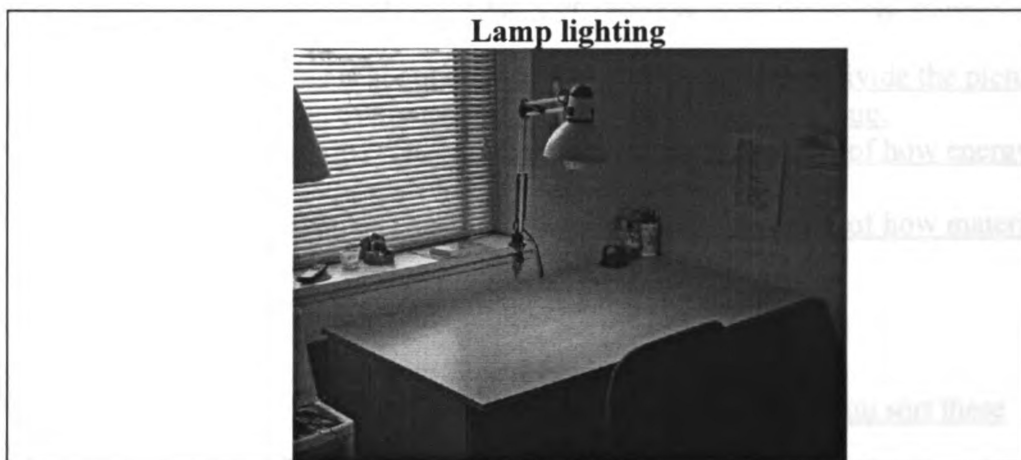
Actor: Car

Enablers: gasoline, air

1. *What does the car need in order to carry the family to Chicago?*
2. *You said that the car needs [gasoline, air]. Do you think that these things help the car to move in the same way? How are they alike or different?*
3. *Why do people use gasoline instead of water to run their cars?*
4. Follow up probes about each enabler:
 - a. *How does gasoline/air helps the car to run?*
 - b. *How does the car use gasoline/air to run?*
 - c. *What happens to the gasoline/air inside the car, when the car runs?*
 - d. Does the car use gasoline/air for energy? How does that work?
 - e. Is gasoline/air always necessary for car running? Why or why not?
5. Follow-up probes on enablers not mentioned
 - a. *Some other students have mentioned gasoline/air. Do you think it is necessary for car running?*
 - b. *[If yes, use same probes as for other enablers.]*
 - c. *[If no] Why not?*
6. Matter
 - a. When your family arrive at Chicago, the gas tank is almost empty? Where does the gasoline go?
 - b. Do you think the gasoline is used up? Or, does it change into other things?
 - c. Does the event of car running change the air? How does that happen?
 - d. **Do you think gasoline contains carbon atoms? If yes, where does the carbon atoms go when the gasoline is used by the car?**
7. Energy
 - a. Does the process of car running requires energy? If yes, where does the energy come from?

- b. Why do you think the things you mentioned have energy?
- c. **If the student associate energy with gasoline, ask: When the car stops, where does the energy of gasoline go? Is it used up? Does it change into materials? Or, is it still energy? Where is it?**
- d. After the car runs for a while, the front part of the car will become very hot. Why?
- e. **If the student mentions heat, ask: how is heat released?**
- f. **You said that the gasoline is burning inside the car. Do you think heat is created in burning, or do you think heat is changed from something else? Please explain.**

--- USING ELECTRICAL APPLIANCES ---



Actor: lamp
Enabler: electricity

1. *The lamp will not light if it is not plugged in. Do you know why?*
2. What does the lamp get from the outlet? If the student mentions electricity or electrical energy, ask the following questions:
 - a. Why can electricity help the lamp to light? Can you use energy to explain that?
 - b. Do you think electricity is related to energy? If yes, what energy form is it?
 - c. Where does electricity come from?
 - d. (If mentions power plants) Where do power plants get the energy from to generate electricity?
3. **About 50% of electricity used in US comes from coals. Do you know how does that happen? Can you use energy to explain this question? Where does the energy of coals come from?**
4. **If the student mentions about burning coals, ask:**
 - a. **Do you think coal has energy? Where does that energy go?**
 - b. **Do you think the coal changes into energy? Or do you think it changes into other things?**

CLASSIFICATION OF EVENTS

1. Elementary, middle and high school students:

Pictures: Plant growth, A baby girl growing, Car running, Tree decaying, Wood/Candle burning, A girl running

- Each of these pictures is about a process or change. Can you divide the pictures into three groups in terms of process or change? Explain each group.
- Please re-group the cards. This time please sort cards in terms of how energy change.
- Please re-group the cards. This time please sort cards in terms of how materials change.

2. Middle and high school students:

Pictures: Tree growing, Girl running, Tree decaying

- Think about the role of these processes in an ecosystem, can you sort these pictures into two groups? Explain each of the groups.

3. High school students:

Pictures: Plant growth, A baby girl growing, Car running, Tree decaying, Wood/Candle burning, A girl running

- **Can you sort these pictures again? This time, please sort the pictures in terms of changes of matter and energy.**

4. High school students:

Pictures: A girl running, Tree decaying, car running

- **Can you think of a reason for putting these pictures together? If not, what processes can put together? Why?**

5. High school students:

Tree growing, girl running, tree decaying

- **Can you think of a reason for putting tree growing separate from the other two pictures?**

CONNECTIONS AND GLOBAL WARMING

Show students all the pictures:

1. *How are all these events connected?*
2. How could they be connected in an ecosystem?
3. How are these processes connected in their ways of using and changing air?
4. How are they related to global warming?
5. How many pictures can you connect together? Please make connections as possible as you can.

APPENDIX C WRITTEN ASSESSMENT ITEMS

Item 1. Sunlight for plant growth

Lower-level Item

Do you think plants need light to live? Why? Please choose the ONE answer that you think is best.

- 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 foods.
- f. Light helps plants breath.

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.)

	
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Higher-level Item

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.)

	
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Item 2. Energy sources for plants

Lower-level/Higher-level Item

Which of the following is/are energy source(s) for plants? Circle yes or no for each of the following and explain your answer.

- a. Water

Yes / No

- | | |
|----------------------------------|----------|
| b. Light | Yes / No |
| c. Air | Yes / No |
| d. Nutrients in soil | Yes / No |
| e. Plants make their own energy. | Yes / No |

Please explain your answers. In particular, explain why the ideas you circled "No" for are NOT sources of energy for the plants.

Item 3. Energy stored in human body

Higher-level item

Where does your body store energy for later use? Please choose the ONE answer that you think is best.

- Energy is stored in the form of matter.
- Energy is stored in the form of chemical energy.
- Energy is stored in the cell, but is separated from the matter of the cell.
- Energy is stored among the cells.
- The body does not store energy. Energy is produced when you need it.
- Other _____

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.)

Item 4. Energy sources for people

Lower-level/Higher-level Item

People need energy to live and grow. Which of the following is/are energy source(s) for people? Circle yes or no for each of the following and explain your answers.

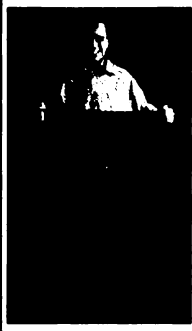
- | | |
|--------------|----------|
| a. Water | Yes / No |
| b. Food | Yes / No |
| c. Nutrients | Yes / No |
| d. Exercise | Yes / No |
| e. Sunlight | Yes / No |

Please explain your answers. How does each material that you circled "Yes" for supply energy for people?

Item 5. Weight loss

Lower-level Item (Item Revised from Project Thinking Like A Biologist)

Jared, the Subway® man, lost a lot of weight by eating low calorie subway sandwiches. Where did the mass of his fat go (how was it lost)?



Higher-level Item (Item Revised from Project Thinking Like A Biologist)

When a person loses weight, what happens to some of the fat in the person's body?

Please choose ONE answer that you think is best.

- a. The fat is broken down and leaves the person's body as water and gas.
- b. The fat is converted into energy
- c. The fat is burned up providing energy for the person's body functions
- d. The fat is broken down and leaves the person's body as feces and urine

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.)

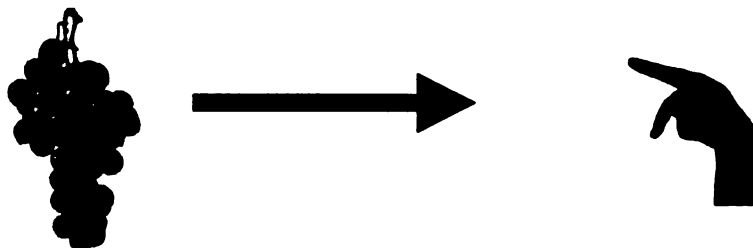
Item 6. Food and finger movement

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



Please explain how the foods you eat help you move your little finger. Tell as much as you can about how food that you eat with your mouth can help your finger to move.

You eat a grape high in glucose content. (Item Revised from DQC Project)



- 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.

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

Item 7. Tree decaying

Lower-level/Higher-level Question

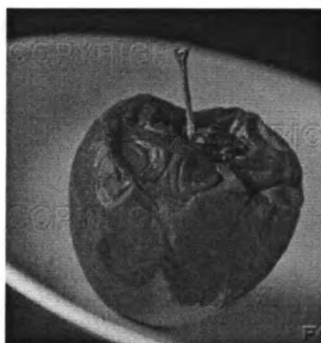
A tree falls in the forest. After many years, the tree will appear as a long, soft lump barely distinguishable from the surrounding forest floor.



- a. What caused the changes in the wood? How did those changes happen? Give as many details as you can about what is breaking the wood down, and how.
b. Do you think that the process of decay involves energy? How?

Item 8. Apple rotting

Lower-level/Higher Level Question



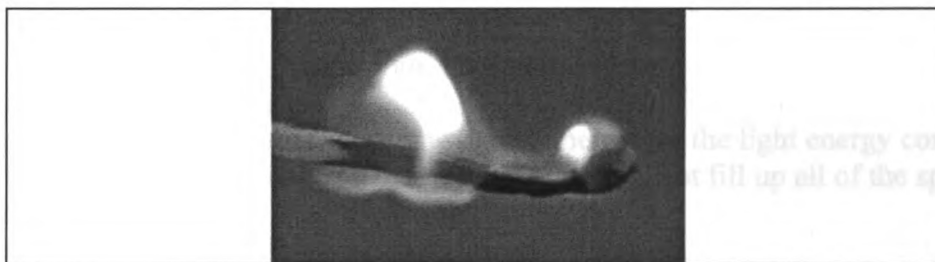
When an apple is left outside for a long time, it rots.

- a. What causes the apple to rot?
b. When the apple is rotting, where does its energy go?

Item Pair 9. Flame burning

Lower-level/Higher-level Item

The picture shows that a match is burning.



Where does the energy of burning come from? Please tell as much as you can about substances and chemical processes.

Item 10. Car running

Lower-level/Higher-level Item

Tom's family went to Chicago on vacation. When they came back, Tom's dad found that their car consumed 50 gallons of gasoline for the trip.

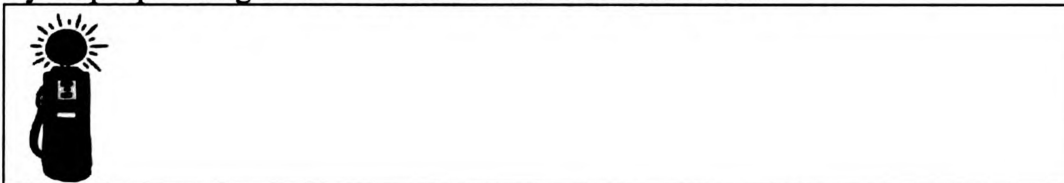
- 1) Where did the 50 gallons of gasoline go?
- 2) Where did the energy of the gasoline go? Does the energy of the gasoline still exist somewhere? Please choose the ONE answer that you think is best.
 - a. The energy of the gasoline was burned up and does not exist anywhere.
 - b. The energy of the gasoline was turned into heat in the environment.
 - c. The energy of the gasoline was stored in the engine.
 - d. The energy went out the tailpipe with the exhaust.
 - e. Other _____

Please explain your answer. Tell as much as you can about intermediate stages and processes.

Item 11. Gasoline and water

Lower-level Question

Why do people use gasoline instead of water to run their cars?



Higher-level Item

Why do people use gasoline instead of water to run their cars? Please tell as much as you can about substances and chemical processes.



Item Pair 12. Lamp lighting

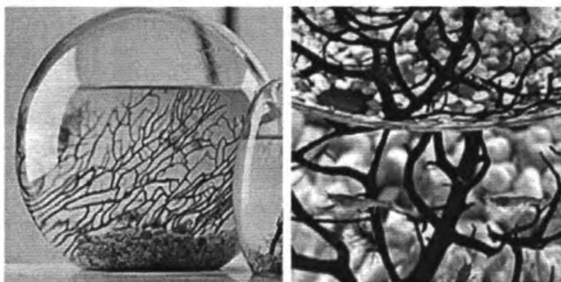
Lower-level/Higher-level Item

When you open the lamp, you can see the light. Where does the light energy come from? Trace the energy back as far as you can. You may or may not fill up all of the spaces in each table.

	What form of energy was it? Where was it?
	Light energy of the light
Before that...	
Before that...	
Before that...	
Before that...	
Before that...	

Item 13. EcoSphere

Higher-level Item



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.

Do you think the EcoSphere has energy exchange with the outside environment?

Circle one: YES / NO

If your answer is NO, why the living things can stay alive without energy exchange with the outside world?

If your answer is YES, what are the energy input and output of the EcoSphere? Please explain the forms of energy.

Item 14. Tropical Rainforest

Higher-level Item (Revised from Energy Concept Inventory)

A tropical rainforest is an example of an ecosystem. Which of the following statements about matter and energy in a tropical rainforest is the most accurate? Please choose ONE answer that you think is best.

- Energy is recycled, but matter is not recycled.
- Matter is recycled, but energy is not recycled.
- Both matter and energy are recycled.
- Neither matter nor energy is recycled.

Please explain why you think that the answer you chose is better than the others.

Item 15. Comparing events

Lower-level/Higher-level Item

		
A. Eating a hamburger	B. Filling up a car with gasoline	C. Watering plants

- The pictures above show that three things are happening. Are they alike or different? Please explain your answer.
- A science teacher says that A and B are similar events, but picture C is different from A and B. Do you know why? Please explain why C is different from A and B.

Item 16. Light bulbs

Higher-level Item

Compared with incandescent light bulb, fluorescent light bulb has higher energy efficiency and can save 66% to 75% energy. Do you think your personal behavior of using fluorescent light bulb instead of incandescent light bulb can contribute to slowing global warming? Please explain your answers.



Incandescent light bulb



Fluorescent light bulb

Item 17. Connections among events

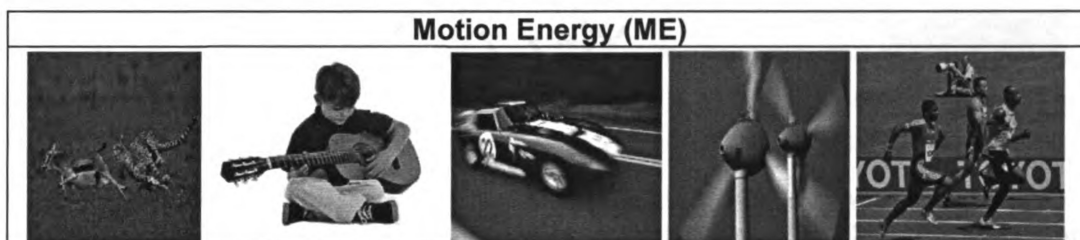
Lower-level/Higher-level Item

How are the three things related to each other?

- A person plugs in an air conditioner in the US
- Trees grow in the Amazon forest
- Ice in Antarctica melts

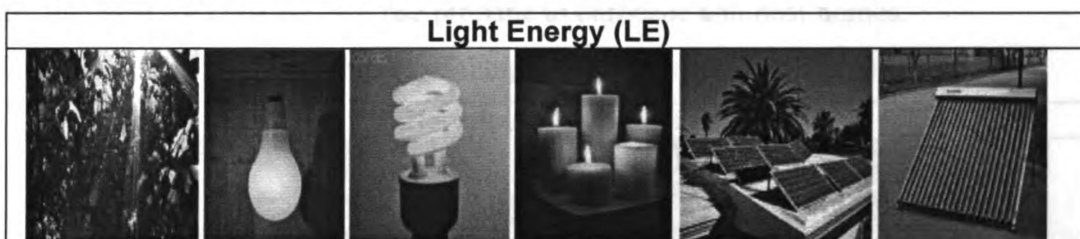
APPENDIX D TOOLS FOR REASONING

Forms of Energy List



Look around you. Many things are moving. They are in motion. Clouds drift across the sky. Leaves fall from the trees. A car speeds by. Birds fly. Whenever there is motion, we “see” **motion energy**. Holland is using **wind energy**, because it is clean and does not cause global warming. Wind energy is a kind of motion energy, because wind is moving air. Sound has energy. **Sound energy** is a special kind of motion energy. It is caused by vibration – the back and forth motion of air molecules.

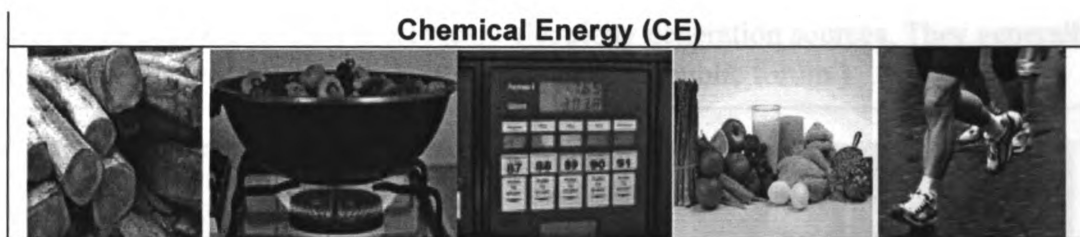
Can you think of other examples of kinetic energy that you see every day?



We use light every day. We use it to see things. Without light, our lives would be very difficult. Light helps our life more than just to help us see things. Sunlight helps plants grow. Doctors use special light to perform surgery. Light has **light energy**. When the lamp is turned on, it gives off light energy. When a candle is burning, the flame gives off light energy.

The light energy from the sun is sometimes called **solar energy**. The sun is a giant ball of burning gas. It gives off light all the time. It will keep shining and giving us energy for millions of years. Plants capture and use light energy to make their own food. Scientists have also invented ways to use light energy. *Solar collectors* on house roofs can capture light energy and use it to heat the water in the house. *Solar cells* on cars and house roofs can also capture light energy and use it to make electricity.

Can you think of other examples of light energy that you see every day?

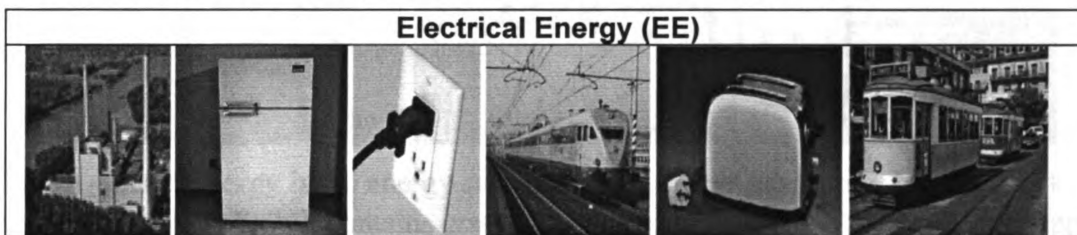


Chemical energy is the energy stored in some special materials. Foods, fuels and body parts of all living things are made of materials that contain chemical energy.

All living things are made of cells. Cells are made of millions or even billions of molecules. The energy is stored in molecules that make up cells. These molecules include carbohydrates, lipids (or fats), and proteins. We call these molecules **high-energy molecules**. The molecules can be found in all living things.

Fossil fuels come from plants and animals that lived millions of years ago. The plant and animal remains were buried underground. Over long periods of time, the remains turned into **fossil fuels**, including oil, natural gas, and coal. The major chemical component of fossil fuels is hydrocarbons. Like carbohydrates and lipids, hydrocarbons are also high-energy molecules. We use fossil fuels everyday. Our cars are powered by gasoline. We use methane for cooking. We use propane to barbecue and heat homes.

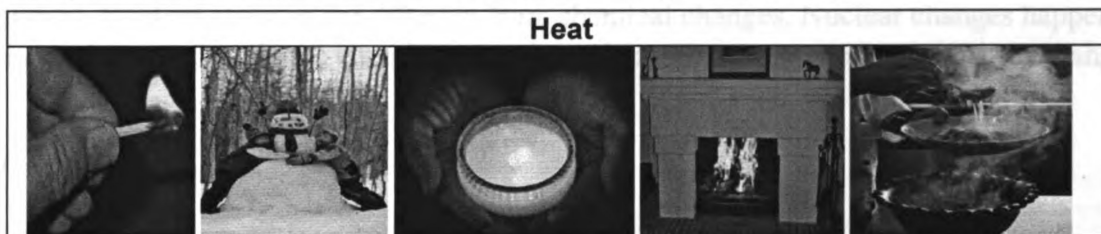
Can you think of more examples of things that have chemical energy?



People use electricity everyday. Your family likely uses many electrical appliances at home. You may watch TV after dinner. Your parents may use a laptop for work. You may use a toaster to toast bread or use a microwave oven to warm your food. To make these machines work, you should plug them into an outlet on the wall. What the machines get from the outlet is electricity. We not only use electricity to power our homes, school, or other buildings, but also use it for transportation. Electric trains or subway trains have engines that run on electricity. These engines get electricity through a metal rail under the train, or from wires at the top of the train. Electricity has **electrical energy**. Electricity is generated by different types of power plants. Wind power plants use wind to generate electricity. Nuclear power plants split uranium atoms to make electricity. Hydropower plants use the energy of moving water to make electricity. Fossil fuel fired power plants burn fossil fuels to generate electricity. In the United States, about 51% of our electricity comes from burning coal.

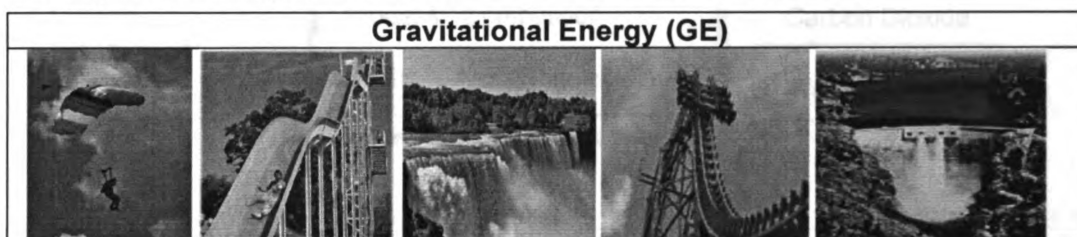
Do you know where your electricity comes from? What type of power plant do you depend on? (As an interesting note, you may want to consult statistics ahead of time from

your local utility as to their most recent electricity generation sources. They generally must post this information on their website or other public forum.)

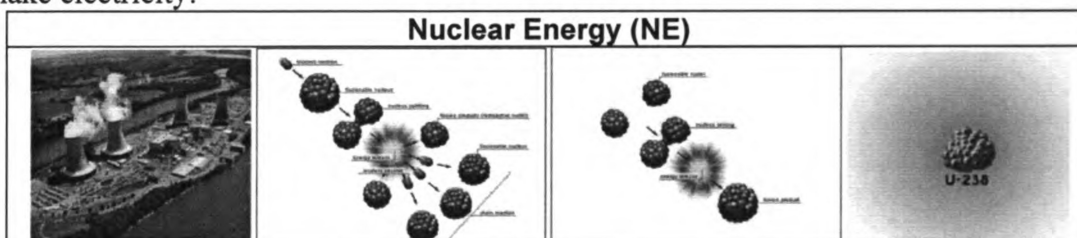


When you run a car for a while, the front of the car becomes very hot. When a flame from a candle or a campfire is burning, you can feel the warmth. When you are exercising, you also feel very hot. Even when you are playing outside on a cold winter day, your body stays warm. Your body temperature always stays close to 98.6° . In all these events, **heat** or heat energy is released.

Heat is a special form of energy. Whenever changes happen, heat is always released as a byproduct. Unlike light energy and chemical energy, heat cannot be “caught” by living organisms to help their body function or to help them move, although its loss can be slowed by various adaptations, such as thick fur or subcutaneous fat.



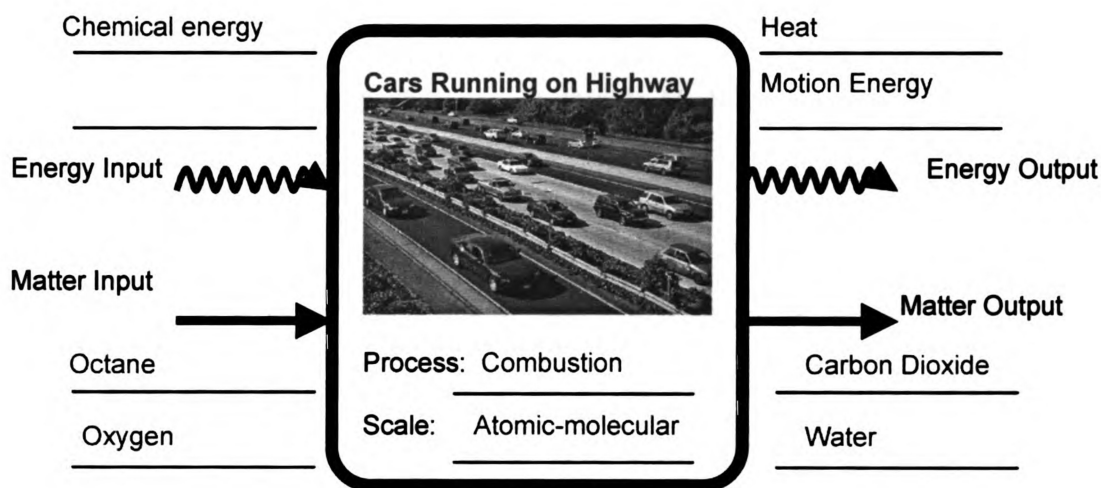
Gravitational energy is the energy stored due to a higher position or place. A rock resting at the top of a hill contains gravitational energy. When the rock loses its support, it will roll down the hill. In this case, the gravitational energy transforms into motion energy. Hydropower, such as water in a reservoir behind a dam, is an example of gravitational energy. Hydropower plants use the gravitational energy of the water to make electricity.



An atom is composed of electrons and a nucleus (neutrons and protons). **Nuclear energy** is the energy of the nucleus of an atom. There are two types of nuclear changes that release nuclear energy: fusion and fission. In fusion, nuclei are combined or “fused” together and nuclear energy is released in the form of heat and light energy. This is how the sun produces its heat and light energy. In fission, the nucleus of an atom splits apart

and nuclear energy is also released in the form of heat and light energy. Nuclear power plants use the heat released from the fission of uranium atoms to generate electrical energy. Nuclear changes are different from chemical changes. Nuclear changes happen inside the atom, while the chemical changes only rearrange the atoms and do not change.

Process Tool



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