A Cross-cultural Study: Comparing Learning Progressions for Carbon-transforming Processes of American and Chinese Student

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Abstract

In this research, we developed a four-level learning progression that described how American and Chinese students from fourth grade to high school reasoned about carbon-transforming processes. We designed an interview protocol that asked students to explain six key macroscopic carbon-transforming processes: tree growth, baby girl growth, girl running, tree decaying, flame burning, and car running. Twenty-four American students participated in interviews both before and after instruction, and twenty-four Chinese students participated a single interview each. We found that students' explanations could be analyzed in terms of two aspects of performances—naming (use of appropriate vocabulary) and explaining (nature of reasoning). Our data analysis indicates three trends: 1) Students in both group tended to rely on similar reasoning patterns to explain events, which are the four explaining levels of the learning progression (Level 1. macroscopic force-dynamic accounts; Level 2. force-dynamic accounts with hidden mechanisms; Level 3. accounts about changes of molecules and energy forms with unsuccessful constraints; Level 4. accounts linking processes with matter and energy as constraints). 2) Levels of explaining performances were similar for the two groups, indicating that even at the high school level most American and Chinese students tended to rely on everyday reasoning to explain the processes. 3) Students in both groups showed more Level 3 and 4 naming performances than explaining performances, but the difference was much larger for Chinese students, indicating that Chinese students were more likely to use scientific terms and statements, but without a deeper understanding of the processes.

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

Introduction

United States and China, the world's two largest emitters of greenhouse gases, are both facing environmental challenges. Most social, economic, and political issues have environmental components. In order to make informed decisions, citizens should develop necessary scientific knowledge and use it as a conceptual tool to analyze these issues. Now, developing scientific literacy and environmental literacy is becoming a major task of K-12 science education in the US and China. However, national and international large-scale assessments and surveys indicate reasons for concern.

In the US, TIMSS 2007 assessment results show that most American students do not achieve the proficient level of science achievement, lagging behind their counterparts from Asian countries (Gonzales, Williams, Jocelyn, Kastberg, & Brenwald, 2008). The Program for International Student Assessment (PISA) assesses students' ability to perform scientific tasks in a variety of situations, ranging from those that affect their personal lives to wider issues for the community or the world. The 2006 PISA results show that United States ranked 33rd among 57 countries in environmental science performance, statistically significantly below average (OECD, 2007). The United States also ranked 21st among 30 countries in all science tasks with 24.4% of American 15-year-olds not reaching the baseline level, at which students begin to demonstrate a basic understanding about science-related life situations (OECD, 2009). In brief, the environmental worry for American students is whether American students understand enough scientific knowledge to develop a basic understanding of environmental issues.

The Chinese education system is exam-driven. Although entrance examinations have been abolished in many cities at elementary and middle school level, high school entrance exams and the national college entrance exams still largely influence the whole education system.

Students scoring at the top of the entrance exams will enter the “key” high schools or top colleges and study a rigorous academic curriculum. Chinese students, especially students from “key” schools, demonstrated strong science knowledge and potential in the nationwide and province-wide exams.

However, the exam-driven education system has also caused many problems. One major problem is the discrepancy between school science learning and students’ life experience. According to the survey from Ministry of Education, only 9.3% of teachers and 5.4% of students see the school curriculum as relevant to their life experience; about 78% of the respondents think that what the exams test are irrelevant to what they need to know as citizens (Liu, 2006). International surveys also indicate that the intensive science learning in schools has not helped Chinese students to develop scientific literacy. The China Association for Science and Technology (CAST) carried out national surveys on people’s scientific literacy. Results of the 2003 survey showed that only two percent of Chinese residents are able to use scientific knowledge to explain natural phenomena (Jia, 2004). In brief, the environmental worry for Chinese students is whether Chinese students understand science in ways that can apply to environmental issues.

Although large-scale assessments and surveys have provided important information about the problems of science education in the US and China, they do not help us to understand the causes of the problems. Classroom assessment research can provide useful complementary information for us to understand the causes of these problems, although quantitative findings cannot be generalized to the national level.

We conducted a cross-cultural interview study to investigate American and Chinese students’ understanding of carbon-transforming processes. On the one hand, understanding carbon-transforming processes is important for promoting environmental literacy. Global warming is one of the most serious environmental problems that every country has to face and deal with, especially for China and United States, the top two carbon emitters in the world. Carbon transforming processes include our energy consumption activities and biological processes such as plant growth and decay of dead organisms. These macroscopic processes are linked to atomic-molecular carbon-transforming processes that generate, transform, and oxidize organic carbon (i.e., photosynthesis, cellular respiration, digestion & biosynthesis, and combustion). The imbalance among these processes is the major cause of global warming. Therefore, understanding carbon-transforming processes is necessary for American and Chinese students to understand how their everyday activities cause global climate change over time.

Understanding carbon-transforming processes is also important to promote scientific literacy, as it reflects the big ideas from the major disciplines taught in secondary schools. These include big ideas from physics (i.e., matter conservation, energy conservation, and energy degradation), chemistry (chemical reactions), and biology (i.e., biological processes including photosynthesis, digestion, biosynthesis, and cellular respiration). Currently, carbon-transforming processes are included in the core content emphasized by curricula and standards of both the US and China. Does current science teaching help students to develop sophisticated understanding of carbon-transforming processes? Are students able to use the knowledge of carbon-transforming processes as conceptual tool to analyze environmental issues?

Our research intends to answer these questions through investigating and comparing how students from the US and China reason about carbon-transforming processes. Our research questions are about the reasoning patterns of American and Chinese students:

1. How do K-12 students from the US and China reason about carbon-transforming processes?
2. How do American and Chinese students progress with respect to reasoning about carbon-transforming processes from elementary to high school?

Literature Review

Our research is part of a larger research project. The project focuses on developing learning progressions in three strands: carbon, water, and biodiversity. Our research is in the carbon strand. Before turning to the specifics of learning progression development, we start with a brief discussion of the cultural and educational differences between the US and China and a general discussion of learning progressions.

Cultural and Educational Differences between the US and China

American and Chinese students are from different socio-cultural and educational contexts. In this study we focus on two major factors that influence students' scientific understanding—native languages and educational contexts. Ideas and information from the research literature about these two factors helped us to develop and revise the interview study.

Native language and 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) and Chinese grammar (Dai, 2005; Lai & Chiang, 2003) 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—actor, enabler, and result: the actor has internal goals and abilities to take certain actions, but it also needs enablers to make changes happen; the result is that the actor uses the enablers to accomplish its goal.

Educational contexts in the US and China. The educational policy, science education standards, curriculum, and classroom culture are very different in the US and China. In US, teachers use national and state standards as guidelines for teaching. Compared with Chinese teachers, they have many more opportunities to choose and design teaching materials and assessments. In China, textbooks and classroom instructions are aligned with the national science standards very closely. Due to the pressure from entrance exams and frequent citywide and province-wide exams, teachers teach to the test. They use provincial assigned curricula, which focus on building strong foundational knowledge and mastery of core concepts (Asia Society, 2006). Chinese teachers also use much more written assessments. Most of the Chinese secondary students in our research had science tests every week. Chinese classes are usually larger than American classes—35 to 50 students for the classes in our study. Hands-on activities are rare in class. Science learning in Chinese classrooms is usually dominated by teacher’s lecture plus intensive practice of problem-solving skills. Chinese students generally spend twice as much time as their American counterparts on study both in school and out of school; their study focuses on practice of problem-solving skills (Asia Society, 2006).

Learning Progressions

According to *Taking Science to School* (National Research Council, 2007), “Learning progressions are descriptions of the successively more sophisticated ways of thinking about a topic that can follow one another as children learn about and investigate a topic over a broad span of time (e.g., six to eight years). They are crucially dependent on instructional practices if they are to occur.” The promise of learning progressions lies partly in their potential to integrate curriculum, instruction, and assessment into a coherent system. The following questions are important for the design and development of learning progressions in cross-cultural studies:

1. Nature and empirical validation of learning progressions: What are learning progressions? How can learning progressions be developed and validated through research?
2. Learning progressions used in cross-cultural studies: How can learning progressions be used to compare the reasoning patterns of students from different social, cultural, and educational contexts? How can we conduct cross-cultural learning progression research?

Our learning progression research was designed based on the analysis of these questions.

Nature and empirical validation of learning progressions. 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 of heredity, which describes the logical relations and orders of the scientific concepts and theories. We argue that 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 develop the learning progression of energy (Liu & McKeough, 2005). They identified the difficulty levels of items about energy-related concepts and theories. The final learning progression is a linear sequence of concepts and theories beginning with energy definition, to energy sources and forms, energy transformation, energy degradation, and energy conservation. Although such learning progressions are developed based on empirical research, they are not systematically validated with empirical data on students' thinking.

Our interest is in learning progressions that are empirically validated. These learning progressions are usually represented as sequences of students' performances (Alonzo & Steedle, 2008; Authors, 2008; Schwarz et al., 2009; Songer, Kelcey, & Gotwals, 2009). For example, Schwarz and her colleagues developed a learning progression for scientific modeling, which not only describes the developmental sequence of students' performances of modeling but also indicates the transition of reasoning from model as duplicate of phenomena to model as explanatory tools. Such studies of performance-based learning progressions provide promising insights for us to define and develop the learning progression.

We suggest that empirically validated learning progressions include (a) a learning progression framework that describes students' science performances and reasoning in terms of developmental levels, (b) associated assessments that effectively elicit students' accounts at each developmental level, and sometimes (c) suggested teaching approaches that facilitate effective and efficient progress towards the upper anchor—the desired scientific reasoning. The work of developing learning progressions is very complicated and cannot be accomplished in a one-shot research cycle, because each of the three interdependent elements of the learning progression—learning progression framework, associated assessments, and suggested teaching approaches—must be empirically validated through research and coordinated with the other elements. The learning progression framework is not only the guideline to construct specific research questions and design assessments but also the product of assessments. The assessments, if they are to be effective, must be continuously refined and revised in order to address the specific questions emerged in the development of learning progression framework. The suggested teaching approaches must be developed based on the learning progression framework and also tested and revised according to assessment results. In this sense, learning progression research has to be an iterative process.

Learning progressions in cross-cultural studies. As an emergent framework for science education research, learning progressions have not been used for cross-cultural studies. In our research, we use learning progression to compare the American and Chinese students' reasoning patterns and progress patterns. We are facing two challenges.

The first challenge is how to identify the reasoning patterns of students from different cultures. International comparative studies such as TIMSS and PISA use large-scale assessment to compare students' science achievement in different countries. Although these studies have provided general pictures of students' achievement in different science topics, they did not provide information about whether and how students from different countries would use different ways of reasoning to explain events. A major reason for this is that large-scale assessments have to rely on written assessments to collect large samples of data and written assessments are limited tools for diagnosing students' specific ways of reasoning. While we do not doubt the usefulness of written assessments, we believe that clinical interview is a power tool to investigate students' thinking and reasoning in cross-cultural studies.

The second challenge is to compare the patterns of change across grade levels of students from different countries. Students' learning performances can be assessed and measured in different dimensions. Since our research compare students' progress patterns in the US and China, an important question is: Which dimensions can capture the differences between American and Chinese students' progress patterns and therefore help educators from both countries to learn from each other?

In summary, learning progressions can be used as powerful tools to promote science learning when they integrate assessment, curriculum, and instruction into a coherent system. We suggest that an effective learning progression used in cross-cultural studies should address the following issues:

1. The focus of learning progressions should be on reasoning; they should represent how students progress from naïve reasoning towards scientific reasoning across grade levels.
2. While large-scale written assessments are a useful tool for comparing students' performances in different countries, clinical interviews can be used to investigate the reasoning patterns of students from different social, cultural, and educational contexts in more detail.

3. It is important to identify dimensions of learning performances that capture the differences between the different reasoning patterns and progress patterns of students from different countries.

Conceptual Framework

Based on the ideas addressed above, we developed our learning progression research. In our research, the learning progression is a system containing two components: the learning progression framework and associated assessments. Teaching experiments play an important role in the development and validation of many learning progressions, but we do not consider them to be part of the "core" learning progression. The learning progression framework represents how students progress from informal reasoning towards the scientific reasoning. The assessments are designed with the intention to diagnose students' intuitive reasoning patterns.

Traditional linear research methods are not effective in developing the complicated learning progression system, so we adopted an iterative research method to develop the three components of the learning progression system. Detailed discussion of the iterative research process (Authors, 2009) is reported in another paper of the project. This paper focuses on our findings about using learning progression framework to compare American and Chinese students' reasoning patterns and progress patterns.

Structure of the Learning Progression Framework

American students and Chinese students are from different social, cultural, and educational contexts. They may use different ways of reasoning to explain the same events. Or, they may use similar reasoning patterns to make accounts, but have different progress patterns.

The learning progression framework should capture both the reasoning patterns and progress patterns.

The structure of the progression framework is presented as Table 1. It contains two parameters—progress variables and levels of achievement. Progress variables are aspects of students' overall performance that differ for students at different levels of achievement. Students' learning performance along each progress variable can be ordered into different levels in terms of the scientific proficiency. They are levels of achievement. They can be organized into three parts: The upper anchor, as the goal of science learning, describes scientific model-based reasoning about carbon transforming processes. The lower anchor is defined by younger students' informal reasoning and knowledge as they enter the age range that we focus on (upper elementary for the current study). The intermediate levels reflect the intersection of school science and students' informal reasoning and knowledge.

[Insert Table 1 Here]

Chinese students and American students may rely on different reasoning patterns and thus demonstrate different levels of achievement along the progress variables. Or, they may rely on similar reasoning patterns, but progress differently along each progress variable. In both cases, students follow different *learning trajectories*. In empirical research, it is usually impossible to collect longitudinal data that track a large sample of individual students' learning over several years. In our research, we collected data from elementary, middle, and high school students during the same time.

In summary, our work of learning progression framework development includes: 1) identifying progress variables that capture important reasoning patterns and progress patterns of American and Chinese students; 2) developing achievement levels for each progress variable; 3) identifying and representing students' progress patterns, or learning trajectories, by distribution graphs—graphs that show the distribution of students' accounts along each progress variable.

The Initial American Learning Progression Framework

Since scientific explanations of carbon-transforming processes are built upon two scientific elements—matter and energy, we can trace students' progress by investigating their understanding of matter and energy. We can also trace students' progress by their accounts (explanations and predictions) of different carbon-transforming processes such as photosynthesis, digestion & biosynthesis, cellular respiration, and combustion. There are also progress variables related to parts or elements of accounts. In the project, we developed the learning progression around two elements of accounts—matter and energy (Table 2) (Authors, 2008). Each progress variable contains four achievement levels. The matter levels and energy levels are aligned by the similar logic reflected in the reasoning patterns.

[Insert Table 2 Here]

In our research we started with this initial American learning progression framework and used the interview study to revise and refine the American learning progression and also to develop the Chinese learning progression. Our work of developing of the three parts of the learning progression framework—upper anchor, intermediate levels, and lower anchor—is elaborated as following.

The upper anchor. The upper anchor was developed based on ideas from environmental science research and disciplinary knowledge. It describes the scientific reasoning about carbon-transforming processes—our goal for environmental science literate high school students. Students who reach the upper anchor are able to describe carbon-transforming processes at multiple scales, from atomic-molecular to global, with matter and energy conservation as constraints. This scientific model-based reasoning is represented in Figure 1—linking processes with constraints.

[Insert Figure 1 Here]

The scientific reasoning addresses carbon-transforming processes at three scales. At the atomic-molecular scale, there are three classes of carbon-transforming processes:

- *Organic carbon generation and harnessing light energy:* Photosynthesis generates carbon-containing organic molecules from water and carbon dioxide. In this process, light energy is harnessed and transformed into the chemical energy of organic materials.
- *Organic carbon transformation and passing on energy*: Digestion & biosynthesis transform carbon-containing organic molecules and pass on chemical potential energy.
- *Organic carbon oxidation and dissipating energy:* Cellular respiration and combustion oxidize carbon-containing organic molecules into water and carbon dioxide. In these processes, energy is released and finally dissipates into heat.

These atomic-molecular processes explain a variety of carbon transforming macro-processes people experience every day. Table 1 listed some examples of these macro-processes (middle row). The atomic-molecular processes are connected to each other. They collectively lead to the global processes of carbon cycling and energy flow among socio-economical systems, biosphere, and atmosphere. The primary cause of global warming is the increasing carbon concentration in the atmosphere resulting from excessive carbon emission from human socio-economical systems.

The processes at multiple scales are all constrained by three principles—matter conservation, energy conservation, and energy degradation. Two aspects of these constraints are important: matter is conserved separately from energy[1]; energy is conserved with degradation and separately from matter.

The lower anchor and intermediate levels. At the lower anchor, students do not use matter and energy for reasoning. Instead, they rely on force-dynamic reasoning to describe changes at the macroscopic scale. At level 2, students begin to reason about the hidden mechanisms involving changes of materials and energy, but generally do not explain in terms of molecules or energy forms and do not constrain matter or energy. At level 3, students begin to reason about molecules and energy forms and attempt to constrain processes, but often cannot successfully apply the matter and energy principles.

Research Methods

In this research, we adopted an iterative process to revise and/or develop the American and Chinese learning progression framework as well as the associated interview protocol. The study contains three research cycles. Each research cycle contains three stages: development of the learning progression framework, conducting interviews and the teaching experiment, and analyzing students' interview accounts. Each stage provides feedback for the design and revision of the approaches used in the next stage.

Our research assesses and compares American and Chinese students' reasoning patterns and progress patterns with respect to carbon-transforming processes. Scientific model-based reasoning highlights understanding carbon-transforming processes across scales with matter and energy conservation as constraints. However, students' experiences are mostly at the macroscopic or human scale. The global and atomic-molecular processes are invisible to many students, especially younger students. This problem has led us to construct the learning progression framework and interviews around eight macro-processes that are familiar to all students in our research. These eight macro-processes are (the middle row in Figure 1): tree growth, baby girl growth, girl running, tree decaying, flame burning, car running, light lighting, and cross processes (classification or connections of all the previous processes).

Interview Protocol

The interview protocol has been continuously revised and refined with feedback from analysis of students' interview accounts. To assess students from a wide range of age and cultural groups, we designed the interview in a branching structure. For each macro-process, we start with a set of general questions—questions that use everyday language to ask about familiar phenomena. Since younger students tend to understand the macro-processes in terms of the actor (e.g., the tree in tree growth; the car in car running.) and its enablers (e.g., water, sun, soil in tree growth; gasoline and engine in car running), the general questions are about what the actor needs in order to make things happen and why/how each enabler helps the actor to do that. Take the macro-process of tree growth as an example. The major general questions are (American Version):

- What does the tree need in order to grow? [The follow-up questions are based on the enablers named by the student in response to this question.]
- You said that the tree needs [sunlight or other enabler] to grow. Then how does it help the tree to grow?
- Do you think that [water or other enabler] will change into other materials inside the tree's body?

- The tree gets heavier as it grows. How does that happen?

These questions use everyday language to ask students about the actor—the tree—and its enablers such as water, sunlight, air, soil, and so on. Students without any experience of school science are able to understand these questions and talk about their own ideas about tree growth. However, these questions are not effective for eliciting higher-level accounts. Hence, we also ask follow-up higher-level questions if the students' responses indicate some understanding of matter or energy. The follow-up questions are more specific about atomic-molecular and global processes. Some examples are:

- Do you think the tree's body structure is made from things outside of the tree? If yes, what are those things? How do these things change into the tree's body structure?
- If the student mentions glucose/starch/cellulous/carbohydrates, ask: Do you think it contains carbon atoms? If yes, where do the carbon atoms come from?
- You said that the sunlight provides energy for the tree to grow. Where does that energy go when it is used by the tree? Do you think it is used up, becomes other things, or something else?
- If the student talks about CO_2—O_2 exchange, ask: You said that the tree needs Carbon dioxide and breathes out oxygen. Where do the carbon atoms of CO_2 go?
- Ask the student to sort three cards—tree growth, girl running, and dead tree decaying. Question: Can you think of a reason for putting tree growth separate from the other two pictures?

- Ask the student to sort six pictures: Plant growth, A baby girl growing, Car running, Tree decaying, Wood/Candle burning, A girl running. Question: Can you sort these pictures in terms of changes of matter and energy?

During interviews, students sometimes recited science terms. In such situations, we asked students what they meant by the terms. The Chinese version interview protocol is similar to the English version, but the scenarios used in the interview were modified to fit Chinese contexts. For example, we changed the US System of units such as pounds into international system of units such as kilogram, changed the story about driving a car to Chicago to the story about driving a car to Suzhou, and so on.

Data Source

We have conducted three cycles of interview study in the US and two cycles of interview study in China. In this paper, we report our findings in the last research cycle. The participants in the last research cycle are twenty-four Chinese students and twenty-four American students from elementary, middle, and high schools.

In China, the participants are twenty-four students (8 elementary students, 8 middle school students, and 8 high school students) from two elementary schools, two middle schools, and two high schools. All schools are located in an area in southeastern China where students have higher-than-average academic performance. One middle school and one elementary school are low resource schools. The middle school is located in a rural area. The elementary school is located in an urban area. Students in both schools are from families with low socioeconomic status. Other schools are “key” schools located in urban areas and have more abundant educational resources. The teachers in these schools also have more professional development opportunities.

In the US, we interviewed twenty-four students (8 elementary students, 8 middle school students, and 8 high school students) twice. We conducted pre-interview before the teaching intervention and post-interview after the teaching intervention. The participant schools are two elementary schools, two middle schools, and two high schools. Among the high school participants, four students were from the math and science center in Michigan. These students were college-bound students who went to the center to take AP courses. All other schools are public schools located in rural areas.

Data Analysis

The learning progression framework is both the product and guideline of data analysis. In this section, we describe the iterative process of developing the learning progression framework and analyzing interview data. Each iterative research cycle contains three stages:

1. *Develop the learning progression framework.* The development of the learning progression framework contains two tasks: Identification of progress variables and development of levels of achievement along each progress variable. We started with the initial American learning progression framework that was built upon two progress variables—matter and energy. In each research cycle, we examined students' interview accounts and identified patterns of performance with respect to each progress variable. Based on these patterns of performance, we developed the levels of achievements for each progress variable. The learning progression framework was continuously revised and refined based on analysis of students' interview accounts.

2. *Conduct the interviews and teaching experiment.* We conducted teaching experiments in the US but not China. Pre-interviews and post-interviews were conducted before and after the teaching experiments. The learning progression framework is the guideline for the development of both interview protocol and teaching materials. In particular, the development and revision of the interview protocol are aimed to address the specific questions emerged in developing the learning progression framework and with feedback from data analysis.

3. *Analyze students' interview accounts.* Analysis of students' interview accounts contains three parts:
    - *Develop the coding rubrics—exemplar workbook.* We used the learning progression framework as the guideline to develop coding rubrics for data analysis. The learning progression framework describes the general patterns of students' performances with respect to each progress variable, while the coding rubrics contain more details about the performances students demonstrated when explaining each macro-process. They have detailed level descriptions associated with representative responses selected from interviews.
    - *Use rubrics to code data.* We divided students' interviews into *account units* and used the exemplar workbook to code each unit. Altogether we have collected 24 Chinese interviews, 24 American pre-interviews, and 24 American post-interviews. We divided each interview into eight account units—all questions and responses about one macro-process constitute one account unit. Seven coders from the project used the rubrics to code American interviews. The first two authors of this paper

coded Chinese interviews. Reliability checks were conducted during this coding process.

- *Generate distribution graphs to depict learning trajectories.* We used the coding results to generate distribution graphs—graphs that show the percentage of students' account units at each achievement level of the progress variables. These distribution graphs enabled us to compare American and Chinese students' different progress patterns. When the graphs indicated that the progress variables were ineffective in capturing the differences between American and Chinese students' progress patterns, we re-examined the data to identify new progress variables.

Results

We report our results in two parts: the revised learning progression framework and learning trajectories represented by a set of distribution graphs.

Revised Learning Progression Framework

In the project, we started with using matter and energy as progress variables to code both interview and written assessment data. It turned out that the separate codes for matter and energy were largely redundant—the correlation between them was 0.96 (Authors, 2009). At the same time, the US-China written assessments showed that rubrics used for coding levels seemed to work better for American students than for Chinese students. Some items appeared to be far more difficult for Chinese than for American students, while on other items the reverse was true. There were no strong correlations between item difficulty and specific processes or the matter and energy progress variables (Authors, 2009). In our cross-cultural study, we also started with using matter and energy as progress variables to code interview data, but found that there were important differences in American and Chinese students' performance that were not captured by the matter and energy progress variables. This led us to develop performance-based progress variables—*Naming and Explaining*—that were more effective for comparing American and Chinese students' different accounts of carbon-transforming processes. This methodology shift is reported in another paper of the project (Authors, 2009). This paper focuses on the findings about American and Chinese students' accounts.

The Explaining progress variable describes the nature of the explanations students gave. The Naming progress variable describes how students used both informal and scientific vocabulary in accounts. After we shifted to the Naming/Explaining progress variables, we investigated students' interviews and identified patterns of students' Naming and Explaining performances. Based on this work, we developed the achievement levels of the Naming and Explaining variables. The revised learning progression framework is represented in Table 3.

[Insert Table 3 Here]

Explaining progression variable. The Explaining progress variable describes the performances of explaining why and how the macro-processes happen. Explanations are constructed based on reasoning and thus always imply certain reasoning patterns. We found that American and Chinese students relied on similar reasoning patterns to explain the macroscopic carbon-transforming processes. These reasoning patterns can be categorized and ordered into four levels of achievement in terms of sophistication and scientific value. These four levels are: macroscopic force-dynamic accounts, force-dynamic accounts with hidden mechanisms, accounts about changes of molecules and energy forms with unsuccessful constraints, and accounts linking processes with matter and energy as constraints. In the following paragraphs, we use examples from both American and Chinese students to describe these achievement levels.

Level 1. Macroscopic force-dynamic accounts. Level 1 accounts rely on a macroscopic force-dynamic reasoning that describes the macroscopic process as an action-result chain: the living or moving actor has the ability to change in an "uphill" direction such as to grow, maintain life, and move, while the dead actor such as the dead tree will naturally change in a "downhill" direction such as decay; the actor may need to use enablers from the environment, because that is how the natural world works; the result of this action is that the actor accomplishes its goal. This action-result chain describes the interactions between the actor and its enablers as a type of physical push-and-pull. Although students may use "matter" or "energy" in their explanations, they do not use them with scientific meanings. Below are two interview excerpts about tree growth.

Tree growth: American pre-interview (4th grader)

Researcher: So you said that the tree needs water to grow. So what happens to the water inside the tree?

KMG: It goes all the way down to the roots. And then it goes all the way to the leaves.

Researcher: Ok. So does the tree need water for energy?

KMG: Yeah.

Researcher: Ok. How does that work? How does the water work for energy?

KMG: It goes from the clouds all the way down and it makes the tree grow.

Researcher: So is water always necessary for the tree to grow?

KMG: Yes.

Researcher: Why?

KMG: Because if it doesn't [have the water], it will die.

Researcher: Ok. Then you said that another thing required for the tree to grow is soil. So what happens to soil inside a tree?

KMG: It helps it grow and it makes it stronger.

Researcher: Ok. So does the tree need soil for energy?

KMG: Yes.

Researcher: Why?

KMG: Because if it don't have no soil, it will die.

Tree growth: Chinese interview (4th grader)

Researcher: How does water help the tree to grow?

LYQ: It is like people drinking water. The tree must have water to grow. If it does not have water, it will dry. The leaves on the tree will turn yellow.

… …

Researcher: Do you think the tree needs sunlight?

LYQ: It should be. I have read an article about that. Sun is good for everything.

Researcher: Why?

LYQ: I think it is like… Sun can kill the bacteria. Like our teachers often ask us to play in the sunlight, so that sunlight can kill the bacteria on our body. I think the sunlight kills the bacteria on the tree, so that the tree can grow.

The American student, KMG, explained that water helped tree to grow by moving inside the tree's body and soil helped the tree to grow by making it stronger. This indicates a force-dynamic reasoning: the enabler—water and soil—can get into the actor—the tree—and physically move in it, but it does not change into the tree's body structure; the result of this interaction is that the tree grows and becomes stronger. Although KMG claimed that the tree used water and soil for energy, his justification for that claim—the tree will die without water and soil—suggests that for KMG "energy" is a kind of generalized enabler rather than a specifically defined resource.

The Chinese student, LYQ, stated that the tree needed water to keep itself hydrated and needed sunlight to kill the bacteria in its body. LYQ's accounts also indicate the force-dynamic reasoning: the tree, as the actor, uses water and sunlight to keep its body in a good condition such as being hydrated and having less bacteria, which in turn causes the result—the tree grows; the interactions between the tree and its enablers do not involve any change or exchange of matter or energy.

Level 2. Force-dynamic accounts with hidden mechanisms. Level 2 accounts still rely on force-dynamic reasoning, focusing on the actors, enablers, abilities, and results. However, they begin to show attention to the hidden mechanisms behind the macroscopic phenomena. Although they do not recognize changes of atoms, molecules, and energy forms, they begin to link the macro-processes with invisible microscopic changes. Below are two interview excerpts about girl running.

Girl Running: American pre-interview (8th grader)

Researcher: So do you think the girl needs food in order to run?

SAM: Uh huh.

Researcher: How does that happen?

SAM: Because if she doesn't have food, she doesn't have energy. And if you have energy you can run without energy you can't.

Researcher: So how does the food provide energy?

SAM: It provides it [energy], because when the food is broken down… the food is broken down into energy and then she can run.

Researcher: So the food changes into energy is that what you mean?

SAM: Yeah.

Girl Running: Chinese interview (6th grader)

Researcher: This is an apple. Could you explain how the apple is related to chemical energy?

YZY: The food itself is chemical energy.

Researcher: Where does the chemical energy go?

YZY: The intestine absorbs it and then it goes into blood.

Researcher: When the girl is running, where does that chemical energy go?

YZY: When the body moves, it becomes sweat and consumed.

The American student, SAM, recognized that behind the macroscopic phenomenon of running is the hidden mechanism that "food is broken down into energy." The Chinese student, YZY also identified the hidden mechanisms behind running. She described the hidden mechanism as food going into the girl's body and then turning into sweat. To be noted is that although YZY mentioned chemical energy, she did not reason in terms of changes of energy forms. Instead, she used chemical energy as another name of "food": "the food itself is chemical energy." Therefore, the Explaining level of this account unit is still Level 2.

Level 3. Accounts about changes of molecules and energy forms with unsuccessful constraints. Level 3 accounts show an initial shift from force-dynamic to scientific discourse, explaining the macro-process in terms of changes of atoms, molecules, and energy forms. Level 3 accounts are not entirely successful in connecting macroscopic and atomic-molecular scale, however. Similarly, Level 3 accounts try to trace matter and energy, but rely on unsuccessful constraints on processes such as matter-energy conversion or conserving energy without degradation. Below are two interview excerpts about flame burning.

Flame Burning: American post-interview (8th grader)

Researcher: Over time there is less wax left, right? So where does the lost material go?

RWD: It's combined with the burning oxygen and creates CO2. And, anything that left turns into a liquid.

… …

Researcher: Okay. So, do you think flame burning is somehow related to energy?

RWD: Yeah.

Researcher: How?

RWD: The flame needs energy to keep burning.

Researcher: Where does that energy come from?

RWD: From the bonds, through the oxygen or materials

Researcher: So you mean the energy comes from the material of the wax and wood?

RWD: Yeah.

Researcher: So where does that energy go? Do you think it's the energy is used up to keep the flame burning or do you think it is still energy and it exists somewhere else?

RWD: I think it's used up to keep the flame burning.

Flame Burning: Chinese interview (11th grader)

Researcher: What kinds of materials are combustible?

CMD: Organic materials.

Researcher: You said that water is organic before. Do you think water can burn?

CMD: Yes. When it becomes ice.

Researcher: Are you saying dry ice?

CMD: No. I said ice, solid water. I saw ice burning in TV.

Researcher: You also said that burning needs oxygen. Why?

CMD: It becomes carbon dioxide, sulfur dioxide, and so on. It depends on the chemical structure of the specific combustible materials.

… …

Researcher: Oxygen does not have carbon atoms in it but carbon dioxide has. How could that happen?

CMD: The carbon comes from wood.

Researcher: Do you think burning has anything to do with energy?

CMD: Energy again. Yes. Burning produces heat energy.

Researcher: Where does heat energy come from? Is it created, or changed from other things?

CMD: When molecules and atoms crash, heat energy is created.

The American student, RWD, described burning as a process involving changes of molecules—wax combined with oxygen to produce carbon dioxide. This account also shows the attempt to conserve matter—wax and oxygen are not used up and they become carbon dioxide. However, she did not identify water as the other product of combustion. RWD also recognized that energy is involved in burning, but did not conserve energy. Rather than describe energy in the "bonds" as being transformed into heat and light energy, she claimed that the energy from wax and oxygen was "used up" to keep the flame burning.

The Chinese student CMD described burning as changes of atoms and molecules—oxygen reacts with wood to produce carbon dioxide; the carbon atoms in carbon dioxide come from the substances of wood. Although CMD stated that combustible materials must be “organic substances” and that wood contained carbon atoms, he did not recognize that “organic substances” contain carbon atoms. Instead, he claimed that water was organic substance and it burned when becoming ice. CMD also identified heat energy from combustion, but explained that heat energy was created when atoms and molecules crashed into each other in chemical reactions.

In brief, both RWD and SLZ explained flame burning in terms of changes involving atoms (e.g., carbon), molecules (e.g., oxygen, carbon dioxide, and molecules of wood or other combustible materials), and energy forms (e.g., heat energy), but they did not correctly describe matter transformation and energy transformation in combustion. Although they begin to show commitment to conservation laws, they did not successfully constrain combustion with matter conservation or energy conservation.

Level 4. Accounts linking processes with matter and energy as constraints. Level 4 accounts rely on scientific reasoning—linking carbon-transforming processes at multiple scales with matter and energy as constraints. There is no Level 4 account from American pre-interviews and Chinese interviews. An American student EJR, consistently used Level 4 reasoning on his post-interview. Below is the interview excerpt about car running.

Car Running: American post-interview (8th grader)

Researcher: What does the car need in order to run?

EJR: Pretty much, again, the same as the candle and match burning. It needs oxygen. It needs a source of fuel, which in the case of the car is going to be gasoline, which is a kind of furious combination of carbon and hydrogen molecules. It uses the oxygen in the air in

> the process of burning the gasoline, which is will be evaporated in the pistons of the car.
>
> Researcher: Okay. So when your dad drives this car from here to Chicago. When the car arrives there at Chicago, he found that all the gasoline ran out. Where did that gasoline go?
>
> EJR: That gasoline is burned within the engine to help move the pistons and when it is burned, it is converted to water vapor and carbon dioxide, which is then released through the exhaust pipe into the atmosphere.
>
> Researcher: And your dad also touched the front part of the car. He found that it is very hot. How could that happen?
>
> EJR: Well when the gas is being burnt, several forms of energy are being released, mainly light and heat. You can’t see the light because it’s contained within the metal, but the heat will spread into the engine and the various parts… …
>
> Researcher: So when the car stops, where does that kinetic energy go?
>
> EJR: It goes into the ground and the air around it in small amounts.
>
> Researcher: What is the energy form of that?
>
> EJR: Can be kinetic, can also be heat energy as like when he touched it and it was hot.

EJR successfully used matter and energy principles to constrain the process of combustion. He explained that, in combustion, gasoline reacted with oxygen and produced carbon dioxide and water and at the same time the chemical energy of gasoline transformed into kinetic energy and heat. EJR was able to separate matter transformation and energy transformation in combustion and recognize degradation (heat dissipation) from the process.

Naming progress variable. The Naming progress variable describes students’ performances of verbatim reproduction of vocabulary. Accounts at different Explaining levels are built upon different sets of words. For example, accounts at Level 1 are basically constructed by using words about actors, enablers, and results, while accounts at Level 3 are built upon words about atoms, molecules, and energy forms. Based on this idea, 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 key words associated with each level are shown in Table 3.

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, and so on.

Level 1.5 Easier hidden mechanism words. Level 1.5 contains words about internal organs of the living actor, 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.

Due to language differences, the empirical adjustments for the American version and Chinese version of Naming levels are slightly different. In English, “combustion” is the scientific term used to refer to the chemical change. In everyday life, people use “burning” to refer to the same process. In Chinese, there is only one word “燃烧”, which is used in both everyday life and science. Similarly, in English, “respiration” is a scientific term referring to the chemical reaction of organic substances oxidized into carbon dioxide and water, while in everyday life people use “breathing” to mean gas exchange—humans and animals take in oxygen and exhale carbon dioxide, while plants take in carbon dioxide and exhale oxygen. In Chinese, there is only one word “呼吸”, which is used to mean both respiration and breathing. Hence, we put combustion and (cellular) respiration in Level 3 in the American version and put 燃烧 and 呼吸 in Level 2.5

in the Chinese version. Also, American elementary teachers often teach “motion energy” rather than “kinetic energy” in their classrooms in order to avoid confusion cause by introducing the unfamiliar word “kinetic”. In Chinese, this is not a problem, since there is only one term—动能—and 动 is a common language word, meaning motion. Hence, in the American version, “motion energy” is at Level 2.5 and kinetic energy is at Level 3, while in the Chinese version, 动能 is at Level 2.5.

The Naming levels are aligned with the Explaining levels in terms of the logical relationships between vocabulary and the nature of explanations. In real situations, students may make accounts indicating different Naming and Explaining Levels.

- Some students give relatively sophisticated explanations using simpler vocabulary. These accounts have higher Explaining Levels than Naming Levels.
- Other students use scientific vocabulary in what are still basically force-dynamic accounts. These accounts have higher Naming Levels than Explaining Levels.

Table 4 shows the Naming and Explaining levels of the account units used as examples for the Explaining levels. All account units except Girl Running (YZY) have aligned Naming and Explaining levels.

[Insert Table 4 Here]

Discrepancy between Naming and Explaining Levels. We found that many Chinese account units have Naming levels higher than their Explaining levels. The interview excerpt is about girl running. The account unit has Naming Level 2 and Explaining Level 1.

Girl Running: Chinese interview (4th grader)

Researcher: Ok. So, how does the food help her to run?

LJQ: The foods provide nutrients to make her body strong. Then she can run.

Researcher: Do you think air can help her to run?

LJQ: Yes. We inhale carbon dioxide and carbon dioxide has nutrients in it.

Researcher: Ok. Do you think the carbon dioxide will change when it goes into the girl's body?

LJQ: [Silence]

Researcher: That's fine. Let's look at the other picture.

LJQ named two Level 2 words: “carbon dioxide” and “nutrients”. However, she did not use these two words to describe any hidden mechanisms that involve changes of matter or energy. Although she mentioned nutrients, she described nutrients as a macroscopic enabler that makes the girl’s body strong. Although she mentioned carbon dioxide, she claimed that carbon dioxide has nutrients in it. The evidence indicates that LJQ did not understand nutrients and carbon dioxide as substances. LJQ’s explanation about how nutrients and carbon dioxide help the girl to run indicates macroscopic force-dynamic reasoning: foods and carbon dioxide are the enablers; they both contain nutrients that make the girl’s body strong; as the result, the girl reaches her goal to run. LJQ described the interactions between the tree and its enablers as macroscopic interactions that do not involve any changes or exchanges of either matter or energy.

The excerpt below is from interview with XYW. It is about the event of baby girl growth. The account unit has Naming Level 3 and Explaining Level 2.

Baby Girl Growth: Chinese interview (6th grader)

Researcher: Where does the food go when people eat it?

XYW: It was digested in the stomach. Then it goes to intestine and colon. The nutritious materials are absorbed and transported by blood and then distributed to the body.

Researcher: Could you talk more about the process of digestion?

XYW: The useful and nutritious materials of food are extracted and separated from useless materials. Useless materials are expelled outside of the body.

Researcher: Do you think the food is made up of molecules?

XYW: It should be.

Researcher: So, what happens to the molecules of food in digestion?

XYW: The molecules decomposed.

Researcher: What do you mean by decompose?

XYW: Food is mixture of nutritious materials and useless materials. Decomposition is that the nutritious materials are separated from useless materials. The body absorbs the useful materials. Useless materials are expelled from the body.

Researcher: What do you mean by "absorb"? Could you talk more about that process?

XYW: The nutritious materials are resolved in blood and then blood takes it to the different parts of the body.

… …

Researcher: Where does that energy come from?

XYW: It comes from food. Food has starch. That's carbohydrates. The body absorbs them. That provides people energy.

Researcher: What do you mean by carbohydrates?

XYW: Like rice has starch.

Researcher: Do you think water is also carbohydrate?

XYW: It seems water is not.

Researcher: Why?

> XYW: Human body needs six important classes of substances. Water and carbohydrates are in different classes.
>
> Researcher: Ok. Do you think carbohydrates are composed of atoms or molecules?
>
> XYW: I don't know.

XYW used the Level 3 word carbohydrates to explain baby girl growth. When the interviewer asked her whether water is a carbohydrate, she replied no and justified this answer by saying that they had learned about six important classes of substances for human body and water was in a different class than carbohydrates. When the interviewer asked her whether carbohydrates are atoms or molecules, she replied that she did not know. All these evidences indicate that XYW used the term carbohydrates without understanding that carbohydrates refer to specific molecules. Although XYW named organic molecules involved in baby girl growth, she did not explain the event as changes in molecules. Instead, XYW explained the event in terms of two "hidden processes"—digestion and absorption. She explained the process of digestion as "useful and nutritious materials of food are extracted and separated from useless materials. Useless materials are expelled outside of the body." When the interviewer asked her what happened to the molecules of the food, she did not explain changes of molecules. Instead, she repeated her explanation of the process of digestion. XYW understands that the true enablers—useful materials—have to be separated from the less useful parts of food, but not the chemical differences between different components of food. Hence, the Explaining Level for this account is Level 2.

We also found accounts that have Explaining level lower than Naming level. Below is an example. The account unit has Explaining Level 3.5 and Naming Level 2.5.

Flame Burning: American post-interview (8th grader)

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

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

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

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

Researcher: The melting candle loses weight as it burns, how does this happen?

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

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

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

Researcher: What is that that floats in the air from the wax?

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

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

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

Researcher: Do you think energy is released from burning?

EJR: Yes.

Researcher: How is it released?

> EJR: I am not sure, I believe it is just; the energy of it is changed from the stored energy into light energy and heat energy.

EJR identified a chemical reaction, although he was not sure what exactly the chemical reaction was: “Not specifically, all I know is that it is a chemical reaction and change and that’s about all I know for sure.” He made the common mistake of thinking that the wick rather than the wax was burning. Given this assumption, though, he was able to construct accounts that conserved both matter (the wax evaporates, but is still present in the air) and energy (the stored energy of the wick changed into light energy and heat energy). Hence, the Explaining level of this account unit is 3.5 since it indicates a reasoning pattern—energy transformation in chemical changes. While the Naming level is relatively lower, 2.5, since the most sophisticated terms in the account unit are three Level 2.5 terms—stored energy, chemical reaction, and molecule and EJR did not mention any specific molecules or combustion.

Learning Trajectories of American and Chinese Students

We used the learning progression framework as the guideline to develop the detailed coding rubrics—the exemplar workbook. We used the exemplar workbook to code each account unit. Each account unit has two scores: one for the Naming Level and the other for the Explaining Level. The coding results were then used to generate distribution graphs, which show the percentage of account units at each level of the Explaining and Naming progress variables.

Figure 2 contains distribution graphs for Chinese interviews, American pre-interviews, and American post-interviews. The three distribution graphs on the first row represent Chinese students’ status quo ante learning trajectory that happens without teaching intervention. The three distribution graphs on the second row show American students’ status quo ante learning trajectory that happens before teaching intervention. The distribution graphs on the third row show the alternate learning trajectory that American students experienced under the teaching intervention.

[Insert Figure 2 Here]

Students' status quo ante learning trajectories in the US and China. The comparison between American and Chinese students' status quo ante learning trajectories shows three trends.

American and Chinese explaining performance. First, both groups show the same patterns of progress with respect to the Explaining performance. For both American and Chinese students, elementary accounts tend towards Level 1 and middle and high school accounts tend towards Level 2, indicating a shift from macroscopic force-dynamic reasoning to force-dynamic reasoning with hidden mechanisms. Both force-dynamic reasoning and hidden mechanism reasoning represent people's informal ways of reasoning and can be learned out of school. The force-dynamic reasoning is implied in English and Chinese grammar. They reflect the informal reasoning people construct as they are using and learning native languages in their everyday life. The hidden mechanism reasoning can also be learned in everyday life. As students expand their experience with the material world, they begin to recognize that the macroscopic cause-effect relationship must be caused by some invisible hidden mechanisms. However, they often do not have the necessary knowledge about the intermediate processes and stages behind the cause-effect relationship. As the result, they often construct intuitive ideas about the invisible hidden mechanisms. In brief, the distribution graphs show that the majority students in both countries relied on informal ways of reasoning that can be gained out of school.

American and Chinese naming performance. Second, American and Chinese students progress differently with respect to the Naming performance and Chinese students demonstrated better Naming performances. From elementary to high school, the peak of American students' Naming performance shifts from Level 1 to Level 2, while the peak of Chinese students' Naming performance shifts from Level 1, via Level 2, to Level 3. We further investigated the account units that are at Naming Level 3 and 4, since these accounts all name one or more scientific words required for sophisticated explanation of carbon-transforming processes. We found that Chinese students tended to use more scientific words and they also tended to use these words more frequently.

The distribution graphs show that Chinese students tend to use scientific words (Level 3 and 4 vocabulary) more frequently. While there is no Naming Level 4 account unit in American interviews, 11% Chinese middle school account units and 9% Chinese high school account units are at Naming Level 4. These account units either name a complete list of reactants and products or a complete list of energy forms involved in the chemical reaction. Across school levels, Chinese distribution graphs have higher percentage of account units at Level 3. This pattern is especially pronounced at the middle and high school levels.

We investigated the specific scientific words named by the Level 3 and 4 account units and found that Chinese students tend to use more scientific words about organic molecules, energy forms, and chemical processes. Table 5 lists the scientific words appearing in Naming Level 3 and 4 American and Chinese accounts.

[Insert Table 5 Here]

Three words are easier for Chinese students due to the difference between English and Chinese. These words are at Naming Level 3 in the American version of learning progression framework and Level 2.5 in the Chinese version of learning progression framework: kinetic/motion energy (动能, Level 2.5), cellular respiration (呼吸作用, Level 2.5), and combustion (燃烧, Level 2.5). Besides these words, Chinese students also mentioned other scientific words that are critical for the construction of scientific explanations for the eight macro-processes. These words are carbohydrate, chemical energy, and oxidation process.

Comparing Naming and Explaining performance. Finally, for both groups, Naming performance is developed ahead of Explaining performance across school levels, while the discrepancy of development of Naming and Explaining performance is much larger for Chinese students. In particular, at the middle and high school levels, both groups show higher percentage of account units at Naming Level 3 and 4 and relatively lower percentage of account units at Explaining Level 3 and 4, indicating that students may name scientific words without understanding. The discrepancy of development is much larger for Chinese students: 49% middle school accounts reach Level 3 and 4 for the Naming performance, but only 11% account units are at Explaining Level 3 and no account unit reaches Explaining Level 4. Similarly, 62% high school account units reach Naming Level 3 and 4, but only 26% account units are at Explaining Level 3 and no account unit reaches Explaining Level 4. The distribution graphs indicate that although Chinese students demonstrated much better Naming performance, the majority of Chinese secondary students, like their counterparts from the US, still tend to rely on Level 2 reasoning—force-dynamic reasoning with hidden mechanism—to reason about processes.

In summary, the comparison of American and Chinese students' status quo ante learning trajectories indicates challenges for both American and Chinese students. The challenge for Chinese students is how to learn science in ways that not only memorize a set of scientific vocabulary but also understand the meanings of the vocabulary and develop scientific model-based reasoning. The challenge for American students is how to learn necessary scientific vocabulary and at the same time develop scientific model-based reasoning.

Comparison of American alternate learning trajectory with status quo ante learning trajectories. To investigate whether it is possible for teaching approaches to facilitate students to progress more effectively, we developed teaching materials that target students' intuitive ways of reasoning—the force-dynamic reasoning and the hidden mechanism reasoning—and aim to foster the scientific reasoning that links processes at multiple scales with matter and energy as constraint (as represented in figure 1). More details of teaching experiment are reported in another paper of the project (Authors, 2009). The comparison between the American post-interview data with the American pre-interview data and Chinese interview data indicates that a more successful learning trajectory could exist under teaching approaches focusing on reasoning.

Improvement at all levels. First, from pre-interviews to post-interviews, the distributions shifted toward higher-level responses for both Naming and Explaining at all three school levels. These shifts are substantial at all three school levels, but especially large at the elementary and middle school levels. At the elementary level, the account units in pre-interviews tend towards Level 1 in both Naming and explaining, while the account units in post-interviews tend towards Level 2 in both Naming and explaining. This indicates that the teaching experiment is effective in helping the elementary participants to recognize the hidden mechanisms behind macroscopic events. At the middle school level, the post-interview distribution graphs show a significant increase in Level 3 and Level 4 accounts.

Discrepancy of development. Second, it is possible that students' Explaining performance could develop on par with or ahead of their Naming performance. The middle school graphs show that students' Explaining performance developed a bit ahead of their Naming performance: 49% account units are at Explaining Level 3 and 4, while 44% account units are at Naming Level 3 and 4. This indicates that it is possible that students are able to understand the scientific reasoning and use it as the conceptual tool to analyze events even they may lack some specific scientific words to construct the explanations.

In summary, the comparison between the distribution graphs of the post-interviews with graphs of the pre-interviews and Chinese interviews indicates a possible existence of an alternate learning trajectory under more appropriate teaching approaches. However, there are two limitations to be noted. First, the American pre-interviews and Chinese interviews were conducted when the high school participants were still taking the biology courses. Hence, the distribution graphs of Chinese high school interviews and American high school pre-interviews are not the learning results of completion of high school biology courses. The post-interviews were conducted after the teachers finished teaching the modules we designed. Hence, the distribution graphs of the post-interviews to certain degree show the results of the teaching. Second, this is an interview study involving 24 American students and 24 Chinese students from elementary, middle, and high schools. Therefore the sample size does not allow us to generate our findings about students' progress patterns—the learning trajectories represented by the distribution graphs—to the classroom or institutional levels.

Conclusion

Large-scale assessments have uncovered serious problems with American and Chinese students' achievement in science learning, but provided little information on the causes of the problems. Our research used detailed clinical interviews to investigate the underlying causes of students' learning difficulties in science. Although our findings cannot be generalized to the institutional, national, or international level, we believe that the implications of our study hold particular promise for understanding the specific learning problems of both American and Chinese students.

First, although American and Chinese students came from different social, cultural, and educational contexts, they tended to rely on similar intuitive reasoning patterns to account for environmental events. In particular, the majority of students participating in the Chinese interviews and American pre-interviews tended to rely on a characteristic pattern of everyday reasoning—force-dynamic reasoning, sometimes with hidden mechanisms. This way of reasoning could be learned from everyday experience: force-dynamic reasoning can be learned as students use their native languages for communication; hidden mechanism reasoning can be gained as students expand their experience with the material world in everyday life. The implication is that current science teaching approaches did not effectively facilitate students to construct the scientific accounts. In order to promote students' science achievement, it is important that science teaching target students' intuitive ways of reasoning and focus on developing the domain-specific scientific reasoning. Our teaching experiments were designed to facilitate students to develop scientific reasoning about carbon-transforming processes—linking processes at multiple scales with matter and energy as constraints. The American post-interview data show an increase of Level 3 and Level 4 account units, indicating that the students were more capable in using scientific terms and began to link macro-processes with atomic-molecular chemical reactions and use matter conservation and energy conservation to constrain processes.

Second, there is discrepancy between Naming performance and Explaining performance in the American and Chinese status quo ante learning trajectories and the discrepancy is much larger in the Chinese status quo ante learning trajectory. A possible cause is the different educational contexts the American and Chinese students engaged in. Since the Naming performance and Explaining performance of American and Chinese elementary school students are similar, we think that the differences we see in older students are probably due more to schooling than to underlying differences in language or culture.

In particular, the intensive practice required in Chinese schools could be a significant contributor to Chinese students' higher Naming performance and larger discrepancy in development. In China, science teaching in classrooms is guided and also constrained by entrance examinations. Hence, we examined the assessment items about carbon-transforming processes in recent high school entrance examinations and national college entrance examinations. The former affects the science teaching at middle school level and the latter largely influences science teaching at high school level.

We found that the items in high school entrance examinations mostly focus on the scientific facts about energy, reactants, and products of the chemical changes. Rather than focusing on tracing matter and tracing energy across scales, these items require students to describe changes at single scale and describe changes of matter and energy in fragmented ways. For example, in the high school entrance examinations, the assessment items about photosynthesis and cellular respiration mostly focus on two differences between photosynthesis and cellular respiration: The opposite gas exchange (oxygen changes into carbon dioxide in cellular respiration; carbon dioxide changes into oxygen in photosynthesis) and the opposite changes between organic and inorganic substances. These two foci represent chemical reactions as two unconnected processes—gas exchange and organic-inorganic substance conversion, which is very different from the Level 4 reasoning that represents chemical reactions as re-arrangement of atoms into new molecules. Obviously, if middle school science teaching focuses on the same aspects, students do not need principled reasoning constrained by conservation of matter.

In the college entrance examinations, assessment items about carbon-transforming processes mostly focus on quantitative problem solving and stages of biological processes at atomic-molecular scale. They focus on the atomic-molecular chemical reactions and do not require students to connect atomic-molecular processes to any macroscopic phenomena. If high school science teaching is guided to this direction, students would not learn the scientific reasoning needed to link processes across scales.

Although the teaching approaches of American teachers vary a lot and are relatively difficult to track, American students’ performances in the pre-interviews indicate that American students, like their Chinese counterparts, largely rely on informal reasoning to make accounts. Besides that, they also lack necessary scientific vocabulary to make accounts.

Therefore, we suggest that science teaching should be based on what we have learned about domain-specific ways of scientific reasoning and students’ informal ways of reasoning. Both American and Chinese science teaching should deal with principled reasoning rather than focusing exclusively on teaching scientific facts and skills. Scientific terms and statements are also very important for students to construct scientific explanations. However, if the scientific terms and statements are taught without addressing the underlying scientific reasoning, what students learn can be vocabulary with either no meaning or intuitive meanings.

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Footnotes

[1] Although this version of the conservation laws does not recognize a relativistic understanding of the relationships between matter and energy, we believe that mastery of models that conserve matter and energy separately is an important developmental step.

Table 1

Learning Progression Framework

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

Table 2

Learning Progression Framework from Earlier Research Cycles

Levels of Achievement		Progress Variables	
		Matter	Energy
Upper Anchor	4. Model-based accounts	Accounts that successfully constrain matter transformation	Accounts that successfully constrain energy transformation
Intermediate Levels	3. "School science" accounts	Atomic-molecular accounts	Accounts about energy forms
	2. Force-dynamic Accounts with hidden mechanisms	Hidden mechanisms about matter	Hidden mechanisms about energy
Lower Anchor	1. Force-dynamic accounts	Force-dynamic accounts that does not involve matter	Force-dynamic accounts that does not involve energy

Table 3

Revised Learning Progression Framework

Explaining Progress Variable		**Naming Progress Variable**	
Level 4. Linking processes with matter and energy as constraints	Linking carbon-transforming processes at atomic-molecular, macroscopic, and global scales with matter and energy as constraints	Level 4. Scientific statements	MATTER: scientifically appropriate names for both reactants and products; both gases and solids/liquids named as material reactants or products ENERGY: all forms of energy involved in the chemical change; heat as byproduct
Level 3. Changes of Molecules and Energy Forms with Unsuccessful Constraints	Link macro-processes with change of molecules and/or energy forms at atomic-molecular or global scale, but cannot successfully conserve matter/energy.	Level 3. Scientific words of organic molecules, energy forms, and chemical change	MATTER (organic molecules): glucose, C6H12O6, monosaccharide, glycogen, lipid, ATP, ADP, carbohydrate, hydrocarbon, octane; ENERGY (bonds, energy forms): C-C bond, C-H bond, light energy, *kinetic energy (American version)*, electrical energy, chemical energy, heat energy PROCESS (chemical reaction): *cellular respiration (American version), combustion (American version)*, oxidation, light reaction, dark reaction
Level 2. Force-dynamic accounts with hidden mechanisms	Link macro-processes with unobservable mechanisms or hidden actors (e.g., decomposer), but the focus is on enablers, actors, abilities, and results rather than transformation of matter and energy.	Level 2.5. Easier scientific words with mixed meanings	MATTER: Fat, sugar, starch, organic matter, carbon, molecule, atom ENERGY: stored energy, motion energy/动能 PROCESS: photosynthesis, decomposition/decomposer, chemical reaction/change, 燃烧，呼吸作用 OTHERS: chloroplast
		Level 2. Hidden mechanism words	MATTER: carbon dioxide, oxygen, nutrients, gas (as in gas, liquid, and solid), ENERGY: calories, electricity PROCESS: digestion, digest, digestive system, break down OHTERS: bacteria, fungi, micro organisms), cell, power plants
Level 1. Macroscopic force-dynamic accounts	Describe macro-processes in terms of the action-result chain: the actor use enablers to accomplish its goals; the interactions between the actor and its enablers are like macroscopic physical push-and-pull that does not involve any change of matter/energy.	Level 1.5. Easier hidden mechanism words	ACTOR: organs (e.g., lung, stomach, heart, etc.), machine parts (e.g., engine, cylinder, piston), material ENABLER: fuels (e.g., gasoline, diesel, oil, coal, petroleum), heat
		Level 1. Words about actors, enablers, and results	ACTOR: body parts (e.g., leaves, roots, leg, etc.) ENABLER: water, air, sunlight, food (e.g., food, milk, bread, etc.), bugs, wind, lighter, etc. RESULT: strong, healthy, grow, run, warm, etc.

Table 4

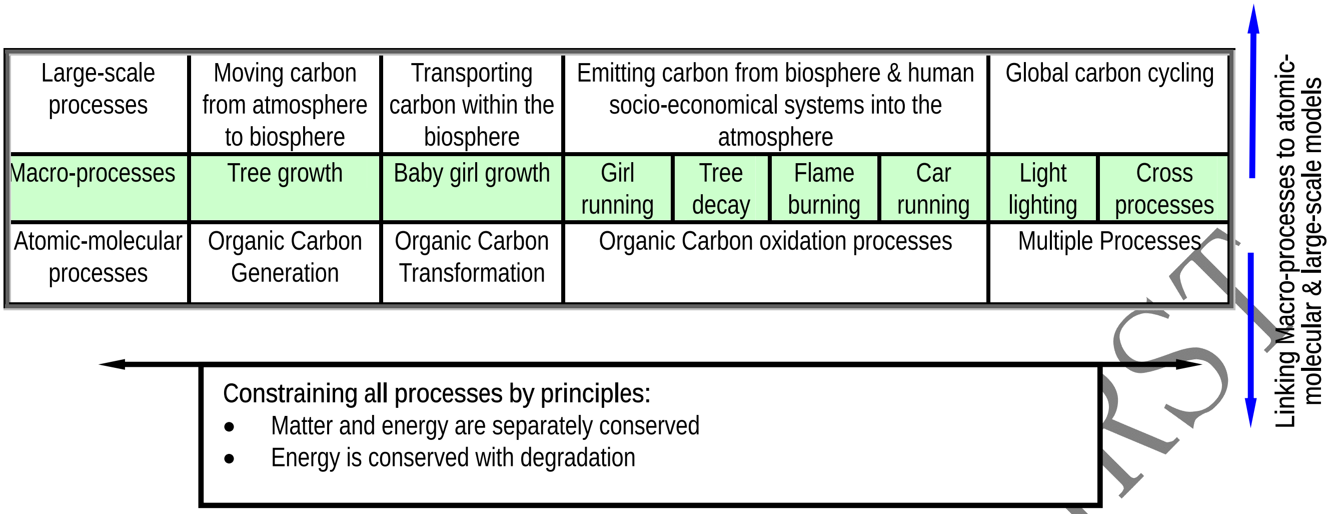
Naming and Explaining Levels of Selected Account Units

		Naming Level	Explaining Level
Tree Growth	KMG	1.5	1
	LYQ	1	1
Girl Running	SAM	2	2
	YZY	3	2
Flame Burning	RWD	3	3
	CMD	3	3
Car Running	EJR	4	4

Table 5

Scientific Words Used in American Pre-interviews and Chinese Interviews

	Organic molecules	Energy forms	Chemical Processes
Chinese Accounts	glucose, carbohydrate glycogen monosaccharide	light energy electrical energy kinetic/motion energy (动能, Level 2.5) chemical energy	oxidation cellular respiration (呼吸作用, Level 2.5) combustion (燃烧, Level 2.5) light reaction, dark reaction
American Accounts	glucose cellulose	Light energy kinetic energy	combustion

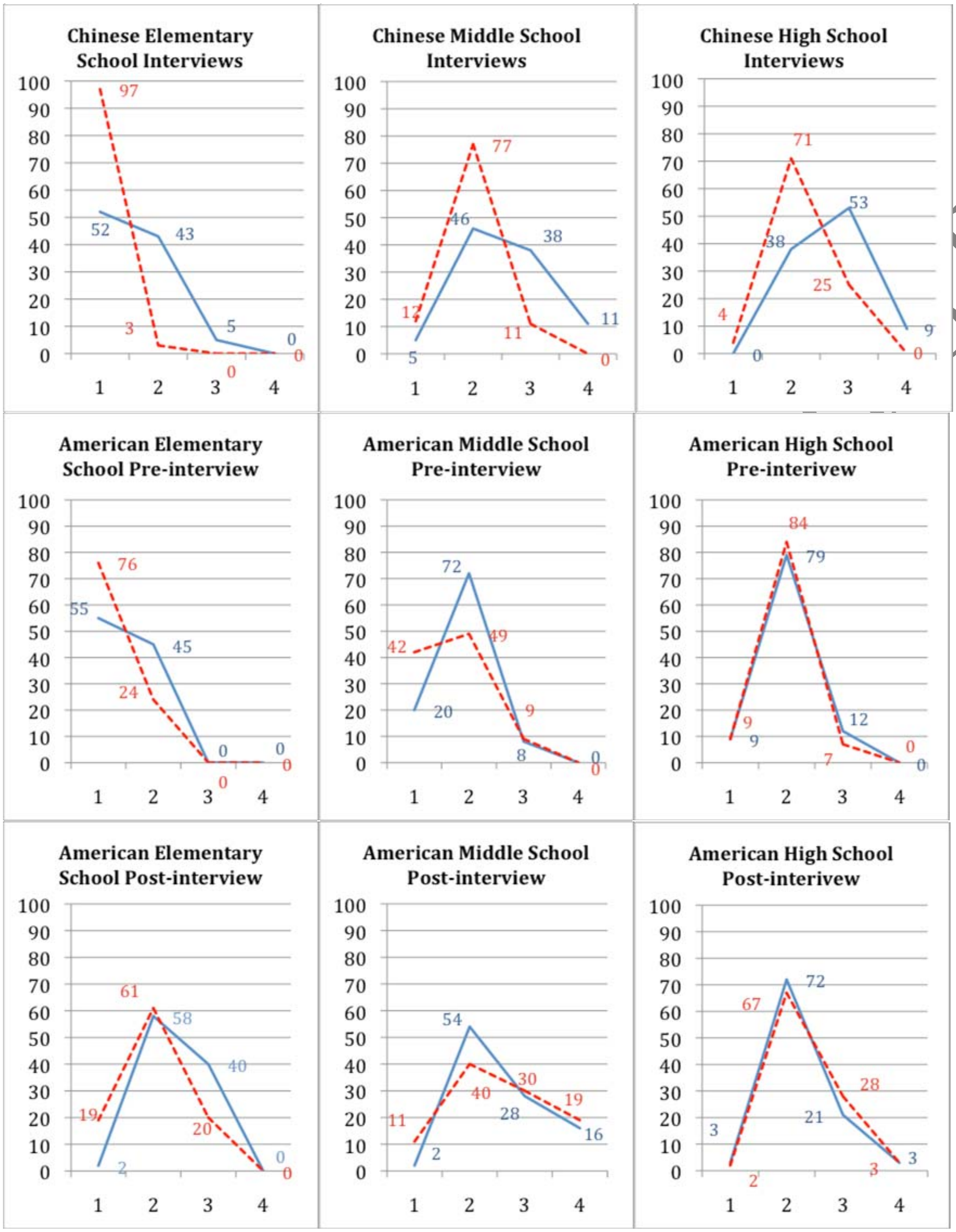


Large-scale processes	Moving carbon from atmosphere to biosphere	Transporting carbon within the biosphere	Emitting carbon from biosphere & human socio-economical systems into the atmosphere				Global carbon cycling	
Macro-processes	Tree growth	Baby girl growth	Girl running	Tree decay	Flame burning	Car running	Light lighting	Cross processes
Atomic-molecular processes	Organic Carbon Generation	Organic Carbon Transformation	Organic Carbon oxidation processes				Multiple Processes	

Constraining all processes by principles:

- Matter and energy are separately conserved
- Energy is conserved with degradation

Figure 1. Upper anchor: linking processes with constraints



Red Dash Line: explaining; Blue Line: naming

Y: Percentage of account units; X: Level

Figure 2. Distribution graphs for interviews