Title

Principles, First and Foremost: A Tool for Understanding Biological Processes

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Abstract

Distinguishing between matter and energy is a difficult task for college students, yet one that has implications beyond their science coursework. Issues of recycling, conservation of natural resources, including energy, and weight loss all have conservation of matter and energy as their foundation. Students often fail to realize the power of using a few foundational principles, such as conservation of matter and energy, rather than relying on a multitude of facts in understanding the world around them. We developed an instructional model that focused on using principles first, foremost, and as tools in a wide variety of contexts. We focused especially on changes in matter and energy in processes that involve carbon in living systems. We implemented this model in a test group of multiple sections of an integrated science course for pre-service elementary teachers who were non-science majors. We compared the test group performance to a comparison group of science majors who were taught with other instructional models. The gain in proficiency was much greater in the test group than in the comparison group. Our results suggest that principle-based reasoning can lead to substantive improvements in students' understanding of core scientific concepts.

All science disciplines have their own “big ideas” which are the basis of course curricula, learning materials, and assessments. Underlying these disciplinary big ideas are a few principles that cross disciplines. Conservation of matter and conservation of energy are such principles. While conservation is a disciplinary big idea in chemistry, it is also a foundational big idea that underlies biology, geology, and climatology. In life science, for example, conservation of energy is exemplified in the transfer of energy in a food chain, with decreasing amounts of chemical energy in food balanced by increased amounts of heat energy transferred to the environment. In geology, conservation of matter is the basic concept of the rock cycle, with atoms changing in location and association with other atoms, but not being destroyed.

The idea that neither energy nor atoms are created or destroyed in physical and chemical changes seems straightforward, but a conceptual understanding of these principles is more problematic than many college faculty realize. College students struggle in distinct ways with these concepts. Some students believe that atoms, and similarly energy, can be used up. In other words, there is no reason to account for atoms or energy in physical or chemical changes since they can cease to exist. Other students believe that atoms can change into energy. A lack of conceptual understanding of conservation of matter and energy prevents students from using these principles to reason scientifically when faced with new problems.

These difficulties become especially confounded in biological processes (e.g., photosynthesis, cellular respiration, and biosynthesis) since the matter under consideration is often food, which serves as both a source of energy and a source of molecules for building the structure of living things. Even college biology students have difficulty in reasoning scientifically. For example, science majors incorporate many more facts into their responses about biological processes at the end of biology courses, but their ability to apply basic conservation principles improved only marginally (Hartley et al. 2011). A core problem in these responses is students not recognizing the difference between facts and guiding principles with which one can reason scientifically (Parker et al. 2012).

Yet it is essential for all college students, science majors or not, to achieve this conceptual understanding which enables them to use scientific reasoning when faced with situations in everyday life. Decisions regarding personal health and consumer choices often involve an understanding of the permanence of atoms (e.g., consumption of mercury-contaminated tuna) and energy units (e.g, recognizing the importance of tracing electrical energy to its sources to understand emissions associated with electric vehicles

Undergraduate students who are future K-8 teachers have an additional need to understand and be able to use conservation principles. Conservation principles are an essential part of middle and high school science standards (National Research Council*.* 2012). Rather than being viewed as one more fact to learn and teach (Duschl et al. 2007), conservation of matter and energy can serve as overarching principles that integrate the broad range of topics K-8 teachers face in Earth, life, and physical science.

Multiple studies show the difficulty of tracing of matter and energy across different scales and through multiple processes (Barman and Mayer 1994; Carlsson 2002a,b; Hartley et al. 2011; Mohan, Chen, and Anderson 2009; Wilson et al. 2006). Recent studies focusing on specific methods of instruction have shown some success in helping students master these concepts. Maskiewicz et al. (2012) reported higher post-instruction scores on assessments of matter and energy conservation with targeted active learning in-class activities compared to lecture.

We wondered if a course that focused on conservation principles first and foremost, emphasizing the differences between broadly applicable principles and specific facts, could be successful in helping students understand conservation and apply it to reason about both science content and relevant issues in their everyday lives. We focused on a course for non-science majors in a teacher education program Its integrated content (life, Earth, and physical science) lent itself to demonstrating the utility of conservation principles across disciplines, and students' learning in this course could affect future K-8 learners' understanding. We were determined to create an instructional model that would support students' use of principle-based reasoning in explaining biogeochemical processes. This article reports on applying conservation principles to biological processes.

Research Methods

Instructional Model - Principles: First, Foremost, and as Tools

We developed an instructional model to help students develop principle-based reasoning skills in a semester-long science course for students in the elementary education program at Michigan State University. While the course curriculum mirrored the breadth of the K-8 science curriculum (e.g., climate, geology, ecology, chemistry), we focused on an overarching theme of matter and energy conservation in physical and chemical changes. Thus, matter and energy are not just the first topics in the course, but conceptual tools whose explanatory power is explicitly explored in every unit and at a range of scales from atomic-molecular to global. Our approach extends the use of these principles from an organizing framework to a tool that can be used in reasoning.

We developed physical models to support students as they developed the conceptual understanding of conservation and the ability to reason using these conservation principles. For our model of matter, we use paper clips, with each paper clip representing one atom, and different colors and sizes of paper clips representing atoms of different elements. The paper clips are connected together to represent molecules. With no additional object (e.g., a stick or a spring) needed to connect atoms, we are able to clarify that bonds are not matter. To illustrate the permanence of atoms in physical and chemical changes, we use pocket scales to mass the paper clips. Identical paper clip groups (representing molecules of the same substance) can be placed on the scales with different spacing between them (representing different states of matter). For chemical changes, several paper clip groups can be massed collectively; then the groupings can be broken apart and new groupings formed which are then massed again. Both of these examples illustrate that an object's mass comes from the total mass of individual "atoms" (Figure 1).

For our energy model, we use paper strips, with each square-inch strip representing one unit of energy and different colors of strips representing different forms of energy. In contrast to putting paper clips on a scale to illustrate permanence, we put paper strips on a paper template of a mathematical equation (Figure 2). Using a math equation shows the equality of energy units before and after any change, whether it is an energy transfer or transformation. The math equation helps students think of energy units as being like numbers - numbers without mass. Thus, students never put the energy strips on a scale.

This "*clips and strips*" model is used explicitly to illustrate conservation of matter and energy during physical and chemical changes, whether the context is life science (germinating bean seeds), Earth science (mining and recycling of Earth materials), or physical science (combustion of fuels). Students practice with their own clips and strips set while completing homework; sets are also used in class to address student errors in discussions and homework.

Subjects and Setting

We compared the work of non-science majors (test group) to that of science majors (comparison group) in biology courses at other post-secondary institutions around the country.

Test Group

The test group consisted of non-science majors in the course described above. Five instructors taught six sections (one instructor taught two sections) of this required junior-level course (class size of 24). These instructors (including two authors) were part of a cohesive instructional team that met weekly to develop, implement, and assess teaching strategies. One section consisted of education majors with an integrated science teaching minor while students in the remaining five sections were earning non-science teaching minors.

Comparison Group

The comparison group consisted of science majors taught by instructors who were part of a faculty development program (D'Avanzo et al., 2012) based on education research. The program was designed to help faculty use formative assessment and targeted active-learning activities to improve student reasoning and understanding of matter and energy in biological systems. These seven instructors taught at six different public institutions (one was a 2-year institution). Five instructors taught introductory biology courses and two taught advanced biology courses. Class size ranged from 50 to 300 students.

Measures

Learning Progression for Carbon Cycling

Students' abilities to use principle-based reasoning in solving science problems can be assessed through the use of learning progressions. Learning progressions are descriptions of increasingly sophisticated ways of thinking about or understanding a topic (Committee on Science Learning 2007). Learning progressions have been developed for a number of science disciplines, including genetics, evolution, and chemistry (Catley et al. 2004; Duncan et al. 2007; Roseman et al. 2006). We used a learning progression for tracing carbon atoms through socio-ecological systems that requires a commitment to matter and energy conservation in biological processes (Mohan et al. 2009). The learning progression describes students' potential, although not inevitable, transition from informal reasoning to explaining scientific phenomena using scientific accounts. This highest level requires students to use conservation principles as a tool to solve problems in different contexts and across different scales.

Diagnostic Question Clusters

To determine students' levels in the learning progression we revised a previously developed Diagnostic Question Cluster (DQC) assessment (see www.biodqc.org; Wilson et al. 2006; Parker et al. 2012). DQCs can give a more complete picture of student understanding by assessing understanding in different contexts, across different scales, and through integrating several concepts. We selected question clusters that were designed to measure student proficiency in accounting for matter and energy in photosynthesis, biosynthesis, and cellular respiration (see www.biodqc.org for introductory biology DQCs). Individual DQC questions are in several formats, including true/false, multiple true/false, and multiple select, with most questions requiring a written explanation for the answer choice.

We administered DQCs at the beginning and end of each course. Students completed one of three different forms of the DQCs. Each form focused primarily on one of the three biological processes, but included questions from one or both of the other question sets. Thus, not all students received all questions. The pre- and post-tests were matched for students in the test group, but not for students in the comparison group. Data from all students in the test group was used. For large courses in the comparison group we randomly selected 60 students per class to analyze.

Interviews

We also conducted a series of interviews with a subset of volunteer students in a test group from the subsequent semester in order to gain deeper insight into students' understanding of conservation at different time points in the semester. Open-ended interview questions focused on examples of conservation of matter and energy in contexts not yet explored in class, thus allowing us to assess students' ability to apply their understanding in a novel context. Interviews (30-60 minutes) were conducted by three post-doctoral science educators, including one author (JD) on three occasions (weeks 1, 7, and 15).

Data Analysis

Students' written explanations to individual DQC questions were coded according to the learning progression framework (Table 1) using levels 2-4 (level 1 is rarely seen in undergraduate students). Using these codes (level 2, 3, or 4) for individual questions, we applied Item Response Theory (IRT)-based methods to calculate students' proficiency. Specifically we used the partial credit model (Masters 1982) designed for test items with two or more ordered categories. To compare student proficiency differences on pre- and post-tests for each group, we used a one-sided Welch's t-test to test for differences between student proficiency on the pre- and post-tests within groups. We also used effect size (ES) to measure gains in student proficiency over time (Vaske et al. 2002). Calculated here for each group using Cohen's d equation (Cohen 1988), ES is the difference between mean-post and mean-pre students' proficiency value divided by pooled standard deviation. Complete analysis of data from student interviews will be the subject of a subsequent article.

Results

Data is shown for the test group (pre n=133, post n=109) and comparison group (pre n=382, post n=430). Differences in pre- and post-test numbers are due to variation in class attendance on the day assessments were administered. The number of students answering a specific question varies due to the use of multiple assessment forms.

Pretest scores on the DQCs were similar between the test and comparison groups ($p=0.94$). Significant gains were seen in student proficiency from the pretest to the post-test in each group ($p < 0.0001$ for each). However, the gain in proficiency was much greater in the test group than in the comparison group (Figure 3). This difference in pre-post gains in proficiency led to a larger effect size for the test group (ES = 1.506) than the comparison group (ES=0.310).

This large difference in student proficiency between the test and comparison groups are a result of differences in the proportion of students at levels 2, 3 or 4 of the learning progression framework in each group. Figure 4 shows the proportion of student responses to DQC questions at each level of the learning progression.

Sample question

The differential gains made between the two groups can be illustrated with a sample question assessing understanding that matter cannot change into energy. The format of the question was true-false with a written explanation for the answer choice.

Once carbon enters a plant, it can be turned into energy for plant growth.

On the pre-test, only 20% of all students chose the correct answer (false). The results were similar on the post-test in the comparison group (17% correct; n=222) while in the test group 75% of students (n=72) chose the correct answer. Differences in students' reasoning emerged between groups in students' written explanations. An explanation commonly seen in the comparison group is "Yes, it (carbon) is turned into ATP for energy which helps to make it grow" while a typical explanation seen in the test group is "Matter can't turn into energy".

Interviews

Nine students (drawn from five different sections) participated in the series of interviews. Table 2 illustrates how a student in the test group was able to apply her understanding of matter and energy to the process of a tree growing *before any instruction* in life science. In a pre-course interview, she responded that sunlight was important for tree growth, suggesting nutrients might come from sunlight. After 8 weeks of instruction in other curriculum units (e.g., physical science, Earth science) she changed her response to explain that light energy is transformed into chemical energy and can be used to rearrange molecules as trees grow.

Discussion

Learning Progression

Our results show that college students can learn and use principle-based reasoning. Students in the test and comparison groups shared a similar lack of understanding of conservation principles at the beginning of their courses, with nearly one-half of students giving informal accounts of biological processes without accounting for matter and energy. The similarity between the groups is not surprisingly since most of the science majors were enrolled in introductory level biology courses while the non-science majors, although at a junior or senior level, had only completed two general education science courses. While both groups improved with course instruction, the post-assessment results were strikingly different between the two groups. Three-fourths of non-science student answers were at level 3 or 4 on the learning progression showing at least an awareness of conservation principles while only 60% of answers of science majors reached this level. The higher performance of the test group is even more apparent when only level 4 answers, showing consistent use of these principles across multiple contexts, are considered. In the test group 42% of student responses were at level 4 while only 18% in the comparison group reached this level.

The sample question from the DQC assessment described in our results highlights the difference in reasoning between science majors and non-majors. The comparison group explanations, while demonstrating knowledge of science terms, commonly showed confusion about the need to account for matter and energy in photosynthesis (Level 3). The test group sample explanations, while simpler in vocabulary, showed a more consistent recognition that the T/F statement violates the principles of conservation of matter and energy (Level 4).

Our student interviews allowed us a second means to assess students' ability to apply conservation principles. Questions such as the one used in Table 3 above, *"What does a tree need to grow?"* revealed students' emerging ability to trace matter and energy independently across different scales from the molecular to the organismal. Initially, this student, like most students in either group, confused matter and energy ("Is there nutrients in the sun?"). However, after 8 weeks in the test course this student recognized the importance of tracing matter and energy independently, even though she still knew nothing about the specific molecules involved. She clearly hypothesized that there must be both change in matter (atoms breaking apart to form new molecules) and a change in energy (light energy transformed into chemical energy).

The student appears to be learning how to reason with conservation principles as she is speaking ("and the energy's, wow I mean maybe the light facilitates that"). Most striking is that this student is able to apply her understanding of matter and energy to the process of a tree growing *before any instruction* in life science topics and biological processes. This is not a simple feat; keeping matter and energy separate in biological processes is challenging since food is a source of energy and a source of molecules for building body parts at all scales.

Instructional Model

We attribute the higher level of performance in the test group to the consistent use of our teaching strategy which put principles first and foremost. (In contrast, instructors in the comparison group shared a professional development experience that emphasized assessment and activities to improve student understanding of matter and energy in biological systems, but no attempt was made at consistency in teaching strategies between these instructors.) Instructors in the test group explicitly invoked conservation principles in each unit in the course. Thus, topics in life, Earth, and physical science all followed a predictable sequence: a focus on the permanence of atoms in the substance under study (e.g., cells, rocks, air, fuel) and the permanence of energy units as energy interacts with this matter and the use of the clips and strips model. It was this consistent practice with and application of conservation principles that made conservation principles first and foremost in the course. We think the impact of this strategy is reflected in the ease with which students refute misconceptions on the inter-conversion of matter and energy with "Matter can't change into energy."

With our emphasis on principles first and foremost, we were able to explore a breadth of topics in life science (cell biology, ecology), Earth science (geology, climatology) and physical science (chemistry). Conservation principles thus formed a foundation on which new topics and disciplines could be approached and integrated, not an easy task with the breadth of topics in the K-8 science curriculum. Edgcomb et al. (2008) reported that even in an integrated, inquiry-based science course pre-service teachers did not see how the physical sciences and life sciences were related. In contrast, the biology courses in the comparison group, while limited to life science, may have included so many specific facts that students remained lost regarding foundational ideas (Parker et al. 2012).

Our physical models helped students practice using conservation principles as tools for reasoning. We found students initially needed these tangible physical models. As simple as these models appear, students made many mistakes (e.g., confusing atoms with molecules, turning matter into energy) during the first weeks of the course. Interestingly, students often needed a reminder to use the models when explaining what happened to matter and energy in a physical or chemical change. It was as if students had a toolbox full of tools, but didn't know when or which tool to use. Students got much better at pulling out the correct tool - whether the actual clips and strips OR just their mental image - throughout the semester. We repeatedly heard students, when working with novel examples of chemical change, saying to each other "*Clips can't become strips*!" Students' spontaneous use of this informal lexicon of conservation of matter and energy was often evidence that students had reached the level of principle-based reasoning.

With these models as a tool to help them remember these basic concepts, students had the foundation on which they could analyze examples of matter and energy conservation in their daily lives. This was especially true in cases of imprecise language such as "energy is lost" (which can sound like energy has been destroyed). With a commitment to principle-based reasoning, these students were less likely to become confused with fuzzy language. As one student phrased it, "I used to think atoms and energy were disposable, but now I know they are forever."

Implications for college biology teaching

Our results may have implications for science majors. Most students in college biology courses can recite the principles of conservation of matter and energy, but only as facts not as *rules* that govern biogeochemical systems. These principles often get lost in the details and complexities of college science courses. A focus on principles may seem to be remedial work, especially since these concepts fall within the high school science curriculum. Rather than being remedial work, repeated practice with these principles in a variety of contexts may give students the opportunity to integrate disjointed threads of understanding and arrive at a level of reasoning that is not shaken when new terms or facts are introduced.

Implications for teaching of non-science majors

While an understanding of these foundational big ideas is crucial for biology majors, it is also essential for all college students, the majority of whom are not science majors. Examples of conservation of matter and energy taken from students' daily lives help make these principles relevant. Understanding and acting upon issues in human physiology (e.g., weight loss and gain, nutritional composition of foods, growth), energy usage (e.g., electric and heating bills, gasoline consumption), and the environment (recycling, climate change) all depend upon an ability to apply principles of conservation. This is reflected in recent frameworks for literacy of different disciplines, such as climate literacy (Earth Science Literacy Initiative, 2009) and Earth science literacy (United States Global Change Research Program, 2009).

A sub-population of college students within this large group of non-science majors is pre-service elementary teachers. Even though pre-service elementary teachers are overwhelmingly non-science majors, they provide years of science education for students in all areas of science - physical, life, and Earth science. Our results suggest that this group of students can learn conservation principles not just at a conceptual level, but as tools for reasoning about scientific phenomena across disciplines. This approach to teaching the K-8 science curriculum holds the possibility of integrating many seemingly disparate everyday phenomena (e.g., plant and animal growth, uses of Earth materials, the water cycle).

Conclusion

This study suggests that non-science major college students can learn and use principle-based reasoning related to conservation of matter and energy in a timely manner. Even novel situations, at any scale, can be understood by applying principled reasoning. When students are committed to using the principles of conservation of matter and energy even factual gaps in content understanding or unknown terminology do not interfere with their ability to reason.

Acknowledgements

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Table 1: Levels in the Learning Progression Framework for Carbon Cycling (Mohan et al. 2009)

Level 1	*Pure force-dynamic accounts*	Students' accounts focus on actors and enablers, using relatively short time frames and macroscopic scale phenomena.
Level 2	*Elaborated force-dynamic accounts*	Students' accounts include actors and enablers, but with added detail and complexity at different scales. They include ideas about what is happening inside organisms and show awareness of connections among phenomena on a large scale such as food chains.
Level 3	*Incomplete or confused scientific accounts*	Students show awareness of important scientific principles across scales, but have difficulty connecting accounts at different scales and applying principles consistently.
Level 4	*Coherent scientific accounts:*	Students successfully apply fundamental principles such as conservation of matter and energy to phenomena at multiple scales in space and time.

Table 2: Example interview excerpts from one student (Kendra) that provide evidence for the ability to transfer the use of principles to unfamiliar scenarios.

Pre-course interview	*Mid-course interview, pre-life science instruction*
INTERVIEWER: So what does a tree need to grow? KENDRA: Water. Soil, the nutrients in the soil. The, like, rainfall, that's water. Like, the carbon, carbon dioxide. Photosynthesis, life cycle, it grows. Space, room to grow. INTERVIEWER: Let's start with photosynthesis. How does it help the plant grow? KENDRA: It's...chloroform, or it's chlorophyll, one of those things, the things that make them green. The sun, oh and sunlight too. The sun, and like the carbon dioxide, it's like soaking, like soaks in and it grows, and then it gives off oxygen, it goes back up, it goes back down, is that the right cycle? One of the two. INTERVIEWER: Okay. So what about the sunlight, what does the sunlight do? KENDRA: Photosynthesis. INTERVIEWER: Why is that important? KENDRA: I'm not positive. Um, does the sun, is there nutrients in the sun, er well or something of that, like something in the sun that is important for, maybe the sun acting with the nutrients in the plant, kind of a reaction…….?	INTERVIEWER: So what does the tree need in order to grow? KENDRA: Air, water, light, like light is a form of energy. So these energy and like molecules. Air molecules, water molecules, light energy. INTERVIEWER: Okay. And what does it do with those things? KENDRA: They interact. When molecules interact, when molecules are changed, there is some interaction with energy there. The same with energy's change, molecules are involved. So, when you have this light energy coming down, you've got water and air molecules, I guess, whatever, coming together and breaking apart new groups and forming new molecules and the energy's, wow I mean maybe the light facilitates that. Light energy facilitates there, that form of energy or the light is like transformed into like a chemical energy and that's when they're like boop-boop break apart, you know, and like reform the groups.

Figure 1: Paper clips, each representing an atom, are connected together to represent a molecule. The total mass of the paper clips is constant whether connected or separate.

Figure 2: Paper strips, each representing a unit of energy, can be transformed into other forms of energy, but the total amount of energy is equal before and after the change.

Figure 3: Mean ± SE student proficiency on pre- and post-tests for the Test and Comparison Groups. Student proficiency was calculated in logits using Item Response Theory analysis.

Figure 4: Proportion of student answers at each level (2 - 4) on the learning progression on pre-and post-tests for the Test and Comparison Groups.

Figure 1

Figure 2

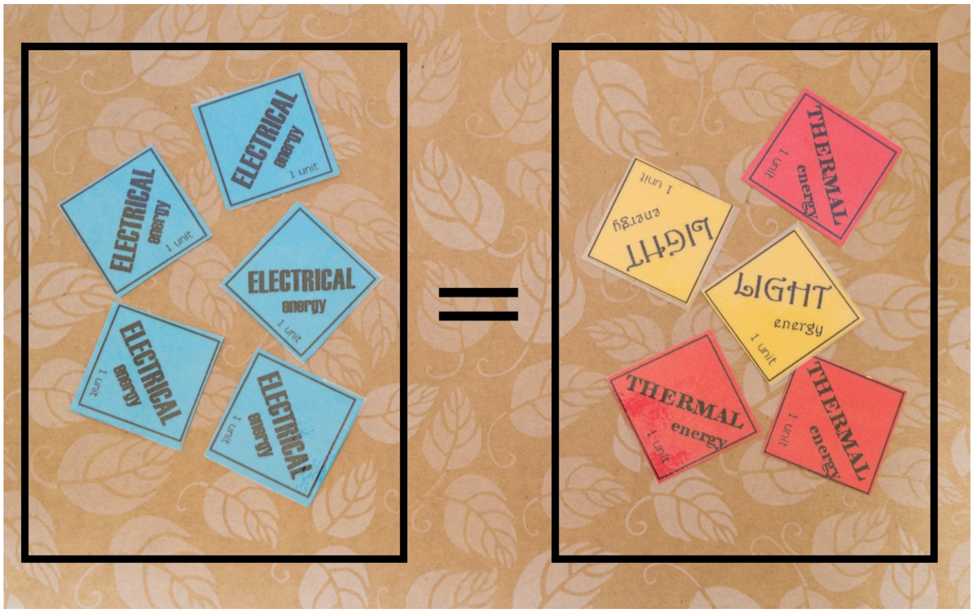

ELECTRICAL energy 1 unit
ELECTRICAL energy 1 unit
ELECTRICAL energy 1 unit
ELECTRICAL energy 1 unit
ELECTRICAL energy 1 unit
=
LIGHT energy 1 unit
THERMAL energy 1 unit
LIGHT energy 1 unit
THERMAL energy 1 unit
THERMAL energy 1 unit

Figure 3

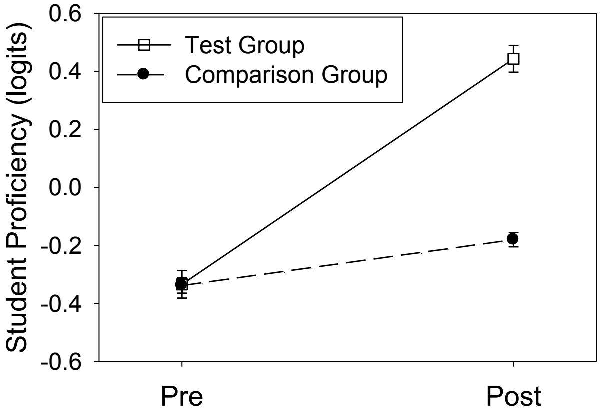
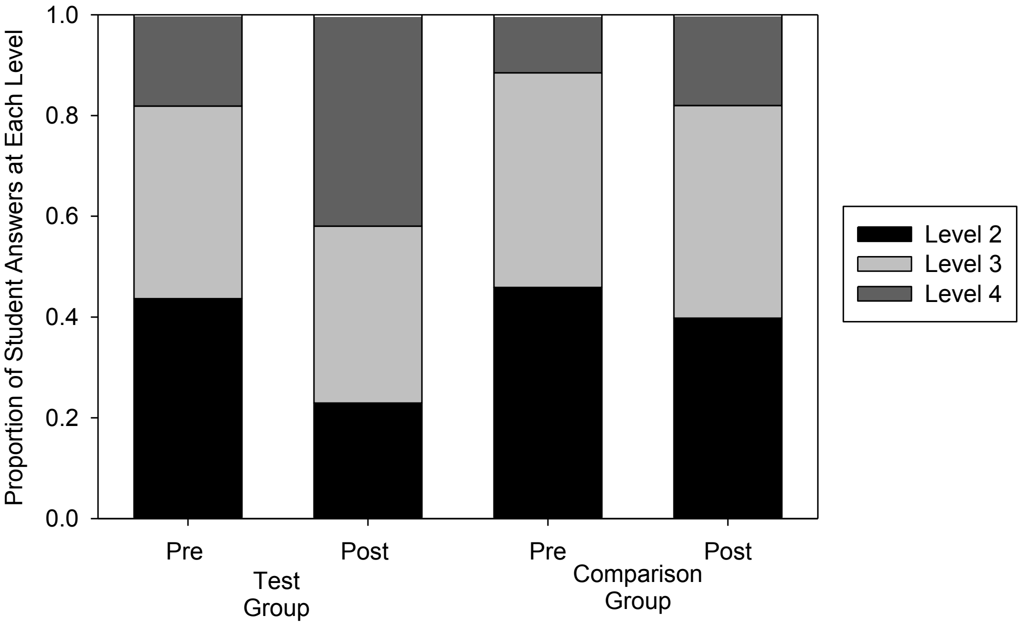

Student Proficiency (logits)
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
Pre
Post
Test Group
Comparison Group

Figure 4


Proportion of Student Answers at Each Level
1.0
0.8
0.6
0.4
0.2
0.0
Pre
Post
Test Group
Pre
Post
Comparison Group
Level 2
Level 3
Level 4