Conservation of energy: An analytical tool for student accounts of carbon-transforming processes

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Abstract

The concepts of energy and energy conservation are powerful concepts for understanding biological systems, but helping students use these concepts as tools for analysis of these complex systems with links to the familiar poses special challenges. This paper focuses on three issues that arise in teaching about energy in biological systems:

1. **Understanding the purpose of the concept of energy**. Conservation of energy is a powerful concept, however, too often students use energy in cause-effect stories related to vitality or animation ("energy is what makes things happen"), rather than treating energy as an enduring entity which can be used as a *tool for analysis*. In instruction, we treat the principles of conservation of energy as "rules to be followed," allowing students to trace energy through processes and see how energy constrains these processes.
2. **Identifying forms of energy in living systems.** Students make tenacious and incorrect associations between energy and cause, vitality, or growth that do not align with scientific conceptions of energy (chemical energy, light, heat, motion). In our instruction, we make simplifications we feel are important for helping students develop a working discourse about energy in science classrooms: we describe energy as taking on different forms, one of which is chemical energy that can be contained in bonds of molecules.
3. **Tracing energy separately from matter.** Students lack a *sense of necessity* for distinguishing between matter and energy (e.g., "glucose is energy;" "fat is transformed into energy when a person exercises and loses weight"). We use physical representations of energy (twist ties) and a framework for scaffolding student explanations of matter and energy separately in order to have students focus on accounting for matter and energy as separate entities.

Introduction: Goals for Teaching about Energy in Living Systems

Energy is a key concept in the K-12 science disciplines, including biology, chemistry, physics, geology and astronomy. In our work we have focused on the fields of biology and environmental science, with a particular focus on carbon-transforming processes. These processes create organic materials (photosynthesis), transform organic materials (biosynthesis, digestion, fermentation), and oxidize organic materials (cellular respiration, combustion). They are the key mechanisms by which energy is transformed in living systems and in human energy systems. It is important for students to understand carbon-transforming processes for many reasons, most importantly that the cause of global climate change is the current worldwide imbalance among these processes.

Helping middle and high school students develop scientific understandings of the role of energy in these processes is especially challenging. Some of these challenges and a learning progression for energy in carbon-transforming processes are described in other publications (Jin & Anderson, 2012; Jin & Wei, this volume). In this chapter we use these previous findings to underpin our focus on implications for curriculum and instruction: We explain appropriate goals for students' knowledge and practices about energy in carbon-transforming processes, suggest three key challenges in meeting those goals, and briefly describe some instructional supports we are developing to help teachers and students meet these challenges.

A Key Goal: Using Energy Conservation as an Analytical Tool

Richard Feynman suggested that the key concept of energy across disciplines is that energy is conserved during processes:

> It is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity and when we add it together it gives "28″—always the same number. It is an abstract thing in that it does not tell us the mechanisms or the reasons for the various formulas. (Feynman, 1964).

Feynman suggests that the conception of energy can be used to create measurements and formulas that allow for prediction, modeling and analysis, even if the mechanism or reason for the formula is unknown. According to this conception, energy should be used as a *tool for analysis,* and one key characteristic makes it a valuable tool: *Energy is conserved in physical and chemical changes.* This conception of energy is supported as a suitable goal for K-12 learning by the *Framework for K-12 Science Education* (NRC, 2011):

> One of the great achievements of science is the recognition that, in any system, certain conserved quantities can change only through transfers into or out of the system. Such laws of conservation provide limits on what can occur in a system, whether human-built or natural…. The supply of energy and of each needed chemical element restricts a system's operation—for example, without inputs of energy (sunlight) and matter (carbon dioxide and water), a plant cannot grow. Hence it is very informative to track the transfers of matter and energy within, into, or out of any system under study. (p. 94)

We note that this passage relies on essentially a 19th-century definition of energy, focusing on chemical and physical changes and not mentioning relativistic and quantum conceptions of energy. We agree with this emphasis; in this chapter we focus on conservation of energy as a tool for analysis of carbon-transforming processes. We feel that this achievement arms a student with tools for interpretation and analysis of multiple situations, including important socio-ecological issues relating to global climate change. In particular, this description emphasizes three characteristics that are essential to a useful scientific model of energy. Energy is: different from matter, without mass and is conserved in physical and chemical processes, and therefore traceable through these processes. So these qualities define our key goals with respect to students' conceptions of energy. If students can understand a model of energy that includes these qualities and apply it successfully to carbon-transforming processes, then they will take a major step toward appreciating and using the power of energy as an analytical tool.

Challenges and Instructional Supports

The power of energy as a concept lies in its application across contexts and disciplines, yet different disciplines offer distinct challenges for teaching and learning. Here we focus primarily on biological systems at multiple scales, from carbon-transforming processes described at the atomic-molecular scale to energy flow through ecosystems and global environmental systems. Discussing energy in biological contexts (e.g. photosynthesis, cellular respiration, digestion) as opposed to energy in physical contexts (e.g., pendulums, projectiles, electrical circuits) exposes unique challenges to student learning. In physical contexts, energy indicators (for example, motion for kinetic or elevation for gravitational potential energy) are often easily observed, and often quantification is often possible. In contrast in biological contexts, which almost always involve chemical energy and heat transfer, energy indicators are more difficult to observe and quantify (as well as more easily observable motion energy and light energy).

Biological systems pose another kind of challenge. Applying physical laws to real-world systems is daunting because of the complexity of the systems themselves. For example, the trajectory of a batted baseball depends on the initial velocity of the ball, wind speed and direction, the spin on the ball, air pressure, the texture of the ball's surface, and other factors. Learners cannot possibly account for all of these factors in explaining or predicting the ball's trajectory. Physical science classes typically deal with this complexity by simplifying the systems; rather than analyzing actual systems in the real world, students analyze idealized, simplified systems (for example balls batted in a vacuum, ideal gases and pure chemicals). This option is usually not available for the life and Earth sciences where learners study real plants, animals, and ecosystems in complex physical settings.

But the need for simplification persists; learners are still unable to analyze living systems in their full complexity. So in order to make our analyses of living systems comprehensible to students, we sometimes must simplify the models and principles instead of simplifying systems. This is a standard practice in all of science. All models simplify the real world, and scientific reasoning always involves choosing the appropriate simplifications for the problems at hand. When we are teaching, though, the "problems at hand" often involve student comprehension rather than systems in the material world. This leads to an important issue that we address in this paper: How can we develop appropriate simplifications of energy-related models and principles for young learners studying living systems? While many agree that a simplified model of energy in complex systems is necessary (Cooper & Klymkowsky 2013, Millar this volume), few have proposed satisfying and specific solutions for simplification in biology instruction. We suggest that appropriate simplifications need to meet at least four criteria. First, they should be comprehensible to students, as indicated by empirical methods like our learning progression research (for example: Mohan et al. 2009, Jin & Anderson, 2012). Second, understanding should be achievable within reasonable constraints on instructional time. Third, simplifications should help to position students to understand more sophisticated models and principles in their future learning. Fourth, they can be used consistently across the range of systems and processes and across spatial and temporal scales.

Through our learning progression work we have identified three core instructional challenges in teaching students to use energy as a tool for analyzing carbon-transforming processes:

1) understanding the purpose of the concept of energy

2) identifying forms of energy in living systems

3) tracing energy separately from matter

In the remainder of this chapter we summarize findings from our research and other research that describe the nature and dimensions of these challenges as we teach students about energy in carbon-transforming processes. We also discuss the implications of these research findings for our goals in teaching middle school and high school students—our judgments about achievable outcomes that students should be expected to learn. Finally, we propose instructional tools and strategies, as well as necessary simplifications of scientific conceptions of energy that we are using to address these challenges and to reach achievable learning outcomes.

In our work we have asked students in grades K-16 about many different carbon-transforming processes at a range of scales. The issues we describe arise consistently across all of these carbon-transforming processes and persist across age groups. In this chapter we will illustrate these issues and our instructional approaches with examples of student responses from two questions: an interview question asking about how trees grow, and a written question asking about what happens to energy when a mouse dies. The questions and examples of responses are included in Table 1. These student responses are part of a larger set of data (approximately 150 interviews and 1100 written responses) collected from 2011-2012 in 6^{th} – 12^{th} grade classrooms of 40 teachers in six states. During the 2012-2013 school year data will be collected that should reveal the effectiveness of the teaching tools and strategies purposed in this paper.

1. Understanding the Purpose of the Concept of Energy

Our research to develop a learning progression framework on carbon transforming processes describes common 4^{th} – 12^{th} grade student accounts that use energy as a resource that enables actors to make events happen (Mohan et al. 2009, Jin & Anderson 2012). Other research has documented how students think of energy as the cause of events more widely in physical and chemical contexts (Trumper, 1990, 1993; Watts 1983). Students often enter biology classrooms with these causal conceptions of energy, which can be compared to Aristotle's concept of energy characterized as being-at-work*,* and explaining why and how events happen (Jin & Anderson, 2012).

For example, middle school students' accounts of how trees grow typically describe a tree as an actor with a purpose in life—to grow. Anything that enables or causes a tree to grow and be healthy is a source of energy for the tree, including water, air, nutrients and sunlight. Examples of students using the concept of energy as causal are in Table 1, where students are talking about energy needed for plants growing, and about what happens to energy after a mouse dies. In the plants growing example, "Student A" associates energy with a cause that results in growth and vitality, which allows the student to incorrectly include water, nutrients, sunlight and carbon all as providers of energy for a tree, whereas agents which do not cause growth or vitality, like caterpillars, do not provide energy. In the mouse dying example, for "Student C," energy is anything that allows the mouse to thrive, including sleep, and when a mouse dies—energy is gone.

Table 1: Sample student responses.

Questions Asked	**Energy is causal**	**Energy is a tool for analysis** - Student doesn't have all the details - Student attempts to trace energy - Energy is an enduring entity
Interview questions including: Does a tree need energy? Where does a tree get energy? What happens to the energy when it is inside a tree?	INTERVIEWER: …What is the difference between the things that give the tree energy and things that don't give the tree energy? STUDENT A: Because things that give the tree energy they are what make it grow so like the water and the nutrients and the sun and the carbon … since they're like the food for the tree it is the tree's energy. And I think it has to do with the cells, like the cells need it for the tree to live. INTERVIEWER: Okay. And what about things that don't give the tree energy? You know what kinds of things that that would not include? STUDENT A: Well certain animals like those caterpillars that eat the tree down. … INTERVIEWER: Okay. Why does a tree need energy? STUDENT A: So that it can live. INTERVIEWER: So it can live? STUDENT A: Grow. INTERVIEWER: And grow? Okay.	INTERVIEWER: Does the tree need energy to grow do you think? STUDENT B: Yeah, it needs the light energy definitely. I don't know about the other ones, but definitely light energy they need to grow. INTERVIEWER: And how does it use the energy to grow? STUDENT B: There's a chemical reaction of some sort. And I don't know — obviously, it's not like a fire, like, burning, but it's some sort of, like, combustion or something that's happening in the molecules inside the plant that is brought on probably by the light energy. INTERVIEWER: And do you think that there's energy in the trees, like bark and wood and leaves or any other parts of the trees? STUDENT B: I mean there's chemical bonds in pretty much every molecule… INTERVIEWER: So do you think the tree stores energy for later? STUDENT B: Yeah I think so cause it seems like in the winter it would be, like, there's less sun and stuff like that, so it would need to store up energy. INTERVIEWER: Where do you think it does that? STUDENT B: Maybe the tree does it in the trunk. I don't know. INTERVIEWER: Does it store it in molecules do you think? Or is it stored in some other way? STUDENT B: Probably, but I never thought about it. I guess molecules would make — well, if it's just in the chemical bonds, then yeah, I guess that would make sense. INTERVIWER: Is there another way do you think it could store energy besides chemical bonds? STUDENT B: Not that I can think of.
Written Questions: A) What kinds of energy are stored in the living mouse? Where did they come from? B) What kinds of energy are stored in the dead mouse (if any)? How are they connected to the energy in the living mouse?	STUDENT C: A) The energy that the living mouse had stored is the food he had ate. He also might have slept and that made him wake up with energy. B) There is no energy in the dead mouse. If there were any he would still be alive	STUDENT D: A) Energy can neither be created or destroyed. I'm not sure what kind of energy the mouse has and where it came from. B) All of the energy is still there, but other organisms who are decomposing the mouse will help convert that energy into breaking down the dead mouse.

The complexity of biological systems permits students to either make or maintain incorrect associations between energy and vitality, animation or growth. These powerful associations made between energy and vitality is often not important in physical contexts. For example, the kinetic energy of a billiard ball can be both a *cause* of transferred motion (the cause for another billiard ball to be struck and move), and also a *tool for analysis* (tracing kinetic energy from one billiard ball to another). In living systems, however, student conceptions of energy (such as Student A and C who associate energy with purpose, need or vitality, Table 2) often do not align with scientific conceptions of energy, and can be particularly distracting when students are explaining biological phenomena (Figure 1).

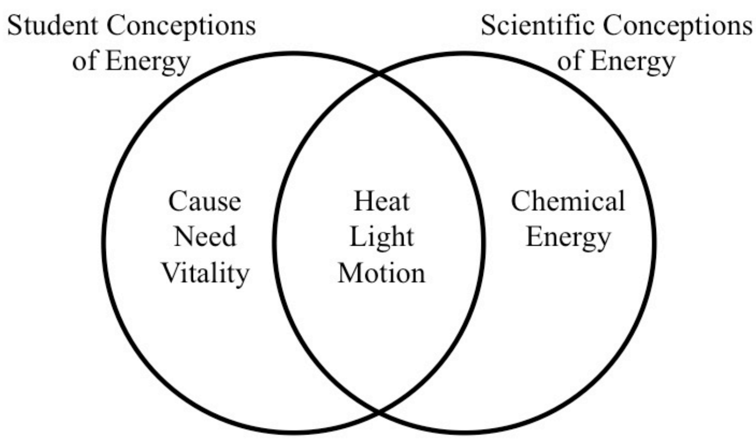

Figure 1: Student conceptions of energy compared to scientific conceptions of energy

Our conclusion is that learning to use energy as a tool for analysis in physical contexts such as pendulums and roller coasters does not address the core learning barriers that students encounter in using energy to analyze living systems. Common middle school definitions of energy such as “the ability to do work” or “the ability to cause a change” can reinforce the idea that causes of events are the same as energy sources, which is especially problematic in living systems. Our instructional approaches must address these problems directly.

Thus our goal is to help students move from accounts where energy is an ephemeral cause into treating energy as a tool for analysis; in their new accounts, energy must be an enduring entity in a system and traceable through processes. This entails (a) developing a sense of necessity about energy conservation in living systems—the same amount of energy must be present at the beginning and end of a process—and (b) helping students to use quasi-quantitative representations of energy in carbon-transforming processes.

*Developing a sense of necessity about energy conservation***.** Student explanations of carbon transforming process are complete only when they have accounted for energy before, during and after processes. In our curriculum materials, we treat the principles of conservation of energy and conservation of matter as rules to be followed rather than relying on students to discover these ideas empirically or to construct them from first principles in the classroom. This is consistent with our conceptualization of energy as a tool for analysis; through meta-cognitive prompts, students use this rule as a tool for analysis of their own accounts of observations, relying on the authority of the laws of conservation as a check-point for their own ideas. These rules make it possible for students to self-assess if their accounts of matter and energy in processes and all systems are constrained by the same rules throughout the curriculum.

The rules for students to follow are embedded in our "Three Questions" learning framework (Table 2). We teach students that adequate scientific accounts of carbon-transforming processes must include answers to all "Three Questions." The first two questions focus on movement of matter and changes in matter; we focus here on the "Energy Question". As Table 1 shows, each question comes with associated "Rules to Follow" including our expression of conservation of energy: "Energy lasts forever in combustion and living systems." (The "Evidence to Look For" relates to indicators of forms of energy, which is discussed below.)

The "Rules to Follow" are particularly important for engendering a sense of necessity about energy conservation. Students are required to apply these rules as they give explanations of carbon transforming processes and when they interpret evidence from classroom investigations about each carbon transforming process. During an investigation of mealworm respiration, for example, students readily recognize that the mealworms are moving, which involves energy. The idea that energy "comes from" food that the mealworms ate is also consistent with students' causal notions about energy. The notion that energy must have been present all along in the food (in the form of chemical energy) and that chemical energy in the food was transformed into the energy of their motion rather than simply causing their motion is new to most students. Even newer is the idea that the energy of the mealworms' motion must still exist in some form after the mealworms stop moving. Thus the "Rules to Follow" are the foundations of instructional strategies to instill a sense of necessity of conservation of energy in the students' accounts. The conception of energy can become a tool for analysis of students' own observations and explanations, requiring them to conserve and trace energy through a process.

Table 2: The Three Questions

Question	Rules to Follow	Connecting Atoms with Evidence
The Location and Movement Question: Where are atoms moving? Where are atoms moving from? Where are atoms going to?	**Atoms last forever** in combustion and living systems All materials (solids, liquids, and gases) are made of atoms	When materials change mass, atoms are moving When materials move, atoms are moving
The Carbon Question: What is happening to carbon atoms? What molecules are carbon atoms in before the process? How are the atoms rearranged into new molecules?	Carbon atoms are bound to other atoms in molecules **Atoms can be rearranged to make new molecules**	The air has carbon atoms in CO_2 Organic materials are made of molecules with carbon atoms • Foods • Fuels • Living and dead plants and animals
The Energy Question: What is happening to chemical energy? What forms of energy are involved? How is energy changing from one form to another?	**Energy lasts forever** in combustion and living systems C-C and C-H bonds have more stored chemical energy than C-O and H-O bonds	We can observe indicators of different forms of energy • Organic materials with chemical energy • Light • Heat energy • Motion

*Quasi-quantitative representations of energy***.** Our basic goal is to enable students to account for energy qualitatively in terms of energy forms and transformations; scientific quantification of energy is impractical in these complex systems. Students should be able to treat energy as an enduring entity, accounting for its forms and transformations during a biological process. However, simply asking students to name forms of energy involved in processes has been insufficient to achieve our goals; we have concluded that accounting for energy and its transformations requires both physical representations of energy and rules for tracing energy.

Students who are using physical representations of energy and rules for conservation of energy are able to move towards explanations that treat energy as an enduring entity and students begin to trace energy through processes. College classes that used a physical accounting system for energy showed substantial progress toward principle-based reasoning about conservation of energy (Rice et al., submitted). We have developed similar strategies for K-12 students. We use physical representations of energy (twist ties, Figure 2) during molecular modeling exercises. Representing energy in this way allows students to develop accounts of energy as an enduring entity that it is separate from matter. Twist ties can be referred to as “units of energy” which allows for accounting for energy before and after a process, without quantifying different forms energy.

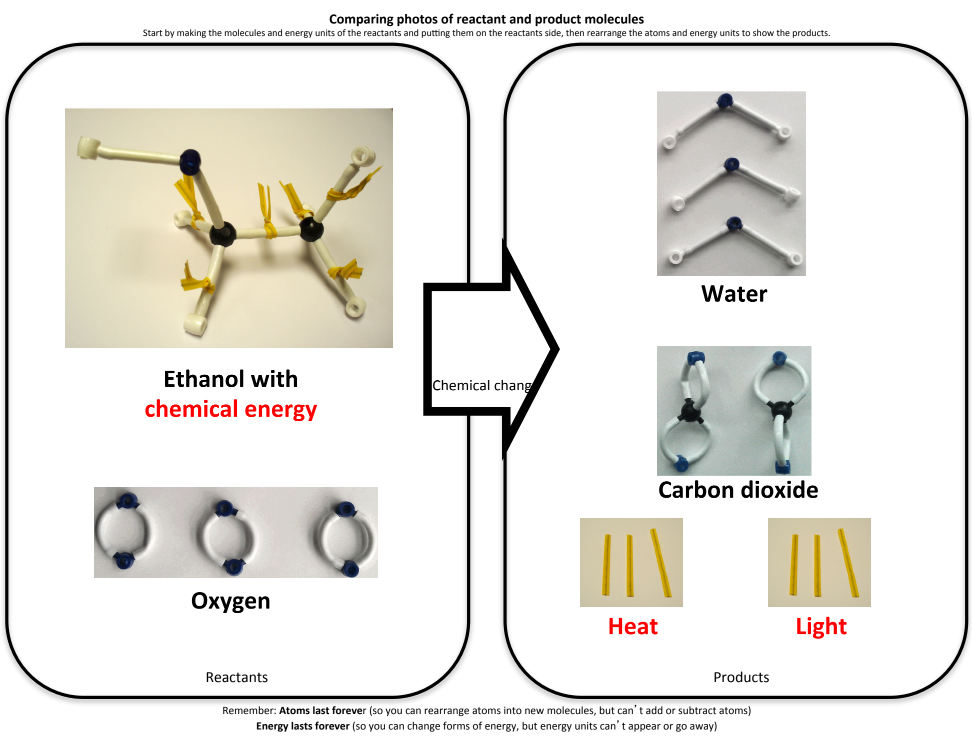

Figure 2: Twist ties and molecular models during an exercise on cellular respiration

When students trace energy through complex biological systems, there are simplifications that help students build a coherent story. For example, in our instruction we simplify the Second Law of Thermodynamics by not mentioning the concept of entropy, though we do emphasize degradation of energy in living systems. Energy is not like matter in that it cannot be recycled, and instead flows through living systems, ultimately being lost as heat. So, all processes change energy from more useful to less useful forms, especially low-grade heat. Degradation of energy through an organism or ecosystem can be illustrated for a student by using twist ties that represent sunlight or chemical energy before a process and then heat after a process.

Examples of student responses that show these practices are in the right-hand column of Table 2. These are students who have developed a sense of necessity about conservation of energy even though they do not understand the details of the processes. In the plant growing response, "Student B" is able to identify the sun as a source of energy, and to trace energy to materials in the trunk of the tree, but is not able to discuss specifics of process of photosynthesis or biosynthesis. In the mouse dying example, "Student D" is not sure about what kind of energy exists in a living mouse, but knows that it will not disappear after a mouse has died, and if it goes somewhere that it is likely to be used by decomposers that are decaying the mouse. This illustrates how when the concept of energy is used as a tool for analysis, and when students are given rules to apply, students are able to begin tracing energy and generating worthwhile unanswered questions about a process. We think that this type of reasoning is both an achievable goal and a useful way for student learning to progress.

2. Identifying forms of energy in living systems

Principles such as conservation of energy are useless if students cannot correctly identify the forms of energy in a process (Lee & Liu, 2010). Yet many researchers have documented students' non-scientific associations with energy (Nordine, et al., 2011; Watts, 1983; Trumper, 1990) that include energy as human-related, depository, activity-related, as an ingredient, product, function or fluid-like substance. As we have documented in our research (Jin & Anderson, 2012), living systems are specifically challenging because students make powerful and incorrect associations between energy and cause, vitality, or growth. For example, students answering the question about a mouse dying often include sleep and exercise as sources of energy for a living mouse, and we commonly talk about energy in similar colloquial ways in our own lives ("my energy is dragging so I'll get more caffeine"). Thus, instruction must help students distinguish between their many colloquial conceptions of energy and a scientific view of how energy is manifested only in specific forms.

In our instruction, we address these problems by making several simplifications. These simplifications include 1) limiting our discussion of energy to specific forms of energy, 2) describing chemical energy as something that can be stored in C-C and C-H bonds, 3) defining "heat" and "work/motion" as forms of energy, and 4) simplifying the second Law of Thermodynamics.

1. First, we limit our treatment of energy to four specific types of energy: chemical energy, light energy, work or motion energy, and heat energy (ignoring gravitational and other forms of energy), each of which is simplified in some way. We limit the discussion of energy to these four forms as students trace energy through carbon-transforming processes.
2. Second, we describe chemical energy as "stored" in high-energy molecules with C-C and C-H bonds and "released" when these molecules are oxidized and those bonds are replaced with lower-energy C-O and H-O bonds. In doing this we follow common practice in biogeochemistry, acknowledging the critical role of oxygen in transforming chemical energy while recognizing that in the Earth's atmosphere organic materials are usually the limiting reactant. Thus substances in equilibrium with the atmosphere do not have available chemical energy, while substances out of equilibrium with the atmosphere, including organic substances, have available chemical energy. The amount of energy available from a particular substance is equal to its heat of combustion—a more complicated measure of energy than we can use with students who have not studied chemistry. However, counting the number of reduced carbon and hydrogen (C-C and C-H) bonds in an organic molecule provides a reasonable approximation of amount of energy available from its oxidation.

3. We also use simplified ideas of work, kinetic energy, and heat. We conflate work and motion energy; we do not distinguish between work as a process of energy transfer and kinetic energy. In the same vein, we do not clearly define "work," using the word to designate a suite of complex metabolic processes involving transport and biosynthesis as well as organismal motion. For heat energy, we do not distinguish between heat as an energy transfer process and thermal energy, or between "heat energy" and infrared electromagnetic radiation into space.
4. As described above, we simplify the Second Law of Thermodynamics by describing waste heat as a product of carbon-transforming processes without mentioning entropy.

With the help of these simplifications, students can trace energy through all carbon-transforming processes we study, using energy labels for twist ties that are limited to the four forms of energy identified above. We feel that the benefits of this approach exceed the costs. In particular, students can learn to avoid the multitude of non-scientific meanings for energy that they bring from their everyday discourse, and they can begin to trace energy through carbon-transforming processes in a rigorous way. We can see this in the example of "Student B" in Table 2 where the student identifies light energy as the source of energy for the tree, and then eventually reasons, with some assistance, that the sunlight energy can be traced to chemical energy in the bonds of the molecules that make up the tree. Because the student was limited to notions of energy (light, heat, motion and chemical energy), tracing energy through transformations becomes easier to deduce.

3. Tracing Energy Separately from Matter

To use energy successfully as a tool for analysis, students must learn to treat energy as an enduring entity and to trace energy through transformations in living systems. Our research suggests that current instructional practices enable very few students (less than 3%) to achieve this practice consistently in their accounts of carbon-transforming processes (Jin & Anderson, 2012). As described previously, less advanced students trace sequences of cause and effect rather than attempting to trace energy as an enduring entity or are unable to distinguish scientific from colloquial meanings of energy. For more advanced students who attempt to trace energy through processes, another substantial barrier remains: these students often conflate forms of matter with forms of energy (e.g., “glucose is energy;” “plants transform sunlight into food;” “the man lost weight by transforming his fat into energy when he exercised.”).

We have documented the problem of students conflating matter and energy in our previously published work (Mohan, Chen, & Anderson, 2009; Jin & Anderson, 2012), identifying it specifically with Level 3, the next-to-highest level in our learning progression. Conflation of matter and energy is particularly problematic when learning about biological systems when there are chemical changes such as cellular respiration that transform solids and liquids into gases. In these cases, students have difficulty conserving and tracing energy because they fail to conserve matter. Students who readily assert that gases have mass still have trouble believing that gases have *enough* mass to account for substantial mass changes in living systems (Mohan et al, 2009). So it is easier for students to believe that “fat is transformed into energy when a person exercises and loses weight” than that “a man who exercised and lost 20 pounds breathed out most of that mass in carbon dioxide and water vapor.” Much of our instruction aims to have students account for matter and energy as separate and enduring entities.

We have described some of the key elements of our instructional strategies for addressing student conflation of matter and energy, including the “Three Questions” framework, which requires separate tracing of matter and energy, the use of molecular models with separate representations of energy (twist ties) and labels for forms of energy. Students learn to construct accounts that trace matter and energy separately for each process through a combination of empirical investigations and direct instruction using molecular models and other representations of systems at multiple scales (e.g., atomic/molecular, cellular, organismal, and large-scale systems). Investigations are necessarily at macroscopic scale and involve observations and measurements of carbon-transforming processes (ethanol burning, mealworms growing and moving, plants in light and dark, bread molding). During investigations students can develop partial answers to the “Movement Question” by tracing mass changes in systems; to the “Carbon Question” by detecting CO_2 using probes, soda lime, or bromothymol blue as an indicator; and to the “Energy Question” by observing indicators such as movement, light, and temperature change.

The investigations do not lead to complete answers to the Energy Question because the observed indicators are insufficient to trace energy through the full process.

Following the investigations, molecular modeling exercises help students address some of their unanswered questions that arose in the investigations (where the carbon in the CO_2 came from, and where the energy was before it was transformed to heat and light). To address these, the students use molecular models to trace carbon atoms in CO_2 back to carbon atoms in fuel molecules to account for carbon atoms before and after the burning. Similarly, students use twist ties to trace heat and light energy back to chemical energy in C-C and C-H bonds in the fuel molecules to account for energy before and after the burning. One final instructional scaffold is the "Matter and Energy Process Tool" (Figure 3), which students use to construct accounts that answer all "Three Questions."

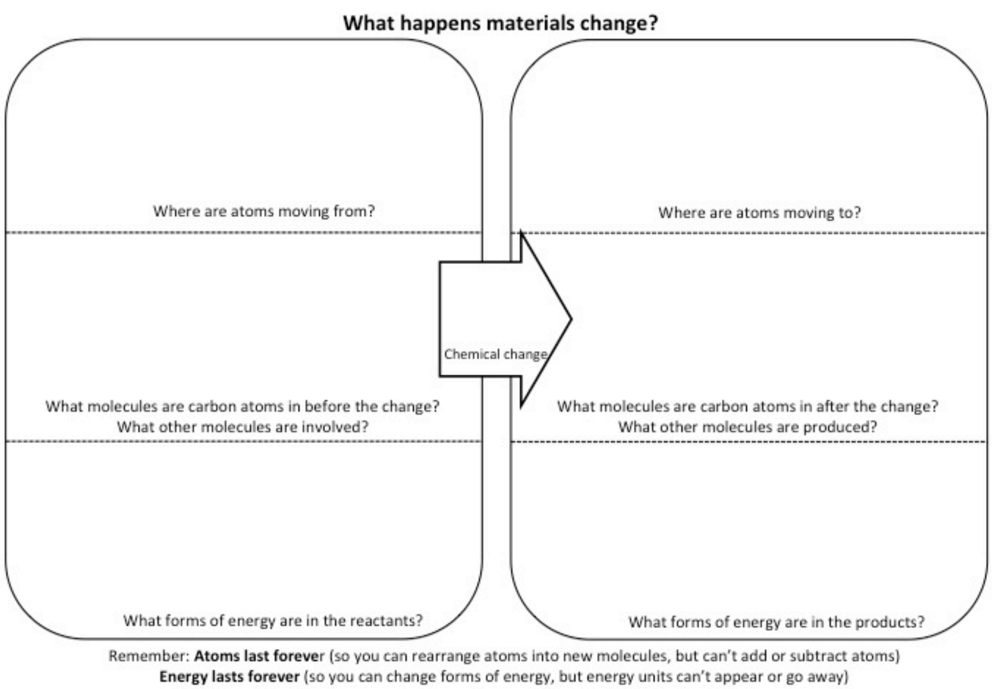

Figure 3: Matter and Energy Process Tool

The process tool is continually revisited by the students, starting with recording initial ideas on sticky-notes of a process tool poster. Then students write their answers to the "Three Questions" on the process tool after the investigation, then again after molecular modeling exercises. By the end of the instruction the students have developed an account of a carbon-transforming process that traces matter and energy separately through the chemical change.

Conclusion

In our work we have developed and applied a learning progression on energy in complex systems. We have focused, in particular, on systems that rely for energy on creation and oxidation of organic compounds; this includes all living systems and human technological systems relying on biomass or fossil fuels—more than 90% of current human energy use worldwide. We have identified the three central goals for student learning around which this paper is organized: Students should (1) understand that a primary purpose of energy-based explanations is to identify constraints on systems, (2) identify forms of energy in complex systems, and (3) trace energy separately from matter. These are important goals for all complex systems. Our learning progression research reveals that students can gain access to the power of energy as an analytical tool in these systems only if we deal directly with their associations of energy with cause, need, and vitality, and if we help them to develop a sense of necessity—a commitment to the principle that all systems are inevitably constrained by the laws of thermodynamics. We argue that studying energy in simplified physical systems such as pendulums and roller coasters is neither necessary nor sufficient to accomplish these goals.

In our work we have developed a set scaffolds and simplifications to make these core insights and practices accessible to middle school and high school students. At the core of these supports are the Three Questions (Table 2) focusing on movement and transformation of matter and energy in complex systems. We teach students didactically that a good explanation of matter and energy transformation in these complex systems must answer each question in ways that satisfy "Rules to Follow" (Column 2 of Table 2, essentially the conservation laws) and "Connect Atoms with Evidence" (Column 3 of Table 2, identifying key indicators for forms of energy and chemical changes). This didactic framework is accompanied by specific simplified models focusing on forms of energy and by quasi-quantitative ways of accounting for "energy units."

We argue that these scaffolds and simplifications in instruction will make it easier for students to develop a sense of necessity about conservation of matter and energy and will also facilitate an understanding of carbon-transforming processes that is both practical (i.e, students can use their understanding for meaningful inquiry and application) and productive (i.e., it prepares students to learn more sophisticated models in the future). When students succeed in using these strategies to analyze familiar systems and events, then we feel they will have made substantial progress toward our overall goal: to uncover the chemical basis of biological and socio-ecological systems. Developing this productive and practical scientific discourse of matter and energy in socio-ecological systems is an important piece of learning to act as informed citizens around issues that involve carbon cycling and its role in climate change.

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