Developing a K-12 Learning Progression for Carbon Cycling in Socio-Ecological Systems

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Presented at the Knowledge Sharing Institute of the Center for Curriculum Studies in Science
Washington, D. C., July 22-5, 2007

The authors would like to thank several people for their invaluable contributions to the work presented in this paper. We would like to thank Yong-Sang Lee at the University of California, Berkeley for his assistance in the data analysis process. We also acknowledge the contributions made by Hui Jin, Hsin-Yuan Chen, and Chris Wilson from Michigan State University and Karen Draney, Mark Wilson, and Jinnie Choi, at the University of California, Berkeley in developing the framework that guided our research.

This paper is in fact an evolving document that has been presented in various forms at prior conference proceedings, including the annual meeting of National Association of Research in Science Teaching in 2006 and the annual meeting of the Ecological Society of America in 2005.

This research is supported in part by three grants from the National Science Foundation: Developing a research-based learning progression for the role of carbon in environmental systems (REC 0529636), the Center for Curriculum Materials in Science (ESI-0227557) and Long-term Ecological Research in Row-crop Agriculture (DEB 0423627. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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Abstract

We used assessment data from elementary, middle, and high school students to develop potential upper and lower anchors for a carbon cycle learning progression and to describe intermediate stages between those two anchor points. An upper anchor understanding of carbon cycling is characterized by principled reasoning about processes related to the generation, transformation, and oxidization of carbon in systems (e.g., commitment to tracing matter through processes such as photosynthesis, combustion, and cellular respiration). Students at this level reason about biogeochemical processes across multiple scales and identify and consistently trace carbon and other elements in and out of various living and non-living systems. Students at the lower anchor explain processes such as growth, decay, and burning primarily through narratives of events at the macroscopic scale, showing little awareness of hidden mechanisms and little inclination to trace materials through processes. At intermediate levels, students' attempts to trace matter are often frustrated by their incomplete understanding of chemical identities of substances (particularly gases) and confusion about forms of matter and energy. Few students showed an understanding sufficient to account for mechanisms of environmental change, including global climate change. Implications of using the proposed carbon cycle learning progression to develop assessment items and curricula are discussed.

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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)" (NRC, 2007). They are anchored on one end by what we know about reasoning of students on specific concepts entering school (i.e., lower anchors). On the other end, learning progressions are anchored by societal expectations (e.g., science standards) about what we want high school students to understand about science (i.e., upper anchors).

Our goal in this research is to develop a learning progression for students taking required science courses from upper elementary through high school, focusing on the role of carbon in socio-ecological systems. We begin with a justification of the scientific and social importance of this topic. We explain the key elements of an understanding of the topic that would support responsible decision-making by citizens (the upper anchor of the learning progression). We present results from assessments that suggest levels and trends in student understanding. Finally we discuss implications of this work for standards, assessment, and curriculum development.

Introduction: Changing Scientific Understanding of Socio-ecological Systems

The term *socio-ecological systems* comes from the Strategic Research Plan of the Long Term Environmental Research Network (LTER Planning Committee, 2007). It reflects the understanding of these scientists that cutting-edge ecological research can no longer be conducted without considering the interactions between ecosystems and the human communities that occupy and manage them.

The global climate is changing and with this change comes increasing awareness that the actions of human populations are altering processes that occur in natural ecosystems. The "carbon cycle" is no longer a cycle, on either local or global scales; most environmental systems—especially those altered by humans—are net producers or net consumers of organic carbon. Humans have altered the global system so that there is now a net flow of carbon from forests and fossil fuels to atmospheric carbon dioxide. Thus previous beliefs in the "balance of nature" and the basic stability of earth systems have been replaced by an understanding of environmental systems as dynamic in nature and changing in ways that human populations need to understand (see, for example, Weart, 2003). Recent evidence has confirmed that humans are influencing the ecological carbon cycle in unprecedented ways:

- Global climate change is happening, caused by rapidly increasingly atmospheric carbon dioxide levels, with inevitable consequences for sea levels, frequency and severity of storms, natural ecosystems, and human agriculture. (Keeling & Whorf, 2005).
- Up to 40% of net photosynthetic output of terrestrial ecosystems is now appropriated for human use (Vitousek, Ehrlich, Ehrlich, & Matson, 1986)

These changes are caused by the individual and collective actions of humans. In a democratic society like the United States, human actions will change only with the consent and active participation of our citizens. These circumstances put a special burden on science educators. We must try to develop education systems that will prepare all of our citizens to participate knowledgeably and responsibly in the decision-making process about environmental systems.

We have chosen carbon as the focus of our research because carbon-transforming processes are uniquely important in the global environment and understanding those processes is essential for citizens' participation in environmental decision-making. In this study, we explore students' explanations about matter transformations during biogeochemical processes and the systems in which these processes occur. We aim to develop a K-12 carbon cycle learning progression that describes sequences students may follow as they develop increasingly sophisticated understanding of carbon cycling.

Environmental Science Literacy

Understanding the ecological carbon cycle is critical to our view of *environmental science literacy*—the capacity to understand and participate in evidence-based discussions about complex socio-ecological systems. Environmental science literate citizens need to understand relationships between seemingly disparate events such as how sea ice available to polar bears in the Arctic is connected to processes inside leaf cells in the Amazon rain forest and to Americans driving their cars to work.

Traditional science curricula obscure rather than reveal these connections. The sea ice in the Arctic might be analyzed in an earth science course as part of a weather and climate system. The leaf cells of Amazon plants might be analyzed in a life science course as part of a hierarchy of biological systems. Cars burning gasoline might be discussed in a physics or chemistry course. Students do not learn to see the key processes that tie systems together—in this case the production and consumption of carbon dioxide and its effect on global climate.

The biogeochemical processes of ecological carbon cycling are currently addressed by state and national science standards and included in most science curricula. Yet, the standards documents underplay the interconnectedness of human and natural systems and the interdisciplinary nature of scientific research.

We have tried to define an upper anchor—environmental science literacy—that is achievable by high school students, but that includes awareness of key connections and the knowledge needed for responsible citizenship. Our definition includes three essential features of environmental science literacy:

1. *Roles and practices*- the numerous public and private roles that citizens play and three critical practices of environmentally literate citizens.
2. *Processes in socio-ecological systems*- the key carbon-transforming processes that connect human and natural systems.
3. *Fundamental principles*- the scientific principles that govern biogeochemical processes and can be used as intellectual resources to understand carbon cycling.

Roles and practices

Within complex socio-ecological systems, citizens are positioned in a number of roles with potential to influence environmental systems. These roles may include private roles, such as consumers, workers, and learners, of which decisions contribute to the collective action of a larger community over time. Citizens may also play public roles such as voters, advocates, and volunteers, which have potential to influence public policies. In each of these roles, citizens make decisions that have consequences on environmental systems and the movement of carbon in those systems.

When making decisions, citizens can potentially consider a complex set of factors that guide their decision-making. Citizens may consider personal or community economics, environmental impact, cultural value (e.g., patriotism, aesthetics, popular media), etc. It is our hope that citizens will see that scientific reasoning is yet another resource that can assist in making decisions. Environmental science literacy includes both understanding the science of socio-ecological systems and recognizing the impacts humans have on these systems in the various roles they play. Citizens who use scientific knowledge as a resource in the various roles that they play will engage in three key practices of environmental science literacy:

1. *Inquiry:* learning from experience, developing and evaluating arguments from evidence.
2. *Scientific accounts:* understanding and producing model-based accounts of environmental systems; using scientific accounts to explain and predict observations
3. *Citizenship*: using scientific reasoning for responsible citizenship

This report focuses specifically on the second practice: using scientific accounts of carbon cycling to explain carbon-transforming processes. Refer to, Tsuruski, Covitt, and Anderson (2007) for a detailed explanation of citizenship practices.

Processes in socio-ecological systems

In order to use science during the decision-making process, citizens must account for the key carbon-transforming processes that connect systems together. Figure 1 is a Loop Diagram[1] that represents what we see as necessary for citizens to make these connections.

The key elements of Figure 1 are two boxes—environmental systems and human social and economic systems—and two large arrows connecting the boxes—human impact and environmental system services. While we advocate that the school curriculum should include both boxes and both arrows, in this report we focus primarily on the part of the loop that is included in the current science curriculum: the environmental systems box.

Figure 1 emphasizes carbon-transforming processes in *environmental systems*. Our key biogeochemical processes include those that *generate organic carbon* through photosynthesis, those that *transform organic carbon* within and between organisms, and those that *oxidize organic carbon* through cellular respiration and combustion. Because these processes are the means by which living and human systems acquire energy and the means by which environmental systems regulate levels of atmospheric CO_2, we have used these processes to describe the environmental systems in which live.

Carbon compounds are equally important to *human systems* because we depend on biomass and fossil fuels for most of our food, energy, transportation, and shelter. The primary product of our activities—carbon dioxide—regulates global temperatures, atmospheric circulation, and precipitation. Thus an understanding of the many processes that transform carbon compounds is central to understanding environmental processes and the human systems that depend on them.

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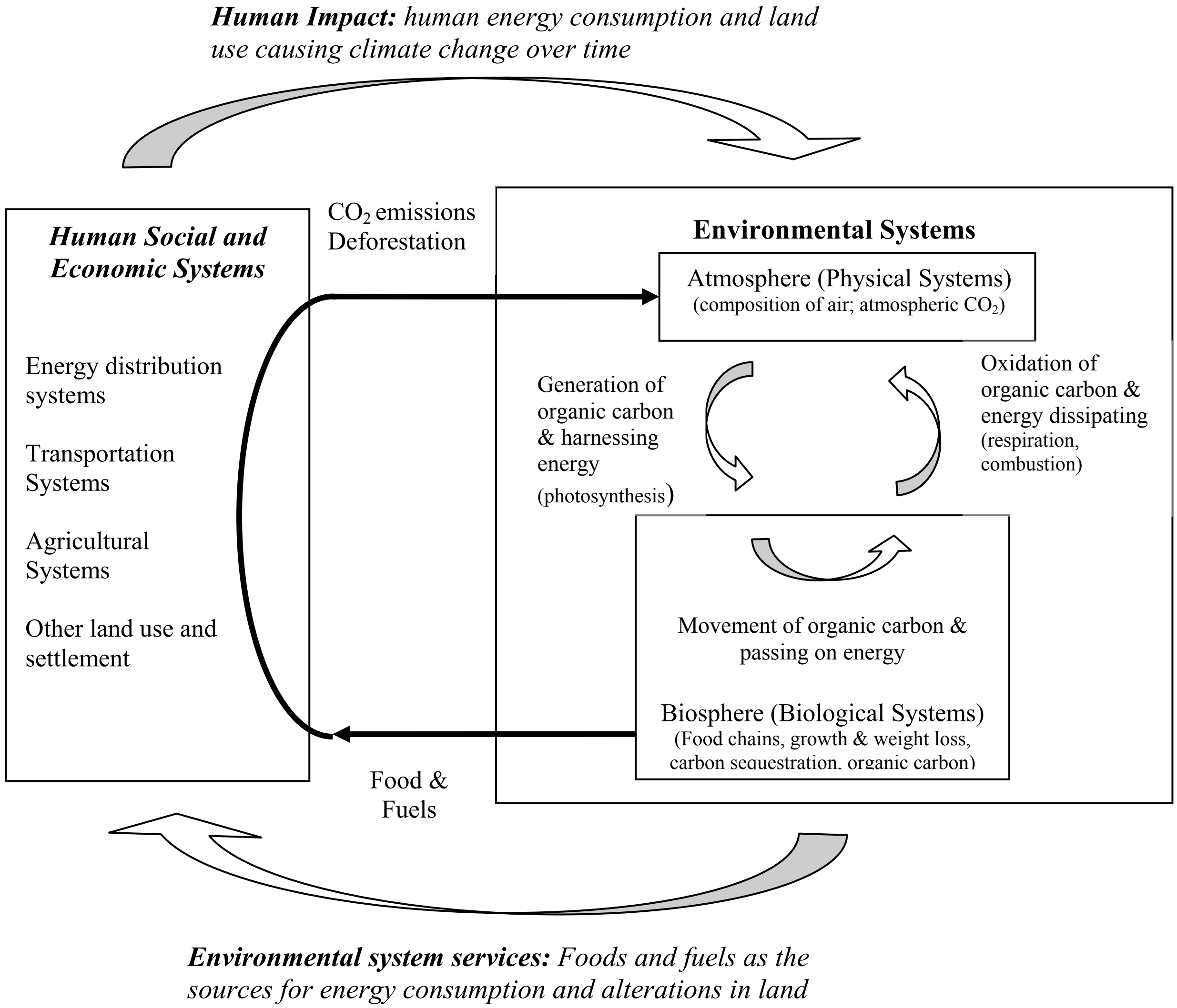
[1] Figure 1 is based on a diagram from the LTER strategic plan (LTER Network, 2007, page 11) describing the structure and function of socio-ecological systems.

Figure 1: Loop diagram for carbon cycling in socio-ecological systems



Note: See Table 1 for an elaboration of the *environmental systems* box

Table 1 further elaborates the domain for our study. The table is organized around the three[2] *Processes in socio-ecological systems* and the three *Fundamental principles* that can constrain reasoning about those processes.

[2] Note that the four columns of Table 1 separate two chemically similar processes—cellular respiration and combustion—involving the oxidation of organic compounds.

Table 1: Domain for carbon

DOMAIN for CARBON				
SYSTEMS	**Living Systems**			**Human Engineered Systems**
PROCESSES in socio-ecological systems	**Generation** Photosynthesis (plant growth, primary production)	**Transformation** Biosynthesis, digestion, food chains, accumulation & sequestration of organic carbon	**Oxidation** Cellular respiration (weight loss, decomposition)	**Oxidation** Combustion of biomass and fossil fuels (global warming, human transportation and energy systems)
Fundamental Principles				
Tracing Matter	Molecular structure of energy-rich biomolecules (organic matter) and CO_2, metabolic processes in single & multi-cellular organisms, cells & organelles, food chains/webs and trophic levels, matter pools & source of carbon fluxes, quantity of carbon fluxes, composition of air and atmospheric CO_2 levels, carbon sequestration			Composition of energy resources & sources (fossil fuels) and composition of air, reactants and products of combustion, energy users & deliverers; engineered fossil fuel systems; transportation systems, quantity of carbon emissions, atmospheric CO_2, air quality
Tracing Energy	Harnessing light energy through photosynthesis, passing on energy in food chains and acquiring energy during digestion (chemical potential energy), energy dissipation (heat); energy-rich materials (foods); quantities of energy consumption			Acquiring energy during combustion (chemical potential energy) and energy dissipation (heat); energy-rich materials (fuels); quantities of energy consumption
Change Over Time	Succession, deforestation, reforestation, agriculture, land use, carbon pools and fluxes			Formation of fossil fuels, industrialization, atmospheric CO_2 levels, carbon emissions & footprints

In this paper we focus on traditional science content: systems, processes, and principles in the Environmental Systems box of Figure 1 that are included in the current national standards (refs). We are investigating, though, how students might develop an understanding of those systems, processes, and principles that would enable them to “connect the Environmental Systems box to the arrows”—to analyze how humans depend on and affect environmental systems.

Fundamental principles

We have identified three fundamental scientific principles that can guide, or be used as constraints, when reasoning about biogeochemical processes and the changes associated with them.

1. *Tracing matter through processes*- this principle uses conservation of matter as a tool in explaining chemical change, both in amount (quantitative conservation of mass) and by identifying the materials or substances—or atoms and molecules—involved in chemical

changes. This principle can be used to guide explanations about what happens to the materials (or "stuff") in environmental systems.

2. *Tracing energy through processes*- this principle uses the conservation of energy as a tool for explaining what drives chemical changes to occur. This principle can be used to guide explanations about *how and why* materials move into and out of systems. Our findings about tracing energy are reported in a separate paper (Jin & Anderson, 2007).
3. *Change over time*- this principle uses both conservation of matter and energy as tools for explaining large-scale, unidirectional change, both regionally and globally, when pressures on systems alter the structure and functions of those systems. In particular, global warming results from an imbalance between processes that generate and processes that oxidize organic carbon.

This report focuses primarily on the first and third principles: *tracing matter* and *change over time.* There is abundant evidence from previous research that most people have difficult applying these principles. A video widely circulated by the Private Universe project shows Harvard and MIT graduates failing to understand that the mass of a tree comes largely from carbon dioxide in the air. Andersson and Wallin (2000) found that many Swedish students confused global warming with ozone depletion. In our own research at the college level, we found that most prospective science teachers—senior biology majors—said that when people lose weight their fat is "burned up" or "used for energy"—even when we offered a better option (the mass leaves the body as carbon dioxide and water). Other studies (e.g., Anderson, Sheldon, & Dubay, 1990; Fisher, et al., 1984; Songer &, Mintzes, 1994; Zoller, 1990) document troubling gaps in adults' understandings of carbon-transforming processes, but they do not address the implications for these limited understandings.

Frameworks and Methods

Data Sources

Our primary data source consisted of 887 paper-and-pencil assessments administered to students taking required science courses in Grades 4-10 during the 2005-06 and 2006-07 school years. The students were taught by 10 different teachers in several rural and suburban Michigan school districts.

The assessments contained items about carbon-transforming processes (see Appendix A for a sample of items). The items were developed during the three-year period using an iterative process of administering assessment items to students and then revising based on the quality of responses we received. The assessments varied in length depending on age level, but typically included 12 or more open-ended questions. In some cases teachers administered "pre" and "post" assessments to their students and used materials that we designed. When given the option, we used post-assessments since the goal of our study was to document the range of responses from students, hoping that post-assessments might provide more sophisticated explanations compared to pre-assessments.

Data Analysis

Our analyses focused on *tracing matter through processes*, in which we further elaborate on the *intermediate* understandings between the upper and lower anchor points of our learning progression with respect to matter. Refer to Jin and Anderson (2007) for a description of *tracing* *energy through processes*. Data analysis was a multi-step process described in more detail by Draney and Wilson (2007).

1. Initial sorting of responses. A small sample of responses (20 to 30) was chosen for selected items representing different processes. These responses were transcribed onto spreadsheets and sorted in terms of quality and other key characteristics. This sorting of responses led to initial identification of key principles, including tracing matter and possible levels of student achievement.

2. Development of exemplar workbooks. Before analyzing the entirety of our data, we initially focused on developing an *exemplar workbook*. The exemplar workbook was a tool we used in order to distinguish between qualitatively different types of student responses, which were grouped and then rank-ordered from least to most sophisticated. One or two student responses were chosen as a representative example of each group of similar-type responses. We used these groups, or patterns of responses, to suggest initial tracing matter levels. As we continued this process, we furthered refined our exemplar workbook and revised our tracing matter levels as we encountered new data or adjusted the organization of our framework. The exemplar workbook and matter levels developed simultaneously.

3. Refinement of levels and reliability checks. The initial exemplar workbooks were used by multiple researchers to score the same samples of responses. Disagreements were discussed and descriptions of student achievement levels were refined.

4. Analysis of a larger sample of responses. In first choosing our data from the pool of data available to us, we first selected 14 assessment items that we felt would illuminate students' explanations about matter during generation, transformation, and oxidation processes. We then selected classes of students in which those items were administered. Whenever possible, we chose to use data during the most recent administration (i.e., 2006-07 school year), however, there are a few instances where data from the previous school year was needed. For items that were administered to all three age groups, elementary, middle, and high, we selected 20 student responses from each group, choosing students responses randomly except for eliminating those that were illegible. In some cases items were only administered to one or two age levels, so the number of responses from each age level was adjusted to have at least 60 responses for the item. Once responses were selected, they were then transcribed into an excel workbook for scoring.

Thus, we have three products that emerge from this analysis: 1) tracing matter levels that describe lower and upper anchors points and the intermediate stages of our learning progression, 2) an exemplar workbook that contains example responses for each item corresponding to each level, and 3) an analysis of 14 assessment items using our current tracing matter levels.

Results

Tracing Matter Levels.

The *Tracing Matter* levels developed over the previous year and have been revised a number of times, based on our theoretical understanding of carbon cycling and the empirical data we received through our assessments. Table 2 presents an abbreviated summary of our current matter levels (see Appendix B for a detailed version of the level descriptions used for scoring items).

Our upper anchor reasoning (described in Figure 1 and Table 1) involves connecting large-scale processes (e.g., global carbon fluxes, ecological carbon cycling) with atomic-molecular processes (e.g., photosynthesis, biosynthesis, digestion, fossil fuel formation, combustion, cellular respiration). Younger students, though, have little awareness of these processes. Therefore, our assessment questions focused largely on events at the macroscopic or human scale that are manifestations of large scale and atomic-molecular processes. These macroscopic processes include:

- *Organic carbon generating processes:* Plant growth, plant needs for sunlight, air, water, and soil minerals.
- *Organic carbon transforming processes:* Digestion, animal growth, food chains
- *Organic carbon oxidizing processes:* Weight loss in animals, breathing, burning of wood and gasoline

Our research indicates that explaining these macroscopic events with their atomic-molecular mechanisms and connecting them to processes in large-scale systems is a major intellectual accomplishment, requiring learners to develop knowledge and practice in several different domains. We describe learners in terms of five levels of achievement, summarized in Table 2, below.

Table 2: Summary of Tracing Matter Levels

Level	Accomplishments	Limitations
Level 5: Qualitative model-based accounts	Model-based accounts of all carbon transforming processes. Ability to understand and use information about chemical composition of organic substances. Clear accounting for role of gases in carbon-transforming processes.	Difficulty with quantitative reasoning that connects atomic-molecular with macroscopic and large-scale processes (e.g., stoichiometry, global carbon fluxes). Difficulty with quantitative reasoning about risk and probability.
Level 4: "School science" narratives about processes	Stories of events at atomic-molecular, macroscopic, and large scales. Gases clearly identified as forms of matter and reactants or products in carbon-transforming processes. Some knowledge of chemical identities of substances.	Mass of gases not consistently recognized. Incomplete understanding of chemical identities of substances and atomic-molecular models of chemical change leads to impossible accounts of what happens to matter in photosynthesis, combustion, cellular respiration (e.g., matter-energy conversions).
Level 3: Causal sequences of events with hidden mechanisms	Stories involving hidden mechanisms (e.g., body organs). Recognition of events at microscopic scale. Descriptions of properties of solid and liquid materials. Tracing matter through most physical changes Coherent stories of food chains.	Matter (especially gases) not clearly distinguished from conditions or forms of energy. O_2-CO_2 cycle separate from other events of carbon cycle (e.g., plant and animal growth, decay, food chains). Macroscopic events (e.g., growth, breathing) are associated with specific organs (e.g., stomach, lungs) rather than cellular processes.
Level 2: Event-based narratives about materials	Coherent stories that focus on causation outside of human agency (e.g., needs of plants and animals). Clear distinctions between objects and the materials of which they are made. Tracing matter through simple physical changes (e.g., pouring, flattening a ball of clay)	Focus on reasons or causes for events rather than mechanisms (e.g., "the wood burns because a spark lit it"). Vitalistic explanations for events involving plants and animals (e.g., "the tree needs sunlight to live and grow"). Carbon-transforming events are not seen as

		changes in matter.
Level 1: Human-based narratives	Coherent stories about macroscopic events such as plant and animal growth, eating, and burning. Naming objects and materials	Focus on human agency and human analogies in stories and explanations. For example, plants and animals are classified by relationship to humans (pets, flowers, weeds) and given human needs and emotions. Human causes of events are emphasized (e.g., "The match burns because you strike it.")

Note: Our Tracing Matter levels include a level 6 (quantified model-based accounts) and level 7 (quantified uncertainty) that are addressed in the discussion but excluded here since our analysis of responses was focused on levels 1-5.

The trends and levels in Table 2 are discussed in detail below. For now, we will note that Level 5 reasoning is the culmination of long learning processes about *structure of systems* and *tracing matter.*

- *Structure of systems:* Younger learners perceive a world where events occur at a macroscopic scale and plants and animals work by different rules from inanimate objects. Gases are ephemeral, more like conditions or forms of energy such as heat and light than like "real matter"—solids and liquids. Level 5 learners perceive a world of hierarchically organized systems that connect organisms and inanimate matter at both atomic molecular and large scales. Solids, liquids, and gases are all mixtures of substances made of atoms, with chemical identities, and clearly distinguished from conditions and forms of energy.
- *Tracing matter:* Younger learners live in a world of events that are caused by triggering events (e.g., striking a match) or conditions (e.g., a person being hungry). They lack the intellectual resources to figure out where the matter in these events comes from and goes to. Level 5 learners recognize conservation of matter, including conservation of atoms in chemical change, as a key constraint on all processes and seek to understand carbon-transforming processes in chemical terms.

We used our emerging levels and exemplar workbook to score 14 items in our data pool. The analyses of these items are presented in multiple "clusters" of items corresponding to our key processes (i.e., generation, transformation, oxidation in living systems, and oxidation in human-engineered systems). Several items were analyzed according to more than one process because the item specifically addressed two processes or because student responses to an item focused on one process when the item was intended for another process (e.g., students focused on photosynthesis rather than biosynthesis when explaining tree growth). For our purpose we included items in multiple clusters.

Generation of organic carbon: Photosynthesis.

Photosynthesis is the process by which producers generate organic carbon (i.e., energy-rich materials) for all living organisms to use. We asked students to respond to multiple items about metabolic processes in plants, at the organismal and large-scale levels (see Appendix B for complete items). Refer to Table 3 for exemplar responses to each *generation* item and Figure 2 for the distributions of student responses with respect to our tracing matter levels.

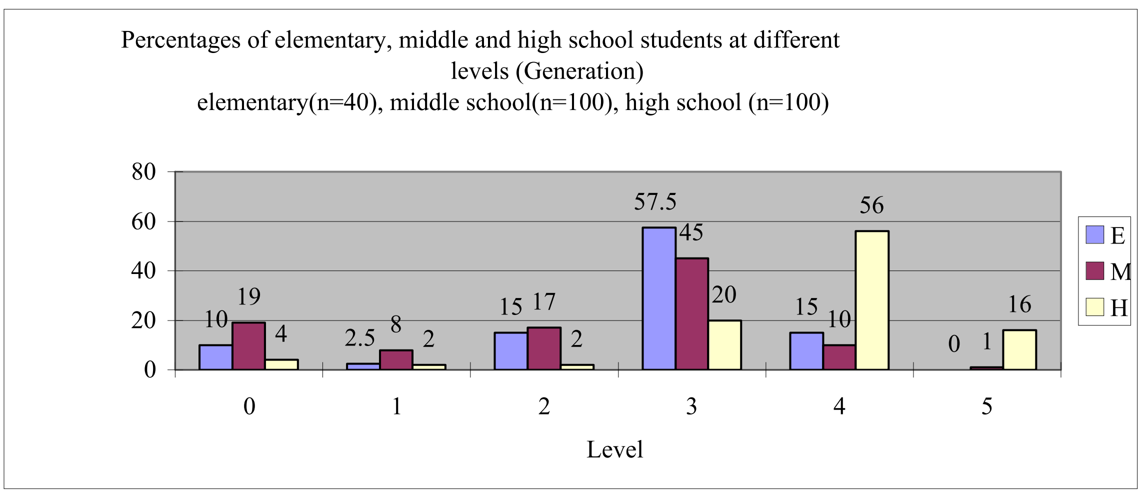
Level 1 and 2 students tend to focus on the life and growth of plants as similar to that of humans or as a natural process that just happens. They explained plant growth by analogy to humans or by referring to parts of plants. For these students tracing matter is not a way to explain how plants live and grow.

When explaining how an acorn grows into a tree, Level 3 students named several materials that the plant needs to grow (e.g., water, air, minerals, etc). Level 3 is also characterized by the inclusion of "sunlight" as "stuff" that plants take inside them. These students have mastered the use of the CO_2-O_2 gas cycle, so they explain that plants take in carbon dioxide and make oxygen. But level 3 students do not understand what happens to these materials or the sunlight once it gets inside the plant. In fact, most students at this level explain that water, minerals, and such are actually food for the plant, indicating they do not clearly understand photosynthesis or the materials involved in that process.

A critical shift to Level 4 happens for many high school students who account for photosynthesis at the cellular and atomic-molecular levels. In our sample over half of the high school students explained photosynthesis in this way, which included an account of the production of sugar or glucose. However, Level 4 students still fail to connect the cellular process of photosynthesis to the macroscopic process of weight gain in plants. Level 4 students explain the reactant and products of the process, but not what happens to sugar after it is made in the leaves.

Between Levels 4 and 5, an interesting transition occurs. For level 5 students, how the acorn grows into a large tree is not only a photosynthesis question, but also includes biosynthesis processes. Level 5 students indicate that plants use glucose and minerals to produce biomolecules that fulfill different functions in the plant. When Level 5 students are asked whether wood is a mixture, they immediately point to products of biosynthesis, rather than products of photosynthesis (i.e., level 4) or materials the plant takes in (i.e., level 3).

Figure 2: Distribution of student explanations for Generation (with items grouped)



Our analysis also indicates that some level 4 and 5 students (which is primarily high school students) more readily make the connections between deforestation and global climate change compared to students at level 3 or below. About 20% of our sample mentioned that carbon dioxide was a substance that might connect these two events, but only one student explicitly mentioned that deforestation would lead to less photosynthetic activity in plants. Interestingly, when asked how human actions might influence tree growth in the Amazon, only 6 of 60 high school students connected plant growth to elevated levels of carbon dioxide in the atmosphere.

Table 3: Exemplar responses for Generation

Items:	*When an acorn grows into a tree, where does the increase in weight come from?*	*What gases do plants take in and how do they use them?*	*How could cutting down trees affect our climate*	*How could human actions influence trees to grow in the Amazon?*
Level 5	The plants increase in weight comes from the CO_2 in the air. The carbon in that molecule is used to create glucose, and several polysaccharides which are used for support	Circled O_2, CO_2 and other gases. Plants take in all gases but not all of them are used. Some gases like nitrogen are excreted and released. The useful gases are then used by the plant for energy production processes such as photosynthesis and cellular respiration.(5-)	Less plants would be doing photosynthesis and more carbon dioxide would be floating around, which could make the atmosphere hotter. (5-)	None
Level 4	Choose sugar that plants make only as food for plants. The weight comes mostly from H_2O it receives which it uses in its light reactions to eventually produce glucose to provide itself with energy.	Circled CO_2 and other. They go through photosynthesis and are created into glucose (food) and oxygen (waste product).	When we cut down trees it leaves a lot of CO_2 in the atmosphere because there are less trees to take CO_2 and make O_2 with more CO_2 in the atmosphere it keeps more heat on earth which is what already is causing global warming.	There is so much CO2 in the air that trees are taking in a lot more which is causing the trees to grow.
Level 3	I think the plant's increase comes from the minerals in the soil help it increase weight	Circled CO_2 and other gases. Plants breathe in carbon dioxide and breathe out oxygen the opposite of humans.	The decrease in trees leads to a decrease in the oxygen production from plants. It changes the oxygen levels in the atmosphere, which means there are fewer gases to shield the sun's harmful rays letting more heat in causing the temperatures in our climates to rise.	I don't know, something to do with global warming
Level 2	I think its leaves. Leaves comes from trees; the weight comes from when a plant grows the weight also grows bigger	Choose CO_2. It makes it grow.	Animals need trees, they are food and shelter to most animals.	I think maybe the growth has occurred because of weather or from the way the environment is.
Level 1	Just like humans plants gain weight as they grow to protect themselves.	Choose O_2 and other. Plants need oxygen like humans to breathe.	No I can't explain their reasoning. Cutting down trees can make more sunlight because there would be less shade. So then more people could get sunburned.	Maybe the people living there planted more trees.

Note: PLANTGAS is about photosynthesis and respiration; AMAZON relates to combustion; see also WOODMIX from Table 4.

Transformation of organic carbon: Digestion, Biosynthesis, Food chains

Transformation of organic carbon is both easy and difficult for students to understand. On the one hand, students master stories about food chains at a fairly young age. On the other hand, biosynthesis and digestion appear to be more difficult for students to understand. The items we analyzed in this paper focused on the latter, but refer to the Grandma Johnson question at the end of the results for a look at how high school students handled a cellular and atomic-molecular account of a food chain. Figure 3 shows the distribution of student responses across the levels and Table 4 contains exemplar responses for each item.

The overall trend on transformation items showed that elementary and middle school students clustered around level 3, indicating they can explain hidden mechanisms and commit to tracing matter in the form of liquids and solids. We found over half of the high school students explained transformation questions at level 4 and 20% explained at level 5.

We asked students to respond to questions about what happens to food ingested by humans. At the elementary and middle school level, students responded to an item about what happens to an apple that we eat. At the high school level, we asked what happens to a glucose molecule from a grape that would allow a person to move their finger. Although the question about apple digestion could be answered at level 5, we had few students answer beyond a level 3 response. Students at level 3 give accounts of the digestive tract, so their explanations focus on the path the apple takes through the digestive organs, and not on the materials that are absorbed from the apple which are then taken to cells. Since the question about glucose from a grape was posed to high school students at an atomic-molecular level, it may have elicited more level 4 type responses. We found that almost a third of high school students gave accounts about the glucose being digested and transported to cells for cellular processes, but only one high school student connected the digestion of the glucose to cellular respiration.

Figure 3: *Distribution of student explanations for Transformation (with items grouped).*

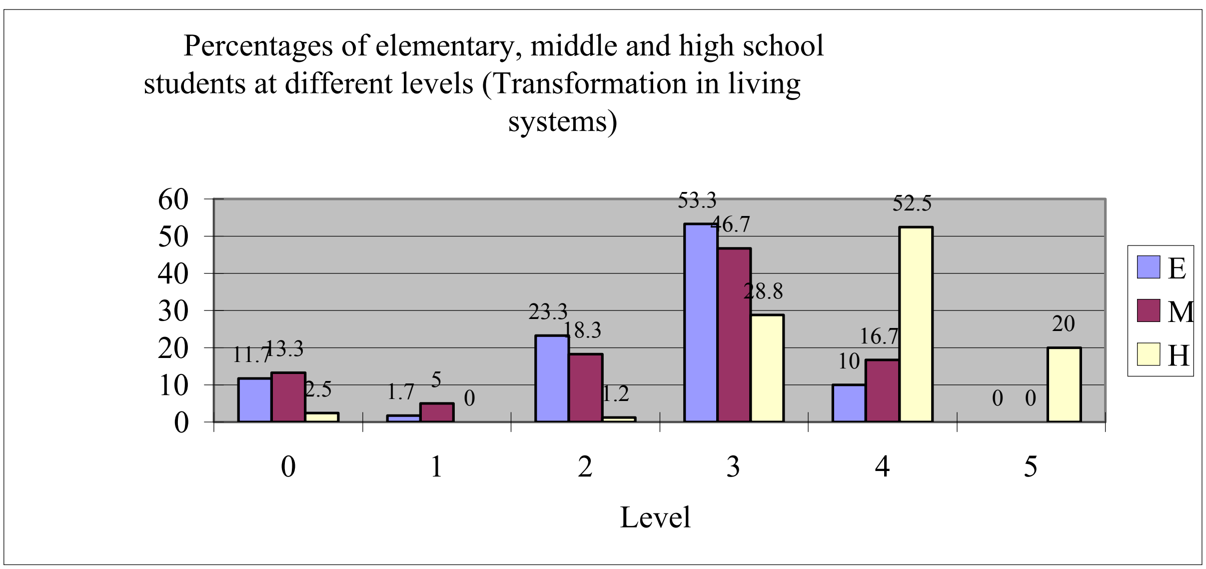


Table 4: Exemplar responses for Transformation

Items:	*Is wood a mixture? Why or why not?*	*What happens to an apple after you eat it?*	*How could a glucose molecule from a grape supply you with energy to move your finger?*
Level 5	Carbon in polysaccharide form in cellulose and lignin of the cell walls of the tree cells.	None	The grape is digested the glucose from the grape goes into the cells and reacts with oxygen called cellular respiration makes ATP, CO2, H2O. The H2O + CO2 is exhaled and the ATP is used as energy to move your finger.
Level 4	Wood is made up mostly of carbon from the air. The carbon goes through photosynthesis and is eventually converted to glucose, which makes up the mass of the wood	None	We take in glucose molecules at O2 to help with cellular respiration which is used to make energy and the energy is used to move our body and our organs and to even move our little fingers.
Level 3	Wood is made up of light, water, different minerals and carbon. Those are all the things that make it grow.	The apple first pushes its way down your esophagus into your stomach then the stuff in their (acid) makes it into like water, then the apple goes through your small intestine where all the nutrients are extracted, then next through your large intestine where all the water is extracted then final it go in your rectum fill its pushed out of your body by your sphincter.	The glucose is stored up as energy and is moved through the blood to tissues and gives the energy to move the finger.
Level 2	Yes. By bark it gets then more falls on it and it sets for a while then becomes a big piece of wood.	After you eat it you swallow it then it goes down your digestive system then in your stomach	The grape provides energy for you so you can move your hand, gives you strength.
Level 1	Because it gets put in a machines and makes it to paper and tables and other stuff.	When you bite into the apple where you bite there will be a white spot and after a while it will turn brown	None

Note: WOODMIX is also about photosynthesis

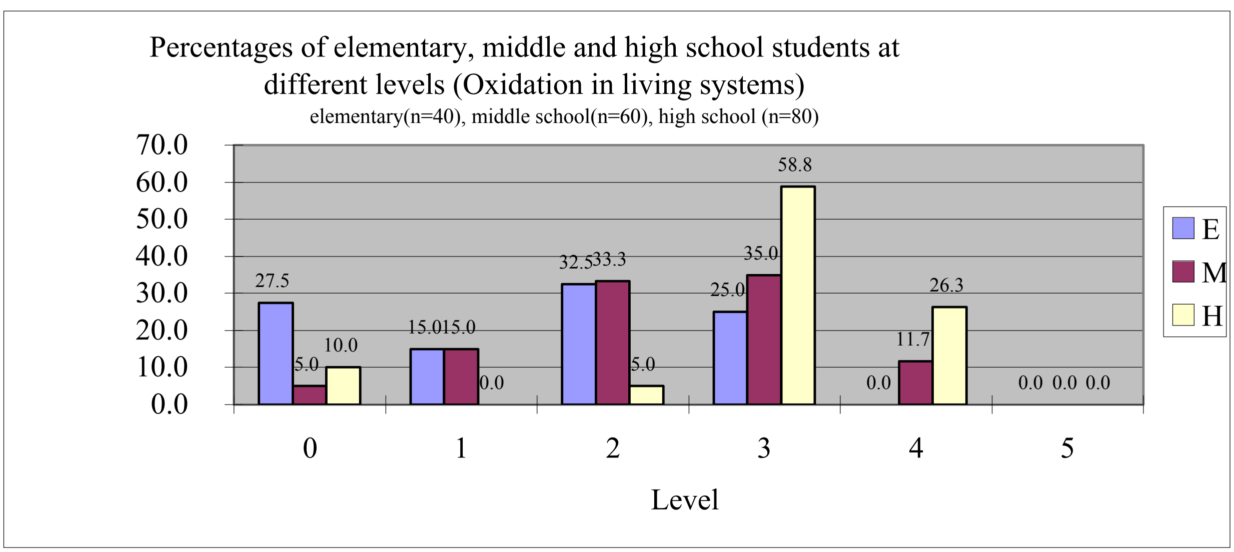
We also asked students about biosynthesis in plants. We found that most students did not recognize that plant growth happens through biosynthesis and that the substances found in plants result primarily from these processes. A majority of students across the age groups explain plant growth through photosynthesis. However, at least half of the high schools students explained that wood was made of cellulose and not glucose. Interestingly none of these students mentioned biosynthesis, and many in fact relied on photosynthesis to explain their ideas. For example, one level 5 response explained, “First of all wood is cellulose and the bark is lignin. But the substance that gives wood its mass is tightly packed CO_2” correctly identifies lignin and cellulose, however confuses these two polysaccharides with “packed CO_2” indicating that the student likely does not completely understand transformation.

Oxidation of organic carbon in living systems: Cellular respiration

Cellular respiration is the process by which all living organisms obtain energy for metabolic processes. The process is essentially the same in plants, animals, and decomposers. We asked students about respiration in these three types of living organisms. Table 5 shows exemplar responses for each item and Figure 4 shows the distribution of student responses across levels. All, but one of these items asked for students to explain a macroscopic event in which matter seemingly "disappears" (e.g., weight loss, decomposition). For this reason cellular respiration questions are arguably the most difficult type of questions for students to conserve matter (i.e., especially the gas products of this process). In general, elementary and middle school students were split between level 2 and 3, indicating that many struggle with conserving matter, which doesn't appear until level 3. High school students are much more committed to conserving matter at level 3, but do not have atomic-molecular accounts of respiration that allow them to conserve the gas products of that process.

We asked students to explain what gases plants take in from their environment, and how the plants then use the gases. This question was only asked to middle and high school students, and was intended to probe their accounts of photosynthesis and respiration. It was not surprising to find that students focused their explanations almost exclusively on photosynthesis. In fact, only 4 of 60 students mentioned respiration in their explanation and only 1 of all students appeared to understand that plants take in oxygen for this process. Before level 4, cellular respiration in plants is not recognized. At level 4, students explain that cellular respiration happens in plants, but they are unsure of the process, especially the reactants and products. By level 5 students can identify both processes in plants and the key reactants and products of each process. Interestingly, this item elicited very sophisticated accounts of photosynthesis in plants (i.e., level 5); however, these same students did not even recognize that the plant also takes in oxygen for respiration.

Figure 4: Distribution of student explanations for Oxidation in living systems



We asked students from each age group to explain what happens to matter during weight loss in humans and decomposition of an apple and a tree on the forest floor. Both types of questions require students to account for matter that was once observable and later is not using a solid-gas transformation. These types of questions appear exceptionally difficult for students in terms of conservation of matter, especially gases. For weight loss in humans, level 2 accounts allow matter, or the fat, to simply disappear and level 3 accounts focus on solid-solid or solid-liquid transformation (e.g., the fat turned to urine, feces, or sweat). Some middle and high school students explain weight loss at an atomic-molecular level focusing on carbon dioxide as an end product of this process. No students had a model-based account of weight loss.

Decomposition showed similar patterns to weight loss. Before level 3, students allow the matter to disappear. By level 3 many students identified "decomposer" or "bacteria" as hidden mechanisms for this change, yet few students identified cellular respiration with carbon dioxide the main product given off. We observed that level 3 students also attempted to use accounts of physical change, such as evaporation, to explain the changes in the apple or the dead tree. In this way, level 3 students conserved matter through a process, but they did not recognize that a chemical, rather than physical, change occurred.

Another interesting pattern that we observed occurred in the level 4 responses. While students at this level identified carbon dioxide as a product of a chemical change process, their stories about cellular respiration did not include oxygen as a reactant, nor could they explain conservation of matter in terms of the rearrangement of atoms. These are features of level 5 understanding, which we did not observe in any students for these particular items.

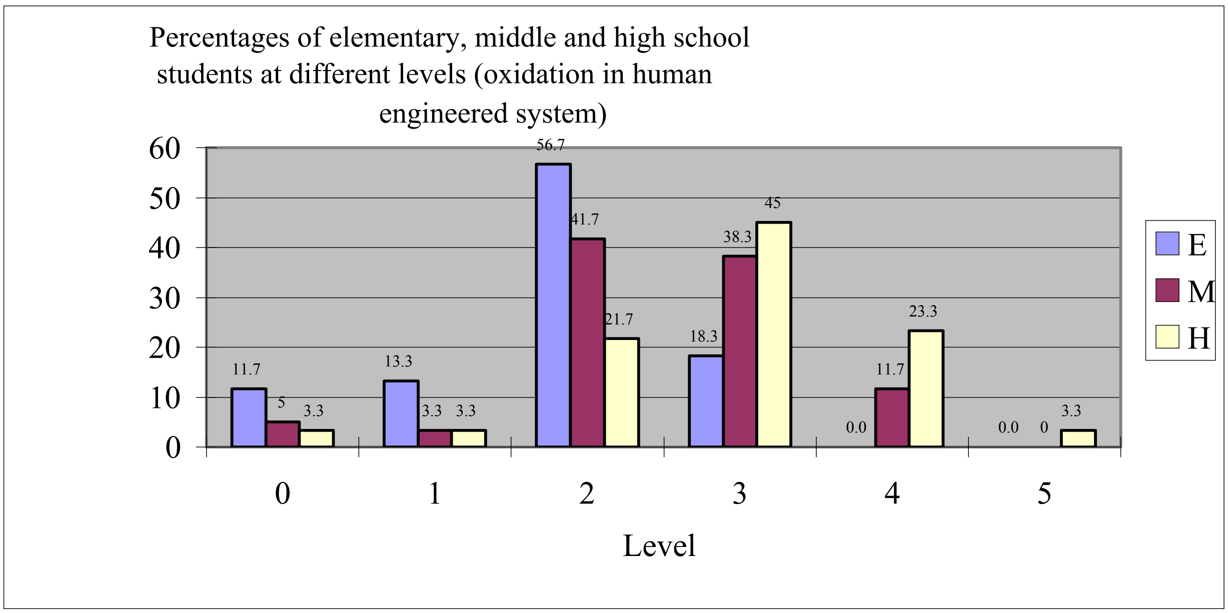
Table 5: Exemplar responses for Oxidation in living systems

Items:	*What gases do plants take in and how do they use them?*	*What causes and apple to rot? What happens to the weight as it rots?*	*A tree falls in a forest. After many years it is only a lump on the forest floor. What happened to the mass that used to be in the tree? What caused those changes and how did they happen?*	*Jared, the Subway® man, lost a lot of weight eating a low calorie diet. Where did the mass of his fat go (how was it lost)?*
Level 5	Circled O_2, CO_2 and other gases. Plants take in all gases but not all of them are used. Some gases like nitrogen are excreted and released. The useful gases are then used by the plant for energy production processes such as photosynthesis and cellular respiration.	None	None	His fat was lost when the bonds of the glucose were broken down into H_20 + CO_2 by cellular respiration. Eating fewer calories meant more fat needed to be used to give him energy
Level 4	Circled CO_2 and other. They go through photosynthesis and are created into glucose (food) and oxygen (waste product).	The apple rots because bacteria and other microscopic organisms begin to eat and pick away at the cells. Also oxidation occurs. Obviously, as the amount of matter an apple contains shrinks. Therefore weight will shrink as well.	You would find it as CO2. Cellular respiration happened as decomposition.	Jared's mass was converted into CO_2 and exhaled by him to lose weight
Level 3	Circled CO_2 and other gases. Plants breathe in carbon dioxide and breathe out oxygen the opposite of humans.	What causes the apple to rot is the bacteria in the air getting to the apple. The weight of the apple as it rots decrease mass because it's losing part of the apple to the bacteria eating it.	You would find the mass of the tree in the soil, broken down. Decomposition is what caused changes in the wood, the changes were caused by decomposers.	He lost it by digesting it and turning it to waste (poop, pee)
Level 2	Choose CO_2. It makes it grow.	It is no longer getting any nutrients to keep it alive. [The weight] goes down. The apple shrivels and loses all moisture.	Soil. The wood was changed from erosion. There are many types of erosion. The wood could have been eroded by wind, water soil, glaciers, etc.	It burns away and you can't feel it
Level 1	Choose O_2 and other. Plants need oxygen like humans to breathe.	Because it gets old like people and gets all weird and wrinkly	None	He ate less calories and worked more.

Oxidation of organic carbon in human-engineered systems: Combustion

Students' accounts of combustion are especially critical for understanding environmental problems in the carbon cycle. Our combustion of fossil fuels is cited as a major reason for rising atmospheric carbon dioxide levels. Yet similar to cellular respiration, an account of combustion requires a student to explain what happens to matter that seemingly disappears. We asked students to explain combustion of a match and gasoline and how using gasoline might affect global warming. Figure 5 shows the distribution of student responses and Table 6 provides exemplar responses for each level.

Figure 5: *Distribution of student explanations for Oxidation in human-engineered systems*



In general elementary students tended toward level 2 accounts, explaining that burning a match or gasoline means both just disappear. Middle school students were split between level 2 and 3, indicating that many students had not committed to conservation of matter. Of the middle and high school students who gave level 3 accounts, they focused primarily on tracing matter through solid-solid transformation (e.g., match turning to ash) or general matter-energy conversions (e.g., gasoline becoming energy). Students that gave level 4 accounts were able to identify carbon dioxide as a product of a chemical change, but very few students could provide accurate explanations of combustion at the atomic molecular level.

Patterns of responses appeared similar to those of respiration. The question about combustion of gasoline elicited numerous accounts of the "evaporation" of gasoline, in which students attempted to conserve matter through a physical change. These students are aware that changes in matter happen because of hidden mechanisms. Furthermore, only the few level 5 accounts recognized that oxygen was a key reactant for combustion. Prior to level 5, if students mention oxygen in their accounts of combustion, it is treated as a condition rather than as a reactant.

Table 6: Exemplar responses for Oxidation in human-engineered systems

ITEMS:	*What happens to a match when it burns?*	*When a gas tank is empty, what happens to the gasoline? What happens to the matter it is made of? Can using gasoline affect global warming?*
Level 5	None	None
Level 4	The wood of a match gets smaller; the match gets lighter because the match is getting smaller and the CO_2 is leaving.	All of the gas is sucked into the engine. The engine needs a combustible liquid or gas to push the pistons. The matter of gasoline turns into CO_2 (carbon). Yes, too much CO_2 in the air can create a thicker layer of atmosphere and when the suns rays can't escape the rays heat up the atmosphere.
Level 3	The wood burns into ash and it loses weight because it's losing mass.	It is burnt up and extracted out the exhaust into the air. The matter turns into a gas. Yes, because when the car extracts the gas as a gas into the air the gas is polluting the air and tarring the ozone layer causing more heat to come through the atmosphere.
Level 2	Because as the match burns the flame moves down the stick and burns the wood until it is gone.	The gasoline gets all burned up from the engine using it. Yes, because it puts some kind of exhaust in the air that could be harmful.
Level 1	The fire kills the wood on the match. The wood loses weight because it is burned up and dead.	None

Connecting multiple processes

We asked high school students to provide a cellular and atomic-molecular account of matter flow in a food chain. We specifically asked students to trace a carbon atom in this system through the processes of decomposition, photosynthesis, and then a food chain. Figure 6 shows the distribution of high school responses to this item and Table 7 shows the Grandma Johnson assessment item and exemplar responses for each level.

An accurate account of the system would include decomposition of Grandma Johnson with carbon dioxide being a key product. The carbon dioxide would then be taken in by the creosote bush for photosynthesis. The plant would be eaten by an herbivore, which is then eaten by the coyote. Additionally, digestion and biosynthesis in the coyote could be explained. While almost half of students recognized decomposition of Grandma Johnson, only 1 of 60 high school students identified carbon dioxide as a product. Only 3 of 60 students recognized the carbon atom would enter the plant for photosynthesis. Almost half the students constructed food chains using appropriate trophic levels. No students mentioned digestion or biosynthesis in the coyote. This item is especially difficult because it requires students to explain multiple matter transformations in multiple processes and we observed that the level of accounts for those processes break down for students in complex systems such as that of the Grandma Johnson item.

Figure 6: Distribution of student explanations for Grandma Johnson

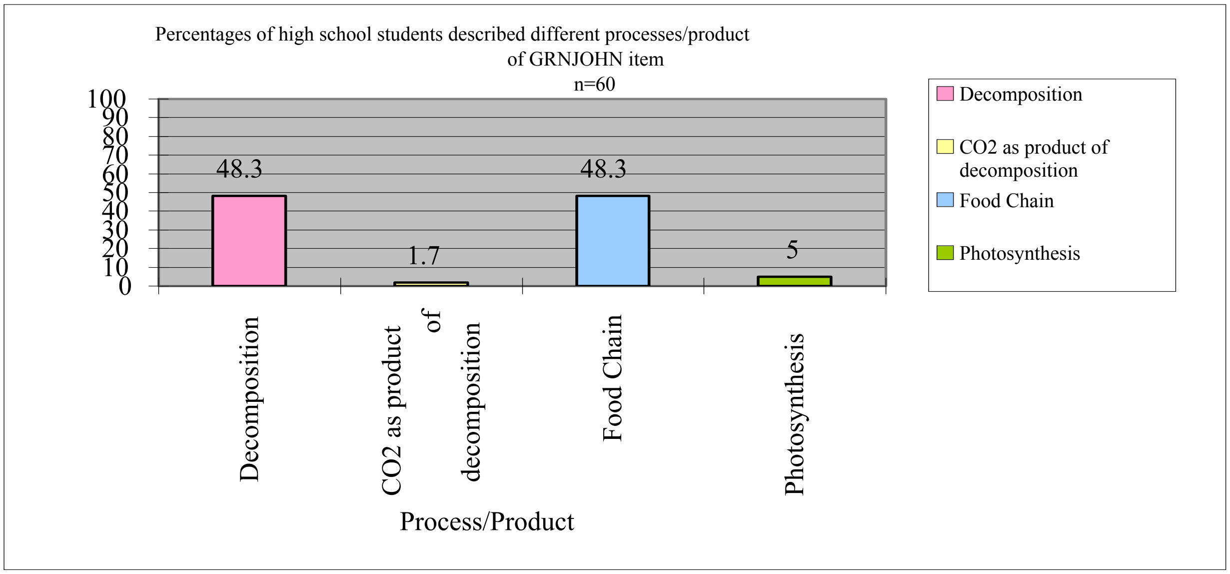


Table 7: Exemplar responses for Grandma Johnson

Item:	*Grandma Johnson had very sentimental feelings toward Johnson Canyon, Utah, where she and her late husband had honeymooned long ago. Because of these feelings, when she died she requested to be buried under a creosote bush in the canyon. Describe below the path of a carbon atom from Grandma Johnson's remains, to inside the leg muscle of a coyote. NOTE: The coyote does not dig up and consume any part of Grandma Johnson's remains.*
Level 5	Grandma Johnson's remains decay and decomposers use respiration and turn it to carbon dioxide. The plants absorb the carbon dioxide. Rodents eat the plants and then the coyote eats the rodent.
Level 4	The carbon is released from Grandma Johnson's body and travels up through the soil and is used during photosynthesis by the plant to make oxygen. A primary consumer would eat the plant some where along the food chain, the coyote receives the carbon atom.
Level 3	The carbon in grandma body is decomposed into the ground. The plants then use the fertile soil to use her carbon atoms. As the soil passes it to the plant, the plant is eventually eaten by the coyote. The carbon atom then travels to its leg.
Level 2	A carbon atom from Grandma Johnson's remains sink into the ground and mixes with the soil. Then when the soil is mixed and churned, it rises to the top of the ground. When the coyote kills something upon that dirt, he may consume it and have some of them.
Level 1	None

Discussion: General trends in our learning progression

We described five levels of achievement in the introduction to the Results section and used those levels to organize our presentation of results. We identified those levels with changes in students reasoning about We now return to a discussion of those general trends.

As students learn more about carbon-transforming processes, they acquire new "lenses" for perceiving the events that happen around them. Their explanations about those events and their settings evolve, taking on new characteristics that often replace or build upon the old ones.

Of the numerous trends that might be observed in our data and proposed levels, we would like to consider three that are most prominent:

1. *Invisible to visible- hierarchy of systems, the connections between systems*
2. *Events to Process- causality, conservation, and connections between processes*
3. *Objects to materials- recognition of mixtures, conservation of gases*

Invisible to visible.

Hierarchy of systems and scale

There are numerous components of environmental and human systems that are invisible to viewers that have not been taught to see beyond their immediate experience. For instance, young students cannot identify the subsystems or parts that things, including living and non-living things, are made of. Nor do they explain macroscopic events by placing them within larger systems. Thus Level 1 and 2 responses generally describe and explain events at the macroscopic scale (e.g., the match gets shorter [when it burns]).

Yet, as students learn more about systems and the processes that occur in those systems, their explanations suggest hidden structures of systems and hidden mechanisms that drive them (e.g., the wood in the match burns and makes ash), a key characteristic of Level 3 responses. In time, they learn to use atomic-molecular and cellular accounts to describe changes at the macroscopic and large-scale (e.g., the match is oxidized to produce carbon dioxide and water). Students at Levels 4 and 5 can do this to varying degrees. Level 4 students are aware of the hierarchy of systems, but they have trouble connecting processes at one scale with processes at other scales.

Level 5 students have a lens about the world that includes more than just macroscopic, observable events, but rather a rich hierarchy of systems. Students with this lens see systems that were once invisible as visible. For example, they are aware of decomposers and detritus-based food chains, thus, a dead tree in a forest is not decomposed by rain and wind, but rather by microscopic organisms. They see ecosystems in terms of trophic dynamics, which position living organisms in relation to other organisms (i.e., producers, first-order consumer, second-order consumers) rather than ecosystems as simply composed of a whole lot of plants and animals. Making connections between the different levels of scale within a complex hierarchy becomes a critical task for students as they transition between level 4 and 5. By level 5, students can fluidly move between scales to explain changes that occur in systems.

Connections between systems.

For young children, systems are viewed as separate entities, especially those that are living compared to those that are not. The systems may have characteristics that allow young children to group them (e.g., cows, grass, humans are all alive), which can then be used for comparison. Connections are made between systems, but these rely on human relationships with those systems, such as those observed in the level 1 accounts. For instance, students may view wood as connected to humans because of the products that we can derive from the wood. Early atomic-molecular connections appear at level 3 in the form of gas-gas cycles, such as claiming plants take in carbon dioxide to make oxygen for humans to breathe. Even though atomic-molecular accounts become more detailed during level 4, very few students get to the point that they can trace materials with consistency between multiple systems in both organic and inorganic forms (e.g., tracing carbon in the Grandma Johnson questions, connecting combustion of fossil fuels to tree growth in the Amazon), which is an important characteristic of level 5 understanding.

Events to Processes

Causes: Needs, conditions, and materials

Changes happen around us all the time. Sometimes these changes happen to individual organisms, while other times they happen to entire ecosystems. As students acquire more sophisticated understanding of systems and processes, their explanations about the causes of those changes evolve. Causality for young children is focused on human intentions (i.e., Level 1), such as people losing weight because they tried hard to lose weight and matches burning because humans intended for them to burn. Level 2 explanations describe causality in terms of needs of living organisms for survival. Living organisms change because they live or die and they grow because growth is a natural progression in life.

By Level 3 students' explanation of causality tend to focus on needs and conditions, including materials going into and out of systems. Living things grow because they take in materials and they die because they did not get those materials. Students may also identify the presence of organisms responsible for changes (e.g., decomposers cause things to decay). However, Level 3 students do not distinguish clearly between materials, conditions, and forms of energy when they explain causes of events.

By level 4, atomic-molecular account is evoked to explain why organisms take in materials. Students say, for example, that carbon dioxide is taken in by plants to make glucose. At this level, students are more practiced at identifying the chemical needs of living organisms for purposes of metabolic processes.

However, even at Level 4, students are not well practiced in explaining why things happen the way they do. One teacher in our sample would tease her high school students during the cellular respiration unit asking them, "Why do plants make glucose? Do they make it for us? How nice of them." Even in this classroom of bright students, many could not respond to this question, let alone recognize it as key for understanding other metabolic processes in plants. Only at Level 5 do students consistently produce model-based explanations of processes as changes in matter driven by energy.

Conservation: Materials do not disappear

Conservation of matter is uniquely important for our learning progression. We are concerned with what happens to the "stuff" during biogeochemical processes and conservation of matter is a key scientific principle for answering that question. The early stages of conservation of matter do not appear for students until they reach Level 3 understanding. We all commonly use the adverbs "up" and "away" to indicate that someone or something is being dismissed from the scene and from consciousness. (For example: he went away; I threw it away; the match burned up; the dog ate it up.) Level 1 and 2 students focus on the visible event, so they feel little need to consider what happens after "up" or "away." They have dismissed the object or material from the scene, and that is that.. If it were only that simple!

Around level 3 students become aware that "There is no away" and attempt to conserve matter using solid-solid (e.g., match becomes ash), solid-liquid (e.g., fat becomes urine), and gas-gas cycles (e.g., carbon dioxide becomes oxygen). Yet, if carbon dioxide (CO_2) becomes oxygen (O_2), where did the carbon go? At level 3, students are unable to answer this question in terms of a chemical change process. By level 4, however, students are able to make solid-gas transformations, so now fat can be breathed out, matches can be transformed to smoke or gas, and carbon dioxide can be used to make glucose.

Students also use their understanding of evaporation of liquids as a resource for explaining changes in systems. At level 3, students attempt to conserve matter through physical rather than chemical changes. They see gasoline as evaporating into the air rather than being oxidized. They see rotting apples as changes because the juice or water in the apple evaporates. Thus, students below level 4 can evoke physical change processes as a means to explain events, but we observed that by level 4, students can distinguish between physical and chemical changes and apply these to situations in which they are relevant.

Connections: Photosynthesis is not the only answer.

Students tend to develop very sophisticated accounts of photosynthesis before they can explain other atomic-molecular processes, and then they tend to “over-apply” it to explain any changes that occur in plants. For example, our “Gases in Plants” question asked students to identify which of three gases plants take in from their environment: oxygen, carbon dioxide, and other. Almost every student in our sample selected carbon dioxide. The responses from students at the high school level were characterized almost exclusively as level 4 and 5 responses with regards to photosynthesis; however, only 4 of our 60 students recognize cellular respiration as a relevant process. Even then, only 1 student selected both oxygen and carbon dioxide and connected the gases correctly to each process. Our data corroborates similar findings by Wilson et al. (2006) and Wilson, Mohan, and Merritt (in prep), who asked high school and college students to explain why radish seeds grown in the dark lose weight. Interestingly, high school and college students focused their explanations on the lack of light for photosynthesis, rather than on the cellular respiration occurring in the plant. Thus, students explained weight loss in plants using detailed accounts of one metabolic process, not even recognizing the centrality of another metabolic process.

We also observed a similar pattern when asking about plant growth and the composition of wood. At level 5, students explain the growth and composition of plants in terms of biosynthesis, or transformation processes. Yet, below level 5, students view these questions as asking about photosynthesis. As such, their explanations focus on materials being taken into the plant for photosynthesis (e.g., water, air) at level 3 and the plants’ production of glucose or “compaction” of carbon dioxide at level 4. In fact, students’ accounts of biosynthesis remain largely nonexistent until they reach level 5 understanding.

The trends in these types of explanations beg the question: how can students have sophisticated, atomic-molecular accounts of one cellular process and not even recognize the relevance of another? One emerging conclusion from our work is that students develop explanations about chemical changes in a single system, largely separate from one another. So photosynthesis that happens in plants is not connected to other metabolic processes that may happen simultaneously. Students' accounts of these processes are constrained by telling the "school science" story that is disconnected from the reality in which it occurs. Only asking students, "How does a plant make glucose? What does it need? Where does this occur?" prevents them from making connections between photosynthesis and other metabolic processes. Instead, questions such as, "Why do plants make glucose? What happens to the glucose once it's made?" challenge students to connect multiple metabolic processes occurring within the same system (e.g., the generation, transformation, and oxidation of organ carbon in a plant).

A second emerging conclusion is that students do not learn to make connections about similar processes across multiple systems, for example, seeing cellular respiration is ultimately the same in plants, animals and decomposers, and that this process can be likened to combustion that happens in non-living systems. As our work continues, we will focus on flushing out these two conclusions, to understand how accounts of processes in systems develop initially separate from one another and what it takes for those separate accounts to be connected.

Objects to Materials.

Recognizing mixtures.

The recognition of mixtures appears to be an important step for students to understand chemical changes. Living and non-living systems are mixtures of many substances, most of which are important materials involved in the chemical changes of those systems. Level 1 and 2 explanations focus on objects, rather than the materials in which those objects are made. Students at this level explain that "wood" as just "wood" or they describe wood as a mixture because of its observable parts, such as leaves, branches, flowers, etc. At these levels, it is still unclear how students interpret or understand the term *mixture*. By level 3, students recognize heterogeneous mixtures and name materials found in the mixture (e.g., water, minerals, air make up the composition of wood), or at least those that contribute to the mixture. By level 4 students not only identify heterogeneous (e.g., wood) and homogenous mixtures (e.g., gasoline), but they can name the chemical identities of substances that may reasonably contribute to the mixture, (e.g., claiming wood is a mixture because it is made of carbon dioxide). By level 5 students can identify mixtures and name or indicate that there are multiple carbon-containing molecules that are part of the mixture (e.g., naming cellulose and lignin as substances in wood; indicating that multiple polysaccharides make up wood without naming them specifically).

Gases are matter, energy is not.

For young students, gases rarely appear in students' accounts. Rather, level 1 and 2 students focus on objects that are observable, such as solid or liquid materials, and can give fairly detailed descriptions of these objects. From level 3 through level 5, gases become increasingly more visible to students, a hugely important step for tracing materials through processes. Before level 3, students explain that objects disappear when going from a solid to a gas (e.g., fat disappears when people lose weight, match disappears when it is burned, decaying leaves or other materials disappear over time) because the gas concept is largely unknown. At level 3 students not only recognize that objects are often made of more than one substance, but they begin to conserve matter using their understanding of materials rather than objects. Yet, because they do not recognize materials in terms of chemical identities, nor conserve them at an atomic-molecular scale, students at level 3 give accounts of solid or liquid materials and still largely ignore gases. A critical transition occurs between level 3 and 4: since level 4 students are aware of atomic-molecular changes and can identify materials, including gases, by chemical identities, they have tools that allow them to conserve gases through processes just as they would conserve solids or liquids.

Characteristic of level 4 accounts, however, is an incomplete description of all the materials involved in a chemical change process. Level 4 students can identify many important materials involved in carbon-transforming processes, so at this level plants are not “objects” but rather living organisms that take in and give off various substances. They may trace specific materials in and out of systems, but still forget key reactants or products. They also view matter-energy conversions as means by which to conserve matter. The fact that matter is composed of atoms and molecules and energy is not, does not seem to be a problem for level 4 students. By level 5 students further refine their understanding of chemical identities and explain why materials are alike or different based on the chemical structure of the materials. They also have a commitment to matter conservation that does not allow matter to be converted to energy.

Conclusions

Change over time and environmental literacy

Getting from level 4 to level 5.

In our work, we have realized that the K-12 science curriculum does a reasonable job of getting students from levels 1, 2, and 3 to level 4 accounts of tracing matter. By level 4 students can give relatively coherent accounts of processes in single systems and name several materials involved in those processes. For passing standardized science assessments, this level of explanation might be sufficient. It is our belief, however, that students need to develop more sophisticated accounts of carbon cycling if they are to understand the global issues that our society faces. The arguments about the causes of global warming and the solutions for this problem abound. A majority, if not all, of these arguments require at least level 5 reasoning to interpret. So even if level 4 students can recall the formula for photosynthesis or combustion, they likely would not see these as relevant to understanding global climate change. A notable limitation for level 4 students is that they cannot consistently explain the role of carbon during key processes, nor can they fluidly move between the hierarchy of systems to explain large-scale change using atomic-molecular accounts, both of which are essential for making sense of the environmental problems that alter global carbon cycling.

These findings lead us to a major challenge that we face as science educators. Our experience and our reading of the available research have convinced us that scientific reasoning about the carbon cycle is a major intellectual achievement, requiring mastery of complex practices and the ability to apply fundamental principles to complex biogeochemical processes. It is unlikely that most students will achieve this understanding without sustained, well-organized support from schools and science teaching that is effective in helping students develop scientific accounts that are essential to understanding evidence-based arguments and participating knowledgeably in responsible citizenship.

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Appendix A: Example Items

1. Energy-rich materials (ENERRICH)

Someone made three groups A, B, and C, like the following:

A. Sugar, meat, bread
B. Water, limestone, sand
C. Coal, gasoline, wood

(a) What makes each group go together?
(b) Why would water go with limestone and sand rather than sugar and meat
(c) Do you think groups A and C have anything in common? Explain your reasoning.

2. Wood Mixture (WOODMIX)

Do you think that wood is a mixture of different things? (Circle one)

YES NO

Please explain your ideas about what makes up wood.

3. Trees and Climate Change (CLIMATE2)

Some people are worried that cutting down forests will increase the rate of global climate change. Can you explain their reasoning? How could cutting down trees affect our climate?

4. Burning Match (BRNMATCH)

What happens to the wood of a match as the match burns? Why does the match lose weight as it burns?

5. Gases in Plants (PLANTGAS)

Which gas(es) do plants take in from their environments? (you may circle more than one)

oxygen carbon dioxide other

Explain what happens to the gases once they are inside the plant.

6. Jared Lost Weight (JAREDM)

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

7. Eating an Apple (EATAPPLE)

Explain what happens to an apple after we eat it. Explain as much as you can about what happens to the apple in your body.

8. Growth of an Acorn (ACORNFOOD and ACORNMASS)

A small acorn grows into a large oak tree.

(a) Which of the following is FOOD for plants (circle ALL correct answers)?

Soil	Air	Sunlight	Fertilizer
Water	Minerals in soil	Sugar that plants make	

(b) Where do you think the plant's increase in weight comes from?

9. Grandma Johnson (GRANJOHN)

Grandma Johnson had very sentimental feelings toward Johnson Canyon, Utah, where she and her late husband had honeymooned long ago. Because of these feelings, when she died she requested to be buried under a creosote bush in the canyon. Describe below the path of a carbon atom from Grandma Johnson's remains, to inside the leg muscle of a coyote. NOTE: The coyote does not dig up and consume any part of Grandma Johnson's remains.

10. Amazon rainforest (AMAZON)

On March 10, 2004, National Public Radio reported that "forests in a remote part of the Amazon are suddenly growing like teenagers in a growth spurt." Though, the radio report added, "This shouldn't be happening in old, mature forests." Scientists have speculated that our actions may have caused this phenomenon. What do you think could be the scientific basis behind such a speculation?

12. The Decomposition of an Apple (APPLEROT)

When an apple is left outside for a long time, it rots.
(a) What causes the apple to rot?
(b) Explain what happens to the weight of an apple as it rots.

13. The Burning of Gasoline and Global Warming (CARGAS and CARGAS_WARM)

When you are riding in a car, the car burns gasoline to make it run. Eventually the gasoline tank becomes empty.
(a) What do you think happens to the gas? What happens to the matter the gasoline is made of?
(c) Can using gasoline in car affect global warming? How?

14. Glucose and your Finger (GLUGRAPE)

You eat a grape high in glucose content. How could a glucose molecule from the grape provide energy to move your little finger? Describe as many intermediate stages **and** processes as you can?

Appendix B: Detailed Tracing Matter Levels (for scoring)

	Living Systems			Human Engineered Systems
Levels	**Generation-** photosynthesis	**Transformation**- food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 5: ***Qualitative model-based accounts across scales*** ***Scale:*** Use qualitative descriptions of carbon movement through multiple processes in multiple scales.	Can use atomic molecular understanding of photosynthesis to explain macroscopic and large-scale phenomena (e.g., plant growth, plants as a carbon sink) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can name chemical identities of all products and reactants during photosynthesis, including gases and organic materials (i.e., glucose). Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). Recognize proteins, lipids, and carbohydrates as key molecules in plants, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. Correctly identifies that plant matter, such as wood is a heterogeneous mixture and names substances or kinds of molecules in this mixture that contain carbon (other than CO_2)- distinguishes mixture from compound and from elements. Identifies that plant processes, such as photosynthesis, can influence and be influenced by levels of atmospheric CO_2 on a large or global scale (i.e., identifies plants as a carbon sink).	Recognizes that matter is being passed through the food chain/web and can conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms through multiple sequences of changes. Describes role of organisms in terms of trophic levels (producers, consumers, decomposers, etc) and can predict changes in one trophic level based on changes in another level. Recognize proteins, lipids, and carbohydrates as key molecules that move within and between organisms, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). Recognize that plant growth occurs when plants transform simple sugars made through photosynthesis into complex sugars/starches or polysaccharides (e.g., cellulose, lignin, etc). May know some details of biosynthesis (e.g., enzymes, carbon fixation), but primarily can only name products. Recognize that growth of humans/animals/decomposers occurs when organisms synthesize	Can use atomic molecular understanding of respiration to explain macroscopic and large-scale phenomena (e.g., weight loss, soil respiration as a carbon source) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can compare/contrast cellular respiration to combustion in terms of characteristics of reactants and products. Can differentiate cellular respiration (aerobic) and fermentation (anaerobic) in terms of the role of O_2 as a reactant. Can name chemical identities of all products and reactants during respiration, including gases and organic materials (e.g., lipids, carbohydrates). Recognizes that molecules are the basic unit to keep substance's identity (e.g., glucose, CO_2). Recognize proteins, lipids, and carbohydrates as key molecules in, and know that these organic molecules are made primarily of atoms of carbon, hydrogen, and oxygen. Identifies that respiration, especially respiration of decomposers, can influence levels of atmospheric CO_2 (i.e., identifies organisms as carbon sources when they respire on a large scale). *Common Errors:* • Cannot use stoichiometric calculations to calculate the amount	Can use atomic molecular understanding of combustion to explain macroscopic and large-scale phenomena (e.g., burning gasoline, carbon fluxes from fossil fuels use) and conserve matter and mass (including gases) at the atomic-molecular level in terms of rearrangement of atoms. Can compare/contrast combustion with cellular respiration. Can name chemical identities of all products and reactants, although may not know exact chemical identities of fossil fuels. Recognizes that molecules are the basic unit to keep substance's identity (e.g., molecule of butane, propane). Correctly identifies gasoline as a homogenous mixture and wood as a heterogeneous mixture and names substances or kinds of molecules in these mixtures that contain carbon. Identifies that the burning of fossil fuels and other organic materials such as wood) produces CO_2 and is a large carbon source that contributes to rising atmospheric CO_2 levels and global warming. *Common Errors:* • Cannot use stoichiometric

	Common Errors: • Cannot use stoichiometric calculations to calculate the amount of certain materials involved in photosynthesis. • Sub-processes, such as light-dependent (light) and light-independent (dark) reactions may still contain errors. • May still confuse photosynthesis with other biosynthesis processes	simple carbohydrates and amino acids into more complex molecules (lipids, proteins, etc). May know some details of biosynthesis, but primarily only name products. Identifies that living organisms on a large scale and sequester large amount of carbon. *Common Errors:* • Details or sub-processes of biosynthesis may be incomplete or contain errors.	of certain materials involved in respiration • Sub-processes in the Krebs cycle, such as the details of the glycolysis & pyruvate oxidation, may contain errors. • May not mention O2 as a reactant, but rather focus on important products, which is a level 5-	calculations to calculate the amount of certain materials involved in combustion. • The exact chemical identity of fuel sources, although the student does know it contains carbon. • May not mention O2 as a reactant, but rather focus on important products, which is a level 5-
Level 4: ***School science narratives of processes*** ***Scale:*** Atomic-molecular narratives about cellular processes and large scale narratives about food chains can explain (to a limited degree) macroscopic events	Can reproduce formulas for photosynthesis (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., where does tree get its mass?). Recognize the need to conserve matter and mass in chemical changes <u>and attempt to conserve matter at the cellular or atomic-molecular level.</u> Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that CO_2 contributes to mass of tree), but may ignore some gas reactants or products. Can name materials by their chemical identity, such as CO_2, O_2 and glucose when asked specifically about photosynthesis, but cannot identify the substances that make up common foods or plants. Neither can students use chemical information about those substances to develop explanations of how they were created. Recognizes that the cell is the basic unit of both structure and function of plants and that plant cells contain organelles (e.g., chloroplasts) and are made of water and organic	Recognizes that matter/energy is being passed through food chain, but cannot consistently identify matter transformation and chemical identities of matter and may not distinguish matter from energy. Describes role of organisms in terms of trophic levels (producers, consumers, decomposers, etc). Plant growth is explained <u>at the cellular or atomic-molecular levels</u> as the accumulations of simple sugars (e.g., glucose) or as the accumulation of carbon dioxide (e.g., compacted CO_2). Correctly identifies that wood is a heterogeneous mixture, but does not name substances or kinds of molecules that contain carbon other than CO_2 or focuses on minor constituents in mixtures (e.g., minerals). Human/animal/decomposer growth is explained <u>at the cellular or atomic-molecular levels</u> in terms of what cells do with the food/substances these organisms eat. *Common Errors:* Details of food chains/webs may:	Can reproduce formula for cellular respiration (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., where does fat go when humans lose weight? What happens to the mass of a decomposing apple? What happens to the plant mass when they receive no light?). Recognize the need to conserve matter and mass in chemical changes <u>and attempt to conserve matter at the cellular or atomic-molecular level.</u> Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that fat leaves body on CO_2) but may ignore gas reactants and products or not be able to explain where gas products came from. Can name materials by their chemical identity, such as CO_2, O_2 and glucose when asked specifically about respiration, but cannot identify the substances that make up the matter in animals. Neither can students use chemical information about those substances to develop explanations of how they were created. Recognizes that the cell is the basic unit of both structure and function of all organisms and that cells contain	Can reproduce formula for combustion (that may be balanced or not), but cannot explain this process in detail or use the formula to explain a macroscopic event (e.g., what happens to mass of a match when it burns). Recognize the need to conserve matter and mass in chemical changes <u>and attempt to conserve matter at the atomic-molecular level</u>. Recognize that gases are matter and attempt to conserve these during chemical changes (e.g., say that a burning match becomes smoke, gas), but may fail to recognize the primary gas products and fail to explain the role of O_2 as a reactant in combustion. Can name products of combustion in terms of their chemical identities (CO_2 and H_2O) but cannot identify substances that make up fuels or use chemical information about those substances to develop explanations of how they created or what happens when they oxidized (may provide more explanation of the burning of wood compared to burning of fossil fuels). Know that gasoline is

	materials. Recognize that plants are an organisms that influence atmospheric CO_2 levels, but does not explain how. *Common Errors:* Details of photosynthesis may: • Be incomplete or contain errors such as matter-energy conversion (e.g., sunlight contributes mass) or gas-gas cycles (saying that photosynthesis converts O_2 to CO_2), but these occur at cellular level. • Focus on minor products or reactants or materials in the systems during cellular processes (e.g. water, minerals contribute to mass of tree through photosynthesis). • Explain changes in plants using photosynthesis but not respiration (e.g., plant loses mass because it could not do photosynthesis).	• Use matter and energy interchangeably when explaining relationships within a food chain or web. • Contain detailed descriptions of one process in the food chain (e.g., photosynthesis) but not details about other processes. • Describe matter flow within a food chain/web in terms of a "general" materials (e.g., food) and not specific substances (e.g., carbohydrates, lipids, proteins). • Cannot explain biosynthesis in terms of cellular processes that combine simpler molecules into more complex molecules (e.g., mass of plant comes of glucose or CO_2 rather than cellulose/polysaccharides and mass of humans comes from lipids in food we eat). • Recognize that air/carbon/carbon dioxide contribute to growth, but may not explain how.	organelles (e.g., mitochondria) and are made of water and organic materials. Recognize that animal cells are different from plant cells. *Common Errors:* Details of respiration may: • Be incomplete or contain errors, such as matter-energy conversion at the cellular level, (e.g., saying that cellular respiration converts glucose to ATP). • Include minor products or reactants or materials (urine, feces) as a product at the cellular level. • Focus only on the chemical identity of products, but not reactants (saying fat is converted to CO_2 and H_2O). • May describe decomposition as analogous to oxidation.	burned through a chemical change of combustion. Recognizes homogenous mixtures (e.g., gasoline) but cannot name substances or molecules in the mixture that contain carbon. *Common Errors:* Details in combustion may: • Be incomplete or contain errors (matter-energy conversions). • Include minor products or reactants of an atomic-molecular process (e.g., ash) or do not recognize the role of key reactants (e.g., asserting that oxygen is needed for combustion but not describing fuel molecules as reacting with oxygen molecules). • If smoke is the only gas product of combustion, then it's a 4-
Level 3: ***Causal sequences of events with hidden mechanisms*** ***Scale:*** Reasoning about materials indicating a hidden mechanism (at the barely visible, microscopic or large scale) responsible for changes at the macroscopic level.	Instead of a cellular process, the focus is on the materials that plants take inside them to help them grow (e.g., list air, water, sunlight, minerals, etc) but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from light energy. Recognize that gases are matter, but no attempts to conserve these at the atomic molecular level. Gases in plants are explained as a gas-gas cycle that is opposite of breathing in humans (CO_2-O_2 cycle) and not associated with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process.	Recognizes food chain as sequences of events. (e.g., rabbit eat grass and coyote eat rabbit) but does not pay attention to the underlying matter movements in those events. Identifies all organisms including decomposers in food chain or present in ecosystems, but not their role as producers, consumers and decomposers (e.g., may think fungi are producers like plants and visible decomposers, such as worms and insects are consumers). Recognizes plants are made of cells but does not recognize the role of the cell in plant growth. Describes growth as a general processes, which may be localized to parts of the plant.	Instead of a cellular process, the focus is on the materials that humans/animals take inside them to help them grow (e.g., food, water), but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from energy. Describe weight loss as a general process that is associated with human/animals needs for energy but not with the cell or cellular processes. Recognize that gases are matter, but no attempts to conserve these at the atomic molecular level. Breathing is commonly explained as a gas-gas cycle (O_2-CO_2 cycle) and not associated with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process.	Focus on materials being burned, but does not recognize molecular structure of materials, identify chemical identities of materials, or distinguish matter from energy. Describe combustion as a general process of "burning" and focus mostly on macroscopic products and reactants and not gases. Recognize gases are matter, but do not use their knowledge to conserve matter involving solid to gas changes during combustion. Recognize that air is needed for combustion, but treat it as a condition rather than as the source of a substance (oxygen) that reacts with the material that is

	Recognizes that plants are made of cells, but does not know the role of the cell in photosynthesis. Recognizes heterogeneous mixtures (e.g., wood is not a uniform compound) and attempts to identify barely visible parts of the mixtures (e.g., wood is made of air, water, minerals). Recognize that plants influence global processes but use incorrect mechanisms to explain this (e.g., focus on oxygen or sunlight absorbed by plant) *Common Errors:* • Focus on gas-gas cycles between plants and humans (e.g., plants make O_2 for humans).	Recognizes heterogeneous mixtures (e.g., wood is not a uniform compound) and attempts to identify barely visible parts of the mixtures (e.g., wood is made of air, water, minerals). Recognizes animals/humans are made of cells (not decomposers), but does not recognize the role of the cell in growth. Describes growth as a general process of incorporating food into the body and focuses on the materials that humans and animals take inside them, which may be localized to parts of the body (e.g., stomach digests food). *Common Errors:* • Explaining animal digestion and growth in terms of processes that are localized in the stomach and intestines. • Sun, soil, minerals, or water are the primary things that contribute to plant growth (and not explain using a cellular process)	May know the name "decomposition" and can associate this with an accurate mechanism (e.g., bacteria), but not with a cellular process, indicating only that they understand this happens at an invisible scale rather than as a cellular process. Typically described as general processes, such as decompose, decay, rot, etc. May also explain decomposition/rotting/decay analogous to evaporation of liquids. *Common Errors:* • Explaining breathing in terms of processes that are localized in the lungs (e.g., our lungs breathe in oxygen and breathe out carbon dioxide) • Explain weight loss through solid-liquid transformation or matter energy conversion, not at cellular level (e.g., fat turns/burns into energy; fat turns into sweat) but as a way to conserve. • Explain decomposition using a general process such as "decomposition", "decay" or possibly "evaporation" but give not products	burning. Recognizes similarity among classes of materials such as foods and fuels (e.g., distinguish between substances that will burn (fuels) and substances that will not), but the distinction is based on experience rather than an ability to describe properties that all fuels share. *Common Errors:* • Describe general processes, such as "burning". • Describe products of the general process (e.g., ash) but do not indicate that these products are from an atomic molecular process. • Gasoline evaporates, b/c this is how liquids become gases
Level 2: ***Event-based narratives about materials*** ***Scale:*** Reasoning about materials at the macroscopic level is not extended to barely visible or microscopic scales and very limited large-scale reasoning.	Focus on observable changes in plants (e.g., plant growth) based on plant needs or vitalistic causality—idea of vital powers; need air, water, good to maintain vitality and health (e.g. plants need water to stay alive). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy (e.g., sunlight gives plants its mass). Recognize materials such as air, water, and soil as fulfilling needs of plants, but do not distinguish between materials that plants need to make food and other things that plants need (e.g., space).	Uses **romantic narratives** to describe relationships and connections among organisms. (e.g., nature videos). Identify plants and animals in food chains, but not decomposers. Identify subclasses of organisms based on macroscopic experiences. Explain plant and animal growth in terms of a natural tendencies or in terms of the visible parts of the organisms that change. *Common Errors:* • Does not identify decomposers in ecosystems or food chains.	Focus on observable changes in humans and animals (e.g., weight loss) bases on human/animal needs or vitalistic causality—idea of vital powers; need air, water, good to maintain vitality and health (e.g. human breathe to stay alive). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy. Recognize materials such as food, air, and water, as fulfilling needs of humans/animals, but do not distinguish between materials that humans/animals need to for growth, living, and energy and other things that humans/animals need (e.g., shelter, exercise). Focus on observable changes in	Focus on observable changes in materials that are burned (e.g., wood, fossil fuels). Not understood in terms of smaller parts or hidden mechanisms or distinguished from conditions or forms of energy. Causes of burning of fuel sources may be related to essential characteristics of materials (e.g., the match burns because wood is flammable; gasoline tank is empty because it makes the engine run) and described in terms of what the fire/flame does to the materials being burned (e.g., fire consumed the match) or what happens to the match (e.g., match gets shorted).

	Does not recognize heterogeneous mixtures of wood or may describe heterogeneous mixtures in terms of macroscopic parts. Does not recognize gases as matter and does not attempt to conserve these during plant processes. Do not recognize that plants are connected to global processes (e.g., global warming/climate change), but do make the connection between forest and animal habits or make connection not through plants at all (e.g., sun directly heats up earth). *Common Errors:* • Wood or plants are made of flowers, branches, and roots.	• Does not recognize growth in terms of internal mechanisms of plants and animals, but rather focus on visible changes or natural growth.	decomposing objects caused by visible or tangible mechanisms (e.g., weather, worms) or decomposing objects disappear or go away. Does not recognize gases as matter and does not attempt to conserve these during weight loss or decomposition (e.g., fat disappears through "burning off" or "going away" *Common Errors:* • Decomposing materials disappear or turn into smaller visible objects (e.g., decomposing leaves go away or turn into soil). • Weight loss happens because the fat just disappears or goes away or is burned off with no attempt to conserve	Does not recognize heterogeneous mixtures of homogenous mixtures comprising fuels sources. Does not recognize gases as matter and does not attempt to conserve these during burning/combustion. *Common Errors:* • Burning materials disappear or turn into smaller visible parts (e.g., burning match disappears or turns into little bits of wood; gasoline in a car disappears).
Level 1: ***Human-based narratives about objects*** ***Scale:*** Reasoning about objects at macroscopic level based on human analogies and personal experiences.	Focus on observable changes of plants, but use human analogy to explain how changes happened (e.g., plant died because it did not get love). Plants are characterized according to their relationships with humans and human uses—food, flowers, etc. *Common Errors:* • Plants need love and care to grow; plants need vitamins like humans. • Classify or explain plants in terms of their use for humans (e.g., grouping vegetables and fruits because humans eat them).	Uses **mythic narratives** to describe relationships and connections among organisms. (e.g. Lion king, Bambi). Explain plant and animals growth in terms of personal experiences or human needs/emotions (e.g., plants grow like humans so they can protect themselves). *Common Errors:* • Relationships among animals are cooperative in the sense of "good will" to fellow animals. • Relationships among animals are judged in terms of human emotions or characteristics: "mean fox" and "innocent bunny".	Focus on observable changes in humans and animals (e.g., weight loss or gain), but use human analogy to explain why changes happen. Animals are characterized according to their relationships with humans—food, pets, etc.—or are understood in human terms (e.g., cartoon movies about animals with human traits and emotions). *Common Errors:* • Animals are associated with human personality and human intentions (e.g., stereotypes of animals from cartoon movies). • Weight loss attributed to effort (e.g., he tried hard to lose weight)	Focus on observable changes in fuel sources (e.g., wood, fossil fuels) and the causes of these changes center around human intentions and effects on humans (e.g., the match burns because someone struck the match). *Common Errors:* • Classify or explain fuels/materials in terms of their use for humans (e.g., gasoline helps cars run, wood is used for furniture, paper, and pencils).