Appendix: Detailed Levels for One Progress Variable

Table 3: Tracing Matter through Processes that Generate, Transform, and Oxidize Organic Carbon

	Living Systems			**Human Engineered Systems**
Levels	**Generation-** photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 7: ***Quantified uncertainty and change*** Use quantitative, accounts at multiple scales to explain large-scale change over time and uncertainty associated with that change.	Quantifies uncertainties associated with specific processes and specific actions and is able to do risk assessment (e.g., can consider the likelihood/ uncertainty that certain actions, such as how using biofuels instead of fossil fuels, will influence the level of atmospheric greenhouse gas levels). Identifies hidden assumptions underlying risk assessments and projections of environmental change. Identifies other processes that should be taken into account in assessing the environmental impact of particular courses of action (e.g., costs of production and land use in switching from fossil fuels to biofuels). May require tools to find relevant information (e.g., searching on Google), but knows enough to access the correct information.			
Level 6: ***Quantitative model-based accounts across scales*** Use qualitative and quantitative descriptions of carbon movement through multiple processes in multiple scales.	Uses quantitative measurements of carbon fluxes through multiple processes in multiple scales. Explains accumulation of carbon dioxide in the atmosphere and global climate change in terms of imbalances among processes that generate and oxidize organic carbon compounds (biomass, foods, and fuels). Can use stoichiometirc calculations to connect atomic-molecular quantities with measures of mass or volume at macroscopic and large scales, but cannot quantify uncertainties of those calculations. (e.g. can calculate how much carbon dioxide a car produces in burning 100 L of gasoline; how much carbon dioxide a tree absorbs in making 100 kg of wood, but cannot use calculations to deal with the uncertainty such as how the making and using biofuels instead of using fossil fuels will influence the level of atmospheric greenhouse gas levels.) Relates measures of energy (megawatt-years) to measures of mass (e.g. gigatons of CO_2). May require tools to find relevant information (e.g., searching on Google), but knows enough to access the correct information.			

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 5: ***Qualitative model-based accounts across scales*** 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.* *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.	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). *Recognizes 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.* *Recognizes that growth of humans/animals/decomposers occurs when organisms synthesize simple carbohydrates and amino acids into more complex molecules (lipids, proteins, etc). May know some details of biosynthesis, but primarily only name products.* *Common Errors:* • Details or sub-processes of biosynthesis may be incomplete or contain errors.	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. *Common Errors:* • Cannot use stoichiometric calculations to calculate the amount of certain materials involved in respiration • Sub-processes in the Krebs cycle, such as the details of the glycolysis & pyruvate oxidation, may contain errors.	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. *Common Errors:* • Cannot use stoichiometric 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.

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 4: ***School science narratives of processes*** 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 and attempt to conserve matter at the atomic-molecular level. *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 materials.* *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). • Focus on minor products or reactants or materials in the systems (e.g. water, minerals contribute to mass of tree). • Explain changes in plants using photosynthesis but not respiration (e.g., plant loses mass because it could not do photosynthesis).	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 at the atomic-molecular levels 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 at the atomic-molecular levels in terms of what cells do with the food/substances these organisms eat.* *Common Errors:* Details of food chains/webs may: • 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 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 or mass of humans comes from lipids in food we eat).	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 and attempt to conserve matter at the atomic-molecular level. *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 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 (matter-energy conversion such as saying that cellular respiration converts glucose to ATP). • Focus on minor products or reactants or materials (urine, feces) or focus only on the chemical identity of products, but not reactants (saying fat is converted to CO_2 and H_2O).	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 and attempt to conserve matter at the atomic-molecular level. *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) 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). • Focus on minor products or reactants (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).

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 3: **Causal sequences of events with hidden mechanisms** 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 that plants are made of cells, but does not know the role of the cell in photosynthesis. Recognizes heterogenous 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). *Common Errors:* • Does not distinguish molecular, cellular, and barely visible levels. • Focus on gas-gas cycles between plants and humans (e.g., plants make O_2 for humans).	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. Recognizes heterogenous 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 digestion and growth in terms of processes that are localized in the stomach and intestines. • Does not distinguish molecular, cellular, and barely visible levels.	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. 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 rusting or by evaporation of liquids. *Common Errors:* • Does not distinguish molecular, cellular, and barely visible levels. • Explaining breathing in terms of processes that are localized in the lungs (e.g., our lungs breathe in oxygen and breathe out carbon dioxide)	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. 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 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:* • Does not distinguish molecular, cellular, and barely visible levels. •

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 2: ***Event-based narratives about materials*** 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). Does not recognize heterogenous mixtures of wood or may describe heterogenous mixtures in terms of macroscopic parts. Does not recognize gases as matter and does not attempt to conserve these during plant processes. *Common Errors:* • Wood or plants are made of flowers, branches, and roots.	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 general process attributed to taking materials into the body that the body needs. *Common Errors:* • Does not identify decomposers in ecosystems or food chains. • Does not recognize growth in terms of internal mechanisms of plants and animals, but rather the materials that plants and animals need (e.g., mass of plants comes from water or dirt, but not gases).	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 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 respiration/weight loss/ decomposition. *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	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). Does not recognize heterogenous 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).

	Generation- photosynthesis	**Transformation-** food chain/web, biosynthesis	**Oxidation-** cellular respiration	**Oxidation-** combustion
Level 1: ***Human-based narratives about objects*** 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 using "natural tendencies" (plants just grow because that's what they do). *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". • Plants and animals grow because that's the way it is.	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).