Learning Progressions toward Environmental Literacy: Carbon Cycling

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We are developing a program of research and development for a K-12 curriculum focusing on *environmental science literacy*—the capacity to understand and participate in evidence-based discussions of the effects of human actions on environmental systems. Environmental science literate high school graduates should be able to engage in two practices that are essential for environmentally responsible citizenship. They should be able to understand and evaluate experts' arguments about environmental issues, and they should be able to decide on policies and personal actions that are consistent with their environmental values.

Environmental science literacy requires understanding of many aspects of science, including chemical and physical change, carbon cycling, diversity and evolution by natural selection, and connecting human actions with environmental systems. These phenomena are currently addressed in many state and national standards documents and in school curricula, but typically they are addressed in disconnected ways—in different courses or in different units in the same course. We argue that they can fit together as a coherent conceptual domain that all of our citizens need to understand. In particular, understanding in all of these domains requires *applying fundamental principles to processes in coupled human and natural systems.*

Our framework includes three components:

1. *Practices*. Environmental science literacy includes three key *practices*:
   a. *Inquiry:* learning from experience, developing and evaluating arguments from evidence
   b. *Scientific accounts:* understanding and producing model-based accounts of environmental systems; using scientific accounts to explain and predict observations
   c. *Citizenship:* using scientific reasoning for responsible citizenship
2. *Principles applied to processes in systems.* Each practice involves applying fundamental *principles* to *processes* in coupled human and natural *systems.*
   a. *Principles.* Key categories of principles include:
      i. *Inquiry principles*, including principles for acquiring data, finding patterns in data, and critiquing and evaluating investigations
      ii. *Structure of systems*, including atomic-molecular, microscopic, macroscopic, and large-scale structures
      iii. *Constraints on processes,* including principles for tracing matter, energy, and information through processes in systems.
      iv. *Change over time*, including principles for understanding multiple causation, feedback loops, and evolutionary changes in populations
      v. *Citizenship principles,* including principles for evaluating conflicting claims and deciding on responsible courses of action.
   b. *Processes in systems.* Key systems and processes include:
      i. *Earth systems,* including the earth, atmosphere, and water.
      ii. *Living systems,* including cells, organisms, populations, and ecosystems.
      iii. *Engineered systems,* including the systems that provide human populations with food, energy, water, and transportation.

3. *Learning progressions.* We seek to develop research-based *learning progressions* that describe how K-12 students could come to master the practices of environmental literacy. Learning progressions are built around (a) an *upper anchor:* the detailed practices that we hope high school graduates will master, (b) a *lower anchor:* what we learn from empirical research about the practices and understandings of children in elementary school, and (c) *progress variables* that can be used to describe a series of reasonable steps from the lower to the upper anchor. We organize these learning progressions around three strands:
    a. *Carbon.* The role of carbon compounds in earth, living, and engineered systems, including carbon dioxide in the atmosphere, energy flow and carbon cycling in ecosystems, and fossil fuels in human energy and transportation systems
    b. *Water.* The role of water and substances carried by water in earth, living, and engineered systems, including the atmosphere, surface water and ice, ground water, human water systems, and water in living systems.
    c. *Biodiversity.* The diversity of living and engineered systems, including genetics and life cycles of individual organisms, evolutionary changes in populations, diversity in natural ecosystems and in human systems that produce food, fiber, and wood.

Working groups consisting of university-based researchers and K-12 teachers are focusing on each strand, reviewing relevant literature, developing assessments that reveal students' reasoning about the topic, and administering the assessments in the teachers' classrooms. Our goal is to produce three kinds of products:

1. *Learning progressions* as described above: research-based accounts of how students enter school thinking about environmental systems, and of the progress variables and learning processes that could lead to the development of environmentally literate practices and understandings.
2. *Assessment resources* that can be used for research and to guide teachers' practice as they assess students' progress toward environmental literacy.
3. *Teaching resources* that teachers can use to help students master the practices and understandings of environmental science literacy in ways appropriate for the students' ages and cultures.

Table 1: Environmental Literacy High School Framework (Draft Upper Anchor)

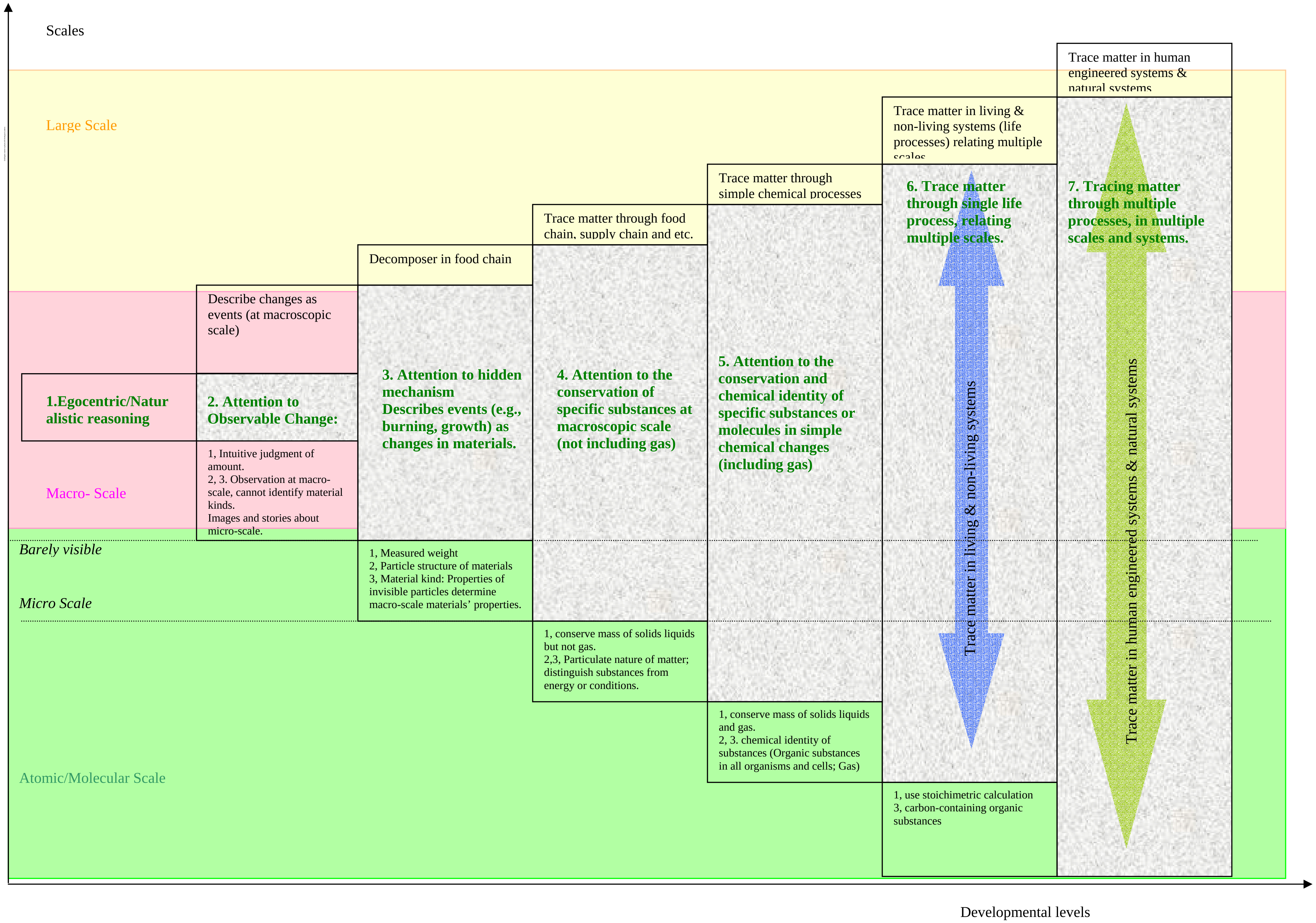
Type of Principle or Practice	Fundamental principles (Big Ideas)	Earth systems: Earth, water, air	Living systems: Producers, consumers, decomposers	Engineered systems: Food, water, shelter, energy, transportation
Practice 1: Scientific Inquiry				
Acquiring data	Standards for data: precision & reproducibility	Acquiring data on earth systems	Acquiring data on living systems	Acquiring data on engineered systems
Finding patterns Developing explanations Predicting effects	Standards for models: fit to data, testability Uncertainty in predictions	Developing data-based explanations and predictions about earth systems	Developing data-based explanations and predictions about living systems	Developing data-based explanations and predictions about engineered systems
Critiquing or evaluating investigations	Standards for arguments from evidence	Critiquing investigations of earth systems	Critiquing investigations of living system	Critiquing investigations of engineered system
Practices 2 and 3: Producing and Using Scientific Accounts				
Applying fundamental principles…		***…to processes in coupled human and natural systems***		
Structure: Hierarchy of Systems	Microscopic (Atomic-molecular, cellular)	Properties of atoms and molecules	Cell structure, biomolecules	Materials in engineered systems
	Macroscopic	Physical and chemical properties of materials	Multicellular organisms	Appliances, automobiles, etc.
	Large scale	Matter pools	Populations, ecosystems	Large engineered systems
Constraints on Processes: Tracing Matter, Energy, and Information	Matter: Air	Wind, weather	Atmospheric CO_2	Air quality
	Matter: Water	Water cycle	Transpiration	Human water systems
	Matter: Carbon	Geological carbon cycle	Ecological carbon cycling, growth	Fossil fuel systems
	Matter: Other materials	Sediments, pollutants, nutrients	(Nitrogen, phosphorous cycles)	Supply chains, waste disposal chains
	Energy	Seasonal cycles, flow of solar energy	Ecological energy flow, photosynthesis & respiration	Human energy systems
	Information		Genetics, life cycles, biodiversity	(Technology, economic and cultural diversity)
Change over Time	Reproduction and selection		Evolution: changes in size, diversity, central tendencies of populations	(Technological evolution in response to economics, regulations)
	Multiple causation, feedback loops	Global climate change, land use	Invasive species, effects of climate change	Changes in technology, voluntary and involuntary lifestyle changes
Practice 4: Responsible Citizenship				
Critiquing experts' arguments	Identifying and critiquing scientific claims in social, economic, political arguments	Critiquing experts' arguments about earth systems	Critiquing experts' arguments about living systems	Critiquing experts' arguments about earth systems
Reconciling values and actions: Cost- and risk-benefit analyses	Identifying agents for issues Identifying consequences that relate to values Balancing costs or risks and benefits	Identifying consequences and analyzing costs and benefits for earth systems	Identifying consequences and analyzing costs and benefits for living systems	Identifying consequences and analyzing costs and benefits for engineered systems

Table 2: Carbon Cycling in Coupled Human and Natural Systems

UPPER ANCHOR- CARBON			
SYSTEMS	**Coupled Human and Natural Systems**		
GENERAL PROCESSES	**Generation (Reduction) of Organic Carbon**	**Modification & Movement of Organic Carbon**	**Oxidation (Destruction) of Organic Carbon**
SPECIFIC PROCESSES	Photosynthesis, plant growth, primary productivity, reforestation	Synthesis of molecules, digestion, growth, accumulation & sequestration of organic carbon, food chains and webs matter flow, succession	Cellular respiration, weight loss, destruction of organic carbon, decomposition, combustion, energy users, transportation and electrical systems, global warming, urbanization, and industrialization
PROGRESS VARIABLES			
Structure of Systems **Description:** **Atomic-Molecular: energy-rich materials (resources & sources), CO_2 & O_2, chemical bonds** **Micro: single cellular organisms, chloroplasts, organelles, cells** **Macro: multi-cellular organisms, energy users, energy sources** **Large: populations & ecosystem, matter pools and reservoirs, energy resources**	Elem: • Identify energy-rich materials from various materials (macroscopic) • Identify and compare organisms living in ecosystems including plants, animals, fungi, and things that are living in soil. (macroscopic) MS & HS: • Explain why glucose, fat and fossil fuels are energy-rich materials in terms of chemical bonds (atomic-molecular) • Describe organic materials in terms of their composition • Explain why fossil fuels are energy resources in terms of chemical bonds and compare these materials to organic molecules used by living organisms (atomic-molecular) • Describe ecosystems in terms of producers, consumers, and decomposers (microscopic, macroscopic, large) • Describe and compare ecosystems in terms of pools of organic matter (large-scale)		
Tracing matter **Description:** **Atomic-Molecular: biomolecules, fossil fuels, CO_2 & O_2** **Micro: cells** **Macro: growth, weight gain and weight loss** **Large: ecological matter flow, fossil fuel and transportation systems, atmospheric CO_2, air quality**	Elem: • Identify and compare living organisms in terms of their food source • Explain why humans and animals need food to grow • Identify the materials that organisms need for growth and energy • Explain what plants need to grow and how they make and use food (for energy) MS & HS: • Explain the process by which organic carbon is generated in plants (i.e., photosynthesis) • Explain the movement, transformation and conservation of matter between the non-living environment and living organisms •	Elem: • Identify and compare living organisms in terms of their food source • Explain why humans and animals need food to grow MS & HS: • Explain the process by which living organisms accumulate organic carbon (i.e., growth) • Explain how organic matter moves through ecosystems (e.g., food chains and webs) • Explain how populations accumulate and sequester organic carbon	Elem: • Identify decomposers and decomposition processes • Describe conditions and materials for combustion MS & HS: • Explain the process by which organic carbon is oxidized in living organisms (i.e., respiration) • Explain the movement, transformation and conservation of matter between the non-living environment and living organisms • Explain the processes by which organic carbon is oxidized in human-energy systems (i.e., combustion)
Energy Flow **Micro: energy resources and sources** **Macro: energy transformations and first and second order energy users, energy deliverers** **Large: ecological energy flow, energy degradation, human energy systems**	Elem: • Identify and compare living organisms in terms of their energy sources MS & HS • Identify energy sources and explain energy transformation in biochemical processes (i.e., photosynthesis) • Identify and compare energy-rich materials	Elem: MS & HS: • Explain energy transformation in biochemical processes • Explain energy transformation in trophic pyramids. • Explain energy transformation in the processes of household electricity use and burning fossil fuels.	Elem: • Identify and compare living organisms in terms of their energy sources • Identify energy resources for human energy-systems (e.g., fuels) • Identify energy sources for human energy systems (e.g., electrical appliances). • Describe how humans use materials (such as fossil fuels) to power homes and for transportation MS & HS: • Identify and compare energy-rich materials

			• Identify energy sources and explain energy transformation in biochemical processes (i.e., respiration) • Explain energy degradation in biochemical processes (i.e., respiration) • Explain energy degradation in trophic pyramid. • Identify energy sources and explain energy degradation in the processes of household electricity use and burning fossil fuels. • Identify energy resources for human energy systems
Change over Time **Description:** **Large: Succession, reforestation, deforestation, agriculture, global warming, industrialization, urbanization**	MS & HS: • Explain how disturbances (e.g., deforestation, farming) affect pools and fluxes of organic carbon • Explain how ecosystems accumulate and sequester organic carbon at different stages of succession		MS & HS: • Describe human sources of atmospheric CO_2 and explain the relationship between atmospheric CO_2 and global warming
Inquiry			
Citizenship			

Tracing Matter Levels



Level	General Description	Quantitative reasoning	Hierarchy of systems at different scales	Material kinds, properties of matter
7	**Tracing matter through multiple processes, in multiple scales and systems.**	Uses quantitative measurements of carbon fluxes through multiple processes in multiple scales. Uses stoichiometric calculations of balanced chemical equations to connect atomic-molecular quantity with macroscopic measures of mass or volume and measurements at large scale.	Traces elements or atoms through multiple processes in multiple scales (macroscopic, microscopic, atomic-molecular scale, and large scale)	Correctly characterizes reactants and products of processes in terms of how they affect organic carbon compounds: Creating (photosynthesis) Moving or altering (eating, digestion, growth, refining fuels) Destroying (combustion, cellular respiration)
6	**Trace matter through single life process, relating multiple scales.**	Uses stoichiometric calculations of balanced chemical equation to connect atomic-molecular quantity with macroscopic measures of mass or volume.	Traces elements or atoms through single life process, relating multiple scales (atomic-molecular, macroscopic, and large scales) Correctly describes living and non-living systems as composed of specific substances and classes of substances: CO2, O2, carbon-containing organic compounds. Relates substances to chemical formula.	Correctly identifies reactants and products of single life process: Substances/molecules and the elements/atoms of which they are composed. Recognizes chemical identity of carbon-containing organic substances and relates it with energy.
5	**Attention to the conservation and chemical identity of specific substances or molecules in simple chemical changes (including gas)** *Chemical identity* of substances: distinguishes between: Organic substances in all organisms; Chemical identity of gases.	Conserves mass in chemical changes or physical changes involving solids, liquids, gases.	Describes movements of matters in simple chemical changes at atomic-molecular scale. (not just events)	Correctly identifies reactants and products in simple chemical changes. Identifies solids, liquids, and gases involved in chemical and physical changes. Identifies some organic molecules in cells and all organisms including decomposers.
4	**Attention to the conservation of specific substances at macroscopic scale (not including gas)** Distinguish matter and non-matter Successful explanations of physical change.	Conserves mass in chemical changes or physical changes of solids and liquids, but not gases. (e. g. matter movement through food chain)	Describe matter movement at macroscopic scale.(not just events). Describes large-scale movements of matter (not just events). (e.g. movement of matter through food chains, supply chains and etc.) Describe physical changes in terms of arrangement and motion of molecules.	Correctly identifies some reactants and products of simple chemical changes. Identifies solids, liquids, but not gases involved in chemical or physical changes. Distinguishes between substances and forms of energy or conditions (e.g., heat, light, temperature) in physical and chemical changes Describe transformation of organic matter.
3	**Attention to hidden mechanism** Identifies *material kind at micro-scale* and constructs a relevant explanatory framework: Macroscopic materials are composed of invisible particles, so macroscopic properties of materials are determined by the properties of individual particles.	Distinguish changes in mass, volume, density. Identifies weight/mass as the most fundamental measure of amount of material. Relies on measured weight over felt weight.	Attention to hidden mechanism. Describes events (e.g., burning, growth) as changes in materials.	Attention to hidden mechanism, but cannot identify any material kinds. Identify properties of substances in physical change and recognizes that physical changes (dividing, melting, freezing) do not change materials.
2	**Attention to Observable Change:** Intuitive judgments of amount. Identifies *material change as events at macro-scale*	Intuitive judgments of amount. (Felt weight such as: A lot or a little, more or less, heavier or lighter, and etc.) No clear distinction among size, mass(weight), volume.	Describe changes as events (at macroscopic scale)	Identify changes by common sense of natural phenomena, but not as changes in materials and cannot identify material kinds.
	Egocentric/Naturalistic reasoning Respondents use human experience or natural/magical ways to explain the process	Does not recognize that the amount of material will not change when the material changes its shape.	Egocentric/Naturalistic Reasoning: Respondents use human analogy to explain the changes in materials. Describes changes in terms of personal actions--how to make them happen as opposed to how or why they happen.	
0	**Unintelligible**	Unintelligible	Unintelligible	