Content Connections
Energy and Matter

Introduction

The STeLLA Program intentionally places student thinking at the foreground of student learning. The purpose of this document is to support and further your own understanding about your students' possible ideas about genetics and ways these ideas may influence their ability to develop a conceptual understanding about how DNA can influence the traits that an organism shows. You can use it to develop your knowledge and skill in anticipating and responding to student ideas and confidently guiding student learning.

The content is written with you, the teacher, in mind. It presents subject matter knowledge that is tied to the lessons you will be teaching in the spring semester of the STeLLA program. It provides a rationale for sequencing and structuring student learning experiences to address shortcomings in typical instruction that have been shown to lead students to miss some important conceptual links between their understanding of genetics and how DNA influences the traits of an organism. Common student ideas are described throughout this document. Although these common student ideas are scientifically inaccurate, these ideas, when surfaced and made explicit to students, can be used as building blocks to a more meaningful and scientifically accurate understanding of the science content.

Next Generation Science Standards

To ensure that the Energy and Matter unit builds toward a conceptual understanding of the ideas, it is important to consider the three-dimensional learning experiences that will help students best develop their understanding. To that end, the *Next Generation Science Standards* are one option that can be used as a guide as a framework for developing lessons. The next page shows the applicable standards from the *NGSS* for an Energy and Matter unit.

As you teach the Energy and Matter Lessons, look for opportunities to make science ideas embodied in the Disciplinary Core Ideas, the Crosscutting Concepts, and the Science and Engineering Practices explicit to students. Although "Developing and Using Models" and "Constructing Explanations and Designing Solutions" are the practices that are the focus of the Performance Expectations, there are many opportunities to make others explicit, such as Using Mathematics and Computational Thinking. In considering Crosscutting Concepts, both "Energy and Matter," "Stability and Change," and "Systems and System Models" are prominent concepts that should be made explicit to students.

HS.Matter and Energy in Organisms and Ecosystems

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Students who demonstrate understanding can:

HS-LS1-5. Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy. [Clarification Statement: Emphasis is on illustrating inputs and outputs of matter and the transfer and transformation of energy in photosynthesis by plants and other photosynthesizing organisms. Examples of models could include diagrams, chemical equations, and conceptual models.] [Assessment Boundary: Assessment does not include specific biochemical steps.]

HS-LS1-6. Construct and revise an explanation based on evidence for how carbon, hydrogen, and oxygen from sugar molecules may combine with other elements to form amino acids and/or other large carbon-based molecules. [Clarification Statement: Emphasis is on using evidence from models and simulations to support explanations.] [Assessment Boundary: Assessment does not include the details of the specific chemical reactions or identification of macromolecules.]

HS-LS1-7. Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed, resulting in a net transfer of energy. [Clarification Statement: Emphasis is on the conceptual understanding of the inputs and outputs of the process of cellular respiration.] [Assessment Boundary: Assessment should not include identification of the steps or specific processes involved in cellular respiration.]

HS-LS2-3. Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions. [Clarification Statement: Emphasis is on conceptual understanding of the role of aerobic and anaerobic respiration in different environments.] [Assessment Boundary: Assessment does not include the specific chemical processes of either aerobic or anaerobic respiration.]

HS-LS2-4. Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem. [Clarification Statement: Emphasis is on using a mathematical model of stored energy in biomass to describe the transfer of energy from one trophic level to another and that matter and energy are conserved as matter cycles and energy flows through ecosystems. Emphasis is on atoms and molecules such as carbon, oxygen, hydrogen and nitrogen being conserved as they move through an ecosystem.] [Assessment Boundary: Assessment is limited to proportional reasoning to describe the cycling of matter and flow of energy.]

HS-LS2-5. Develop a model to illustrate the role of photosynthesis and cellular respiration in the cycling of carbon among the biosphere, atmosphere, hydrosphere, and geosphere. [Clarification Statement: Examples of models could include simulations and mathematical models.] [Assessment Boundary: Assessment does not include the specific chemical steps of photosynthesis and respiration.]

The performance expectations above were developed using the following elements from the NRC document *A Framework for K-12 Science Education*:

Science and Engineering Practices

Developing and Using Models

Modeling in 9–12 builds on K–8 experiences and progresses to using, synthesizing, and developing models to predict and show relationships among variables between systems and their components in the natural and designed worlds.

- Use a model based on evidence to illustrate the relationships between systems or between components of a system. (HS-LS1-5),(HS-LS1-7)
- Develop a model based on evidence to illustrate the relationships between systems or components of a system. (HS-LS2-5)

Using Mathematics and Computational Thinking

Mathematical and computational thinking in 9-12 builds on K-8 experiences and progresses to using algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials and logarithms, and computational tools for statistical analysis to analyze, represent, and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions.

- Use mathematical representations of phenomena or design solutions to support claims. (HS-LS2-4)

Constructing Explanations and Designing Solutions

Constructing explanations and designing solutions in 9–12 builds on K–8 experiences and progresses to explanations and designs that are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories.

- Construct and revise an explanation based on valid and reliable evidence obtained from a variety of sources (including students' own investigations, models, theories, simulations, peer review) and the assumption that theories and laws that describe the natural world operate today as they did in the past and will continue to do so in the future. (HS-LS1-6),(HS-LS2-3)

Connections to Nature of Science

Scientific Knowledge is Open to Revision in Light of New Evidence

- Most scientific knowledge is quite durable, but is, in principle, subject to change based on new evidence and/or reinterpretation of existing evidence. (HS-LS2-3)

Disciplinary Core Ideas

LS1.C: Organization for Matter and Energy Flow in Organisms

- The process of photosynthesis converts light energy to stored chemical energy by converting carbon dioxide plus water into sugars plus released oxygen. (HS-LS1-5)
- The sugar molecules thus formed contain carbon, hydrogen, and oxygen: their hydrocarbon backbones are used to make amino acids and other carbon-based molecules that can be assembled into larger molecules (such as proteins or DNA), used for example to form new cells. (HS-LS1-6)
- As matter and energy flow through different organizational levels of living systems, chemical elements are recombined in different ways to form different products. (HS-LS1-6),(HS-LS1-7)
- As a result of these chemical reactions, energy is transferred from one system of interacting molecules to another. Cellular respiration is a chemical process in which the bonds of food molecules and oxygen molecules are broken and new compounds are formed that can transport energy to muscles. Cellular respiration also releases the energy needed to maintain body temperature despite ongoing energy transfer to the surrounding environment.(HS-LS1-7)

LS2.B: Cycles of Matter and Energy Transfer in Ecosystems

- Photosynthesis and cellular respiration (including anaerobic processes) provide most of the energy for life processes. (HS-LS2-3)
- Plants or algae form the lowest level of the food web. At each link upward in a food web, only a small fraction of the matter consumed at the lower level is transferred upward, to produce growth and release energy in cellular respiration at the higher level. Given this inefficiency, there are generally fewer organisms at higher levels of a food web. Some matter reacts to release energy for life functions, some matter is stored in newly made structures, and much is discarded. The chemical elements that make up the molecules of organisms pass through food webs and into and out of the atmosphere and soil, and they are combined and recombined in different ways. At each link in an ecosystem, matter and energy are conserved. (HS-LS2-4)
- Photosynthesis and cellular respiration are important components of the carbon cycle, in which carbon is exchanged among the biosphere, atmosphere, oceans, and geosphere through chemical, physical, geological, and biological processes. (HS-LS2-5)

PS3.D: Energy in Chemical Processes

- The main way that solar energy is captured and stored on Earth is through the complex chemical process known as

Crosscutting Concepts

Systems and System Models

- Models (e.g., physical, mathematical, computer models) can be used to simulate systems and interactions—including energy, matter, and information flows—within and between systems at different scales. (HS-LS2-5)

Energy and Matter

- Changes of energy and matter in a system can be described in terms of energy and matter flows into, out of, and within that system. (HS-LS1-5), (HS-LS1-6)
- Energy cannot be created or destroyed—it only moves between one place and another place, between objects and/or fields, or between systems.(HS-LS1-7),(HS-LS2-4)
- Energy drives the cycling of matter within and between systems. (HS-LS2-3)

*The performance expectations marked with an asterisk integrate traditional science content with engineering through a Practice or Disciplinary Core Idea.

	photosynthesis. *(secondary to HS-LS2-5)*	

Connections to other DCIs in this grade-band: **HS.PS1.B** (HS-LS1-5),(HS-LS1-6),(HS-LS1-7),(HS-LS2-3),(HS-LS2-5); **HS.PS2.B** (HS-LS1-7); **HS.PS3.B** (HS-LS1-5),(HS-LS1-7),(HS-LS2-3),(HS-LS2-4); **HS.PS3.D** (HS-LS2-3),(HS-LS2-4); **HS.ESS2.A** (HS-LS2-3); **HS.ESS2.D** (HS-LS2-5)

Articulation across grade-bands: **MS.PS1.A** (HS-LS1-6); **MS.PS1.B** (HS-LS1-5),(HS-LS1-6),(HS-LS1-7),(HS-LS2-3); **MS.PS3.D** (HS-LS1-5),(HS-LS1-6),(HS-LS1-7),(HS-LS2-3),(HS-LS2-4),(HS-LS2-5); **MS.LS1.C** (HS-LS1-5),(HS-LS1-6),(HS-LS1-7),(HS-LS2-3),(HS-LS2-4),(HS-LS2-5); **MS.LS2.B** (HS-LS1-5),(HS-LS1-7),(HS-LS2-3),(HS-LS2-4),(HS-LS2-5); **MS.ESS2.A** (HS-LS2-5); **MS.ESS2.E** (HS-LS1-6)

Common Core State Standards Connections:

ELA/Literacy –

RST.11-12.1	Cite specific textual evidence to support analysis of science and technical texts, attending to important distinctions the author makes and to any gaps or inconsistencies in the account. (HS-LS1-6),(HS-LS2-3)
WHST.9-12.2	Write informative/explanatory texts, including the narration of historical events, scientific procedures/ experiments, or technical processes. (HS-LS1-6),(HS-LS2-3)
WHST.9-12.5	Develop and strengthen writing as needed by planning, revising, editing, rewriting, or trying a new approach, focusing on addressing what is most significant for a specific purpose and audience. (HS-LS1-6),(HS-LS2-3)
WHST.9-12.9	Draw evidence from informational texts to support analysis, reflection, and research. (HS-LS1-6)
SL.11-12.5	Make strategic use of digital media (e.g., textual, graphical, audio, visual, and interactive elements) in presentations to enhance understanding of findings, reasoning, and evidence and to add interest. *(HS-LS1-5),(HS-LS1-7)*

Mathematics –

MP.2	Reason abstractly and quantitatively. (HS-LS2-4)
MP.4	Model with mathematics. *(HS-LS2-4)*
HSN-Q.A.1	Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays. (HS-LS2-4)
HSN-Q.A.2	Define appropriate quantities for the purpose of descriptive modeling. *(HS-LS2-4)*
HSN-Q.A.3	Choose a level of accuracy appropriate to limitations on measurement when reporting quantities. (HS-LS2-4)

Common Student Idea #1
Photosynthesis occurs during the day and cellular respiration occurs at night.

Students may understand that photosynthesis requires sunlight and therefore takes place during the day; but understanding its relationship to cellular respiration can be challenging. Cellular respiration is sometimes described as being the reverse of photosynthesis. Students may misinterpret this description as meaning that it takes place at night. Cellular respiration is used to provide chemical energy needed by plants to carry out life functions such as building cell structures, repairing damage, and catalyzing chemical reactions. These critical life functions must be carried out all the time, day and night. So, while photosynthesis does take place only in the day time, cellular respiration proceeds both day and night.

Common Student Idea #2
During photosynthesis, energy from sunlight is transformed into sugar.

While it is true that energy from sunlight is an input to photosynthesis and sugar is an output of photosynthesis, it is not correct to describe sunlight being transformed into sugar. Energy is not a molecule; it is not matter. Rather, students should understand that during the process of photosynthesis, solar energy is collected and transformed into chemical energy. Likewise, cellular respiration doesn't make energy. It provides energy by forming strong oxygen bonds in carbon dioxide and water and breaking weaker bonds in sugars.

Common Student Idea #3
Plants increase in mass by taking up chemicals from the soil.
Students may assume that plants increase in mass by taking up chemicals from the soil because of two different but related misconceptions. First, they may find it hard to accept that an invisible gas like carbon dioxide can contribute mass to something solid like a tree trunk. It is important to stress that most of the mass increase in plants comes from carbon-containing polymers, especially cellulose. Cellulose in turn is built from glucose, a product of photosynthesis. A second misconception may arise from an incomplete understanding of what plants take up from the soil. Certainly, plants take up water from the soil. But water is made up of just two elements: hydrogen and oxygen. So, water cannot be the source of carbon-containing biomass. Dissolved in the water taken up by plants are important nutrients and minerals. The most essential of these nutrients are nitrogen, phosphorous, and potassium. Understanding the importance of carbon fixation is the key understanding students need to acquire.

Common Student Idea #4
Fertilizer is food for plants.
Plants do not eat food in the sense that we and other animals do. Plants produce their own food through photosynthesis. So, if fertilizer is not accurately described as plant food then what is it? It can be thought of as a supplemental nutrient, not that different from say a calcium pill you took during breakfast. The food produced by photosynthesis in is the form of carbohydrates. Carbohydrates contain the essential elements of carbon, oxygen, and hydrogen. But there are other essential elements that plants need to be healthy. For example, nitrogen is needed to make proteins and phosphorus is needed to make nucleic acids. Potassium is needed for many physiological processes such as opening and closing stomata, producing Adenosine Triphosphate (ATP), and regulating water balance. Plants obtain these essential elements by uptake through their roots. If one or more of these essential elements are missing, then fertilizer is used to make up for the deficiency.

Common Student Idea #5
Plants use undergo cellular respiration to provide CO_2 to make sugars.
This belief can arise when students recall that photosynthesis requires CO_2 to make carbohydrates and it is also produced by the process of cellular respiration. Plant cells do not create CO_2 in order to supply it for photosynthesis. Carbon dioxide is a gaseous waste product of cellular respiration. It does not stay within the cell to be used by photosynthesis. Instead it leaves the plant through the stomata and enters the atmosphere. Carbon dioxide also enters plant cells through the stomata and it is this CO_2 that is used for photosynthesis.

Common Student Idea #6

Photosynthesis takes place in plants while cellular respiration takes place in animals.

When students learn about photosynthesis, they understandably associate the process with green plants. They also recall that photosynthesis does not occur in animal cells. In a similar way, animal cells are associated with cellular respiration. Students may erroneously believe that cellular respiration is restricted to animal cells. It is important to remember the different purposes of photosynthesis and cellular respiration. Photosynthesis is used by plants to produce the food, or chemical energy, that they need to power various cellular processes needed to sustain life. In contrast, animals obtain their food by ingesting it from plants or other animals. Cellular respiration is the process whereby cells release chemical energy in food and store it in Adenosine Triphosphate (ATP) molecules. These ATP molecules then provide the chemical energy needed to power thousands of chemical reactions associated with biosynthesis, growth, and repair. Both plants and animals need to obtain chemical energy from food, so both types of organisms must carry out cellular respiration.

Common Student Idea #7

Cellular respiration is the opposite of photosynthesis.

When studying photosynthesis and cellular respiration, each process is often simplified to its summary equation. They look like this:

Photosynthesis

$$6CO_2 + 6H_2O + \text{sunlight} \longrightarrow C_6H_{12}O_6 + 6O_2$$

Cellular Respiration

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

These summary equations do look like the reverse of each other. The CO_2 and H_2O inputs of photosynthesis are the same as the outputs of cellular respiration. Likewise, the $C_6H_{12}O_6$ and O_2 inputs of cellular respiration are the same as the outputs of photosynthesis. The reality however is more complicated. Each summary equation is a shorthand description for a long sequence of chemical reactions that are not the reverse of each other.

First, photosynthesis takes place in chloroplasts while cellular respiration takes place in mitochondria. Photosynthesis begins with the chlorophyll-dependent absorption of sunlight. Cellular respiration ends with the production energy, but of course not sunlight. Instead, it transfers chemical energy from glucose to ATP. The long series of enzyme-mediated reactions that characterize photosynthesis and cellular respiration are not the reverse of each other. To give one example, an enzyme called Rubisco catalyzes the reaction that takes CO_2 from the air and fixes it into a hydrocarbon molecule. Rubisco is not found in mitochondria and is not involved in cellular respiration. Instead, CO_2 is released by a different chemical reaction.

Common Student Idea #8

Cellular respiration and breathing are the same thing.

The use of the word "respiration" can be confusing. For most students, the term respiration suggests the physiological process of breathing: inhaling and exhaling. Cellular respiration however is a sequence of chemical reactions that transfers the chemical energy of glucose to molecules of ATP that are used as an energy currency to power other cellular processes. Many organisms such as plants and insects do not have lungs, so they cannot breathe as we do. Instead they get oxygen through stomata in plants and tiny tubes called tracheae in insects. Nevertheless, these organisms do respire; they undergo cellular respiration.

Common Student Idea #9

Cellular respiration and anaerobic respiration are unrelated to each other.

In eukaryotic cells, oxygen is a required input for cellular respiration. This fact may cause some students to believe that cellular respiration and anaerobic respiration are not related to each other. Cellular respiration is divided into three stages: Glycolysis, the Krebs Cycle, and the Electron Transport Chain. The first stage glycolysis takes place in the cell cytosol and can occur in the absence of oxygen. This means that anaerobic respiration is actually a normal part of cellular respiration. If oxygen is present, then the pyruvate produced by glycolysis is transported into the mitochondria where it moves on through the Krebs cycle and the electron transport chain producing the large majority of ATP associated with cellular respiration. Sometimes however, eukaryotic cells undergo anaerobic respiration. When muscle cells are working very hard, they can exhaust their oxygen supply. In such a case, the cells use an anaerobic pathway that produces lactic acid and ATP.

Common Student Idea #10
Energy is released whenever chemical bonds are broken.
This idea is prevalent because students focus on bond breaking and not on the bond formation process. For all chemical reactions, energy is required to first break chemical bonds. Energy is released when new chemicals bonds are formed. A covalent chemical bond is result of a system lowering its potential energy. For example, in hydrogen gas (H_2), the atoms are close to each other. Attractive and repulsive forces are involved. The resulting bond length between the two atoms represents an equilibrium where attraction and repulsion are balanced. When this bond is broken, the atoms are pulled away from each other, increasing the potential energy.

Common Student Idea #11
Energy is a fuel
Students should understand that fuel, whether we're talking about petroleum or the food we eat is a source of energy, but not energy itself. Fuels can react with oxygen to produce energy.

Common Student Idea #12
Energy can be recycled.
Matter of course is recycled. It cannot be created or destroyed. The same is true for energy. It cannot be created or destroyed; however, it is not recycled, but instead flows through an ecosystem. During cellular respiration, the carbon-carbon bonds in glucose are broken and combined with oxygen to form carbon dioxide. During this rearrangement of chemical bonds, energy is released and used to carry on any number of life processes. Ultimately however, the fate of this energy is to be lost as heat.