IS2 Living Earth Instructional Segment 2: History of Earth's Atmosphere: Photosynthesis and Respiration

In the middle grades, students explained the role photosynthesis plays in cycling of matter by the production of sugars (food) using light energy and carbon dioxide (MS-LS1-6), and developed a model of how food molecules can be rearranged to extract usable energy (MS-LS1-7). They also are already familiar with cycles of matter within a system from their investigation of the water cycle (5-LS2-1, MS-ESS2-4). In this instructional segment, students explore the **cycling of matter [CCC-5]** between the biosphere and the rest of Earth's **systems [CCC-4]**.

LIVING EARTH INSTRUCTIONAL SEGMENT 2: EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND RESPIRATION

Guiding Questions

- How do living things acquire energy and matter for life?
- How do organisms store energy?
- How are photosynthesis and cellular respiration connected?
- How do organisms use the raw materials they ingest from the environment?
- How has the cycling of energy and matter changed over Earth's history?

Performance Expectations

Students who demonstrate understanding can do the following:

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.]*

LIVING EARTH INSTRUCTIONAL SEGMENT 2: EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND 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-LS2-5. 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.]*

HS-ESS1-6. Apply scientific reasoning and evidence from ancient Earth materials, meteorites, and other planetary surfaces to construct an account of Earth's formation and early history. [Clarification Statement: Emphasis is on using available evidence within the solar system to reconstruct the early history of Earth, which formed along with the rest of the solar system 4.6 billion years ago. Examples of evidence include the absolute ages of ancient materials (obtained by radiometric dating of meteorites, moon rocks, and Earth's oldest minerals), the sizes and compositions of solar system objects, and the impact cratering record of planetary surfaces.]

HS-ESS2-6. Develop a quantitative model to describe the cycling of carbon among the hydrosphere, atmosphere, geosphere, and biosphere. [Clarification Statement: **The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere. (CA)** Emphasis is on modeling biogeochemical cycles that include the cycling of carbon through the ocean, atmosphere, soil, and biosphere (including humans), providing the foundation for living organisms.]

HS-ESS2-7. Construct an argument based on evidence about the simultaneous coevolution of Earth's systems and life on Earth. [Clarification Statement: Emphasis is on the dynamic causes, effects, and feedbacks between the biosphere and Earth's other systems, whereby geoscience factors control the evolution of life, which in turn continuously alters Earth's surface. Examples of include how photosynthetic life altered the atmosphere through the production of oxygen, which in turn increased weathering rates and allowed for the evolution of animal life; how microbial life on land increased the formation of soil, which in turn allowed for the evolution of land plants; or how the evolution of corals created reefs that altered patterns of erosion and deposition along coastlines and provided habitats for the evolution of new life forms.] *[Assessment Boundary: Assessment does not include a comprehensive understanding of the mechanisms of how the biosphere interacts with all of Earth's other systems.]*

HS-ESS3-6. Use a computational representation to illustrate the relationships among Earth systems and how those relationships are being modified due to human activity.* [Clarification Statement: Examples of Earth systems to be considered are the hydrosphere, atmosphere, cryosphere, geosphere, and/or biosphere. An example of the far-reaching impacts from a human activity is how an increase in atmospheric carbon dioxide results in an increase in photosynthetic biomass on land and an increase in ocean acidification, with resulting impacts on sea organism health and marine populations.] *[Assessment Boundary: Assessment does not include running computational representations but is limited to using the published results of scientific computational models.]* (Introduced but not fully assessed until IS6)

LIVING EARTH INSTRUCTIONAL SEGMENT 2: EARTH'S ATMOSPHERE: PHOTOSYNTHESIS AND RESPIRATION

The bundle of performance expectations above focuses on the following elements from the NRC document *A Framework for K–12 Science Education*:

Highlighted Science and Engineering Practices	Highlighted Disciplinary Core Ideas	Highlighted Crosscutting Concepts
[SEP-2] Developing and Using Models [SEP-5] Using Mathematics and Computational Thinking [SEP-6] Constructing Explanations (for science) and Designing Solutions (for engineering) [SEP-7] Engaging in Argument from Evidence	LS1.C: Organization for Matter and Energy Flow in Organisms LS2.B: Cycles of Matter and Energy Transfer in Ecosystems PS1.C: Nuclear Processes PS3.D: Energy in Chemical Processes ESS2.D: Weather and Climate ESS2.E: Biogeology ESS3.D: Global Climate Change	[CCC-1] Patterns [CCC-4] Systems and System Models [CCC-5] Energy and Matter: Flows, Cycles, and Conservation [CCC-7] Stability and Change

Highlighted California Environmental Principles and Concepts:

Principle II The long-term functioning and health of terrestrial, freshwater, coastal, and marine ecosystems are influenced by their relationships with human societies.

Principle III Natural systems proceed through cycles that humans depend upon, benefit from and can alter.

Principle IV The exchange of matter between natural systems and human societies affects the long-term functioning of both.

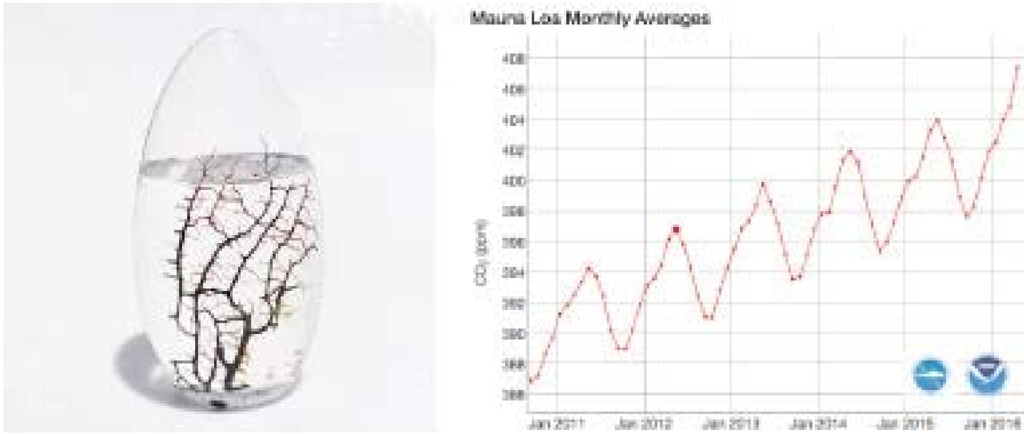
CA CCSS Math Connections: N-Q.1–3; F.IF.5; S-ID.6.a–c; MP.2, MP.4

CA CCSS for ELA/Literacy Connections: SL.11–12.5; RST.11–12.1; WHST.9–12.2a–e, 5, 8, 9

CA ELD Connections: ELD.PI.11–12.1, 5, 6a–b, 9, 10, 11a

Students can consider the phenomenon of a sealed glass sphere that supports the survival and growth of both algae and brine shrimp (figure 7.3 left). How do they survive without air flowing in? On a more advanced level, they can observe how the global atmospheric CO_2 concentrations on Earth follow a distinctive **pattern [CCC-1]** each year (figure 7.3, right; because there is more land in the northern hemisphere and therefore more respiration during the growing season of the northern hemisphere summer). They should be able to explain and model each of these processes by the end of this instructional segment.

Figure 7.3. Phenomena Illustrating Relationship Between Photosynthesis and Respiration



A sealed sphere that supports survival of both brine shrimp and algae (left). CO_2 levels are highest in June each year and cycle annually (right). *Source*: Ecosphere Associates Inc. 2013 and National Oceanic and Atmospheric Administration (NOAA) 2016b

All living organisms need energy, and high school students further refine an understanding that began in elementary school when they first traced energy in ecosystems back to plants and the Sun. Photosynthesis by producers involves two interdependent cellular processes: capturing sunlight/light energy by chloroplasts and using that energy to fix atmospheric carbon dioxide into glucose molecules. Plants either use the glucose directly or store energy by connecting glucose molecules together to form starch (which is easier to store).

Opportunities for ELA/ELD Connections

Working with a partner, students select a law of thermodynamics to research and then explain how energy is transferred and conserved and how energy can be harnessed to perform useful tasks. Each pair must research multiple print and digital sources, synthesize and summarize the key points, and present their findings using a visual display (e.g., poster, slides, handouts). The presentation should include a general description/definition of the law plus an example demonstrating the application of the principle.

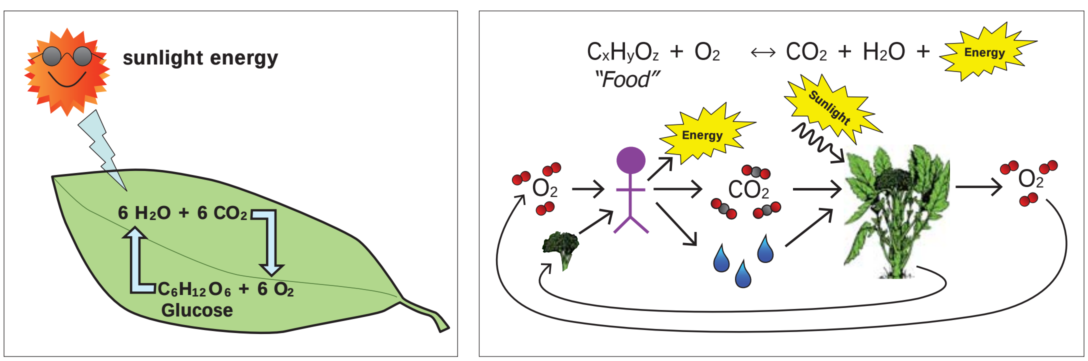
CA CCSS for ELA/Literacy Standards: RST.9–12.1, 2, 7, 9; WHST.9–12. 7, 8
CA ELD Standards: ELD.PI.9–12.6, 9

Heterotrophs (consumers or animals) ingest producers as food that they use for energy and building blocks for growth. Consumers often store energy in stacked glucose molecules in the form of glycogen (in higher animals, glycogen is stored in liver and muscle tissues). Both plants and animals use cellular respiration as the process by which organic molecules are broken down to release energy and form molecules of adenosine triphosphate (ATP).

The process of cellular respiration uses up oxygen and releases carbon dioxide. The ATP formed in cellular respiration has high levels of potential energy that allow cells to do work; and therefore, if there is no ATP then there is no life. The energy from ATP is released when it is converted back into adenine diphosphate (ADP). Students do not need to know the individual biochemical steps of these two processes but rather need to understand the connections between them. Students will need to understand that these processes happen so that organisms can make ATP, the molecular source or currency of energy for the cell.

The products of photosynthesis are used as the reactants for cellular respiration and vice versa. Students can create **models [SEP-2]** of these processes using chemical equations or pictorial models that emphasize the **energy and matter [CCC-5]** inputs and outputs from each process (HS-LS1-5, HS-LS1-7; figure 7.4). Sometimes both processes occur in the same organism, and sometimes the respiration occurs in a consumer after it has eaten the producer. With each cycle of organisms eating or being eaten, there is less **usable** energy available to the organism (a consequence of the second law of thermodynamics, HS-PS3-4). In this way, ecosystems are constantly losing usable energy and therefore rely on the Sun to provide a constant influx of energy.

Figure 7.4. Models of Photosynthesis and Respiration



Two models showing how photosynthesis and respiration are mirrors of one another, involving the same basic ingredients. Matter cycles within the Earth system between the two processes, but energy must constantly flow in as sunlight to replace the energy put to work by organisms to grow and survive. Diagrams by M. d'Alessio and V. Vandergon

Engineering Connection: Wastewater Treatment Facilities

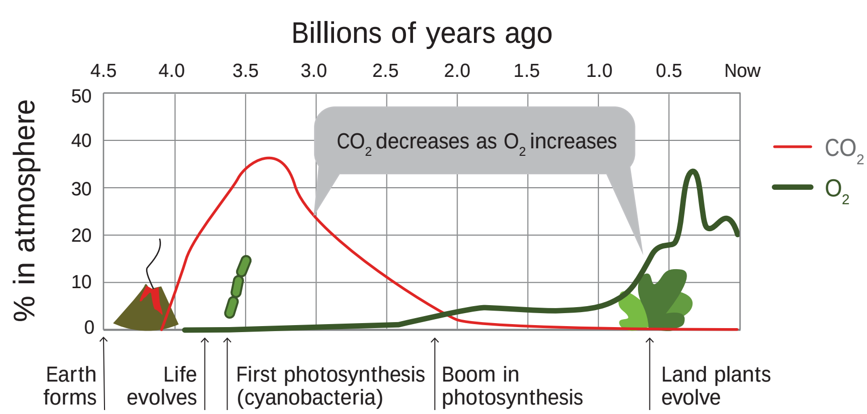
When raw sewage flows into waterways, it can impact the health of both humans and ecosystems (EP&Cs II, IV), which is why wastewater treatment facilities are an important part of all California cities. Engineers have learned to put biological processes to work to process human waste in wastewater treatment facilities. Students can **obtain information [SEP-8]** about the different stages of sewage treatment, some of which involve bacteria that rapidly decompose organic waste. Students can make physical **models [SEP-2]** of this process by using sugars to represent the organic waste, yeast to represent the waste-processing bacteria, and glucose test strips to measure the concentration of simulated waste in the water. Performing investigations using these models, students can develop techniques for speeding up the wastewater treatment process. Is there an optimal amount of yeast to add? Does the treatment process speed up or slow down when students add air or seal the container? What techniques can they develop for efficiently adding air? Students can **construct an explanation [SEP-6]** about how the change in oxygen in the bacteria's environment affects their respiration rate (HS-LS2-3).

A detailed model of photosynthesis and respiration can include the unique chemical properties of carbon. Carbon is structurally important to building all biological molecules, including the glucose molecule. What is so special about carbon? Carbon can covalently bond to four other atoms and forms single and double bonds with other atoms because of its electron structure and configuration. The same raw materials can be recombined in different configurations with different chemical potential energy, allowing carbon-based molecules to store or release energy during these changes. Students should be able to use computer simulations of this process to help them **construct explanations [SEP-6]** about how organisms build a wide range of organic molecules such as amino acids (HS-LS1-6).

Students can build a physical **model [SEP-2]** of a glucose molecule and show how to split it apart (with an emphasis on the components needed to build the glucose and the components left after the breakdown of the glucose). They should start with the atoms of carbon, hydrogen, and oxygen and make the simple molecules of CO_2, H_2O, and O_2 and then trace the movement of these molecules, much like they did in MS-LS1-7, but with added detail about what happens at each stage in the process. For example, the carbon dioxide and water are raw ingredients to photosynthesis and then are released as waste again in cellular respiration. CO_2's role in both processes means that photosynthesis and respiration are crucial parts of the global carbon cycle.

When did the **cycling of energy and matter [CCC-5]** start on Earth and how is cycling maintained? When asked what the Earth might have looked like 4.6 billion years ago when it first formed, students' *images* might be informed by prior knowledge that may include non-scientific sources and may not be consistent with the scientific understanding that Earth was lifeless. Teachers may need to explicitly discuss existing ideas and their sources before beginning instruction. When Earth first formed, its interior was still very hot and its interior rapidly convected (ties to HS-ESS2-3). Hot magma rising up is part of convection, so rapid convection caused volcanic activity in Earth's early history. When these volcanoes erupted, they released large amounts of gas that enriched our early atmosphere with CO_2. Around 3.4 billion years ago, organisms evolved that could perform photosynthesis, which disassembles CO_2. This marked the beginning of life's interaction with the global carbon cycle, an example of Earth's interacting **system [CCC-4]** of systems (biosphere interacts with atmosphere). In the CA NGSS, students must use evidence like the graph in figure 7.5 and their model of photosynthesis (HS-LS1-5) to **construct an argument [SEP-7]** that life has been an important influence on other components of the Earth system (HS-ESS2-7; HS-LS2-5). Early on, ocean water and chemical reactions with rock material absorbed much of the oxygen that plants produced. By examining records from rock layers, students can reconstruct aspects of Earth's early history (HS-ESS1-6). They can see evidence of biosphere-geosphere interactions in deep red colored rock layers called banded iron (because they are rich in iron oxides) that accumulated at the bottom of the ancient ocean. The oldest banded iron formations provide evidence of when plants first evolved, and thick deposits of banded iron about 2.4–1.9 billion years ago reveal another major **change [CCC-7]**—the expansion of multicellular cyanobacteria and a boom in photosynthesis.

Figure 7.5. CO_2 and O_2 in the Atmosphere



Concentrations of CO_2 and O_2 in Earth's atmosphere over its history. Dramatic changes happened as plants used CO_2 to grow biomass and released O_2 during photosynthesis. Diagram by M. d'Alessio, based on data from Holland 2006

Examining the carbon cycle will help students understand how Earth **systems [CCC-4]** maintain life. The exchange of carbon between the atmosphere and the biosphere is just one of many important interactions between Earth's systems that involve the movement of carbon. In fact, one of the few additions that California made in adopting the CA NGSS was to add this sentence to the Clarification Statement for HS-ESS2-6: "The carbon cycle is a property of the Earth system that arises from interactions among the hydrosphere, atmosphere, geosphere, and biosphere." Scientists track the movement of carbon atoms through the carbon cycle much like they track the movement of water molecules through the water cycle. In both cases, scientists think about the **cycle of matter [CCC-5]** within a closed **system [CCC-4]** because at this point in Earth's history, very little water or carbon leaves the planet or arrives from space. We simply need to track the movement of the matter that is already here. A biological model of the carbon cycle is shown in IS1.

In the CA NGSS, students must develop a quantitative **model [SEP-2]** of the carbon cycle (HS-ESS2-6), which needs to include the following:

1. Places where carbon accumulates within the Earth system (called *reservoirs*, reminiscent of the storage of water in the water cycle)
2. Processes by which carbon can be exchanged within and between reservoirs (called *flows*)
3. The relative importance of these reservoirs and processes is based on the amount of carbon they hold or transfer

Various representations exist for the carbon cycle, including simple pictures like figure 7.2. Interactive animations (such as WGBH "Carbon Dioxide and the Carbon Cycle" http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link5), hands-on experiments (see OMSI "Experiment: Burning Issues" http://www.cde.ca.gov/ci/sc/cf/ch7.asp#link6), and kinesthetic activities build on the static illustrations to help students develop conceptual **models [SEP-2]** of the reservoirs and processes by which carbon is exchanged between reservoirs. For example, students can develop a simple physical **model [SEP-2]** of the atmosphere-ocean **system [CCC-4]** by adding pH indicator to water in a closed container (see IS1 of the chemistry course). Students can use this model to **investigate [SEP-3]** what happens as a plant grows, a candle burns, or a person exhales through a straw into the water. They notice that pH changes as CO_2 from these sources interacts with the water to form carbonic acid. This same chemical reaction happens at the global scale with interactions between the atmosphere and the hydrosphere (PS1.B; IS6 of the chemistry course), making Earth's oceans one of the biggest reservoirs of carbon on the planet (see table 7.2 for the relative sizes of different reservoirs). Students will **explain [SEP-6]** how the concentration of CO_2 in the atmosphere affects the rate of a chemical reaction in HS-PS1-5 and the final concentration of acid in the ocean is an example of a system in equilibrium as explored in HS-PS1-6. Because the system is near equilibrium, massive amounts of carbon (about 80 gigatons) are absorbed into the ocean while massive amounts are also released back to the atmosphere. These opposite flows are similar in magnitude but do not balance out—the ocean absorbs about 2.5 gigatons per year more of carbon from the atmosphere than it releases back, causing the ocean to become more acidic. An acidic ocean can **cause [CCC-2]** major damage to plankton (that form the base of the ocean food chain, LS2.A, LS2.B) and coral reefs (which host a large portion of the ocean's biodiversity), both of which **affect [CCC-2]** sea life (LS3.C) (IS6 addresses human impacts). Scientists use complex computer models to calculate the expected changes in ocean chemistry based on different human activities, and the CA NGSS pushes students to use simple computer representations of **models [SEP-2]** to illustrate the relationships between different Earth **systems [CCC-4]** and **quantify [CCC-3]** how human activities change these systems (HS-ESS3-6; see IS6).

Table 7.2. Carbon Reservoirs and Atmospheric Flows

CARBON RESERVOIRS AND ATMOSPHERIC FLOWS			
RESERVOIR	**FORM OF CARBON**	**AMOUNT IN RESERVOIR**	**FLOW RATE WITH ATMOSPHERE**
Atmosphere	Mainly carbon dioxide (gas)	840 Gt	Greenhouse gases are increasing due to human activities.
Biomass (*biosphere*)	Sugar, protein, etc. (solid, liquid)	2,500 Gt (mostly in plants and soil)	About 120 Gt per year into and out of air. Currently absorbing about 2.5 Gt per year
Ocean (*hydrosphere*)	Mostly dissolved bicarbonate salts	41,000 Gt	About 80 Gt per year into and out of air. Currently absorbing about 2.5 Gt per year
Sedimentary rocks (*geosphere*)	Carbonate minerals (solid)	60,000,000 Gt	Negligible annually but important over very long time scales.
Fossil Fuels (*geosphere/ anthrosphere*)	Methane (gas) Petroleum (liquid) Coal (solid)	10,000,000 Gt	About 9 Gt per year into atmosphere, mostly from burning as fuels for energy.
Units are Gigatons (Gt) of carbon. 1 Gt = 1 billion tons			

Table by Dr. Art Sussman, courtesy of WestEd

Table 7.2 also reveals that the single largest reservoir of carbon is not in the air or water, but in rocks. How does it get there? After students learn about the chemical composition of life (LS1.C), they are able to explain why carbon is so important for so many of life's **systems [CCC-4]** (HS-LS1-6). Living organisms are therefore a large reservoir of carbon. When those organisms die, the carbon stored in their bodies can accumulate in layers that are buried over geologic time (discussed more in IS3). Heat and pressure, caused by burial, speed up chemical reactions that slowly reorganize the carbon and other elements into new, easily combustible molecules that we call fossil fuels, including oil (petroleum) and natural gas (including methane). To ensure that students see the connection between past life and oil formation, students can draw the stages of oil formation to summarize an article (The National Energy Education Development Project 2012, 13, 57). Extracting oil and gas from deep within the Earth and burning it harnesses energy that ancient plants and animals collected millions of years ago and that has been stored as chemical potential energy in materials trapped underground for millions of years. These materials are incredibly valuable for generating electricity, fueling our vehicles, and generally enabling modern society to thrive. Unfortunately, fossil fuels form very slowly and only under specific conditions and therefore are considered non-renewable because we consume them more quickly than they form. Access to fossil fuels occurs in specific places on Earth and California has large deposits, though extracting them can often leak or spill toxic chemicals into the air, land, and water (EP&C II, IV). While they are very convenient (EP&C V), they also disrupt the natural carbon cycle (EP&C III). Students weigh the cost and benefits of these fuels in the Physics of the Universe course.

IS3 Living Earth Instructional Segment 3: Evidence of Common Ancestry and Diversity

Evolutionary scientist Theodor Dobzhansky made the now famous quote, "Nothing in biology makes sense except in the light of evolution." Therefore, one option is for evolution to occur early in this course and much of the rest of the course explains the detailed mechanisms that **cause [CCC-2]** the **patterns [CCC-1]** introduced in this instructional segment.