Where did the light go?

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Introduction

St. Georges Technical High School is one of four public vocational-technical high schools in New Castle County, Delaware. The students represent diverse backgrounds – urban Wilmington, suburban Newark, and rural Middletown. The unique draw for a technical high school like ours is the ability for students to study a trade and graduate with a certification or license with the opportunity to dive directly into the workforce. Our students apply to St. Georges for a variety of reasons: learn a family trade, learn in a safer school environment when compared with a feeder high school, or earn a certification to join the workforce instead of continuing to a post-secondary school. With each graduating class, approximately fifty percent of students directly enter the workforce, an apprenticeship, or post-secondary trade school. The remaining fifty percent continue on to a four-year college/university, or a branch of the military.

The technical trades school environment offers students a distinctive high school experience. Each student earns a certificate or license in their field of study upon graduation. The trades offered to our students are as diverse as the students themselves; ranging from nursing to carpentry, web design to culinary, automotive technology to early childhood education, and a dozen other options. According to the school's data inventory, in the school year 2018—2019, out of 802 upperclassmen (sophomores, juniors, and seniors), 20% study a trade in the Public/Consumer Services cluster, 23% study a Construction trade, 35% study in the Health Career cluster, and 23% study in the Business and Technology cluster.

St. Georges, as a technical trade school, is considered a branch of the public-school system. Therefore, students have access to their career classes in addition to the state-mandated academic courses offered within St. Georges. I am one of the science instructors within the building; teaching biology to sophomores. This unit has been developed for biology, a required course for graduation by the state of Delaware. The topics covered in this course are as follows: ecology, cell biology, genetics, and evolution. This unit is intended to be incorporated into the ecology section of the course and can be revisited throughout multiple components of the ecology unit.

As a fully-inclusive school, students of all ability levels, both regular education and special education students, are placed in the same class and therefore it becomes important for the instructor to be able to differentiate each lesson. Following the blended learning educational model, this unit provides students with several choices in how they learn, express their knowledge, the pace at which they learn, and utilize technology to enhance their overall learning experience. Within the blended model, the teacher becomes a facilitator while the student becomes the gatherer, organizer, and applier of information. My role as a facilitator is to provide students with appropriate resources and experiences to extract information and scaffold the lesson. It is important that the teacher carefully identifies multiple modes of formative assessment throughout the unit to ensure all students are able to display their full understanding of the content.

The state of Delaware has adopted the Next Generation Science Standards (NGSS) and is currently implementing these standards into the high schools. There has been an increase in the number of standards being taught in tenth-grade biology; therefore, the amount of depth we are able to reach is limited. The goal is to increase student engagement and motivation into their own learning through the exploration of skills. Beginning with a phenomenon, students create their own questions, cultivating their own interest in Biology. The main skills assessed in this unit are investigating scientific concepts, supporting claims using evidence, and utilizing models to explain scientific ideas.

Rationale

This first portion of the unit is designed for students to investigate the role light energy plays in photosynthesis; the transformation of solar energy into chemical energy, and the release of chemical energy during cellular respiration back to the atmosphere in the form of heat. Photosynthesis and cellular respiration are taught twice during the biology course; first, as important life processes for living organisms, and for a second time during the study of calculating bond energy within an equation. This unit focuses on life processes as a means of conserving matter and energy through the lens of photosynthesis and cellular respiration. Conservation of energy is an important theme through the entire ecology unit, approximately a third of the biology course; yet students struggle with the intangibleness of energy and its ability to change forms as it moves. Understanding how light energy as an input is absorbed, converted to chemical energy, and stored within the chemical bonds of molecules during a chemical reaction helps students comprehend that the energy released during other reactions was simply stored within the molecular bonds of the reactants. Students use this knowledge in the second part of this unit when beginning their study of energy transfer through trophic levels and food webs. The unit continues with following the transfer of chemical energy, that had originated as solar energy, through trophic levels in an ecosystem.

Photosynthesis and cellular respiration are parts of a larger unit that covers ecosystem interactions and the carbon cycle, yet these two life processes are important in understanding conservation of matter and conservation of energy. This unit asks students to investigate the inputs and outputs of systems, through the examples of photosynthesis and cellular respiration. The creation of physical models allows students to transfer their knowledge and develop their own model to apply to other ecosystems. Within the analysis section of the unit, students distinguish that not all of the light energy is absorbed; some is reflected back to the atmosphere, but the energy absorbed is transferred to other systems on Earth. The ideas of absorption and reflection is explained through a discussion of why leaves are green. Students brainstorm why temperature and light intensity affect the rate of photosynthesis in plants. Students are able explain the absorption, transformation, and storage of energy while creating molecular models to demonstrate conservation of both matter and energy. Throughout the components of this unit, students build molecular models, draw their own models, and analyze systems to assess content understanding.

Trophic levels trace the incoming solar energy as it moves between organisms through consumption and back to the atmosphere at each level. Conservation of energy is a key concept during ecology; therefore, this segment of the unit introduces students to food chains and energy transfer withing ecosystems. After having studied energy through life processes in the first section of this unit, students extend their understanding of energy transfer and the cycling of matter to an entire ecosystem, rather than simply moving from between atmosphere and biosphere.

As a result of completing the curriculum unit, students have the ability to explain conservation of energy and conservation of matter through the processes of photosynthesis, cellular respiration, and trophic levels. Students are able to incorporate knowledge learned about the capture, the reflection, and the transformation of solar energy into their written responses. This unit gives students a foundation to continue following the flow of energy during the unit on food chains and the unit of calculating bond energy. By the end of the unit, students have a greater understanding of life processes that impact all organisms on earth.

Teachers can extend this unit to other areas of their curriculum. Extensions can include the differentiation between aerobic and anaerobic respirations, bond energy calculations, or differences between endothermic and exothermic reactions. Students are also able to apply conservation of energy to the carbon cycle, tracing the original solar energy to plants, fossil fuels, and eventually to the atmosphere by human activities. Traditionally, the carbon cycle focuses on conservation of matter; however, with students understanding the storing of energy in glucose, they should be able to explain where and how energy is transferred as carbon moves between reservoirs.

Content Objectives

With the completion of this unit, students will be able to:

- Explain photosynthesis and cellular respiration at the molecular level.

- Explain how energy is conserved during both photosynthesis and cellular respiration.
- Explain the energy transformations that take place during photosynthesis.
- Explain the transfer and conservation of energy as it moves between trophic levels.

Background

Life Processes

Photosynthesis is the chemical process occurring in the chloroplast of plant cells to convert solar energy into stored chemical energy, as glucose. This form of energy is usable by the plant, and other organisms, for daily metabolic processes. The inorganic molecular reactants of photosynthesis are six molecules of carbon dioxide and six molecules of water. Carbon dioxide is an atmospheric gas absorbed through the stoma on the leaf's surface and water is absorbed primarily by the roots from the soil. Within the chloroplast are chlorophyll, capturing solar energy entering the chloroplasts, providing the energy required to break the bonds between atoms in both carbon dioxide and water molecules. The loose atoms are rebuilt into a single organic glucose molecule and six oxygen molecules; the products of the chemical reaction. The oxygen is released back into the atmosphere as a waste product and the glucose, or other sugar, molecules are stored within the plant. This process is unique to plants as a food-making process that strictly occurs when sunlight is available to activate the reaction. Although plants are able to complete both photosynthesis and cellular respiration simultaneously, under ideal conditions, the rate of photosynthesis is thirty times greater than the rate of respiration in the same leaf tissue.[1] Due to the unique nature that photosynthesis require sunlight, this process is only able to occur during day time. Cellular respiration on the other hand is able to consistently occur, and is necessary to take place at all times.

Chlorophyll, pigment located in the plant's leaves, has the ability to absorb a large bandwidth of wavelengths, with the exception of yellow and green wavelengths, which are reflected back to the atmosphere. The two types of chlorophyll, chlorophyll a and chlorophyll b, absorb the longer wavelengths of red and shorter wavelengths of blue, respectively.[2] The absorption of these red and blue wavelengths means that only the yellow and green light incident on the leaves is reflected, which is why leaves appear green to our eye. When solar energy, in the form of photons, enters the cell, the absorption of the photons promotes the electrons to higher orbitals, or energy states. Only the lowest excited energy state is active in the chemical process of photosynthesis; when photons of shorter wavelength (higher energy) are absorbed, they promote the electron to one of many levels with even higher energy, but the electron falls back to the lowest-energy excited state prior to being used in photosynthesis.[3] In order for electrons to fall back toward a lower energy state, heat must be released.[4] The heat released is part of the system's inefficiency and inability to utilize all of the solar energy. Photosynthesis can increase until the point when all pigment molecules are engaged in absorbing and converting sunlight; this is a plant's saturation point.[5] During the time when the light intensity begins to decrease, i.e. autumn, chemical changes in the pigments occur, causing plants to begin to absorbing and reflecting different wavelengths. For example, the carotenoids, another pigment within leaves, absorb wavelengths mainly in the blue and green part of the spectrum, reflecting the red, yellow, and orange parts of the spectrum and creating the "autumn colors".[6] Both pigments absorb light for the plant to continue photosynthesis.

There are additional aspects to the process of photosynthesis, such as the two light reactions including the electron transport chain, thylakoid membrane, ATP (adenosine triphosphate), and ATP's transformation to ADP and NADPH as electron carriers. These are not referenced in this section because they are no longer part of the Next Generation Science Standards. The standards ask students to understand the inputs, outputs, and transfer of energy. If you are looking for additional information, please see section: An In-depth Look at Photosynthesis, at the bottom of the Background.

Cellular respiration occurs in all living organisms; converting the chemical energy stored in the bonds of glucose and other sugar molecules into usable energy, ATP. The mitochondria break down the sugar and oxygen gas to release the stored energy in the forms of heat and ATP. Carbon dioxide and water are products of this metabolic process. The carbon dioxide is removed from the organism as waste and the water is either removed or transported to a different part of the cell. The organism uses the released energy to complete daily metabolic processes, loses some of the energy as heat, and a portion of the energy is stored as muscle or fat. ATP is transported around the body to bring energy to necessary locations. The ATP molecule releases one of its phosphate groups, converting the molecule into ADP, and releasing the stored energy in the cell. Under typical aerobic respiration conditions, 38 ATP molecules are produced, while under anaerobic conditions, 2 ATP molecules are produced. The amount of ATP is important to understand when delving deeper into the differences between aerobic and anaerobic respiration, although the discussion of ATP to ADP is no longer a necessity.

Energy Transfer Among Trophic Levels

The solar energy absorbed by plants, also known as producers, is transformed into chemical energy for the plant to either use or store. Producers, or autotrophs, are organisms capable of converting inorganic molecules, such as carbon dioxide and water, into organic ones, such as glucose. Most terrestrial and aquatic plants perform photosynthesis; however, there are some exceptions of producers producing energy via chemosynthesis – another food-making process that does not require sunlight. This unit focuses on those producers capable of photosynthesis.

The stored chemical energy, initially produced during photosynthesis, is transferred to other organisms, heterotrophs, through the process of consumption. Heterotrophs, or consumers, are considered to be any organism unable to produce their own food source and must consume another organism. There are different types of heterotrophs: herbivores, who eat strictly producers; carnivores, who eat strictly other animals, and; omnivores, who eat both producers and other animals. Each of these types of consumers fits into one or more of the ecosystem's trophic levels. Primary consumers, organisms gaining energy from autotrophs, breakdown the chemical energy during cellular respiration for their own use and storage. Some of this released energy is in the form of heat and is discharged back into the atmosphere. This is a repetitive process by which one organism consumes another, to acquire energy for their own metabolic processes to sustain their life. Organisms who fill the primary consumer level, or first consumer, are either herbivores or omnivores. Beyond this primary consumer level, the next levels are only able to be filled by omnivores or carnivores. Students need to understand that when analyzing a food web, it is not describing whom eats whom, but where the energy is transferred.

This process of gaining chemical energy to break and build bonds continues as trophic levels increase. Approximately only ten percent of the energy from the previous trophic level is available to be transferred. The remaining ninety percent had been used in daily metabolic processes or lost as heat by the organism prior to being consumed. Due to this ten-percent transfer rule, the available energy decreases drastically after each round of consumption; therefore, limiting the number of organisms at higher trophic levels. For example, a population of grass produces one hundred percent of the available energy to the biosphere. The rabbit population would gain ten percent of the original one hundred percent of the energy. The fox, who consumed the rabbit, gains one percent of the original energy. This example of the grass, rabbit, and fox is only three trophic levels, containing two consumers. Food webs typically don't include more than three or four consumers; including the producer, this is four or five trophic levels. There is too little available energy for those higher-level consumers. These organisms typically conserve their energy and only expend it when absolutely necessary; hunting.

The Law of Conservation of Energy states that energy is not able to be created nor destroyed, only transformed; holding true as energy flows through an ecosystem. Although energy must be conserved at the larger scale, the energy from the Sun is constantly being added to Earth's system. Of all the energy reaching Earth's surface from the Sun, only one percent is available to be used by plants.[7] The solar energy enters Earth's biosphere through absorption by plants' leaves to complete photosynthesis. The remaining energy not absorbed by plants is absorbed by Earth's surface, or reflected back to space or the atmosphere. Of the 10 billion tons of fixed carbon globally each year – carbon that has been converted from carbon dioxide to glucose – humans rely on one third, while two-thirds is available for the remainder of the biosphere.[8]

Students are taught that energy flows, while matter cycles. This is best explained as the energy input from the Sun to Earth, does not return back to the Sun and is instead moved between organisms. Much of the energy does not transfer to the next trophic level and is instead released to the atmosphere in the form of heat. The majority of this heat remains in the atmosphere, while some escapes Earth's system. The cycling of matter is reinforced with the example of carbon dioxide; it is an input for photosynthesis but an output for cellular respiration. Eventually, through both metabolic processes, the carbon atoms are able to return to their original form in their location of origin.

An In-depth Look at Photosynthesis

Both chlorophyll pigments and carotenoid pigments are located within the thylakoid membrane, found inside of the chloroplast. It is here that the photons from the sun excite electrons from chlorophyll molecules in the thylakoid membrane.[9] This movement of electrons is perpetuated by the splitting of water molecules that give up an electron to replace the excited electron.[10] This process creates hydrogen ions whose energy is used to convert ADP into ATP by adding an additional phosphate group, and NADP into NADPH by adding an additional hydrogen ion, and the oxygen gas that is eventually released from the leaf.[11] There are two electron transport chains, one to produce the ATP and the other to produce the NADPH. When these molecules are broken apart during cellular respiration, the added phosphate group and hydrogen ions are removed and energy is released.

Strategies

This unit is designed to incorporate the school's literacy focus and the Next Generation Science Standards to create a scientific understanding of energy transformation from solar energy to chemical energy and its transfer through living organisms. Tenth grade biology students participating in this unit are assessed on their content knowledge by a district-mandated unit assessment and their literacy skills by the PSAT. These results will then be used to measure the effectiveness of teachers. To comply with the school-wide implementation to improve literacy, the unit contains writing, listening, and speaking opportunities for students. The Next Generation Science Standards ask students to construct and communicate explanations based upon evidence through writing and modeling. Group modeling provides students with the evidence that they will use in their written analysis of the activity. Written responses are collected as informal assessments for the instructor to gauge student progress and understanding.

Modeling is an important classroom strategy allowing students use to make connections between concepts in a physical way. Kinesthetic learning builds memories that other types of learning do not. Students are to move, build, discuss, and collaborate in the modeling of photosynthesis and cellular respiration. Each team member is provided a role in the cell and must retrieve the appropriate inputs and release the proper outputs.

The modeling is a physical means of demonstrating the absorption of solar energy into the plant cell and the storage into a glucose molecule. It also demonstrates the release of the once-solar energy pieces in cellular respiration.

Peer discussions and collaboration are utilized during the analysis component of the unit. Students work together to build a stronger understanding of the material. It is important that the instructor takes care in organizing groups to ensure the best group dynamic for learning and discussion. The analysis questions are initially completed as individuals, providing students time to process their own understanding, followed by a time period of small-group discussion.

Card sorting is one tool to promote critical thinking and to visibly see a student’s thought process. Students collaborate to analyze and organize images based upon the order best describing the processes of photosynthesis and cellular respiration. A class discussion can be used as a follow up technique to hear students’ rationale for sorting a set of cards in a particular way.

Peer assessment is a skill students are able to practice during a class gallery walk in this unit. Providing students an opportunity to move around the classroom allows their brain to take a break and students to stretch their legs. A gallery walk allows students from different groups to share their thoughts and reasoning. The instructor must remind students the goal of the gallery walk; identify similarities and differences between their own thoughts and those of their peers. It is important that after the gallery walk, the class follow up with a discussion about observations, both similarities and differences, made between groups.

Stations are a strategic way to cover a lot of content in a relatively short period of time. It also allows the instructor to either act as one of the stations and provide small group discussion or provides the instructor with the ability to circulate to all students and gauge understanding and student needs. Stations provide the ability to create ways of building a large foundation of knowledge simultaneously that can be used to pull multiple concepts together in a single discussion. The use of stations in this unit is for the purpose of creating a large foundation of knowledge to support the remaining topic of food chains and food webs. Each of the stations asks students to discover a different concept; connections between stations are discussed as a whole group at the end of the day or the beginning of the next class period, depending on time.

Classroom Activities

Modeling Photosynthesis and Cellular Respiration

Prior to class, the instructor must design a basic plant cell, complete with labeled chloroplast, stoma, mitochondria, and vacuole, count out twenty-four metal washers that would fit over the bonds of a molecular model kit. Students model the inputs and outputs of photosynthesis in teams of four. Each team member is given a role within a plant cell: stoma, mitochondria, root, chloroplast. The stoma student is responsible for gathering, one at a time, carbon dioxide from the atmosphere and returning it to the leaf cell. The mitochondria student does not have a role in the first portion of the exercise since the mitochondria is not important until cellular respiration. The root student is responsible for gathering the water molecules from underground and returning to the leaf cell with their other team members. The chloroplast retrieves the washers – representing solar energy – and returns to the leaf cell. This student is also the leader for breaking down the inputs and create the outputs. Although this building step is assisted by all team members, the chloroplast is considered to be the manager of the task. It is important for one molecule of water and one molecule of carbon dioxide to be collected at a time by the appropriate parts of a plant to reinforce the ideas of conservation of matter and conservation of energy. All of the molecules brought to the leaf must be broken down and used to build the products. The students are not able to bring over more than they need to build the products.

As students build their glucose molecules, one metal washer is placed on each bond to represent the solar energy transferring from the sun to the chemical bonds of glucose. The finished glucose molecule should have one washer per bond, for a total of twenty-four. The chloroplast student had gathered the correct amount of energy tokens, washers, at the beginning of the activity and is instructed to use all of the solar energy in their product to ensure conservation of energy within the system. There needs to be a break between the photosynthesis model and the upcoming cellular respiration model to discuss conservation of matter an energy up to this point and to brainstorm what could happen to the original solar energy now that it is in the glucose molecule. As students break down their glucose molecule during cellular respiration, a pile of washers is produced and moved to the mitochondria. It is discussed that the energy released from the sugar is no longer in the form of solar energy and is used in other metabolic activities around the cell or is lost as heat. Students are able to model conservation of energy through the movement of the washers in the activity.

One modification for this activity is to place a time limit on the length of time students have to complete the process of photosynthesis. I allotted students twenty-four minutes, to represent the twelve hours of daylight. In this time frame, teams were to gather their reactants, build their products, and return waste products to the appropriate location – atmosphere or underground. As time comes to a close, the lights are turned off in the room to represent night time. Photosynthesis is unable to occur anymore. The goal is for all groups to have successfully built a molecule of glucose that remains in the leaf, and six molecules of oxygen that have been returned to the atmosphere. If any group is not successful, it should be used as a teachable moment to discuss the impacts of a plant not receiving sugar. Those unsuccessful groups are unable to begin cell respiration until the “next day” after completing photosynthesis. All remaining groups are able to use the mitochondria student to begin breaking down the glucose and gathering oxygen from the atmosphere during the night and continuing into the next day.

To follow up the modeling, one important discussion to have with students is addressing how do trees grow so large. Students need to understand that not all of the glucose produced is used for cellular respiration; some of the glucose is stored in the tree allowing for the growth. It important for students to understand that although energy is conserved, it is not a cycle – typically confused with cycling of matter. None of the solar energy is returned to the original location in the classroom, it has either been trapped and stored by glucose, released to the mitochondria to be used, or released as heat. As part of their analysis, students brainstorm how temperature and light intensity affect the rate of photosynthesis. Students explain by developing their own model the absorption, transformation, and storage of energy to demonstrate conservation of both matter and energy.

Photosynthesis and Cellular Respiration Shuffle

Students organize a set of cards represented with an aquatic ecosystem; four cards depict photosynthesis and four show aspects of cellular respiration. Students work in pairs to determine which process each of the cards demonstrate. Some images have plants and fish, and others have a microscopic view of mechanisms taking place inside of plant or fish cells. Students organize the images based on inputs, outputs, and organisms and cell types involved.

Students have five minutes to sort the cards with a partner into two categories – photosynthesis and cellular respiration – before students are instructed to move around the room to gallery walk and see how their peers organized the cards. Students should have attempted to sort them based on cellular process as well as placing the steps in order. After a short walk, the answer is discussed as a class with students sharing their order and rationale. Pairs are encouraged to fix their sorting as necessary. Once cards all of the cards are properly sorted, students are provided descriptive cards that are read and placed under the appropriate image. After five minutes, the instructor facilitates a second class discussion surrounding the proper descriptions.

Energy Transfer Stations

Stations represent various aspects of food chains, food webs, and energy transfer among trophic levels. This is an introduction to the topic; therefore, one of the stations should be a preview of all of the vocabulary students are going to be exposed to during this part of their curriculum. In order to understand energy transfer, students calculate the amount of energy passed from one trophic level to the next. The calculations should reveal that approximately ten percent of the previous level’s energy is moved to the next organism. Some of the stations ask students to apply their knowledge of energy; decide if they prefer to eat a cookie or bowl of pasta in varying situations. Students explain why it is better to eat pasta the night before a marathon versus eat a cookie a few minutes before a sprint. It is expected students understand that there is more stored solar energy in starch, composed of many sugar molecules bonded together, when compared to a cookie made of simple sugars. The ultimate goal for this activity is for students to explain how energy is transferred in an ecosystem and how the energy is conserved with the system.

Students are encouraged to move about the stations as individuals, yet work with peers when necessary. Responses to questions posed at each station are recorded on a worksheet that students refer back to when reviewing content as a whole class, either at the end of this class day or the beginning of the following day. The instructor is constantly circulating the room, moving between each station to answer student questions as they arise. These questions are used to guide the class discussion at the end of the station rotation. It is imperative that the instructor monitor discussions and spend time with each student throughout the allotted station time.

Bibliography

Hall, D. O., and K. K. Rao. 1999. *Photosynthesis: Studies in Biology, Sixth Ed.* Cambridge University Press.

This resource is used for background information on photosynthesis and is written at the teacher level of understanding.

Johnson, George B., and Peter H. Raven. 2001. *Biology: Principles and Explorations.* Austin: Holt, Rinehart, and Winston.

This textbook is appropriate for a tenth grade high school classroom. It was used as a reference for specific grade-level appropriate details of photosynthesis and cellular respiration.

Karp, Gerald. 1984. *Cell Biology Second Edition.* New York: McGraw Hill.

This resource is used for background information on photosynthesis and is written at the teacher level of understanding.

Smith-Sebasto, Nicholas. 2019. *Energy and Ecosystems - Use Some Lose Some.* Accessed December 1, 2019. https://web.extension.illinois.edu/world/energy.cfm.

This resource is used for background information on energy transfer and is written at the teacher level of understanding.

William K. Purves, David Sadava, Gordon H. Orians, H. Craig Heller. 2004. *Life: The Science of Biology Seventh Ed.* Sunderland, MA: Sinaur Associates, Inc.

This resource is used for background information and is written at the teacher level of understanding. It is a college text book.

Appendix 1

Next Generation Science Standards

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.

This standard is addressed in the second half of the modeling activity. It is a branch off of the photosynthesis activity. The metal washers denote energy and students break their glucose molecule in order to release the energy and show the conservation in the amount of energy.

HS-LS1-5: Use a model to illustrate how photosynthesis transforms light energy into stored chemical energy.

This standard is addressed in both the modeling activity, using the molecular kits and metal washers, as well as the card sort. In both models, students observe the movement of light energy into a plant cell and transform into stored chemical energy.

HS-LS2-4: Use mathematical representations to support claims for the cycling of matter and flow of energy among organisms in an ecosystem.

This standard is partially met through the energy transfer stations. Students calculate the amount of energy passed between trophic levels and discover the ten percent rule. Students trace the solar energy to stored chemical energy as it passes between organisms and the release of heat as a by-product.

Notes

[1] (Hall and Rao 1999)
[2] (Johnson and Raven 2001)
[3] (Karp 1984)
[4] (Karp 1984)
[5] (Johnson and Raven 2001)
[6] (Johnson and Raven 2001)

[7] (Smith-Sebasto 2019)
[8] (William K. Purves 2004)
[9] (Johnson and Raven 2001)
[10] (Johnson and Raven 2001)
[11] (Johnson and Raven 2001)