Name: ______________________________________ Period: ____

Module 9, Introduction: Energy, Entropy, and Life

Chapter Correspondence: Campbell, Chapter 8

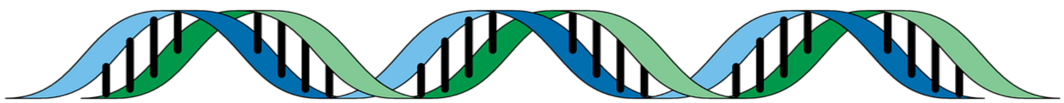
Learning Objectives

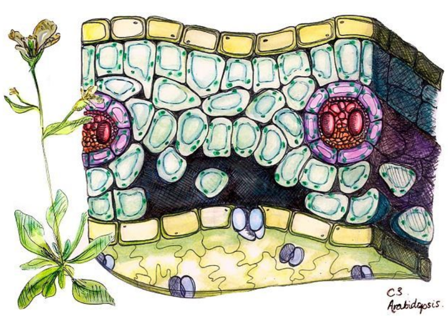
1. LO 2.1:The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow and to reproduce. (EK: 2A1)
2. LO 2.2:The student is able to justify a scientific claim that free energy is required for living systems to maintain organization, to grow or to reproduce, but that multiple strategies exist in different living systems (EK: 2A1)
3. LO 2.3:The student is able to predict how changes in free energy availability affect organisms, populations and ecosystems. (EK: 2A1)

They Say *I say*

Energy, Entropy, and Life

Living things are highly adapted, organized systems. You see this in every level of organization. Just think about a molecule like DNA, with its billions of bases organized to store and transmit genetic information.





You can see it in this cross section of a leaf, with different tissues adapted to optimize photosynthesis while minimizing water loss. It's the opposite of random. It's an organized adaptation that promotes a plant's survival and reproduction, which is what life is all about.

Creating organized adaptations involves work. It requires getting energy from the environment, and then using that energy to perform the work involved in growing, developing, maintaining homeostasis, and then reproducing.

In this reading, we're going to to examine what energy is, and how living things use energy to do the work of staying alive.

TYPES OF ENERGY

You can define **energy** as t*he ability to do work, or to cause a change in a system*. As a biology student, there are only a few forms of energy you need to know about.

- **Chemical energy** is the energy stored in the chemical bonds that make up molecules. Living things, for example, can store energy in the chemical bonds of carbohydrates (like glucose) and lipids (like triglycerides). They can also release energy by breaking down these carbohydrates and lipids into simpler substances, like carbon dioxide and water.
- **Kinetic energy** is energy of motion. Living things are constantly transforming chemical energy into kinetic energy, such as when an animal moves its body, or when it moves a part of its body. As we've learned in our study of membranes, chemical energy can be used to create kinetic energy, as in active transport. As we'll see later in the course, kinetic energy on the molecular level can also be used to create chemical bond energy.
- **Heat energy** is random movement of atoms or particles. It's connected to kinetic energy at a molecular level, because the more heat in a system, the more its particles are moving

around. Mammals, birds, and other organisms that maintain a constant body temperature use a great deal of the chemical energy in the food they eat to maintain their high body temperatures, enabling them to lead their (comparatively) active lifesyles.

- **Light energy** involves the movement of photons, which are particles of light energy. Plants use light energy to power photosynthesis, which creates stored chemical energy in the form of glucose (which can then be converted into other carbohydrates, such as starch, or into other molecules).
- **Potential energy** refers to energy that is stored, waiting to be released as heat, light, or kinetic energy. If I place a toy train up on the top of a piece of elevated track, it has potential energy. When I give the train just a little push (to overcome friction) that potential energy gets transformed into kinetic energy (and heat energy, as the wheels of the train experience some friction with the track, the wheel axles, etc). A match has has potential energy, but in this case, it's potential chemical energy. If I provide a bit of heat, in the form of friction, that potential chemical energy can be released as heat, light, and kinetic energy. On the cellular/molecular level, living things use chemical energy to power active transport of ions across membranes. That creates a diffusion gradient, which is a form of potential kinetic energy that can later be used to do all sorts of work, such a spinning a bacterial flagellum to power movement, or powering the enzymes that create ATP, the cell's immediate form of chemical energy.

THE LAWS OF THERMODYNAMICS

Now that we know about the types of energy used by living things, let's look at two of the laws that guide energy and energy transfer. This is a part of physics that's known as *thermodynamics*, and there are two laws of thermodynamics that we need to track.

1. The first is the **principle of conservation of energy**. This law states that energy can be transferred from one system to another, and/or transformed from one form into another, but it can't be created or destroyed. When I light a match, I'm transforming potential chemical energy into light, heat, and kinetic energy. But the total amount of energy is the same before lighting the match and after lighting it. The same is true of rolling a rock down a hill, or pumping water into a reservoir.
2. The second is the **law of entropy**. As energy flows through a system, the overall level of randomness or disorder in the system increases. In other words, the general trend of systems is to become less organized, more random. When a concentrated drop of ink diffuses to become uniformly distributed throughout a liquid, that's entropy. When you burn a match and create ash, carbon dioxide, and water molecules, that's entropy. When ice melts, that's entropy.

ENERGY COUPLING, AND GIBBS FREE ENERGY

If the universe is constantly becoming more entropic, how can we explain the fact that life is so highly organized? Living things are examples of *negentropy* (negative entropy): they're little currents of organization in an stream of entropy. That organization involves work, and living things accomplish this work through *energy coupling*. They pair together processes that require energy (growing, adapting, reproducing, etc.) with process that release energy. And to understand that, we need one more energy-related concept: the concept of **Gibbs free energy**. Gibbs was the 19th century scientist who developed this concept, and all you need to remember about him is the letter "G" that starts his name, because the mathematical symbol for Gibbs free energy is "ΔG." (The "Δ" is the Greek letter delta, and it means "change.")

ΔG is a quantity, and it can be positive or negative. If a process or reaction has a negative ΔG (a negative free energy change) that means that

- It can occur spontaneously
- It's releasing energy that can be harvested to power reactions or processes that have a positive ΔG.

If a reaction or process has a positive ΔG, that means that

- It won't occur spontaneously
- It requires an input of energy from some other reaction or process that has a negative free energy change.

Note that the meaning of *spontaneous* here is a bit different from what we're used to. In common speech, *spontaneous* means something pretty close to "unpredictable." But here, all it means is that outside of a little push that you might need to supply in order to start the process, it can happen on its own. When a toy train rolls down a slope, it's spontaneous. To move it up the slope involves work (which is non-spontaneous). Also, spontaneous doesn't imply anything about how much time will pass before a reaction happens. As we'll see, the breakdown of sugar to carbon dioxide and water is a spontaneous process...but sugar can sit in the presence of oxygen for thousands of years and not react with it. Just remember that "spontaneous" is not connected to time.

Determining whether ΔG is negative or positive (which means whether a reaction or process is spontaneous or not) can be done mathematically, but we're mostly going to do this intuitively.

Here's the equation for ΔG:

$$\Delta G = \Delta H - T\Delta S$$

Don't panic. Let's just move from left to right.

- ΔG is what we're figuring out. It's free energy. We're going to figure out whether it's negative (releasing energy for work) or positive (requiring energy in order to occur).
- ΔH is *enthalpy*, a term that means the total energy of the system.
- T is temperature
- ΔS is the change in the system's entropy, or disorder.

Let's work through a few examples, and refer to the formula to see if the result is a negative or positive ΔG.

Example 1: Consider our train on the top of a slope. You give it a push, and it rolls down to the bottom. If you think of the train on the track as a system, then the total energy (ΔH) of that system is lower when the train is on the bottom of the slope than when it's on the top. So, if a system's overall energy is dropping, then other things being equal (because we haven't change T or the system's entropy), then we can assume that ΔG is negative. That means that it can happen spontaneously, and that this transition can be a source of energy to various types of work.

Example 2: I put a drop of ink into a cup of water. The ink is going to diffuse throughout the container. We're going from a more organized state to a less organized state. We've increased entropy (ΔS). Remember that in the equation $\Delta G = \Delta H - T\Delta S$, we subtract $T\Delta S$. In other words, lots of entropy pushes the right side of the equation into negative territory (because we're subtracting it). All other things being equal, if a process or a reaction increases entropy, then it can happen spontaneously. That means that its ΔG is negative, and it can be a source of energy to get some work done.

Example 3: During photosynthesis, the gas carbon dioxide is combined with water to create sugars. Just study the equation for a moment.

$$6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$$

Note that we're going from 12 molecules on the left side of the arrow to seven molecules on the right (one glucose and six oxygen). We've increased order, which means that we've *decreased* entropy (ΔS). We've *increased* the total energy of the system, because the glucose and oxygen have much more energy in their chemical bonds than do carbon dioxide and water molecules. Because entropy is decreasing and total energy is increasing, you can assume that photosynthesis's ΔG is positive. That means that photosynthesis is *not* a reaction that's going to happen spontaneously, and that it requires an input of energy in order to move forward.

So that's it: $\Delta G = \Delta H - T\Delta S$. For the most part, we're going to ignore T because while it's important in chemistry, biology happens at pretty moderate temperatures. However, it's fun to remember that if you increase T, you make ΔG more negative, increasing spontaneity. That's why one way you can get a match to to burst into flame is to heat it up, either by friction or by putting it in an oven.

Two terms connect with what we've learned above about spontaneous and non-spontaneous reactions. **Exergonic** reactions release free energy, which means that they have a negative ΔG. Cellular respiration, which is the reaction by which living things get energy from sugars, is an exergonic reaction. As glucose is combined with oxygen to produce carbon dioxide and water, 686 kCal (kilocalories, the kind listed on a food package) of energy are released for every mole of glucose that enters the reaction, as shown in this equation.

$$C_6H_{12}O_6 + 6O_2 \text{ -> } 6CO_2 + 6H_2O + \text{energy } (-686\text{kCal/mole})$$

Endergonic reactions, by contrast, need to absorb free energy from the environment in order to move forward. That means that they have a postive ΔG. Photosynthesis, which combines carbon dioxide and water into glucose and oxygen, is endergonic. It requires a constant input of free energy in the form of light in order to move forward. When the sun sets, that energy is gone, and photosynthesis stops.

RESPOND IN THE SPACE BELOW

1. What the main idea of this article?
2. What determines whether a reaction or process will occur spontaneously?
3. Whereas endergonic reactions….exergonic ones…
4. In plain English, $\Delta G = \Delta H - T\Delta S$ means that...