Free Energy
Where does the energy come from that keeps all living things alive?

Why?
All living things require a constant flow of energy. This is one of the big ideas in science. If the flow of energy to an ecosystem is cut off, like an extended lack of sunlight or food, then all the living things in the ecosystem will die. But you have heard of the Law of Conservation of Energy, so why wouldn’t there always be enough energy to go around?

Model 1 – Spontaneous Processes

<table>
<thead>
<tr>
<th>Process Description</th>
<th>Change in Enthalpy (ΔH)</th>
<th>Change in Entropy (ΔS)</th>
<th>Spontaneous?</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Two pure substances → Homogeneous mixture</td>
<td>- 0</td>
<td>Increasing</td>
</tr>
<tr>
<td>B</td>
<td>Solute on one side of membrane → Solute on both sides of membrane</td>
<td>- 0</td>
<td>Increasing</td>
</tr>
<tr>
<td>C</td>
<td>Polypeptide chain → Individual amino acids</td>
<td>Exothermic (negative)</td>
<td>Increasing (positive)</td>
</tr>
<tr>
<td>D</td>
<td>( C_4H_8 \rightarrow 5O_2 \rightarrow 3CO_2 + 4H_2O )</td>
<td>Exothermic</td>
<td>Increasing</td>
</tr>
<tr>
<td>E</td>
<td>( 6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2 )</td>
<td>Endothermic</td>
<td>Decreasing</td>
</tr>
<tr>
<td>F</td>
<td>Glucose → Starch</td>
<td>Endothermic</td>
<td>Decreasing</td>
</tr>
<tr>
<td>G</td>
<td>Water → Ice</td>
<td>Exothermic</td>
<td>Decreasing</td>
</tr>
<tr>
<td>H</td>
<td>Cold water (25 °C) → Hot water (60 °C)</td>
<td>Endothermic</td>
<td>Increasing</td>
</tr>
</tbody>
</table>

1. Consider Model 1.
   a. What two terms are used to describe the enthalpy changes for the reactions?
      
      **Enthalpy changes are described as endothermic or exothermic.**
   
   b. What is the symbol for the change in enthalpy?
      
      ΔH.
   
   c. What sign (+ or –) does the change in enthalpy have when the reaction releases heat energy to the surroundings?
      
      **Energy is released to the surroundings when the process is exothermic. The ΔH in that case is negative.**
2. Refer to Model 1. For each process below indicate if the change would be endothermic or exothermic.
   
   a. A plant making glucose from carbon dioxide and water.
      
      *Endothermic.*
   
   b. An ice cube melting.
      
      *Endothermic.*
   
   c. Amino acids forming a polypeptide chain.
      
      *Endothermic.*

Read This!

The net energy change for a reaction is related to the strength and number of bonds that are broken and formed during the reaction. Breaking bonds requires energy while forming bonds releases energy. If more or stronger bonds are formed than are broken, then the reaction will be *exergonic* (a net release of energy will be observed). If more or stronger bonds are broken than are formed, then the reaction will be *endergonic* (a net absorption of energy will be observed).

3. According to Model 1, are all exothermic reactions spontaneous? If no, provide a counter example from Model 1.

   *No. Process G is only spontaneous under certain conditions.*


   a. What is the symbol for the change in entropy of a system?
      
      \( \Delta S \).
   
   b. When the entropy of a system increases, what sign (+ or –) is used?
      
      *An increase in entropy is signified by a positive value.*

5. According to Model 1, is there a correlation between the change in enthalpy and the change in entropy for a system? If yes, describe the correlation.

   *There is no correlation. There are examples in Model 1 of both endothermic and exothermic reactions that have an increase in entropy.*

6. Refer to Model 1. For each process below indicate if the entropy would increase or decrease.

   a. Food coloring mixing into water.
      
      *This is an increase in entropy.*
   
   b. A hot substance cooling to room temperature.
      
      *This is a decrease in entropy.*
   
   c. The respiration of glucose and oxygen to produce carbon dioxide and water.
      
      *This is an increase in entropy.*
7. For each of the processes in Model 1, decide as a group if the molecules in the substances have more order (are more organized) before or after the reaction. Circle the side of the reaction with more order.

See Model 1.

8. Is there a correlation between the level of organization in the molecules and a change in entropy according to the examples in Model 1? Justify your reasoning.

Yes, there is a correlation between the level of organization in the molecules and the change in entropy. As the system becomes more disorganized (more random, less organized) the entropy increases.

Read This!

The entropy of a system can be thought of as a measurement of the amount of disorder in the molecules that make up the system. The study of entropy is based in statistics. There are only a few ways in which a system can be organized and have low entropy, but there are usually many more ways in which a system can be disorganized and have high entropy. Therefore, systems are more likely to exist in higher entropy states. Just think of your bedroom at home. If you do not spend energy to clean it, is it likely to be organized or disorganized?

9. Predict if the following processes would have an increase in entropy or a decrease in entropy based on what you have learned from Model 1.

a. Water evaporating from a wet sidewalk.

This would be an increase in entropy.

b. Separating a mixture into pure substances.

This would be a decrease in entropy.

c. A plant using raw materials to build a leaf in the spring.

This would be a decrease in entropy.

d. Leaves decomposing in winter.

This would be an increase in entropy.

10. Is an increase in the entropy of a system sufficient to make a process spontaneous? Justify your reasoning with evidence from Model 1.

No, process H in Model 1 has increasing entropy of the system and is only spontaneous under certain conditions.
Read This!

Some of the processes in Model 1 are spontaneous—that is, they will occur without any additional work being done on the system. For example, a solute will diffuse across a membrane until the concentrations of both sides are equal. However, glucose will not spontaneously form from carbon dioxide and water in the atmosphere. The Second Law of Thermodynamics states that a process will be spontaneous when it results in an increase of total entropy in the universe. In other words, either the system or the surroundings must have an increase in entropy, or both.

(Please note that the term “spontaneous” does not imply that the change will happen quickly. Rusting is spontaneous under the right conditions, but it can still occur very slowly.)

11. Consider the exothermic reactions in Model 1. When those reactions occur, what typically happens to the temperature of the surroundings?

   *The energy released from the exothermic reaction typically increases the temperature of the surroundings.*

12. Predict the change in entropy of the surroundings for an exothermic reaction. *Hint:* Find a system that changed temperature in Model 1.

   *Because the temperature will go up, the entropy of the surroundings increases.*

13. Predict the change in entropy of the surroundings for an endothermic reaction.

   *Because the temperature will go down, the entropy of the surroundings decreases.*

14. Provide the letter of at least one process from Model 1 that illustrates each of the following conditions that will result in a spontaneous reaction.

   a. Both the system and surroundings have an increase in entropy.

      *Processes C and D.*

   b. The increase in entropy of the system exceeds the decrease in entropy of the surroundings.

      *Process H above 60 °C.*

   c. The increase in entropy of the surroundings exceeds the decrease in entropy of the system.

      *Process G below 0 °C.*
Read This!

When a process is spontaneous it can be used to do work. For example, the respiration of glucose is used in organisms to run cellular processes like the production of enzymes. The amount of work that can be done by a spontaneous process is called **Gibbs Free Energy**, named after the mathematician that developed the concept in 1873. Josiah Willard Gibbs proposed the equation that scientists now use to calculate the free energy change for a process.

\[ \Delta G = \Delta H - T\Delta S \]

When \( \Delta G \) is negative, the process is spontaneous and can do work (*exergonic*). When \( \Delta G \) is positive, the process is not spontaneous. Work must be done on the system to make it happen (*endergonic*). Note that the temperature in the equation is in Kelvin and will always be a positive number.

15. Consider process C in Model 1.
   
   a. Would the \( \Delta H \) term in the Gibbs free energy equation be positive or negative?
      
      *The reaction is exothermic, so \( \Delta H \) is negative.*
   
   b. Would the \( \Delta S \) term in the Gibbs free energy equation be positive or negative?
      
      *There is an increase in entropy, so \( \Delta S \) is positive.*
   
   c. Show how the change in enthalpy and entropy of process C in Model 1 would result in a spontaneous reaction at all temperatures.
      
      \[ \Delta G = \Delta H - T\Delta S \]
      
      *A negative number minus a positive number will always result in a negative number. Therefore, \( \Delta G \) will always be negative at all temperatures, and the reaction will always be spontaneous.*

16. Use the Gibbs free energy equation to show how the change in enthalpy and entropy of process E in Model 1 would not result in a spontaneous reaction.

   *In process E, the change in enthalpy is positive and the change in entropy is negative.*

   \[ \Delta G = \Delta H - T\Delta S \]
   
   *A positive number minus a negative number will always result in a positive number. Therefore, \( \Delta G \) will always be positive at all temperatures, and the reaction will never be spontaneous.*

17. Processes A and B in Model 1 have very minimal energy changes. Explain why those processes are spontaneous.

   *In these processes, the change in enthalpy is near zero so the only factor that must be considered is the entropy of the system. Both processes have an increase in the entropy of the system (\( \Delta S \) is positive) and therefore \( \Delta G \) will be negative at all temperatures.*
18. Consider process G in Model 1.
   a. What is the entropy change for the system?
      \textit{Process C has a decrease in entropy.}
   b. What is the entropy change for the surroundings?
      \textit{The process is exothermic, so the entropy of the surroundings increases.}
   c. Which factor must be larger when the temperature is above 0 °C (273 K), the entropy change of the system or the entropy change of the surroundings? Explain your reasoning.
      \textit{Above 0 °C the entropy change of the system is larger, preventing the formation of ice at that temperature.}

\textbf{Read This!}

In biological systems, exergonic processes are often coupled with endergonic processes. This is what allows for the great degree of organization that we see in organisms. The organisms are not violating the Second Law of Thermodynamics. Rather, they are leaving a wake of disorder around them as they eat, breathe, and grow.

19. If you have ever been camping, you may have used coupled processes to make yourself some hot cocoa in the evening.

\begin{align*}
\text{firewood} + \text{O}_2 & \rightarrow \text{hot water} \\
\text{CO}_2 + \text{H}_2\text{O} & \rightarrow \text{cold water}
\end{align*}

   a. Which of the processes above is exergonic, and does work?
      \textit{The burning of firewood is exergonic.}
   b. Which of the processes above is endergonic, and has work done to it?
      \textit{The heating of water is endergonic.}

20. Consider the coupled processes below.

\begin{align*}
\text{glucose} + \text{O}_2 & \rightarrow \text{ATP} \\
\text{CO}_2 + \text{H}_2\text{O} & \rightarrow \text{ADP} + \text{Phosphate}
\end{align*}

   a. Which of the processes above is exergonic, and does work?
      \textit{The respiration of glucose in the cells is exergonic.}
   b. Which of the processes above is endergonic, and has work done to it?
      \textit{The formation of ATP is endergonic.}

\textbf{STOP}