Cellular Respiration and Photosynthesis
-- Important Concepts, Common Misconceptions, and Learning Activities

Dr. Ingrid Waldron, University of Pennsylvania, copyright 2011[1]

I. Energy, ATP and Cellular Respiration

A. What is **energy**?

- Ability to do work
- Can make things move, e.g. muscle contraction or pump ions across cell membrane
- Includes kinetic energy of moving leg, molecules, etc. and potential energy, including chemical energy stored in glucose or ATP

Energy can be changed from one type to another, but energy is not created or destroyed (First Law of Thermodynamics).

- E.g. Chemical energy stored in ATP can be converted to kinetic energy of muscle contraction

If energy is never destroyed, why do we "run out of energy" at the end of a race or at the end of the day?

- Every energy transformation is inefficient; i.e. some of the energy is converted to heat (Second Law of Thermodynamics). Therefore, as our bodies constantly use chemical energy for necessary cellular processes, we need to replace the molecules that provide chemical energy.
- Also we need to dispose of accumulated metabolites and waste products and repair micro-damage.

B. The Importance of **ATP**

Different types of organisms get their energy input from different sources (e.g. food, sunlight), but all organisms use a two-step process to provide the energy needed for most of their biological processes.

- First, chemical energy from organic molecules like glucose is used to produce ATP in a process called cellular respiration.
- Then, ATP provides the energy for most biological processes.

Our cells are constantly using energy from organic molecules like glucose to make ATP and using the ATP molecules to provide the energy for biological processes (e.g. muscle contraction, synthesizing molecules, and pumping ions and molecules into and out of cells). On average, each ATP molecule in our body is used and re-synthesized more than 30 times per minute when we are at rest and more than 500 times per minute during strenuous exercise.

[1] These teacher notes and multiple activities for teaching biology are available at http://serendip.brynmawr.edu/exchange/bioactivities. Hands-on, minds-on activities for teaching biology are available at http://serendip.brynmawr.edu/sci_edu/waldron/.

C. How does the structure of **ATP** relate to the function of ATP?

ATP (adenosine triphosphate) has three negatively charged phosphates. When ATP breaks down to ADP (adenosine diphosphate) and a phosphate, negatively charged phosphates are separated and energy is released. This energy is used for cellular processes such as synthesizing organic molecules, pumping ions across the cell membrane, and muscle contraction.

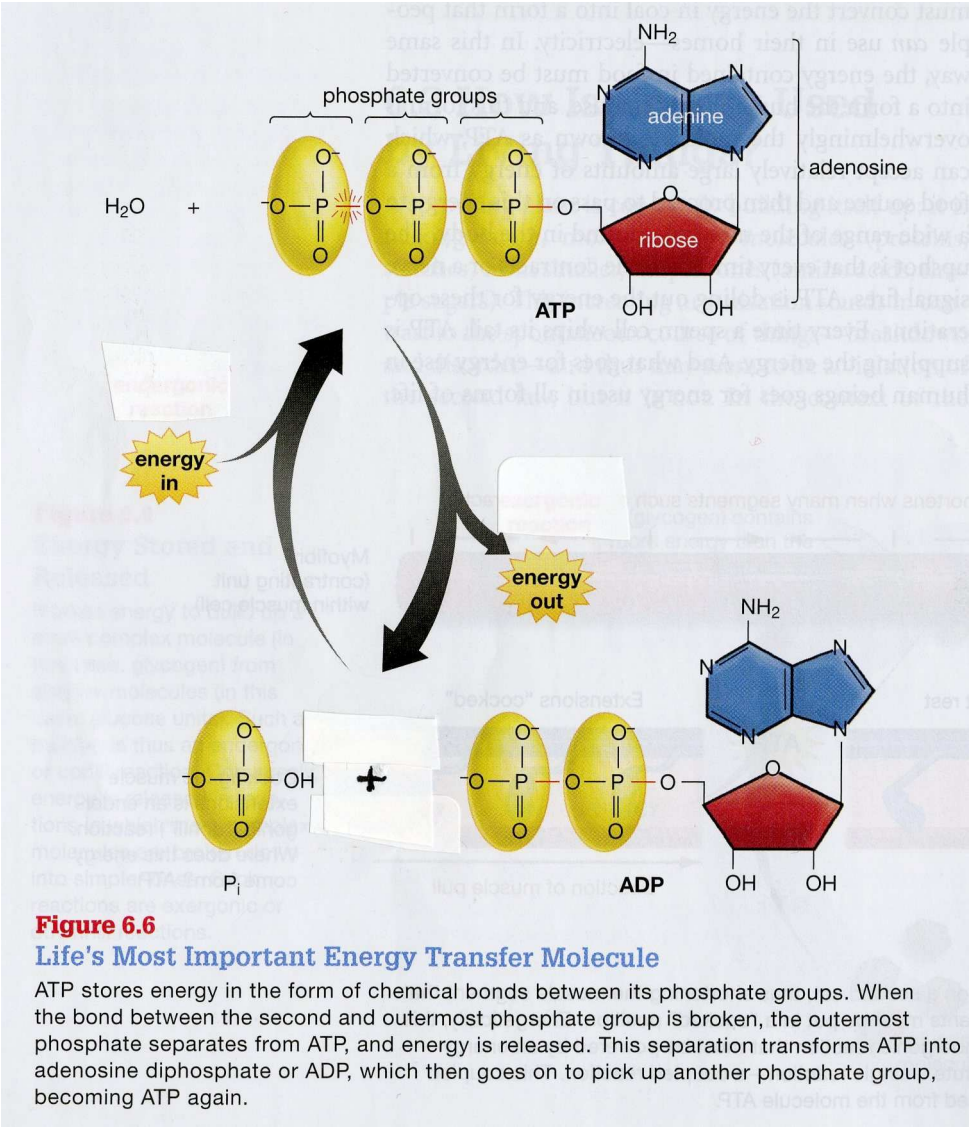


Figure 6.6
Life's Most Important Energy Transfer Molecule
ATP stores energy in the form of chemical bonds between its phosphate groups. When the bond between the second and outermost phosphate group is broken, the outermost phosphate separates from ATP, and energy is released. This separation transforms ATP into adenosine diphosphate or ADP, which then goes on to pick up another phosphate group, becoming ATP again.

(adapted from Krogh, Biology -- a Guide to the Natural World, Fifth Edition)

ATP is produced by the chemical reaction, ADP + P_i --> ATP. Energy is required to add a negatively charged phosphate to the two negatively charged phosphates in ADP. The following pages explain how cellular respiration of organic molecules like glucose provides the energy needed to produce ATP.

D. **Cellular Respiration** is the process that transfers some of the chemical energy in glucose or another organic molecule to chemical energy in ATP, so energy is available in a form that is useful for biological processes. The following pair of chemical equations gives a simplified overview of the cellular respiration of glucose:

$$C_6H_{12}O_6 + 6\,O_2 \text{ ----> ----> ----> } 6\,CO_2 + 6\,H_2O$$

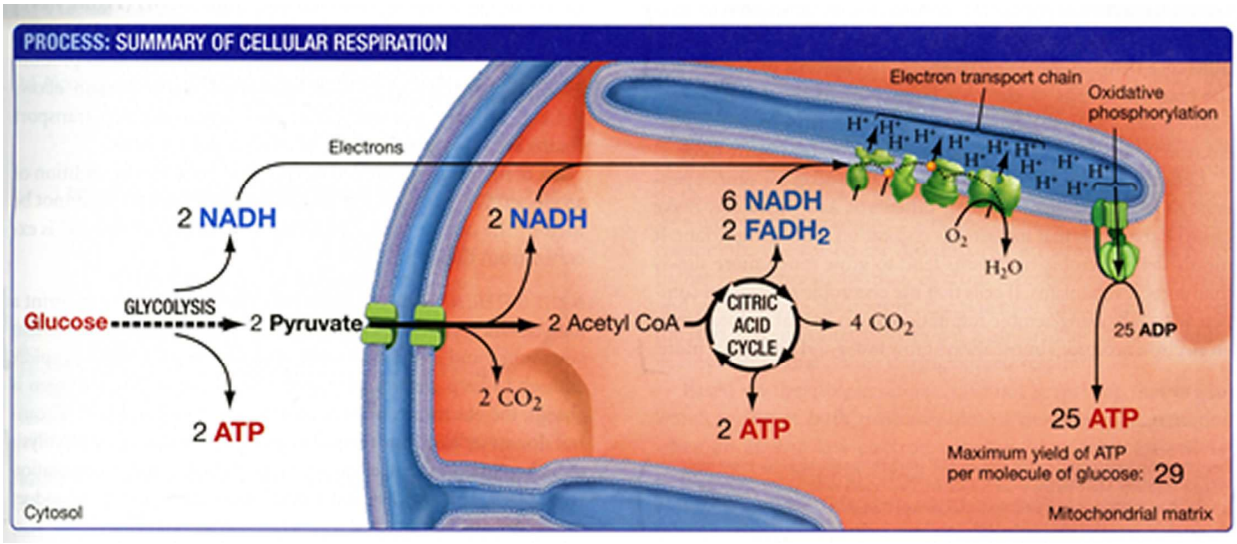
$$\downarrow$$

energy

$$\downarrow$$

$$ADP + P_i \text{ ---------> } ATP$$

The multiple arrows indicate that cellular respiration consists of a series of multistep processes, as shown in the figure below.



(From Scott Freeman, Biological Science , Fourth Edition, 2011)

The number of ATP molecules produced per molecule of glucose is variable because cellular respiration consists of a complex sequence of processes rather than a simple chemical reaction.

- The number of NADH and $FADH_2$ generated is known and consistent; these molecules move to the electron transport chain which provides the energy to pump H+ (protons) across the inner mitochondrial membrane.
- Then protons move through the ATP synthase enzyme, powering the synthesis of ATP.
- There is some variation in the number of protons that are moved across the membrane and additional variation in the number of protons needed for each ATP molecule produced.

Recent evidence indicates that a maximum of 29 molecules of ATP is produced per molecule of glucose, which is fewer than previously believed. This revised estimate is based on newly discovered complexities and inefficiencies in the function of the electron transport chain and ATP synthase enzyme (Nicholson, 2003, Biochemistry and Molecular Biology Education 31:2-4, available at http://www.bambed.org). These recent findings are interesting as an example of how scientific understanding is subject to revision based on ongoing research; science progresses by successive improvements in our understanding and knowledge

It should also be mentioned that:

- Not all of the energy released from glucose by cellular respiration is captured in ATP; some of the energy is converted to heat.
- Input molecules for cellular respiration include not only glucose, but also glycerol, fatty acids and amino acids.

E. **ATP supplies energy for many biological processes** via coupled reactions in which the first reaction provides the energy required for the second reaction, e.g.:

Muscle Contraction:

many ATP --------> many ADP + P_i
\/
energy
\/
muscle relaxed ---->---->---->----> muscle contracted

Protein Synthesis:

4 ATP --------> 4 ADP + P_i
\/
energy
\/
polypeptide with n amino acids ---->---->---->----> polypeptide with n +1 amino acids

Learning Activities for sections A-E

How Biological Organisms Use Energy -- This discussion/worksheet activity is designed to help students understand the basic principles of how biological organisms use energy, with a focus on the roles of ATP and cellular respiration. The overview developed by this activity provides a useful introduction to cellular respiration and an important conceptual background for students who will be learning the complex specifics of cellular respiration.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/energy

Cellular Respiration and Breathing -- The questions in this discussion/worksheet activity help students understand the relationship between cellular respiration, O_2, CO_2, and the familiar activity of breathing.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/cellrespirbreath

F. To use energy from **food**:

- Large organic food molecules such as starch and triglycerides are digested to small organic molecules such as glucose and fatty acids that can travel in the blood and serve as input for cellular respiration.
- Cellular respiration transfers energy in organic molecules such as glucose to energy in ATP.
- Then, ATP is used to provide energy for cellular processes.

Common Misconception: Food = calories = energy
Food, calories and energy are related, but not equivalent concepts. Food contains organic molecules which have chemical energy stored in the bonds between atoms. There are many other types of energy, including the kinetic energy of moving muscles and heat (the kinetic energy in the random motion of atoms and molecules). In addition to energy, food provides atoms and molecules needed for growth and repair of our bodies. A calorie is a unit of measure of energy.

Learning Activity

Food, Energy and Body Weight -- This discussion/worksheet activity helps students to understand the relationships between food molecules as a source of energy, cellular respiration, physical activity, and changes in body weight.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/foodenergy

G. Aerobic cellular respiration requires O_2 as an electron acceptor at the end of the electron transport chain. When O_2 is not available, cells use a different process to make ATP: glycolysis followed by **fermentation.** Glycolysis produces 2 ATP per glucose molecule and fermentation restores molecules needed for glycolysis to continue.

Learning Activities

Barley & Oat's Brewing Backfire! -- In this discussion/worksheet activity, students compare aerobic cellular respiration and alcoholic fermentation and then interpret evidence to figure out why a micro-brewer's beer has no alcohol.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/brewing

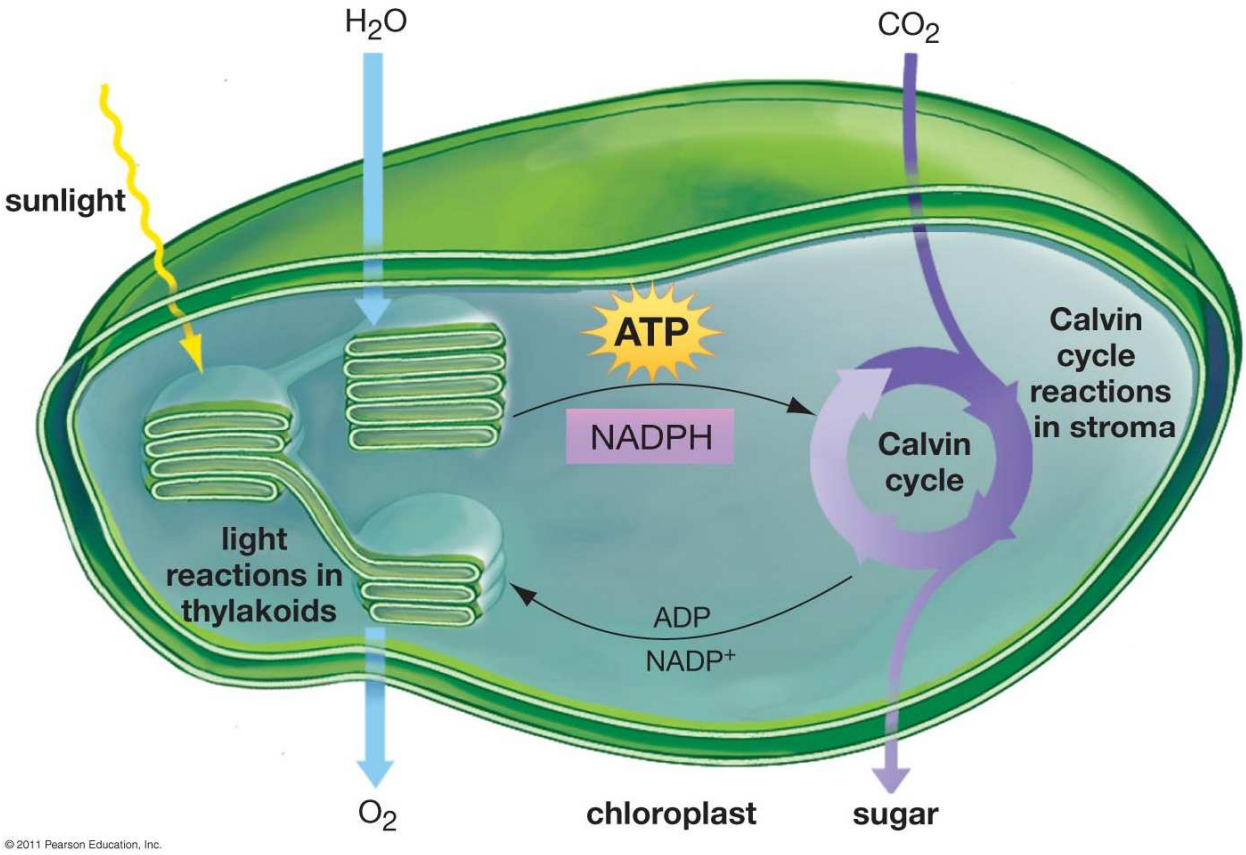
Alcoholic Fermentation in Yeast -- Students learn about the basics of cellular respiration and alcoholic fermentation and design and carry out experiments to test how variables such as sugar concentration influence the rate of alcoholic fermentation in yeast. In an optional extension activity students can use their yeast mixture to make a small roll of bread.
Student Handout and Teacher Preparation Notes available at
http://serendip.brynmawr.edu/sci_edu/waldron/#fermentation

II. **Photosynthesis**

sunlight, chloroplasts

$6\ CO_2 + 6\ H_2O$----> ----> ----> ----> ----> ----> ---> $6\ O_2 + C_6\ H_{12}O_6$

The multiple arrows indicate that photosynthesis consists of a series of multistep processes, as summarized in the figure below.



Summary of Photosynthesis in the Chloroplasts of Plant Cells
(From Krogh, Biology -- a Guide to the Natural World, Fifth Edition)

- Photosynthesis begins with light reactions which convert the energy in sunlight to chemical energy in ATP and NADPH.
- In the second stage of photosynthesis, known as the Calvin cycle, ATP and NADPH provide the energy and H needed to convert CO_2 to a 3-carbon molecule which is converted to glucose.
- Glucose can be converted to sucrose which moves throughout the plant and provides input molecules for cellular respiration. Glucose can also be used to produce starch (a storage molecule) and cellulose (a major structural molecule in plants).

Common Misconception: Students often do not understand that most of a plant's biomass comes from CO_2.
This misconception is addressed in the following learning activity.

Learning Activity
Where Does a Plant's Mass Come From? -- The questions in this worksheet/discussion activity help students to understand that a large part of a plant's mass consists of water, most of the

biomass comes from carbon dioxide, and minerals from the soil contribute only a tiny amount of the plant's mass.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/plantmass

III. **Relating Photosynthesis and Cellular Respiration**

Learning Activity
Photosynthesis and Cellular Respiration -- Students use puzzle pieces which represent the components of the chemical equations for both photosynthesis and aerobic cellular respiration and answer questions about these processes.
Student Handout available at
http://serendip.brynmawr.edu/exchange/bioactivities/photocellrespir

Common Misconception: Many students believe that only animals carry out cellular respiration and plants only carry out photosynthesis; they do not understand that plants also need to carry out cellular respiration to provide ATP for cellular processes.
This misconception can be addressed with the learning activity described below and/or with the question, "Cells in plant leaves have both chloroplasts and mitochondria. If plants can carry out photosynthesis, why do plant cells need mitochondria?"

Learning Activity
Plant Growth Puzzle -- This discussion/worksheet activity presents a structured sequence of questions to challenge students to explain why plants that grow in the light weigh more than the seeds they came from, whereas plants that grow in the dark weigh less than the seeds they came from.
Student Handout and Teacher Notes available at
http://serendip.brynmawr.edu/exchange/bioactivities/plantgrowth

IV. **Additional Activities on Cellular Respiration and Photosynthesis**
Multiple additional activities, including "The Demise of a Halloween Pumpkin", are available at
http://www.nclark.net/PhotoRespiration