Energy

Energy is often defined as the ability to do work. There are many forms of energy. A few examples include; Gravitational energy, Kinetic energy (energy of motion), Thermal energy (heat energy), Potential energy. Potential energy is the energy something has based on its position in the universe. A stretched elastic band has potential energy. A rock held up in the air has potential energy based on its position.

Chemical energy is type of potential energy. It is the form energy that powers all of the chemical reactions life processes that take place inside the cells of all living organisms. The chemical energy contained in any given molecule, is found within the bonds that hold the atoms together. This chemical energy is found in the foods we eat, and it provides our cells with the energy they need to survive. The energy is actually found within a few types of high energy bonds that make up the carbs, lipids, and proteins we eat. The chemical energy stored in the bonds between the carbon, hydrogen and oxygen atoms of these foods we eat, provide us the energy we need to carry out all of life's processes. Chemical Reactions are categorized based on whether they consume energy or release energy.

Endothermic Reactions

Endothermic (Endergonic) reactions **require energy** (low energy reactants converted to high energy products). If the energy required to break the bonds in the reactants is greater than the energy given off by the formation of the bonds in the products then the reaction is **endothermic.** Our example is photosynthesis.

Photosynthesis

The major biochemical endothermic reaction that occurs within plants. Photosynthesis involves the decomposition of water molecules with their hydrogen atoms transferred to carbon atoms to make organic molecules like glucose.

$6CO_2 + 6\ H_2O \longrightarrow C_6H_{12}O_6 + 6O_2 = +686\ kcal$

Exothermic Reactions

Exothermic (Exergonic) reactions **release energy** (high energy reactants converted to low energy products). If the energy given off by the formation of the bonds in the products is greater than the energy required to break the bonds in the reactants then the reaction is **exothermic.** Our example is cellular respiration.

Cellular respiration

The major biochemical exothermic reaction that occurs within our bodies. Energy rich molecules like glucose are broken down inside the mitochondria releasing their energy.
The process is called cellular respiration.

$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6\ H_2O = -686\ kcal.$

The same equation describes the burning of glucose, and the same amount of free energy is released. But the energy of burning is released as heat, which is of little value to cells. The achievement of mitochondria is their ability to release the energy of glucose in small, discrete steps so that some of the energy can be trapped in ATP (adenosine triphosphate).

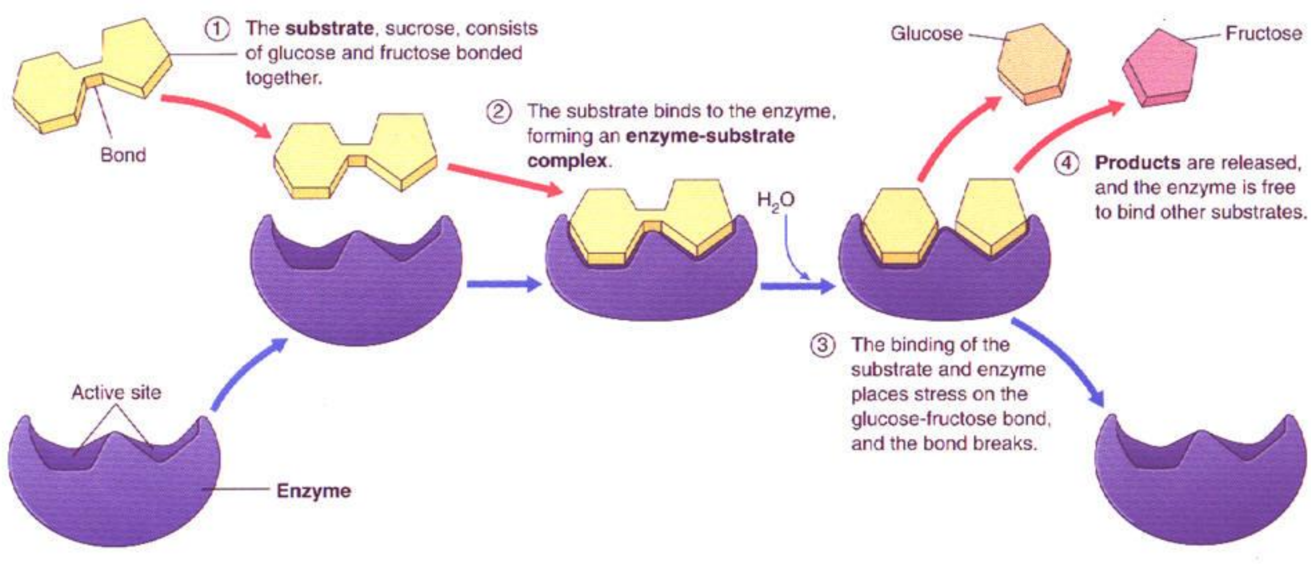
Units of Energy Measurement

The unit of measure for energy is a **calorie (cal)**. It is defined as the amount of energy required to warm 1 gram of water 1 degree Celsius. Therefore 1 **kilocalorie** (**kcal**) is the amount of heat needed to warm 1 liter of water 1 degree Celsius. However, when dealing with calories found in food, things get a little confusing. On ingredient lists of foods, calories is written with a capital "C" and actually represents one thousand calories or 1 kcal. Therefore if 1 cup of cereal is said to contain 150 Calories it actually contains 150 000 calories or 150 kcal, but because society and the food industry uses Calories (with the capital C) it is reported as 150 Cal. Therefore 1 Cal = 1 Kcal = 1000 cal

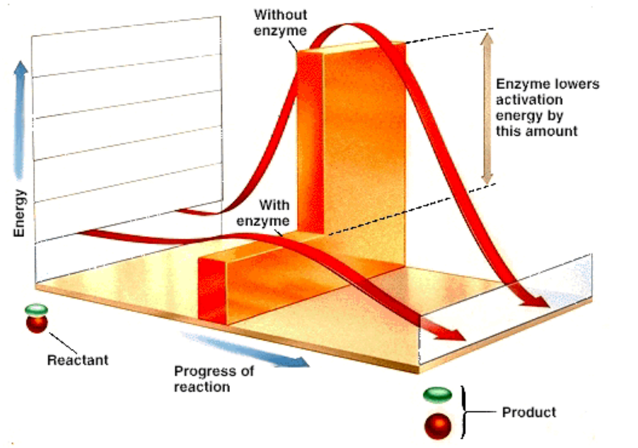
Enzymes

Catalysts are chemicals that control the rate or speed of chemical reactions. The catalysts themselves are not changed in the process, they are simple used to help chemical reactions occur.

Enzymes are special **protein catalysts** that control the rates of reactions that occur in living cells. Usually this means allowing the reactions to occur at lower "safer" temperatures for the cell. There are thousands of different enzyme in the human body, each designed to catalyze a particular reaction. Enzymes can be thought of as either "molecular scissors", that cut larger molecules in half, like a restriction enzyme cuts up DNA, or a set of "molecular hands" that hold smaller molecules together until they are glued or boned to form a larger molecule.

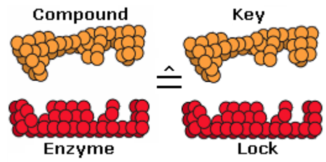


The **activation energy** is the energy required to initiate a chemical reaction. Enzymes bind temporarily to one or more of the reactants of the reaction they catalyze. In doing so, they lower the amount of **activation energy** needed and thus speed up the reaction.



How do enzymes operate?

First an enzyme binds to the reactant(s), called the substrate. The active site of the enzyme is the area of the protein that combines with the substrate. Successful binding of enzyme and substrate requires that the two molecules be able to approach each other closely over a fairly broad surface. Thus the analogy that a substrate molecule binds its enzyme like a key in a lock.



This requirement for complementarity in the configuration of substrate and enzyme explains the remarkable **specificity** of most enzymes. Generally, a given enzyme is able to catalyze only a single chemical reaction or, at most, a few reactions involving substrates sharing the same general structure.

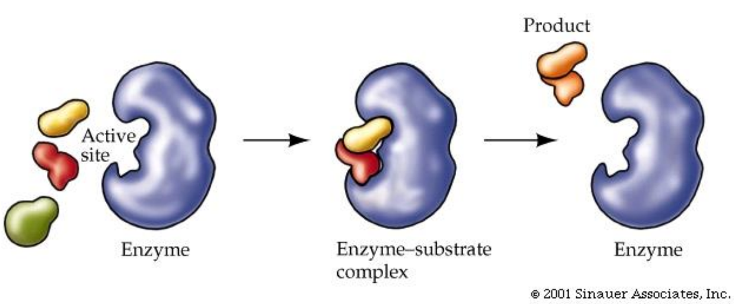
<u>Catabolic Enzymes</u>

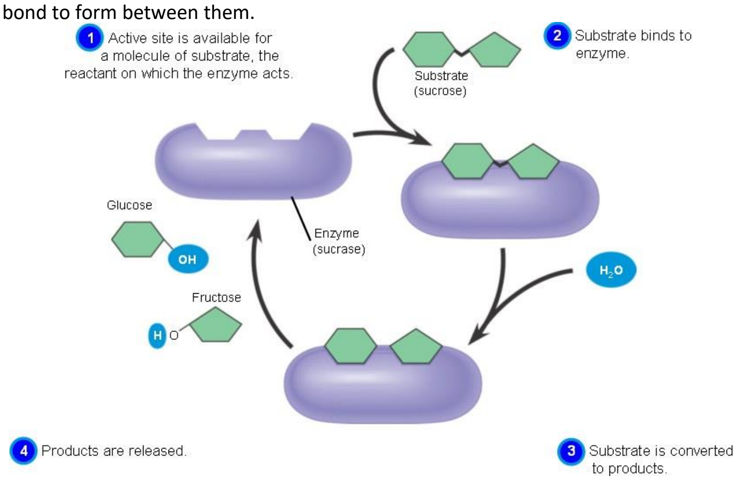
Some enzymes are involved in reactions where larger molecules are broken apart. These are often referred to as catabolic reactions. Digestive enzymes like amylase provide an example.

Many catabolic reactions (or digestive reactions) break down larger energy rich molecules.
This digestion often releases the energy in the form of ATP, which is then often used for other anabolic reactions which often require energy to build molecules.

<u>Anabolic Enzymes</u>

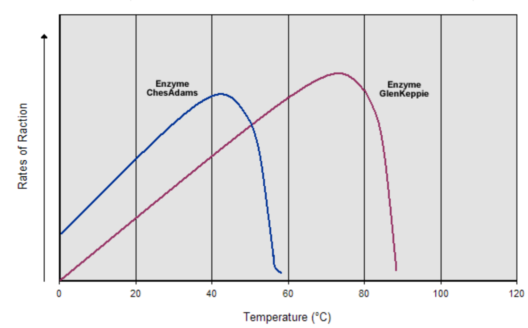
Other enzymes are involved in reactions where two smaller molecules are linked together. These are often referred to as anabolic reactions. DNA Polymerase is an example.
In this case, the enzyme holds the nucleotides together at the precise angle needed for a bond to form between them.





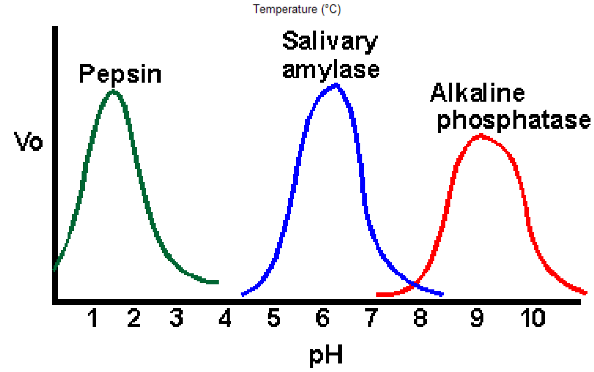
<u>Factors Affecting Enzyme Action</u>

5 general factors affect the rate of enzyme activity.
1) Temperature
2) pH
3) Concentration of substrate molecules
4) Inhibitors (competitive and non-competitive)
5) Feedback loops

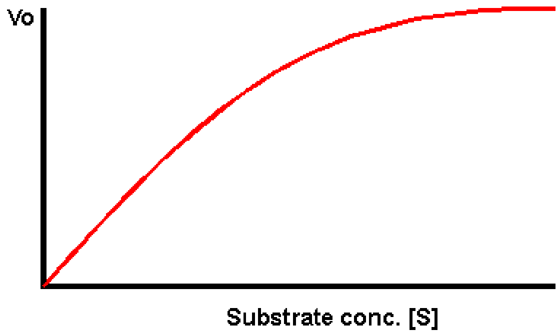


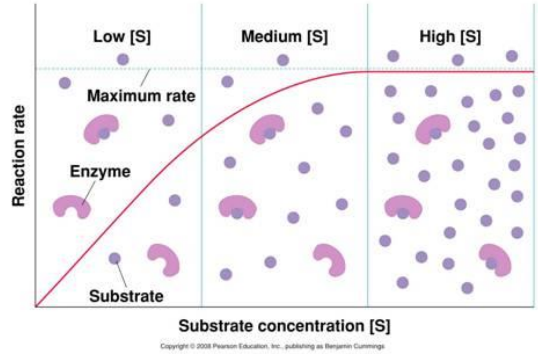
1) The temperature.
The activity of enzymes is strongly affected by **temperature.** If the temperature is above or below the optimal range for a given enzyme, the enzyme activity decreases sharply.

2) The pH.
The activity of enzymes is also strongly affected by **pH.** If the pH is above or below the optimal range for a given enzyme, the enzyme activity decreases sharply.



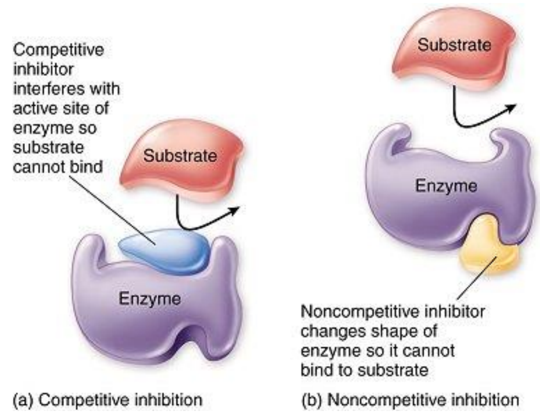
3) Concentration of substrate.
Enzyme activity can also be affected by the **concentration of the substrate molecules**. Generally the greater the concentration of the substrate molecules, the greater the number of collisions, the greater the rate of reaction. However, once the concentration of the substrate molecules exceeds the concentration of the enzyme molecules, the rate levels off due to a lack of enzyme binding sites.



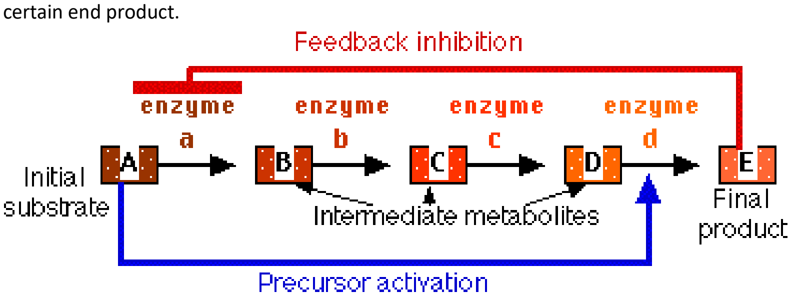


4) Inhibitors.
The necessity for a close, if brief, fit between enzyme and substrate explains the phenomenon of inhibition. There are two types of inhibitors.
a) Competitive
b) Non-competitive

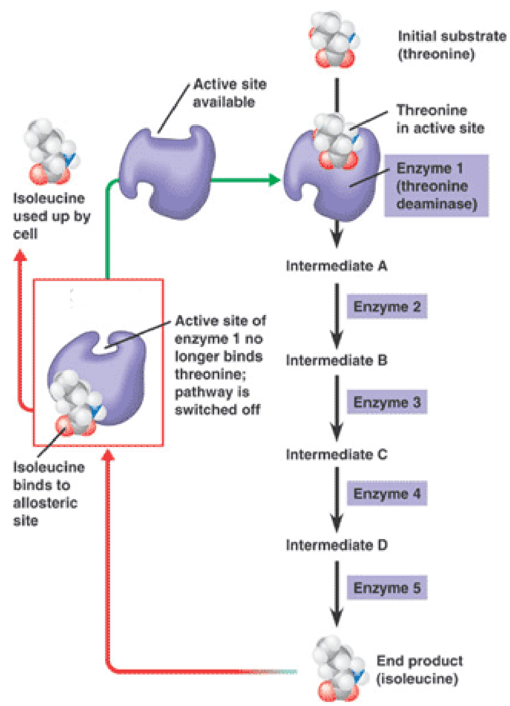
a) Competitive inhibitors have shapes very similar to that of the substrate. They “compete” with the substrate for the activation sites of enzymes and thus “get in the way” of the reaction.
b) Non-competitive inhibitors have the ability to bind to the “back end” of the enzyme (called the allosteric site) which changes the shape of the active site of the enzyme so it can no longer bind to the substrate.



5) Feedback loops.
There are 2 types of feedback loops.
a) Feedback Inhibition
b) Precursor Activation
Metabolic pathways are a series of chemical reactions of which work sort of like an assembly line to produce a certain end product.

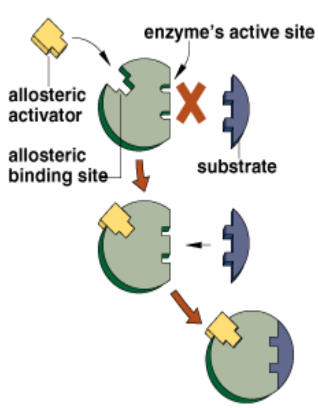


a) Feedback Inhibition
If the product of a metabolic pathway begins to accumulate within the cell, it is wasteful for the cell to continue to make that product. In fact it might even be toxic for the cell to produce any more of that final end product as the levels of that end product might be out of the tolerable range. Feedback inhibition uses enzymes, and their amazing ability to change shape, to slow down or stop a metabolic pathway. It does this by binding to the enzyme’s allosteric site, which in turn alters the enzyme’s activation site, and actually degrades the “fit” of the enzyme-substrate complex. Thus further production of the enzyme is halted.

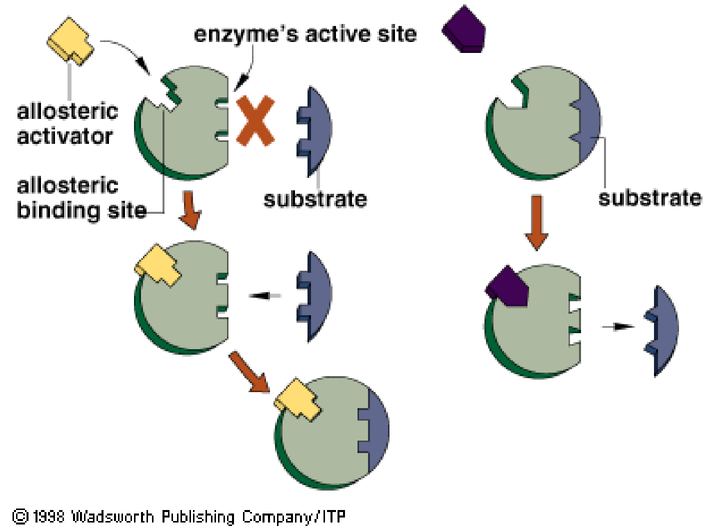


b) Precursor Activation
If the initial substrate of a metabolic pathway begins to accumulate within the cell, it is usually in the cells best interest to use up the substrate and not continue to leave it “laying around”. In fact it might even be toxic for the cell to have this excess material present as the levels of that material might be out of the tolerable range. Precursor activation uses enzymes, and their amazing ability to change shape, to speed up a metabolic pathway.

It does this by binding to the enzyme’s allosteric site, which in turn alters the enzyme’s activation site, and actually improves the “fit” of the enzyme-substrate complex. Thus speeding production of the enzyme is halted.



In the case of feedback inhibition and precursor activation, the activity of the enzyme is being regulated by a molecule which is **not** its substrate. In these cases, the regulator molecule binds to the enzyme at a different site than the one to which the substrate binds. When the regulator binds to its site, it alters the shape of the enzyme so that its activity is changed. This is called an **allosteric** effect.



Energy Storage and Transformation

ATP (Adenosine Triphosphate) is a nucleotide that performs many essential roles in the cell. Besides pairing with thymine in DNA (A pairs with T), adenosine can be modified to play the crucial role of energy provider for cells. ATP is the major **energy currency** of the cell, providing the energy for most of the energy-consuming activities of the cell. The ATP molecule is like a "molecular rechargeable battery" that can be changed and discharged over and over again.

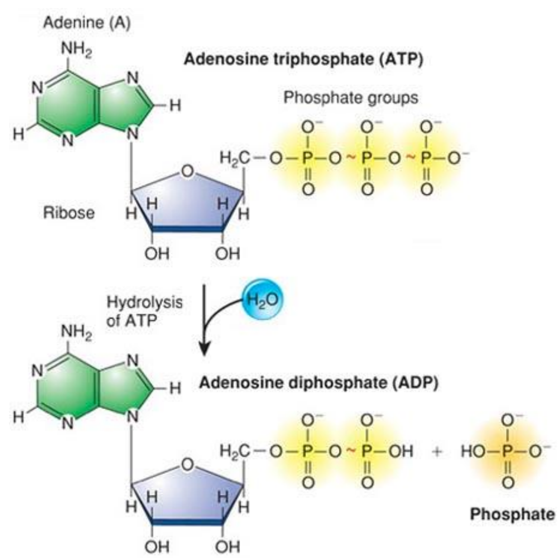
Examples of where ATP is used (discharged).

Most anabolic reactions in the cell are powered by ATP.
a) assembly of amino acids into proteins
b) assembly of nucleotides into DNA and RNA
c) synthesis of polysaccharides such as glycogen and starch
d) synthesis of triglycerides

Other cell processes that are powered by ATP include:
a) Active transport
b) Nerve impulses
c) Maintenance of cell volume by removing excess water
d) Muscle contractions
e) Beating of cilia and flagella

Examples of where ATP is produced (charged).

In the cytosol during glycolysis
In mitochondria during cellular respiration
In chloroplasts during photosynthesis



How does ATP store energy?
The energy is stored in the bonds that hold the third phosphate group onto the ATP molecule.

How is the energy released from ATP?
ATP is the high energy form of the molecule. When the third phosphate group of ATP is removed, energy is released. The exact amount depends on the conditions, but on average 7.3 kcal per mole is released. With the third phosphate removed, we no longer call the molecule ATP, it is now called ADP or adenosine diphosphate.

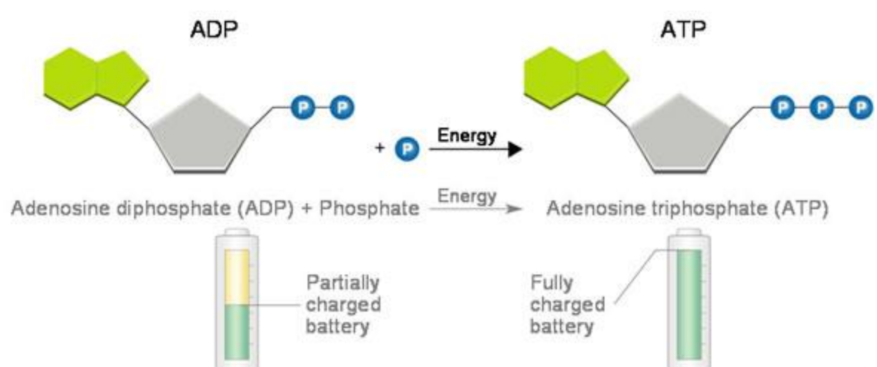
The chemical equation that represents this release of energy is as follows.

ATP + H_2O → ADP + P (energy)

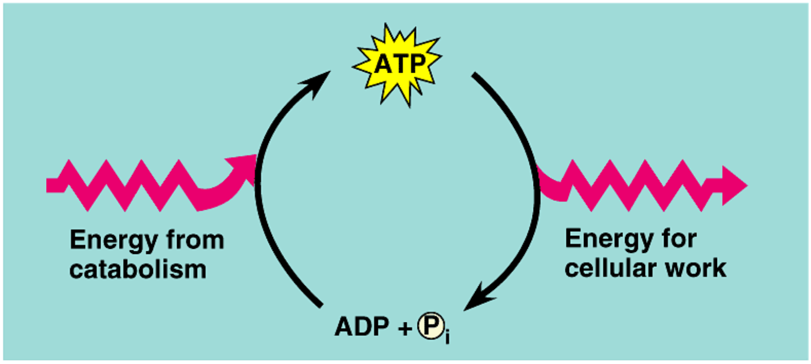
How is the molecule "charged back up"?
ADP is the low energy form of the molecule. It can be charged back up into ATP by having the third phosphate added back into position. To do this, the same amount of energy must be consumed. Again, the exact amount depends on the conditions, but on average 7.3 kcal per mole is required. With the third phosphate back in position, we no longer call the molecule ADP, it is now called ATP or adenosine triphosphate. This process of adding a phosphate group to a molecule is called **phosphorylation**.

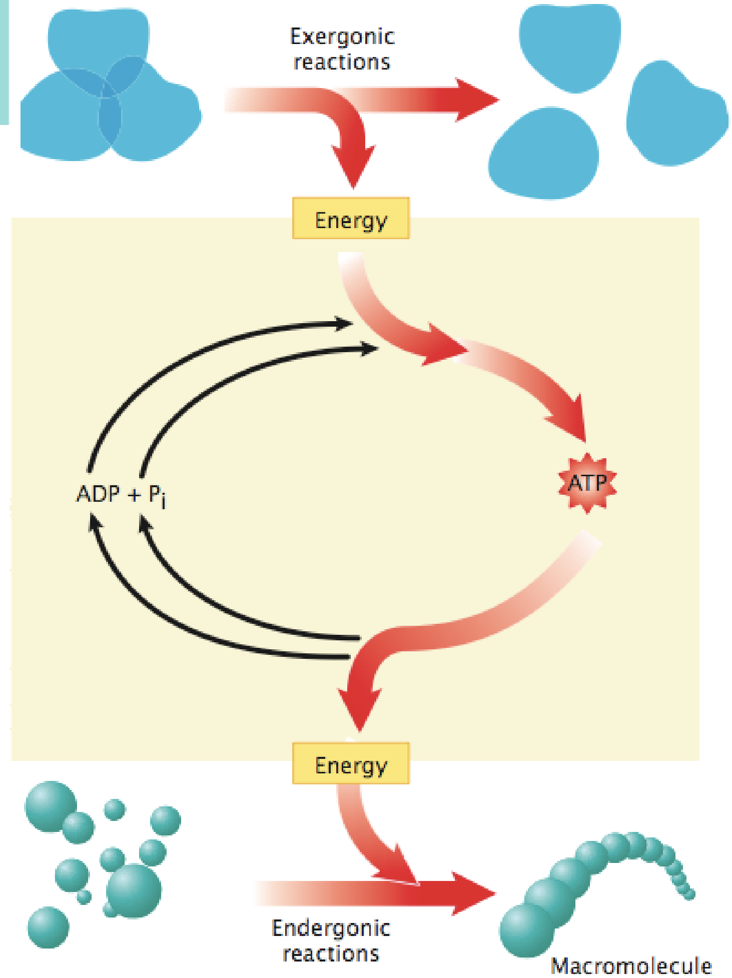
The chemical equation that represents this release of energy is as follows.

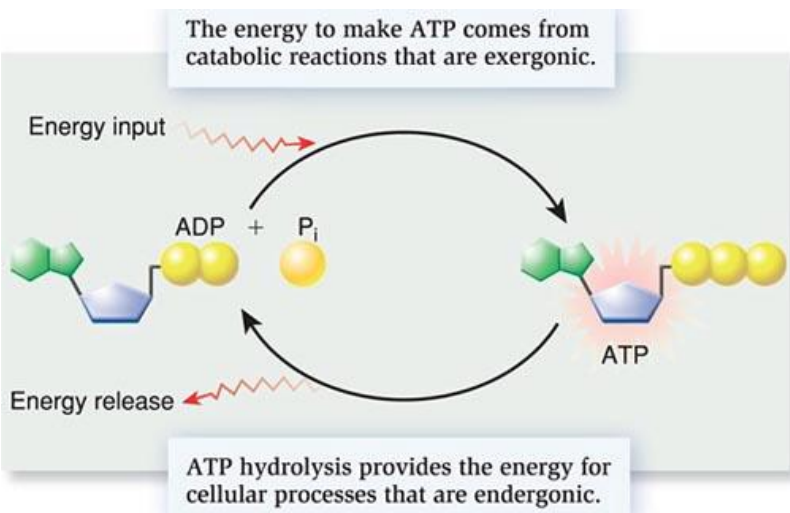
ADP + P + (energy) → ATP + H_2O

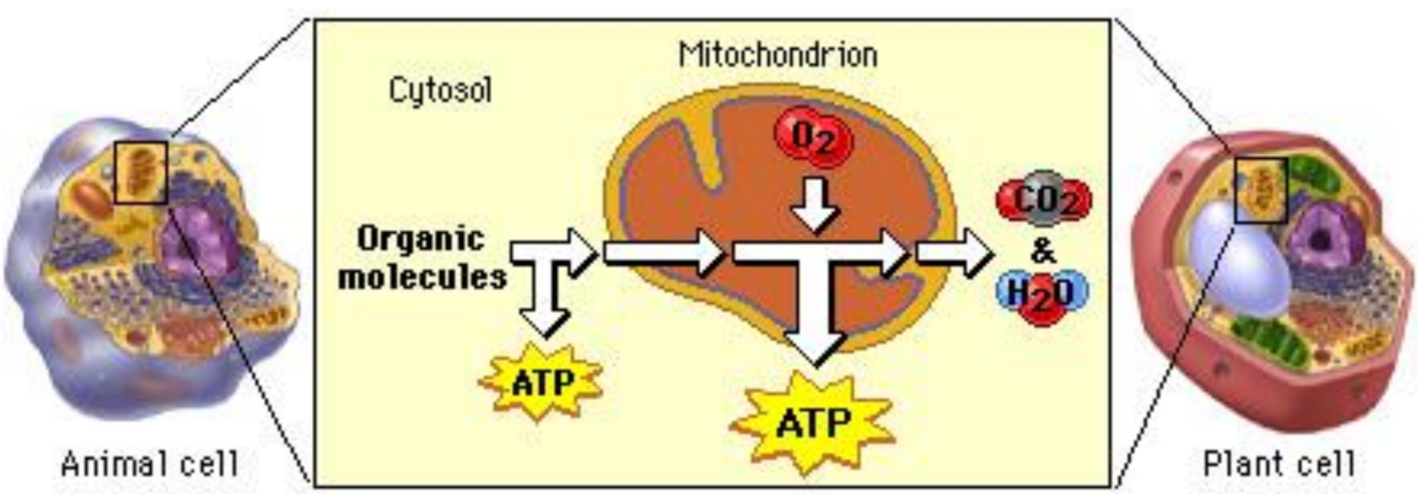


The ATP Cycle



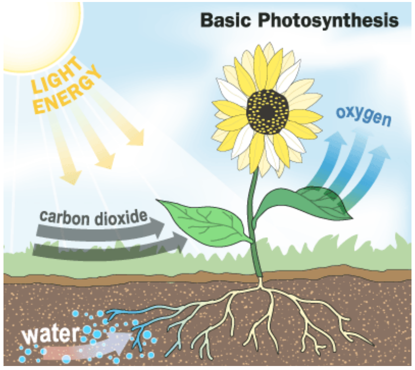


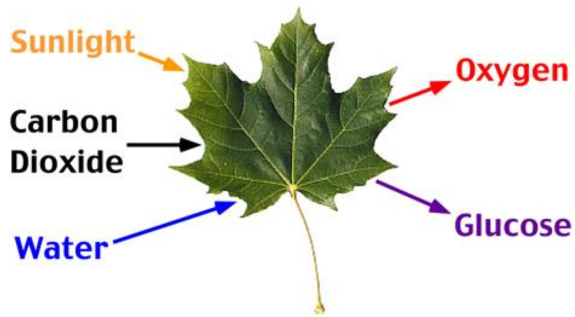




Photosynthesis

Sunlight plays a much larger role in our sustenance than we may expect. All the food we eat and all the fossil fuel we use is a product of photosynthesis, which is the process that converts energy in sunlight to chemical forms of energy that can be used by biological systems.





The word equation is as follows:

carbon dioxide + water ---→ glucose + oxygen

The balanced chemical equation is as follows:

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

Leaves and Leaf Structure

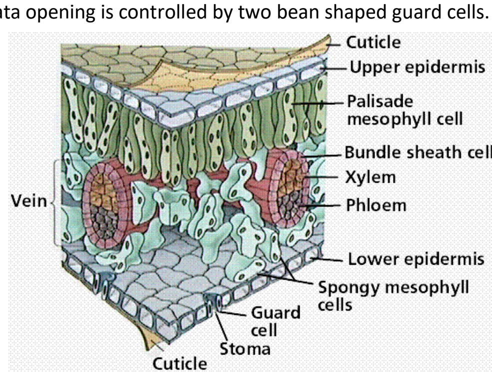
Plants are the only photosynthetic organisms to have leaves (although not all plants have leaves). A leaf may be viewed as a solar collector crammed full of photosynthetic cells.

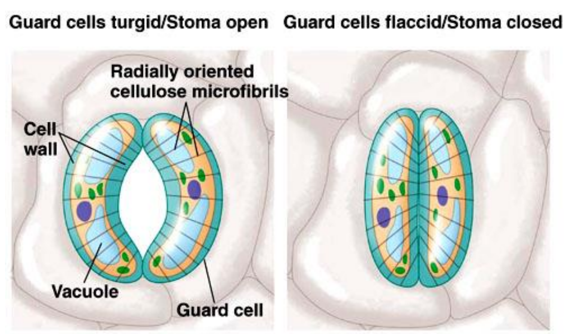
There are two important types of conductive tissue in plant cells.

1) Xylem – carry water from the roots to the leaves.
2) Phloem – carry glucose from the leaves to the rest of the plant.

The raw materials of photosynthesis, water and carbon dioxide, enter the cells of the leaf, and the products of photosynthesis, sugar and oxygen, leave the leaf. Pictured below as a cross section of a leaf.

The stomata is the opening in the leaf in which the carbon dioxide enters the leaf and the oxygen exits. The stomata opening is controlled by two bean shaped guard cells.





(a) Changes in guard cell shape and stomatal opening and closing (surface view)

The Nature of Light

Light travels in waves. Different wavelengths of light are perceived by us as different colors. White light is separated into the different colors of light by passing it through a prism or water drops in a rain cloud.

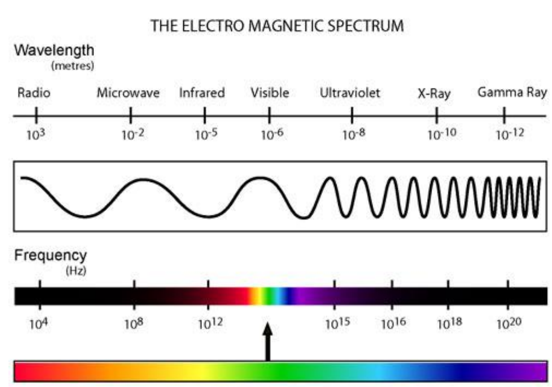
Chlorophyll and Accessory Pigments

A pigment is any substance that absorbs light. The color of the pigment comes from the wavelengths of light reflected (in other words, those not absorbed). **Chlorophyll,** the green pigment common to all photosynthetic cells, absorbs all wavelengths of visible light except green, which it reflects to be detected by our eyes.

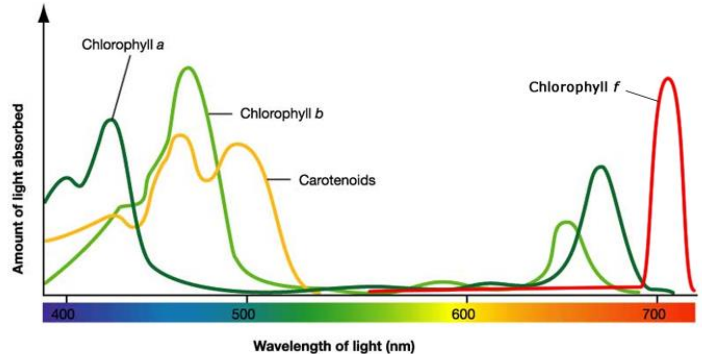
We perceive objects to be the color they are because of the light they reflect.

Black pigments absorb all of the wavelengths that strike them.

White pigments/lighter colors reflect all or almost all of the energy striking them.



A spectrometer is used to measure which wavelengths of light are absorbed by a given pigment. As we would expect, chlorophyll absorbs most colors of light except green…which it reflects.



<u>The Structure of the Chloroplast and Photosynthetic Membranes</u>

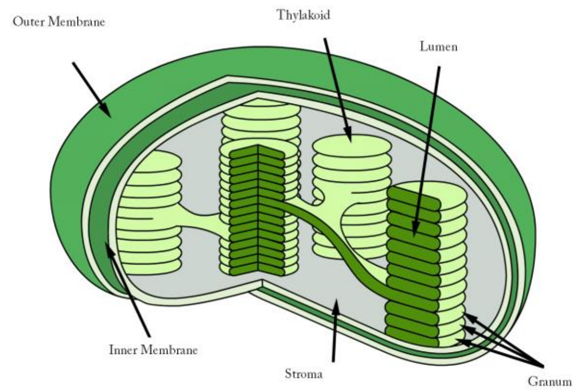
The organelles responsible for photosynthesis are the chloroplasts. Inside the chloroplasts are **thylakoids,** the structural units of photosynthesis. Thylakoids are stacked like pancakes into stacks known as **grana.** The space surrounding the grana is referred to as the **stroma.**

Photosynthesises is a two-step process.
Step 1 The Light Reaction – takes place inside the thylakoids
Step 2 The Carbon Fixation Cycle – takes place in the stroma

<u>The Two Reactions of Photosynthesis</u>

1. Light Dependent Processes (Light Reactions)

In the Light Dependent Processes light strikes chlorophyll in such a way as to excite electrons to a higher energy state. In a series of reactions (along the ETS) the energy is converted into **ATP and NADPH**. Water is split in the process, releasing oxygen as a by-product of the reaction. The **ATP and NADPH** provide the energy and some of the matter for the Carbon Fixation Cycle.

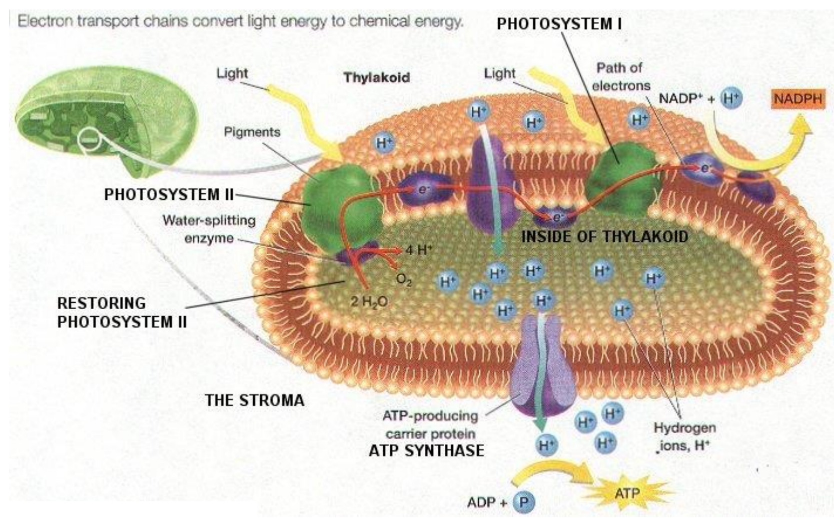


The light reaction goes as follows.

Energy from light is absorbed by a chlorophyll complex at PSII and an electron is pumped down one site along the ETS. To replace the missing electron, PSII steals an electron from water (water is the electron loser) splitting the water into H^+ ions and O. The oxygen pair up forming O_2 and are given off as waste. The H^+ ions (called protons) are left to build up inside the thylakoid and help increase the proton gradient across the thylakoid membrane. The electron from the water is passed along the ETS like a hot potato from one electron acceptor to the other. Along its travels down the ETS the "excited" electron is used to pump H^+ across the membrane into the thylakoid also helping increase the proton gradient. When the electron reaches PSI it is re-energized by another unit (photon) of light. This time the excited electron is used to reduce $NADP^+$ turning it into NADPH (here one might say the electron hops into the electron taxi cab called NADPH). The proton gradient gives ATPsynthase the energy to convert ADP into ATP (this is called photophosphoralation - in other words converting ADP into ATP). The end result is NADPH and ATP are produced.

<u>2. Carbon Fixation Cycle (Light Independent Process or Dark Reaction)</u>

In the carbon fixation cycle carbon dioxide from the atmosphere (or water for aquatic organisms) is captured and modified by the addition of Hydrogen to form carbohydrates such as glucose. The incorporation of carbon dioxide into organic compounds is known as **carbon fixation**. The energy for the carbon fixation cycle comes from the light reaction on the form of ATP and NADPH.



The carbon fixation cycle goes as follows.

The 2 products of the light reaction (ATP and NADPH) are now used to drive the carbon fixation cycle. The ATP releases its energy and the NADPH drops off the electrons and protons (H^+) it picked up from water in the light reaction. The carbon fixation cycle starts as 3 CO_2 molecules enter the stroma and are grabbed by the enzyme RuBisCo and each is added to a 5 carbon chain. Through a series of reactions and shuffling of atoms, 6 molecules of glyceraldehyde 3-phosphate (G_3P) are produced. One G_3P is removed and the other 5 G_3P are reshuffled and used to regenerate the cycle. The end result is G_3P which is a 3 carbon chain that can be thought of as a half a sugar. Two turns of the cycle are therefore required to produce 1 sugar molecule.

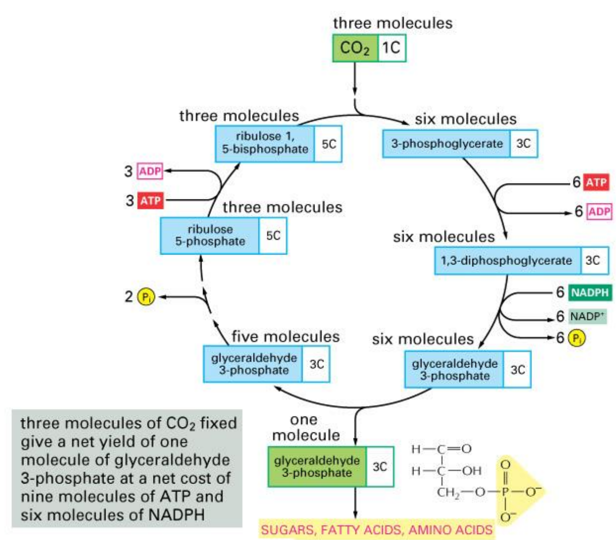
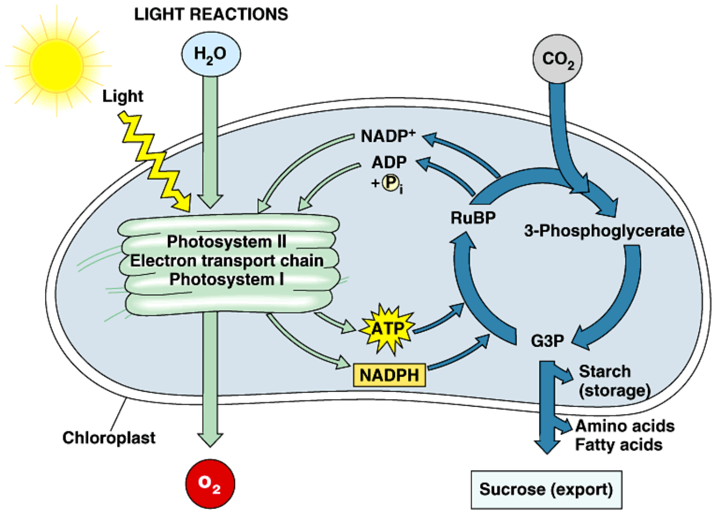
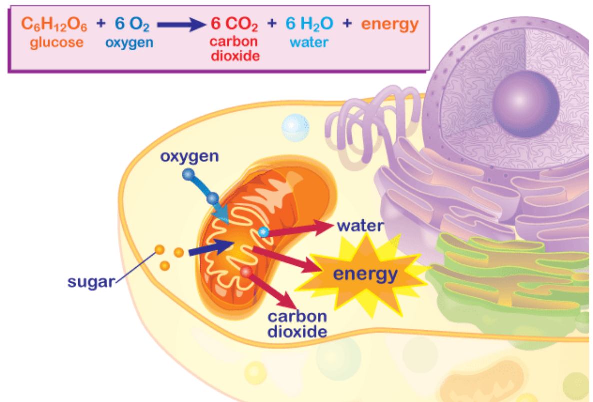


Figure 14-39 Essential Cell Biology, 2/e. (© 2004 Garland Science)

Summary of Photosynthesis





Cellular Respiration

Cellular respiration is the process of oxidizing food molecules, like glucose, to carbon dioxide and water. The energy released is trapped in the form of ATP for use by all the energy consuming activities of the cell.

The word equation is as follows:
Glucose + oxygen ---→ carbon dioxide + water

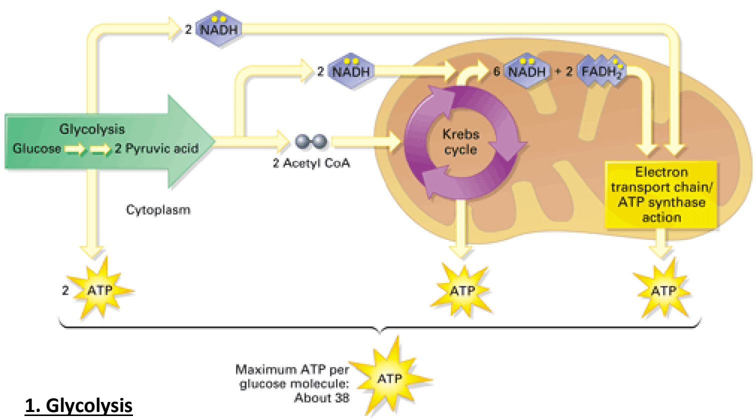
The balanced chemical equation is as follows:
$C_6H_{12}O_6 + 6O_2 \text{ ----> } 6CO_2 + 6\ H_2O$

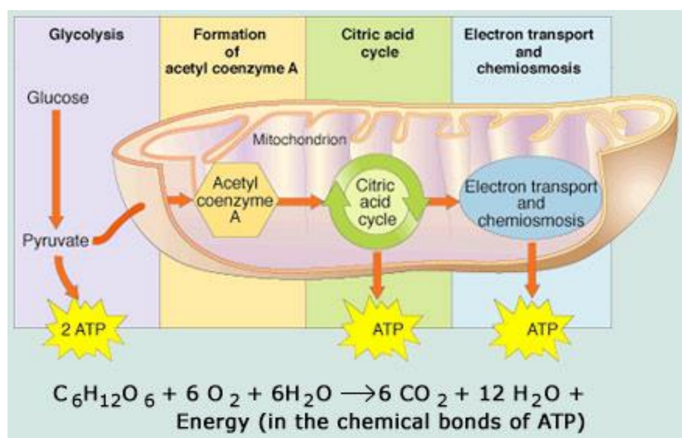
The process occurs in three stages:

1. **Glycolysis** – splitting of glucose in half into two ½ sugars called pyruvate.

   The Transition Step – technically known as the "**Formation of Acetyl Coenzyme A**" is a mini-step that occurs between steps 1 and 2. Here pyruvate is converted into Acetyl CoA.

2. **Citric Acid Cycle (Kreb's Cycle) –** the further breakdown Acetyl CoA into CO_2.
3. **Electron Transport System –** majority of the ATP production - high energy NADH and $FADH_2$ are "cashed in" to ATP.

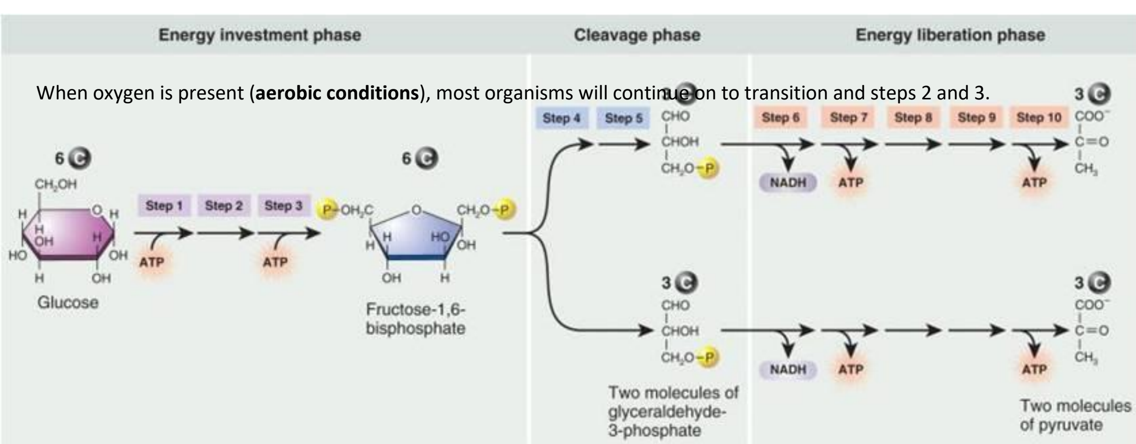


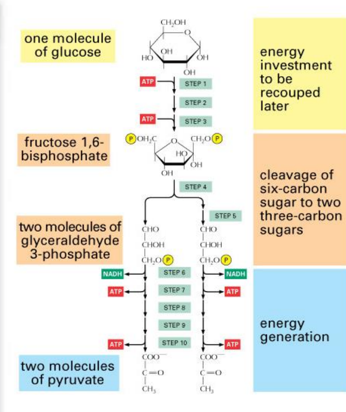


1. Glycolysis

Glycolysis occurs in the cytoplasm. **Glycolysis** is the metabolic process in which a 6-carbon glucose is split into two 3-carbon pyruvate molecules. A **net of 2 ATP and 2 NADH are produced for every glucose broken down**. Glycolysis is not technically a part of cellular respiration but we will refer to it as step 1 of 3.

When oxygen is present (**aerobic conditions**), most organisms will continue on to transition and steps 2 and 3.





1. **Glycolysis** – splitting of glucose in half into two ½ sugars called pyruvate.

   The Transition Step – technically known as the "**Formation of Acetyl Coenzyme A**" is a mini-step that occurs between steps 1 and 2. Here pyruvate is converted into Acetyl CoA.

2. **Citric Acid Cycle (Kreb's Cycle) –** the further breakdown Acetyl CoA into CO_2.
3. **Electron Transport System –** majority of the ATP production - high energy NADH and $FADH_2$ are "cashed in" to ATP.

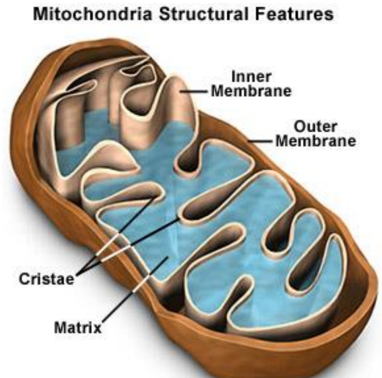


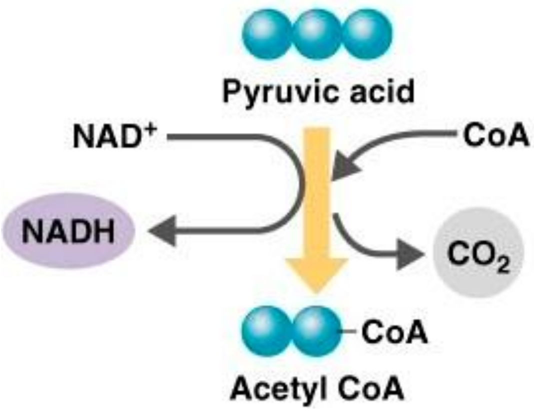
Figure 1

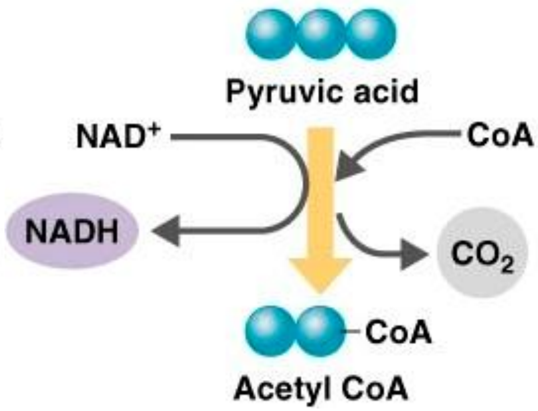
<u>The Mitochondrion</u>

The mitochondrion is the power house of the cell. Steps 2 and 3 of aerobic cellular respiration occur in the mitochondrion. There are 2 membranes inside the mitochondrion. Between the inner and outer membrane is the intermembrane space. The interior of the mitochondrion is called the matrix.

<u>The Transition Step</u>

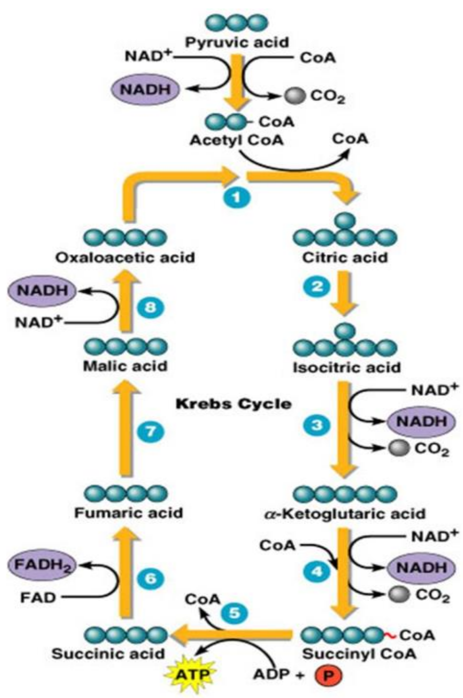
Technically known as the "**Formation of Acetyl Coenzyme A**". Just as the pyruvate (a 3-carbon chain) enters the mitochondria, each pyruvate is shortened by 1 carbon forming two 2-carbon chains. The carbons that are removed each form a carbon dioxide and are released. The remaining two 2-carbon chains called Acetyl CoA are ready to enter the mitochondrion for step 2. Two **more NADH** are produced in the process.





<u>2. Citric Acid Cycle (Kreb's Cycle)</u>

One at a time, each of the two Acetyl Co-A (2-C chains) is attached to a 4-C chain (oxaloacetic acid). The 2-C and 4-C make form a 6-carbon chain called Citric acid (why it's AKA the Citric Acid Cycle). During the rest of the cycle, the atoms are shuffled around, and the carbons that entered the cycle are released as carbon dioxide. The energy released during these endothermic steps are captured in the form of ATP, GTP, NADH and $FADH_2$. GTP transfers its energy directly to ATP. **Net result of Citric Acid Cycle for every glucose broken down (two turns of the cycle) is 6 NADH, 2 GTP, and 2 $FADH_2$.**



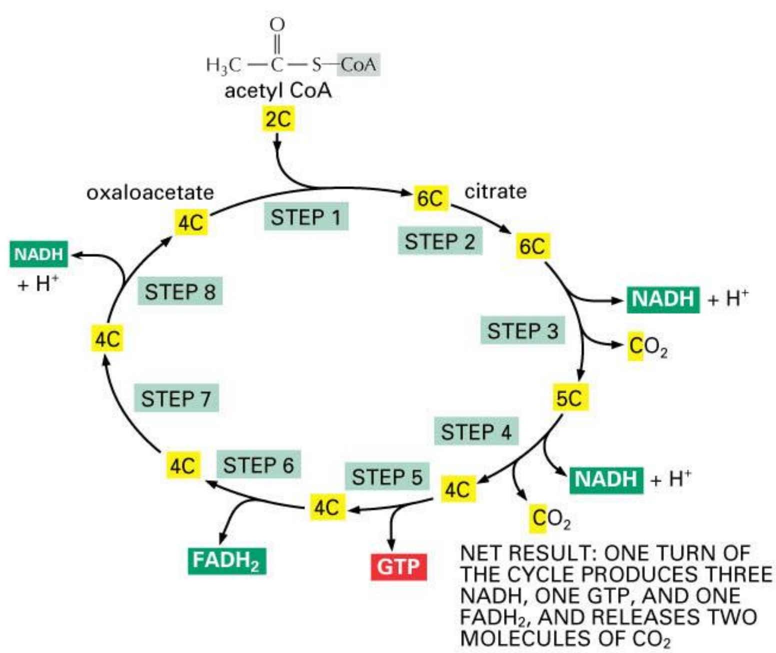


Figure 13-11 Essential Cell Biology, 2/e. (© 2004 Garland Science)

3. Electron Transport System

Whereas Citric Acid Cycle occurs in the matrix of the mitochondrion, the Electron Transport System (ETS) is embedded in the membranes known as the cristae. In the ETS, the higher energy molecules produced in the Citric Acid Cycle are cashed in, producing ATP. This is achieved by creating a proton gradient in the intermembrane space. Here's how.

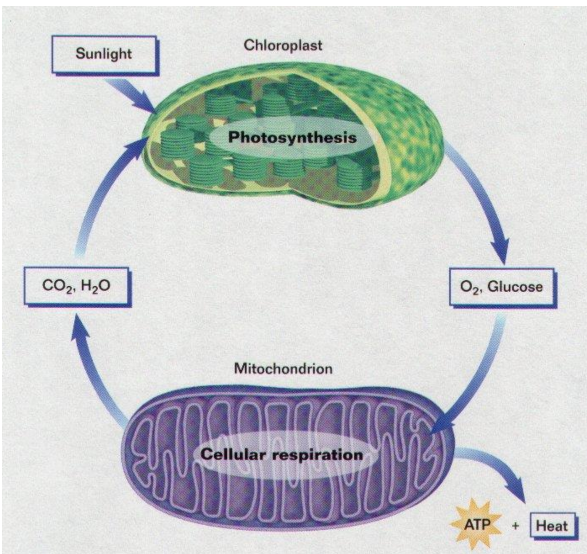
The NADH and $FADH_2$ act like taxi cabs and drop their electrons and protons off at the ETS (they are oxidized back into NAD^+ and FAD^+).

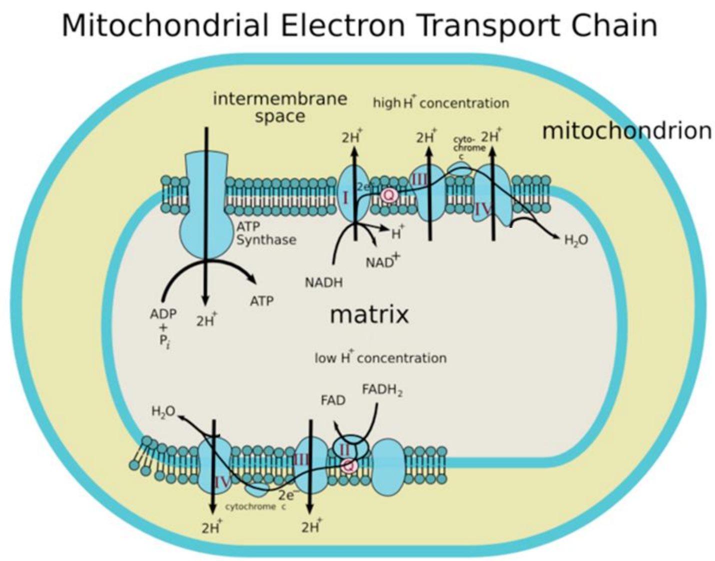
The "dropped off" electrons travel along the ETS pumping "dropped off" protons (H^+) into the intermembrane space building the proton pressure (gradient). Eventually the electrons are picked up at the end of the ETS by an oxygen atom and join with 2 H^+ to form water.

Finally the proton pressure in the intermembrane space is relieved as the protons are released through the ATPsynthase back into the matrix, converting 36 ADP into 36 ATP.

The process of generating ATP in this way is called **oxidative phosphorylation**.

Photosynthesis and Cellular Respiration





Anaerobic Pathways

Without oxygen to accept the electrons the ETS backs up as does the Citric Acid Cycle. Under these anaerobic conditions (the absence of oxygen) pyruvic acid can be routed by the organism into one of two pathways:

1. lactic acid fermentation
2. alcohol fermentation

Lactic acid Fermentation

Many organisms will also ferment pyruvic acid into other chemicals such as **lactic acid**. Humans ferment lactic acid in muscles where oxygen becomes depleted, resulting in localized anaerobic conditions.

Alcohol Fermentation

Is the formation of alcohol from sugar. Yeast, when under anaerobic conditions, convert glucose to pyruvic acid via the glycolysis pathways, then convert pyruvic acid into **ethanol**, a C-2 compound.

The ratio of ATP produced anaerobically Vs aerobically is 2:38 or 1:19 (per glucose).

Anaerobically only the 2 ATP from glycolysis are gained, the two NADH produced in glycolysis require the ETS to be "cashed in" to ATP. Instead, the NADH are oxidised (regenerated) to NAD^+ with the energy being used to break down the pyruvate into lactate or ethanol.

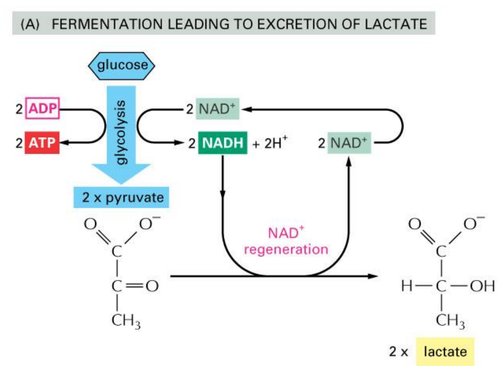


Figure 13-4 part 1 of 2 Essential Cell Biology, 2/e. (© 2004 Garland Science)

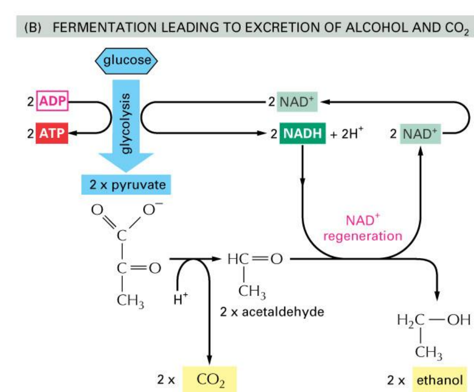


Figure 13-4 part 2 of 2 Essential Cell Biology, 2/e. (© 2004 Garland Science)

Summary of Energy Produced **Aerobically** Per Glucose Molecule

Glycolysis	
2 ATP	2 ATP
2 NADH x 3	6 ATP
Transition	
2 NADH x 3	6 ATP
Kreb's Cycle	
6 NADH x 3	18 ATP
2 GTP x 1	2 ATP
2 $FADH_2$ x 2	4 ATP
Total	38 ATP