Chapter 5

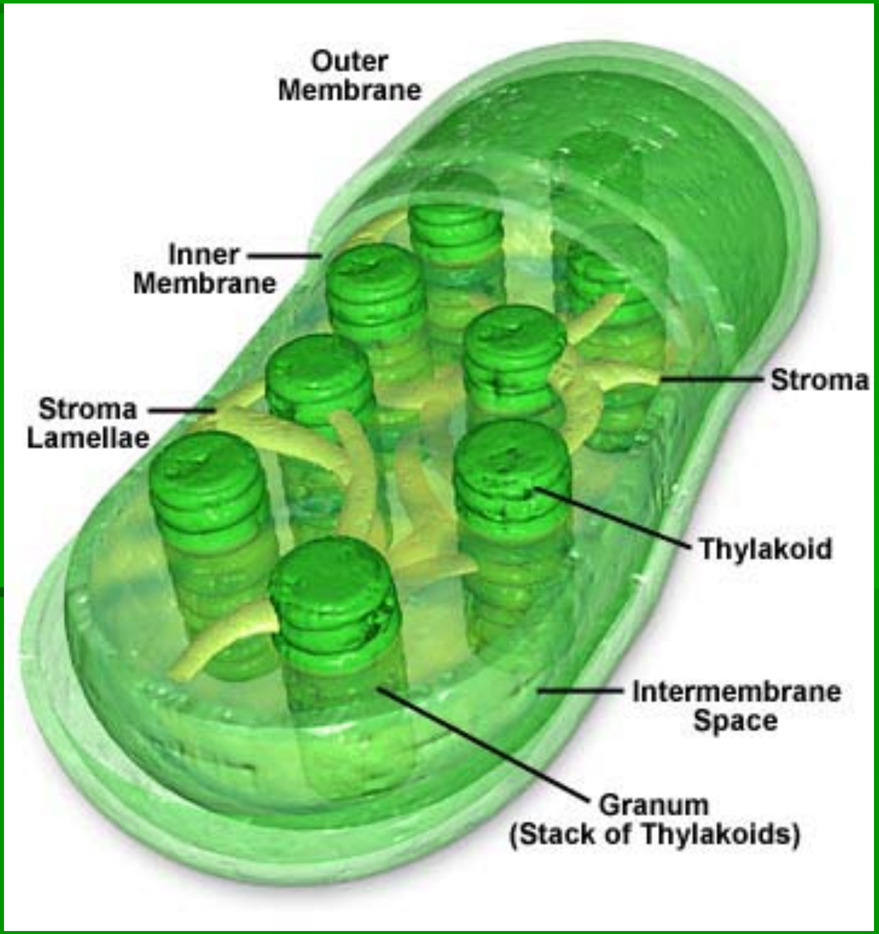
Photosynthesis & Cellular Respiration

5.1 – Matter and Energy Pathways in Living Systems

- Both cellular respiration and photosynthesis are examples of biological processes that involve matter & energy
- During photosynthesis, energy from the sun is stored in the chemical bonds of glucose
- This energy is released during cellular respiration

The Chloroplast

- The chloroplast is the site of photosynthesis
- They consist of a series of membranes

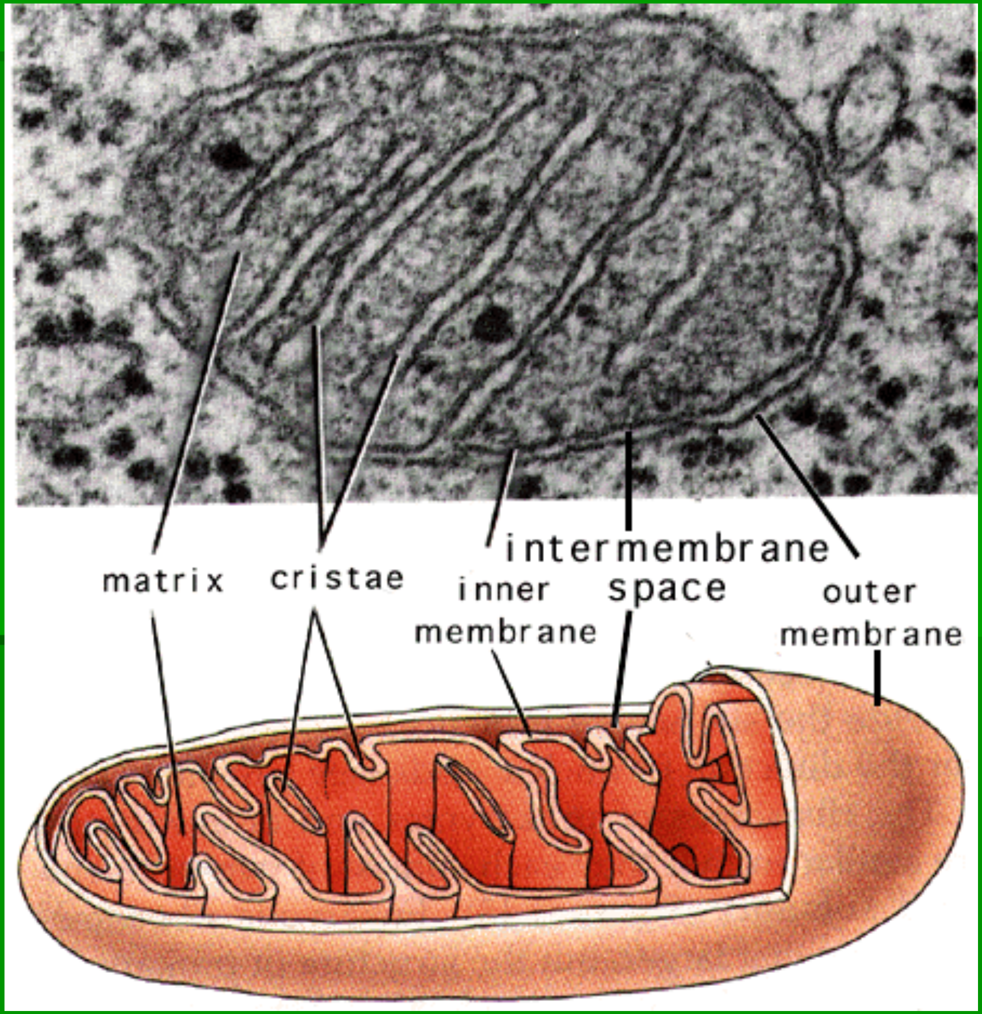


The Chloroplast

- The inner and outer membranes surround the stroma
- The stroma is a fluid that contains proteins and chemicals required for photosynthesis
- A third type of membrane is the thylakoid, which creates a series of flattened sacs
- These thylakoids are stacked in structures known as grana

The Mitochondria

- The mitochondria is the site of cellular respiration
- They are found in all organisms



Endosymbiosis

The Mitochondria

- The mitochondria has two membranes
- The fluid-filled space within the inner membrane is known as the matrix
- This matrix contains many of the chemicals and proteins required to break down carbohydrates

Metabolic Pathways

- The common chemical equations that represent both photosynthesis and cellular respiration are only *net* reactions
- Both of these processes use a series of pathways that are set up in step-by-step sequences

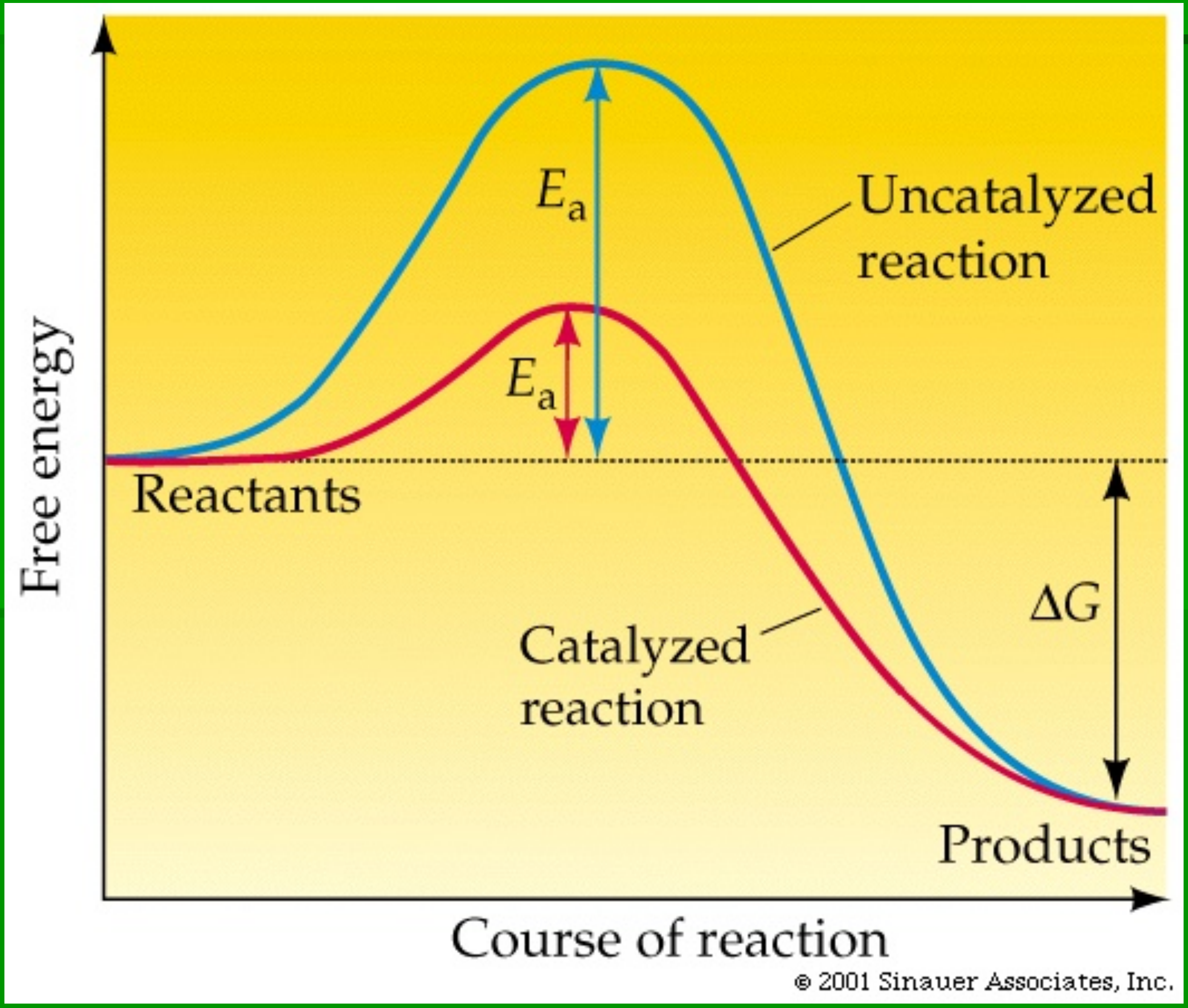
The Role of Enzymes

- Metabolism (the sum of the processes within a cell) can be broken into two distinct types of reactions
- Anabolic reactions & pathways create larger molecules from small subunits
- Catabolic reactions & pathways break down large molecules into smaller pieces

The Role of Enzymes

- Often these reactions will not naturally occur because they require energy to start
- This energy required to start a reaction is known as activation energy
- Catalysts and enzymes reduce the activation energy, allowing the reactions to proceed more rapidly
- Enzymes are protein catalysts within cells

Activation Energy – Catalyzed vs. Uncatalyzed



Oxidation & Reduction

- Recall that oxidation is a reaction where an atom or molecule loses electrons (LEO – Loses Electrons = Oxidation)
- When a reaction occurs where an atom or molecule gains electrons, it is known as reduction (GER – Gains Electrons = Reduction)
- However, free electrons from oxidation cannot exist on their own

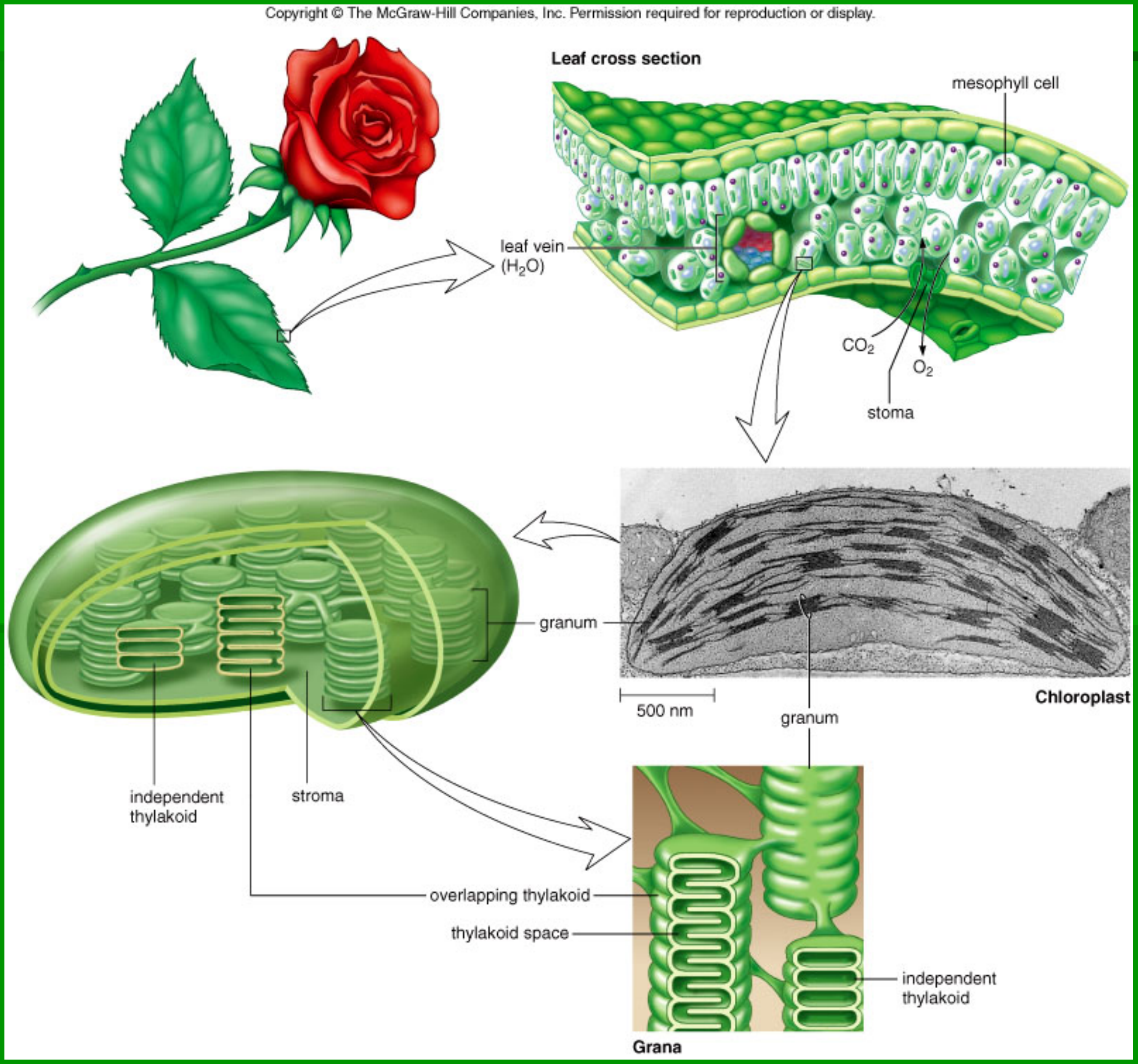
Oxidation & Reduction

- As a result, the electrons that are lost through oxidation of one substance cause the reduction of another compound
- Therefore, oxidation and reduction reactions must occur at the same time

5.2 - Photosynthesis

- Overview of Photosynthesis:
- Flowering plants as photosynthesizers
  - Photosynthesis occurs in the green parts of plants
  - Leaves contain mesophyll tissue specialized for photosynthesis
  - Water is taken up by roots and transported to leaves by vascular tissue (veins / xylem)
  - Carbon dioxide and oxygen enter / exit through openings in the leaves called *stomata*
  - Light energy is absorbed by photopigments in thylakoids of chloroplasts

Leaf Structure Revisited - Sci 10



Photosynthetic Reactions

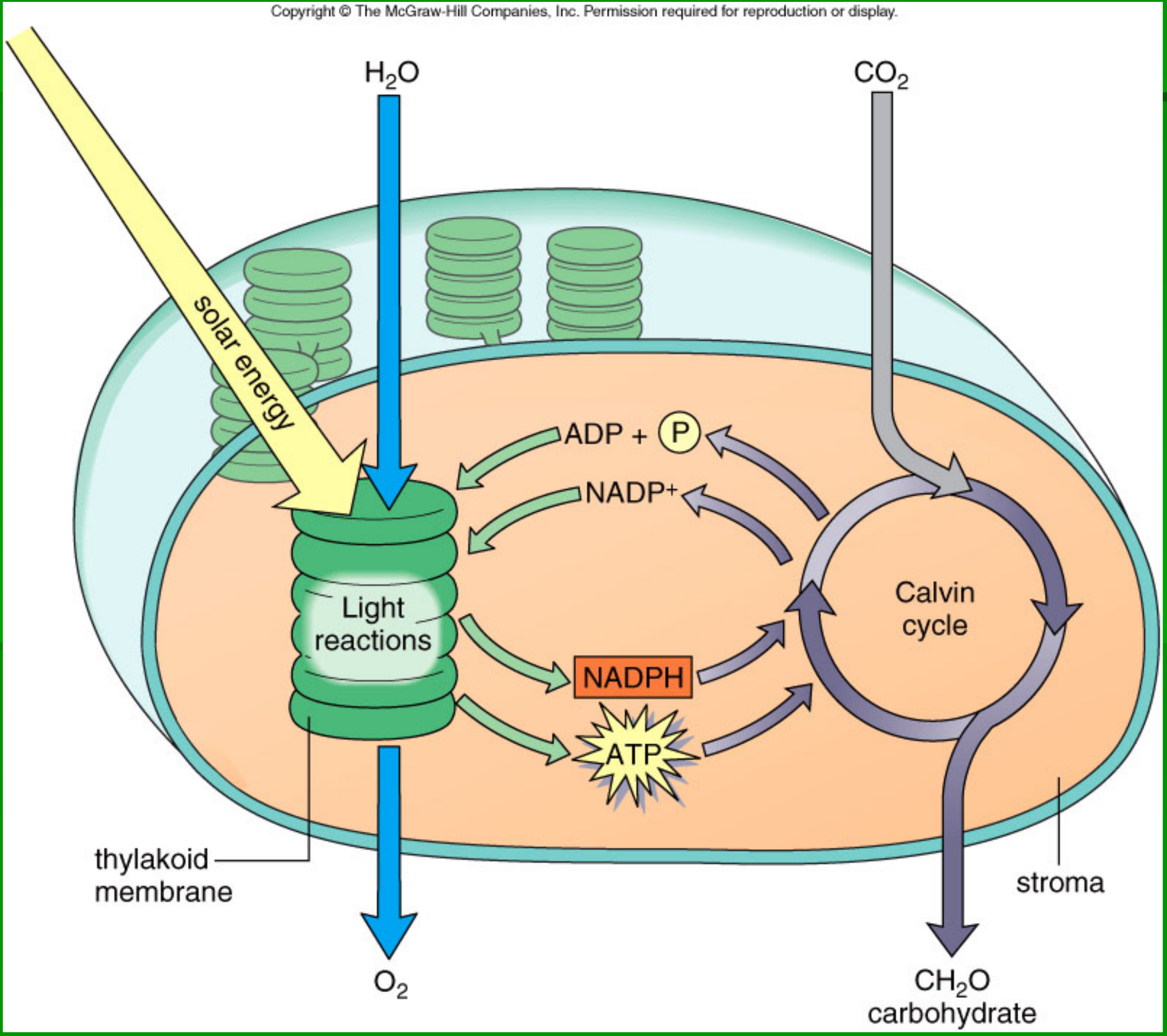
- Photosynthesis actually involves over 100 individual chemical reactions that work together
- Photosynthetic reaction

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

- Carbon dioxide is reduced to form glucose
- Water is oxidized to form oxygen, therefore the oxygen given off by photosynthesis comes from water
- These reactions can be summarized in two groups:

  1. Light-Dependent Reactions
  2. Light-Independent Reactions

Overview of Photosynthesis



Solar Energy Capture

- Visible light
  - Visible light is a part of the electromagnetic spectrum
  - Visible light includes the colors blue, violet, green, yellow, orange, and red
  - Blue-violets have the shortest wavelengths and the highest energy content
  - Photopigments chlorophyll a and b and carotenoids absorb specific portions of the light spectrum
  - Blue, violet, and red are best absorbed
  - Green is reflected

Cosmos
ep 5 30:50 in

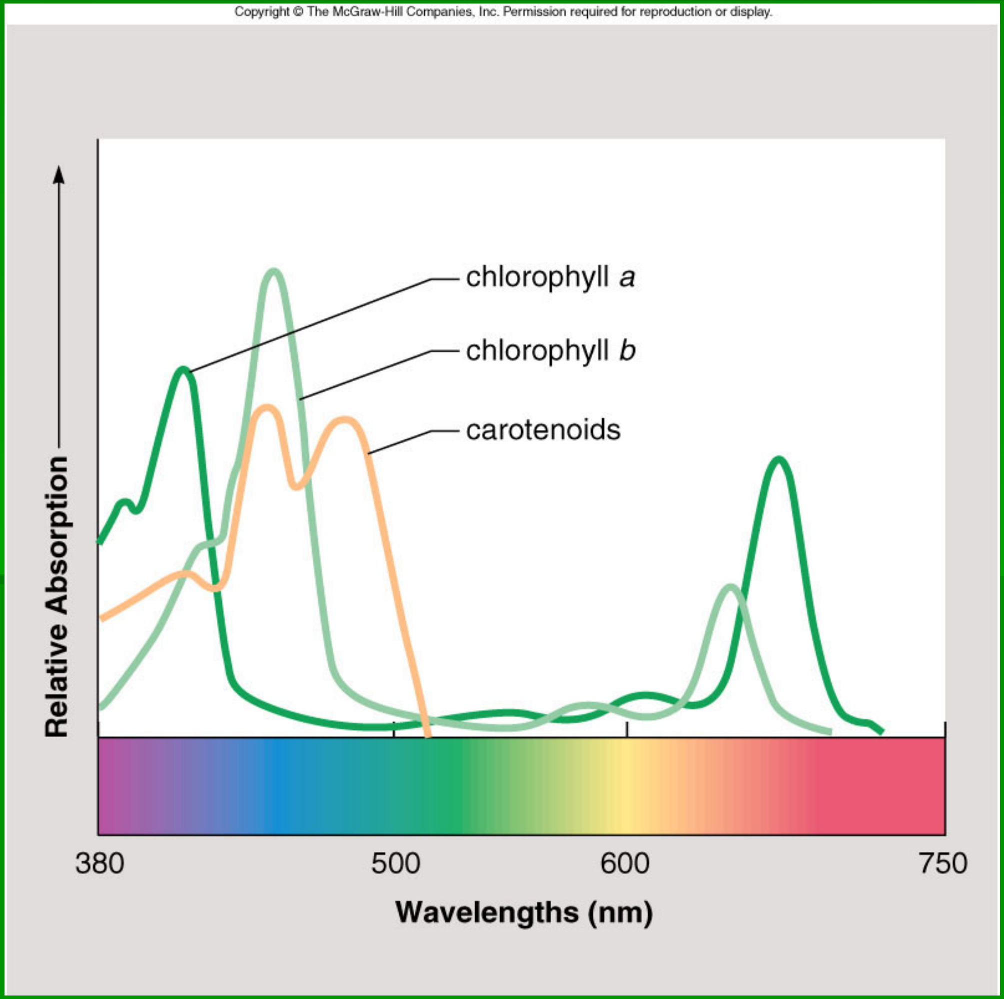
Light-Dependent Reactions

- During these reactions, the pigments contained inside the thylakoid absorb light energy
- Although plants have a number of pigments, the most important for photosynthesis is chlorophyll

Chlorophyll & Light

- Chlorophyll appears green, so it absorbs all but yellow and green light
- However, other pigments also contribute to photosynthesis
- For instance, Beta-carotene appears to be orange, which means that blue and green light are absorbed

Absorption Spectrum – Chlorophyll & Carotenoids

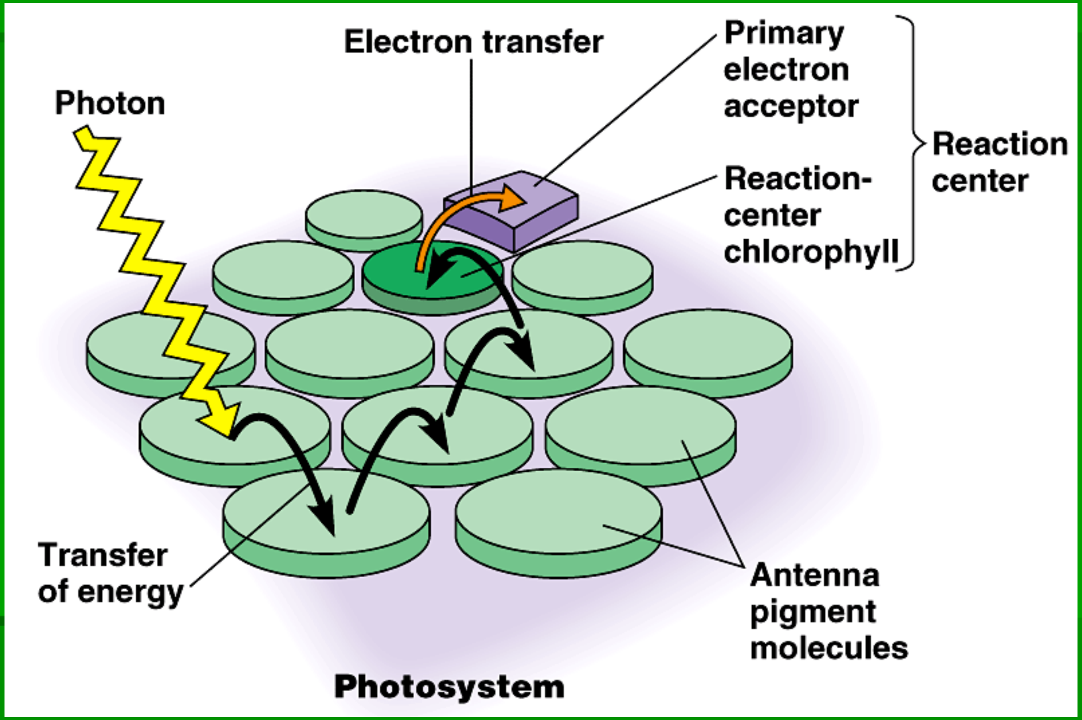


Photosystems

- In the thylakoid membrane, chlorophyll is organized along with proteins and smaller organic molecules into **photosystem II** and **photosystem I**.
- A photosystem acts like a light-gathering "antenna complex" consisting of a few hundred chlorophyll *a,* chlorophyll *b,* and carotenoid molecules.

Photosystems

- The various pigment molecules produce free electrons when light hits them
- These free electrons are passed along to the *reaction center*, a specialized chlorophyll a molecule



Photosystems

- When the electron in the reaction center is “excited” by the addition of energy, it will enter one of two pathways – non cyclic or cyclic. The main process is non cyclic and involves both PII and PI.
- In the non cyclic path, ATP and NADPH are produced
- A series of steps then takes place:

Step 1

- The electron leaves the reaction center of photosystem II and joins with the electron acceptor
- This reduces (GER) the electron acceptor and puts it at a high energy level
- This leaves an "electron hole" in photosystem II
- Electrons are replaced when enzymes break down a water molecule, which releases H^+ ions, electrons, and oxygen (this is the step in photosynthesis that produces oxygen gas)

$$H_2O \rightarrow 2H^+ + 2e^- + \frac{1}{2}O_2$$

Step 2

- The electron acceptor transfers the energized electron to a series of electron-carrying molecules (known as the electron transport chain)
- As the electron moves through this system, it loses energy
- The “lost” energy from the electrons are used to push H^+ ions across the stroma, across the thylakoid membrane and into the thylakoid space

Step 2 continued

- The movement of the H^+ ions into the thylakoid space produces a concentration gradient (the pH within the thylakoid space is about 5, while the pH in the stroma is about 8)
- This concentration gradient serves as a source of potential energy

Step 3

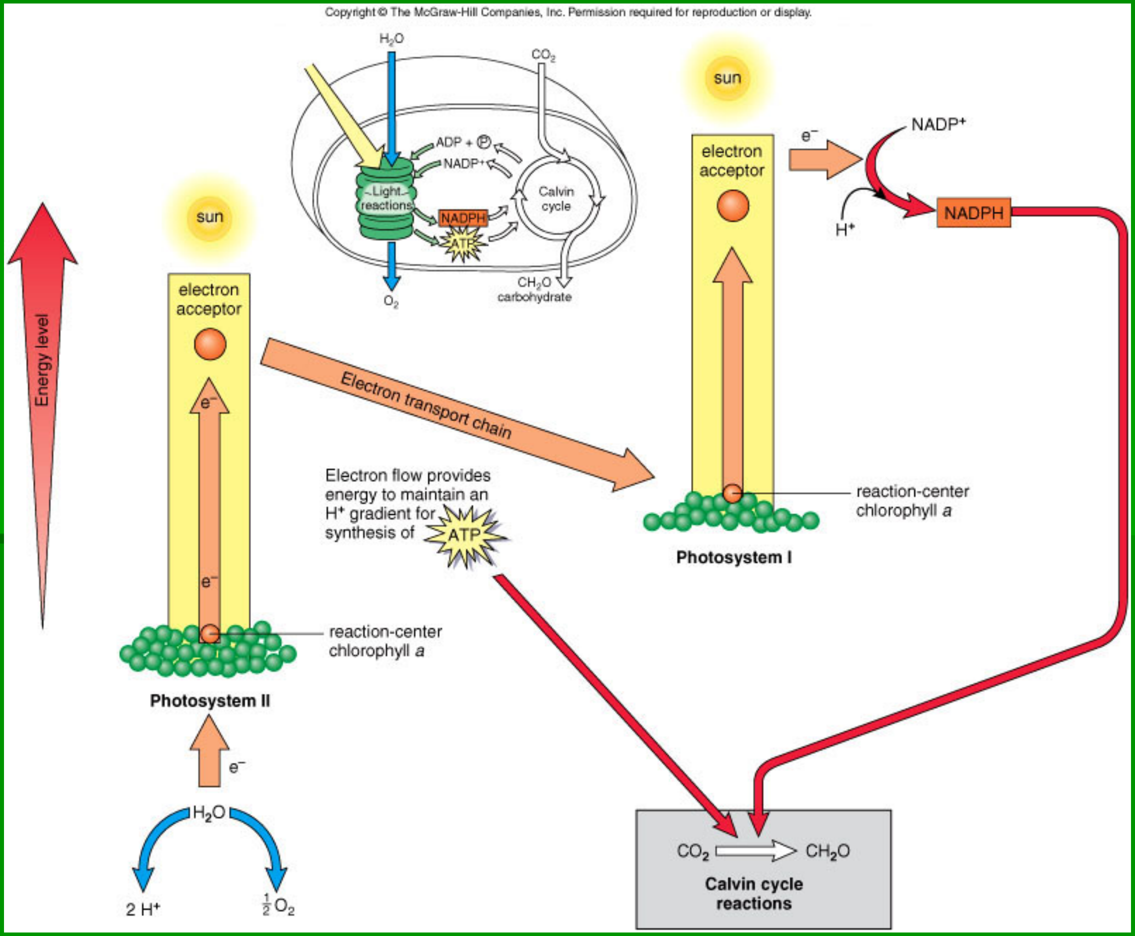
- While steps 1 & 2 are taking place, photosystem I is absorbing light
- Again, an electron is released from the reaction center and is passed to a high-energy electron-acceptor
- The electron lost from photosystem I is replaced by the electron arriving through the electron transport chain from photosystem II

Step 4

- The electron from photosystem I is used to reduce $NADP^+$ to form NADPH
- NADPH's reducing power is then used later in the light-independent reactions

A Summary of the Non Cyclic Pathway:

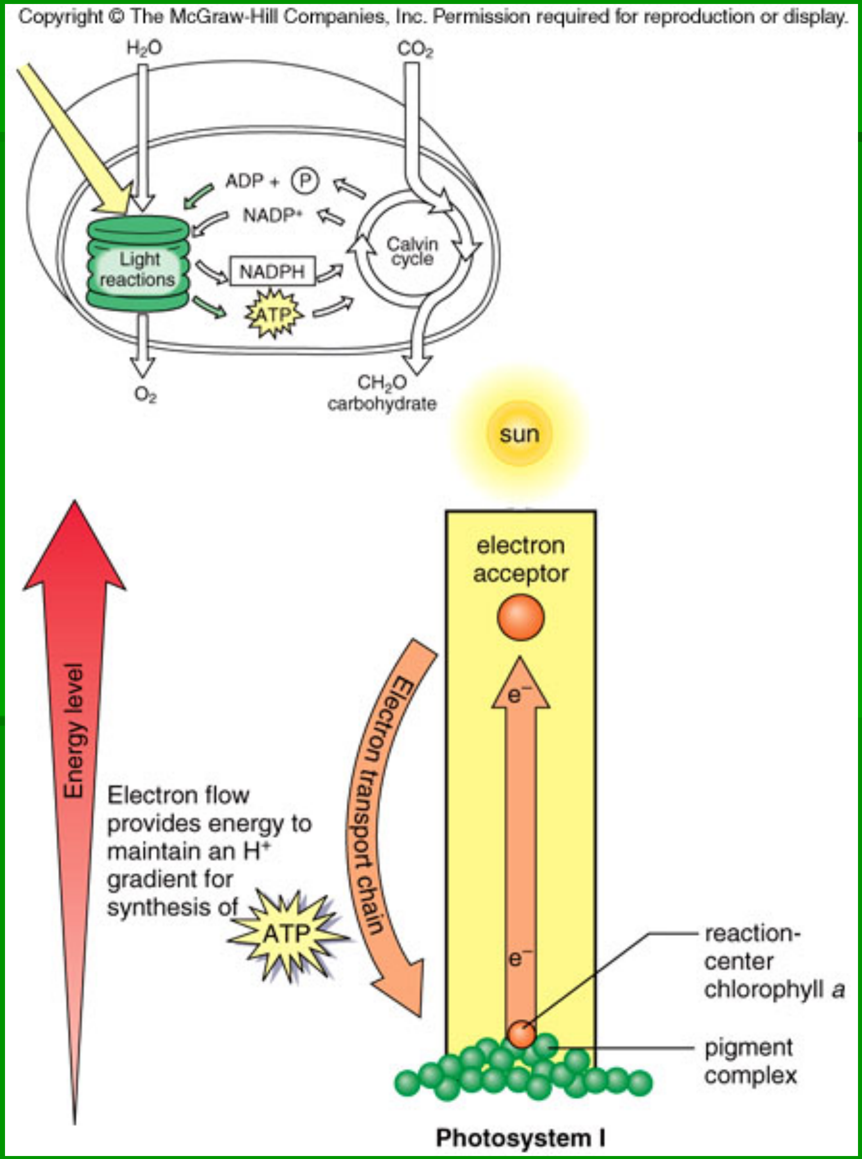
- The light reactions use the solar power of photons absorbed by both photosystem I and photosystem II to provide chemical energy in the form of ATP and reducing power in the form of the electrons carried by NADPH.



The Cyclic Electron Pathway

- Generates only ATP
- PSI absorbs solar energy and electrons from chlorophyll a are removed
- Electrons pass down an ETC
- Energy released is stored in an electrochemical gradient for chemiosmosis
- ATP is produced (not NADPH)
- Electrons lost by PSI chlorophyll a can be replaced by those from PSII in the noncyclic pathway

The Cyclic Electron Pathway



ATP Production - Chemiosmosis

- The energy from the electrons in photosystem II is used to produce ATP indirectly
- As previously mentioned, the energy of the electrons is used to push H^+ ions against the concentration gradient into the thylakoid space

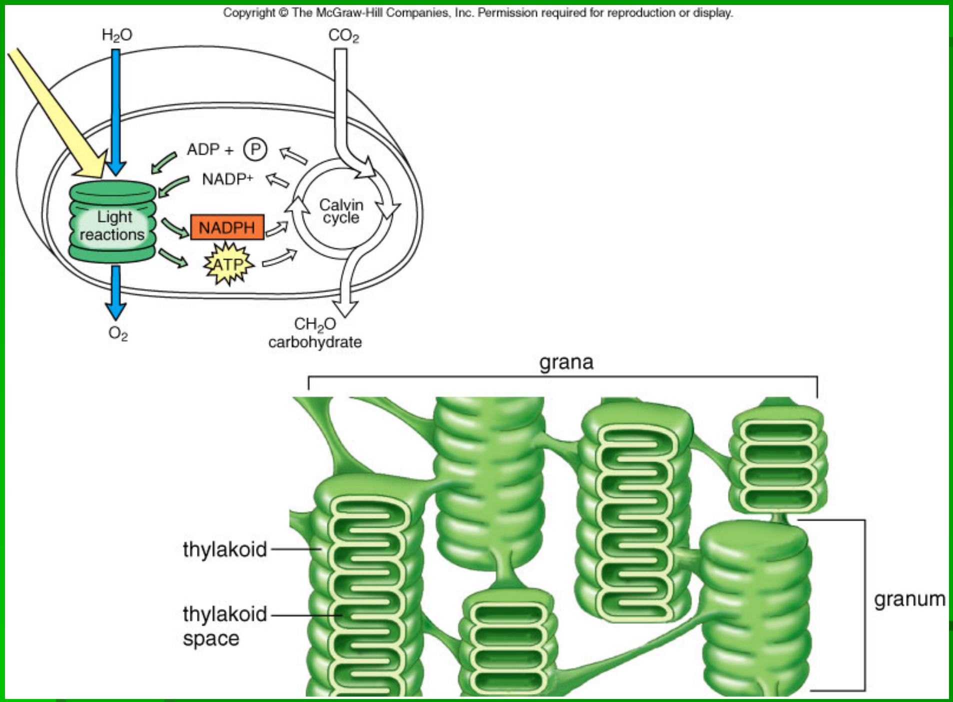
What Happens During Chemiosmosis?

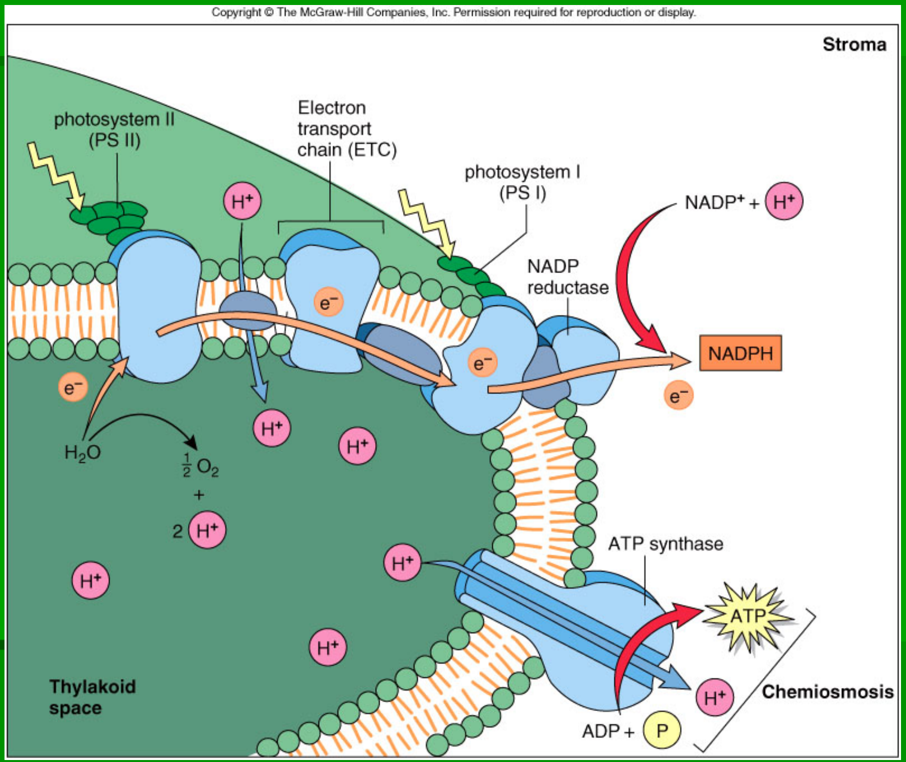
1. H^+ ions move into the thylakoid space through active transport
2. To return to the stroma, the H^+ ions must move through a structure known as ATP synthase
3. ATP synthase uses the movement of the H^+ ions to run a mechanism that bonds together ADP and free phosphates to form ATP

Organization of Thylakoid

- Thylakoid space acts as reservoir of hydrogen ions
- Hydrogen ions flow down gradient through an ATP synthase complex in thylakoid membrane to produce ATP
- Thylakoid membranes contain the following complexes:
  - PS I and II
  - ETC
  - ATP synthase complexes
  - NADPH reductase

Organization of Thylakoid

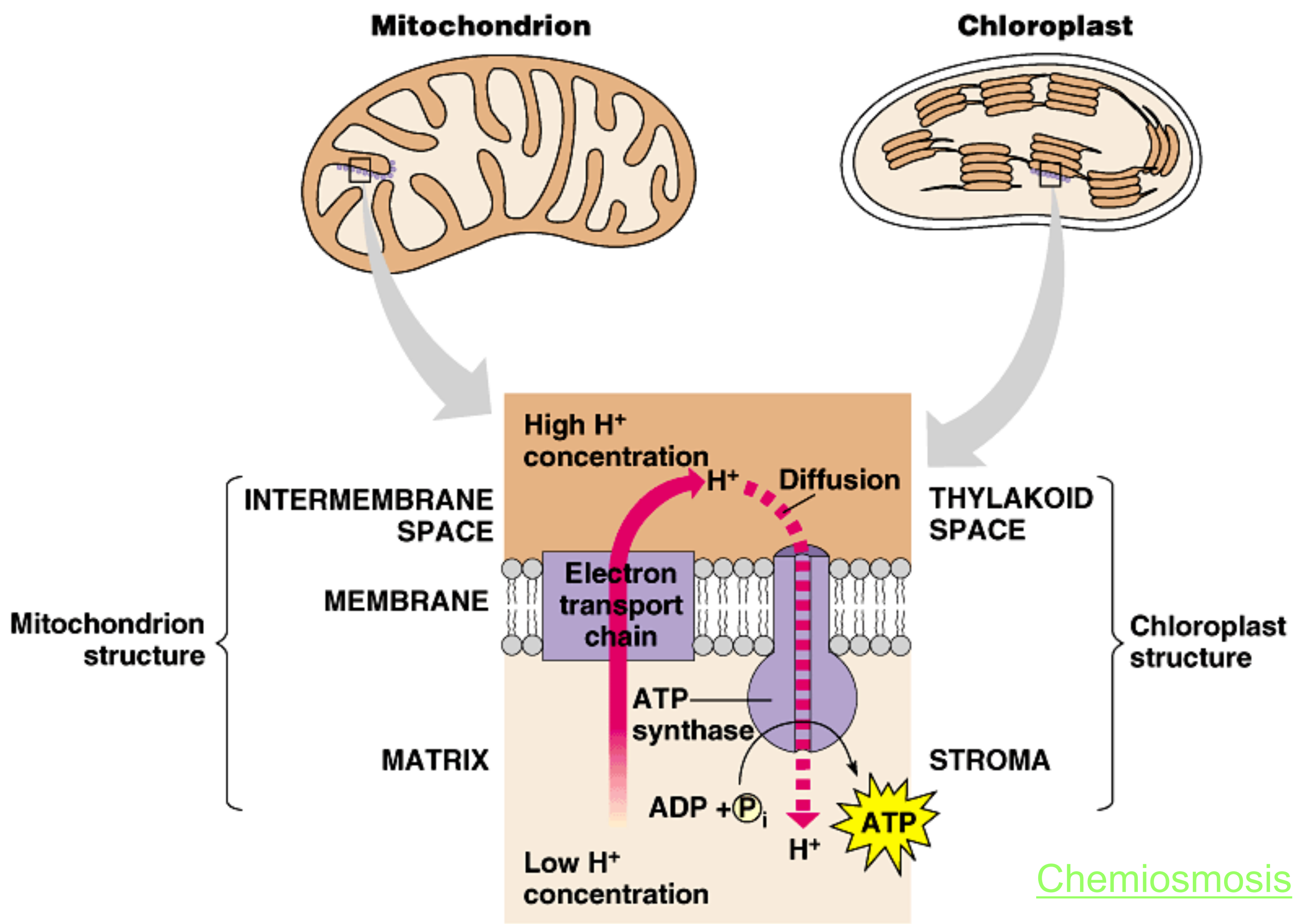




Good Light rxn vid   CC Photosynthesis

Amoeba sisters

Chemiosmosis

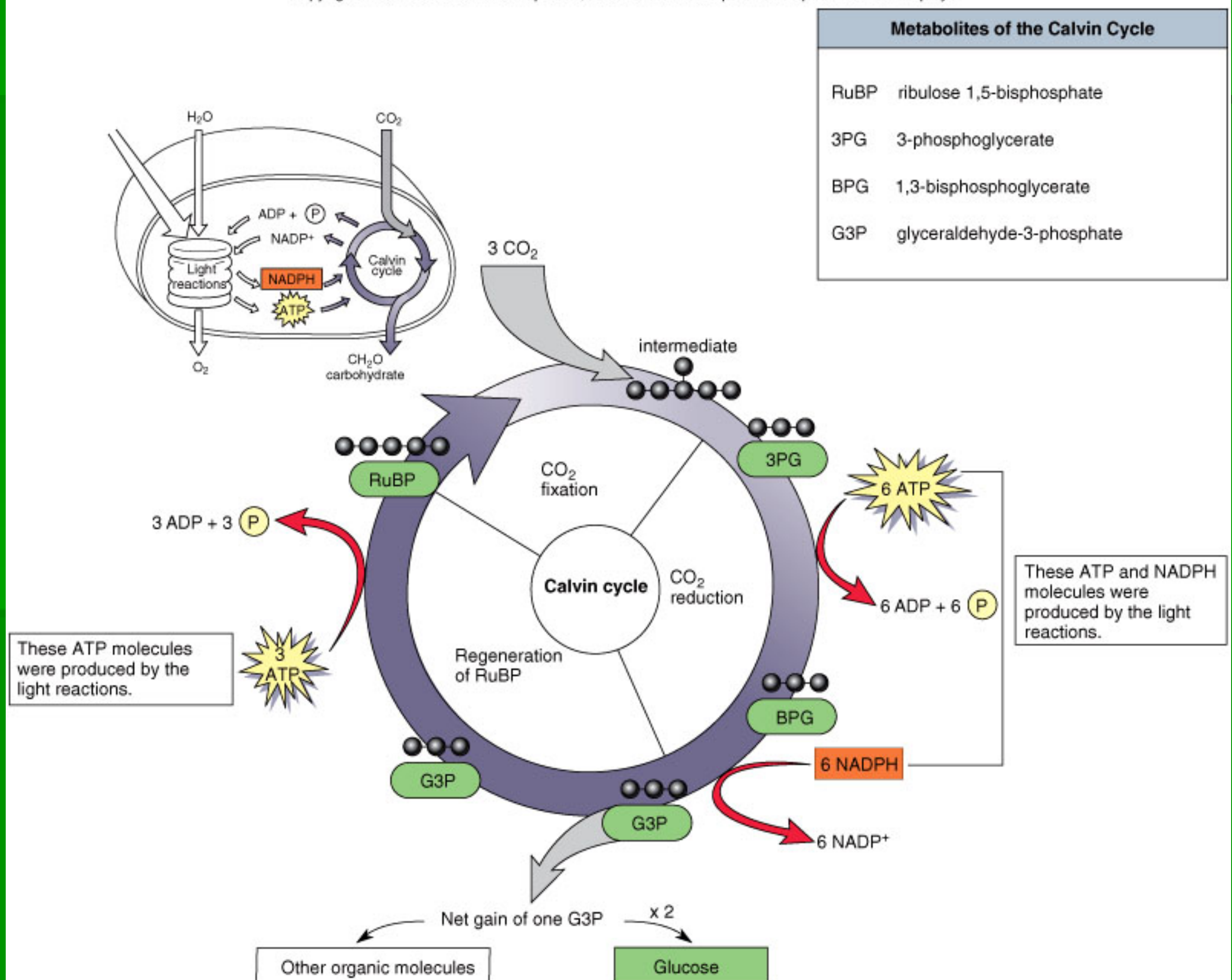


Chemiosmosis

The Light-Independent Reactions

- Once enough ATP and NADPH has been produced by the chloroplasts, glucose can be synthesized
- This involves a series of reactions known as the Calvin-Benson cycle

The Calvin-Benson Cycle



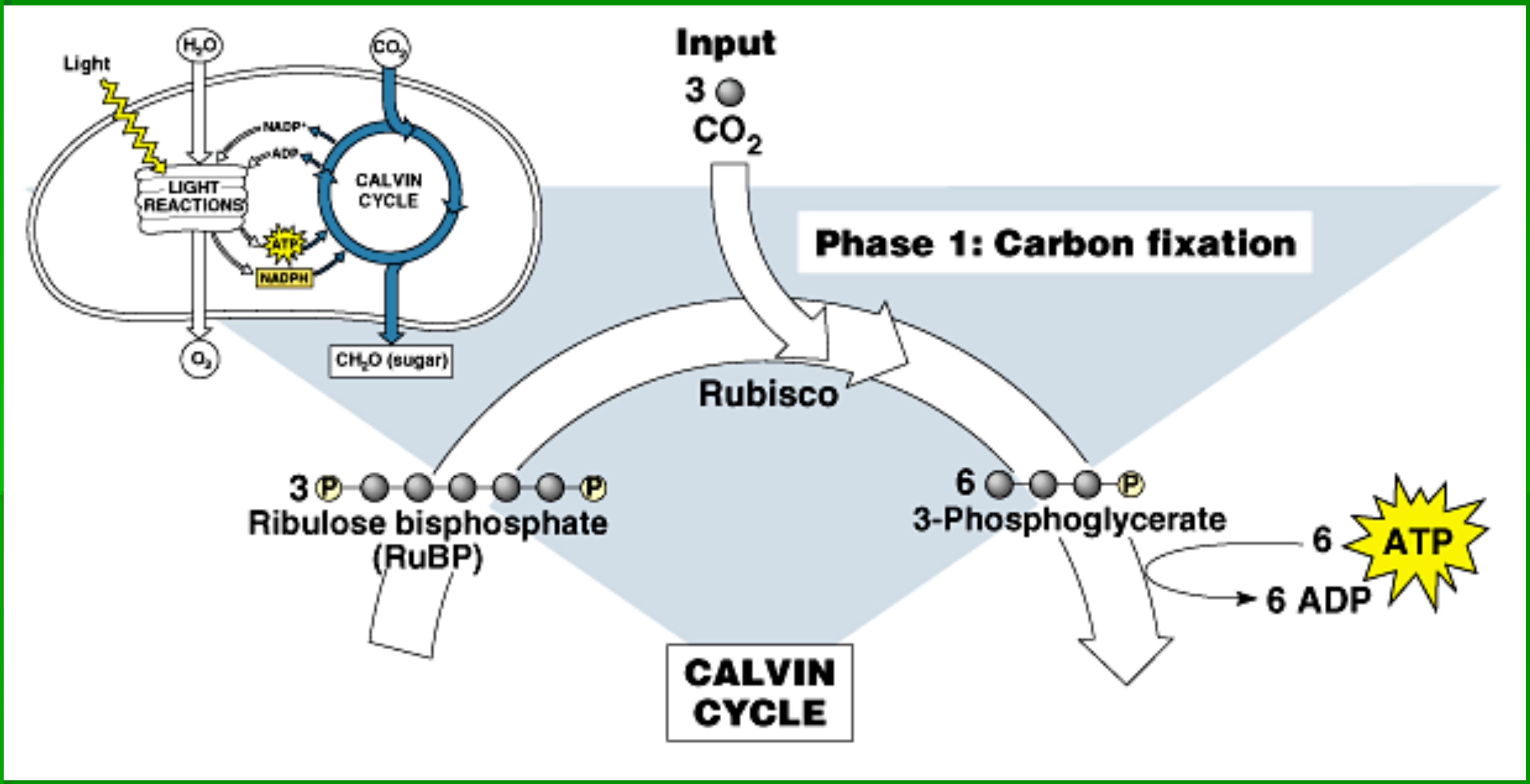
The Calvin-Benson Cycle

- The Calvin cycle regenerates its starting material after molecules enter and leave the cycle
- CO_2 enters the cycle and leaves as sugar
- The cycle spends the energy of ATP and the reducing power of electrons carried by NADPH to make the sugar
- The actual sugar product of the Calvin cycle is not glucose, but a three-carbon sugar, **G3P (aka PGAL)**

The Calvin-Benson Cycle

- Each turn of the Calvin cycle fixes one carbon dioxide.
- For the net synthesis of one G3P molecule, the cycle must take place three times, fixing three molecules of CO_2.
- To make one glucose molecules would require six cycles and the fixation of six CO_2 molecules.
- The Calvin cycle has three phases:

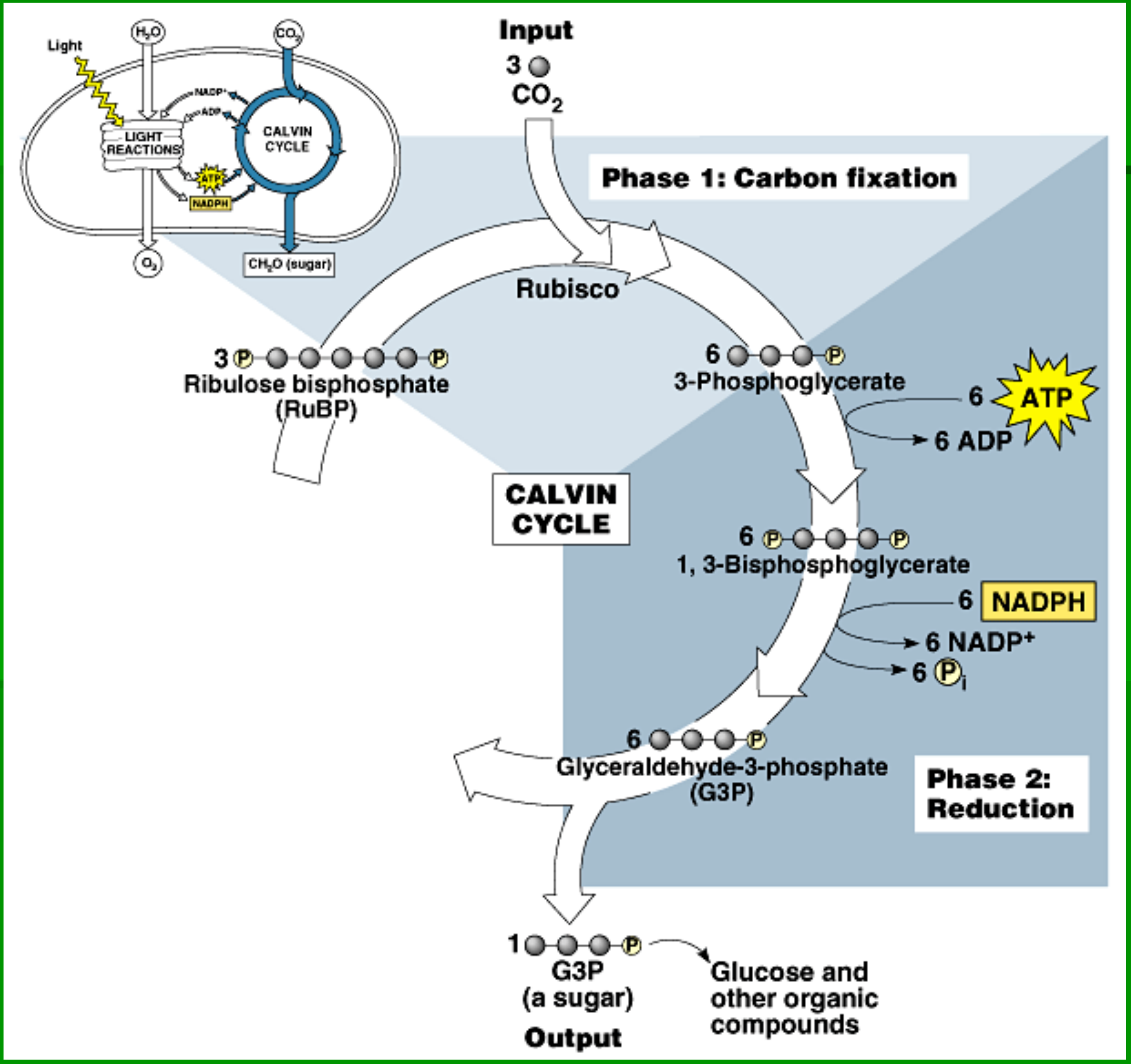
Phase 1 – Carbon Fixation



Phase 1 – Carbon Fixation

- In the carbon fixation phase, each CO_2 molecule is attached to a five-carbon sugar, ribulose bisphosphate (RuBP).
  - This is catalyzed by RuBP carboxylase or **rubisco**.
  - The six-carbon intermediate splits in half to form two molecules of 3-phosphoglycerate (3PG) per CO_2.

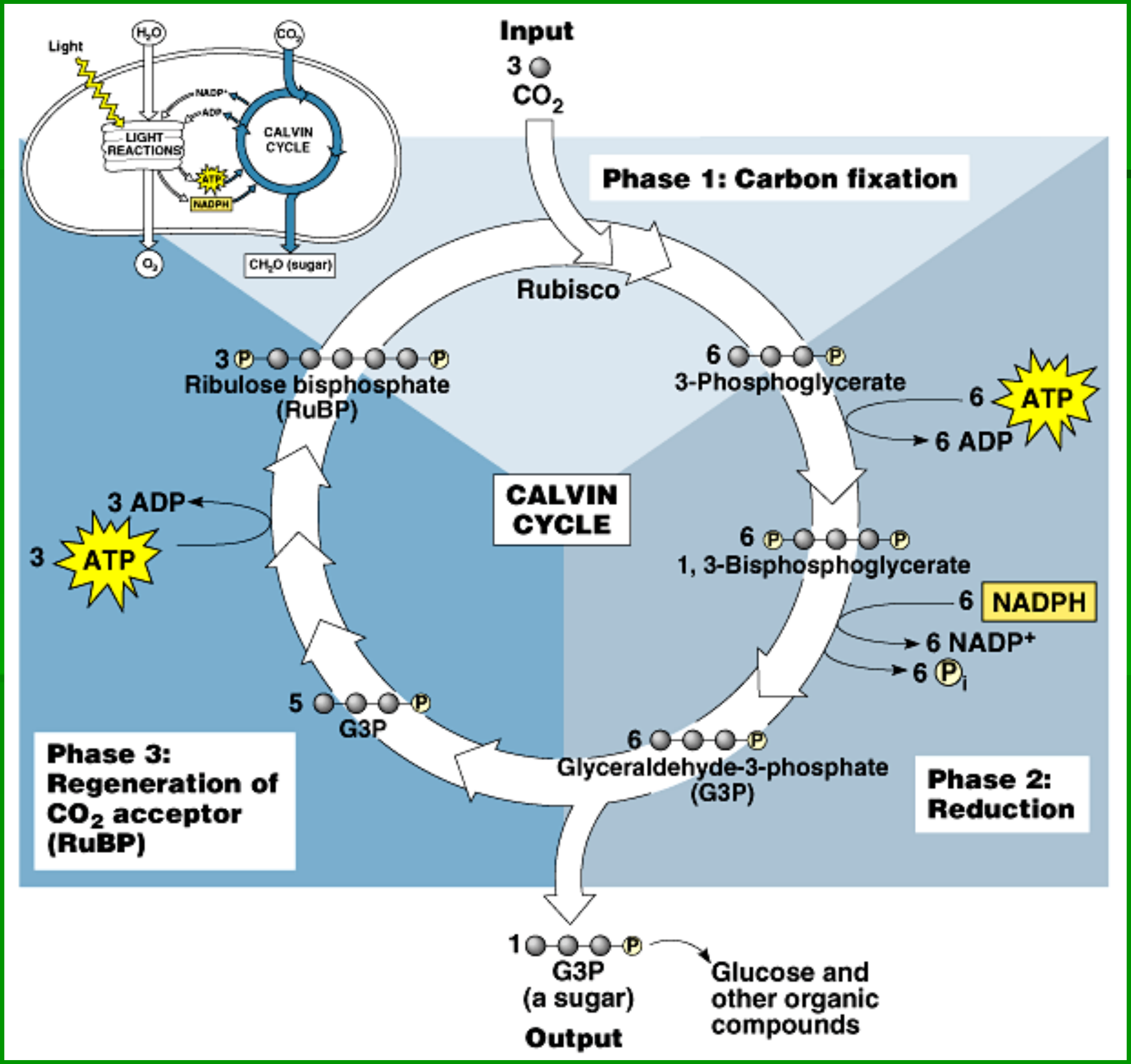
Phase 2 - Reduction



Phase 2 - Reduction

- During reduction, each 3PG receives another phosphate group from ATP to form 1,3 bisphosphoglycerate (BPG).
- A pair of electrons from NADPH reduces each BPG to G3P (PGAL).

Phase 3 - Regeneration



Phase 3 - Regeneration

- In the last phase, five G3P (3-C) molecules are rearranged to regenerate 3 RuBP (5-C) molecules.
- To do this, the cycle must spend three more molecules of ATP (one per RuBP) to complete the cycle and prepare for the next.

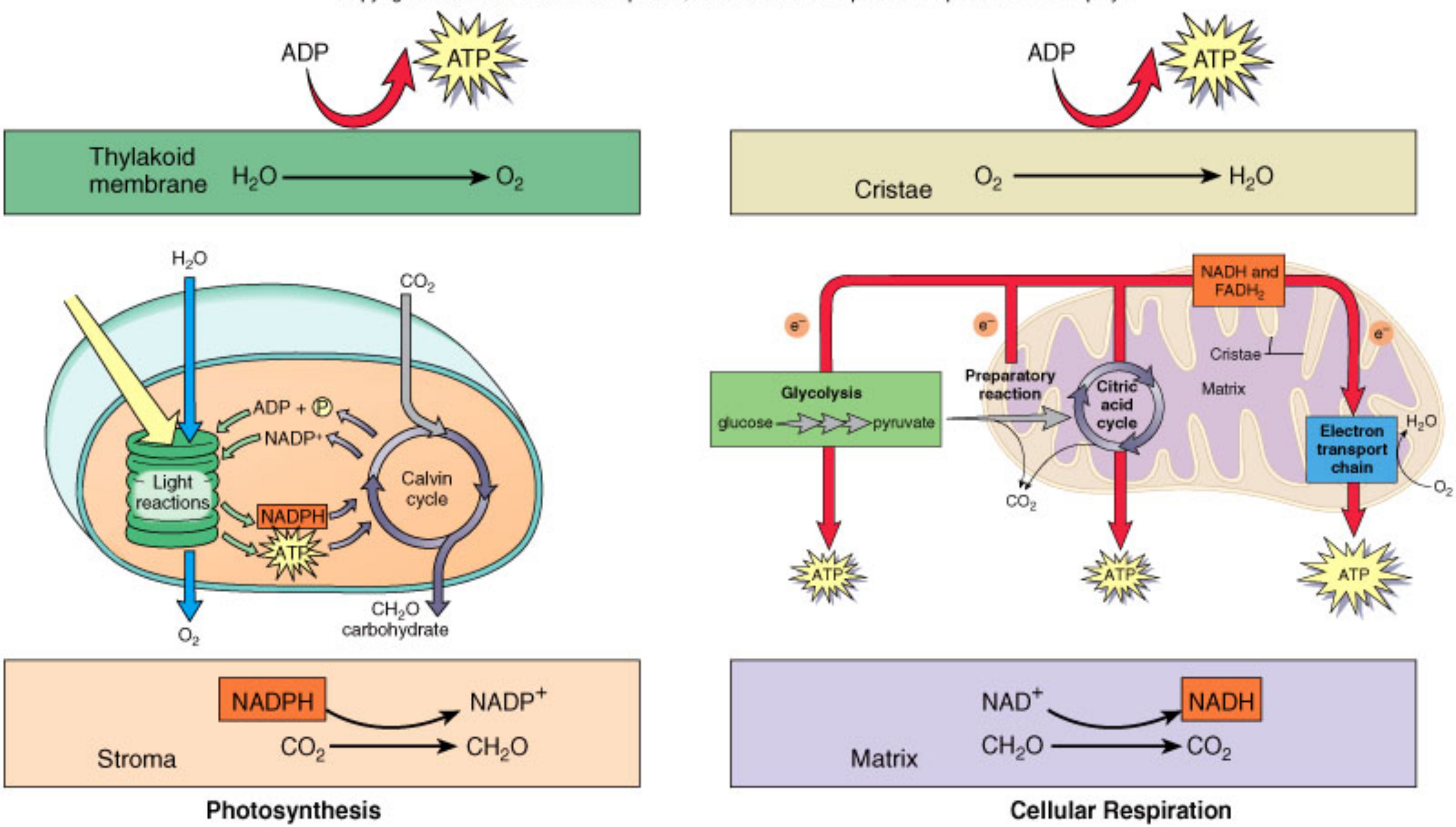
Overall Costs:

- For the net synthesis of two G3P molecules (or 1 glucose), the Calvin cycle consumes 18 ATP and 12 NAPDH.
  - It “costs” three ATP and two NADPH per CO_2 (6 molecules).
- The G3P from the Calvin cycle is the starting material for metabolic pathways that synthesize other organic compounds, including glucose and other carbohydrates.

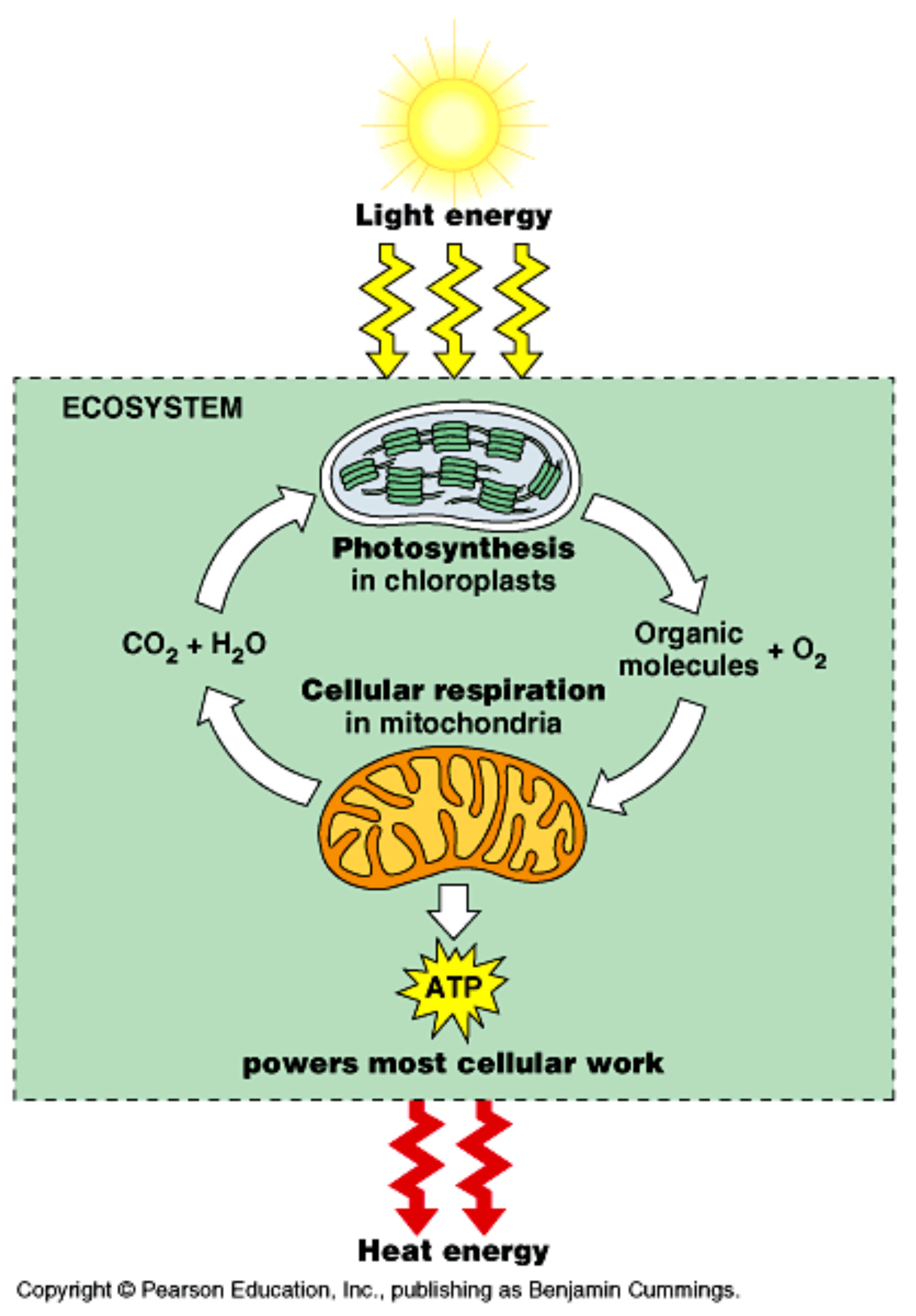
5.3 – Cellular Respiration Releases Energy from Organic Compounds

- During photosynthesis electrons and hydrogen ions are chemically bonded to carbon dioxide reducing it to produce glucose molecules
- Cellular respiration is the reverse of this
- Glucose is oxidized to carbon dioxide while releasing energy and water

Photosynthesis vs Cellular respiration



Photosynthesis & Cellular Respiration are complimentary processes

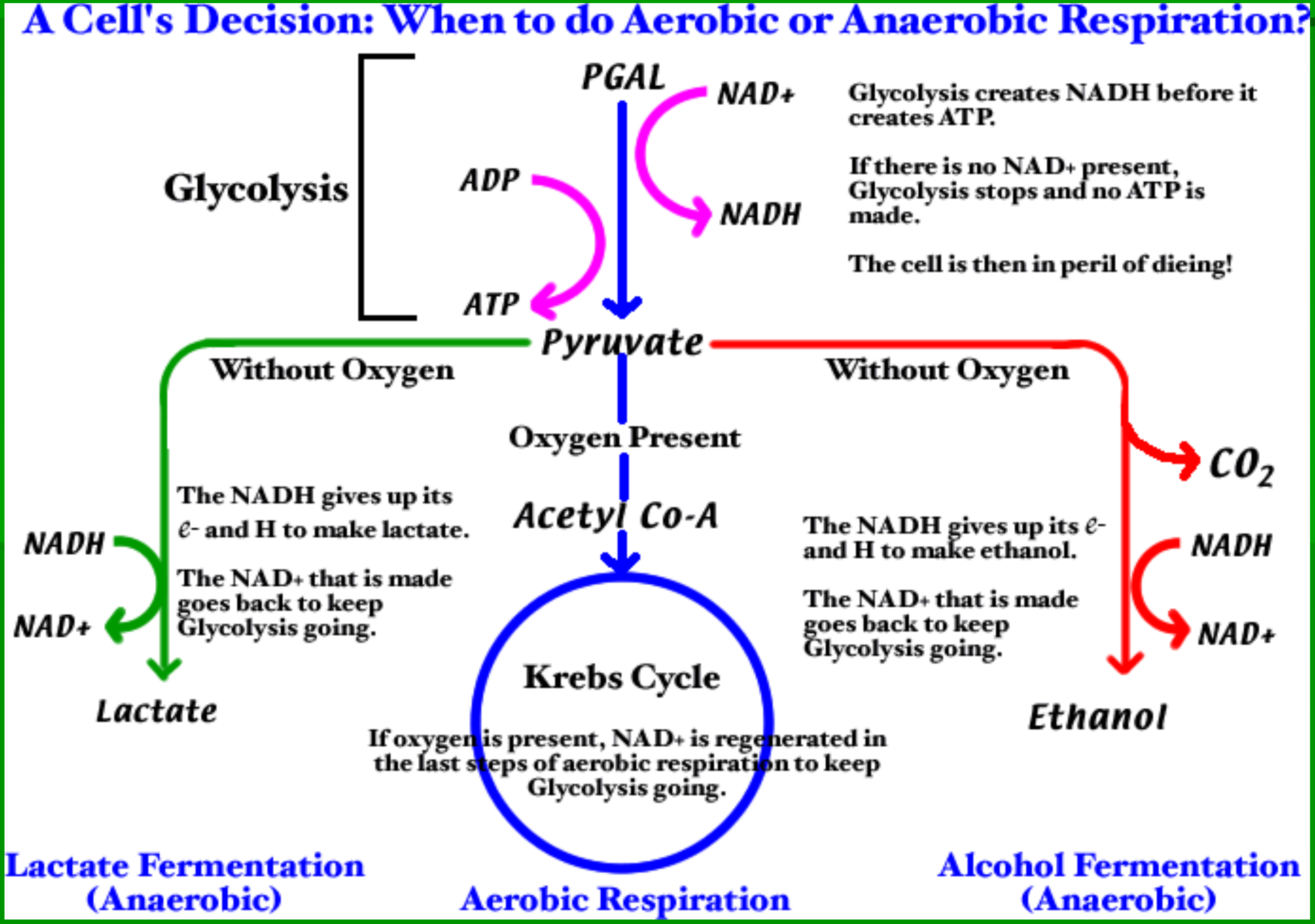


Releasing Stored Energy

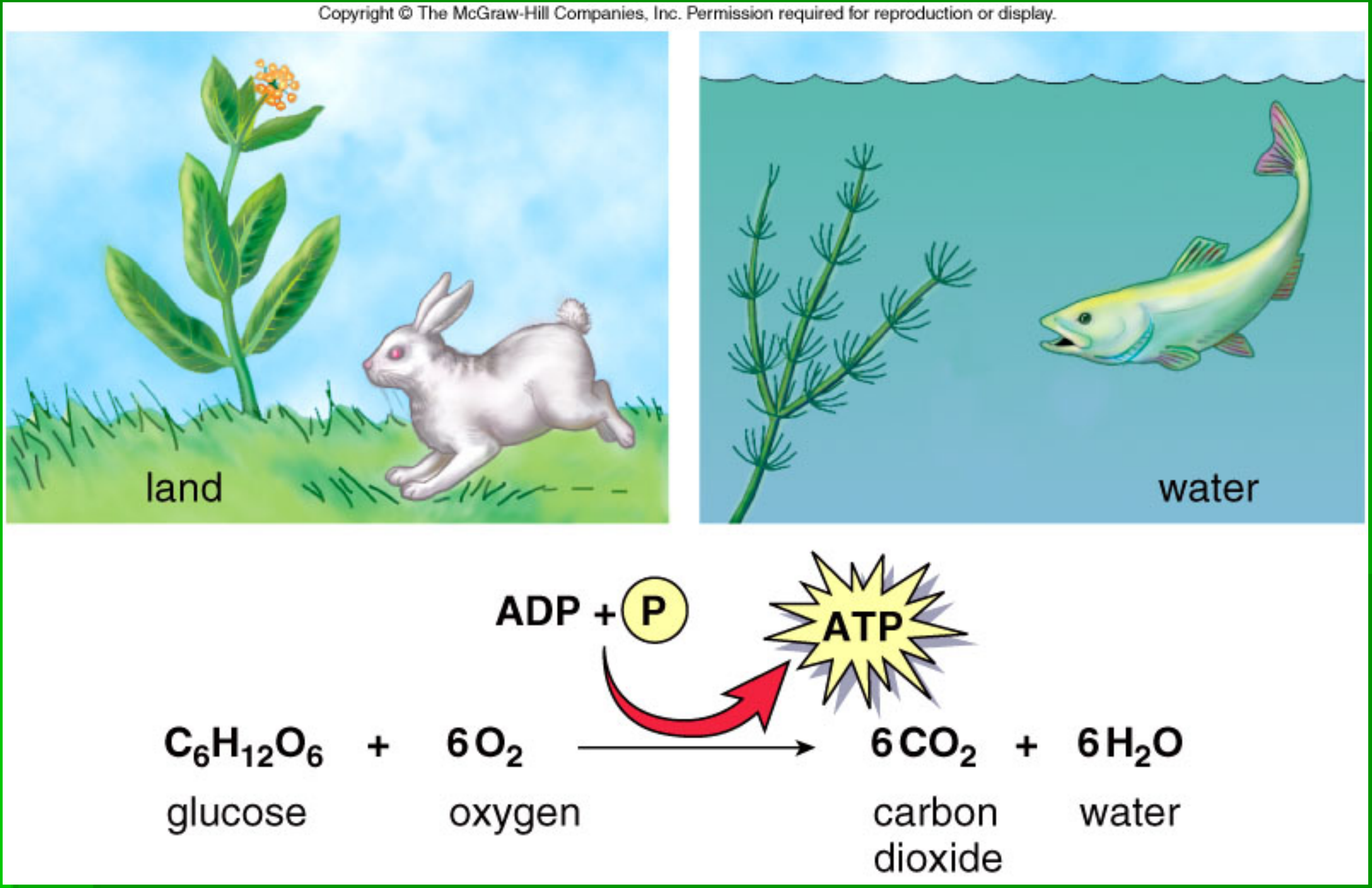
- There are three ways of releasing the energy stored in food:

1. Aerobic Cellular Respiration is carried out by organisms that live in oxic (oxygen containing) environments
2. Lactate Fermentation (aka anaerobic cellular respiration) is carried out by animals, fungi, and some bacteria - can only be performed in anoxic (low oxygen) environments
3. Ethanol Fermentation. This process is a modified form of lactate fermentation that only happens in yeast and some bacteria

Aerobic vs. Anaerobic Respiration



Aerobic Cellular Respiration



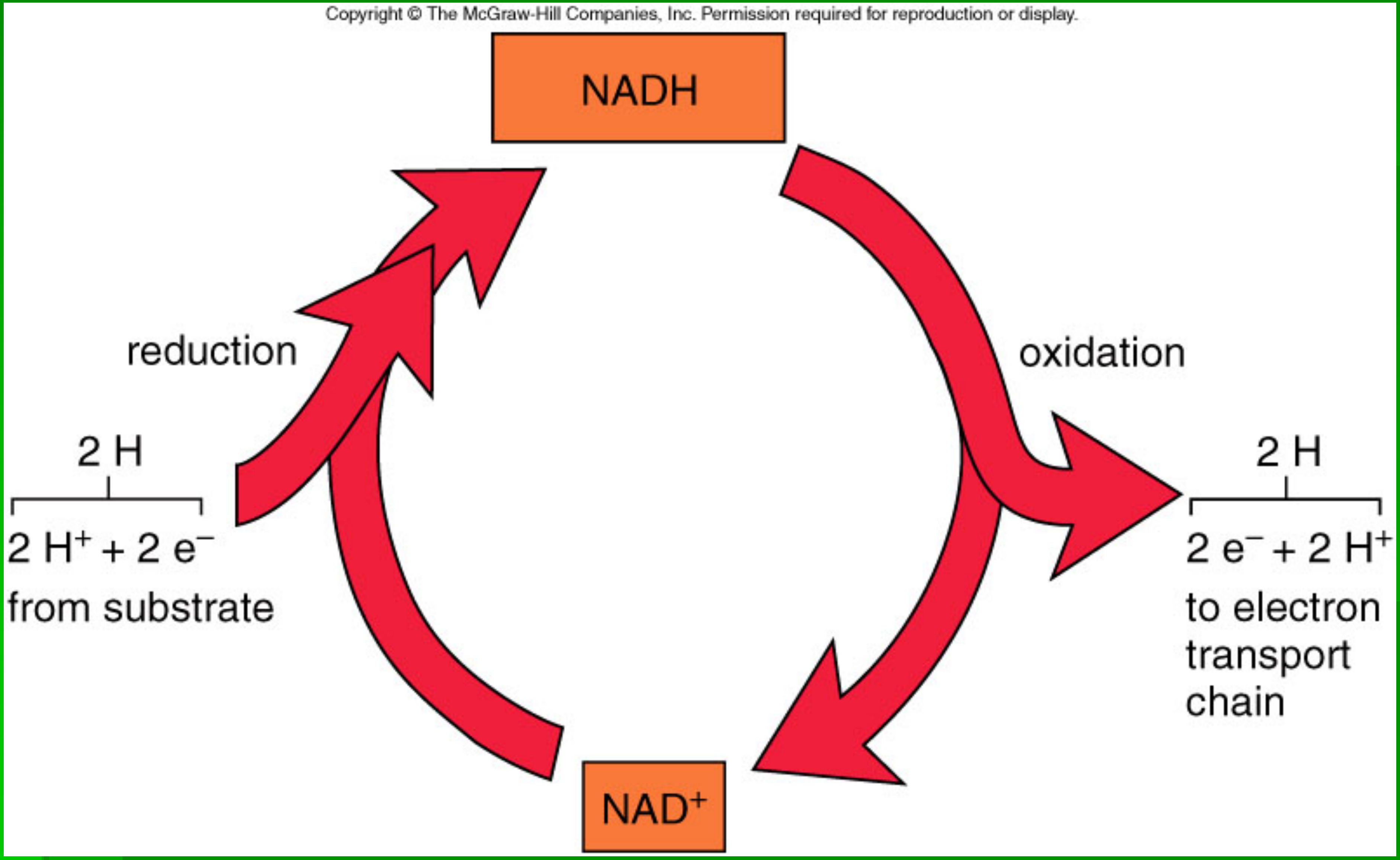
Aerobic Cellular Respiration - Overview

- This is series of oxidation reactions in which e^- are transferred from high-energy glucose to (eventually) oxygen to make water
- Most of the energy in plants, animals and most eukaryotic cells is produced in this process
- Exothermic reaction used to drive ATP synthesis which is endothermic
- 4 phases of respiration
- The process starts with glycolysis, an anaerobic reaction in the cytoplasm

Aerobic Cellular Respiration - Overview

- Oxidation of glucose involves the removal of hydrogen atoms from redox coenzymes NAD^+ and FAD
  - NAD^+ is reduced to NADH
  - FAD is reduced to $FADH_2$
  - $FADH_2$ and NADH carry electrons to the electron transport chain (ETC)

The NAD$^+$ cycle



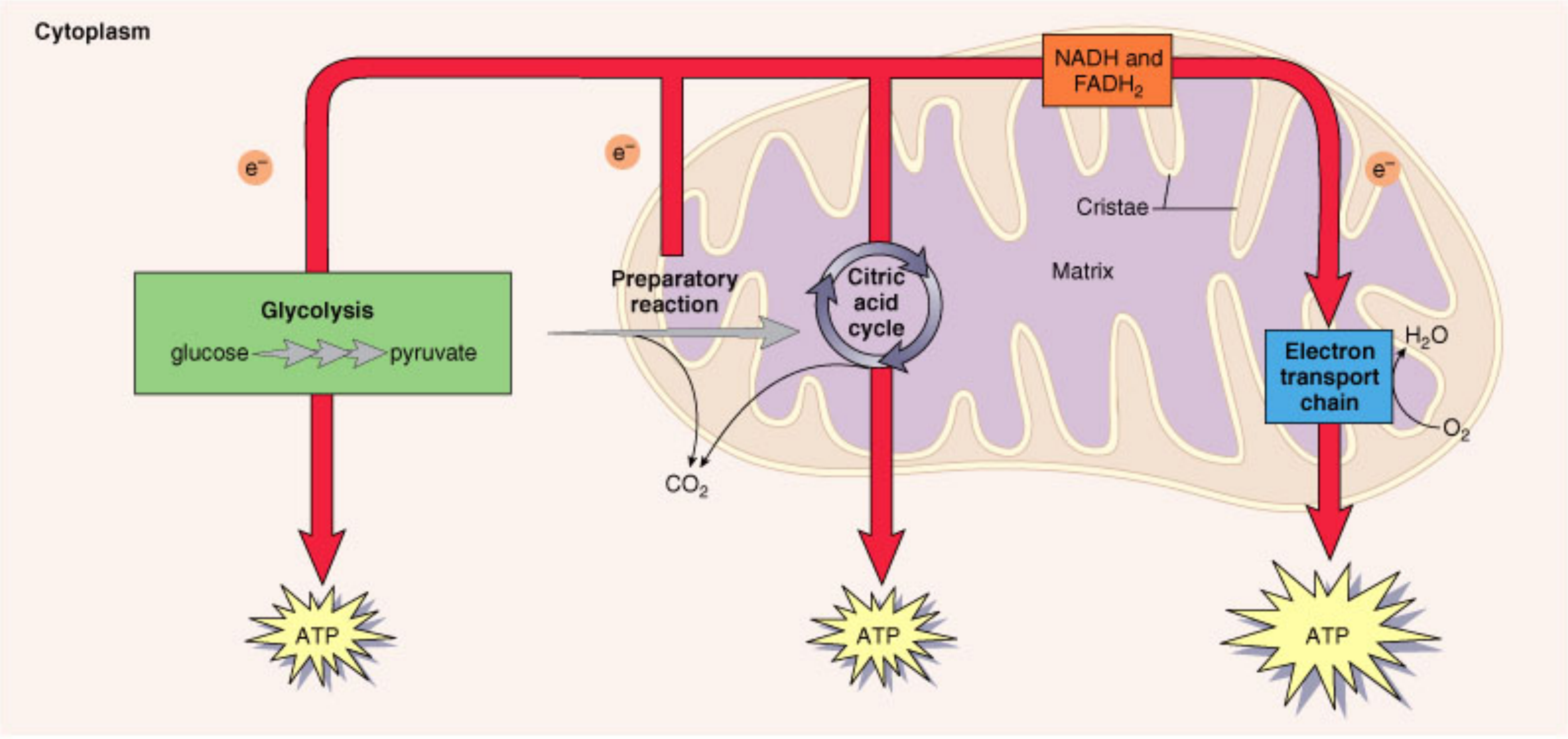
4 Phases of Cellular Respiration

1. Glycolysis – in cytoplasm
   - Breakdown of glucose to 2 molecules of pyruvate
   - Oxidation by removal of hydrogens releases enough energy to make *net* 2 ATP
2. Preparatory reaction – in mitochondria
   - Pyruvate oxidized to acetyl CoA and carbon dioxide is removed
   - Prep reaction occurs twice because glycolysis produces 2 pyruvates
3. Citric acid cycle (aka Krebs cycle) – in mitochondria
   - Acetyl CoA is converted to citric acid and enters the cycle
   - Cyclical series of oxidation reactions that produces 1 ATP and carbon dioxide
   - Citric acid cycle turns twice because 2 acetyl CoA's are produced per glucose

4 Phases of Cellular Respiration

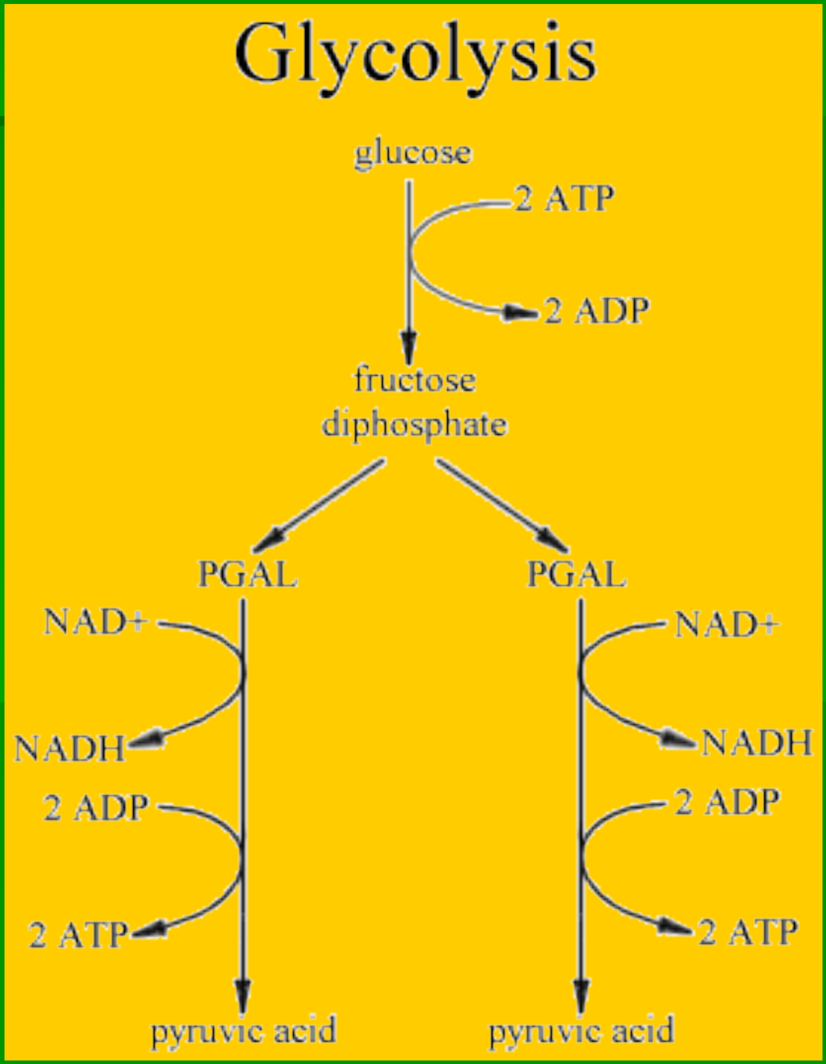
4. Electron transport chain (ETC) – in mitochondria
   - Series of electron carrier molecules
   - Electrons passed from one carrier to another
   - As the electrons move from a higher energy state to a lower one, energy is released to make ATP
   - Under aerobic conditions 32-34 ATP per glucose molecule can be produced
   - Pyruvate
     - Pivotal metabolite in cellular respiration
     - If no oxygen is available, pyruvate is reduced to lactate (in animals) or ethanol and carbon dioxide (in plants) in a process called fermentation

4 Phases of Cellular Respiration



Glycolysis

- Outside the mitochondria, in glycolysis, a glucose molecule is converted into two molecules of pyruvic acid
- 2 *net* ATP and 2 NADH are also produced



Steps in Glycolysis

Energy Investment Phase:

1. 2 ATP are used to activate glucose (change glucose to fructose diphosphate)
2. The fructose molecule is split into two molecules of PGAL (or G3P)

Energy Harvesting Phase:

3. The G3P molecules are oxidized and their electrons and H^+ ions are donated to NAD^+ to form 2 NADH
4. Finally, the molecules are converted to pyruvate and 4 molecules of ATP are produced

General Notes Regarding **Glycolysis**

- Note that oxygen is NOT required for glycolysis
- Glycolysis occurs in the cytoplasm of cells, not in the mitochondria
- Glycolysis produces 4 ATP while consuming 2 ATP, providing a net outcome of 2 ATP
- 2 reduced NADH molecules are also produced and are used to carry e^- to ETC

The Fate of Pyruvate

- Pyruvate contains large amounts of chemical energy
- If there is no oxygen present the pyruvate proceeds to fermentation
- When there is sufficient oxygen, the pyruvate is transferred to the mitochondria for further oxidation

Mitochondria Structural Features

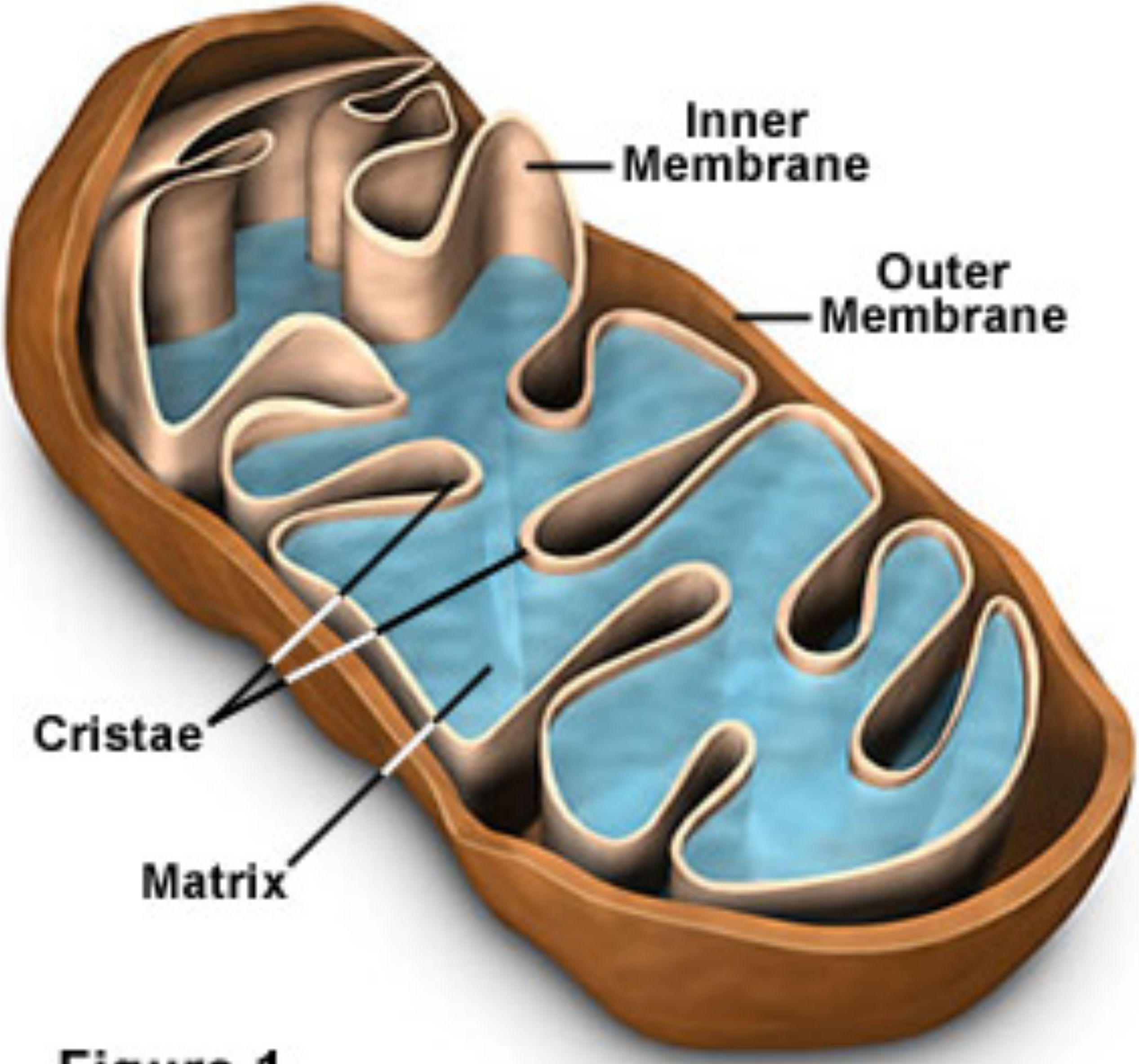


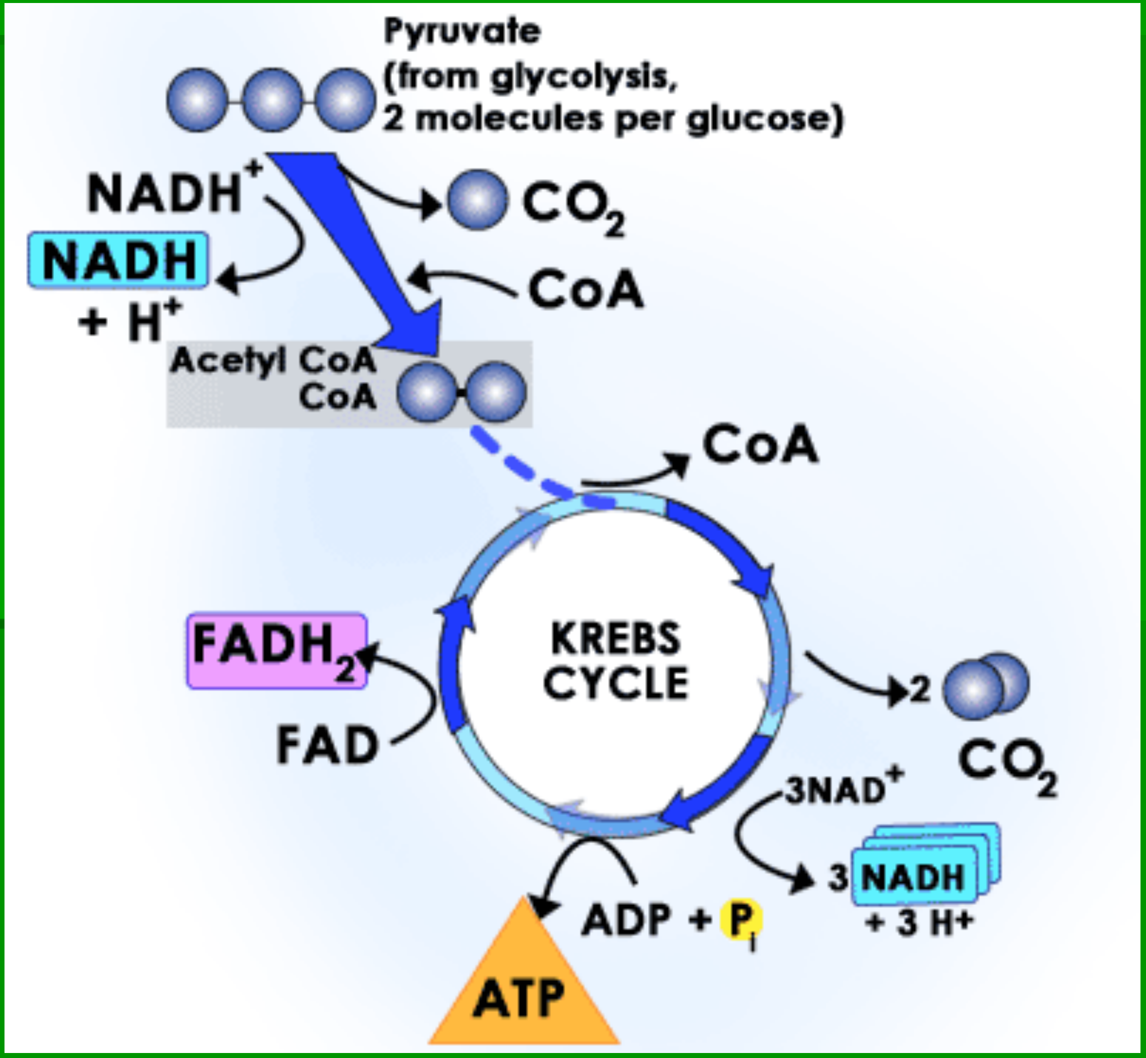
Figure 1

Preparatory Reaction

- Each pyruvate (3C) loses a carbon in the form of carbon dioxide
- When this occurs, another molecule of NAD^+ is reduced to form NADH
- The remaining 2 carbon atoms from pyruvate attach to a molecule called Coenzyme A
- Coenzyme A "tows" the 2-C (acetyl) group into the Krebs cycle (in the form of acetyl-CoA), which all takes place in the mitochondria
- Prep reaction occurs twice (once for each pyruvate) – so 2 NADH made

The Krebs Cycle

- aka Citric Acid cycle
- During this cycle ATP and reduced compounds are formed (NADH & $FADH_2$)



Steps in the Krebs Cycle

1. Acetyl CoA (2-C) binds with a 4-carbon molecule to form a 6-carbon molecule. CoA returns to prep reactions.
2. The 6-carbon molecule loses a carbon in the form of CO_2. This releases an electron and a hydrogen atom to form NADH from NAD^+.
3. The new 5-carbon molecule loses a carbon in the form of CO_2. This releases an electron and a hydrogen atom to form NADH from NAD^+. As well, ATP is formed.

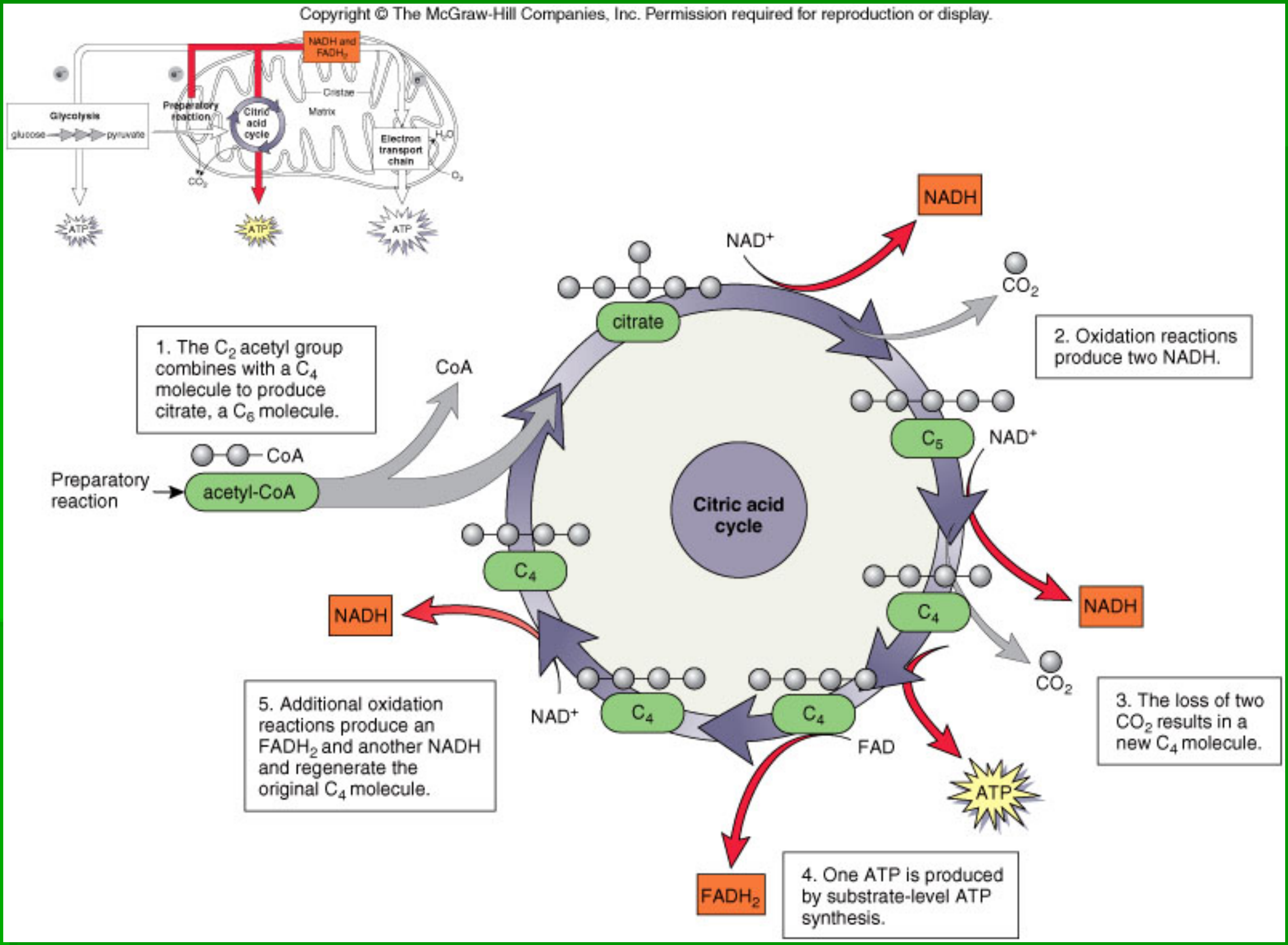
4. The four-carbon molecule undergoes a series of structural changes that release more electrons, allowing the production of 1 $FADH_2$ molecule from FAD, and the production of another NADH molecule from NAD^+
5. The four-carbon molecule is now the same as the original molecule that started the cycle binding to acetyl-coA

Krebs Cycle Animation

Krebs Cycle Totals

- EACH turn of Krebs cycle produces:
  - 3 NADH and 1 $FADH_2$
  - 1 ATP
  - 2 CO_2
- Cycle turns twice per glucose, so:
  - Total yield: 6 NADH, 2 $FADH_2$, 2 ATP, 4 CO_2

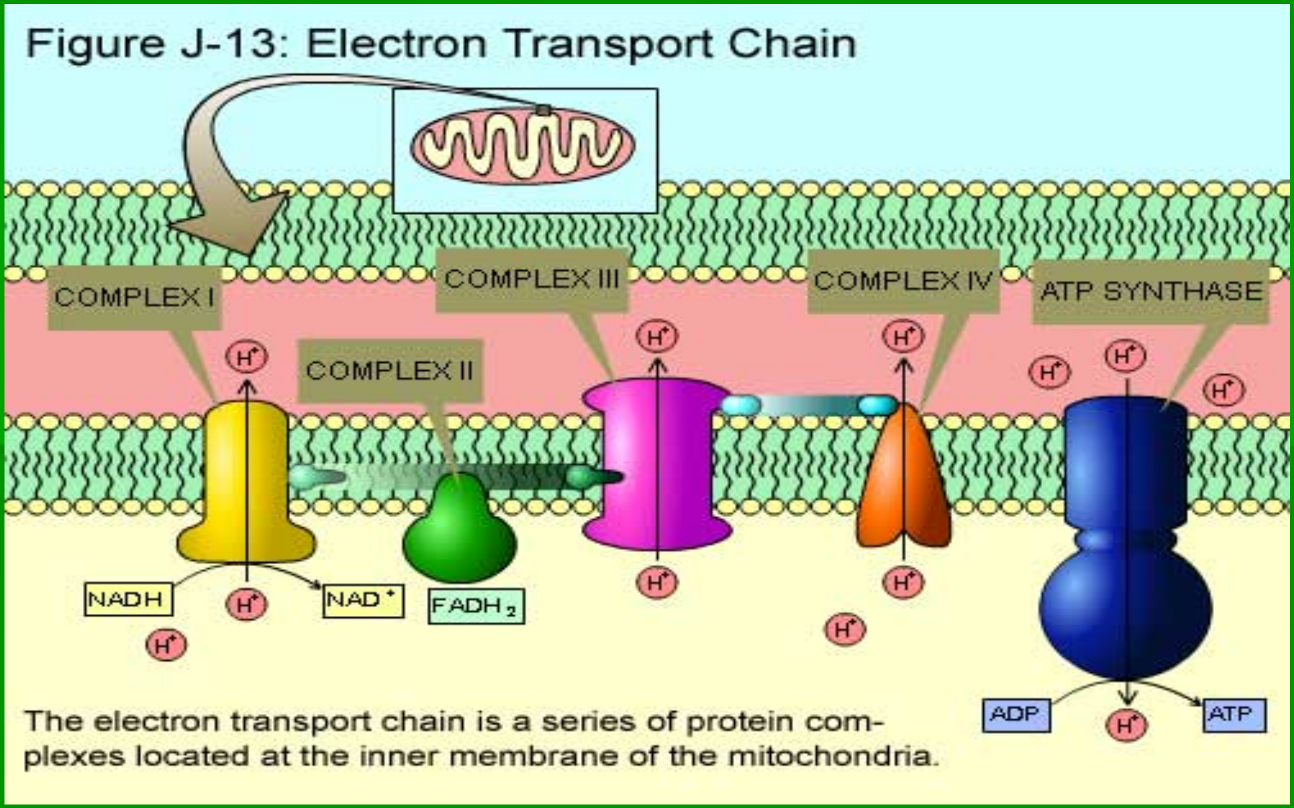
Citric Acid Cycle



The Electron Transport Chain

- Electron transport produces large amounts of ATP during cellular respiration
- Similar to photosynthesis the high energy electrons are passed down a chain within the mitochondrion membrane
- The energy is used to drive hydrogen pumps to get hydrogen across the membrane

- This pumping of hydrogen creates a concentration gradient
- This can be used to power the formation of ATP from ADP in chemiosmosis



[Chemiosmosis & ETC]

Oxygen & Electron Transport

- The electron transport chain requires oxygen in aerobic respiration
- As electrons move down the electron transport chain they eventually reach the final electron acceptor, which is oxygen
- The oxygen is reduced, picking up hydrogen & its electrons and forming water

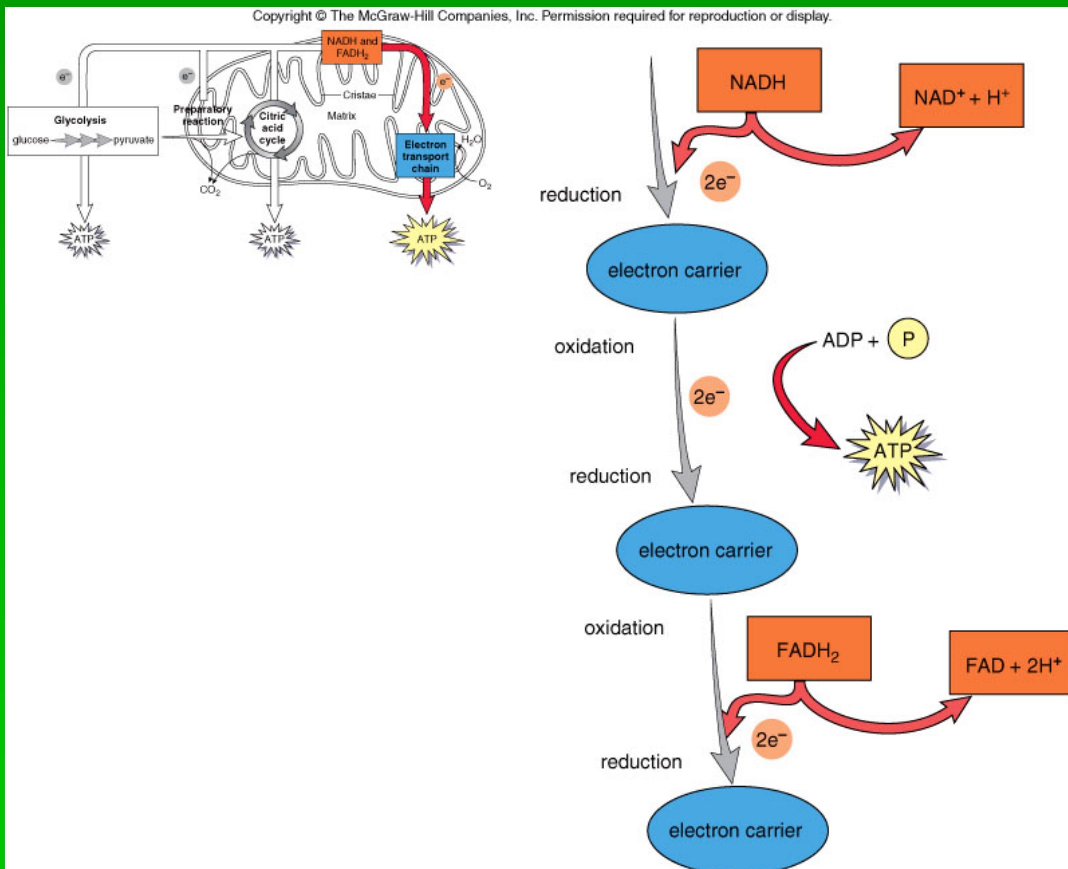
- If oxygen were not present at this final point, it would prevent electrons from passing from the previous electron receptor
- Without it the reaction would cease, much like a traffic jam backing up the freeway

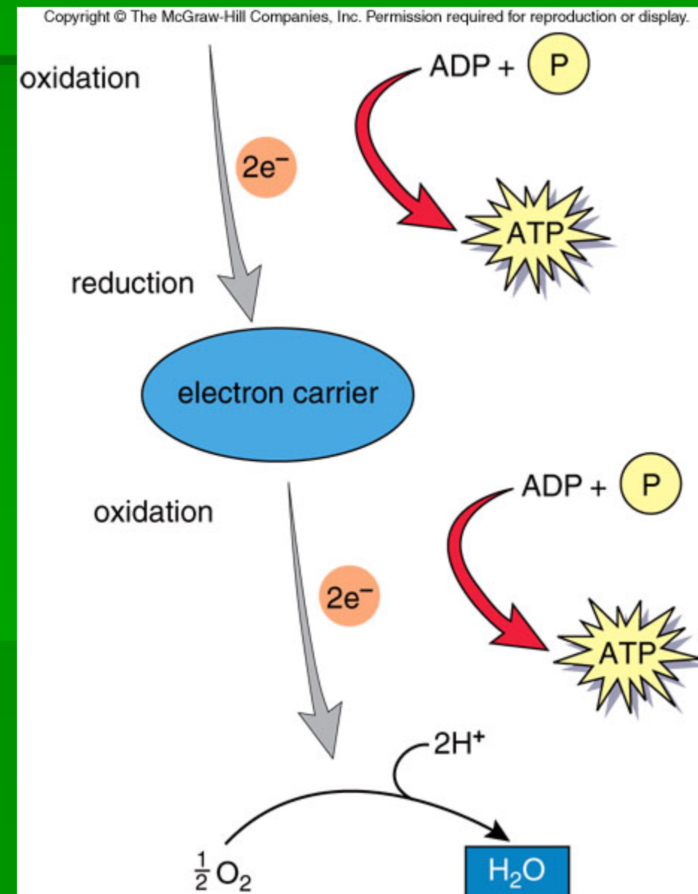
- Each preceding reaction would not be able to take place all the way back to glycolysis
- Glycolysis only produces 4 ATP molecules while the electron transport system produces 24 ATP molecules
- As well, NADH and $FADH_2$ molecules would remain in their reduced forms, unable to receive new electrons, further reducing the amount of energy produced

Final Review Vid

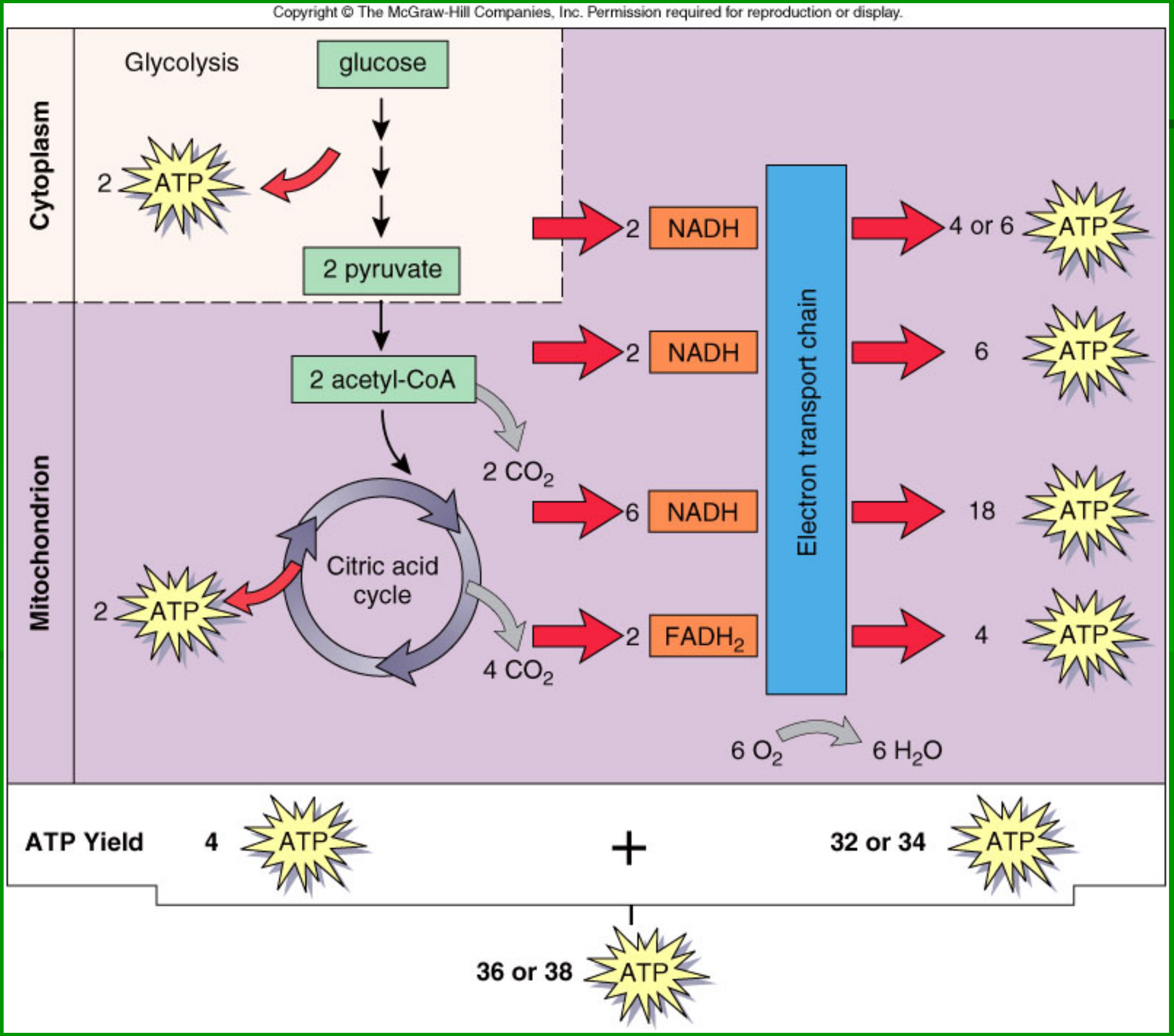
Cellular Respiration Review Animation

Overview of the ETC





Total Production of ATP



Anaerobic Respiration

- When oxygen is not available as the final electron acceptor, other molecules are used
- Anaerobic respiration is not as efficient at aerobic
- The organisms that live in these types of environments use inorganic chemicals such as sulfate, nitrate and carbon dioxide as acceptors

Fermentation

- Fermentation is the metabolic pathway to produce ATP when organisms lack oxygen
- This pathway produces only the ATP that is generated during glycolysis, therefore, it is less efficient than aerobic respiration
- There are two types of fermentation:

Lactate Fermentation

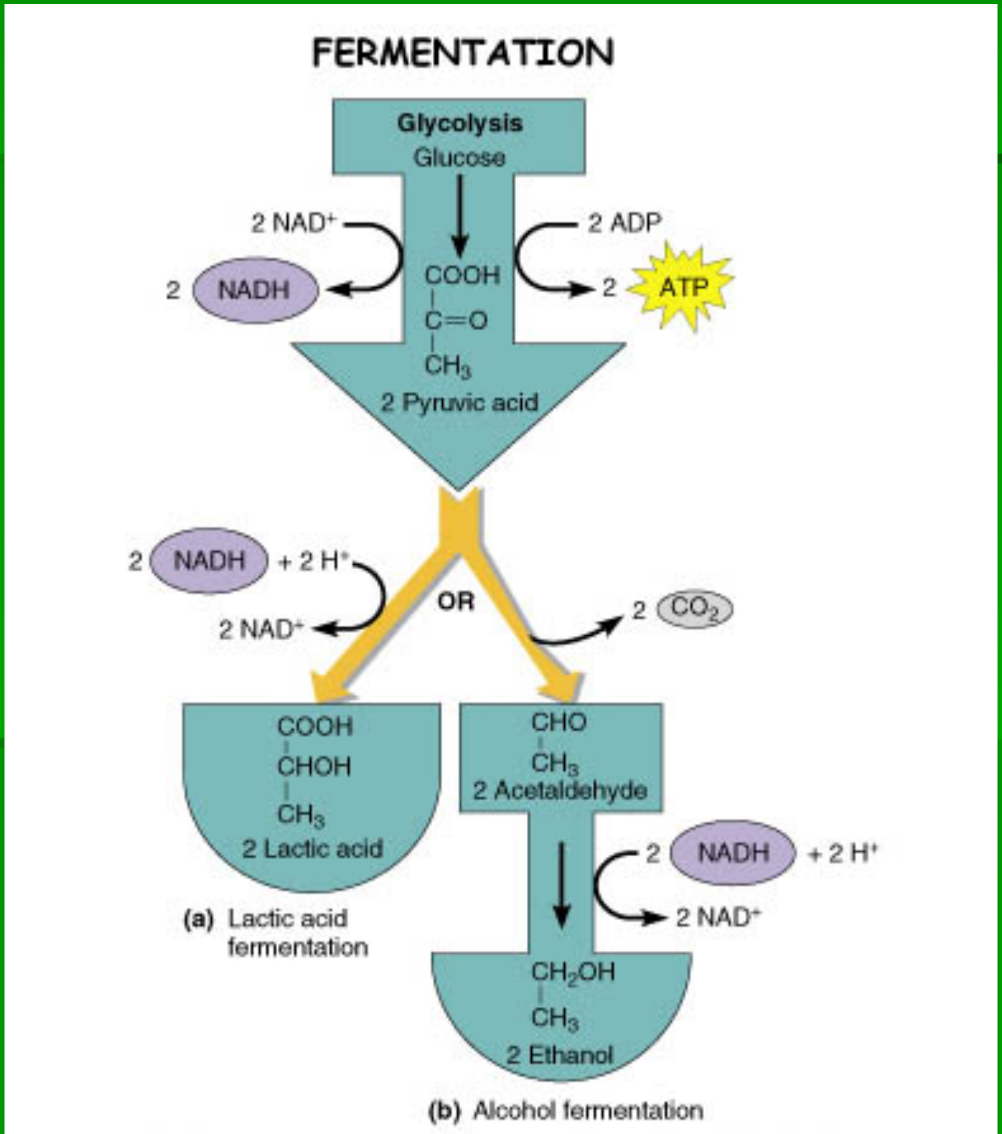
- Cells that are temporarily without oxygen carry out lactate fermentation
- The cells convert pyruvate to a molecule called lactate or lactic acid
- This lactate is then stored
- When the oxygen content increases the lactate is converted to pyruvate (in the liver) which can then continue in the Krebs cycle in the aerobic pathway

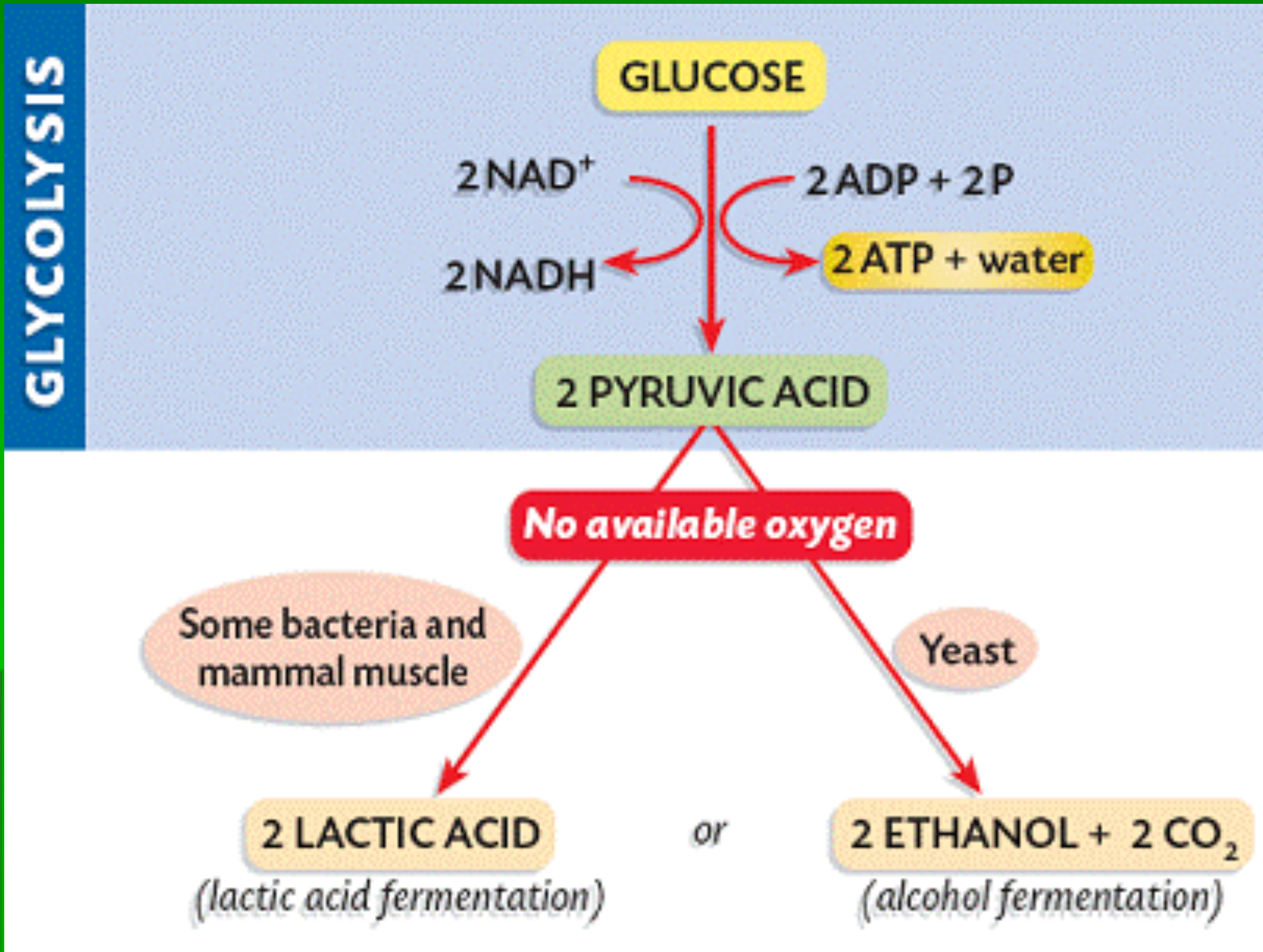
Ethanol Fermentation

- Some organisms (like yeast) can function both aerobically and anaerobically
- When they function anaerobically they carry out ethanol fermentation
- This process involves two steps:

1. After glycolysis produces pyruvate the pyruvate is converted into a two carbon compound by the release of CO_2
2. This two carbon compound is then reduced by NADH to form ethanol

Fermentation Pathways




GLYCOLYSIS
GLUCOSE
2 NAD+
2 NADH
2 ADP + 2 P
2 ATP + water
2 PYRUVIC ACID
No available oxygen
Some bacteria and mammal muscle
Yeast
2 LACTIC ACID
(lactic acid fermentation)
or
2 ETHANOL + 2 CO2
(alcohol fermentation)

Fermentation

- Energy yield of fermentation
  - Produces only a net of 2 ATP per glucose through direct substrate phosphorylation by allowing glycolysis to continue
  - Following fermentation most of the potential energy from glucose is still waiting to be released
  - Fermentation is a way to continue an ATP supply to cells when oxygen is in short supply