Chapter 5

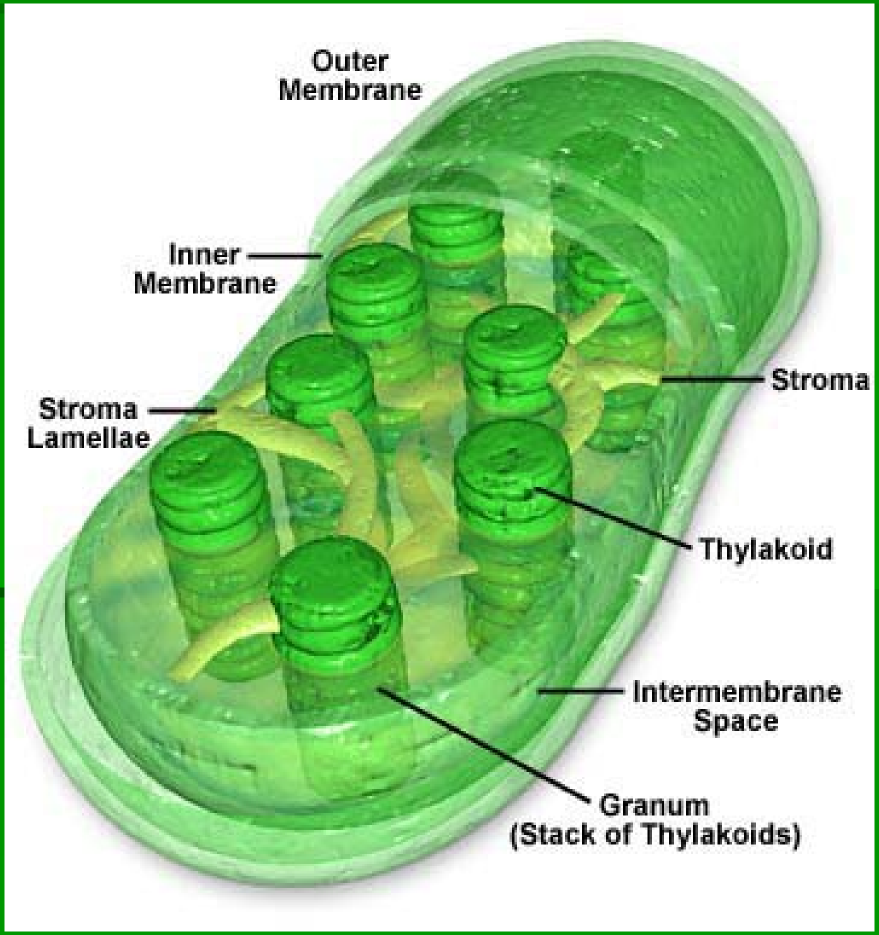
Photosynthesis & Cellular Respiration

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

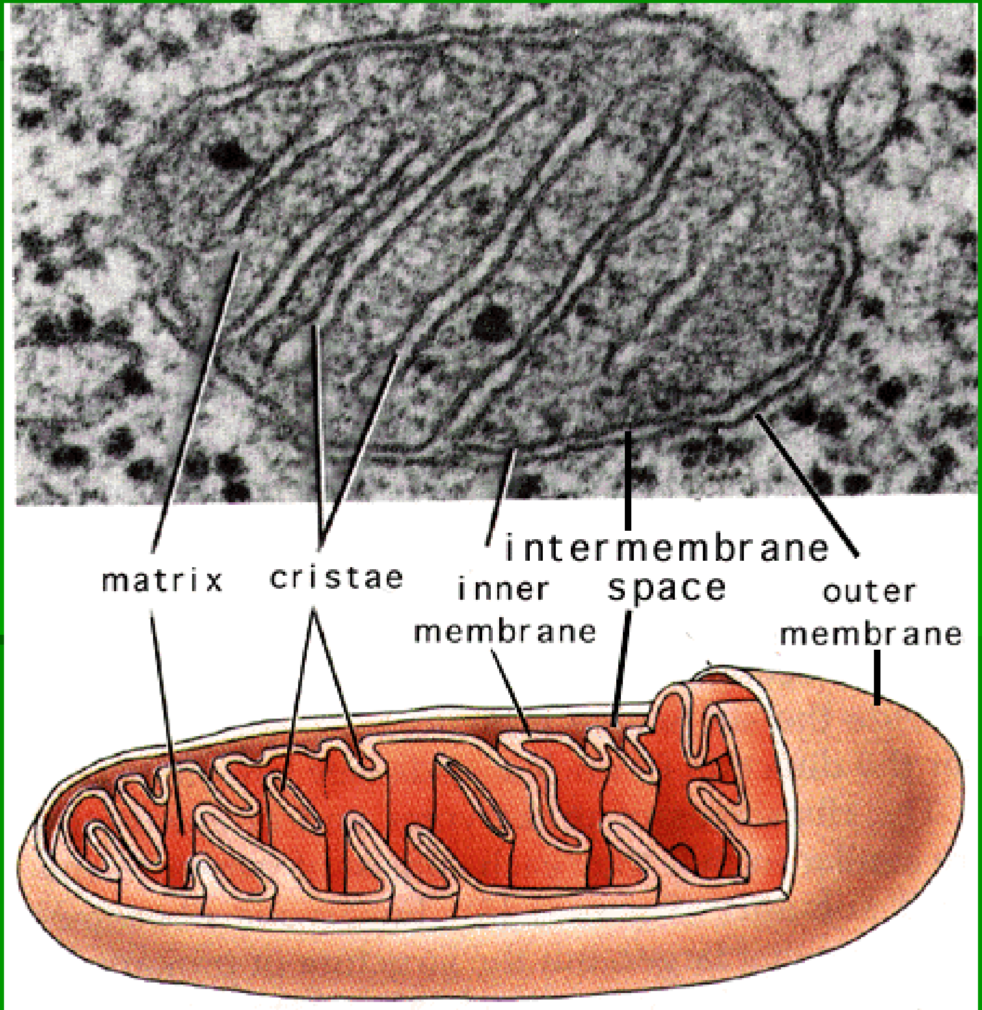
- The chloroplast is the site of photosynthesis
- They consist of a series of membranes



- The 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



- 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

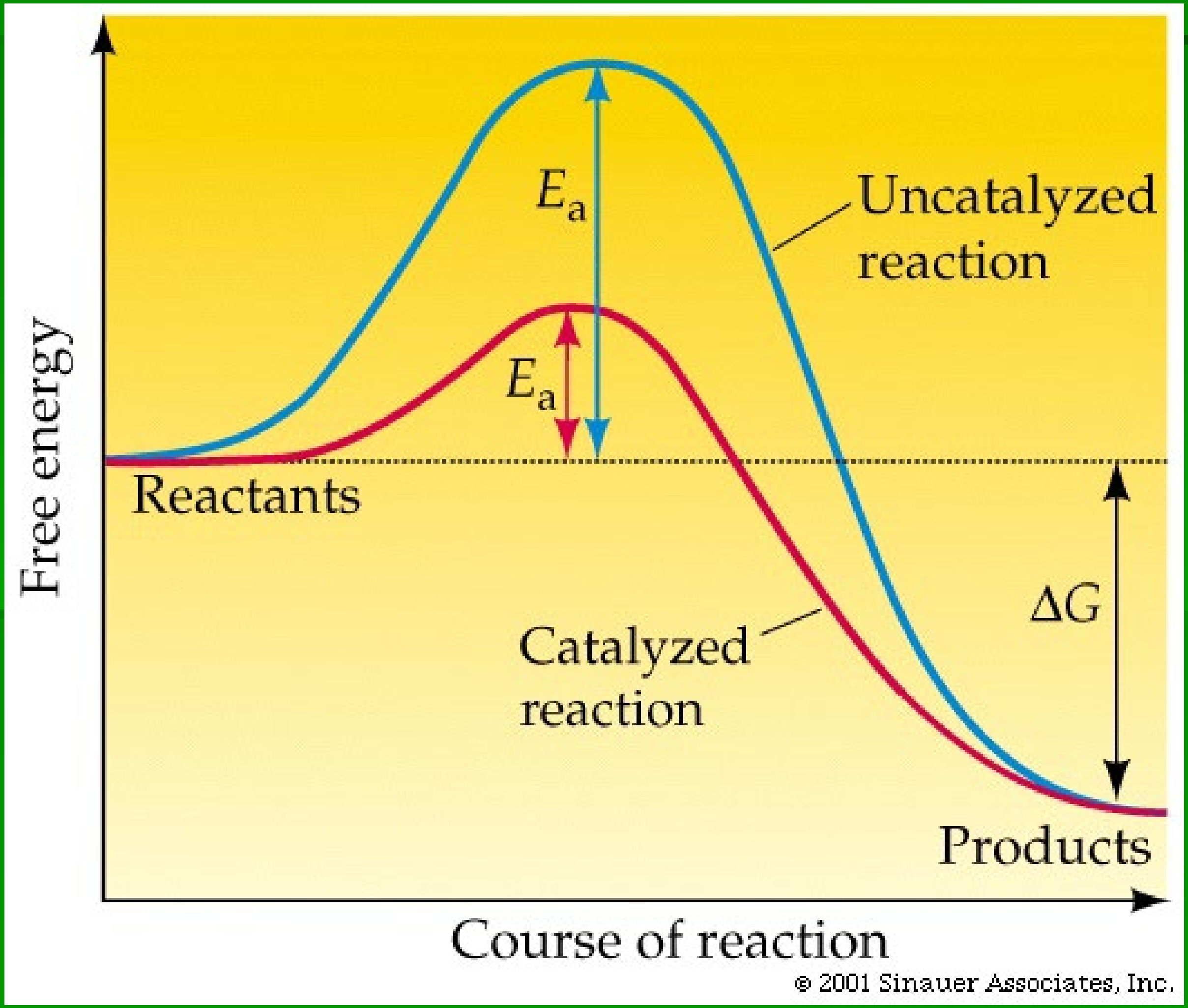
- The common chemical equations that represent both photosynthesis and cellular respiration are only *net* reactions
- Both of these processes use a series of pathways that are set up in step-by-step sequences

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

- 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



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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

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

5.2 - Photosynthesis

- Photosynthesis actually involves over 100 individual chemical reactions that work together
- These reactions can be summarized in two groups:

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

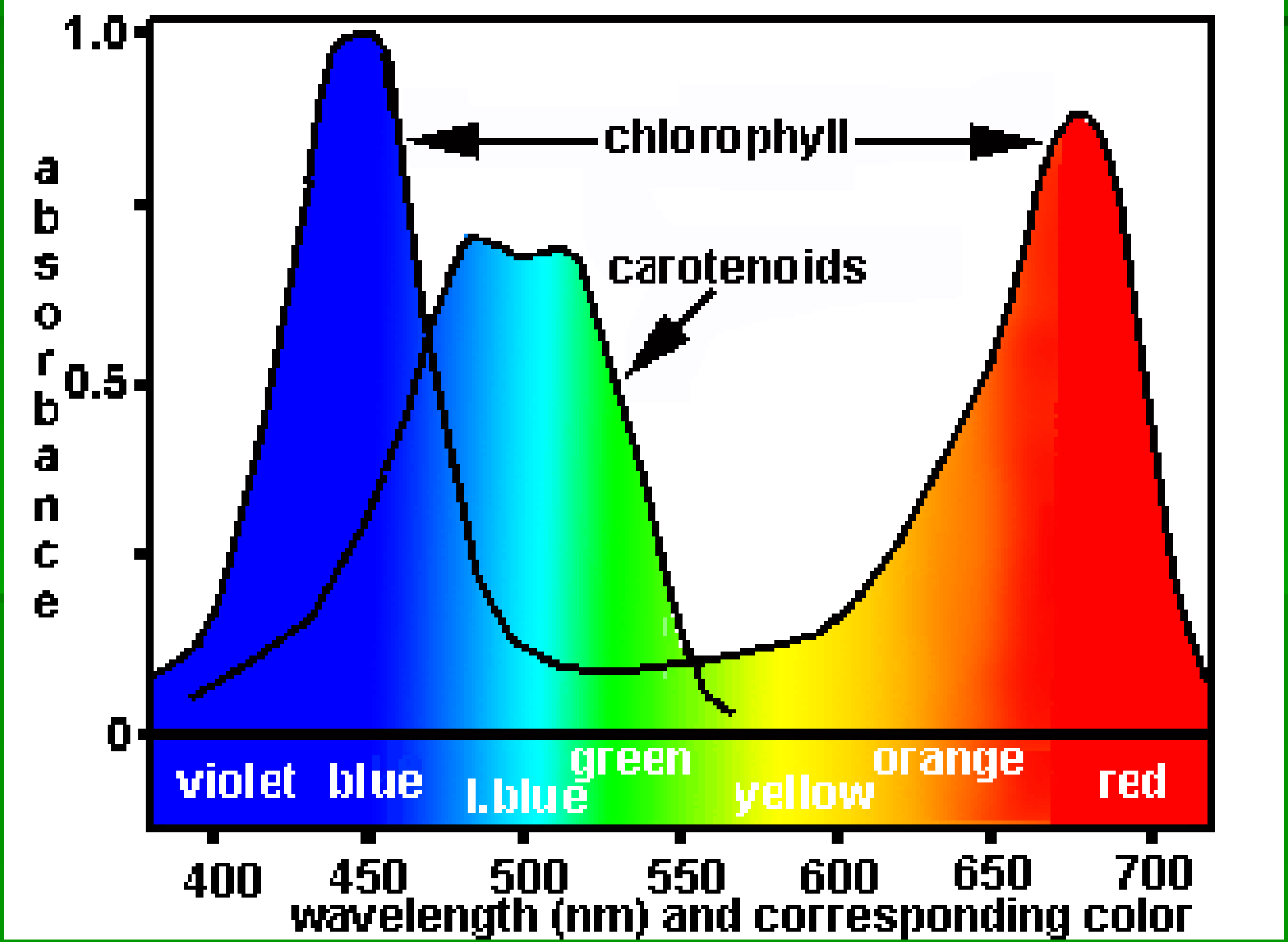
Light-Dependent Reactions

- 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

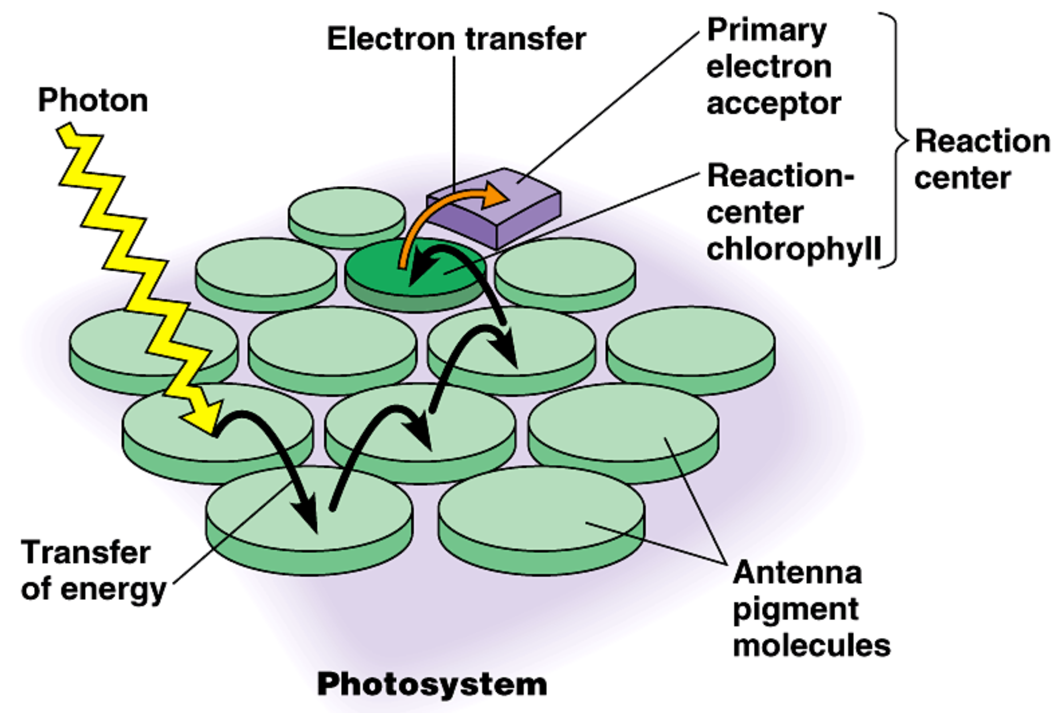


http://generalhorticulture.tamu.edu

Photosystems

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

- 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



- When the electron in the reaction center is “excited” by the addition of energy, it passes to the electron-acceptor molecule
- This reduces the electron acceptor and puts it at a high energy level
- 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 leaves an “electron hole” in photosystem II
- Enzymes break down a water molecule, which releases H^+ ions, electrons, and oxygen (this is the step in photosynthesis that produces oxygen gas)

Step 2

- The electron acceptor transfers the energized electron to a series of electron-carrying molecules (known as the electron transport system)
- 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

- 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 system 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 Steps:

- 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.

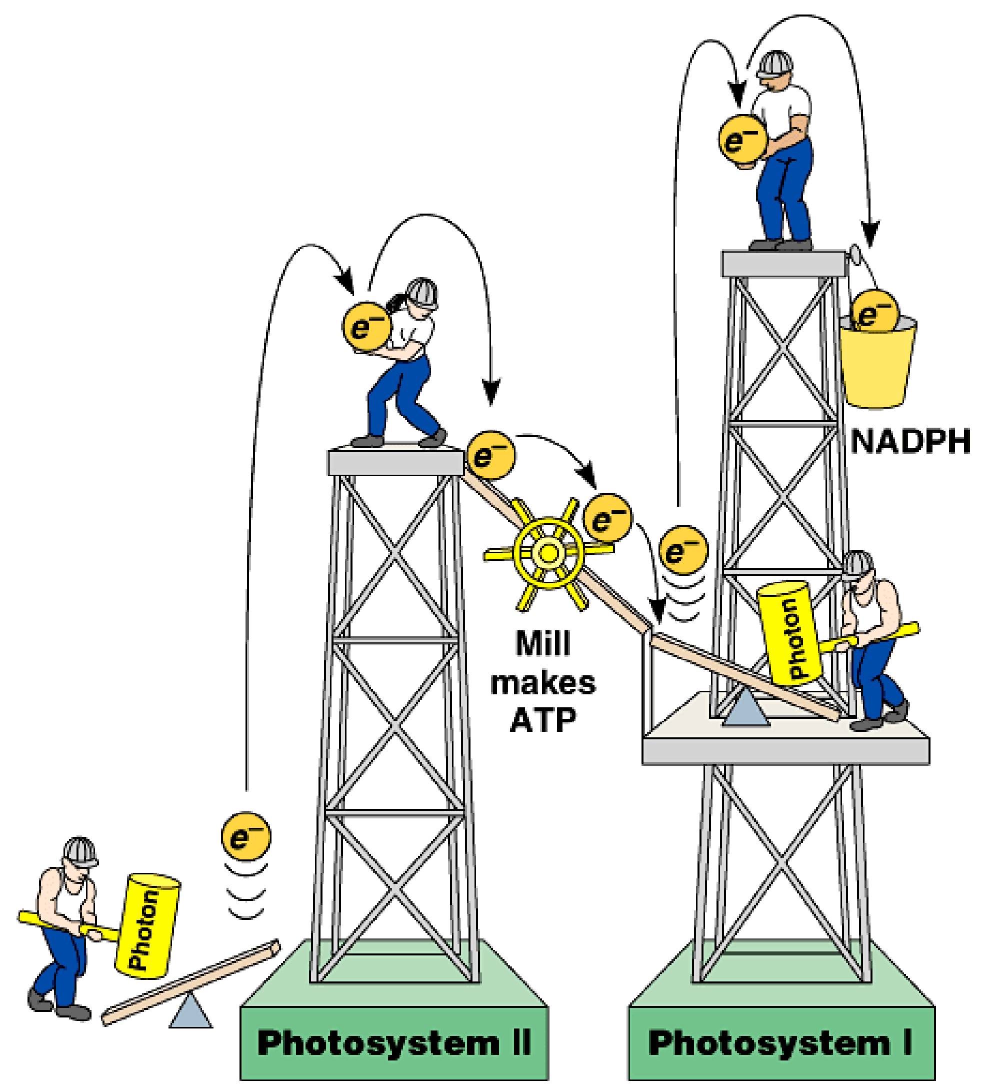


Fig. 10.13

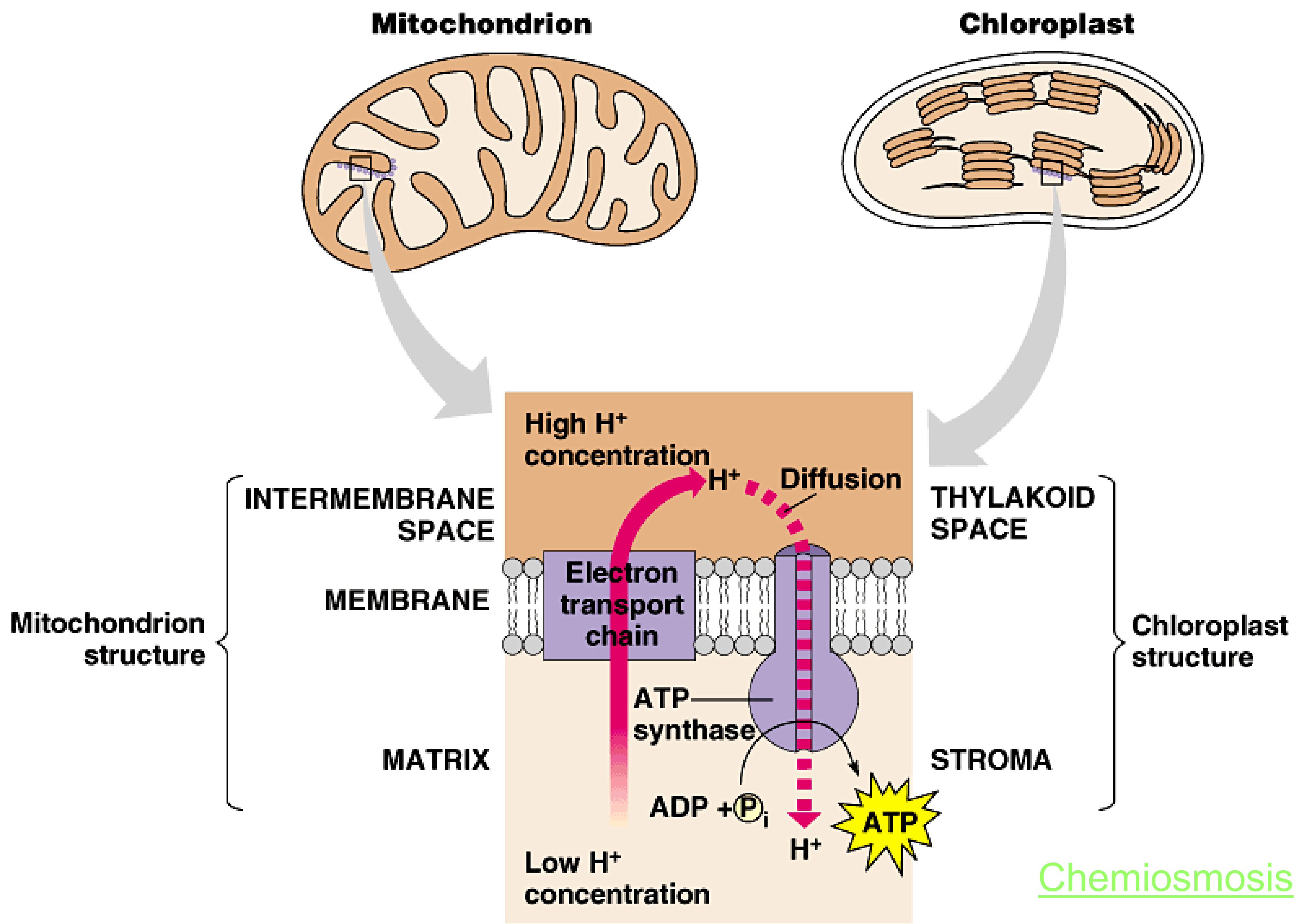
ATP Production - Chemiosmosis

- 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

Chemiosmosis



Chemiosmosis

A Model for Efficient Energy?

- Current methods of energy generation are relatively inefficient
- Current solar power technology is not efficient – it produces too little energy per unit of area to be practical
- Most of our energy right now comes from fossil fuel sources, which contribute to global warming

- Hydrogen can be used as a clean fuel, but the production of hydrogen gas requires large amounts of energy
- Recall that photosystem II produces hydrogen ions (but not gas) from water using only light energy and enzymes
- Scientists hope that a similar artificial system might be developed to obtain hydrogen gas efficiently from water to use in energy generation

The Light-Independent Reactions

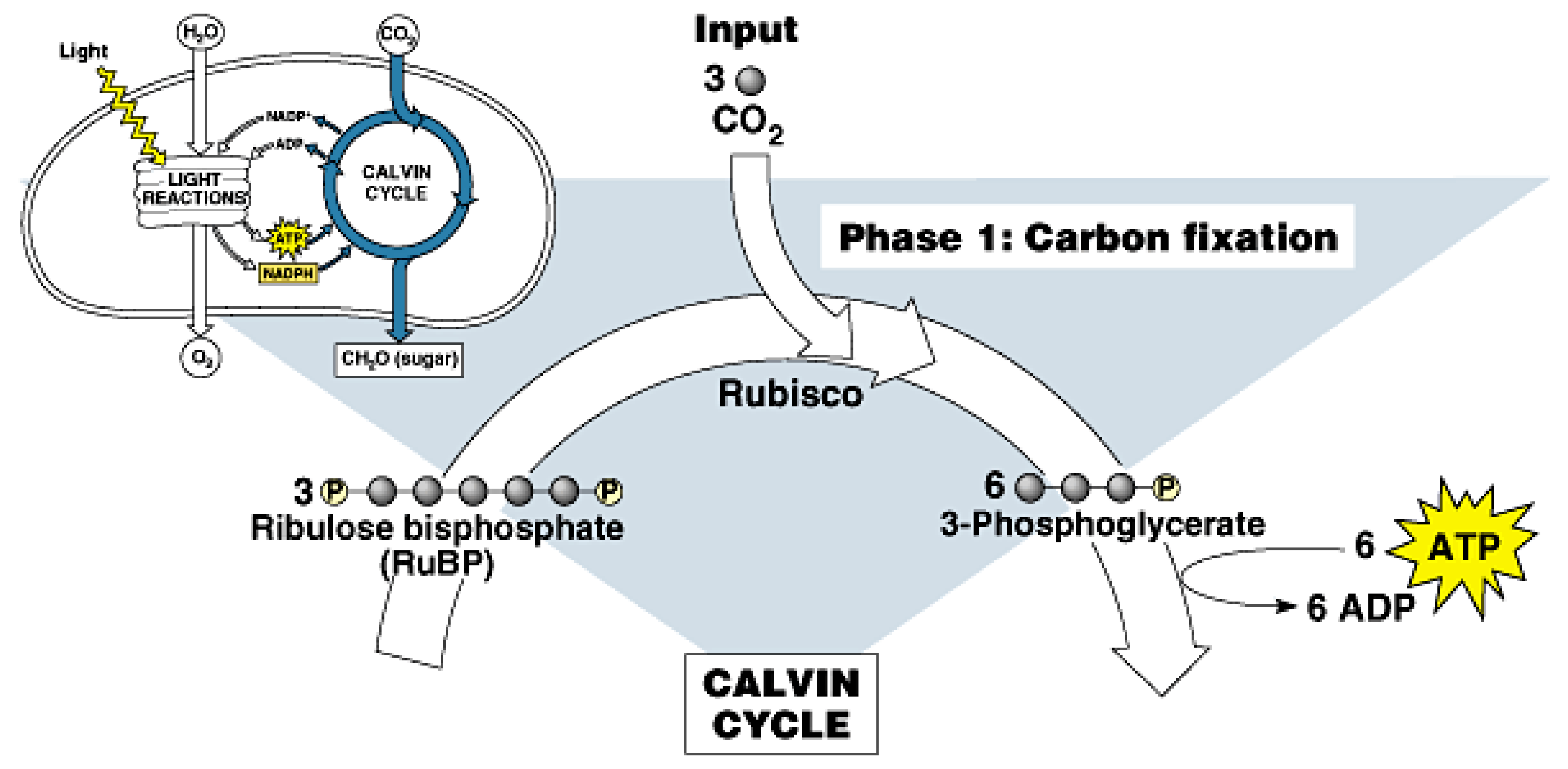
- Once enough ATP and NADPH has been produced by the chloroplasts, glucose can be synthesized
- This involves a series of reactions known as the Calvin-Benson cycle

The Calvin-Benson Cycle

- The Calvin 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, **PGAL**

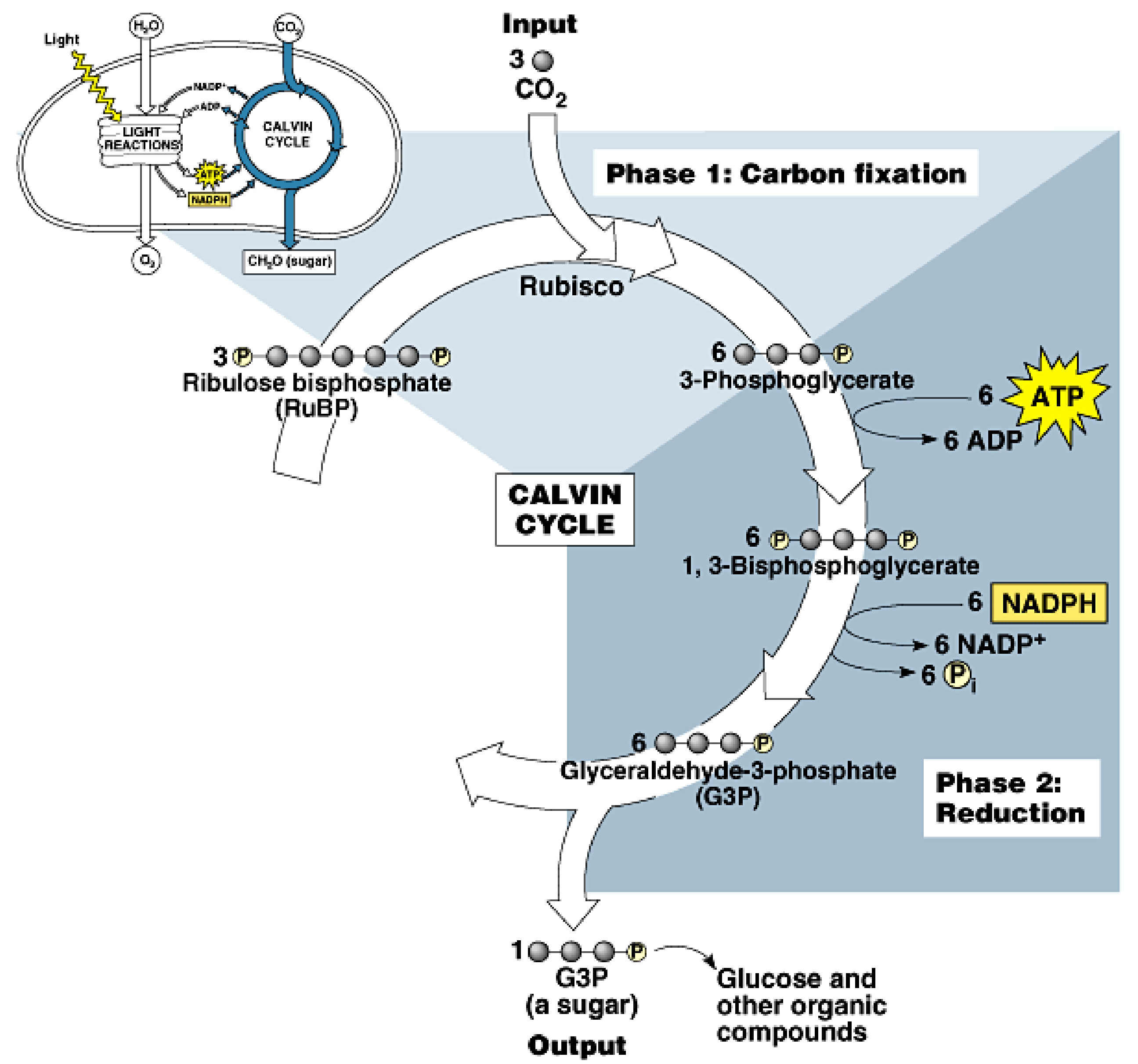
- Each turn of the Calvin cycle fixes one carbon.
- For the net synthesis of one PGAL molecule, the cycle must take place three times, fixing three molecules of CO_2.
- To make one glucose molecules would require six cycles and the fixation of six CO_2 molecules.
- The Calvin cycle has three phases.

Phase 1 – Carbon Fixation



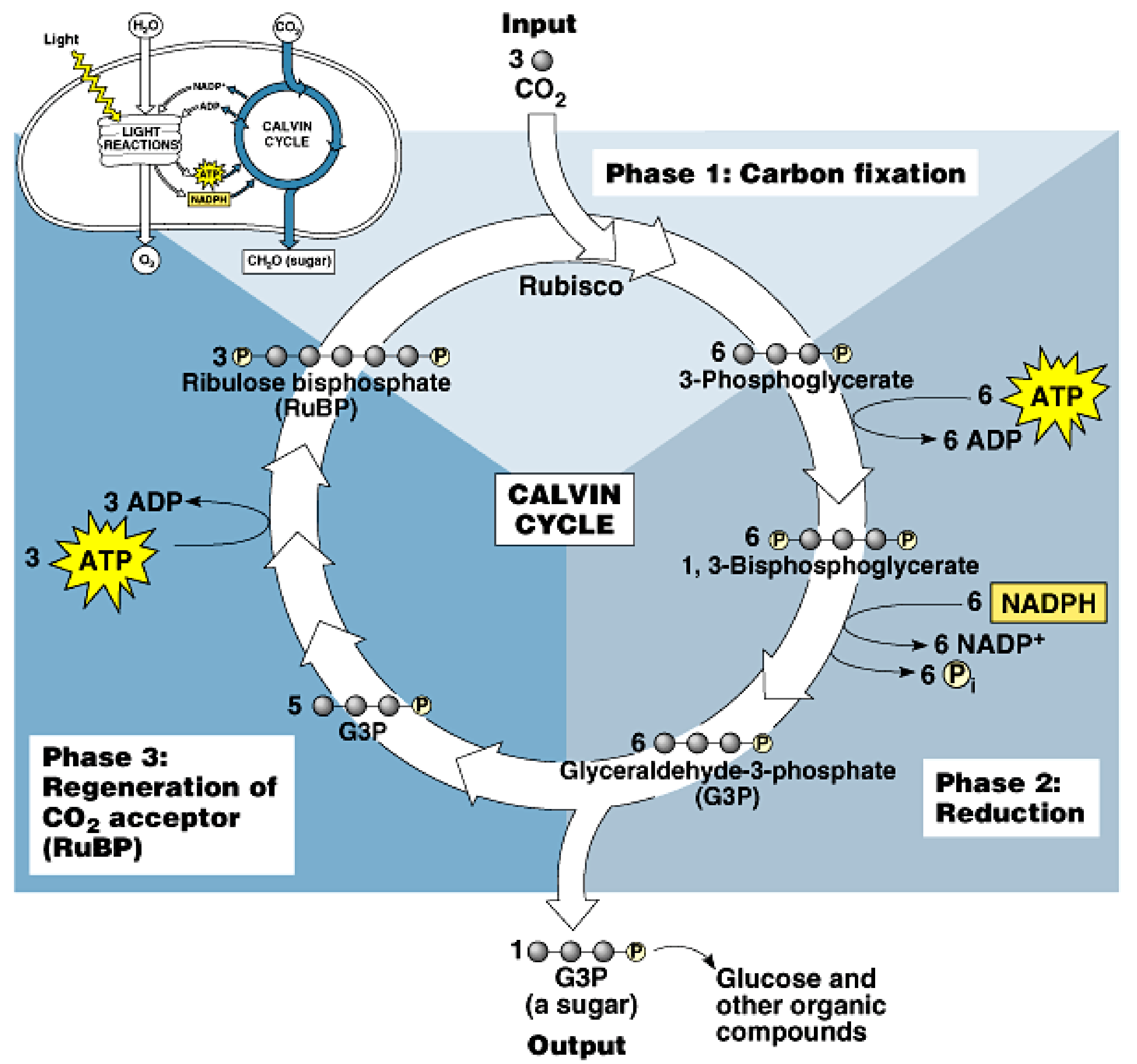
- In the carbon fixation phase, each CO_2 molecule is attached to a five-carbon sugar, ribulose bisphosphate (RuBP).
  - This is catalyzed by RuBP carboxylase or **rubisco**.
  - The six-carbon intermediate splits in half to form two molecules of 3-phosphoglycerate per CO_2.

Phase 2 - Reduction



- During reduction, each 3-phosphoglycerate receives another phosphate group from ATP to form 1,3 bisphosphoglycerate.
- A pair of electrons from NADPH reduces each 1,3 bisphosphoglycerate to G3P (PGAL).
  - The electrons reduce a carboxyl group to a carbonyl group.

Phase 3 - Regeneration



- In the last phase, regeneration of the CO_2 acceptor (RuBP), these five G3P (PGAL) molecules are rearranged to form 3 RuBP 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.

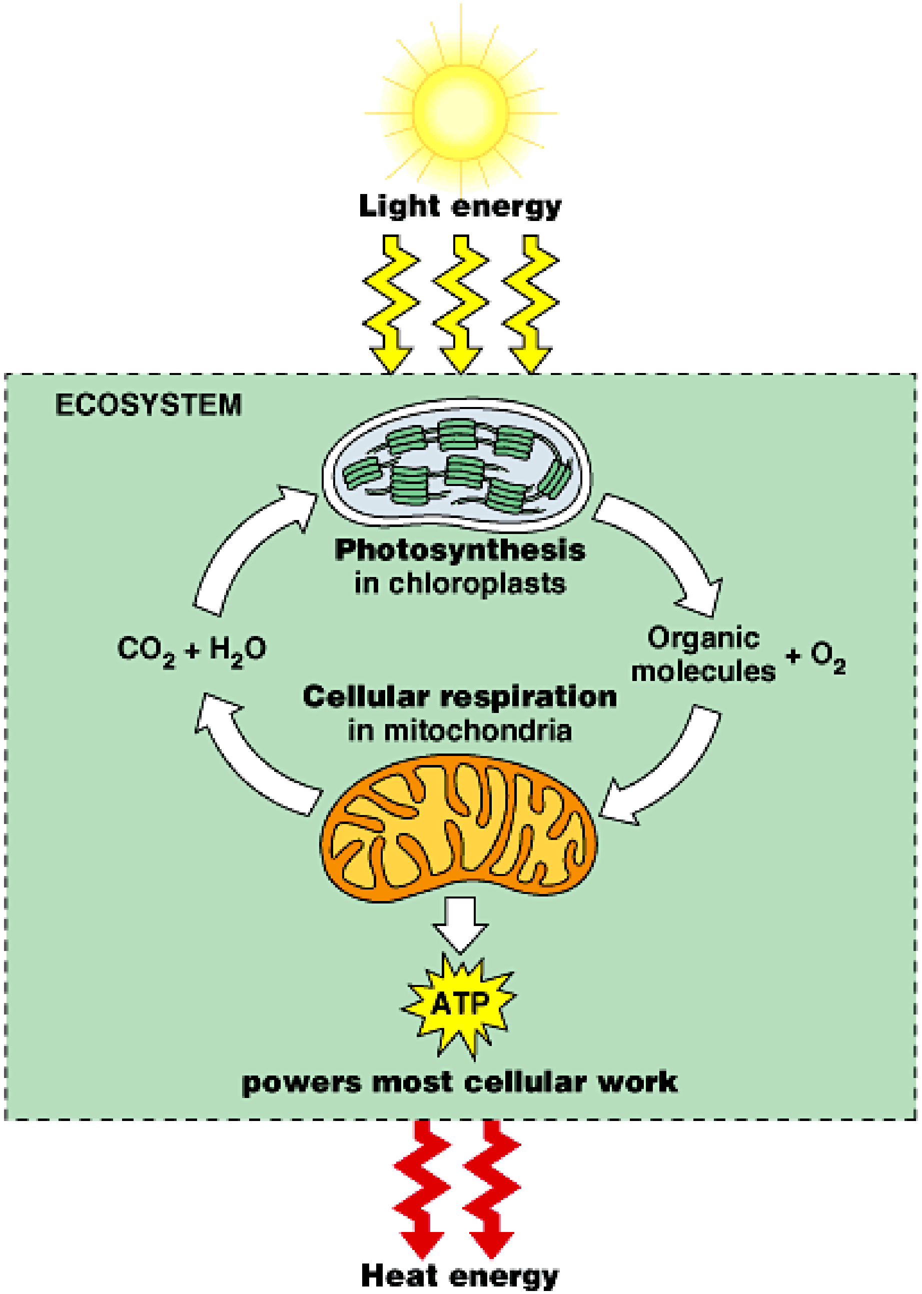
Overall Costs:

- For the net synthesis of one G3P molecule, the Calvin recycle consumes nine ATP and six NAPDH.
  - It “costs” three ATP and two NADPH per CO_2.
- 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 & Cellular Respiration are complimentary processes

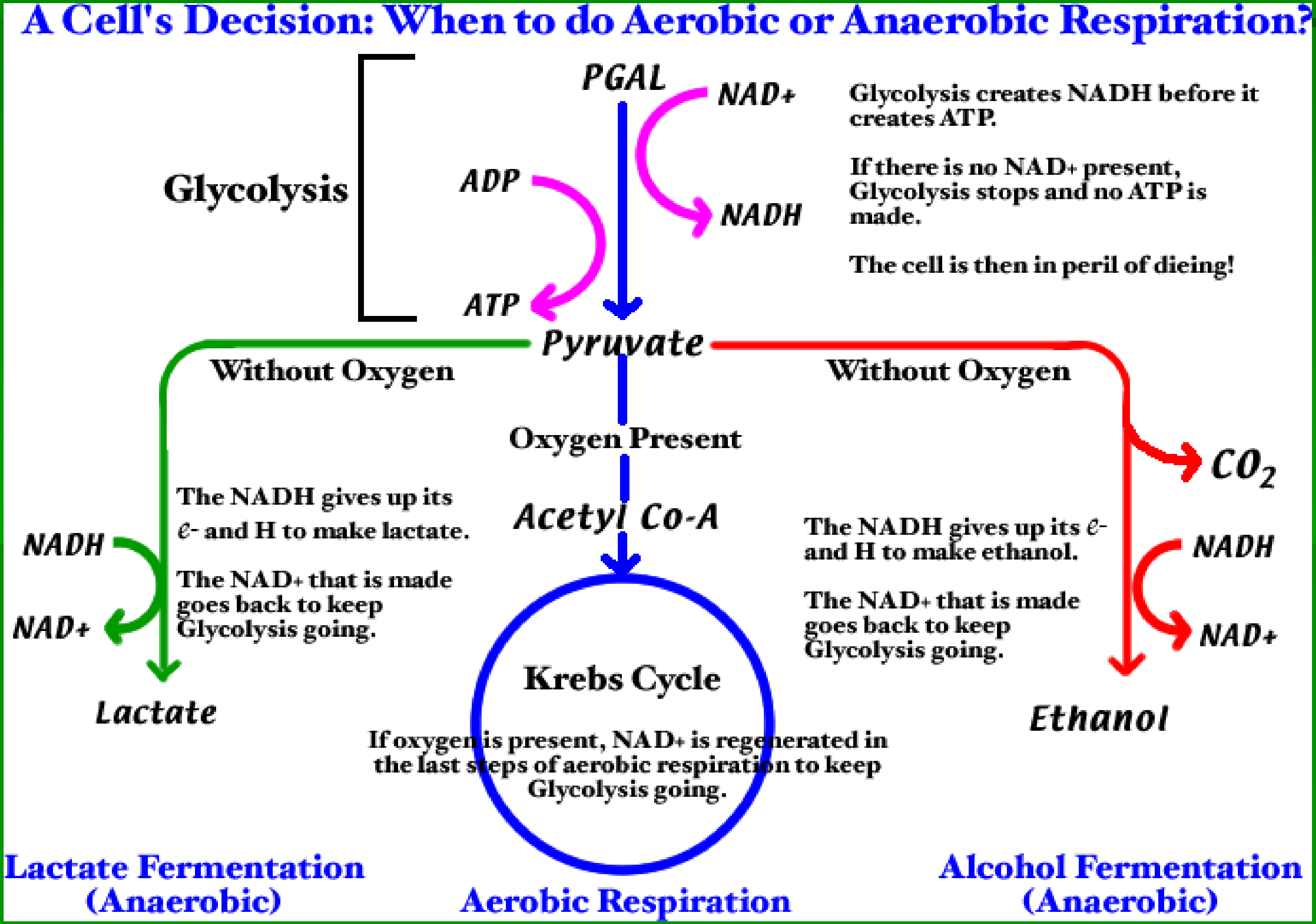


Releasing Stored Energy

- 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. Anaerobic cellular respiration is carried out by organisms that live in anoxic (no-oxygen containing) environments
3. A third pathway for energy release is fermentation. This process is a modified form of anaerobic cellular respiration

Aerobic vs. Anaerobic Respiration



A Cell's Decision: When to do Aerobic or Anaerobic Respiration?

Glycolysis creates NADH before it creates ATP.

If there is no NAD+ present, Glycolysis stops and no ATP is made.

The cell is then in peril of dieing!

The NADH gives up its e- and H to make lactate.

The NAD+ that is made goes back to keep Glycolysis going.

The NADH gives up its e- and H to make ethanol.

The NAD+ that is made goes back to keep Glycolysis going.

If oxygen is present, NAD+ is regenerated in the last steps of aerobic respiration to keep Glycolysis going.

Lactate Fermentation (Anaerobic)

Aerobic Respiration

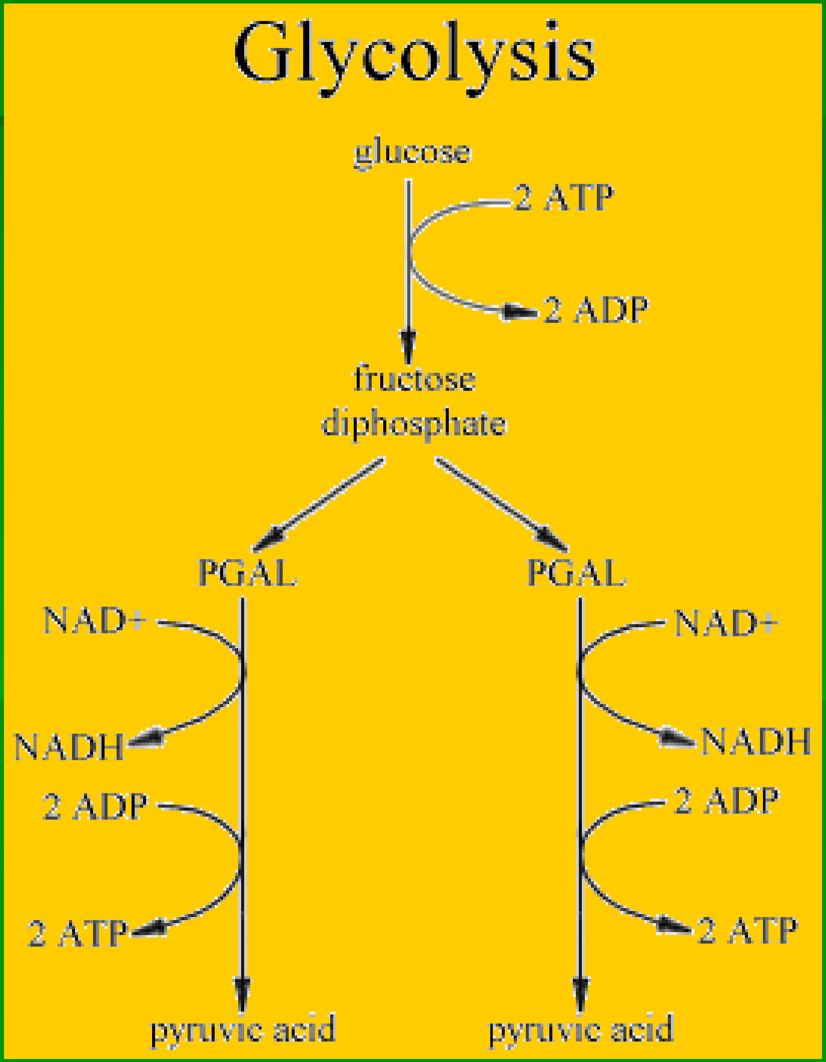
Alcohol Fermentation (Anaerobic)

Aerobic Cellular Respiration

- This is an oxidation reaction in which reactions transfer electrons from high-energy molecules to oxygen
- Most of the energy in plants, animals and most eukaryotic (membrane bound nucleus) cells is produced in this process
- The process starts with glycolysis, an anaerobic reaction in the cytoplasm

Glycolysis

- In glycolysis, a glucose molecule is converted into two molecules of pyruvic acid
- ATP and NADH are also produced



Steps in Glycolysis

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

Glycolysis Animation

The Fate of Pyruvate

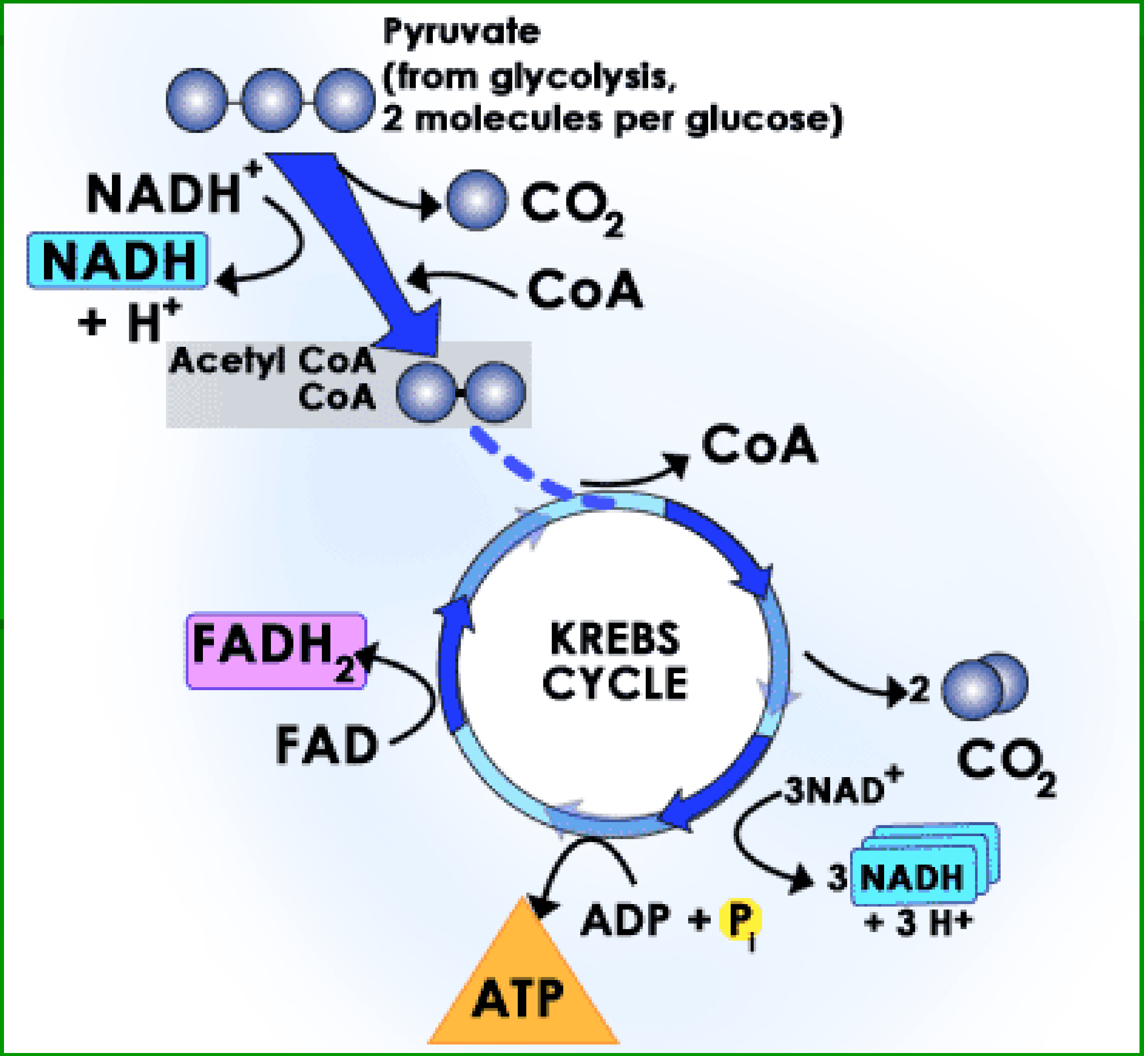
- Pyruvate contains large amounts of chemical energy
- If there is no oxygen present the pyruvate proceeds to fermentation
- When there is sufficient oxygen, the pyruvate is transferred to the mitochondria

Pyruvate & Coenzyme A

- Pyruvate 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 acetyl group into the Krebs cycle (in the form of acetyl-CoA)

The Krebs Cycle

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



Steps in the Krebs Cycle

1. Acetyl CoA binds with a 4-carbon molecule to form a 6-carbon molecule.
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

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

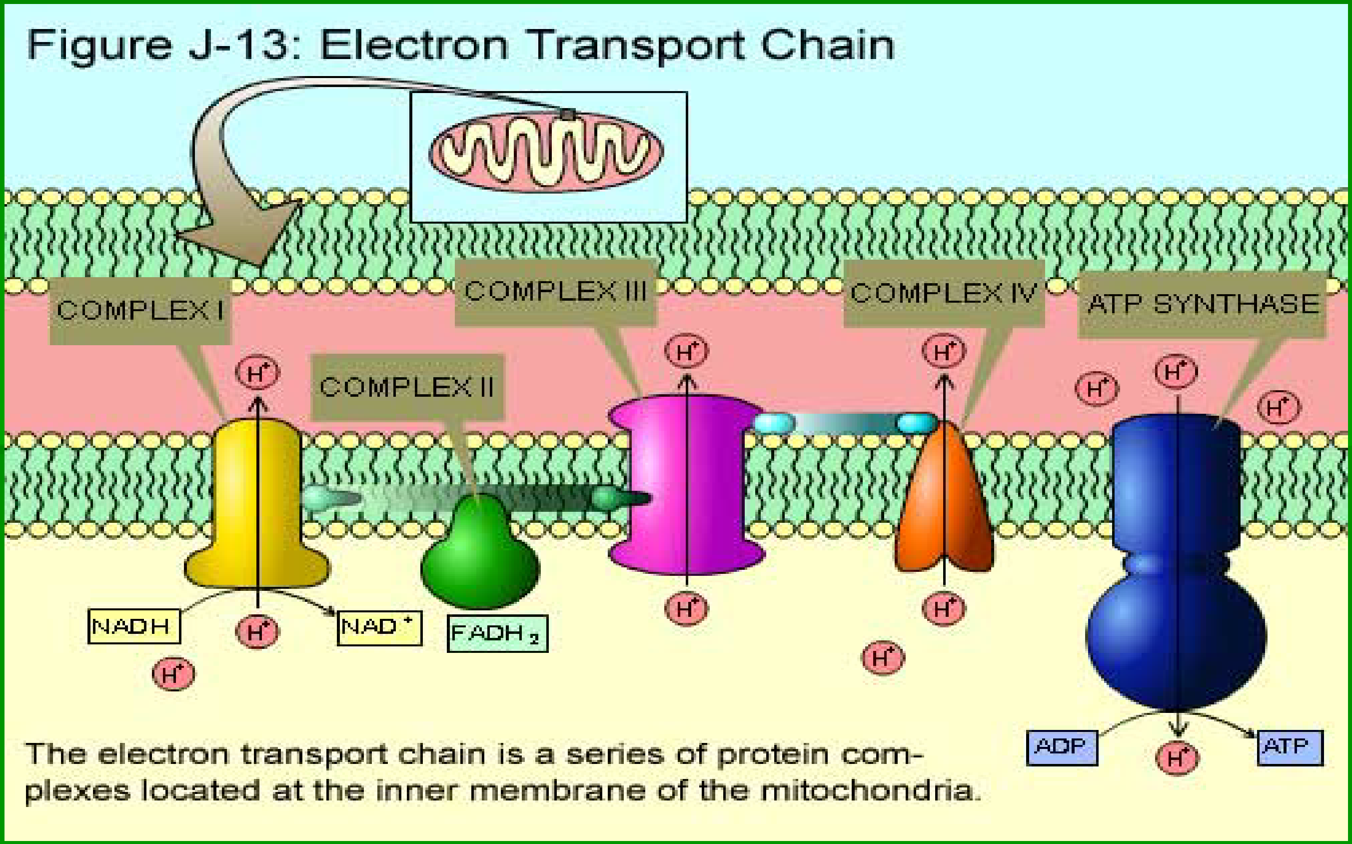
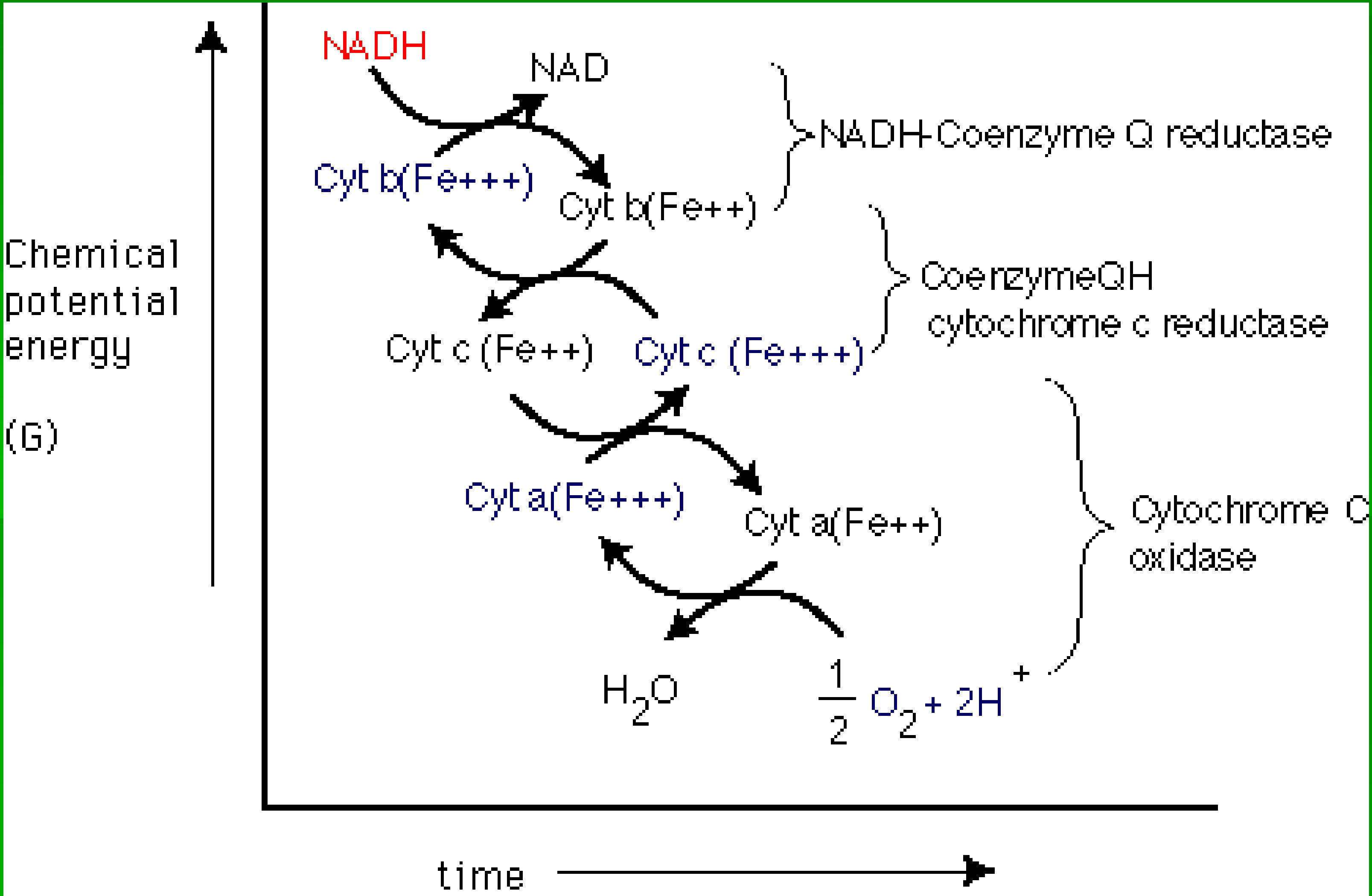


Figure J-13: Electron Transport Chain

The electron transport chain is a series of protein complexes located at the inner membrane of the mitochondria.

Chemiosmosis Animation

Components of the Electron Transport Chain



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

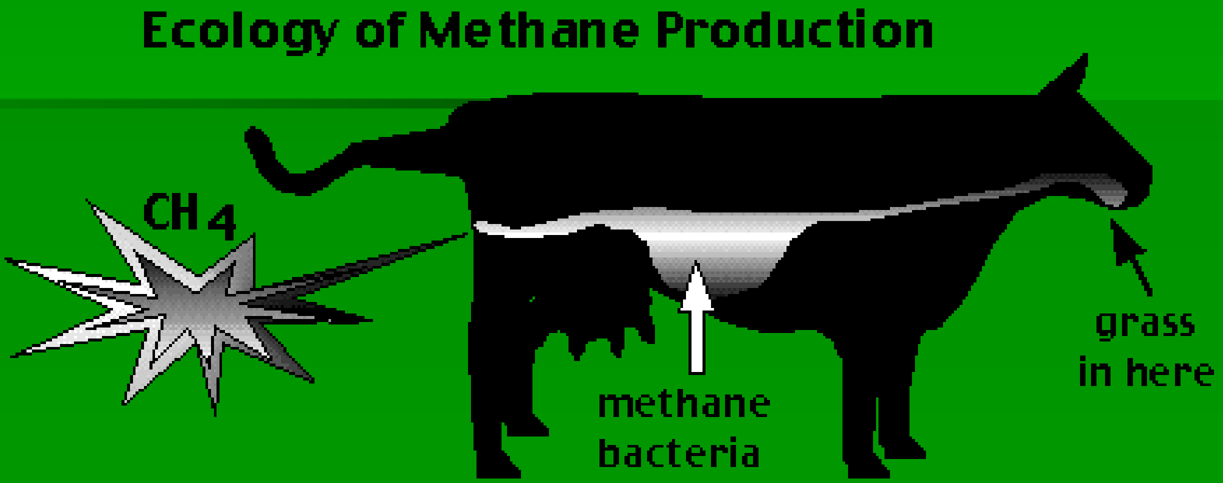
Cellular Respiration Review
Animation

Anaerobic Respiration

- When oxygen is not available the final electron acceptor in an anoxic environment 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

The Products of Anaerobic Respiration

- The final byproducts are sulfur, nitrite, nitrogen and methane (bacteria living in large intestines live in an anaerobic environment)


Ecology of Methane Production

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

What Carries out Fermentation?

- Many single-celled organisms carry out fermentation
- Fermentation can also occur deep within tissues that are not near an oxygen source such as submerged plant tissue
- 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 which continues in the Krebs cycle in the aerobic pathway

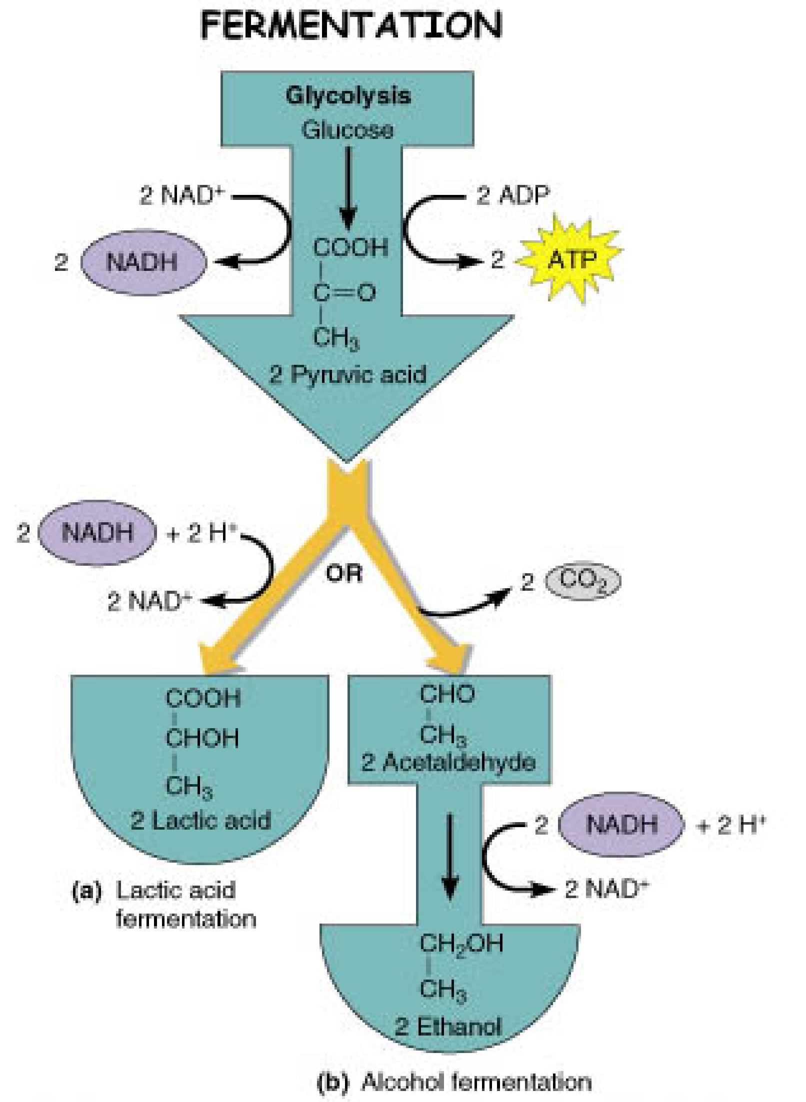
Ethanol Fermentation

- Some organism can function both aerobically and anaerobically
- When they function anaerobically they carry out ethanol fermentation
- This process involves two steps:

Ethanol Fermentation

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



(a) Lactic acid fermentation

(b) Alcohol fermentation

Uses of Fermentation Products

- During WWI large amounts of butanol and acetone were needed
- Previously this attained by burning wood without oxygen
- The yield was low – about 100:1
- A scientist discovered the fermentation pathway and could convert molasses or grain to butanol and acetone with yields of 100:24 and 100:12 respectively

- The process of fermentation produces large amounts of ethanol which humans learned long ago could be burned
- Ethanol is being produced on a large scale to add to or in some cases replace hydrocarbons as a fuel source
- Most commonly it is produced from the fermentation of corn or wheat
- The starch is converted to glucose by enzymes which the yeast then anaerobically produce ethanol

- This can be distilled producing almost pure ethanol
- Burning of ethanol results in carbon dioxide, however, this produces less carbon monoxide and other volatile organic compounds that contribute to smog

In 2007, the IndyCar series switched the type of fuel used by their cars to 100% ethanol

Manure as Fuel?

- Manure from pigs and cattle can be captured, stored in an oxygen free container, allowed to decompose in the presence of anaerobic bacteria to produce methane and carbon-dioxide
- The methane can be burned to produce heat, light or electricity
- One family of 4-6 could use the manure from 5 pigs for their daily needs of heating rather than 11 kg of propane

But Wait – What About that Pesky Carbon Dioxide I keep Hearing About?

- The advantage of this is that the carbon that is created from the fermentation is recycled from the glucose created from the plants, therefore it is carbon neutral
- When we burn fossil fuels we are releasing carbon that has been stored for millions of years after being taken out of circulation
- The large amounts that are being released over a short time now are concentrating it in the environment more than any other time in history with devastating effects