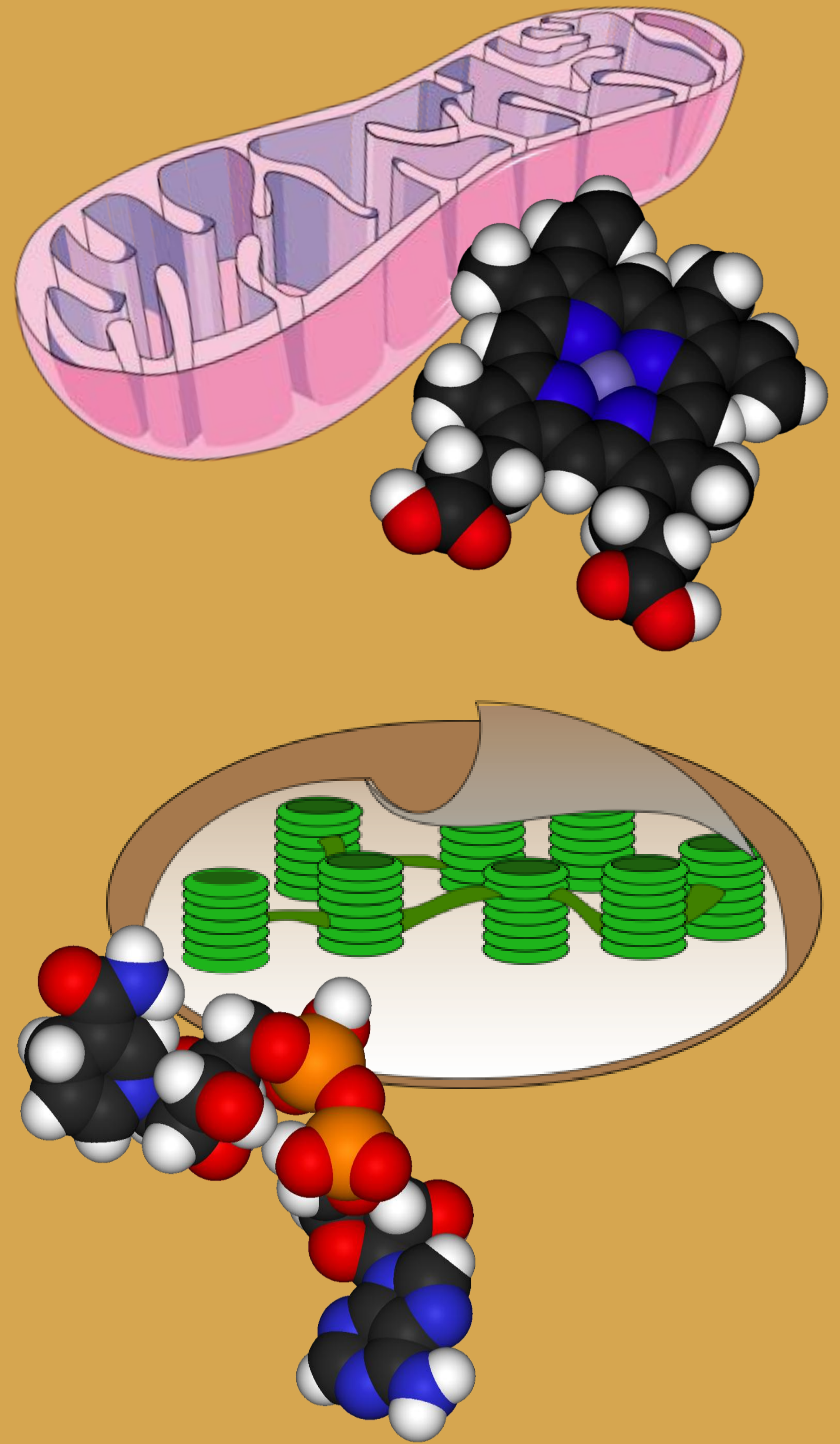
Cell Biology & Biochemistry Series:

Set 5

Cellular Energetics

Version: 1.0

BIOZONE



Energy

- All organisms require **energy** to grow, reproduce, move and carry out fundamental maintenance and repairs.
- Energy can not be created or destroyed, but it can be converted from one form to another.
- The ultimate source of energy is the sun.

Photo credit: NASA

Energy Producers

Most plants are **autotrophs**.

- Organisms which are capable of producing their own energy are called **autotrophs**.
- **Photosynthetic autotrophs** (e.g. plants, algae and some bacteria) convert light energy into chemical energy.
- **Chemosynthetic autotrophs** derive their energy from inorganic sources such as sulfur or ammonia. Some bacteria are **chemoautotrophs**.

Anabaena sphaerica (left) is a cyanobacterium, and is an example of an **autotrophic** bacteria.

Energy Consumers

- **Heterotrophs** are organisms which cannot make their own energy. All animals, fungi and some bacteria are heterotrophs.
- **Chemosynthetic heterotrophs** consume other organisms to obtain their energy and carbon sources.
- **Photosynthetic heterotrophs** are able to convert light energy, but still require organic compounds as a carbon source. Some bacteria are **photoheterotrophs**.

The Laws of Thermodynamics

Thermodynamics is the study of energy changes in a system. A system can be a whole organism or simply a set of substrates (reactants) and products. Biological systems are open systems, in that they can exchange matter and energy with the surroundings.

First Law of Thermodynamics

Energy cannot be created or destroyed, but it can be transformed from one type into another and transferred from one object to another.

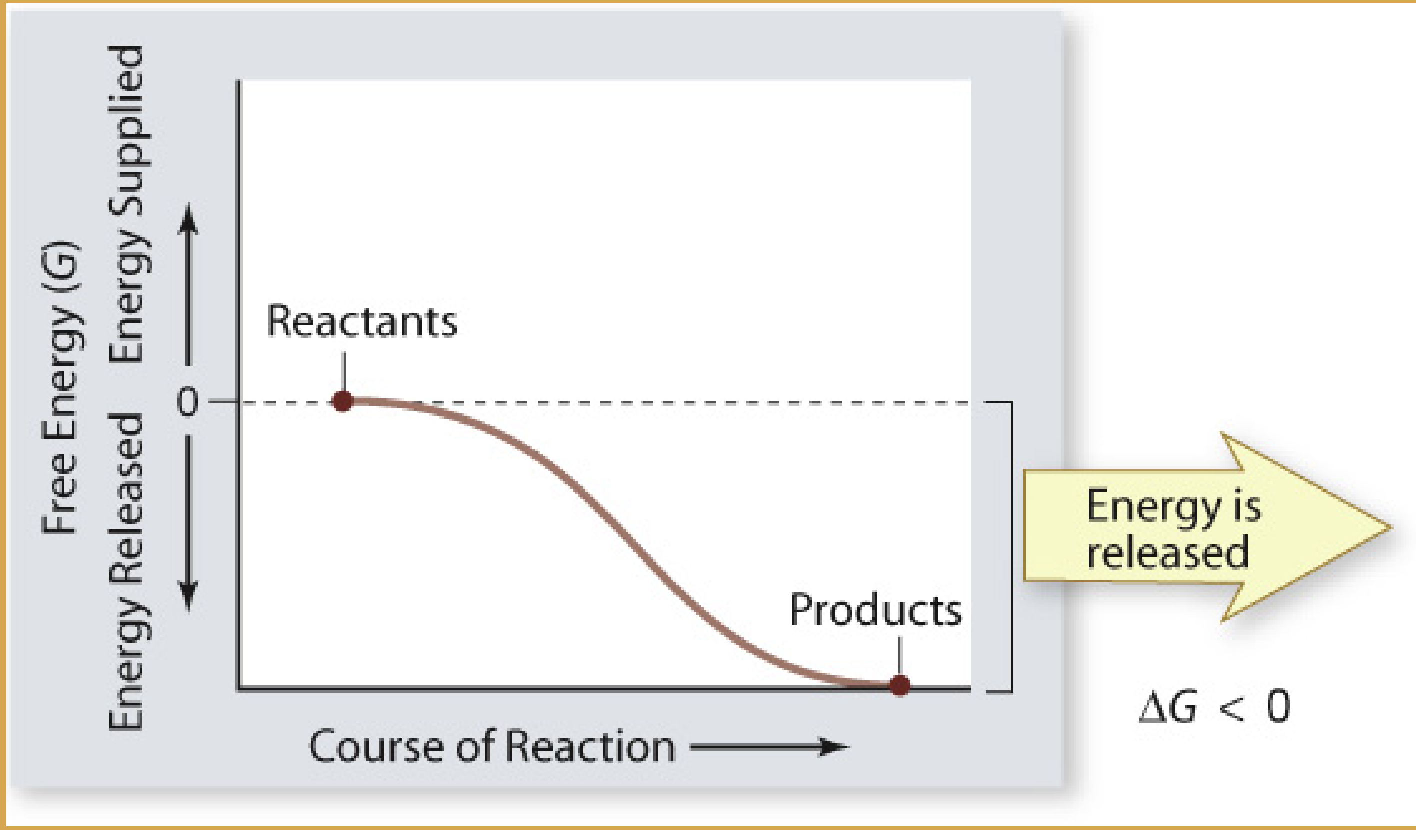
Second Law of Thermodynamics

During any process, the universe tends towards disorder. **Entropy**

Endergonic and Exergonic Reactions

In **exergonic** reactions:

- ΔG is negative
- the products contain less free energy than the reactants
- the reactions proceed spontaneously
- free energy is released in the form of heat



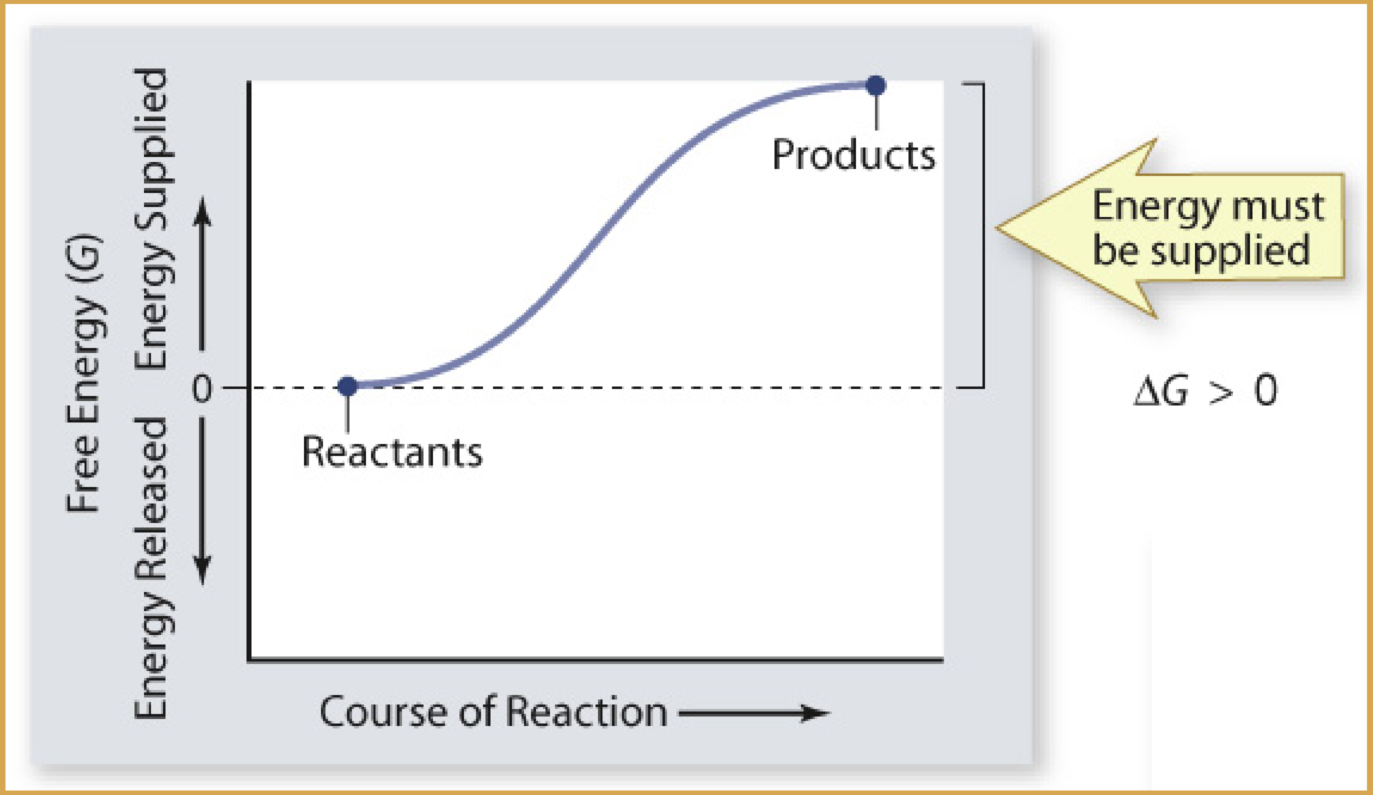
In an exergonic reaction, the products contain less energy than the reactants, and excess energy is released.

Endergonic and Exergonic Reactions

The change in free energy can be used to predict whether a chemical reaction is spontaneous or not.

In **endergonic** reactions:

- ΔG is positive
- the products of the reaction contain more free energy than the reactants
- the reactions do not proceed spontaneously—they require an input of energy

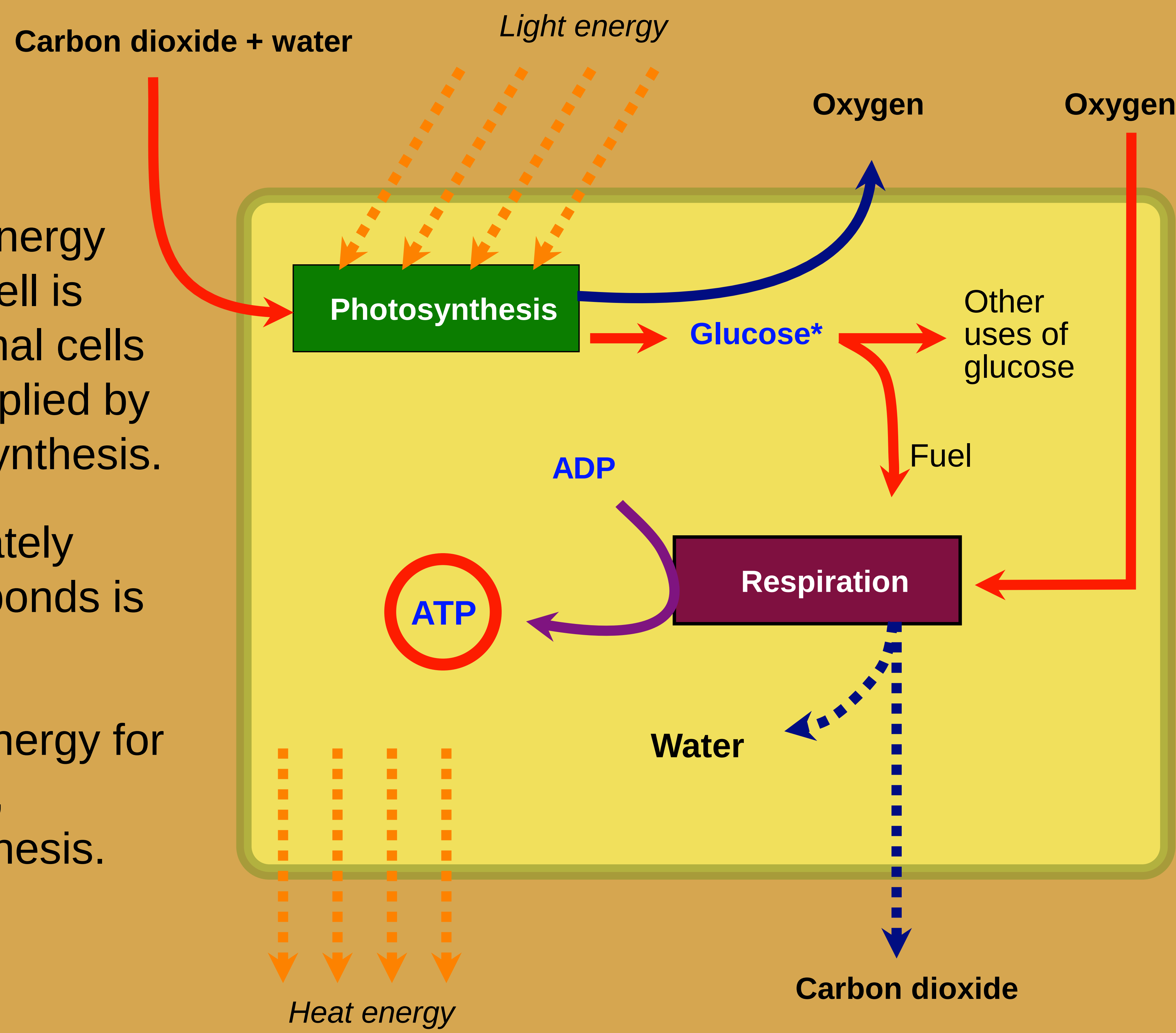


In an endergonic reaction, the products of the reaction contain more energy than the reactants, and energy must be supplied for the reaction to proceed.

Continued…

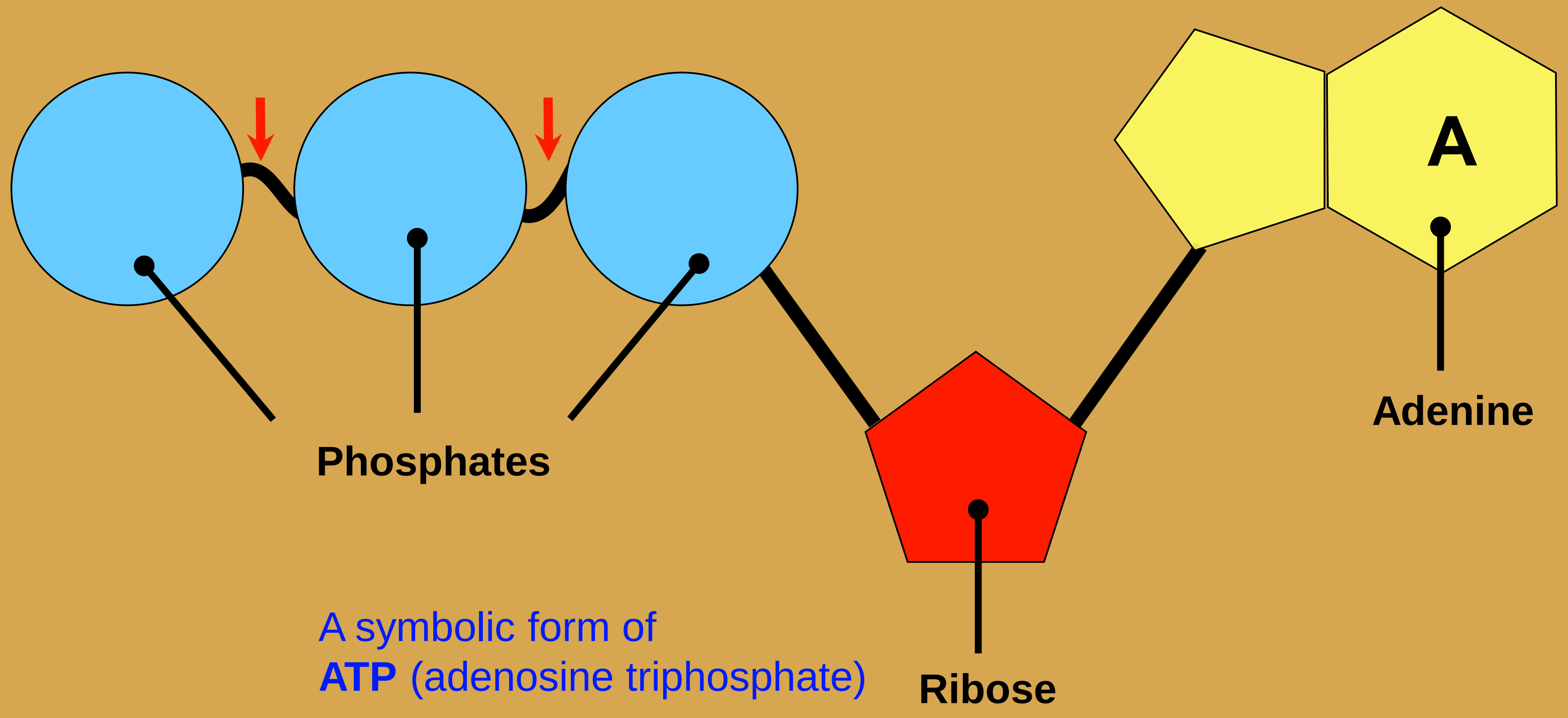
Energy in Cells

- A summary of the energy flow within a plant cell is shown here. In animal cells the **glucose*** is supplied by feeding, not photosynthesis.
- Energy not immediately stored in chemical bonds is lost as **heat**.
- **ATP** provides the energy for metabolic reactions, including photosynthesis.



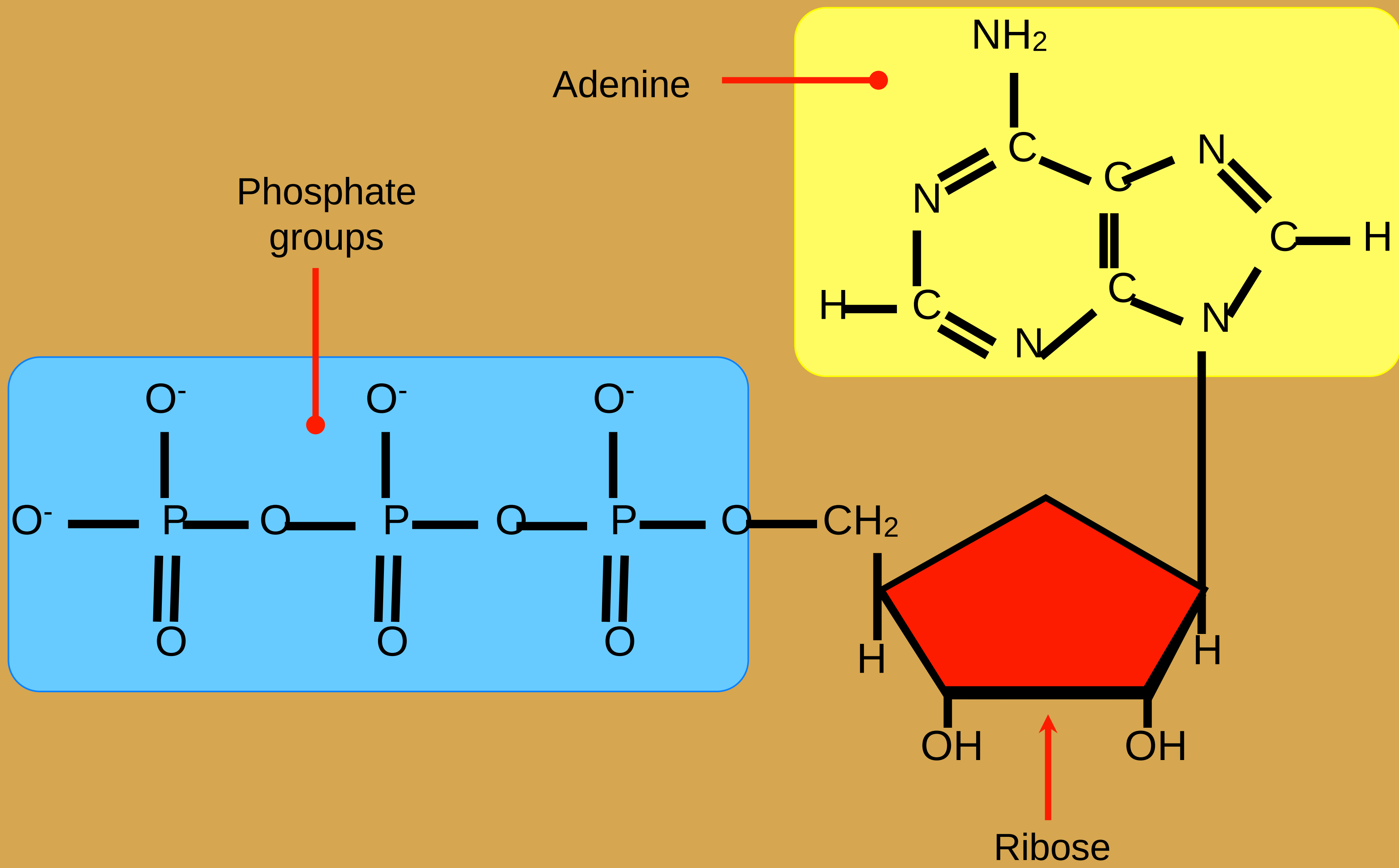
ATP Structure

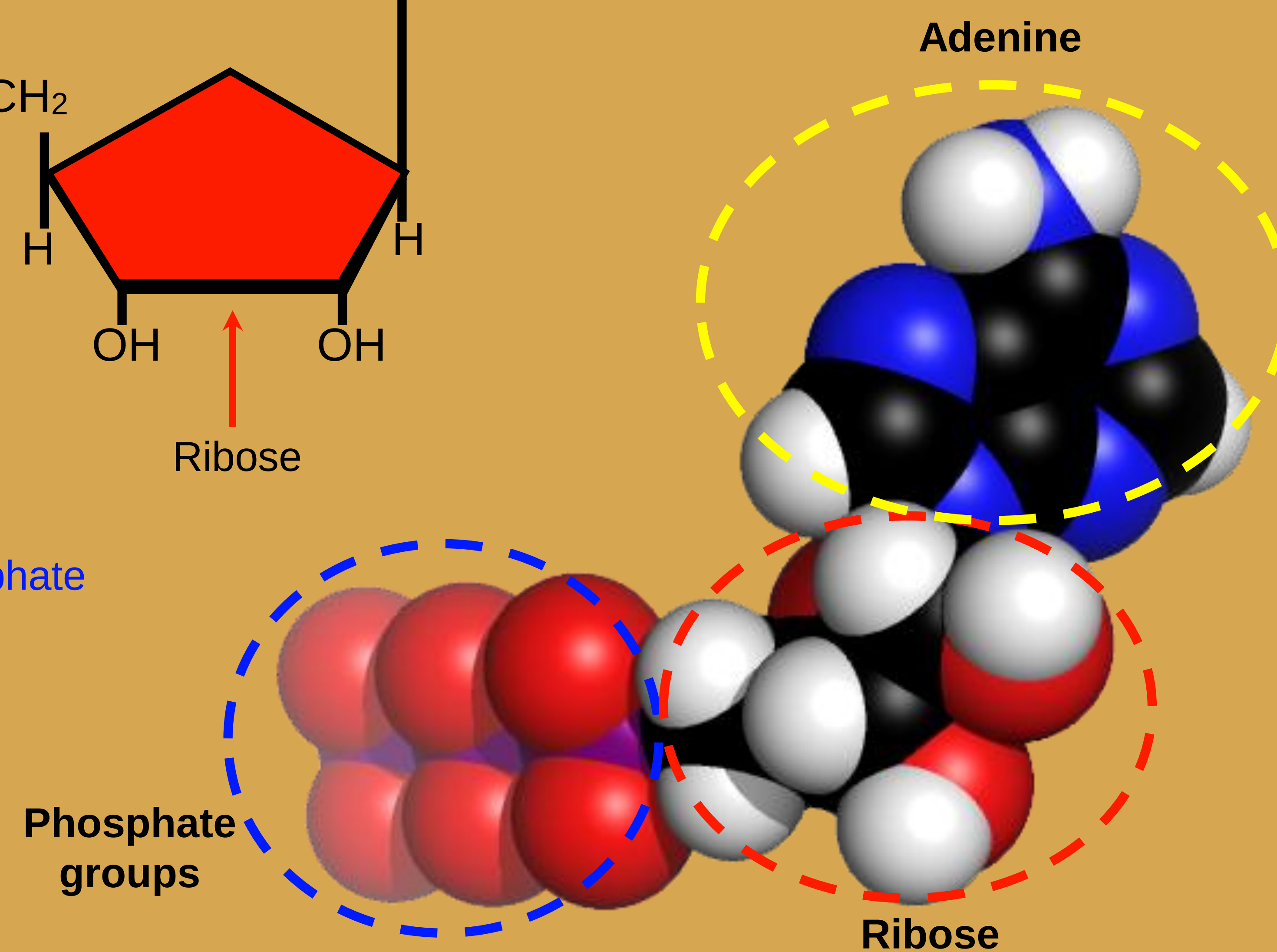
- **Adenosine triphosphate (ATP)** is the universal energy carrier for cells.
- ATP is classed as a nucleotide and is composed of **adenine**, **ribose** and **three phosphate groups**.
- Covalent bonds join the two terminal phosphate groups to the nucleotide.



A symbolic form of
ATP (adenosine triphosphate)

ATP Structure

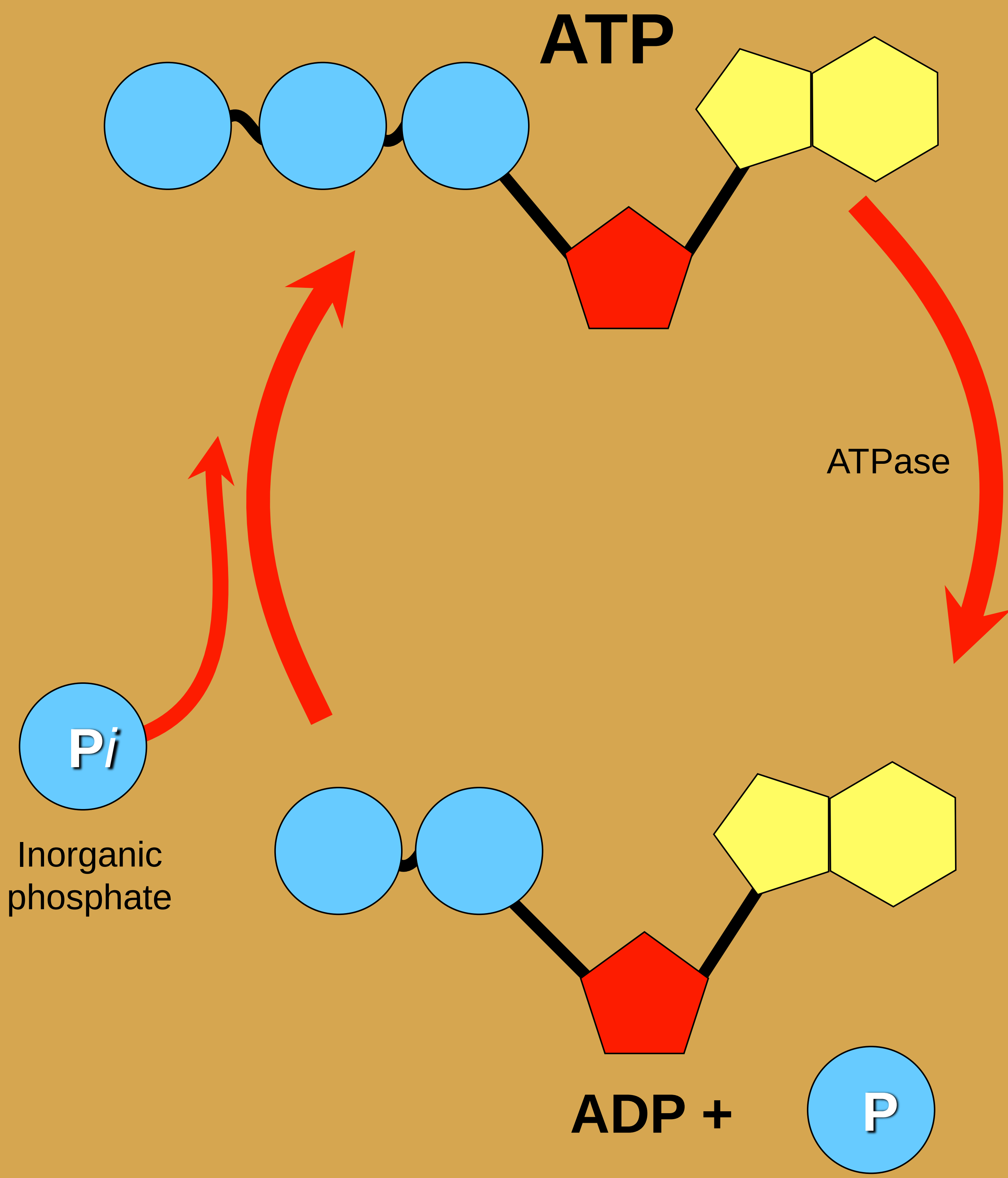




The chemical structure of adenosine triphosphate (ATP), and a space filling molecule (right).

The Role of ATP in Cells

- ATP can release its energy quickly by hydrolysis of the terminal phosphate.
  - This reaction is catalyzed by the enzyme **ATPase**.
- Once ATP has released its energy, it becomes **ADP (adenosine diphosphate)**.
  - ADP is a low energy molecule that can be recharged by adding a phosphate.



The Role of ATP in Cells

The **energy released** from the loss of a phosphate is available for immediate work inside the cell.

ATPase

P

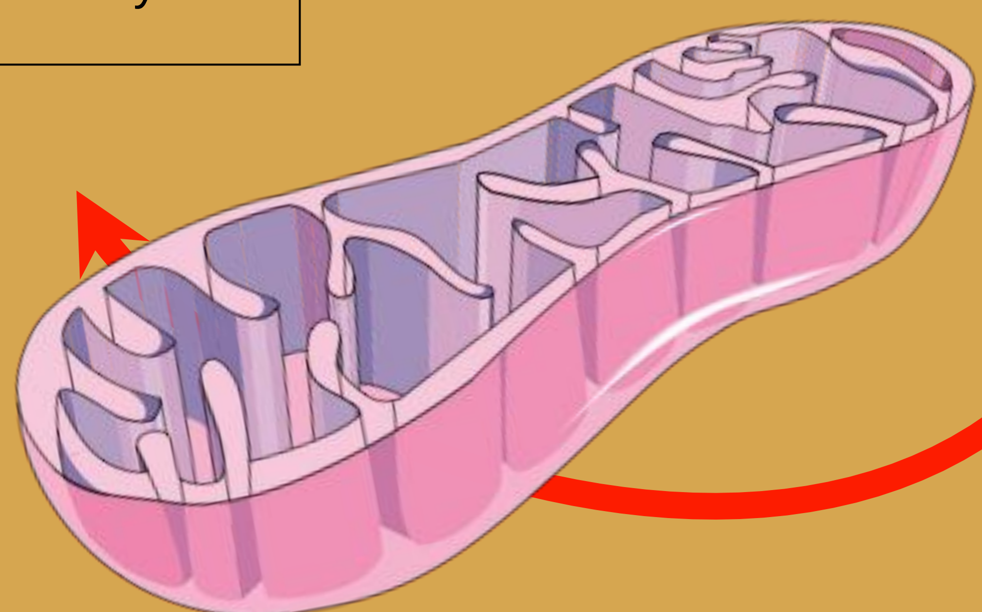
A free phosphate is released from the ATP. This may be reused to regenerate ATP from ADP again.

Adenosine triphosphate ATP

A **high energy** compound able to supply energy for metabolic activity.

Adenosine diphosphate ADP

A **low energy** compound with no available energy to fuel metabolic activity.



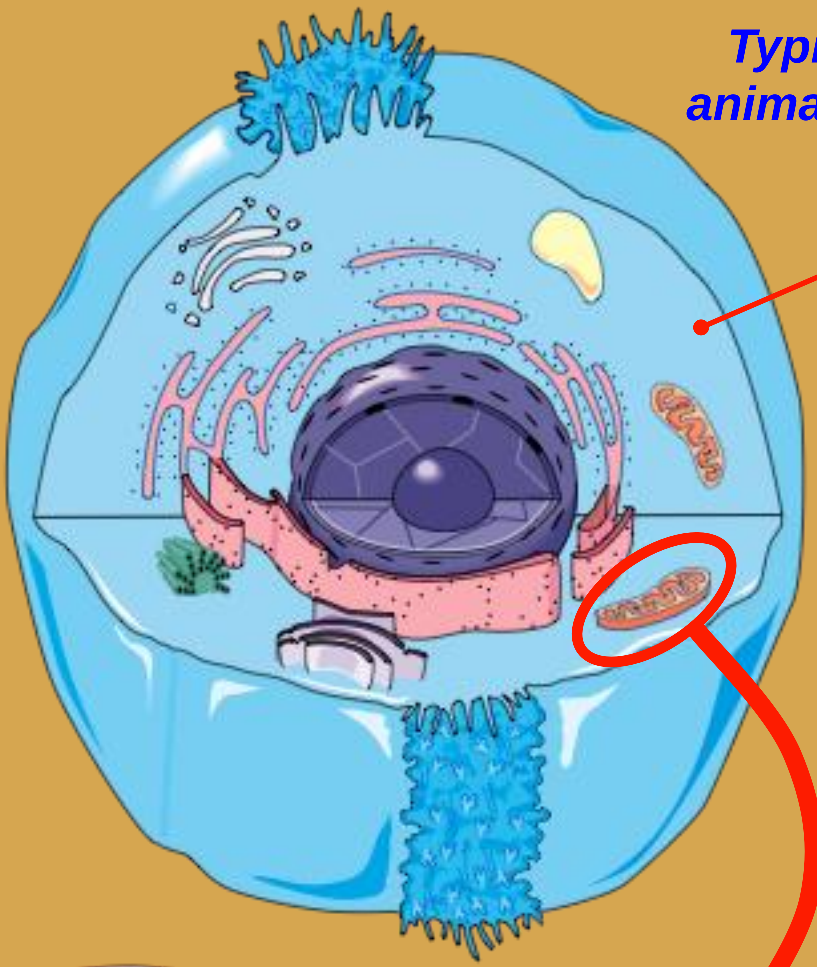
In **cellular respiration**, glucose is oxidized in a step-wise process that provides the energy to make high energy ATP from ADP.

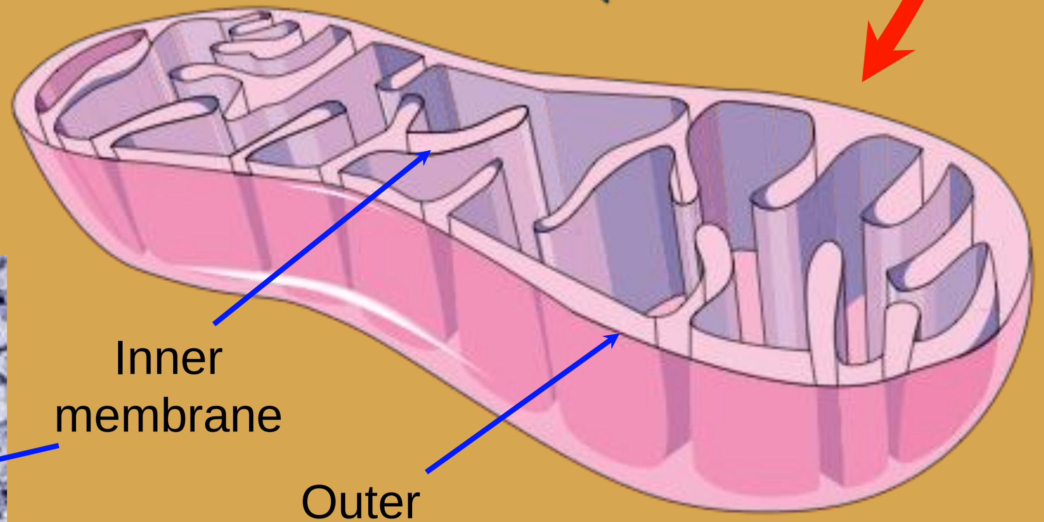
Apart from glycolysis, these processes occur in the mitochondria.

Pi

Cellular Respiration

- **Cellular respiration** is a catabolic, energy-yielding pathway.
  - It is the process by which organisms break down energy rich molecules, such as glucose, releasing energy for the synthesis of ATP.
  - **Aerobic** respiration requires oxygen.
  - Forms of cellular respiration that do not require oxygen are said to be **anaerobic**.





Mitochondrion (false colored) taken by TEM. Magnification x 14,000

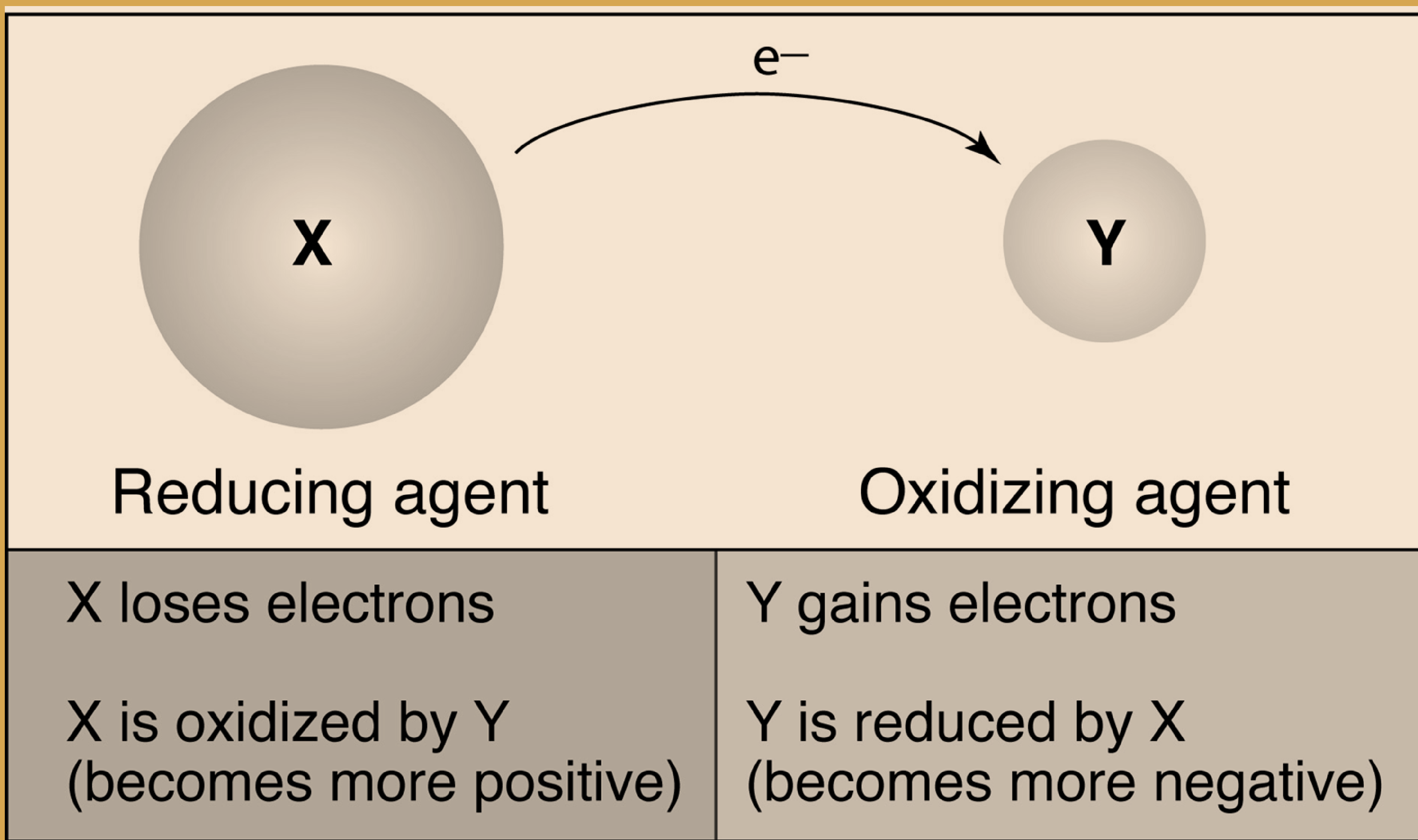
Redox Reactions

- As well as using ATP, cells can transfer energy through the transfer of electrons in what are called oxidation-reduction reactions.
  - **Oxidation** is the chemical process in which a substance loses electrons.
  - **Reduction** is the chemical process in which a substance gains electrons.
  - Because oxidation and reduction reactions occur simulatenously, they are called **redox reactions**.
  - In cells, redox reactions usually involve transfer of a hydrogen atom rather than just an electron.
- In cellular respiration, redox reactions release the energy stored in food moleules so that ATP can synthesized using that energy.

In a fire (**combustion**), fuels are oxidized rapidly to produce water and carbon dioxide.

Rusting is another familiar example of a redox reaction. When iron rusts, the iron (II) loses electrons to form iron(III) oxide.

Redox Reactions



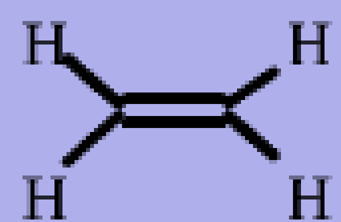
Redox Reactions

Gain of Electrons is *Reduction* **Loss of Electrons is *Oxidation***

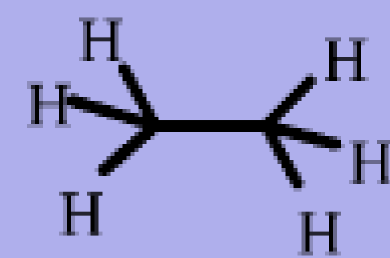
$$M^{3+} \underset{-e^- \text{ is Oxidation}}{\overset{+e^- \text{ is Reduction}}{\rightleftharpoons}} M^{2+}$$

Gain of Hydrogen* is *Reduction* **Loss of Hydrogen* is *Oxidation***

* Or other electropositive element

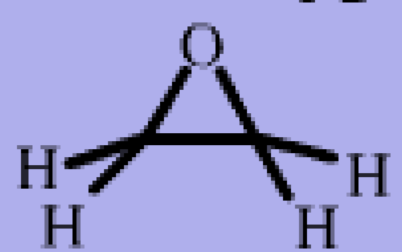


$$\underset{-2H \text{ is Oxidation}}{\overset{+2H \text{ is Reduction}}{\rightleftharpoons}}$$

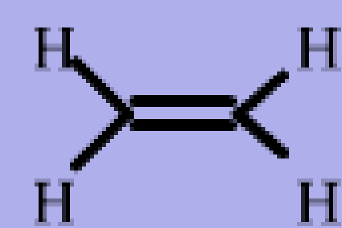


Loss of Oxygen* is *Reduction* **Gain of Oxygen* is *Oxidation***

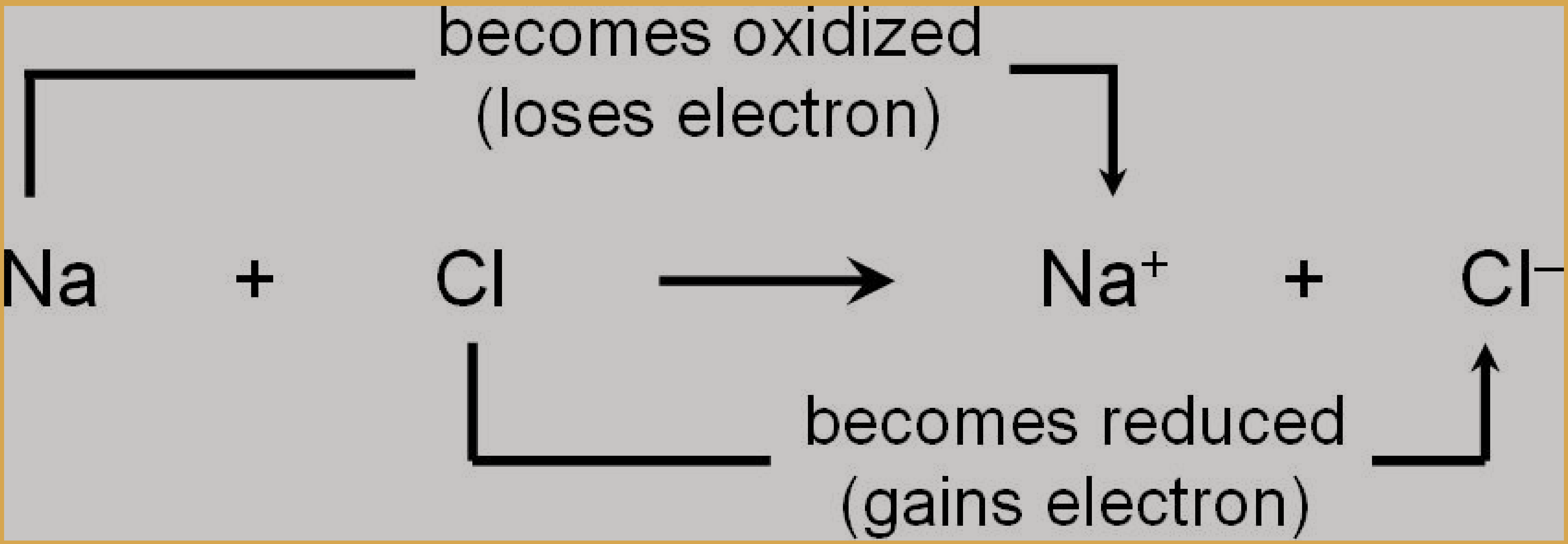
* Or other electronegative element



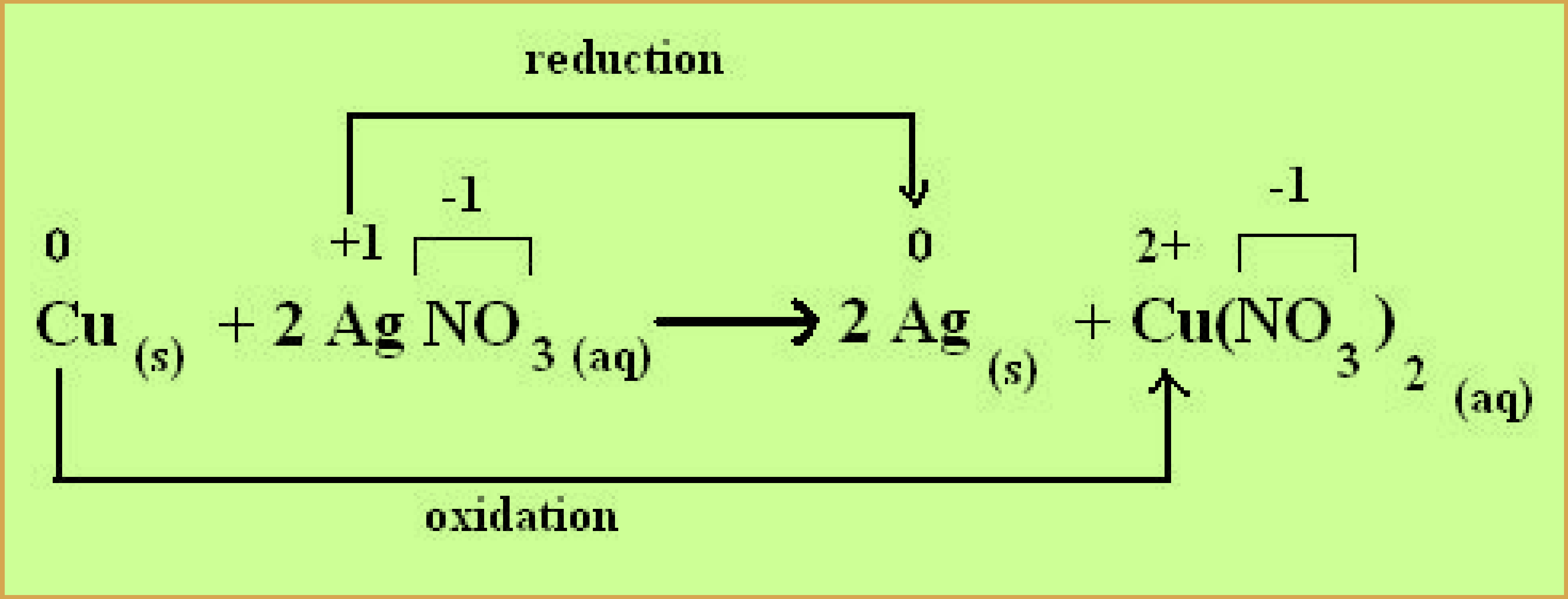
$$\underset{+O \text{ is Oxidation}}{\overset{-O \text{ is Reduction}}{\rightleftharpoons}}$$

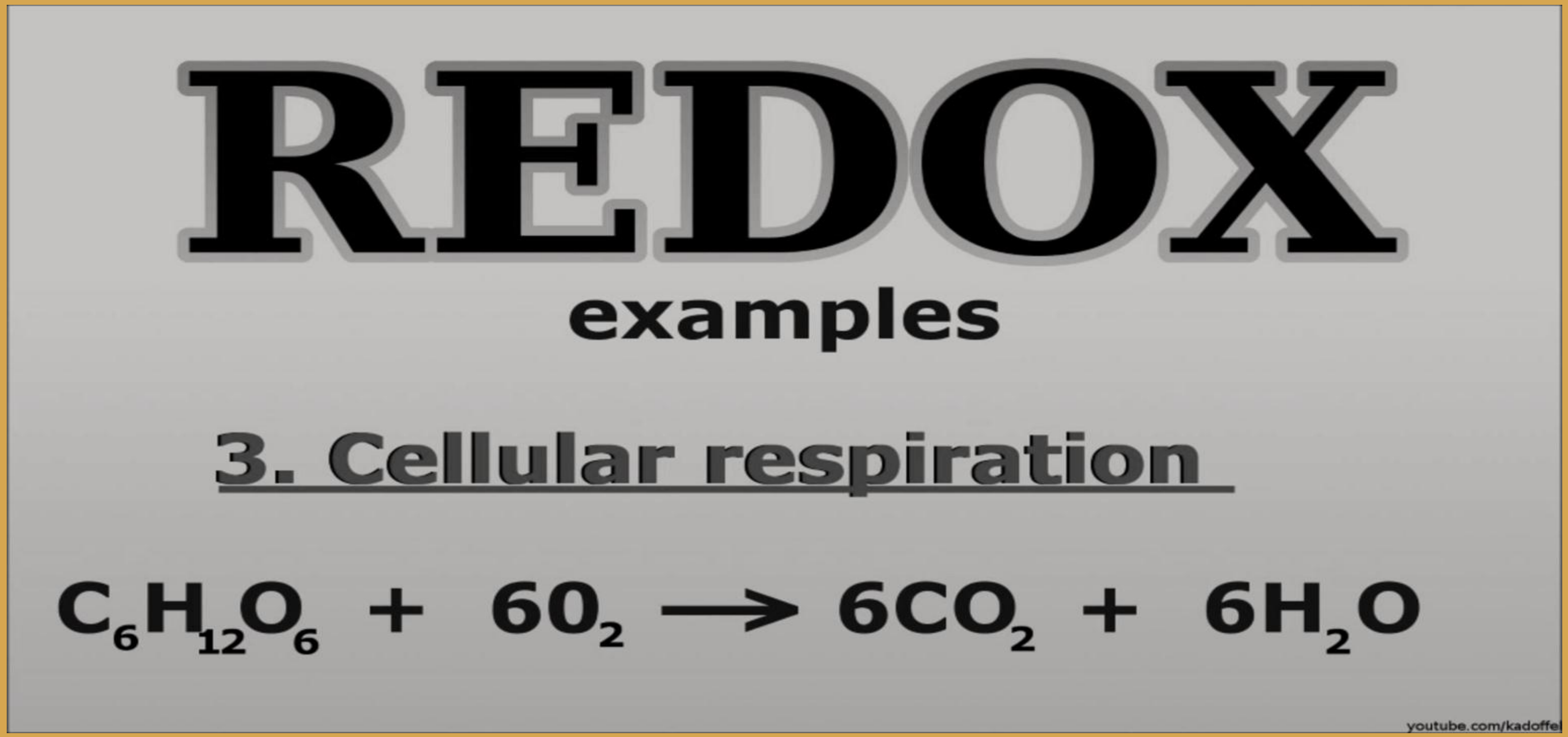


Redox Reactions

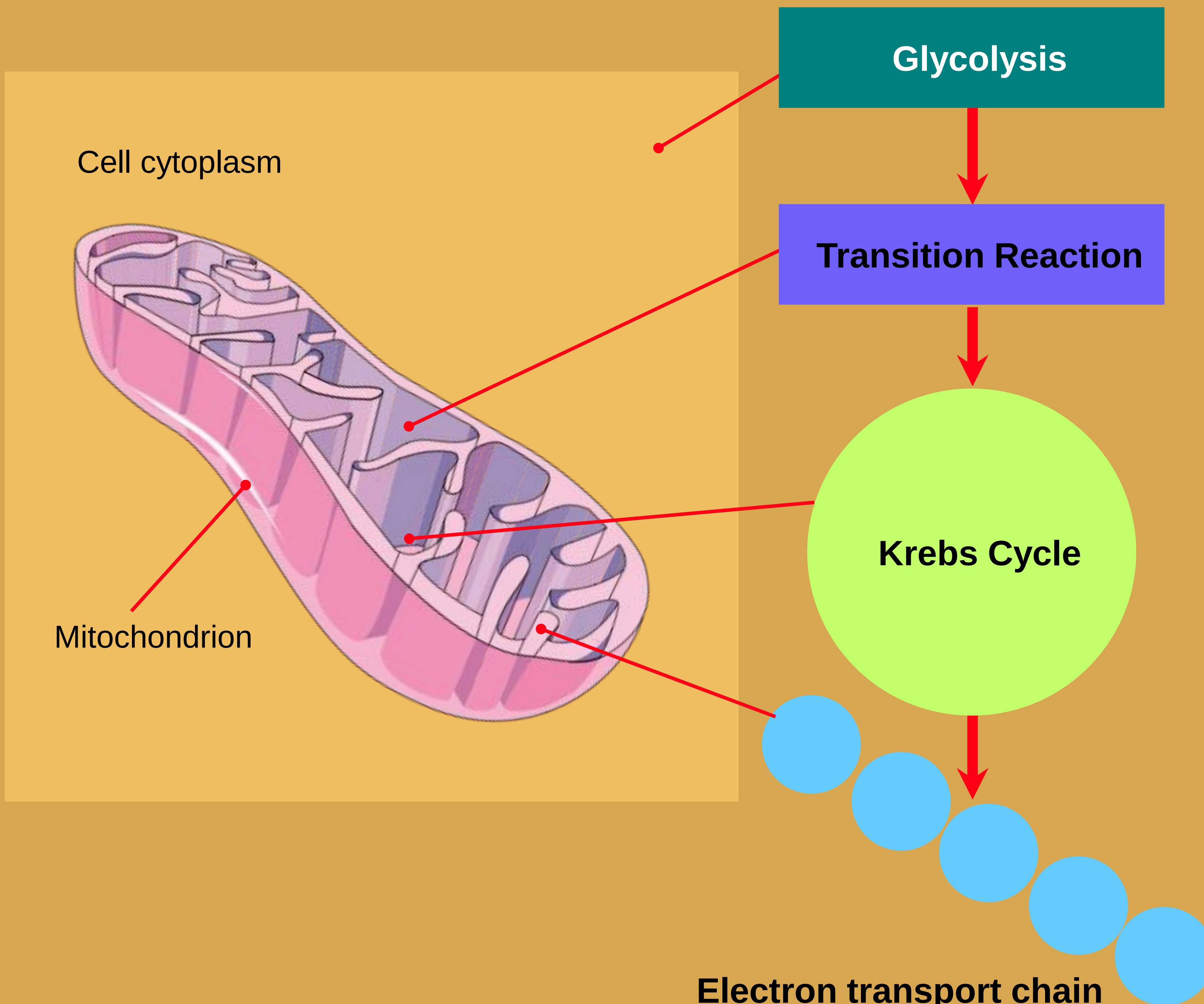


Redox Reactions





A Summary of Aerobic Respiration



Glycolysis
Location: cytoplasm
Process: Glucose is broken down into two molecules of pyruvate.

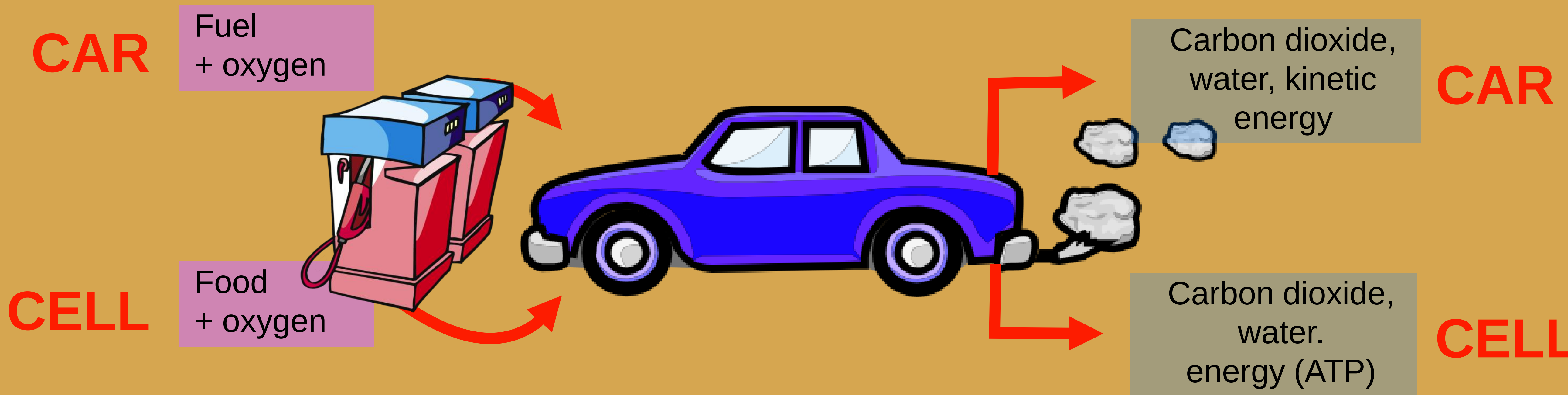
Transition reaction
Location: mitochondrial matrix
Process: Formation of acetyl coenzyme A from pyruvate.

Krebs cycle
Location: mitochondrial matrix
Process: A series of reactions producing carbon dioxide, ATP and hydrogens.

Electron transport chain
Location: mitochondrial cristae
Process: H_2 is oxidised to water using oxygen. Energy is released as ATP.

Cellular Respiration

Cellular respiration can be simplified by comparing it with the combustion reaction required to power a car.

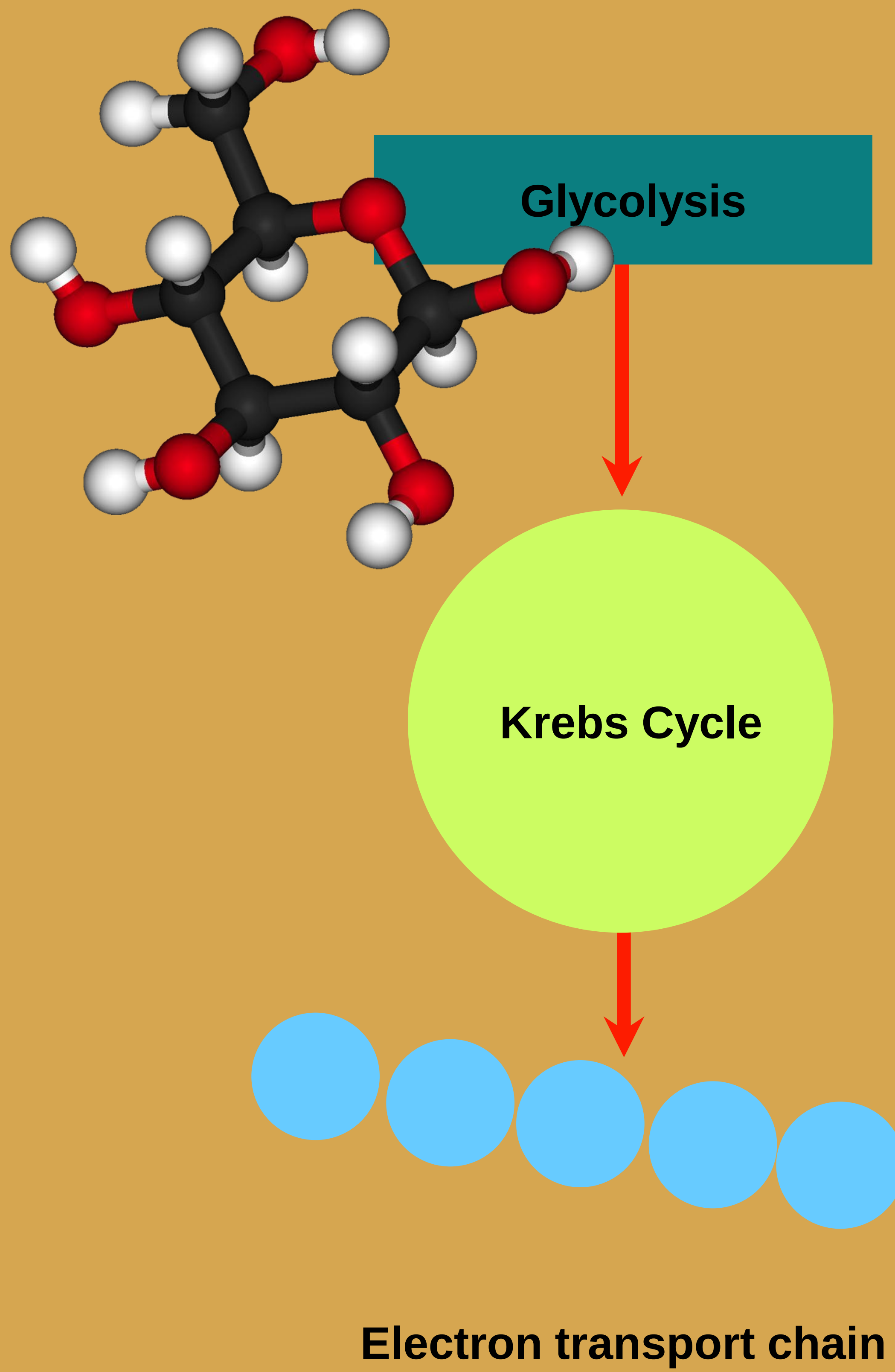


	Car	Cell
Fuel	Petrol, diesel, or gas	**Glucose*** and other carbohydrates, fat, protein
Oxidizer	Oxygen	Oxygen
Location	Engine	Cell cytoplasm and mitochondria
Exhaust products	Carbon dioxide water	Carbon dioxide, water, Energy (ATP)

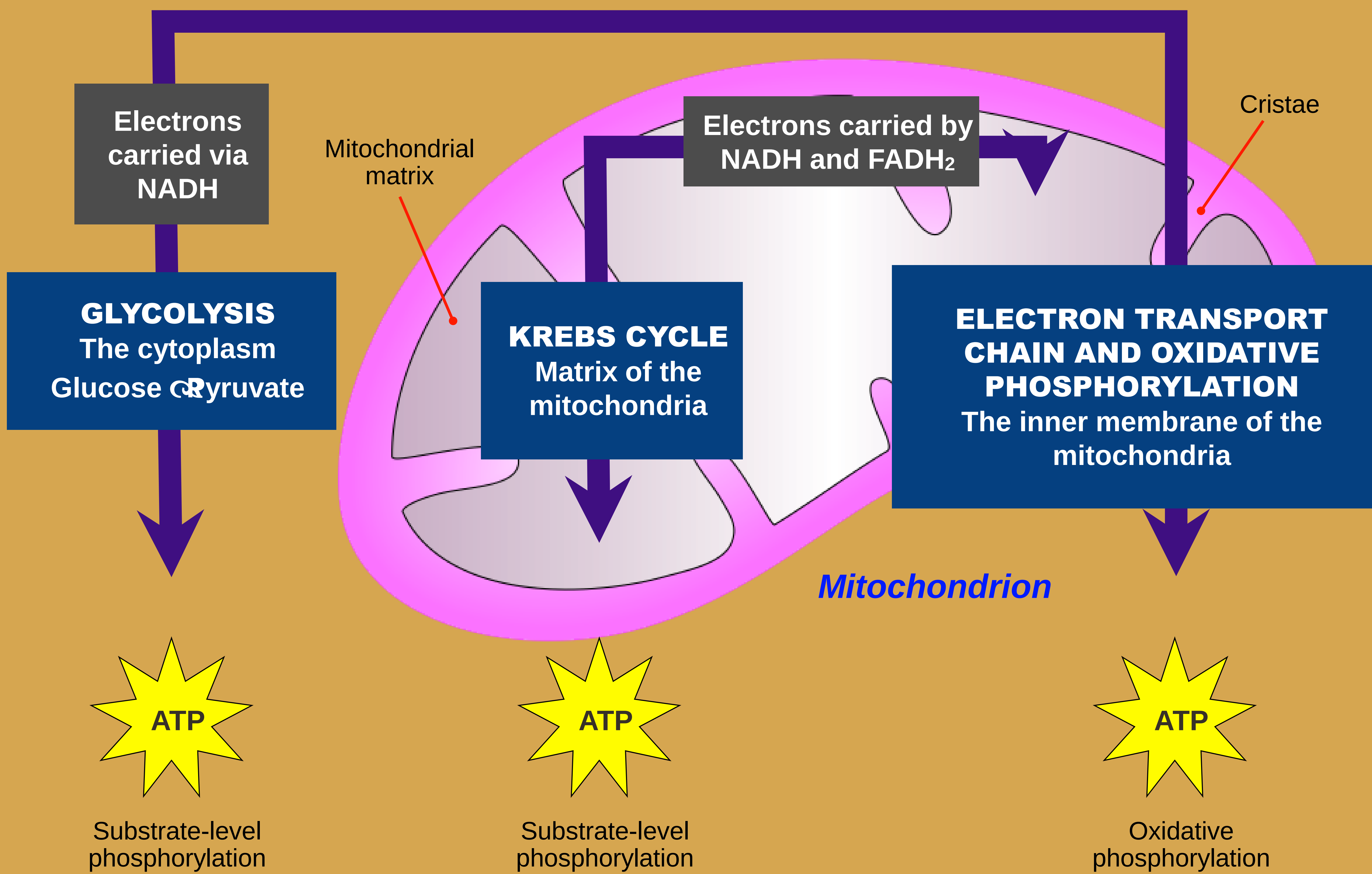
***Glucose** is the major fuel source for cellular respiration

Glucose Metabolism

- The breakdown of glucose and other organic fuels (such as fats and proteins) to simpler molecules is **exergonic**.
  - It releases energy for the synthesis of the high energy molecule, **ATP**.
- **Glycolysis** begins glucose metabolism in all cells. It occurs in the cytoplasm.
- **Aerobic respiration** uses oxygen from the environment to completely convert the products of glycolysis to carbon dioxide through a set of metabolic pathways. These reactions take place in:
  - the mitochondrial matrix (Krebs cycle)
  - the inner membranes of the mitochondrion (electron transfer chain and oxidative phosphorylation)

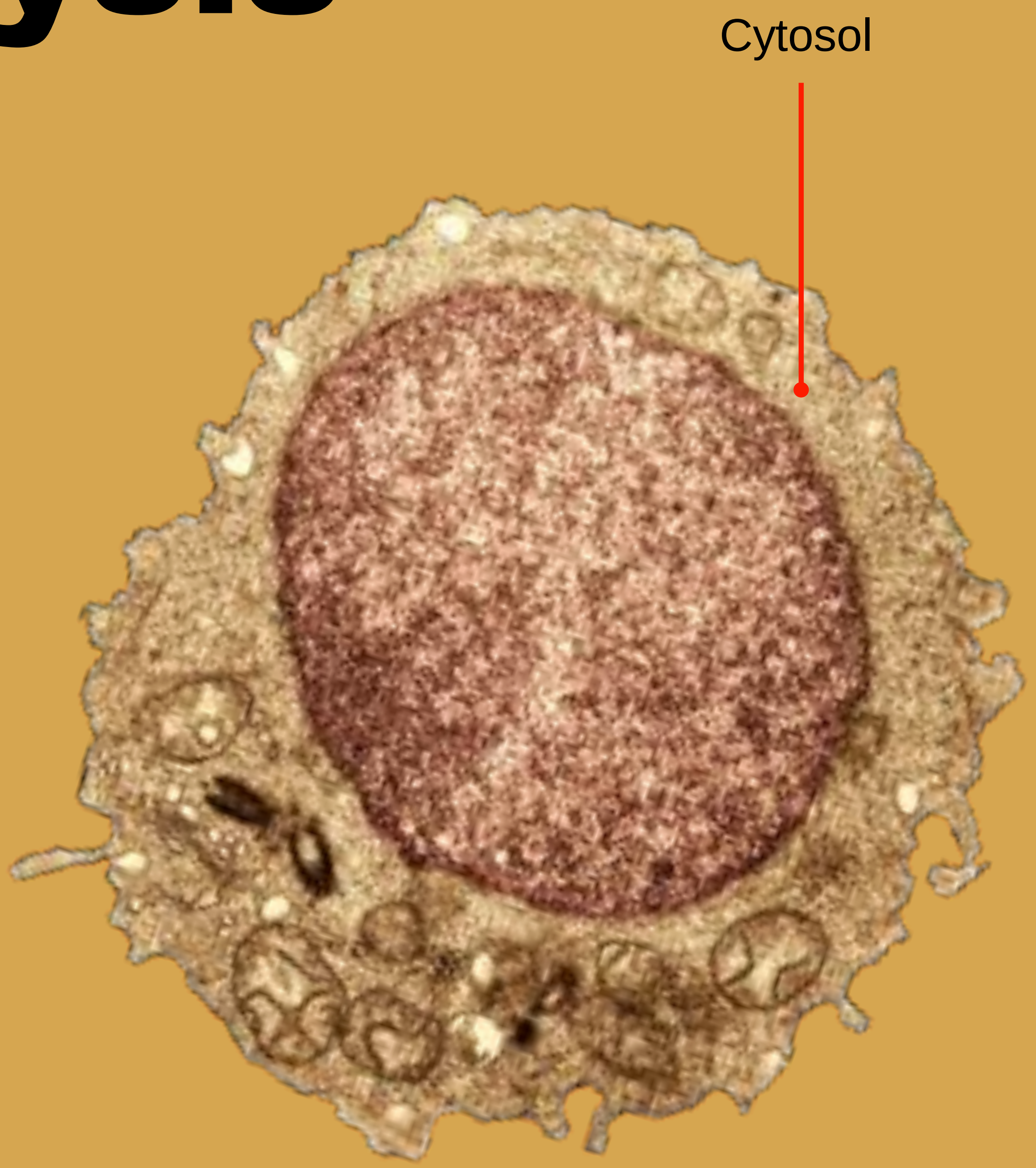


Cellular Respiration



Glycolysis

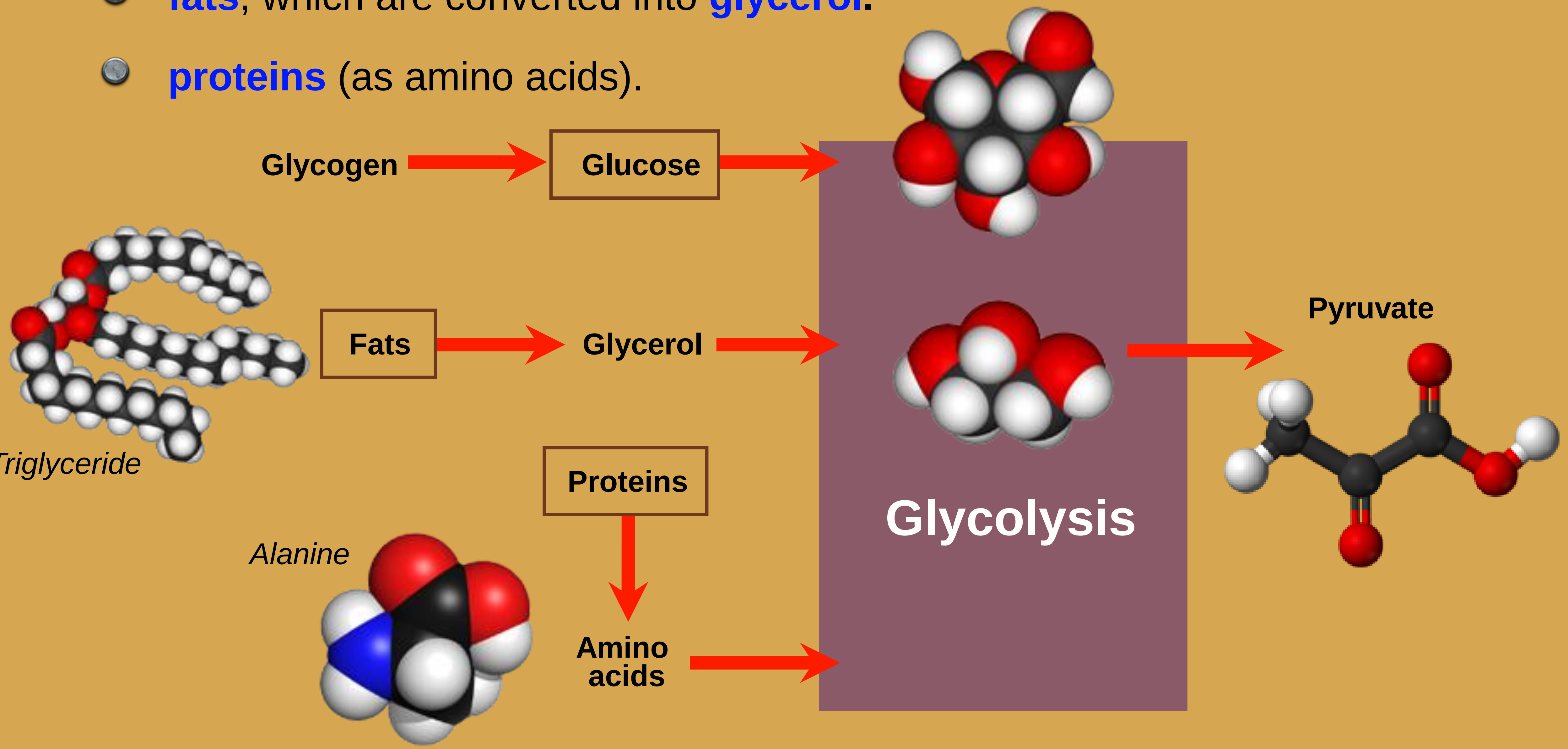
- **Glycolysis** comes from Greek words meaning **sugar splitting**.
- Glycolysis is the first step of cellular respiration. It converts **glucose** into **pyruvate**.
- It occurs in the cell **cytosol**.
- Glycolysis has three main functions:
  - Production of cellular energy sources (ATP and NADH) for anaerobic and aerobic respiration.
  - Production of pyruvate for use in the citric acid cycle.
  - The production of intermediate carbon compounds, which can be removed for other cellular purposes.



This TEM image is of a human lymphocyte cell taken from bone marrow tissue. The **cytosol** is clearly visible around the large central nucleus.
Magnification X 25 710.

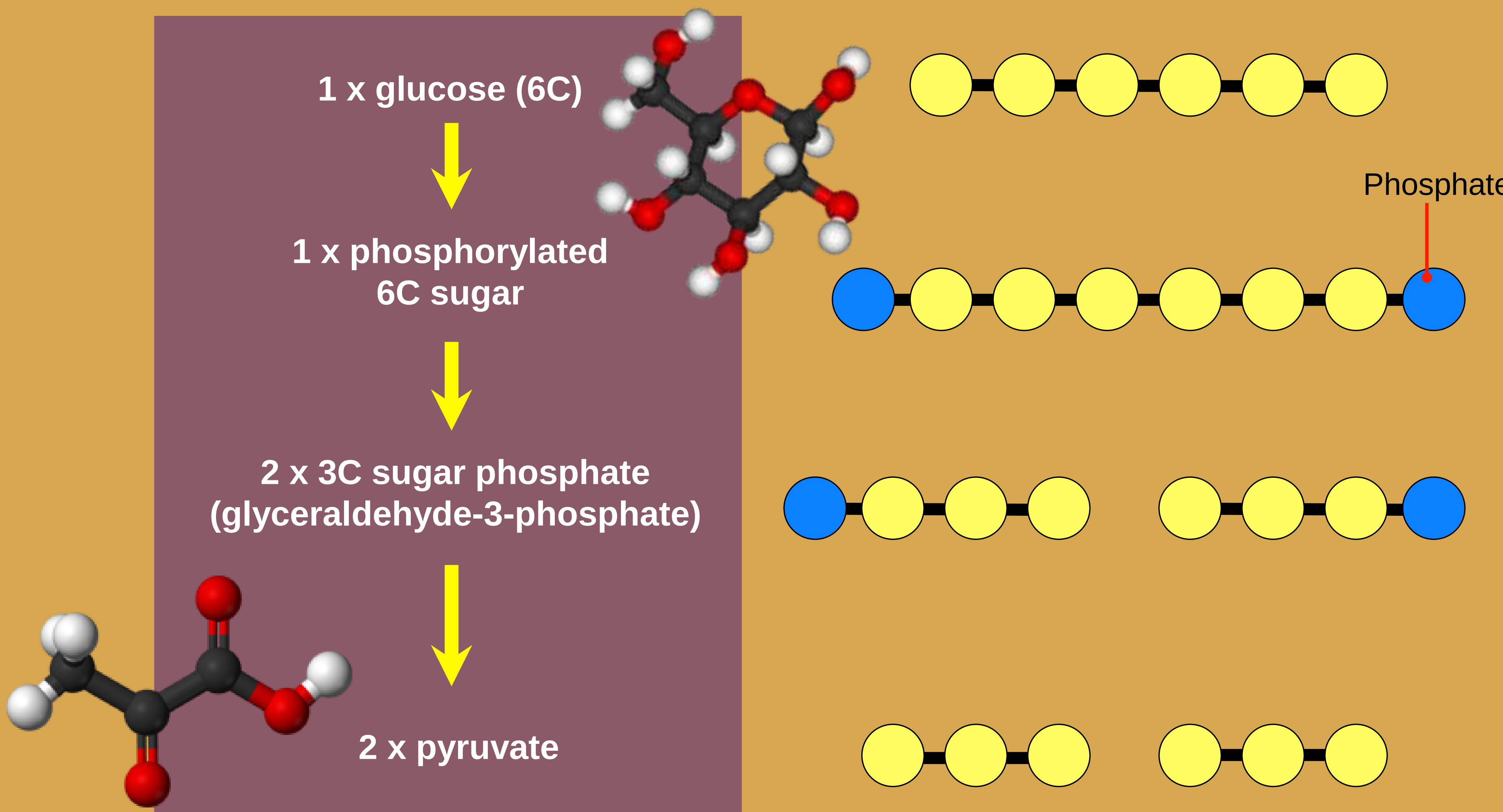
Substrates for Glycolysis

- **Glucose** is the main fuel for glycolysis. **Glycogen** can also be used as a feed substrate, but must first be converted into glucose.
- Other substrates also enter the glycolytic pathway at later phases. These include:
  - **fats**, which are converted into **glycerol**.
  - **proteins** (as amino acids).



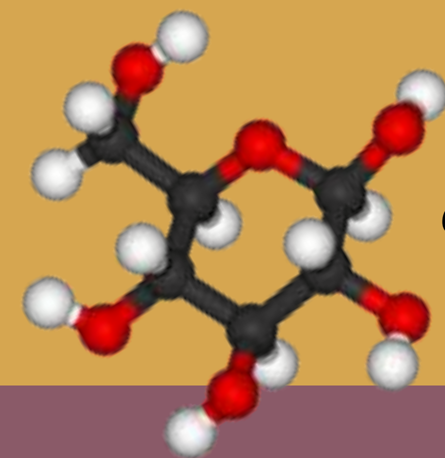
The Glycolysis Process

- During glycolysis, one **glucose** molecule (**6** carbon sugar) is converted into two **pyruvate** (**3** carbon acid) molecules.
- Several intermediate products are produced, which may be utilized at any time in other cellular processes.

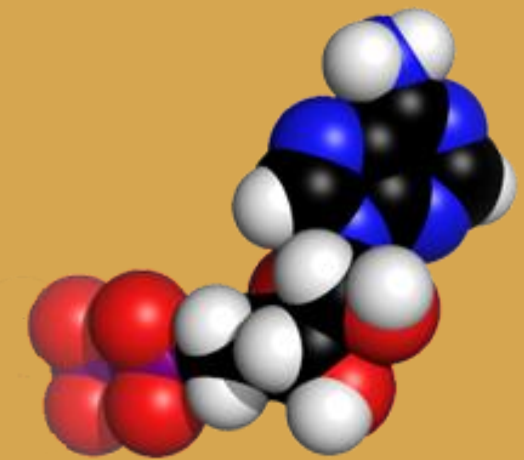


Glycolysis Yield

- For every glucose molecule, glycolysis yields:
  - 2 **ATP** net
  - 2 **NADH + 2H$^+$**
  - 2 **pyruvate** molecules



Glucose



2 ADP + 2P*i*

1 x glucose (6C)

↓

1 x phosphorylated 6C sugar

↓

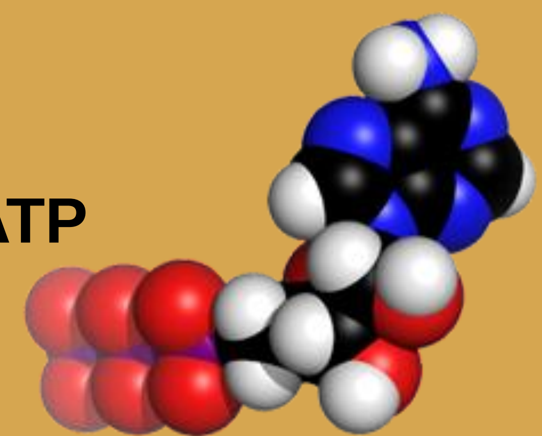
2 x 3C sugar phosphate (glyceraldehyde-3-phosphate)

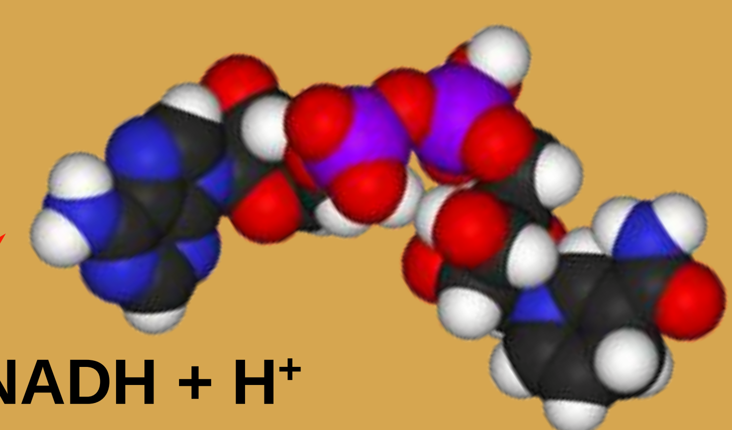
↓

2 x pyruvate

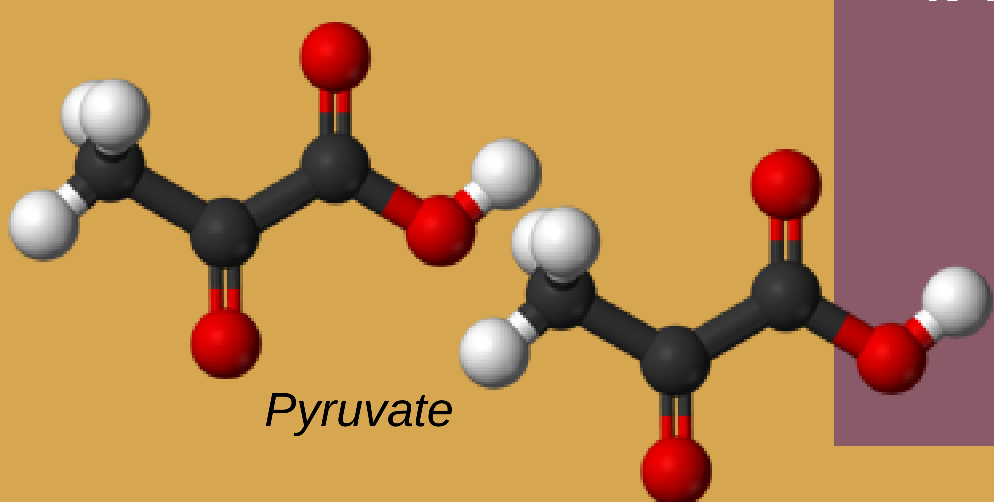
4 ATP are produced but 2 ATP are consumed

2 ATP





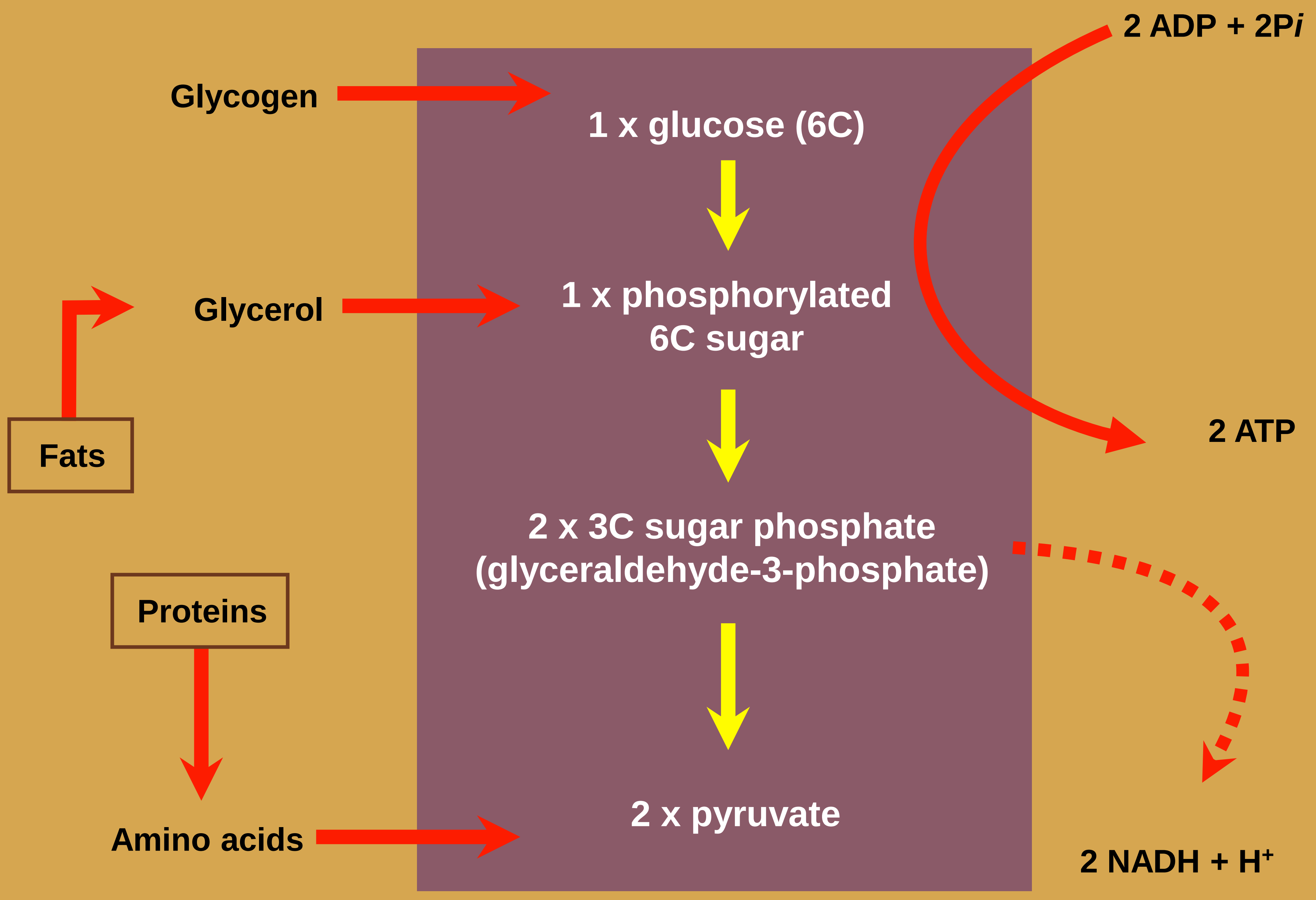
2 NADH + H$^+$



Pyruvate

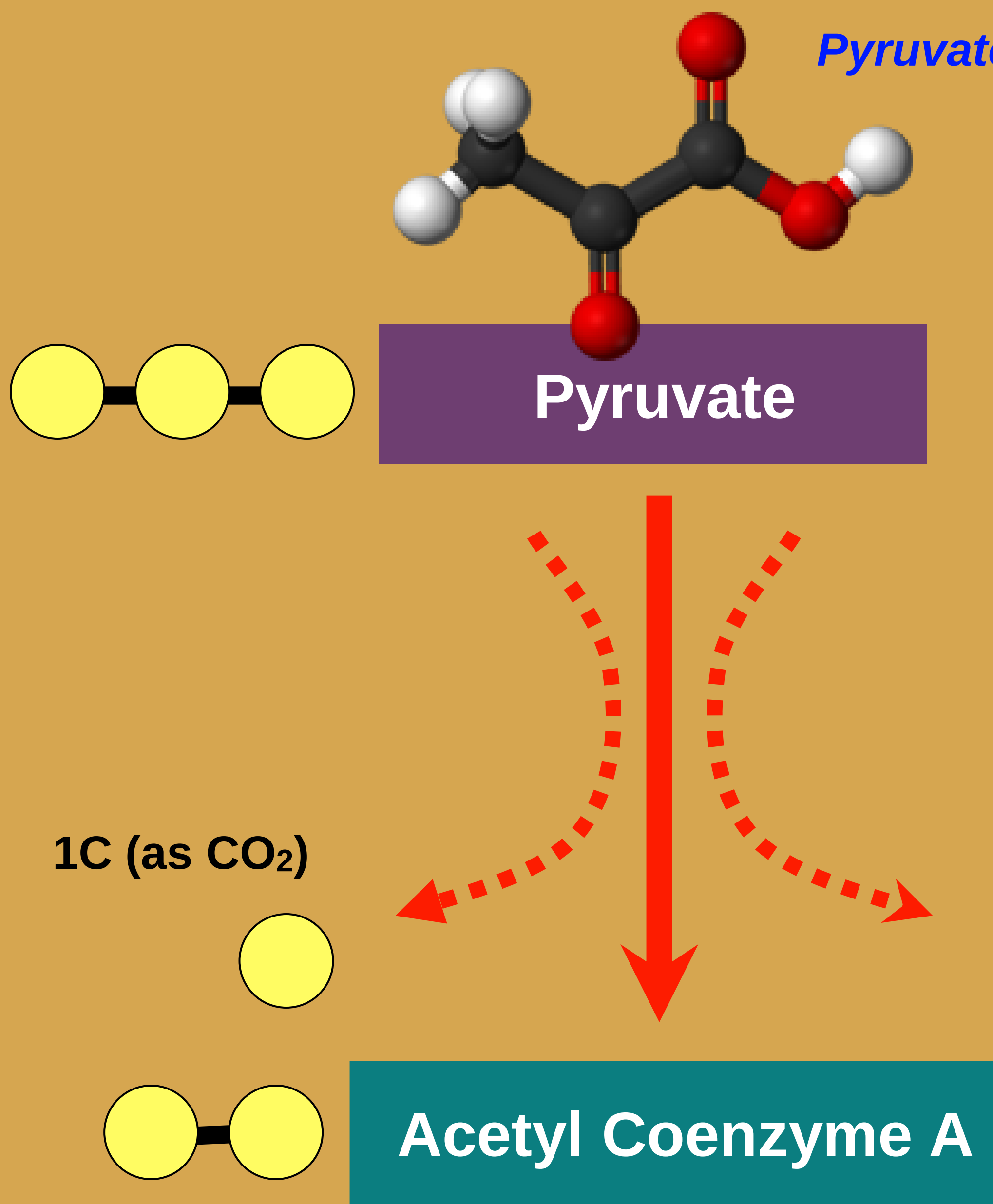
Glycolysis in Review

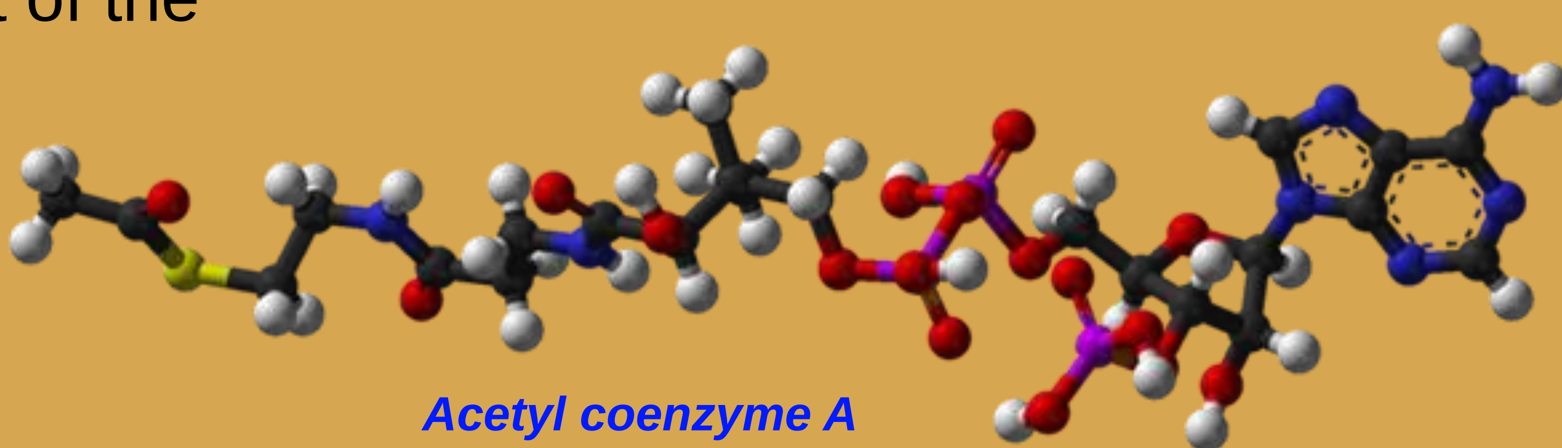
- The diagram below gives an overview of glycolysis.
- The key inputs, outputs and intermediate molecules are given.



Transition Reaction

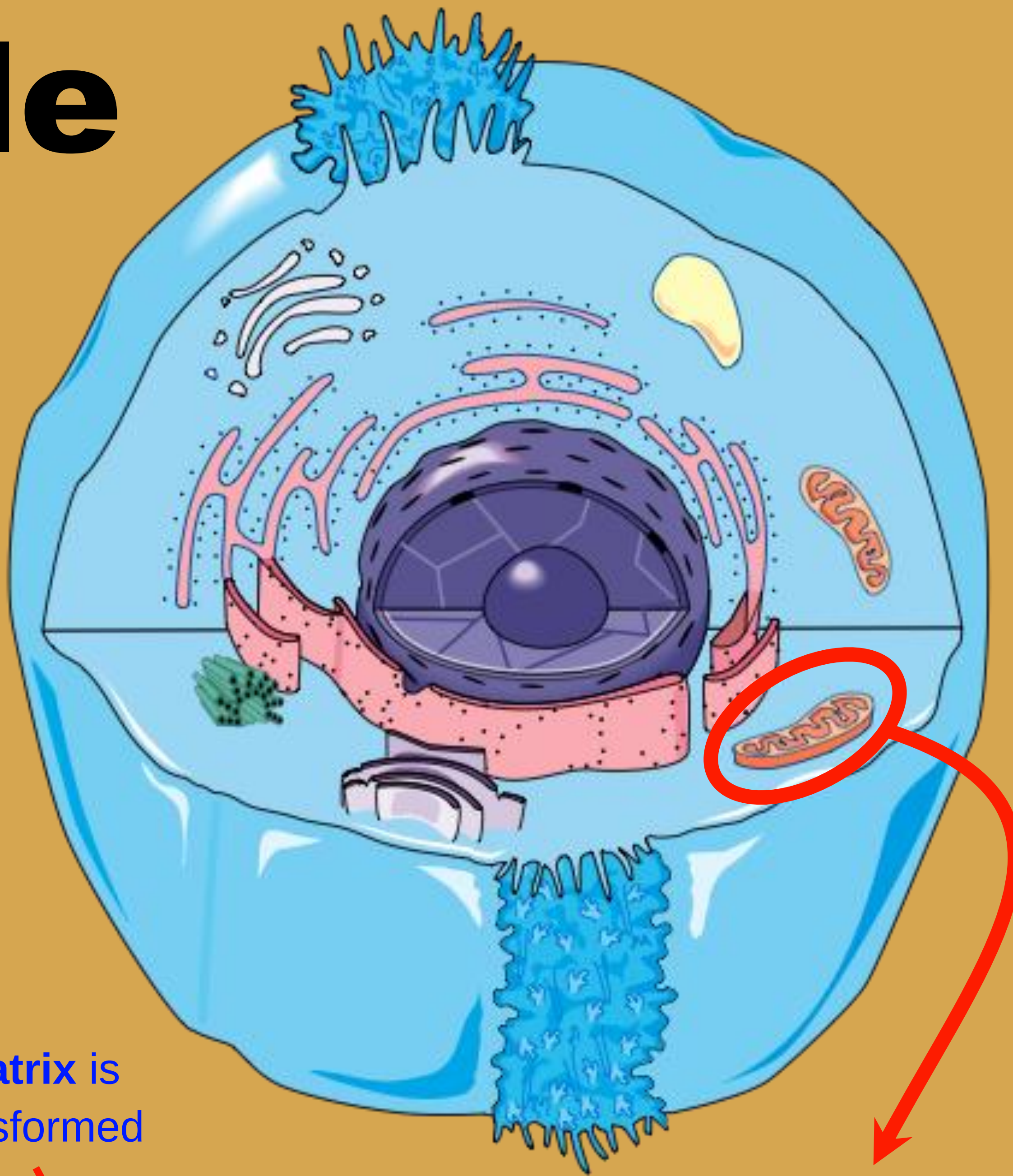
- A **transition reaction** is required to link **glycolysis** to the **Krebs cycle**.
- In the transition reaction, the pyruvate molecules produced as the end product of glycolysis are converted to **acetyl coenzyme A**.
  - This occurs in the **matrix** of the mitochondrion.
  - During the reaction a carbon is removed as carbon dioxide.
- **Coenzyme A** (CoA) picks up the remaining **2-carbon** fragment of the pyruvate to form acetyl coenzyme A (right).





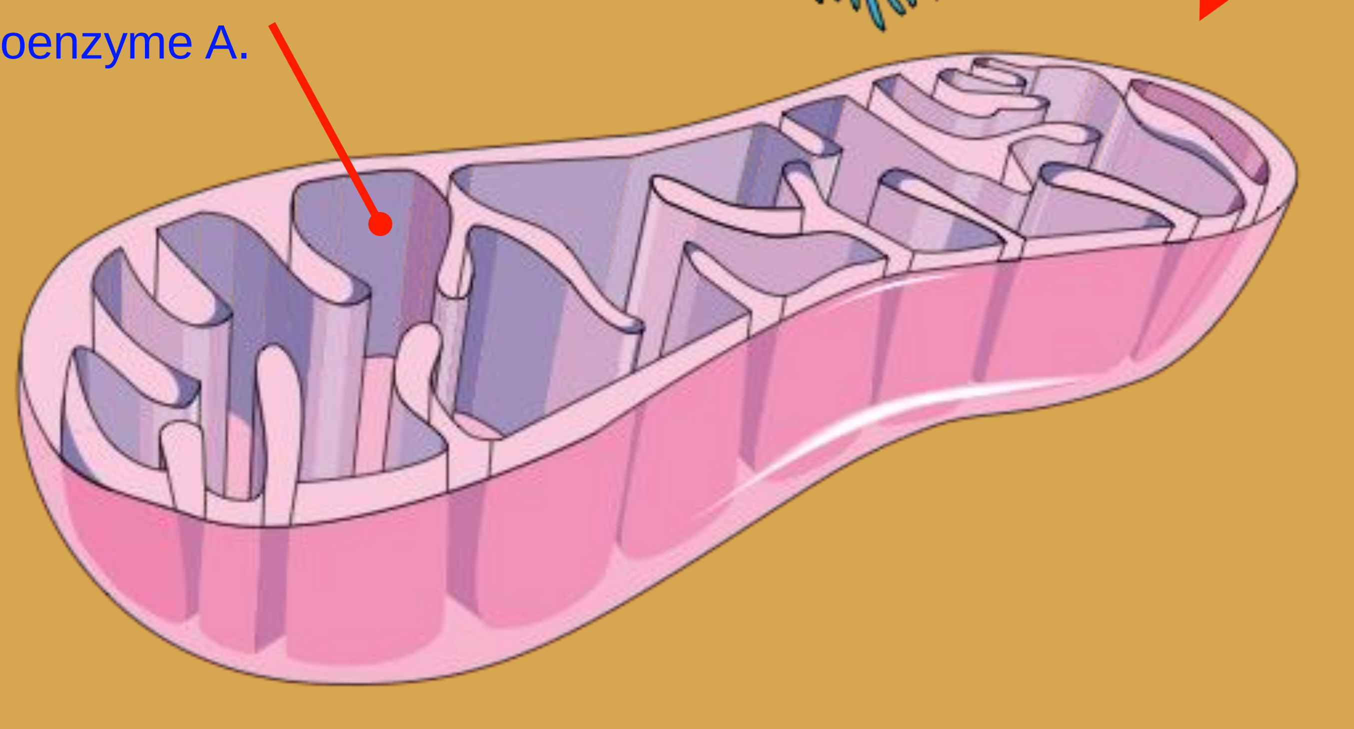
The Krebs Cycle

- The **Krebs cycle** (or citric acid cycle) is the second step in the process of cellular respiration.
- The Krebs cycle occurs in the **matrix** of the mitochondria.



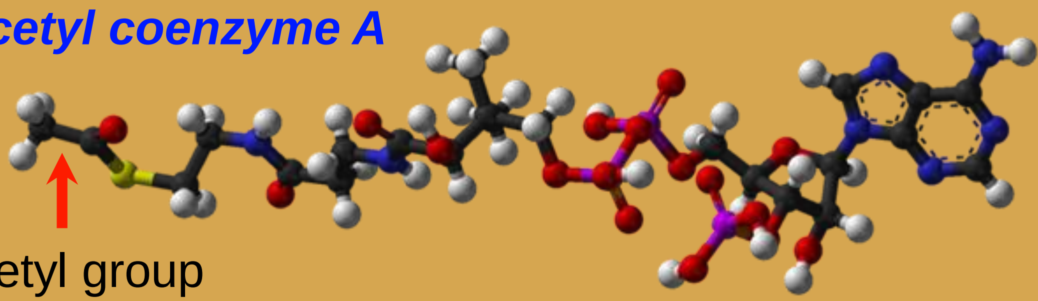
This TEM cross section through a single mitochondrion shows the folded inner membrane and the matrix (arrowed).

The **mitochondrial matrix** is where pyruvate is transformed into acetyl coenzyme A.



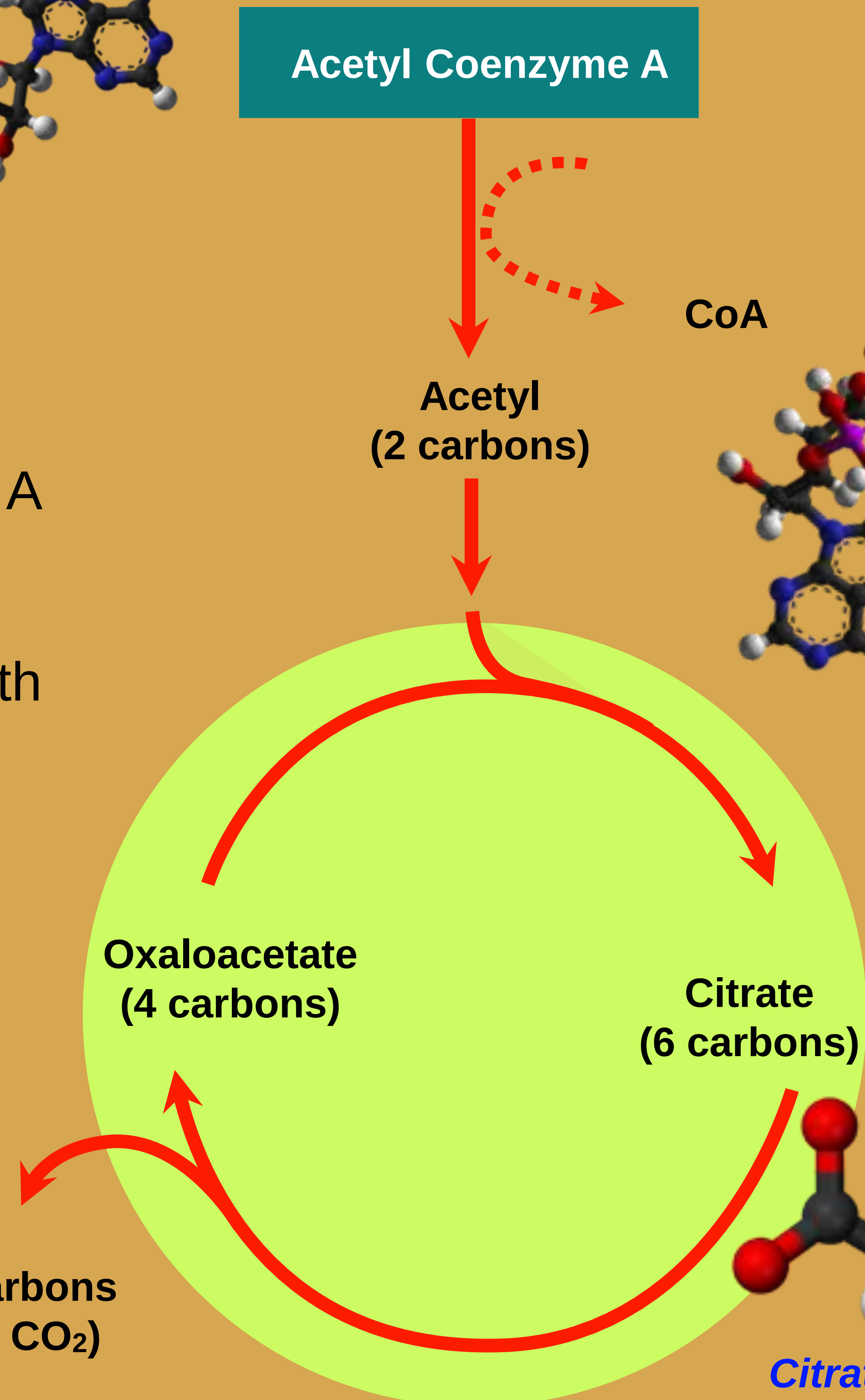
The Krebs Cycle

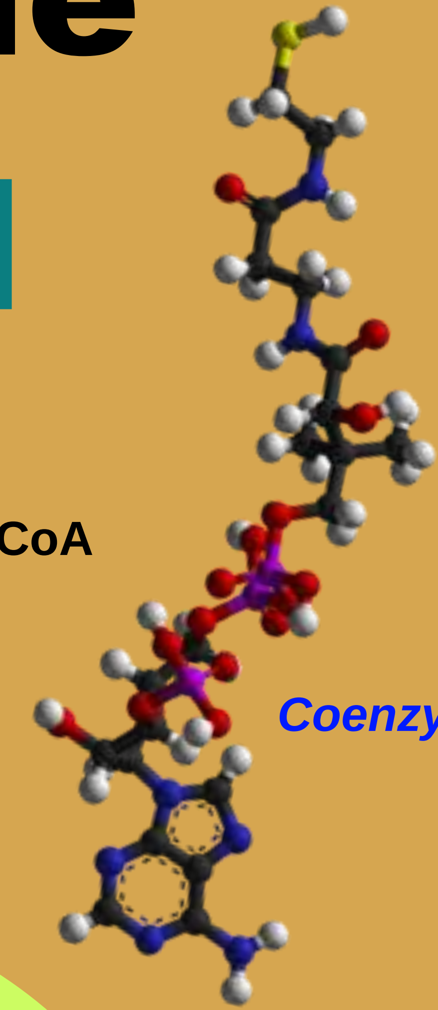
Acetyl coenzyme A



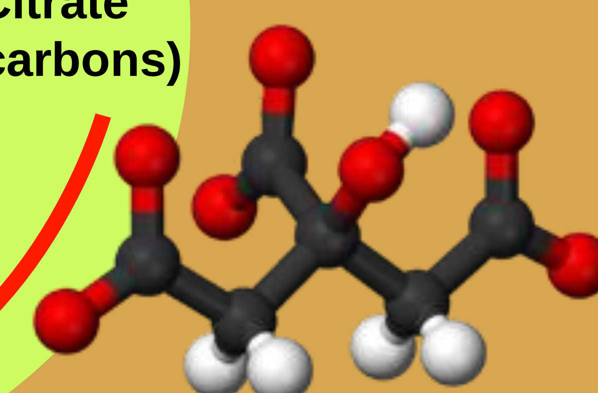
Acetyl group

- **Acetyl coenzyme A** is the feed molecule for the Krebs cycle.
- Acetyl CoA is split releasing the 2-carbon **acetyl** group. Coenzyme A is formed.
- The acetyl compound combines with **oxaloacetate** (a 4 carbon compound) to form citrate (a 6 carbon compound).
- **Oxaloacetate** is regenerated via a number of steps as two carbon groups are subsequently lost as carbon dioxide.

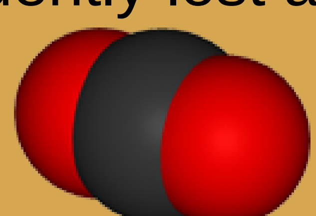




Coenzyme A



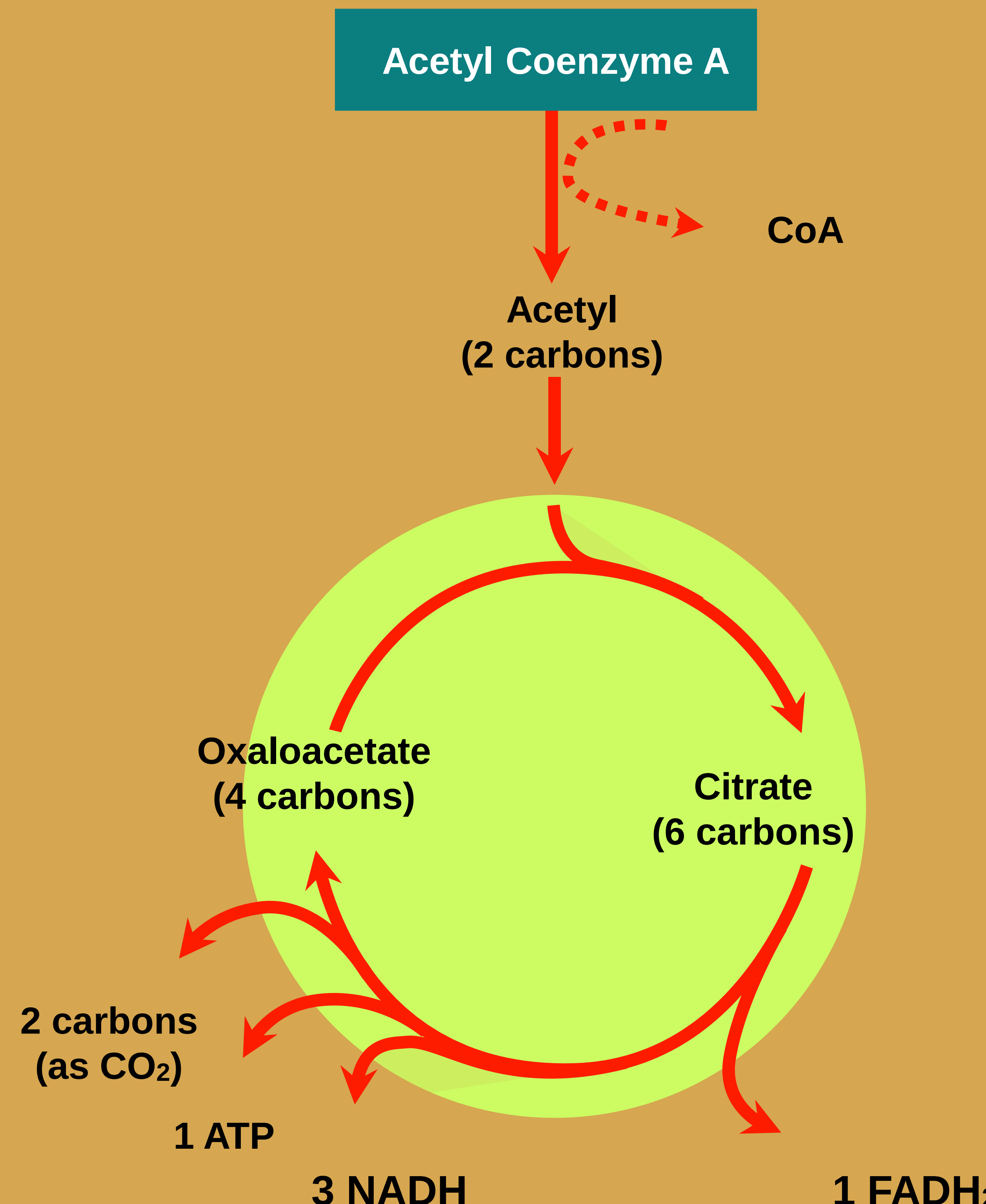
Citrate



Carbon dioxide

The Krebs Cycle Yield

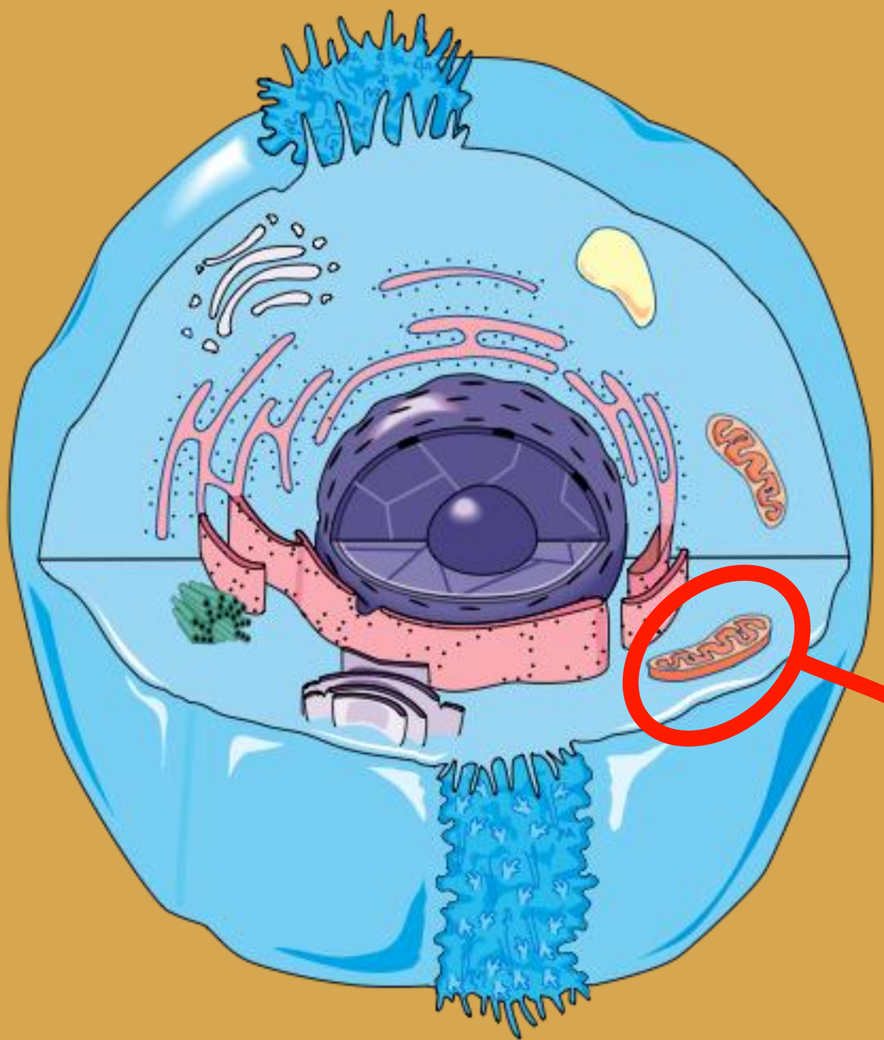
- **Two turns** are required to completely oxidize one glucose molecule.
- Two turns of the Krebs cycle yields:
  - 4 **CO_2**
  - 2 **ATP**
  - 6 **NADH + H^+**
  - 2 **$FADH_2$**
- The Krebs cycle yields a small amount of energy in the form of ATP, but a lot of potential energy in the form of reducing power in **NADH** and **FADH**.
- The energy value from the Krebs cycle is realized when the NADH and $FADH_2$ molecules (which act as electron carriers) are used to generate ATP in the next stage of glucose metabolism.

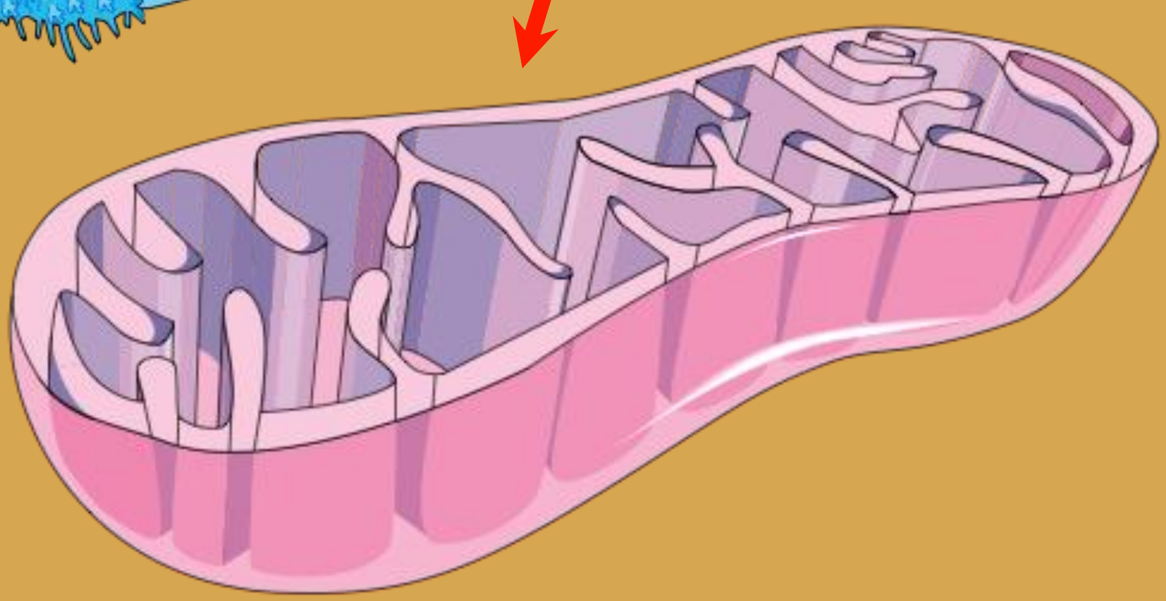


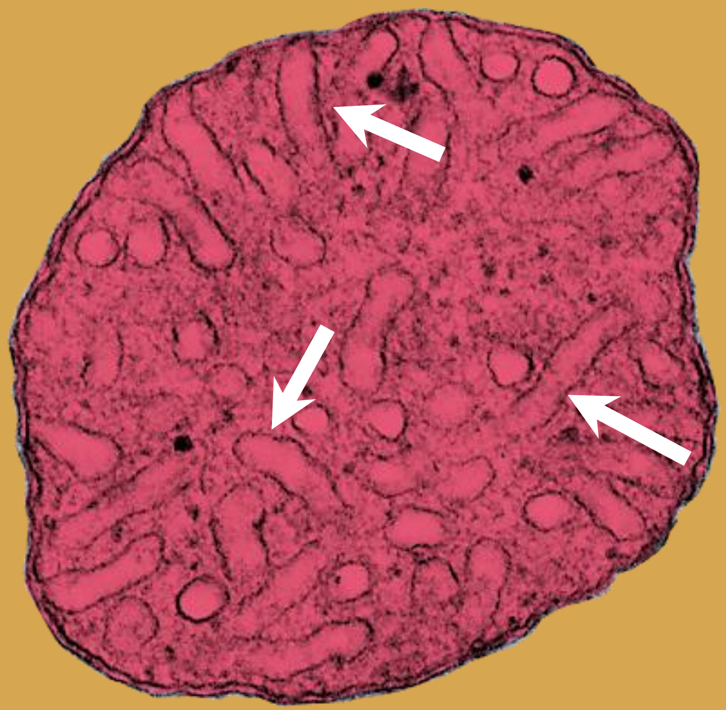
This diagram represents **one turn** of the Krebs cycle. Actual yields are doubled as two turns are required to oxidize glucose completely.

Electron Transport Chain

- The **electron transport chain (ETC)** is the final stage in cellular respiration.
- The electron transport chain is a series of hydrogen and electron carriers, located on the membranes of the mitochondrial **cristae**.
- This final stage involves **oxidative phosphorylation** and ATP generation.



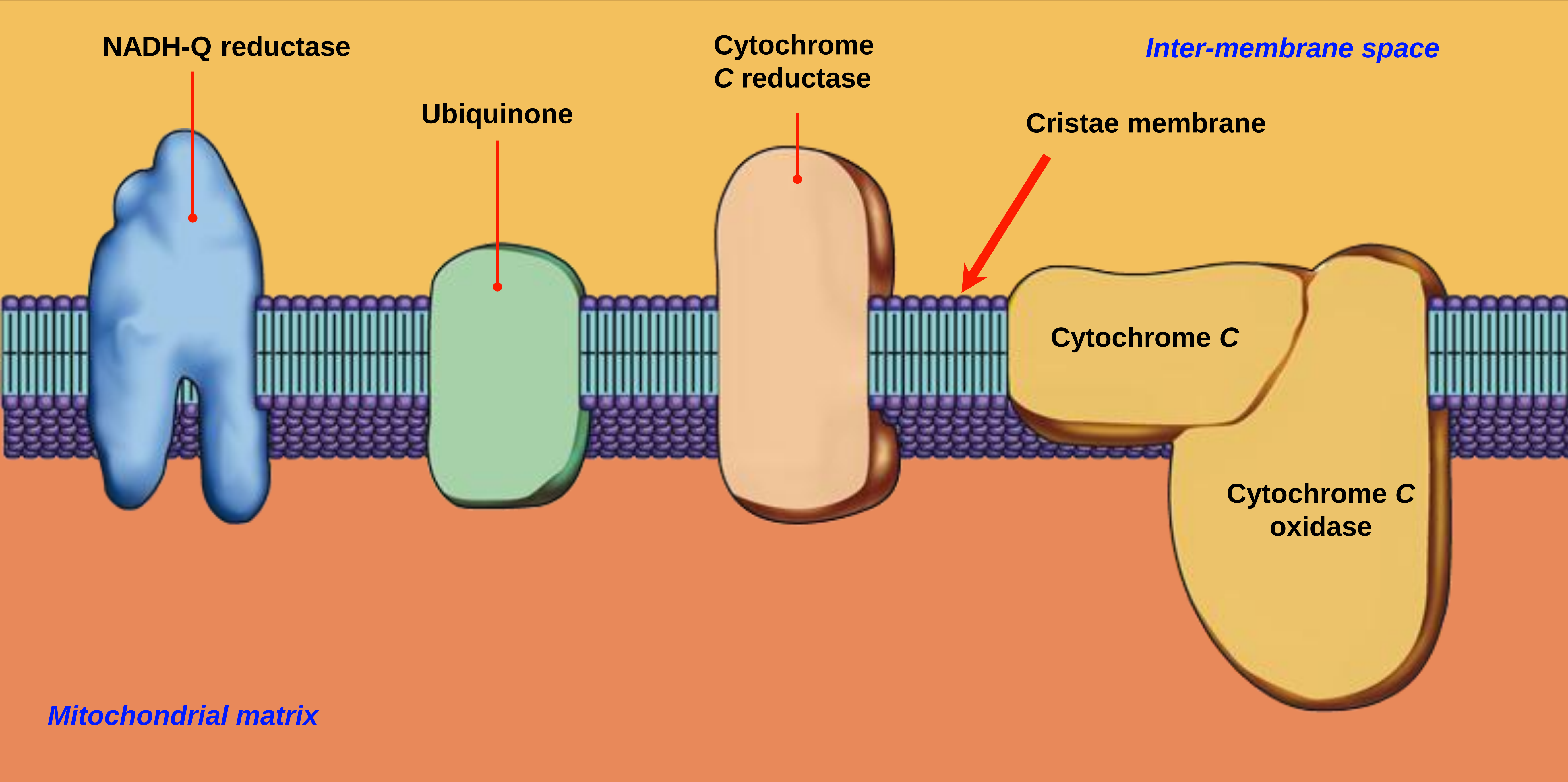




This TEM cross section through a single mitochondrion shows the outer membrane and the inner cristae (arrowed)

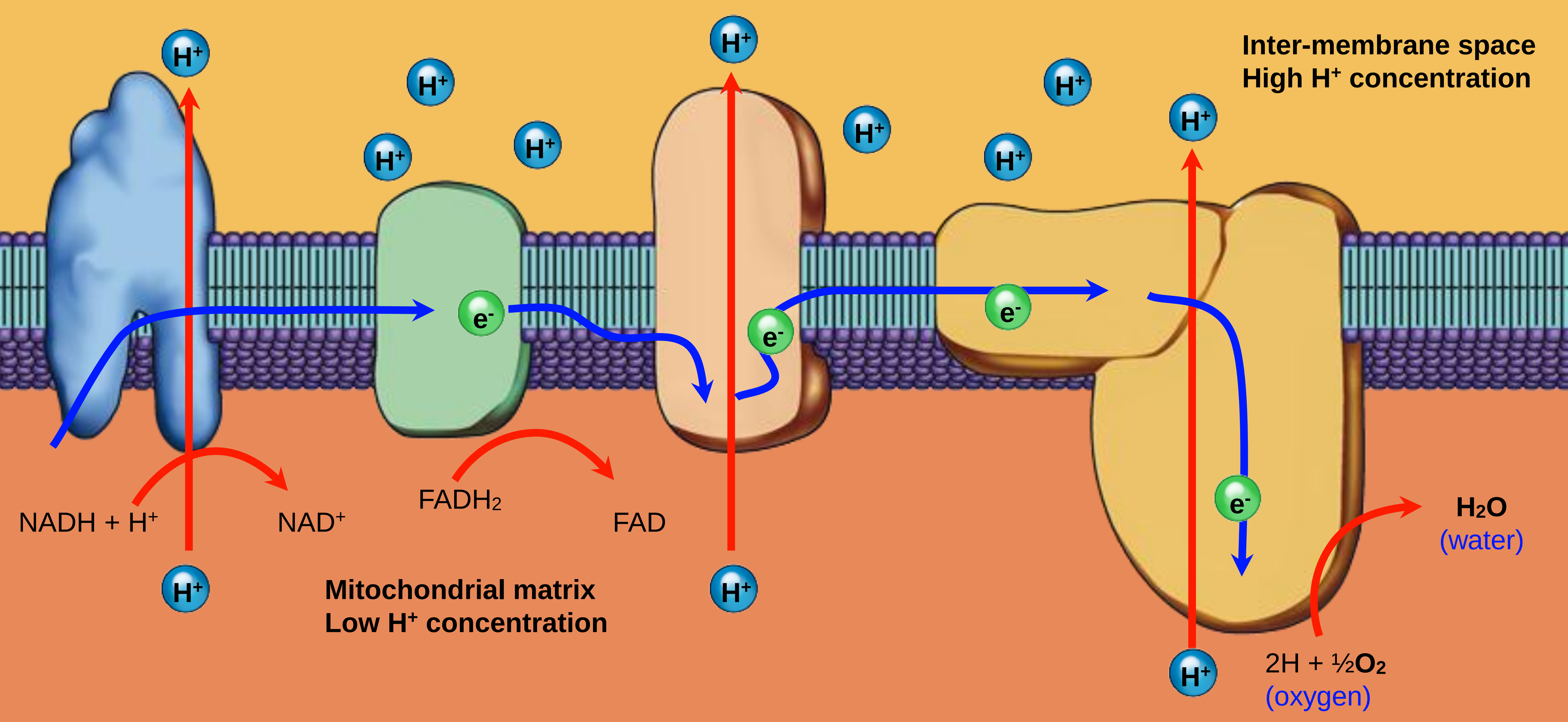
Electron Transport Chain

- The electron transport chain consists of many linked proteins embedded in the **cristae**.
- These proteins are **electron carriers** and alternately *reduced* and *oxidized* as they *accept* and *donate* electrons.



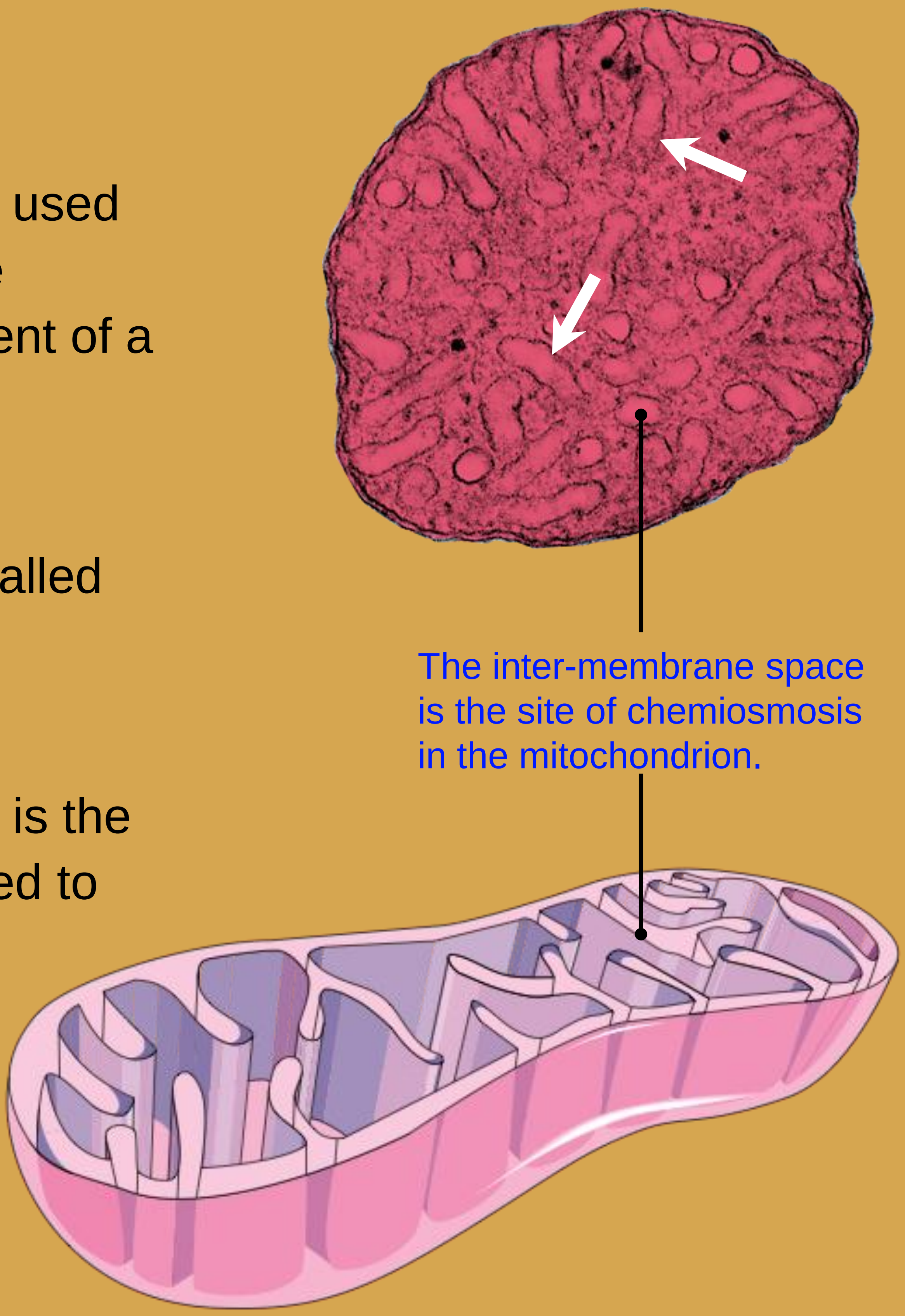
Electron Transport Chain

- Electrons from glycolysis and the Krebs cycle are transported to the electron transport chain as **NADH** and **$FADH_2$**. The hydrogens or electrons donated from NADH and $FADH_2$ are passed from one carrier protein to the next.
  - Oxygen is the final electron acceptor in the chain, and it is reduced to water.
- The electron transport chain yields **34 ATP** and water.



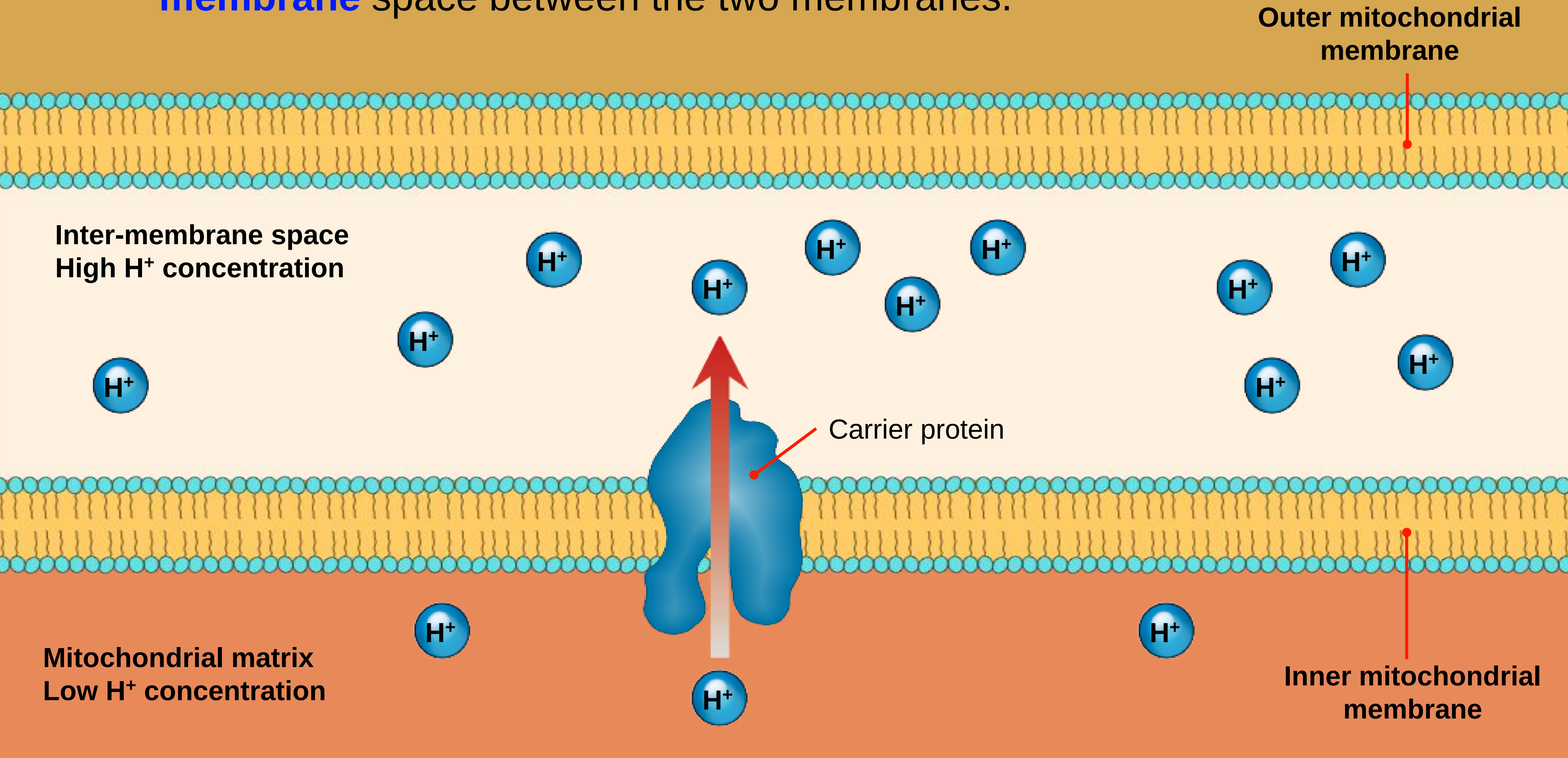
Chemiosmosis

- The energy released from the electrons is used to transport hydrogen ions (H^+) across the membrane. This results in the establishment of a **proton gradient**.
- The proton gradient couples the electron transport to ATP synthesis by a process called **chemiosmosis**.
- Chemiosmosis takes place in the inter-membrane space of the mitochondria and is the process where electron transport is coupled to ATP synthesis.



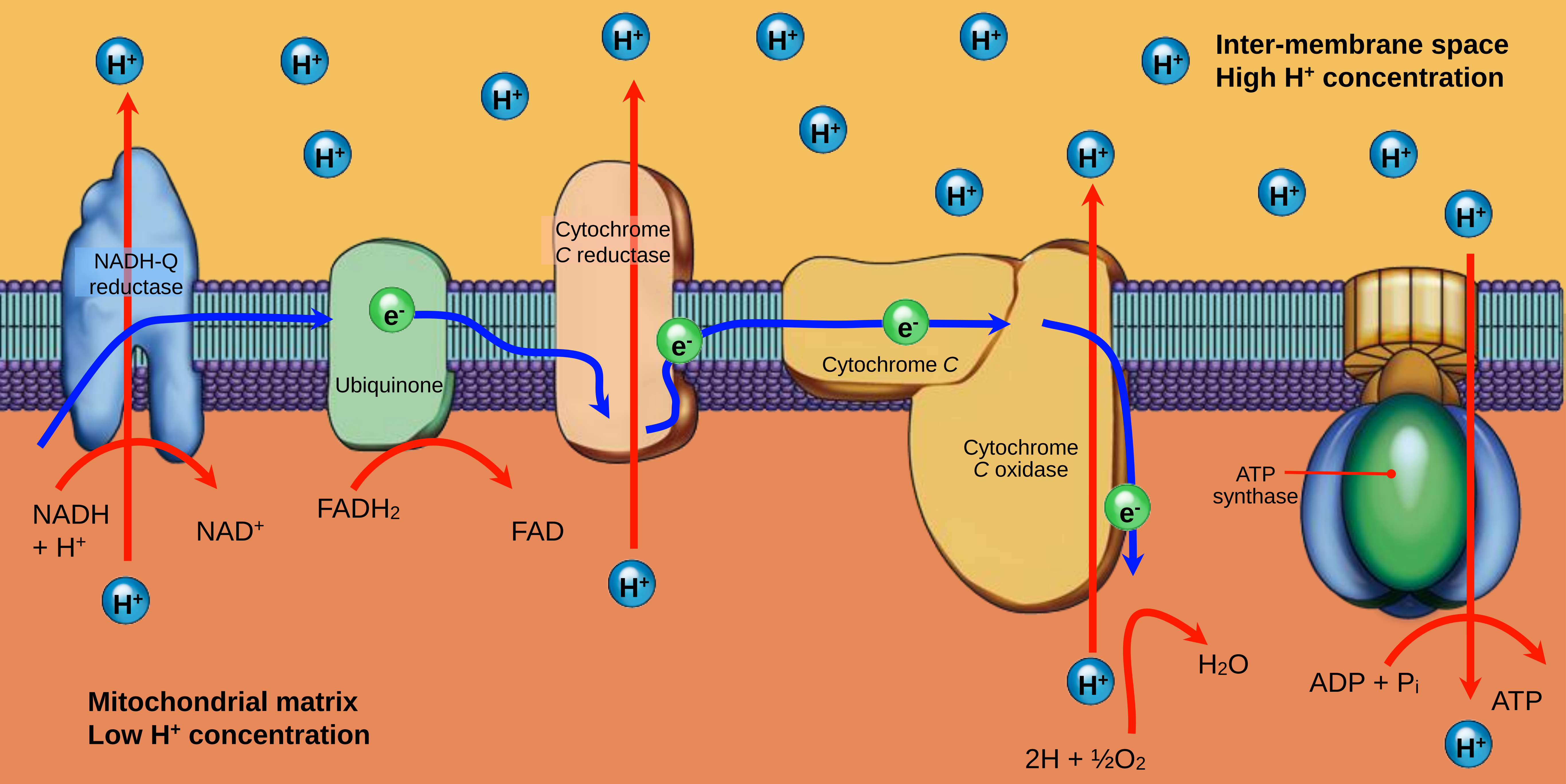
Chemiosmosis

- Energy from the oxidation of NADH + H^+ and $FADH_2$ (in the electron transport chain) is used to move protons **against** their concentration gradient (from a low H^+ concentration to a high H^+ concentration).
- The protons move from the **mitochondrial matrix** into the **inter-membrane** space between the two membranes.



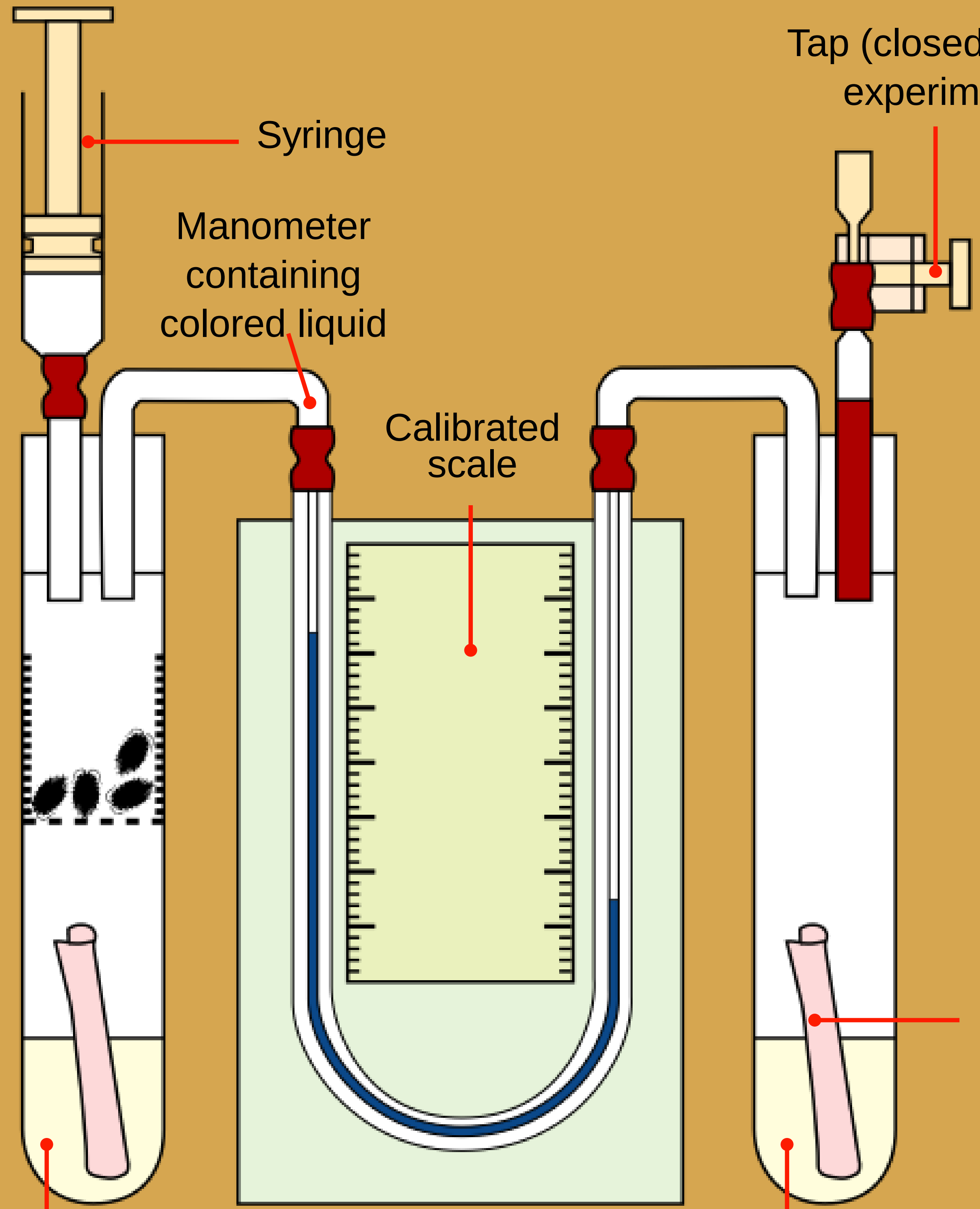
Chemiosmosis

- The protons flow back down their concentration gradient via an enzyme called **ATP synthase**. This molecule uses the energy released from the H^+ flow to produce **ATP**.
- This coupling of H^+ production to ATP production is shown below.



Respiration Quotient

- In small animals or germinating seeds, the rate of cellular respiration can be measured using a simple **respirometer**.
  - A respirometer is a **sealed unit**.
  - Carbon dioxide (CO_2) produced by the respiring tissues is absorbed by **soda lime**.
  - The volume of oxygen consumed is detected by fluid displacement in a **manometer**.



In this simple **respirometer**, small invertebrates are contained in a perforated gauze basket and the volume of oxygen consumed is measured by fluid displacement in the manometer.

Respiratory Quotient

- The **respiration quotient (RQ)** can be used as an indication of the **primary fuel source** for cellular respiration and metabolism, for example, fat or carbohydrate.
- The respiratory quotient (RQ) is the simple ratio of the amount of CO_2 produced during cellular respiration to the amount of oxygen consumed:

$$RQ = \frac{CO_2 \text{ produced}}{O_2 \text{ consumed}}$$

- Different substrates produce typical RQ values when respired (table right):
  - The oxidation of pure carbohydrate produces an RQ of 1.0.
  - Organisms usually respire a mix of substrates (RQ values of 0.8-0.9).

RQ	Substrate
>1.0	Carbohydrate with some anaerobic metabolism
1.0	Carbohydrates, e.g. glucose
0.9	Protein
0.7	Fat
0.5	Fat with associated carbohydrate synthesis
0.3	Carbohydrate with associated organic acid synthesis

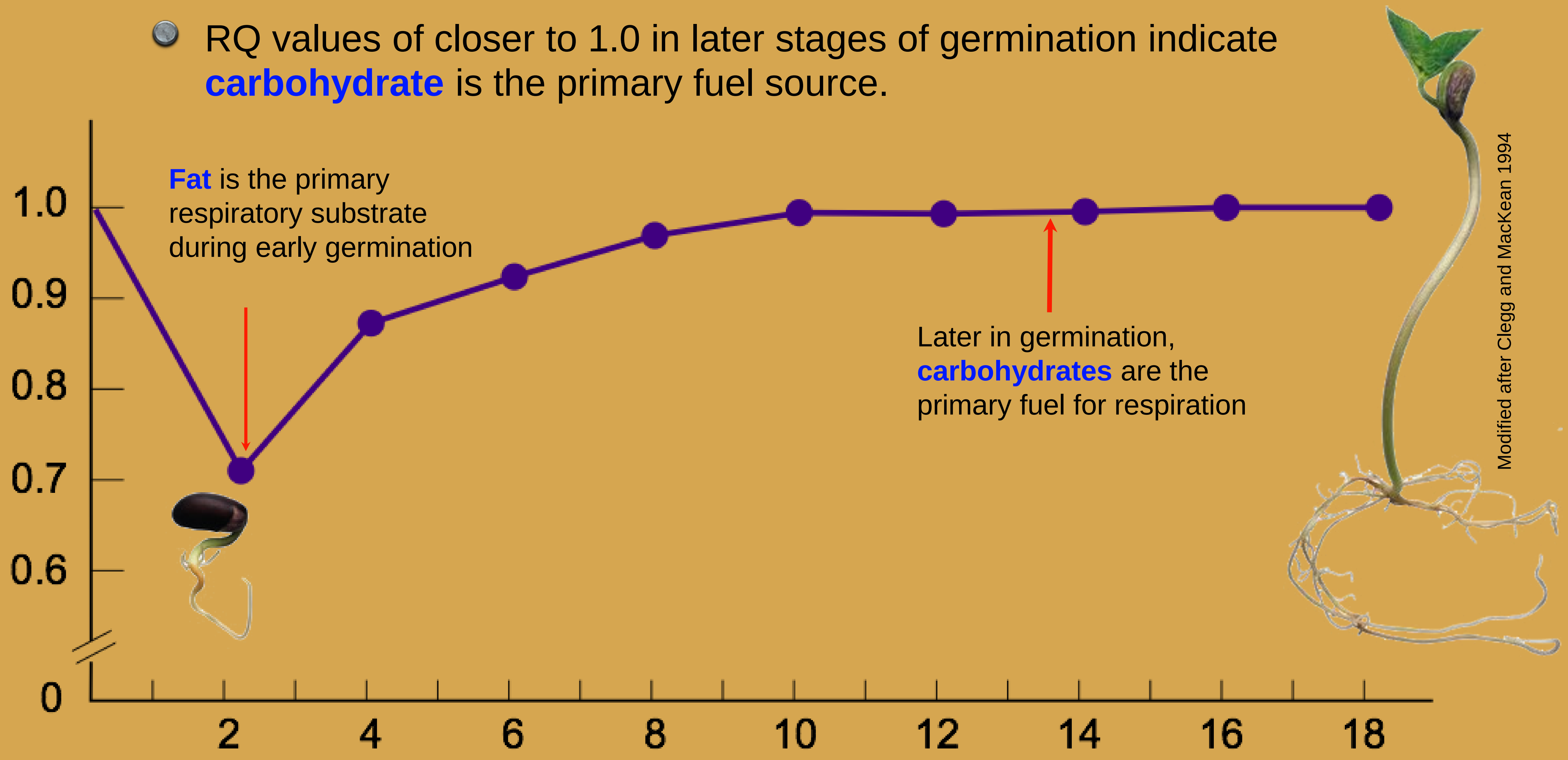
More oxygen required for oxidation

RQs are lower in substrates requiring more oxygen for their complete oxidation

Germinating seeds typically respire a mix of fats and carbohydrates

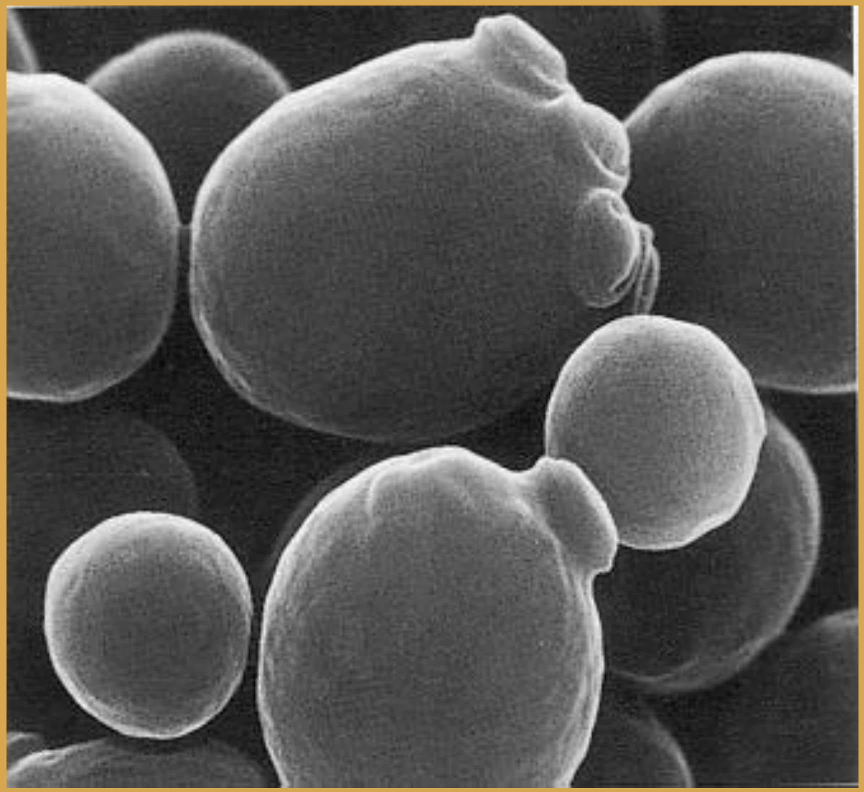
Measuring Respiration

- The graph below shows RQ values obtained from respirometer experiments of germinating wheat seeds (*Triticum sativum*). The RQ values reveal the substrates utilized for respiration.
  - Low RQ values in early germination indicate **fat** is being utilized.
  - RQ values of closer to 1.0 in later stages of germination indicate **carbohydrate** is the primary fuel source.



Anaerobic Pathways

- All organisms can metabolize glucose **anaerobically** (without oxygen) using **glycolysis** in the cytoplasm.
- Fermentation pathways for glucose metabolism do not use oxygen as a final electron acceptor.
- The energy yield from fermentation is **low**, and few organisms can obtain sufficient energy for their needs this way.
- An alternative electron acceptor is required in the absence of oxygen, or glycolysis will stop.
  - In **alcoholic fermentation** the electron acceptor is **ethanal**.
  - During **lactic acid fermentation** the electron acceptor is **pyruvate** itself and the end product is lactic acid.



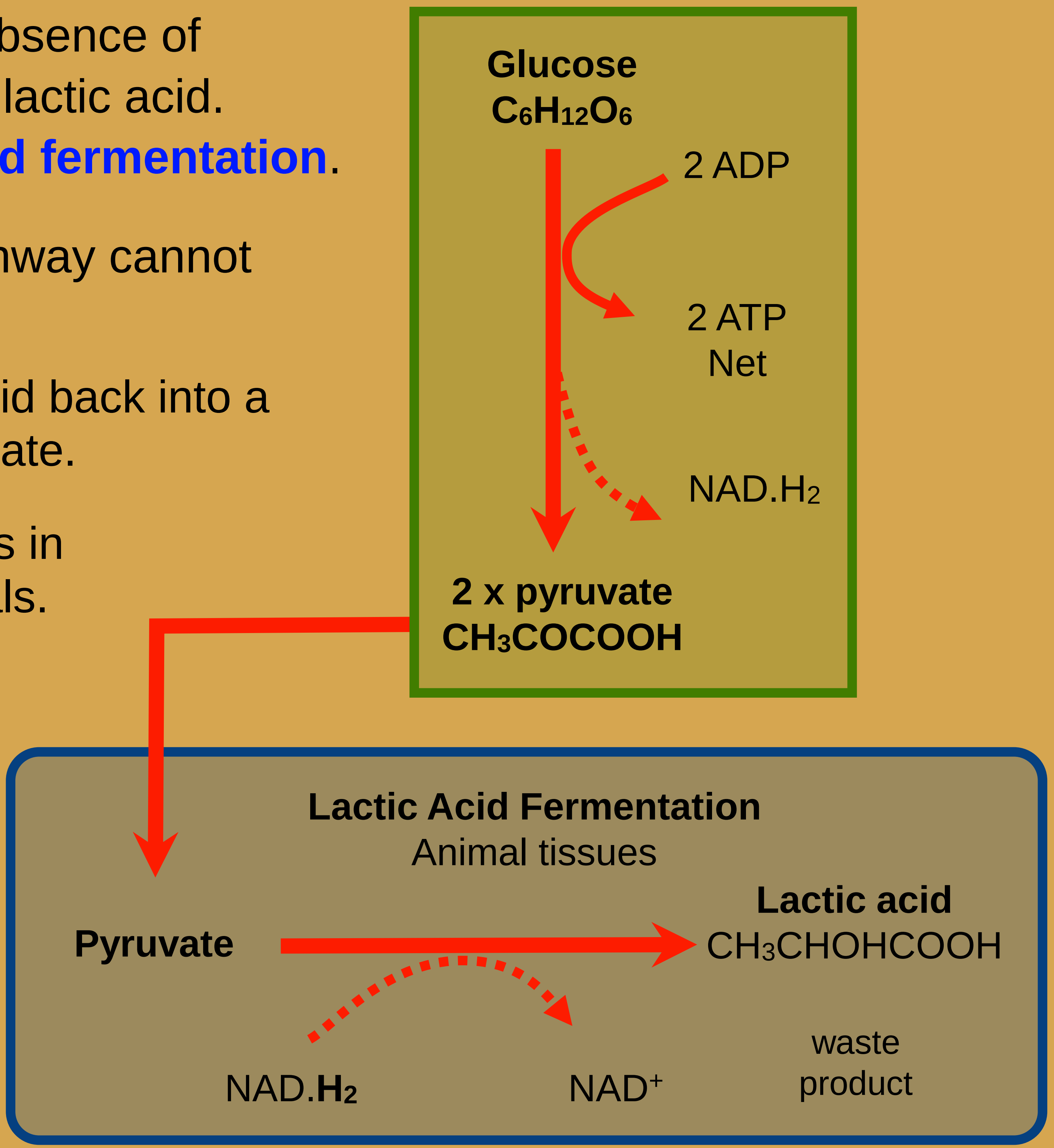
Alan Wheals, University of Bath

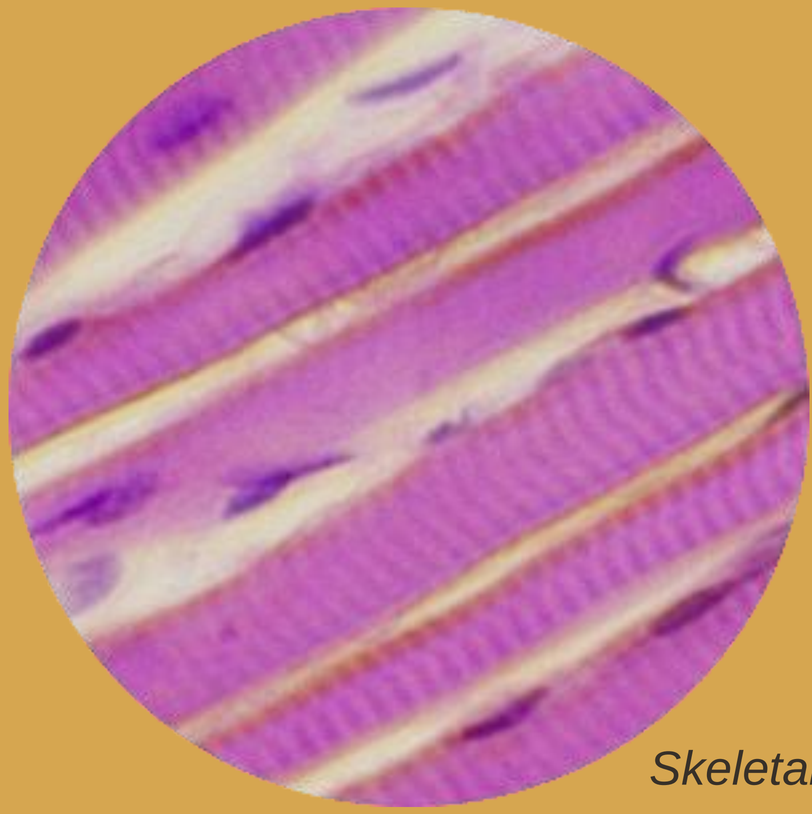
Alcoholic fermentation in yeast, (*Saccharomyces cerevisiae*), is the basis of the brewing and baking industries.

Fermentation is distinct from **anaerobic respiration**. Respiration always involves hydrogen ions passing down a chain of carriers to a terminal acceptor and this does not happen in fermentation. In anaerobic respiration, the terminal H^+ acceptor is a molecule other than oxygen, e.g. Fe^{2+} or nitrate.

Lactic Acid Fermentation

- Glycolysis can continue in the absence of oxygen by reducing pyruvate to lactic acid. This process is called **lactic acid fermentation**.
- Lactic acid is **toxic** and this pathway cannot continue indefinitely.
  - The liver converts the lactic acid back into a harmless respiratory intermediate.
  - Lactic acid fermentation occurs in the skeletal muscle of mammals.

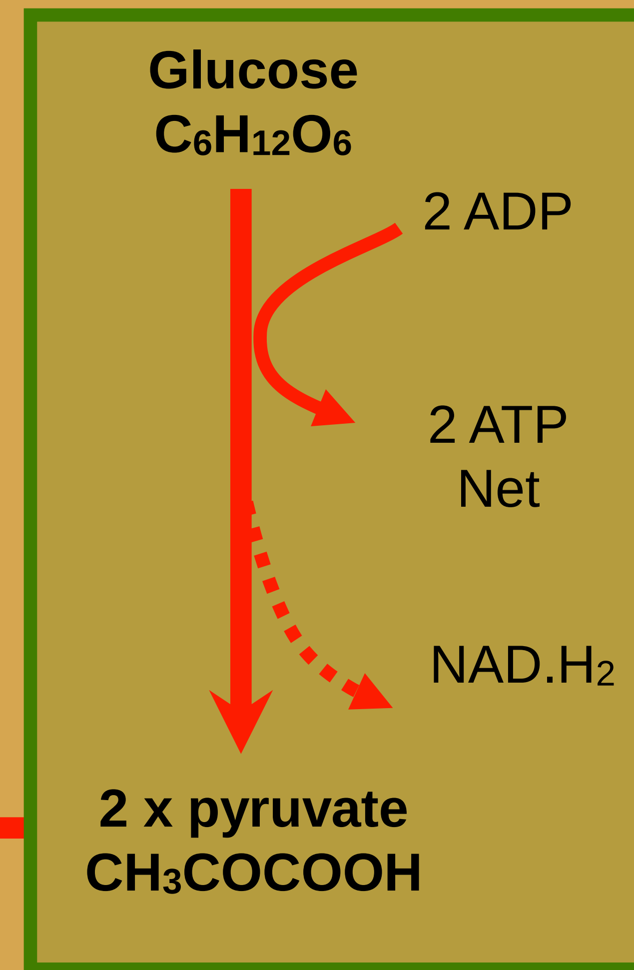


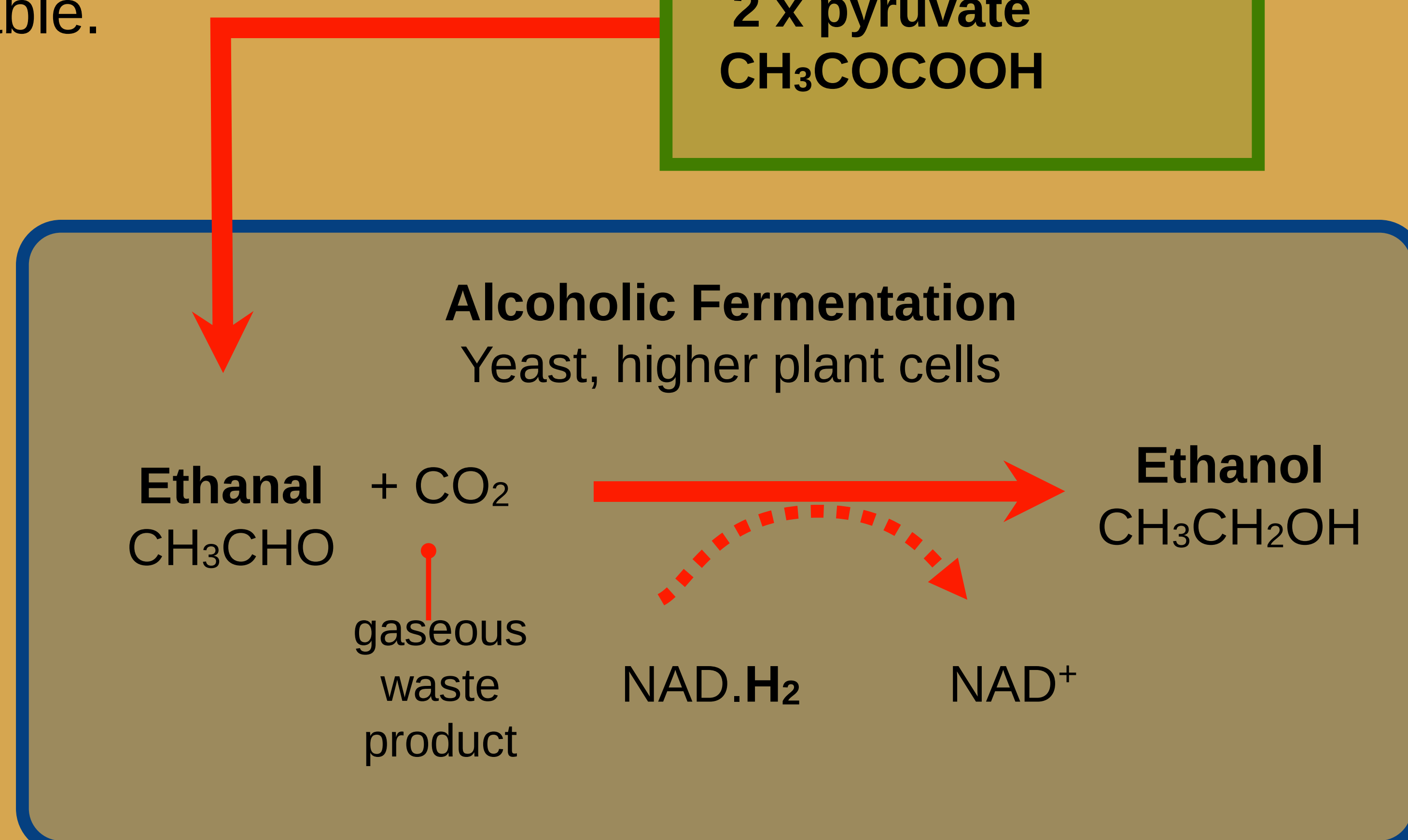


Skeletal muscle

Alcoholic Fermentation

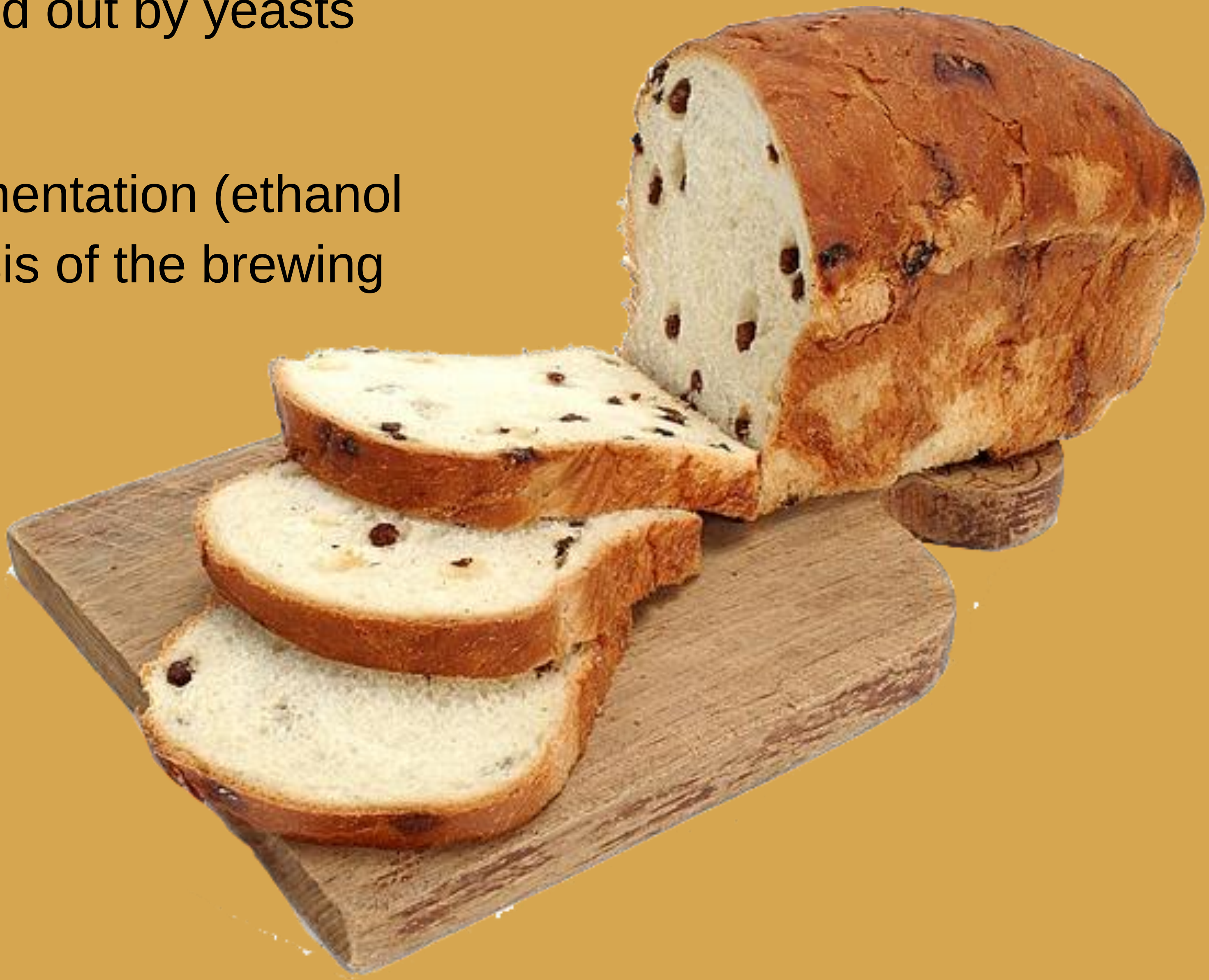
- Yeasts respire aerobically when oxygen is available but can use **alcoholic fermentation** when it is not.
- Such organisms are called **facultative anaerobes**.
- At ethanol levels above 12-15%, fermentation is toxic to the yeast cells. Alcoholic fermentation cannot be used indefinitely.
- The root cells of plants also use fermentation as a pathway when oxygen is unavailable.
- As **ethanol** is **toxic**, it must be converted back to respiratory intermediates and respired aerobically to reduce its levels.





Alcoholic Fermentation

- **Alcoholic fermentation** is carried out by yeasts and some types of bacteria.
- The by-products of alcoholic fermentation (ethanol and carbon dioxide) form the basis of the brewing and baking industries.

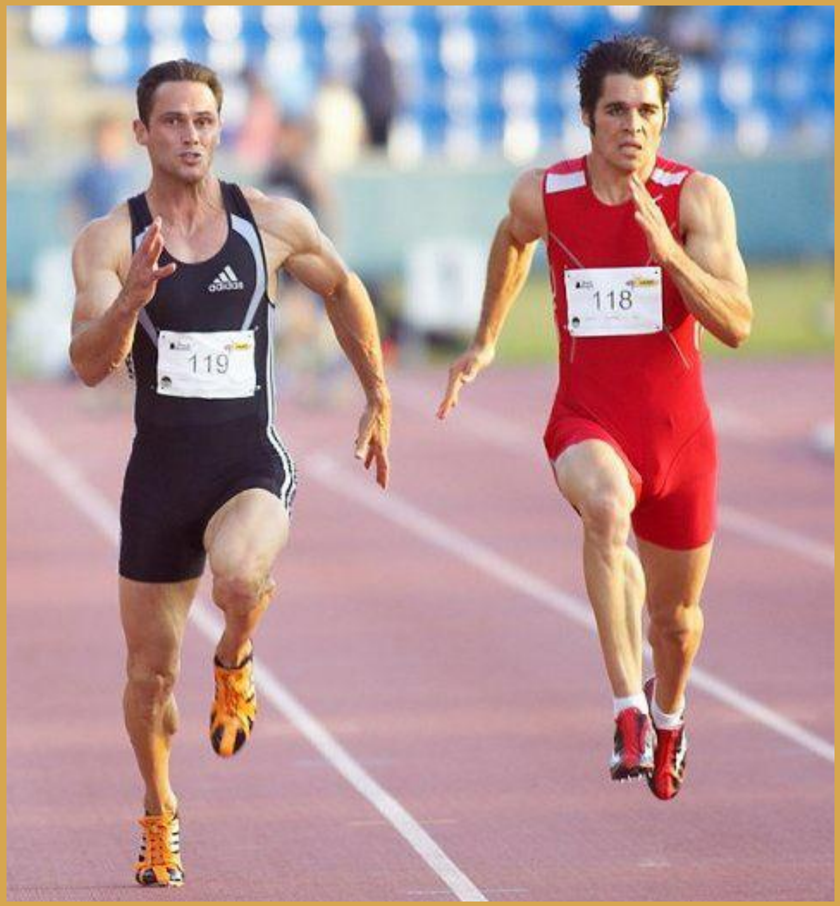


Bread (above) rises during baking as a result of the carbon dioxide given off during alcoholic fermentation.

Alcoholic beverages such as **beer** (left), derive their alcohol content from the ethanol produced from alcoholic fermentation.

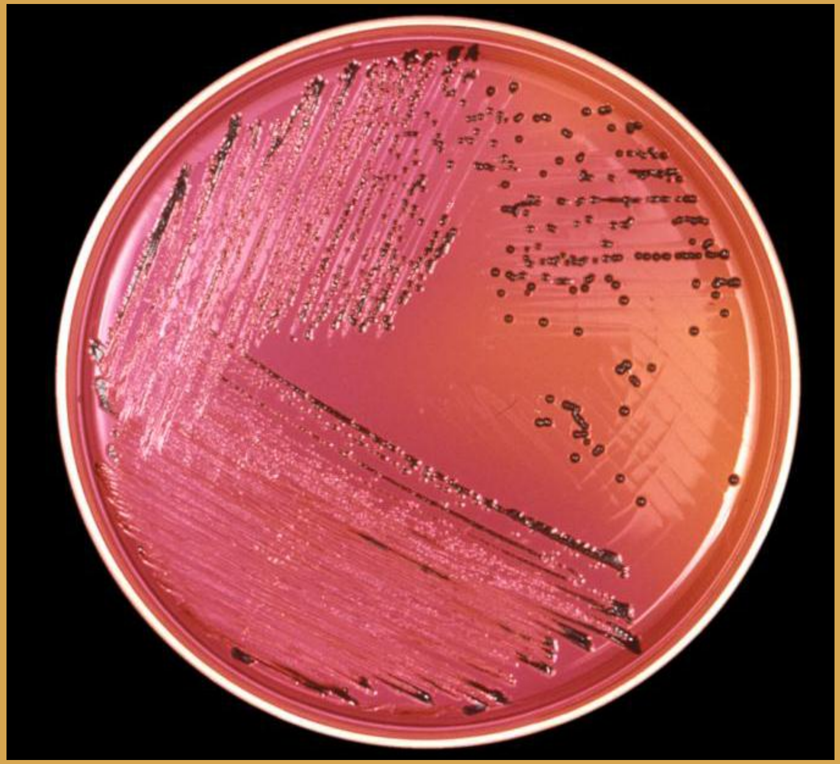
Facultative Anaerobic Metabolism

- **Facultative anaerobic metabolism** occurs when organisms or tissues can produce ATP using aerobic respiratory pathways when oxygen is present, and anaerobic pathways if oxygen is absent.
- Examples of facultative anaerobes include the bacteria *Listeria* and *Salmonella*, and some yeasts, e.g. *Saccharomyces*.
- Vertebrate skeletal muscle is facultatively anaerobic because it has the ability to generate ATP for a short time in the absence of oxygen (e.g. during sprints).



Athletics NZ

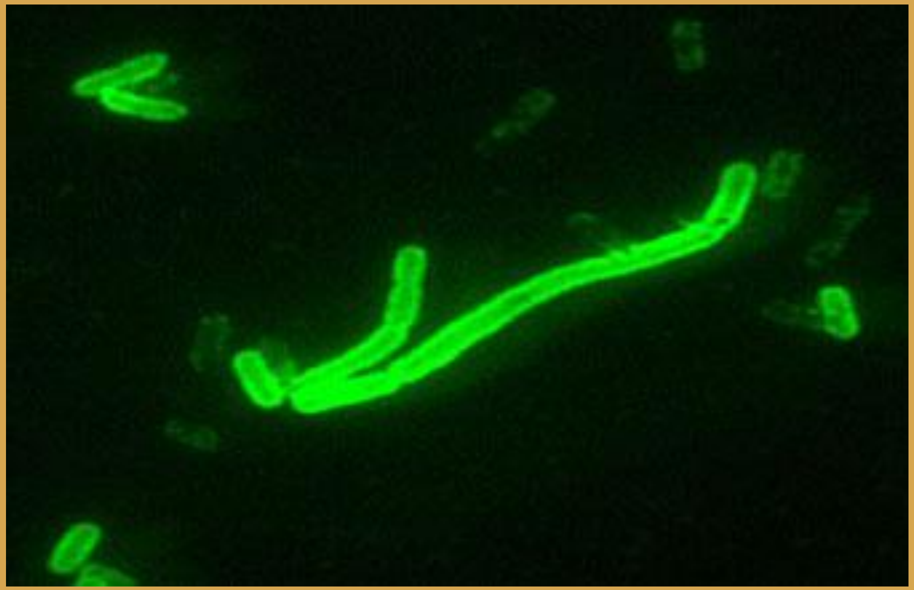
During short, hard muscular efforts, human muscle performs anaerobically.


CDC

Salmonella is a facultative anaerobe

Obligate Anaerobes

- Some organisms respire only in the absence of oxygen; oxygen is toxic to them. Such organisms are called **obligate anaerobes**.
- Some are **bacterial pathogens** and the by-products of their metabolism are highly toxic and cause diseases such as tetanus, gangrene (right), and botulism.
- Obligate anaerobes generate ATP using various fermentative pathways or anaerobic respiration in which the terminal electron acceptor is a molecule other than oxygen.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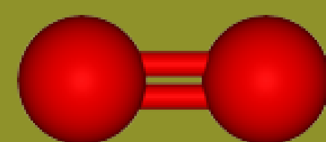
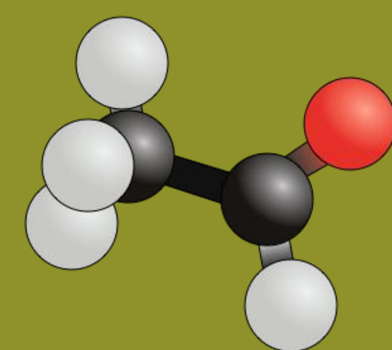
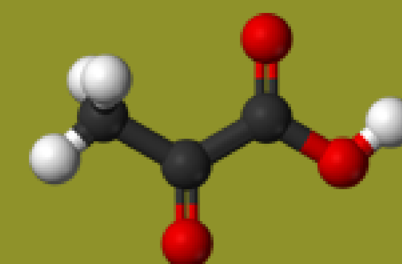
CDC

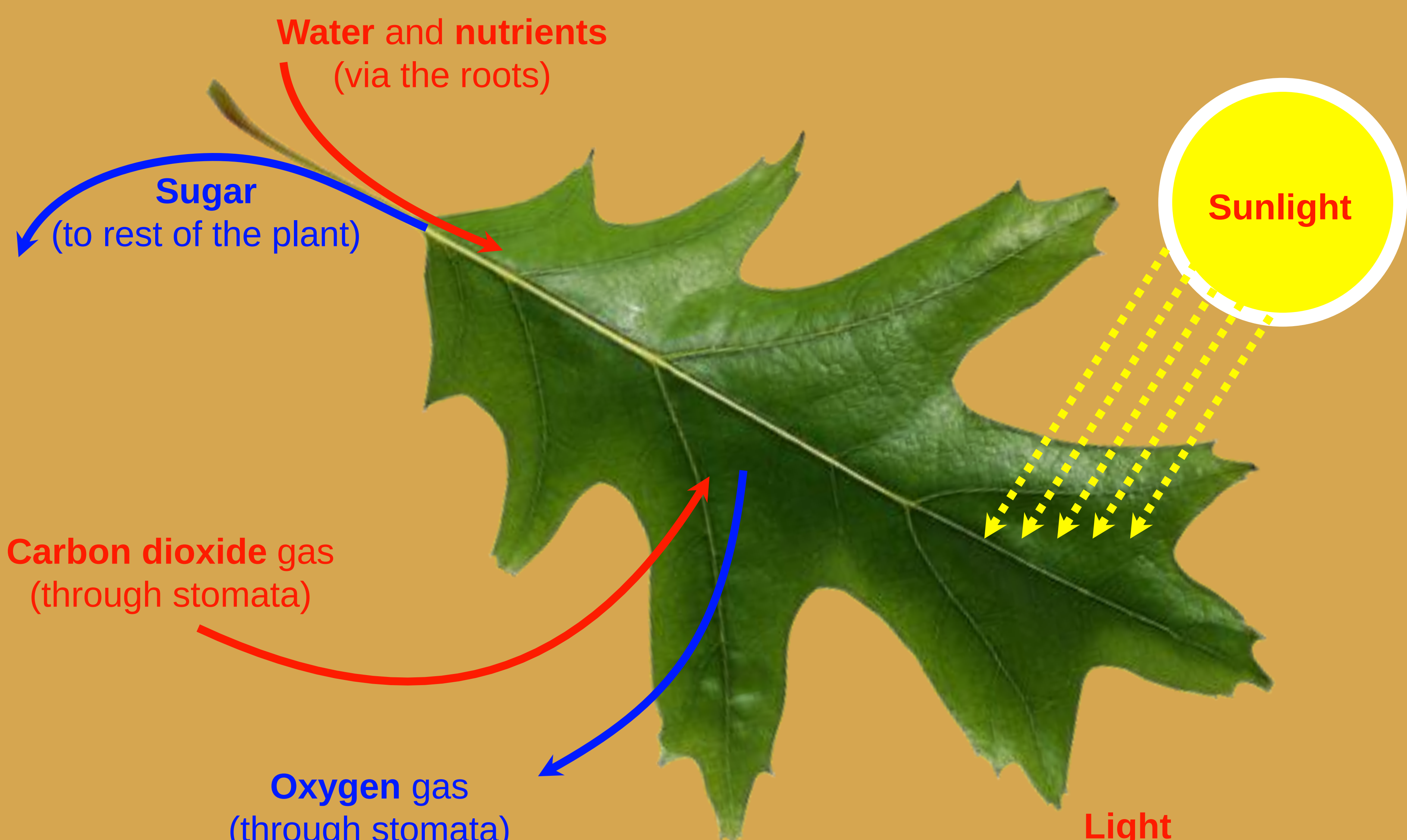
The bacterium *Yesinia pestis* (left), causes **bubonic plague**. **Gangrene** (seen in the hand above) is a common manifestation of the plague.

Aerobic & Anaerobic Pathways Compared

	Aerobic Respiration	Anaerobic Pathways	
		Alcoholic fermentation	Lactic acid fermentation
H^+ acceptor	Oxygen 	Ethanal 	Pyruvate 
Products	CO_2 + water	Ethanol + CO_2	Lactic acid
Phosphorylation type	Substrate level and oxidative	Substrate level	Substrate level
Comments	Most energy is produced during the Krebs cycle	Toxic when ethanol levels are >12-15%	Lactic acid is toxic and must be removed

Photosynthesis

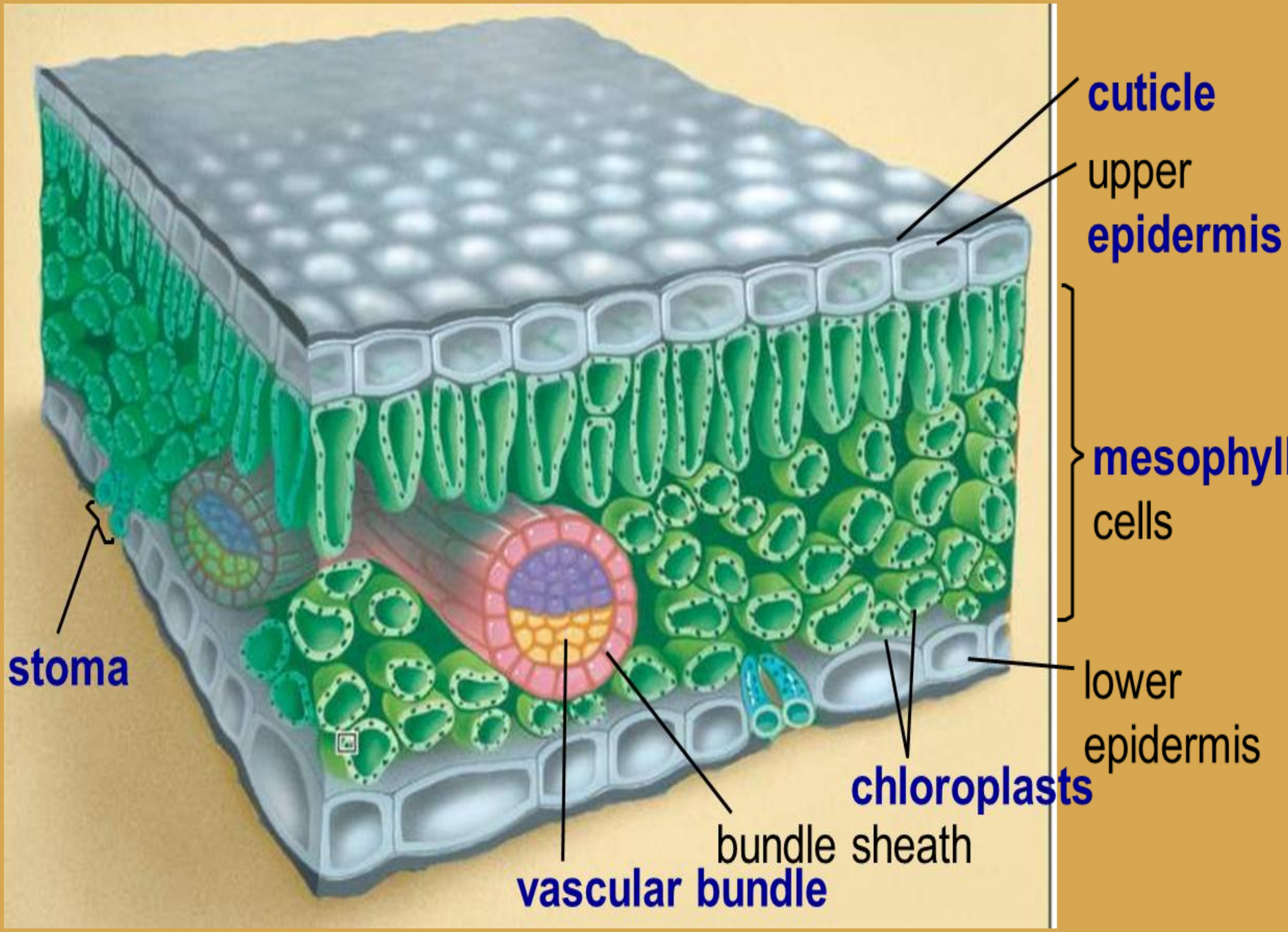
- **Photosynthesis** is the action of transforming **sunlight energy into chemical energy**. Photosynthesis produces:
  - **energy** for use by the autotroph and for use later down the food chain.
  - **oxygen** gas, essential for the survival of advanced life forms.



$$6CO_2 + 12H_2O \xrightarrow[\text{Chlorophyll}]{\text{Light}} C_6H_{12}O_6 = 6O_2 + 6H_2O$$

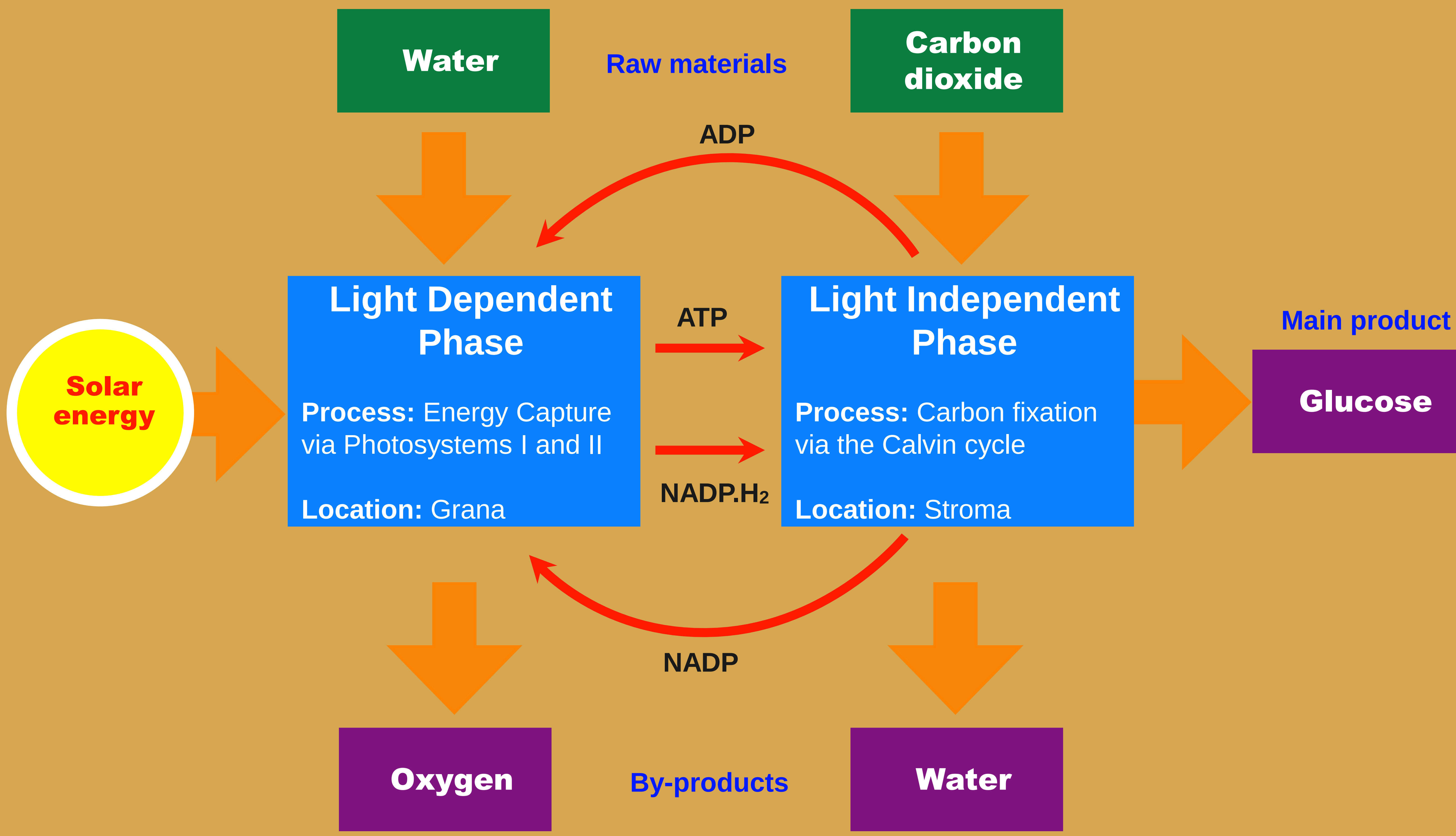
Internal Leaf Structure

- a) Cuticle: Waxy layer water proofing upper leaves.
- b) Upper epidermis: Upper layer of cells. No chloroplasts. Protection.
- c) Palisade Mesophyll: Tightly packed upper layer of chloroplast containing cells.
- d) Spongy Mesophyll: Lower layer of chloroplast containing cells. Air spaces around them.
- e) Lower Epidermis: Lower external layer of cells in leaf.
- f) Vascular Bundle: Bundle of many vessels (xylem and phloem) for transport.
- g) Xylem: Living vascular system carrying water & minerals throughout plant.
- h) Phloem: Living vascular system carrying dissolved sugars and organic compounds throughout plant.
- i) Guard Cells: 2 cells surrounding stomata that control rate of gas & water exchange.
- j) Stomata: Opening between guard cells for gas & water exchange.


cuticle
upper epidermis
mesophyll cells
stoma
lower epidermis
chloroplasts
bundle sheath
vascular bundle

A Summary of Photosynthesis

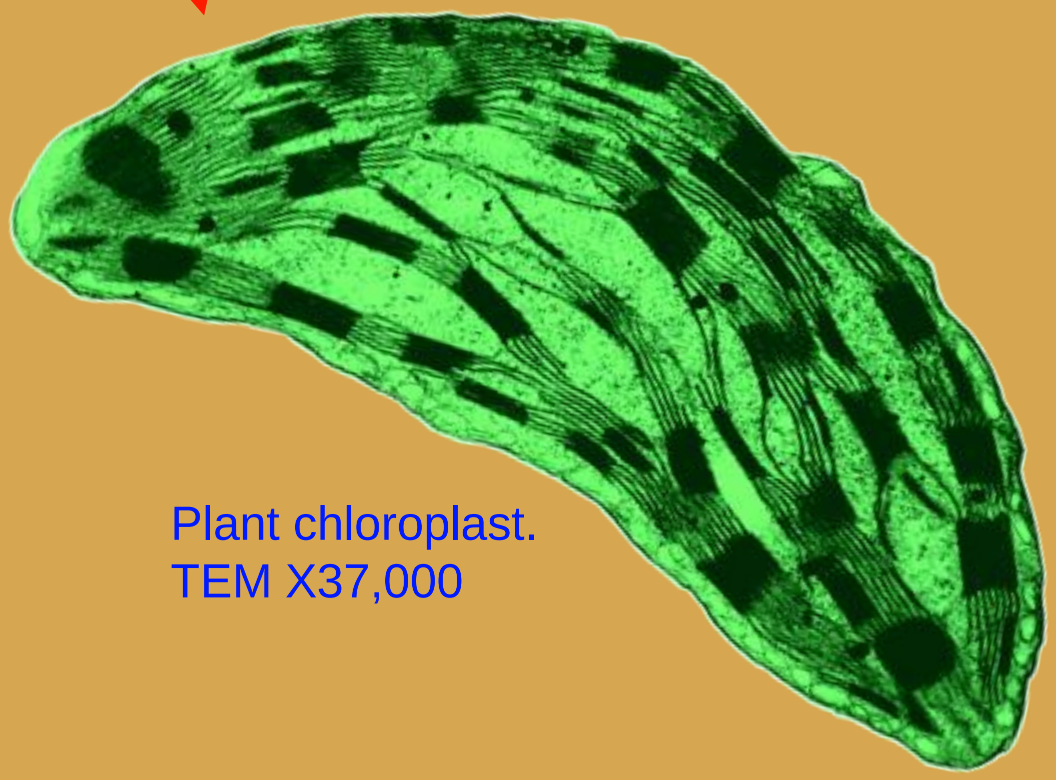
- A basic overview of photosynthesis is presented in the diagram below.



Photosynthesis

- Photosynthesis is carried out by plants, algae, some bacteria and some protists.
- In plants and photosynthetic protists, photosynthesis takes place in membrane-bound organelles called **chloroplasts**.
  - Chloroplasts are filled with a green pigment called **chlorophyll**. This is what gives plants their green coloring.
- In photosynthetic bacteria, the reactions of photosynthesis take place within the cell itself, not within a discrete organelle.

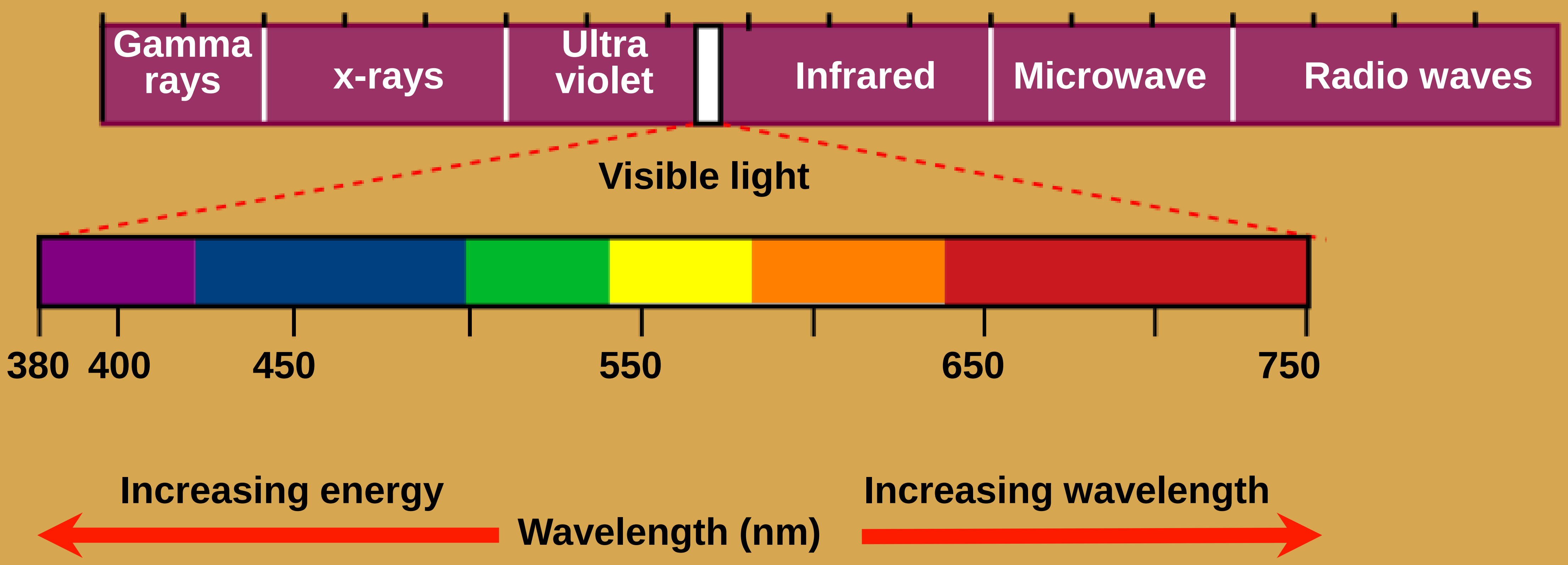
A plant mesophyll cell with a chloroplast highlighted.



Plant chloroplast.
TEM X37,000

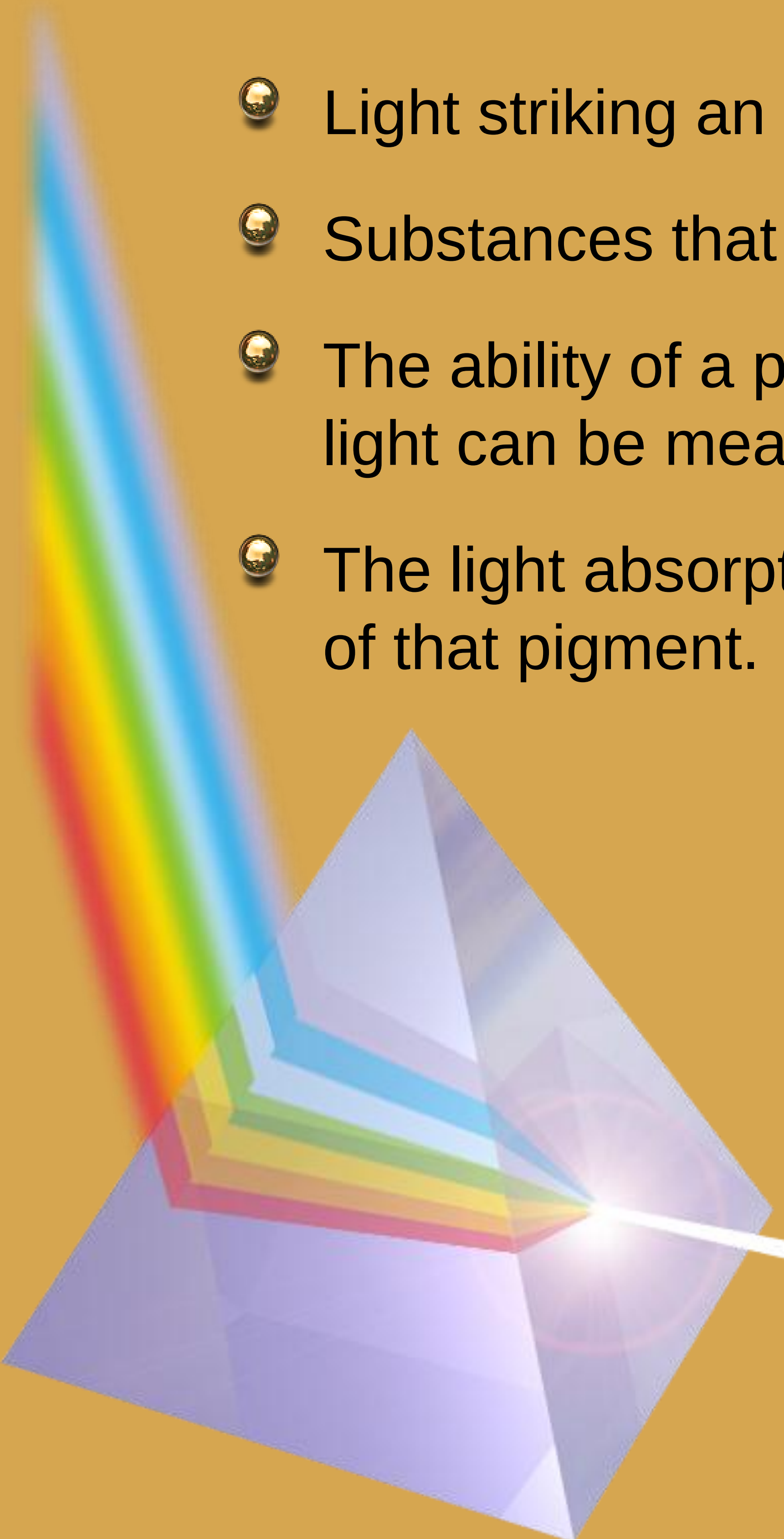
The Electromagnetic Spectrum

- Light is a form of energy known as **electromagnetic radiation**.
- The segment of the electromagnetic spectrum most important to life is the narrow band between about 380 and 750 nanometres (nm).
  - This radiation is known as **visible light** because it is detected as colors by the human eye.
  - Visible light drives photosynthesis.



Pigments & Light Absorption

- Light striking an object it is either **reflected**, **transmitted** or **absorbed**.
- Substances that **absorb** visible light are called **pigments**.
- The ability of a pigment to absorb particular wavelengths of light can be measured with a **spectrophotometer** (below).
- The light absorption vs the wavelength is called the **absorption spectrum** of that pigment.

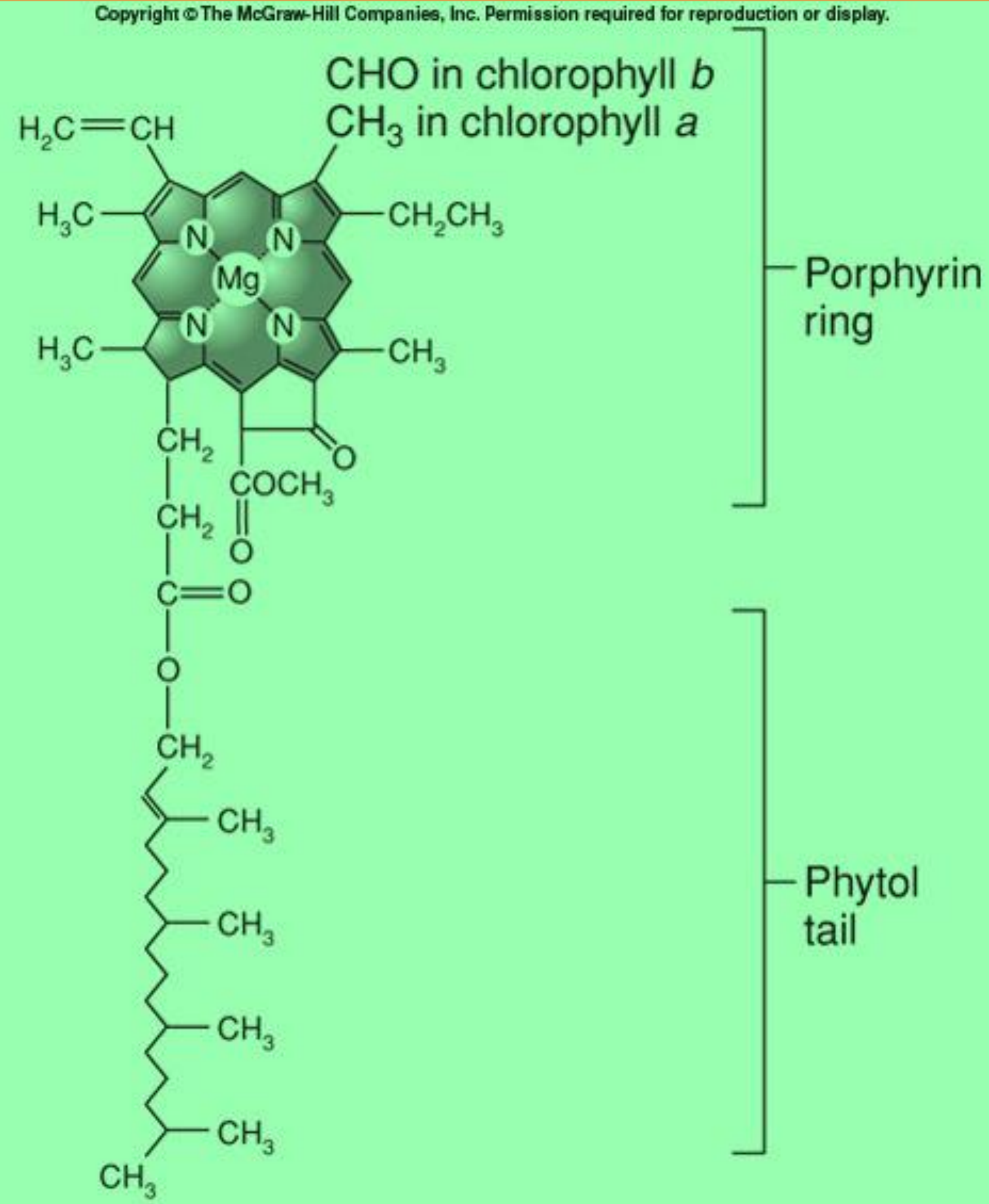


Photosynthetic Pigments

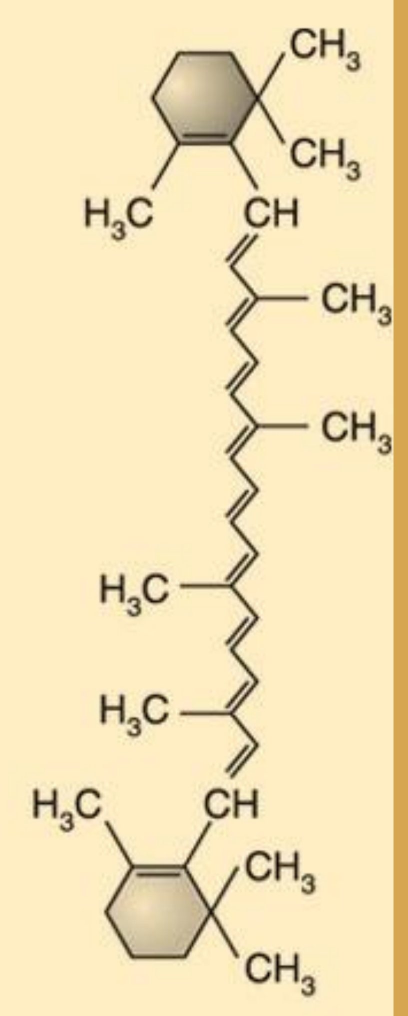
- The photosynthetic pigments of plants fall into two categories:
  - **Chlorophylls**, which absorb red and blue-violet light. They are the main photosynthetic pigment in plants and give leaves their green color (below).
  - **Carotenoids**, which absorb strongly in the blue-violet and appear orange, yellow, or red. They are considered to be associate pigments. Carotenoids give carrots their orange color (right).

Photosynthetic Pigments

- Chlorophyll a
- Chlorophyll b
- Carotenoids



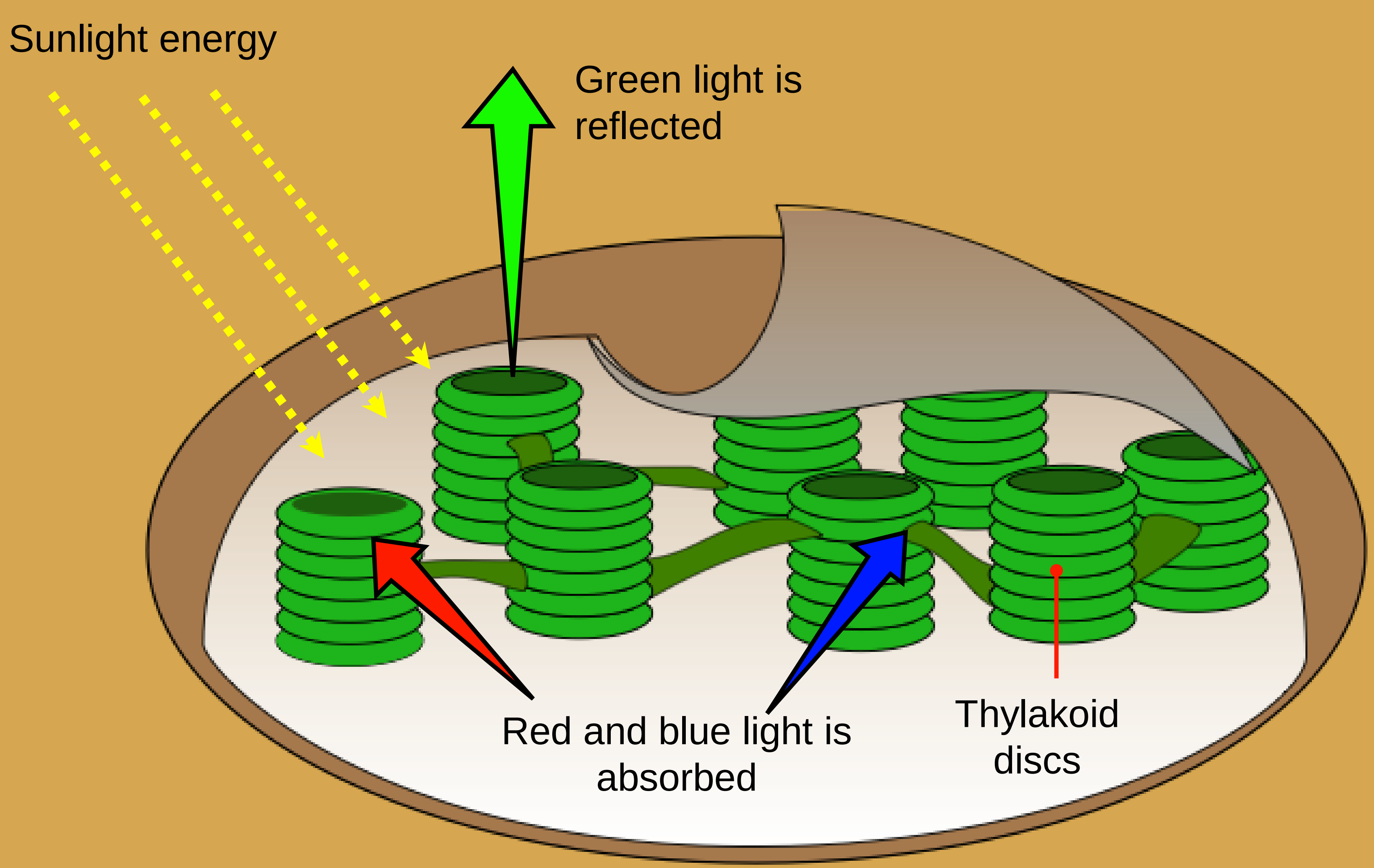
(a) Chlorophylls *a* and *b*



(b) β-carotene (a carotenoid)

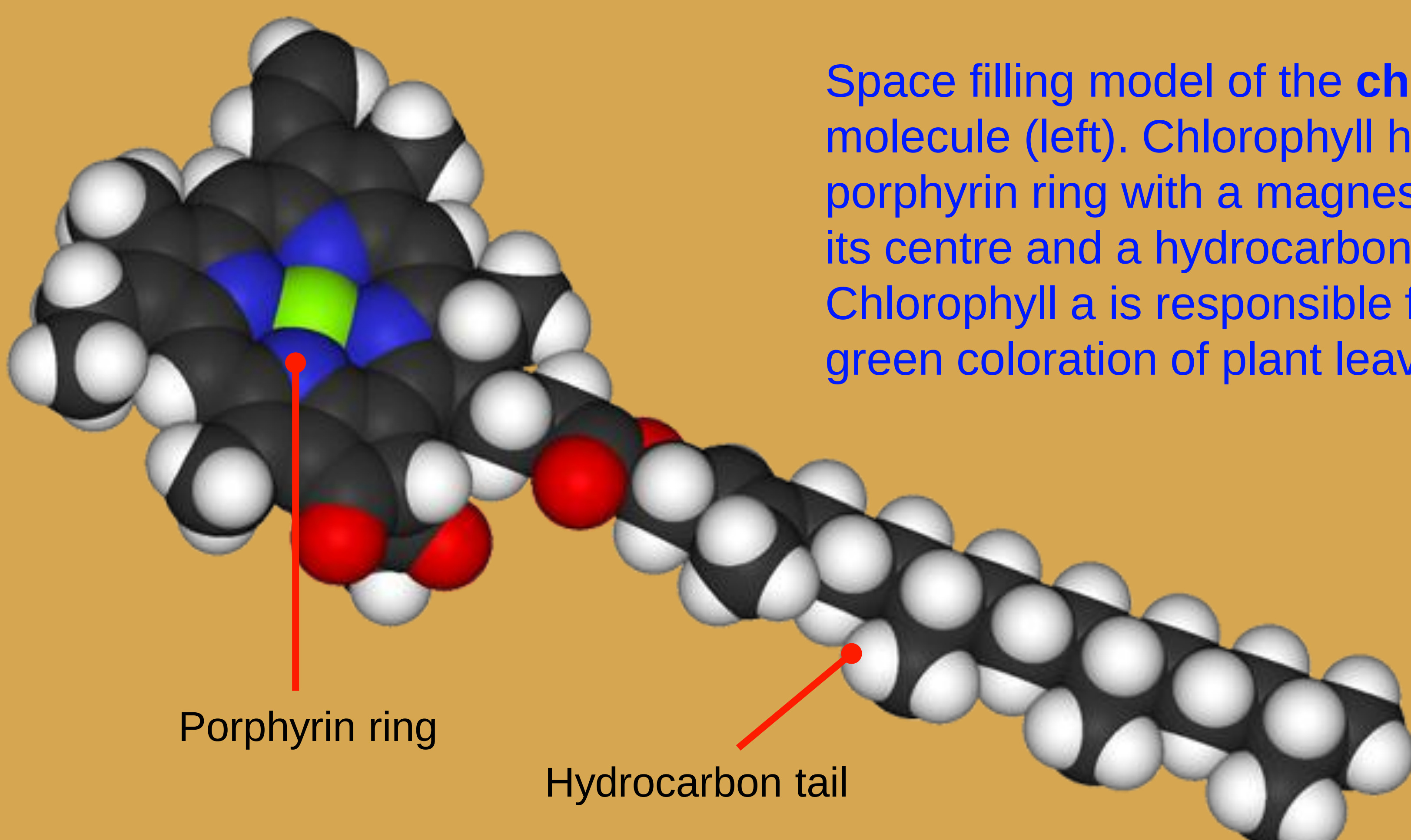
Photosynthetic Pigments

- The photosynthetic pigments of the **chloroplasts** in higher plants absorb blue and red light, and the leaves therefore appear green (which is reflected).
- Plant leaves also contain accessory pigments, which capture light outside the wavelengths captured by chlorophyll.

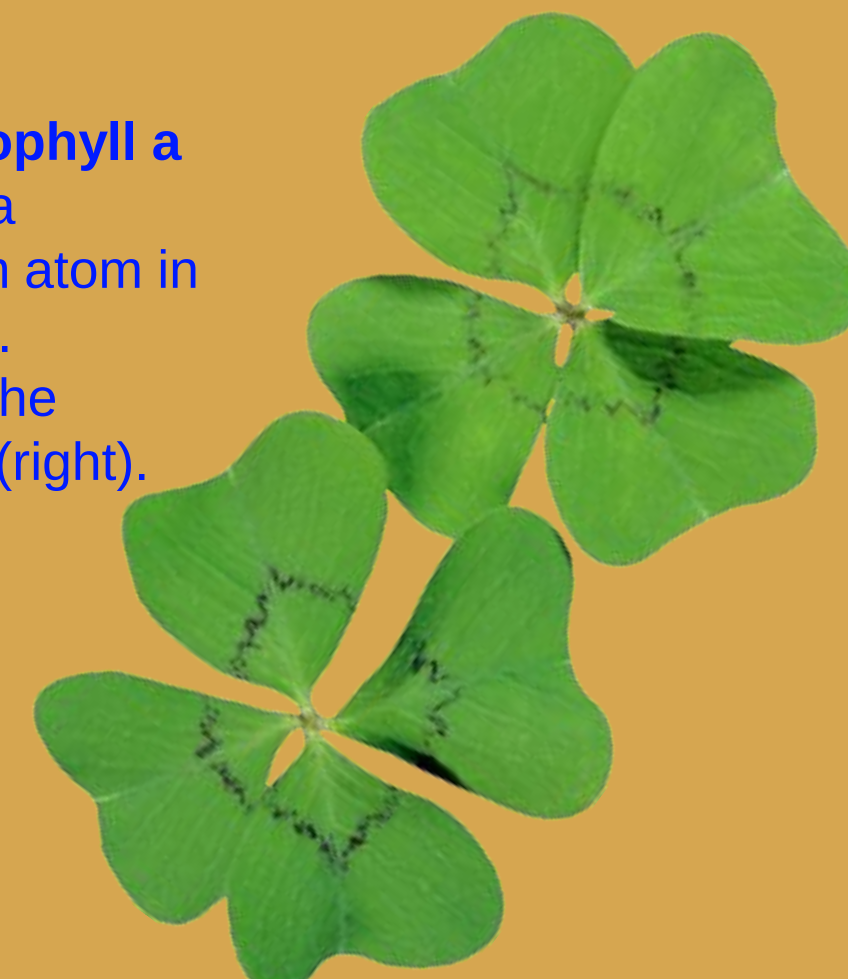


Photosynthetic Pigments

- Each photosynthetic pigment has its own characteristic absorption spectrum.
- Although only **chlorophyll a** can participate directly in the light reactions of photosynthesis, the accessory pigments (**chlorophyll b and carotenoids**) can absorb wavelengths of light that chlorophyll a cannot.
- The accessory pigments pass the energy (photons) to chlorophyll a, thus broadening the spectrum that can effectively drive photosynthesis.

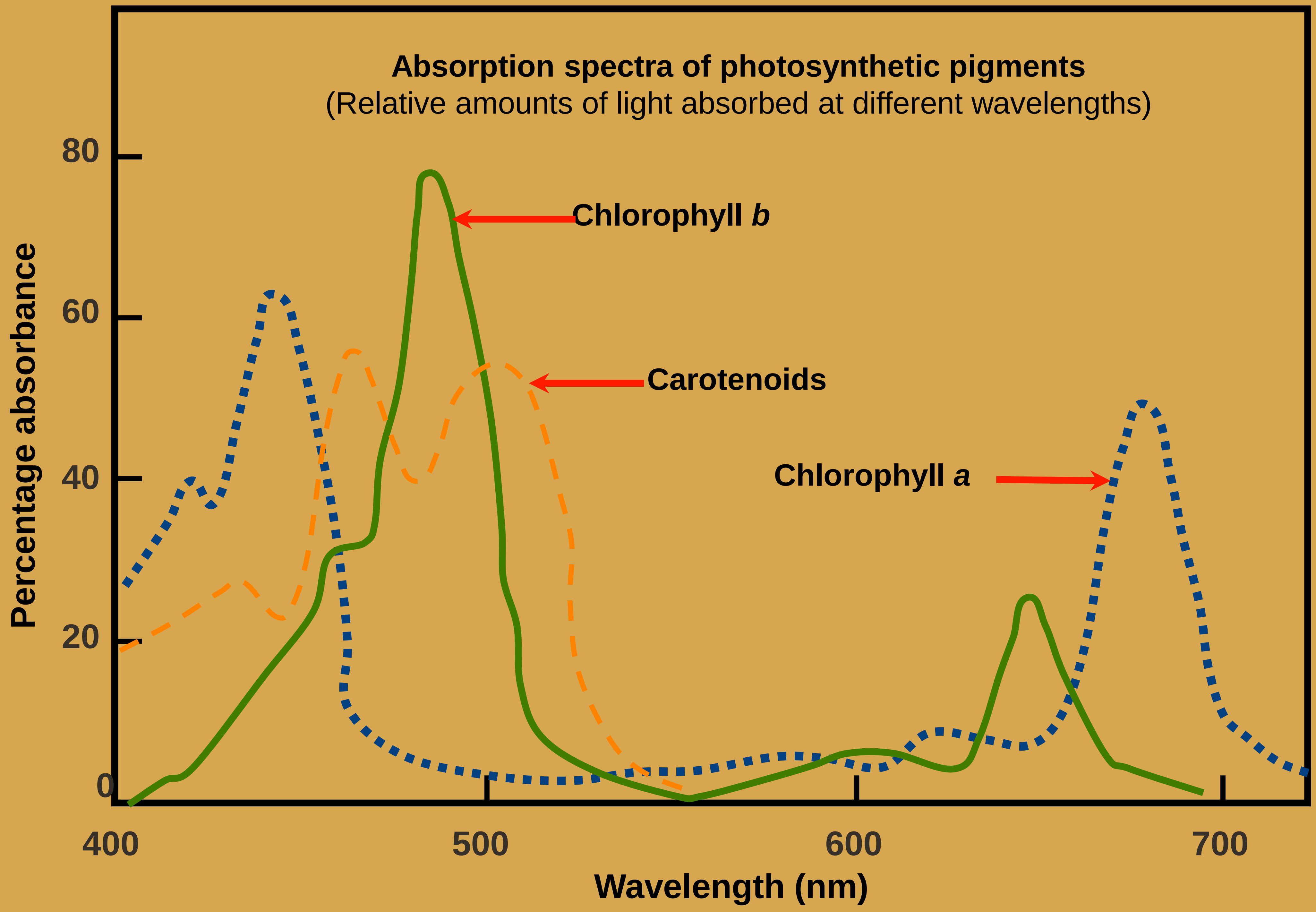


Space filling model of the **chlorophyll a** molecule (left). Chlorophyll has a porphyrin ring with a magnesium atom in its centre and a hydrocarbon tail. Chlorophyll a is responsible for the green coloration of plant leaves (right).



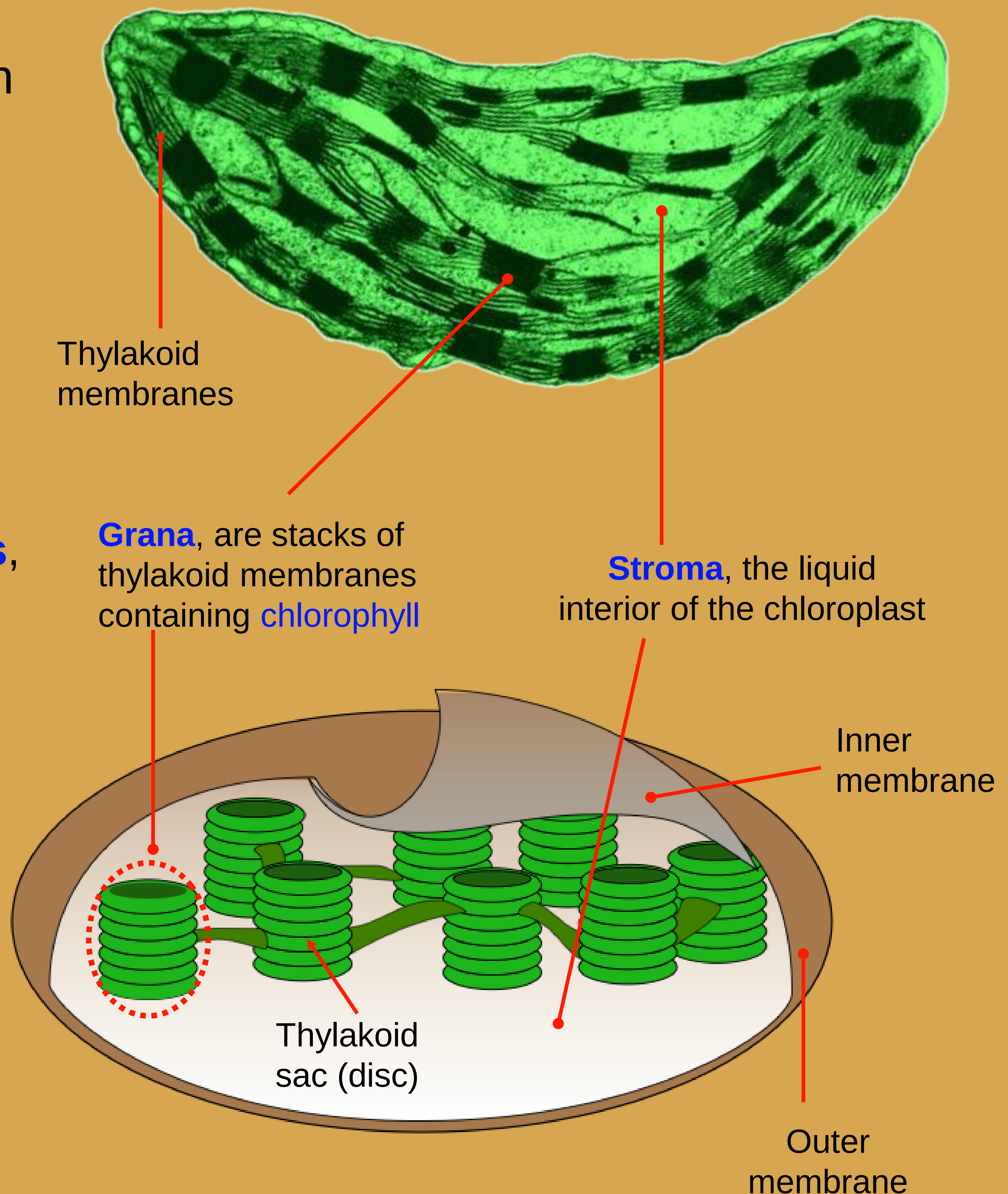
Absorption spectrum

- The **absorption spectrum** of different photosynthetic pigments provides clues to their role in photosynthesis, since light can only perform work if it is absorbed.



The Chloroplast

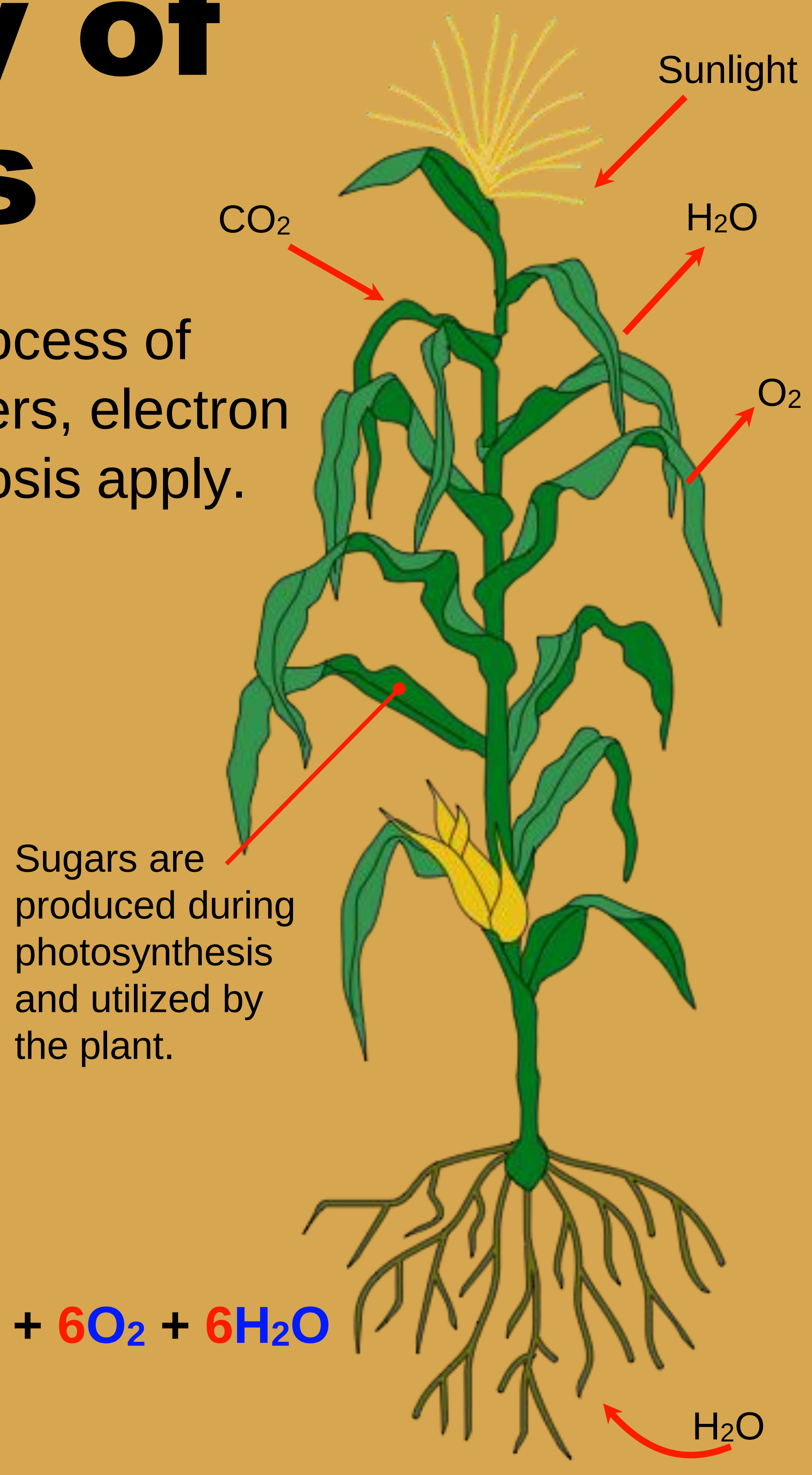
- The chloroplast is enclosed by an envelope consisting of two membranes separated by a very narrow intermembrane space.
- Membranes also divide the interior of the chloroplast into compartments:
  - flattened sacs called **thylakoids**, which in places are stacked into structures called **grana**.
  - the **stroma** (fluid) outside the thylakoids.
- They contain DNA and also ribosomes, which are used to synthesize some of the proteins within the chloroplast.



The Biochemistry of Photosynthesis

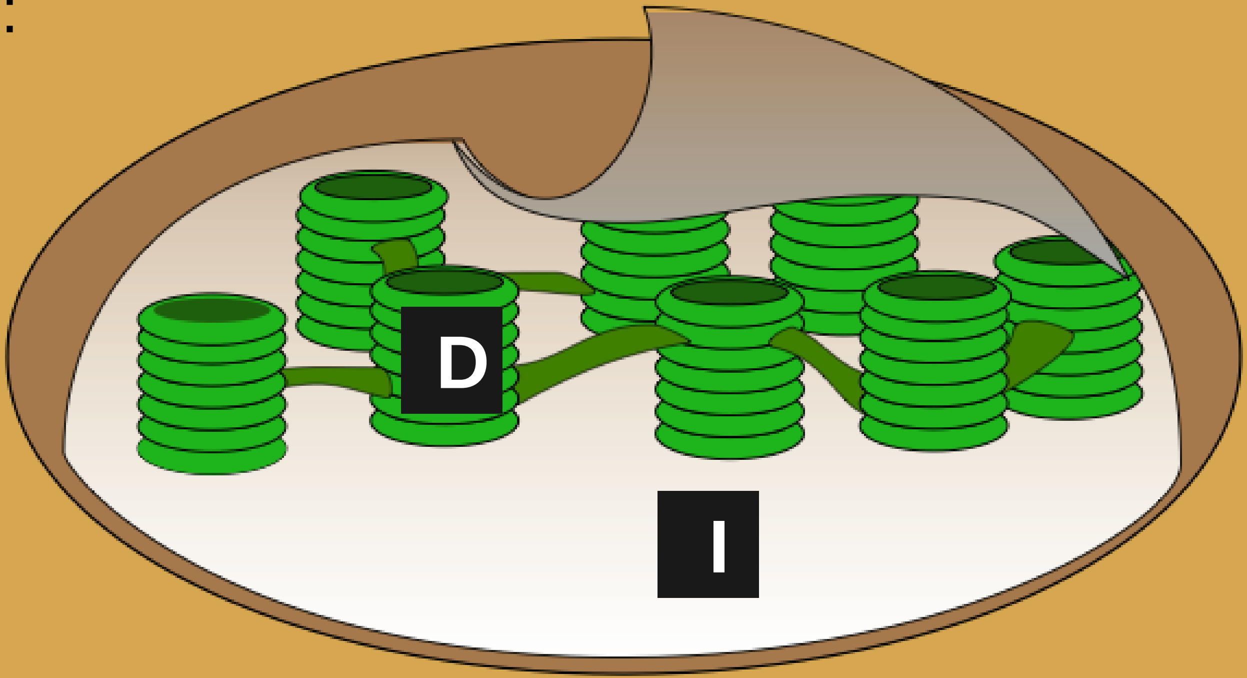
- Photosynthesis is, in many ways, the **reverse** process of respiration. The same principles of electron carriers, electron transfer, and ATP generation through chemiosmosis apply.
  - Water is split and electrons are transferred together with hydrogen ions from water to CO_2. The CO_2 is reduced to sugar.
  - Sugar, oxygen and water are produced as by-products.
  - The electrons increase in potential energy as they move from water to sugar. The energy to do this is provided by light.
- Photosynthesis can be summarized as the following chemical reaction:

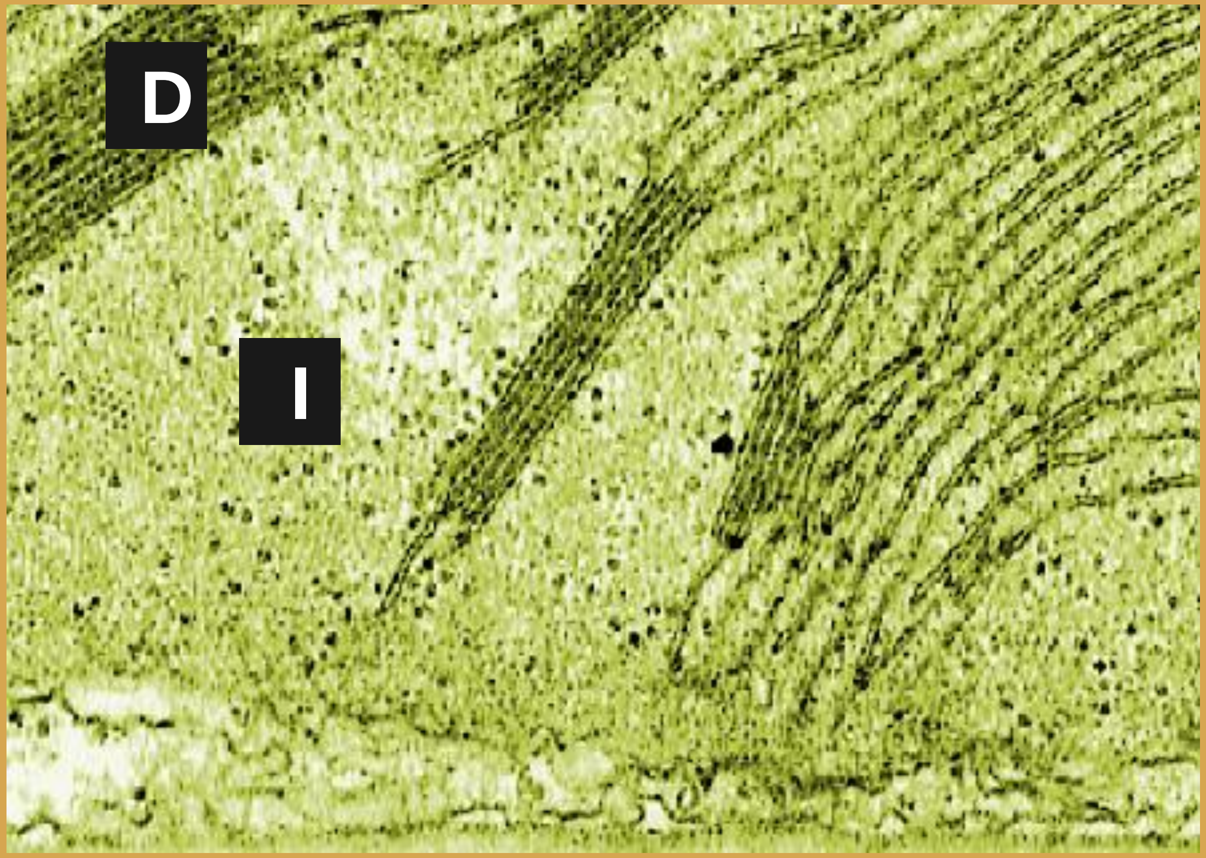
$6CO_2 + 12H_2O$ + light energy → Glucose ($C_6H_{12}O_6$) + $6O_2 + 6H_2O$



Photosynthesis

- There are two phases in photosynthesis:
  - The **light dependent phase** (D), which occurs in the **thylakoid membranes** of a chloroplast.
  - The **light independent phase** (I), which occurs in the **stroma** of chloroplasts.





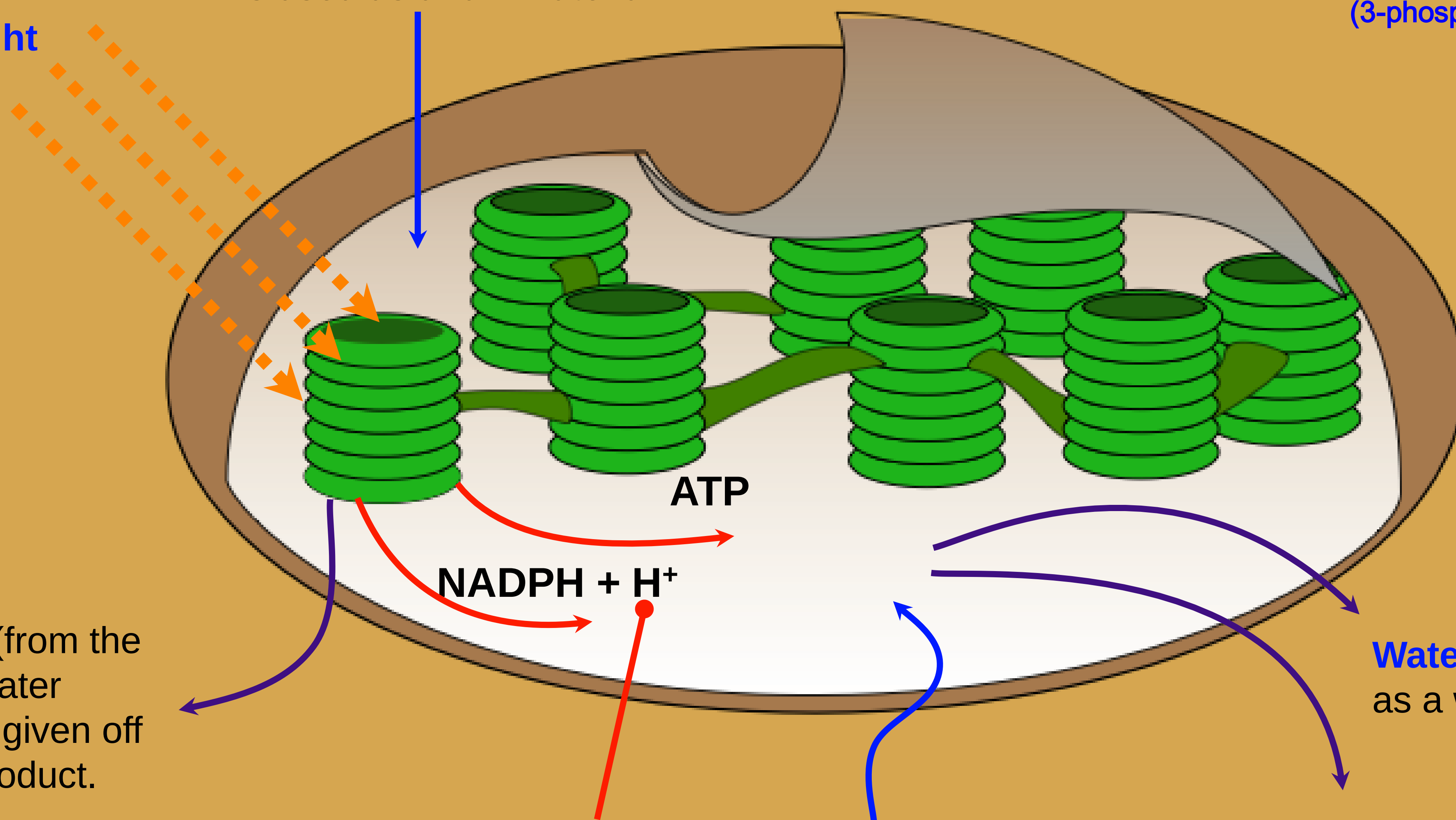
Diagrammatic representation(top) and false colored electron micrograph (left) of a plant chloroplast showing the sites of the light dependent and light independent phases of photosynthesis.

Photosynthesis in C_3 Plants

- The diagram below summarizes photosynthesis in a C_3 plant.

A plant that utilizes the C_3 carbon fixation pathway as the sole mechanism to convert CO_2 into an organic compound

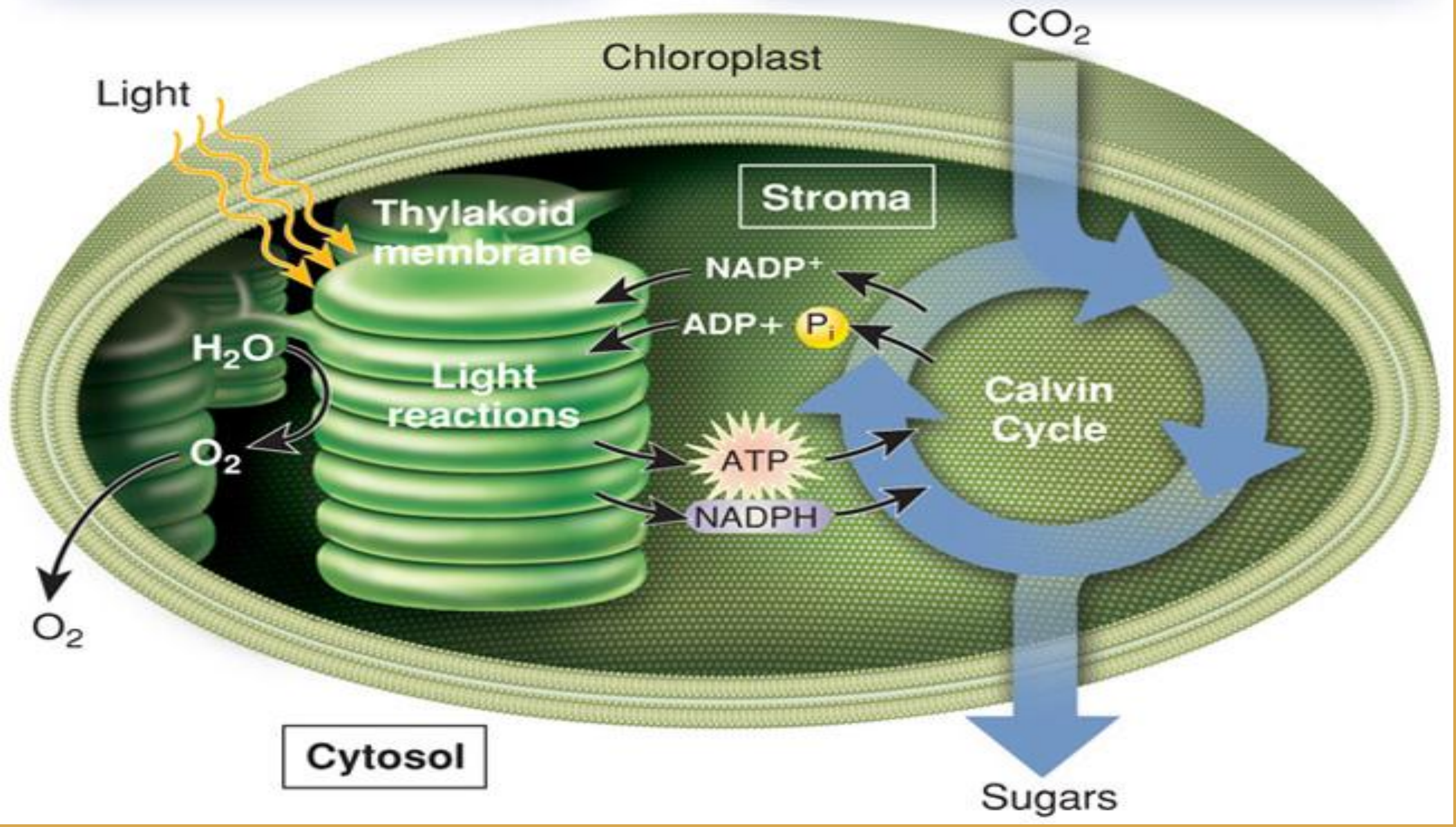
(3-phosphogylcerate).



Photosynthesis in C_3 Plants

The light reactions in the thylakoid membrane produce O_2, ATP, and NADPH.

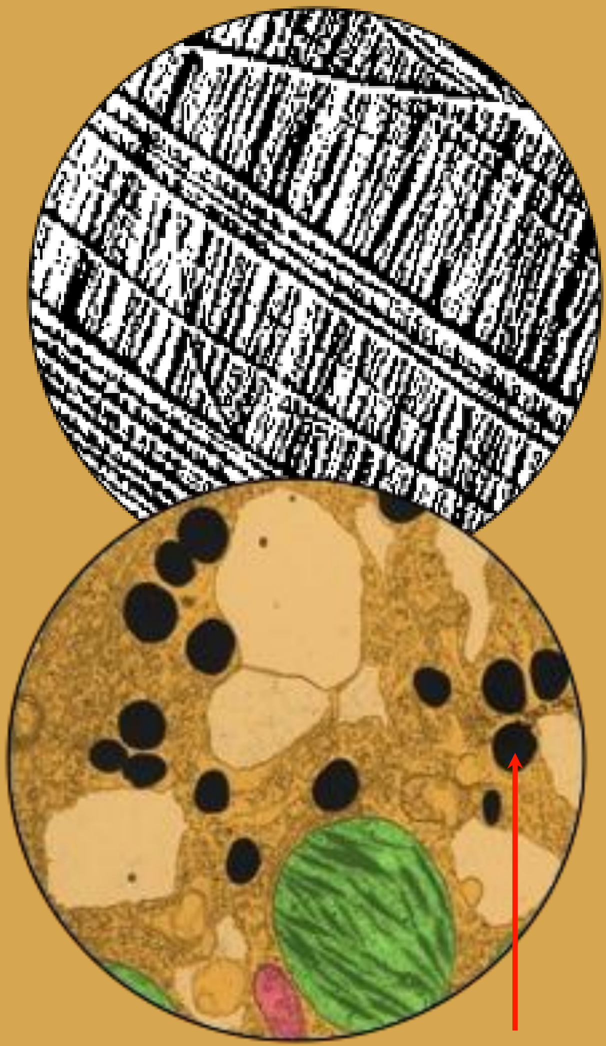
The Calvin cycle in the stroma uses CO_2, ATP, and NADPH to make carbohydrates such as sugars.



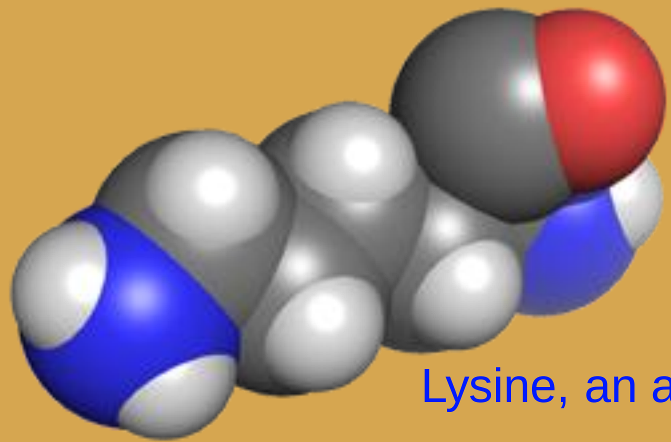
Conversion of Triose Phosphate

- **Triose phosphate**, produced during photosynthesis, is the base product leading to the formation of many other molecules. It is converted to:
  - **Glucose**, the fuel for cellular respiration; supplies energy for metabolism.
  - **Cellulose**, a component of plant cell walls is formed using glucose as a building block.
  - **Starch** granules act as a reserve supply of energy, to be converted back into glucose when required.
  - **Disaccharides**. Glucose is converted to other sugars such as fructose, found in ripe fruit, and sucrose, found in sugar cane.
  - **Lipids** and **amino acids**.

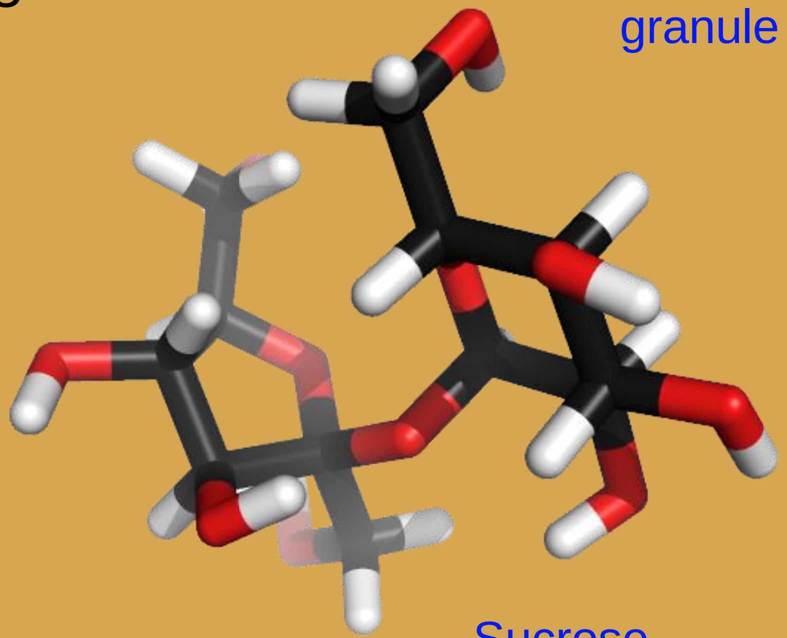
Cellulose



Starch granule



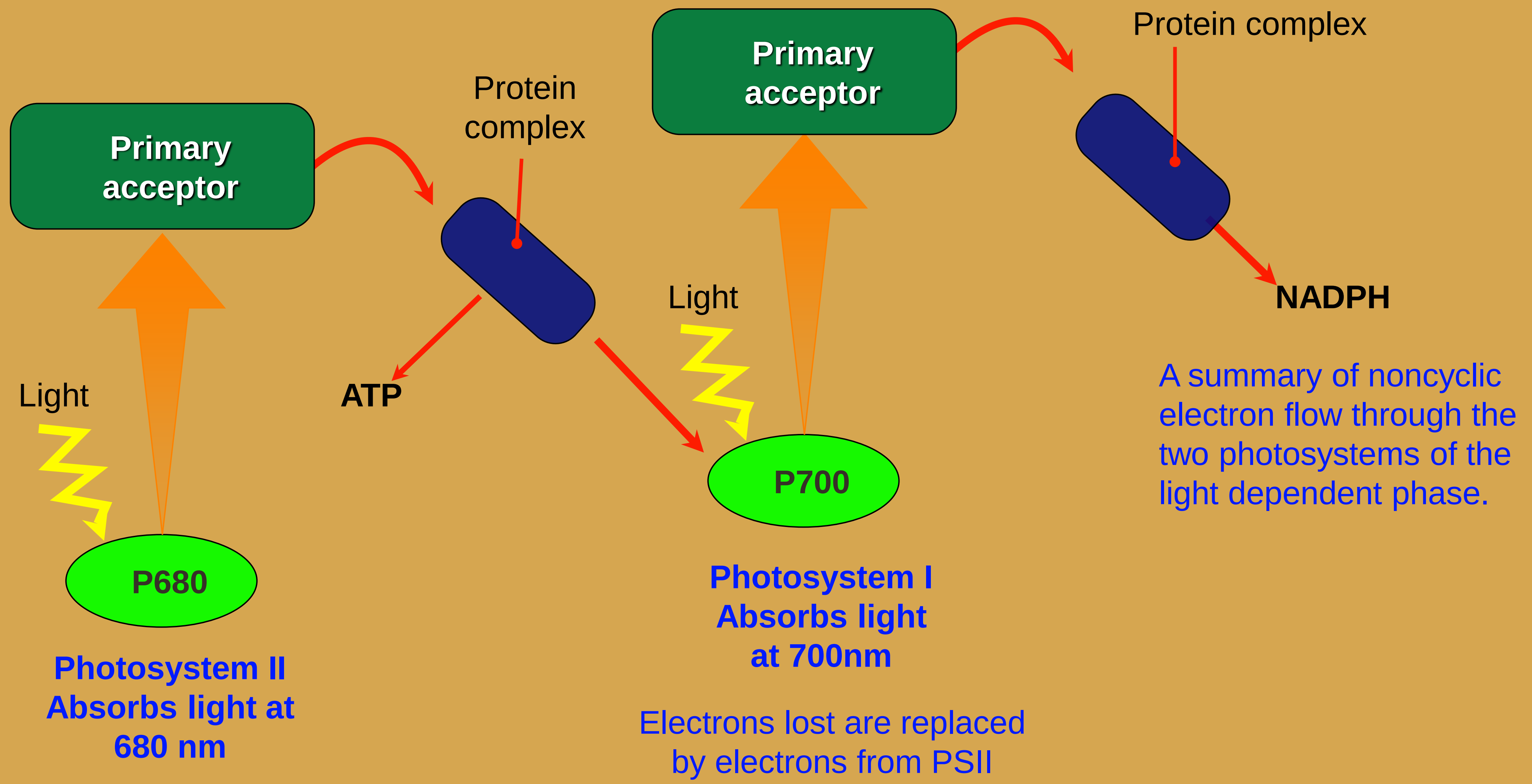
Lysine, an amino acid



Sucrose

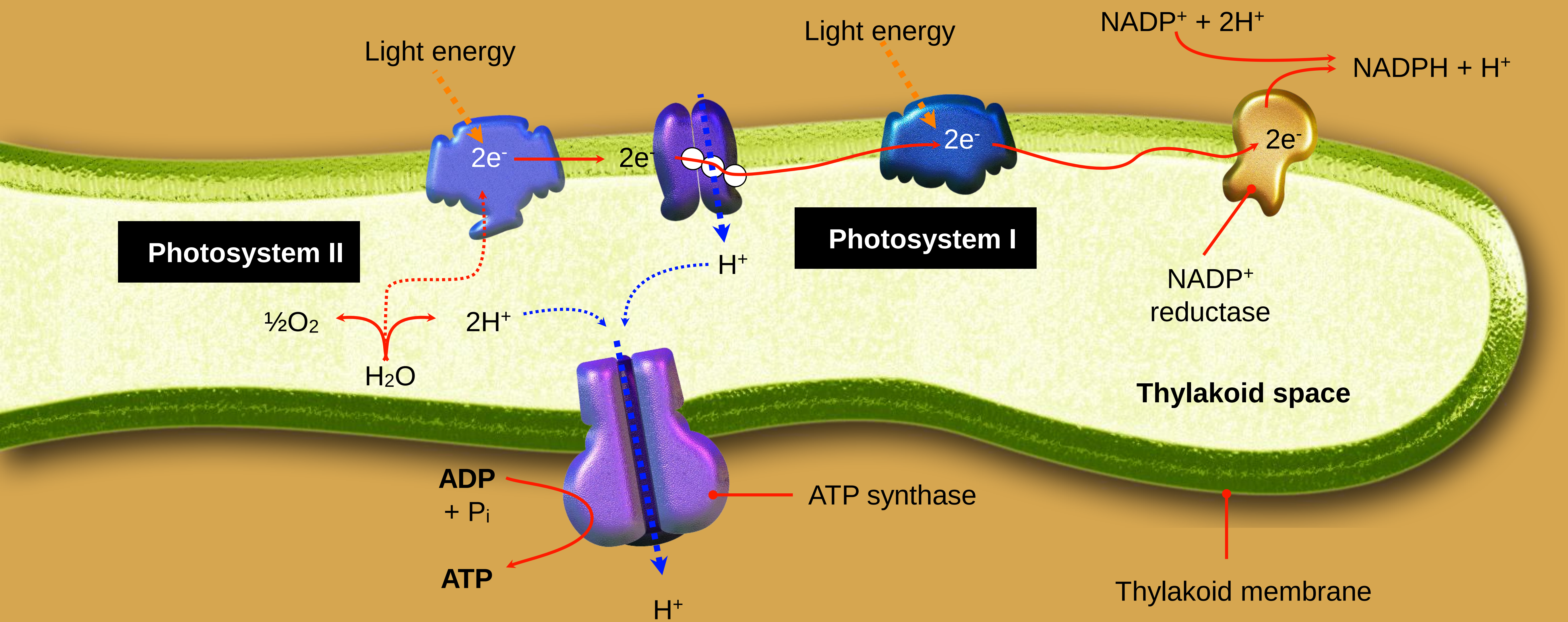
Photosystems

- The **photosystems** in green plants are protein complexes used to harvest light energy so it can be converted into chemical energy (**ATP** and **NADPH**) in the thylakoids of the chloroplasts
- The photosystems are associated with the light dependent phase of photosynthesis.
- They absorb light energy and elevate electrons to a higher energy level.



Light Dependent Phase

- When chlorophyll molecules absorb light, an electron is excited to a higher level. This electron is replaced to photosystem II in one of two ways:
  - In **non-cyclic phosphorylation** (below), the electrons lost to the electron transport chain are replaced by splitting a water molecule.
  - In **cyclic phosphorylation** electrons lost from photosystem II are replaced by those from photosystem I. ATP is generated but not NADPH.

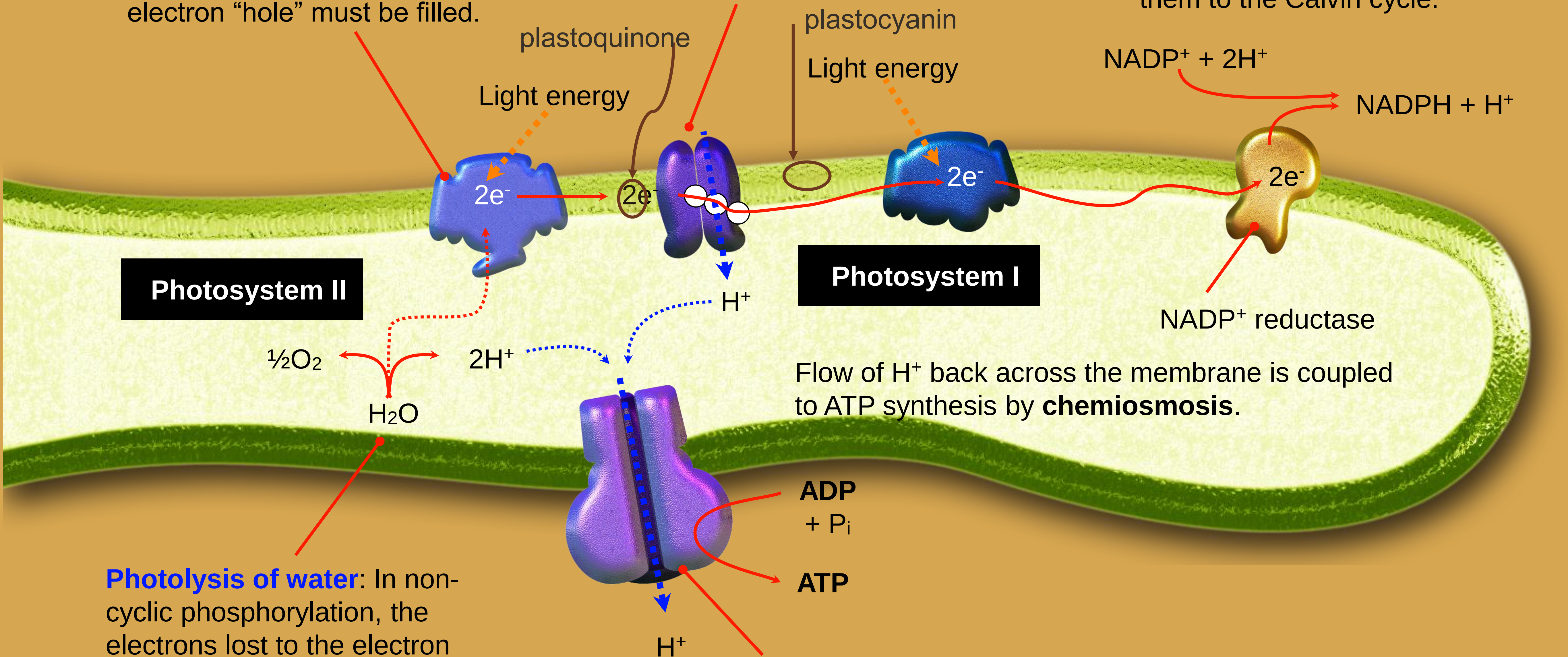


Light Dependent Phase

When **chlorophyll** molecules absorb light, an electron is excited to a higher level. This electron "hole" must be filled.

Electron transport chain: Each electron is passed from one electron carrier to another; losing energy as it goes. This energy is used to pump hydrogen ions across the thylakoid membrane.

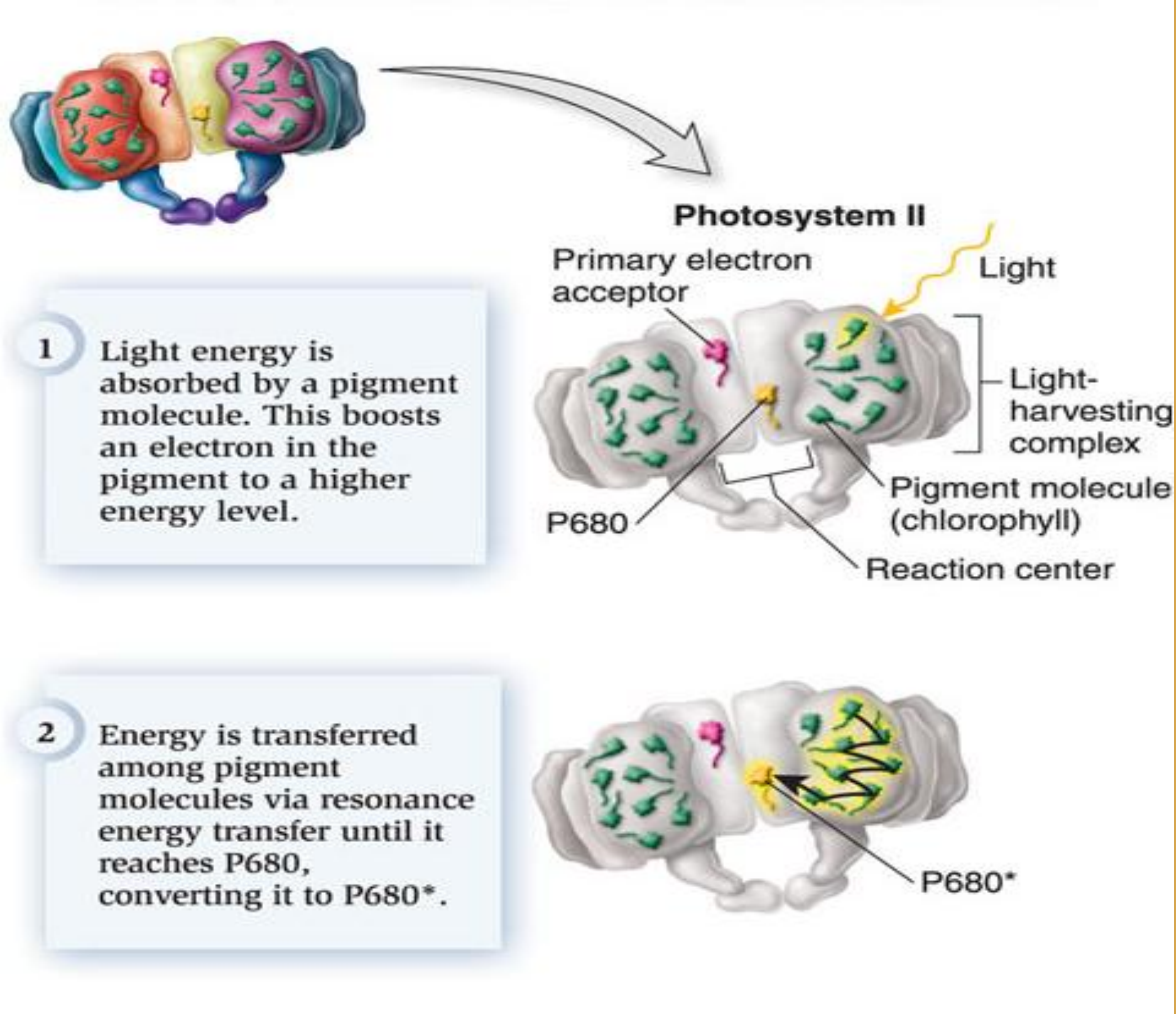
NADP is a hydrogen carrier picking up H^+ from the thylakoid and transporting them to the Calvin cycle.



Photolysis of water: In non-cyclic phosphorylation, the electrons lost to the electron transport chain are replaced by splitting a water molecule (**photolysis**) by Z protein releasing oxygen gas and hydrogen ions.

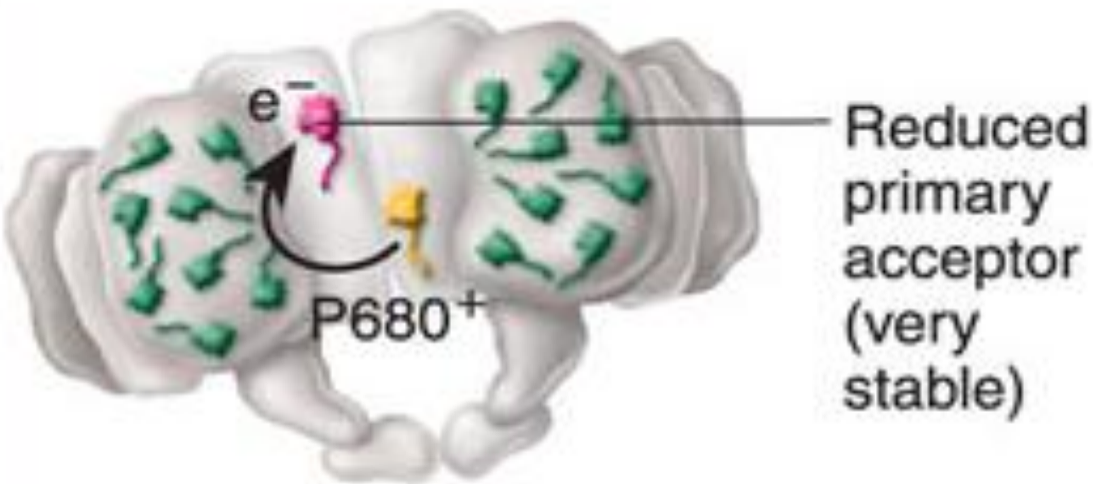
ATP synthase catalyzes the production of ATP from ADP and inorganic phosphate (P_i)

Photosytem II (PSII)

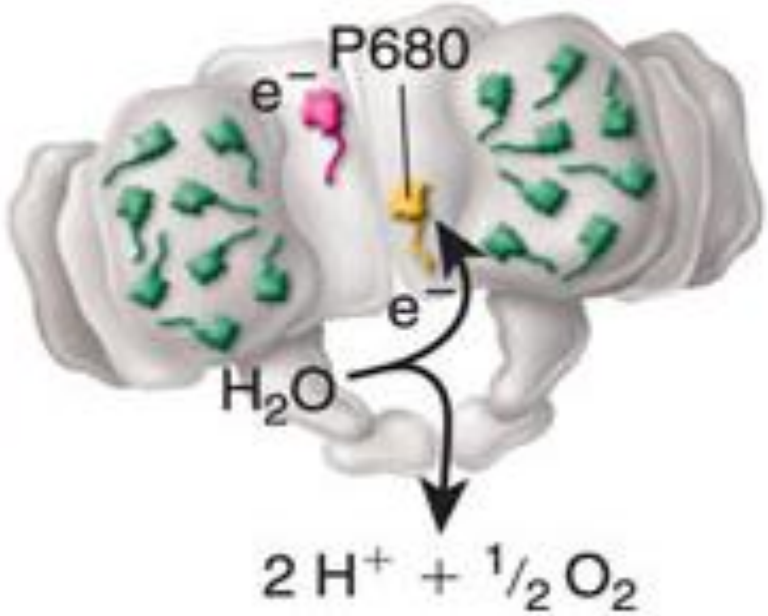


Photosytem II (PSII)

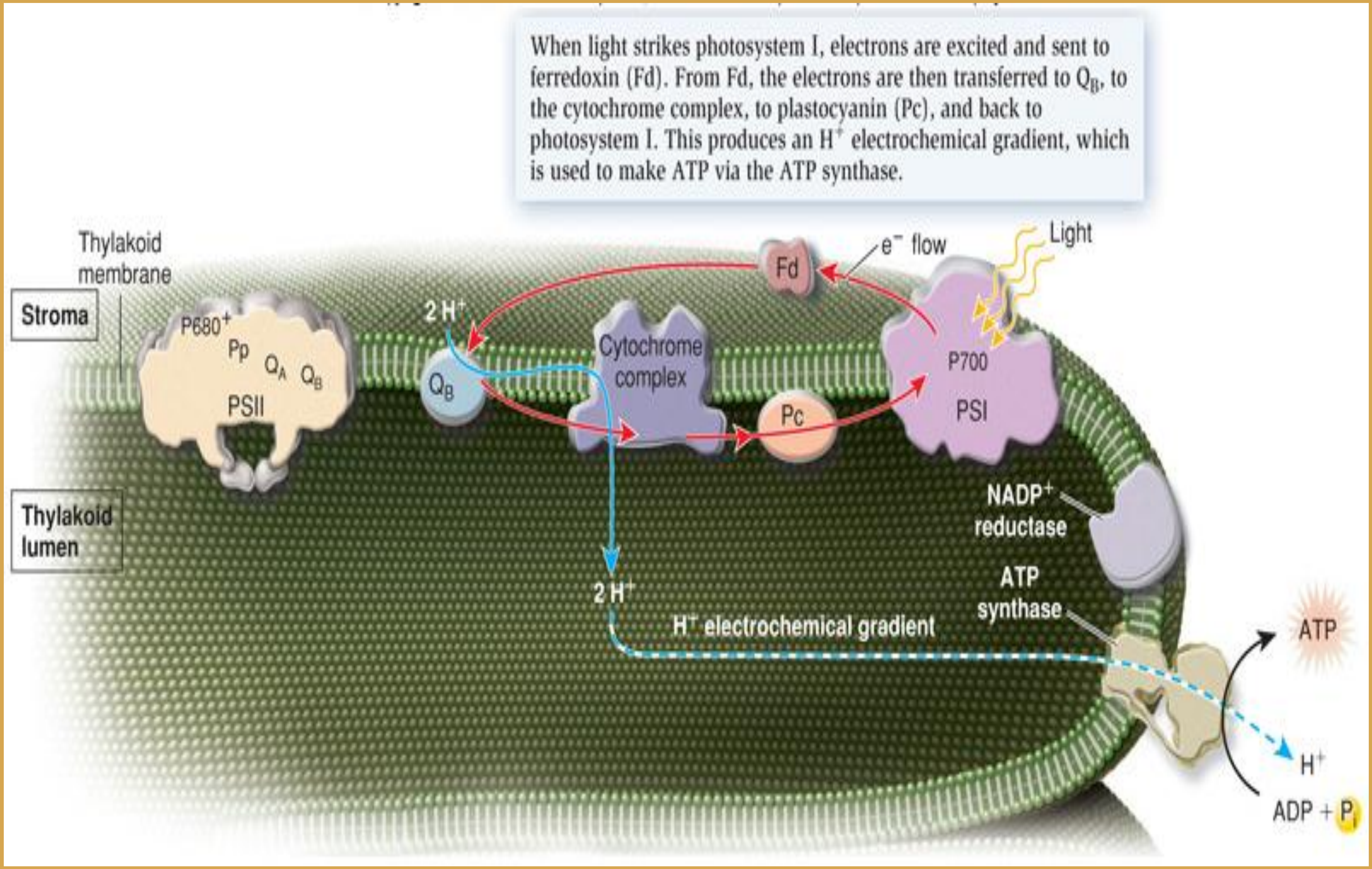
3 The high-energy electron on P680* is transferred to the primary electron acceptor, where it is very stable. P680* becomes P680$^+$.



4 A low-energy electron from water is transferred to P680$^+$ to convert it to P680. O_2 is produced.

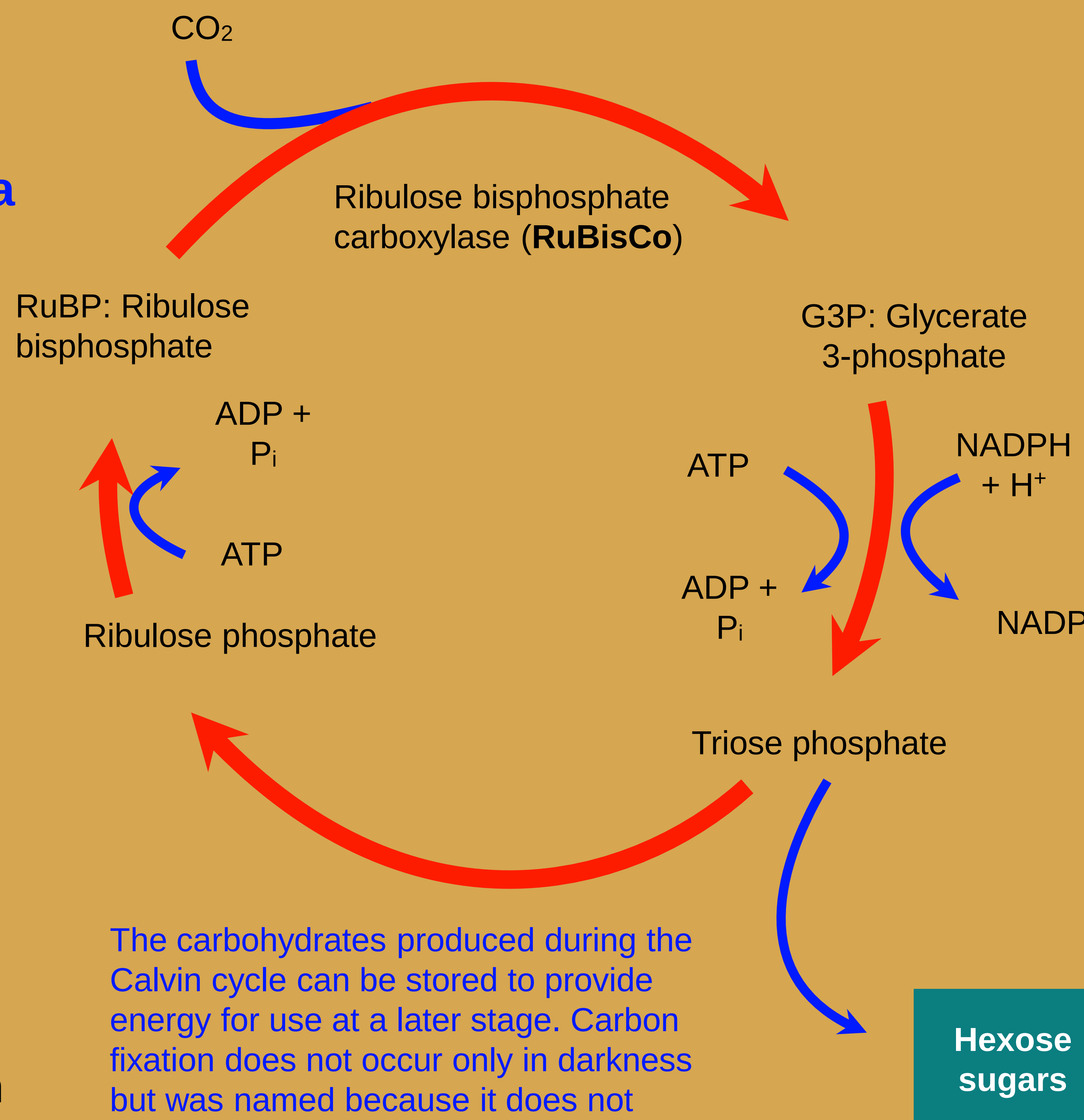


Photosytem I (PSI)



Light Independent Phase

- The light independent phase or **Calvin cycle** (carbon fixation) occurs in the **stroma** of the chloroplast.
- In the Calvin cycle, carbon atoms from CO_2 are incorporated into existing organic molecules.
  - Hydrogen (H^+) is added to CO_2 and a five carbon intermediate molecule to make carbohydrate.
  - The reducing power for carbon fixation is supplied by NADPH.
  - The enzyme involved, RuBisCo, works optimally in low oxygen environments.

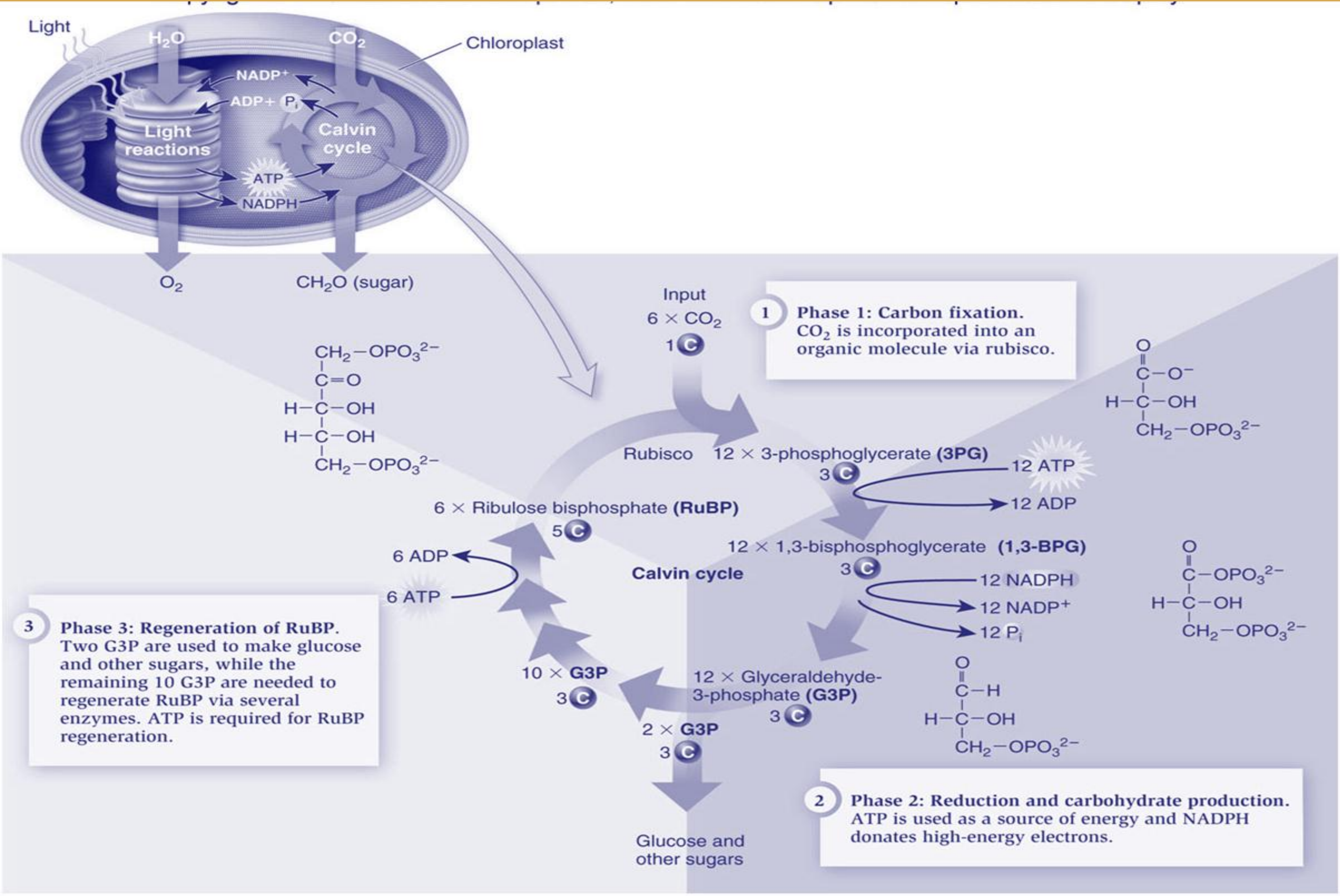


The carbohydrates produced during the Calvin cycle can be stored to provide energy for use at a later stage. Carbon fixation does not occur only in darkness but was named because it does not require light to proceed. The H+ and ATP are supplied by the light dependent phase.

3 phases

1. Carbon fixation
   - CO_2 incorporated in RuBP using rubisco
   - 6 carbon intermediate splits into 2 3PG
2. Reduction and carbohydrate production
   - ATP is used to convert 3PG into 1,3-bisphosphoglycerate
   - NADPH electrons reduce it to G3P
   - 6 $CO_2 \rightarrow$ 12 G3P
     - 2 for carbohydrates
     - 10 for regeneration
3. Regeneration of RuBP
   - 10 G3P converted into 6 RuBP using 6 ATP

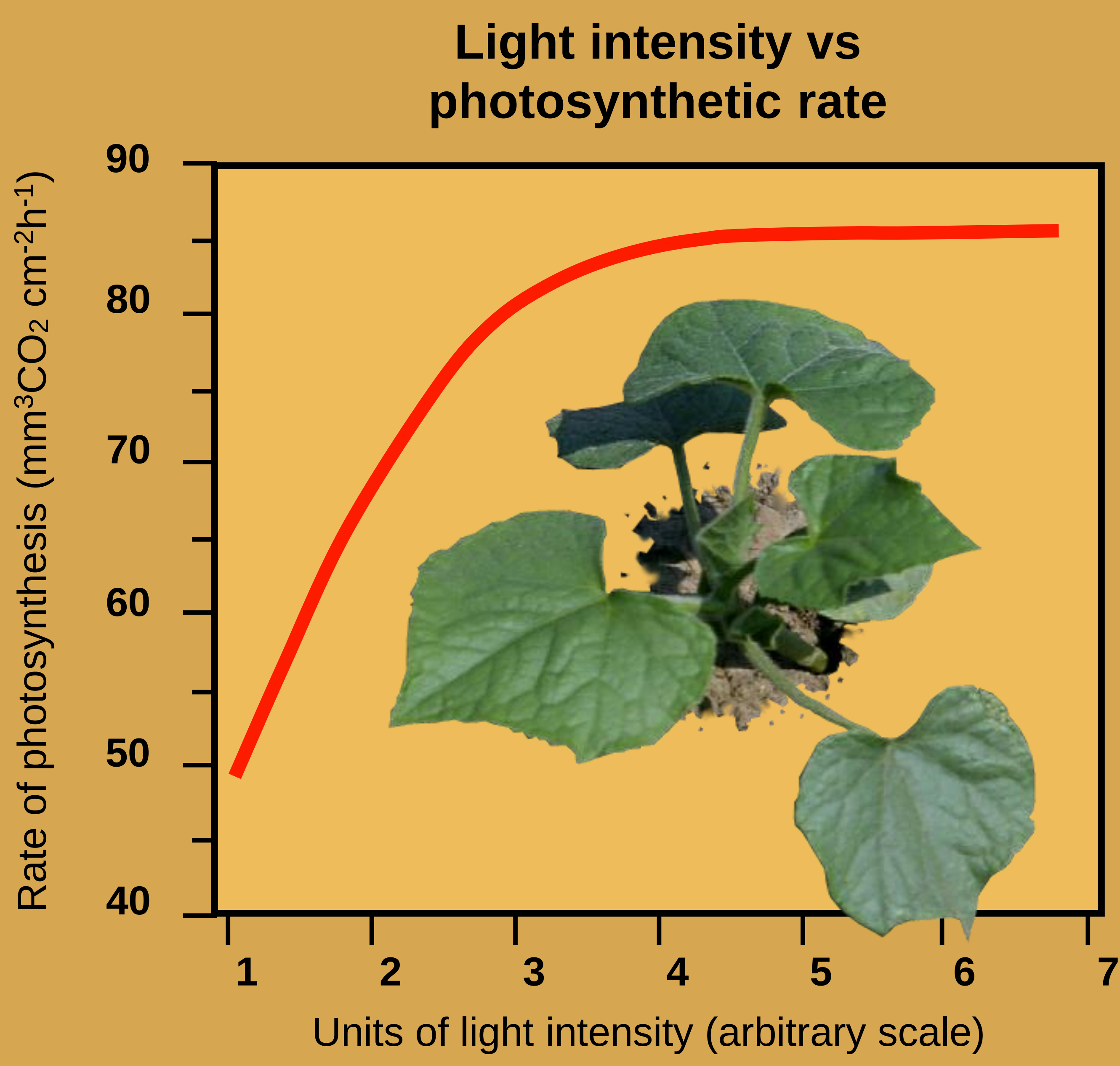
Calvin-Benson cycle



Factors Affecting Photosynthetic Rate

- The rate at which plants can make food (the **photosynthetic rate**) is dependent on environmental factors. Some factors have a greater effect than others. These include:
  - the amount of **light** available.
  - the level of **carbon dioxide** (CO_2).
  - the **temperature**.

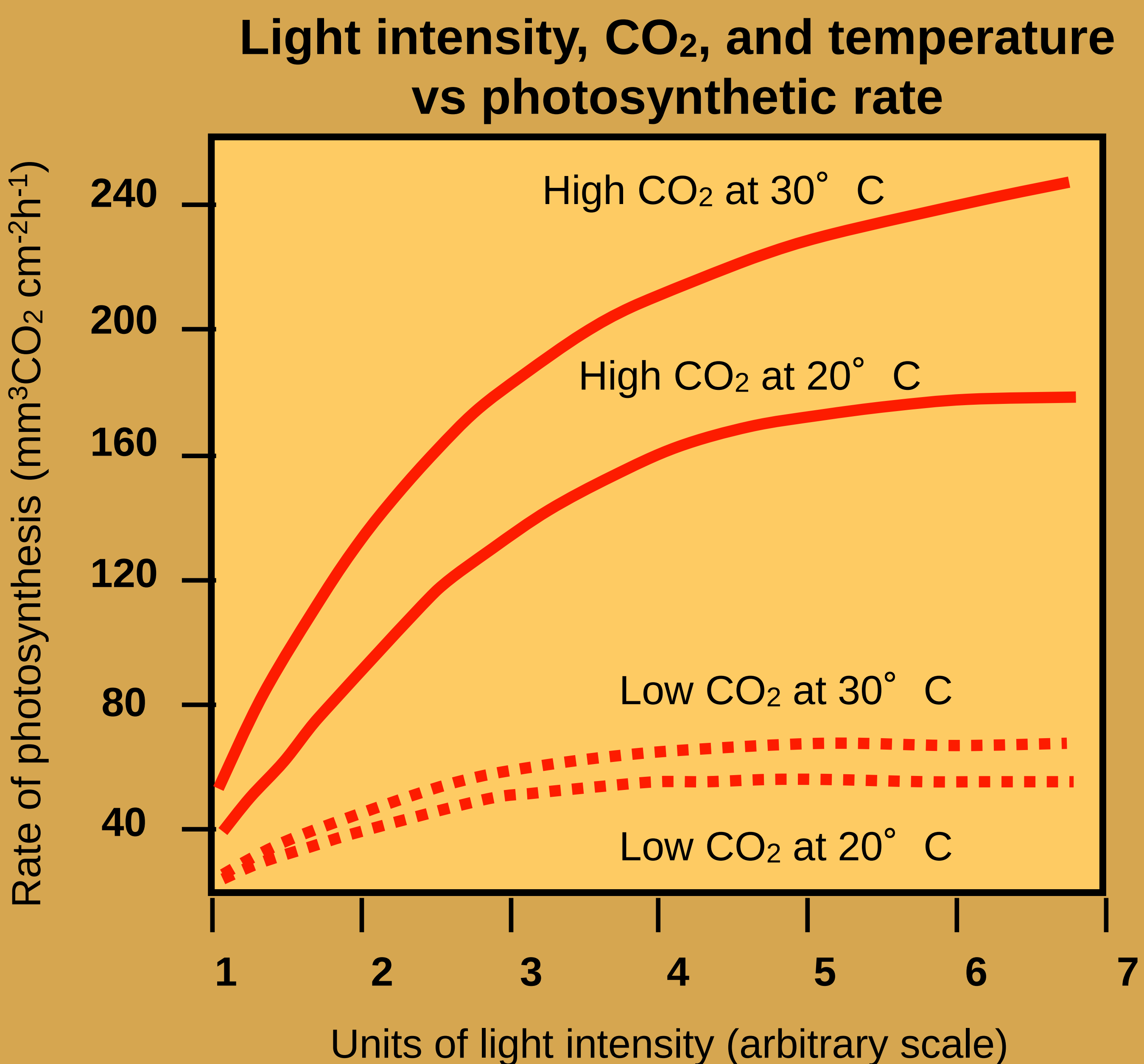
Factors Affecting Photosynthetic Rate



- The effect of **light intensity** on photosynthetic rate is shown in this experiment using cucumber plants.
- The experiment was carried out at a constant temperature and constant carbon dioxide level.
- The rate of photosynthesis increases exponentially with light intensity until a maximum rate is achieved. At this point increasing the light intensity has no effect on photosynthetic rate and the rate of photosynthesis reaches a **plateau**.

Factors Affecting Photosynthetic Rate

- This graph shows how temperature and CO_2 levels affect photosynthetic rate in cucumber plants.
- Photosynthetic rate increases as the **CO_2 concentration** increases. At high concentrations, the rate of photosynthesis begins to slow as limiting factors other than CO_2 become important.
- An increase in **temperature** increases photosynthetic rate because of its effect on enzyme activity. However, temperatures exceeding the **optimum** will eventually decrease photosynthetic rates because of the detrimental effects of heat on enzyme structure.



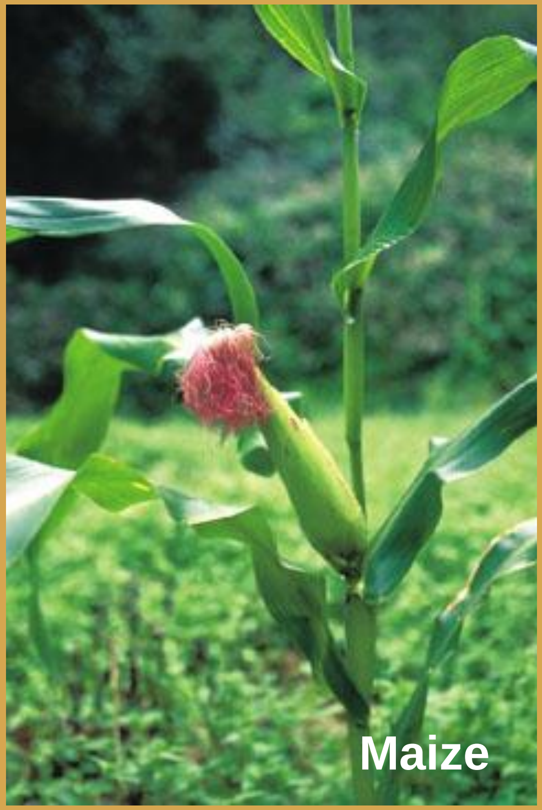
Increasing the temperature when CO_2 is limiting has little effect on photosynthetic rate.

Photorespiration

- RuBP + $CO_2 \rightarrow$ 2 3PG
  - Rubisco functions as a carboxylase
  - C_3 plants make 3PG
- Rubisco can also be an oxygenase
  - Adds O_2 to RuBP eventually releasing CO_2
  - Photorespiration
  - Using O_2 and liberating CO_2 is wasteful
- More likely in hot and dry environment
- Favored when CO_2 low and O_2 high

Photosynthesis in C_4 Plants

- In many plants, the first detectable compound made during photosynthesis is a 3-carbon compound called **glycerate 3-phosphate** (3GP)**.** Plants that produce 3GP are termed **C_3 plants**.
- In some plants, **oxaloacetate**, a 4-carbon molecule, is the first compound to be made. Plants that produce this compound are termed **C_4 plants**.
- C_4 plants include the tropical monocots important as food crops:
  - Sugar cane (*Saccharum officinarum*)
  - Maize (*Zea mays*)
  - Sorghum (*Sorghum bicolor*)



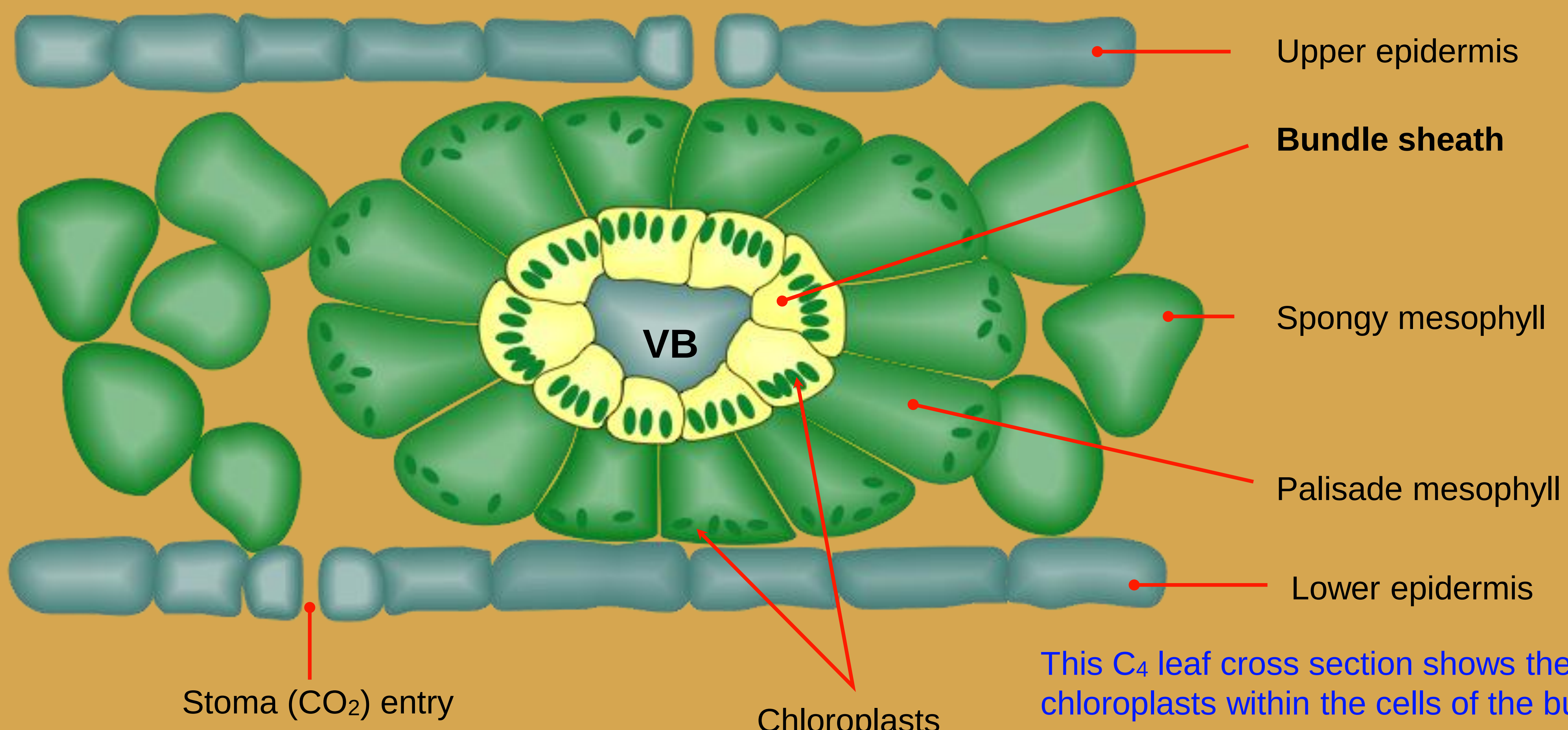
Photosynthesis in C_4 Plants

- C_4 plants are capable of **high rates of photosynthesis** in high temperature-high light environments.
- C_4 plants have a **high yield of photosynthetic products** compared to C_3 plants, giving them a competitive advantage in tropical environments.
- This characteristic is also an advantage for commercial crop plants such as maize and sugar cane.

C_4 plants thrive in hot, humid tropical conditions such as those found in **Hawaii** (top right) and **Fiji** (bottom right).

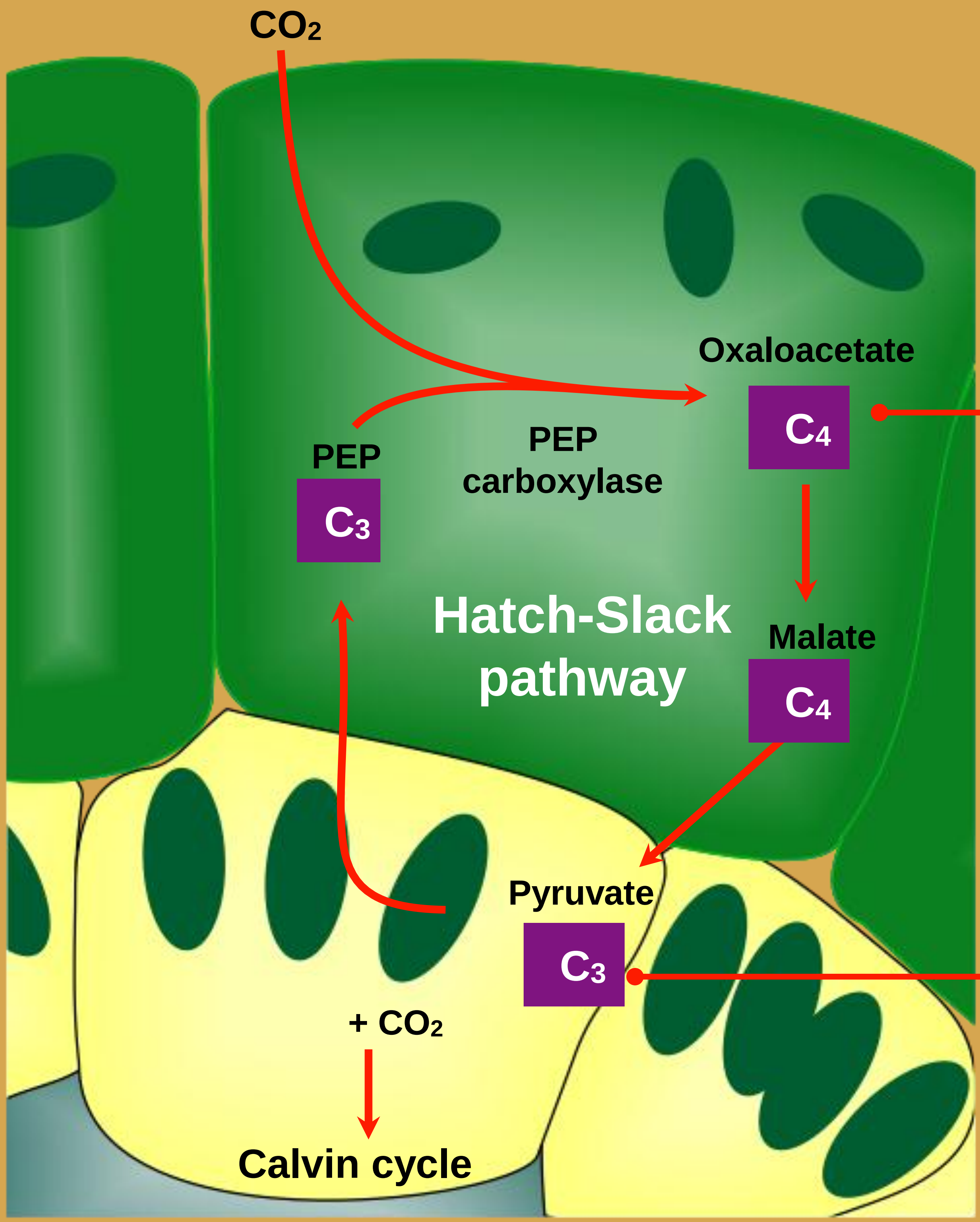
Photosynthesis in C_4 Plants

- C_4 plants have chloroplasts in both the mesophyll and the bundle sheath cells.
- They increase photosynthetic rates by separating **Rubisco** from atmospheric oxygen, fixing carbon as 4-carbon intermediates in the mesophyll cells and using these to ferry the fixed carbon to Rubisco in the bundle-sheath cells.



This C_4 leaf cross section shows the chloroplasts within the cells of the bundle sheath and the palisade mesophyll. Tightly packed mesophyll cells keep oxygen away from the **bundle sheath** cells, which surround the vascular bundle (**VB**).

Photosynthesis in C_4 Plants



A low oxygen environment is essential for the enzyme **ribulose bisphosphate carboxylase** (Rubisco) to function optimally in the Calvin cycle. By protecting RuBisCo from oxygen, C4 plants achieve high photosynthetic rates.

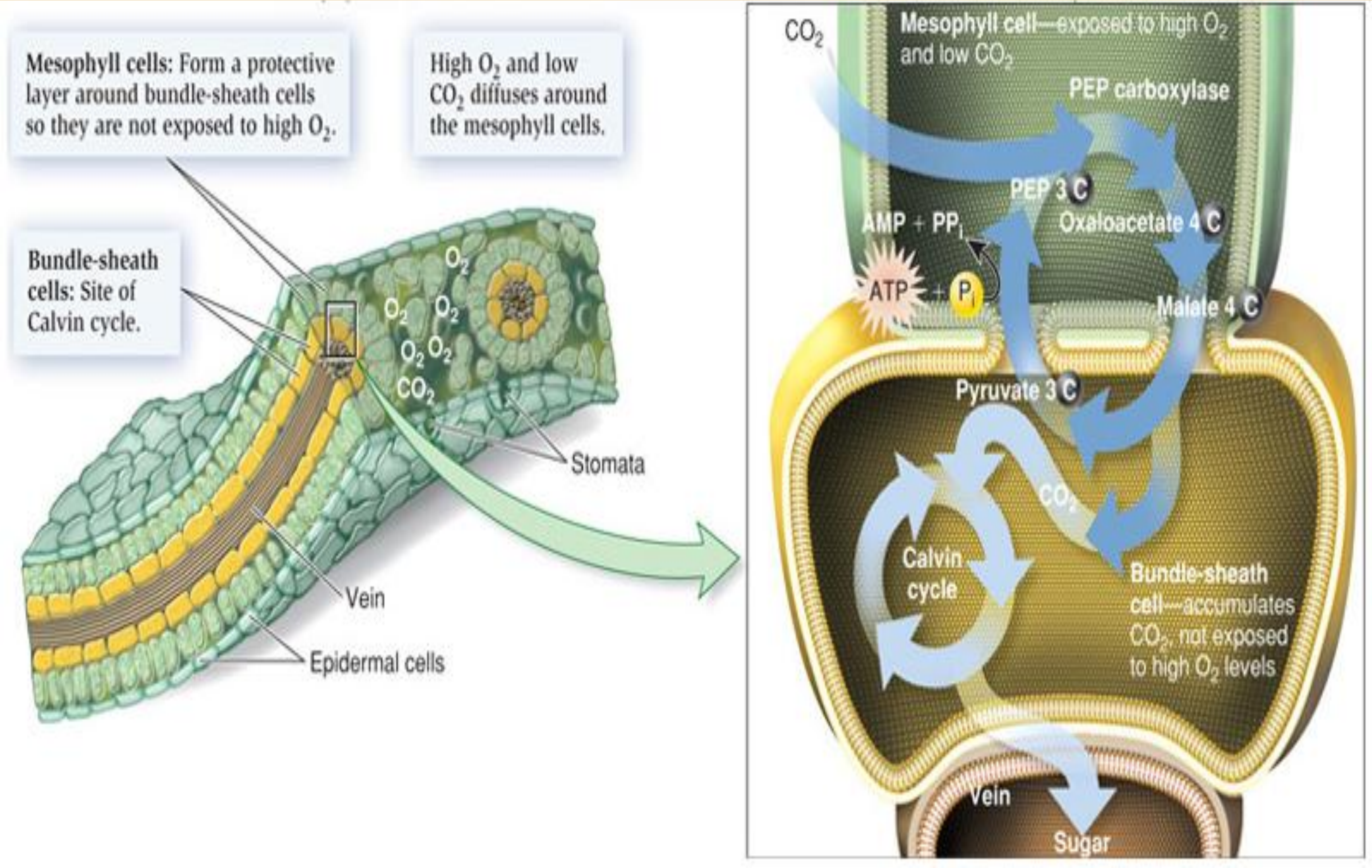
1 Hatch and Slack pathway

Photosynthesis in the **palisade mesophyll cells** captures light energy in the chloroplasts and fixes CO_2 (as a 4C intermediate) in the cytoplasm. C_4 plants can fix large quantities of CO_2 because the enzyme **PEP carboxylase** has a high affinity for CO_2 and can incorporate it into the 3C compound phophoenol pyruvate (PEP) at low levels.

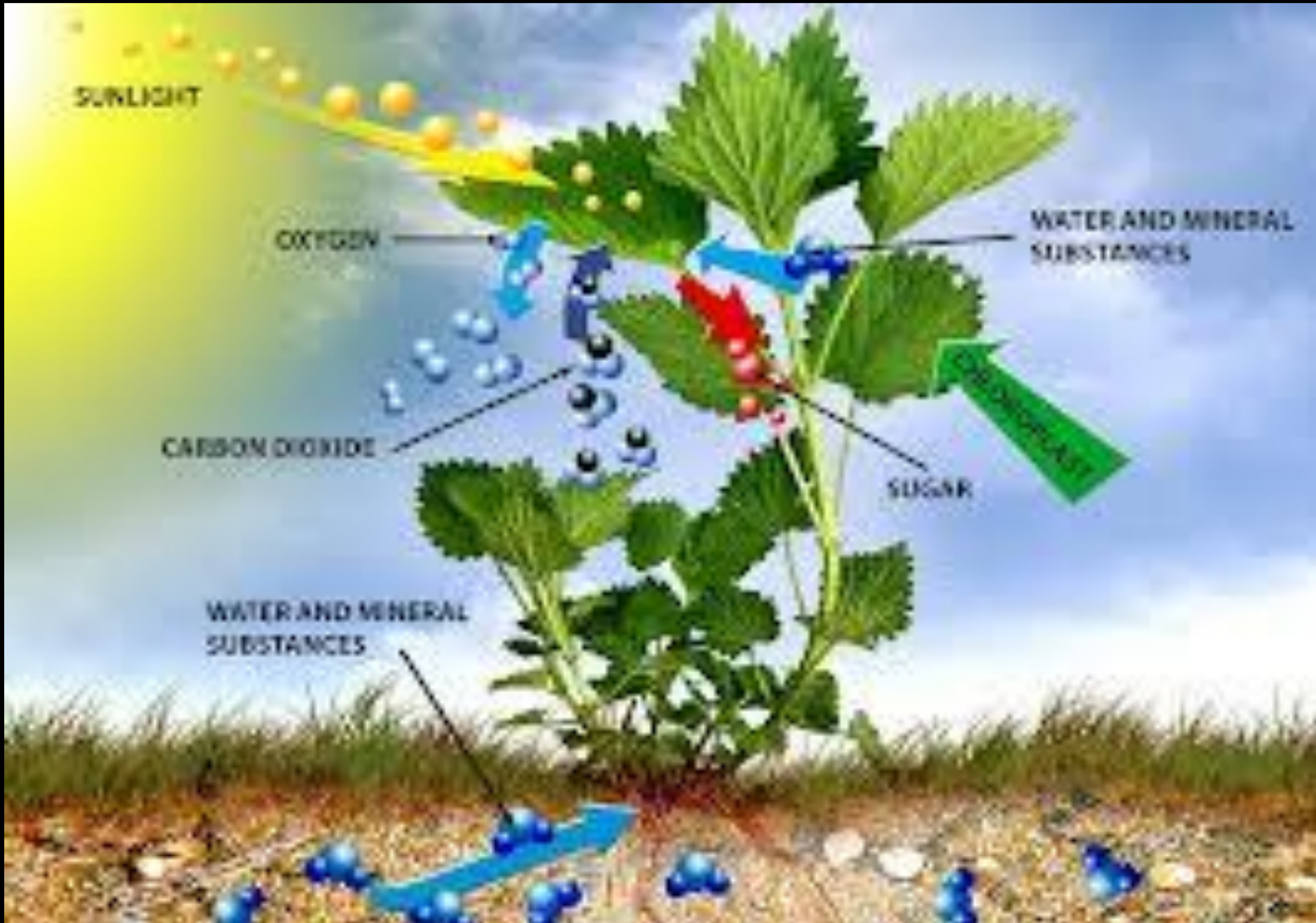
2 Calvin cycle (bundle sheath)

Malate is transfered from the palisade cells to the inner bundle sheath where it is broken down to pyruvate. CO_2 is released for use in the Calvin cycle.

C_4 plants



Mesophyll cells: Form a protective layer around bundle-sheath cells so they are not exposed to high O_2.
High O_2 and low CO_2 diffuses around the mesophyll cells.
Bundle-sheath cells: Site of Calvin cycle.
O_2
O_2
O_2
O_2
O_2
O_2
CO_2
Stomata
Vein
Epidermal cells
CO_2
Mesophyll cell—exposed to high O_2 and low CO_2
PEP carboxylase
PEP 3 C
AMP + PP_i
Oxaloacetate 4 C
ATP + P_i
Malate 4 C
Pyruvate 3 C
CO_2
Calvin cycle
Bundle-sheath cell—accumulates CO_2, not exposed to high O_2 levels
Vein
Sugar


SUNLIGHT
OXYGEN
WATER AND MINERAL SUBSTANCES
CARBON DIOXIDE
SUGAR
WATER AND MINERAL SUBSTANCES