Big Idea 2: Biological systems utilize free energy and molecular building blocks to grow, to reproduce and to maintain dynamic homeostasis.

Enduring understanding 2.A: Growth, reproduction and maintenance of the organization of living systems require free energy and matter.

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

a. Autotrophs capture free energy from physical sources in the environment.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Photosynthetic organisms capture free energy present in sunlight.

2. Chemosynthetic organisms capture free energy from small inorganic molecules present in their environment, and this process can occur in the absence of oxygen.

- Process Energy

Chemical Energy

- The activities of cells, tissues, organs or even whole organisms depend on chemical energy
- This chemical energy is used to produce ATP ("cellular gasoline")
- The ultimate source of energy used by cells to produce ATP and the mechanism of ATP production does vary somewhat between life forms

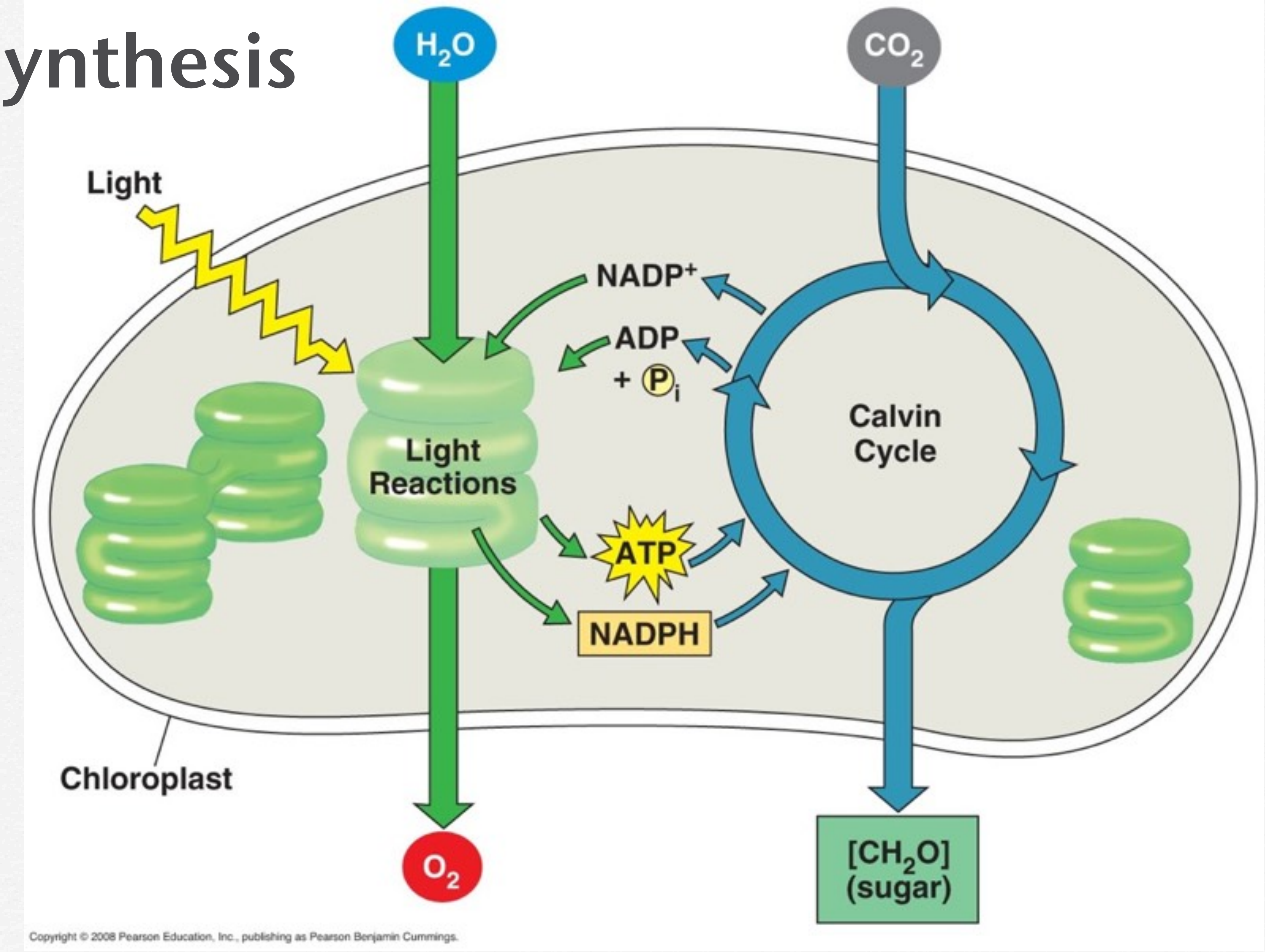
Processing Energy

- THE ULTIMATE SOURCE OF ENERGY (FOR MOST) LIVING ORGANISMS COMES FROM THE SUN!
- THE MAJORITY OF ENERGY PROCESSING OCCURS THROUGH PHOTOSYNTHESIS AND CELLULAR RESPIRATION
- Phototrophs: obtain energy from light
- Chemotrophs: obtain energy from chemicals

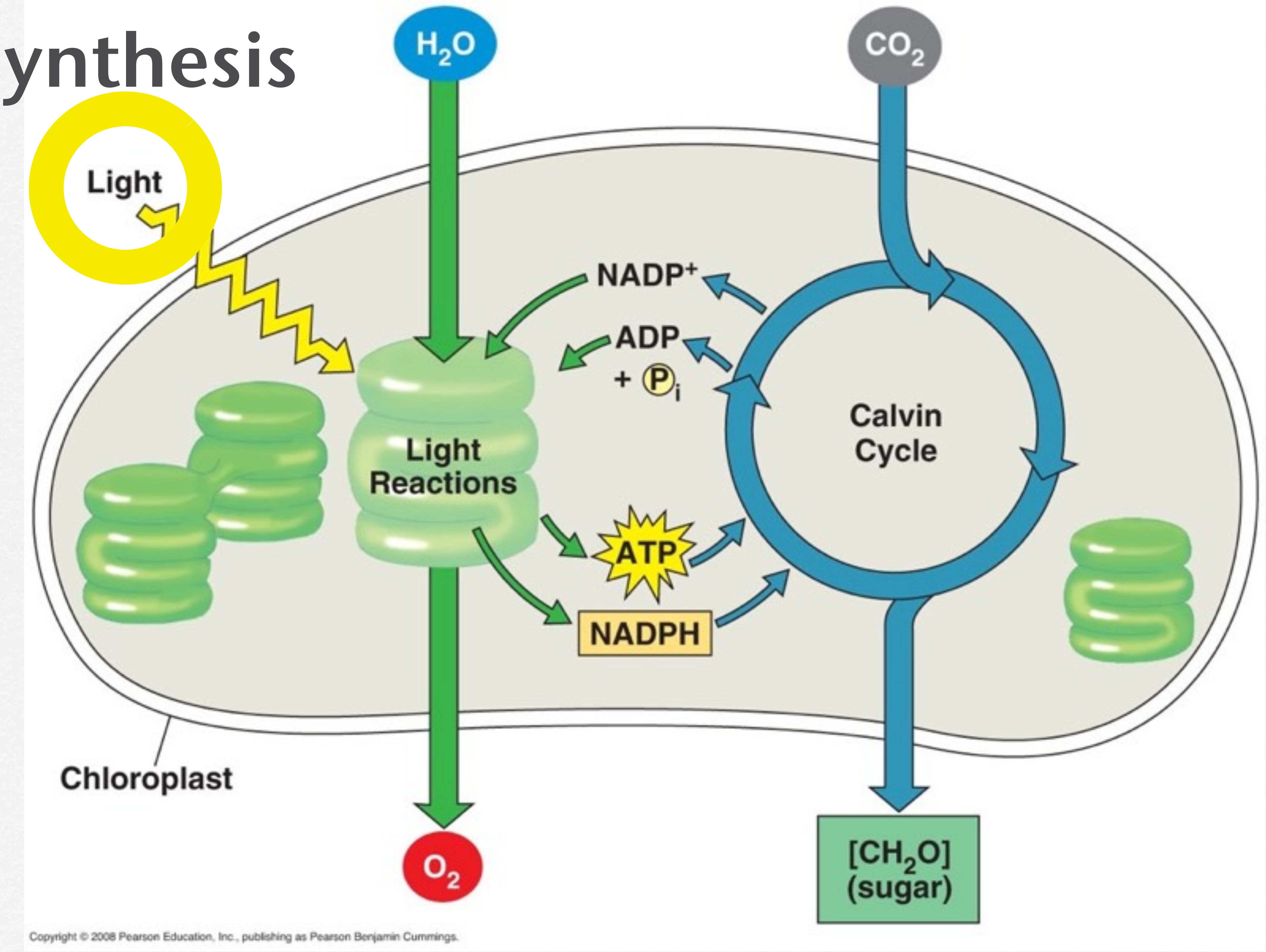
Processing Energy

- Phototrophs: obtain energy from light
  - The process of photosynthesis converts light energy into chemical energy.
  - Light energy takes carbon dioxide and water and converts them into sugars. These sugar molecules store energy in their chemical bonds

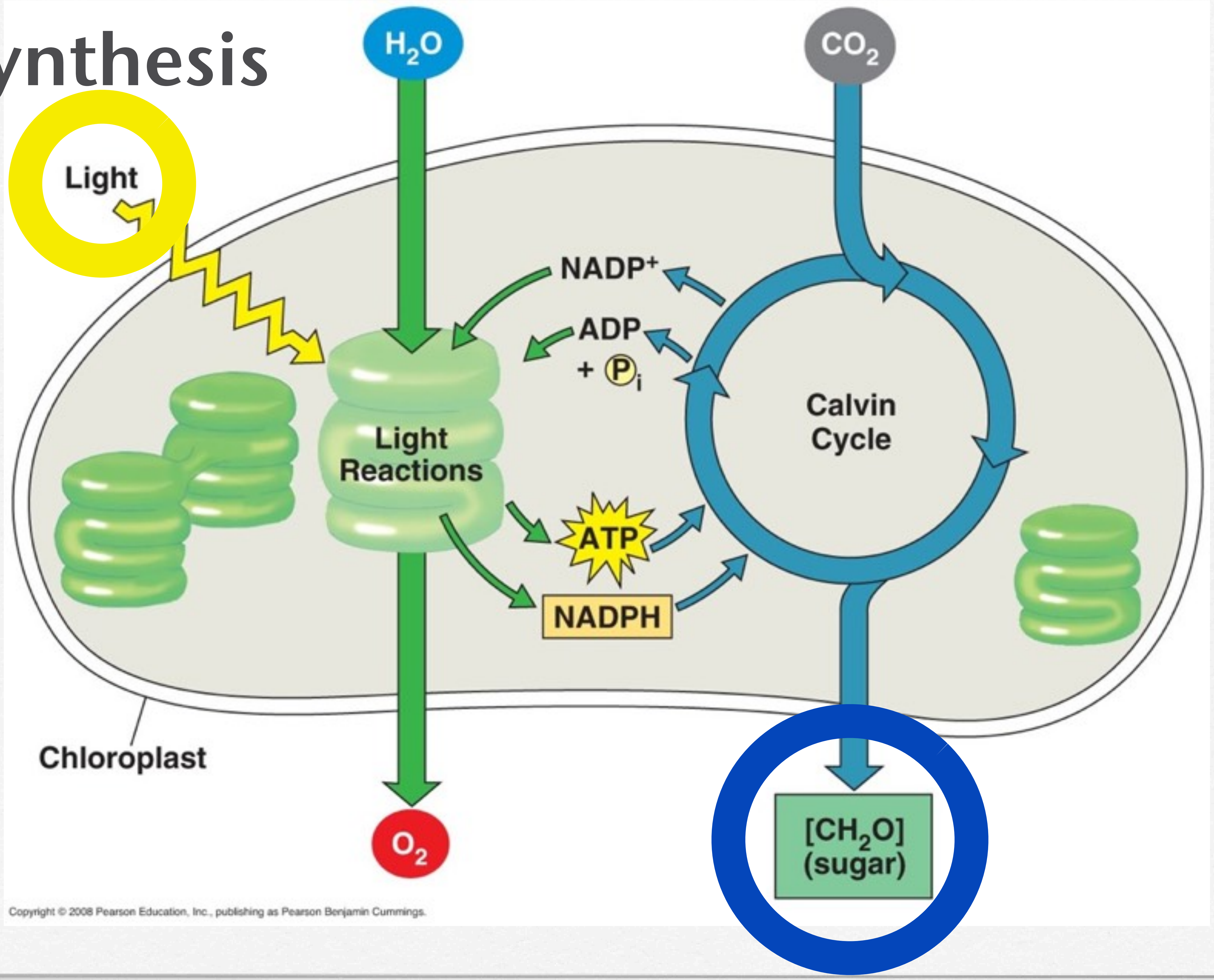
Photosynthesis



Photosynthesis



Photosynthesis



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Processing Energy

- Chemotrophs: obtain energy from chemicals
  - All cells use harness the energy in chemical bonds to produce a molecule called ATP.
  - The process that produces ATP from sugars (most of time)is called cellular respiration.
  - In general all cells do cellular respiration, they use sugar to make ATP, the big distinction lies in whether the organism makes its own sugars or has to consume its sugars

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

b. Heterotrophs capture free energy present in carbon compounds produced by other organisms.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Heterotrophs may metabolize carbohydrates, lipids and proteins by hydrolysis as sources of free energy.

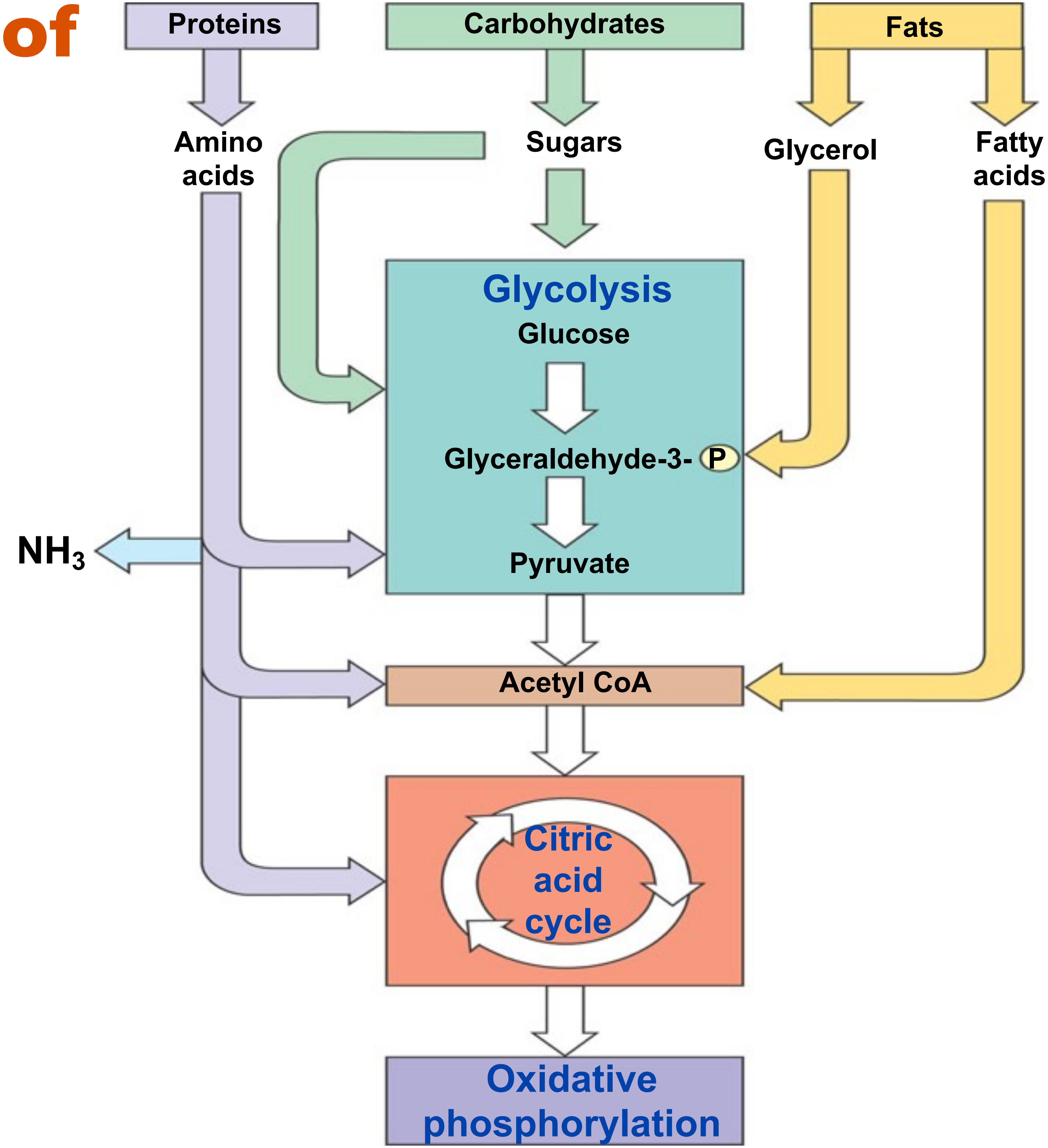
2. Fermentation produces organic molecules, including alcohol and lactic acid, and it occurs in the absence of oxygen.

✘ Specific steps, names of enzymes and intermediates of the pathways for these processes are beyond the scope of the course and the AP Exam.

Versatility of Catabolic Pathways

- Glucose is the standard fuel used when teaching/learning about cellular respiration. Free glucose is however not common in most diets.
- Cells use a variety of other "food fuels" such as fats, proteins and other types of sugars.
- When these other fuels are used they are oxidized into smaller subunits which are then fed into the metabolic pathways of cell respiration at various points along the path.

Versatility of Catabolic Pathways



Versatility of Catabolic Pathways

- Sugars are most commonly used, they are the first fuel of choice by most cells.
- Fats actually have 2X more potential energy per gram than sugars.
  - This makes fats an excellent choice for a storage fuel.
- Proteins can also be used by cells to generate ATP, but this is the cells last choice.
  - Most amino acids are needed for building blocks, not fuel.
  - Furthermore the catabolism of amino acids produces a very toxic by product in ammonia

Versatility of Anabolic Pathways

- Metabolism is both versatile and adaptable.
- Not all food is used for ATP production, cells need the molecules from food to build, grow and repair as well.
    - Intermediates from the citric acid cycle can be used to generate half of all 20 amino acids.
    - Intermediates from glycolysis can be used to generate fats (stored energy for later) when fuel is abundant.
        - This is why eating to much sugar can make you fat.

Whether these food molecules are used for energy or building blocks, the implication is that cells have the ability to decide. This must mean that they can detect the environment and respond accordingly.

Cell Respiration

Main Idea: There are alternate ways to make ATP that do not require the presence of oxygen.

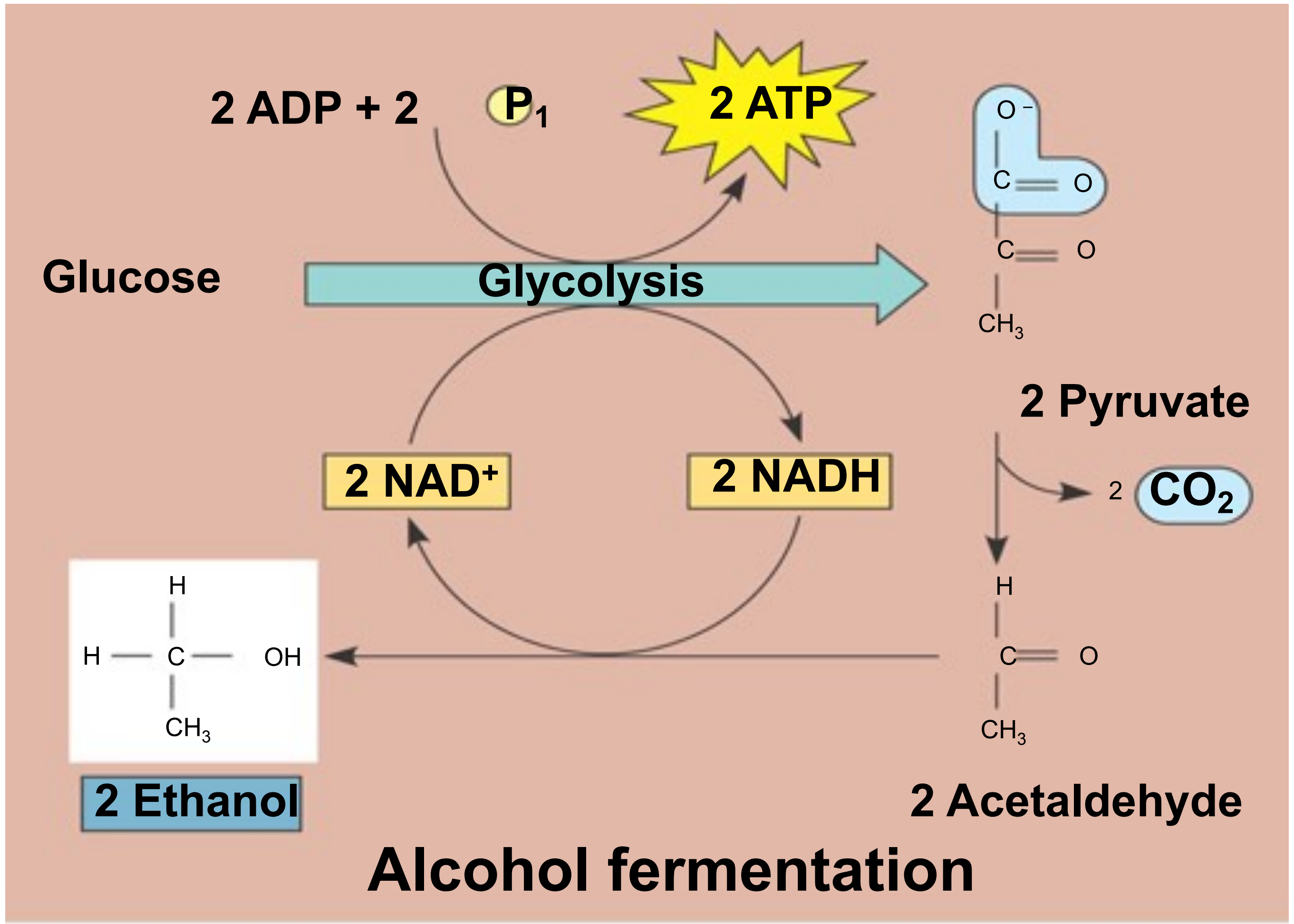
Fermentation

- Fermentation is a mechanism that harvests chemical energy (ATP) without oxygen and without an electron transport chain.
- Glycolysis oxidizes organic compounds with or without oxygen and without an electron transport chain.
- Fermentation is an extension of glycolysis that allows for the continuous production of ATP by substrate level phosphorylation.
  - It does require however a continuous supply of electron carriers (NAD^+)

Fermentation

- A continuous supply of electron carriers (NAD^+) is not a problem when oxygen is present because NADH can pass its electrons into the mitochondria.
- Without oxygen NADH needs to "dump" its electrons somewhere else.
- Fermentation is the extension of glycolysis involves NADH transferring its electrons to pyruvate, so that it is free to oxidize more fuel (glucose).
  - There are two types of Fermentation
    - Lactic Acid Fermentation
    - Alcohol Fermentation

Two Types of Fermentation



Alcohol fermentation

Many bacteria and yeasts use this alcohol fermentation in anaerobic conditions, they are used in brewing and baking

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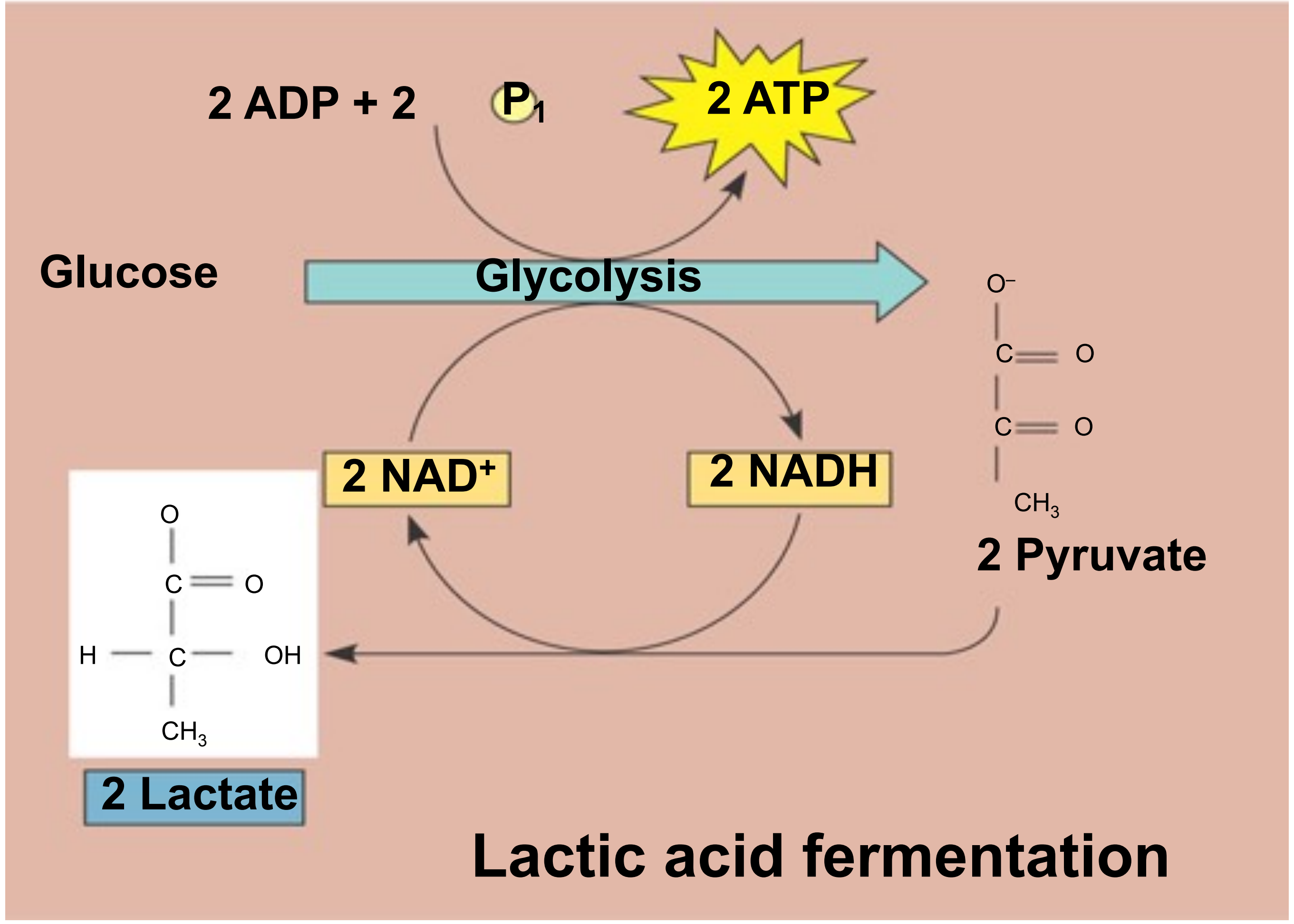


Lactic acid fermentation

Bacteria and fungi that use this lactic fermentation are used in the dairy industry to make cheeses and yogurts

also used by muscle cells but will discuss later

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

c. Different energy-capturing processes use different types of electron acceptors.

To foster student understanding of this concept, instructors can choose an illustrative example such as:

1. NADP in photosynthesis

2. Oxygen in cellular respiration

Catabolic Pathways in General

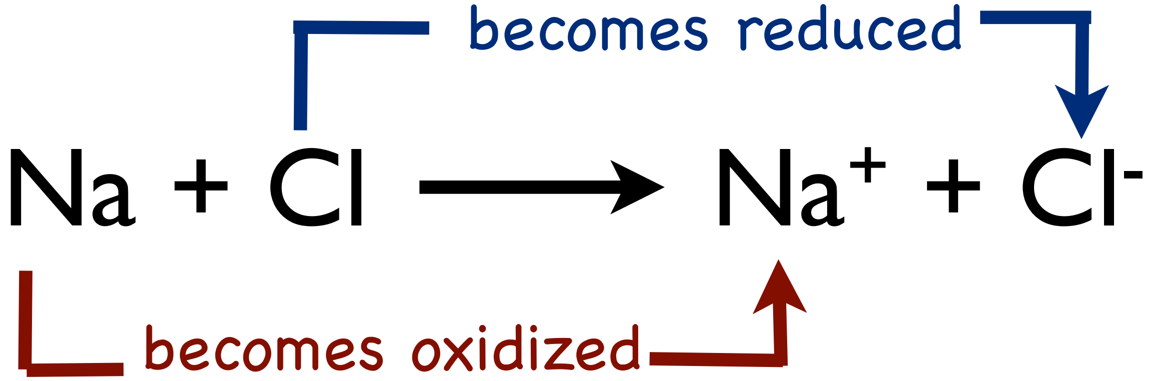
- Chemical bonds store potential energy.
- The more bonds, the more potential energy.
    - Larger molecules have more bonds thus more potential energy.
- Breaking these bonds releases the potential energy.
- A cell is able to capture some of this energy and use it ultimately to do work.
- Thermodynamics reminds us that not all the energy can be transferred and thus heat is also liberated in these reactions.

Catabolic Molecules

- The molecules that can be used for fuel are sugars, fats and proteins.
  - *Glucose* is the most common large organic molecule used for fuel and consequently the one addressed in this powerpoint.
- The energy released from the catabolism of glucose is -686 kcal per mole.
- The energy released from glucose far exceeds the required energy need for most cellular work.
- As a result this energy must be transferred to many smaller molecules (ATP) each with potential energy that is more on scale with cellular work

The principle of the “redox reaction”

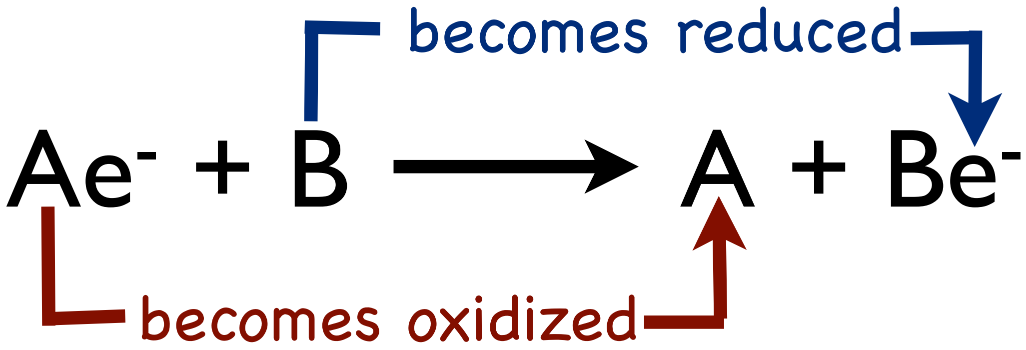
- Oxidation Reactions- removes electrons from a substance
- Reduction Reactions- adds electrons to a substance



becomes reduced

$$Na + Cl \longrightarrow Na^+ + Cl^-$$

becomes oxidized



becomes reduced

$$Ae^- + B \longrightarrow A + Be^-$$

becomes oxidized

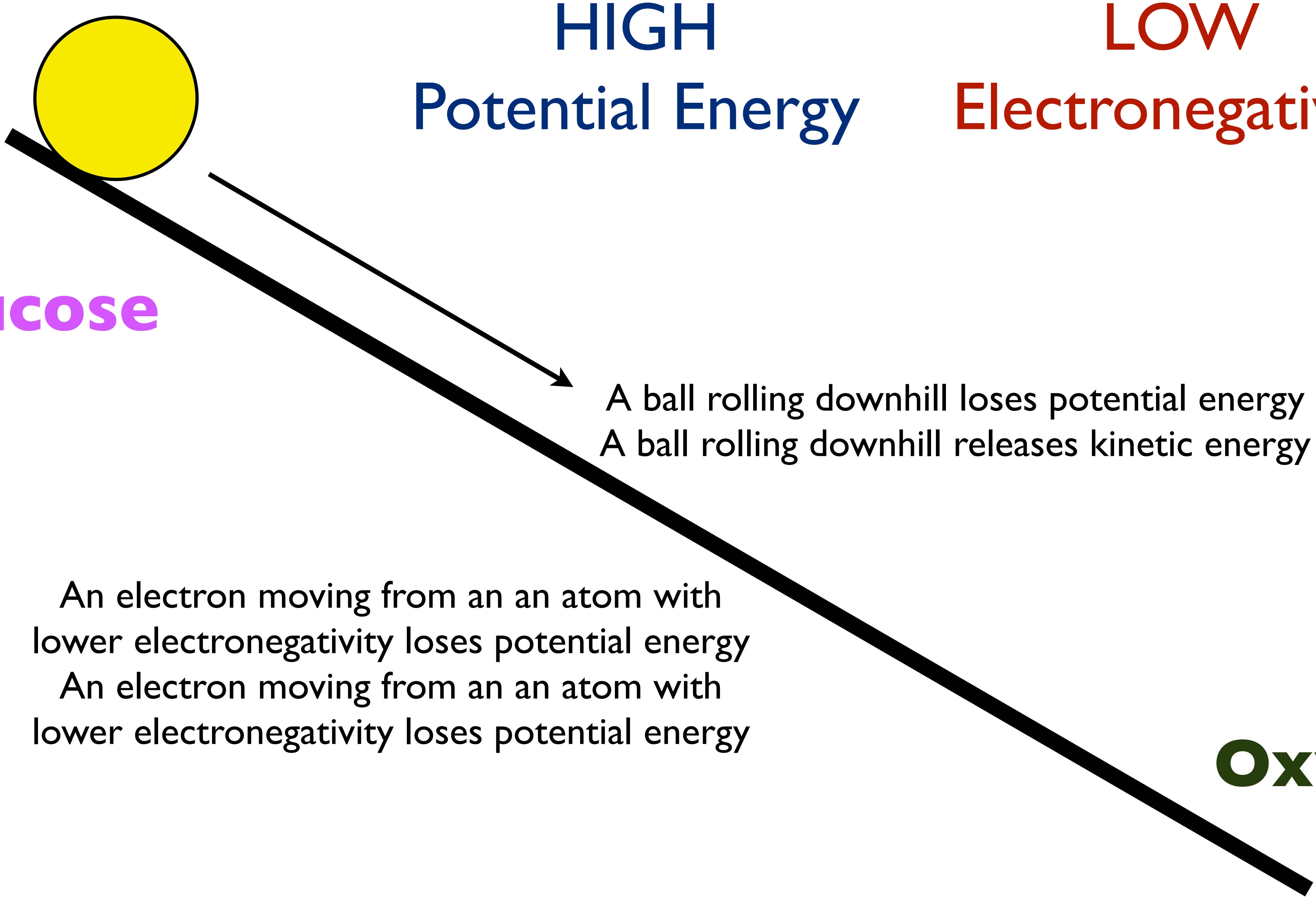
Ae⁻ the “electron donor” is the ***reducing agent***

B the “electron acceptor” is the ***oxidizing agent***

Redox Rxns Release Energy

- Energy is required to pull electrons away from an atom.
- The more electronegative the atom, the more energy is needed to pull away that/those electrons.
    - *recall: electronegativity measures the pull that atom exerts on its electrons*
- An electron(s) loses potential energy if moves from a less electronegative atom to a more electronegative atom.

Recall Redox Analogy



HIGH
Potential Energy

LOW
Electronegativity

Glucose

A ball rolling downhill loses potential energy
A ball rolling downhill releases kinetic energy

An electron moving from an an atom with
lower electronegativity loses potential energy
An electron moving from an an atom with
lower electronegativity loses potential energy

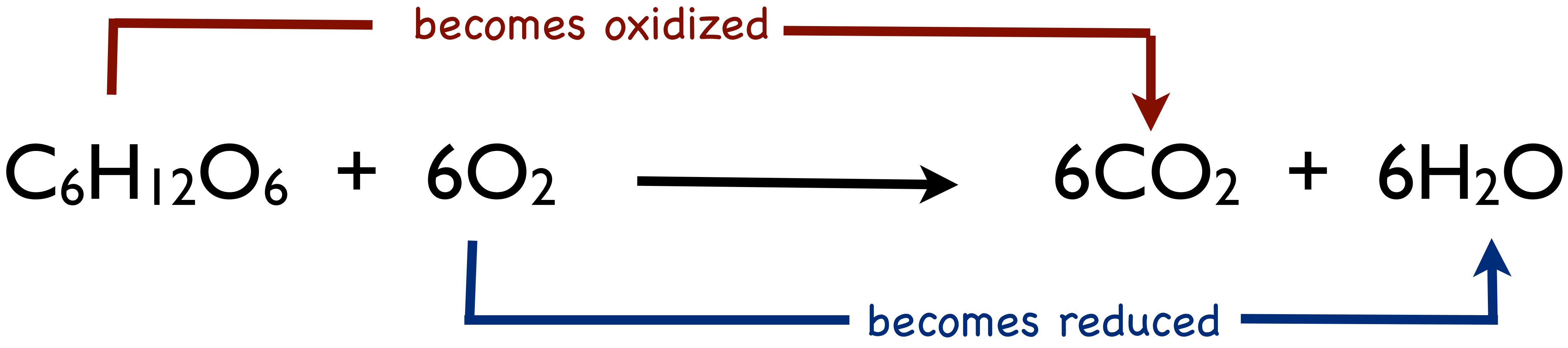
Oxygen

LOW
Potential Energy

HIGH
Electronegativity

Cell Respiration is a “redox reaction”

- Recall the following
  - Oxidation Reactions- removes electrons from a substance
    - catabolic / breaking down a substance / releases energy
  - Reduction Reactions- adds electrons to a substance
    - anabolic / building down a substance / requires energy



becomes oxidized

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

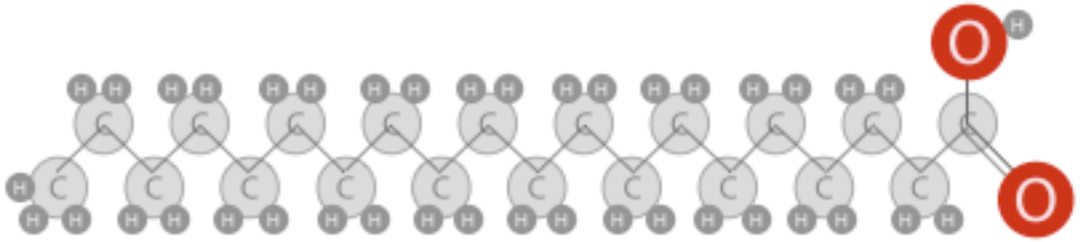
becomes reduced

Cell Respiration is a “redox reaction”

- As electrons make their way to oxygen energy is released.
- The challenge for the cell is two fold:
  - 1. move the electrons to oxygen in the most controlled manner, in order to capture the maximum energy
  - 2. use this captured energy to do cellular work
- In general molecules with lots of hydrogens make good fuels:
  - they have lots of electrons, each with lots of potential energy

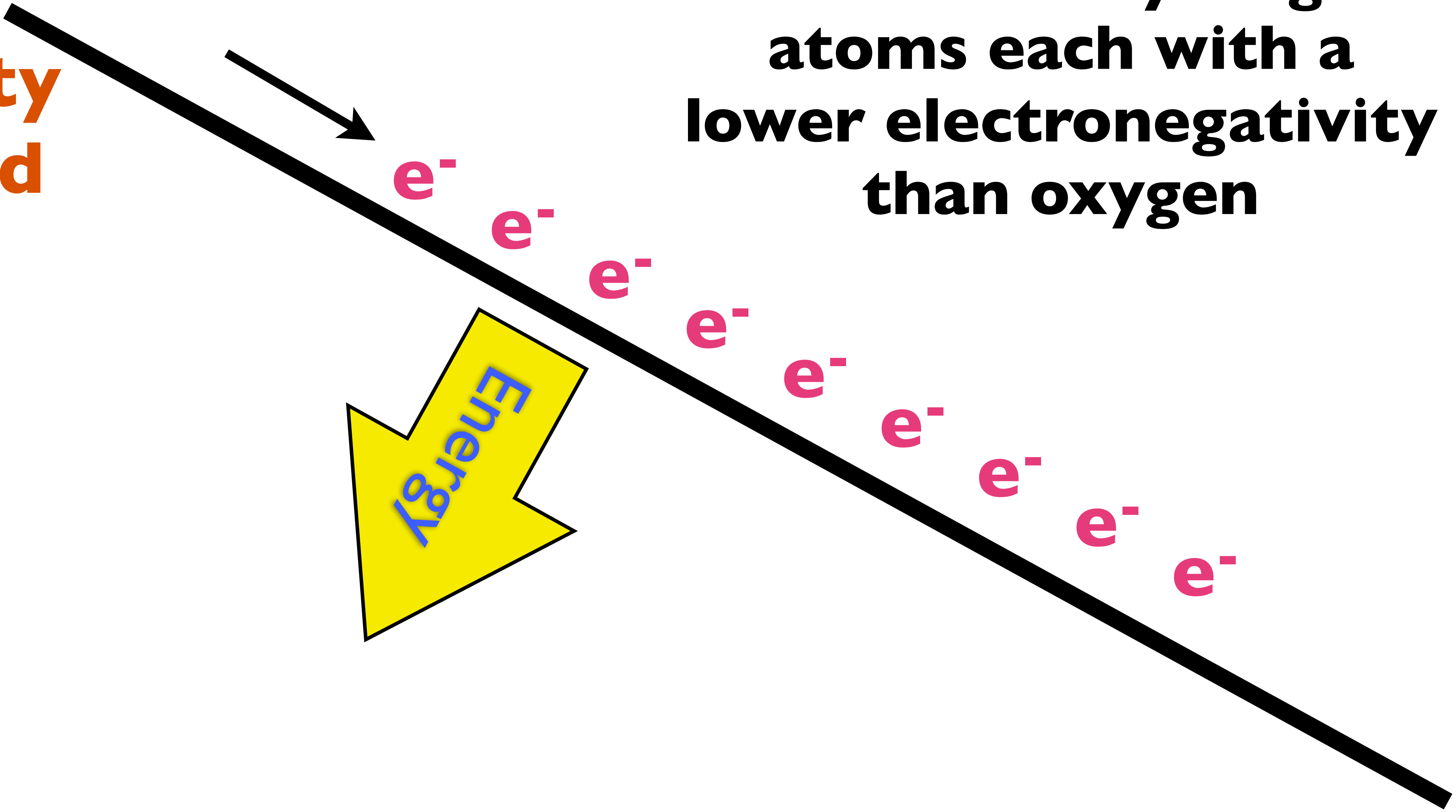
HIGH Potential Energy

Lower Electronegativities



80 Electrons between carbon and hydrogen atoms each with a lower electronegativity than oxygen

Fatty Acid



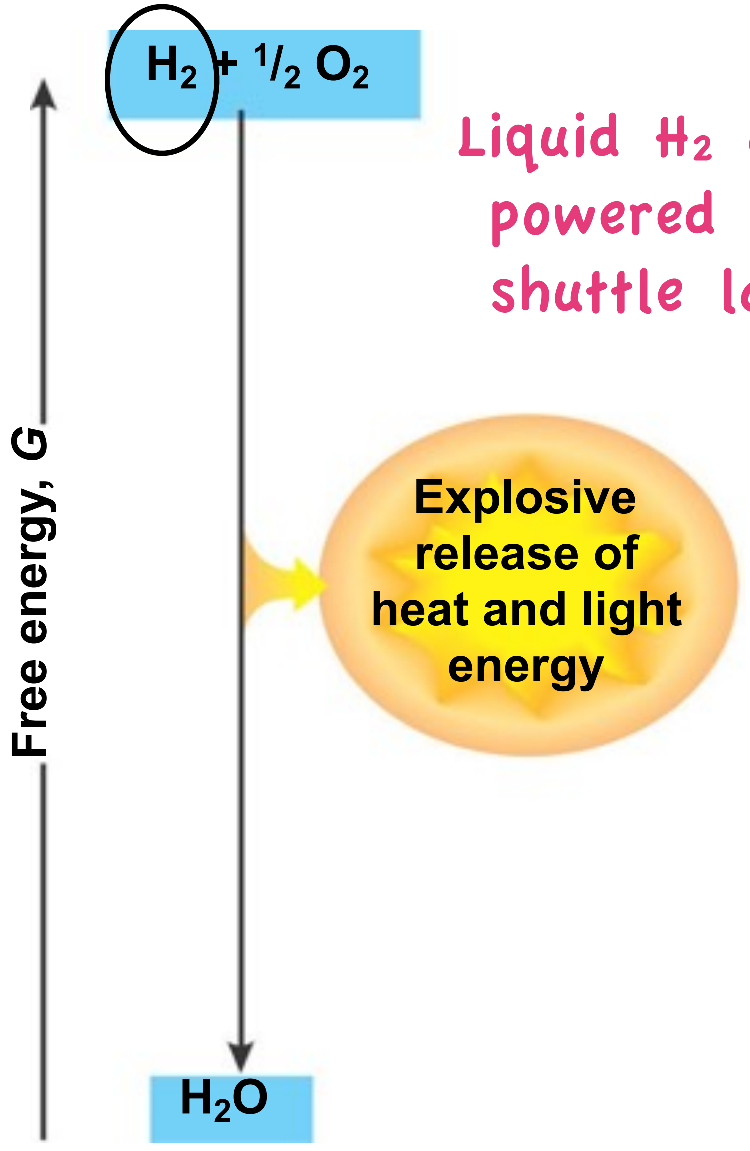
LOW
Potential Energy

HIGH
Electronegativity

Oxygen

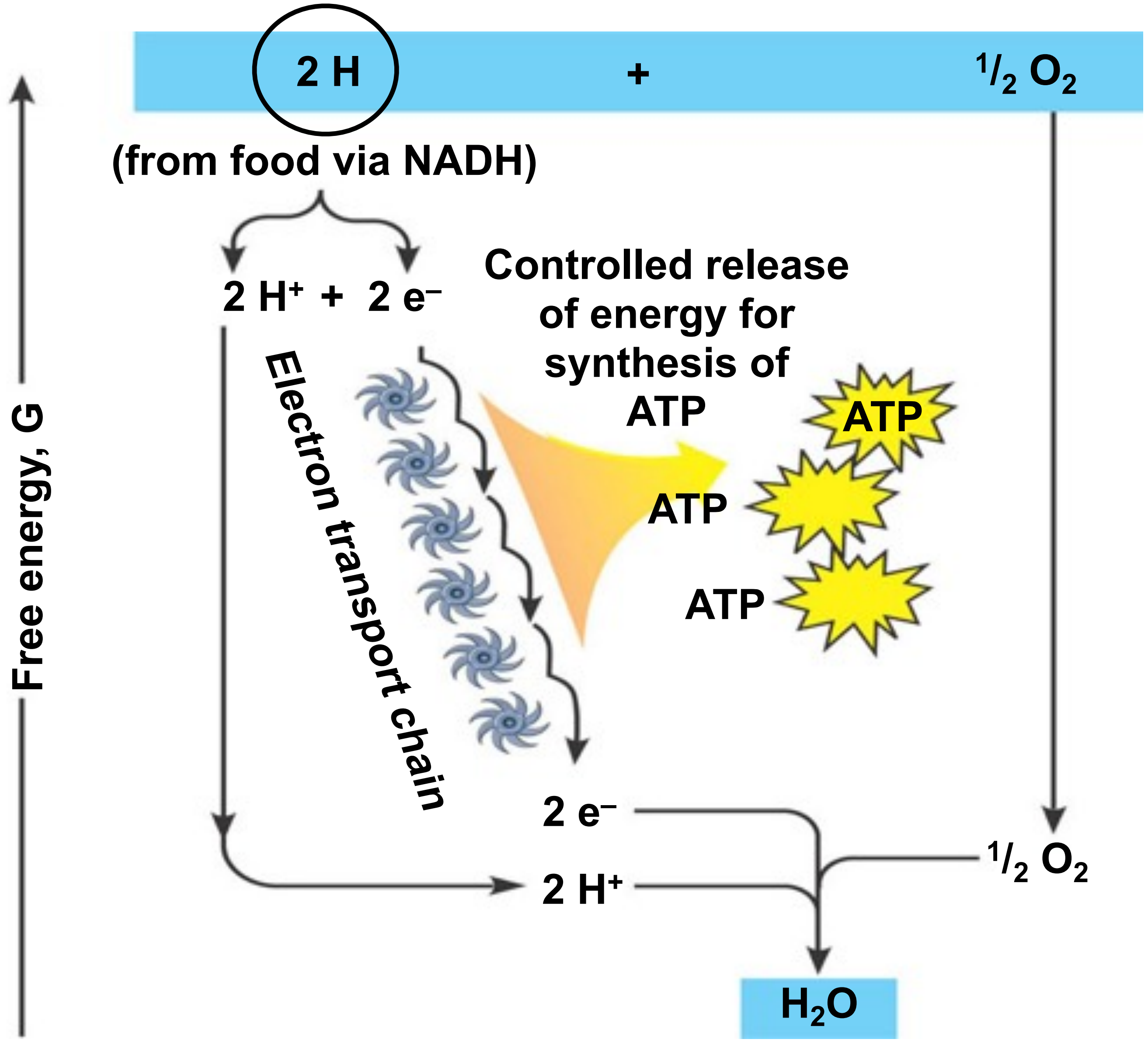
Harvesting Energy from Electrons

- To effectively harvest energy from a fuel to do constructive work you must slowly, in step like fashion extract the energy.



Liquid H_2 and O_2 powered space shuttle launch

VS.

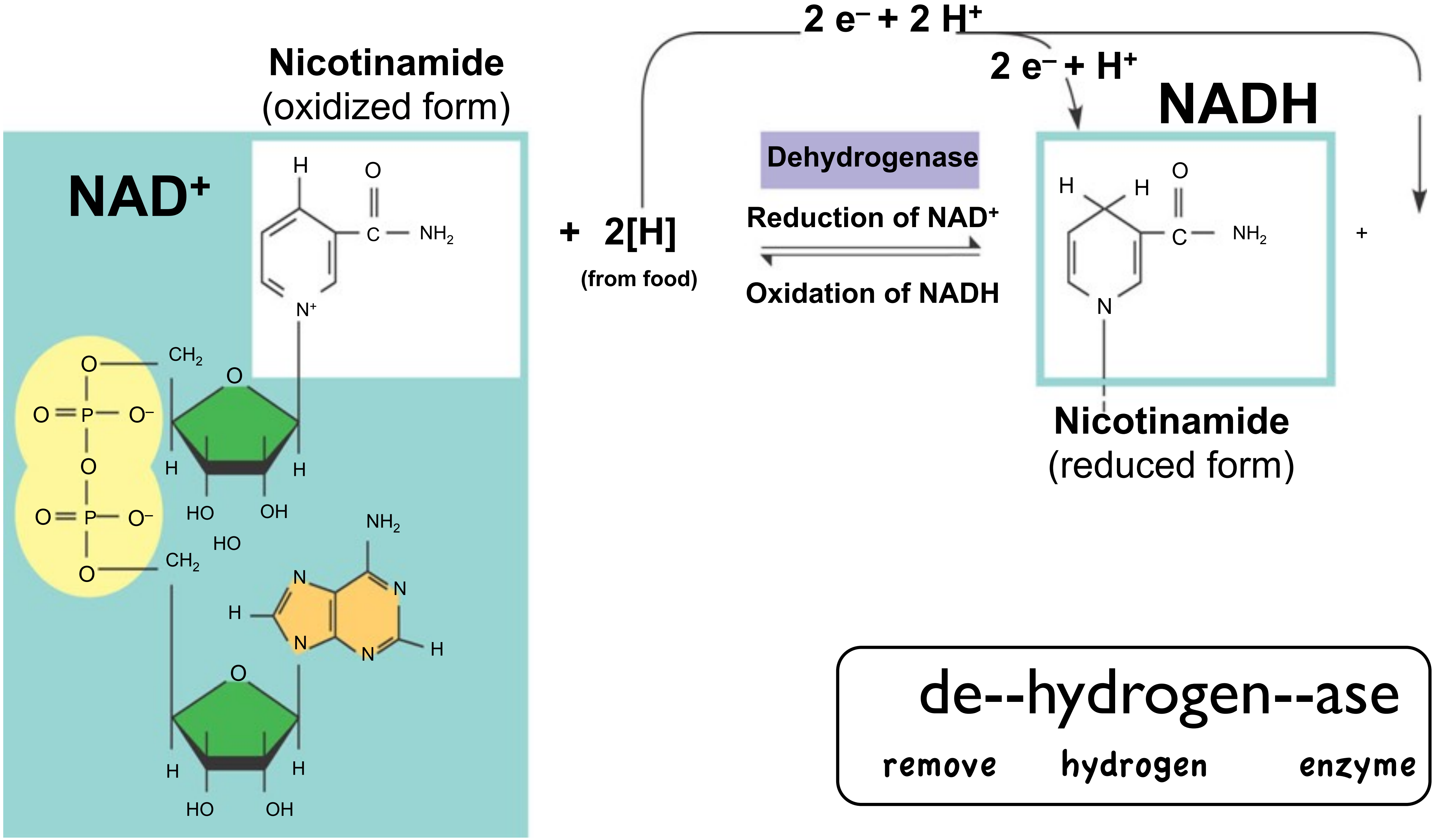


Uncontrolled reaction- (car explosion)

Cellular respiration- combustion engine

Electron Acceptors & Transport

- The first molecule that usually accepts electrons from organic molecules is a coenzyme called *Nicotinamide adenine dinucleotide*.

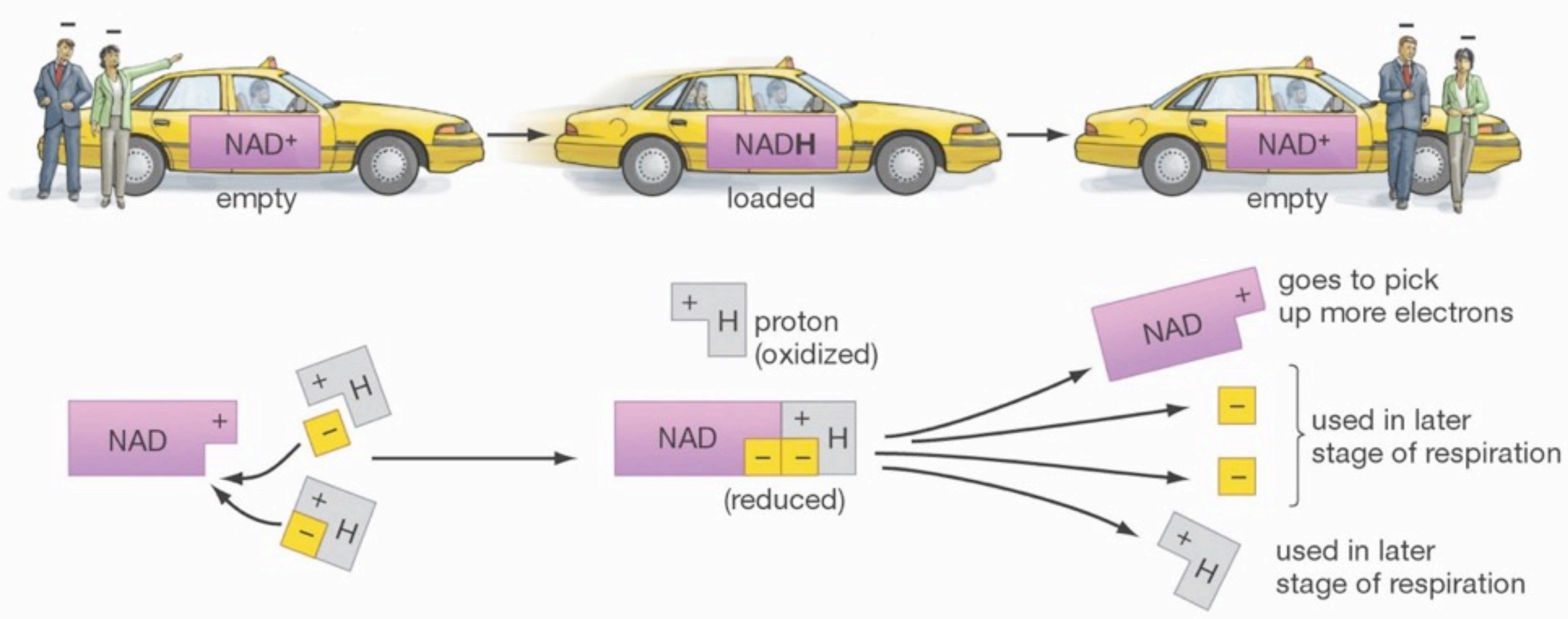


de--hydrogen--ase

remove **hydrogen** **enzyme**

Electron Acceptors & Transport

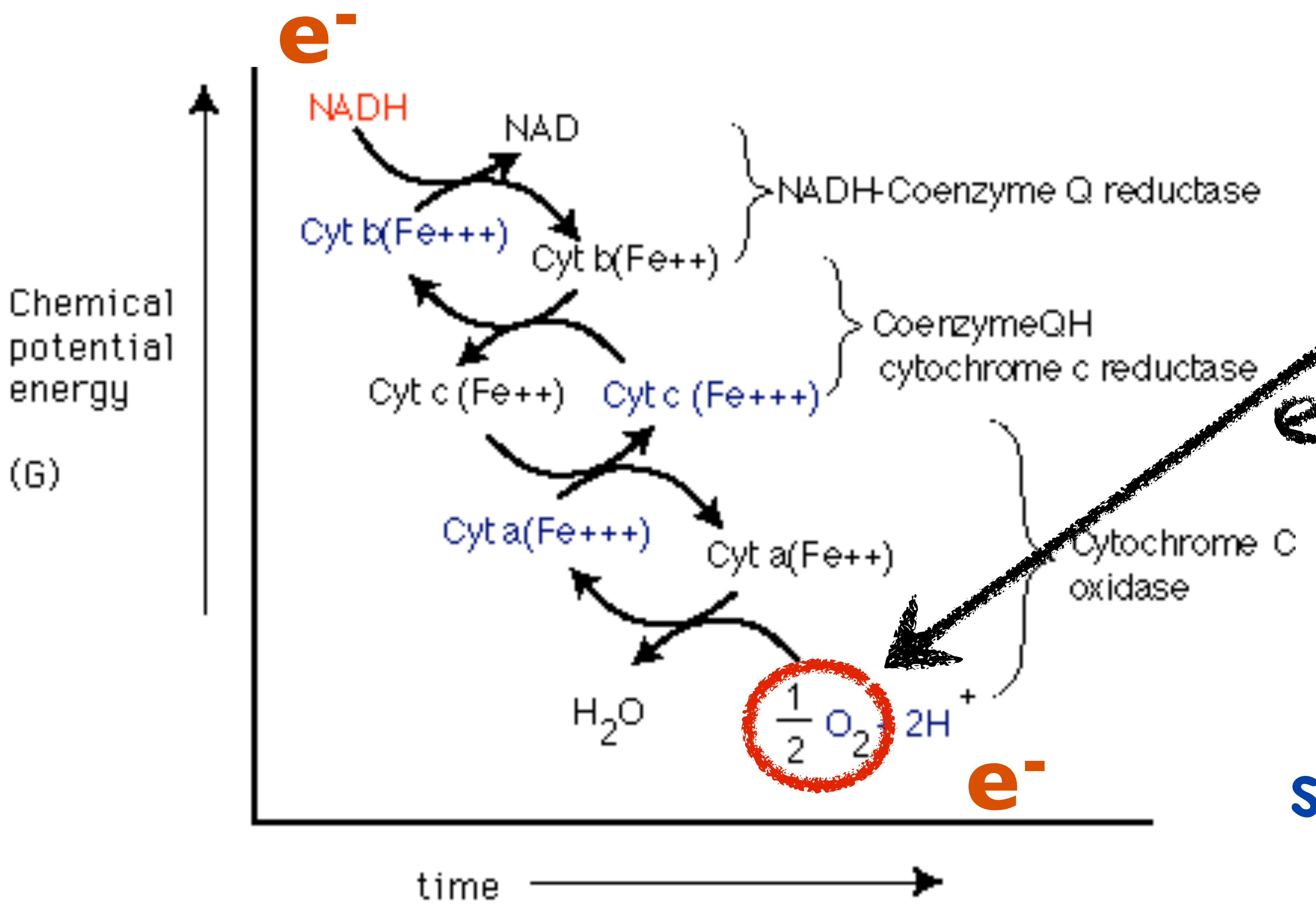
- The first molecule that usually accepts electrons from organic molecules is a coenzyme called *Nicotinamide adenine dinucleotide*.



1. NAD+ within a cell, along with two hydrogen atoms that are part of the food that is supplying energy for the body.
2. NAD+ is reduced to NAD by accepting an electron from a hydrogen atom. It also picks up another hydrogen atom to become NADH.
3. NADH carries the electrons to a later stage of respiration then drops them off, becoming oxidized to its original form, NAD+.

Electron Acceptors & Transport

- The NADH then passes the electrons to another molecule, and so on and so forth.
- Each molecule slightly more electronegative than the prior one



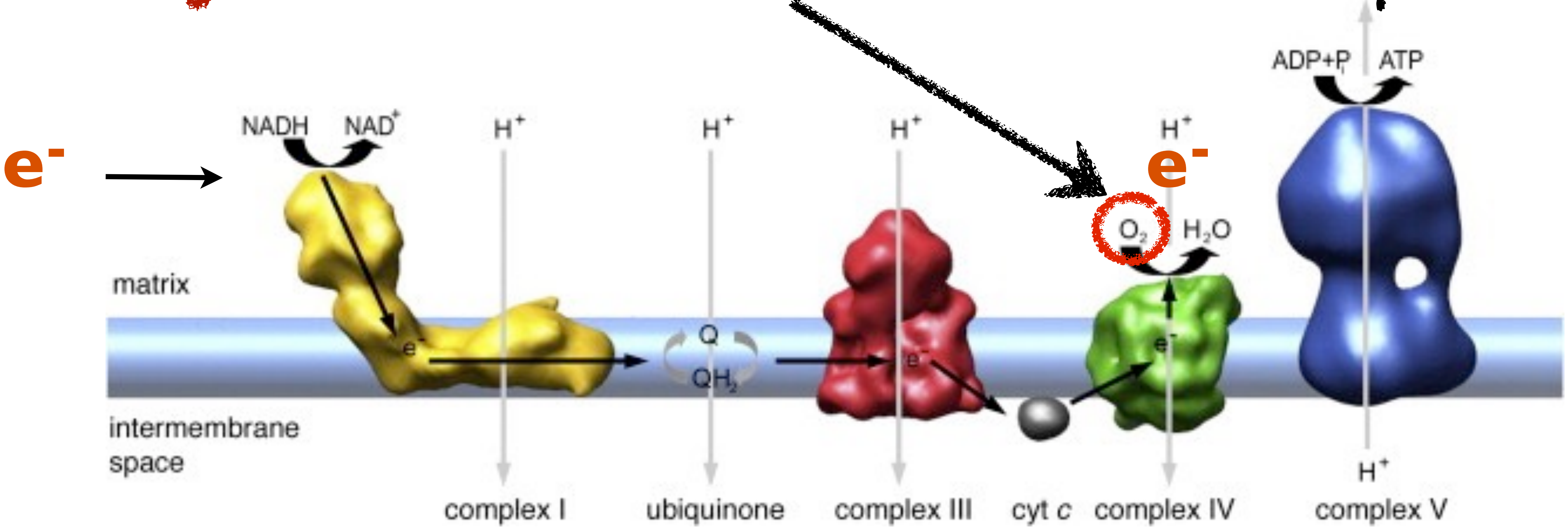
Oxygen, the final electron acceptor

Each step releasing small amounts of energy that is more easily captured by the cell

Electron Acceptors & Transport

- The *electron transport chain* consists of mainly proteins, embedded into a membrane.
    - *in eukaryote's inner mitochondrial membrane, in eukaryote's thylakoid membranes and prokaryote's plasma membrane*
- The e^- transfer from NADH to O_2 releases -53 kcal/mol of energy.

Oxygen, the final electron acceptor



Here is an analogy to help you understand

To effectively harvest energy from a fuel to do constructive work you must slowly, in step like fashion extract the energy.

Harvesting Energy from Electrons

- Energy released from a fuel, say gasoline, all at once may be useful in Hollywood movies but is useless for constructive work, like driving the car below.

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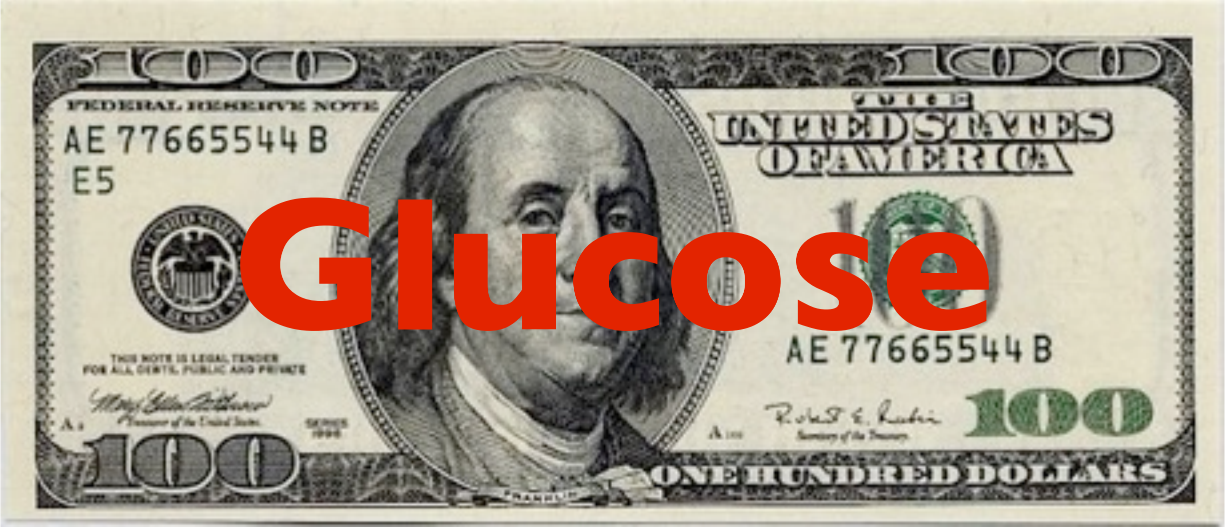
Harvesting Energy from Electrons

- Energy released from a fuel, say gasoline, all at once may be useful in Hollywood movies but is useless for constructive work, like driving the car below.

Harvesting Energy from Electrons

- Like the car...Energy released from glucose, all at once would be destroy the cell or at least be extremely wasteful.



Imagine going to a county fair. To enjoy the fair you decide to bring money, in order to buy food and play games. The cost of food and games are each just a few dollars at most. You bring five 100$ bills to fair, thinking that should be more than enough (each bill would easily cover the cost of food item or game). Not long after you arrive you realize that no vendor has change for a 100$ bill. You have 2 choices: 1. Use a 100$ bill for each purchase, over paying for everything and run out of money fast or 2. do not buy anything. Neither choice is reasonable.

What should you have prior to coming to the fair?

Here is an alternative solution! Take the 100$ bills to the bank. Change the 100$ into smaller currency say 1$ bills. Now your ready to go to the fair.

What does the bank represent in my analogy?

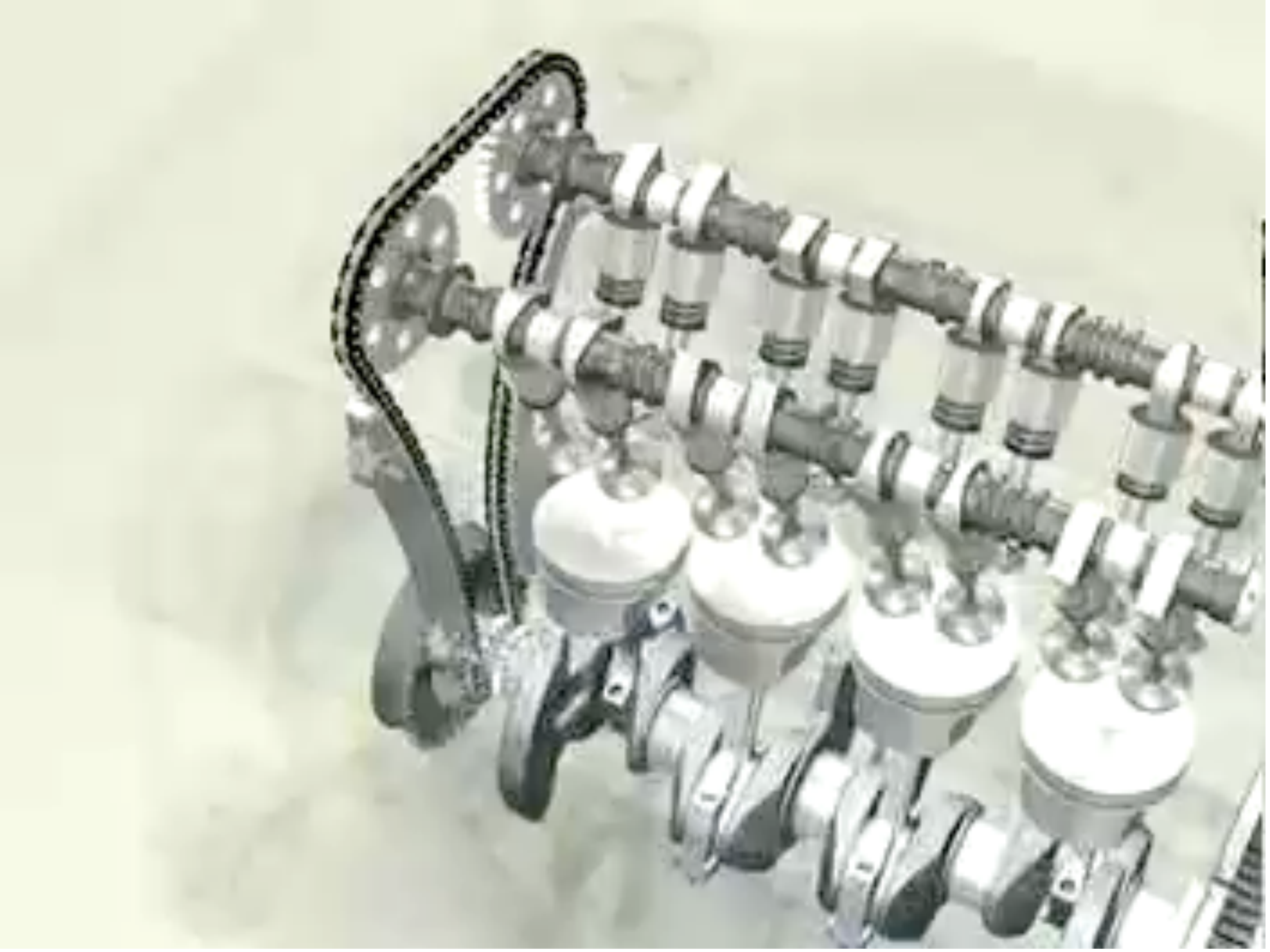
Here is an alternative solution! Take the 100$ bills to the bank. Change the 100$ into smaller currency say 1$ bills. Now your ready to go to the fair.

What does the bank represent in my analogy?

Mitochondria, Cell Respiration

Harvesting Energy from Electrons

- To effectively harvest energy from a fuel to do constructive work you must slowly, in step like fashion extract the energy.

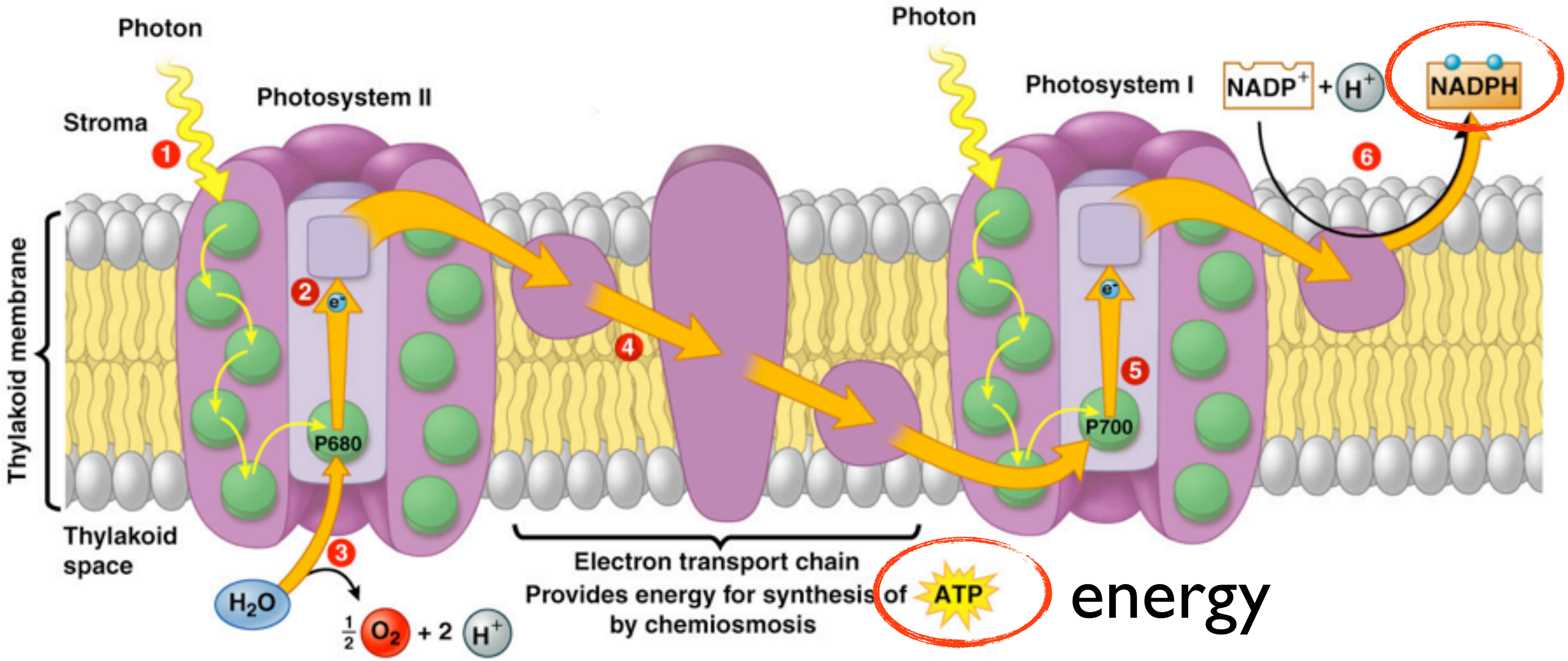


This concept can be seen in photosynthesis as well

Photosystem I and II

- To complete the light reactions plants require 2 different photosystems working together to harvest the energy and electrons needed to build sugar.
  - Photosystem I was the first one discovered but it turns out that it the second photosystem used in the light reactions.

electrons



energy

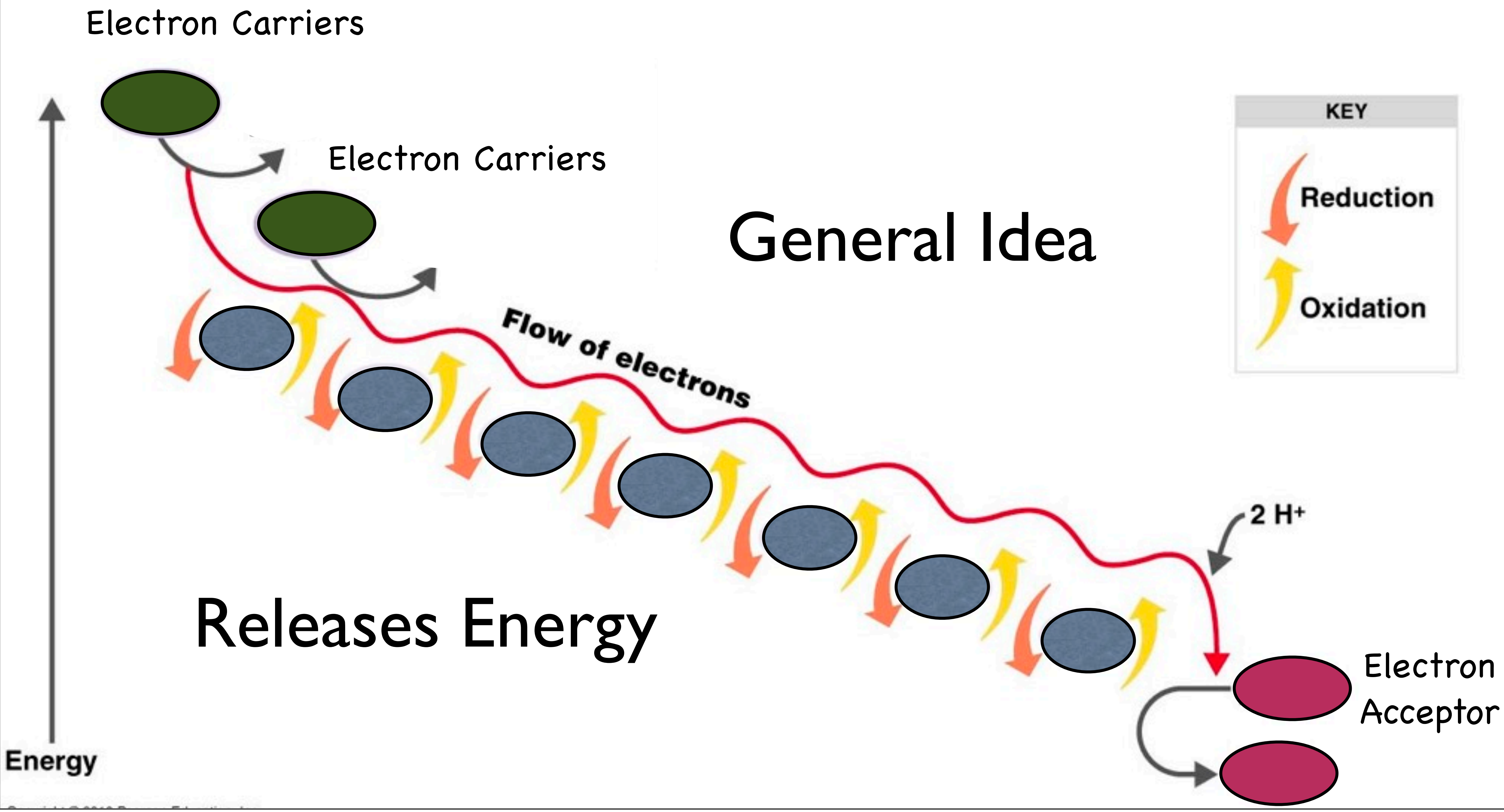
E.T.C. Establishes a H$^+$ ion Gradient

- The ***electron transport chain*** makes no ATP.
- The e$^-$ transfer releases energy as the electron moves through the chain, this energy is used to pump H$^+$ ions through a membrane.
  - *This generates a electrochemical gradient with great potential energy*

E.T.C. and Chemiosmosis

- Stored energy in the form a H^+ ion gradient across a membrane is called the ***proton motive force,*** it is used to produce ATP (or drive other cellular work), which is called ***chemiosmosis***.
- ***Chemiosmosis*** *is an energy coupling mechanism that uses energy stored in in the form of H+ ion gradients across membranes to drive cellular work*
  - *Osmosis is the diffusion of water*
  - *Chemiosmosis is the diffusion of H^+ ions*
- Specifically an enzyme ATP synthase uses the energy to produce ATP from ADP

Electron Acceptors & Transport



General Idea

Releases Energy

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

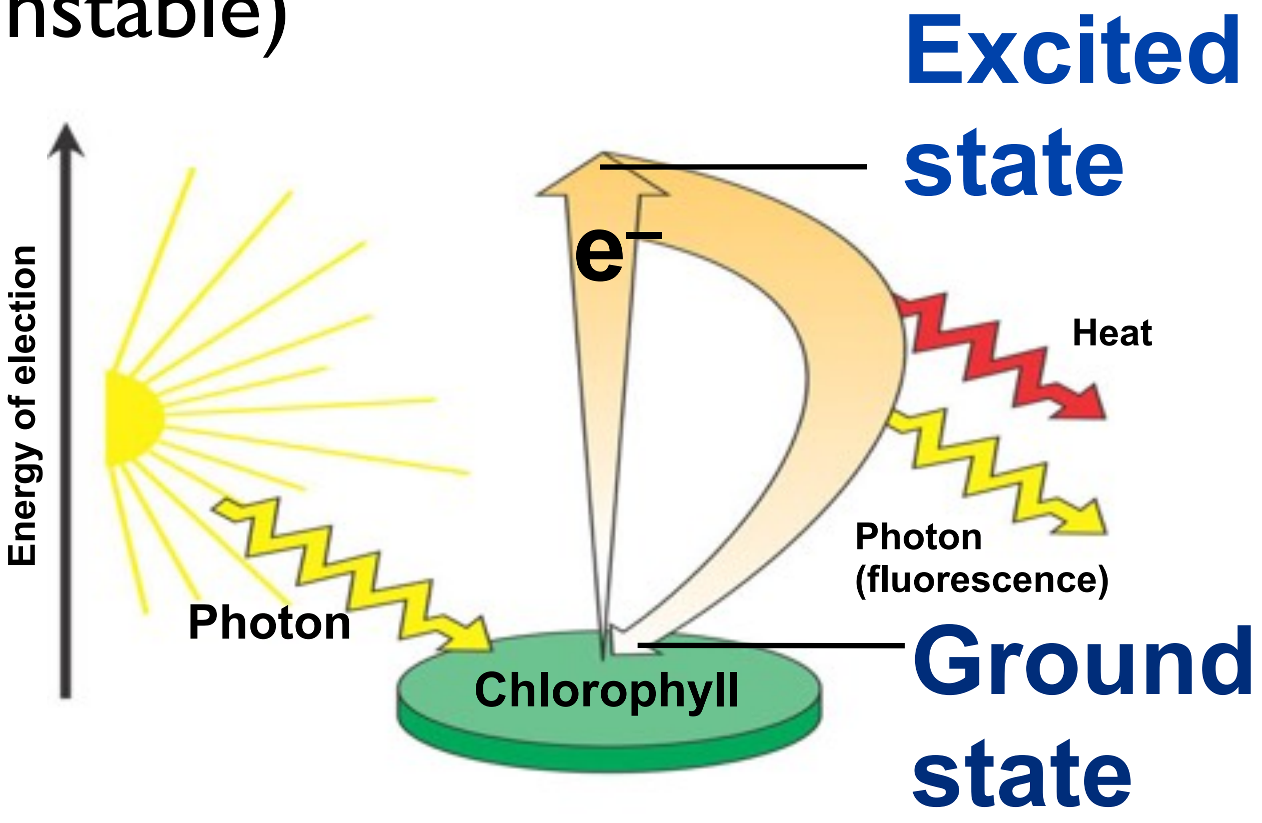
d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated reaction pathways that capture free energy present in light to yield ATP and NADPH, which power the production of organic molecules.

Evidence of student learning is a demonstrated understanding of each of the following:

1. During photosynthesis, chlorophylls absorb free energy from light, boosting electrons to a higher energy level in Photosystems I and II.

Exciting Chlorophyll by Light

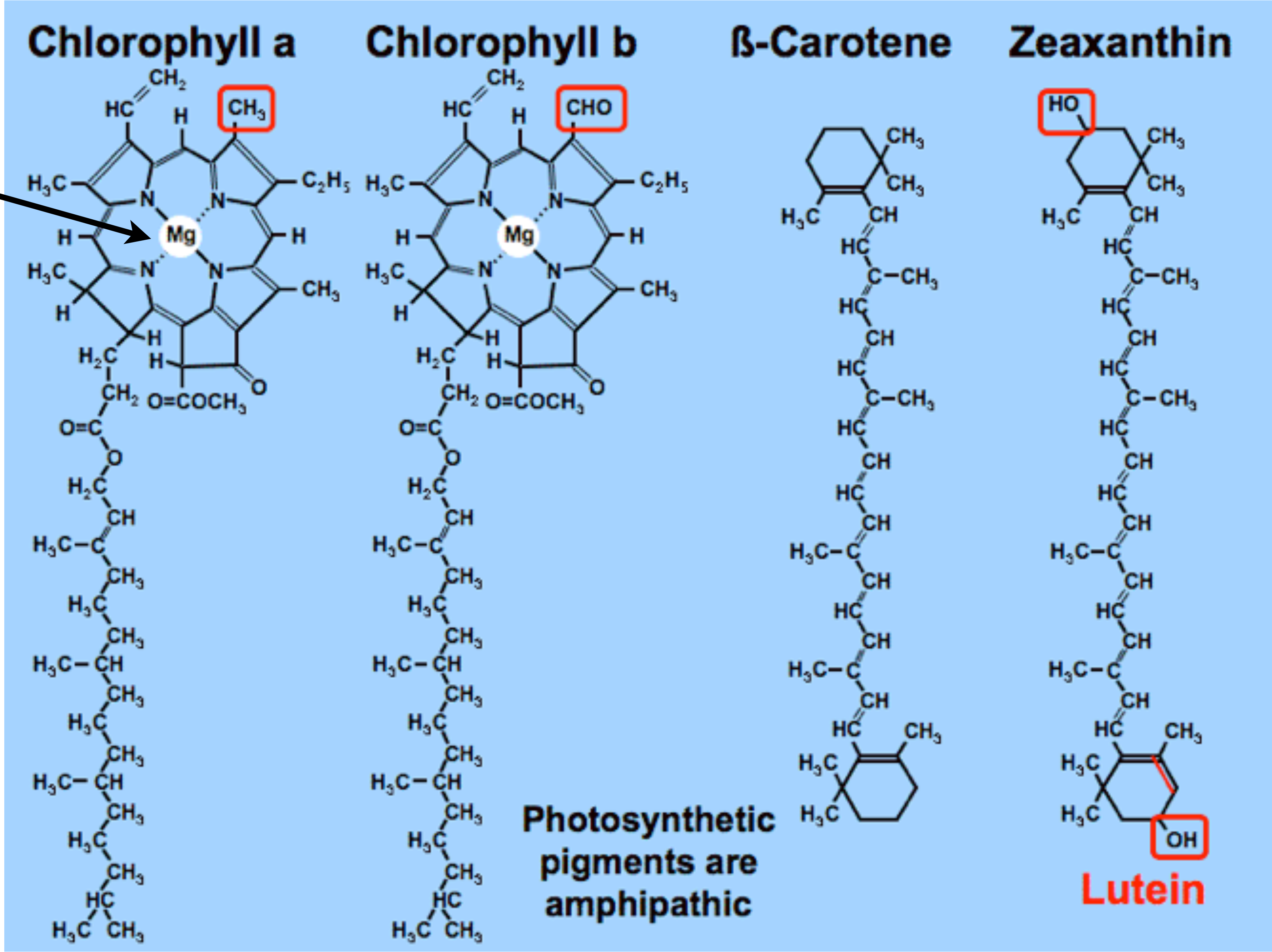
- When a pigment absorbs a wavelength(s) of light that wavelength disappears but the energy can not!
- Remember light also acts as particles, when *photons* hit molecules they impact can send "electrons flying"
- Electrons in their normal energy level are said to be in their ***ground state***. (they are stable)
- Photons can boost electrons to higher energy levels called their ***excited state***. (they are unstable)



- Each photon carries a certain quantity of energy, this energy is equal to the difference between ground and excited states.
- The energy to boost electrons varies depending on the molecule which explains why some pigments absorb certain wavelengths and not others

Electrons in the rings, particularly the metals are the ones excited

Where do suppose you might find these long chains?

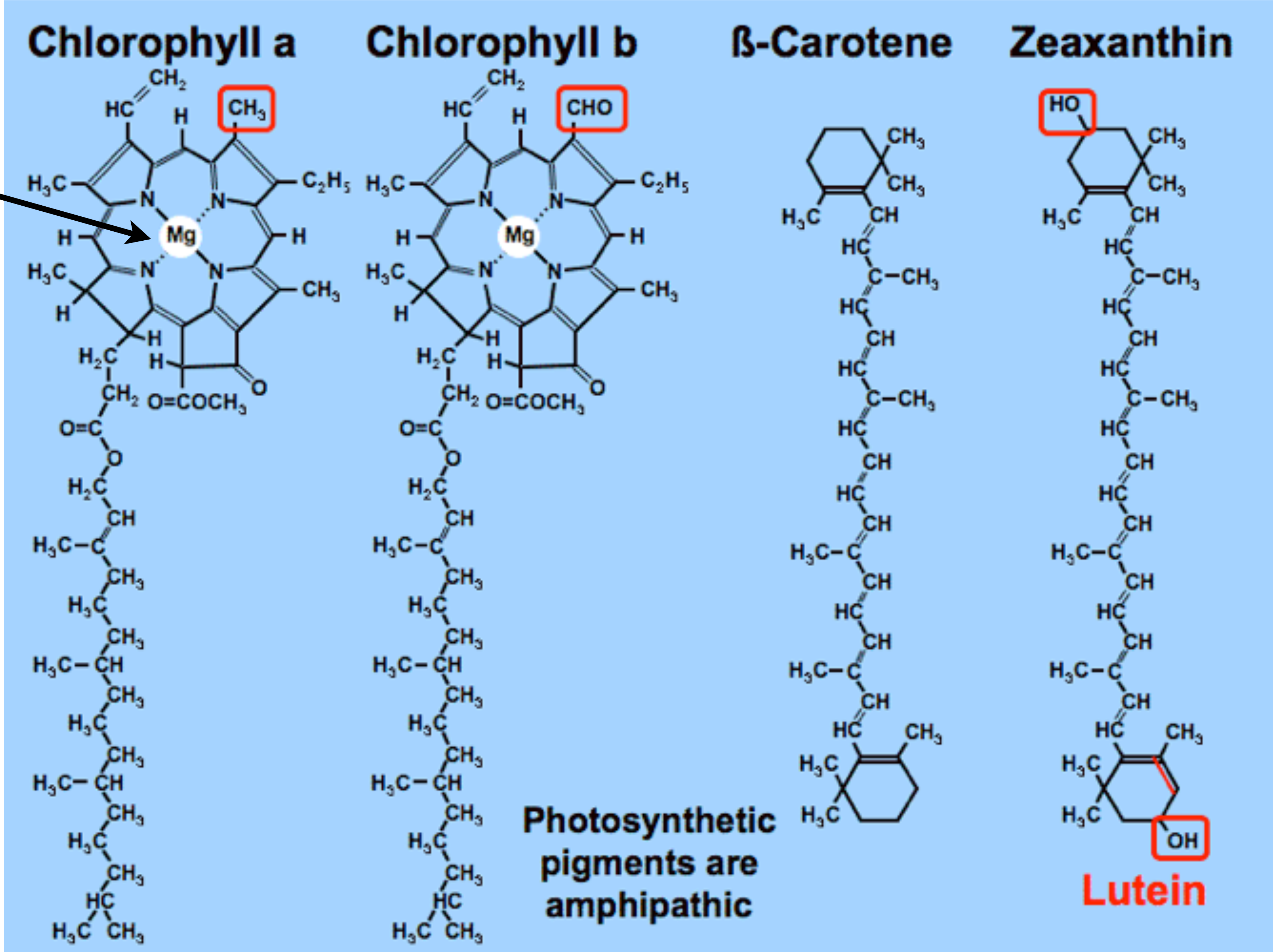


- Each photon carries a certain quantity of energy, this energy is equal to the difference between ground and excited states.
- The energy to boost electrons varies depending on the molecule which explains why some pigments absorb certain wavelengths and not others

Electrons in the rings, particularly the metals are the ones excited

Where do suppose you might find these long chains?

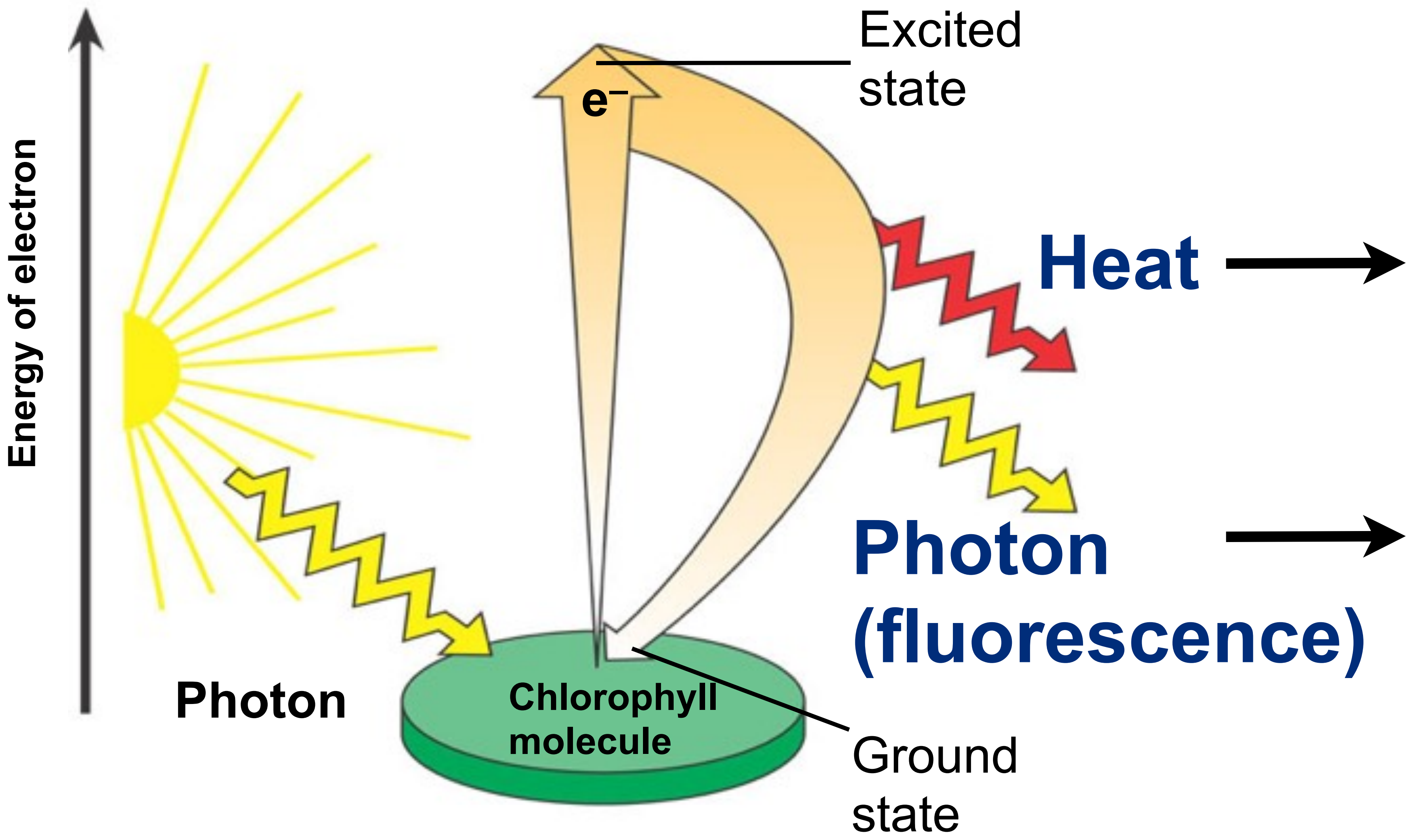
In membranes, of the chloroplast of course



Photosynthetic pigments are amphipathic

Exciting Chlorophyll by Light

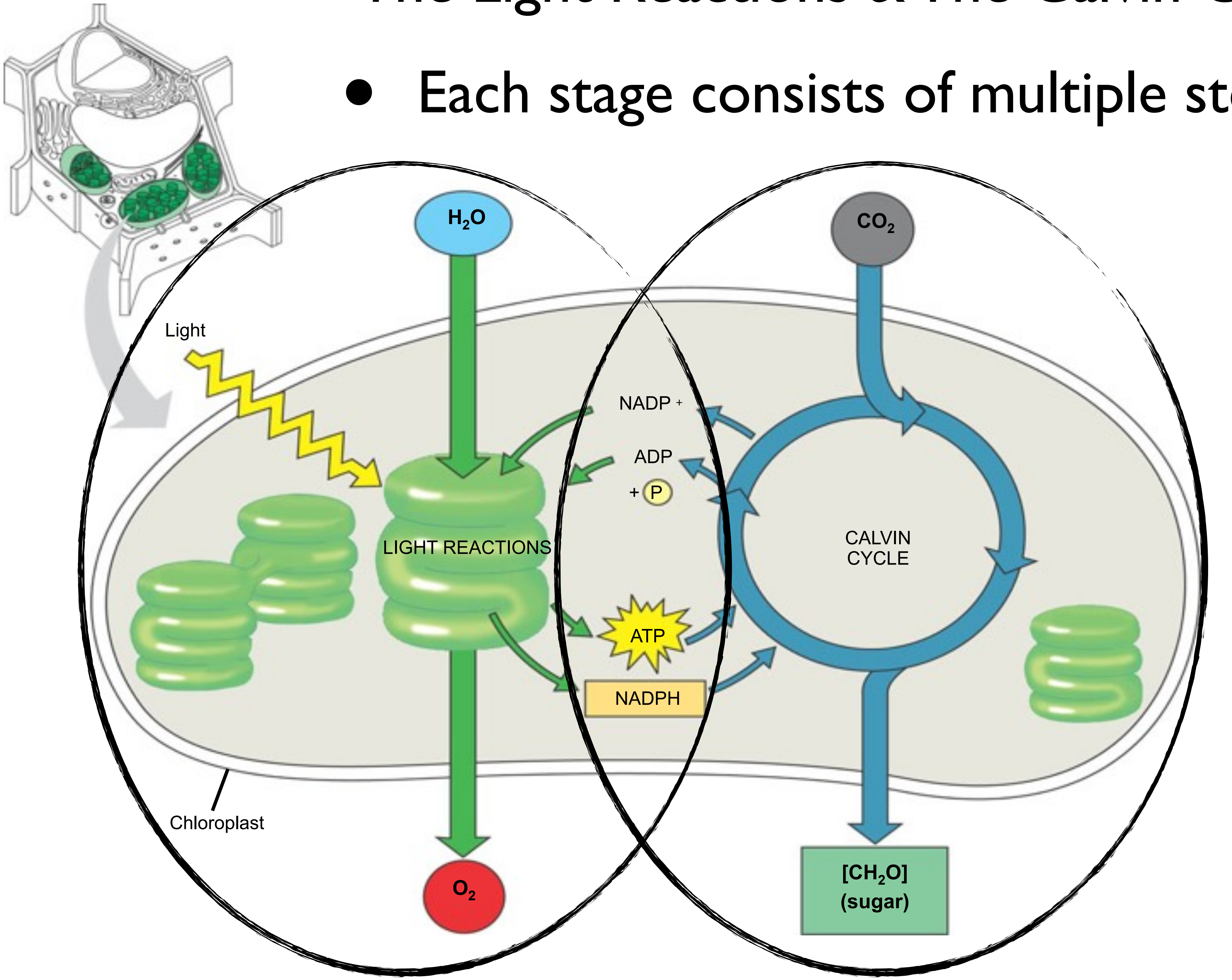
- An electron can not stay in the unstable, excited state.
    - In a billionth of second it falls back to the ground state
        - releasing the excess energy as heat and sometimes light
- In isolation chlorophyll releases heat and light (fluorescence).



Lets catch our breath and examine the big picture

Photosynthesis: Occurs in Two Stages

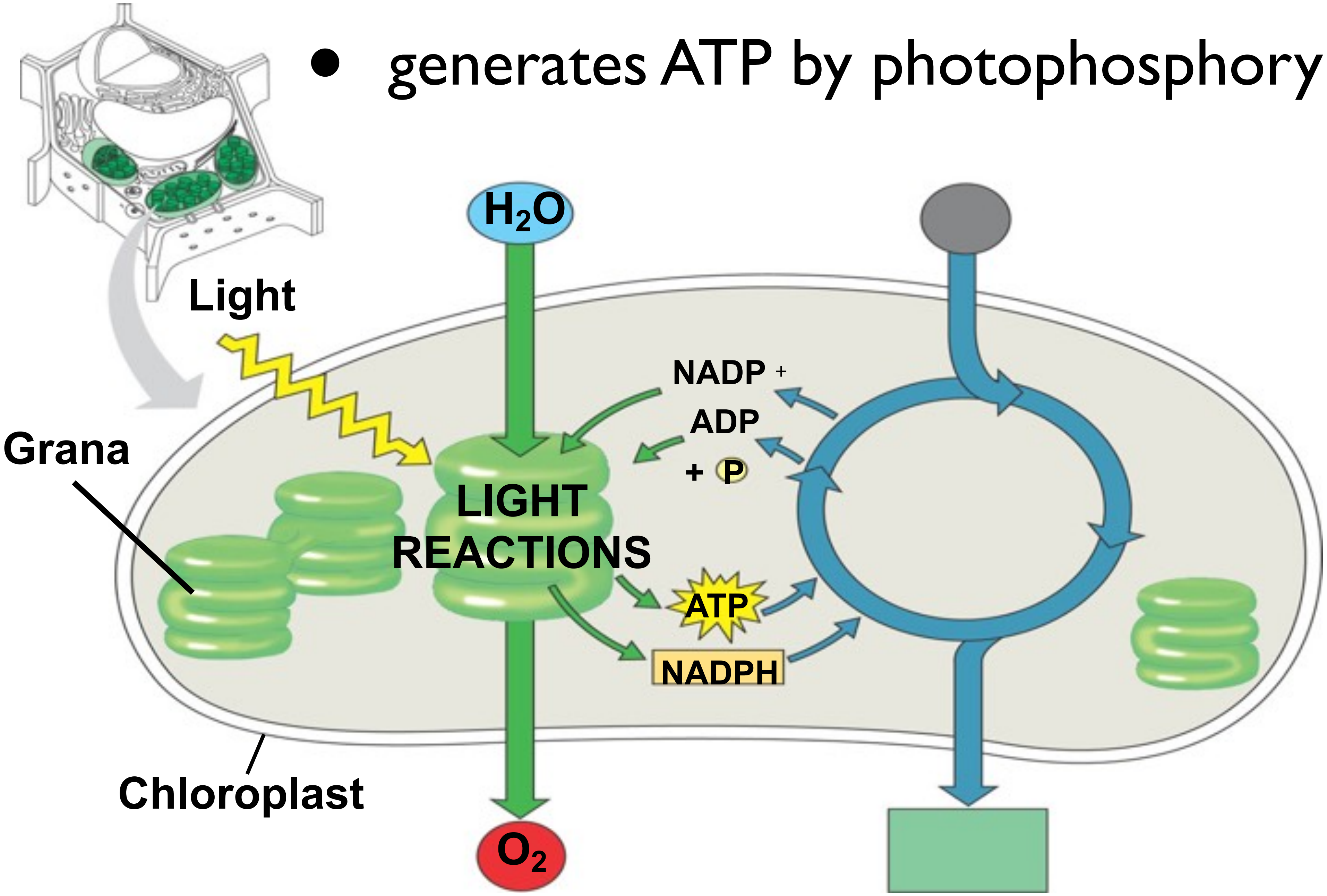
- Photosynthesis takes place in two stages:
    - The Light Reactions & The Calvin Cycle
        - Each stage consists of multiple steps



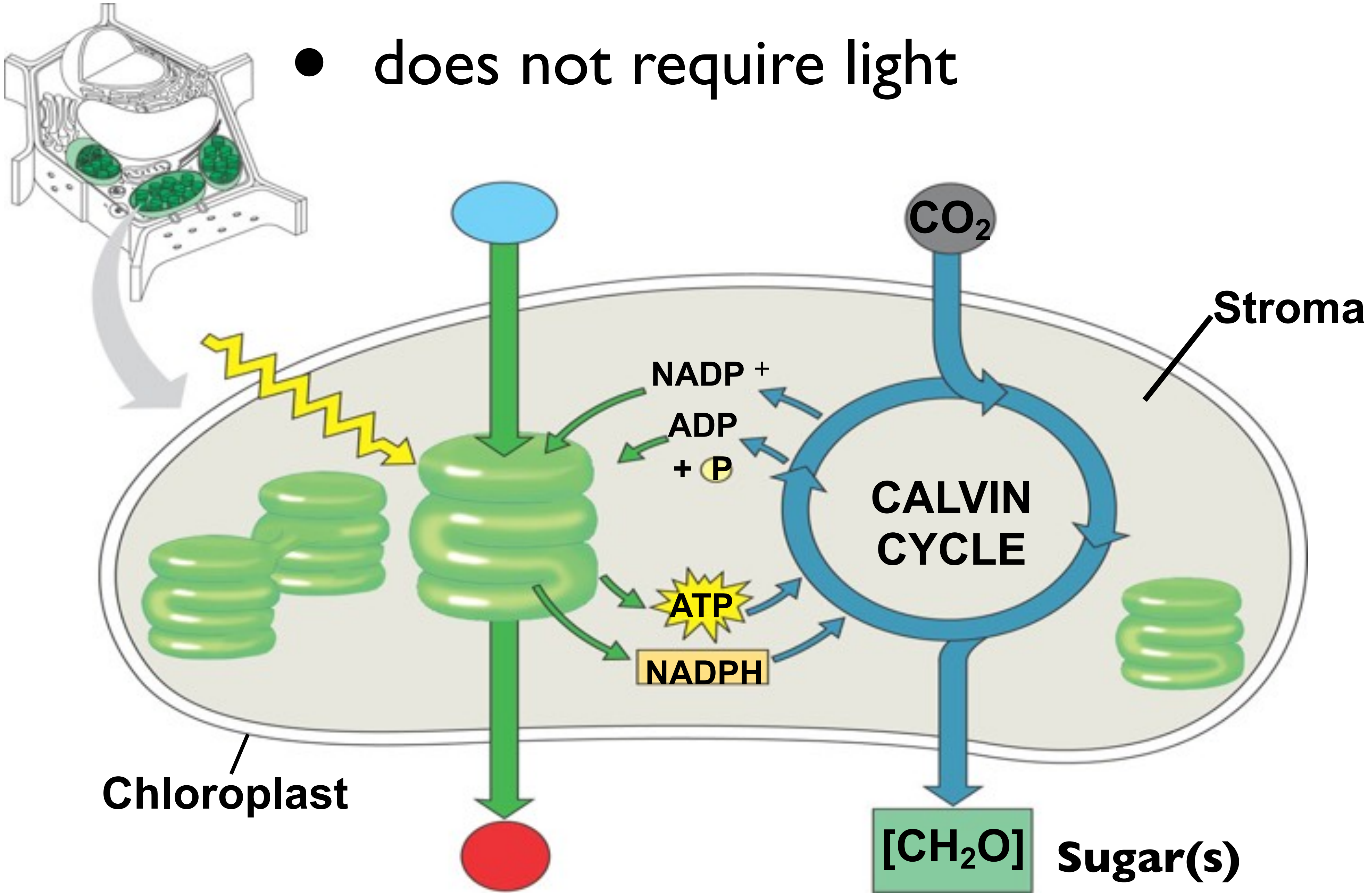
“The Big Picture Before We Continue”

- **Building sugar in stage 2 of photosynthesis (Calvin Cycle) requires:**
  - **building blocks,**
  - **electrons,**
  - **energy**
- The building blocks (carbon) simply come from atmosphere via carbon dioxide.
- But the electrons (carried by NADPH) have to come from the light reactions via water
- And the energy (ATP) has to also come from the light reactions

- **Light Reactions**
  - occurs in the grana (thylakoid membranes)
    - converts solar to chemical energy (NADPH & ATP)
      - harvests electrons and hydrogens from water
        - generates ATP by photophosphorylation



- **Calvin Cycle**
  - occurs in the stroma
    - uses chemical energy (NADPH & ATP) to make sugar
      - builds sugars using carbon from CO_2
        - does not require light



this step is the carbon fixation portion of photosynthesis

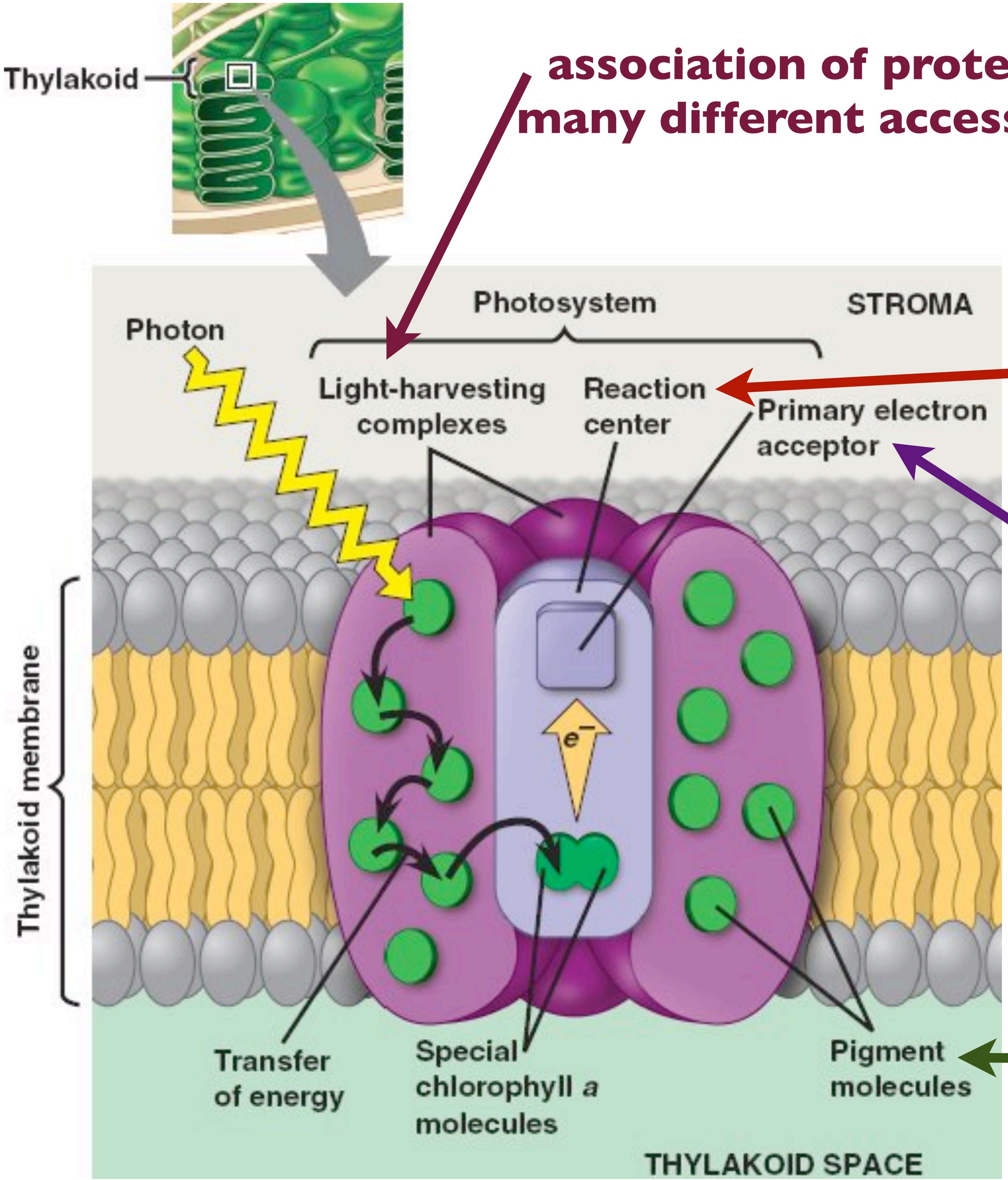
Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated reaction pathways that capture free energy present in light to yield ATP and NADPH, which power the production of organic molecules.

Evidence of student learning is a demonstrated understanding of each of the following:

2. Photosystems I and II are embedded in the internal membranes of chloroplasts (thylakoids) and are connected by the transfer of higher free energy electrons through an electron transport chain (ETC). [See also 4.A.2]

General Photosystem



association of proteins holding a many different accessory pigments

association of proteins holding chlorophyll *a* pigments

a molecule (similar to chlorophyll) that captures an electron, it is "reduced"

accessory or antennae pigments which transfer energy to special chlorophyll *a* pigments

Linear Electron Flow

1. Photon of light strikes pigments in PSII, excites electron, electron falls and energy excites electron of nearby pigment, this continues until the electrons of the P680 chlorophyll are excited

e^- e^-

e^-

e^-

e^-

1.

Linear Electron Flow

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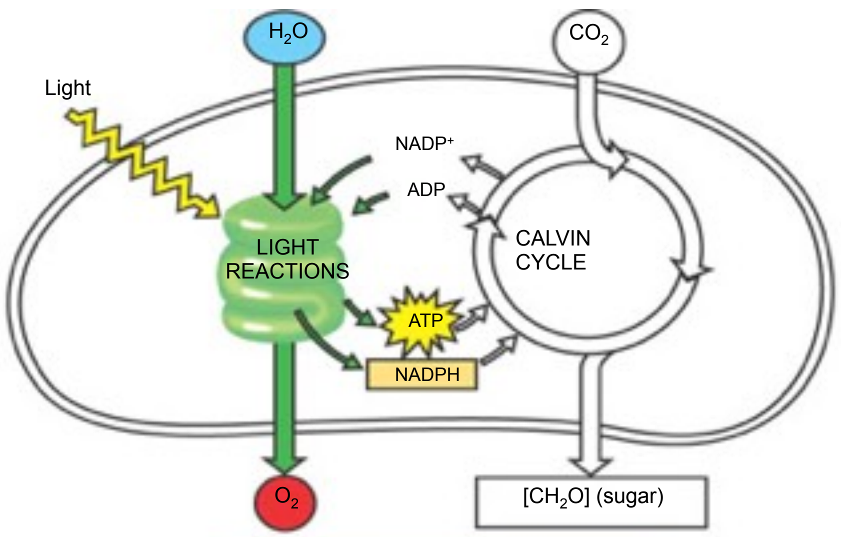
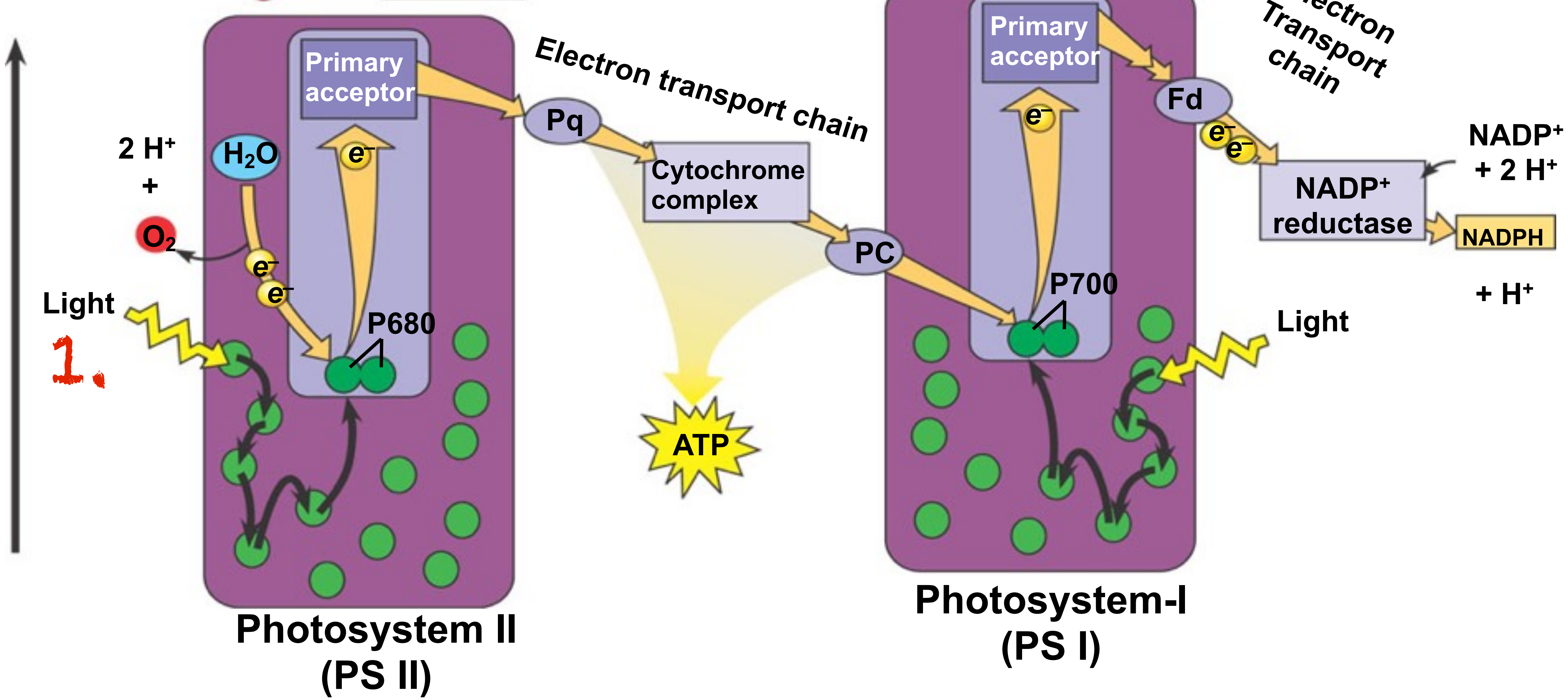




Linear Electron Flow

2. P680 chlorophyll is excited and loses its electron to the primary acceptor in PSII

e^- e^-

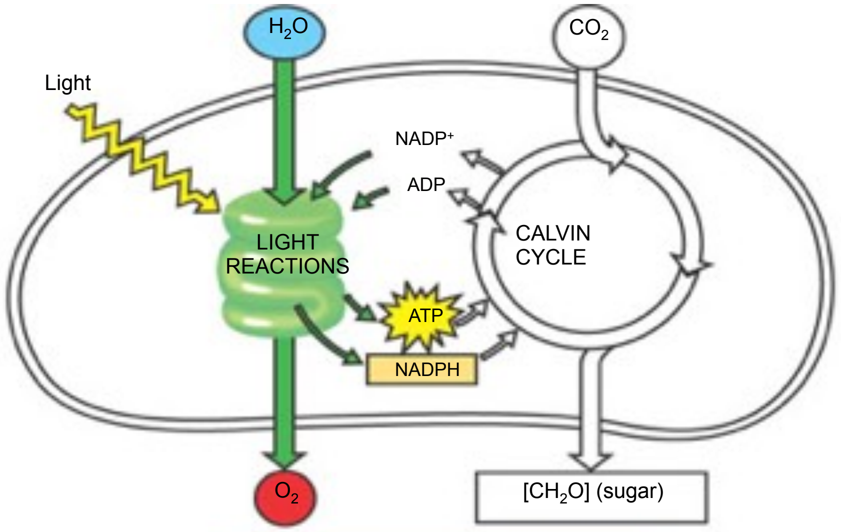
e^-

2.

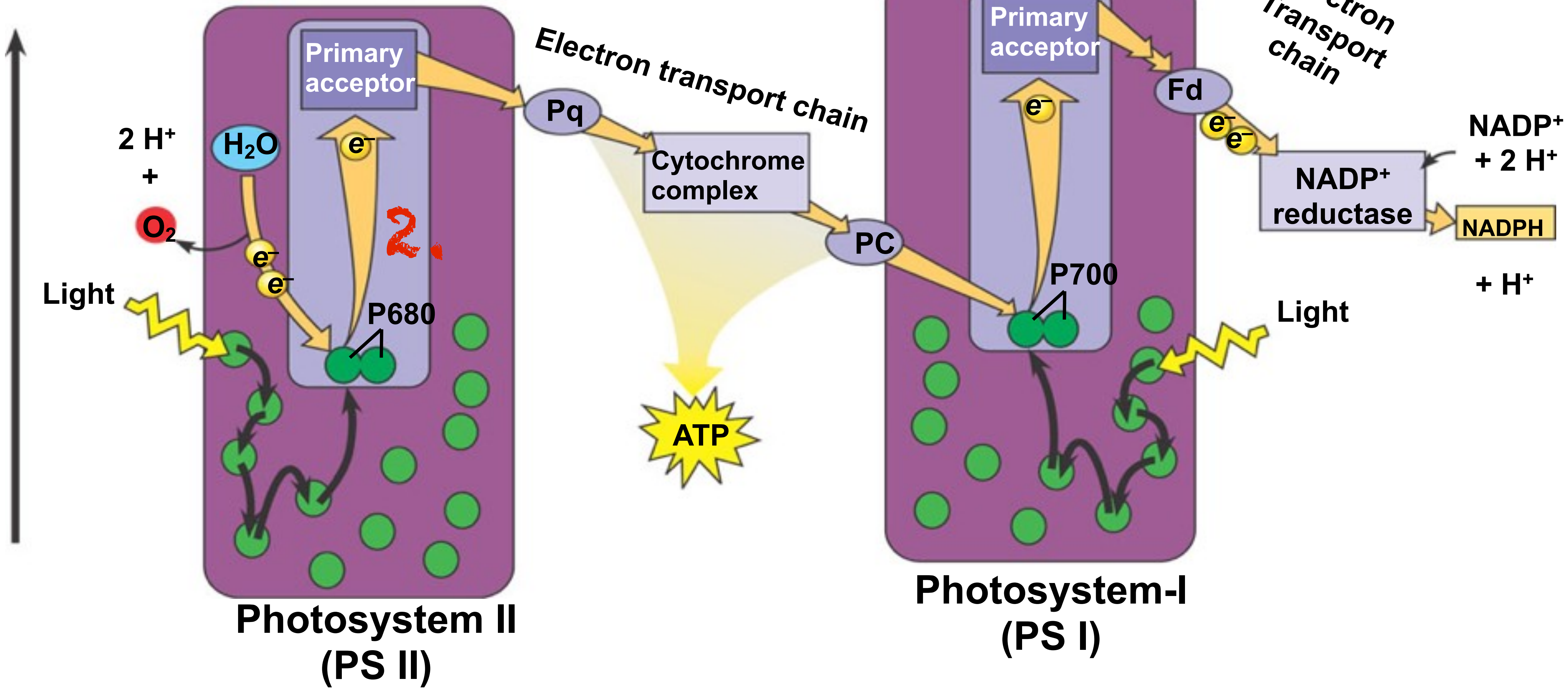
e^-

e^-

Linear Electron Flow



2. P680 chlorophyll is excited and loses its electron to the primary acceptor in PSII



Linear Electron Flow

3. An enzyme catalyzes the splitting of water, thus removing its electrons, transferring and replacing them to the P680 pigment, meanwhile two oxygen atoms combine to form water and the hydrogen ions are released into thylakoid lumen

3.

e^- e^- e^-

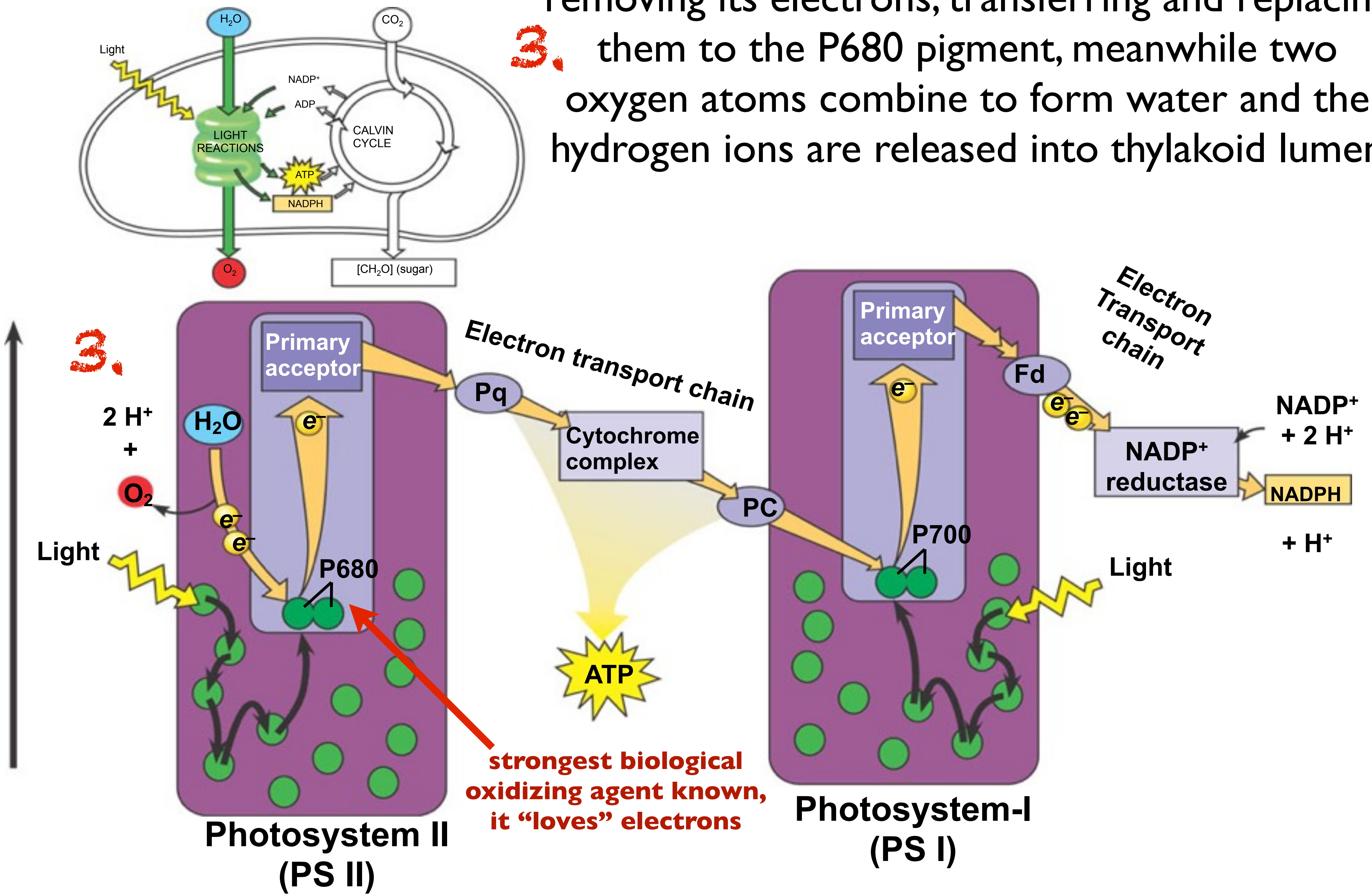
e^-

e^-

strongest biological oxidizing agent known, it "loves" electrons

Linear Electron Flow

3. An enzyme catalyzes the splitting of water, thus removing its electrons, transferring and replacing them to the P680 pigment, meanwhile two oxygen atoms combine to form water and the hydrogen ions are released into thylakoid lumen



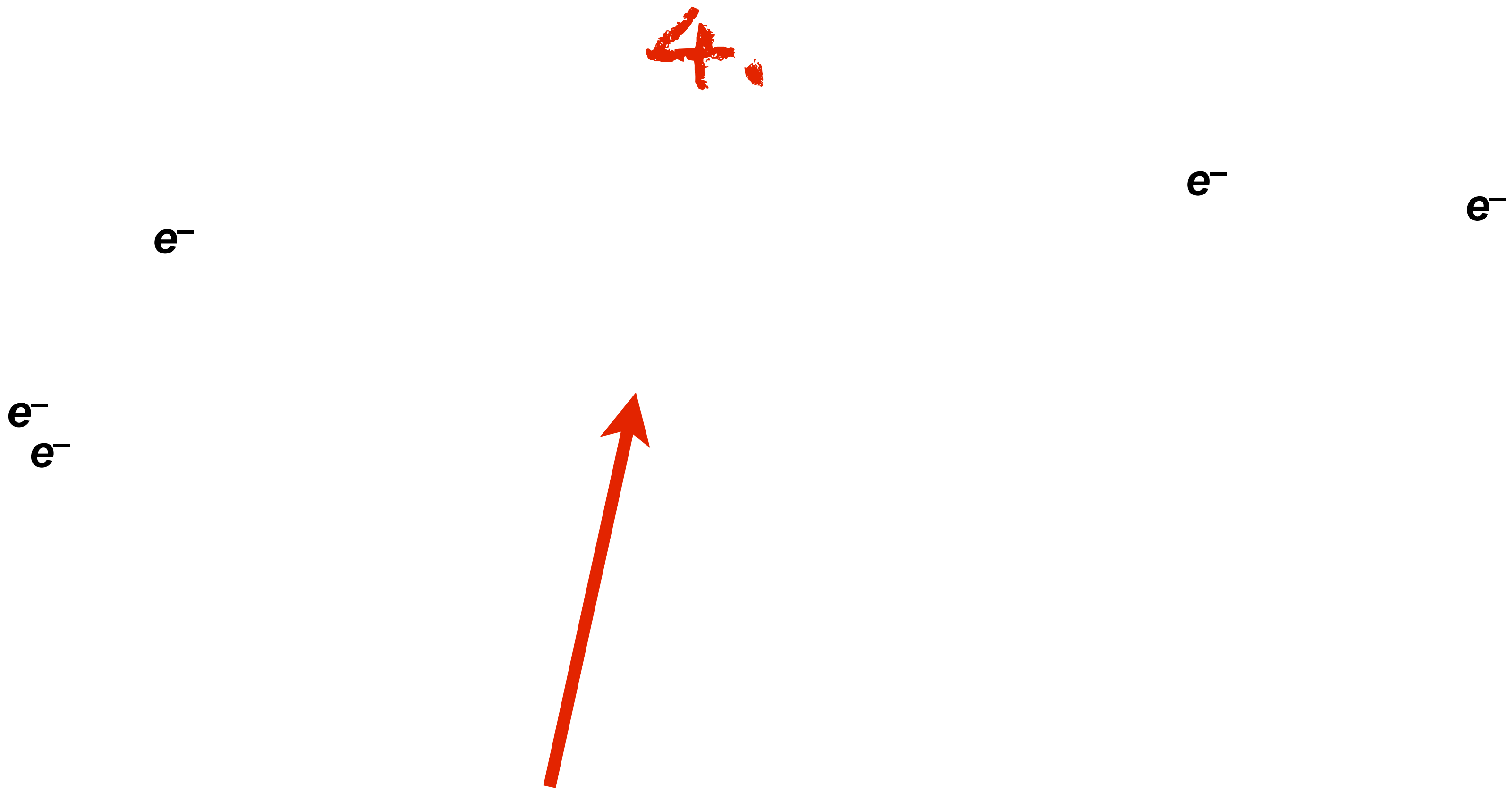
strongest biological oxidizing agent known, it "loves" electrons

Photosystem II (PS II)

Photosystem-I (PS I)

Linear Electron Flow

4. Each electron moves from PSII to the P700 chlorophyll pigment in the PSI via of an electron transport chain, a series of molecules each with a slightly higher electronegativity



transfers redox energy to proton motive force that is used to make ATP we will see shortly

Linear Electron Flow

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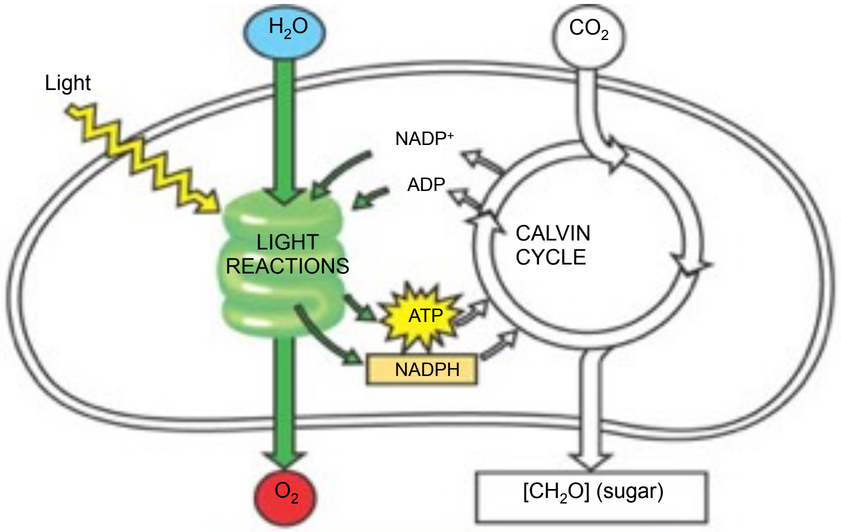

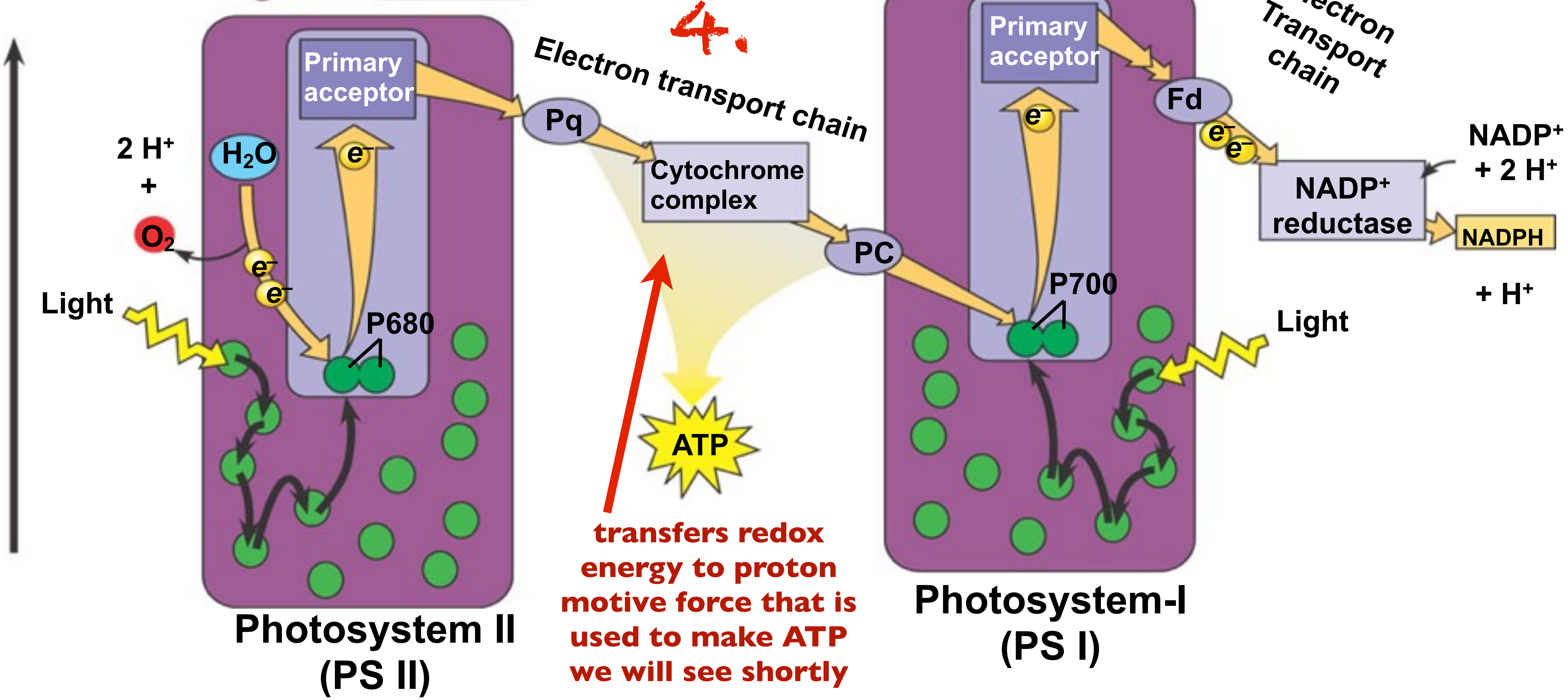

4.

transfers redox energy to proton motive force that is used to make ATP we will see shortly

Linear Electron Flow

5. The energy released from the electrons "fall" is used to pump H^+ into thylakoid lumen, creating a H^+ (proton) gradient

e^- e^-

e^-

e^-
e^-

5.

Linear Electron Flow

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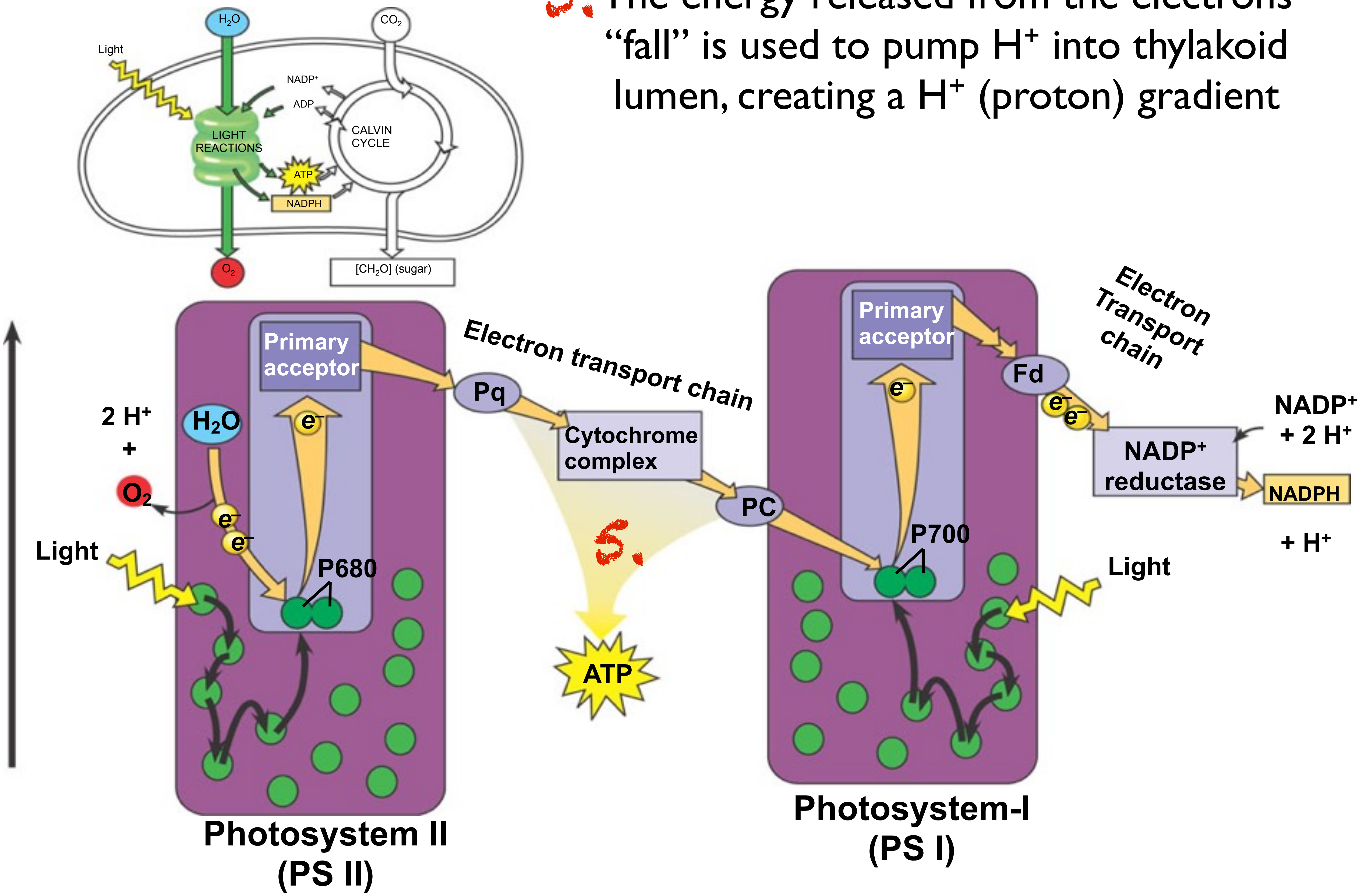

Linear Electron Flow

6. Photon of light strikes pigments in PSI, excites electron, electron falls and energy excites electron of nearby pigment, this continues until P700 chlorophyll is excited and loses its electron to the acceptor, the electrons are continuously replaced by incoming electron from from PSII

e^- e^-

e^-

e^-

e^-

6.

Linear Electron Flow

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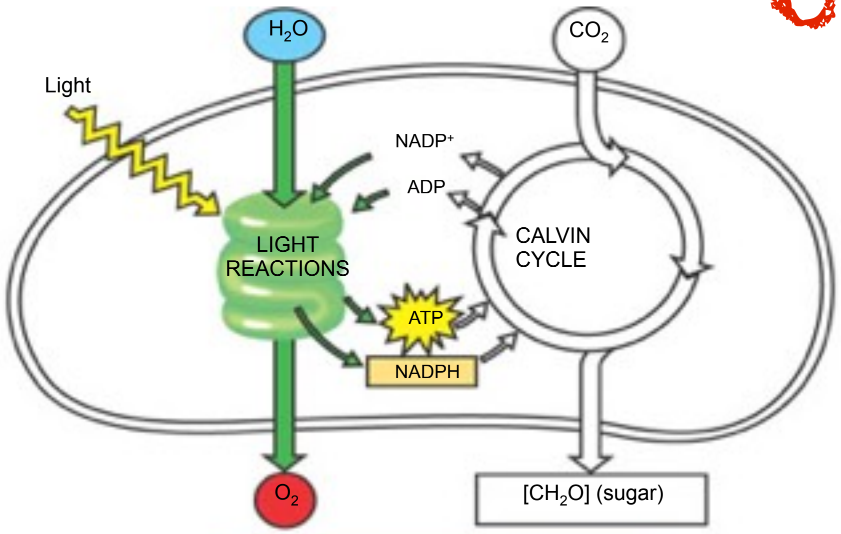
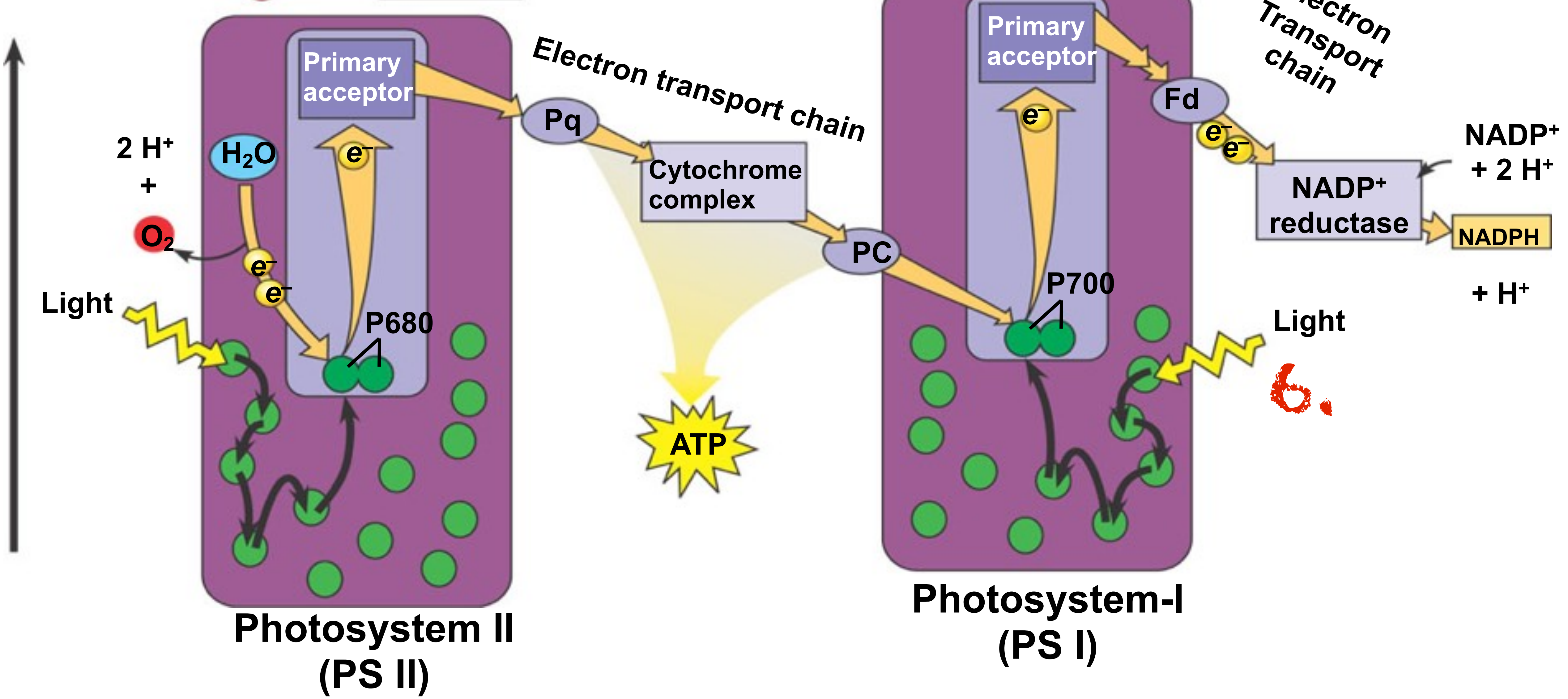




6.

Linear Electron Flow

7. Each electron moves from PSI to $NADP^+$ via of an electron transport chain, but proton a gradient is not produced and thus no ATP is produced

7.

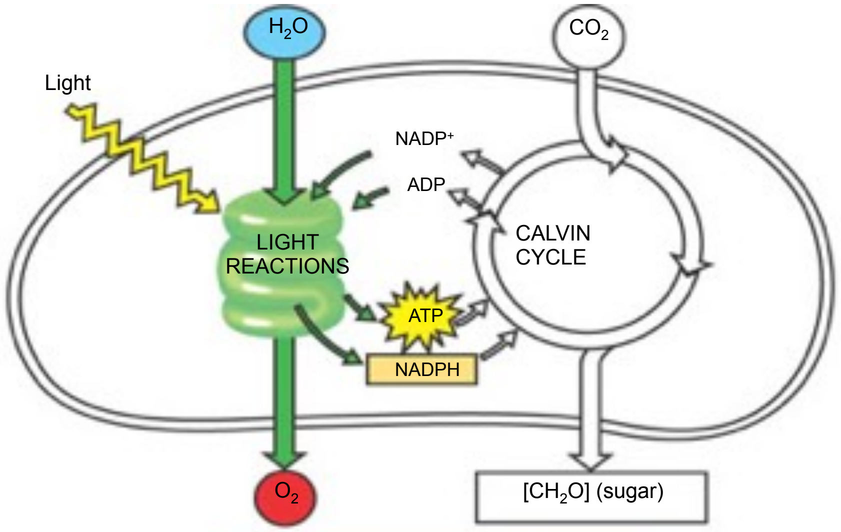
e^- e^-

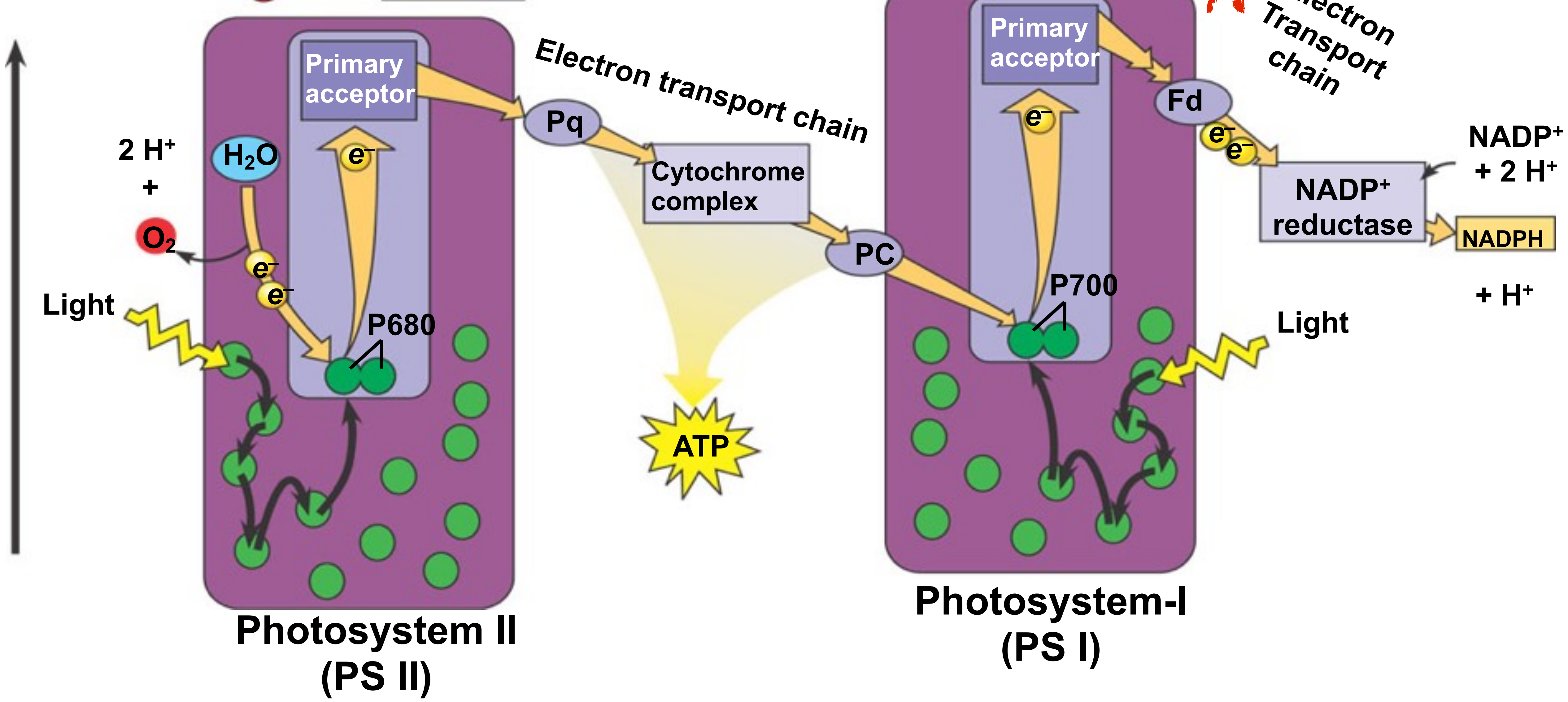
e^-

e^-
e^-

Linear Electron Flow

7. Each electron moves from PSI to NADP$^+$ via of an electron transport chain, but proton a gradient is not produced and thus no ATP is produced





7. Electron Transport chain

Linear Electron Flow

8. An enzyme transfers 2 electrons to NADP$^+$ thus reducing it to NADPH, the H$^+$ come from the stroma, the electrons in NADPH are at a higher energy level then water and thus easier to use in the Calvin Cycle

e^- e^-

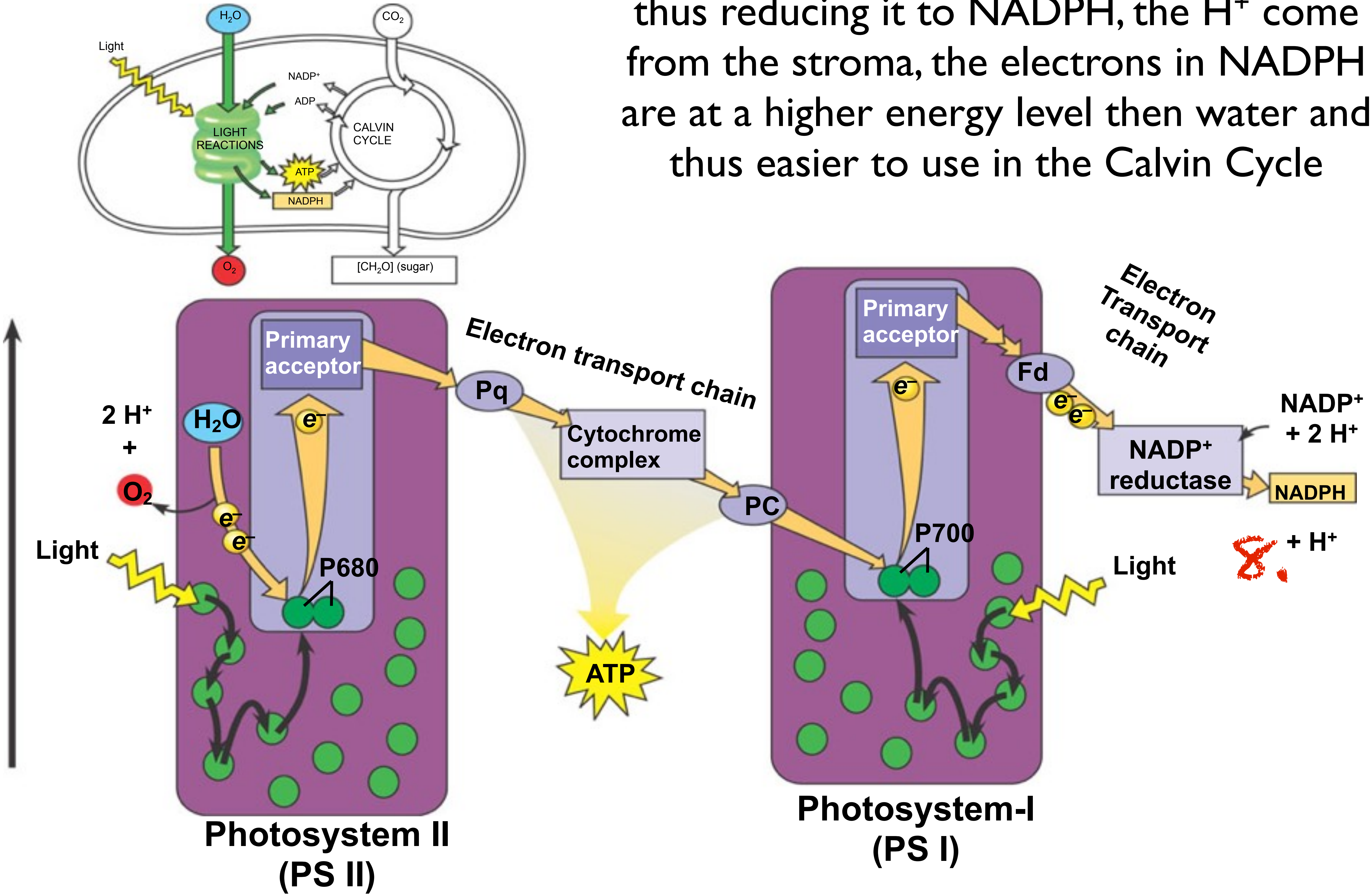
e^-

e^-
e^-

8.

Linear Electron Flow

8. An enzyme transfers 2 electrons to $NADP^+$ thus reducing it to NADPH, the H^+ come from the stroma, the electrons in NADPH are at a higher energy level then water and thus easier to use in the Calvin Cycle



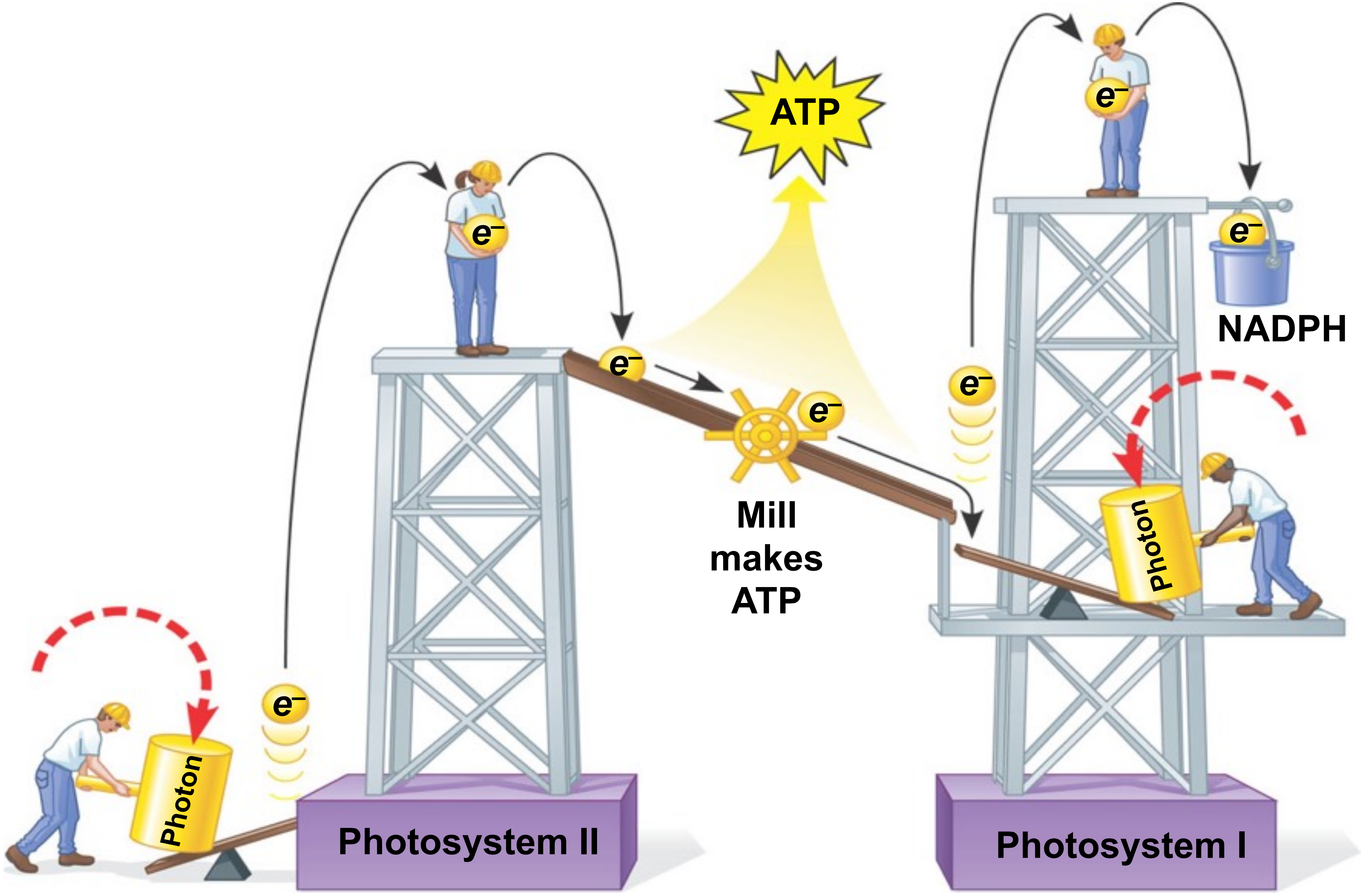
Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated reaction pathways that capture free energy present in light to yield ATP and NADPH, which power the production of organic molecules.

Evidence of student learning is a demonstrated understanding of each of the following:

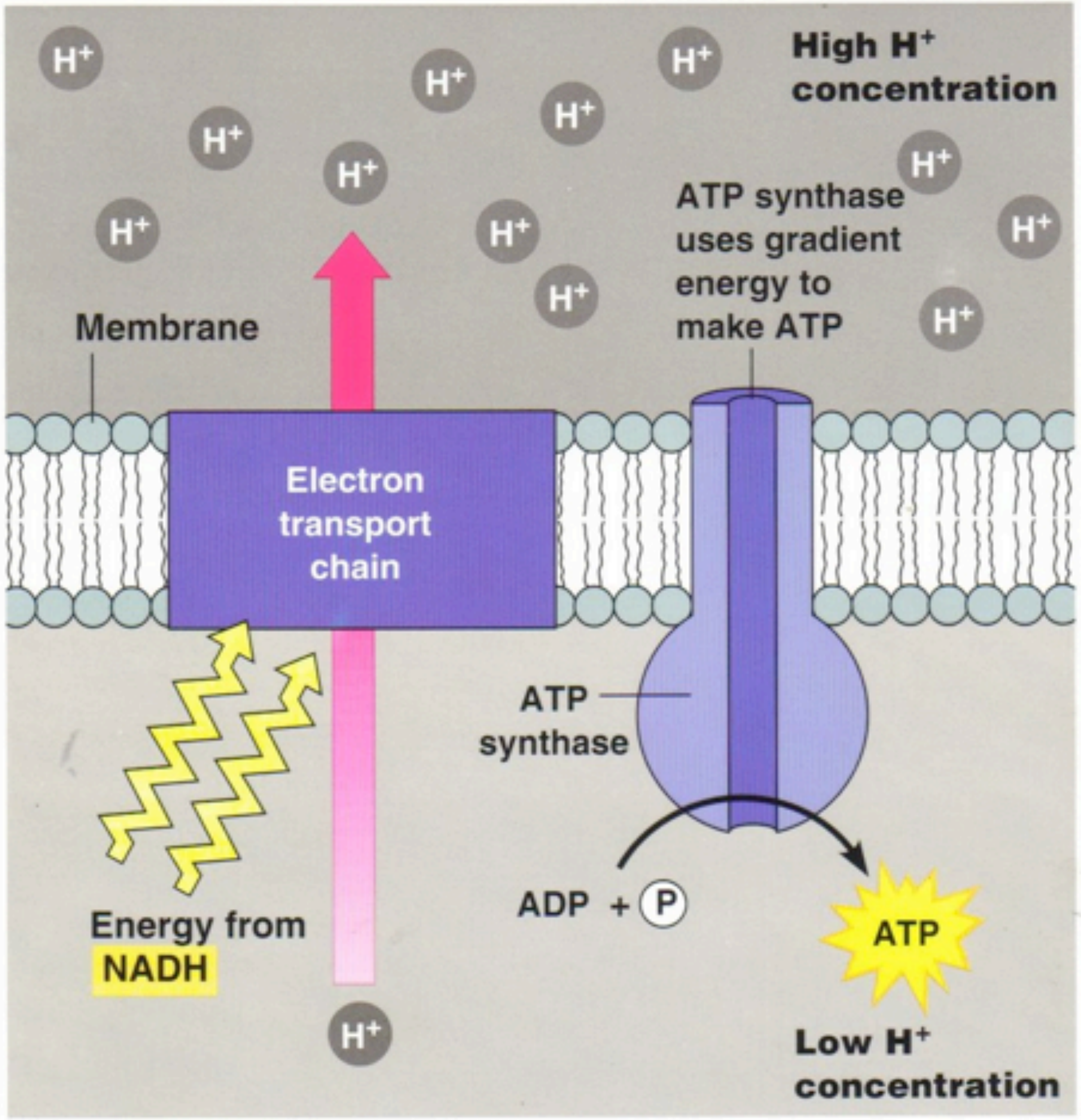
3. When electrons are transferred between molecules in a sequence of reactions as they pass through the ETC, an electrochemical gradient of hydrogen ions (protons) across the thykaloid membrane is established.

Light Reactions- Mechanical Analogy



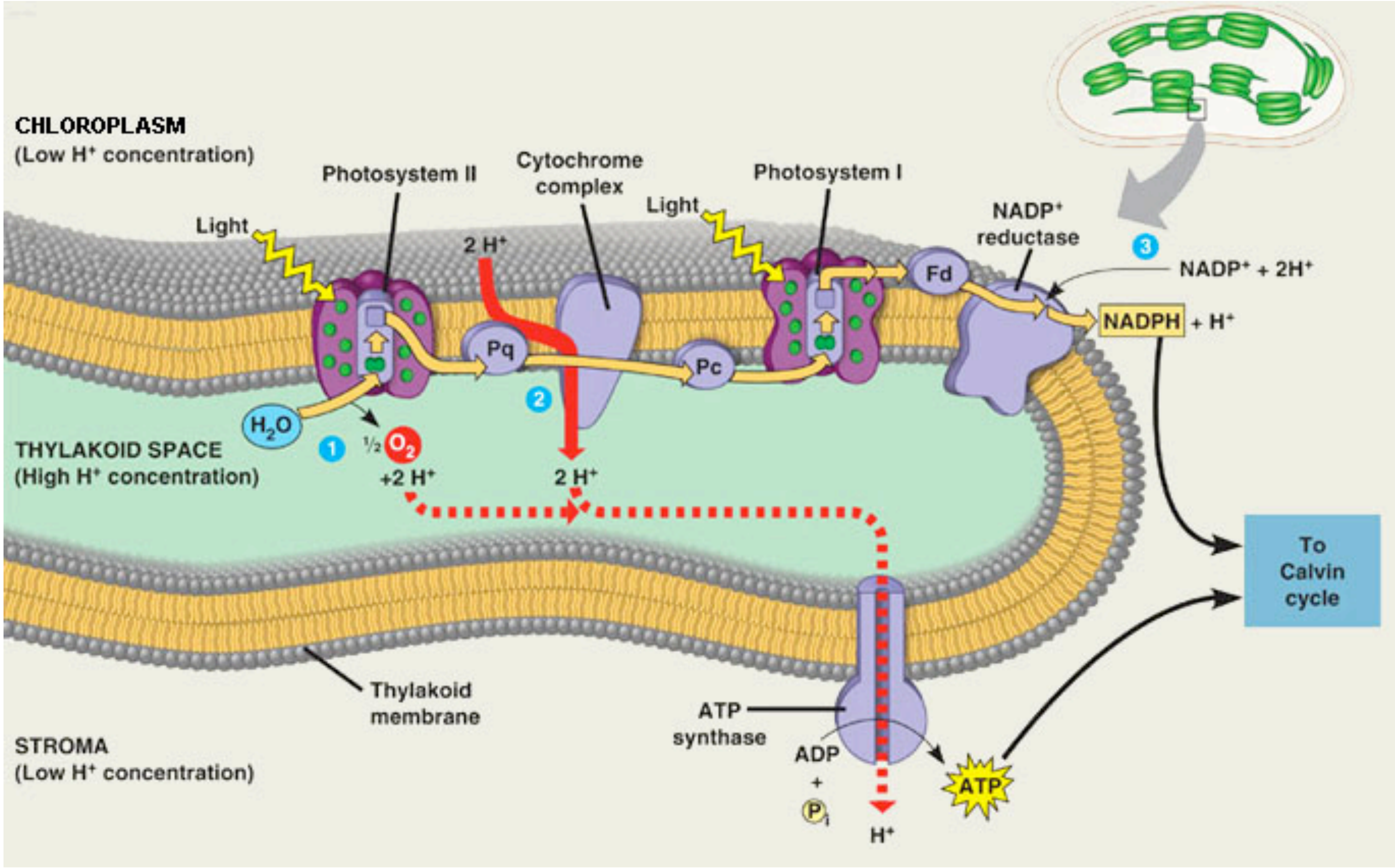
Chemiosmosis

- Chemiosmosis is an energy coupling mechanism that uses energy stored in the form of an H^+ gradient across a membrane to drive cellular work
  - it employs an electron transport chain & ATP synthase
  - it can be found in prokaryotes & eukaryotes
  - it is used in photosynthesis & cell respiration (as well as other cellular processes)



Photophosphorylation

- Chloroplasts are able harness solar energy (photo) to produce ATP (ADP + P = phosphorylation)
  - it does so through chemiosmosis



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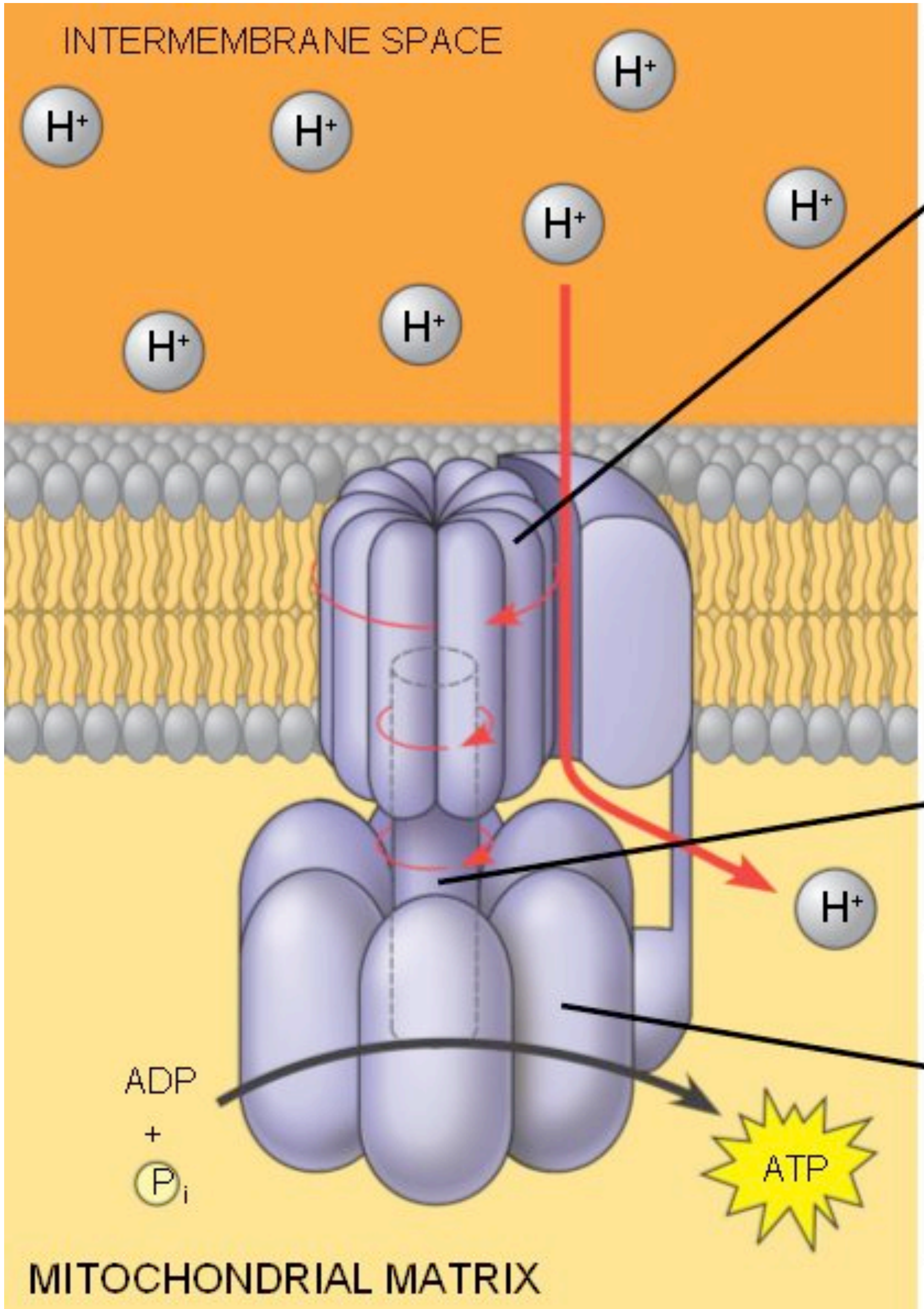
d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated reaction pathways that capture free energy present in light to yield ATP and NADPH, which power the production of organic molecules.

Evidence of student learning is a demonstrated understanding of each of the following:

> 4. The formation of the proton gradient is a separate process, but it is linked to the synthesis of ATP from ADP and inorganic phosphate via ATP synthase.

ATP Synthase



A **rotor** within the membrane spins clockwise when H^+ flows past it down the H^+ gradient.

A **stator** anchored in the membrane holds the knob stationary.

A **rod** (or "stalk") extending into the knob also spins, activating catalytic sites in the knob.

Three catalytic sites in the stationary **knob** join inorganic Phosphate to ADP to make ATP.

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

d. The light-dependent reactions of photosynthesis in eukaryotes involve a series of coordinated reaction pathways that capture free energy present in light to yield ATP and NADPH, which power the production of organic molecules.

Evidence of student learning is a demonstrated understanding of each of the following:

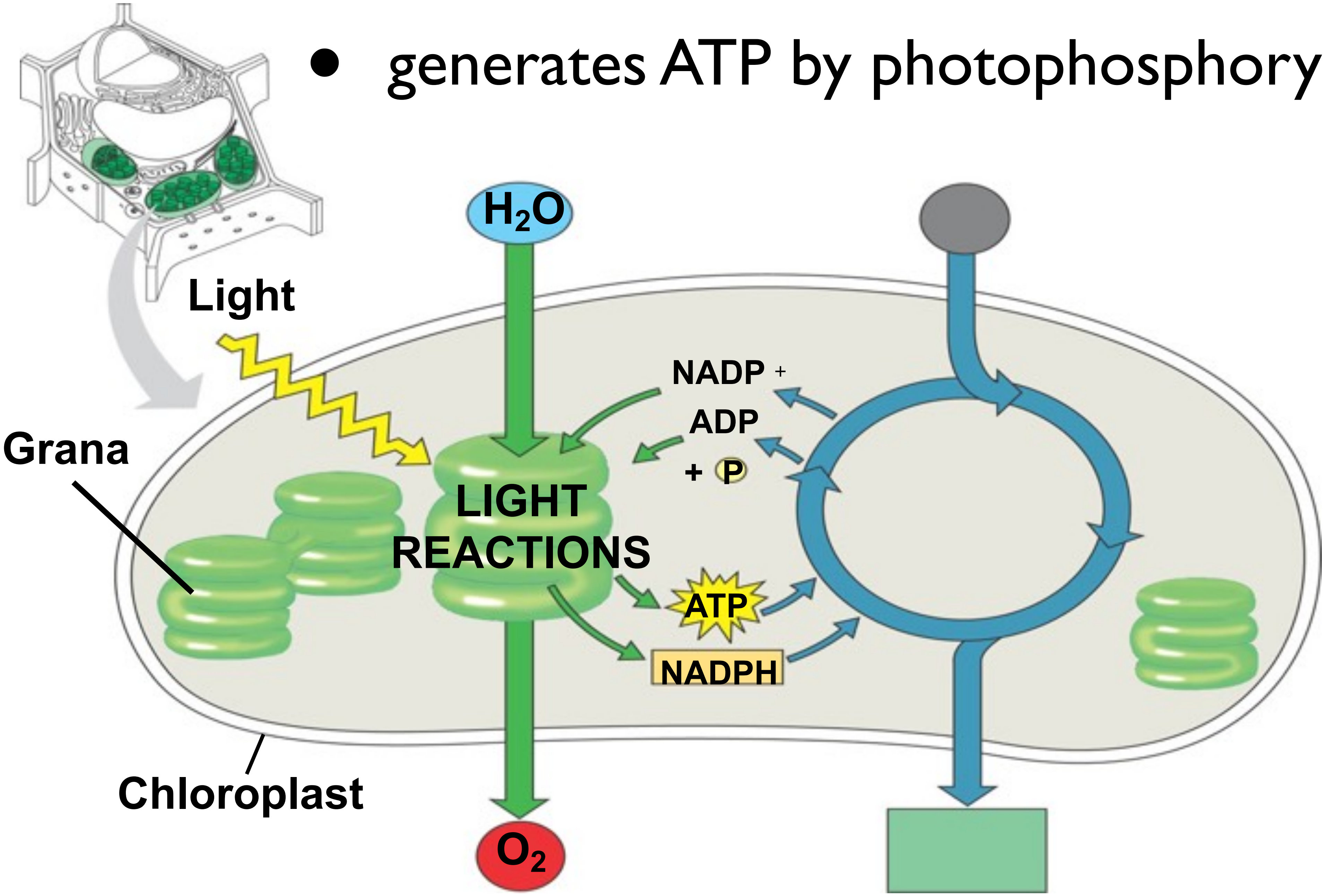
5. The energy captured in the light reactions as ATP and NADPH powers the production of carbohydrates from carbon dioxide in the Calvin cycle, which occurs in the stroma of the chloroplast.

✘ Memorization of the steps in the Calvin cycle, the structure of the molecules and the names of enzymes (with the exception of ATP synthase) are beyond the scope of the course and the AP Exam.

“The Big Picture Before We Continue”

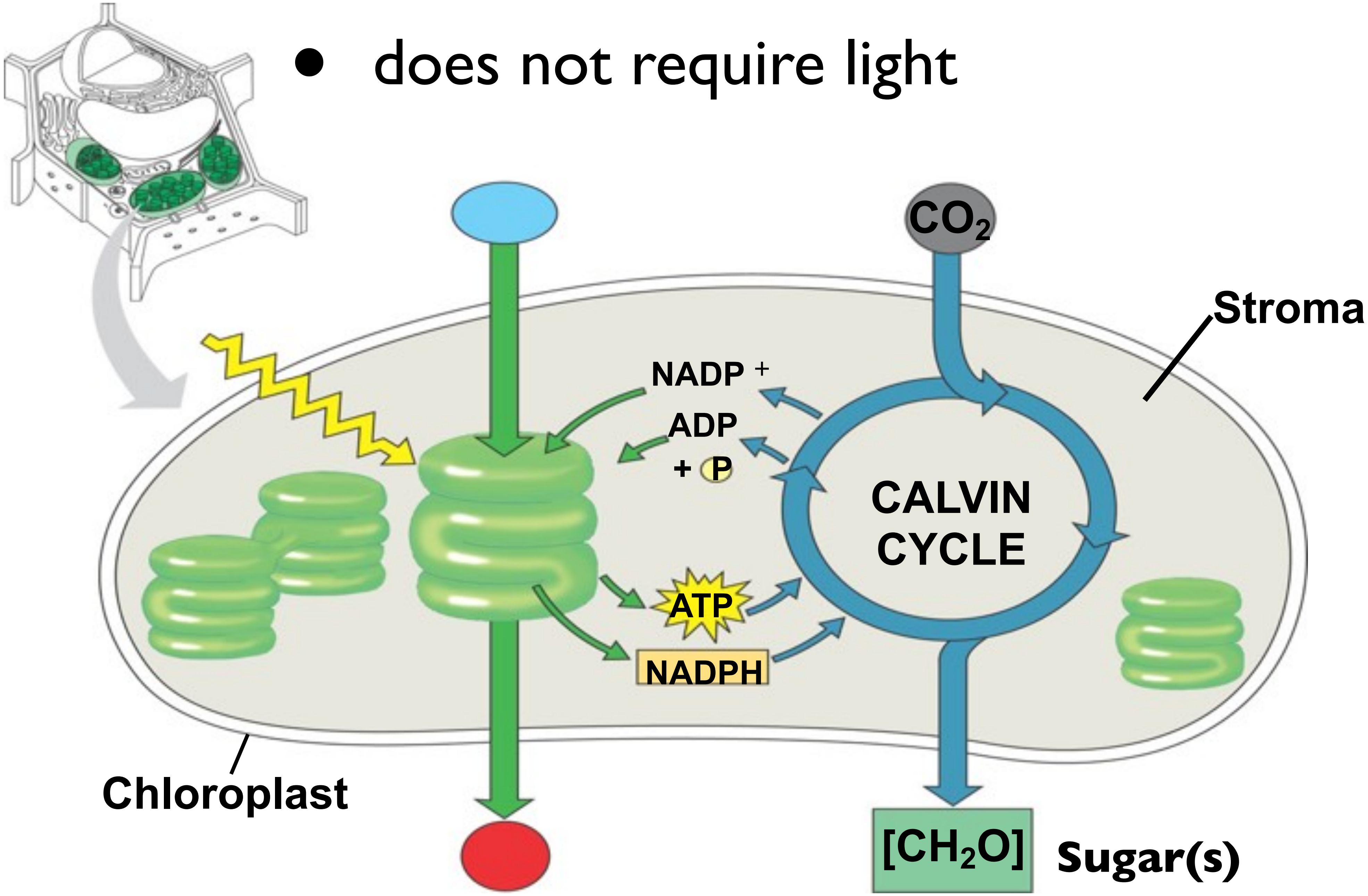
- **Building sugar in stage 2 of photosynthesis (Calvin Cycle) requires:**
  - **building blocks,**
  - **electrons,**
  - **energy**
- The building blocks (carbon) simply come from atmosphere via carbon dioxide.
- But the electrons (carried by NADPH) have to come from the light reactions via water
- And the energy (ATP) has to also come from the light reactions

- **Light Reactions**
  - occurs in the grana (thylakoid membranes)
    - converts solar to chemical energy (NADPH & ATP)
      - harvests electrons and hydrogens from water
        - generates ATP by photophosphorylation



Calvin Cycle

- occurs in the stroma
  - uses chemical energy (NADPH & ATP) to make sugar
    - builds sugars using carbon from CO_2
      - does not require light



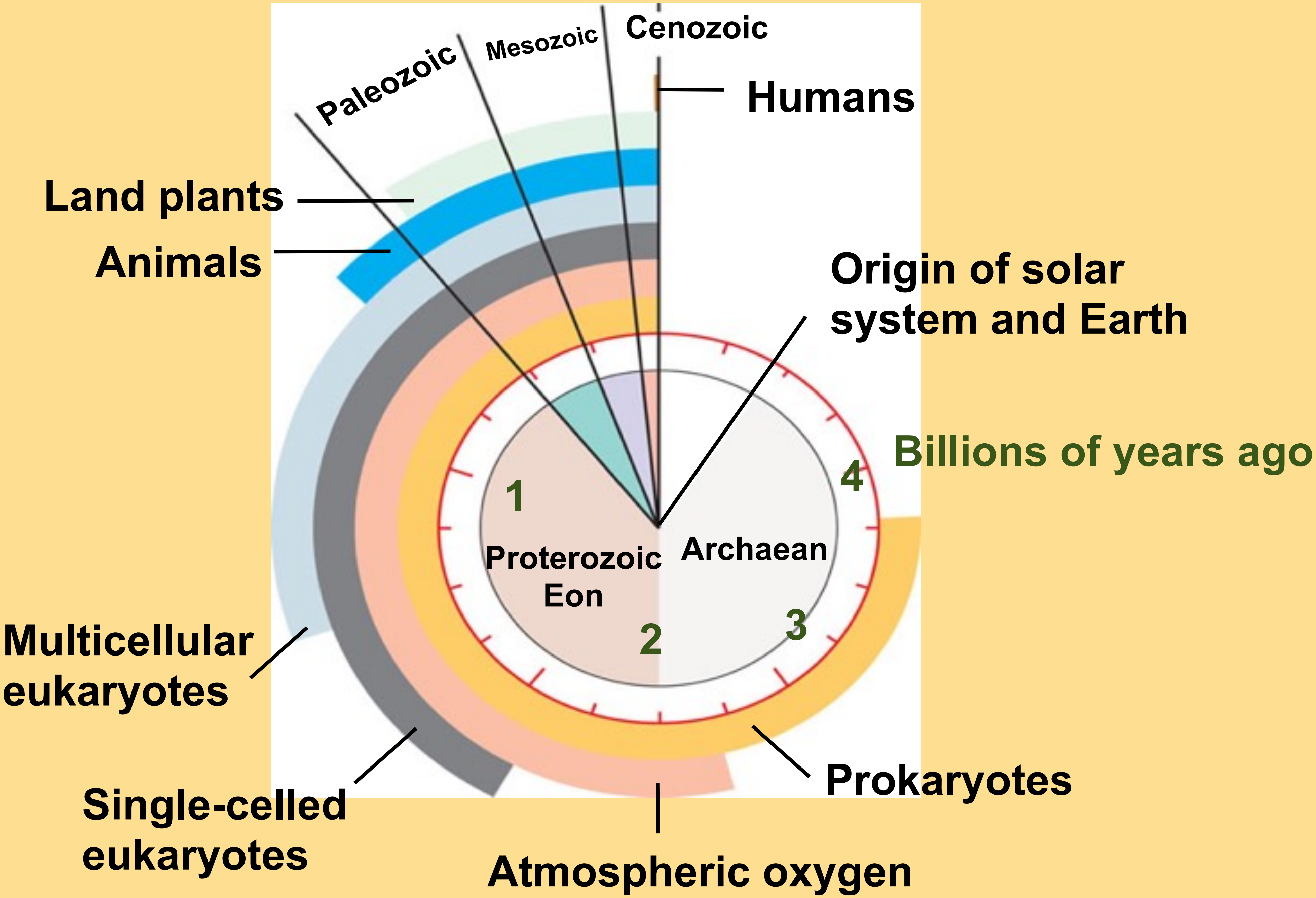
this step is the carbon fixation portion of photosynthesis

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

e. Photosynthesis first evolved in prokaryotic organisms; scientific evidence supports that prokaryotic (bacterial) photosynthesis was responsible for the production of an oxygenated atmosphere; prokaryotic photosynthetic pathways were the foundation of eukaryotic photosynthesis.

Major Events in Earth History

- **Formation of earth and abiogenesis 3.8 bya**



What did the first cells look like?

- Nobody can say for sure. (I have found conflicting information but here is what I can say)
- Science agrees the first cell was a very simple prokaryotic.
- Science agrees that the first cell would have been anaerobic (does not require oxygen)
- Science also agrees that this prokaryote was a chemotroph (uses chemicals for energy source)
- Most feel that these prokaryotes were heterotrophs (carbon source from organic compounds)
  - *Some sources feel believe that the first cell would have used carbon dioxide as its carbon source thus making it an autotroph.*

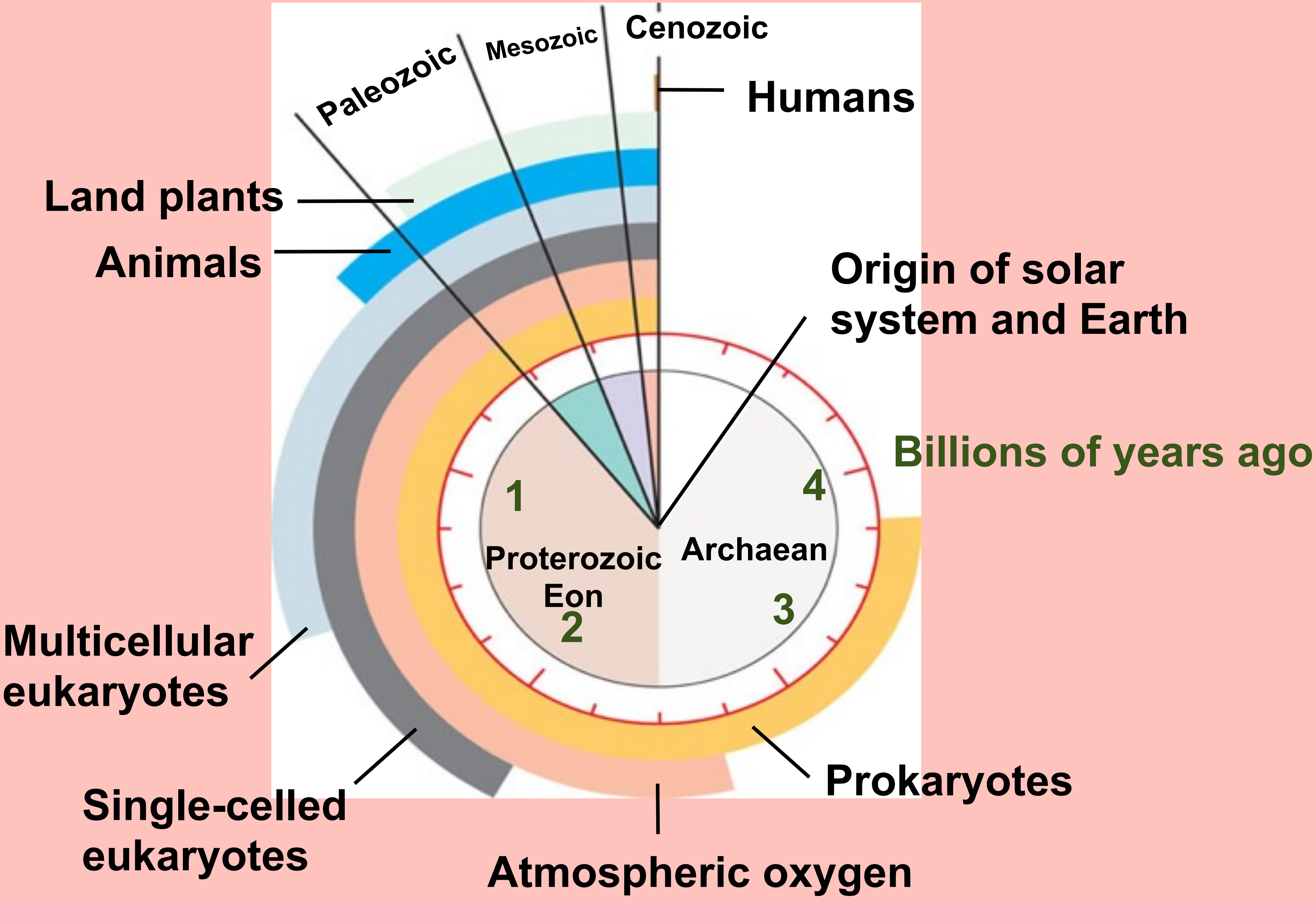
Final Verdict: **Anaerobic Chemoheterotrophic Bacteria**

What did the earliest fossils look like?

- The earliest known fossils date back to 3.5 billion years ago.
    - **Stromatolites** are rock like structures composed of layers of bacteria and sediment.
- Life itself likely evolved prior to this as result we estimate the first cells evolved somewhere around 3.8 billion years ago.

Major Events in Earth History

- **Atmospheric Oxygen ~2.5 bya**



Major Events in Earth History

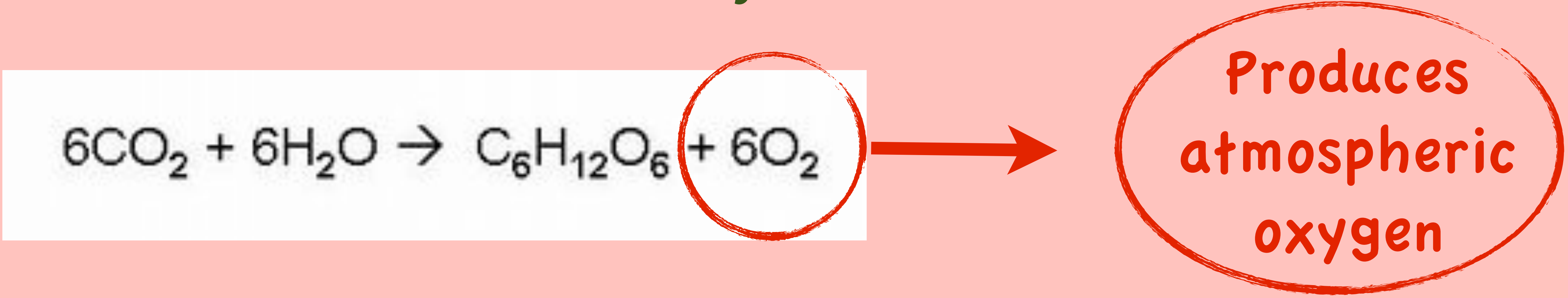
- The earliest metabolism likely produced ATP via glycolysis.

↓

- The earliest form of photosynthesis likely used the electrons from hydrogen sulfide (used up quickly).

↓ Life's First Major Crisis

- The earliest form of photosynthesis likely used the electrons from water. (cyanobacteria)



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

Produces atmospheric oxygen

Major Events in Earth History

- **The production of oxygen accumulates on earth around 2.3 - 2.7 billion years ago.**
  - ***theme...biotic effecting the abiotic***
- **The oxygen rich atmosphere has a significant effect on the evolution of living organisms**
  - ***theme...abiotic effecting the biotic***

Major Events in Earth History

- **The oxidative (degradative) atmosphere posed a challenge to living organisms.**

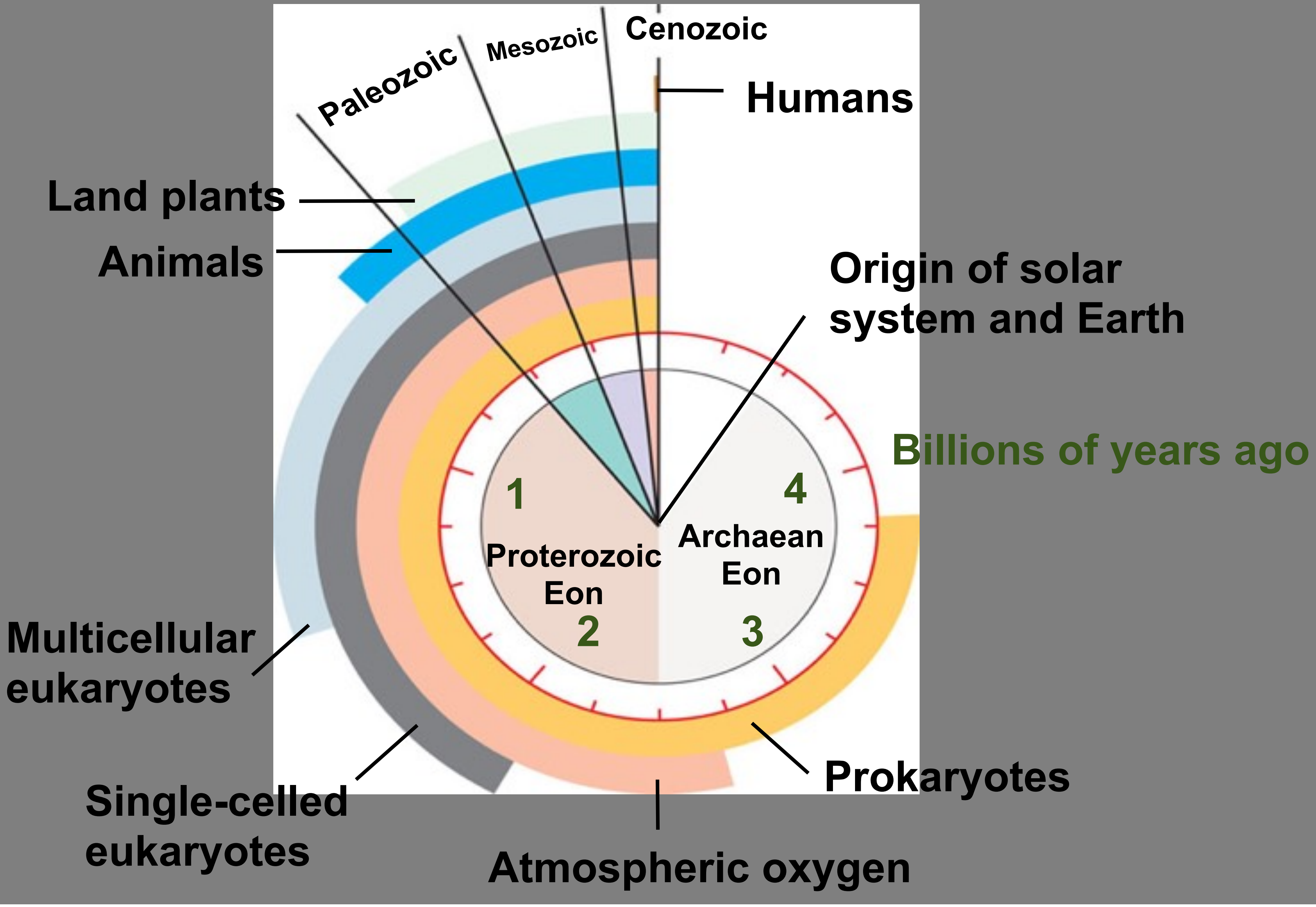
  Second Major Crisis

- **The oxidative atmosphere also provided an opportunity for living organisms to gain energy.**

  Aerobic Respiration- A Major Innovation

Major Events in Earth History

- Evolution of Eukaryotes 2.1 bya

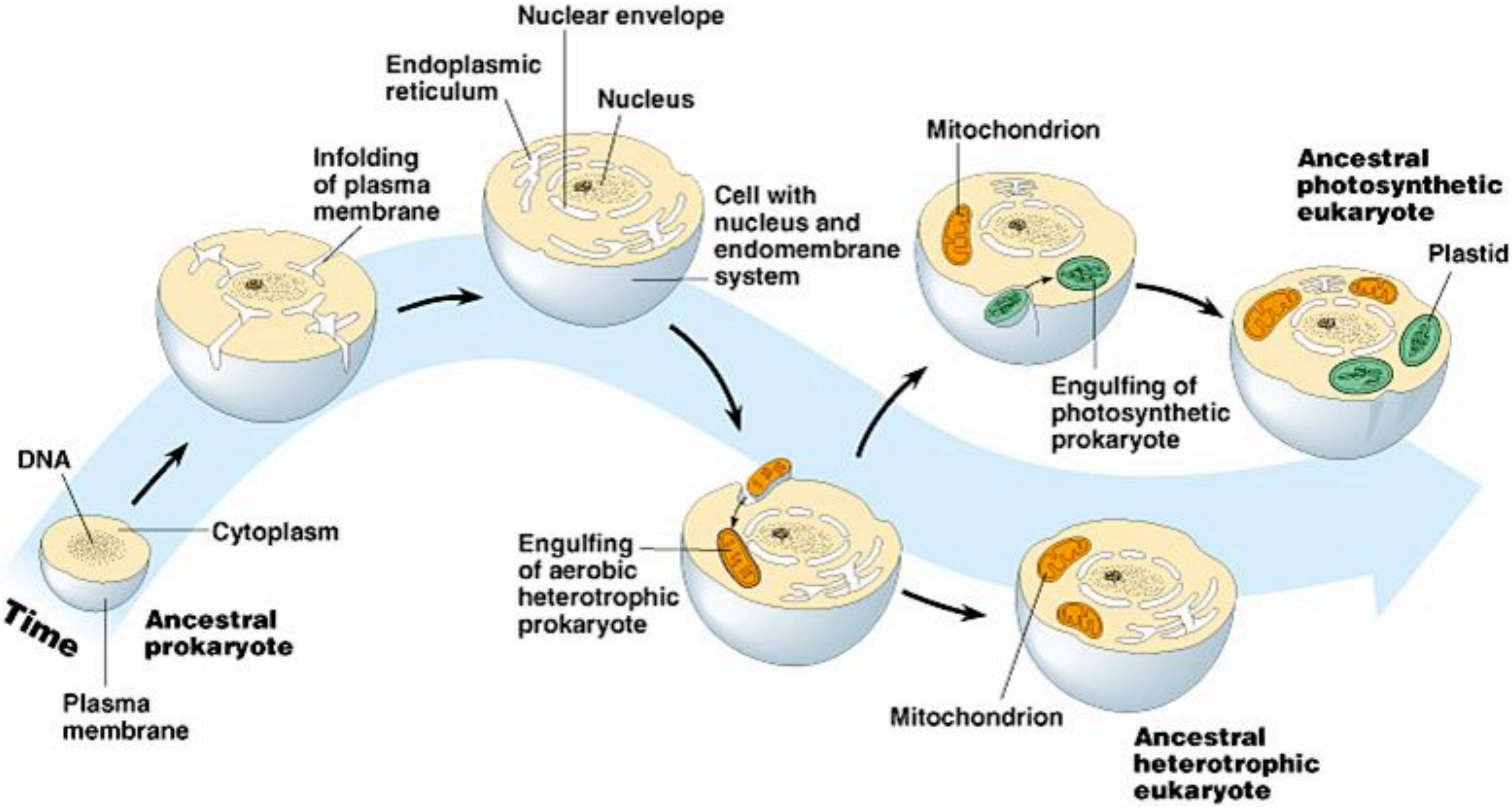


Major Events in Earth History

- **Evolution of Eukaryotes dates back to 2.1 BYA**
- **It is possible that the oxygen revolution provided the selective pressure for eukaryotic evolution.**
- **These cells are more complex than prokaryotes**
  - **They possess membrane organelles**
    - ***nucleus, mitochondria, chloroplasts, etc***
  - **They possess a cytoskeleton**
  - **The endosymbiont theory explains how this may have occurred.**

Endosymbiont Theory

...could have been undigested prey or a parasite



Major Events in Earth History

- The endosymbiont lives within the host cell.
- The prey/parasite form a mutualistic relationship.
- At some point the host and the prey/parasite become dependent on one another.
  - It is likely that the heterotroph/mitochondria came first.
  - Then later the autotrophic bacteria/chloroplast came second.

There is an overwhelming amount of evidence to support this theory and and these ideas.

Evidence for Endosymbiosis

Prokaryotes	**Mitochondria & Chloroplasts**
plasma membrane enzymes	membrane enzymes homologous to prokaryotic plasma membrane
plasma membrane transport systems	membrane transport proteins homologous to prokaryotic plasma membrane
replicate via binary fission	replicate similar to binary fission
single, circular chromosome with no histones	organelles both posses their own single circular chromosome also with no histones even though eukaryotic chromosomes have histones
ribosomes have unique size and sequence	organelles posses their own ribosomes, which are equal in size to the prokaryotes and their RNA sequences are nearly identical

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

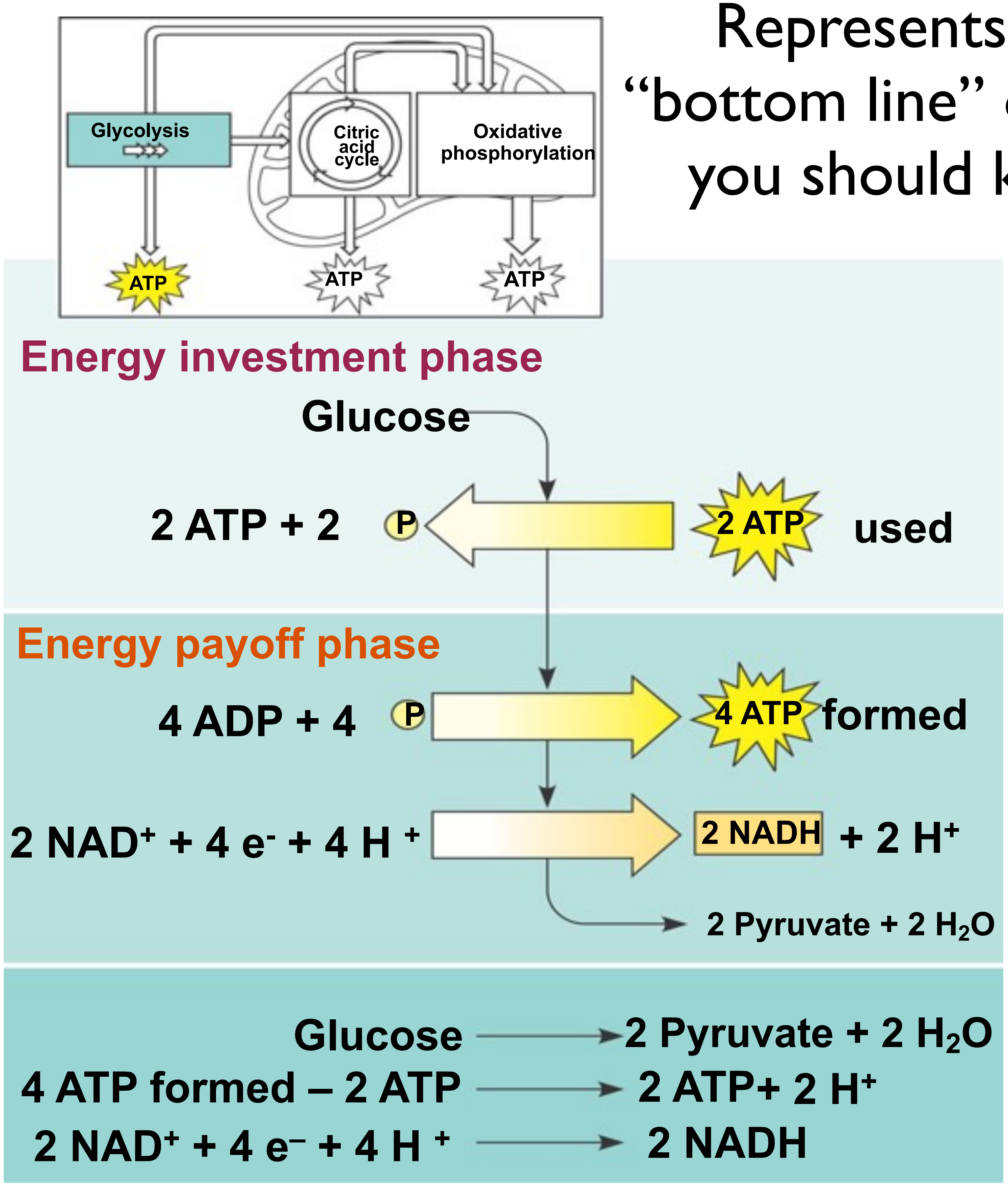
f. Cellular respiration in eukaryotes involves a series of coordinated enzyme-catalyzed reactions that harvest free energy from simple carbohydrates.

Evidence of student learning is a demonstrated understanding of each of the following:

1. Glycolysis rearranges the bonds in glucose molecules, releasing free energy to form ATP from ADP and inorganic phosphate, and resulting in the production of pyruvate.

An Overview of Glycolysis

Represents the "bottom line" of what you should know



Energy investment phase

Glucose

2 ATP + 2 P ← 2 ATP used

Energy payoff phase

4 ADP + 4 P → 4 ATP formed

2 NAD^+ + 4 e^- + 4 H^+ → 2 NADH + 2 H^+

→ 2 Pyruvate + 2 H_2O

Glucose → 2 Pyruvate + 2 H_2O

4 ATP formed – 2 ATP → 2 ATP+ 2 H^+

2 NAD^+ + 4 e^- + 4 H^+ → 2 NADH

Glycolysis only extracts 25% of the potential energy, the rest still resides in pyruvate

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

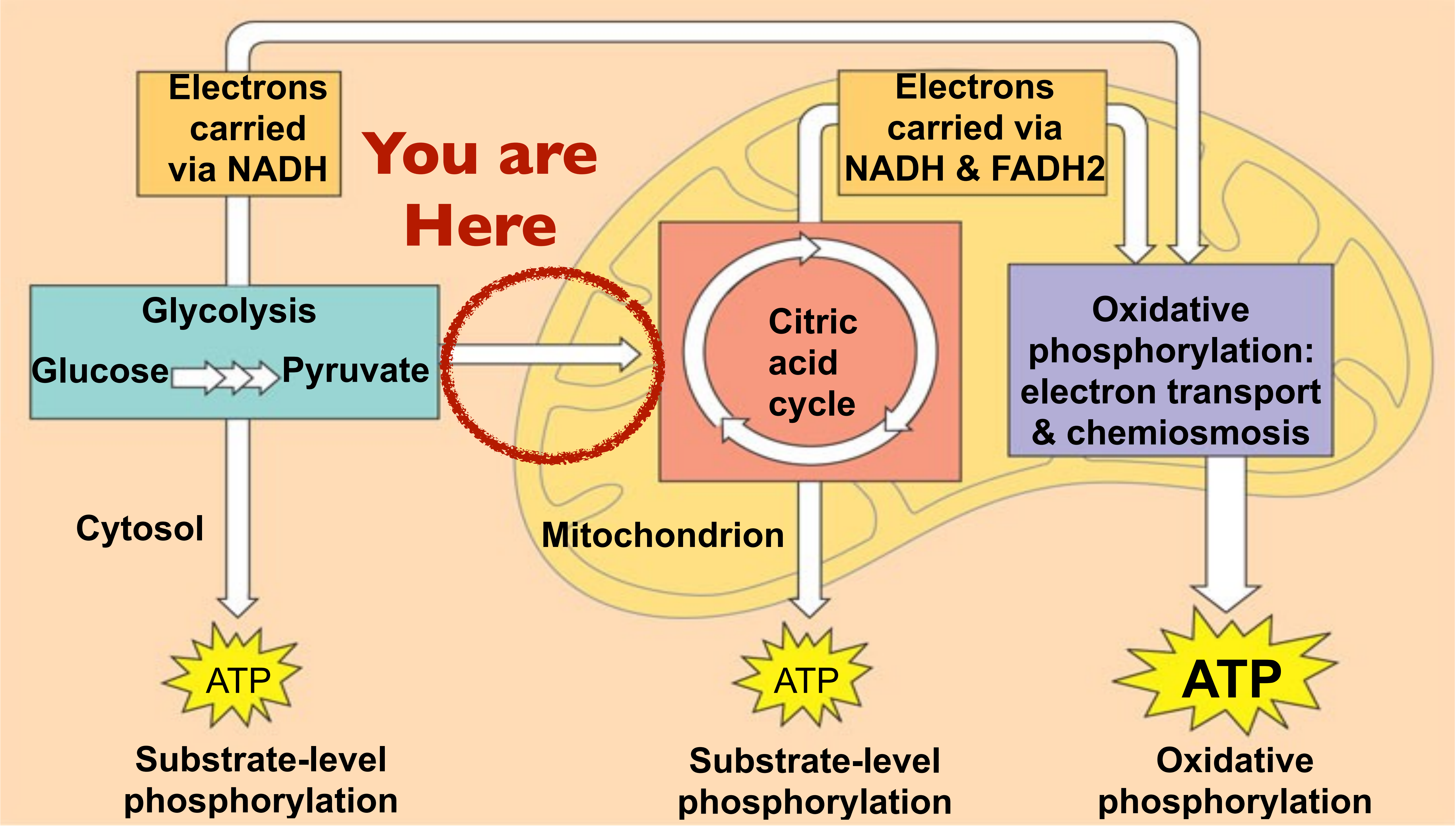
f. Cellular respiration in eukaryotes involves a series of coordinated enzyme-catalyzed reactions that harvest free energy from simple carbohydrates.

Evidence of student learning is a demonstrated understanding of each of the following:

2. Pyruvate is transported from the cytoplasm to the mitochondrion, where further oxidation occurs. [See also 4.A.2]

An Overview of Cellular Respiration

- Focus on the location, the input(s) and the output(s) for each the three stages.



Electrons carried via NADH

You are Here

Electrons carried via NADH & FADH2

Glycolysis

Glucose → Pyruvate

Citric acid cycle

Oxidative phosphorylation: electron transport & chemiosmosis

Cytosol

Mitochondrion

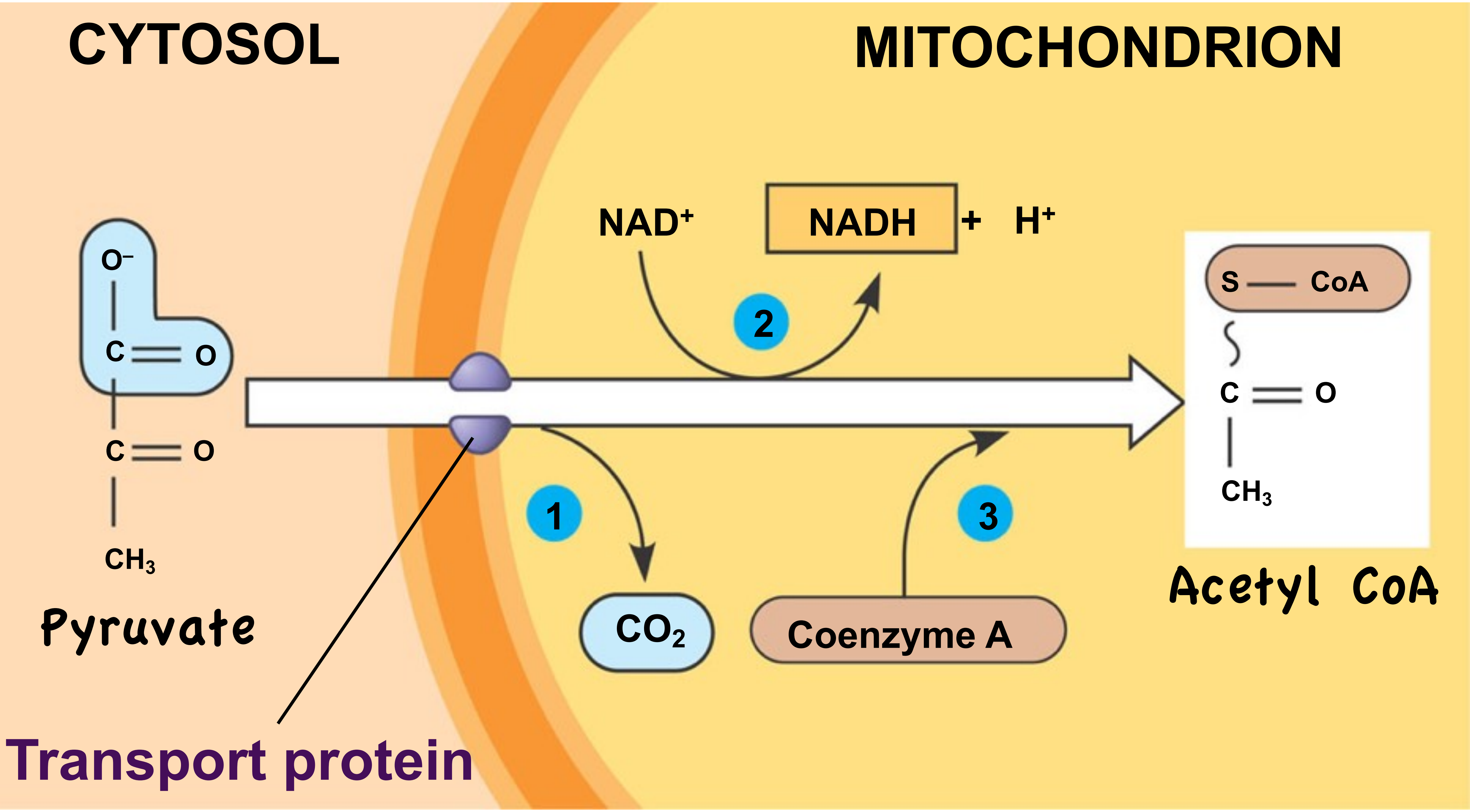
Substrate-level phosphorylation

Substrate-level phosphorylation

Oxidative phosphorylation

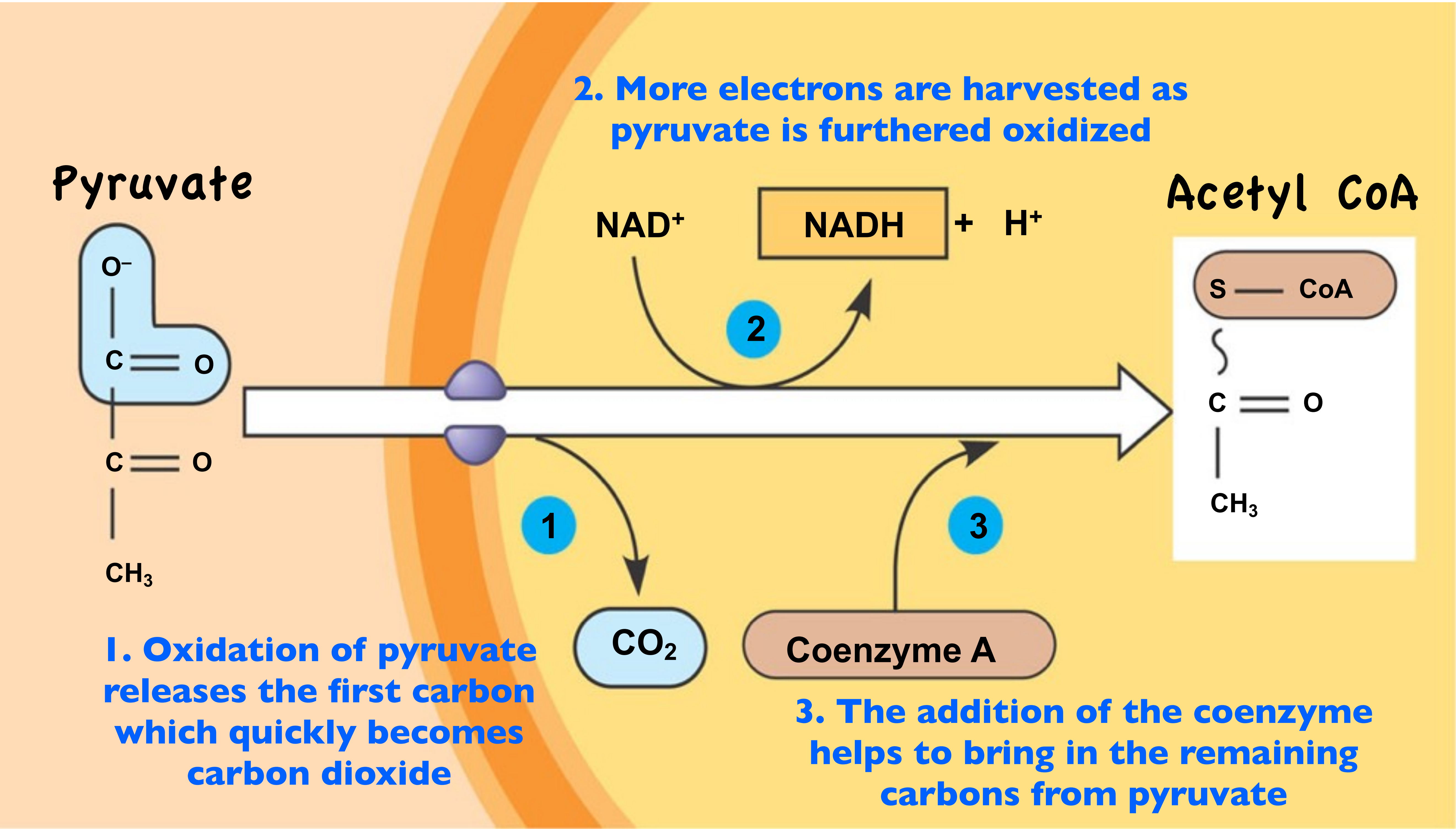
Transport of Pyruvate into Mitochondria

- Pyruvate can not pass freely through the mitochondrial membrane (too large and charged), it must be actively transported across.



The "Prep Step"

- Pyruvate can not enter the Citric Acid cycle, it must be converted to Acetyl Coenzyme A.



2. More electrons are harvested as pyruvate is furthered oxidized

1. Oxidation of pyruvate releases the first carbon which quickly becomes carbon dioxide

3. The addition of the coenzyme helps to bring in the remaining carbons from pyruvate

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

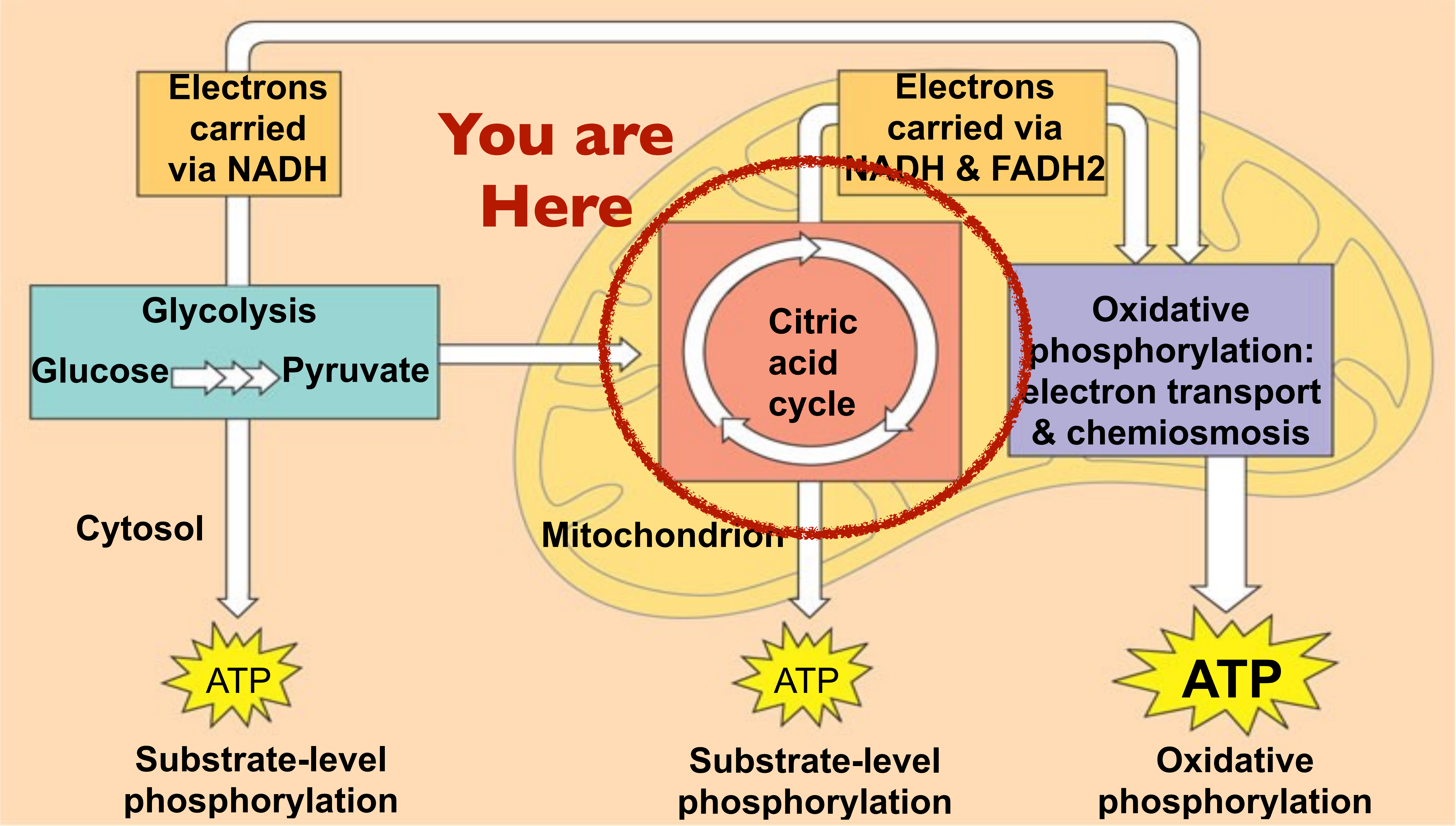
f. Cellular respiration in eukaryotes involves a series of coordinated enzyme-catalyzed reactions that harvest free energy from simple carbohydrates.

Evidence of student learning is a demonstrated understanding of each of the following:

3. In the Krebs cycle, carbon dioxide is released from organic intermediates ATP is synthesized from ADP and inorganic phosphate via substrate level phosphorylation and electrons are captured by coenzymes.

An Overview of Cellular Respiration

- Focus on the location, the input(s) and the output(s) for each the three stages.

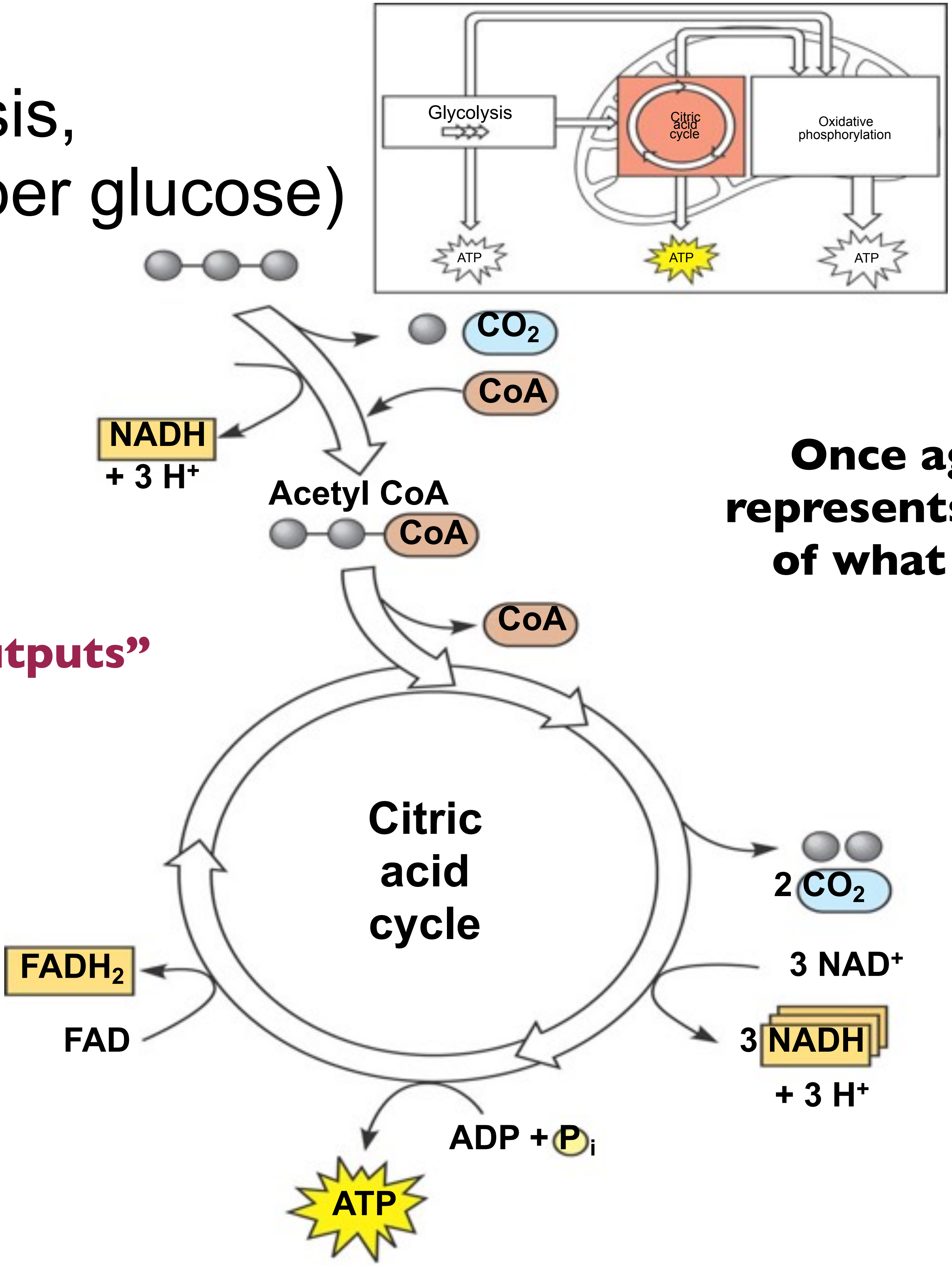


The Citric Acid Cycle or Krebs Cycle

- Harvests the remaining electrons from acetyl CoA (originally from glucose).
- In addition, it generates some more ATP via substrate level phosphorylation.
- Carbon dioxide is released as a waste product.
    - Ultimately each of the six original carbons in glucose will be released as six carbon dioxide molecules.
        - 2 of the 6 in the prep step
        - 4 of the 6 in the citric acid cycle

An Overview of the Citric Acid Cycle

Pyruvate
(from glycolysis,
2 molecules per glucose)



Once agin the overview represents the "bottom line" of what you should know

Focus on "inputs" and "outputs"

PER TURN

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

f. Cellular respiration in eukaryotes involves a series of coordinated enzyme-catalyzed reactions that harvest free energy from simple carbohydrates.

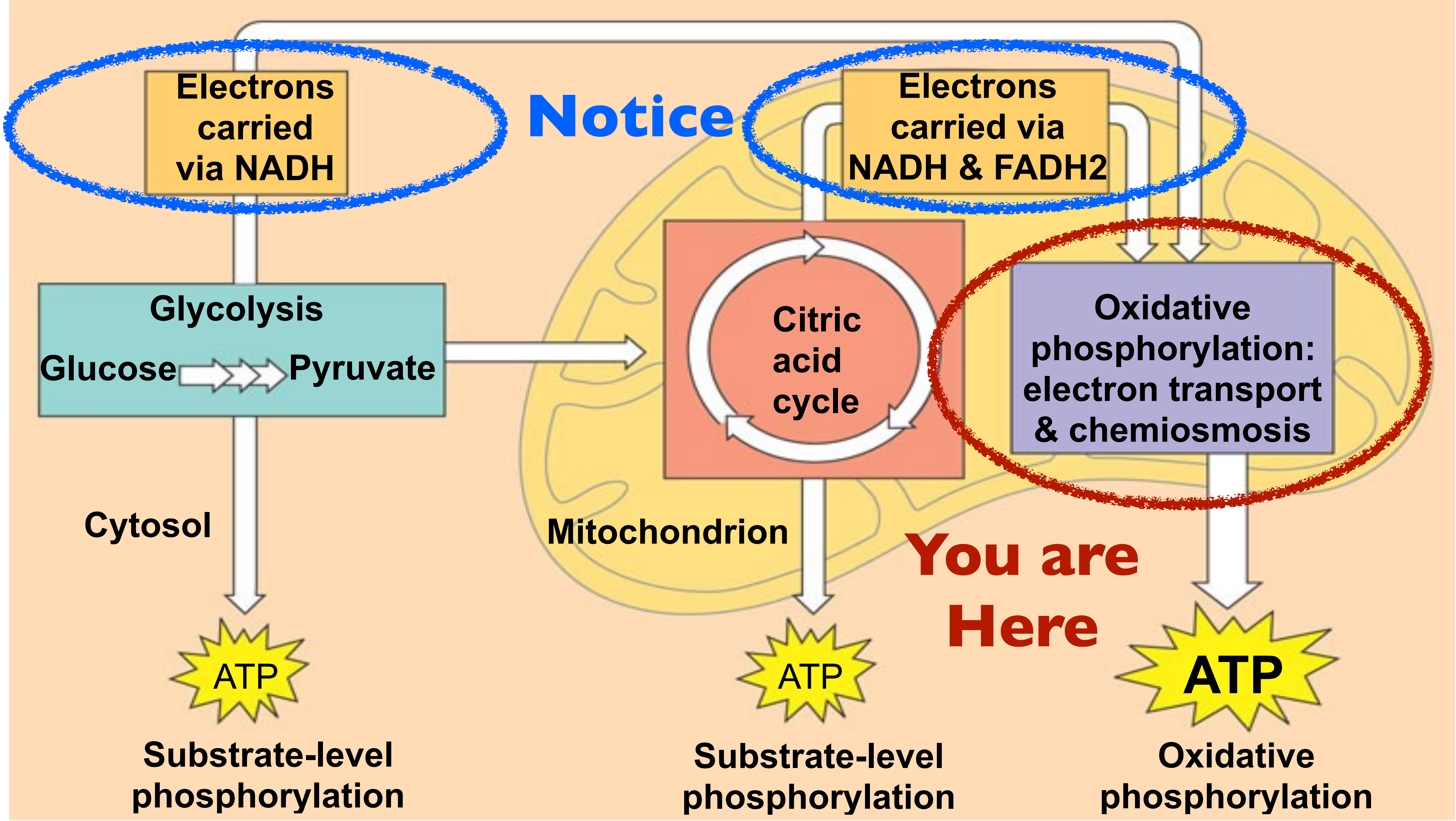
Evidence of student learning is a demonstrated understanding of each of the following:

4. Electrons that are extracted in the series of Krebs cycle reactions are carried by NADH and FADH2 to the electron transport chain.

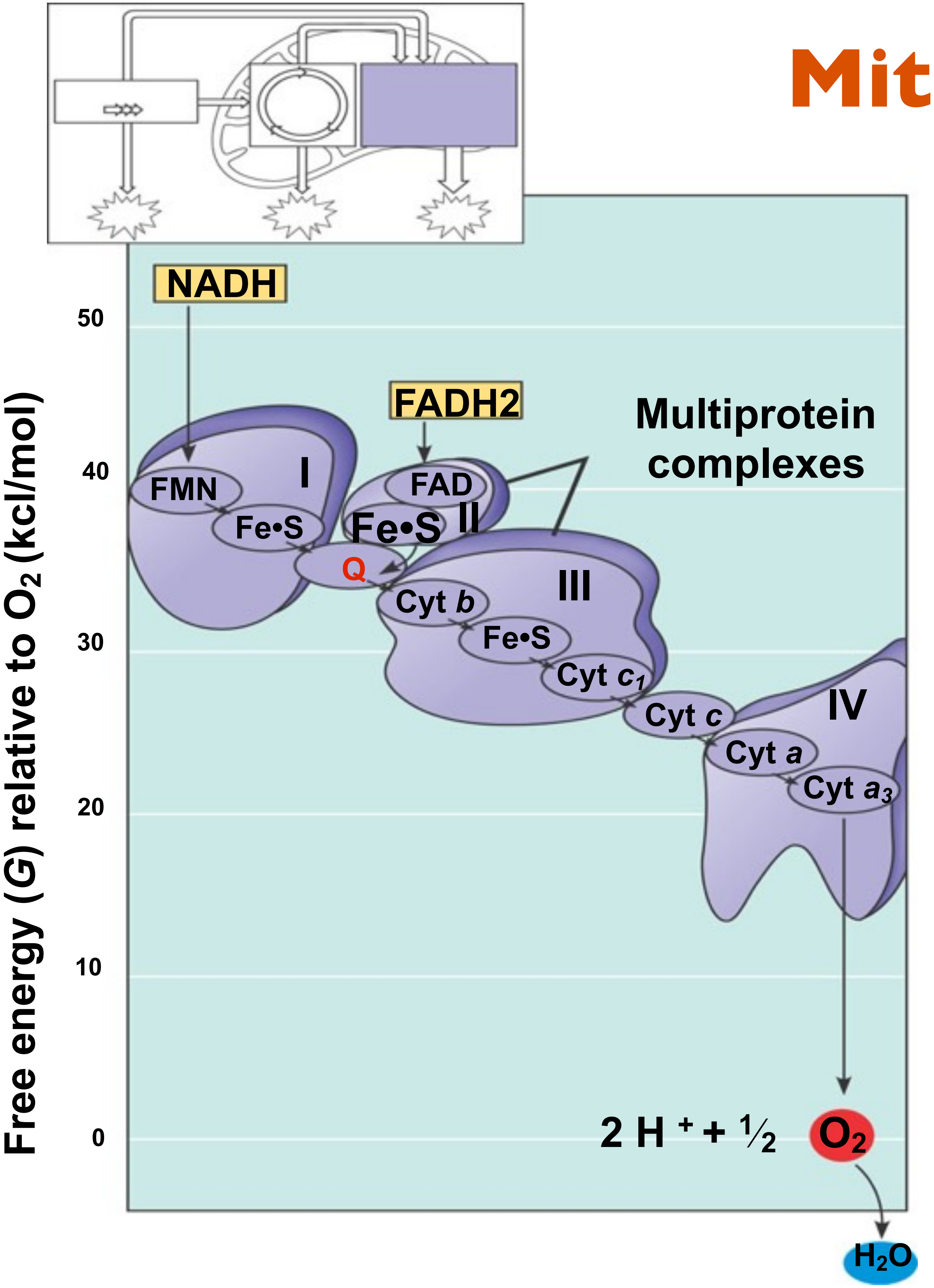
✘ Memorization of the steps in glycolysis and the Krebs cycle, or of the structures of the molecules and the names of the enzymes involved, are beyond the scope of the course and the AP Exam.

An Overview of Cellular Respiration

- Focus on the location, the input(s) and the output(s) for each the three stages.



Mitochondrial E.T.C.



located on the folded inner membrane of the mitochondria

Q is the only non protein, it is called ubiquinone or CoQ often sold as a nutritional supplement

Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

g. The electron transport chain captures free energy from electrons in a series of coupled reactions that establish an electrochemical gradient across membranes.

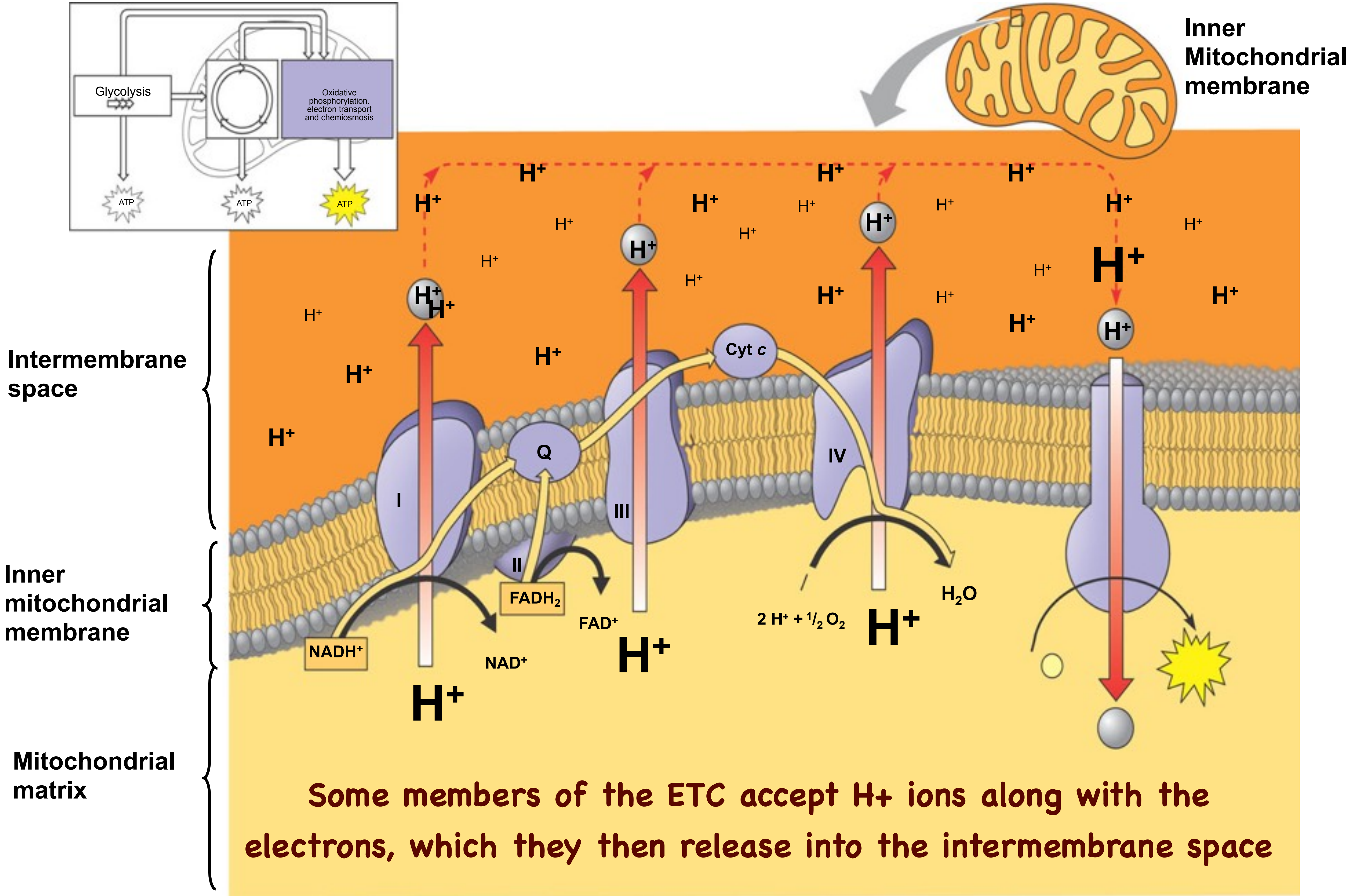
Evidence of student learning is a demonstrated understanding of each of the following:

1. Electron transport chain reactions occur in chloroplasts (photosynthesis), mitochondria (cellular respiration) and prokaryotic plasma membranes.

E.T.C. Establishes a H^+ ion Gradient

- The ***electron transport chain*** makes no ATP.
- The e^- transfer releases energy as the electron moves through the chain, this energy is used to pump H^+ ions through a membrane.
  - *This generates a electrochemical gradient with great potential energy*

E.T.C. and Chemiosmosis



Some members of the ETC accept H+ ions along with the electrons, which they then release into the intermembrane space

E.T.C. and Chemiosmosis

- Stored energy in the form a H^+ ion gradient across a membrane is called the ***proton motive force,*** it is used to produce ATP (or drive other cellular work), which is called ***chemiosmosis***.
- ***Chemiosmosis*** *is an energy coupling mechanism that uses energy stored in in the form of H+ ion gradients across membranes to drive cellular work*
  - *Osmosis is the diffusion of water*
  - *Chemiosmosis is the diffusion of* H^+ *ions*
- Specifically an enzyme ATP synthase uses the energy to produce ATP from ADP

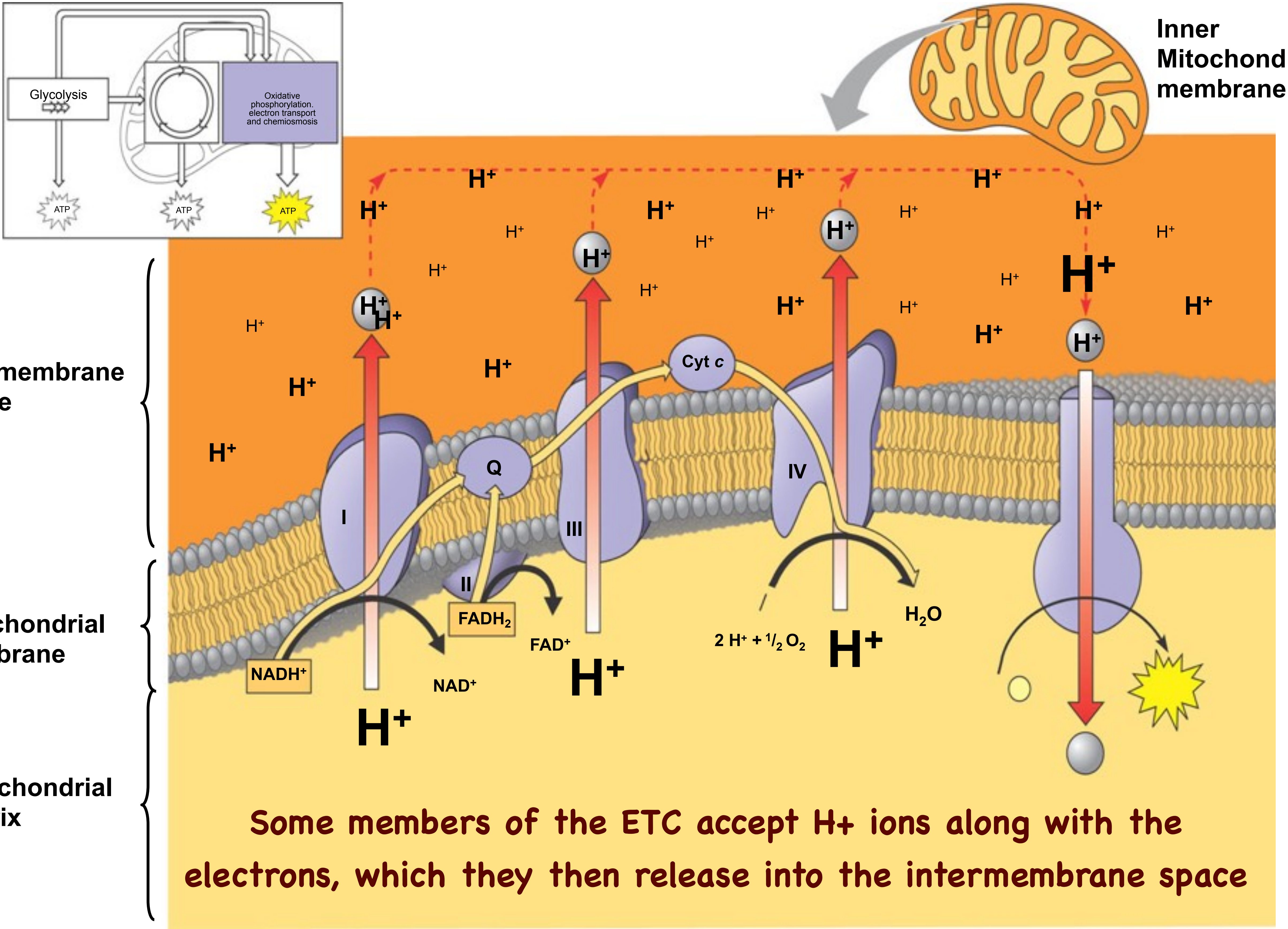
Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

g. The electron transport chain captures free energy from electrons in a series of coupled reactions that establish an electrochemical gradient across membranes.

Evidence of student learning is a demonstrated understanding of each of the following:

2. In cellular respiration, electrons delivered by NADH and FADH2 are passed to a series of electron acceptors as they move toward the terminal electron acceptor, oxygen. In photosynthesis, the terminal electron acceptor is NADP+.

E.T.C. and Chemiosmosis



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E.T.C. and Chemiosmosis

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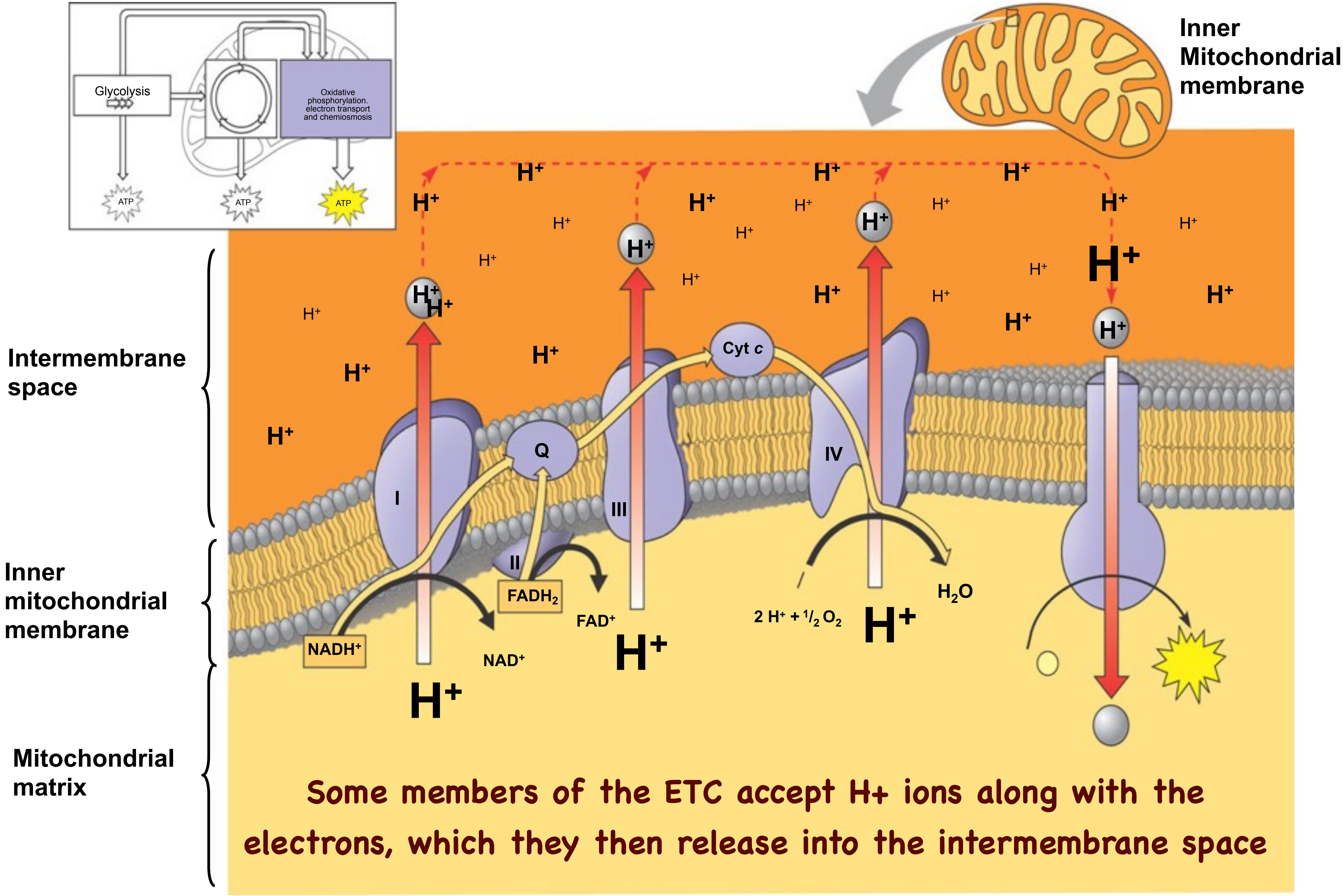
g. The electron transport chain captures free energy from electrons in a series of coupled reactions that establish an electrochemical gradient across membranes.

Evidence of student learning is a demonstrated understanding of each of the following:

3. The passage of electrons is accompanied by the formation of a proton gradient across the inner mitochondrial membrane or the thylakoid membrane of chloroplasts, with the membrane(s) separating a region of high proton concentration from a region of low proton concentration. In prokaryotes, the passage of electrons is accompanied by the outward movement of protons across the plasma membrane.

E.T.C. and Chemiosmosis



Some members of the ETC accept H+ ions along with the electrons, which they then release into the intermembrane space

E.T.C. and Chemiosmosis

- Stored energy in the form a H^+ ion gradient across a membrane is called the ***proton motive force,*** it is used to produce ATP (or drive other cellular work), which is called ***chemiosmosis***.
- ***Chemiosmosis*** *is an energy coupling mechanism that uses energy stored in in the form of H+ ion gradients across membranes to drive cellular work*
  - *Osmosis is the diffusion of water*
  - *Chemiosmosis is the diffusion of* H^+ *ions*
- Specifically an enzyme ATP synthase uses the energy to produce ATP from ADP

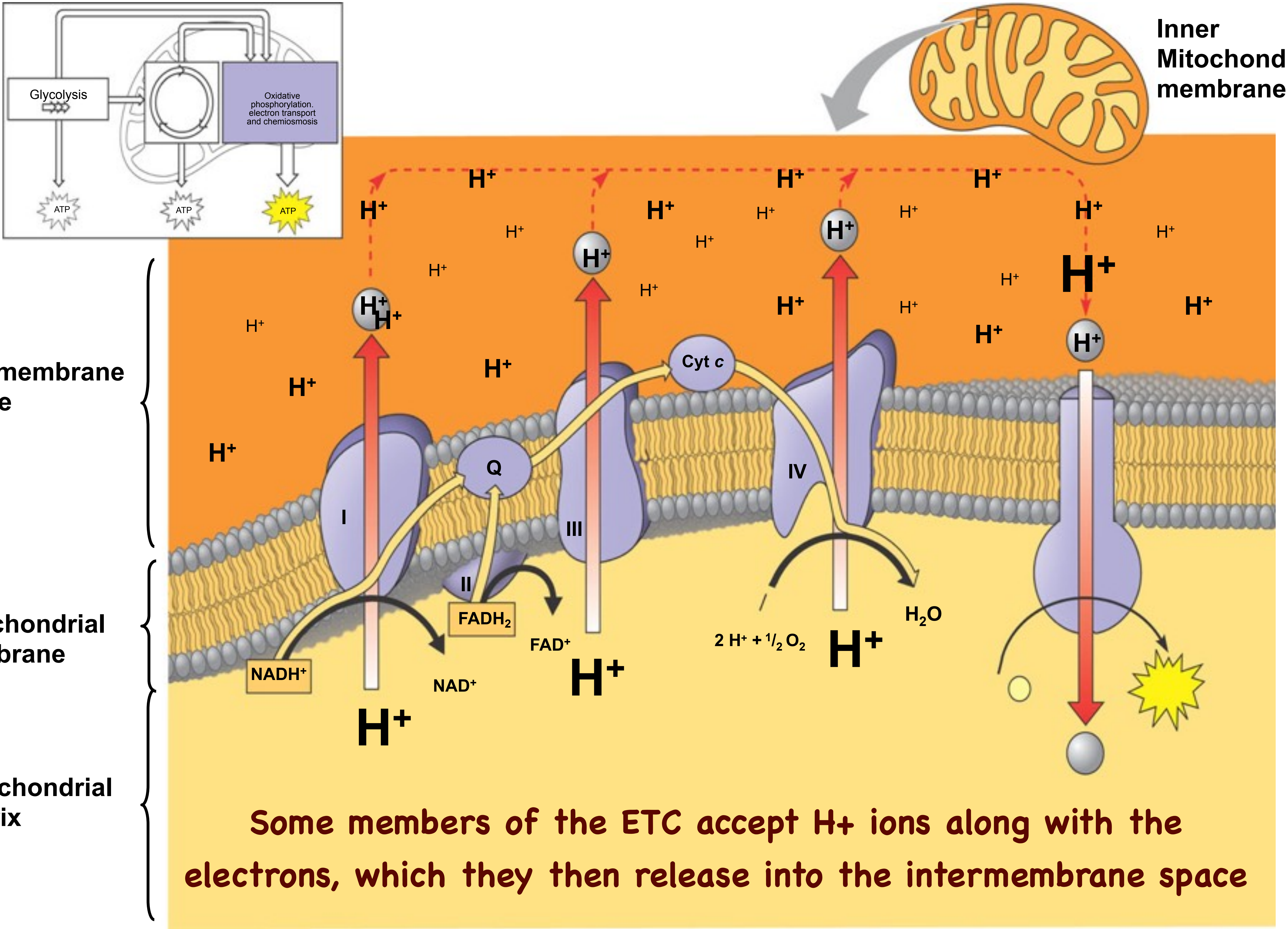
Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

g. The electron transport chain captures free energy from electrons in a series of coupled reactions that establish an electrochemical gradient across membranes.

Evidence of student learning is a demonstrated understanding of each of the following:

4. The flow of protons back through membrane-bound ATP synthase by chemiosmosis generates ATP from ADP and inorganic phosphate.

E.T.C. and Chemiosmosis



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E.T.C. and Chemiosmosis

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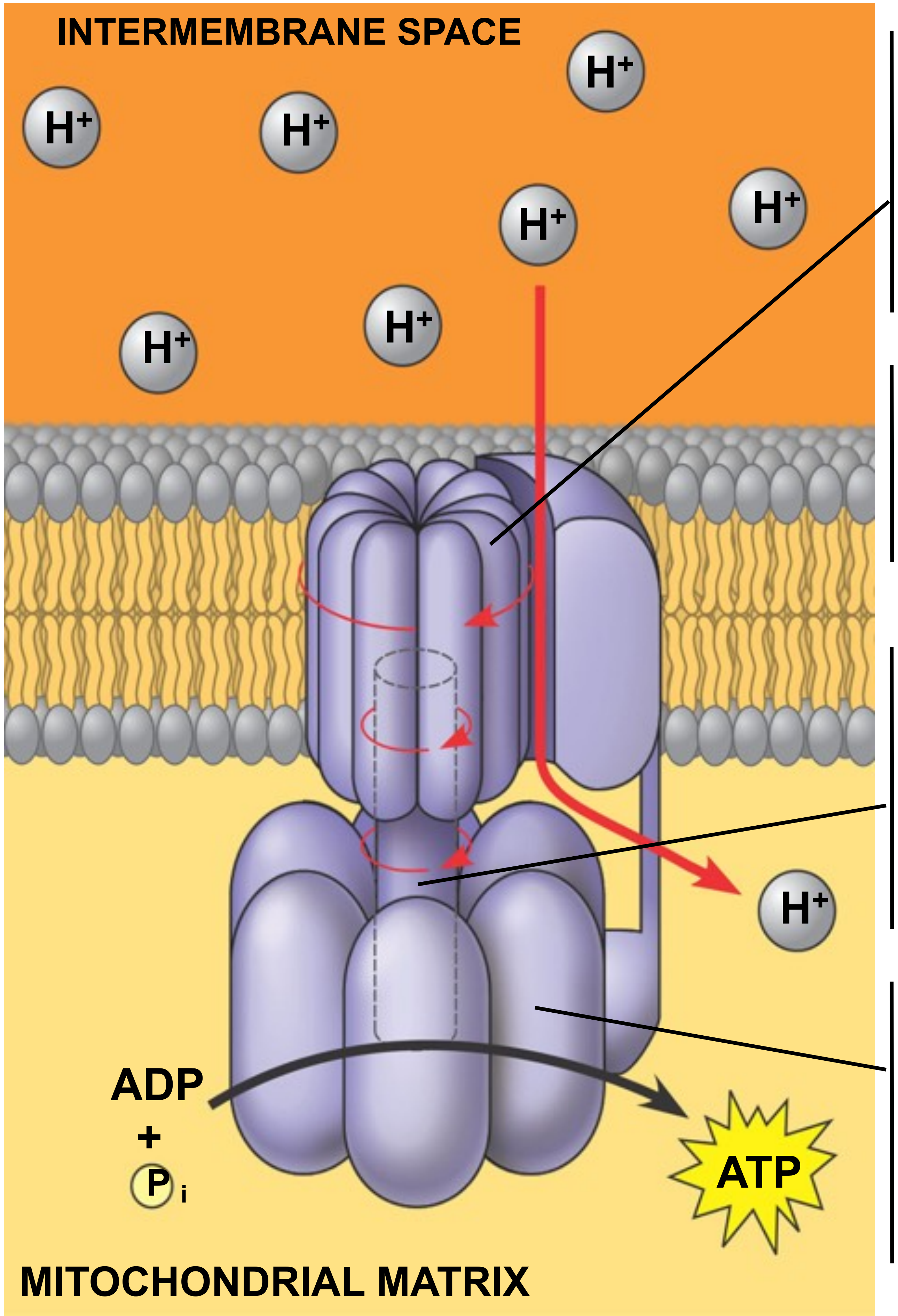
ATP Synthase

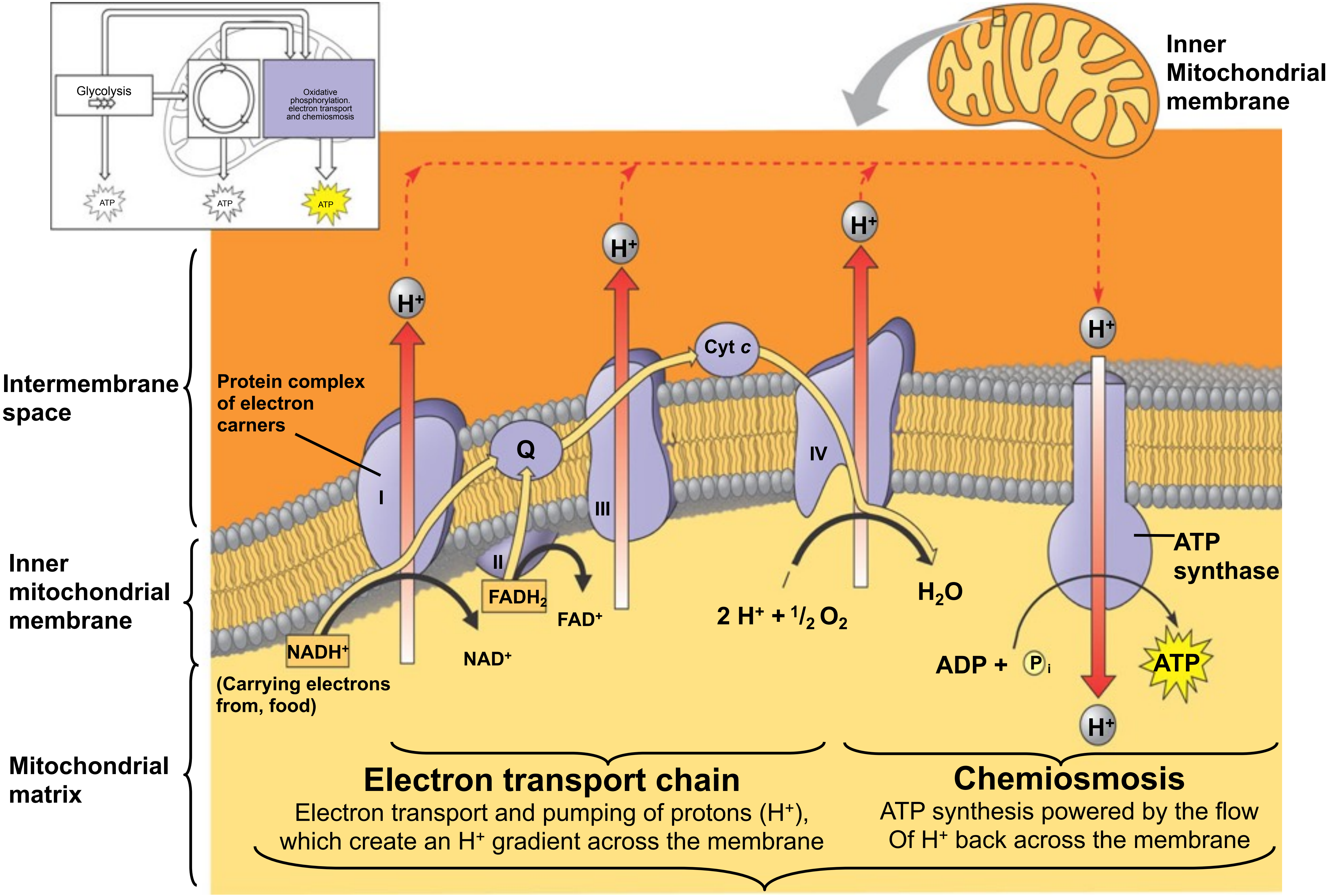


A **rotor** within the membrane spins clockwise when H$^+$ flows past it down the H$^+$ gradient.

A **stator** anchored in the membrane holds the knob stationary.

A **rod** (for "stalk") extending into the knob also spins, activating catalytic sites in the knob.

Three catalytic sites in the stationary **knob** join inorganic Phosphate to ADP to make ATP.



Electron transport chain

Electron transport and pumping of protons (H^+), which create an H^+ gradient across the membrane

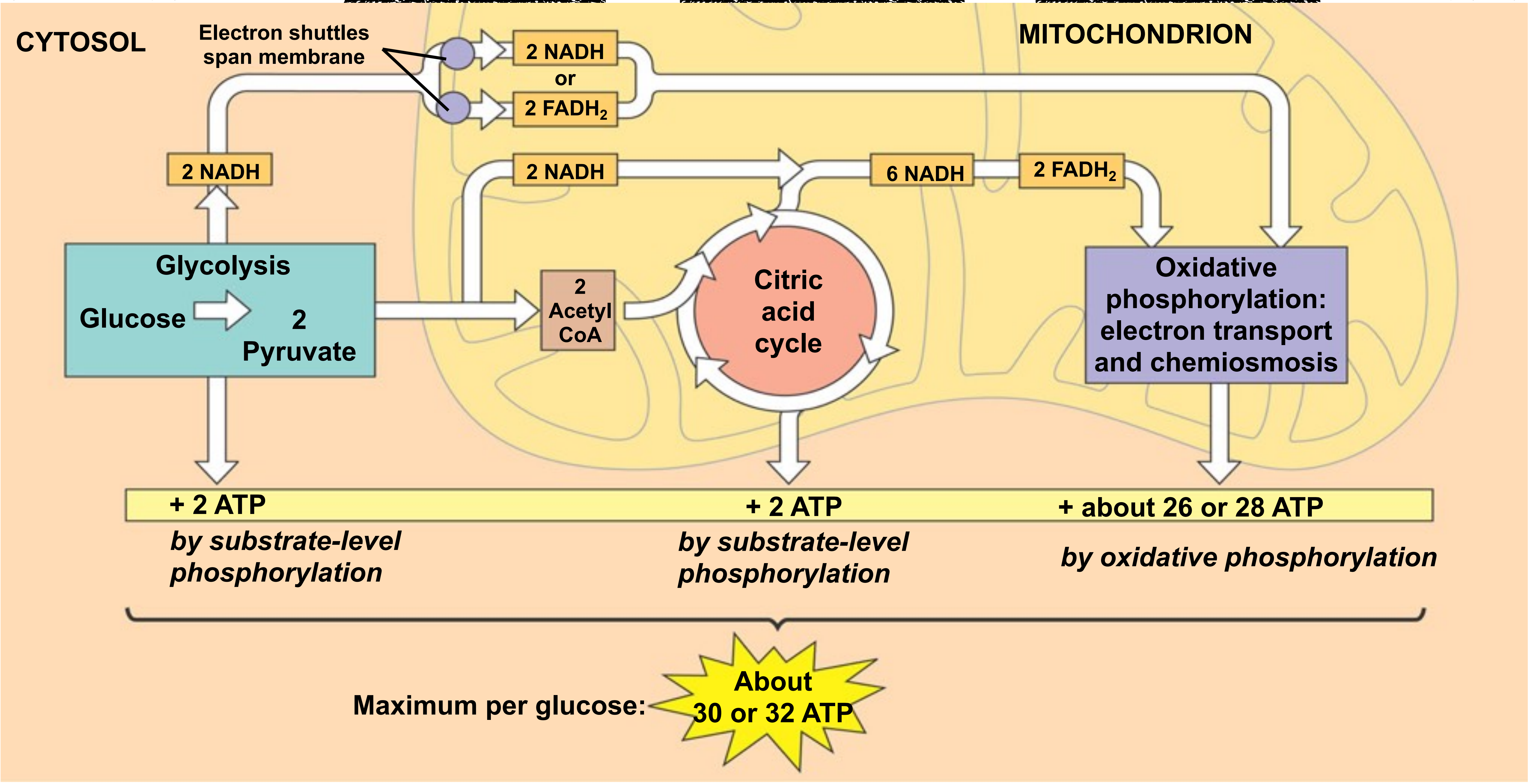
Chemiosmosis

ATP synthesis powered by the flow Of H^+ back across the membrane

Oxidative Phosphorylation

Tracking Energy Flow & ATP Production

Glucose → **Electron Carriers** → **Electron Transport Chain** → **Proton Motive Force** → **ATP**



Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

g. The electron transport chain captures free energy from electrons in a series of coupled reactions that establish an electrochemical gradient across membranes.

Evidence of student learning is a demonstrated understanding of each of the following:

5. In cellular respiration, decoupling oxidative phosphorylation from electron transport is involved in thermoregulation.

✘ The names of the specific electron carriers in the ETC are beyond the scope of the course and the AP Exam.

Respiration Efficiency

Glucose contains -686 kcal/mol energy

ATP contains -7.3 kcal/mol energy

Max ATP production = 32

(32)(-7.3) = -233.6 kcal/mol energy

-233.6/-686 = 0.34 or 34% efficiency

Respiration at 34% is very efficient, most man made machines are far less efficient. Also, the energy lost as heat is used for something useful like maintaining body temperature. In most machines this energy is simply lost to its surroundings

Hibernation & Respiration Efficiency

- There are times when respiration inefficiency is actually favored...during hibernation!

Hibernation & Respiration Efficiency

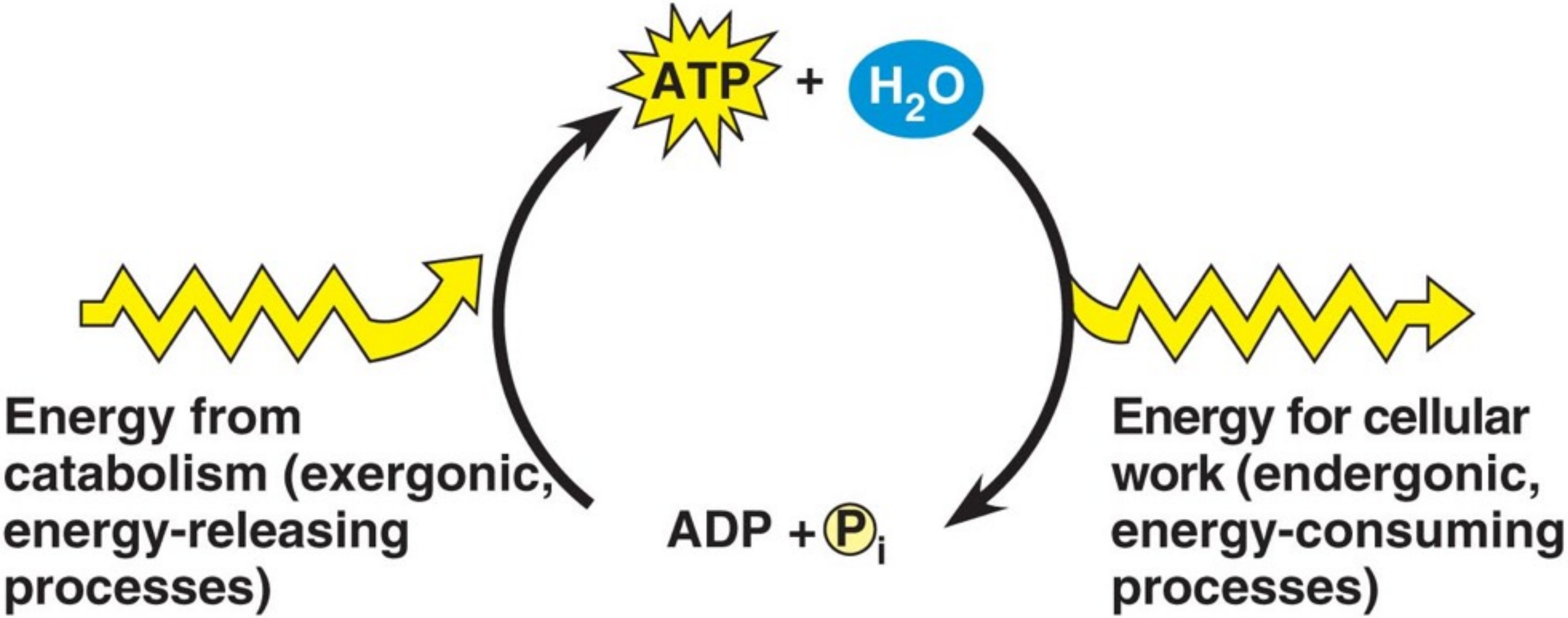
- A hibernating animal needs to generate heat, without making ATP, throughout the winter
- If hibernating animals continued to use simple cell respiration, it would eventually shut down.
    - ATP would build up in the cells because animal is inactive, as ATP builds a feedback loop would shut down respiration thus stopping ATP production AND HEAT PRODUCTION
- Hibernating animals have brown fat, a cell with many mitochondria that have a unique structure that allows them to carry out respiration without making ATP!

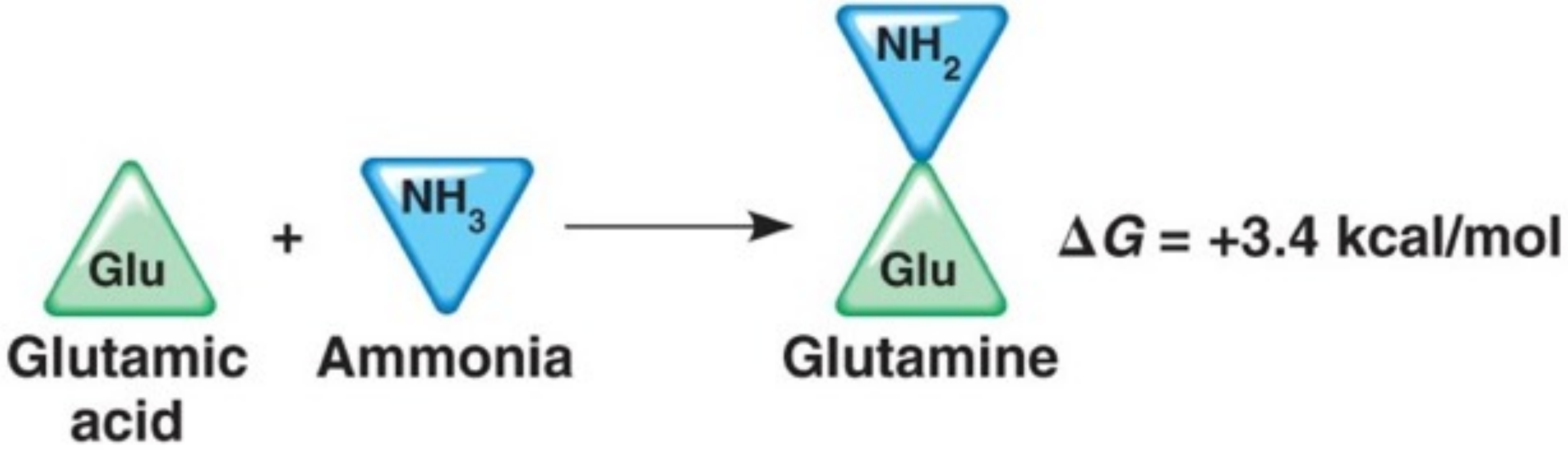
Essential knowledge 2.A.2: Organisms capture and store free energy for use in biological processes.

h. Free energy becomes available for metabolism by the conversion of ATP---->ADP, which is coupled to many steps in metabolic pathways.

The Regeneration of ATP

- ATP is hydrolyzed continuously.
- ATP is renewable and can be regenerated
- The ATP cycle below can consume and regenerate 10 million per second

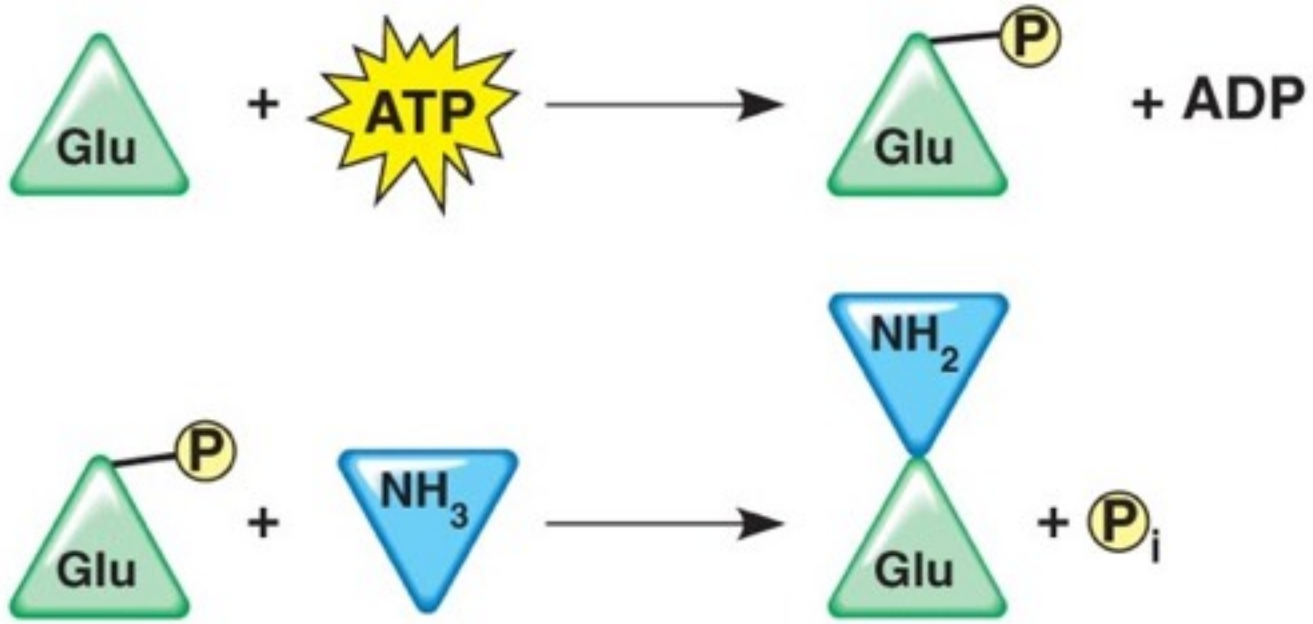




(a) Endergonic reaction

① ATP phosphorylates glutamic acid, making the amino acid less stable.

② Ammonia displaces the phosphate group, forming glutamine.



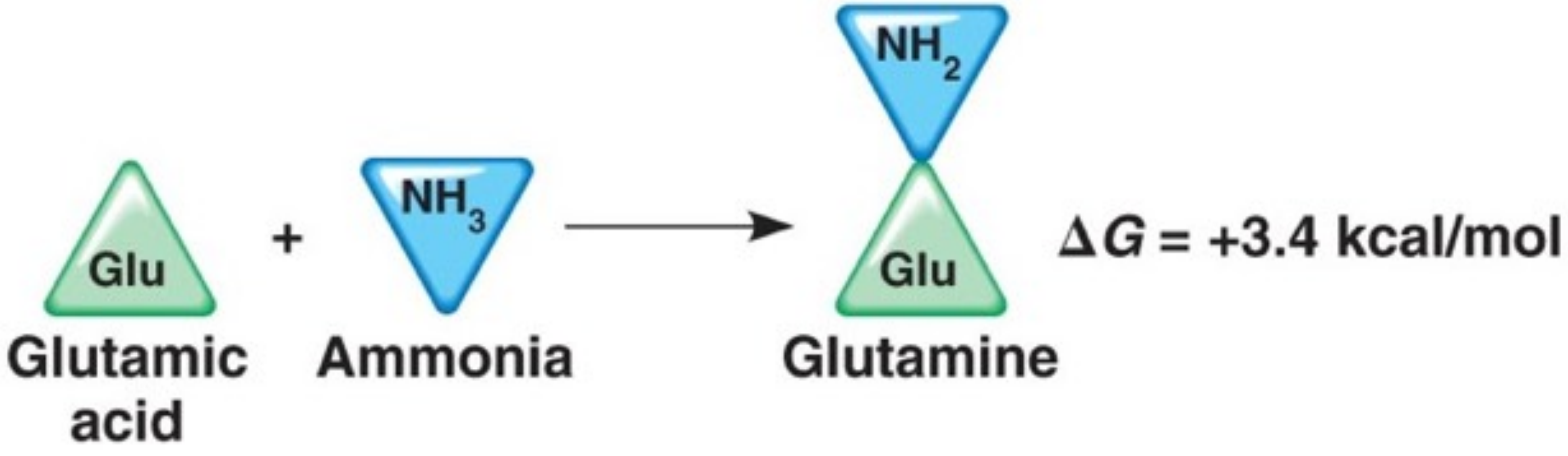
(b) Coupled with ATP hydrolysis, an exergonic reaction

$\text{Glu} + \text{NH}_3 \longrightarrow \text{Glu—NH}_2$ $\quad \Delta G = +3.4$ kcal/mol

$\text{ATP} \longrightarrow \text{ADP} + \text{P}_i$ $\quad \Delta G = -7.3$ kcal/mol

Net $\Delta G = -3.9$ kcal/mol

(c) Overall free-energy change



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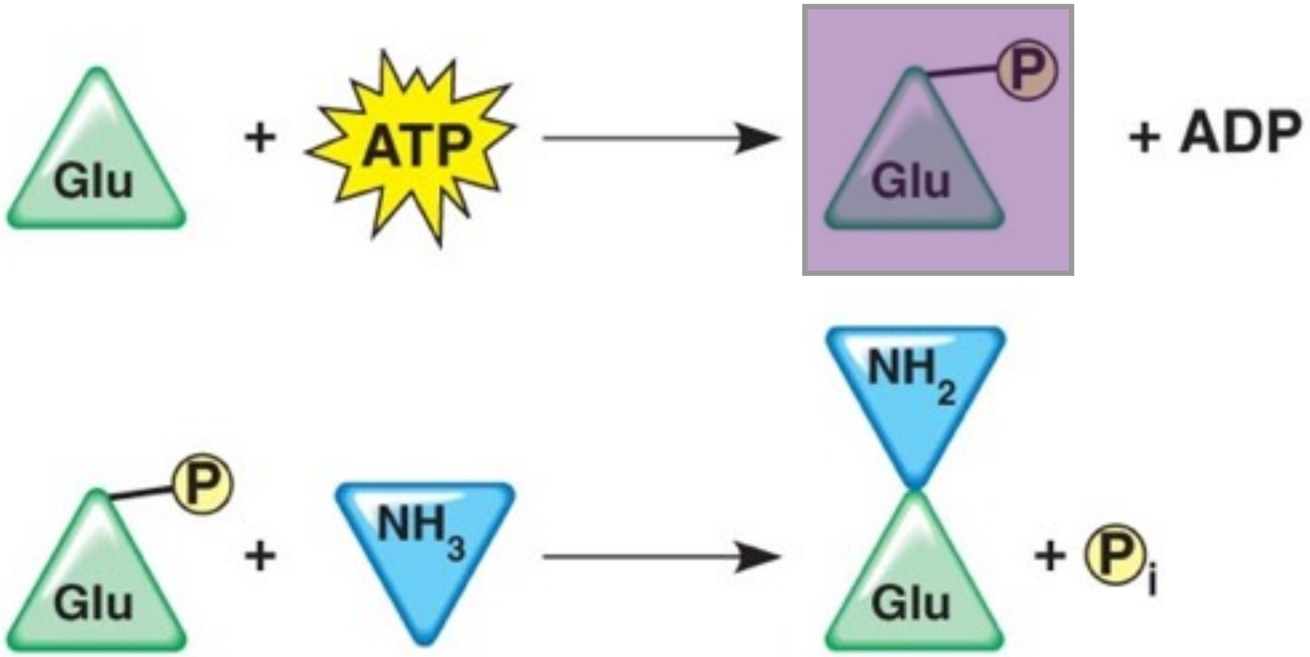

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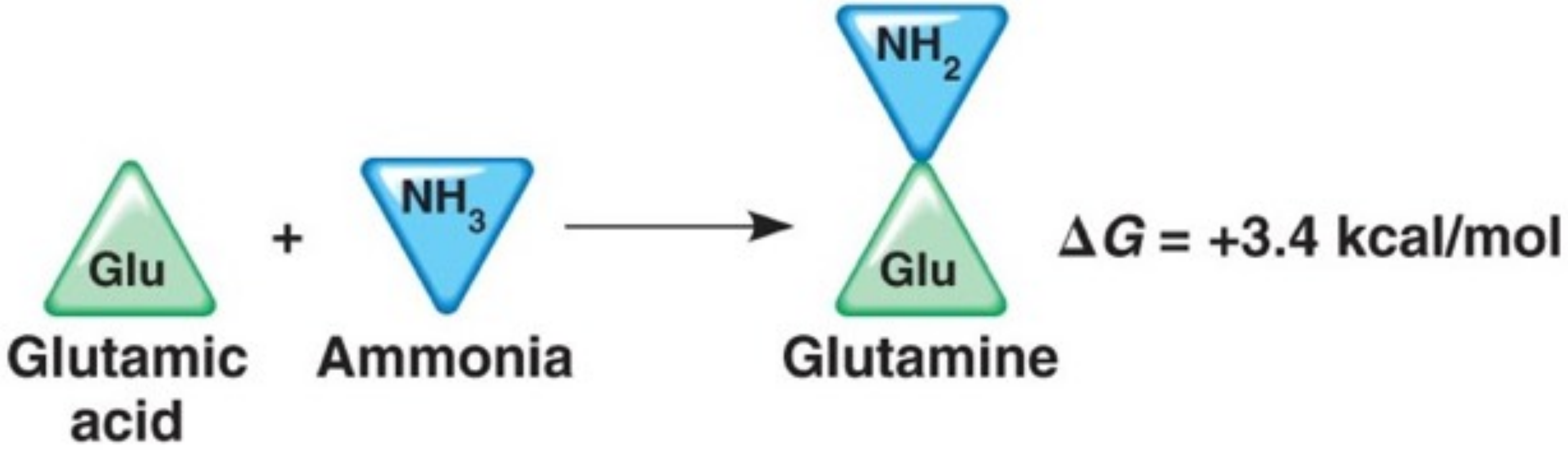
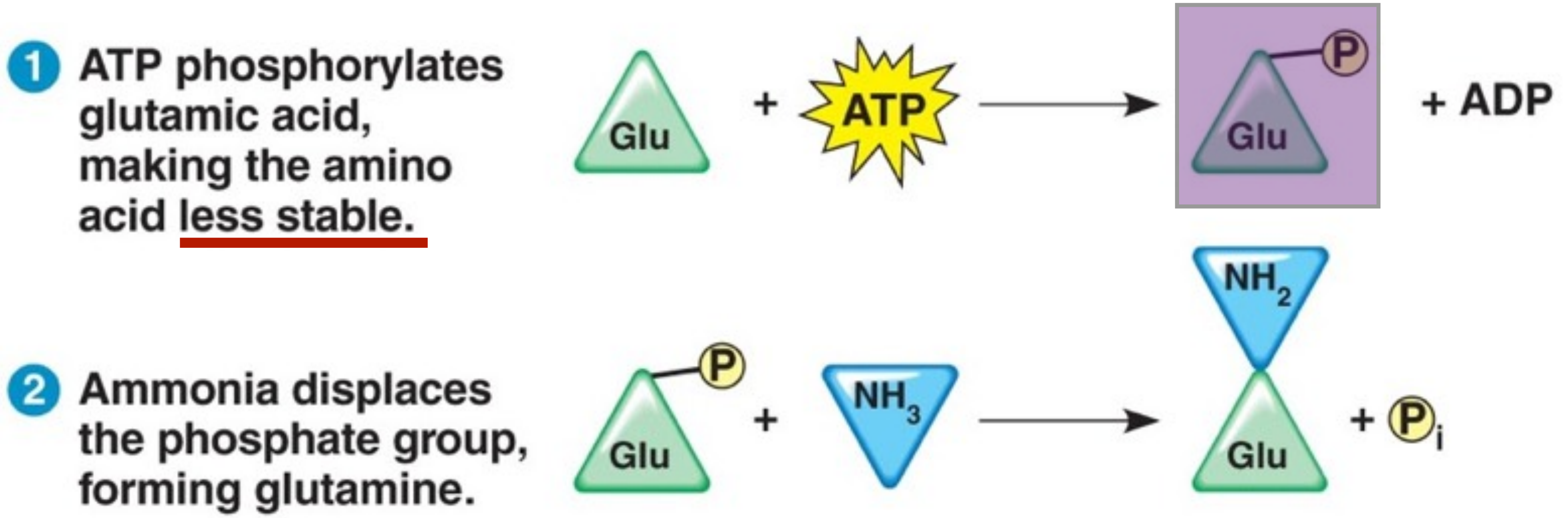


(a) Endergonic reaction

less stable



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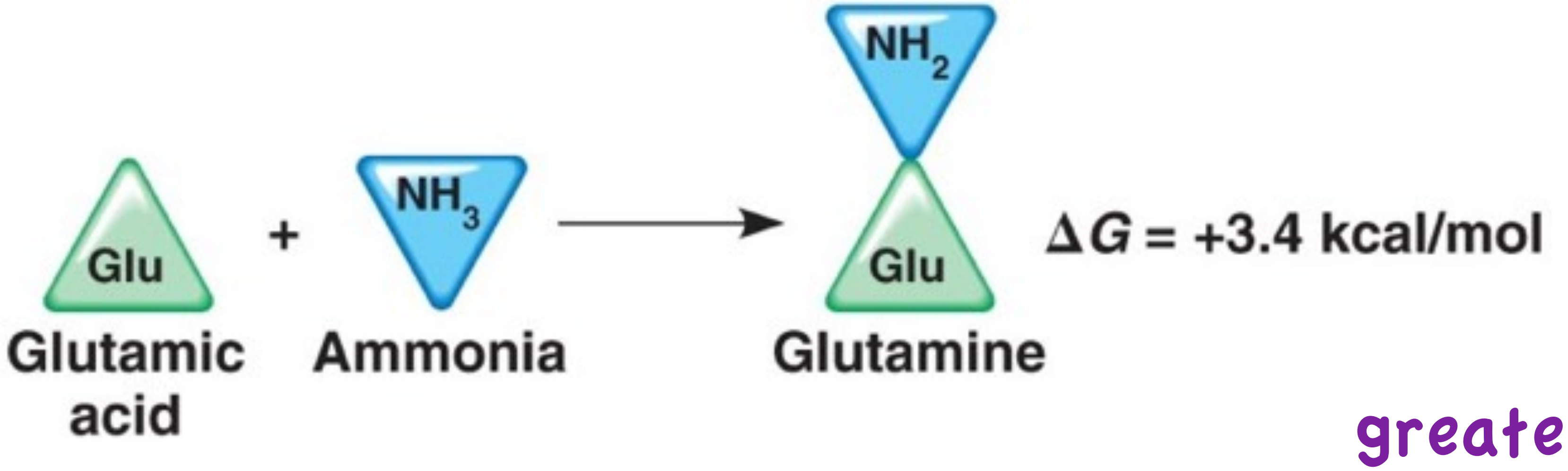

(a) Endergonic reaction

less stable greater potential energy

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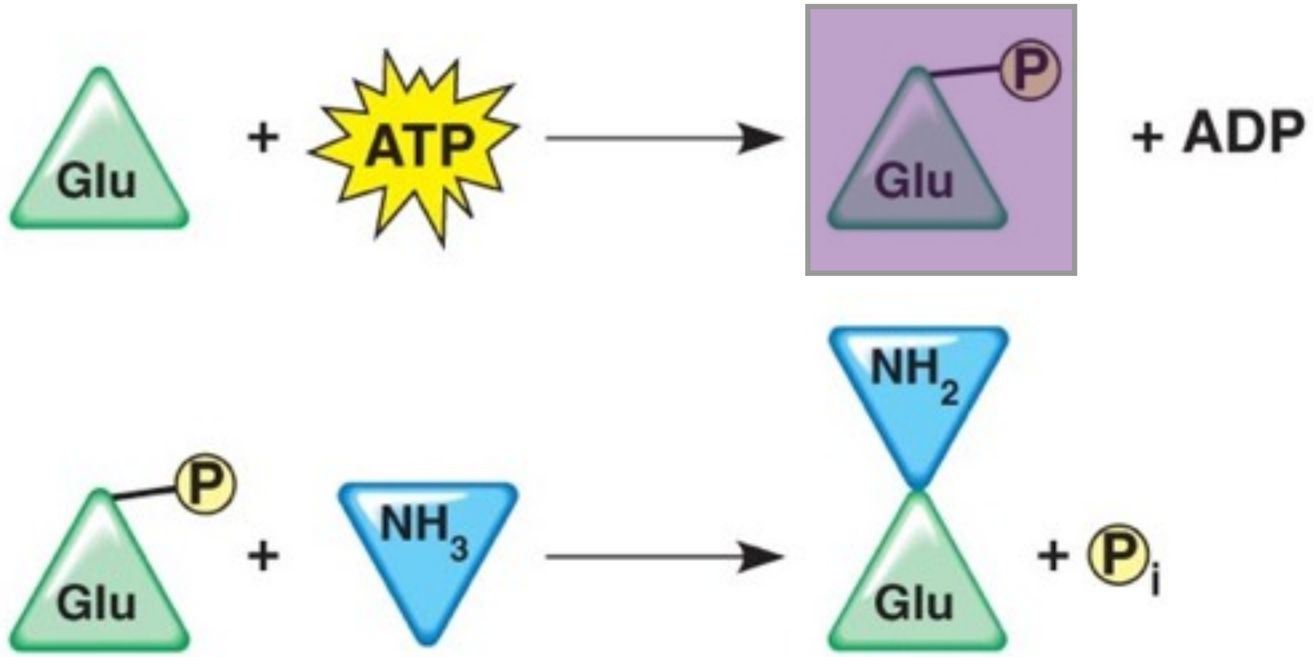
② Ammonia displaces the phosphate group, forming glutamine.



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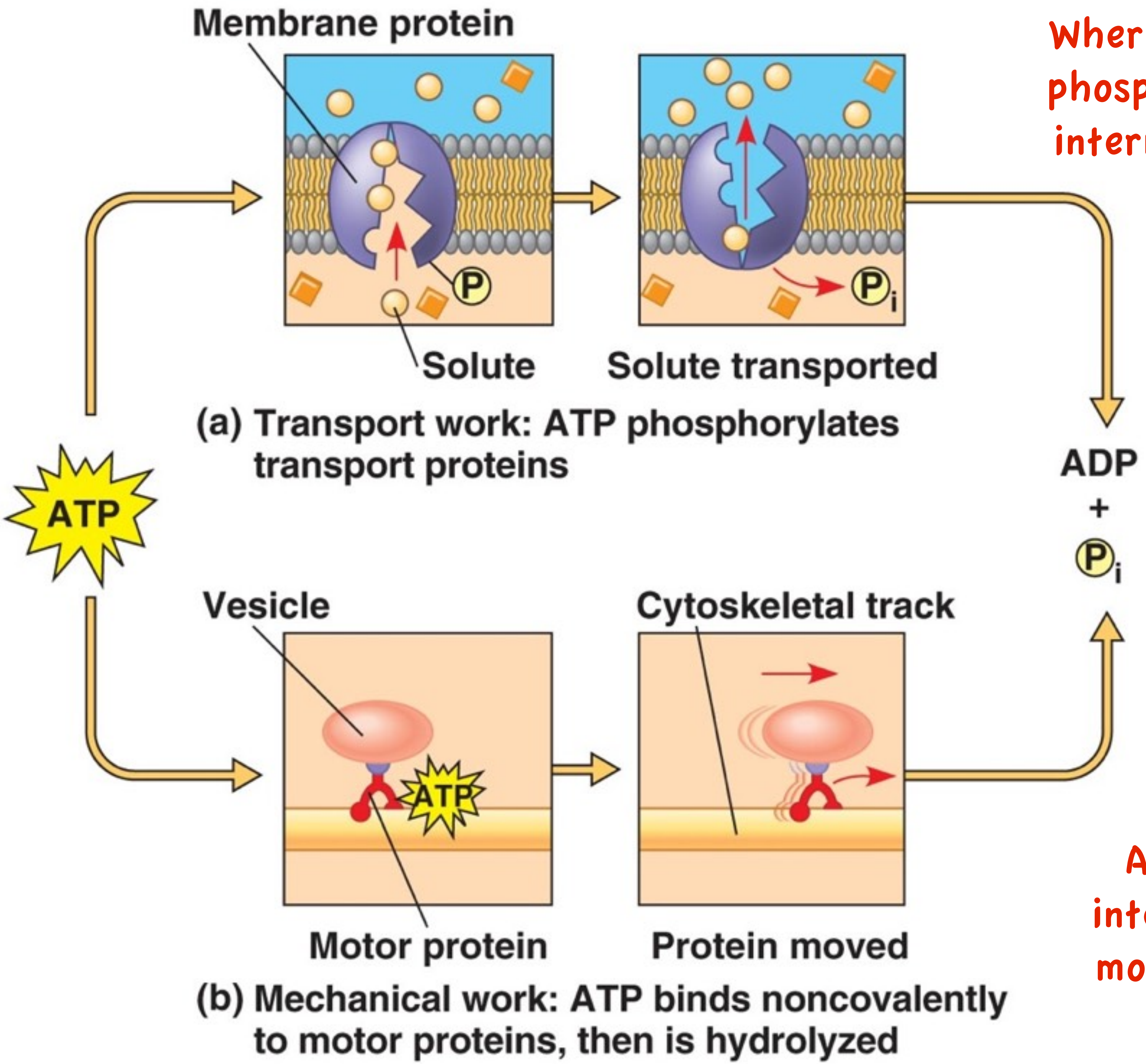

(a) Transport work: ATP phosphorylates transport proteins

(b) Mechanical work: ATP binds noncovalently to motor proteins, then is hydrolyzed

Where are the phosphorylated intermediates?

Are these intermediates more or less stable?

Learning Objectives:

LO 2.4 The student is able to use representations to pose scientific questions about what mechanisms and structural features allow organisms to capture, store and use free energy. [See SP 1.4, 3.1]

LO 2.5 The student is able to construct explanations of the mechanisms and structural features of cells that allow organisms to capture, store or use free energy. [See SP 6.2]

LO 2.41 The student is able to evaluate data to show the relationship between photosynthesis and respiration in the flow of free energy through a system. [See SP 5.3, 7.1]