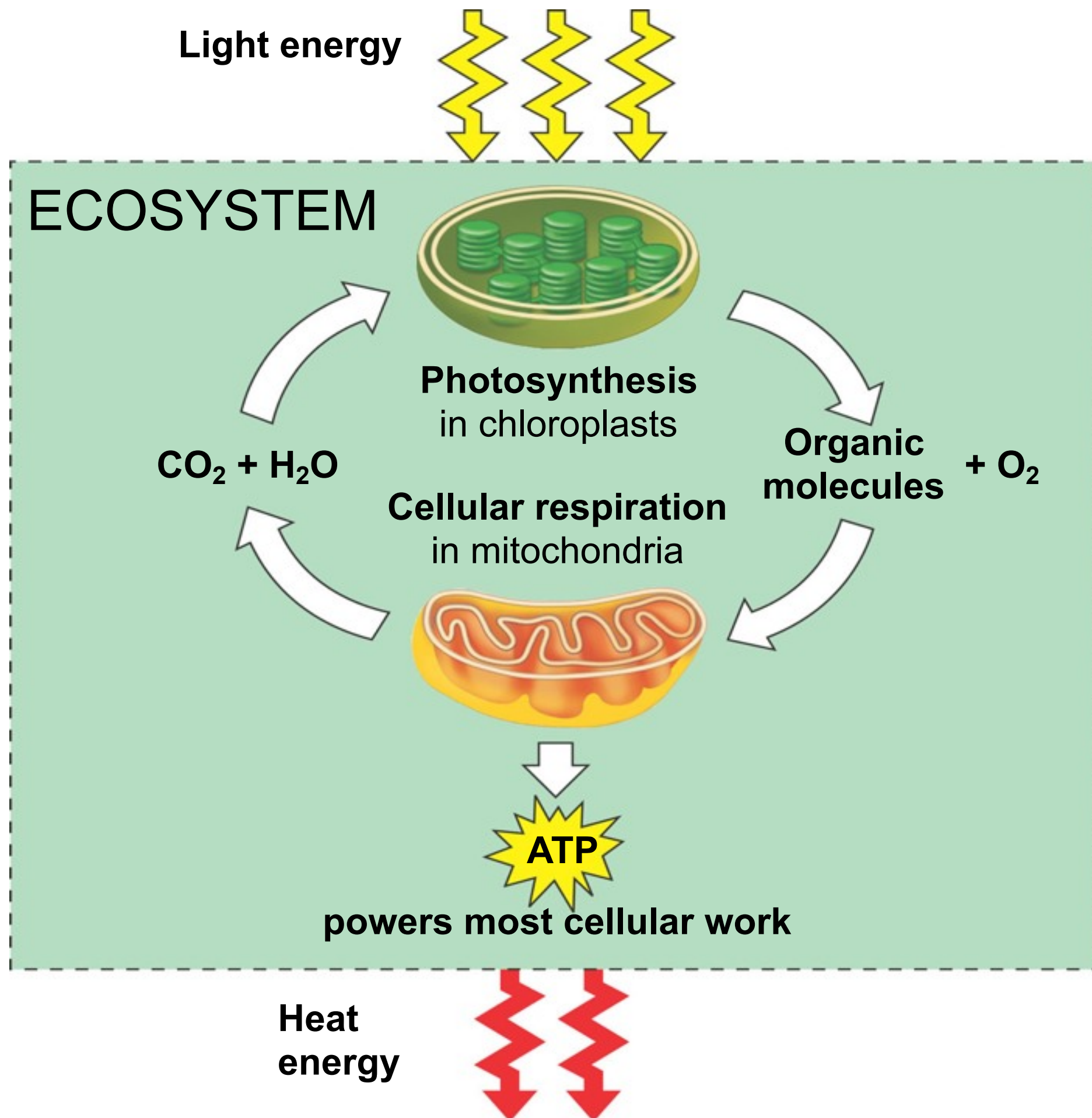


CELL RESPIRATION

PREFACE

- Cellular processes require energy.
- ATP is the cellular energy choice (fuel) that powers cell processes.
- Cell respiration is the process that transfers the chemical bond energy of large organic compounds into the chemical bonds of ATP.
- Photosynthesis builds these large organic molecules using CO₂ as building blocks and solar radiation as the energy source.
- The sun is the ultimate source of energy that powers cellular work.



Cell Respiration

I.

Main Idea: Catabolic (breaking) reactions result in a net release of energy and moving electrons play an important part in this.



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.

Specific Catabolic Pathways

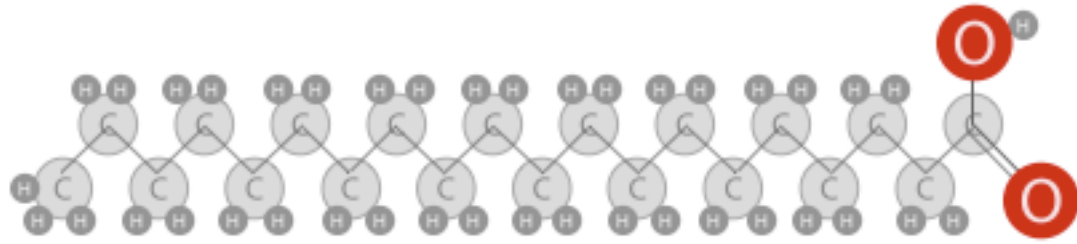
- **Fermentation-** is the partial degradation of organic molecules and does not require oxygen.
- **Aerobic Respiration-** involves the degradation of organic molecules and oxygen as a final electron acceptor.
- **Anaerobic Respiration-** involves the degradation of organic molecules and some other molecule that acts as the final electron acceptor in place of oxygen.

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

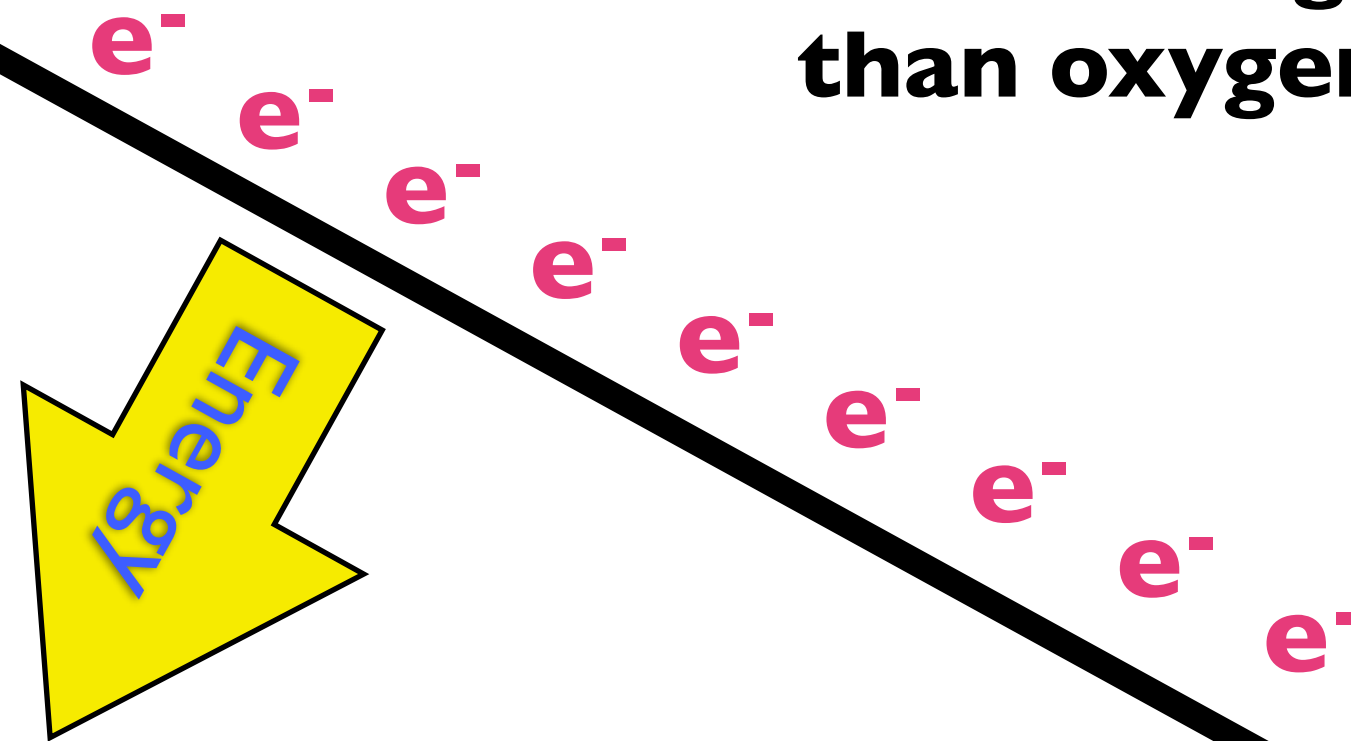
HIGH Potential Energy

Lower Electronegativities



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

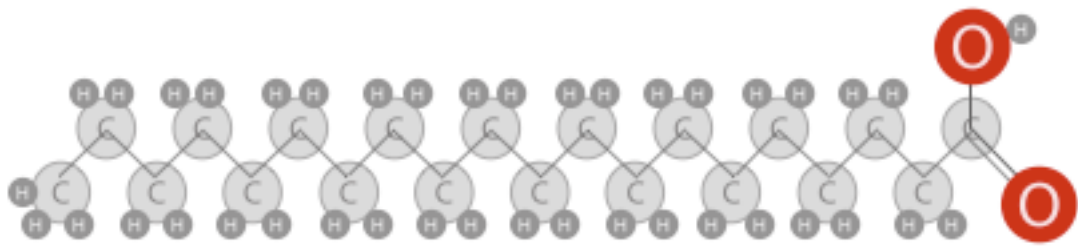
Fatty Acid



LOW
Potential Energy

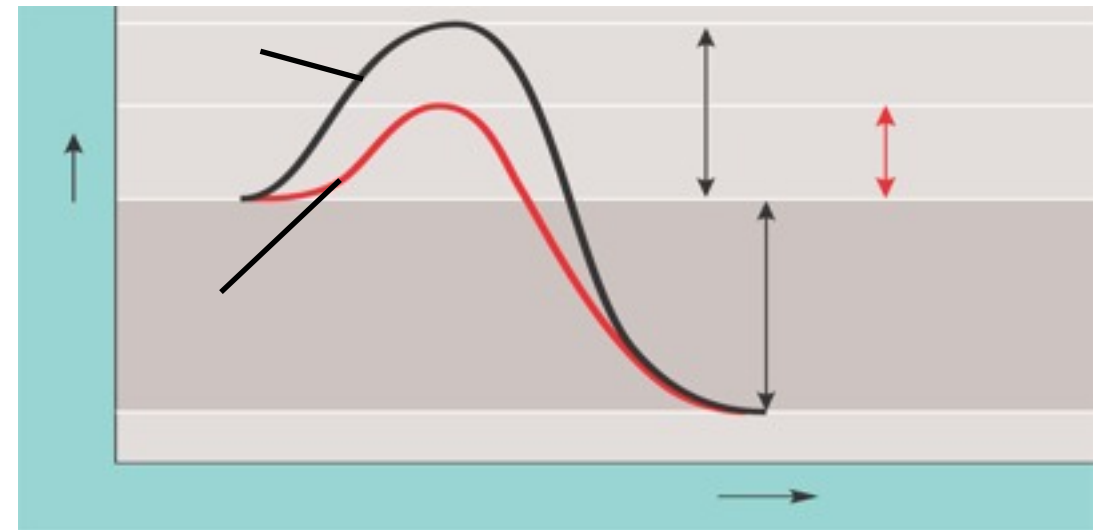
HIGH
Electronegativity

Oxygen



The Activation Energy barrier is the only reason why these electrons do not spontaneously “roll down” the hill

Body temp is not high enough to overcome A.E.



What lowers the activation energy so that these electrons DO “roll down” the hill?

ENZYMES



Oxygen

Harvesting Energy from Electrons

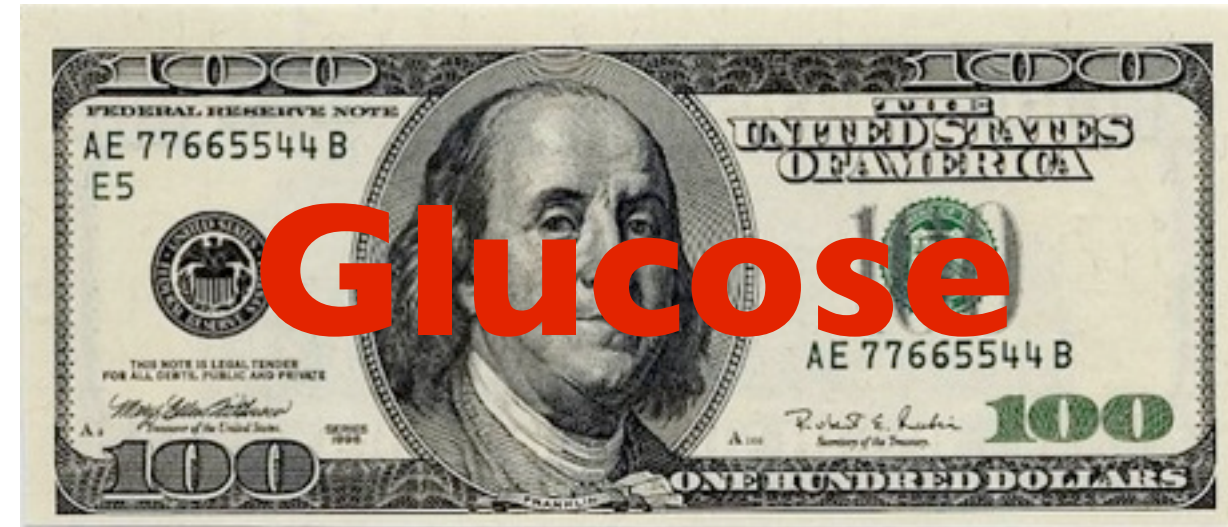


- Energy released from a fuel, say gasoline, all at once may be useful in Hollywood movies but is useless for constructive work, like driving the car below.

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.

A Cell

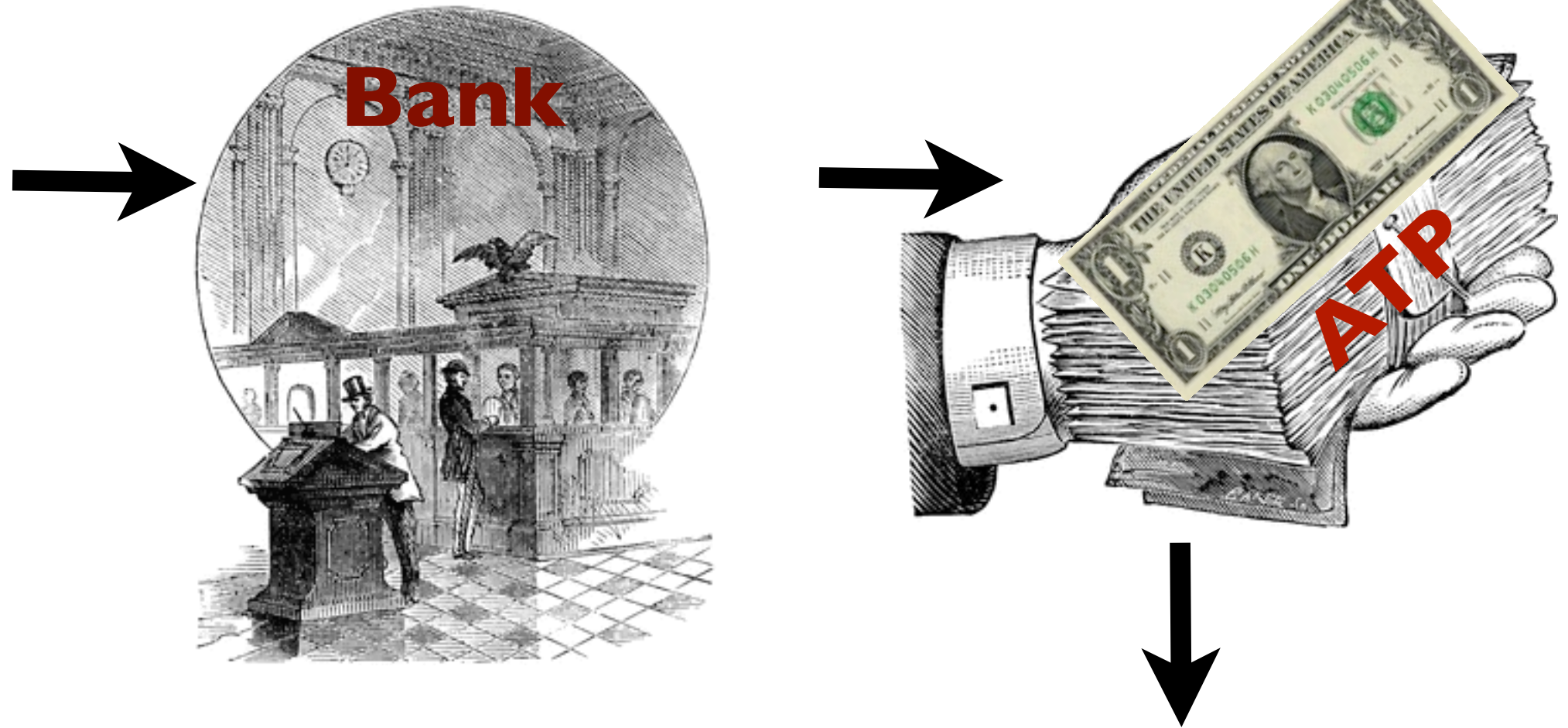


Imagine going to a county fair. To enjoy the fair you decide to bring money, in order to buy food and play games. The cost of food and games are each just a few dollars at most. You bring five 100\$ bills to fair, thinking that should be more than enough (each bill would easily cover the cost of food 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.



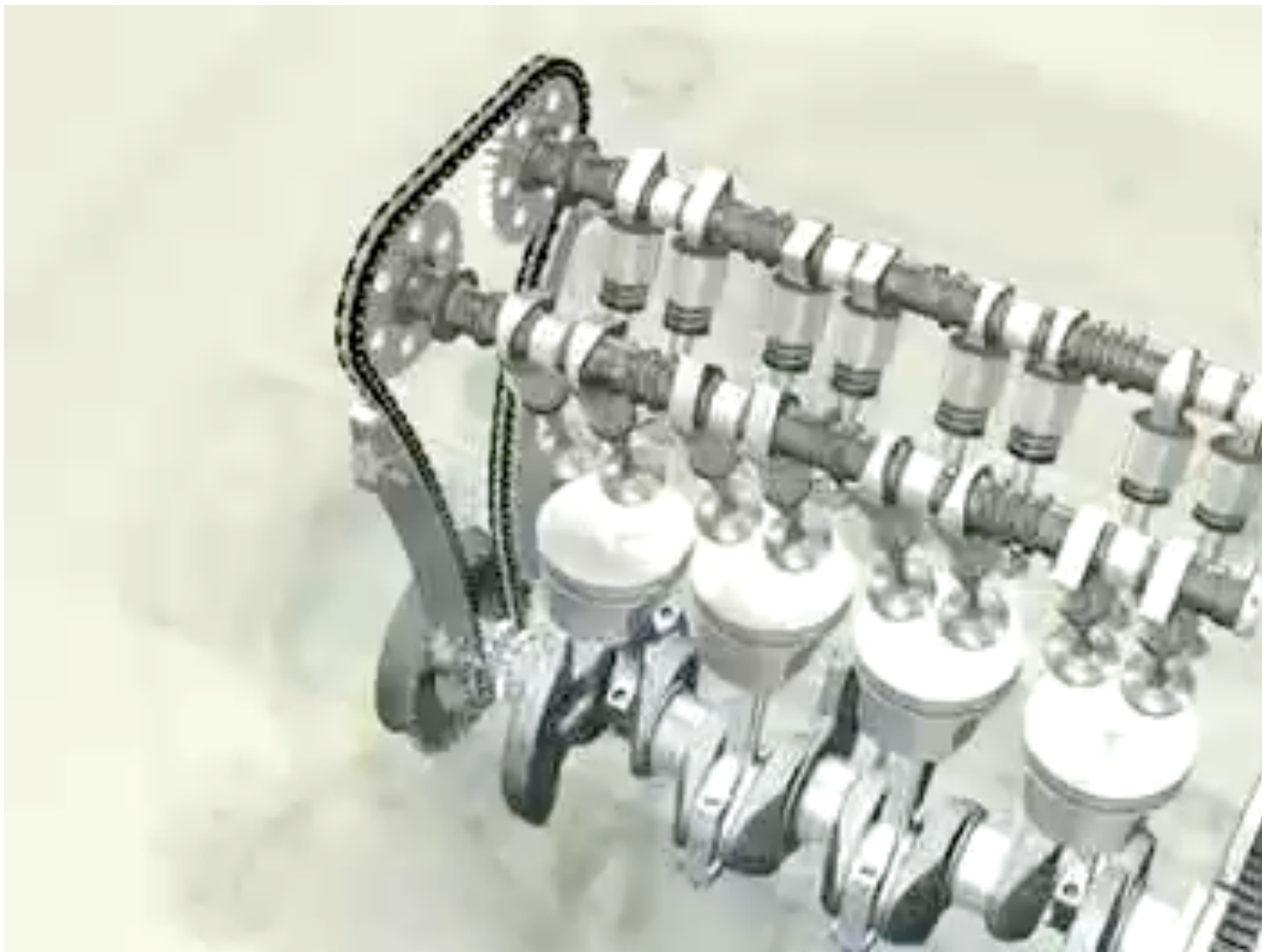
What does the bank represent in my analogy?

**Mitochondria,
Cell Respiration**



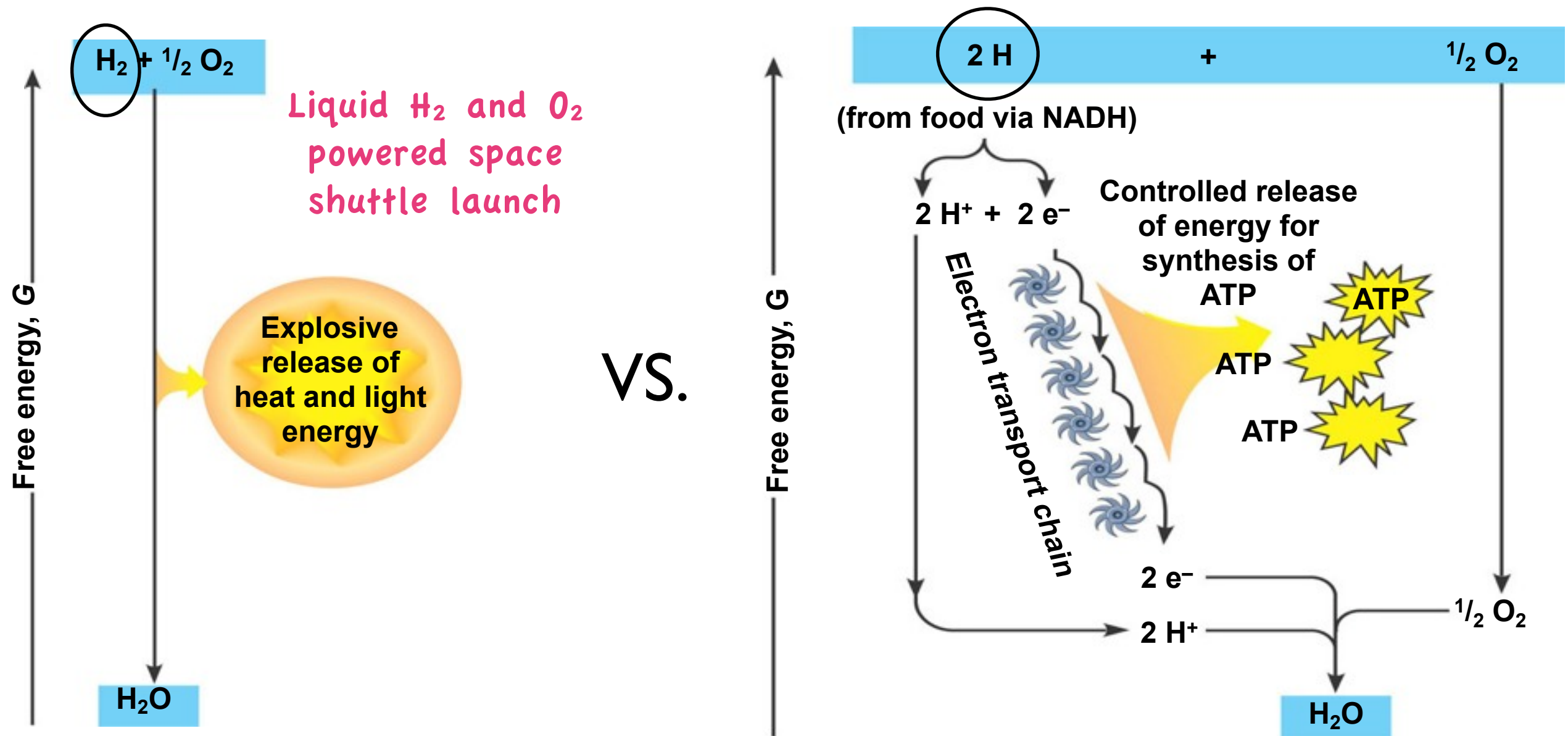
Harvesting Energy from Electrons

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



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.

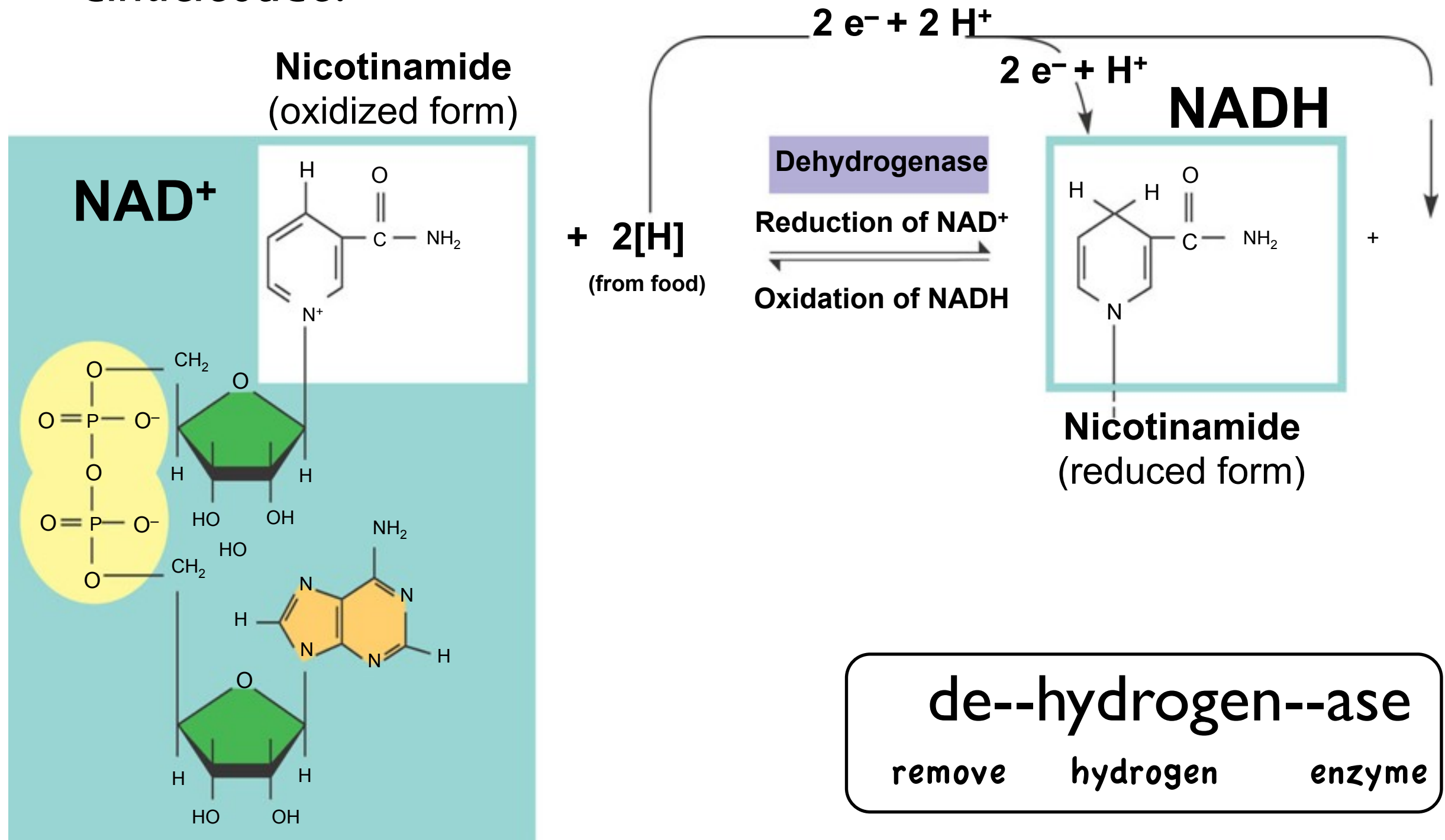


Uncontrolled reaction- (car explosion)

Cellular respiration- combustion engine

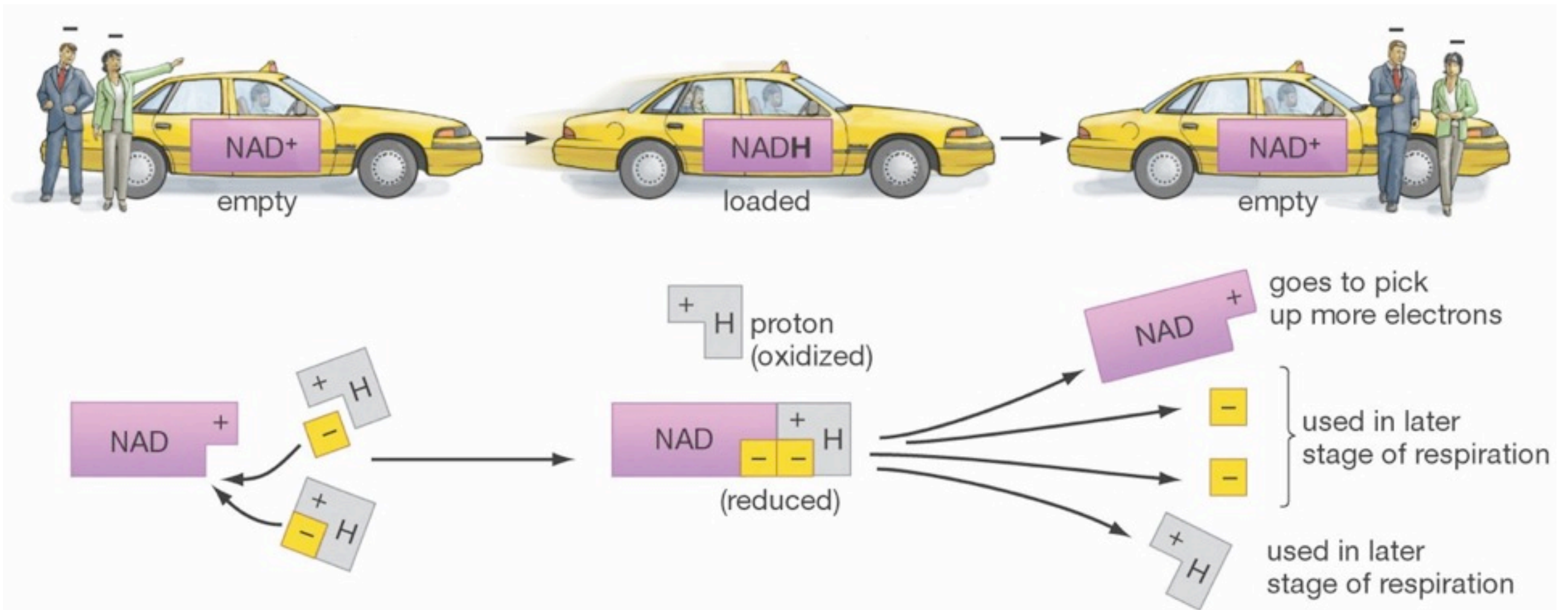
Electron Acceptors & Transport

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



Electron Acceptors & Transport

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



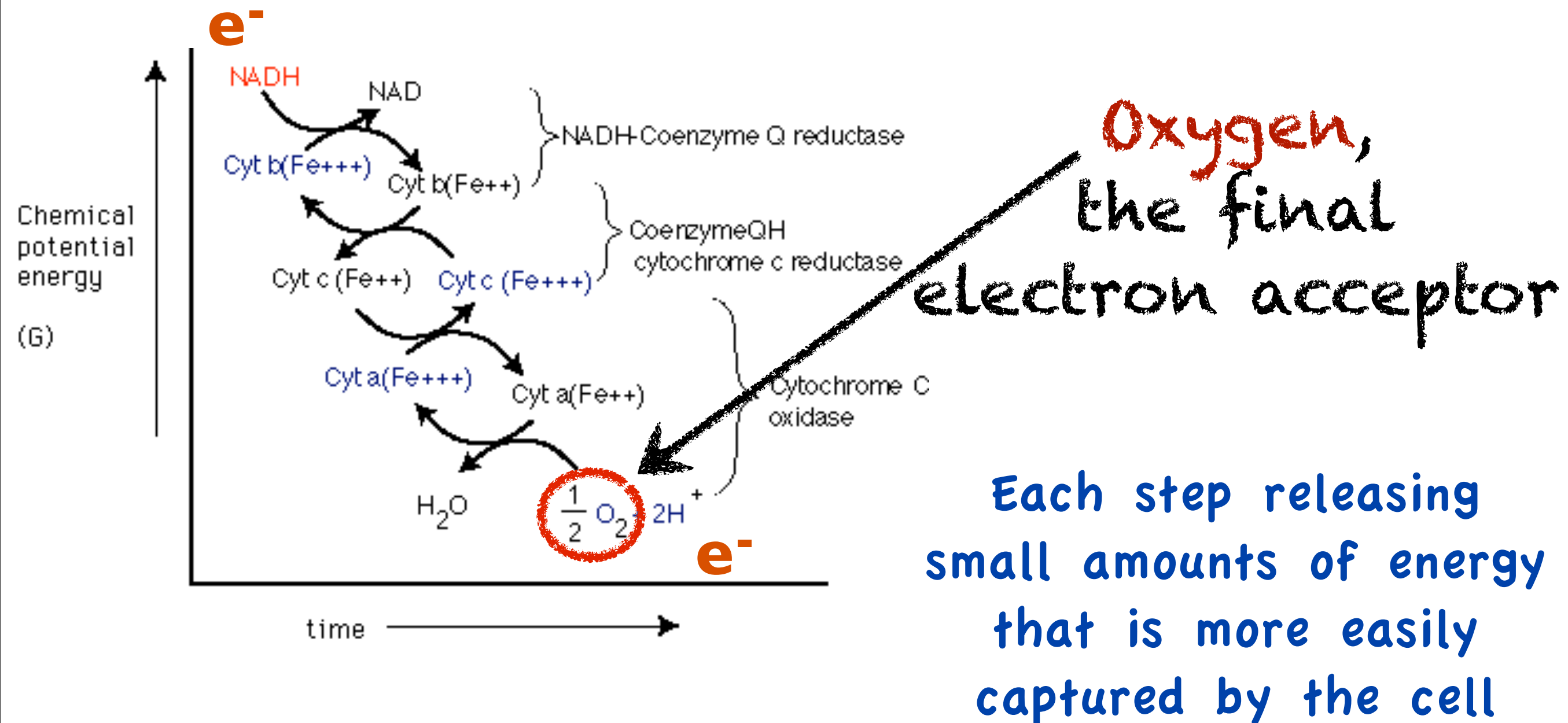
1. NAD^+ within a cell, along with two hydrogen atoms that are part of the food that is supplying energy for the body.

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

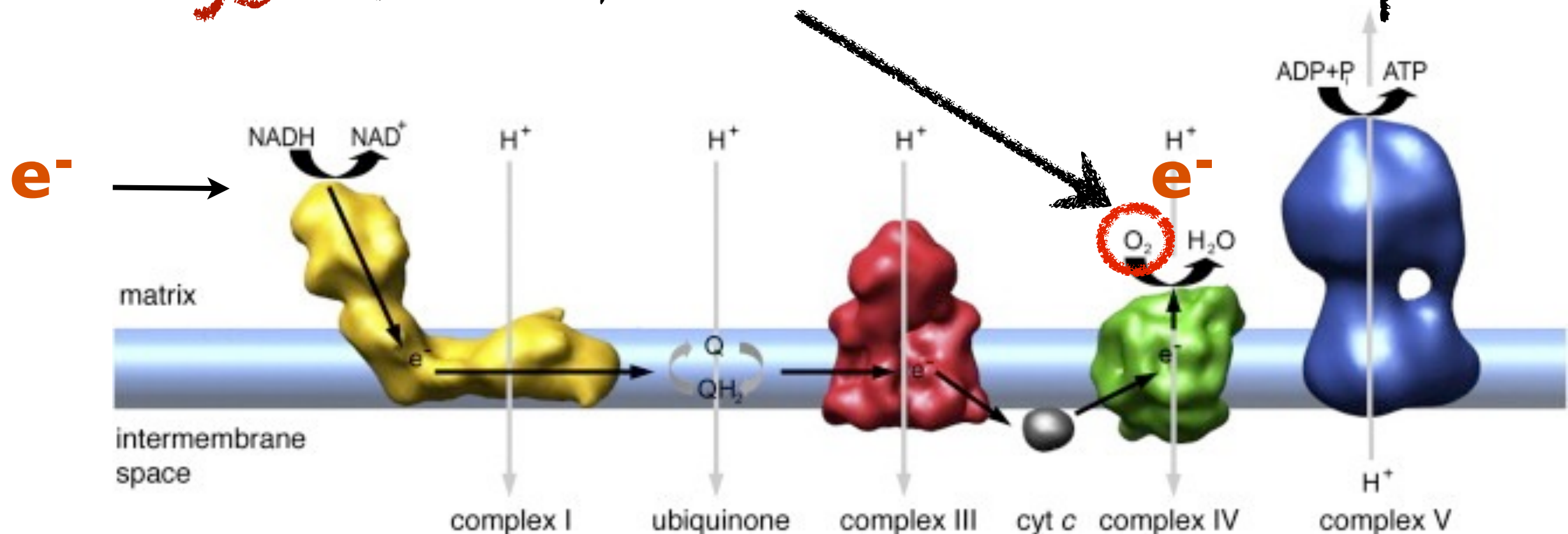
- The NADH then passes the electrons to another molecule, and so on and so forth.
- Each molecule slightly more electronegative than the prior one



Electron Acceptors & Transport

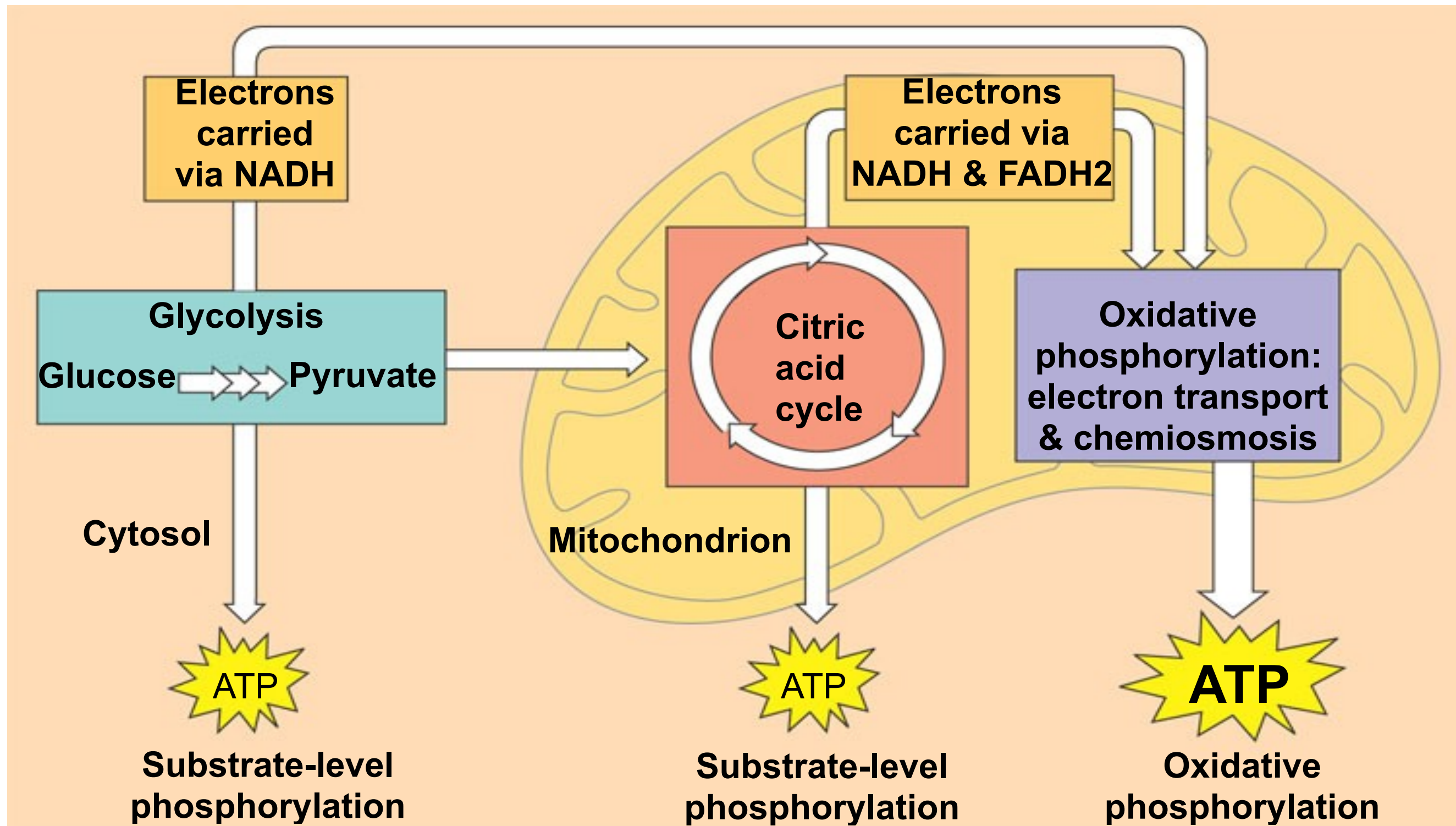
- The *electron transport chain* consists of mainly proteins, embedded into a membrane.
- *in eukaryote's inner mitochondrial membrane, in eukaryote's thylakoid membranes and prokaryote's plasma membrane*
- The e^- transfer from NADH to O_2 releases -53 kcal/mol of energy.

Oxygen, the final electron acceptor



An Overview of Cellular Respiration

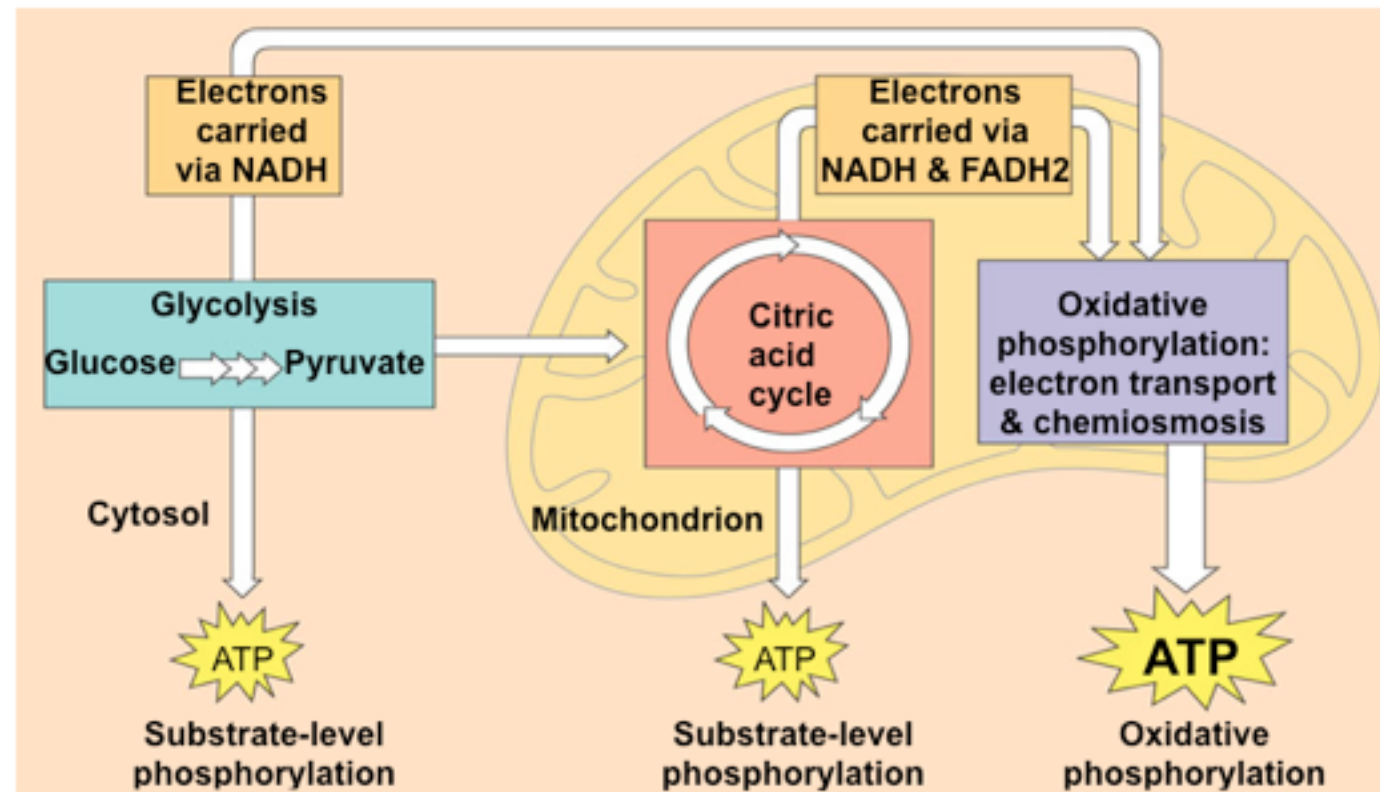
- Focus on the location, the input(s) and the output(s) for each the three stages.



An Overview of Cellular Respiration

Strictly speaking cell respiration only includes steps 2 & 3 however the so many cells use the products of glycolysis to feed the Citric acid cycle, glycolysis is often included loosely in cell respiration

Each ATP has
7.3 kcal/mol
of free energy



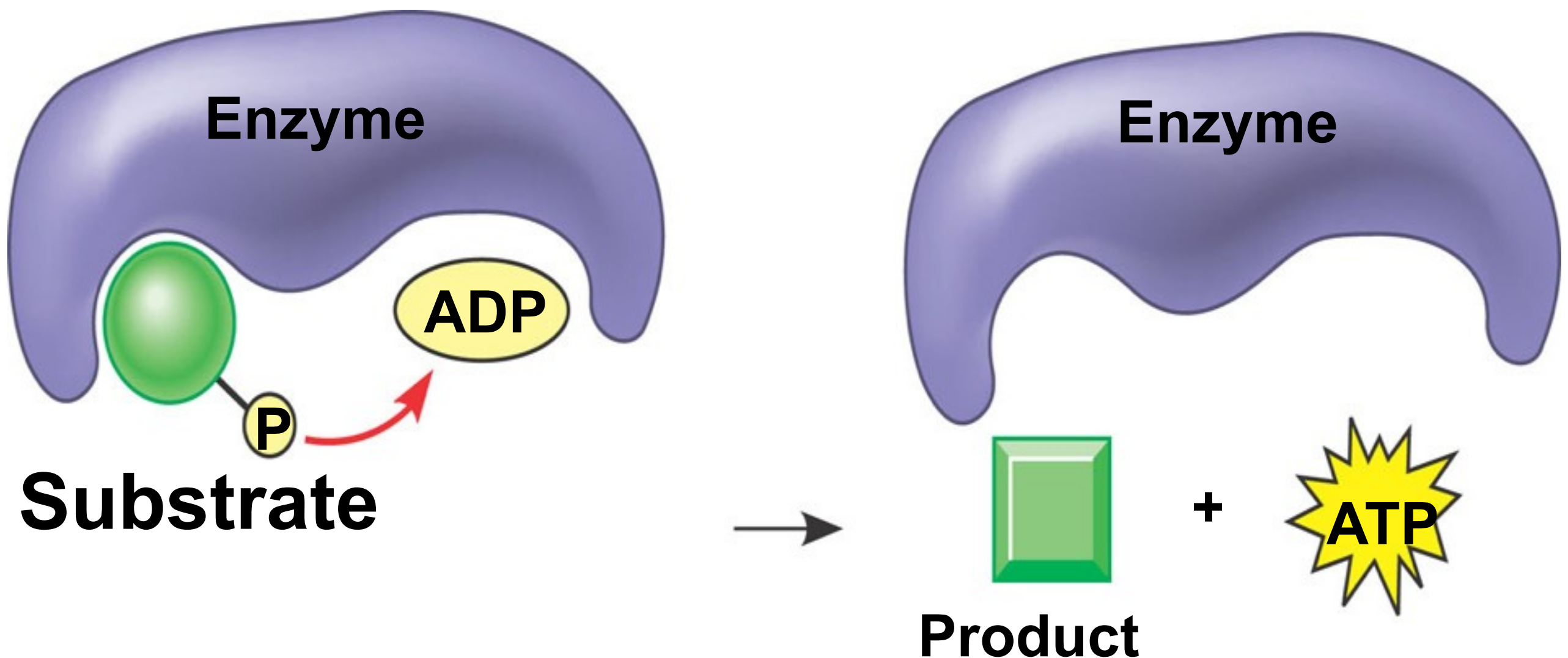
The ETC and chemiosmosis takes place in plasma membrane of bacteria

Accounts for 10%
of ATP production

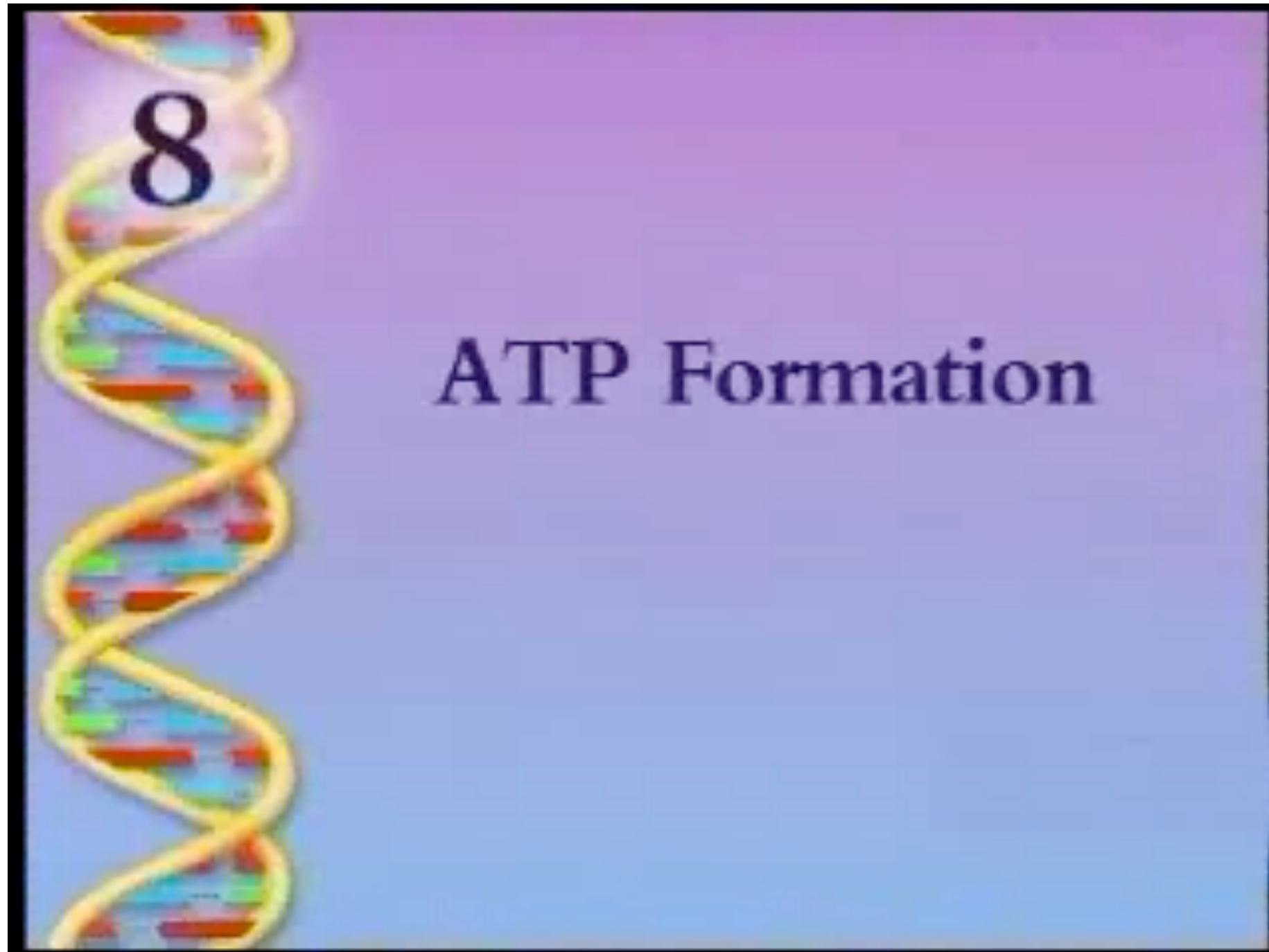
Accounts for 90%
of ATP production

ATP Production

- Most ATP is produced via oxidative phosphorylation and these details will be discussed on later slides.
- The remaining ATP is produced via **substrate level phosphorylation**.
- This involves moving a phosphate group from one molecule to ADP.



ATP the Molecule & Its Formation



Cell Respiration

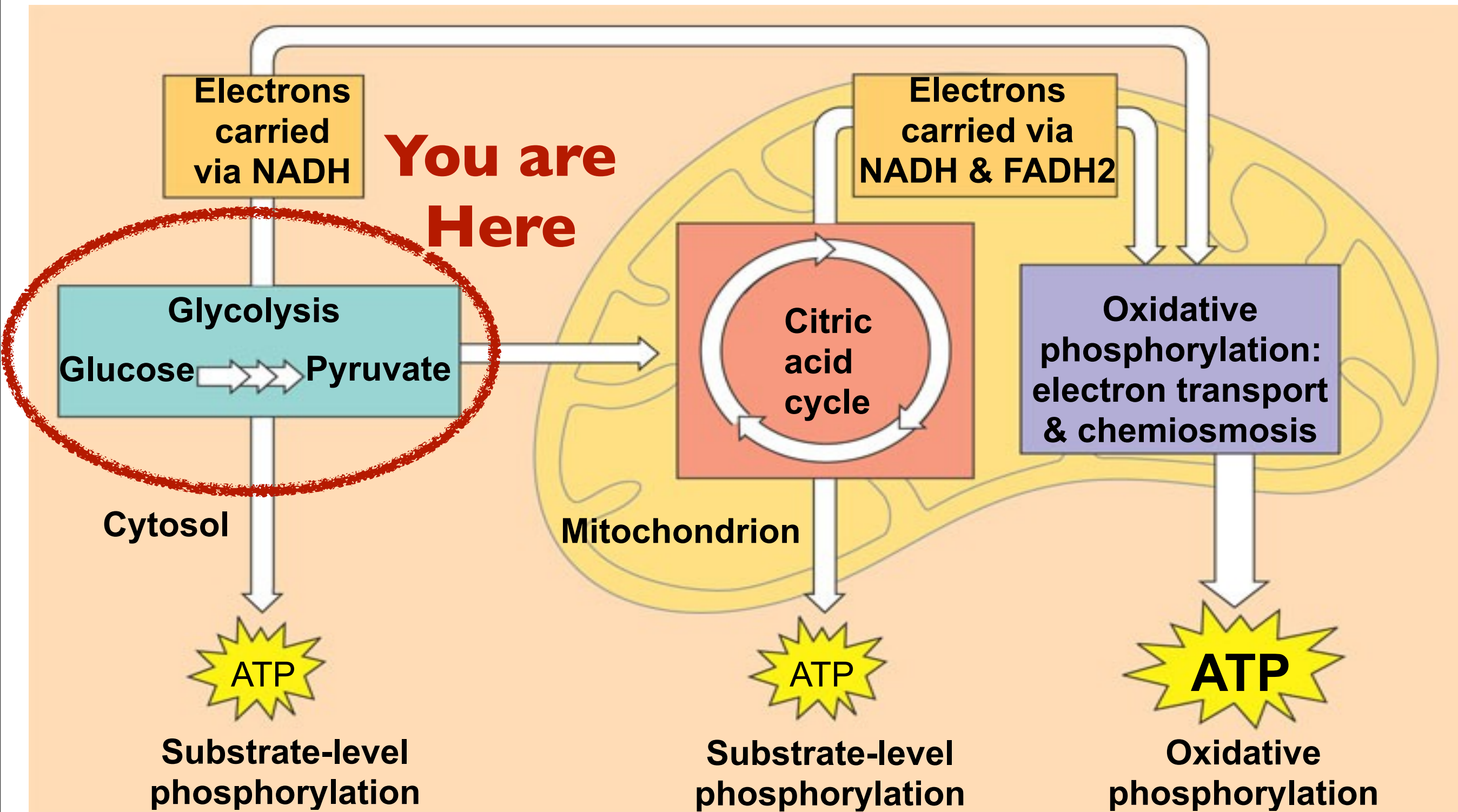
II.

Main Idea: The first step in cell respiration (catabolism of glucose) is to simply cut the 6 carbon glucose into two 3 carbon products.



An Overview of Cellular Respiration

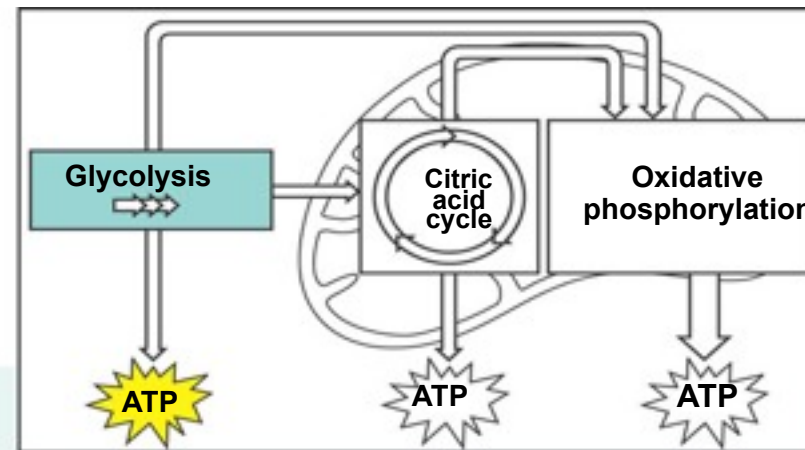
- Focus on the location, the input(s) and the output(s) for each the three stages.



An Overview of Glycolysis

- Glycolysis translated means “sugar splitting”.
- Glycolysis occurs in the cytosol
- Glycolysis is a ten step enzymatically driven metabolic pathway
- Glycolysis can be broken into two parts:
 - *the Energy Investment Phase & the Energy Pay-Off Phase*
- Glycolysis both requires ATP and produces ATP
- Glycolysis requires electron acceptors
- Glycolysis does not require oxygen not does it produce carbon dioxide.
- Glycolysis produces 2 pyruvate molecules

An Overview of Glycolysis



Represents the
“bottom line” of what
you should know

Energy investment phase

Glucose

$2 \text{ ATP} + 2$

P



used

Energy payoff phase

$4 \text{ ADP} + 4$

P



formed

$2 \text{ NAD}^+ + 4 \text{ e}^- + 4 \text{ H}^+$

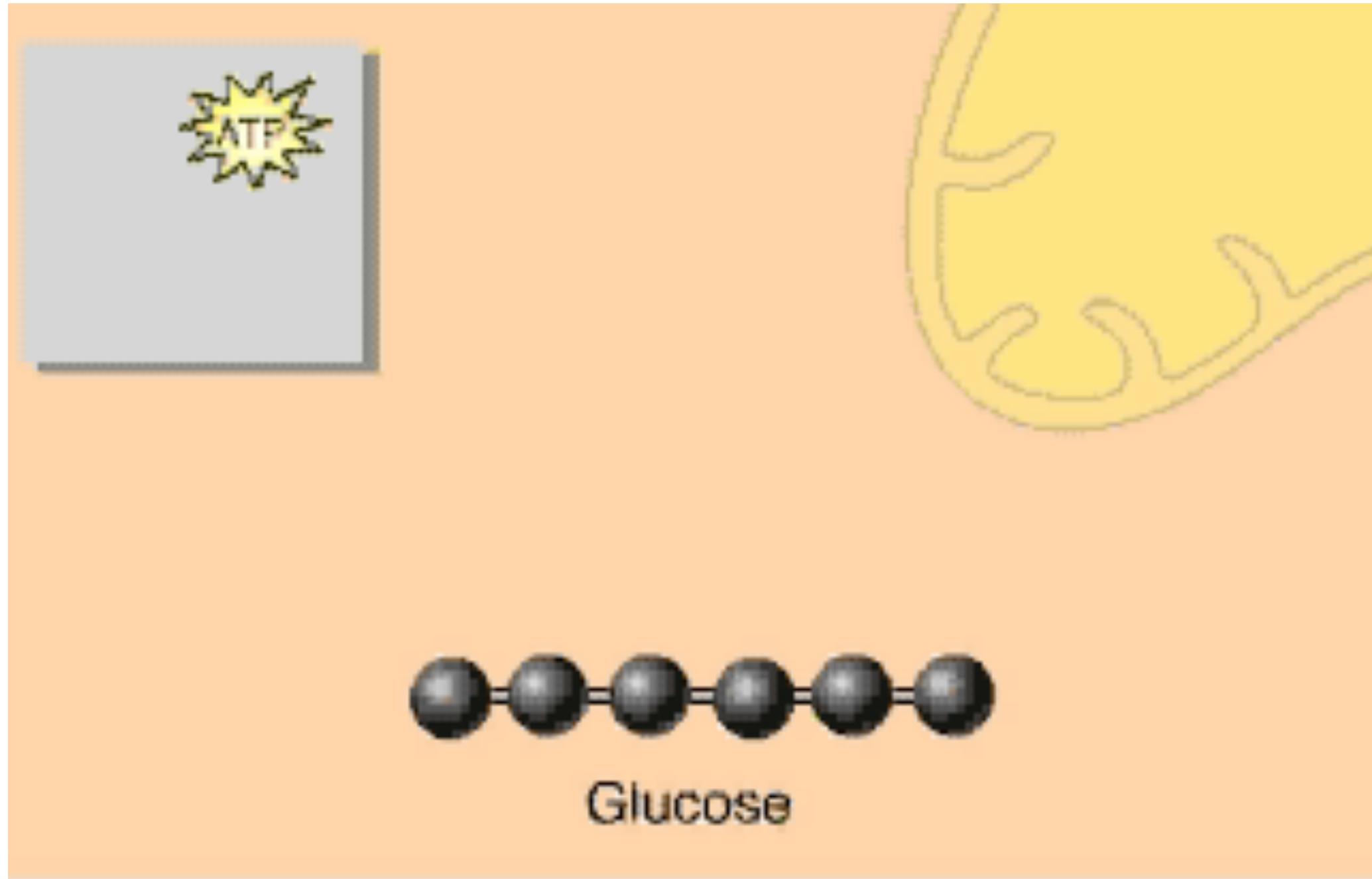
$2 \text{ NADH} + 2 \text{ H}^+$

$2 \text{ Pyruvate} + 2 \text{ H}_2\text{O}$

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

Glucose	→	$2 \text{ Pyruvate} + 2 \text{ H}_2\text{O}$
$4 \text{ ATP formed} - 2 \text{ ATP}$	→	$2 \text{ ATP} + 2 \text{ H}^+$
$2 \text{ NAD}^+ + 4 \text{ e}^- + 4 \text{ H}^+$	→	2 NADH

An Overview of Glycolysis



©1999 Addison Wesley Longman, Inc.

Cell Respiration

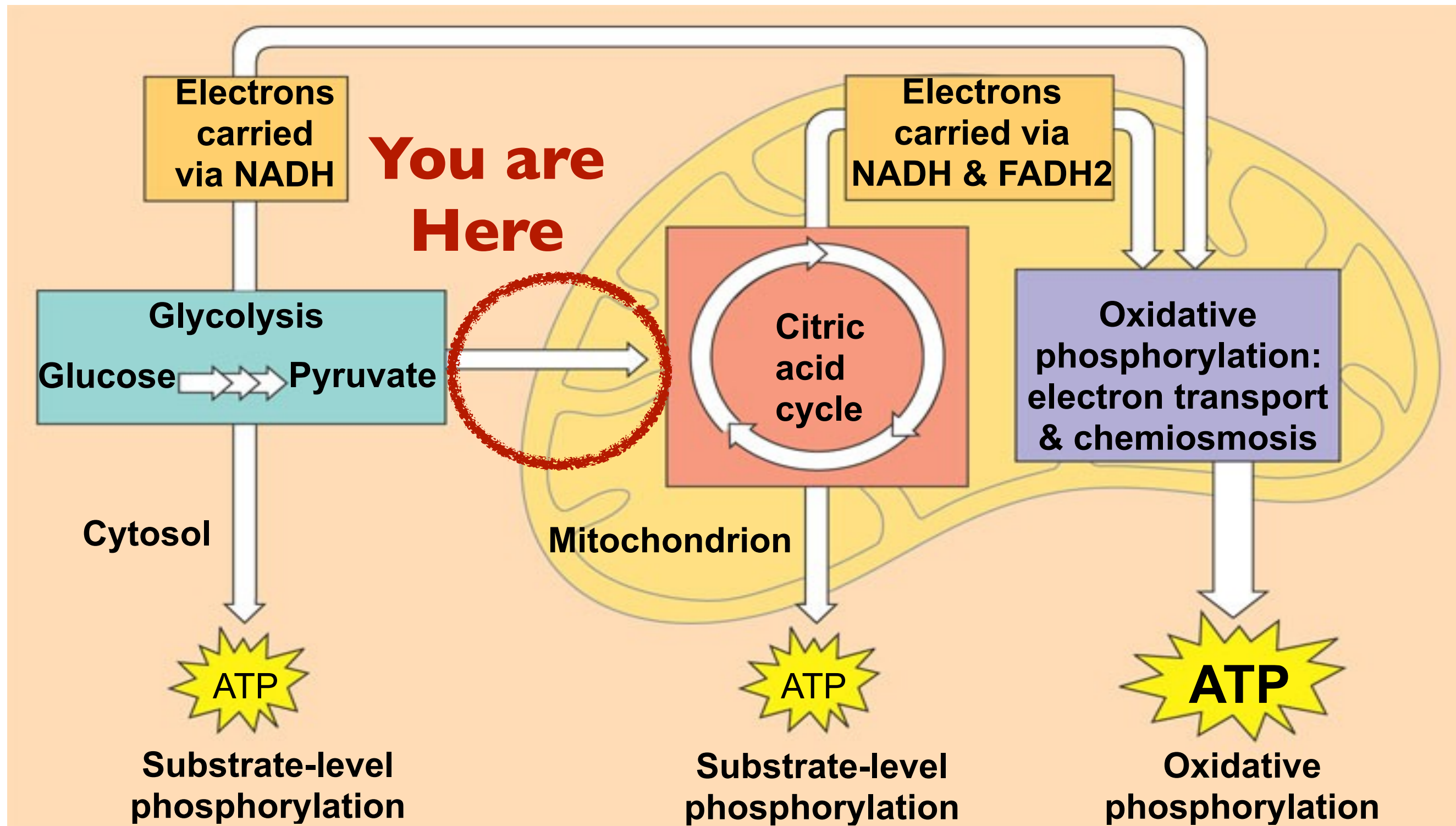
III.

Main Idea: Pyruvate must be transported across the outer membrane of the mitochondria and converted to different molecule in order to the enter the next step of cell respiration.



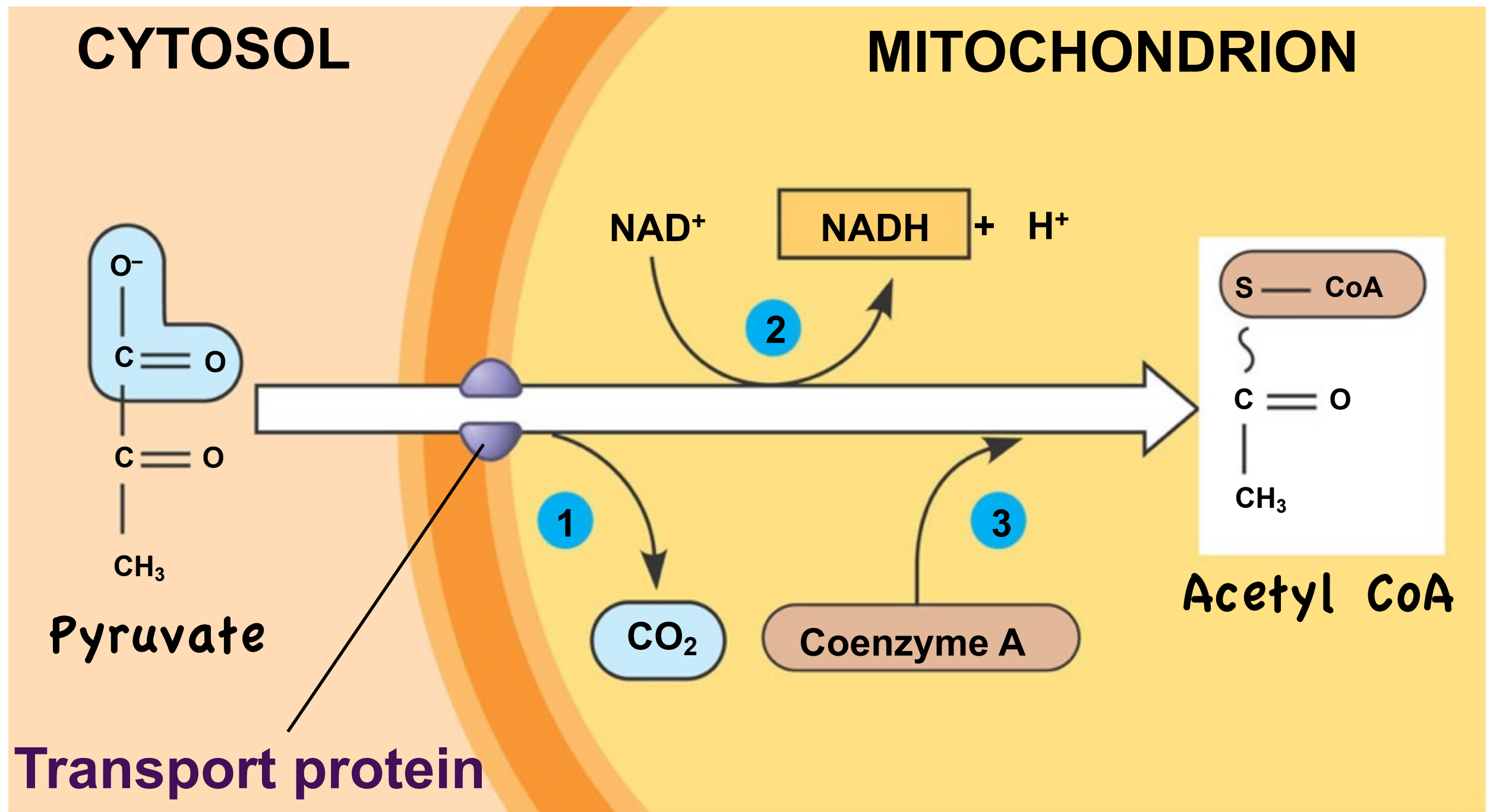
An Overview of Cellular Respiration

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



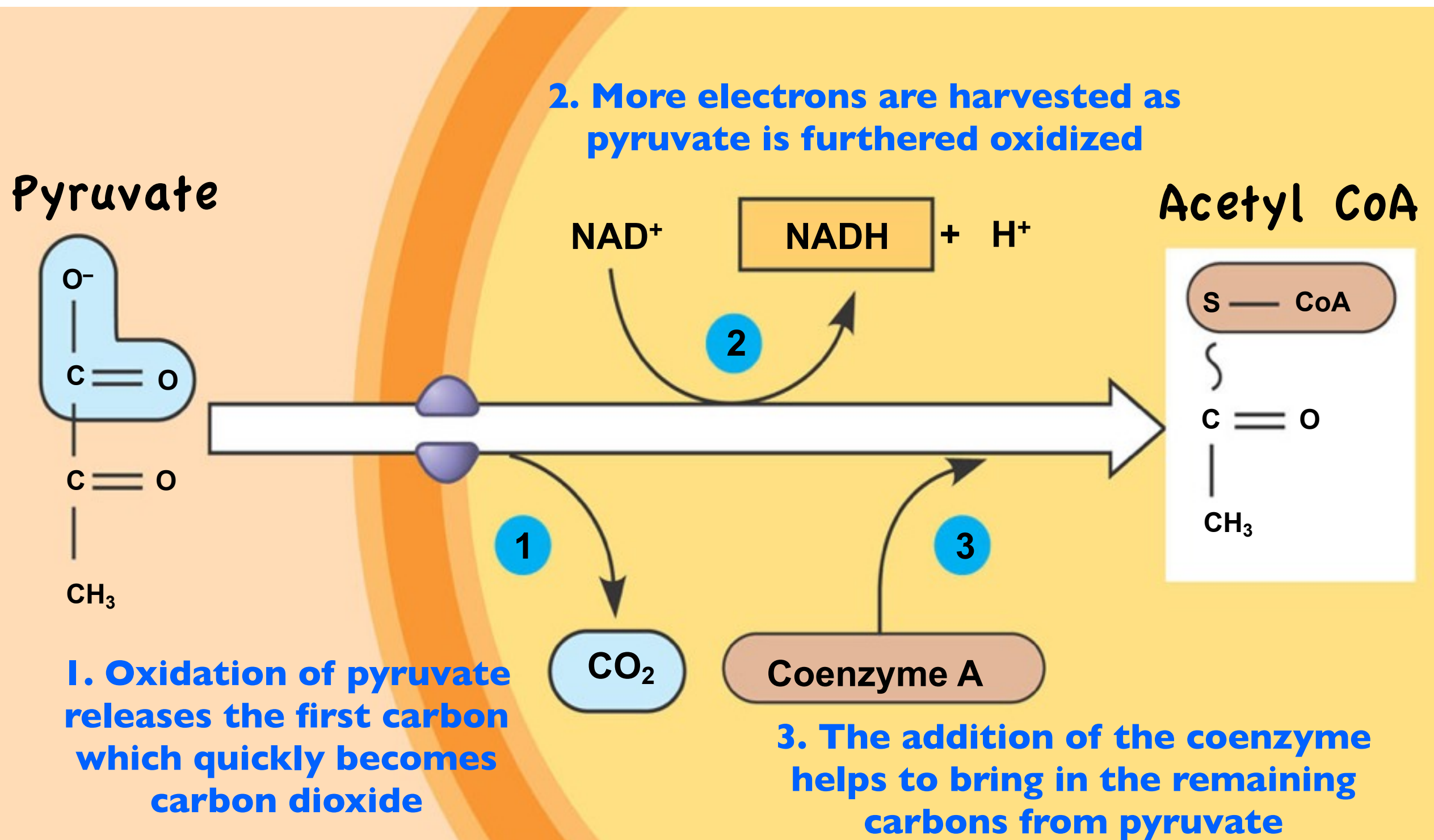
Transport of Pyruvate into Mitochondria

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



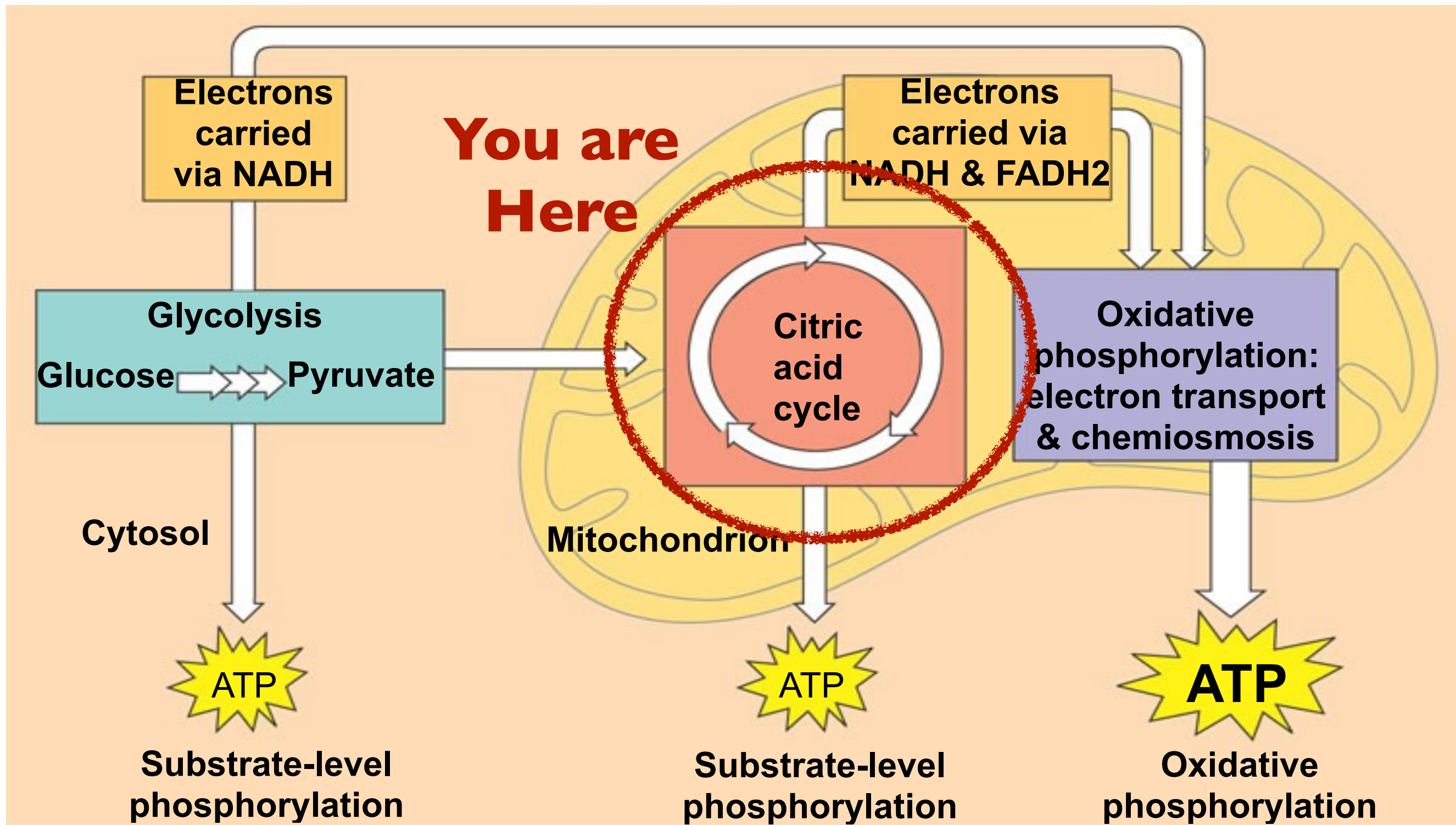
The “Prep Step”

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



An Overview of Cellular Respiration

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



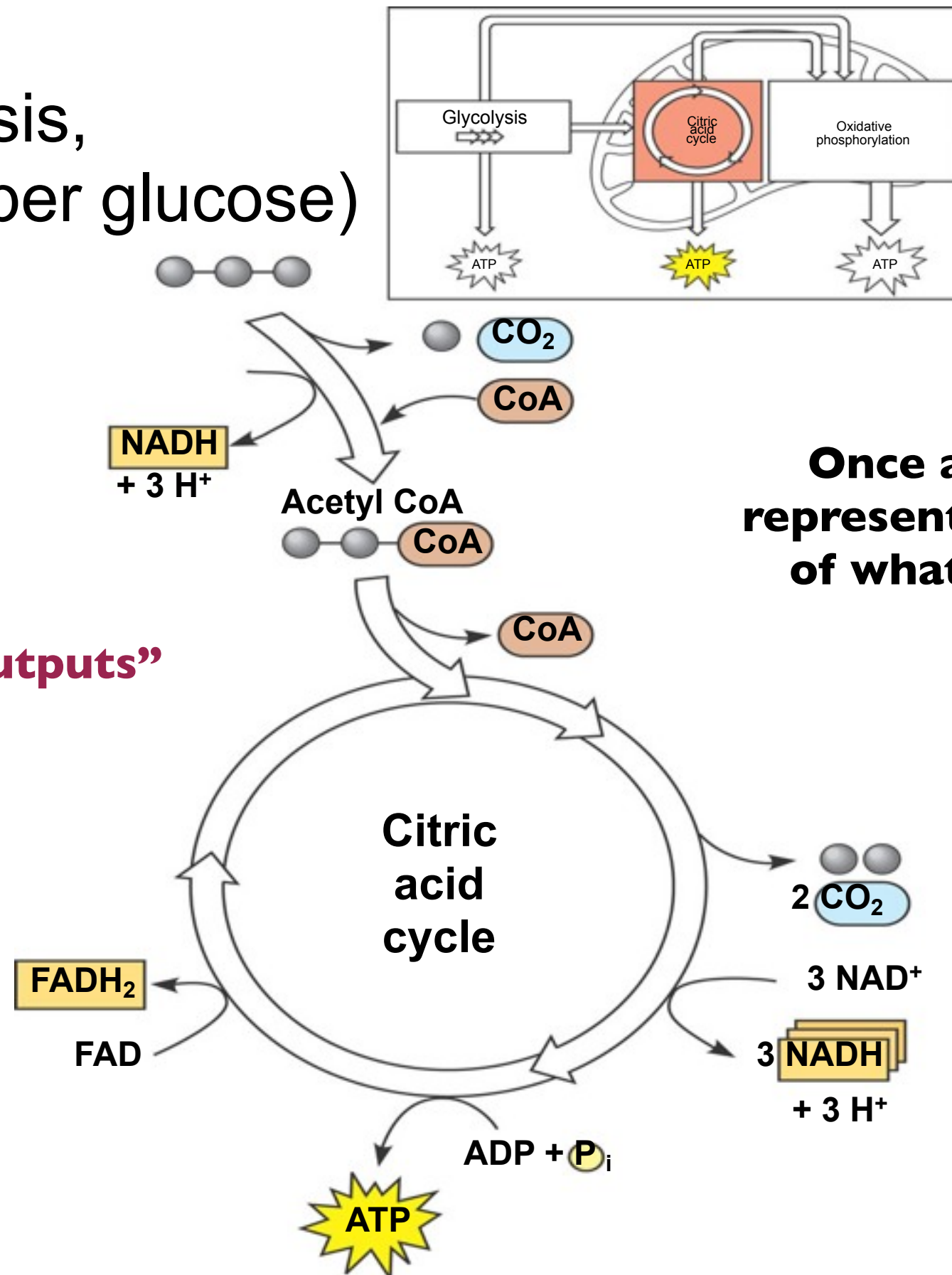
The Citric Acid Cycle or Krebs Cycle

- 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)

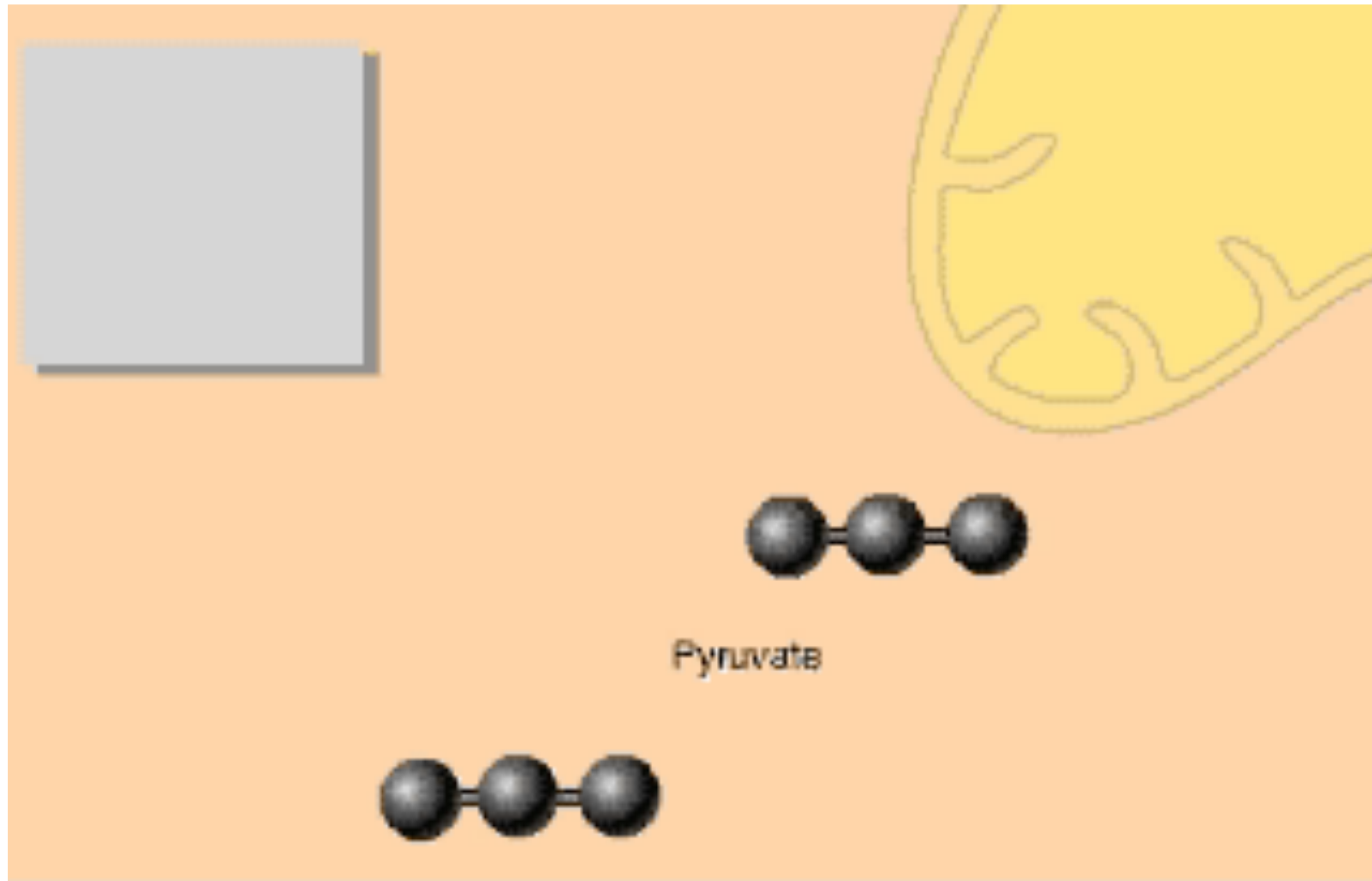


Focus on
“inputs” and “outputs”

Once again the overview
represents the “bottom line”
of what you should know

**PER
TURN**

The Citric Acid Cycle



©1999 Addison Wesley Longman, Inc.

Cell Respiration

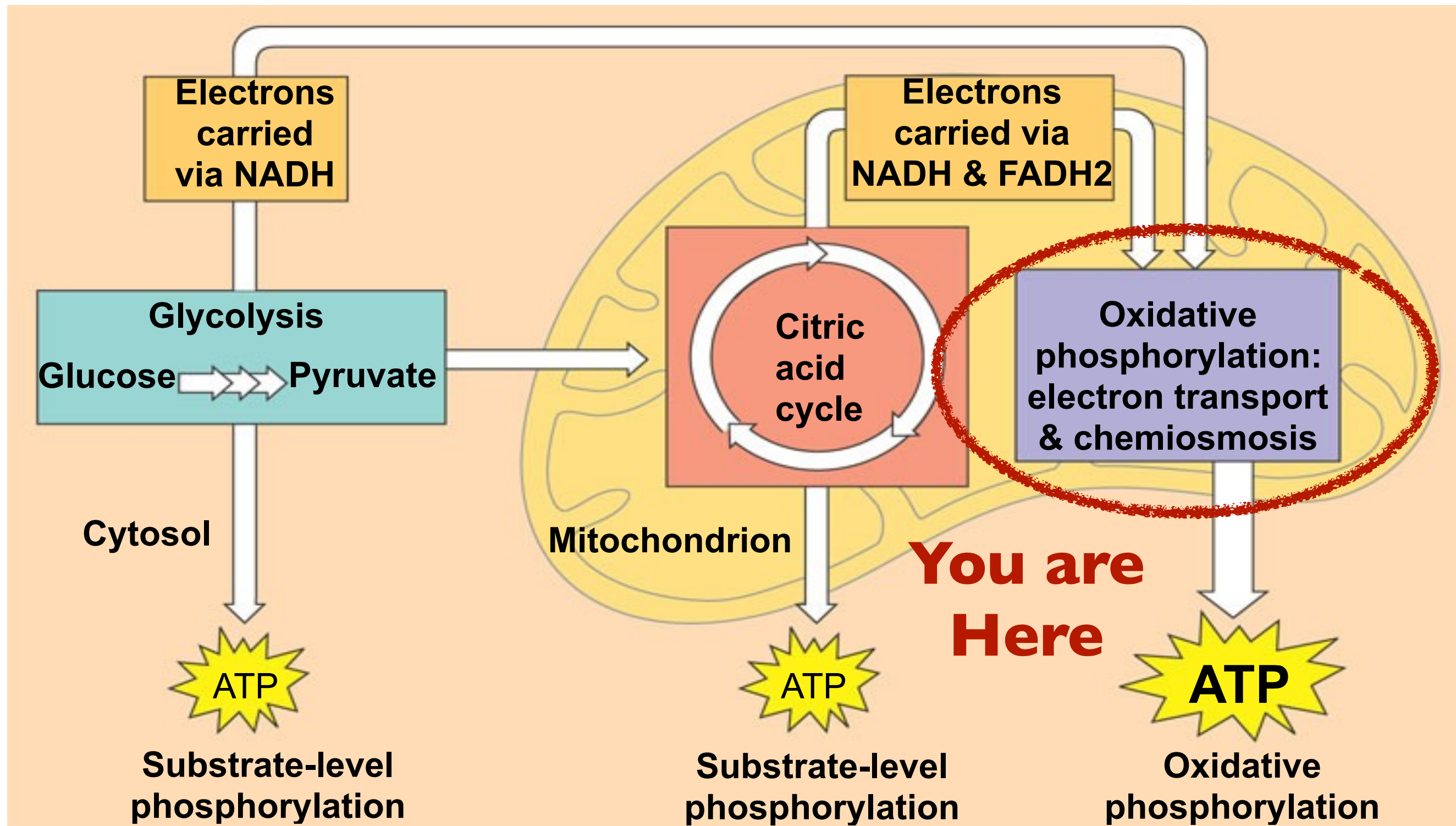
IV.

Main Idea: The electrons harvested in glycolysis and the citric acid cycle are used to power the production of ATP through oxidation phosphorylation.



An Overview of Cellular Respiration

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

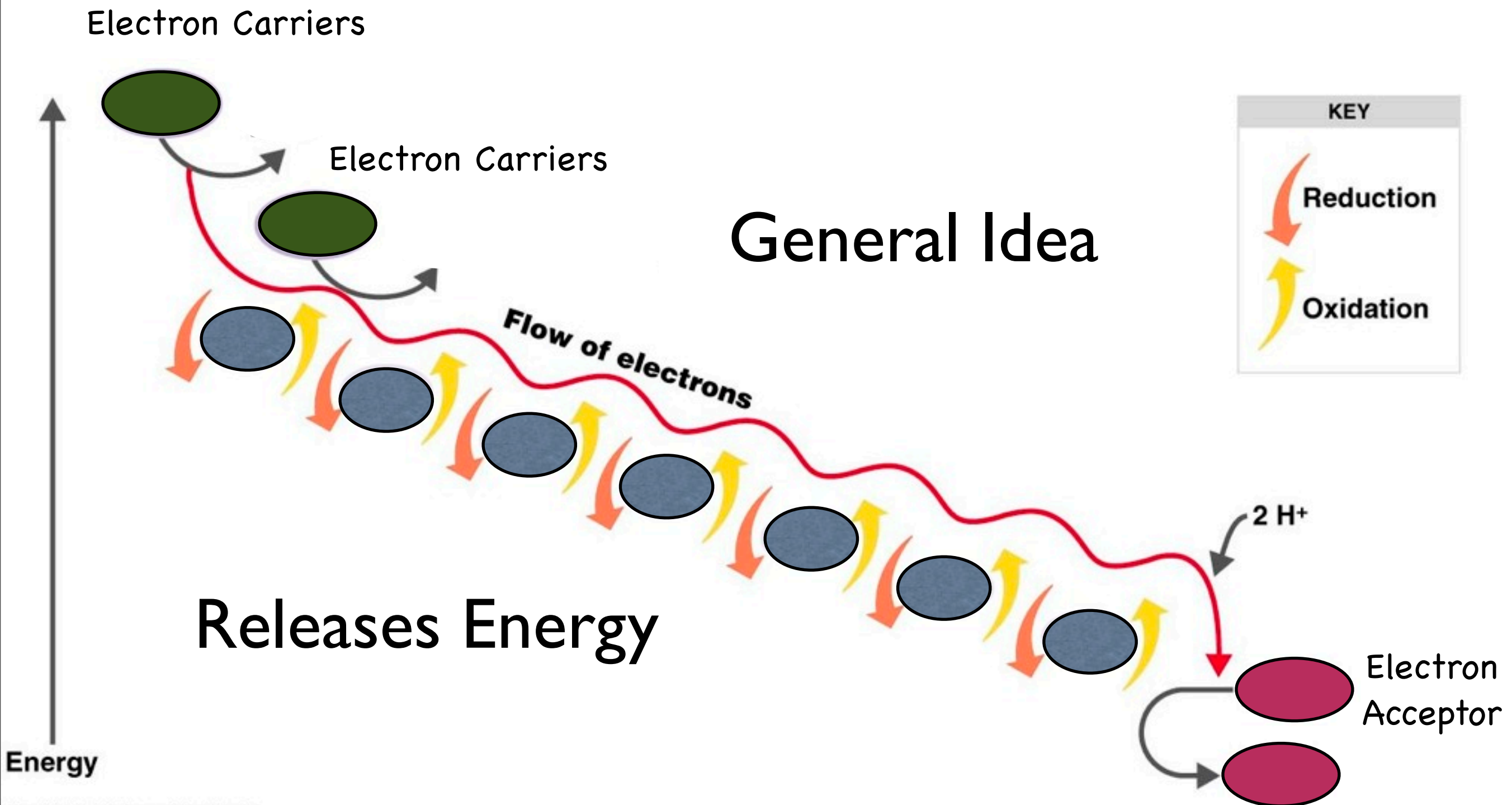


Electron Acceptors & Transport

- To get electrons from photosystem II to photosystem I requires an **electron transport chain**.
- 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*
- An electron carrier passes the electrons to another molecule, that is more electronegative, and so on and so forth
 - *Each molecule slightly more electronegative than the prior one*

Electron Acceptors & Transport

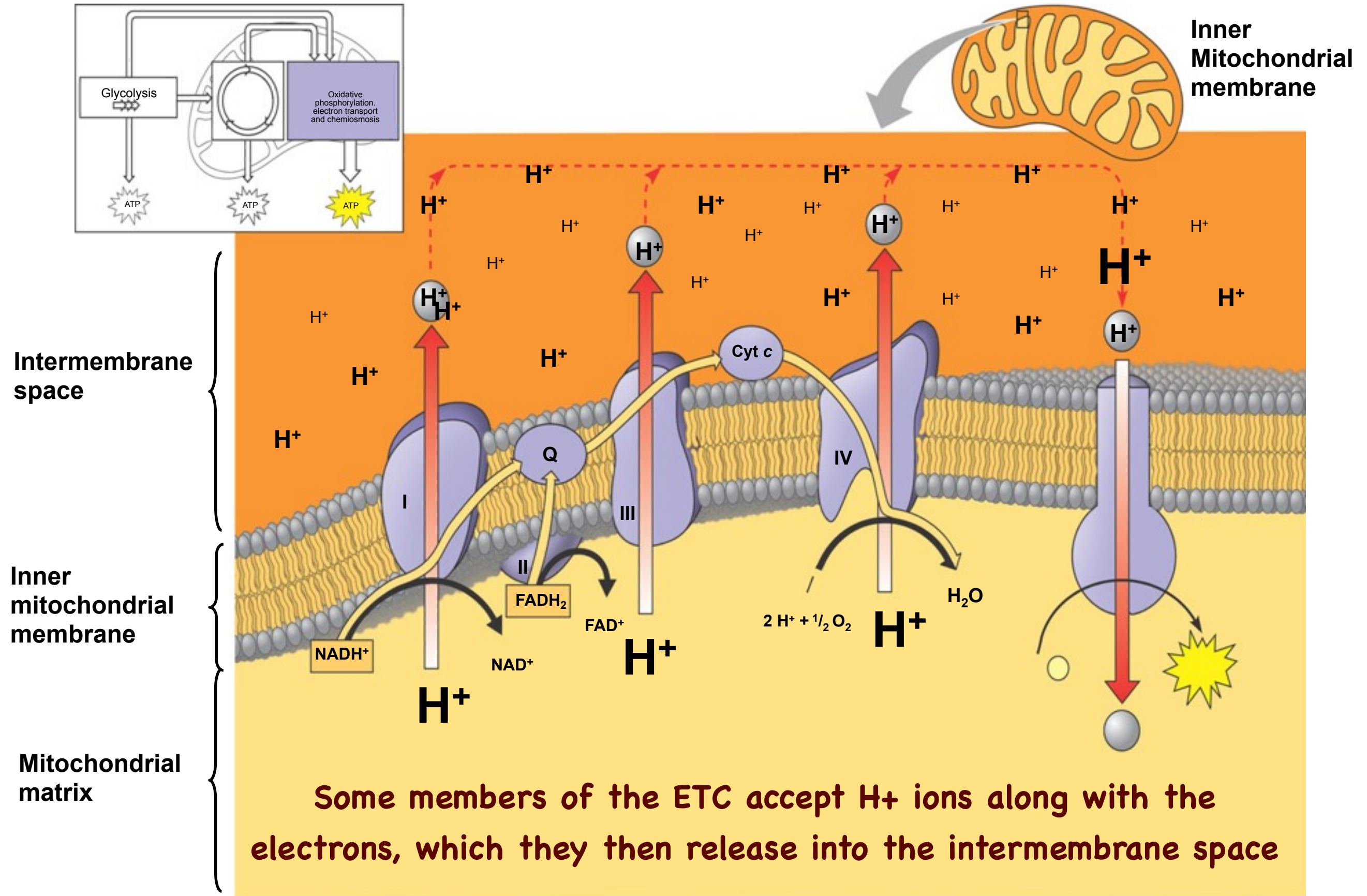
REVIEW



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

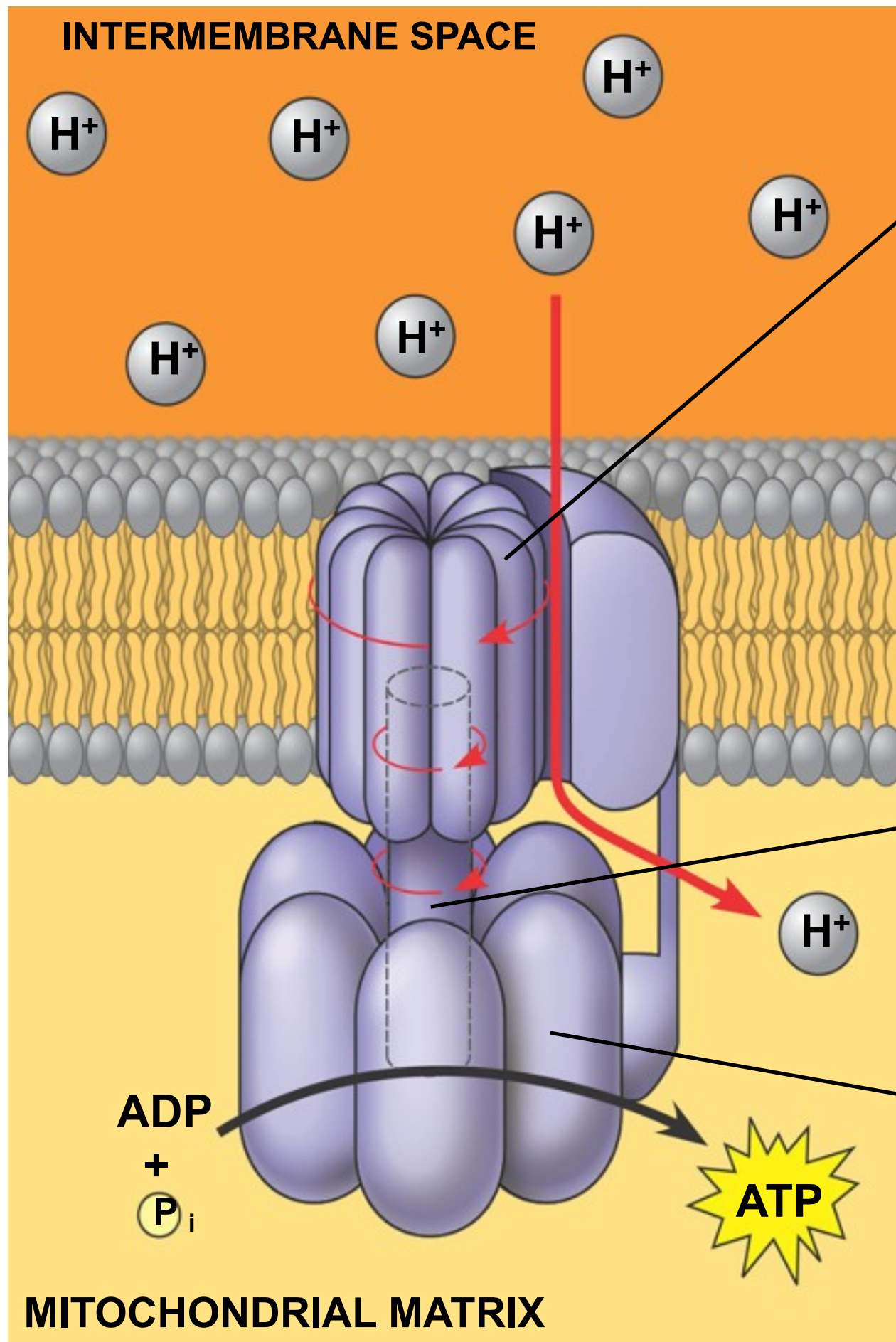
- The ***electron transport chain*** makes no ATP.
- The e^- transfer releases energy as the electron moves through the chain, this energy is used to pump H^+ ions through a membrane.
- *This generates a electrochemical gradient with great potential energy*

E.T.C. and Chemiosmosis



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



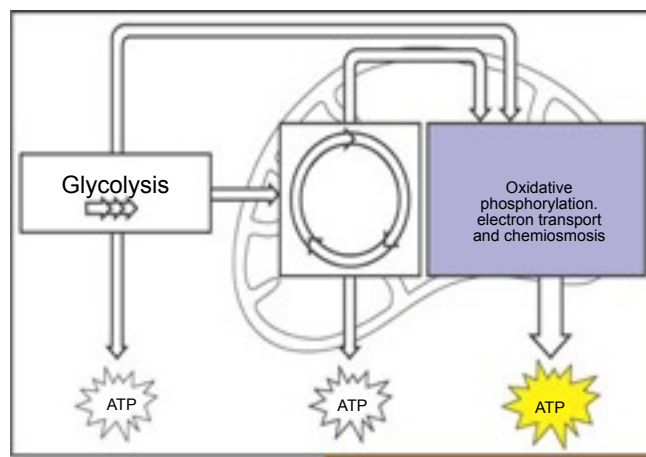
ATP Synthase

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.



Intermembrane space

Inner mitochondrial membrane

Mitochondrial matrix

Protein complex of electron carriers

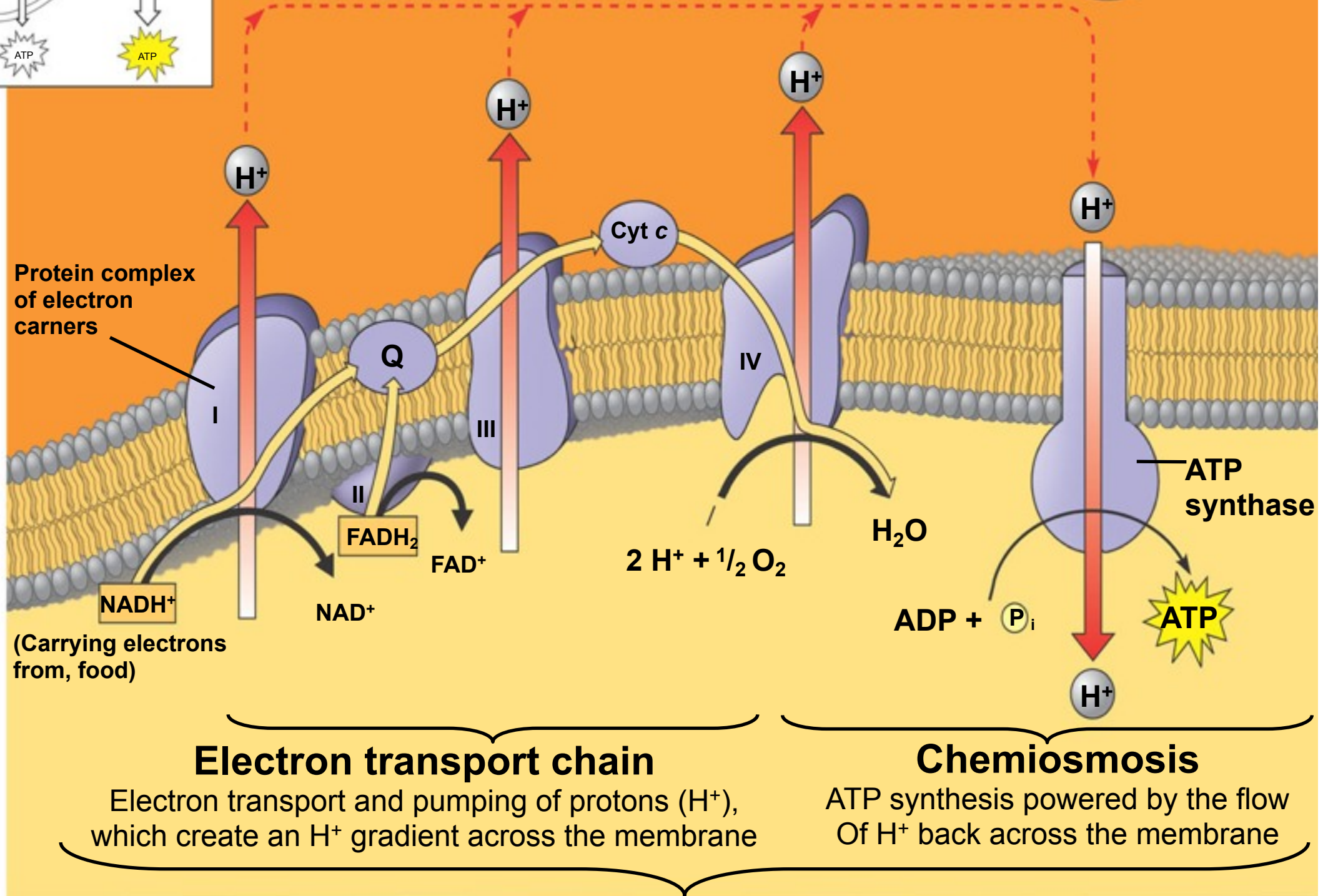
(Carrying electrons from, food)

Electron transport chain

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

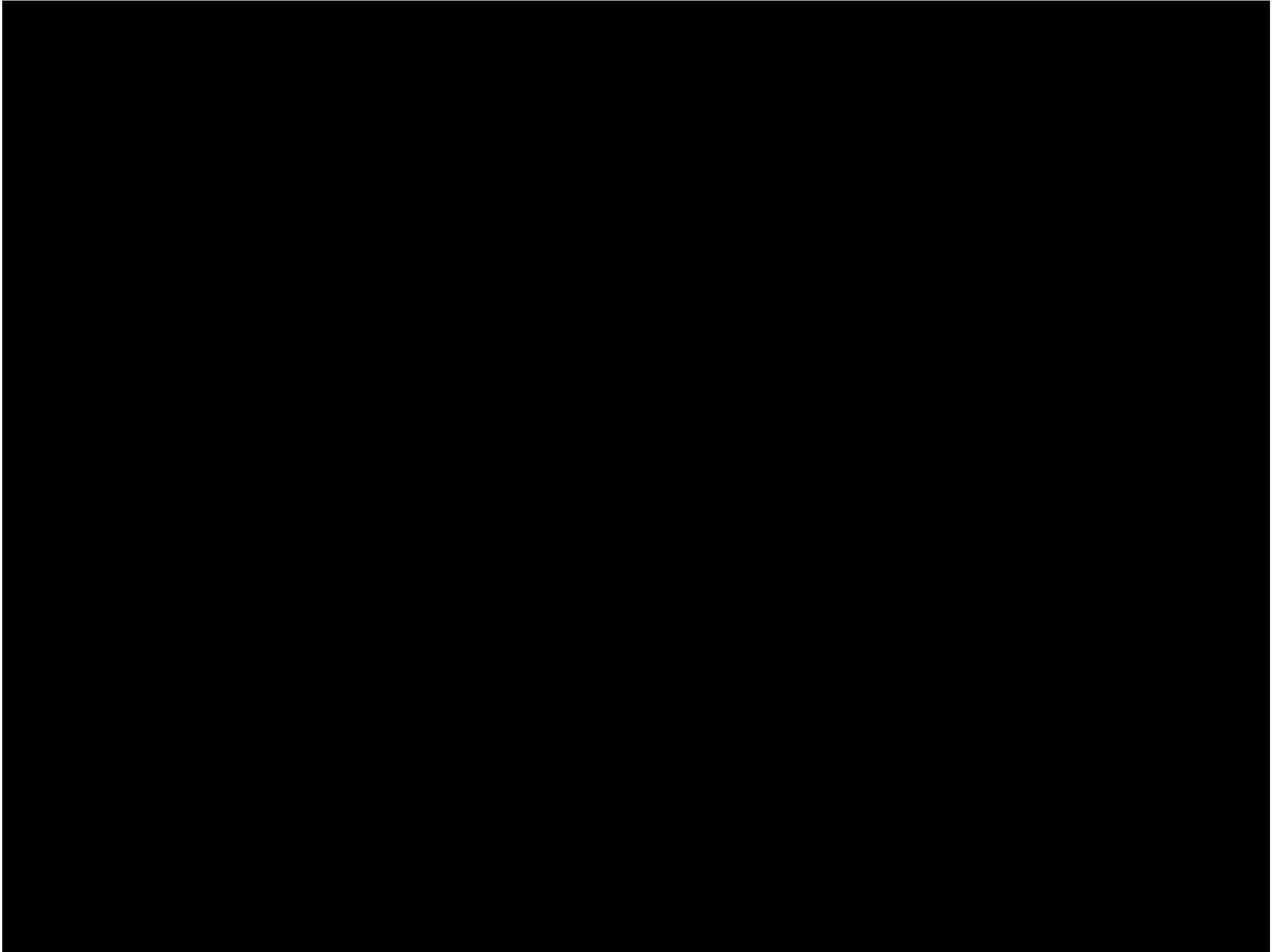
Chemiosmosis

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

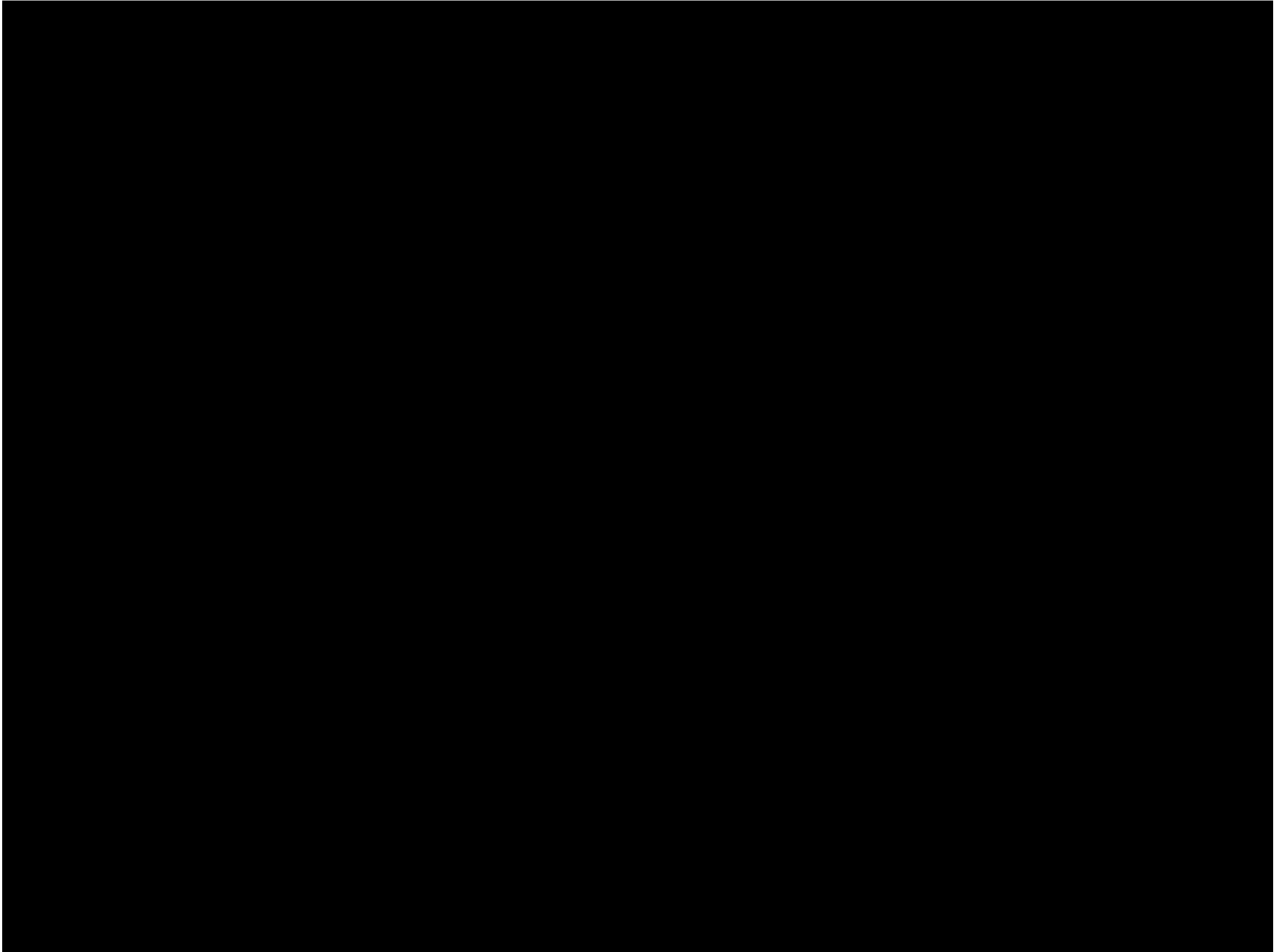


Oxidative Phosphorylation

E.T.C. and Chemiosmosis



ATP Synthase



Chemiosmosis- SIMILARITIES

Chloroplasts vs. Mitochondria

- Both generate ATP
- Both employ an Electron Transport Chain
- Both generate a Proton Motive force
- Both use ATP synthase to generate ATP
- Both have chemiosmosis occurring in the inner membrane of the organelle

Chemiosmosis- DIFFERENCES

Chloroplasts vs. Mitochondria

Chloroplasts

photophosphorylation

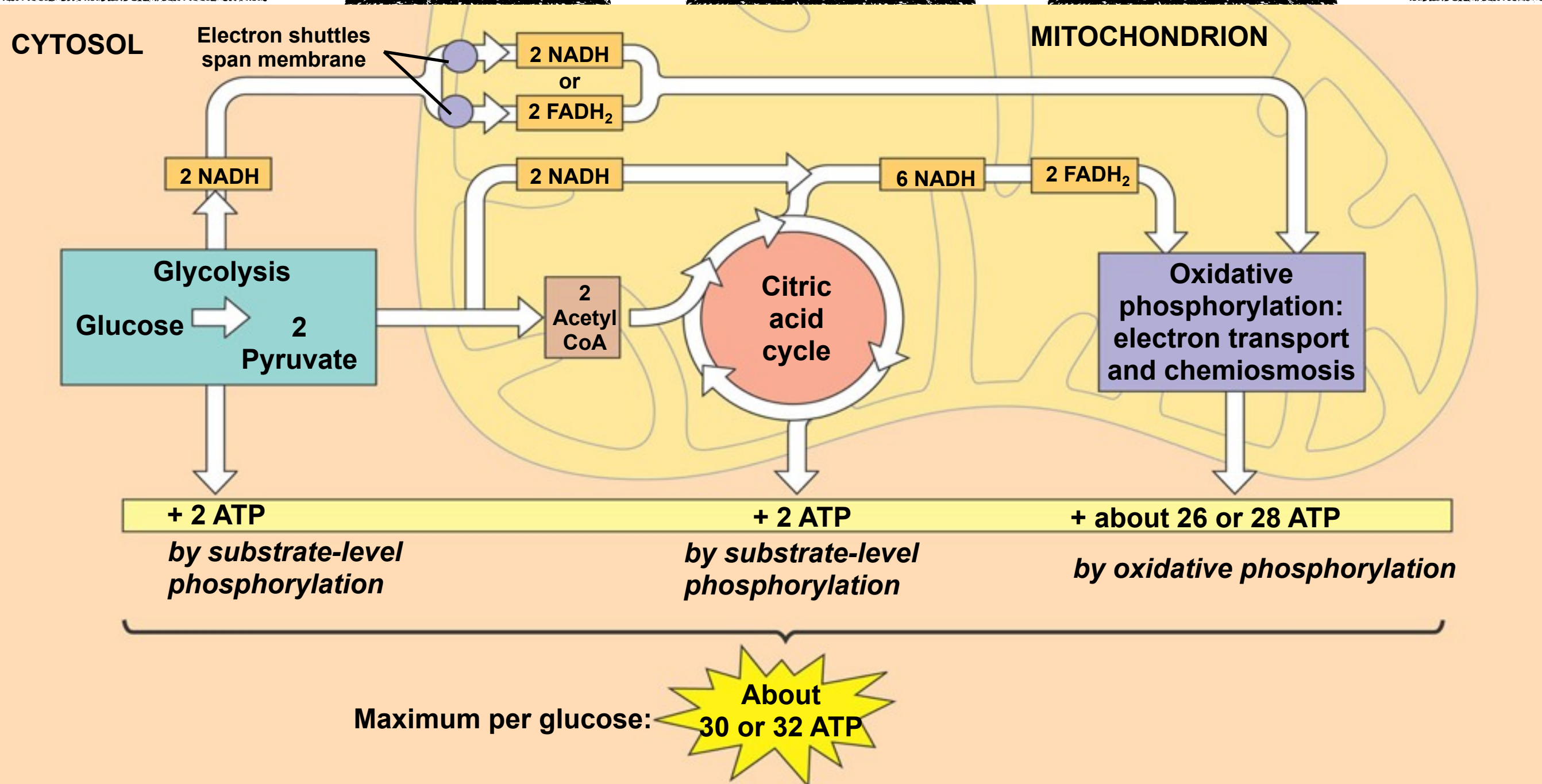
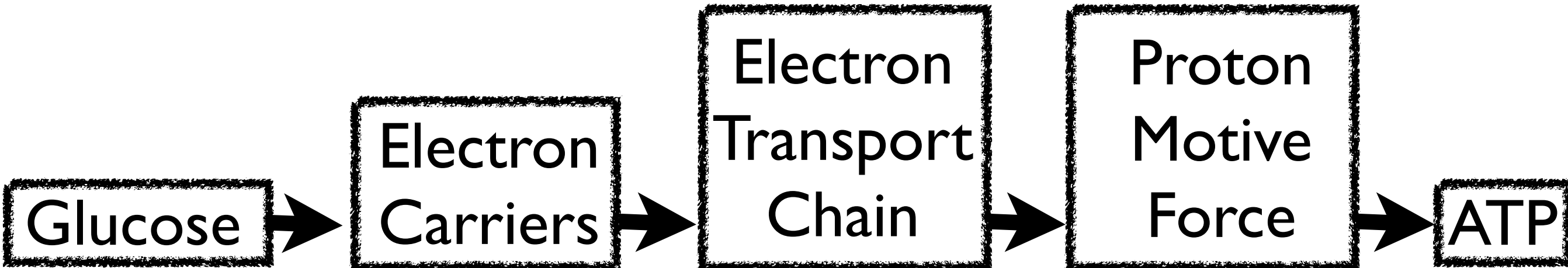
- Electrons come from “water”
- H^+ pumped into thylakoid space
- Light energy drives electron flow
- Spatial organization differs

Mitochondria

oxidative phosphorylation

- Electrons come from “food”
- H^+ pumped out into intermembrane space
- Chemical energy drives electron flow
- Spatial organization differs

Tracking Energy Flow & ATP Production



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!

Cell Respiration

V.

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



Fermentation & Anaerobic Respiration

- Aerobic respiration requires oxygen, and with oxygen generates the greatest amount of ATP
- Cells have alternate ways of making ATP when oxygen is not available.
 - Fermentation
 - Anaerobic Respiration
- The distinction between them lies in the presence or absence of electron transport chains.
 - Fermentation- does not have Electron Transport Chains
 - Anaerobic Respiration- has Electron Transport Chains

Anaerobic Respiration

- Anaerobic respiration takes place in bacteria in environments devoid of oxygen.
- They use Electron Transport Chains
- They use a Proton Motive Force
- They use ATP synthase
- The machinery resides in their plasma membrane.
- The final electron acceptor is sulfate ions (SO_4^{2-})
- They produce H_2S instead of H_2O
 - *hence the smell of rotten eggs in mangroves due to H_2S*

Fermentation

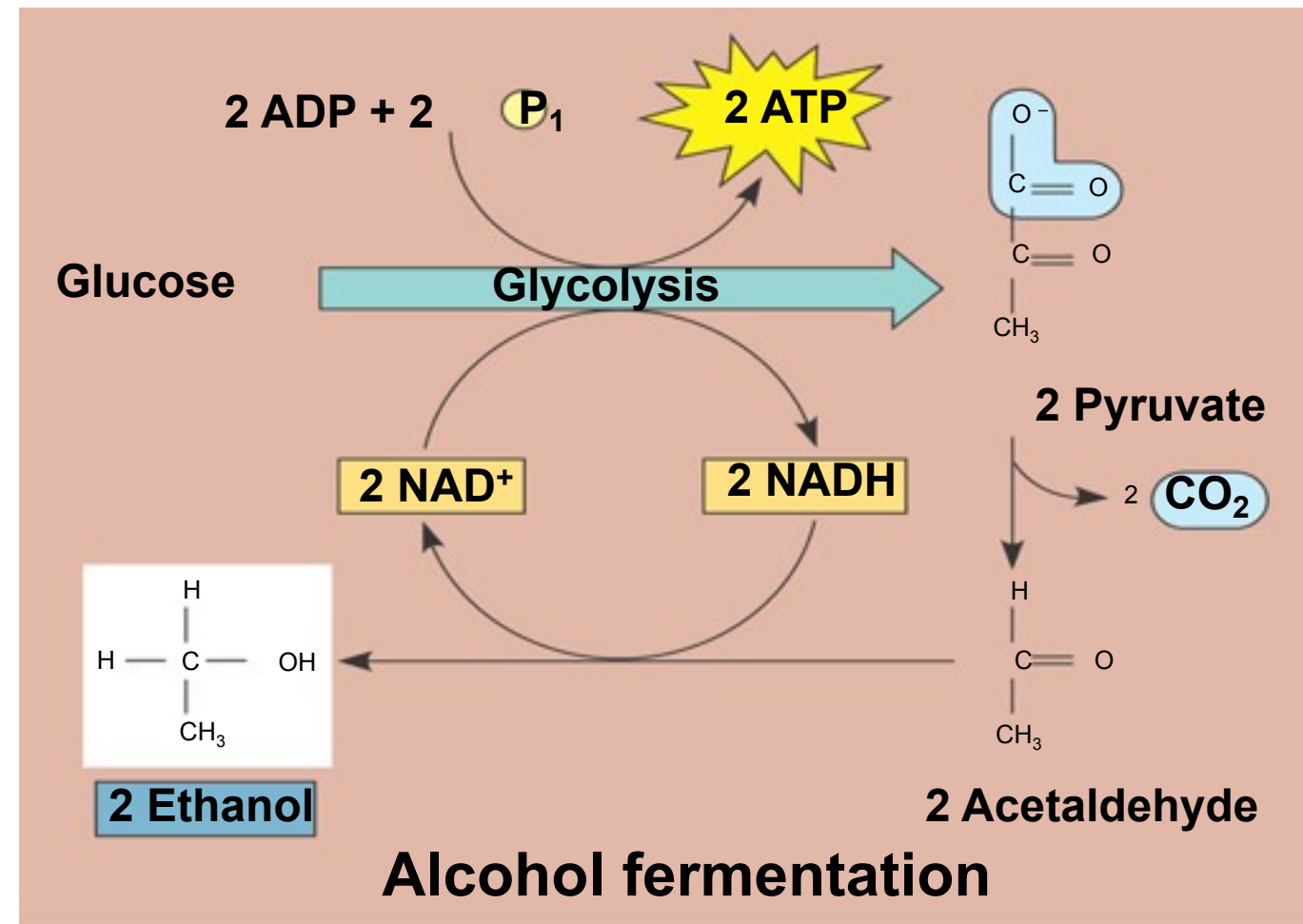
- Fermentation is a mechanism that harvests chemical energy (ATP) without oxygen and without an electron transport chain.
- Glycolysis oxidizes organic compounds with or without oxygen and without an electron transport chain.
- Fermentation is an extension of glycolysis that allows for the continuous 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

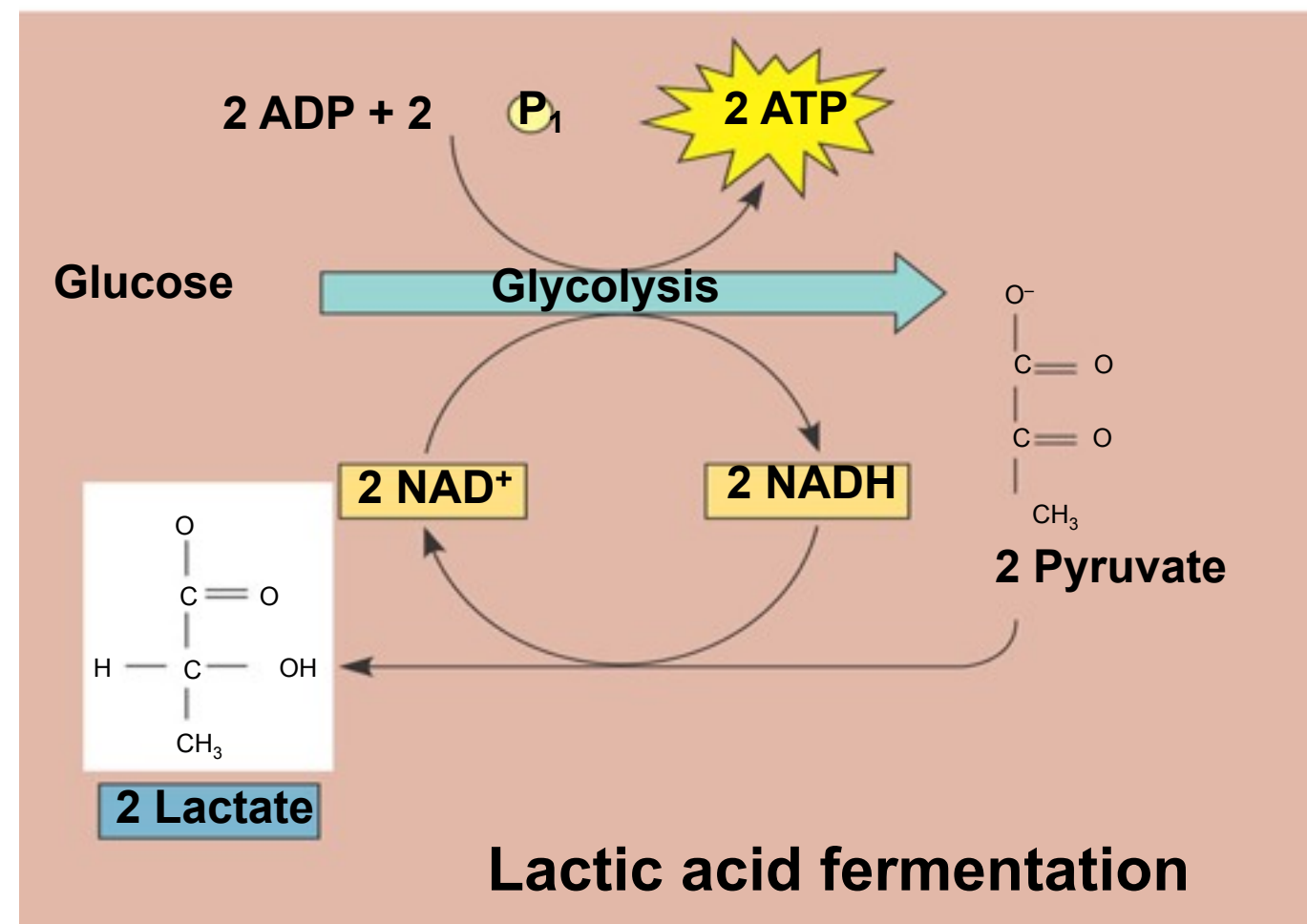
Two Types of Fermentation

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



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*



A Summary & Comparisons

- 3 Ways to make ATP
 - Fermentation
 - Anaerobic Respiration
 - Aerobic Respiration

- Similarities

- **All harvest chemical energy from “food”**
- **All use glycolysis**
- **All make 2 ATP, via substrate level phosphorylation**
- **All use NAD^+ as their initial electron carrier**

A Summary & Comparisons

- Differences

- **Mechanism that converts NADH back to NAD⁺**

- Fermentation: electrons passed to organic compound either pyruvate or acetaldehyde
- Anaerobic Respiration: electrons passed to E.T.C. and then to electronegative inorganic molecule (H₂S)
- Aerobic Respiration: electrons passed to E.T.C. and then to electronegative inorganic molecule (O₂)

Diversity in ATP Production

- **Obligate Anaerobes**- organisms/cells use only fermentation or anaerobic respiration
 - ex. clostridium bacteria
- **Obligate Aerobes**- organisms/cells use only aerobic oxidation
 - ex. brain cells
- **Facultative Anaerobes**- organisms/cells use either fermentation or aerobic respiration
 - ex. yeasts

The Evolution of Glycolysis

- Glycolysis is likely the most ancient and most common way to produce ATP.
- The cytosolic location implies antiquity
- The fact that no oxygen is required implies antiquity
- The fact that no membrane is required also implies antiquity
- And finally that the fact that it is found in virtually every cell also implies antiquity

Cell Respiration

VI.

Main Idea: Metabolic Pathways are diverse and those discussed (glycolysis and the citric acid cycle) are simply intersections for many more catabolic and anabolic pathways.



Versatility of Catabolic Pathways

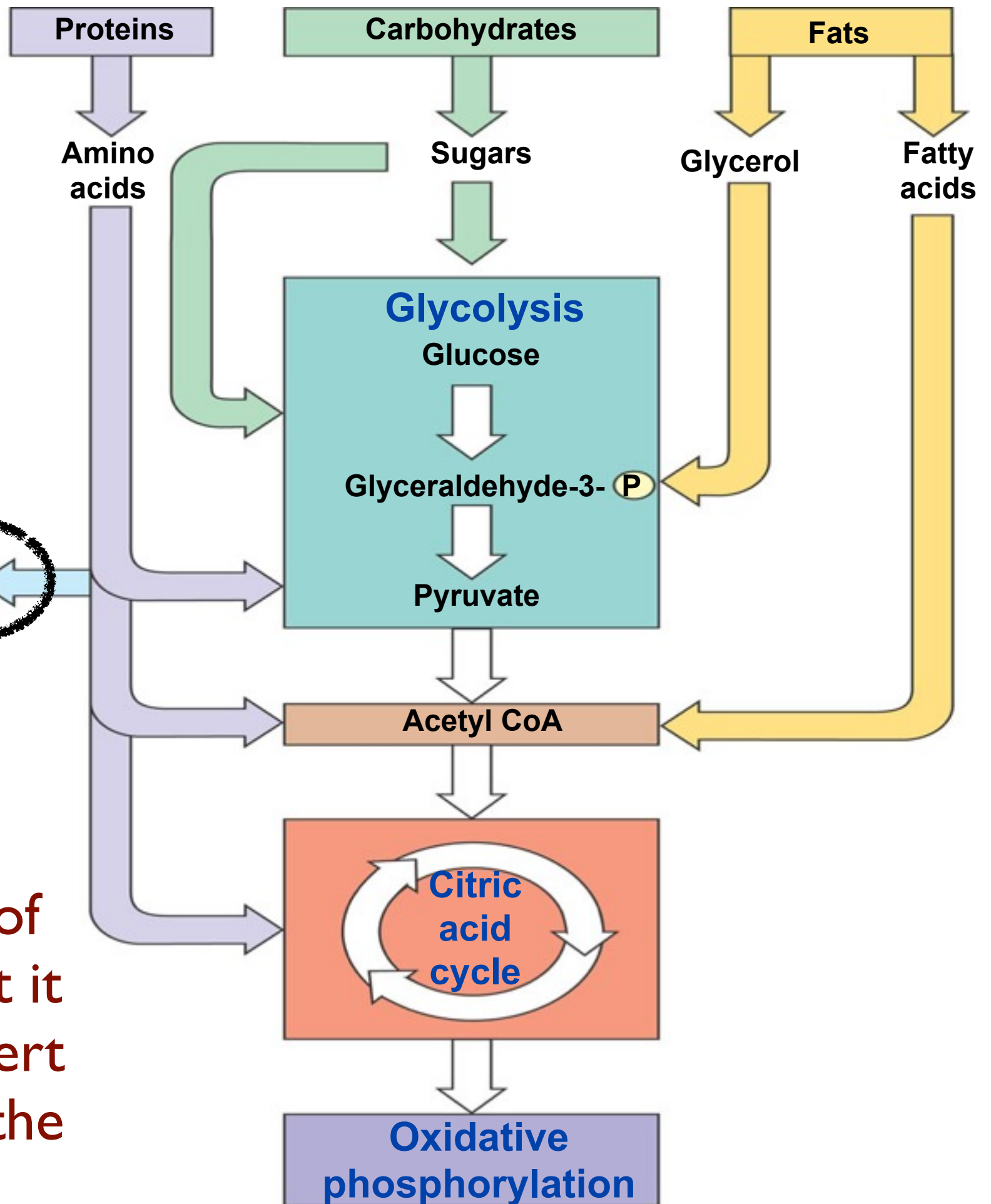
- Glucose is the standard fuel used when teaching/learning about cellular respiration. Free glucose is however not common in most diets.
- Cells use a variety of other “food fuels” such as fats, proteins and other types of sugars.
- When these other fuels are used they are oxidized into smaller subunits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

Versatility of Catabolic Pathways

* Recall in C.C. Water & Waste, Ammonia waste produced from protein catabolism!



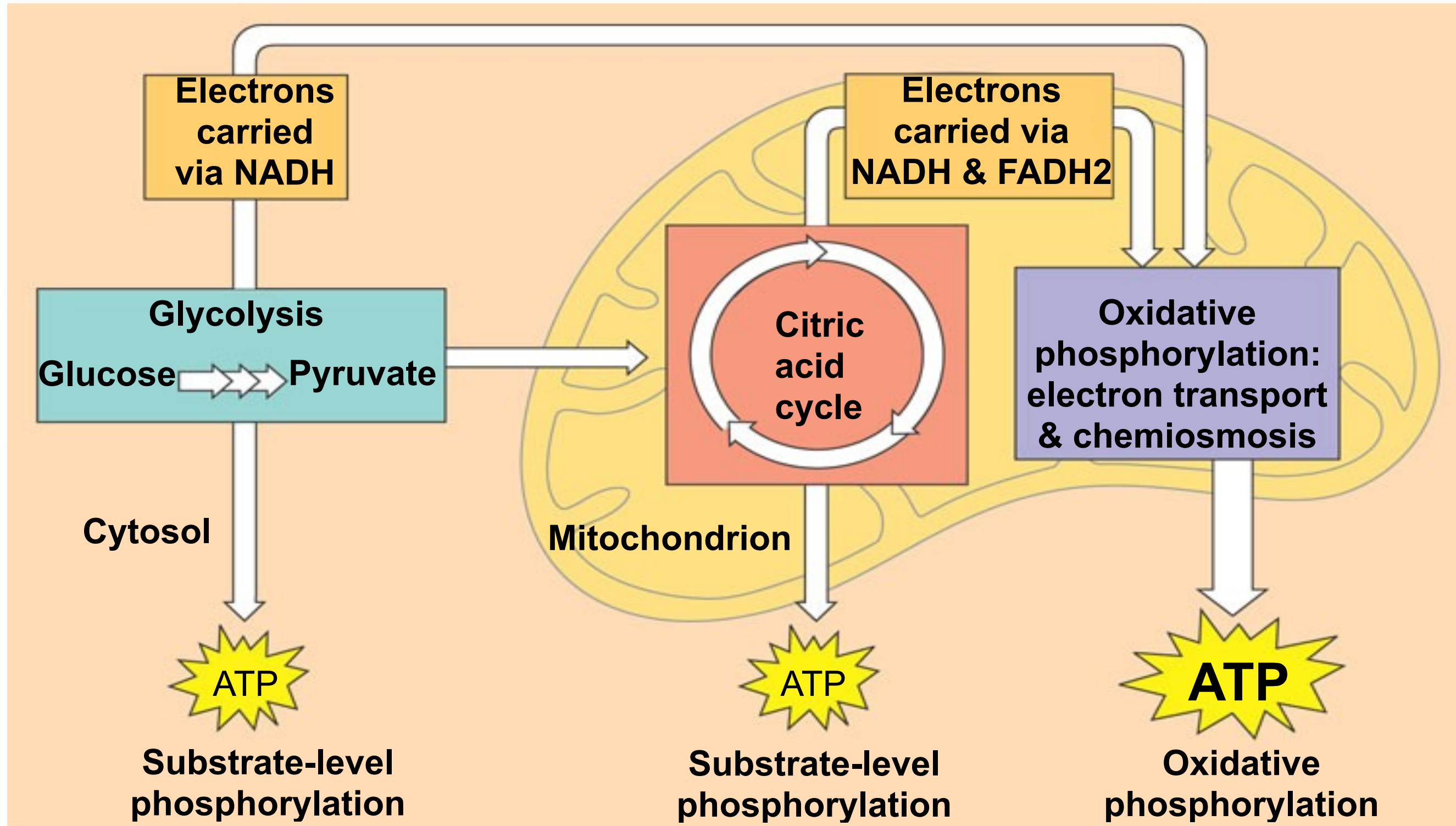
Which animals get rid of ammonia, which convert it to uric acid, which convert to uric acid.? What are the trade offs for each?



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

An Overview of Cellular Respiration



Ecological viewpoint of Cellular Respiration

- Remember Cell Respiration does not make energy it simply releases the energy stored in molecules.
- The SUN is ultimate source of energy!

