Lesson 4:
From Eating to Energy

BIOL 1441

Cell & Molecular Biology

Learning Objectives (a.k.a. Study Guide)

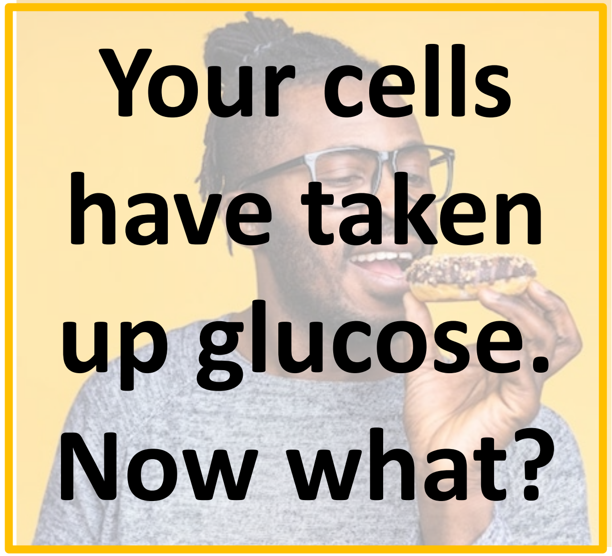
By the end of this lesson, students will be able to:

1. Explain why the human body needs to eat.
2. Define the term “metabolism”
3. Describe the function of chemical bonds.
4. Explain how the structure of ATP makes it good for storing & releasing energy.
5. Explain what happens in catabolic & anabolic reactions.
6. Explain what happens in endergonic & exergonic reactions.
7. Describe the relationship between catabolic, anabolic, endergonic, and exergonic reactions.
8. Explain how ATP & ADP are related.
9. Explain what happens during redox reactions.
10. Write the overall chemical equation for cellular respiration.
11. Identify the location where each step of cellular respiration occurs in the cell.

Learning Objectives (a.k.a. Study Guide)

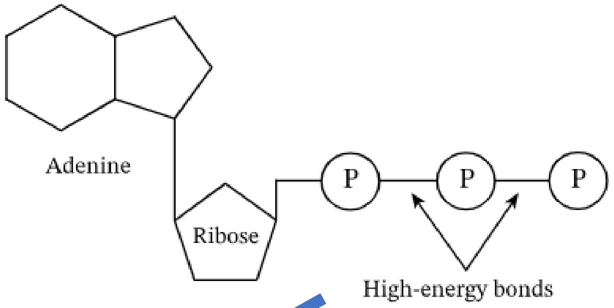
By the end of this lesson, students will be able to:

12. Differentiate between substrate-level phosphorylation & chemiosmosis.
13. List the number of carbons found in glucose & pyruvate.
14. Identify the starting materials & products created by each of these processes: glycolysis, pyruvate oxidation, the Citric Acid Cycle (a.k.a. Krebs Cycle), and the Electron Transport Chain (and oxidative phosphorylation).
15. Explain the function of electron carriers in cellular respiration.
16. Explain how electrons are used to build a proton gradient across the inner mitochondrial membrane.
17. Explain how the movement of protons is used to build ATP.
18. Describe the role of oxygen in the process of cellular respiration.
19. Describe the purpose of fermentation.
20. Explain how alcohol & lactic acid fermentation occur, including types of organisms using each pathway
21. Explain the role of feedback inhibition in regulating cellular respiration.

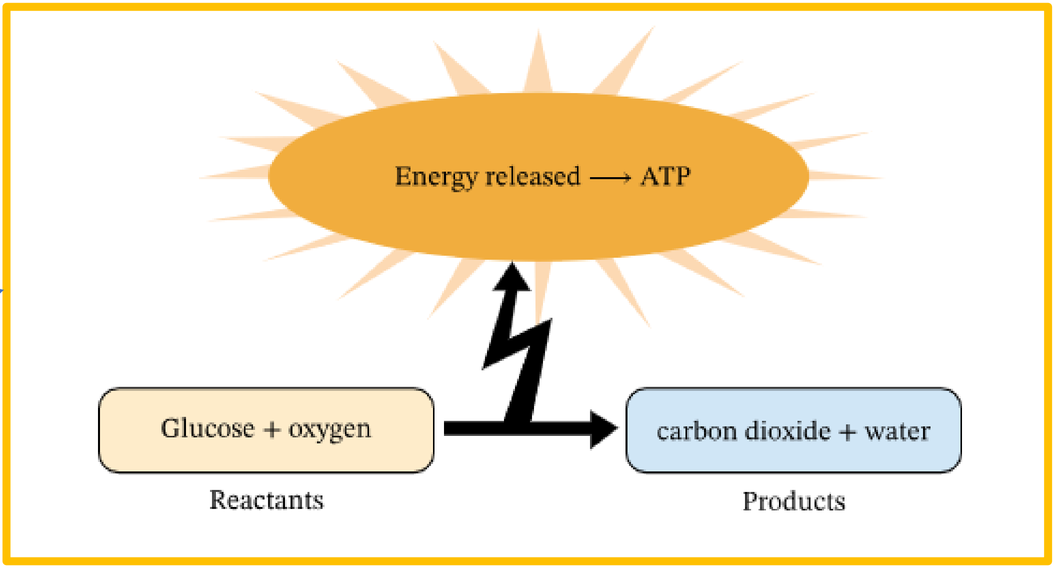


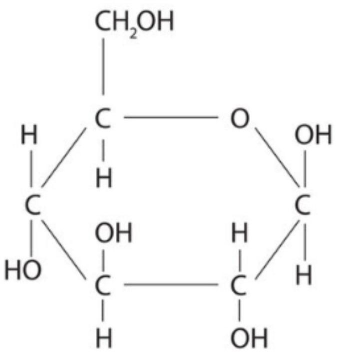
Your cells have taken up glucose. Now what?

In **cellular respiration** the energy is transferred to the bonds between the phosphate groups ATP.



ATP can be used by cells as a source of energy by breaking the high energy phosphate bonds.





The energy in glucose is stored in the chemical bonds between the atoms. It is not directly available for your cells to use.

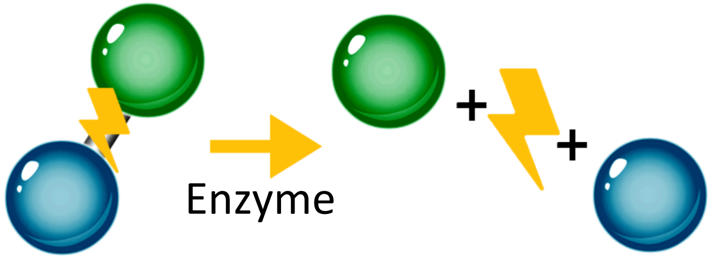
From Eating to Energy

On the most basic level, you need to eat to get the energy required to survive

- Energy is required for building **macromolecules** (like proteins & nucleic acids)
- Energy is required for life-sustaining processes like active transport

Foods store energy in their **chemical bonds**

- By breaking those chemical bonds, that energy is released into your cells
- Your cells can use that energy immediately or store it by forming new chemical bonds



Metabolism is the sum of <u>all the chemical reactions</u> that occur in your cells to keep you alive

Refresher: Metabolism Terminology

The chemical reactions of metabolism can be classified as catabolic or anabolic

Catabolic reactions *break* large polymers into smaller monomers

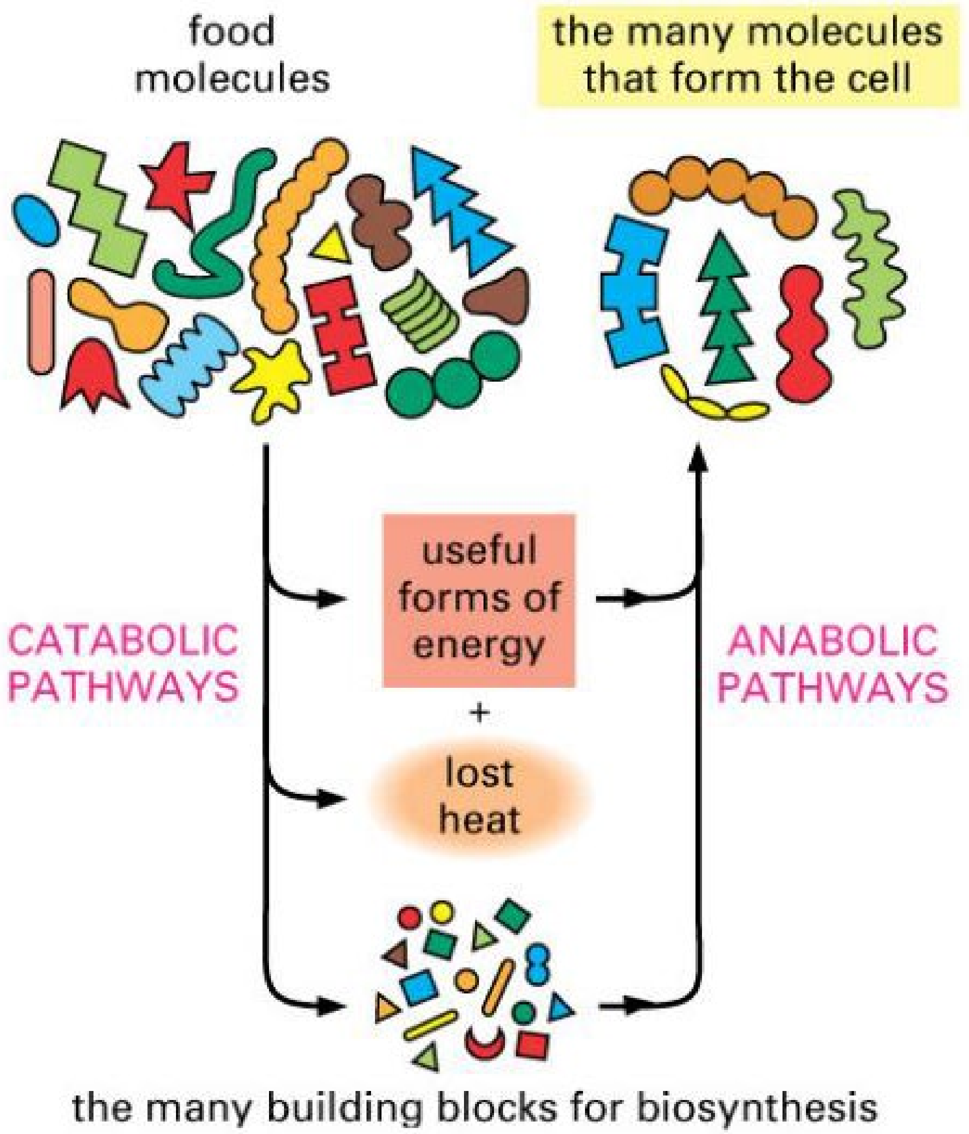
- These reactions <u>release</u> energy

Anabolic reactions *build* large polymers from smaller monomers

- These reactions <u>require</u> energy

Catabolic & anabolic reactions are paired

- The *monomers* made in catabolic reactions are used to build *polymers* in anabolic reactions

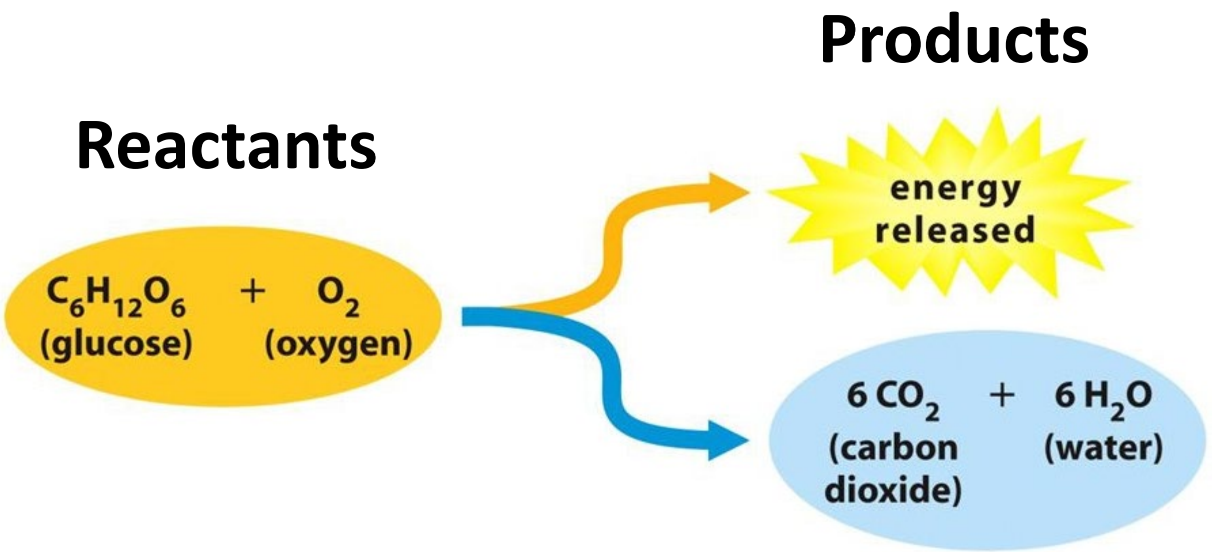


Metabolism Terminology

The chemical reactions of metabolism can also be classified as exergonic or endergonic

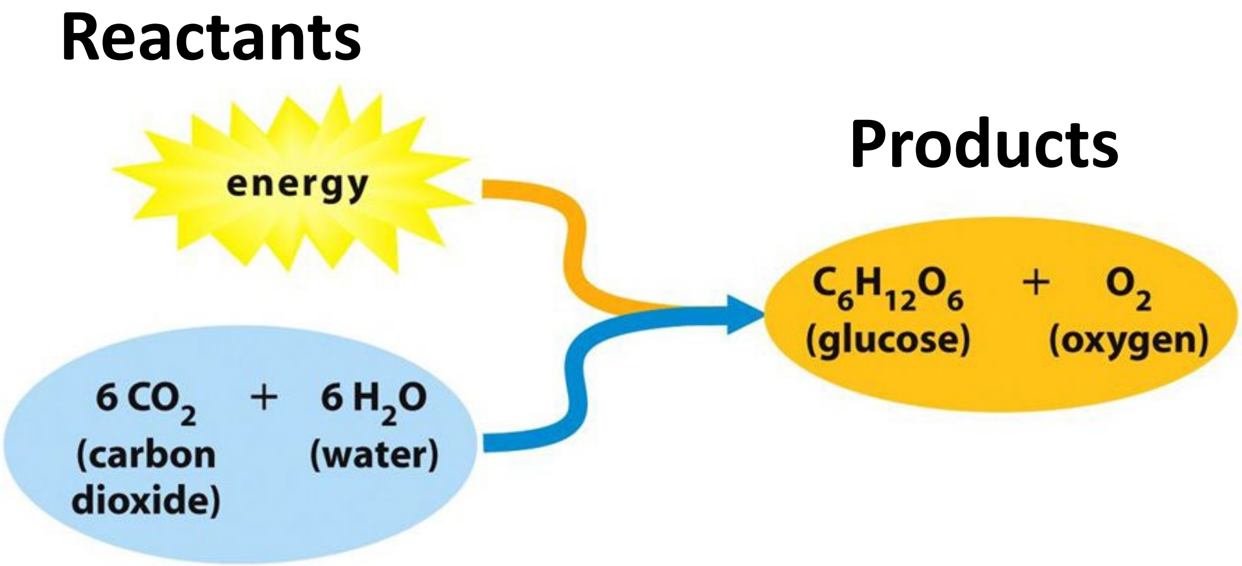
Exergonic reactions <u>release</u> energy

- This is because the *products* of the reactions have LESS energy than the *reactants*



Endergonic reactions <u>require</u> energy

- This is because the *products* of the reactions have MORE energy than the *reactants*

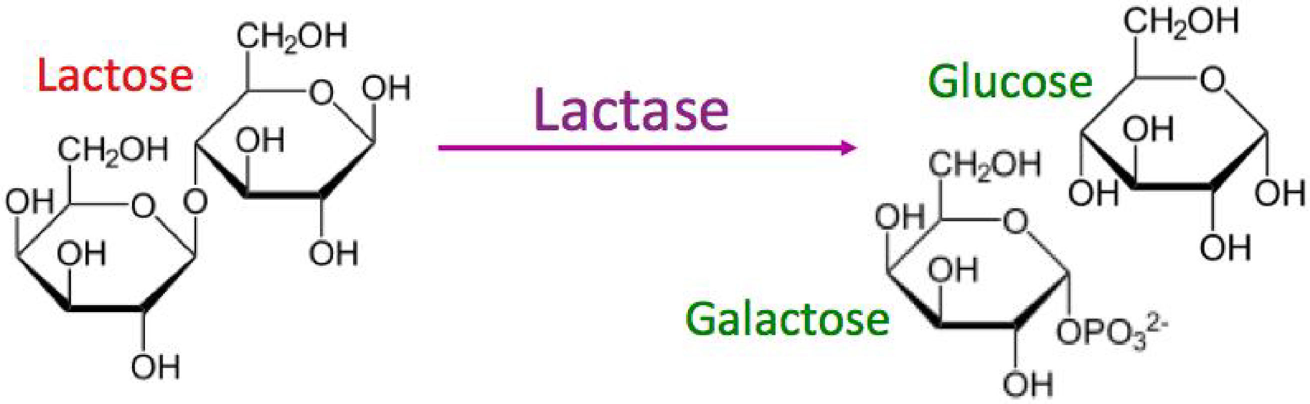


Exergonic & endergonic reactions are paired

- The energy *released* in exergonic reactions is used to *power* endergonic reactions

Enzymes

- Speed up the rate of chemical reactions
- Without enzymes, reactions would occur much too slowly for organism functioning
- Enzymes facilitate both anabolic and catabolic reactions
- Enzymes act on **substrates** (in this example, lactose) to make **products** (in this case glucose and galactose)



Let's Practice!

Anabolic reactions

RELEASE / REQUIRE

energy.

Catabolic reactions

RELEASE / REQUIRE

energy.

Endergonic reactions

RELEASE / REQUIRE

energy.

Exergonic reactions

RELEASE / REQUIRE

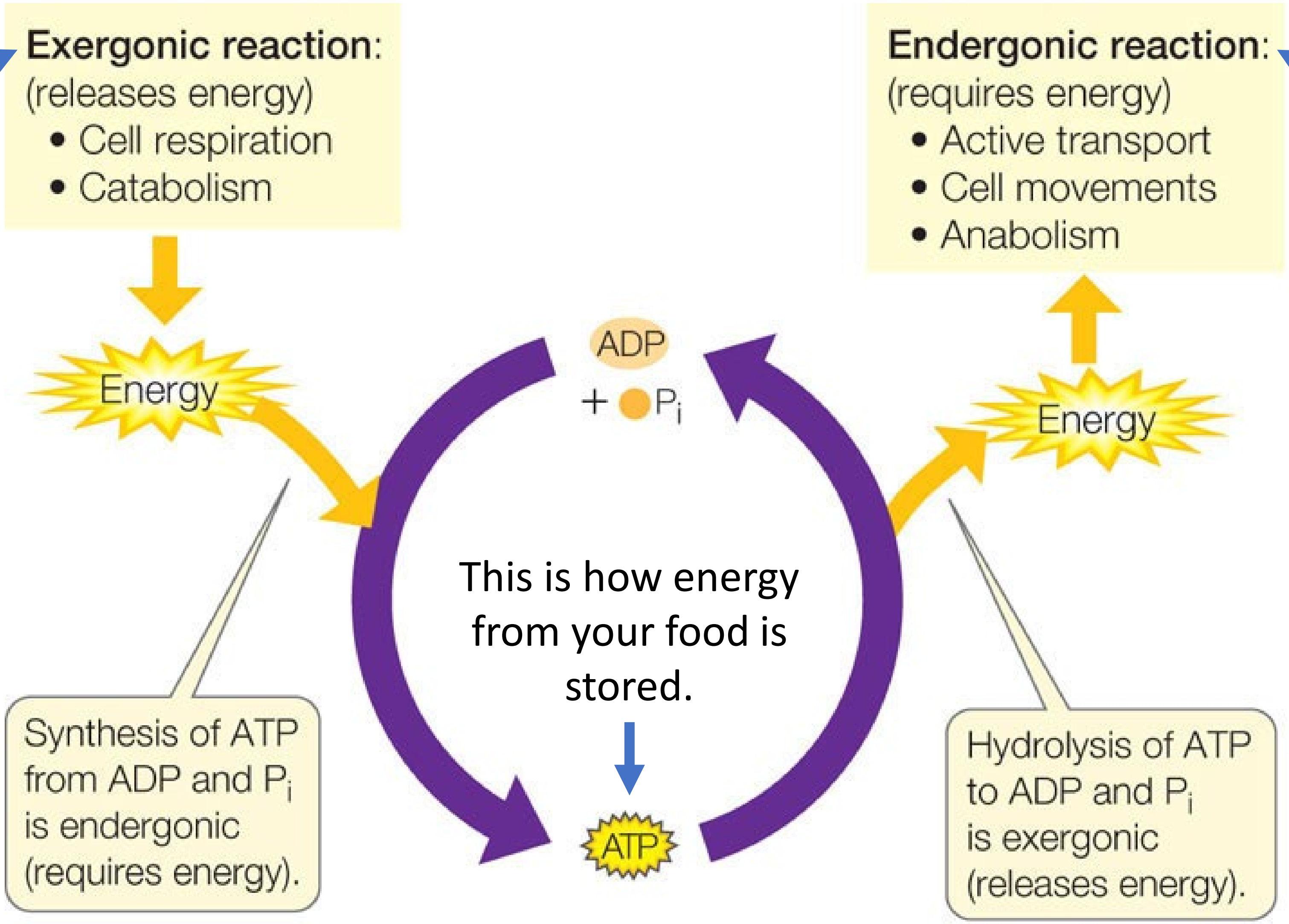
energy.

Based on energy requirements, **anabolic** reactions are the same as _______________ reactions.

Based on energy requirements, **catabolic** reactions are the same as _______________ reactions.

Metabolism: An Overview

These are the reactions that happen when you **eat food** & break it down in your body.



This is how energy from your food is stored.

These are the reactions that are necessary for organism functioning.

ATP & ADP

ATP & ADP are the main forms of chemical energy in a cell

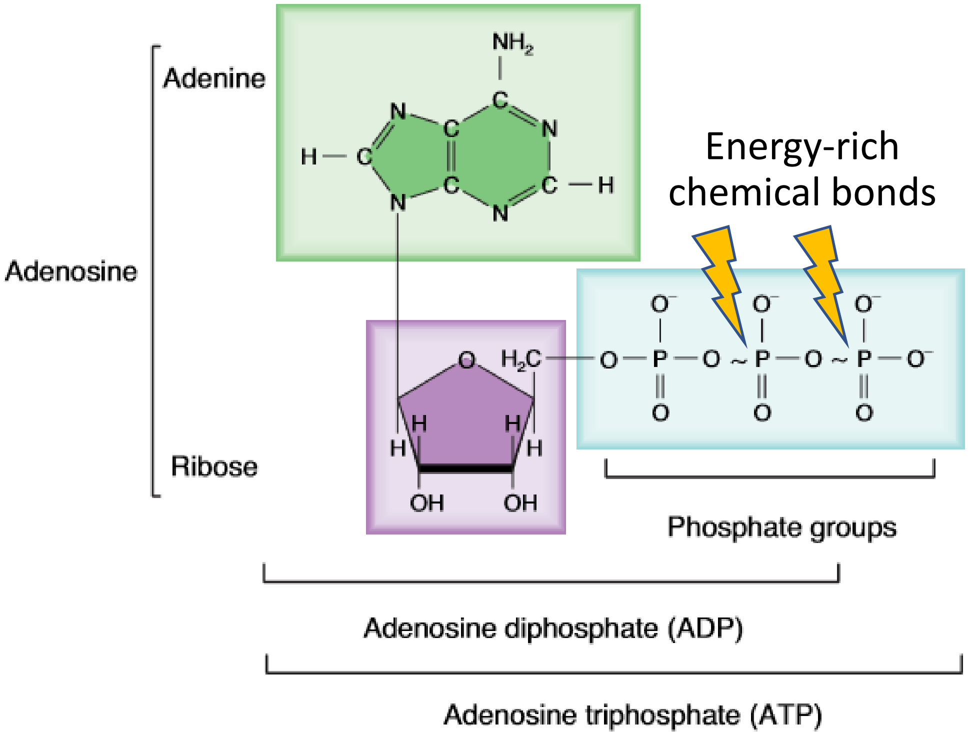
- Energy is stored in the energy-rich chemical bonds between their phosphate groups

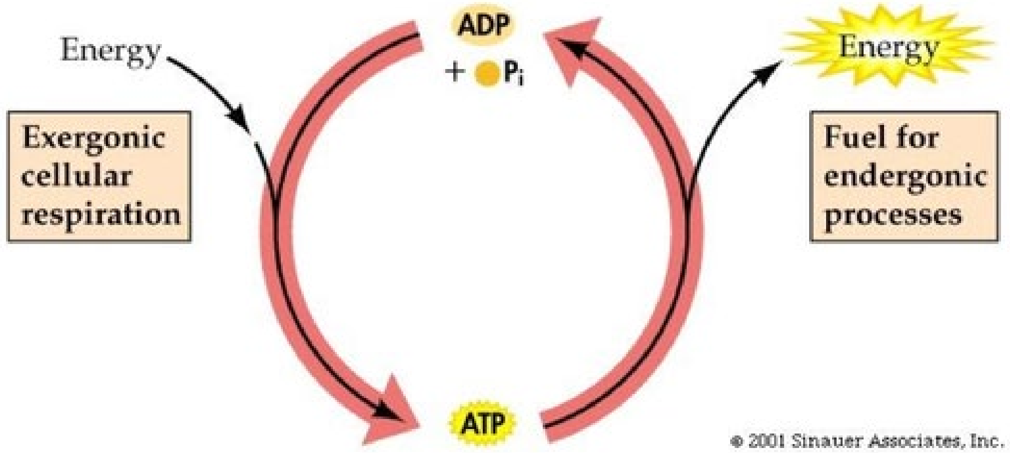
ATP = adenosine <u>**tri**</u>phosphate

- ATP has 3 phosphate groups, so it has A LOT of energy
- ATP is made when the cell has **extra** energy

ADP = adenosine <u>**di**</u>phosphate

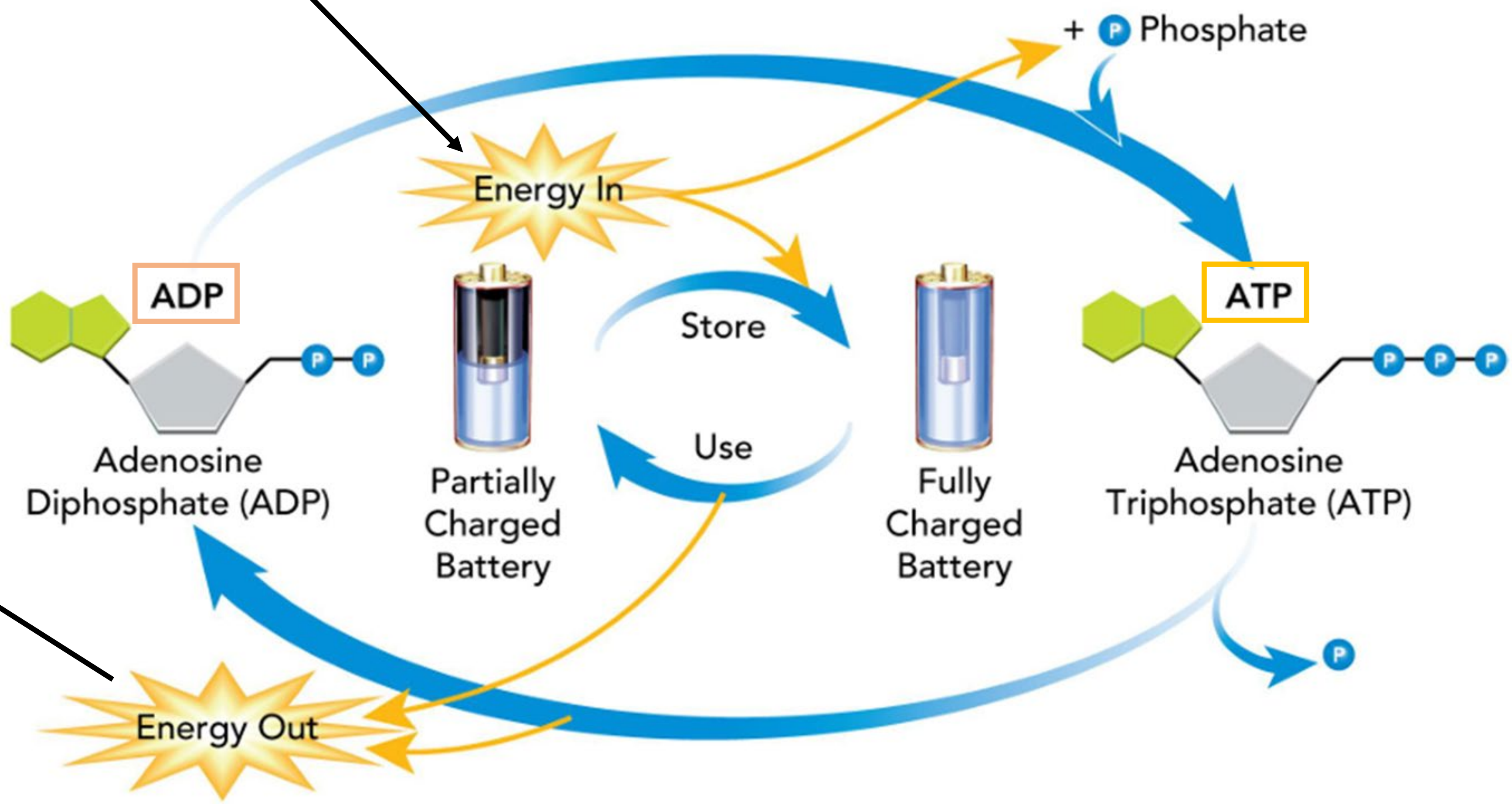
- ADP has 2 phosphate groups, so it has *some* energy
- ADP is made when the cell **uses** the energy in ATP (by removing one of its phosphate groups)





This energy comes from catabolic (exergonic) chemical reactions.

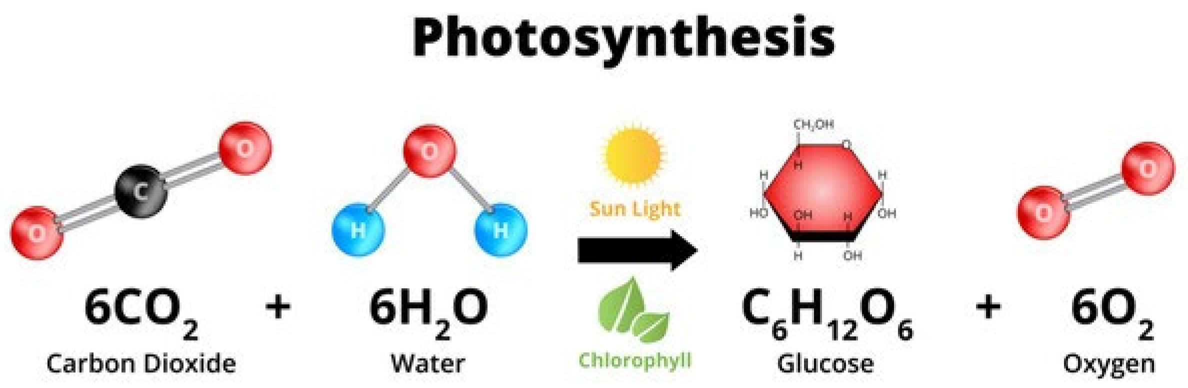
Example: digesting food



This energy goes into anabolic (endergonic) chemical reactions.

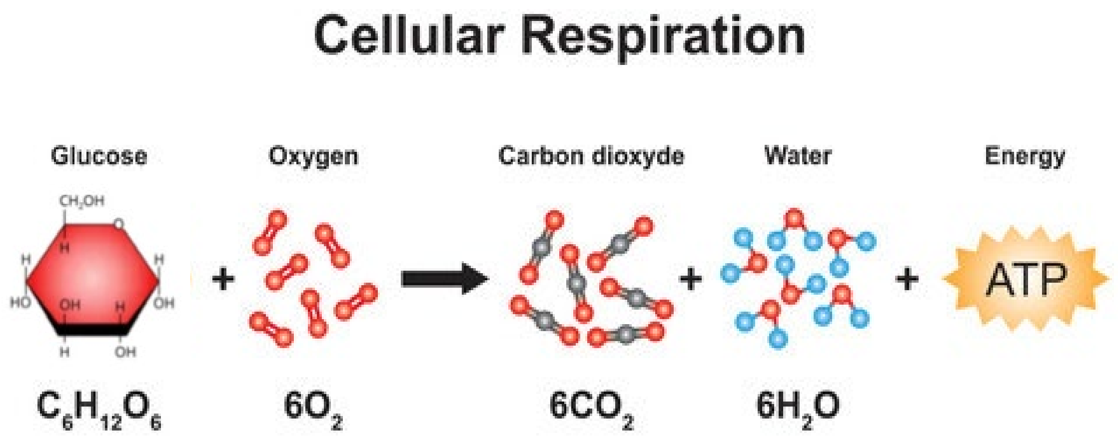
Example: building new proteins

Let's Practice!



- Is this catabolic or anabolic?
- Is this endergonic or exergonic?

How can you tell?



- Is this catabolic or anabolic?
- Is this endergonic or exergonic?

How can you tell?

Oxidation & Reduction

In metabolism, chemical bonds are broken & built

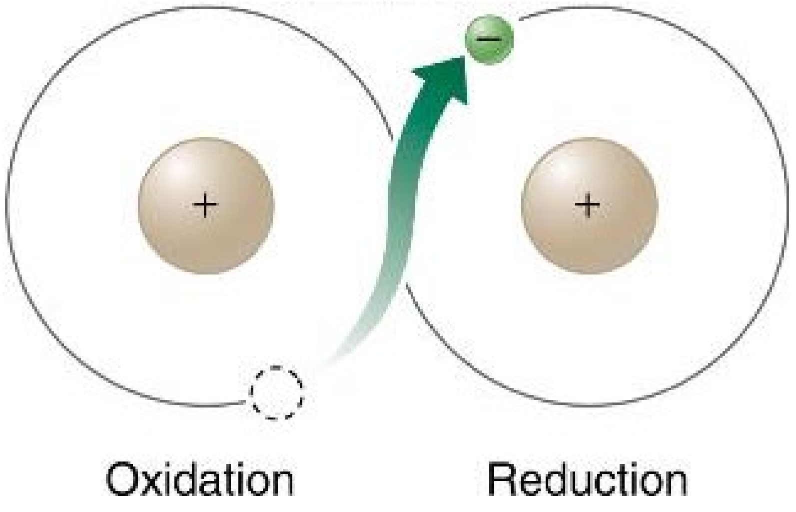
- Chemical bonds are made of electrons

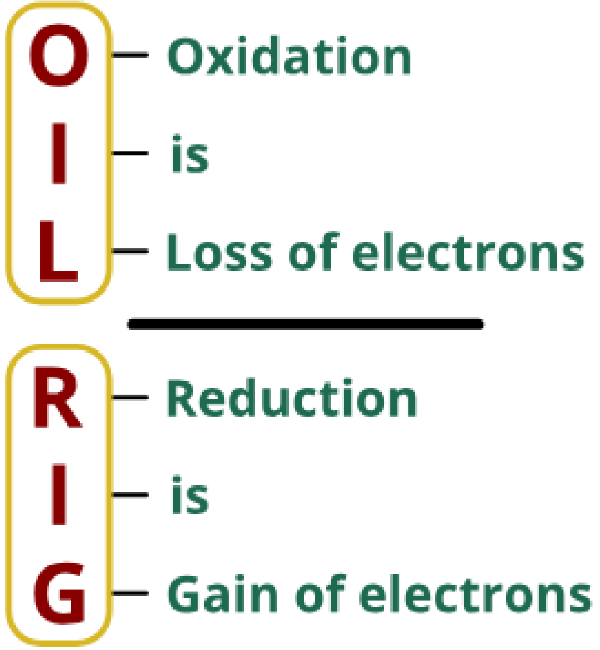
When a molecule loses electrons, it becomes **oxidized**

- Often, this loss is seen as the breaking of a chemical bond
- Oxidation can also generate a positively-charged ion

When a molecule gains electrons, it becomes **reduced**

- Often, this is seen as a the building of a new chemical bond
- Reduction can also generate a negatively-charged ion





Let's Practice:
NAD^+ & NADH

The **oxidized** form of this molecule is NAD^+.

Has the oxidized form gained or lost electrons?

$$NAD^+ + H^+ + 2e^- \rightleftharpoons NADH$$

The **reduced** form of this molecule is NADH.

Has the reduced form gained or lost electrons?

Cellular Respiration

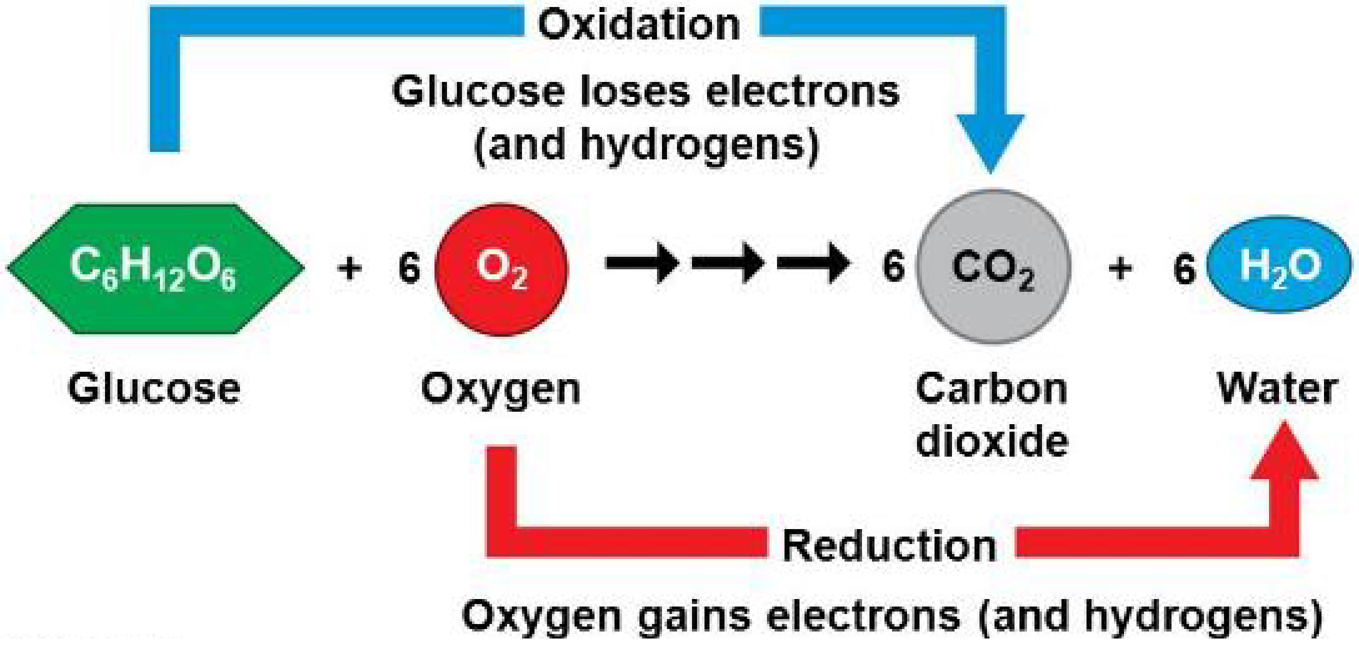
Cellular respiration is the process your cells use to generate energy from glucose

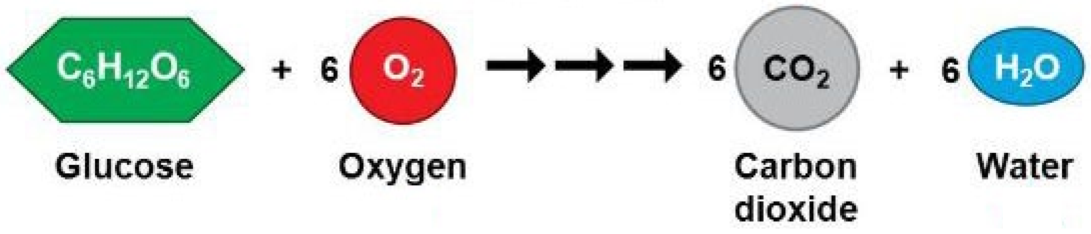
When glucose is oxidized, the energy stored in its chemical bonds is released

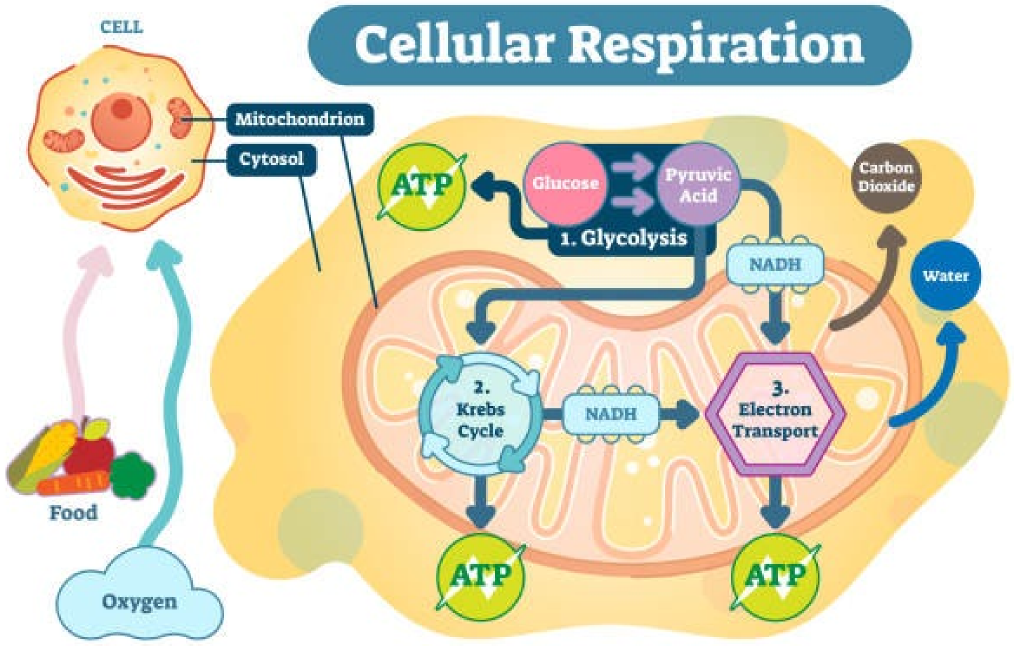
- This energy is then captured in the chemical bonds of newly-formed **ATP** molecules

Ultimately, energy-poor electrons are given to oxygen

- This means oxygen is reduced



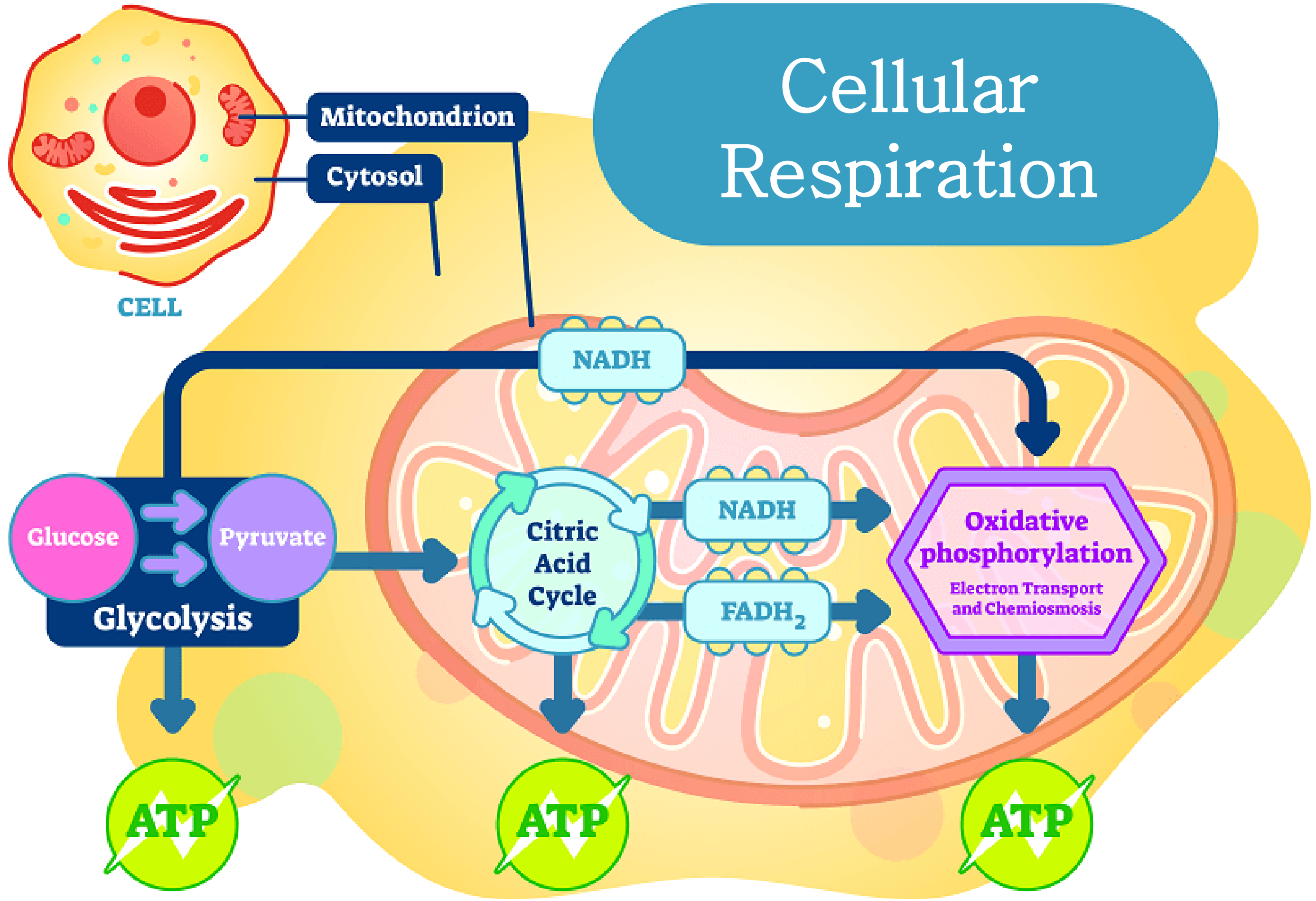




This version of the chemical equation for **cellular respiration** makes it look very simple.

In reality, cellular respiration requires ***several*** different processes that occur in ***multiple*** locations in the cell and involves **many** enzyme-mediated steps (not pictured).

How Do You Make ATP from Glucose?



Step 1: glycolysis

- Split the glucose into pyruvate molecules

Step 2: pyruvate oxidation

- Move the pyruvates into the mitochondria & process them

Step 3: the Citric Acid (Krebs) Cycle

- Remove energy-rich electrons from the processed pyruvates

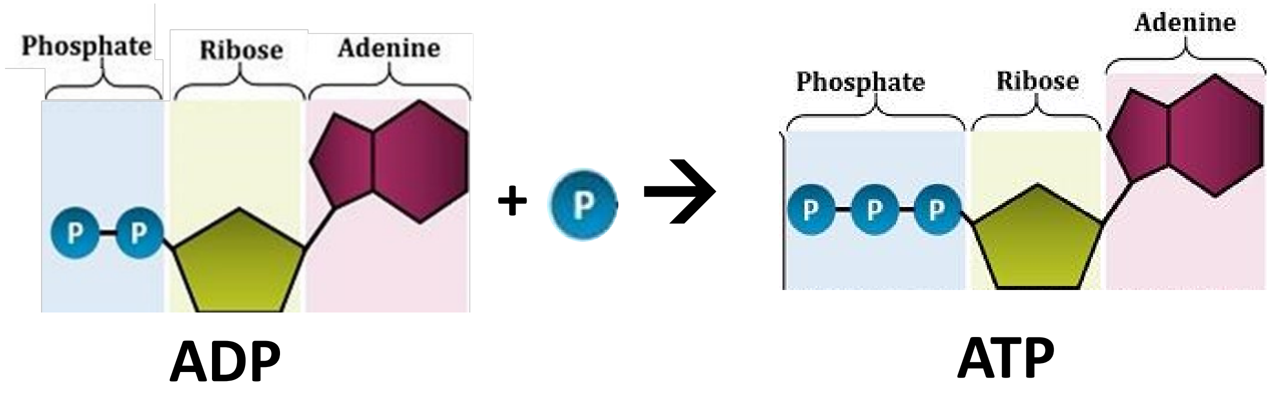
Step 4: oxidative phosphorylation

- Use the energy from those high-energy electrons to build ATP

Building ATP

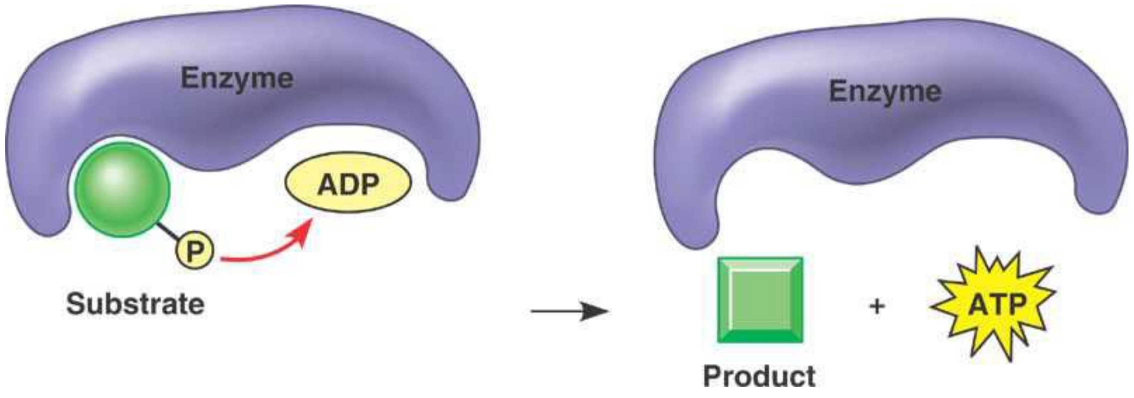
ATP is built by **phosphorylating** ADP

- This means a new chemical bond is built between ADP & a phosphate group
- The energy of ATP is stored in that chemical bond



In glycolysis & the Citric Acid Cycle, ATP synthesis occurs using **substrate-level phosphorylation**

- A phosphate group is removed from one molecule (the substrate)
- It is then directly attached to ADP

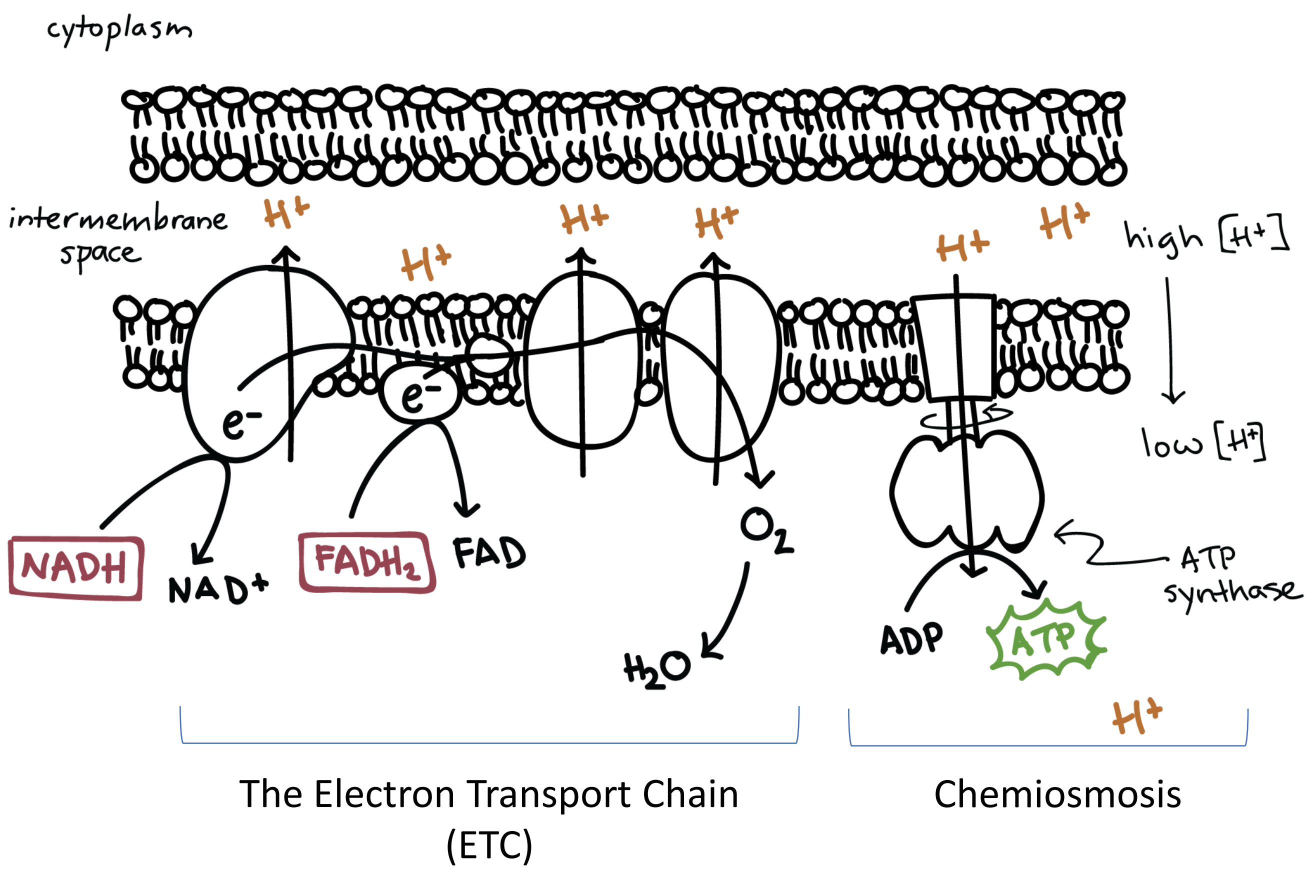


Building ATP

ATP can also be made using **oxidative phosphorylation**

Oxidative phosphorylation uses the Electron Transport Chain (ETC) & Chemiosmosis

- First, the ETC creates a proton (H^+) **concentration gradient** across the inner mitochondrial membrane
- Then, ATP synthase uses the energy of that gradient to build ATP in a process called chemiosmosis



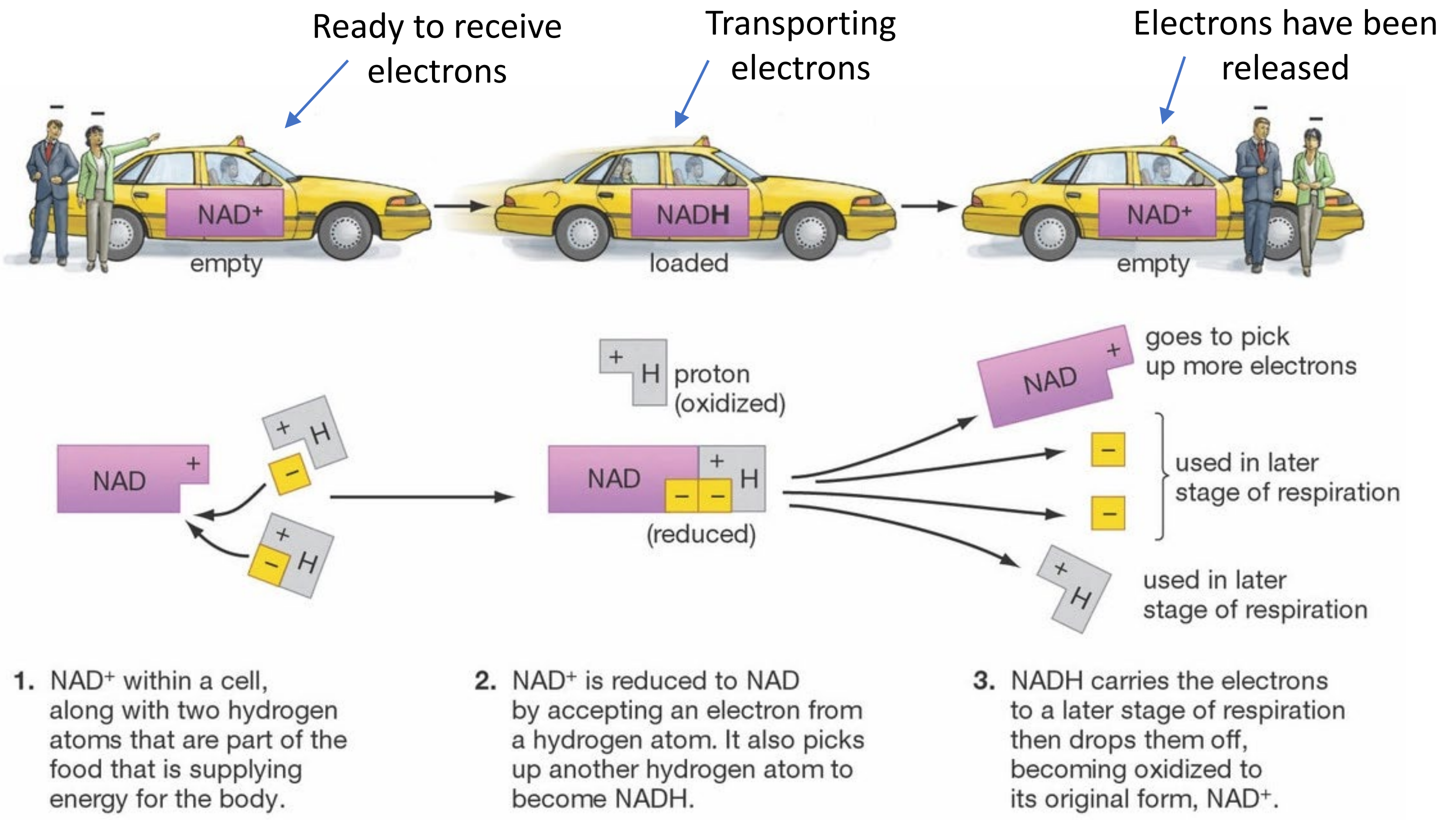
Electron Carriers

The Electron Transport Chain (ETC) uses energy from **electron carriers** to create the H^+ concentration gradient

Electron carriers "capture" the energy from one chemical reaction & transport it to a different part of the cell to be used

- Electron carriers like the Uber for electrons

In cellular respiration, the primary electron carriers are NAD^+ / NADH & FAD / $FADH_2$



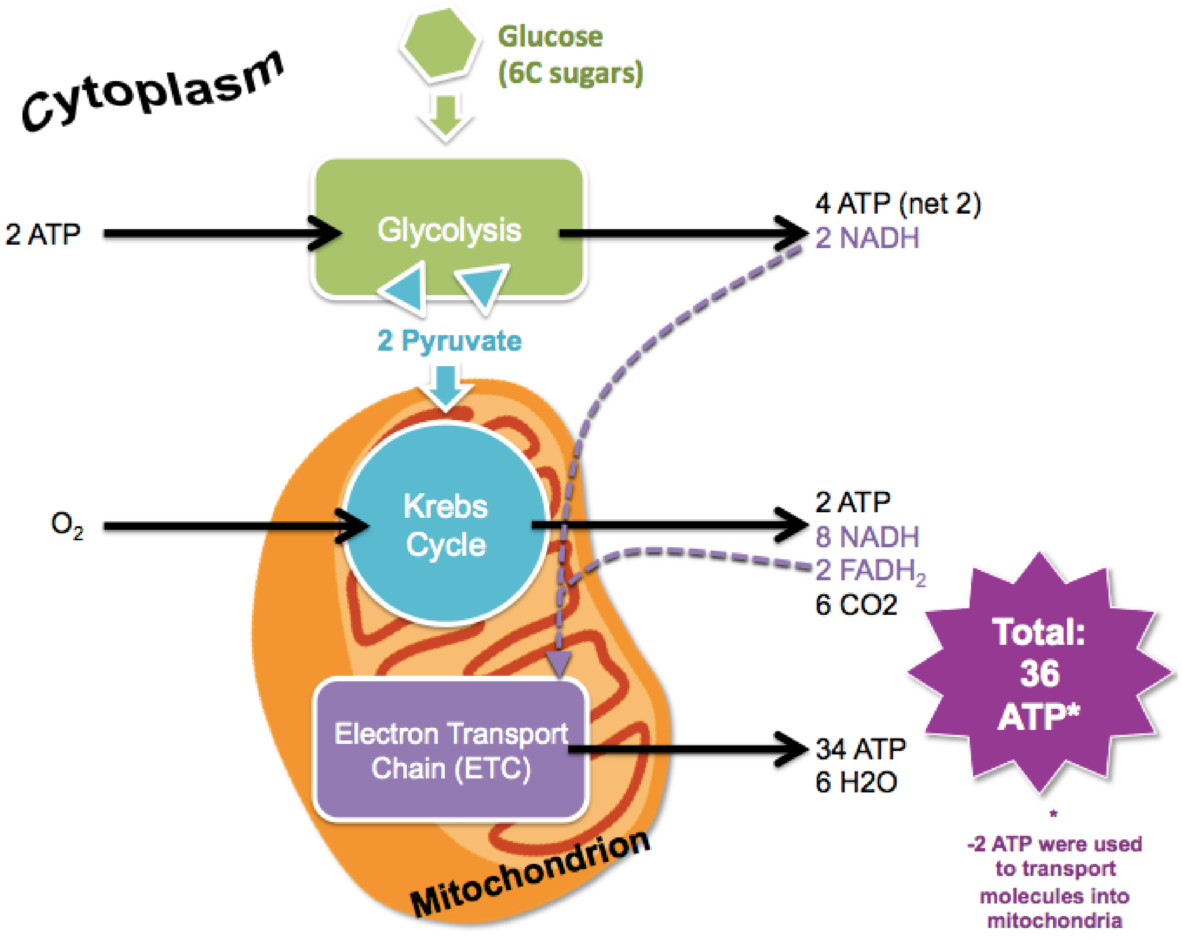
Cellular Respiration: The Big Picture

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O + \sim 36\ ATP$$

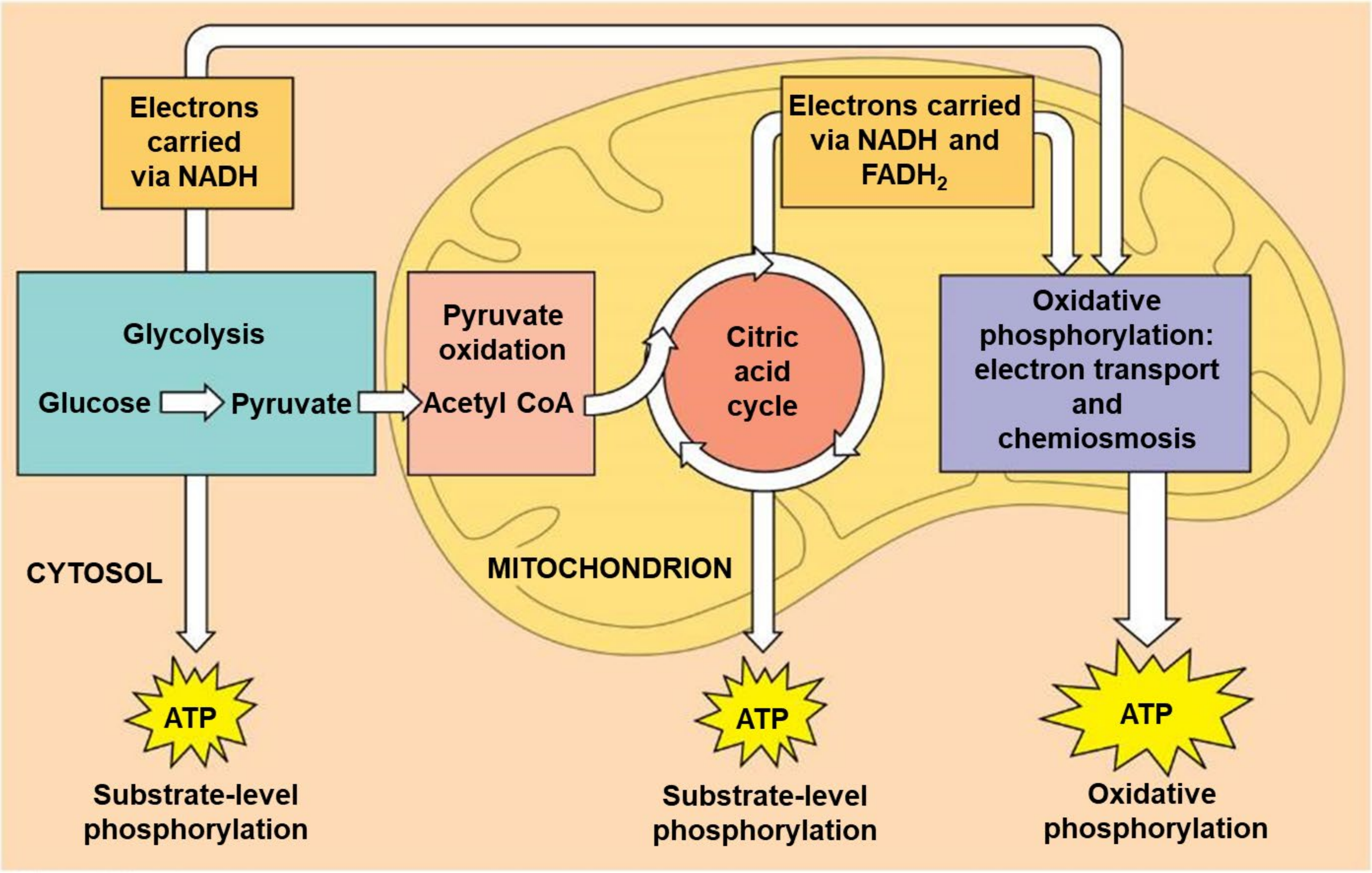
Energy-rich glucose ($C_6H_{12}O_6$) is broken into energy-poor carbon dioxide (CO_2)

Two forms of energy are created: ATP & energized electron carriers (NADH & $FADH_2$)

Ultimately, the energy of electron carriers is also transformed into ATP using the Electron Transport Chain



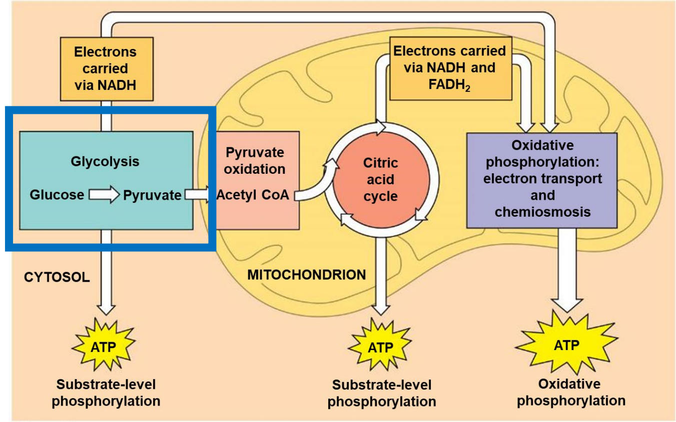
Note: Krebs Cycle and Citric Acid Cycle are the same thing.



For each process, know these things:

- What does it **start** with?
- What does it **end** with?
- **Where** does it occur?
- Does it build **ATP**?
- Does it build energized **electron carriers**?

Step 1: Glycolysis

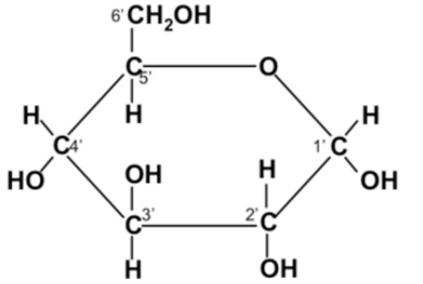


Glycolysis is the initial glucose-breaking process

- Many chemical reactions break its chemical bonds, rearrange its elements, and harvest *some* of its energy

Starting materials: glucose ($C_6H_{12}O_6$) + 2 ATP + 2 NAD^+

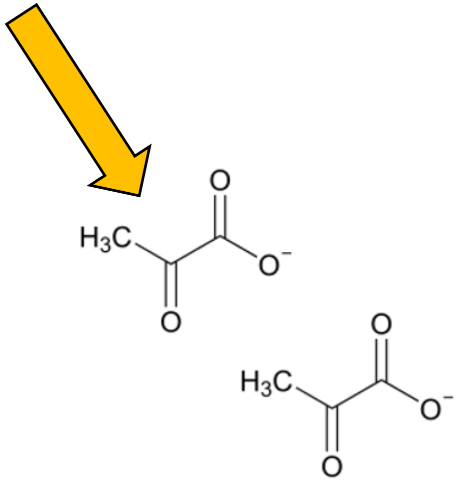
Oxygen (O_2) is NOT required for this process!



Glucose

Ending materials: 2 pyruvate ($C_3H_4O_3$) + 2 (*net*) ATP + 2 NADH

- Technically, 4 ATP are made, but 2 ATP are required, so the cell only *gains* 2 ATP
- This ATP is made through **substrate-level phosphorylation**

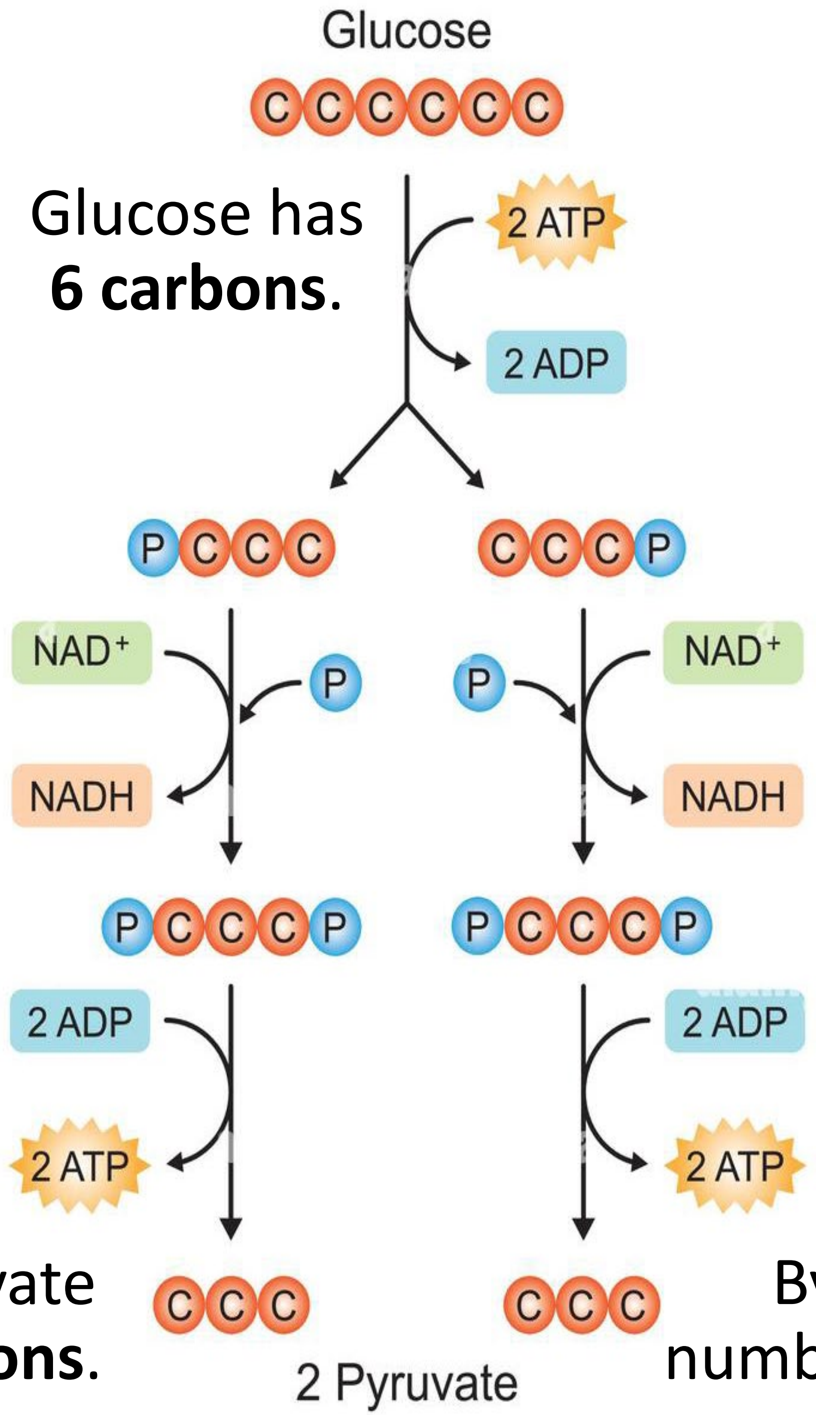


Location: the cytoplasm

2 Pyruvate

Glycolysis: A Closer Look

Glucose has **6 carbons**.



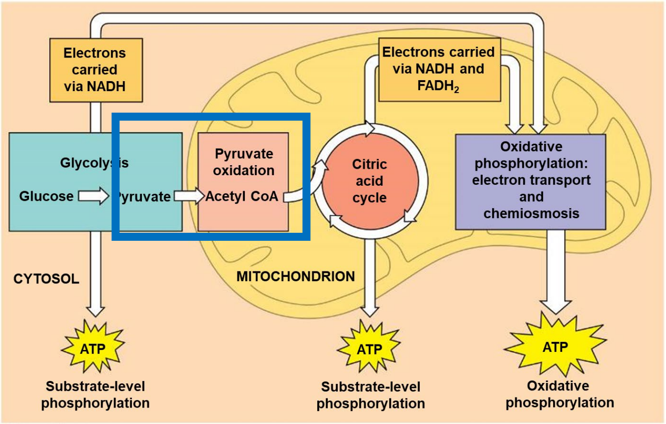
Each pyruvate has **3 carbons**.

By making **two pyruvate**, the number of carbons does not change.

Remember!

Glycolysis generates two forms of energy: ATP & NADH

Step 2: Pyruvate Oxidation



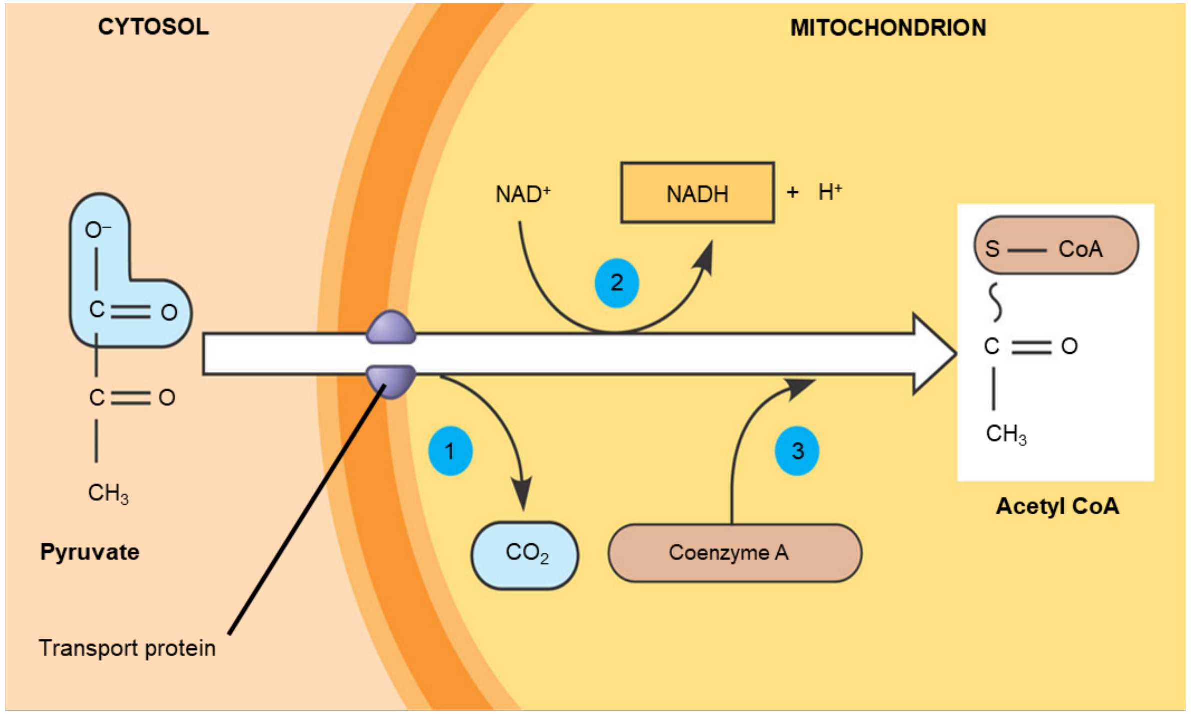
Each 3-carbon pyruvate still has A LOT of energy

- The pyruvates are transported into the mitochondria so that energy can be harvested

Starting materials: 2 pyruvate + 2 NAD^+ + 2 Coenzyme A complexes

Ending materials: 2 acetyl coenzyme A (acetyl CoA) + 2 CO_2 + 2 NADH

Location: the mitochondrial **matrix** (a.k.a. its center)



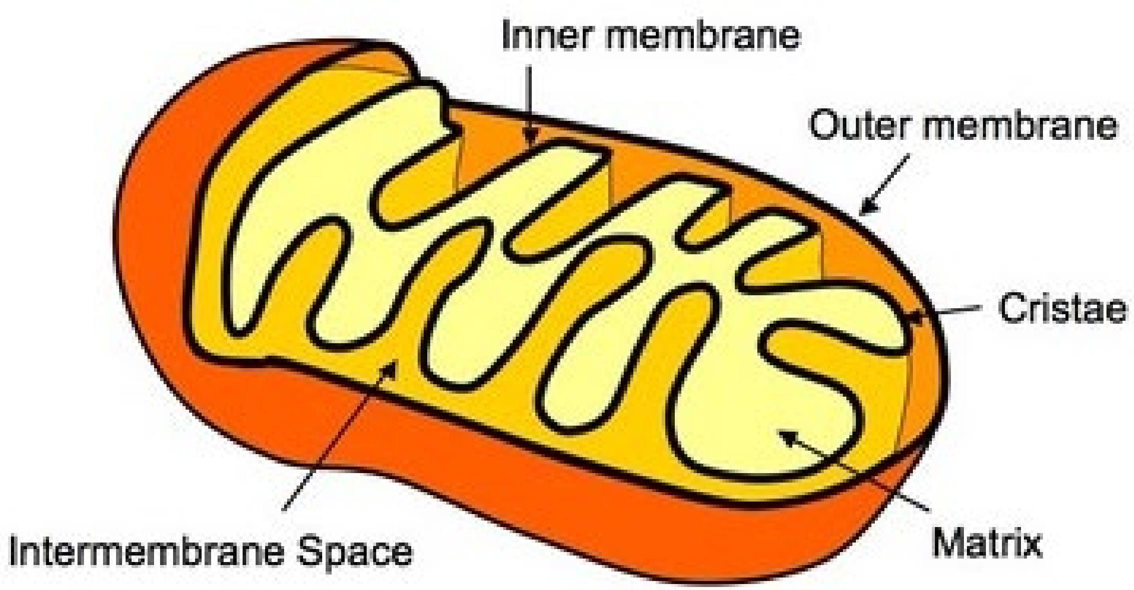
Mitochondrial Structures

The outer mitochondrial membrane divides it from the cytoplasm

The inner membrane is the location of the Electron Transport Chain (ETC)

The **intermembrane space** (between the membranes) is where the ETC pumps H^+ ions into

- As H^+ re-enter the matrix through the ATP Synthase enzyme, ATP is built



The **matrix** is the central fluid-filled area of the mitochondria

- It is the site of the Citric Acid (Krebs) Cycle

Step 3: The Citric Acid (Krebs) Cycle

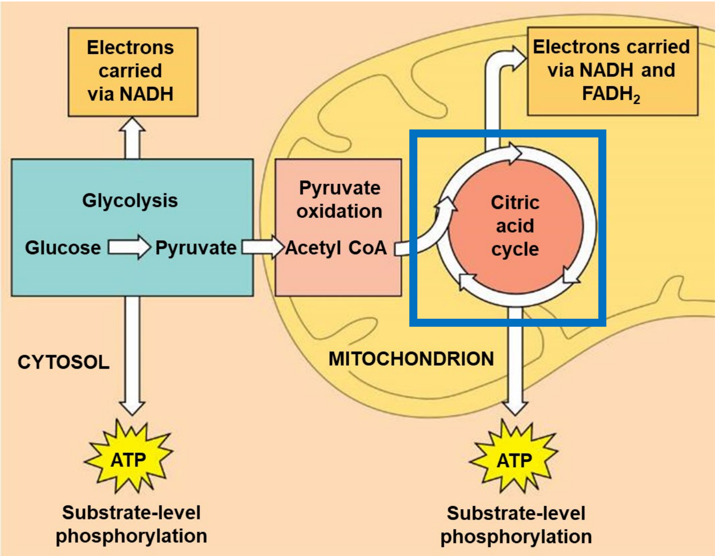
The Citric Acid Cycle harvests all the remaining energy in Acetyl Coenzyme A (Acetyl CoA)

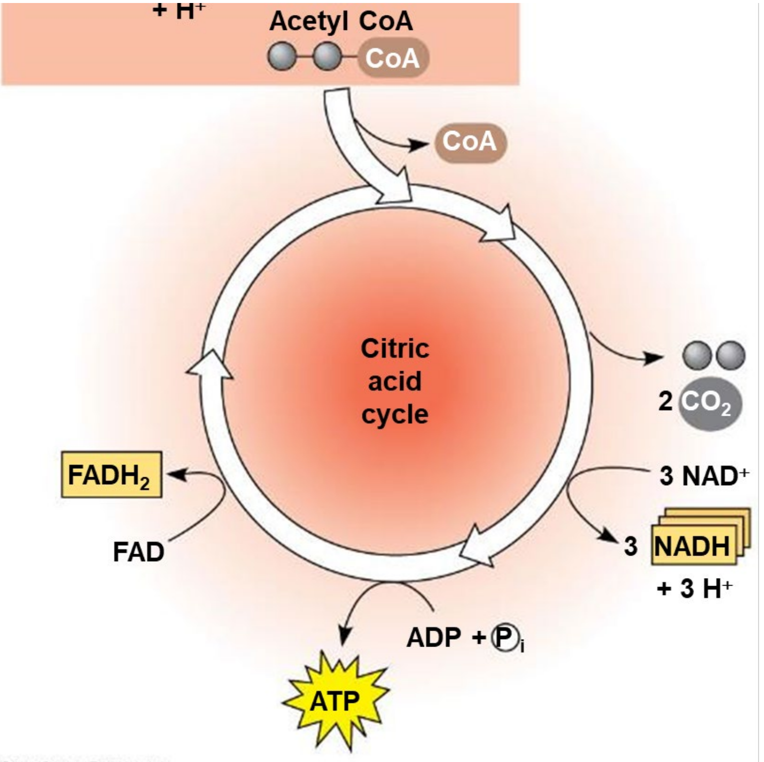
- REMEMBER: one glucose molecule makes two acetyl CoA's!

Starting materials: 2 acetyl CoA + 6 NAD^+ + 2 FAD (+ oxaloacetate)

Ending materials: oxaloacetate + 4 CO_2 + 2 ATP + 6 NADH + 2 $FADH_2$

Location: the mitochondrial **matrix** (a.k.a. its center)





The Citric Acid Cycle: A Closer Look

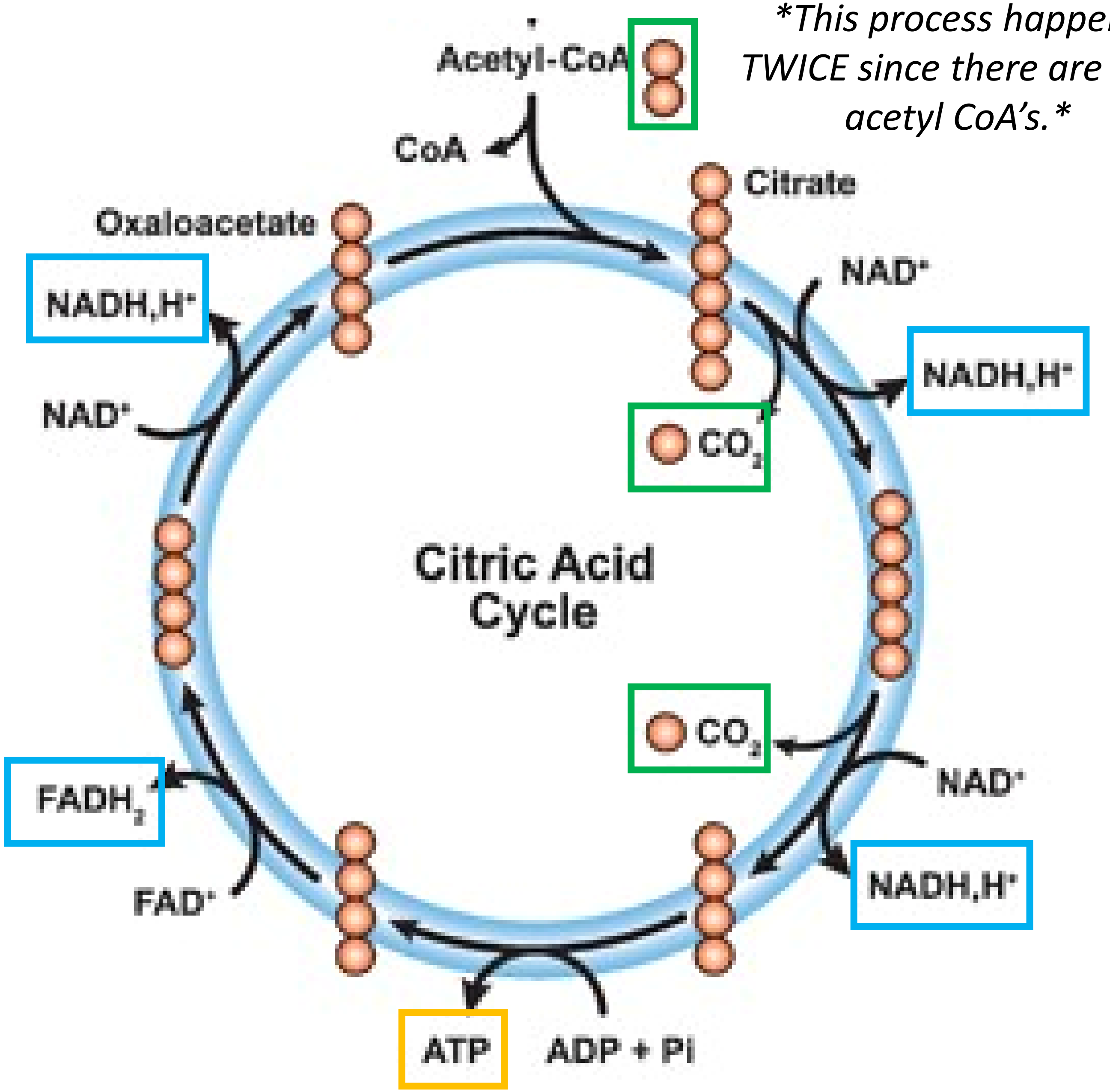
The Citric Acid Cycle begins with a **4-carbon** molecule (oxaloacetate).

2 carbons are added when acetyl-CoA enters the cycle.

Those **2 carbons** leave the cycle as CO_2 molecules, generating **NADH.**

As the remaining **4 carbons** rearrange their structure, **ATP** & more energized **electron carriers** are made.

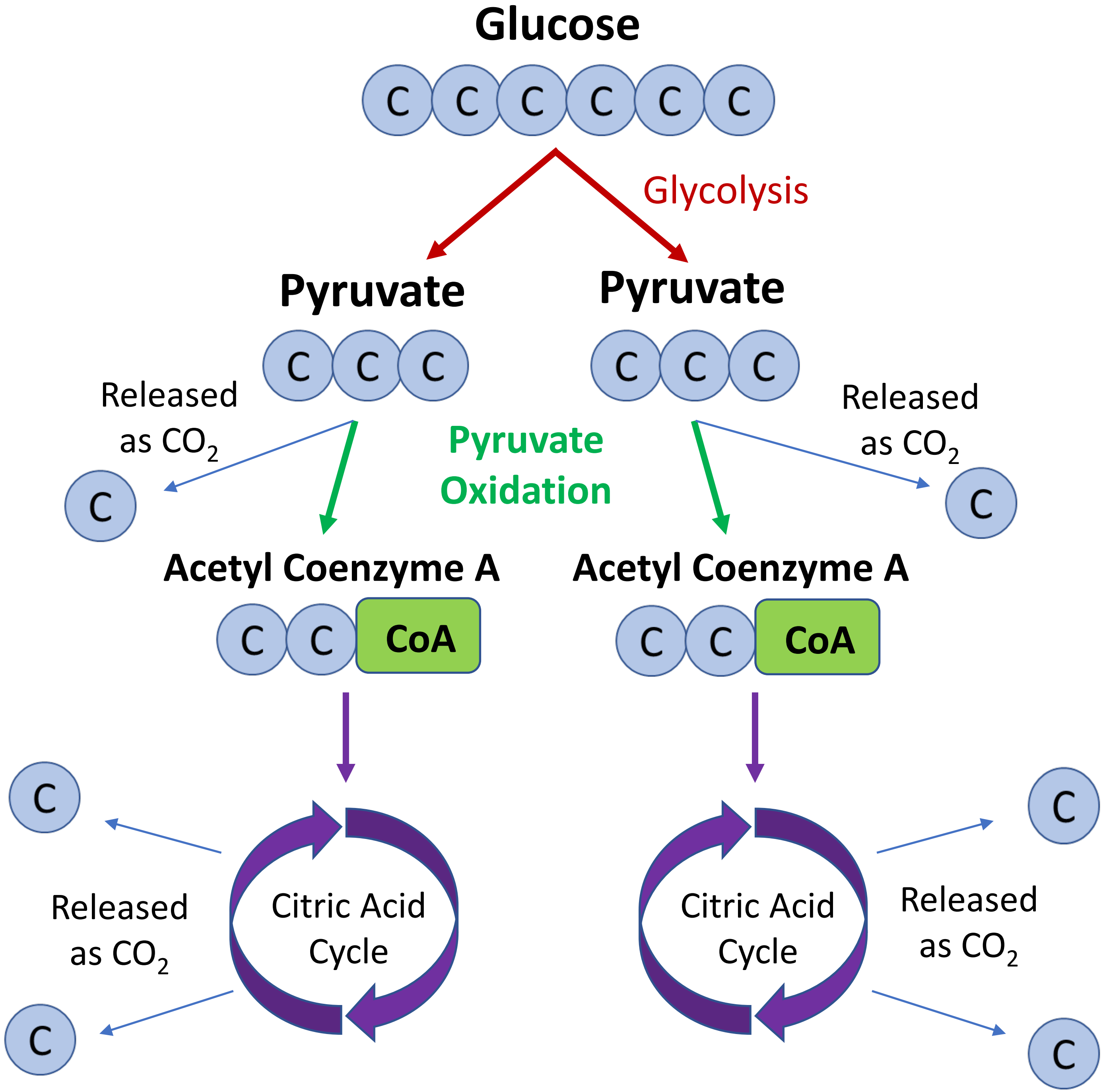
This process happens TWICE since there are two acetyl CoA's.



So, Where's the Glucose?

Glucose has 6 carbons

By the end of the Citric Acid Cycle, all 6 carbons have been separated from one another & released as **CO_2** (carbon dioxide)



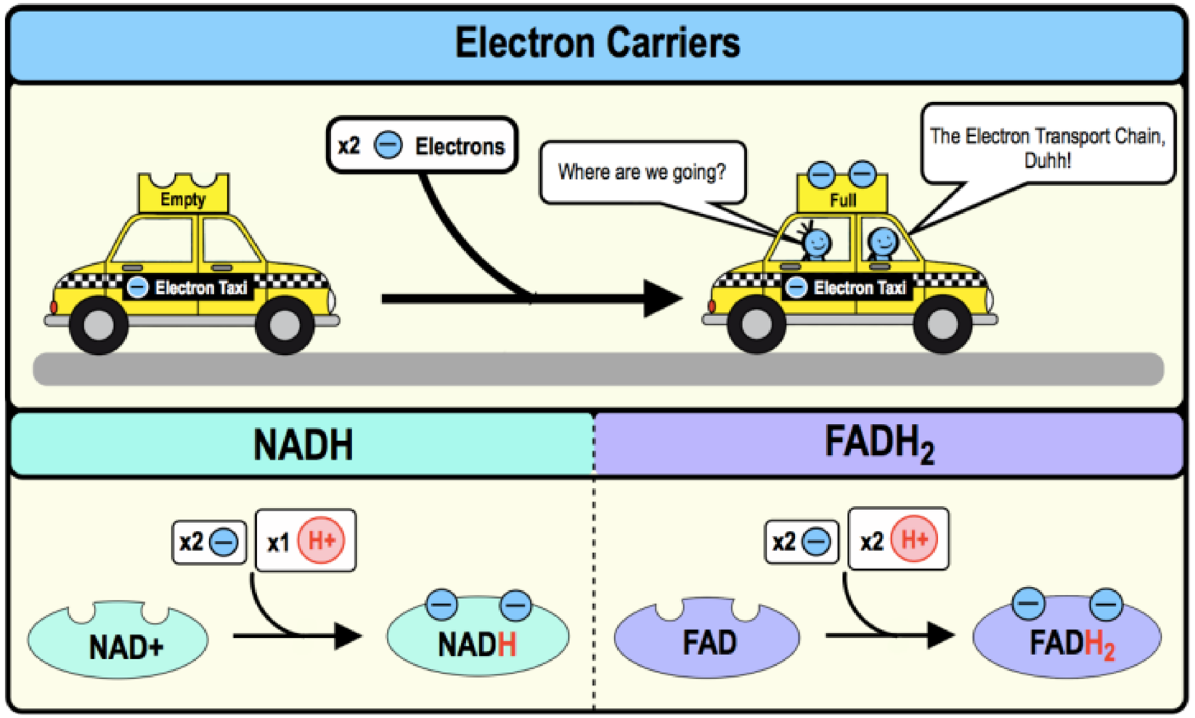
And Where's the Energy?

At the end of the Citric Acid Cycle, only 4 ATP have been made

- 2 (net) ATP from glycolysis
- 2 ATP from the Citric Acid Cycle

The rest of the energy is stored in **electron carriers**

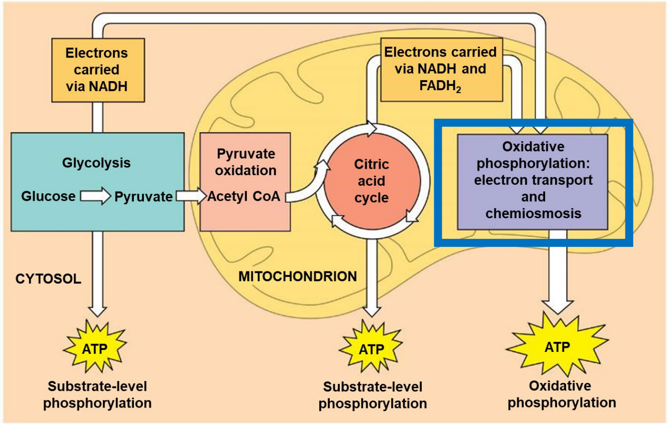
- 10 NADH (from glycolysis, pyruvate oxidation, & the Citric Acid Cycle)
- 2 $FADH_2$ (from the Citric Acid Cycle)

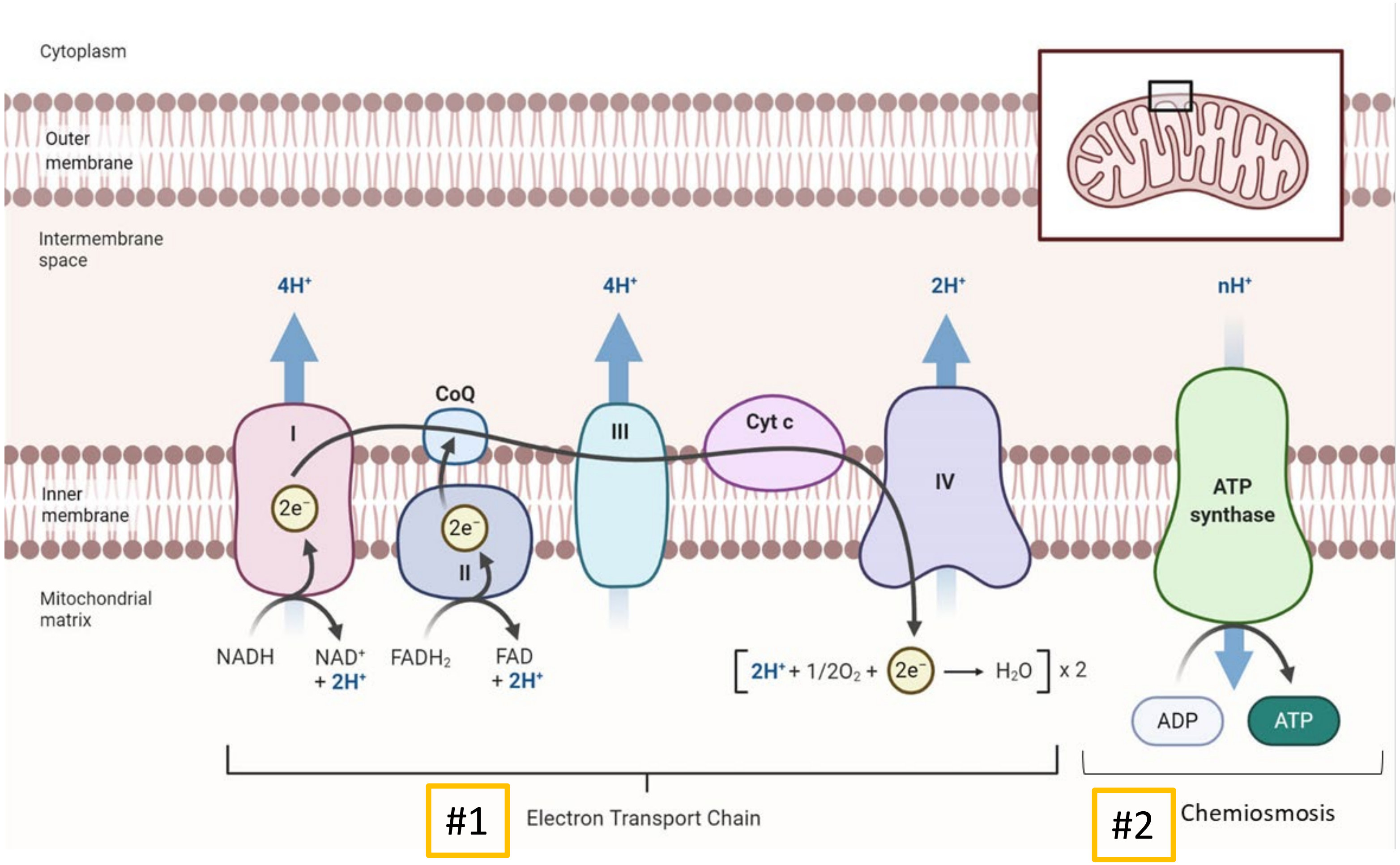


Oxidative phosphorylation transforms the energy in those electron carriers into ATP

Oxidative Phosphorylation

Oxidative phosphorylation builds *most* of the ATP generated through cellular respiration.





First, the Electron Transport Chain (ETC) creates an H^+ concentration gradient across the inner mitochondrial membrane.

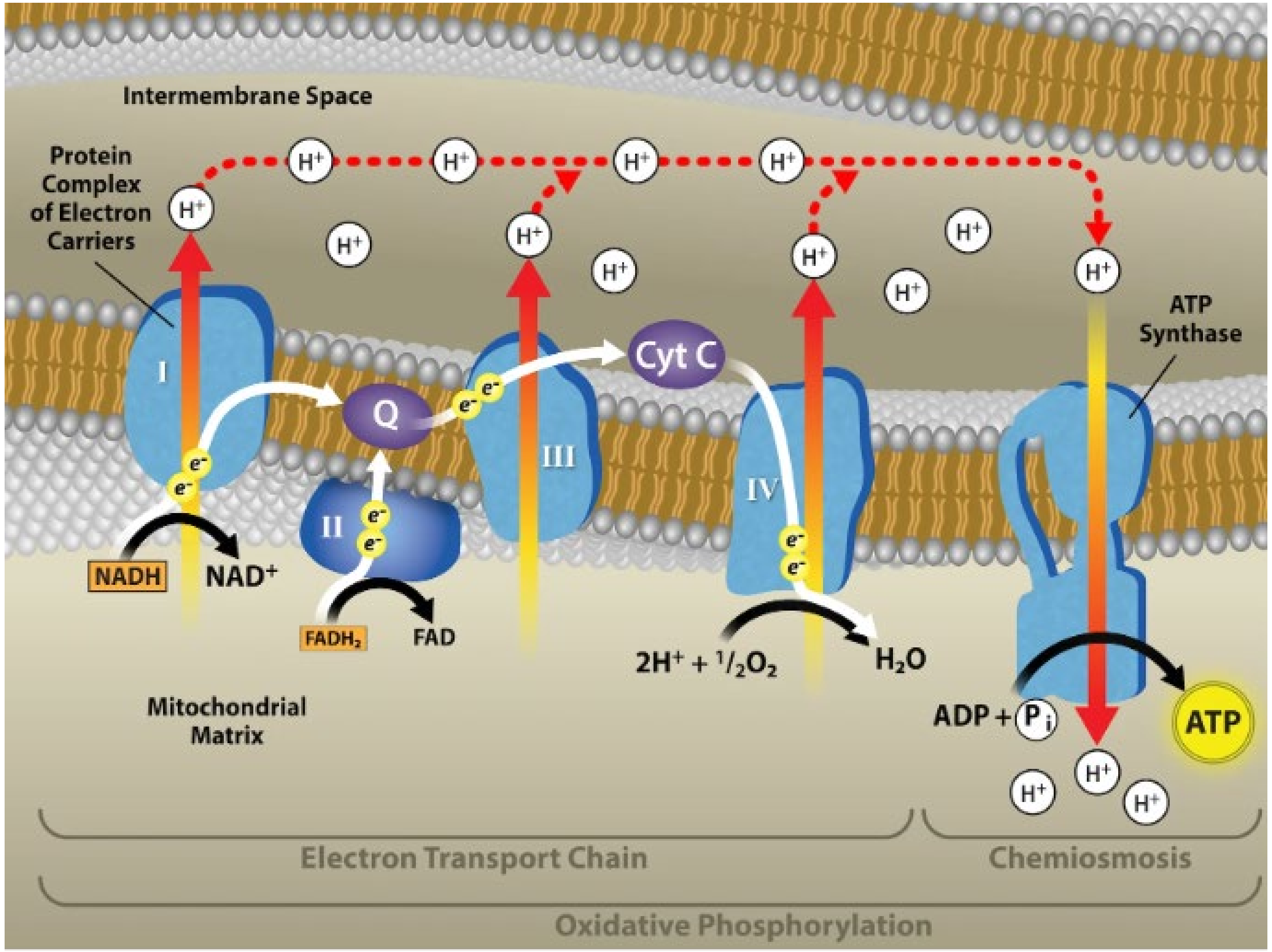
Then, during chemiosmosis, ATP synthase uses that gradient to build ATP.

The Electron Transport Chain (ETC)

Electrons (from NADH & $FADH_2$) travel through each of the ETC protein complexes.

Their energy is used by the proteins to pump H^+ ions (a.k.a. protons) into the intermembrane space.

By the end of the ETC, the electrons no longer store any energy & are combined with O_2.



Chemiosmosis

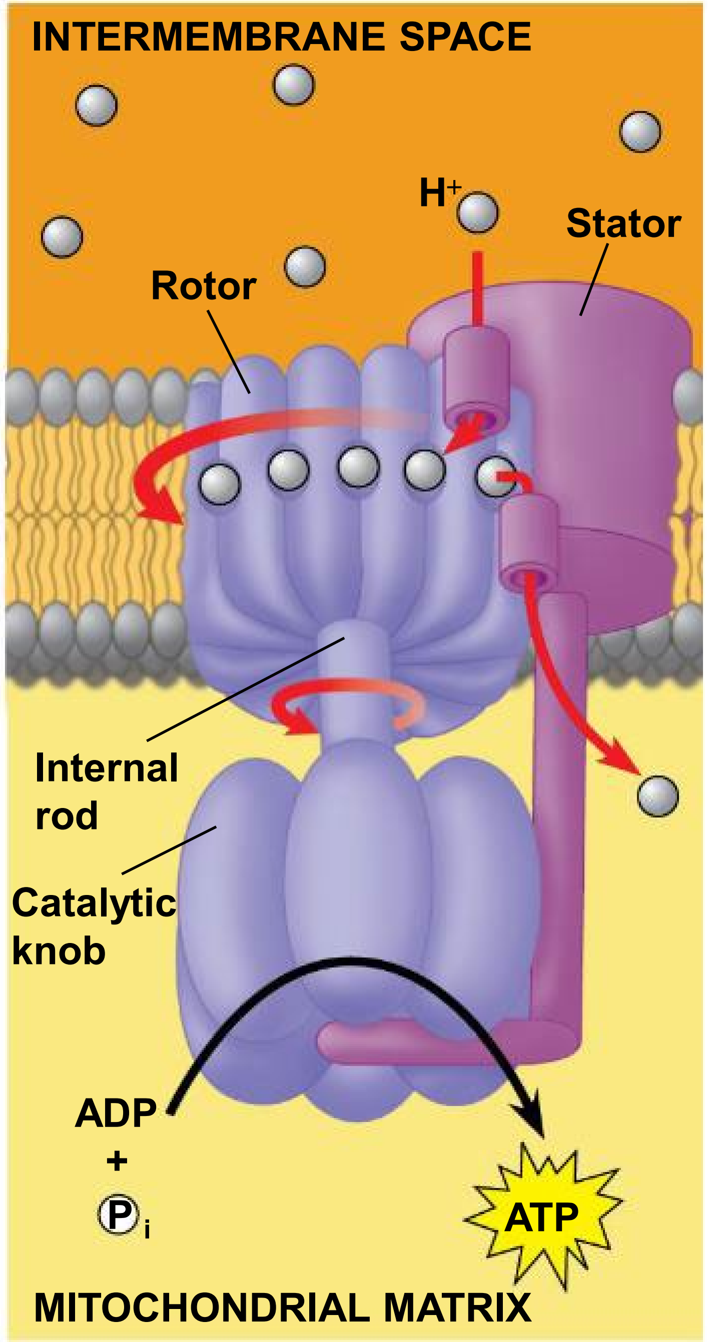
ATP Synthase is the ATP-generating protein of oxidative phosphorylation

The concentration of H^+ (protons) is very high in the intermembrane space & much lower in the matrix

- ATP synthase – which is embedded in the inner mitochondrial membrane – allows protons to move back into the matrix
- The energy that is released when these protons move back in is called **proton motive force**

ATP synthase uses the power of proton motive force to create new ATP

- It takes the movement of 4 protons (H^+) to make 1 molecule of ATP

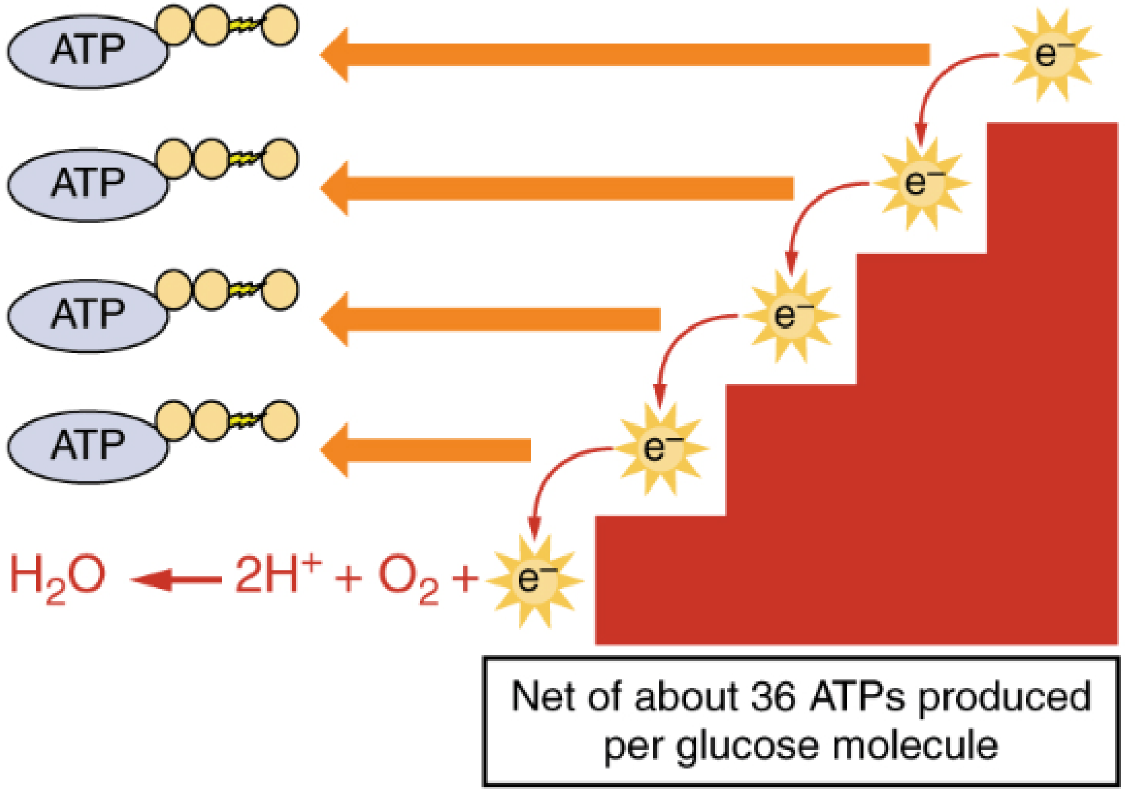


The Role of Oxygen

Oxidative phosphorylation is the only cellular respiration process that requires oxygen (O_2)

O_2 is the final electron acceptor at the end of the Electron Transport Chain (ETC)

- Energy-poor electrons are donated to O_2, making space for other electrons to continue to move through the ETC
- If oxygen was not present, electrons would build up in the Electron Transport Chain & electron carriers would remain permanently reduced



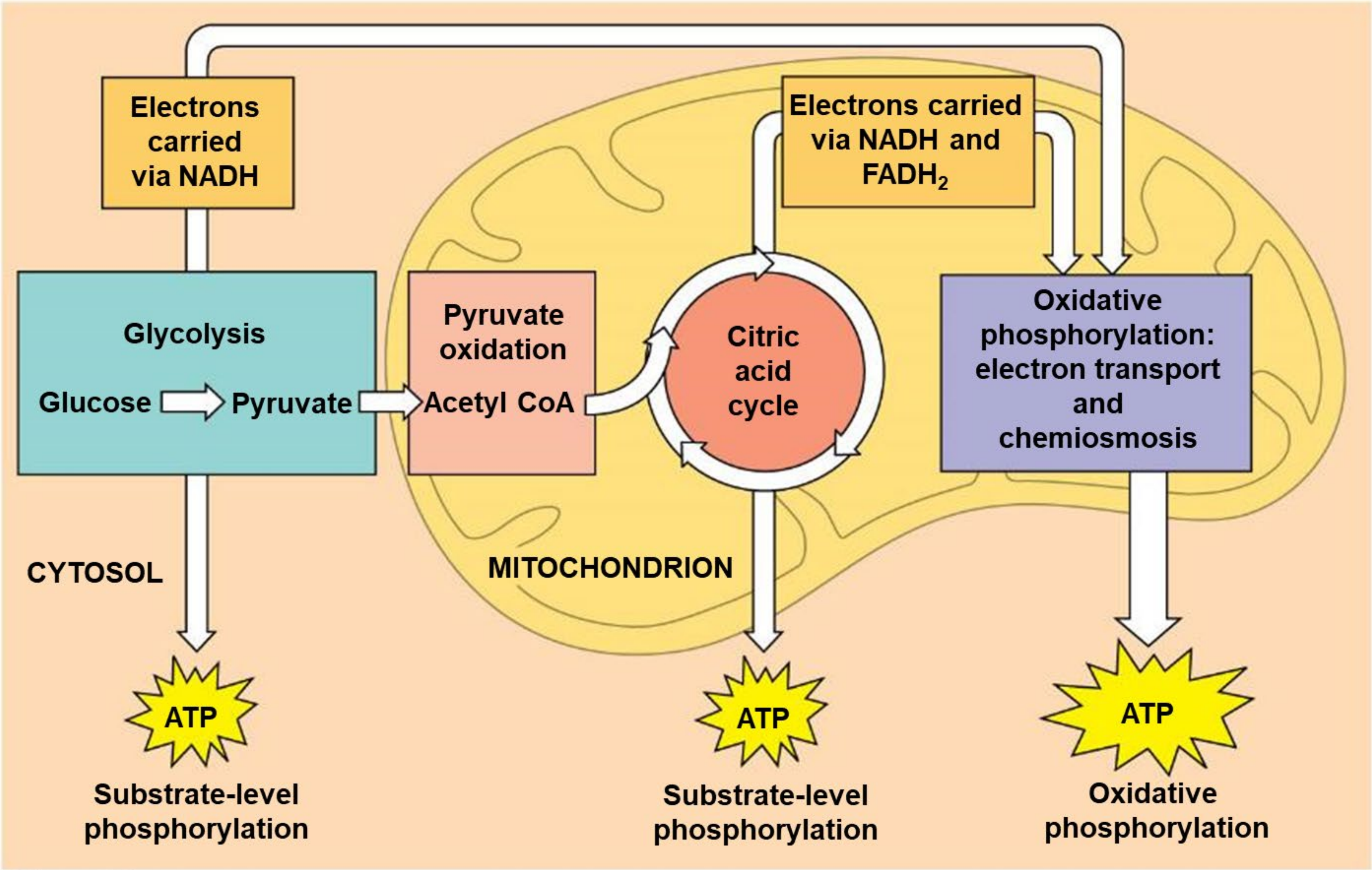
Cellular Respiration: A Review

Respiration begins with glucose ($C_6H_{12}O_6$).

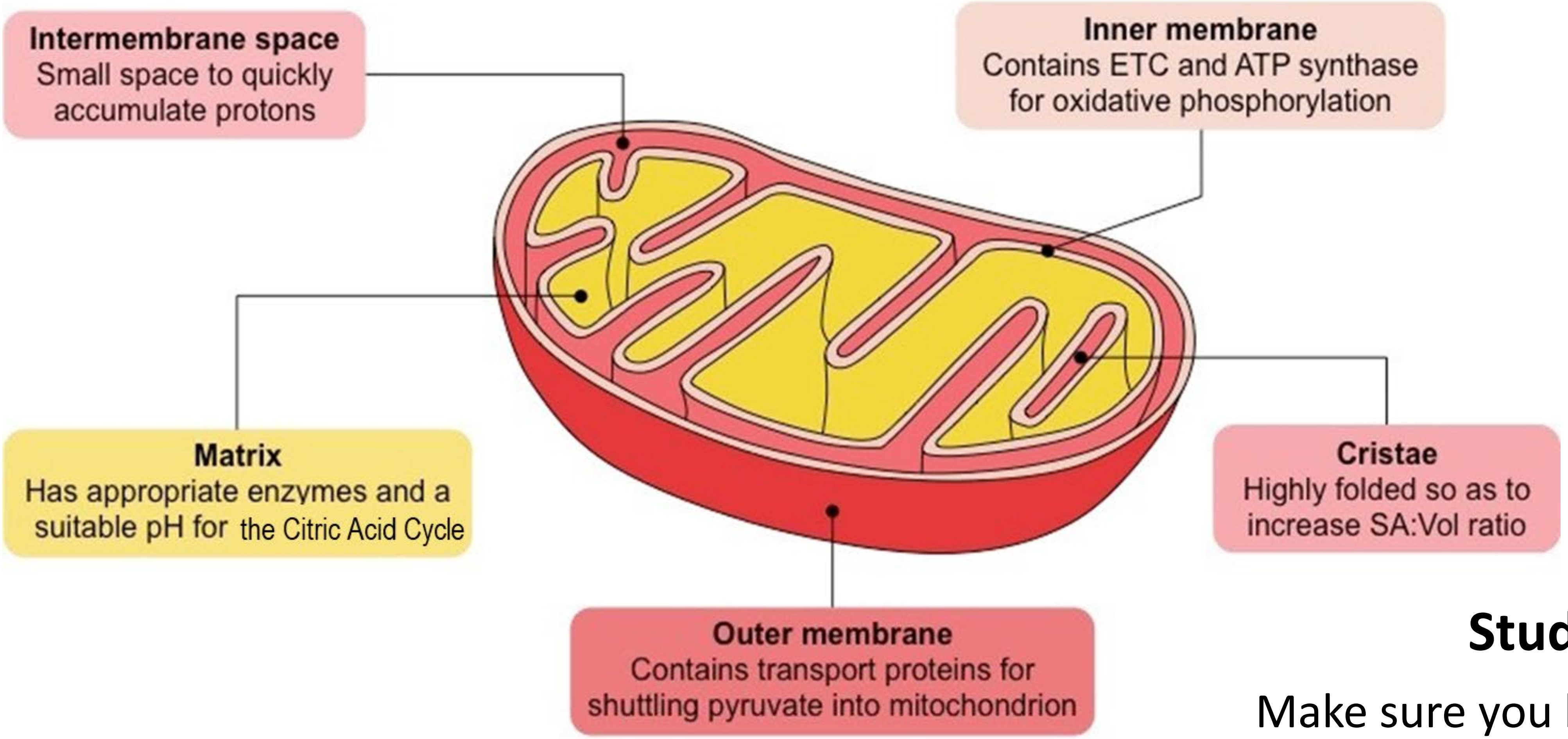
The glucose is split into pyruvate in the cytoplasm, then transported into the mitochondria.

As the pyruvate is processed further, both ATP & energized electron carriers are made.

Ultimately, the most ATP is built through oxidative phosphorylation, the process that harnesses the energy stored in electron carriers.



Respiration Processes & Their Mitochondrial Locations



Study Tip:

Make sure you know where each cellular respiration process occurs!

	Location	Starts with:	Ends with:	Stored Forms of Energy (ATP, NADH, or $FADH_2$)
Glycolysis				
Pyruvate oxidation				
The Citric Acid Cycle				
Oxidative Phosphorylation				

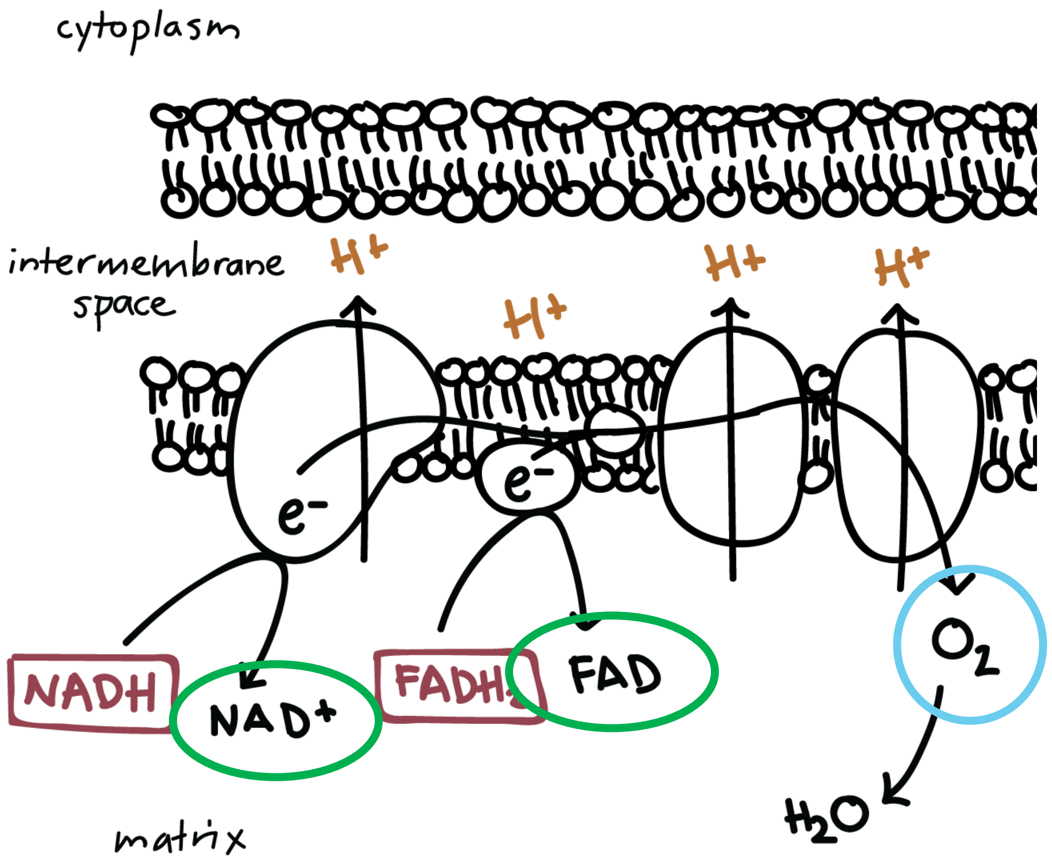
Oxygen & Cellular Respiration

The only part of cellular respiration that *directly* uses oxygen is the Electron Transport Chain (ETC)

- O_2 removes low-energy electrons from the ETC, allowing new electrons to constantly enter it

Electrons in the ETC come from NADH & $FADH_2$

- Donating electrons to the ETC oxidizes the carriers to **NAD^+** & **FAD**, the form needed for all the other parts of cellular respiration
- If the electron carriers can't be oxidized, ALL cellular respiration stops

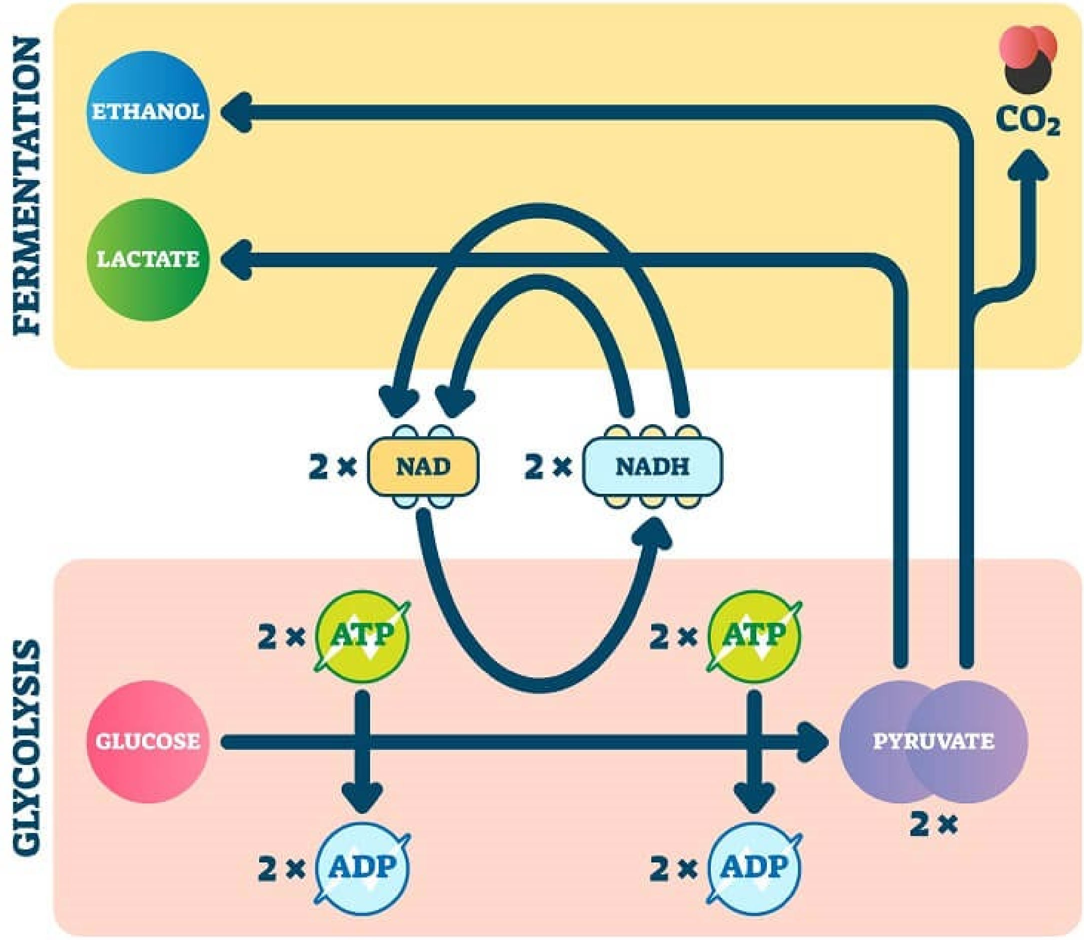


Fermentation

Cells use **fermentation** when there is no oxygen present

The goal of fermentation is to regenerate the oxidized electron carrier NAD^+

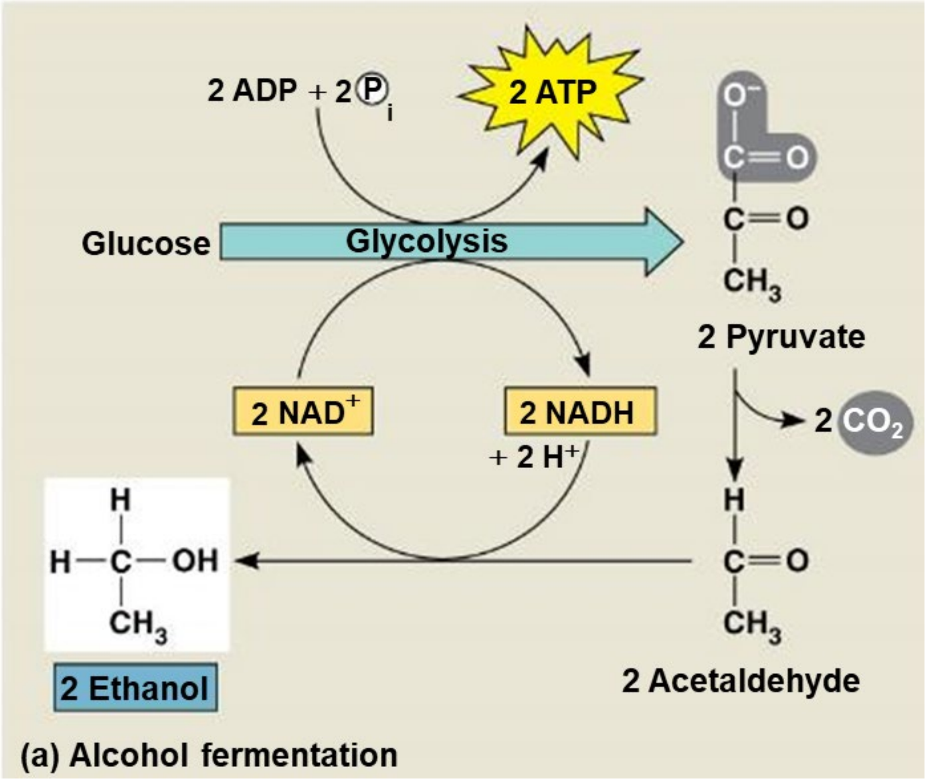
- Without this carrier, glycolysis cannot occur, and…
- Without glycolysis, a cell has no ways to make ANY ATP



Alcohol Fermentation

Alcohol fermentation is used by <u>yeast</u> to regenerate NAD^+

- The pyruvate (made by glycolysis) is transformed into **ethanol**
- This transformation requires electrons, which NADH provides, oxidizing it back into NAD^+



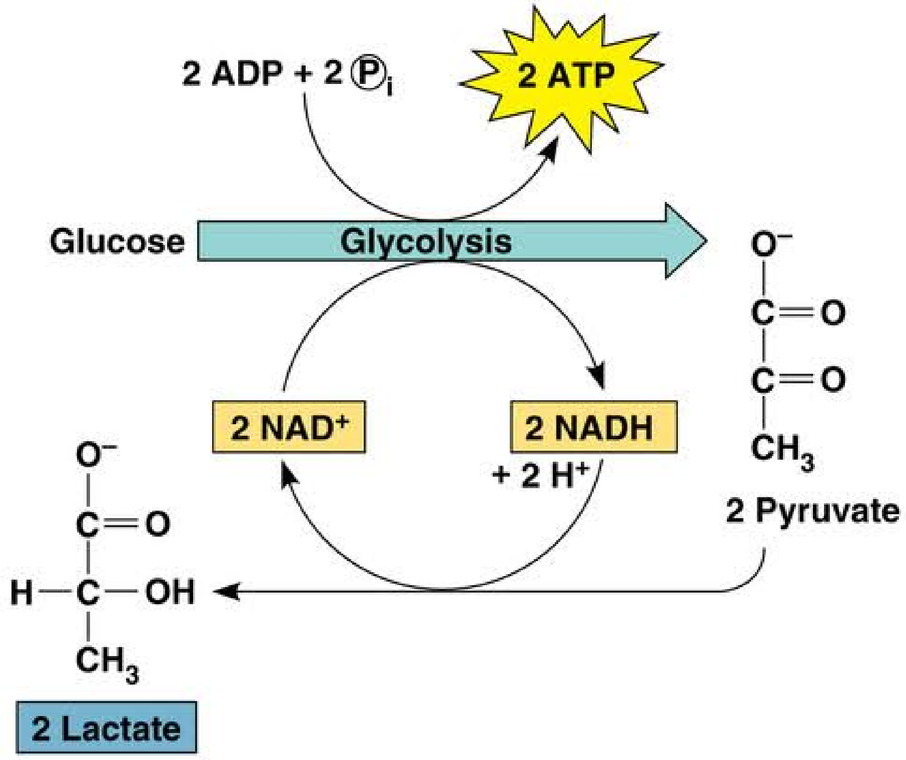
Alcohol fermentation is used in brewing & wine-making

- This process generates a lot of CO_2
- Fermentation tanks have valves to help relieve the pressure this gas creates

Lactic Acid Fermentation

Lactic acid fermentation is used to regenerate NAD^+ in bacteria, fungi, & mammals

- The pyruvate (made by glycolysis) is transformed into **lactic acid**
- This transformation requires electrons, which NADH provides, oxidizing it back into NAD^+



(b) Lactic acid fermentation

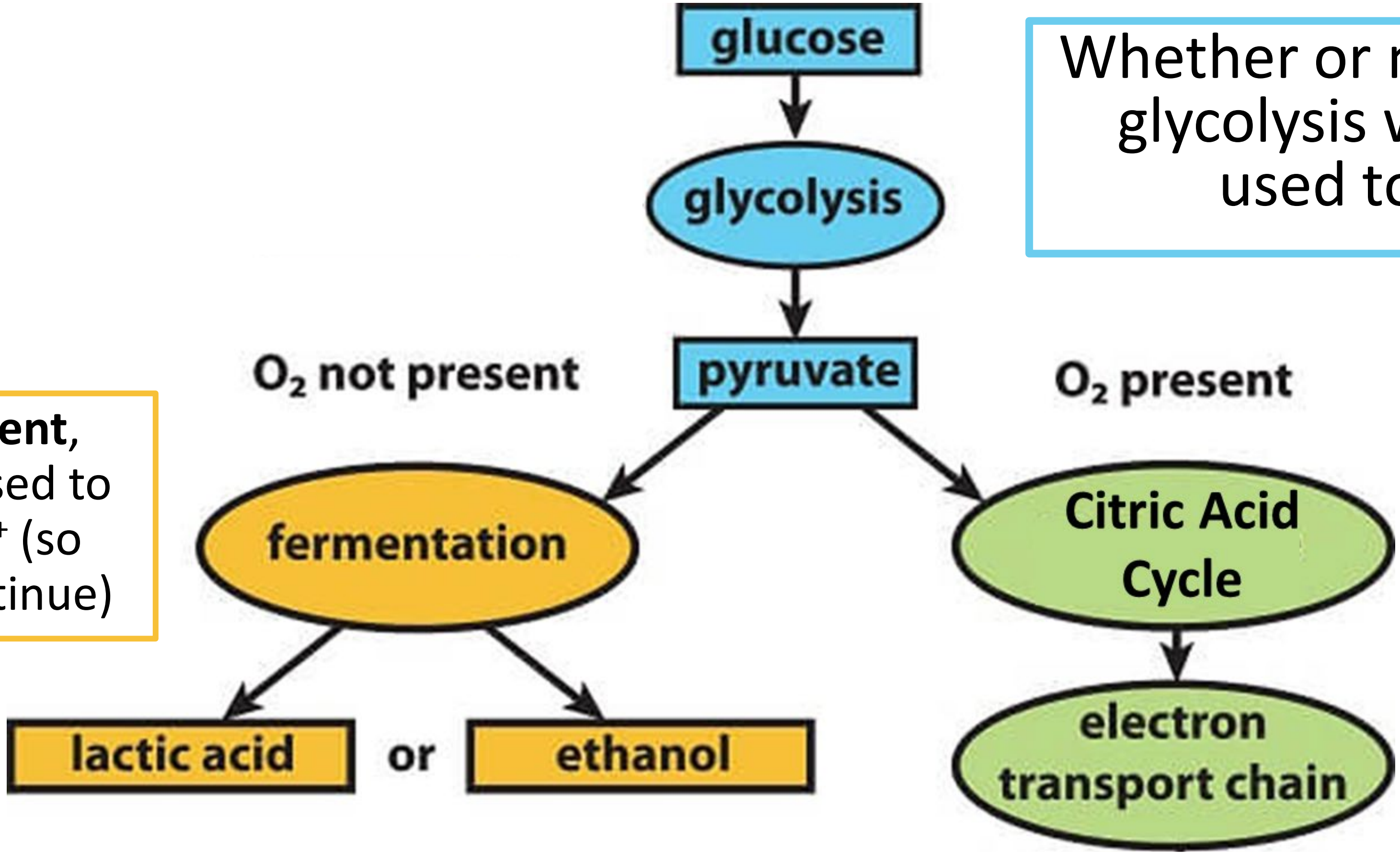
Lactic acid fermentation is used to make many different foods

- Examples: yogurt, cheese, sourdough bread
- Lactic acid leads to a tangy taste in these foods

Summary of Aerobic and Anaerobic Pathways

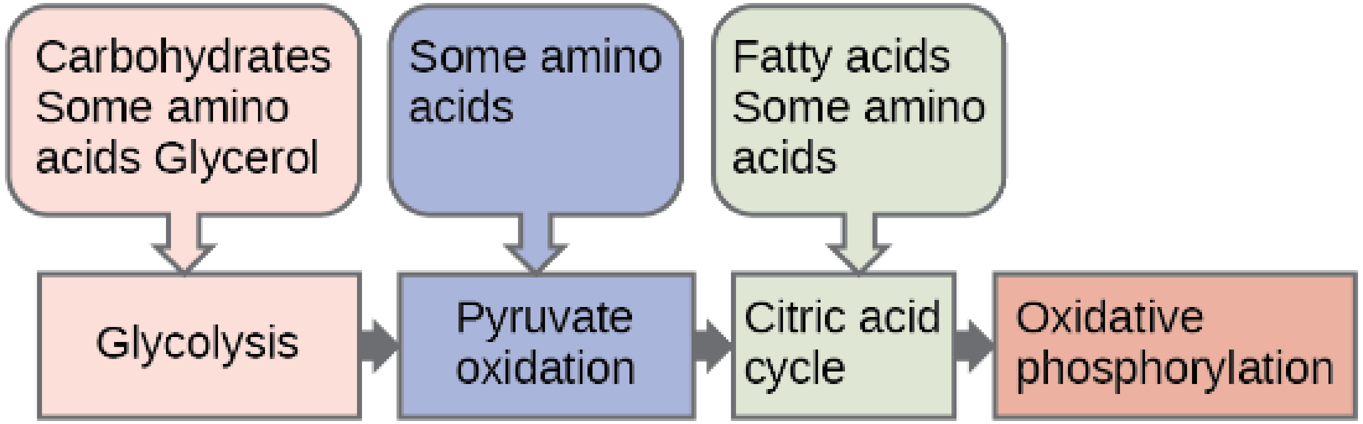
Whether or not O_2 is present, glycolysis will **ALWAYS** be used to make ATP

If O_2 is **NOT present**, fermentation is used to regenerate NAD^+ (so glycolysis can continue)



If O_2 **IS present**, the cell makes A LOT of ATP with the Citric Acid Cycle & oxidative phosphorylation

Macromolecules besides carbohydrates can be catabolized using some of the same metabolic pathways as glucose



Regulating Cellular Respiration

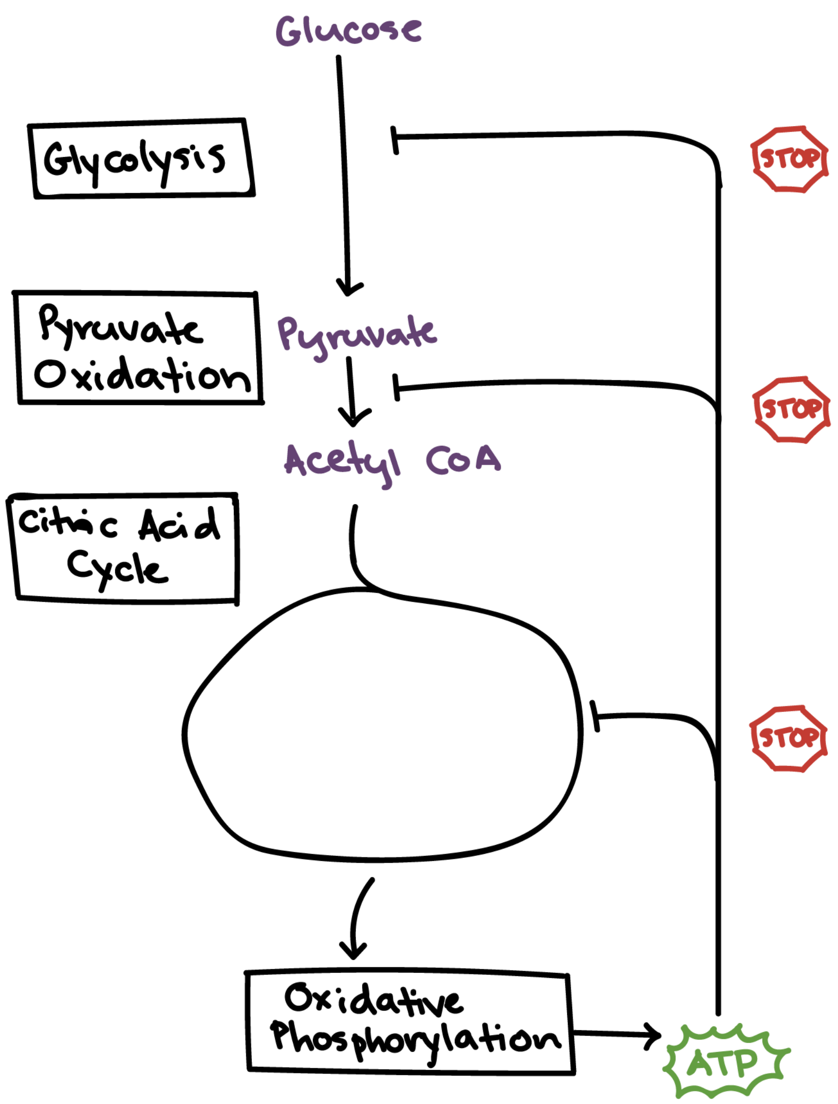
The steps of cellular respiration are regulated using **feedback inhibition**

- This means that the products of the chemical reactions can inhibit the continuation of the chemical reaction

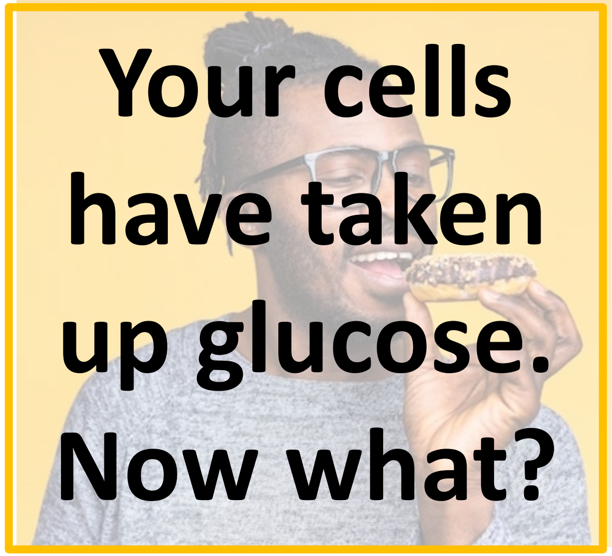
Many of the enzymes involved in respiration are sensitive to ATP

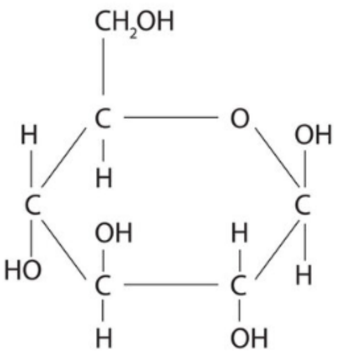
- If A LOT of ATP is present, they are inactive
- If A LITTLE ATP is present, they are active

Other factors (like pH changes due to lactic acid buildup) can also influence enzyme activity



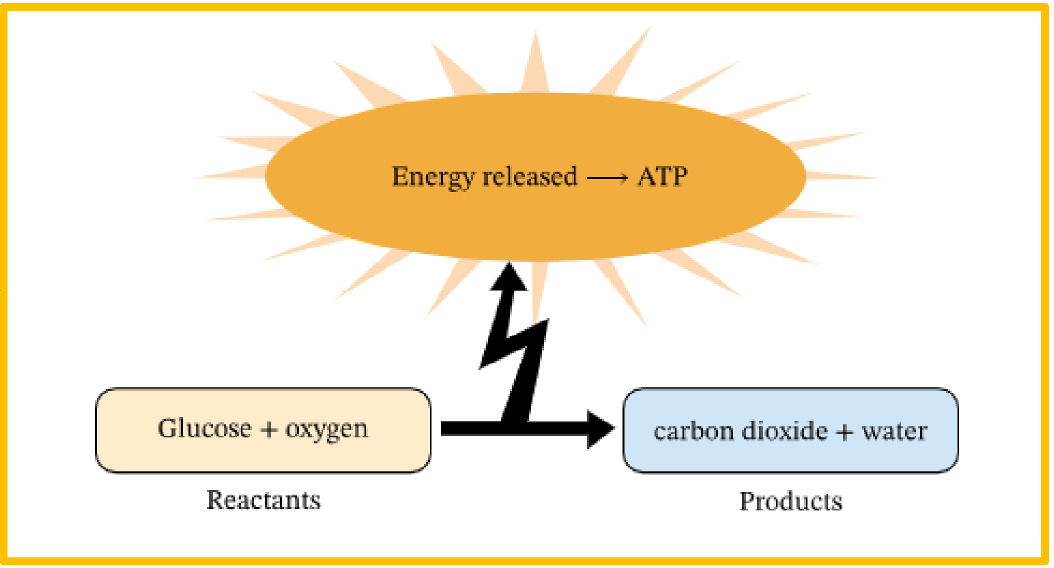
Your cells have taken up glucose. Now what?

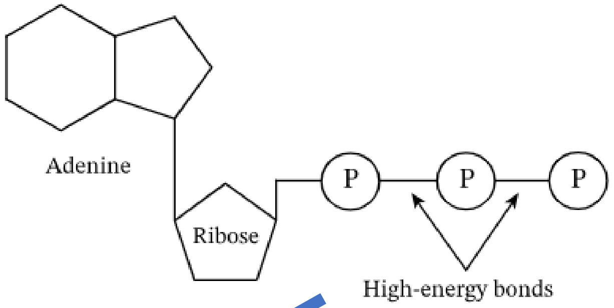




The energy in glucose is stored in the chemical bonds between the atoms. It is not directly available for your cells to use.

In **cellular respiration** the energy is transferred to the bonds between the phosphate groups ATP.





ATP can be used by cells as a source of energy by breaking the high energy phosphate bonds.

To Prepare for Next Class…

- ❑ Review your class notes
  - Use the eTextbook & Other Helpful Resources to supplement your lecture notes

- ❑ Complete the homework assignment and use it to direct your studying

- ❑ Print the slides for Lesson #5- Green Energy