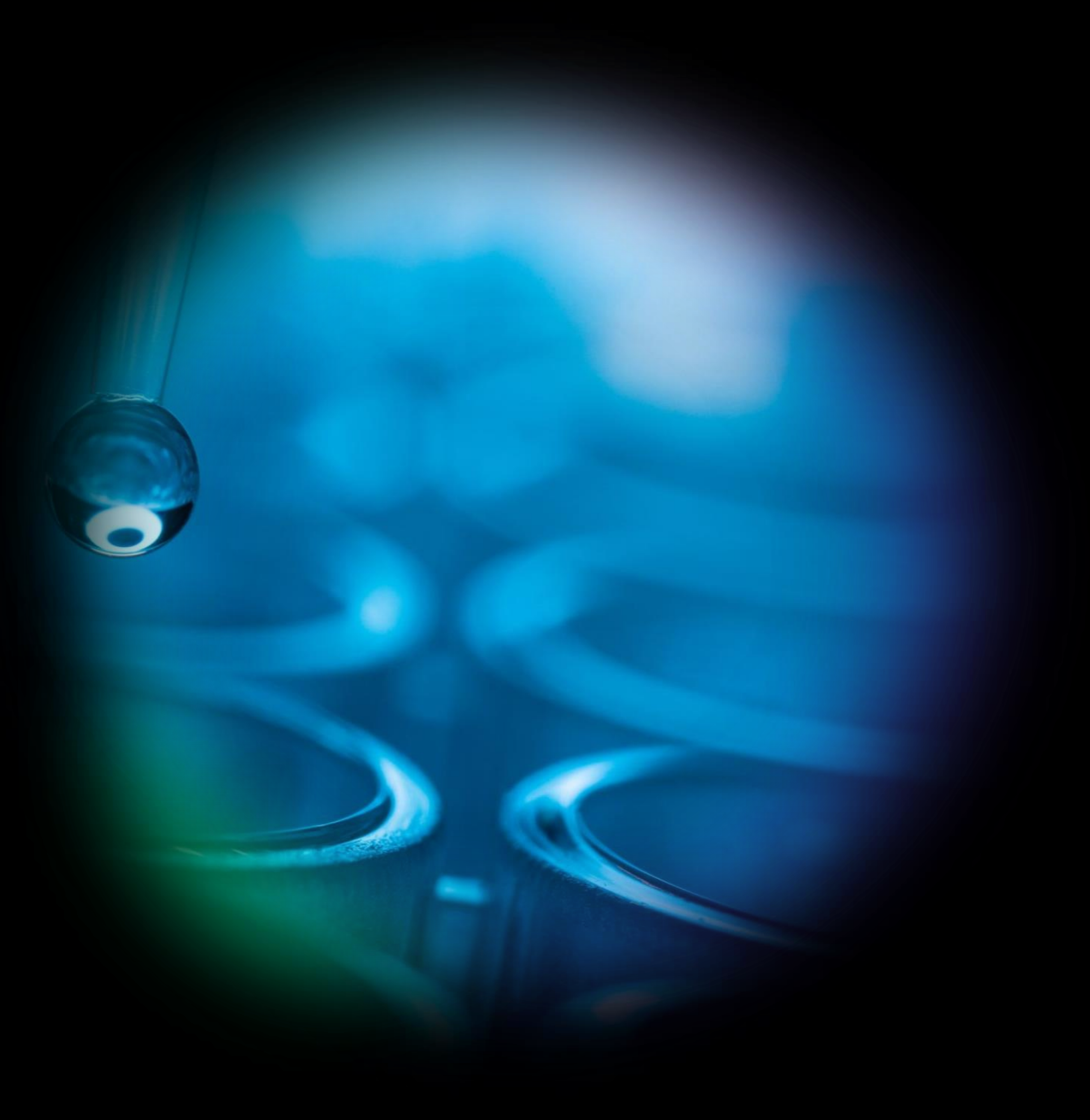


Biochemistry

Photosynthesis

Trees: A *Massive* Conundrum

Conservation of Mass: Mass cannot be created or destroyed.

Discuss: Where does most of the mass in a tree come from?

a) The soil
b) The water
c) The air
d) The sunlight
e) Other: specify

Design an experiment to test your prediction.

Jan Van Helmont's Experiment

https://www.youtube.com/watch?v=2KZb2_vcNTg&ab_channel=Veritasium

Jan Van Helmont's Experiment

Procedure:

- Measure mass of pot of dry soil; measure mass of seedling
- Plant seedling; water regularly for 5 years

Result: Tree gained 75 kg, but the mass of the soil was unchanged.

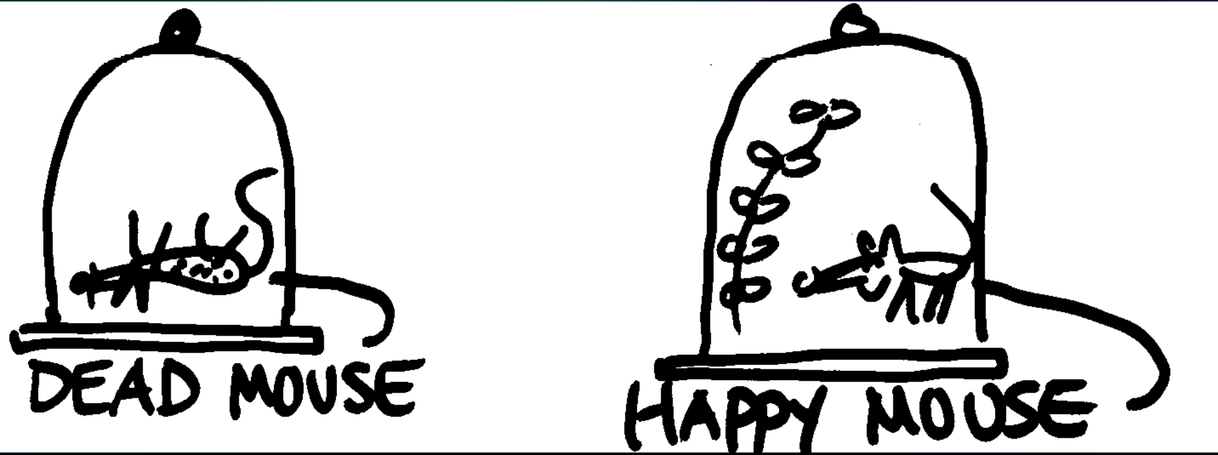
Conclusion: Most of the mass comes from the water.

Do we agree with Helmont's conclusion? Why or why not?

Joseph Priestley's Experiment

Observations:

- A mouse will go unconscious (and eventually die) if you leave it in a sealed jar.
- A mouse will regain consciousness if you put a mint plant into the jar.



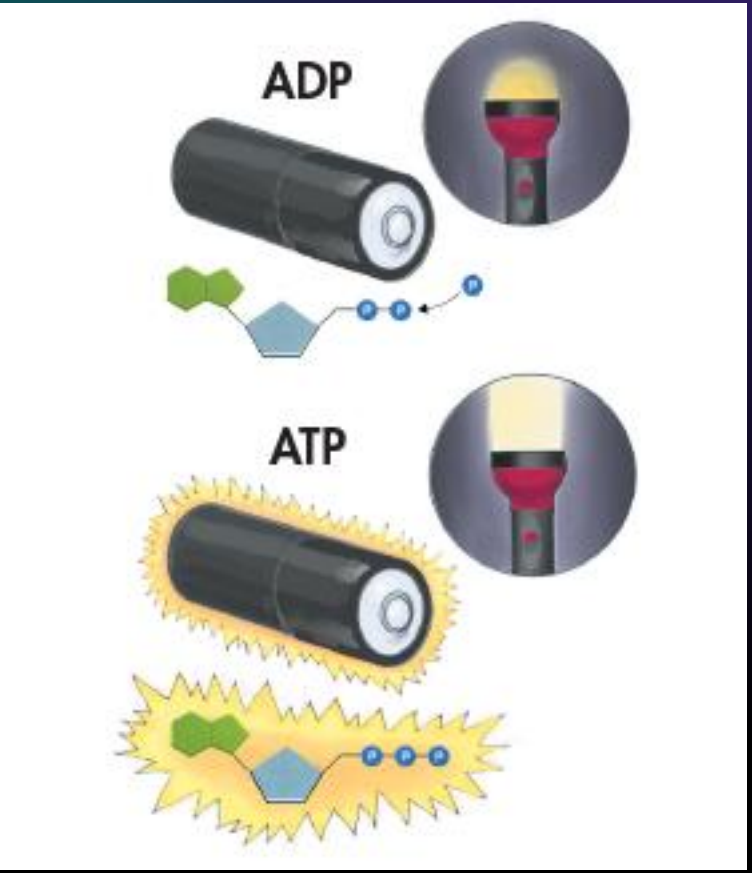
Conclusion:

- Plants produce something that the mouse needs to live.

ATP: Life's Battery

Adenosine triphosphate (ATP) is an important compound for storing and releasing energy.

- Structure contains 3 phosphate groups
- Breaking a phosphate bond releases energy and converts ATP to ADP
- Reforming a phosphate bond costs energy and converts ADP to ATP



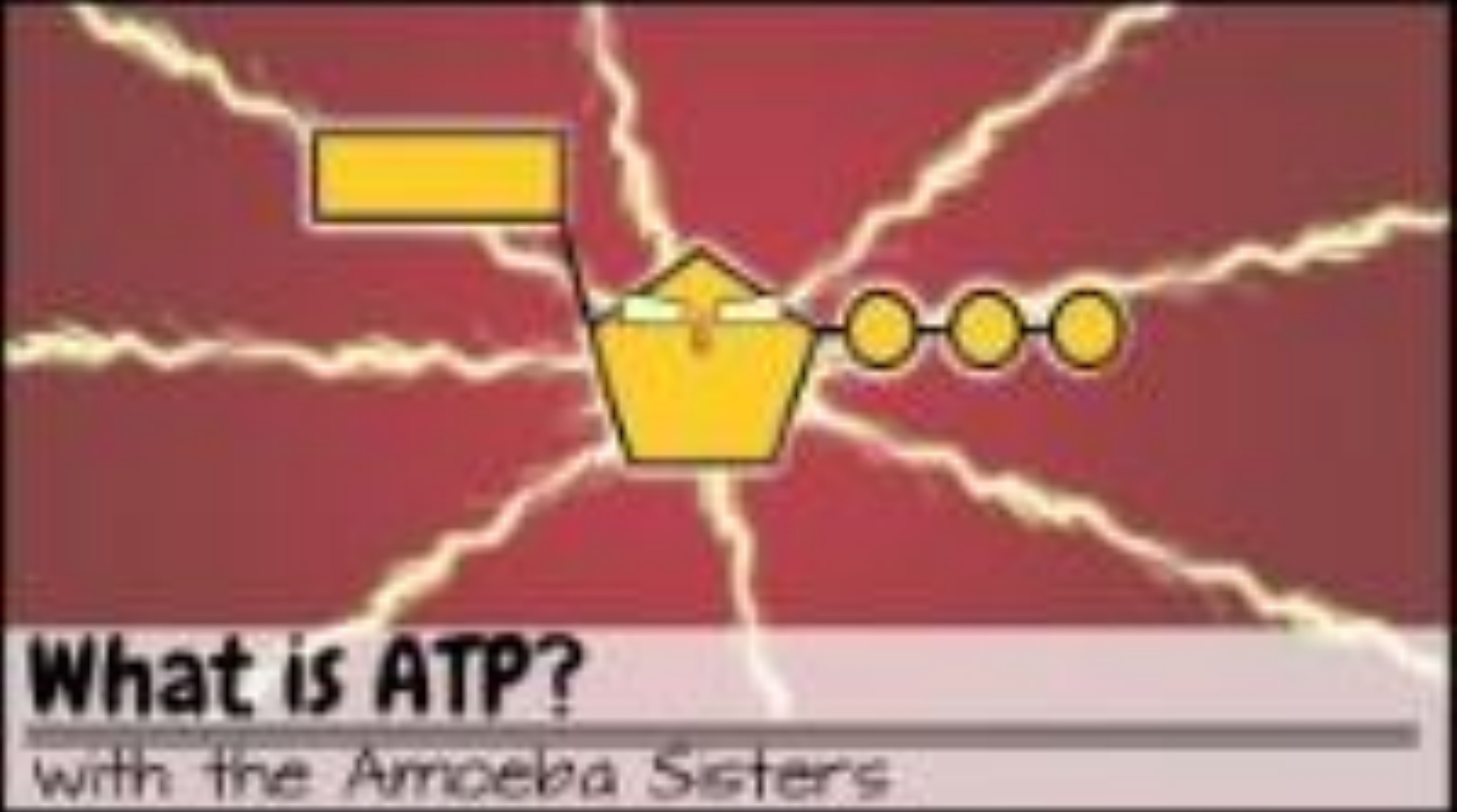
ATP: Life's Battery

Cells use ATP energy for:

- Active transport
- Movement (cilia, flagella, muscle contractions)
- Synthesizing materials

ATP is for short-term energy storage.
It can be regenerated from ADP using the energy in glucose.

> In this chapter, we will encounter other energy storage molecules.
> Just like ADP/ATP, there is NADP+/NADPH, NAD+/NADH.


What is ATP?
with the Amoeba Sisters

Cell Structures Review

Chloroplast:

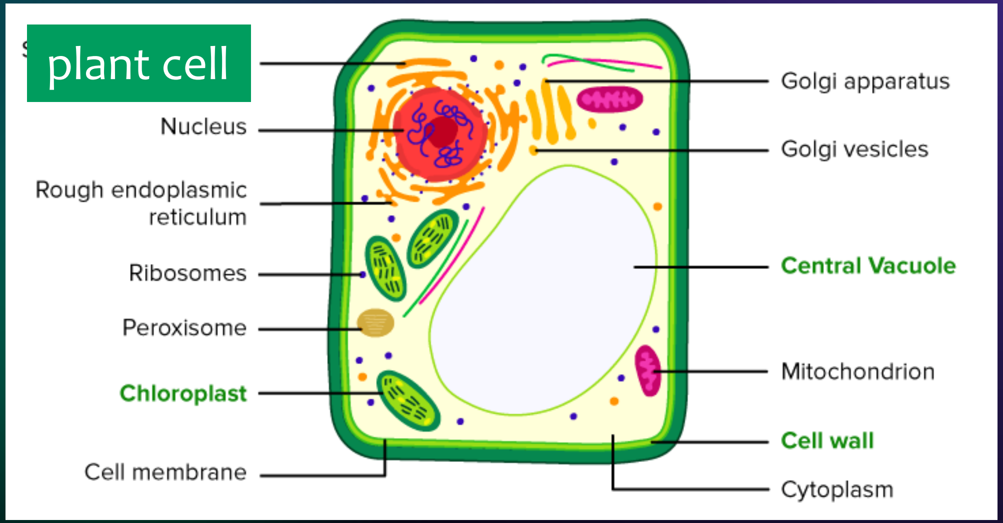
- Plant cells only
- Does photosynthesis

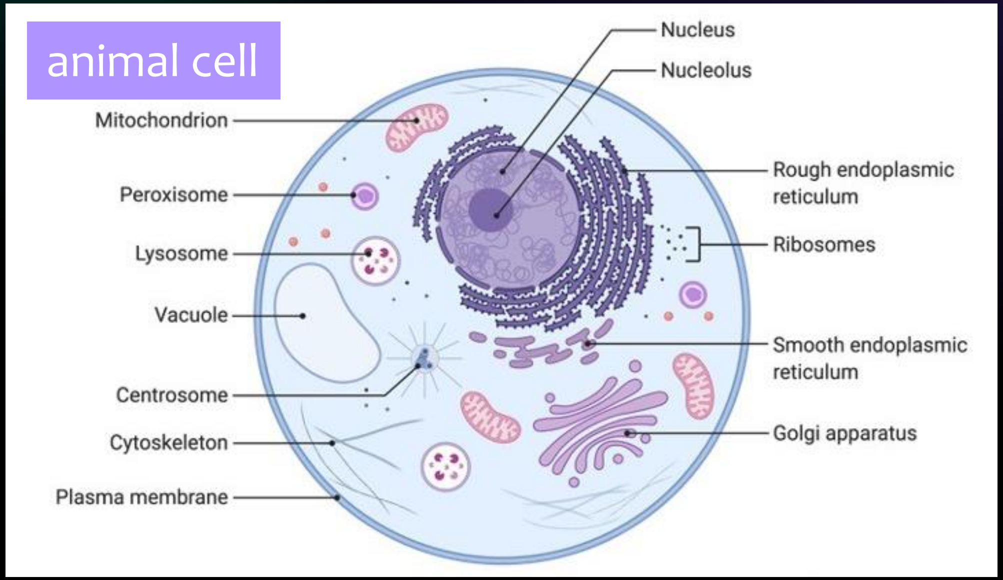
Mitochondria:

- Plant and animal cells
- Does cellular respiration

Cytoplasm:

- The fluid 'insides' of a cell, contains cell structures





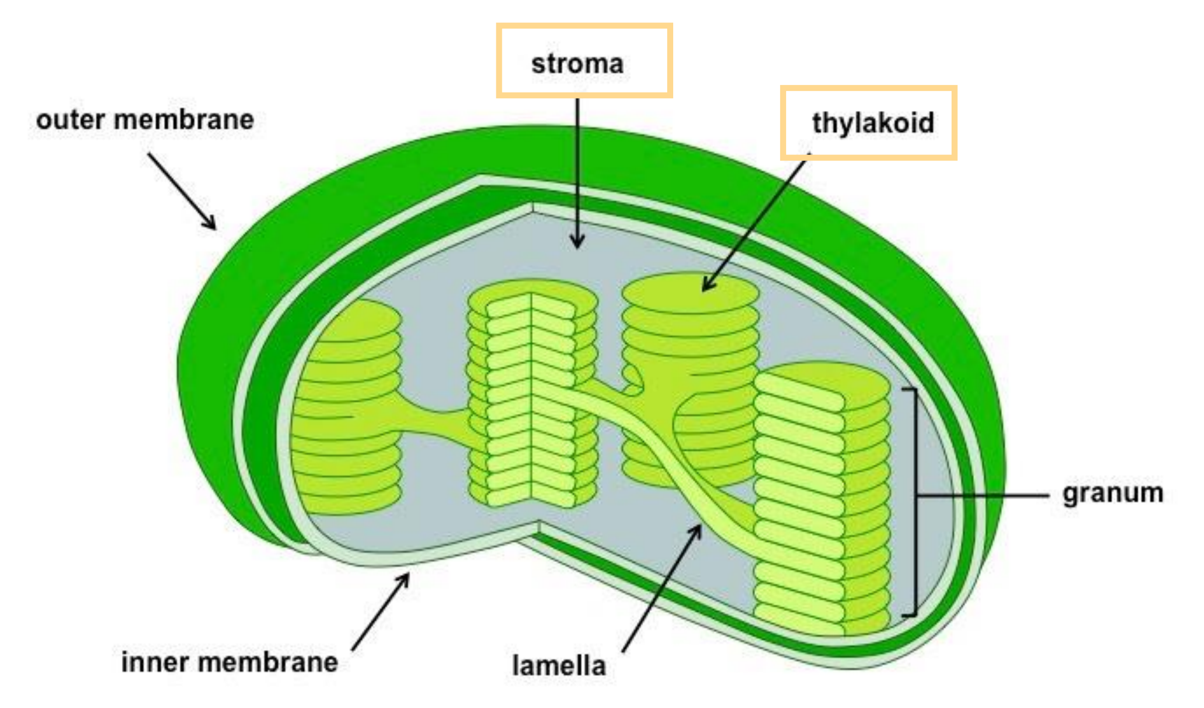
Chloroplast Structure

Stroma:

- Fluid-filled interior of the chloroplast, where thylakoids are located

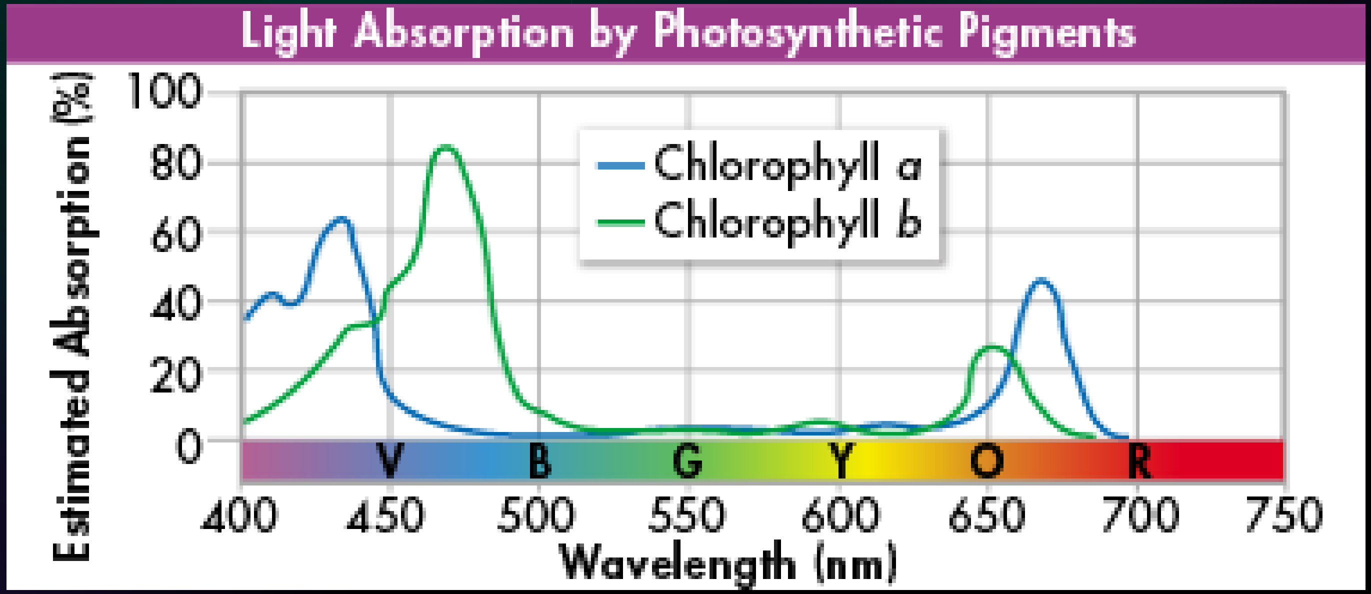
Thylakoids:

- Sac-like photosynthetic membranes
- Contains photosynthetic pigments (chlorophyll)



Photosynthetic Pigments

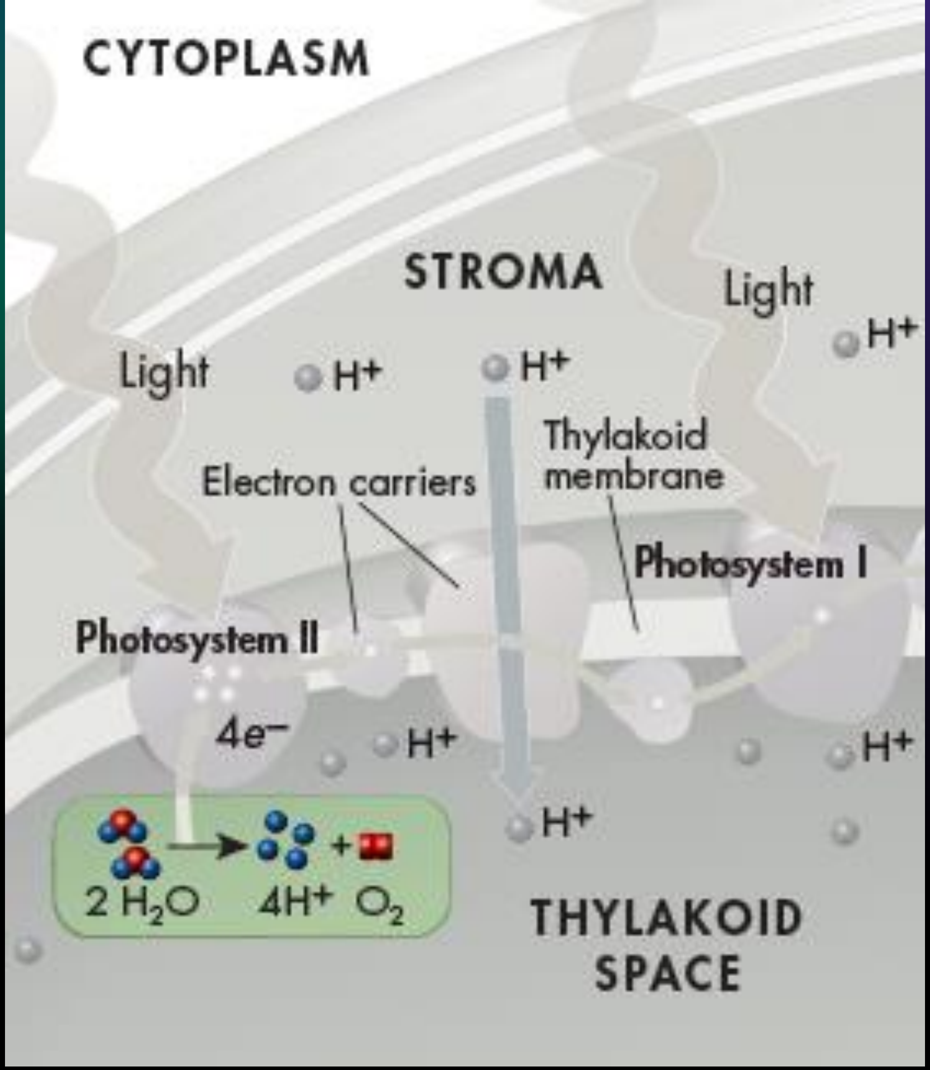
- Primary pigment in plants is **chlorophyll**.
- Each pigment absorbs certain wavelengths of light (e.g. chlorophylls absorb orange, yellow, and blue).



Stage 1: Water Splitting

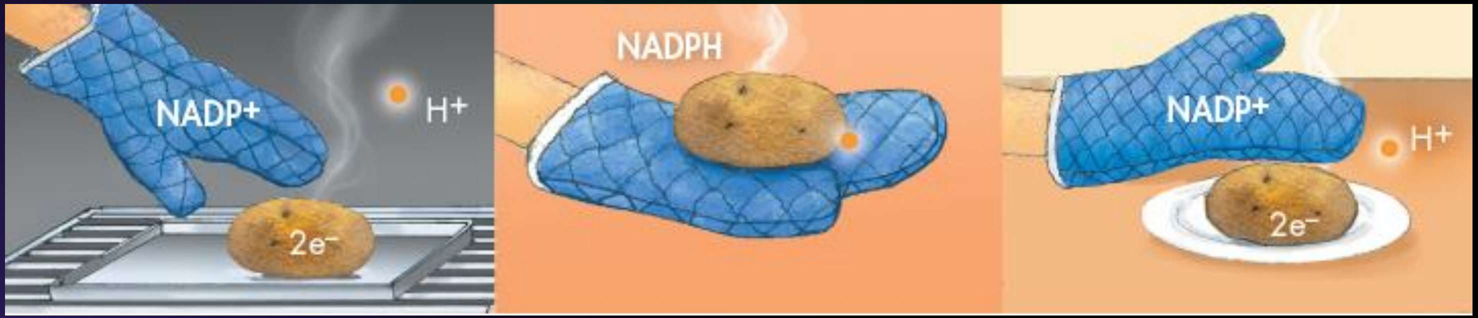
Inside the thylakoid, an enzyme breaks up water molecules into:

- Oxygen → diffuses out into the air
- H^+ ions → released inside the thylakoid
- Electrons → used to replace electrons used in the next step



Stage 2: Energy Collection (PSII)

1. Chlorophylls in photosystem II absorb light energy.
2. Energy is transferred to an electron, which becomes excited.
3. High-energy electrons are highly reactive. They need an **electron carrier** molecule to carry them safely.
   (Note: the electrons are always accompanied by a hydrogen.)



Low-energy state	High-energy state
NADP+	NADPH
NAD+	NADH
FAD+	FADH

A Thought Experiment

https://www.youtube.com/watch?v=Z6eNu7ItXAY&ab_channel=WaltDisney4Life

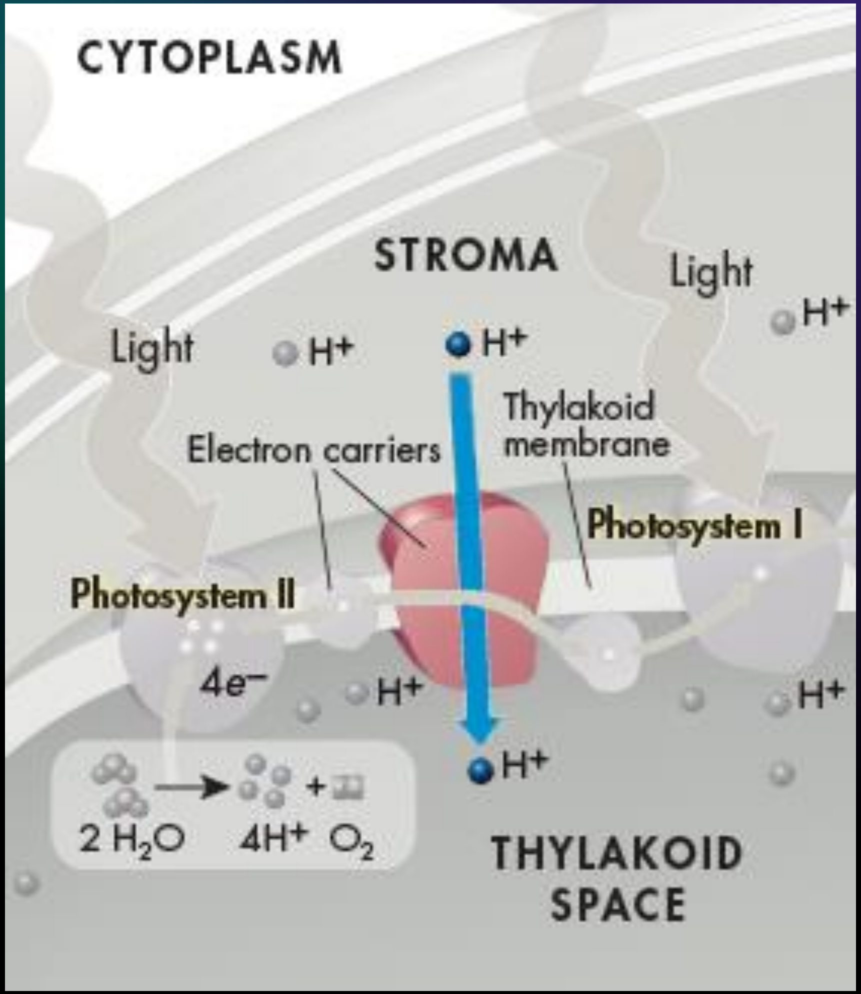
- A lightning bolt contains enough energy to power a house for 55 days.
- How come, in Ratatouille, the lightning *only cooks a mushroom*?

The most efficient way to use energy is by using a little at a time. When released all at once, more of it is converted into unwanted forms of energy (e.g. heat).

Stage 3: Electron Transport Chain (PSII)

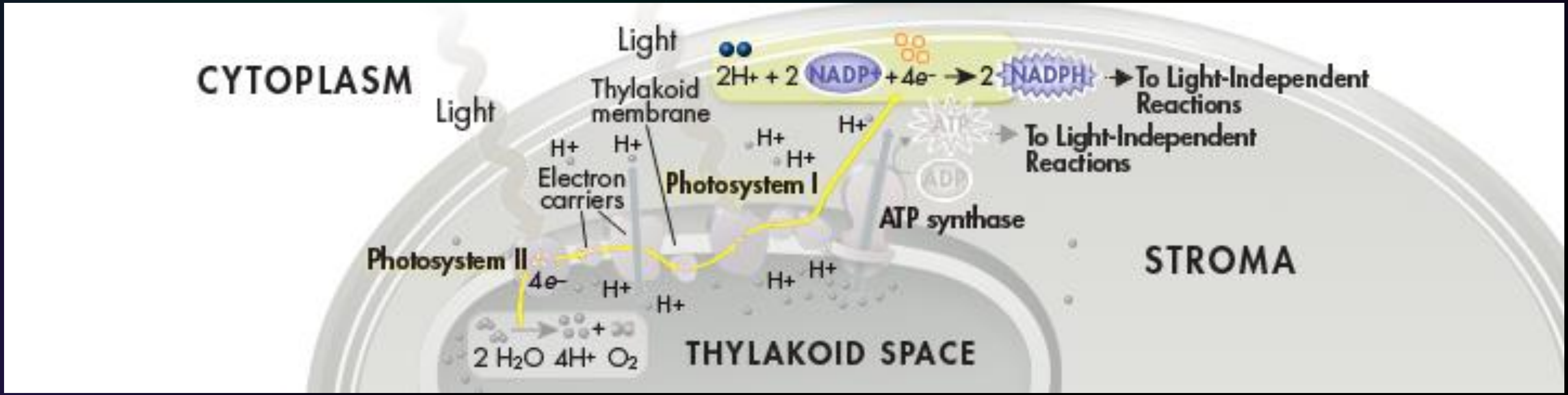
As high-energy electrons are passed from one electron carrier to another, some of the energy is used to pump H^+ ions from the stroma into the thylakoid.

An Electron Transport Chain is like a game of Hot Potato where each person takes a bite out of the potato.



Stage 4: Rinse and Repeat! (PSI)

1. Pigments in Photosystem I use light to re-excite electrons.
2. Electrons pass through a different electron transport chain, pumping H^+ ions into the thylakoid space.
3. At the end, the electrons are picked up by $NADP^+$, forming NADPH.



Stage 1-4 Recap

Legend

✓ Fully accounted for (end of story)

✗ Not yet accounted for (not yet used)

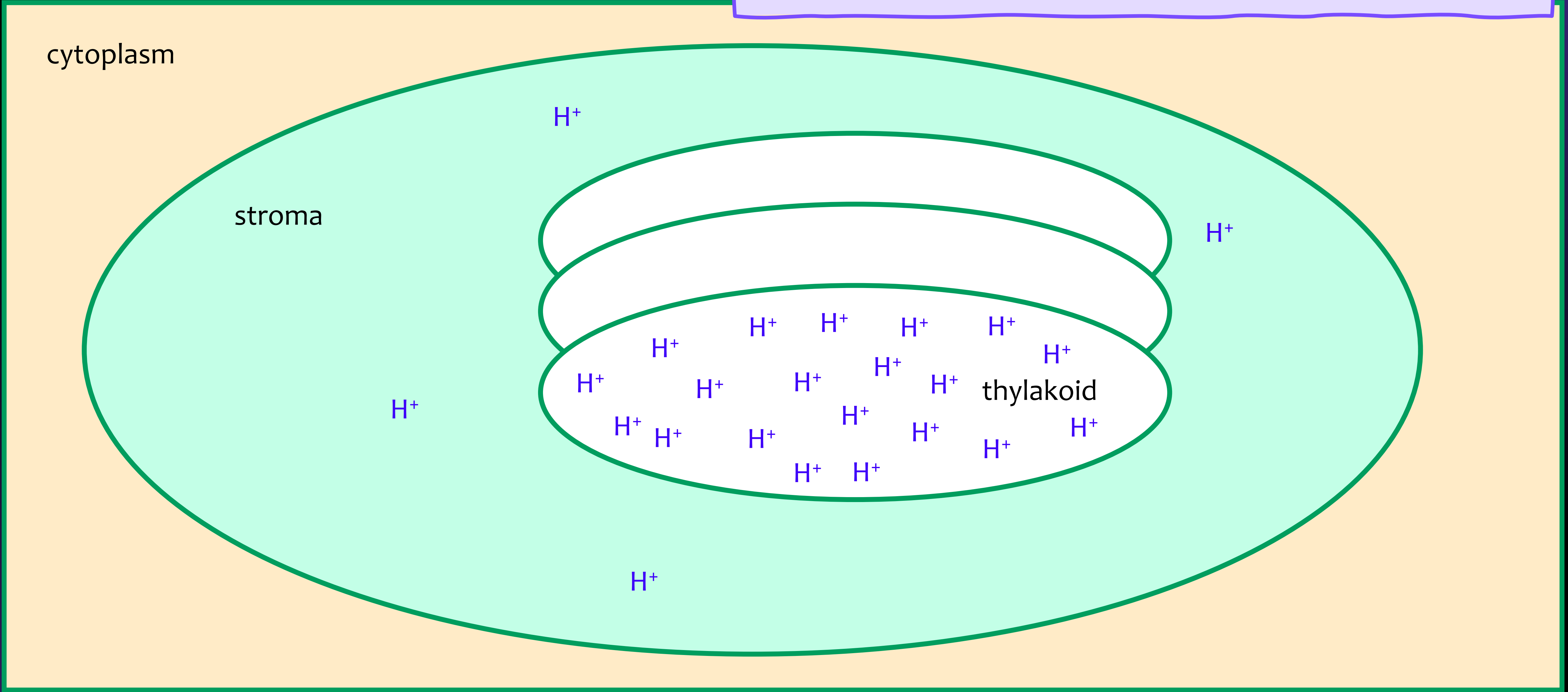
What have we accomplished through photosystems II and I?

Inputs	Outputs
Water ✓	**Oxygen** released ✓
Light energy ✓	**H^+** pumped into thylakoid ✗ (this happened 3 times: water split, ETC in PSII, ETC in PSI)
	NADPH produced ✗

Stage 1-4 Recap

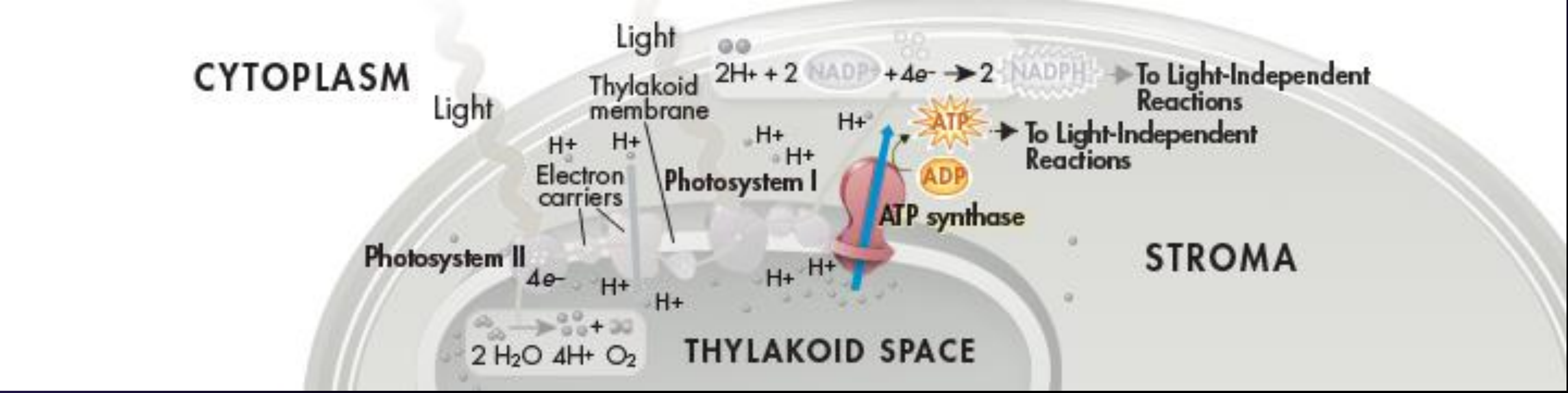
Stages 1-4 set up a concentration gradient in the chloroplast.

Discuss: Where will H^+ ions 'want' to diffuse to?



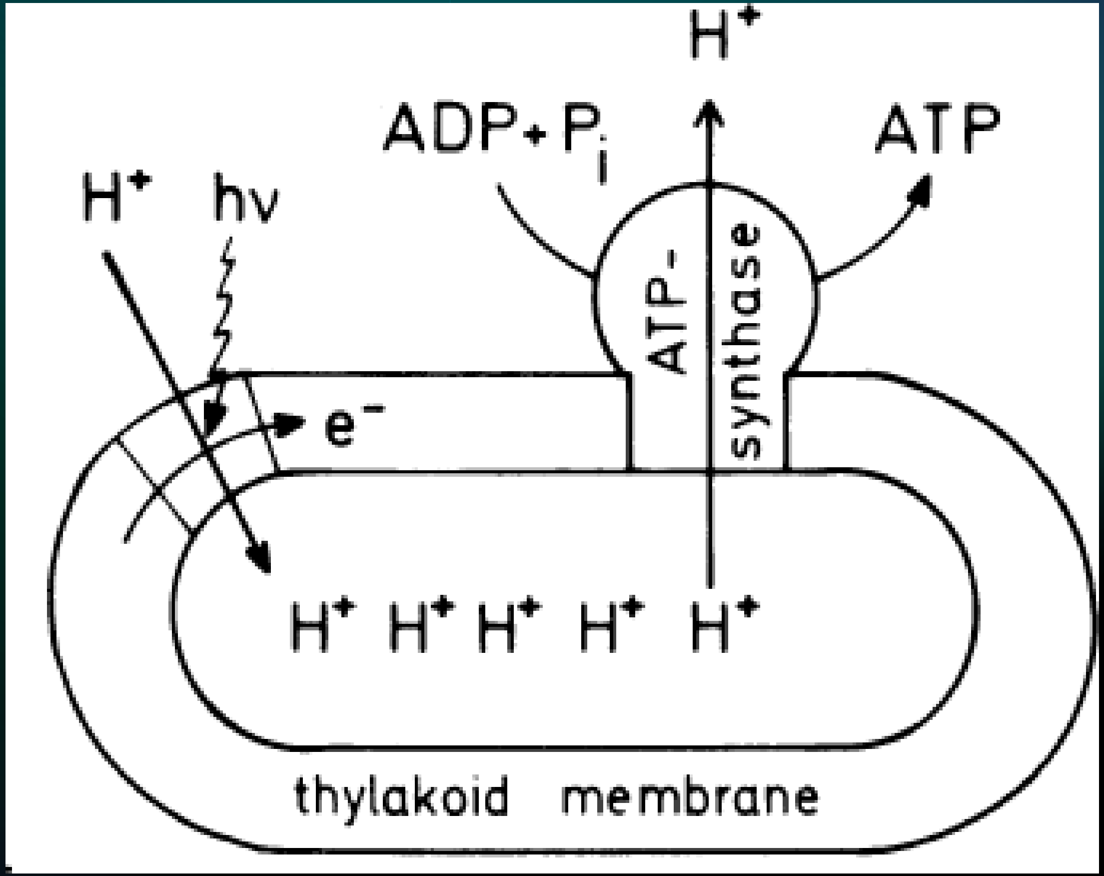
Stage 5: ATP Formation!!!!

- **Concentration gradient:** H^+ concentration much higher inside thylakoid than the stroma
- H^+ cannot diffuse freely through thylakoid membrane
- H^+ enters stroma via ATP synthase, driving a 'turbine' which converts ADP to ATP



Atp synthase video (1:20- https://www.youtube.com/watch?v=3y1dO4nNaKY&ab_channel=ndsuvirtualcell

Stage 5: ATP Formation!!!!



Discuss: would ATP synthase ***best*** be described as a channel protein, carrier protein, or protein pump?

https://www.nature.com/scitable/topicpage/mitochondria-14053590/

Light-dependent Reactions

"Stages 1-5" are referred to as the light-dependent reactions, because they require light.

Overall, the following are accomplished through the light dependent reactions:

- Water and light energy are used
- Oxygen gas, ATP, and NADPH are produced in the chloroplast

Stage 1-5 Recap

Legend

✓ Fully accounted for (end of story)

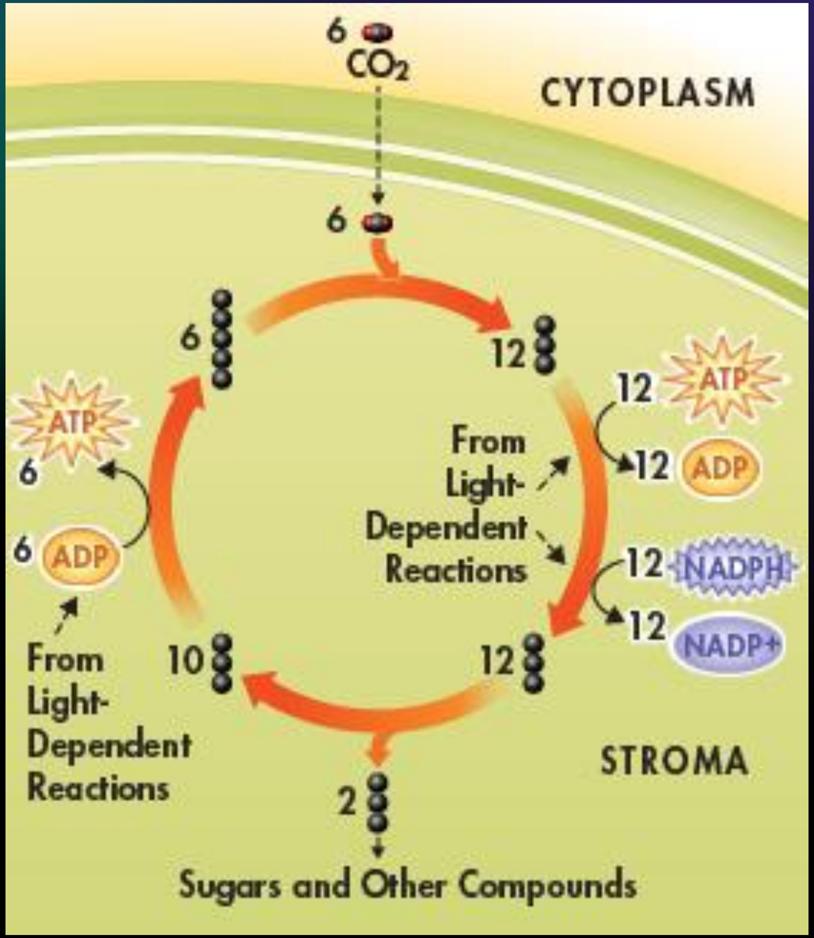
✗ Not yet accounted for (not yet used)

What have we accomplished?

Inputs	Outputs
Water ✓	Oxygen released ✓
Light energy ✓	~~H^+ pumped into thylakoid~~ ✓ ~~(this happened 3 times: water split, ETC in PSII, ETC in PSI)~~
	ATP produced ✗
	NADPH produced ✗

Stage 6: Calvin Cycle (Light-independent Reactions)

- Carbon dioxide from the atmosphere enters the Calvin cycle
- A series of chemical reactions uses energy from ATP and NADPH (from light-dependent reactions) to convert the carbon dioxide into sugar and regenerate starting materials of cycle



Stage 1-6 Recap

Legend

✓ Fully accounted for (end of story)

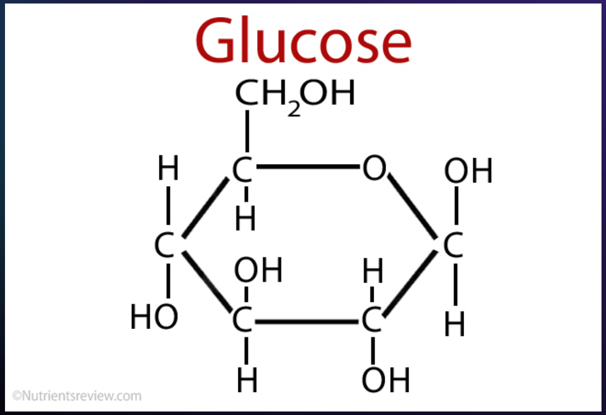
X Not yet accounted for (not yet used)

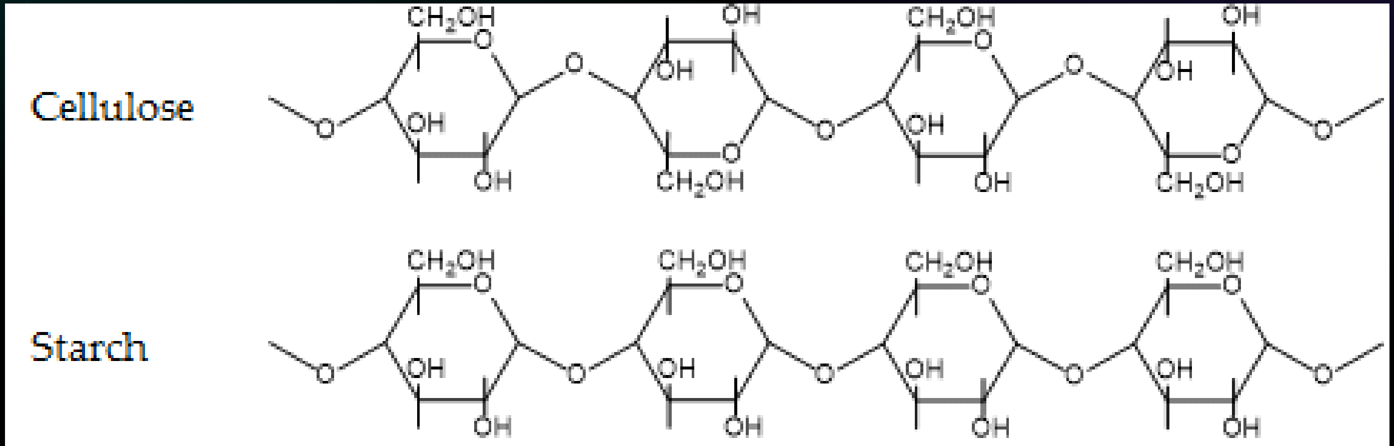
What have we accomplished?

Inputs	Outputs
Water ✓	Oxygen released ✓
Light energy ✓	~~H^+ pumped into thylakoid (this happened 3 times: water split, ETC in PSII, ETC in PSI)~~ ✓
Carbon dioxide ✓	ATP produced ✓
	NADPH produced ✓
	Glucose (sugar) produced

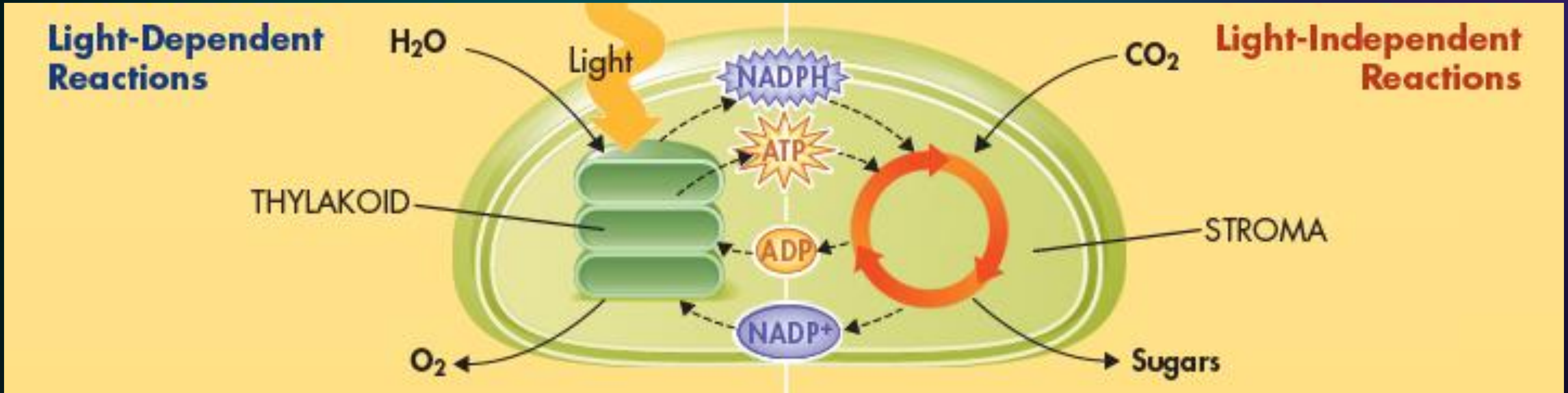
How do Plants Use Sugar?

- Used by mitochondria in cellular respiration (convert ADP to ATP which is used as energy for life processes)
- Build new molecules (e.g. carbohydrates, proteins, fats)
  - **Starch** is a carbohydrate used by plants for long-term sugar storage





Photosynthesis Summary



- Light-dependent reactions: Light energy is converted to ATP and NADPH energy. Water is split; oxygen is released.
- Light-independent reactions: ATP and NADPH energy is used to convert carbon dioxide into sugar.
- Overall: light + H_2O + CO_2 → $C_6H_{12}O_6$ + O_2

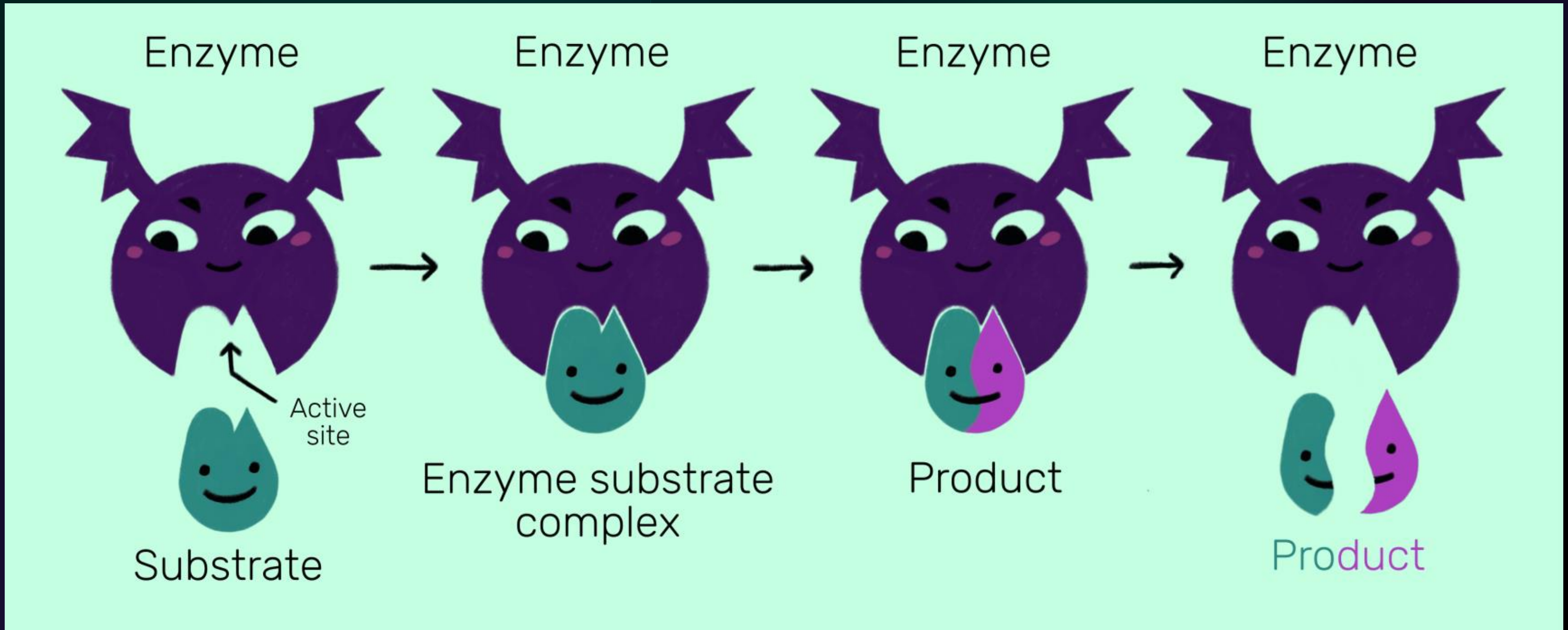
Discussion Questions

1. What would happen if the thylakoid membrane was ‘leaky’ and allowed H^+ ions to move freely through it?
2. When is light energy required in photosynthesis? What does it accomplish?
3. Why is the Calvin Cycle sometimes called the light-independent part of photosynthesis?
4. Explain how the structure of a chloroplast allows photosynthesis to take place.

RuBisCO: the worst enzyme

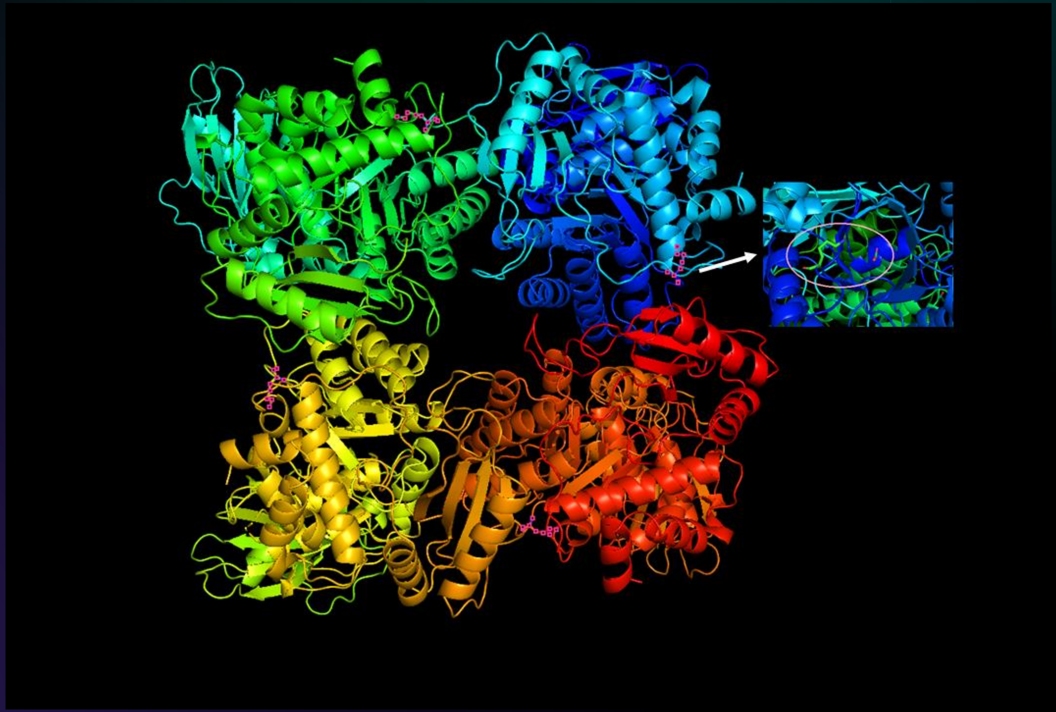
Biochemical reactions do not happen magically. You need:

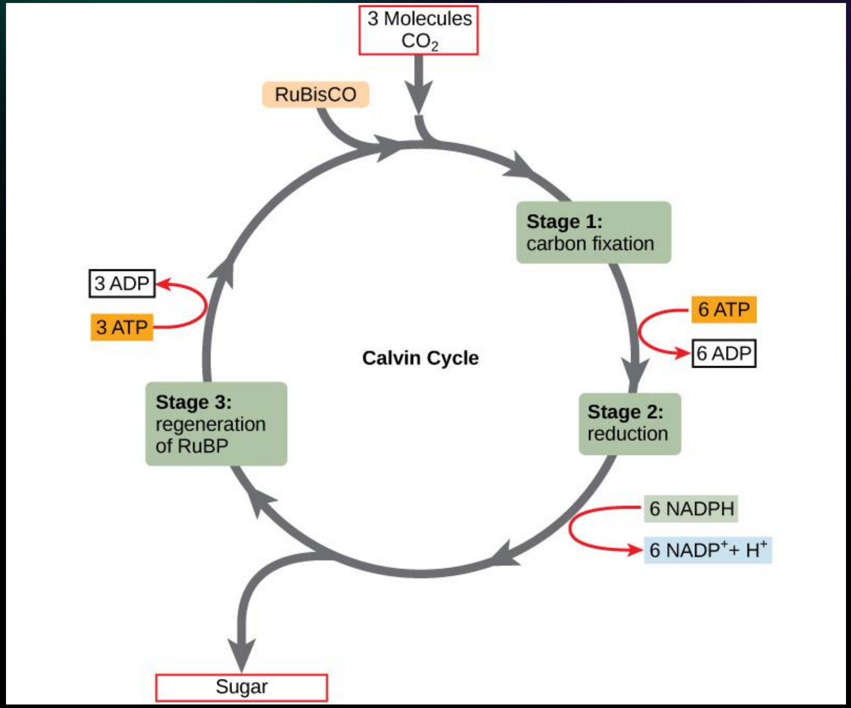
- Reactants
- A specific enzyme to catalyze the reaction



RuBisCO: THE WORST ENZYME

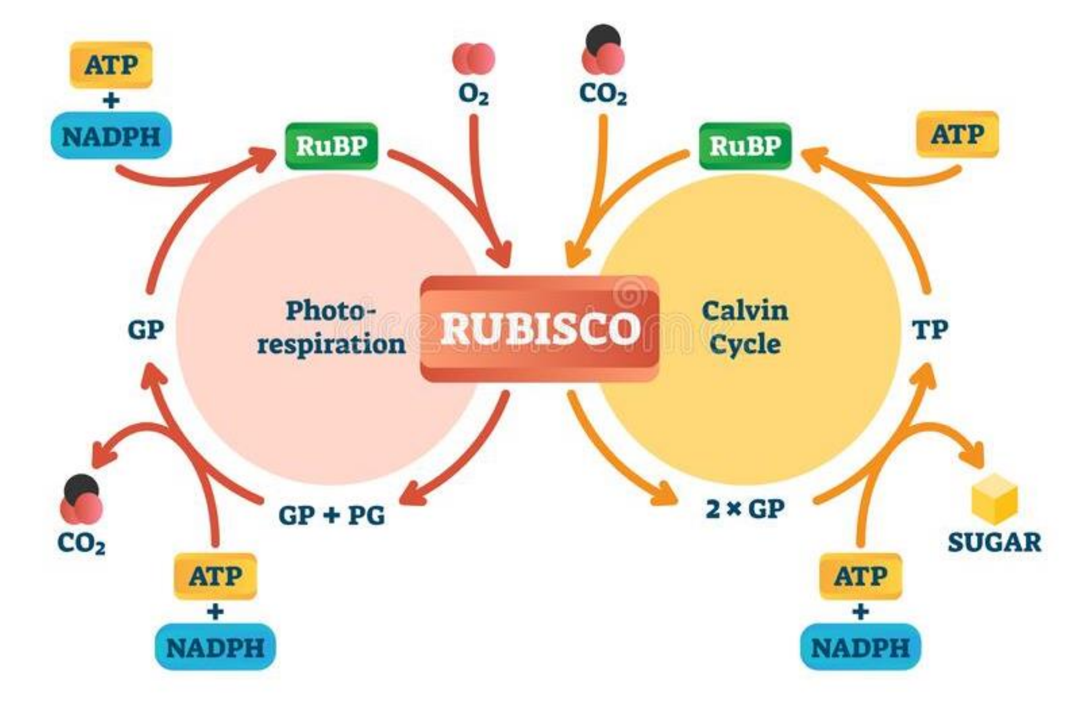
RuBisCO is the enzyme that catalyzes the first step of the Calvin Cycle: 'fixing' the carbon from CO_2 into a biologically useful form.





RuBisCO: the worst enzyme

- RuBisCO evolved 2.4 billion years ago, when there was no oxygen in the atmosphere. As photosynthetic organisms flourished, the concentration of oxygen in the atmosphere increased.
- Problem: if oxygen is available, RuBisCO also catalyzes the reverse reaction, ‘undoing’ the Calvin Cycle. This makes RuBisCO the most inefficient enzyme on the planet.



Solutions for RuBisCO

1. Evolve a better RuBisCO. ✗

Not possible*. After 2.4 billion years of evolution, RuBisCO is still terrible.

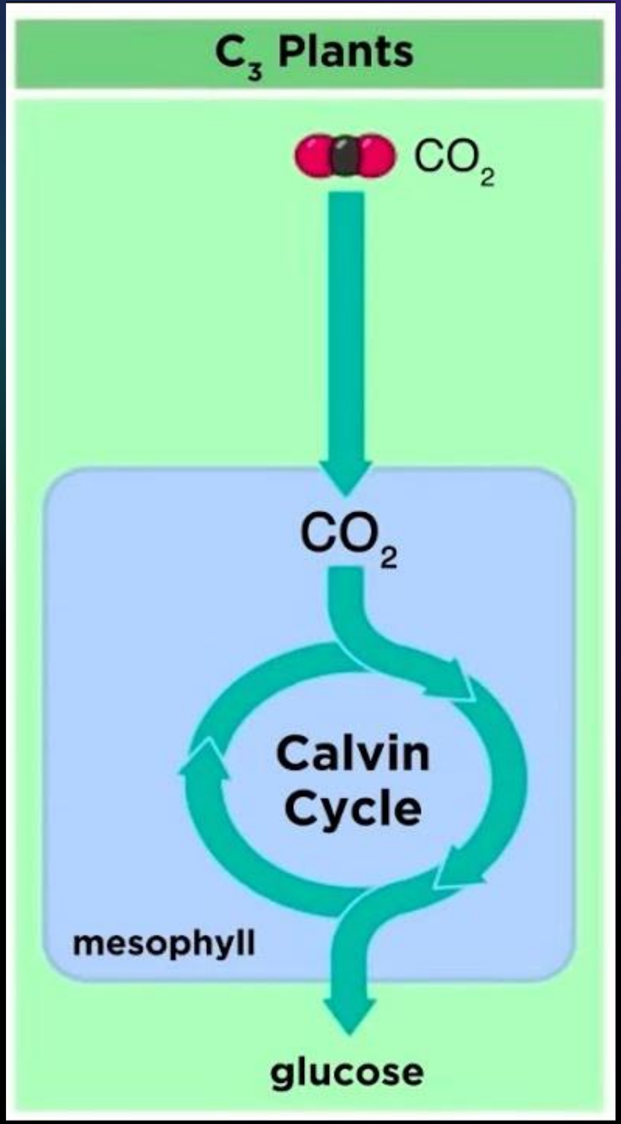
(*Biologists are working on it, though, just in case. Think of all the world problems you would solve if you could make photosynthesis happen faster!)

SOLUTIONS FOR RUBISCO

2. Make more RuBisCO. ☑

85% of all plants are C3 plants and use this strategy (e.g. rice, wheat, soybeans, trees).

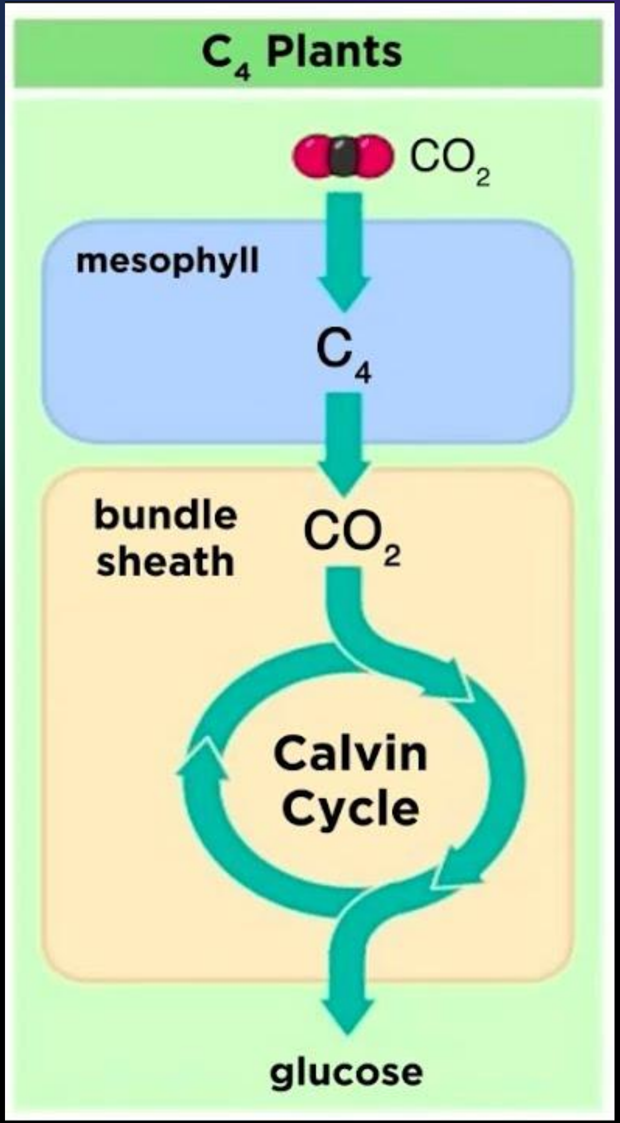
As a result, RuBisCO is the most abundant enzyme on the planet.



Solutions for RuBisCO

3. Don't let oxygen near RuBisCO. ☑

C4 plants (e.g. corn, sugarcane, millet) separate the light-dependent and light-independent reactions into two different cell types.

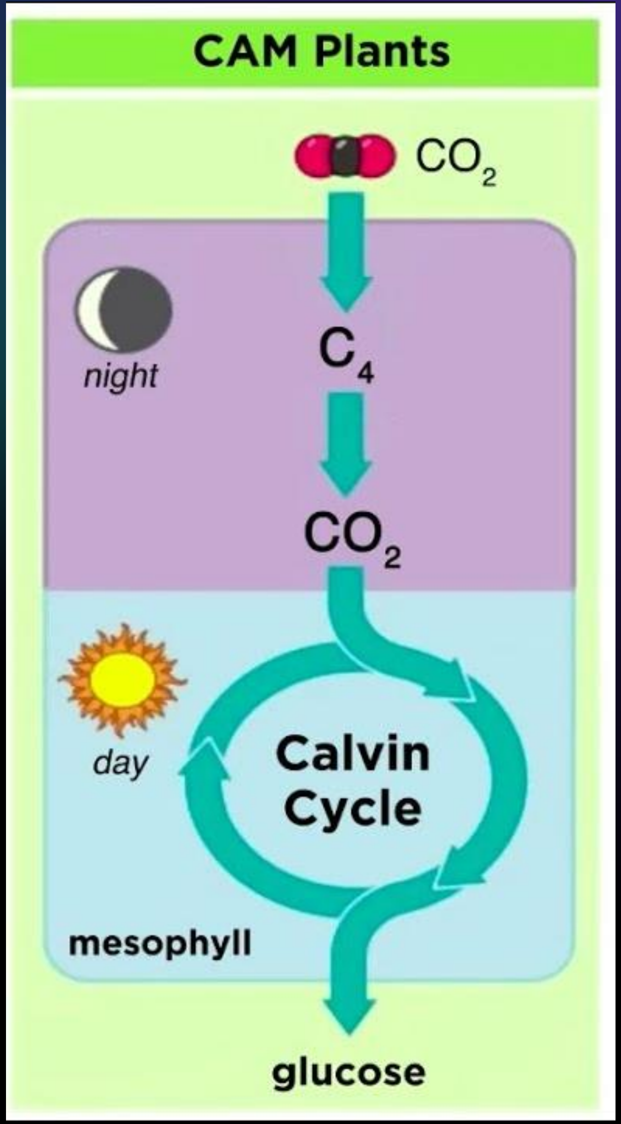


Solutions for RuBisCO

3. Don't let oxygen near RuBisCO. ☑

CAM plants (e.g. cacti, pineapples, succulents):

- Day: open pores, fix CO_2 into carbon compounds
- Night: close pores, undo daytime reactions to release CO_2 for Calvin cycle



Cellular Respiration

Cellular Respiration

Cellular respiration: the process of converting chemical energy from glucose to ATP.

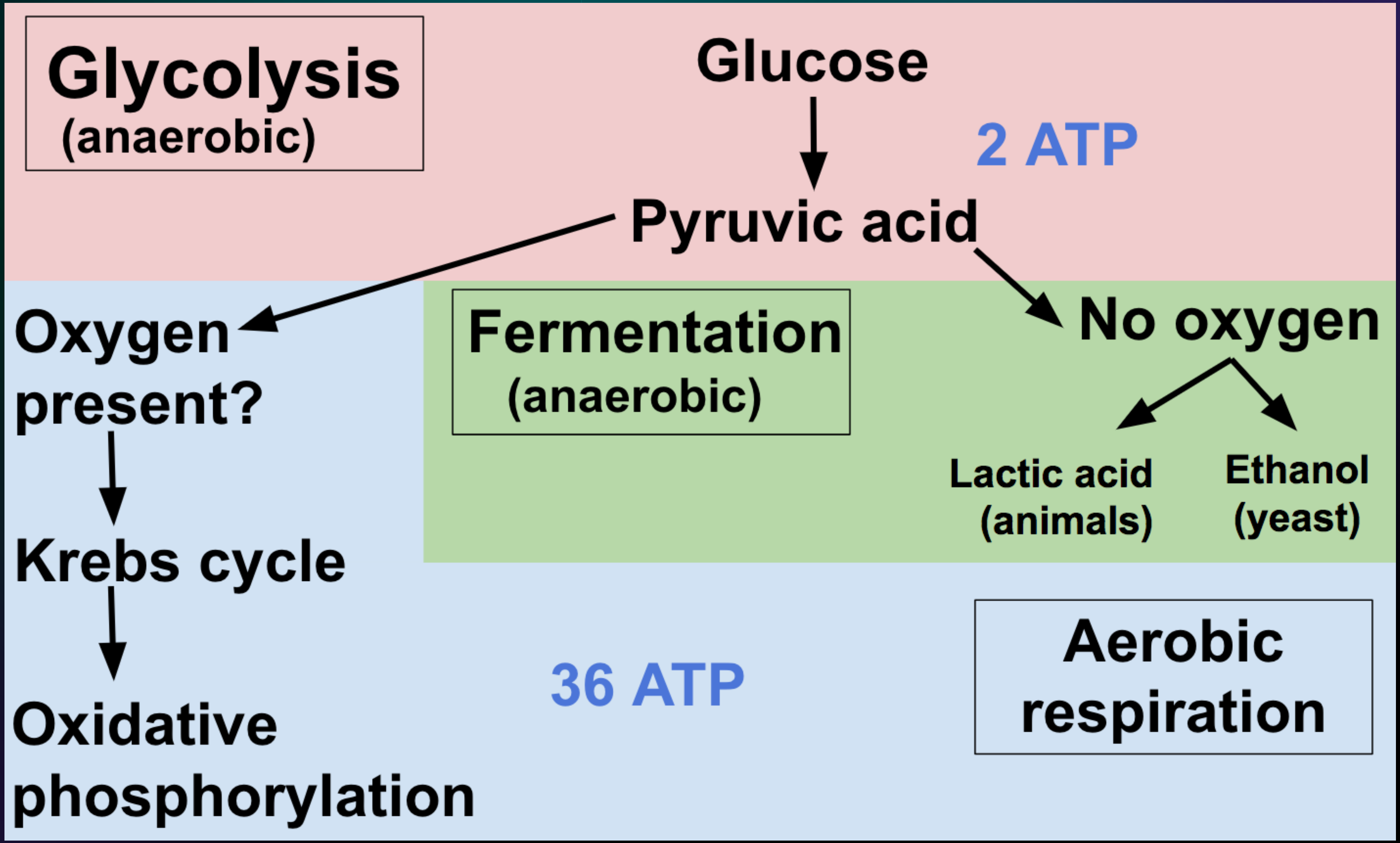
Aerobic respiration:

- Requires oxygen
- Produces 36 ATP per glucose

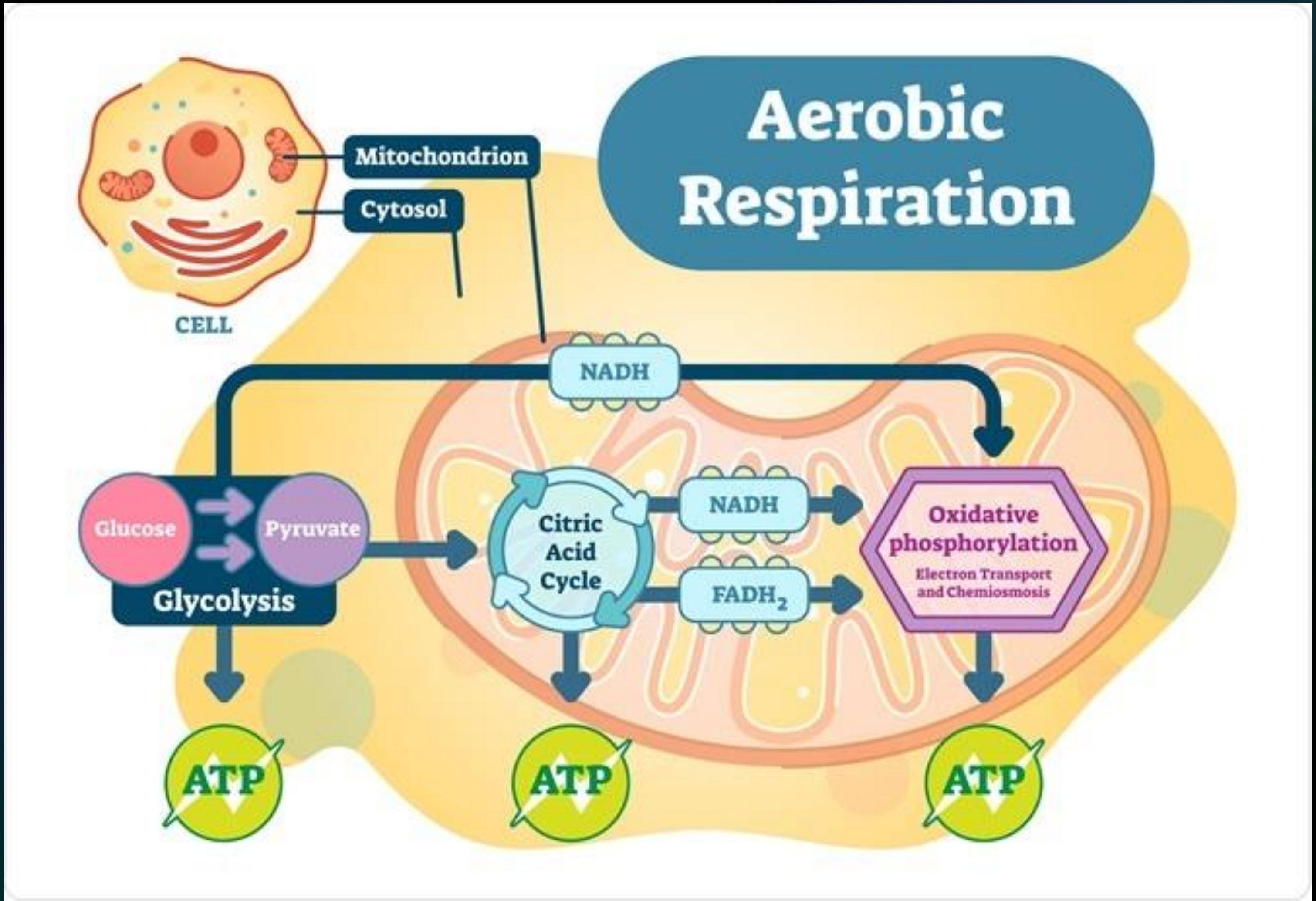
Anaerobic respiration:

- Does not require oxygen
- Produces 2 ATP per glucose

Summary: Cellular Respiration



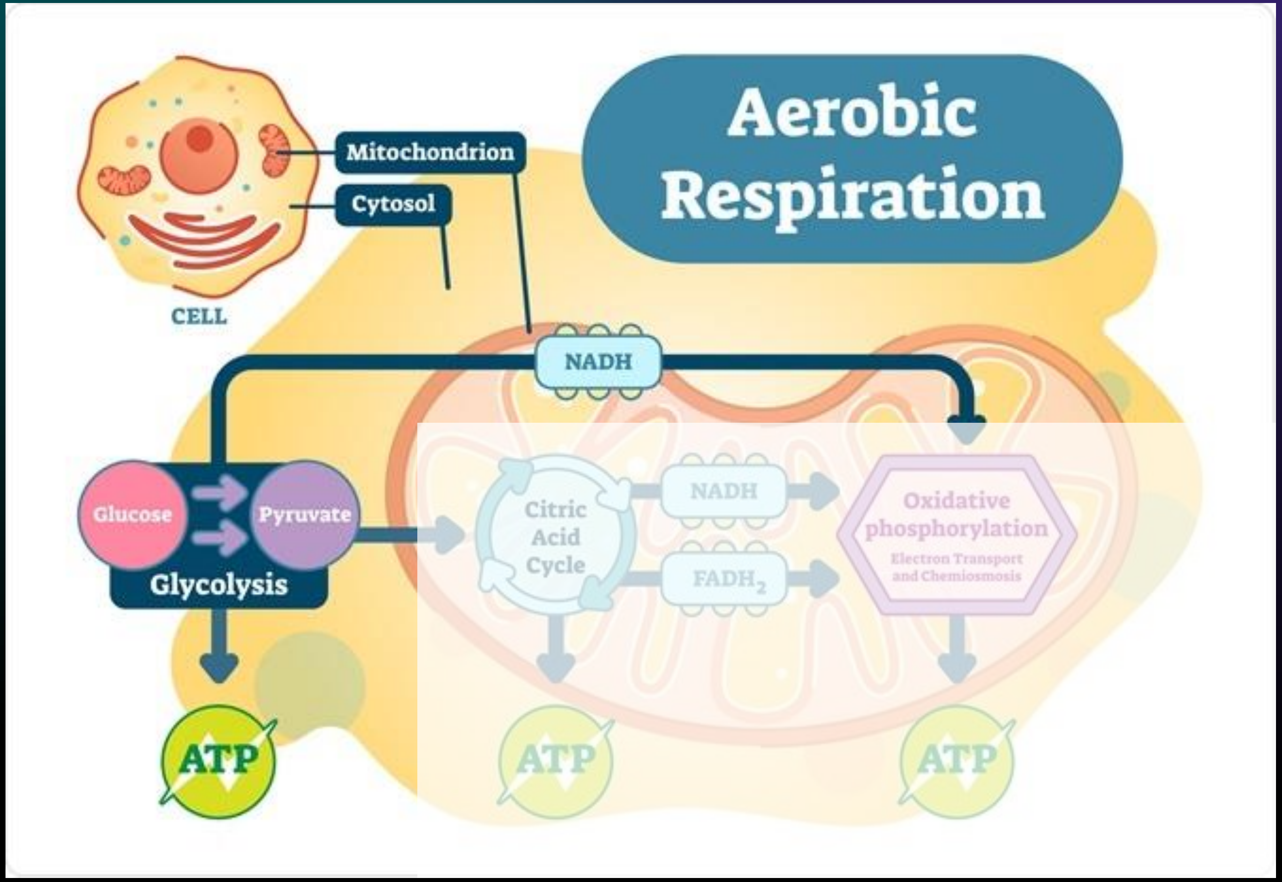
Aerobic Respiration



Stage 1: Glycolysis

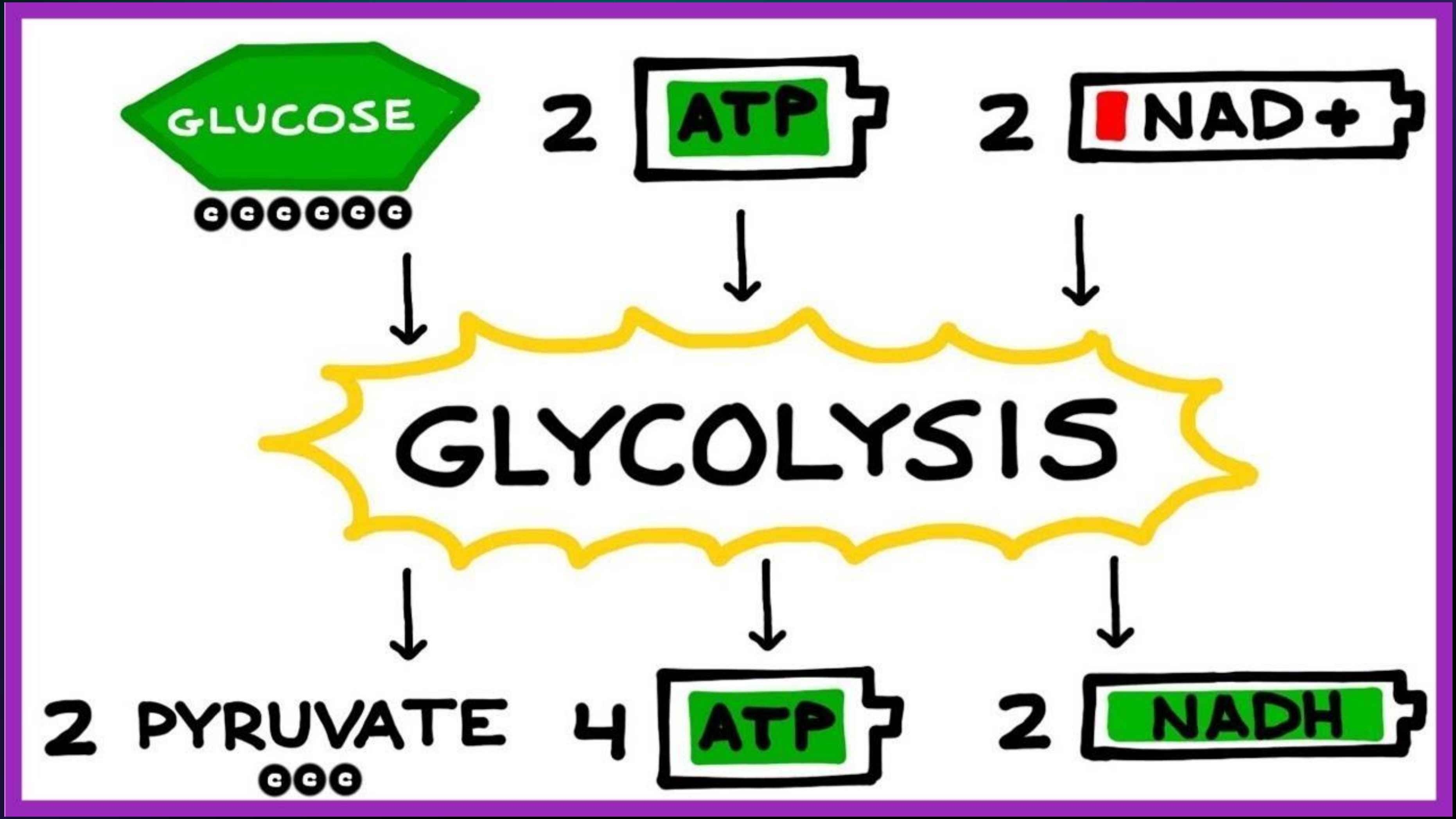
- Location: cytoplasm
- Glucose is broken down into pyruvate

Inputs	Outputs
Glucose	Pyruvate
NAD^+	NADH
ATP (2)	ATP (4)

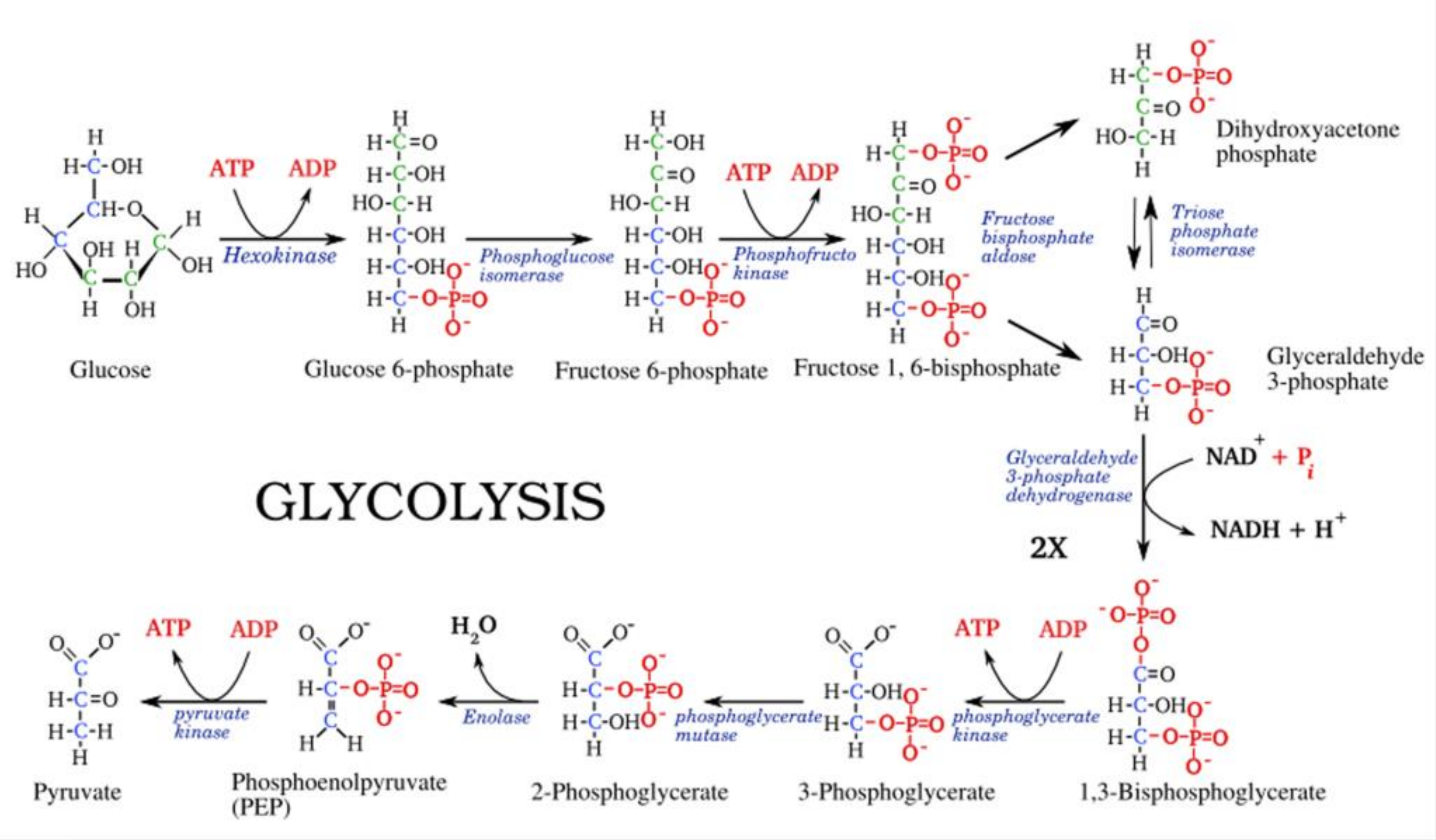


Do not memorize how many ATP, NADH, etc. are used/produced.

Stage 1: Glycolysis (easy mode)

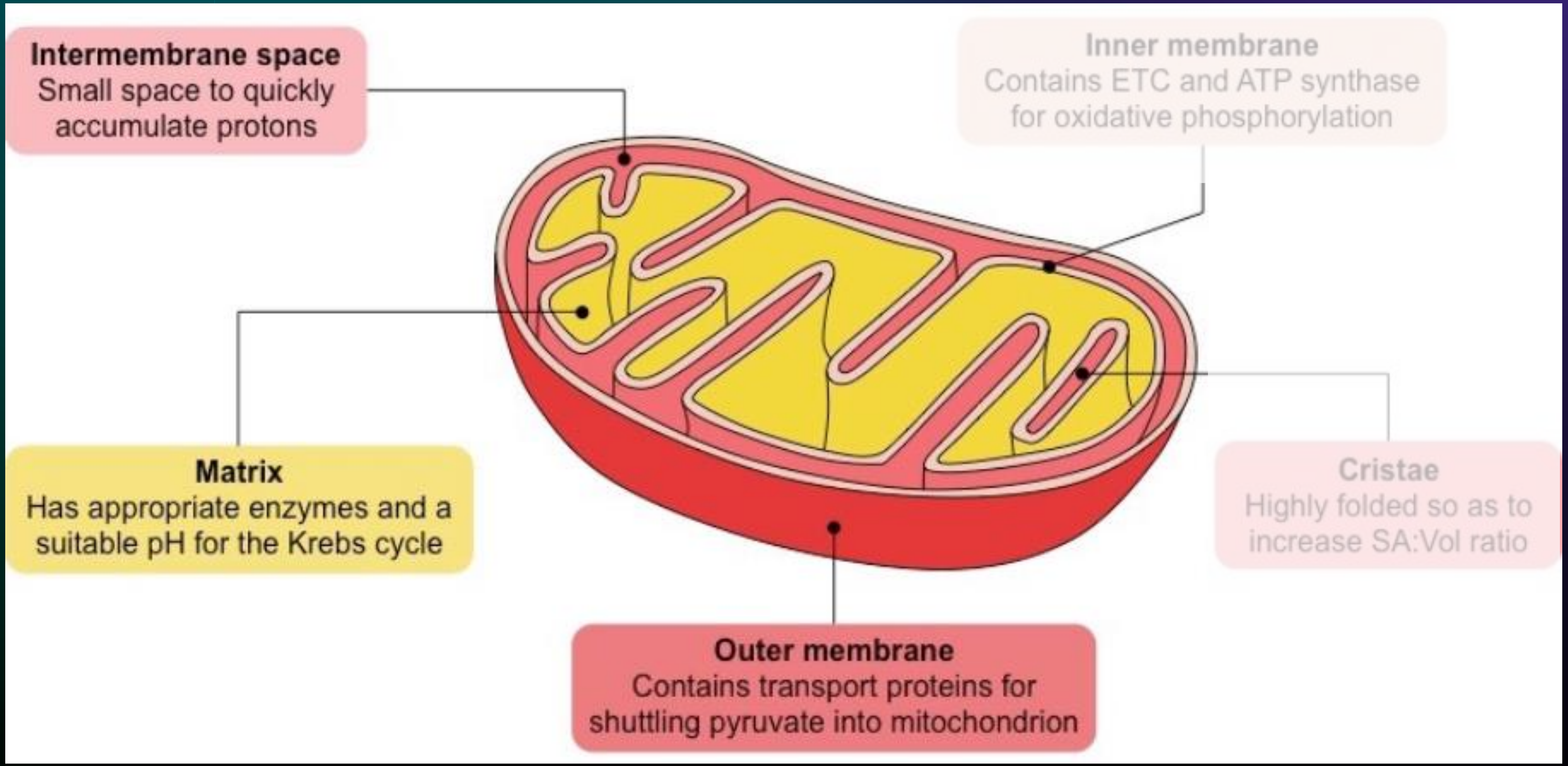


Stage 1: Glycolysis (hard mode)



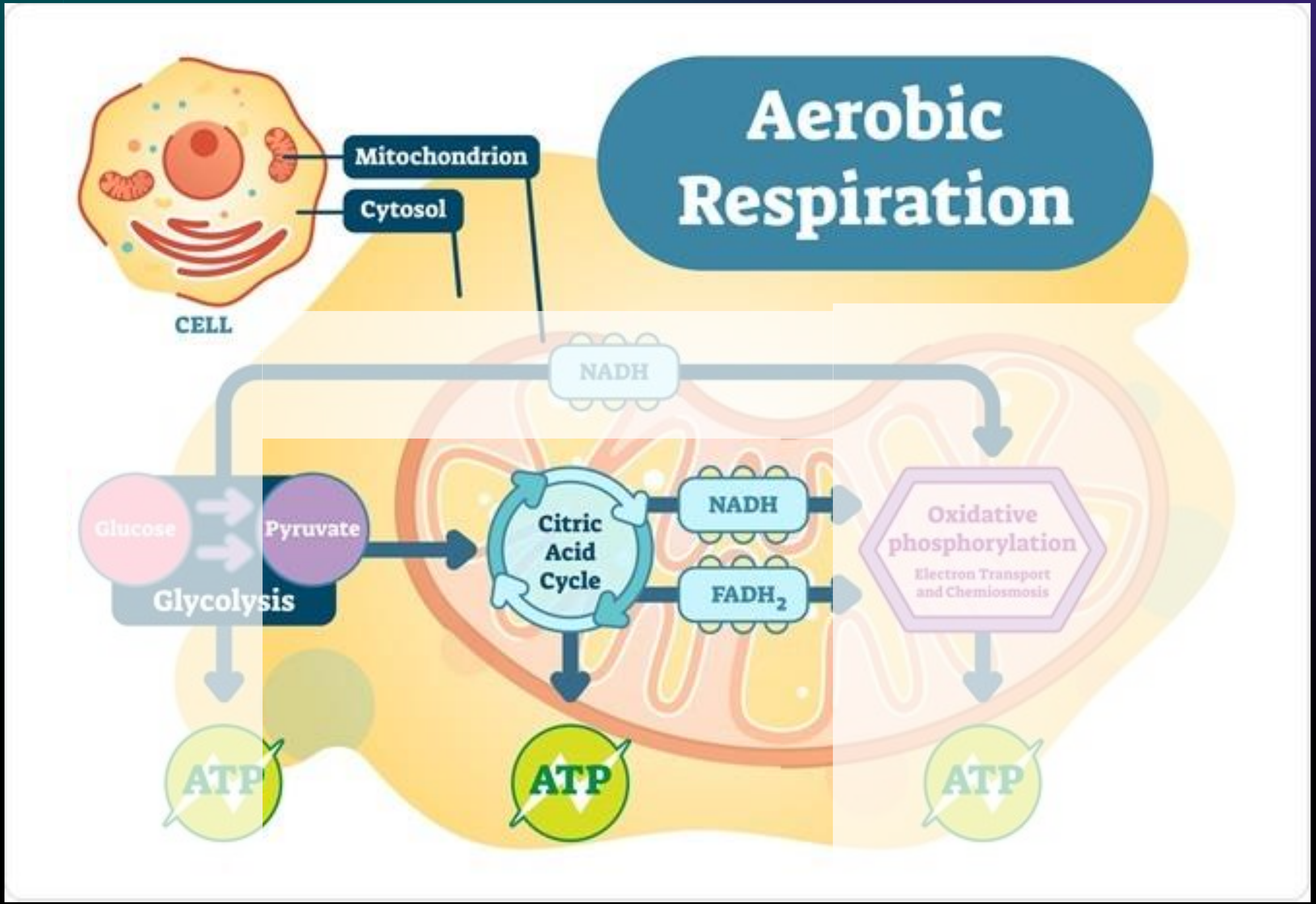
Mitochondria Structure

- Eukaryotes use mitochondria to perform aerobic respiration
- Some prokaryotes can also do aerobic respiration, using their cell membranes

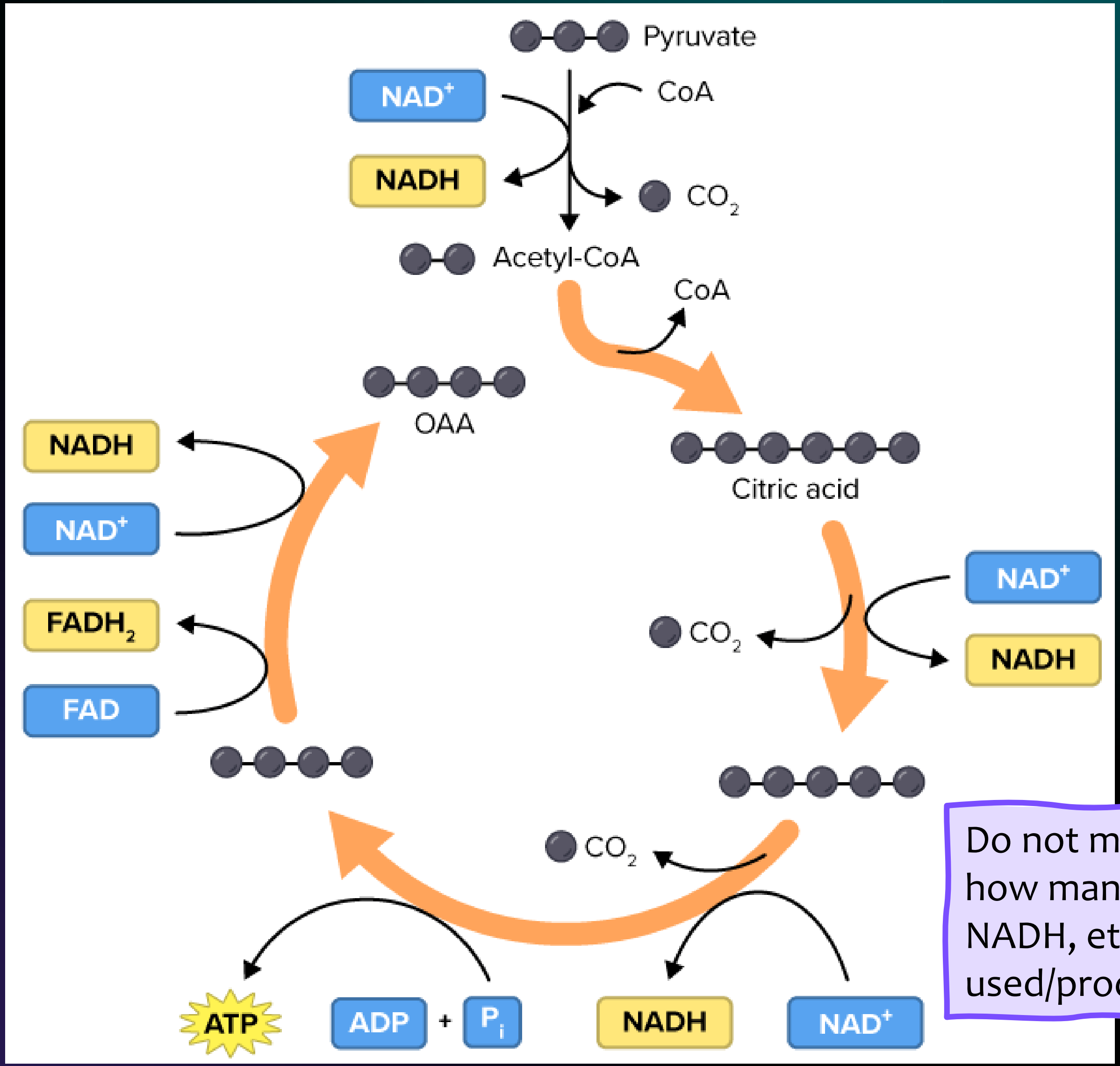


Stage 2: The Krebs Cycle

- Pyruvate enters the mitochondrial matrix and is broken down
- Energy is used to produce high-energy compounds
- Also known as "Citric Acid Cycle"



STAGE 2: THE KREBS CYCLE



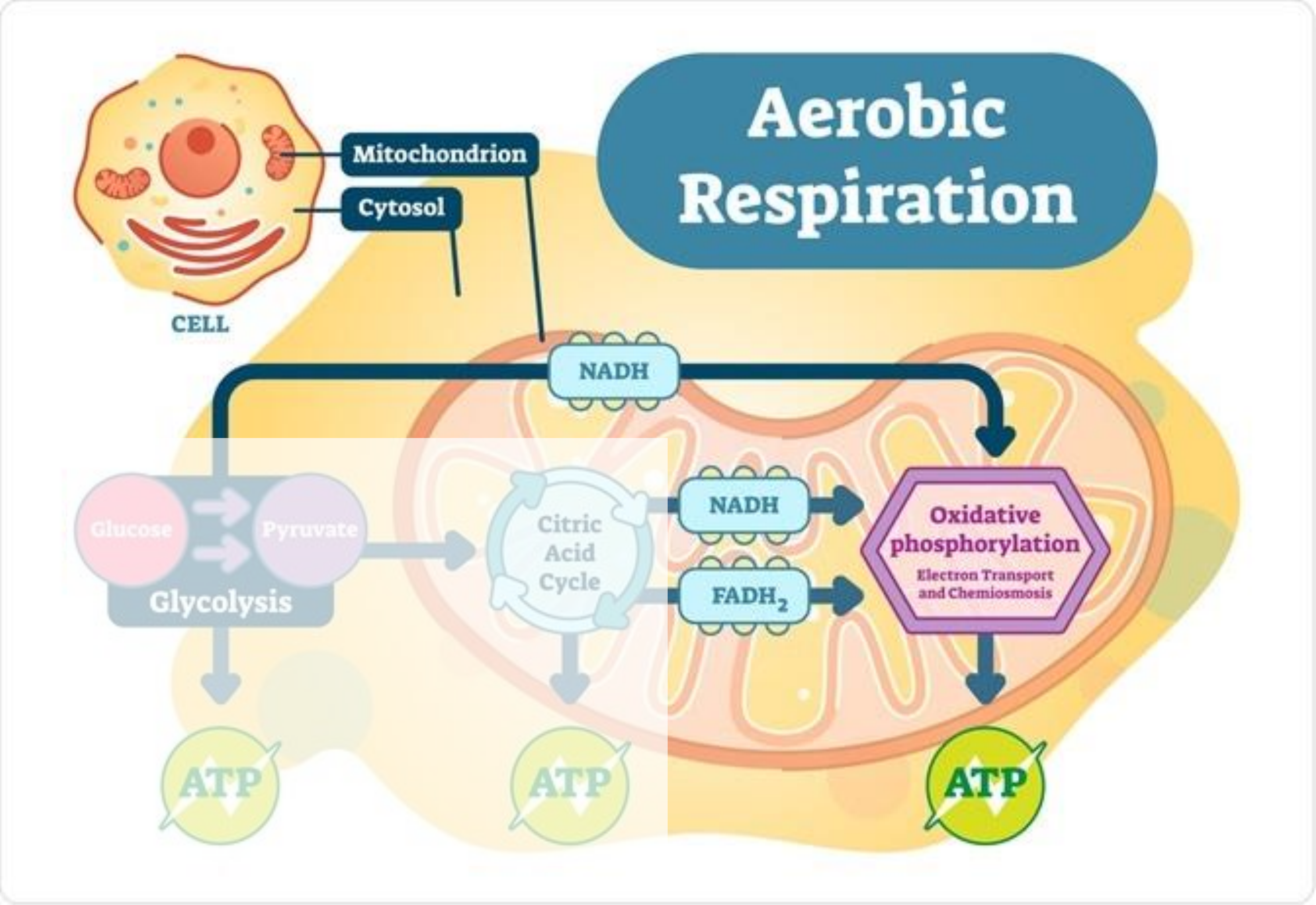
Inputs	Outputs
pyruvate	CO_2 (diffuses out)
NAD^+	NADH (high-energy)
FAD	$FADH_2$ (high-energy)
ADP	ATP (a little)

Do not memorize how many ATP, NADH, etc. are used/produced.

Stages 3-4 Preview (Summary)

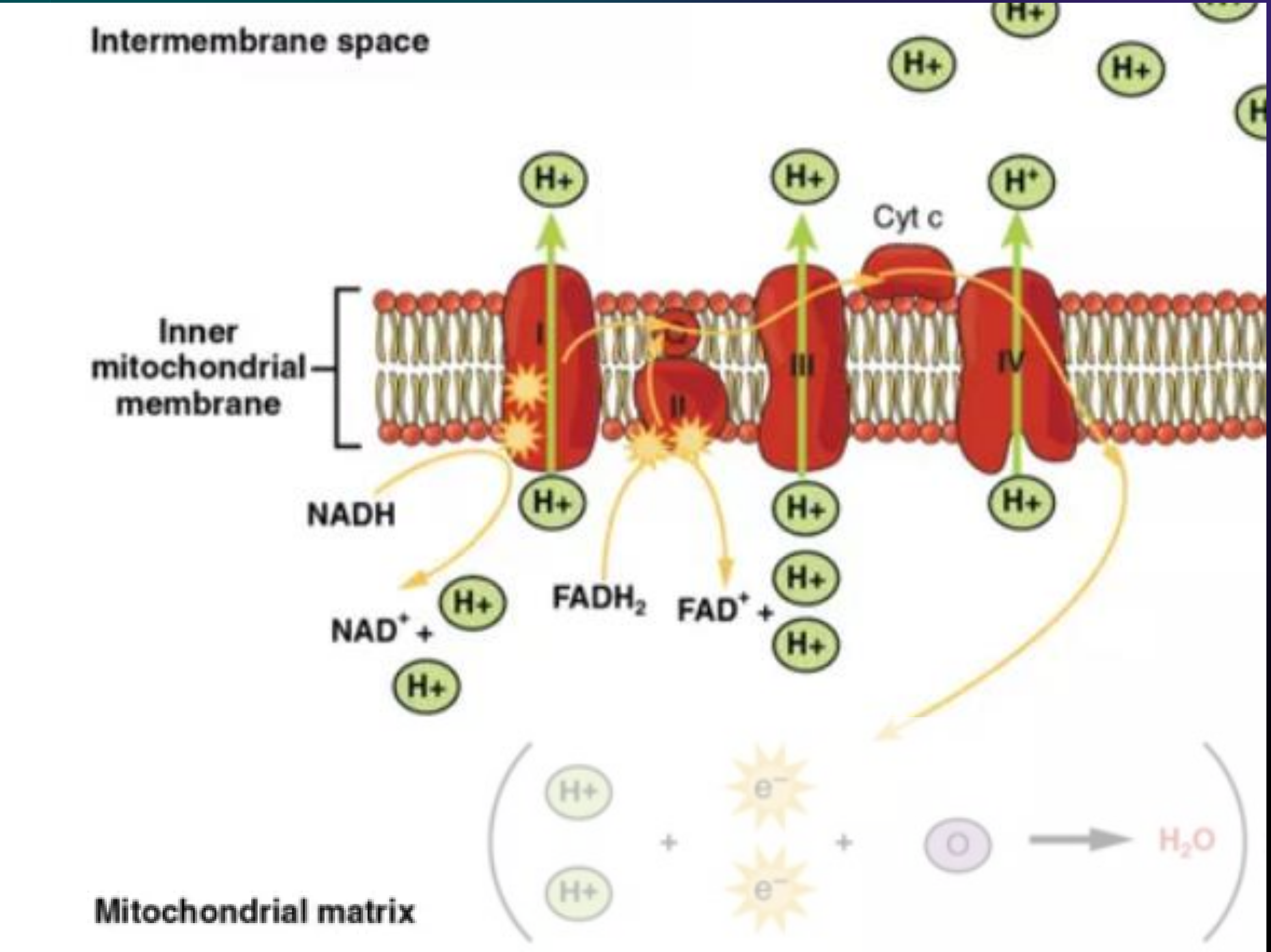
- $NADH$ and $FADH_2$ energy used to produce ATP

Inputs	Outputs
O_2	H_2O
NADH	NAD^+ (reused: Krebs)
$FADH_2$	FAD (reused: Krebs)
ADP	ATP (a ***lot***)



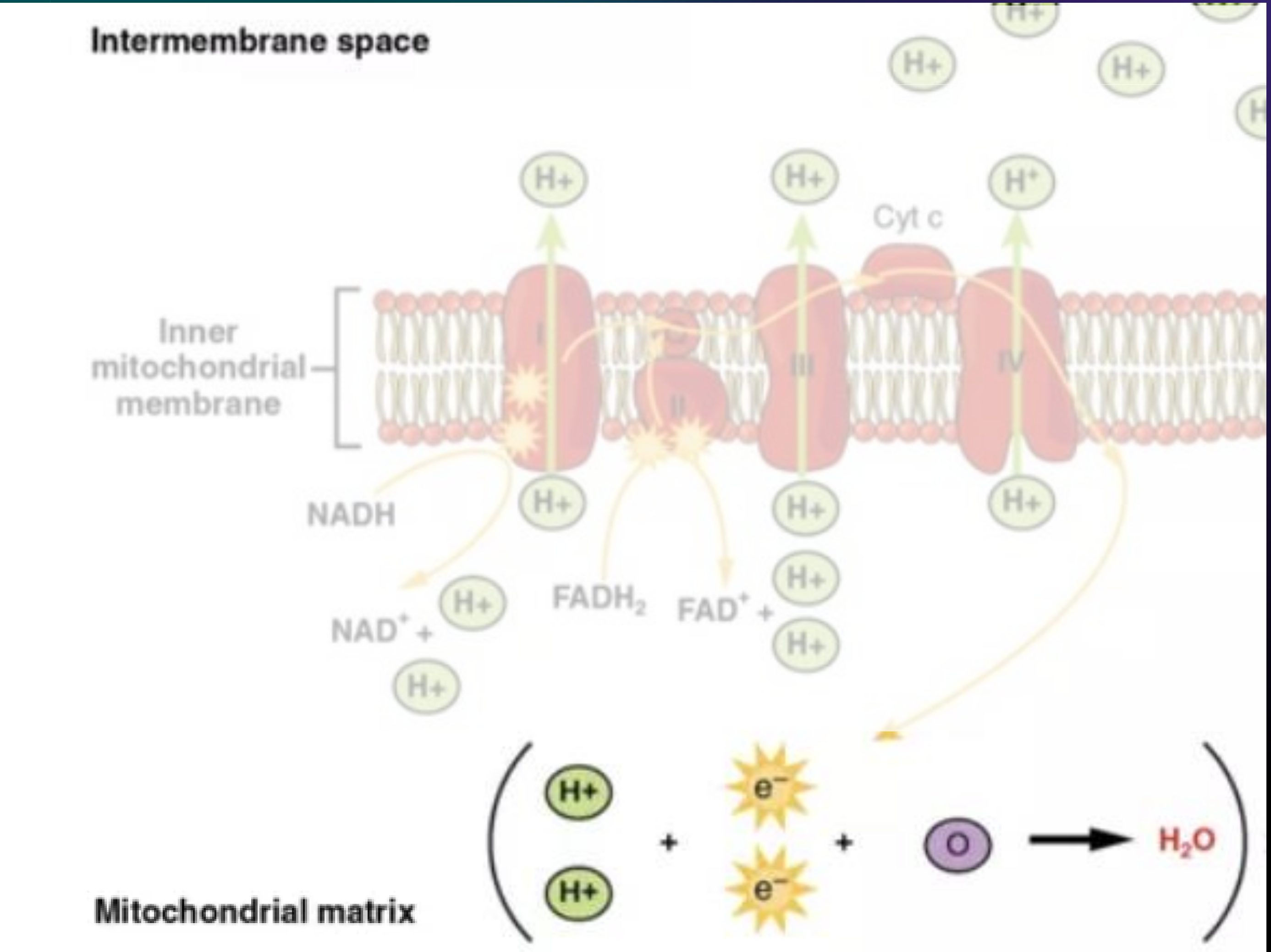
Stage 3: Electron Transport Chain

- NADH and $FADH_2$ pass their high-energy electrons through electron transport chains
- Energy from NADH and $FADH_2$ used to pump H^+ into the intermembrane space



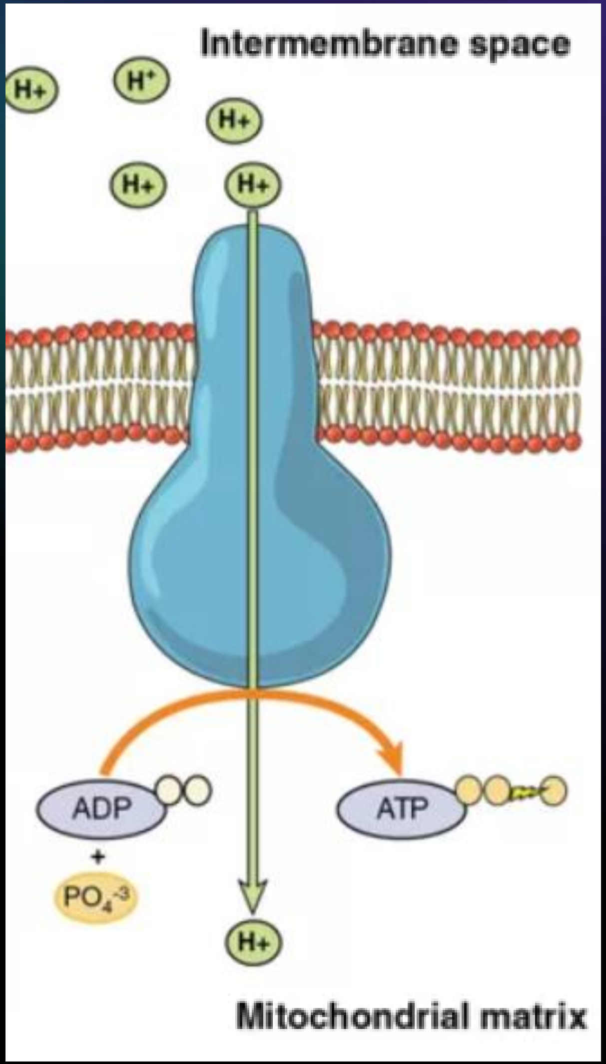
Stage 3: Electron Transport Chain

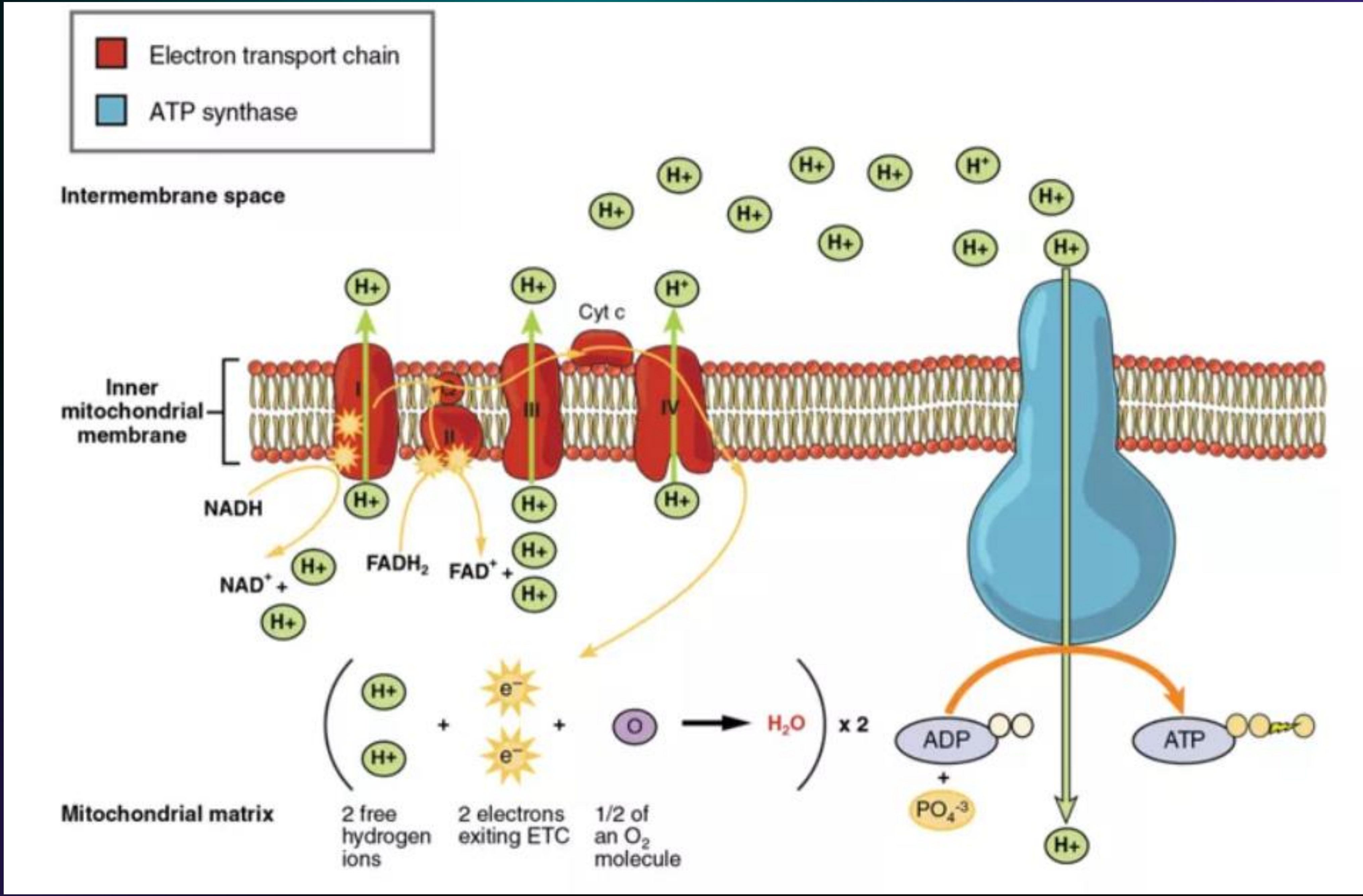
- Lower-energy electrons combine with H^+ and O_2 and produce H_2O



Stage 4: ATP Production

- H^+ moves through ATP synthase from the intermembrane space to the matrix
- ATP synthase converts ADP to ATP



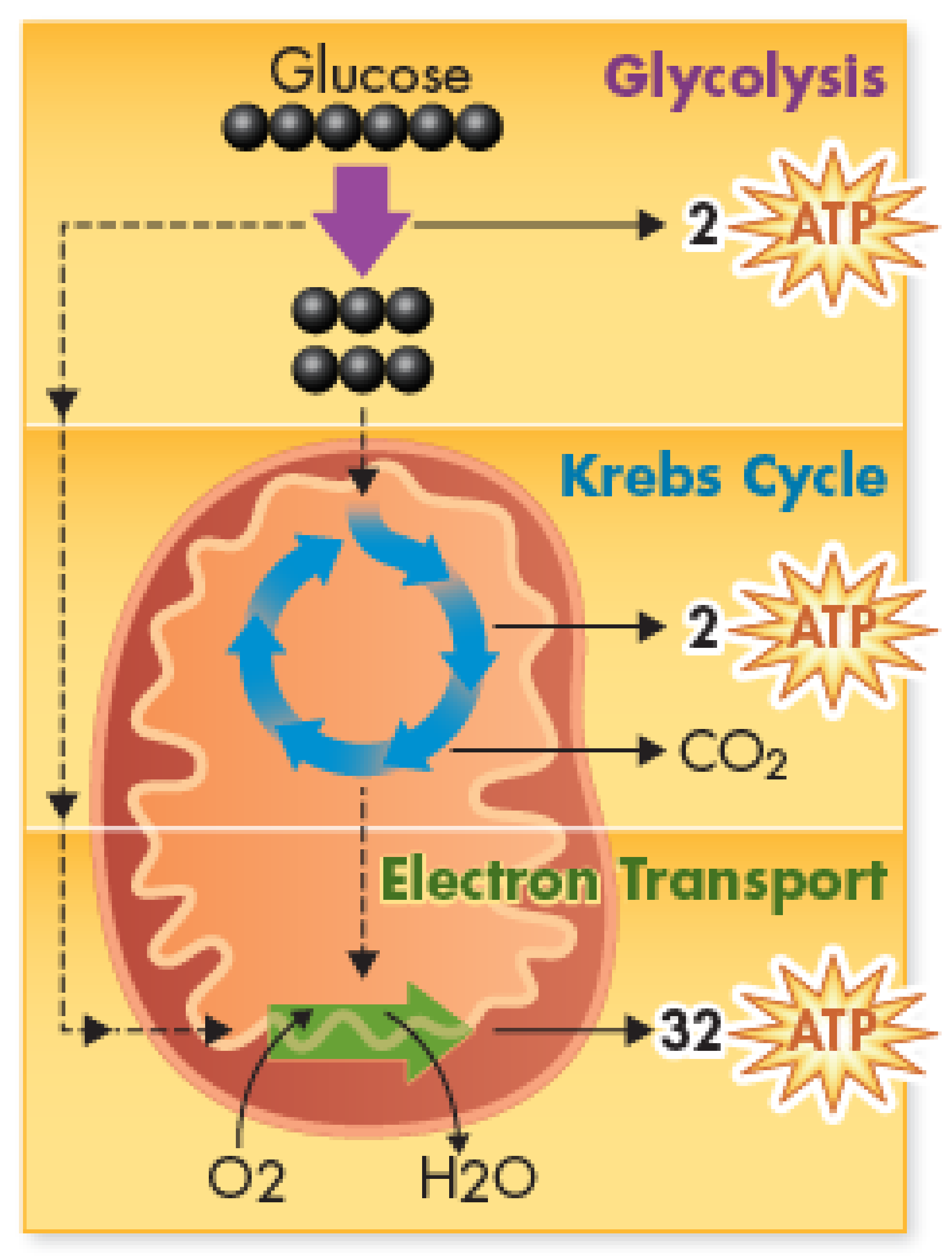


Electron transport chain
ATP synthase
Intermembrane space
H+
Cyt c
I
II
III
IV
Inner mitochondrial membrane
NADH
NAD^+ +
$FADH_2$
FAD^+ +
e⁻
O
H_2O
x 2
ADP
+
PO_4^{-3}
ATP
Mitochondrial matrix
2 free hydrogen ions
2 electrons exiting ETC
1/2 of an O_2 molecule

Cellular Respiration Summary

$C_6H_{12}O_6 + O_2 \rightarrow$

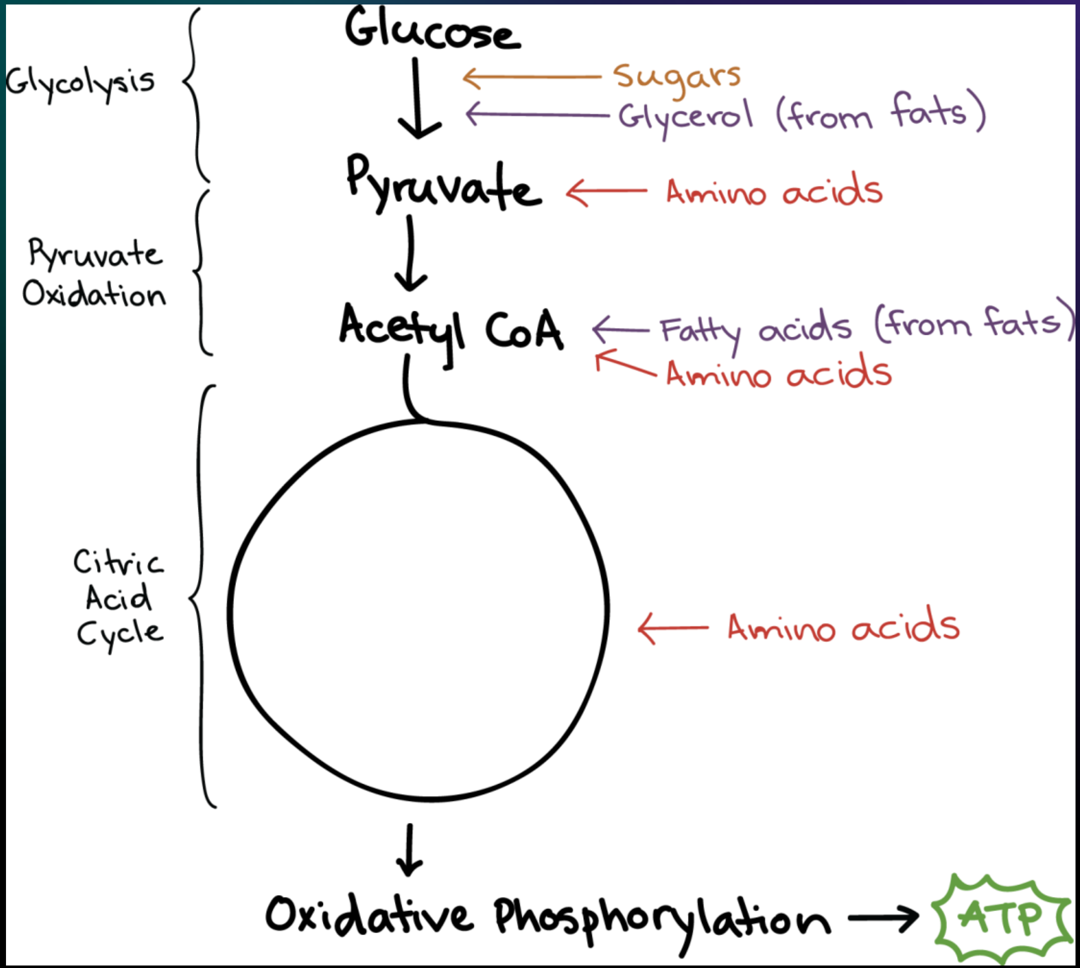
$CO_2 + H_2O$ + ATP energy



Using Other Molecules for Energy

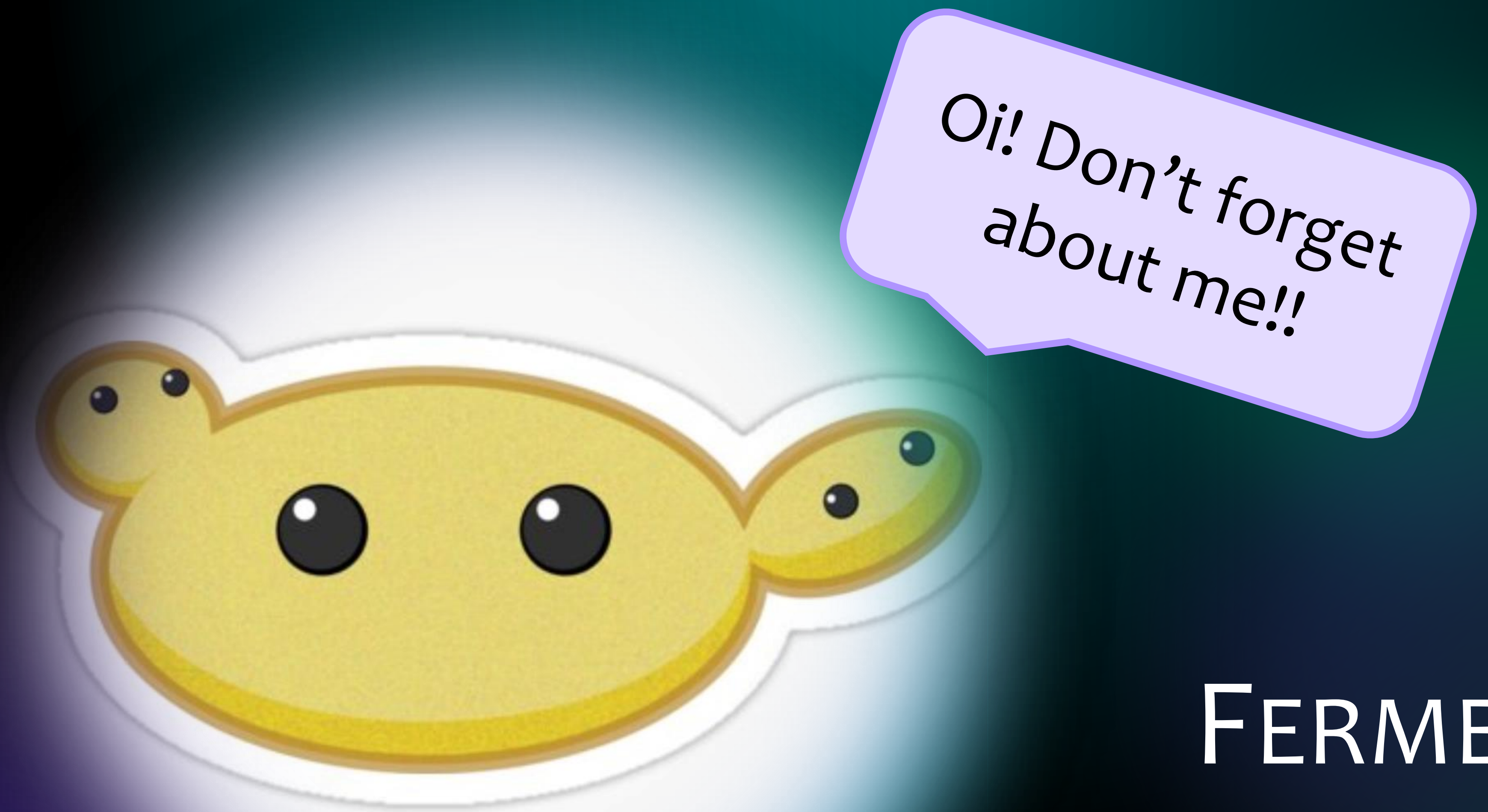
Proteins, fats, and complex carbohydrates can all be used for energy, too!

They simply enter cellular respiration at different points.



Pop Quiz!

1) Summarize the products of each stage:
   a) Glycolysis
   b) Krebs cycle
   c) Electron transport chain
   d) ATP synthesis



Fermentation

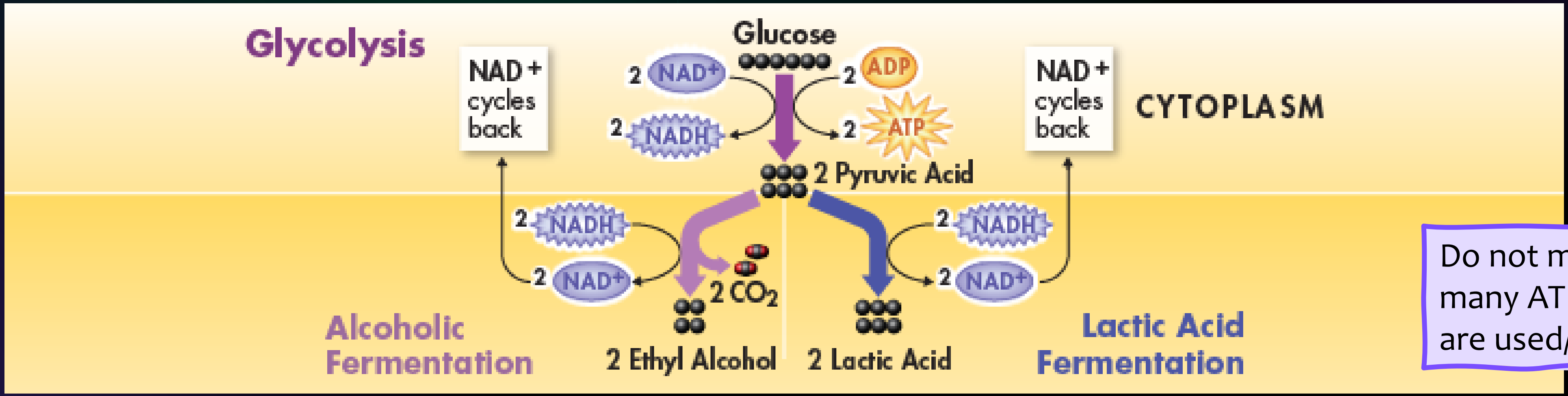
Fermentation (Anaerobic Respiration)

- Glycolysis reminder:

  2 ATP + 2 NAD^+ + glucose → **4 ATP** + 2 NADH + 2 pyruvate

- If oxygen is not available, fermentation occurs after glycolysis
- Purpose of fermentation:

  convert NADH to NAD^+ so it can be re-used in glycolysis

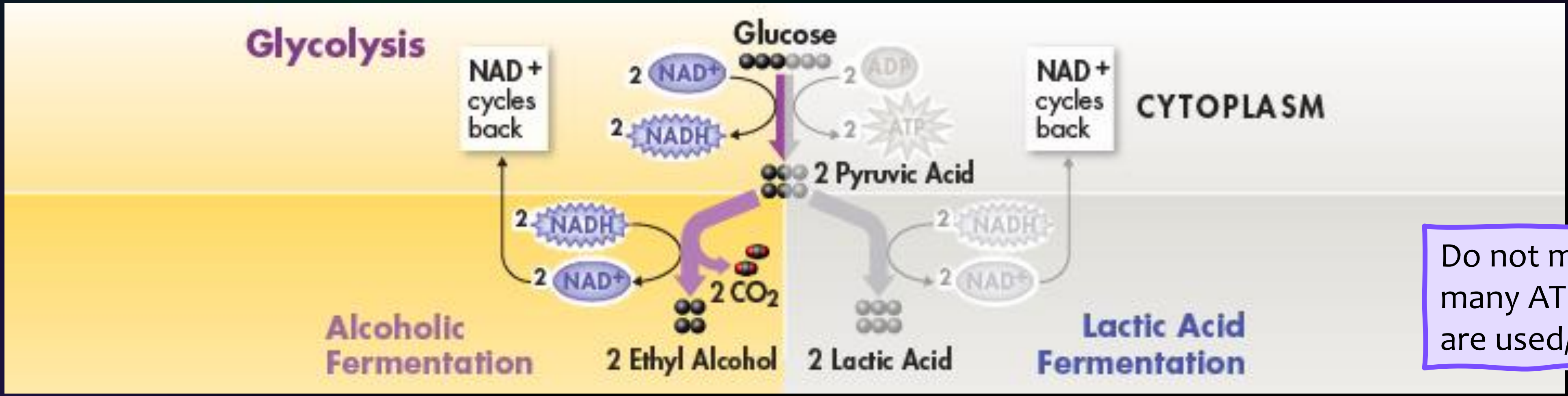


Do not memorize how many ATP, NADH, etc. are used/produced.

Alcoholic Fermentation

- Yeast and other micro-organisms
- Use by humans: make alcoholic beverages, make bread rise

NADH → NAD^+ pyruvate → alcohol and CO_2

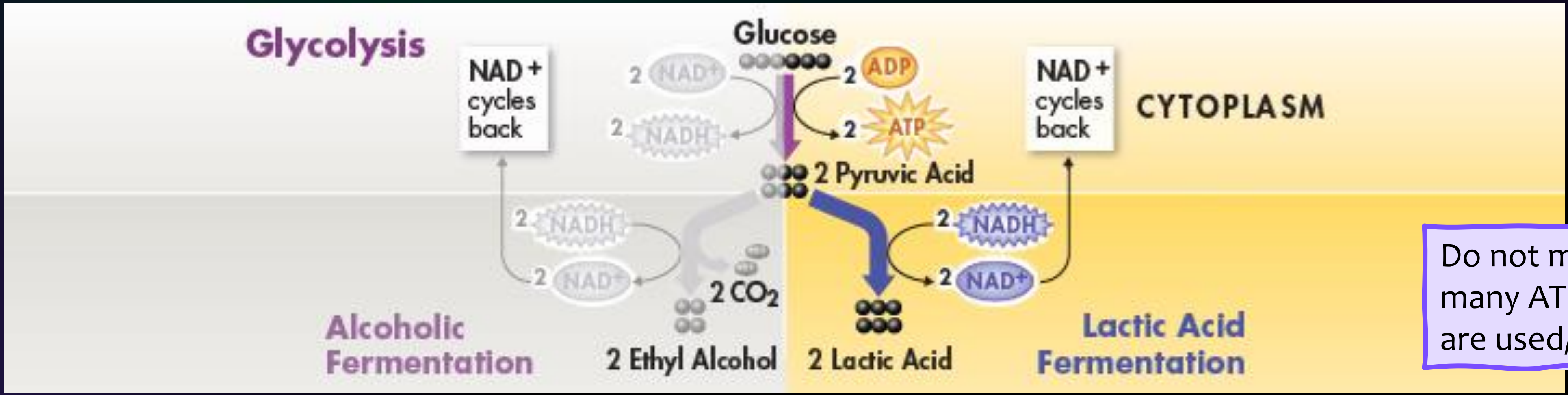


Do not memorize how many ATP, NADH, etc. are used/produced.

Lactic Acid Fermentation

- Most prokaryotic and eukaryotic organisms
- Occurs in human muscle cells during intense exercise when oxygen is low

NADH → NAD^+ pyruvate → lactic acid



Do not memorize how many ATP, NADH, etc. are used/produced.

Case Study: Diets and Exercise

1. What types of cellular respiration are used in short-term, high-intensity exercise vs long-term, low-intensity exercise?
2. What are the recommended diets for sprinters vs marathon runners? Why does this ‘make sense’ in light of what you know about cellular respiration?

Sources

- Textbook chapter 6 (pg 112-135)
- Various internet sources