Warm-Up

1. Write out the chemical equation for cellular respiration.
2. Which molecule in the equation stores the most free energy?
3. What type of chemical reaction(s) is respiration? (Exergonic or endergonic? Anabolic or catabolic?)
4. Which organelle is involved in aerobic cellular respiration?

Chapter 7 Warm-Up

Define:

- Glycolysis
- Respiration
- Chemiosmosis
- Phosphorylation
- Fermentation
- ATP (draw and label)
- Electrochemical gradient
- FAD → $FADH_2$
- NAD^+ → NADH

1. What is the role of phosphofructokinase? How does it "work"?

2. Explain "glycolysis". Where does it occur? How does it "work"?

Chapter 7 Warm-Up

1. What is the chemical equation for cellular respiration?
2. Remember: OILRIG
   A. In the conversion of glucose and oxygen to CO_2 and H_2O, which molecule is reduced?
   B. Which is oxidized?
   C. What happens to the energy that is released in this redox reaction?
3. NAD^+ is called a(n) ____________________.
   Its reduced form is ________.

Chapter 7 Warm-Up

1. What is 1 fact you remember from yesterday's sugar article?
2. Why is glycolysis considered an ancient metabolic process?
3. Where in the cell does glycolysis occur?
4. What are the reactants and products of glycolysis?

Mitochondria Article

- **Here's what!**
  - Summarize the main ideas in this article
  - What is the research about?
- **So what?**
  - Why is the research being conducted?
  - What is the importance of this work?
  - What is the data showing?
- **Now what?**
  - What are the next steps?
  - What do scientists hope to accomplish in the future with this information?

Chapter 7 Warm-Up

1. Which has more energy available:
   a. ADP or ATP?
   b. NAD^+ or NADH?
   c. FAD^+ or $FADH_2$?
2. Where does the Citric Acid Cycle occur in the cell?
3. What are the main products of the CAC?

Chapter 7 Warm-Up

1. How is the proton gradient generated?

2. What is its purpose?

3. Describe how ATP synthase works.

Chapter 7 Warm-Up

1. Where are the proteins of the ETC located?
2. Where does the ETC pump H^+ ions into?
3. In cellular respiration, how many ATP are generated through:
   A. Substrate-level phosphorylation?
   B. Oxidative phosphorylation?

Chapter 7 Warm-Up

1. In fermentation, how is NAD^+ recycled?
2. You eat a steak and salad. Which macromolecule cannot be broken down to make ATP?
3. Think about the structure of a fat molecule. What feature of its structure makes it a better fuel than a carbohydrate (like glucose)?
2. Explain where the fat goes when you lose weight.

Chapter 7 Warm-Up

1. In fermentation, how is NAD^+ recycled?
2. What is the function of the enzyme phosphofructokinase?
3. You eat a steak and salad. Which macromolecule cannot be broken down to make ATP?
2. Explain where the fat goes when you lose weight.

Chapter 7: Respiration

What you need to know:

- The summary equation of cellular respiration including the source and fate of the reactants and products.
- The difference between fermentation and cellular respiration.
- The role of glycolysis in oxidizing glucose to two molecules of pyruvate while releasing free energy to form ATP.
- How pyruvate is moved from the cytosol into the mitochondria and introduced into the citric acid cycle.
- How electrons from NADH and $FADH_2$ are passed to a series of electron acceptors to product ATP by chemiosmosis.
- The roles of the mitochondrial membrane, proton (H^+) gradient, and ATP synthase in generating ATP.

In open systems, cells require E to perform work (chemical, transport, mechanical)

E flows into ecosystem as Sunlight

↓

Autotrophs transform it into chemical E

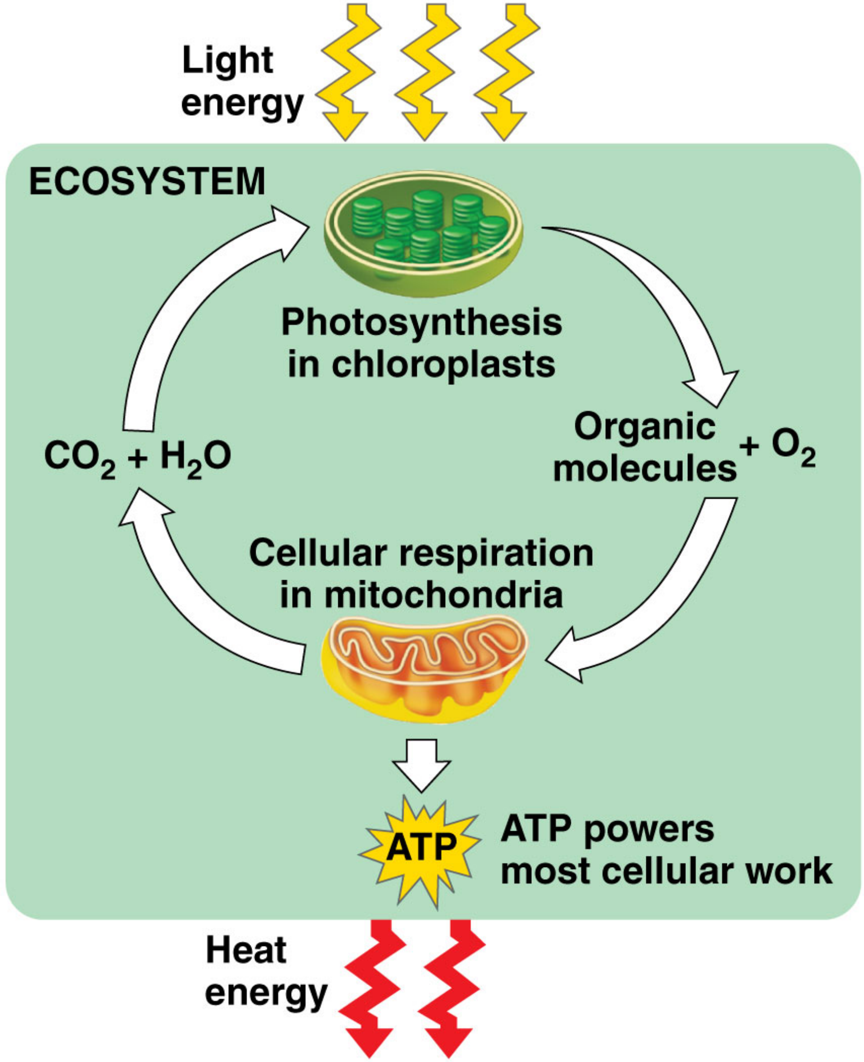
O_2 released as byproduct

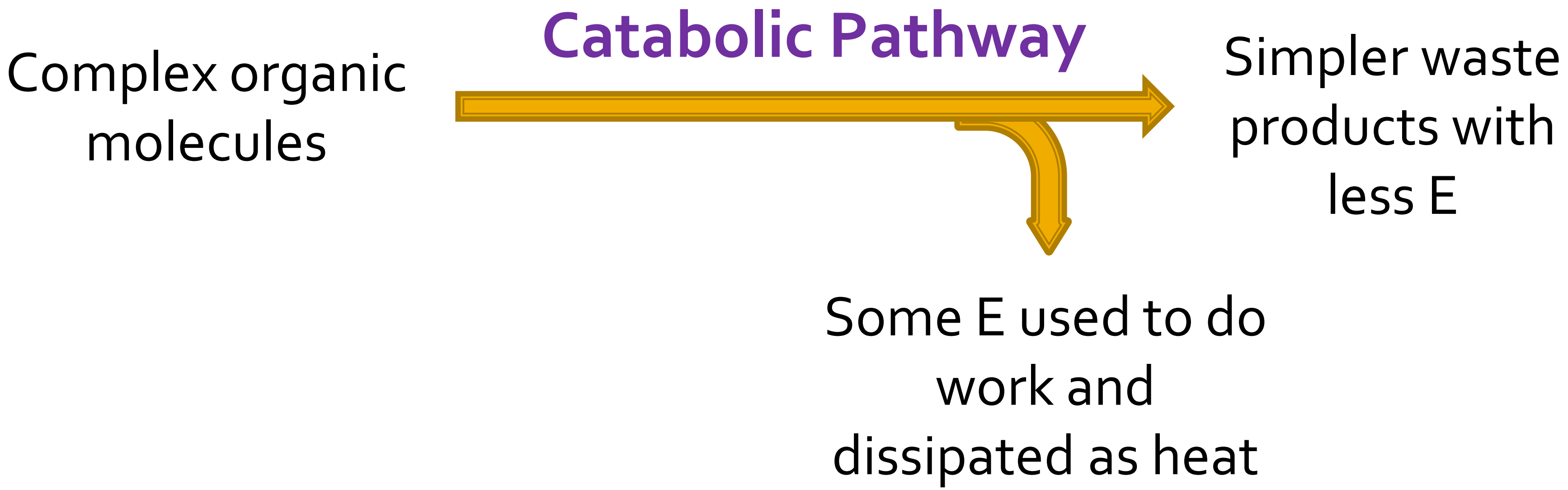
↓

Cells use some of chemical E in organic molecules to make ATP

↓

E leaves as heat




Catabolic Pathway
Complex organic molecules
Simpler waste products with less E
Some E used to do work and dissipated as heat

Respiration: exergonic (releases E)

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2 + \textbf{ATP} \text{ (+ heat)}$$

Photosynthesis: endergonic (requires E)

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

Redox Reactions (oxidation-reduction)

oxidation (donor) lose e^-

$$Xe^- + Y \rightarrow X + Ye^-$$

reduction (acceptor) gain e^-

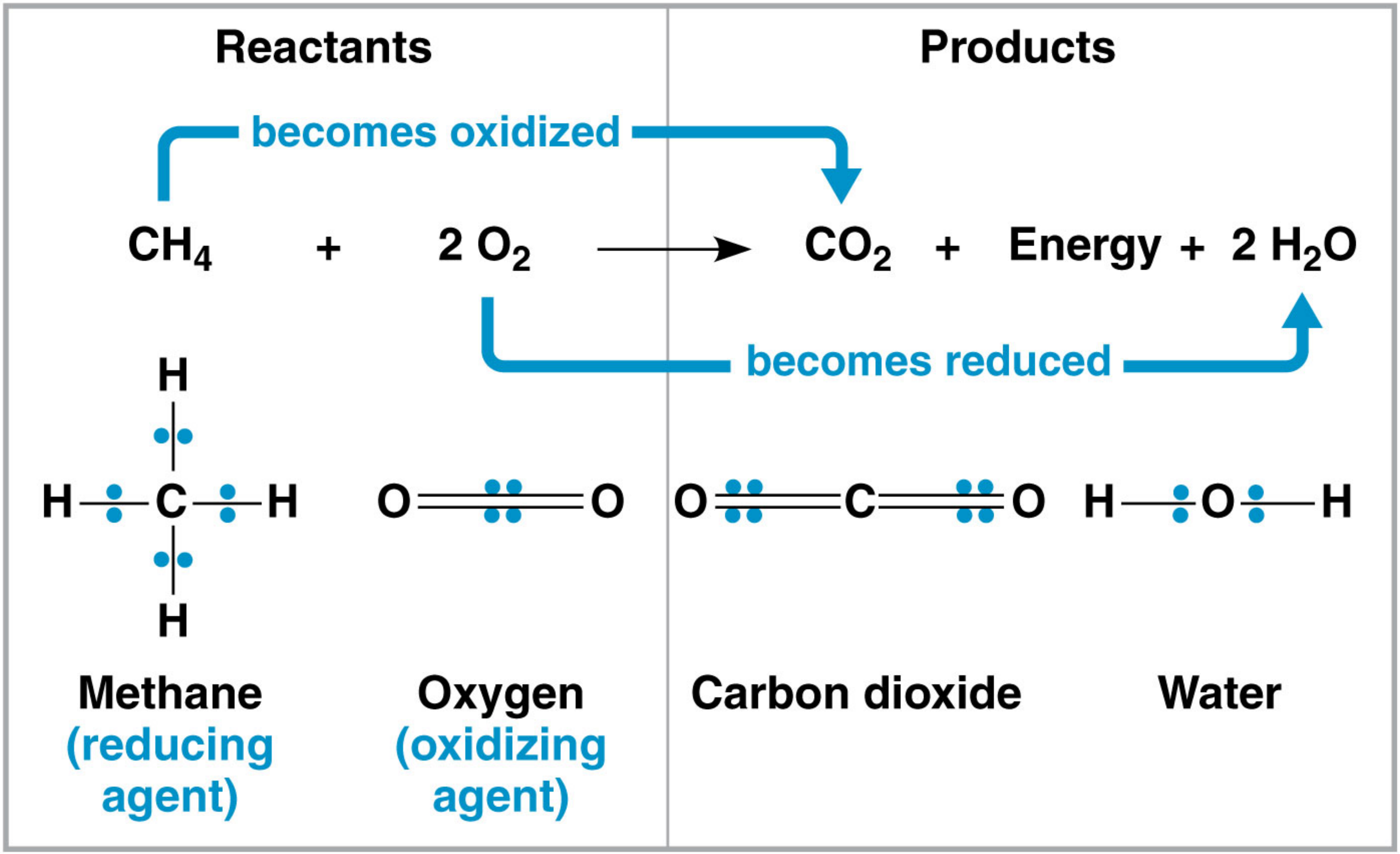
- Oxidation = lose e^-
- Reduction = gain e^-

OiLRiG or LeoGer

oxidation

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

reduction


Reactants
Products
becomes oxidized
CH4 + 2 O2 → CO2 + Energy + 2 H2O
becomes reduced
Methane
(reducing agent)
Oxygen
(oxidizing agent)
Carbon dioxide
Water

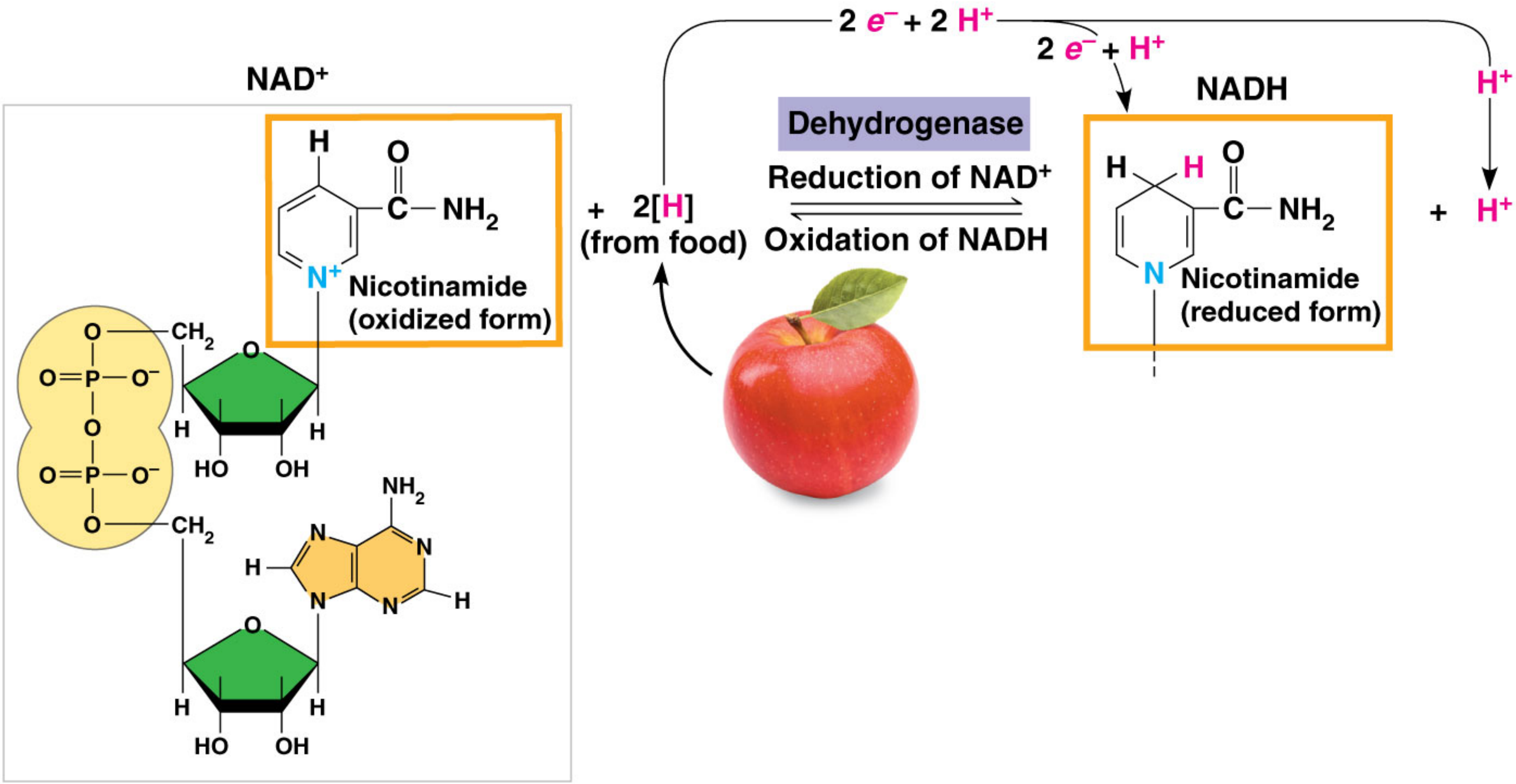
Energy Harvest

- Energy is released as electrons "fall" from organic molecules to O_2
- Broken down into steps:

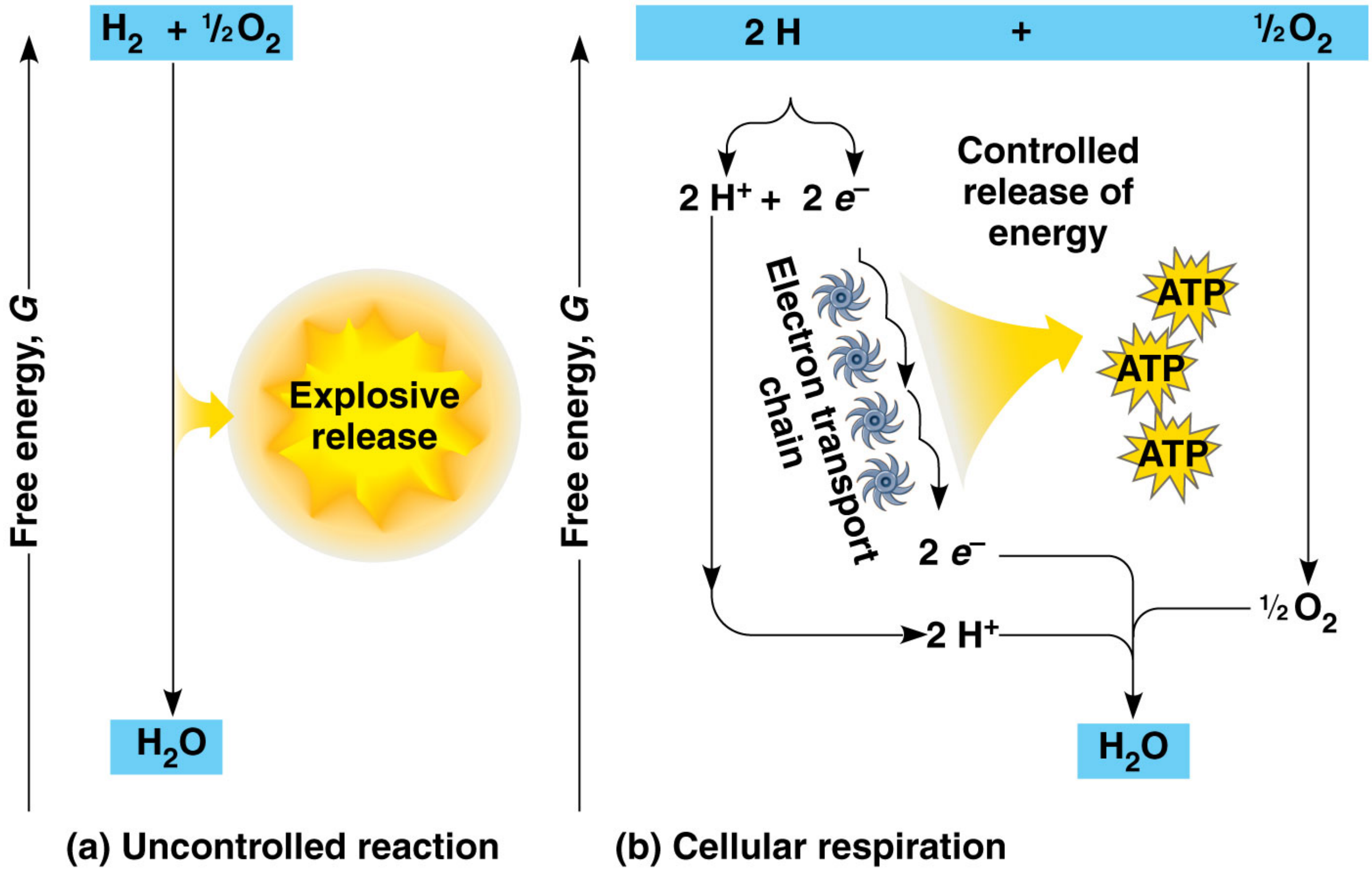
  Food (Glucose) → NADH → ETC → O_2

  - Coenzyme NAD^+ = electron acceptor
  - NAD^+ picks up $2e^-$ and $2H^+$ → NADH (stores E)
  - NADH carries electrons to the electron transport chain (ETC)
  - ETC: transfers e^- to O_2 to make H_2O ; releases energy

NAD$^+$ as an electron shuttle



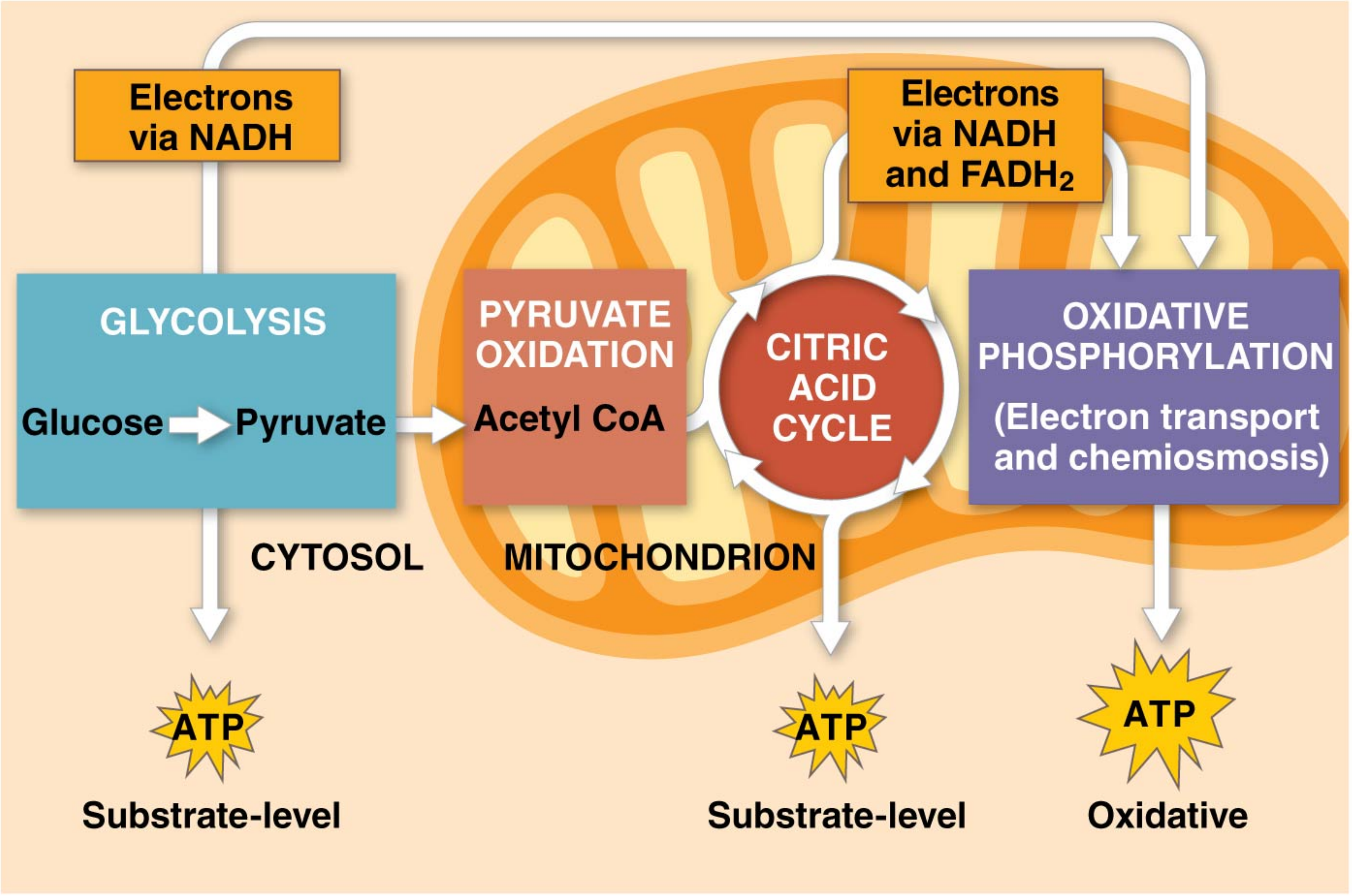
Electron Transport Chain



Stages of Cellular Respiration

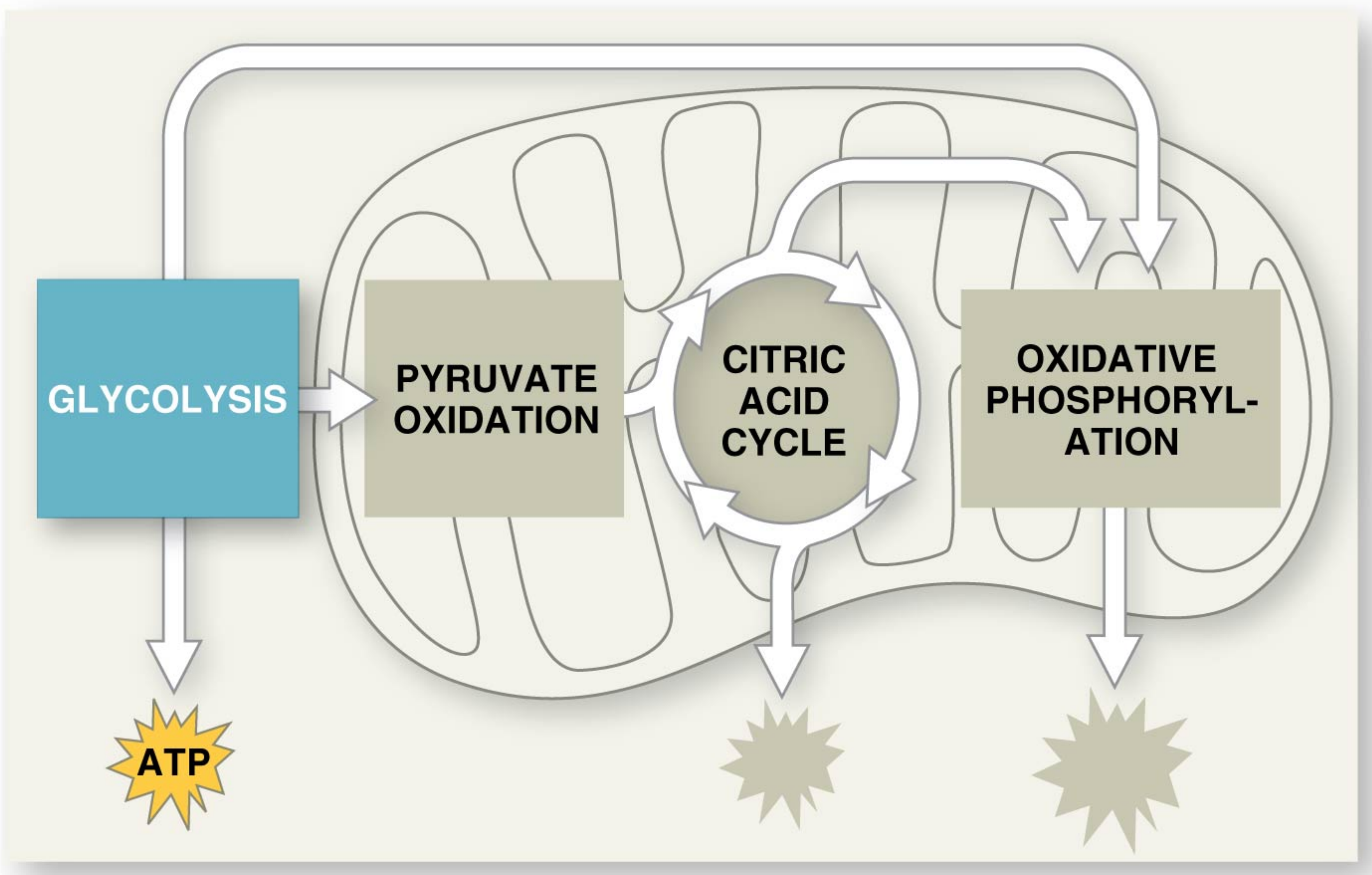
1. Glycolysis
2. Pyruvate Oxidation + Citric Acid Cycle (Krebs Cycle)
3. Oxidative Phosphorylation (electron transport chain (ETC) & chemiosmosis)

Overview of Cellular Respiration



Cellular Respiration

Stage 1: Glycolysis


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL- ATION
ATP

Glycolysis

- “sugar splitting”
- Believed to be ancient (early prokaryotes - no O_2 available)
- Occurs in cytosol
- Partially oxidizes glucose (6C) to 2 pyruvates (3C)
- Net gain: **2 ATP** + **2NADH**
- Also makes **$2H_2O$**
- No O_2 required

Glycolysis

Stage 1: Energy Investment Stage

- Cell uses ATP to phosphorylate compounds of glucose

Stage 2: Energy Payoff Stage

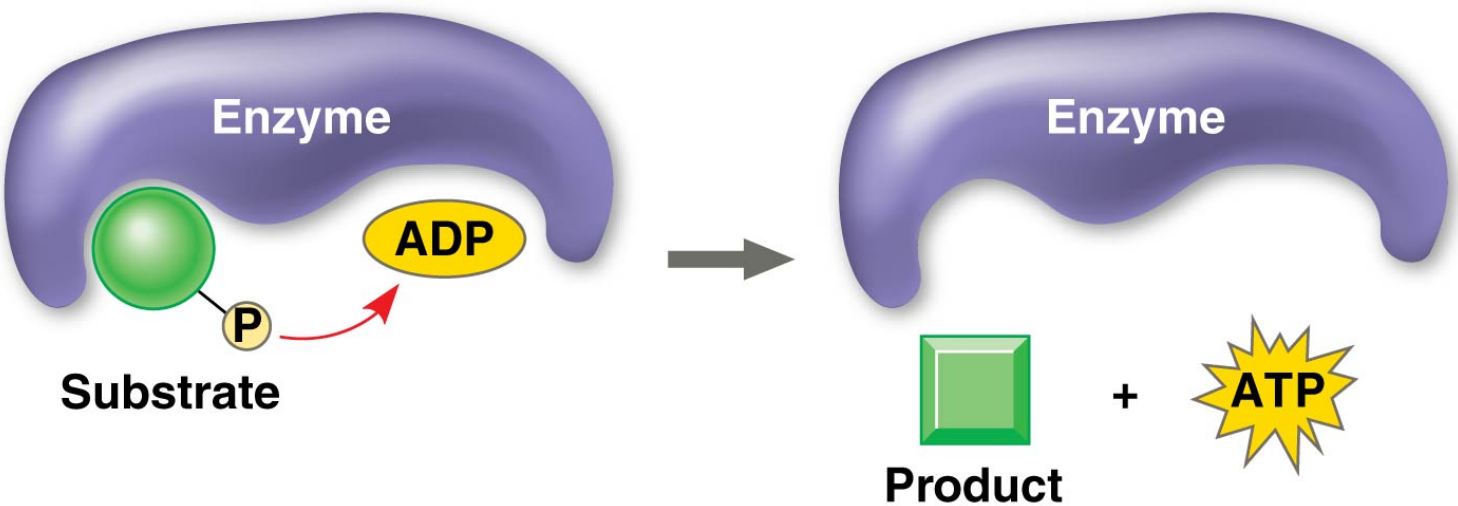
- Two 3-C compounds oxidized
- For each glucose molecule:
  - 2 Net **ATP** produced by substrate-level phosphorylation
  - 2 molecules of NAD^+ → **NADH**

Substrate-Level Phosphorylation

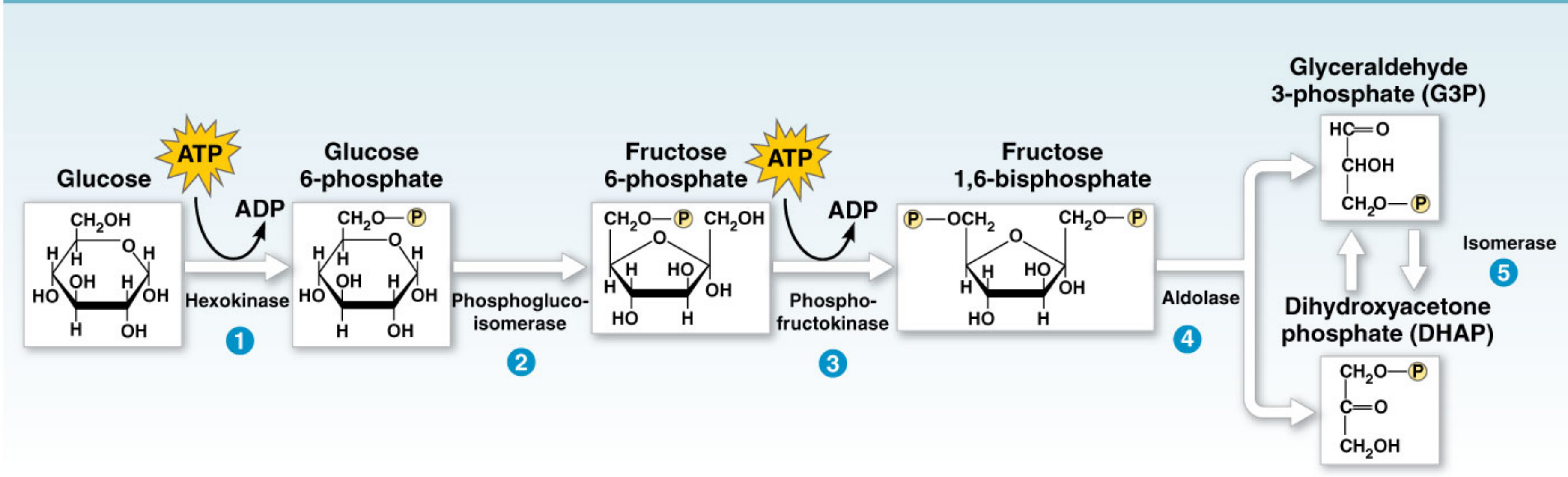
- Generate small amount of **ATP**
- Phosphorylation: enzyme transfers a phosphate to other compounds

  Ⓟ **+** **compound**

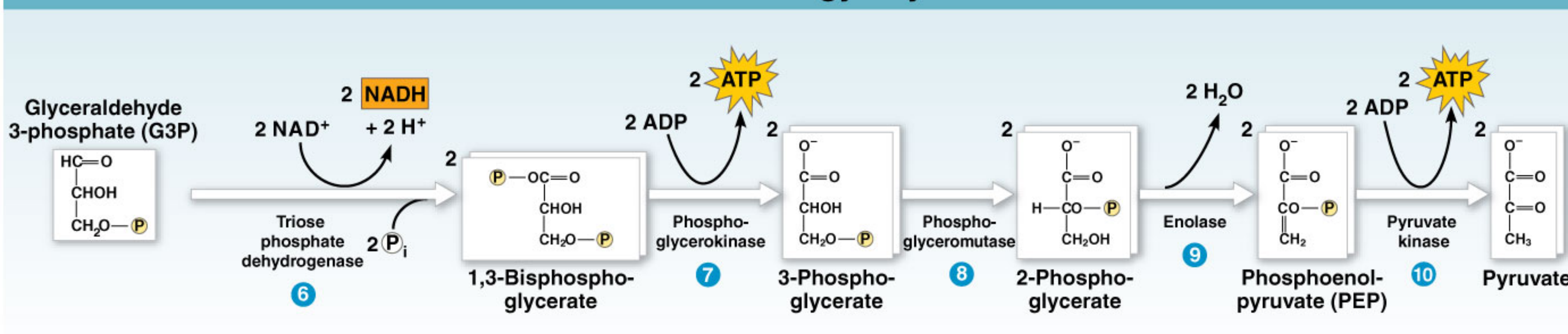
- ADP + P_i → **ATP**



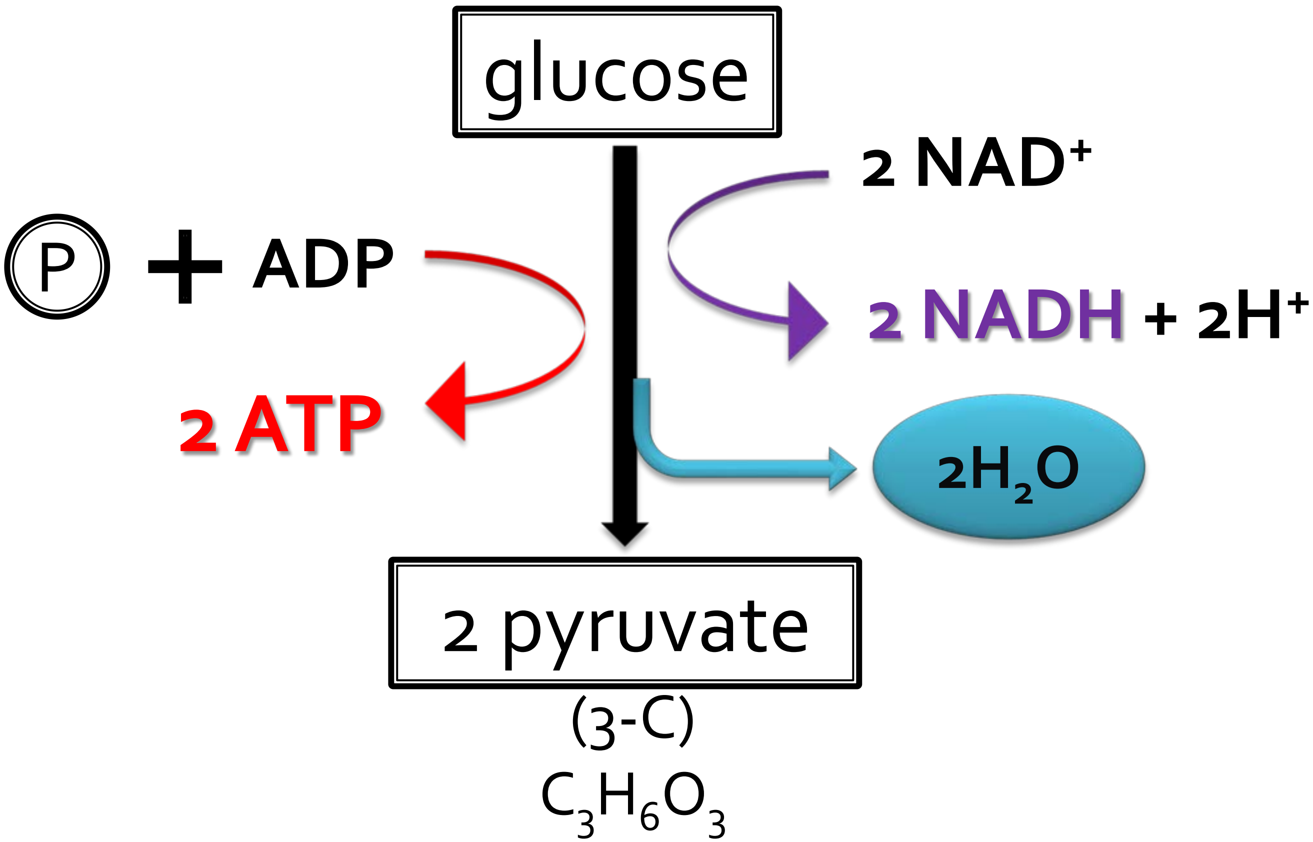
GLYCOLYSIS: Energy Investment Phase



GLYCOLYSIS: Energy Payoff Phase

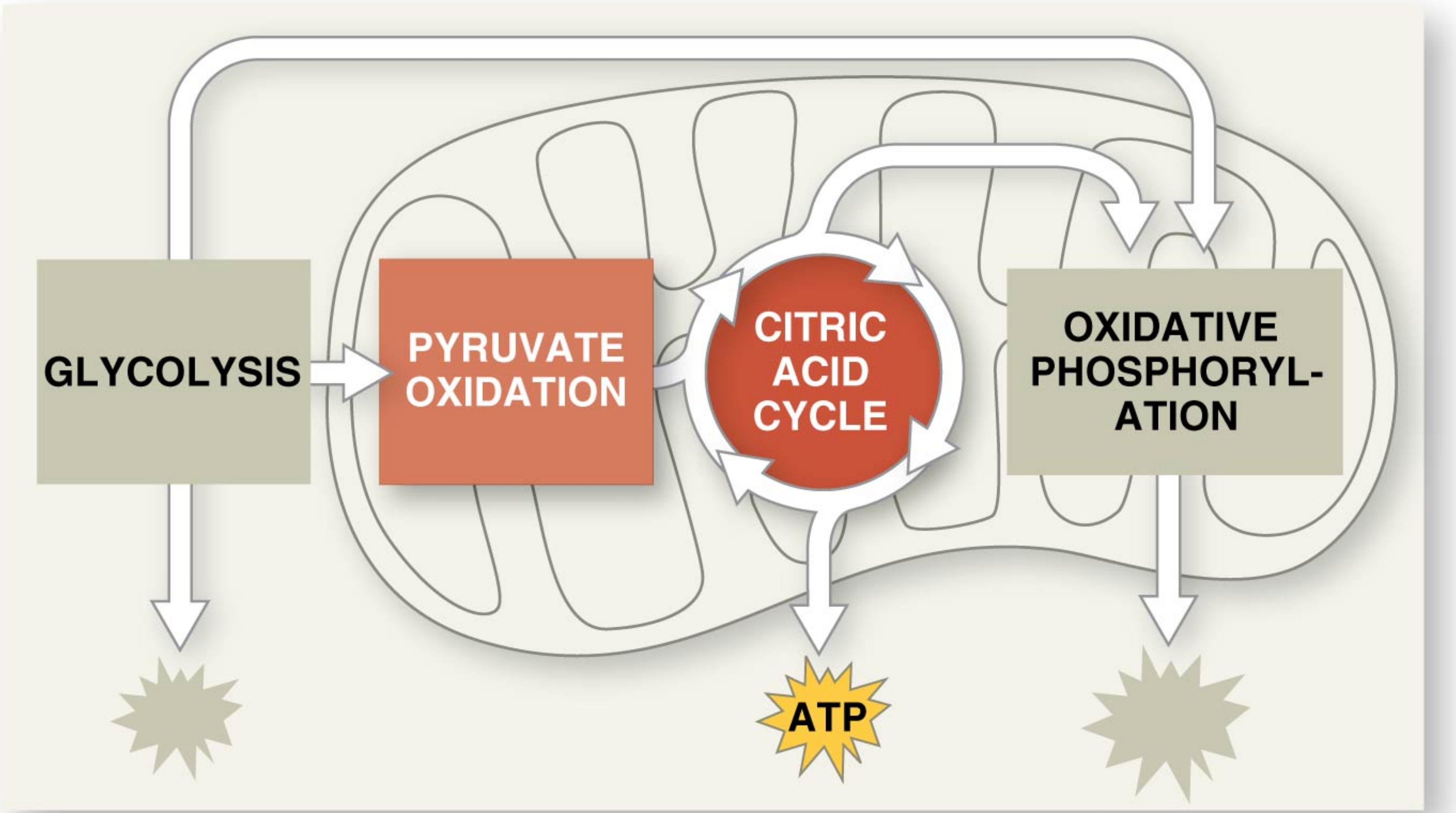


Glycolysis (Summary)



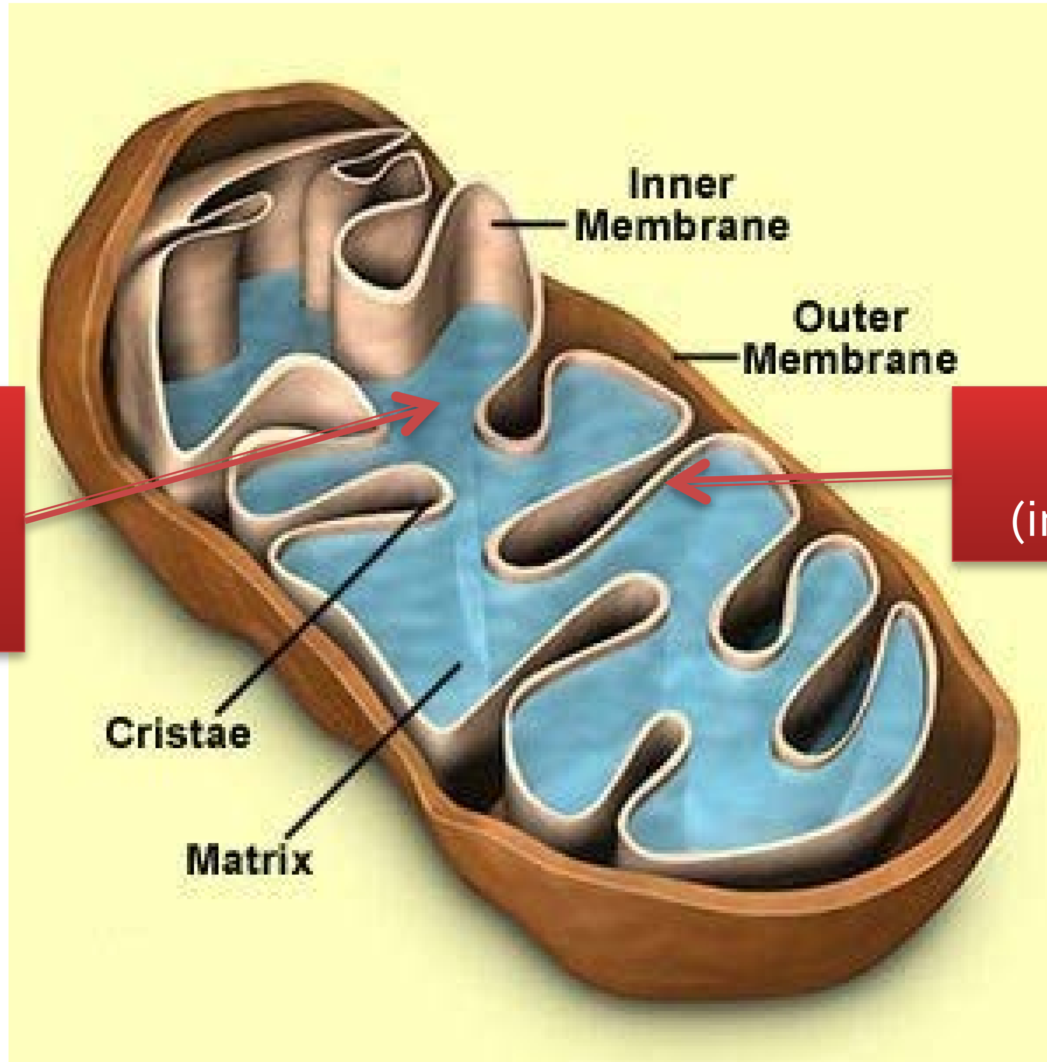
Cellular Respiration

Stage 2: Pyruvate Oxidation + Citric Acid Cycle

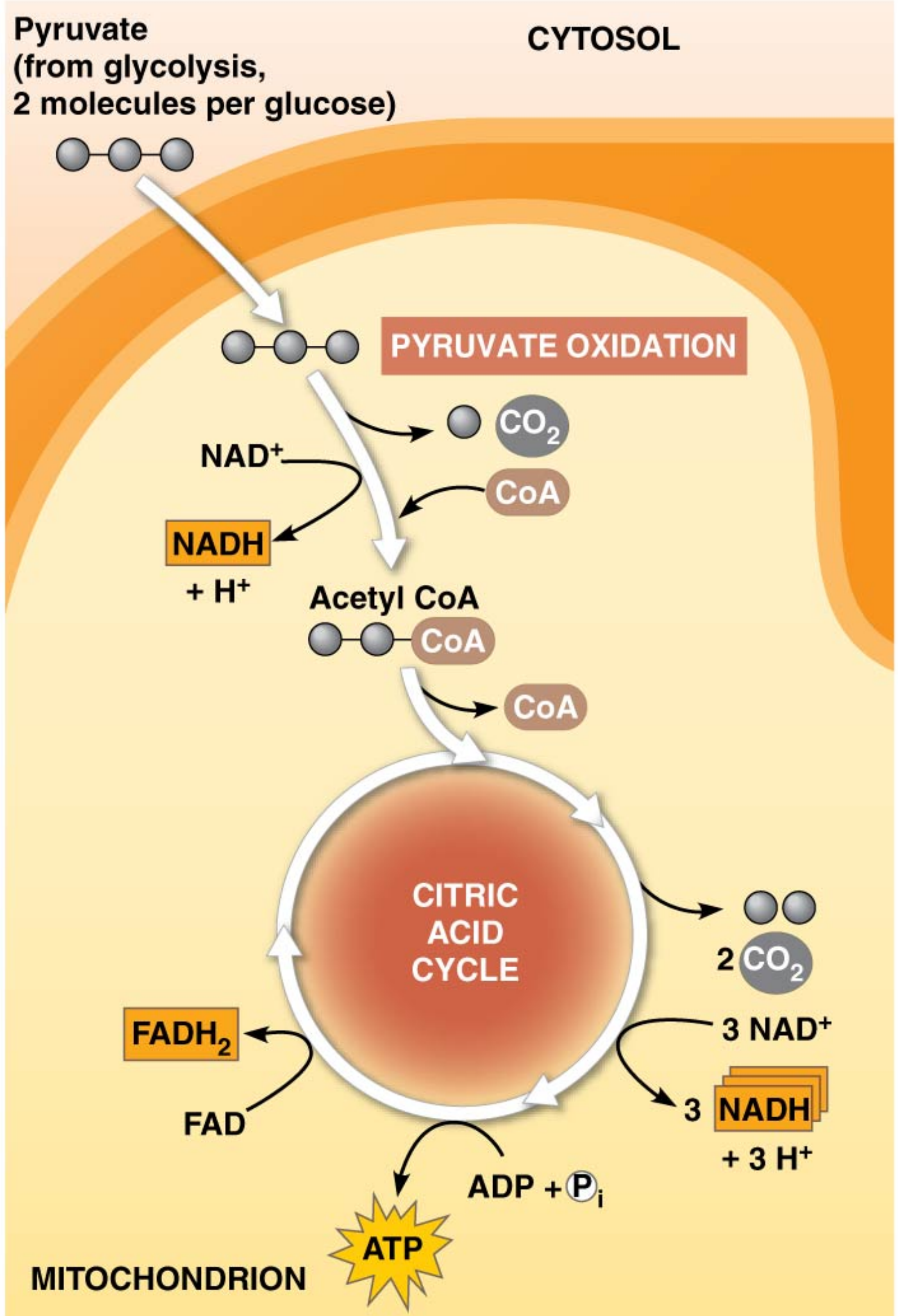

GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Mitochondrion Structure

Citric Acid Cycle
(matrix)

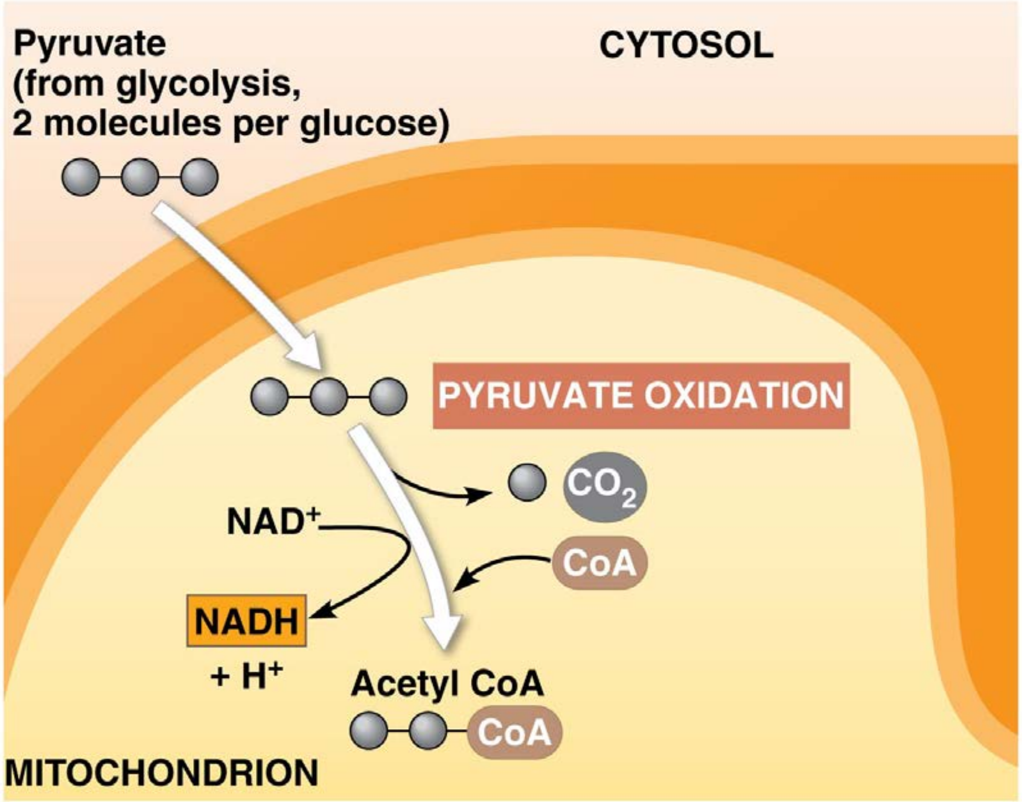


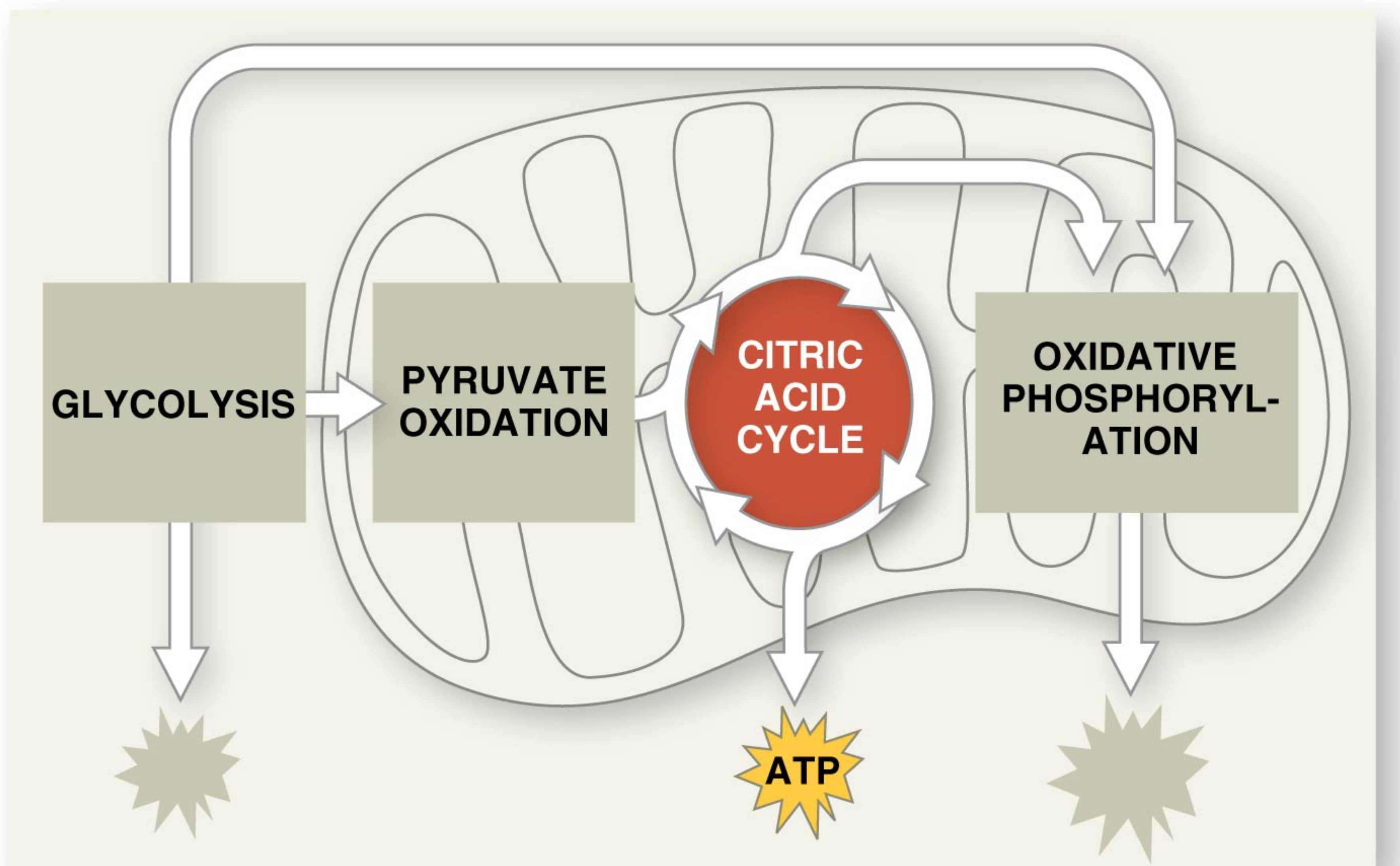
ETC
(inner membrane)


Pyruvate
(from glycolysis,
2 molecules per glucose)
CYTOSOL
PYRUVATE OXIDATION
CO_2
NAD+
CoA
NADH
+ H+
Acetyl CoA
CoA
CoA
CITRIC
ACID
CYCLE
2 CO_2
3 NAD+
3 NADH
+ 3 H+
$FADH_2$
FAD
ADP + P_i
ATP
MITOCHONDRION

Pyruvate Oxidation

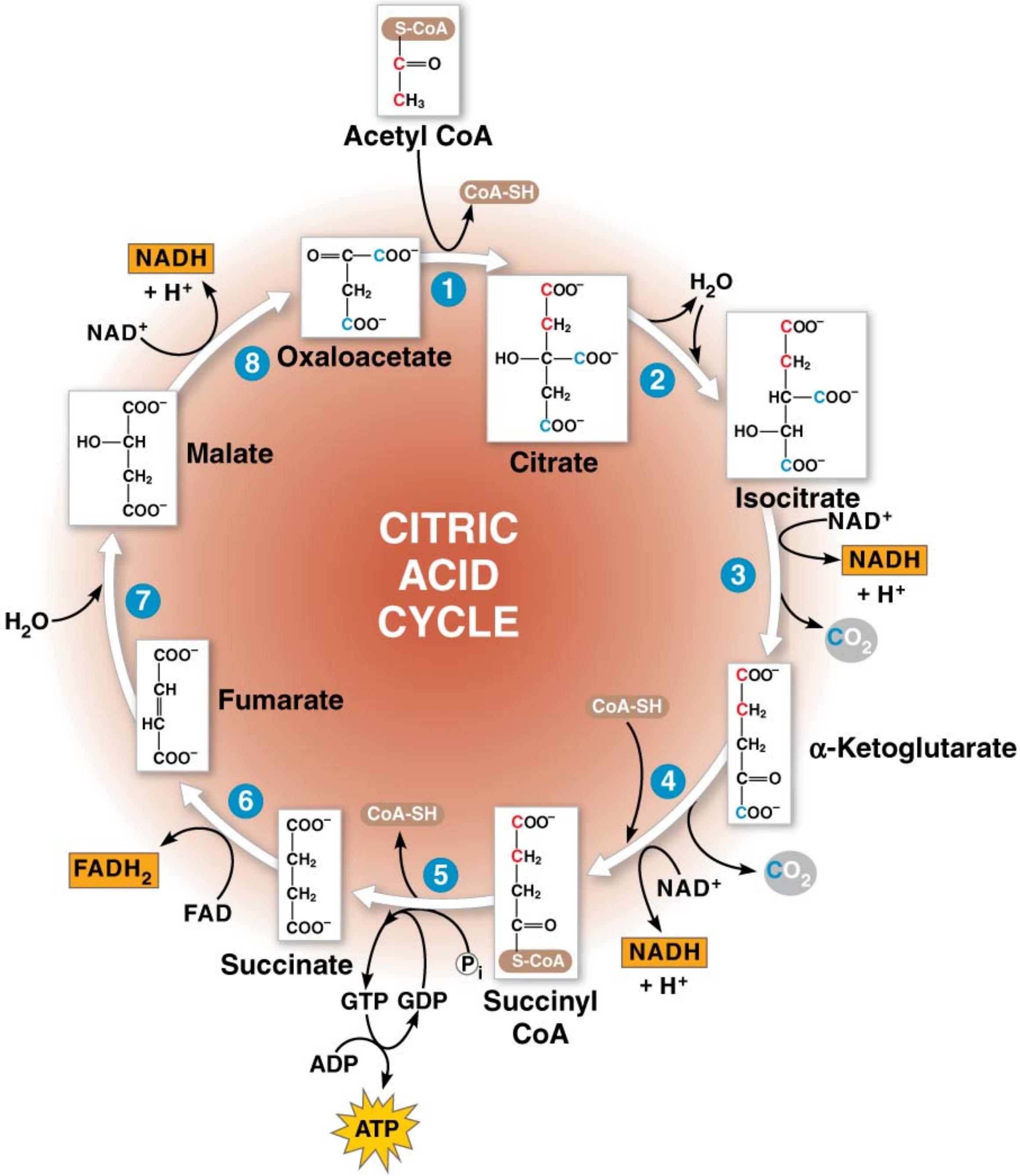
- Pyruvate → Acetyl CoA (*used to make citrate*)
- CO_2 and **NADH** produced




GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

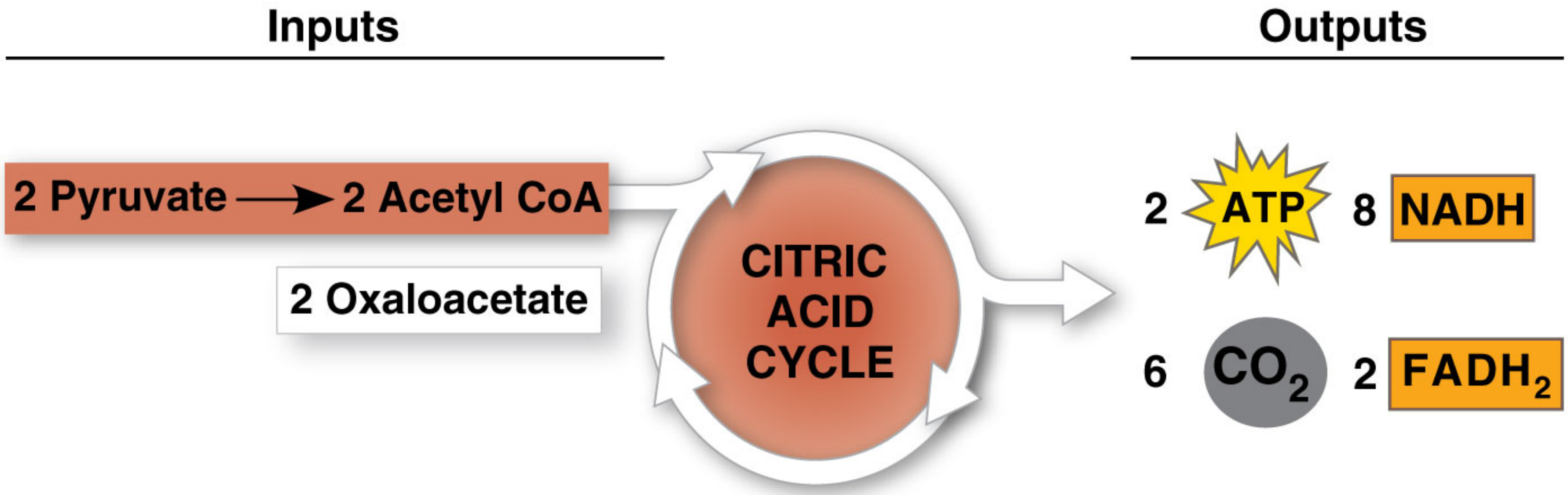
Citric Acid Cycle (Krebs)

- Occurs in mitochondrial matrix
- Acetyl CoA → Citrate → CO_2 released
- Net gain: **2 ATP**, **6 NADH**, **2 $FADH_2$** (electron carrier)
- **ATP** produced by substrate-level phosphorylation



Acetyl CoA
S-CoA
CoA-SH
CITRIC ACID CYCLE
Oxaloacetate
Citrate
Isocitrate
α-Ketoglutarate
Succinyl CoA
Succinate
Fumarate
Malate
H_2O
NAD+
NADH
+ H+
CO_2
CoA-SH
GTP GDP
ADP
ATP
P_i
FAD
$FADH_2$
1
2
3
4
5
6
7
8

Summary of Citric Acid Cycle

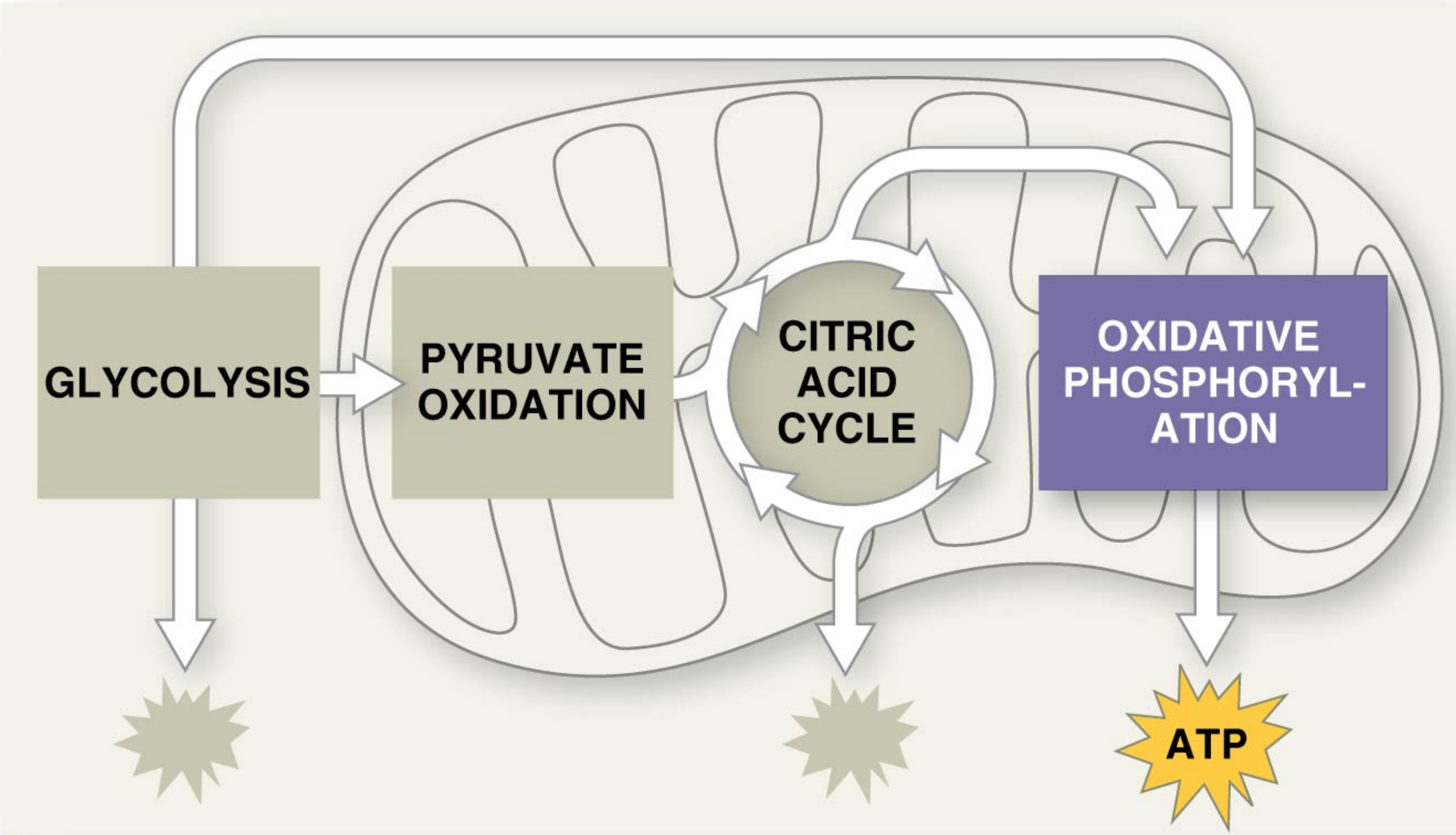


http://multimedia.mcb.harvard.edu/anim_mitochondria.html

BioVisions at Harvard: The Mitochondria

Cellular Respiration

Stage 3: Oxidative Phosphorylation


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Oxidative Phosphorylation

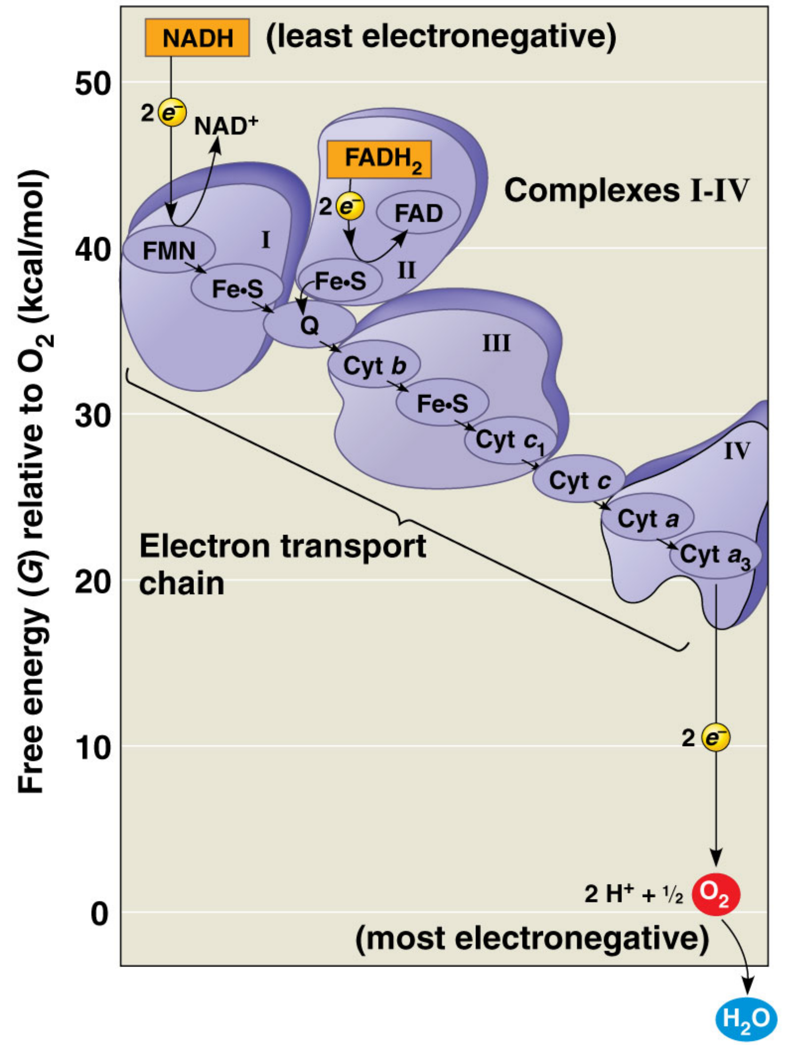
ELECTRON TRANSPORT CHAIN	CHEMIOSMOSIS

- Occurs in inner membrane of mitochondria
- Produces **26-28 ATP** by oxidative phosphorylation via chemiosmosis

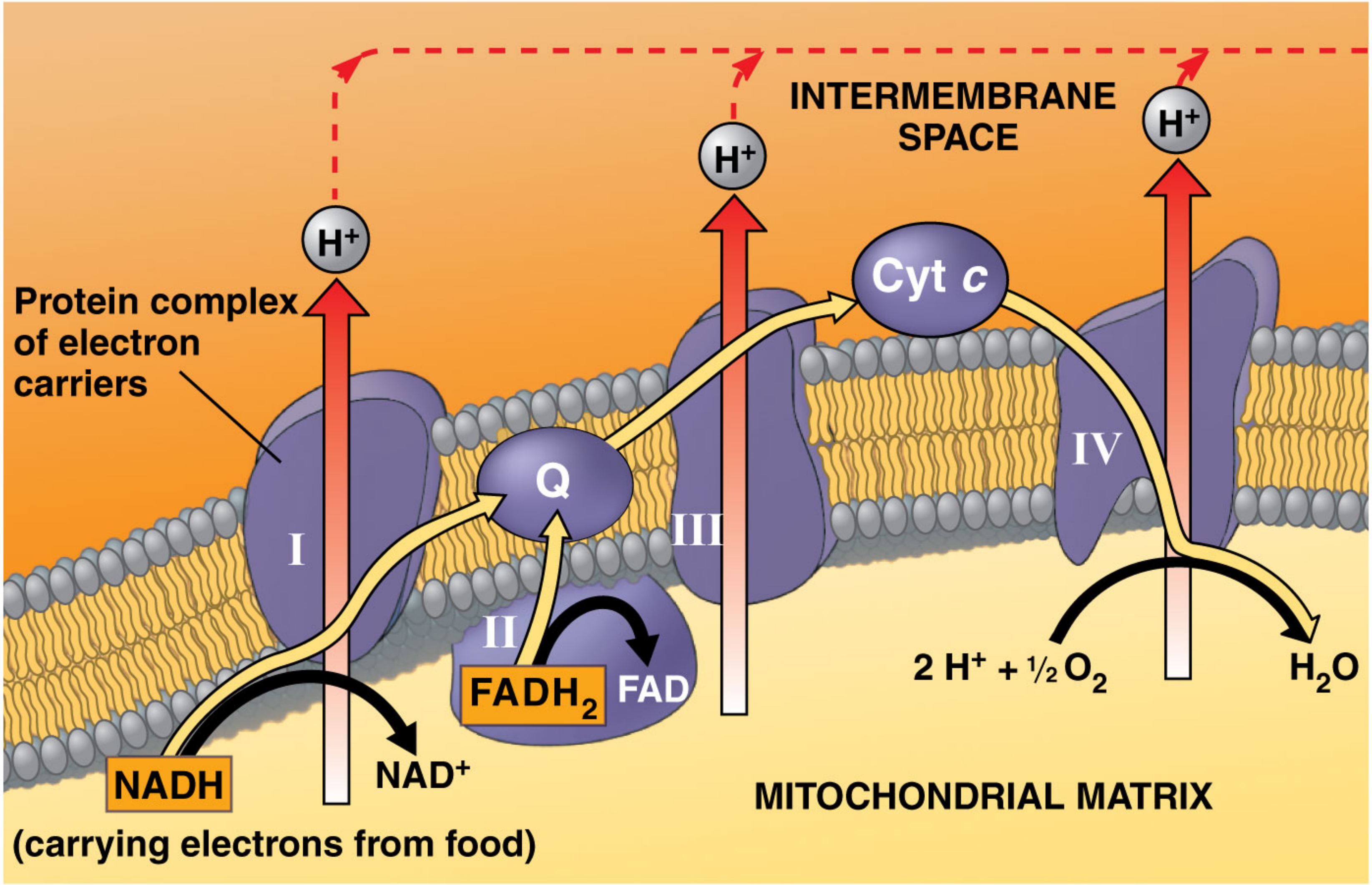
- H^+ ions pumped across inner mitochondrial membrane
- H^+ diffuse through ATP synthase (ADP → ATP)

Electron Transport Chain (ETC)

- Collection of molecules embedded in inner membrane of mitochondria
- Tightly bound protein + non-protein components
- Alternate between reduced/oxidized states as accept/donate e$^-$
- Does <u>not</u> make ATP directly
- Ease fall of e- from food to O_2
- $2H^+ + ½ O_2 \rightarrow$ **H_2O**



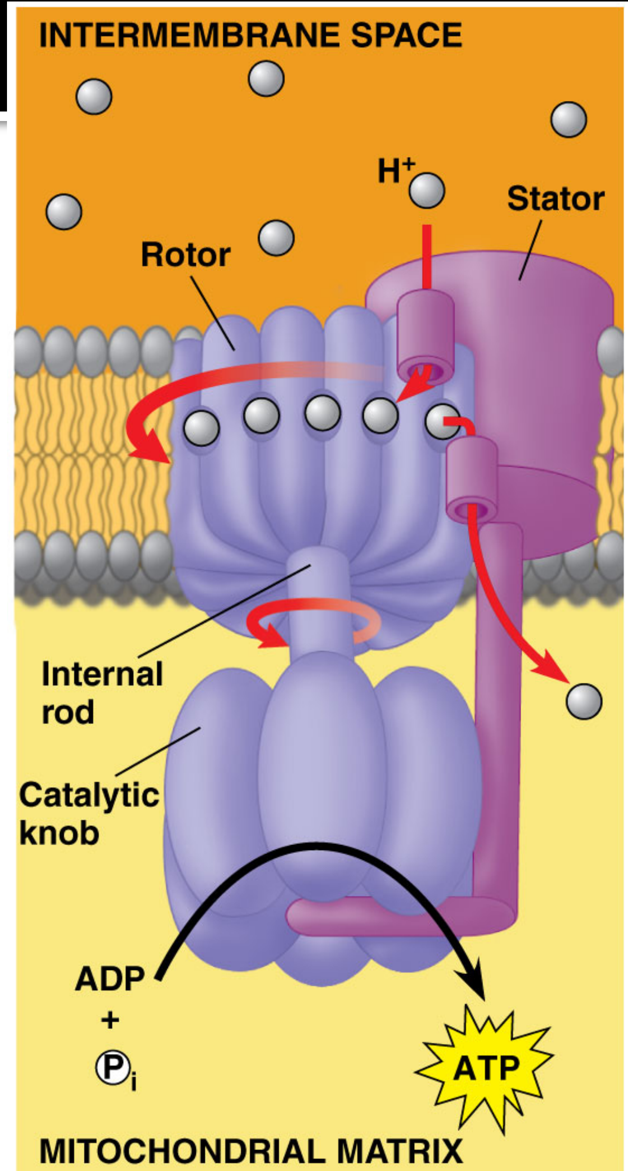
As electrons move through the ETC, proton pumps move H^+ across inner mitochondrial membrane



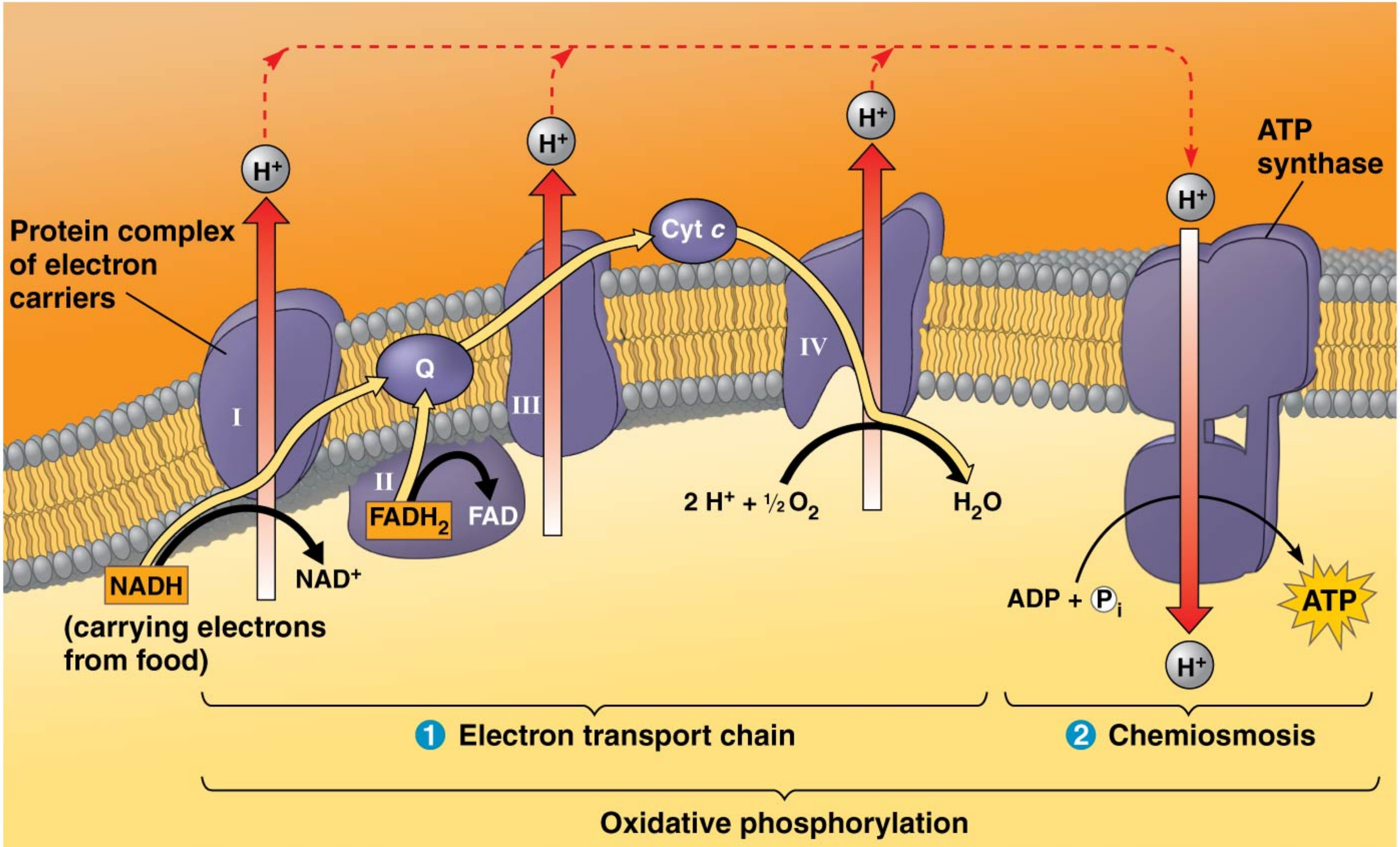
Chemiosmosis: Energy-Coupling Mechanism

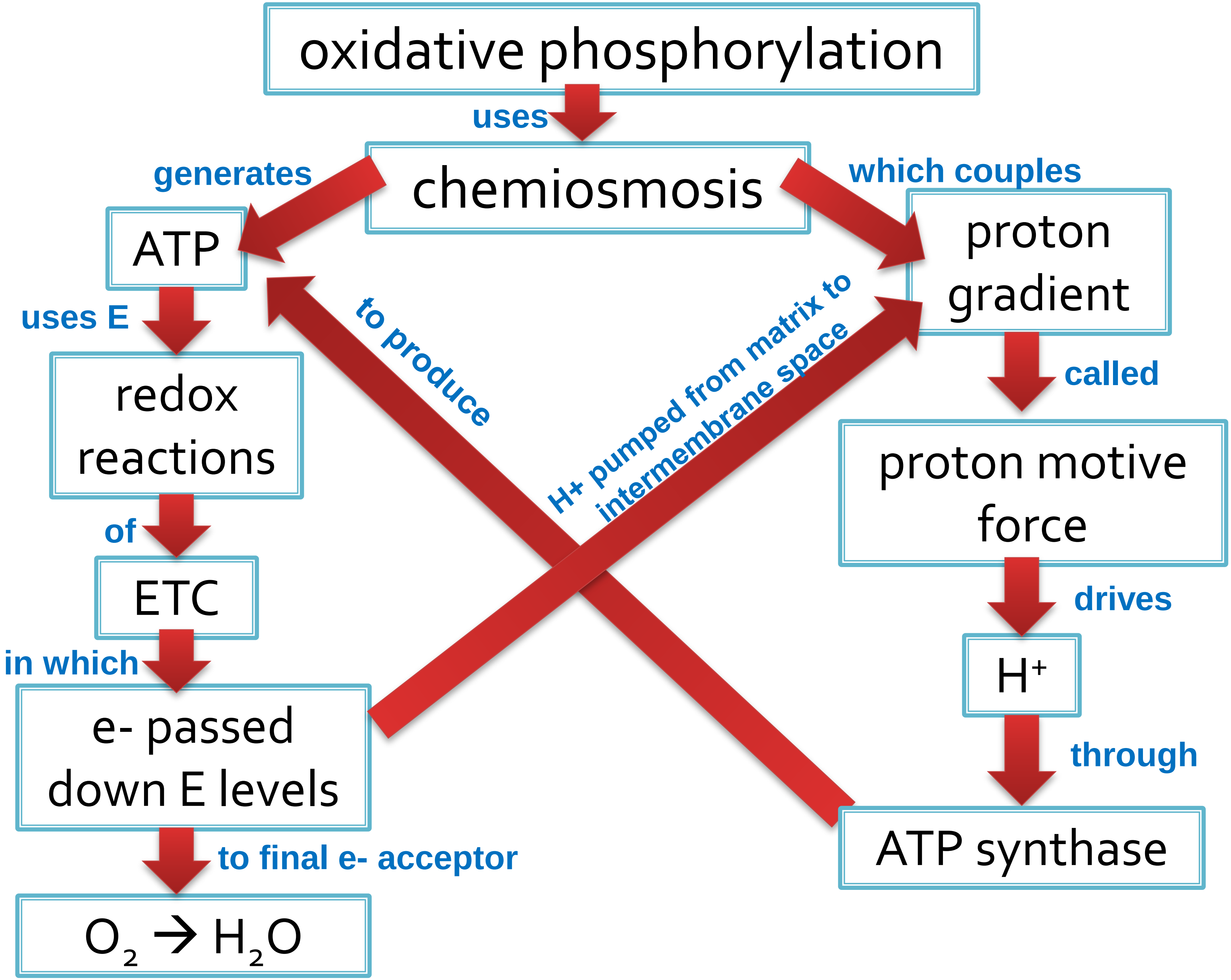
- **Chemiosmosis** = H^+ gradient across membrane drives cellular work
- **Proton-motive force**: use proton (H^+) gradient to perform work

- **ATP synthase**: enzyme that makes ATP
- Use E from proton (H^+) gradient – flow of H^+ back across membrane



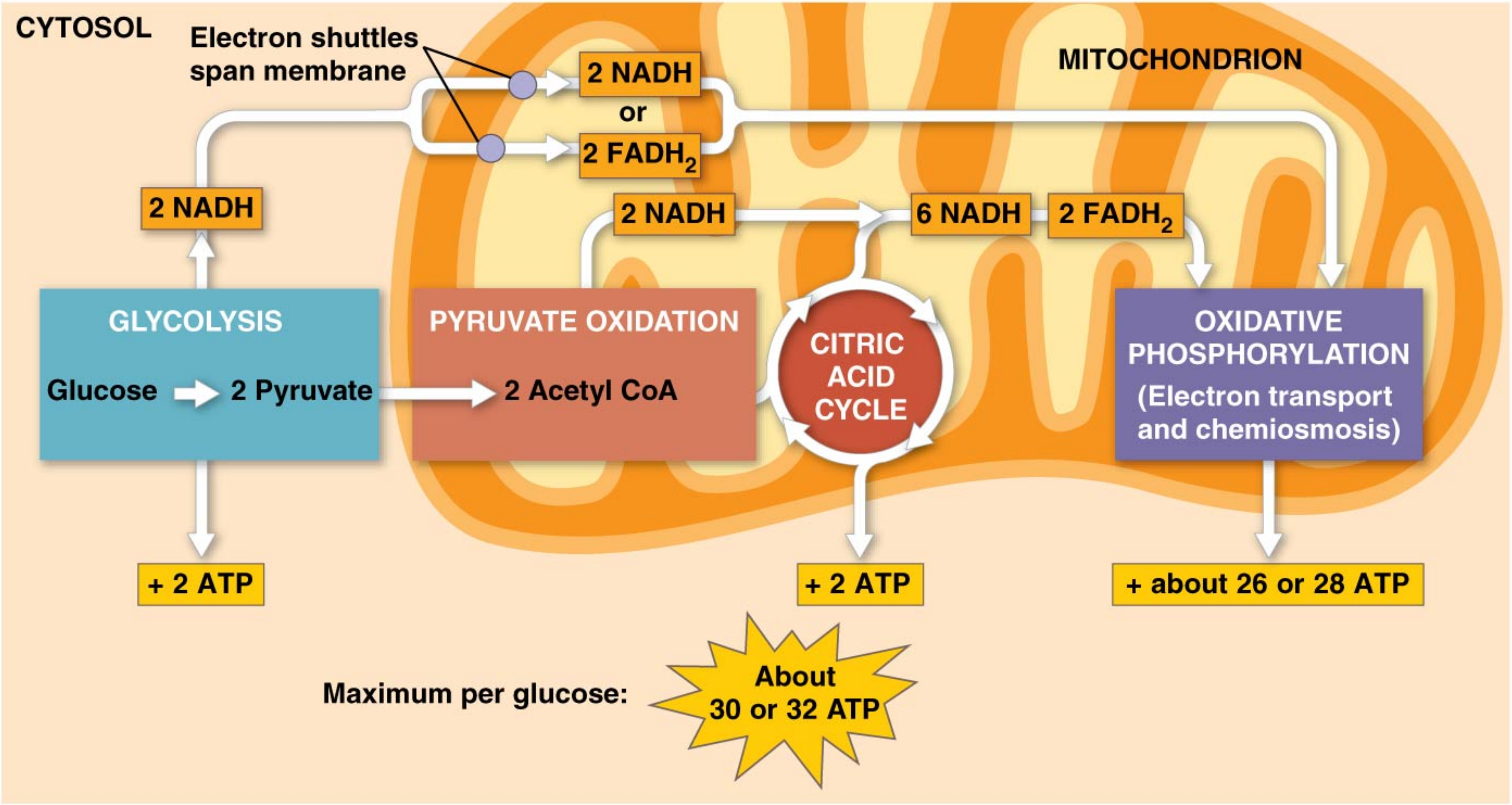
Chemiosmosis couples the ETC to ATP synthesis





oxidative phosphorylation
uses
chemiosmosis
generates
ATP
which couples
proton gradient
uses E
redox reactions
to produce
H+ pumped from matrix to intermembrane space
called
proton motive force
of
ETC
drives
H^+
in which
e- passed down E levels
through
ATP synthase
to final e- acceptor
$O_2 \rightarrow H_2O$

ATP yield per molecule of glucose at each stage of cellular respiration

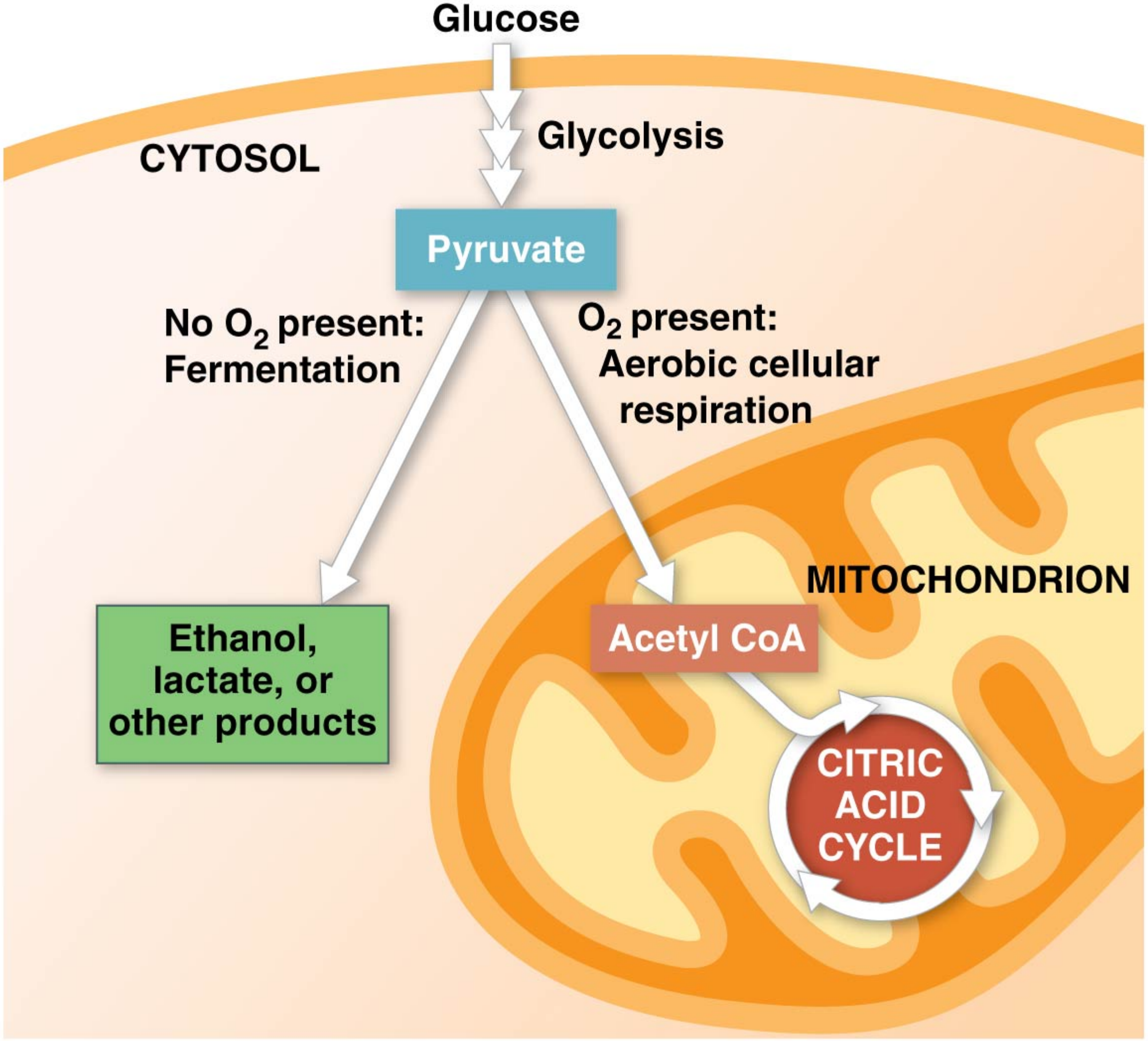


BioFlix: Cellular Respiration

- **Anaerobic Respiration**: generate ATP using other electron acceptors besides O_2
  - Final e^- acceptors: sulfate (SO_4), nitrate, sulfur (produces H_2S)
  - Eg. **Obligate anaerobes**: can't survive in O_2

- **Facultative anaerobes**: make ATP by **aerobic respiration** (with O_2 present) or switch to **fermentation** (no O_2 available)
  - Eg. human muscle cells

Fermentation = glycolysis + regeneration of NAD^+



Glycolysis

Without O_2 | O_2 present

FERMENTATION

- Keep glycolysis going by regenerating NAD^+
- Occurs in cytosol
- **No oxygen** needed
- Creates **ethanol** [+ CO_2] or **lactate**
- **2 ATP** (from glycolysis)

RESPIRATION

- Release E from breakdown of food with O_2
- Occurs in mitochondria
- **O_2 required** (final electron acceptor)
- Produces CO_2, H_2O and **up to 32 ATP**

Types of Fermentation

ALCOHOL FERMENTATION

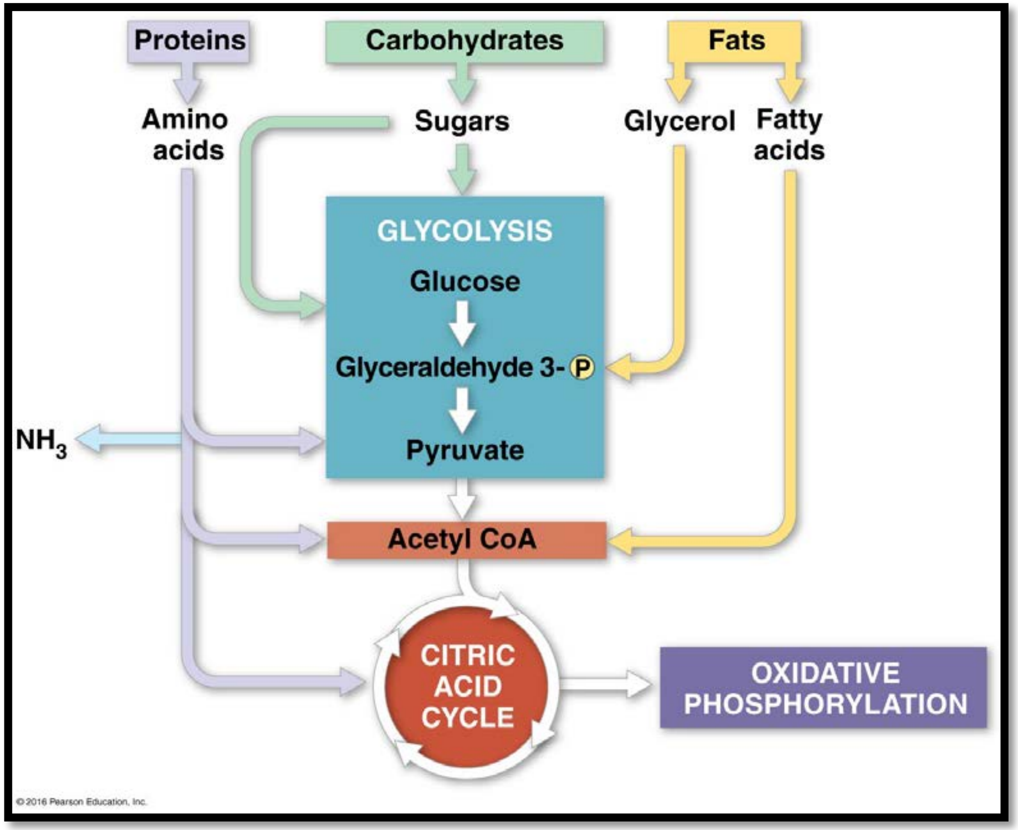
- Pyruvate → Ethanol + CO_2
- Ex. bacteria, yeast
- Used in brewing, winemaking, baking

LACTIC ACID FERMENTATION

- Pyruvate → Lactate
- Ex. fungi, bacteria, human muscle cells
- Used to make cheese, yogurt, acetone, methanol
- Note: Lactate build-up does NOT causes muscle fatigue and pain (old idea)

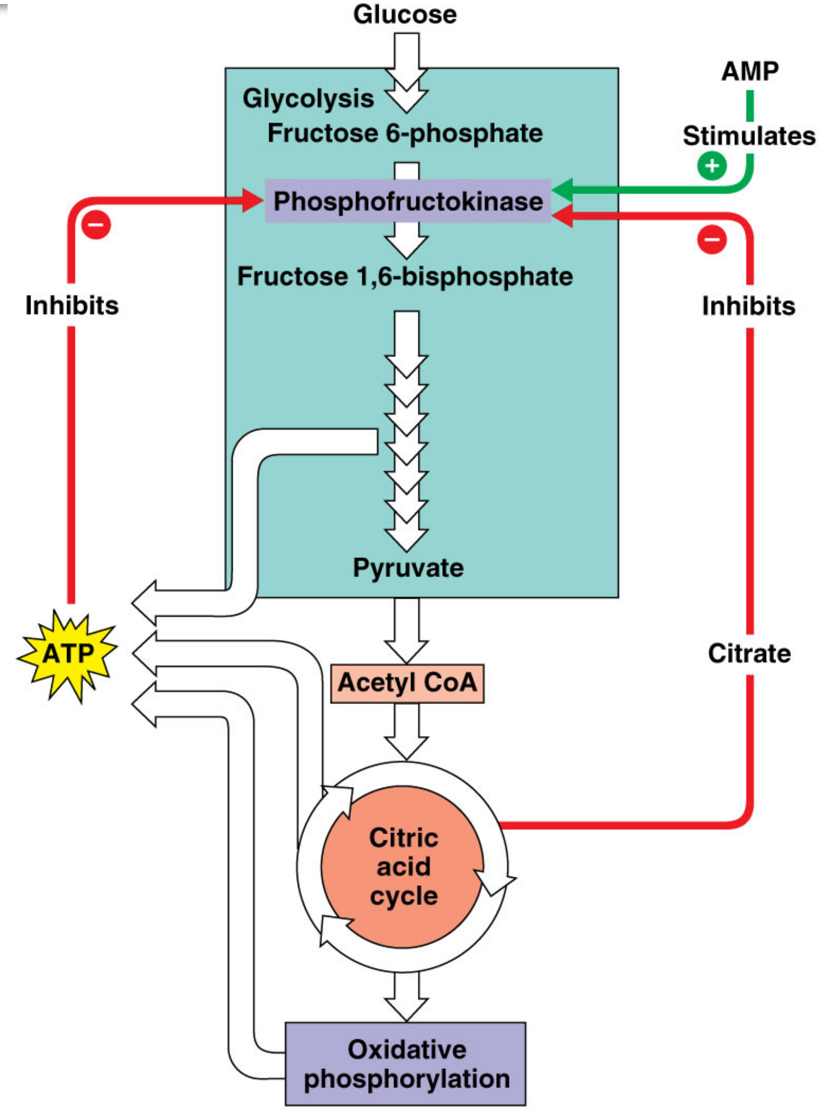
Various sources of fuel

- Carbohydrates, fats and proteins can ALL be used as fuel for cellular respiration
- Monomers enter glycolysis or citric acid cycle at different points

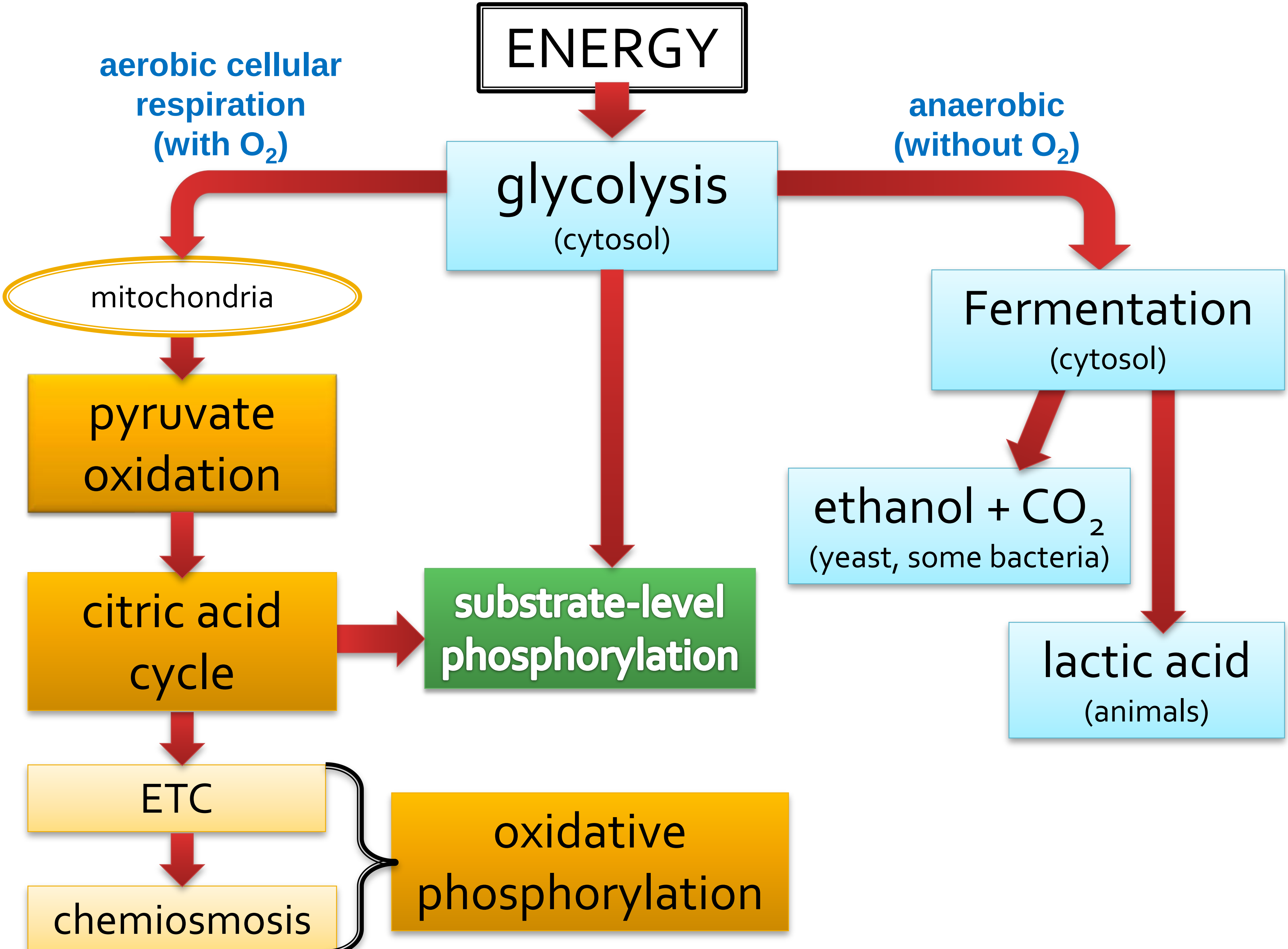


Phosphofructokinase (PFK)

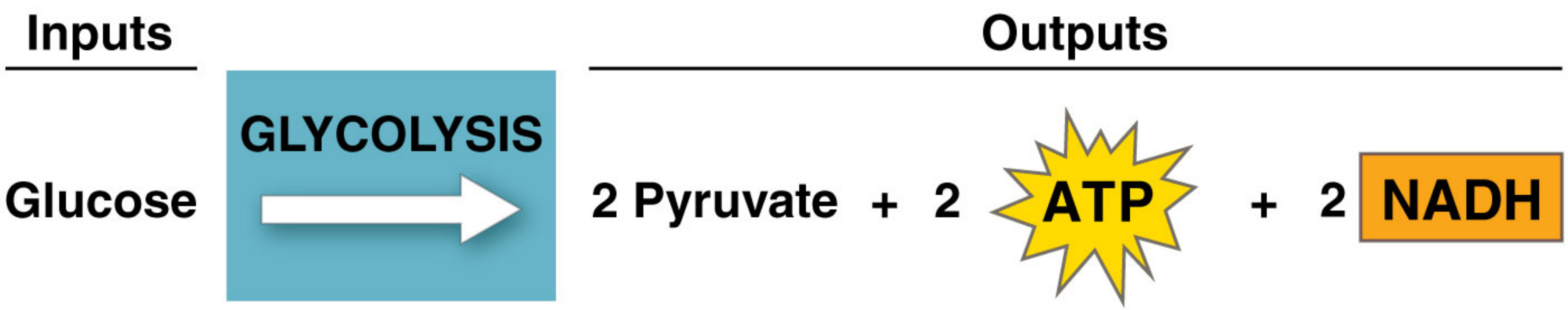
- Allosteric enzyme that controls rate of glycolysis and citric acid cycle
- Inhibited by ATP, citrate
- Stimulated by AMP
  - AMP+ P + P → ATP

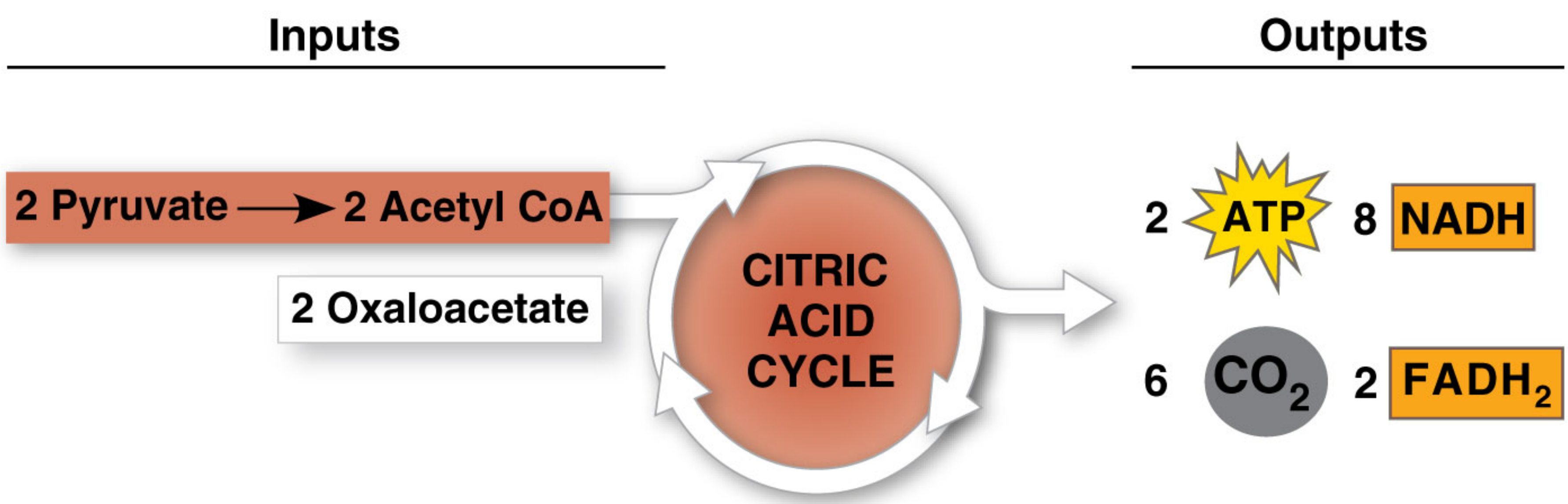


Respiration: Big Picture

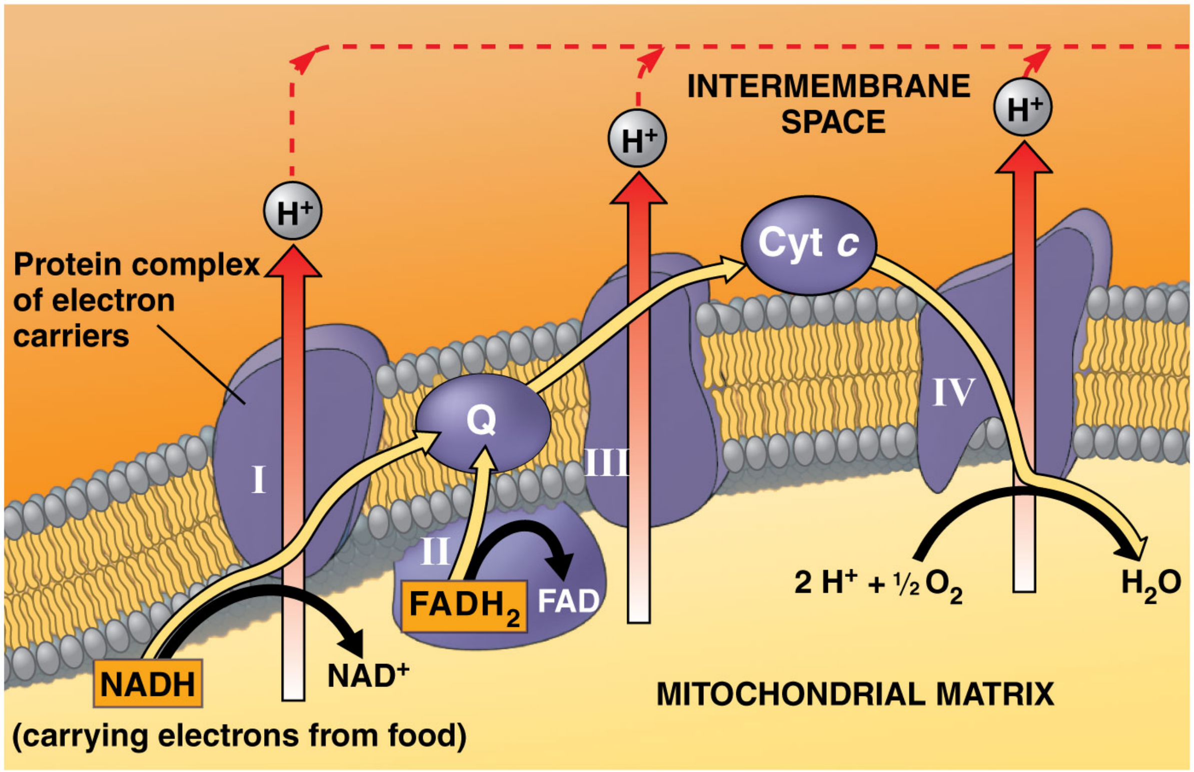

ENERGY
aerobic cellular respiration (with O_2)
anaerobic (without O_2)
glycolysis
(cytosol)
mitochondria
Fermentation
(cytosol)
pyruvate oxidation
ethanol + CO_2
(yeast, some bacteria)
citric acid cycle
substrate-level phosphorylation
lactic acid
(animals)
ETC
chemiosmosis
oxidative phosphorylation

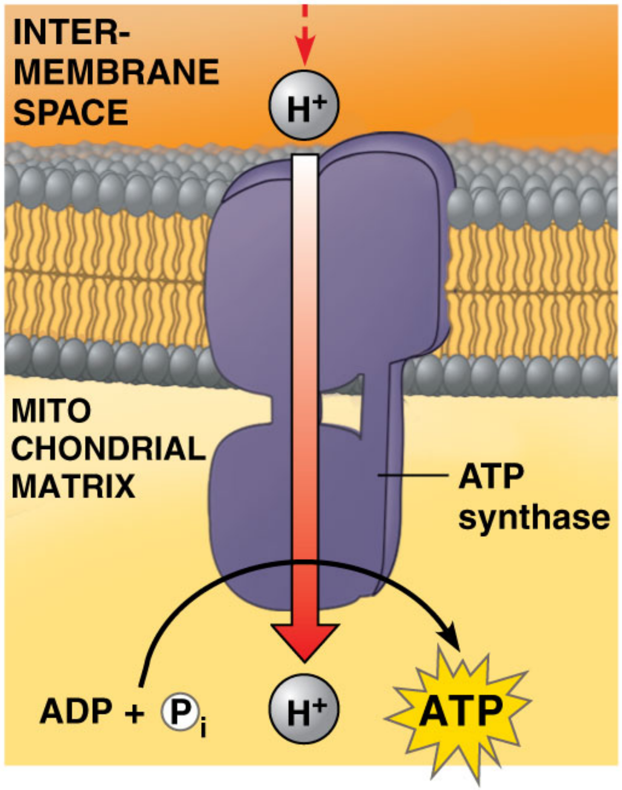
Glycolysis & Citric Acid Cycle





Oxidative Phosphorylation





Electron Transport Chain **Chemiosmosis**