Chapter 7: Respiration

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

E flows into ecosystem as Sunlight

↓

Autotrophs transform it into chemical E

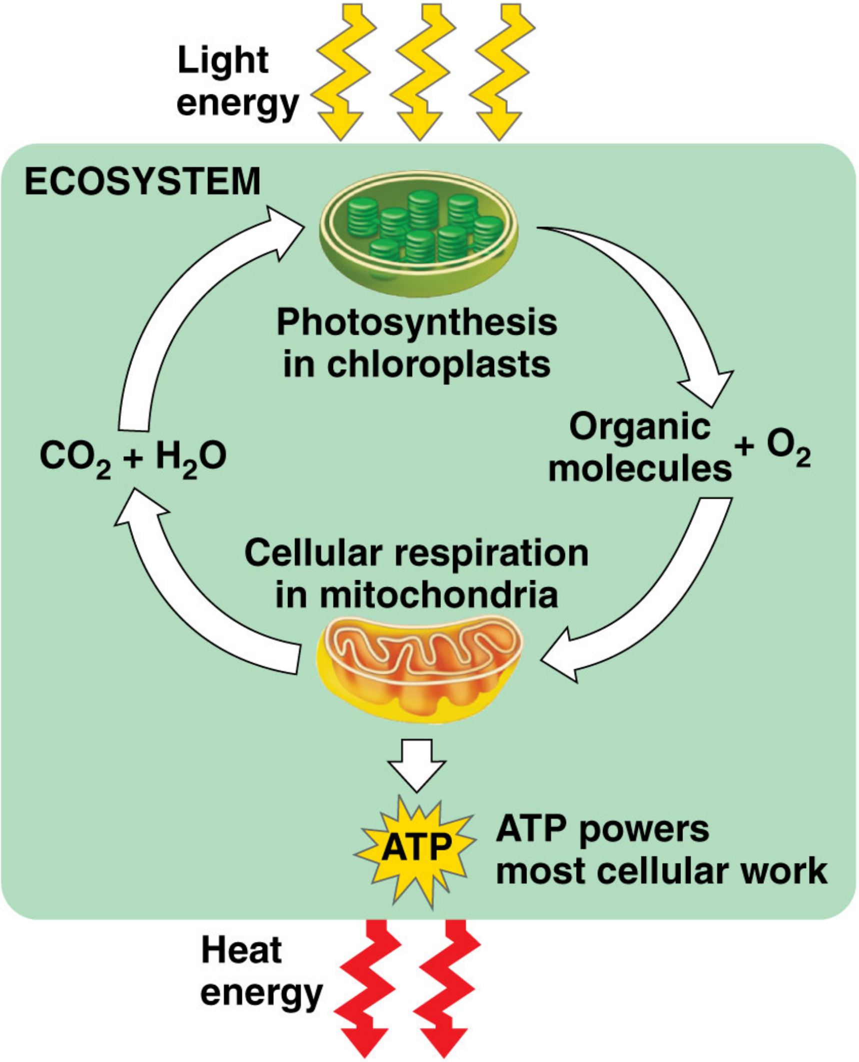
O_2 released as byproduct

↓

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)

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

(+ heat)

Photosynthesis: endergonic (requires E)

$6H_2O + 6CO_2 +$ **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^-

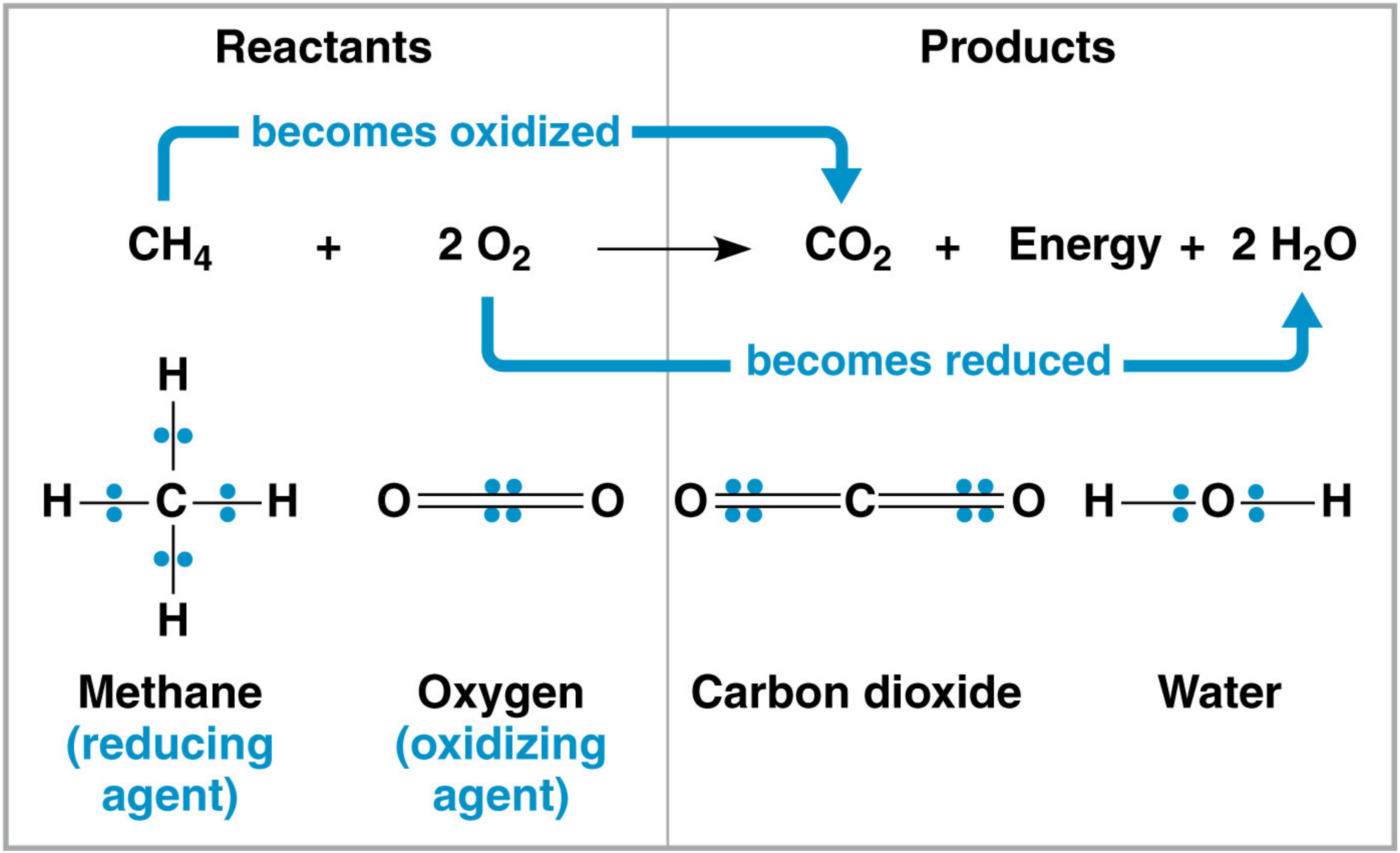
- Oxidation = lose e^-
- Reduction = gain e^-

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
H
H C H
H
O O
O C O
H O H
Methane
(reducing agent)
Oxygen
(oxidizing agent)
Carbon dioxide
Water

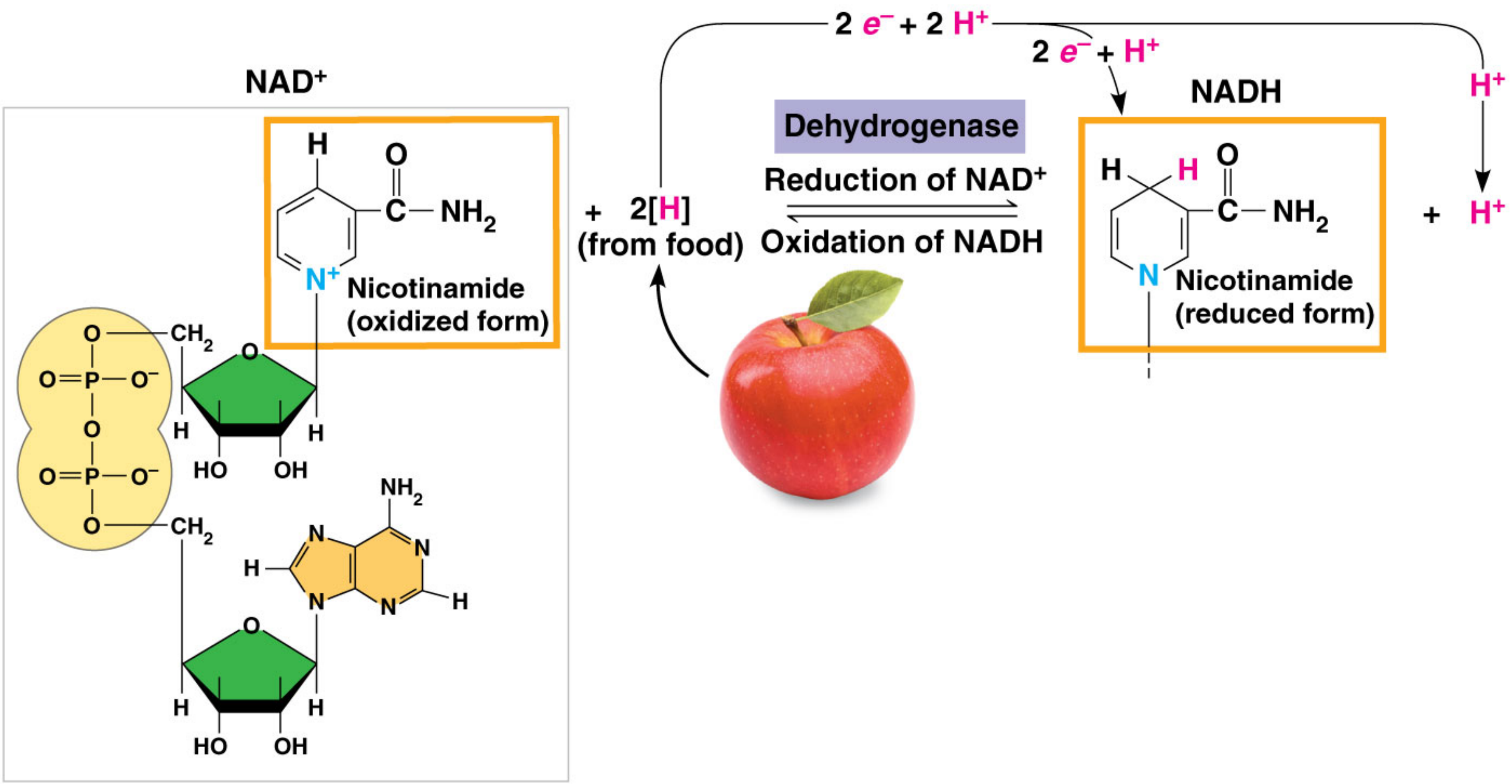
Energy Harvest

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

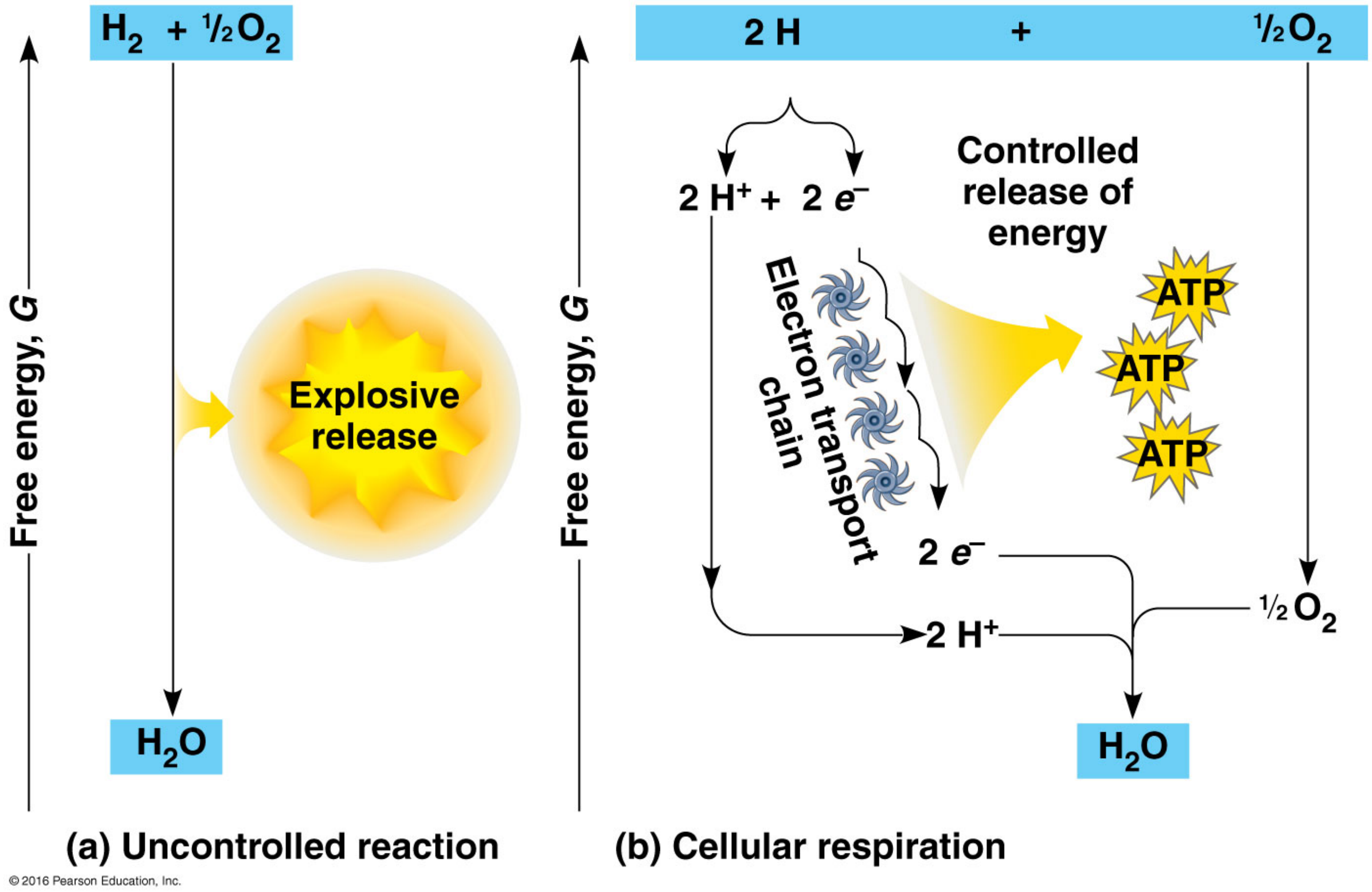
Food (Glucose) → NADH → ETC → O_2

  - 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



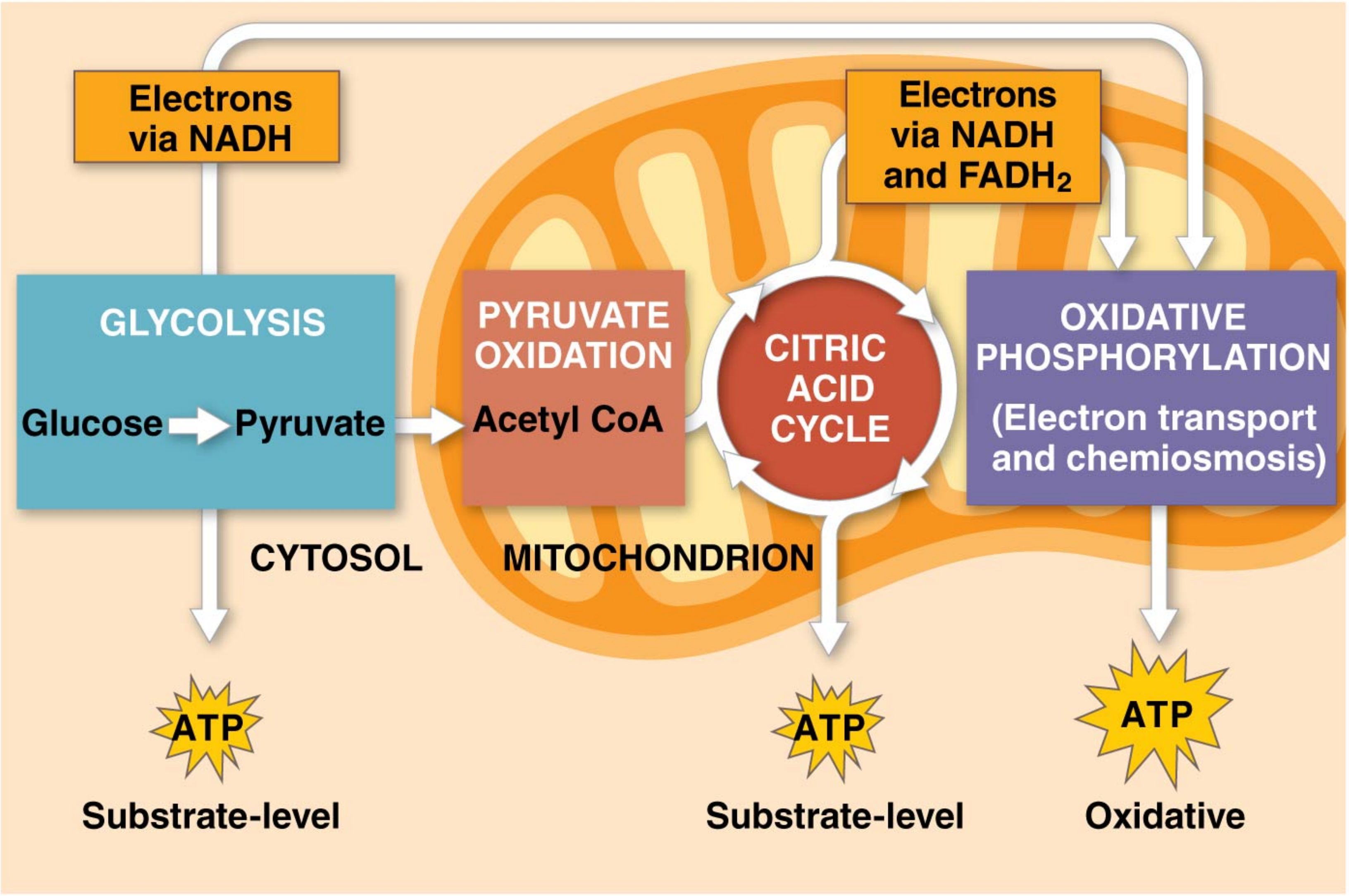
Electron Transport Chain



Stages of Cellular Respiration

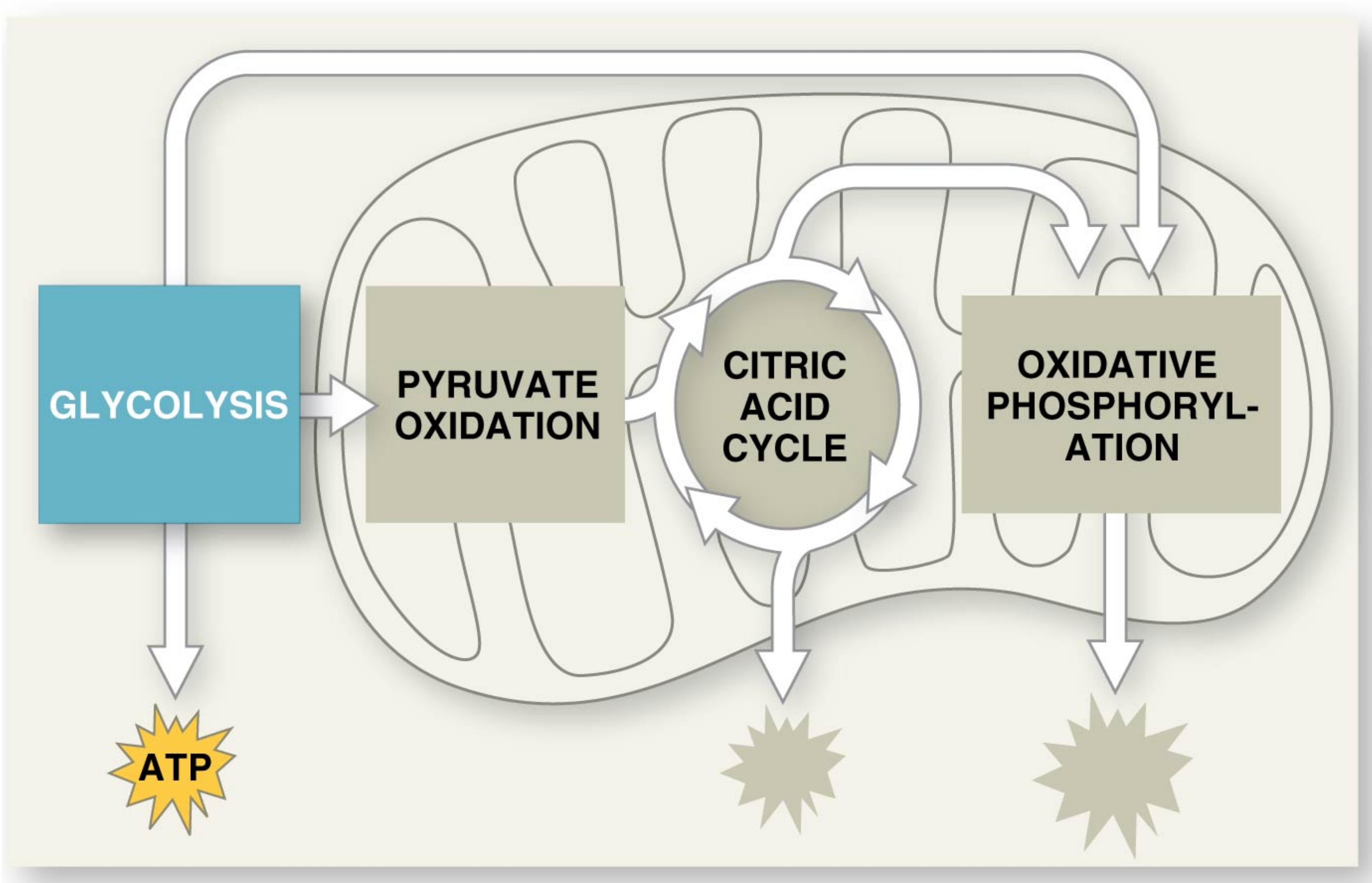
1. Glycolysis
2. Pyruvate Oxidation + Citric Acid Cycle (Krebs Cycle)
3. Oxidative Phosphorylation (electron transport chain (ETC) & chemiosmosis)

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

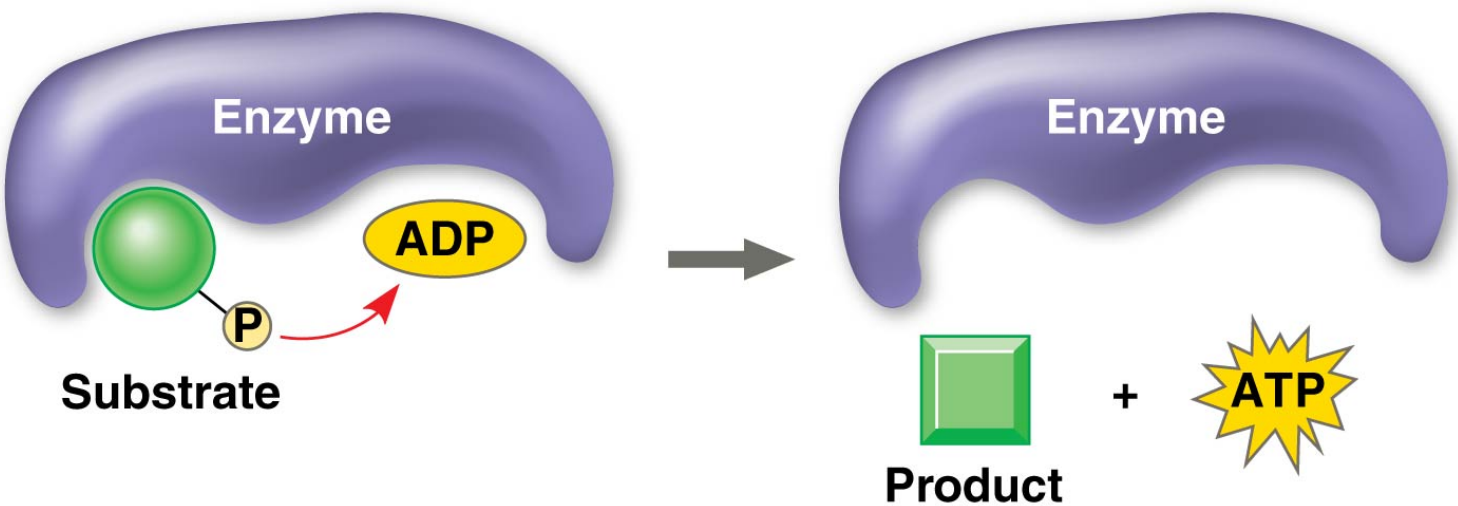
- Two 3-C compounds oxidized
- For each glucose molecule:
  - 2 Net **ATP** produced by substrate-level phosphorylation
  - 2 molecules of NAD^+ → **NADH**

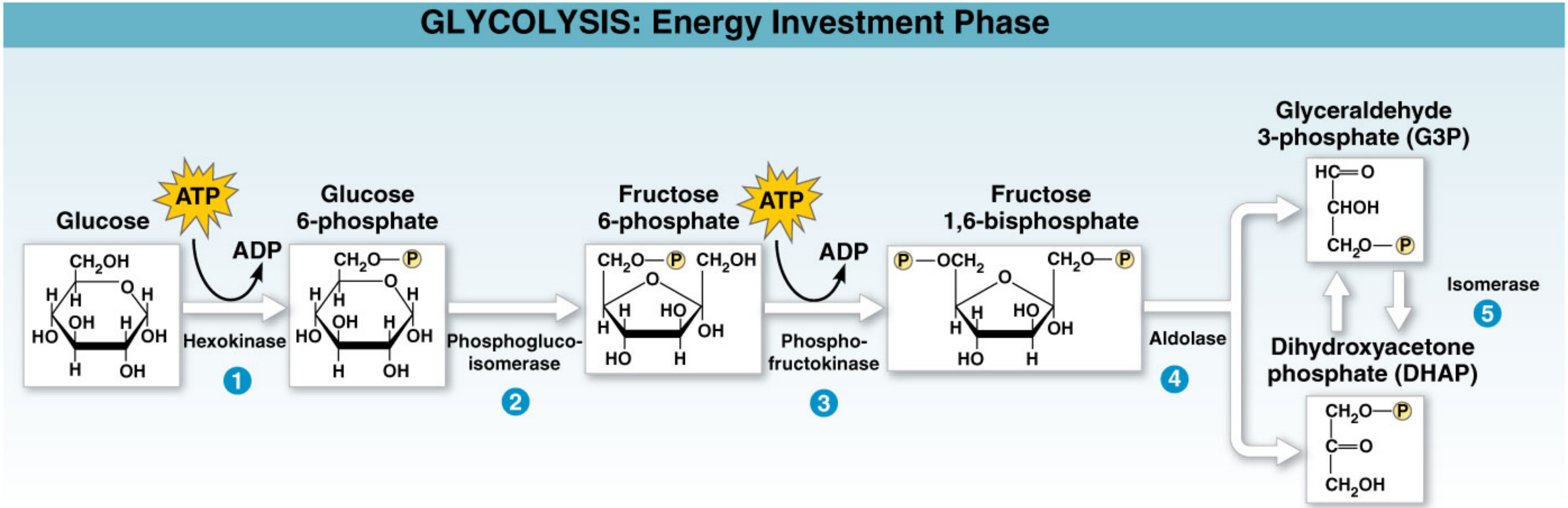
Substrate-Level Phosphorylation

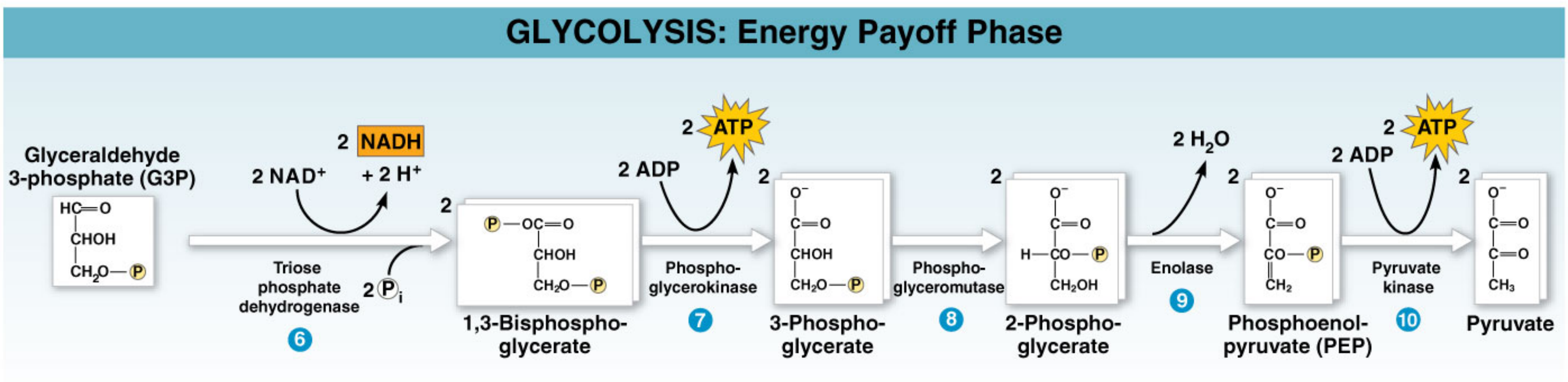
- Generate small amount of ATP
- Phosphorylation: enzyme transfers a phosphate to other compounds

(P) + compound

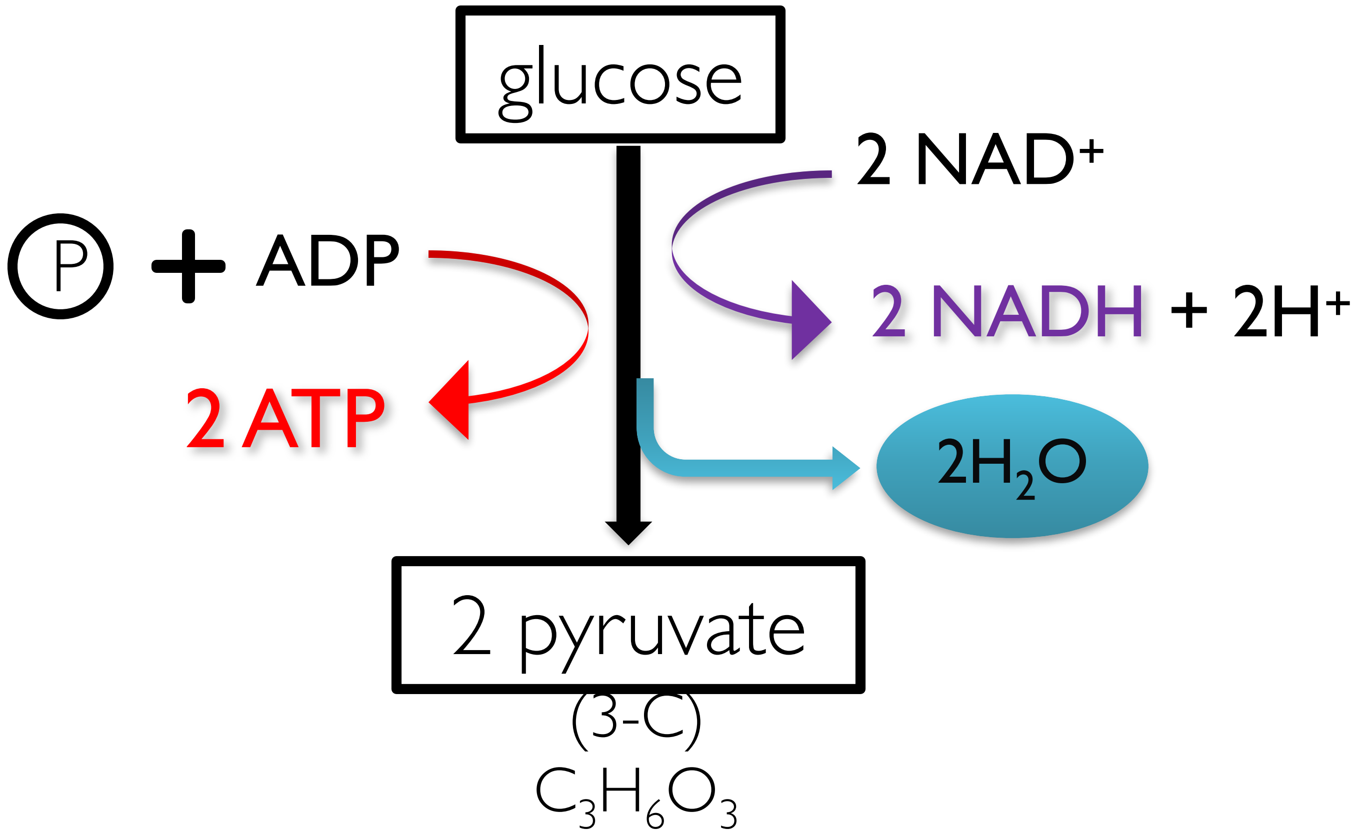
- ADP + P_i → ATP




GLYCOLYSIS: Energy Investment Phase
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphogluco-isomerase
2
Fructose 6-phosphate
ATP
ADP
Phospho-fructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Glyceraldehyde 3-phosphate (G3P)
Isomerase
5
Dihydroxyacetone phosphate (DHAP)

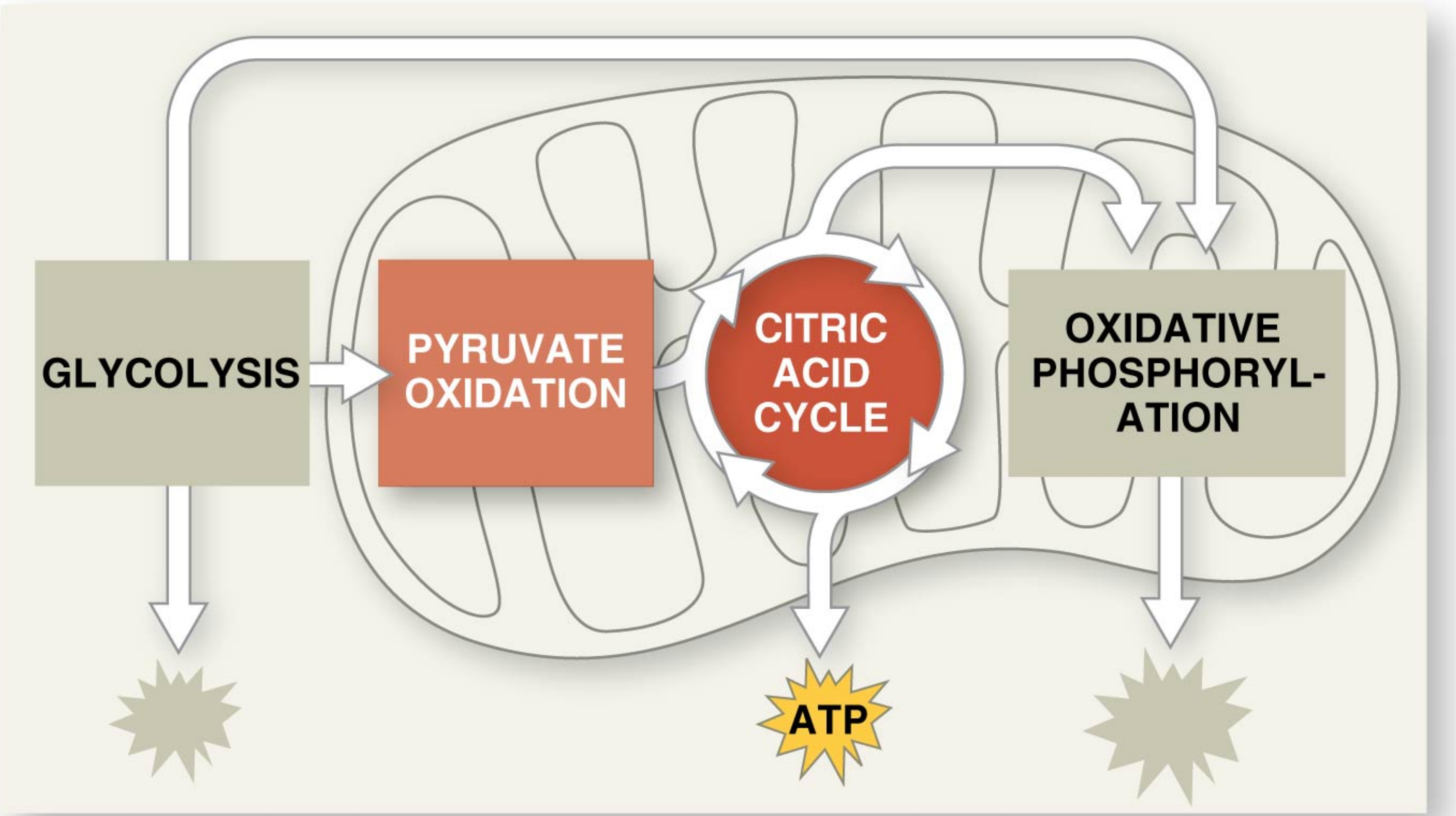

GLYCOLYSIS: Energy Payoff Phase
Glyceraldehyde 3-phosphate (G3P)
2 NAD+
2 NADH
+ 2 H+
Triose phosphate dehydrogenase
2 Pi
6
2
1,3-Bisphosphoglycerate
2 ADP
2 ATP
Phospho-glycerokinase
7
2
3-Phosphoglycerate
Phospho-glyceromutase
8
2
2-Phosphoglycerate
2 H2O
Enolase
9
2
Phosphoenolpyruvate (PEP)
2 ADP
2 ATP
Pyruvate kinase
10
2
Pyruvate

Glycolysis (Summary)

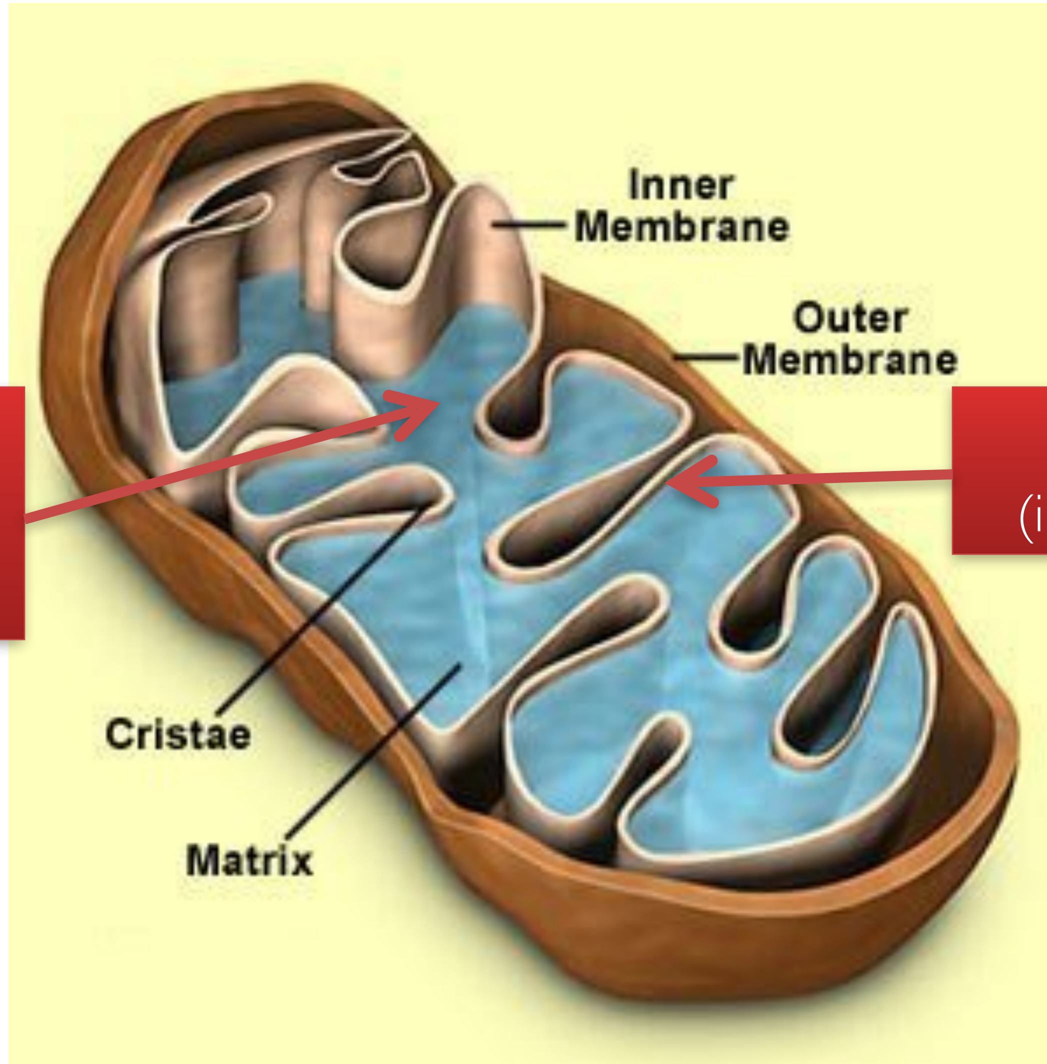


Cellular Respiration

Stage 2: Pyruvate Oxidation + Citric Acid Cycle

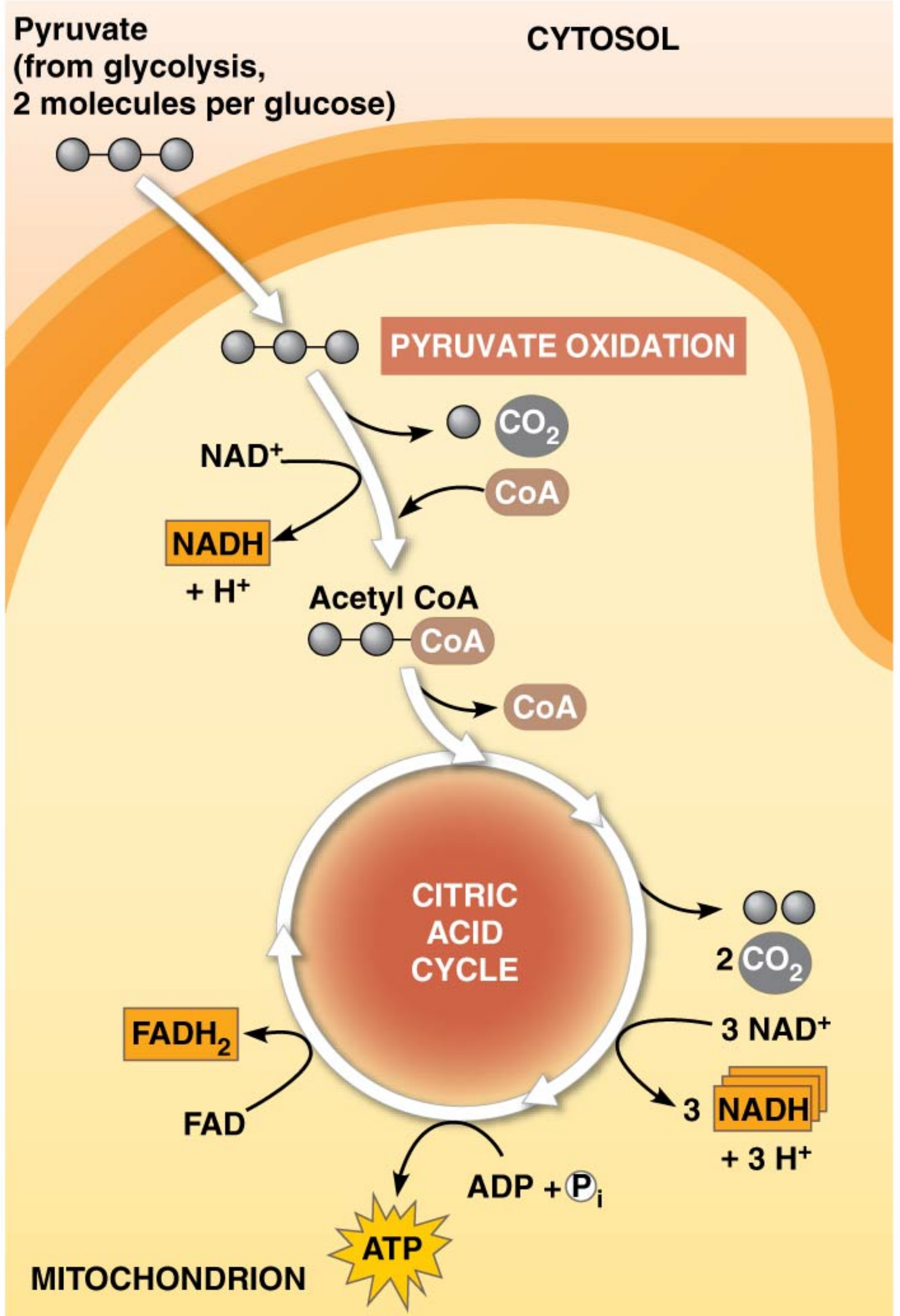

GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL- ATION
ATP

Mitochondrion Structure



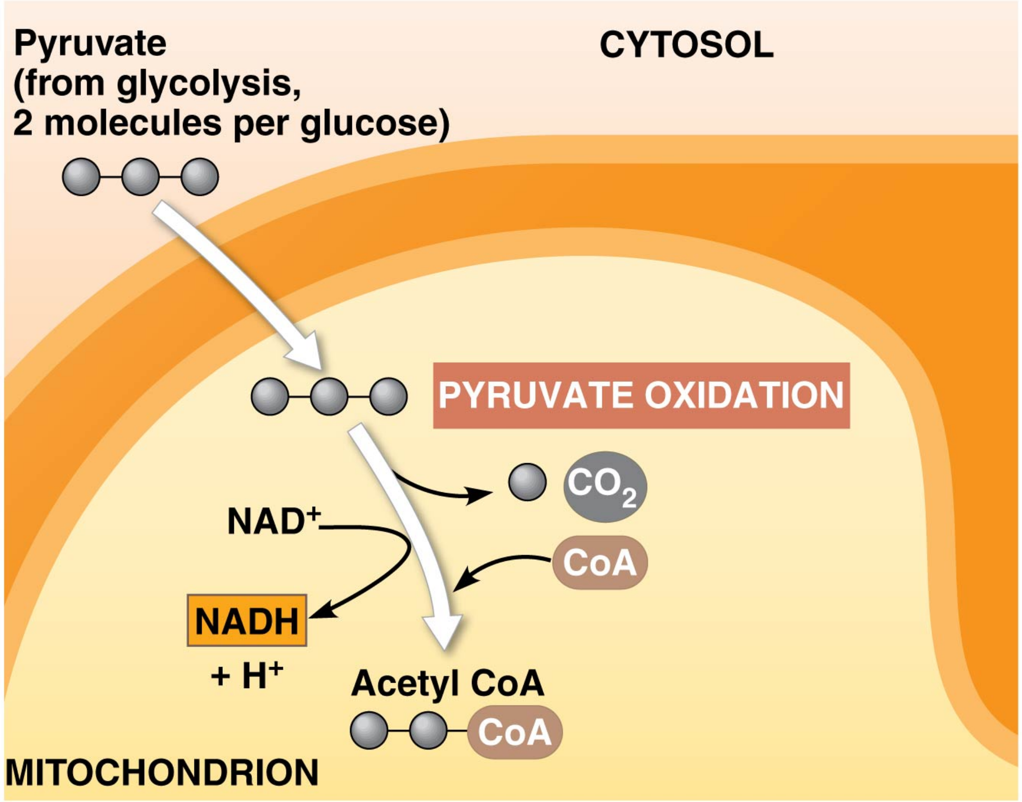
Citric Acid Cycle
(matrix)

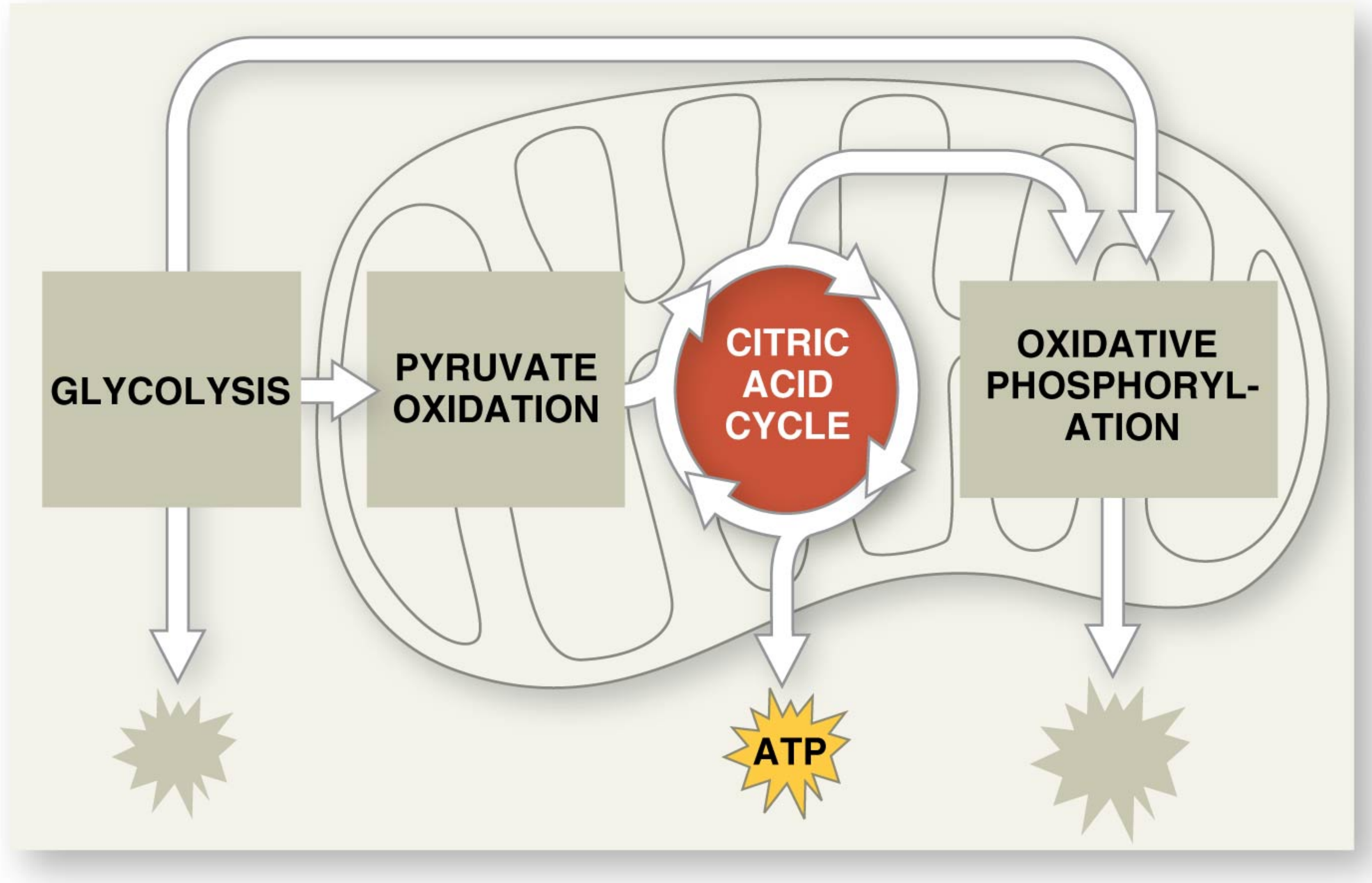
ETC
(inner membrane)


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

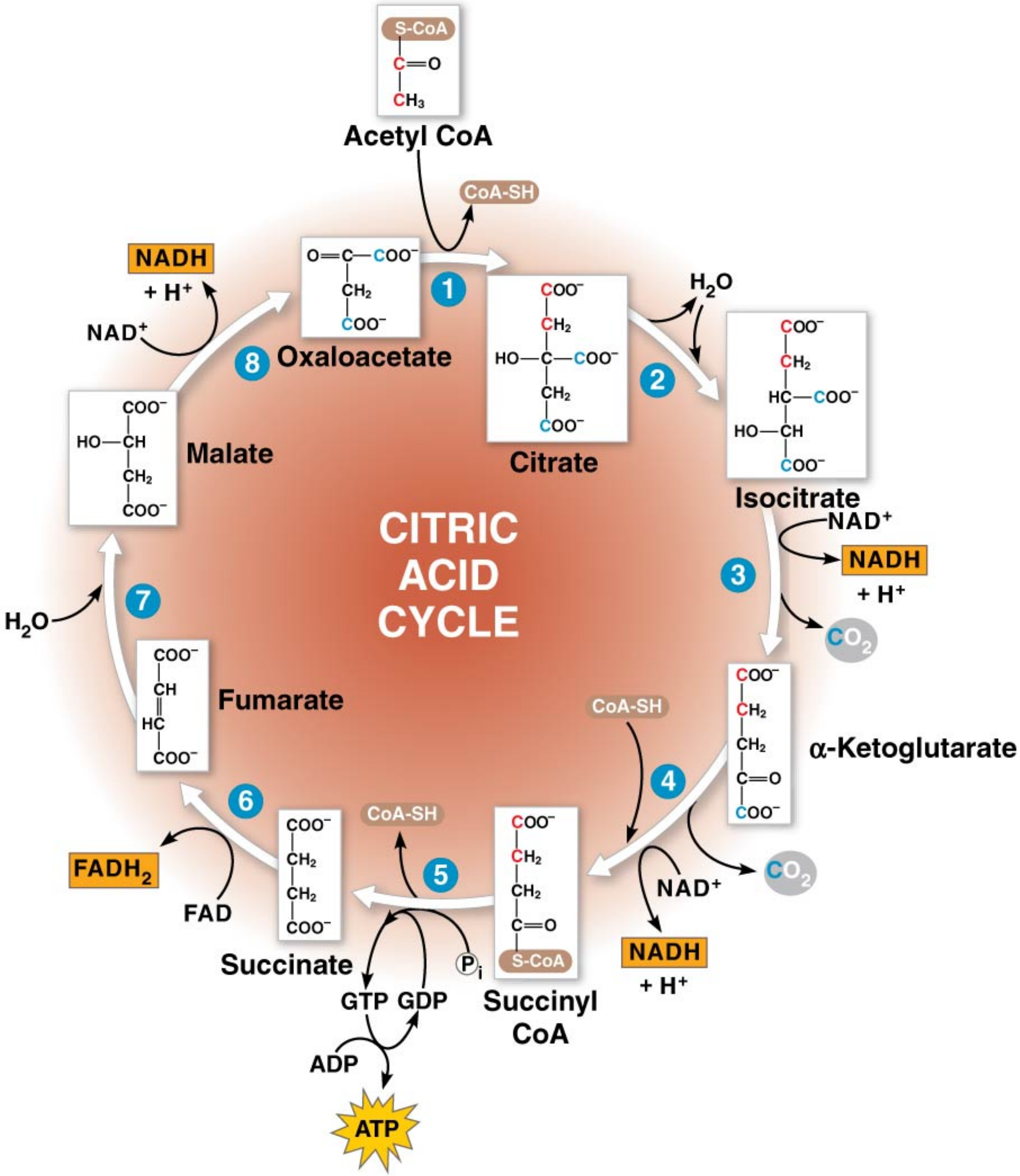
- Pyruvate → Acetyl CoA (*used to make citrate*)
- CO_2 and NADH produced




GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL- ATION
ATP

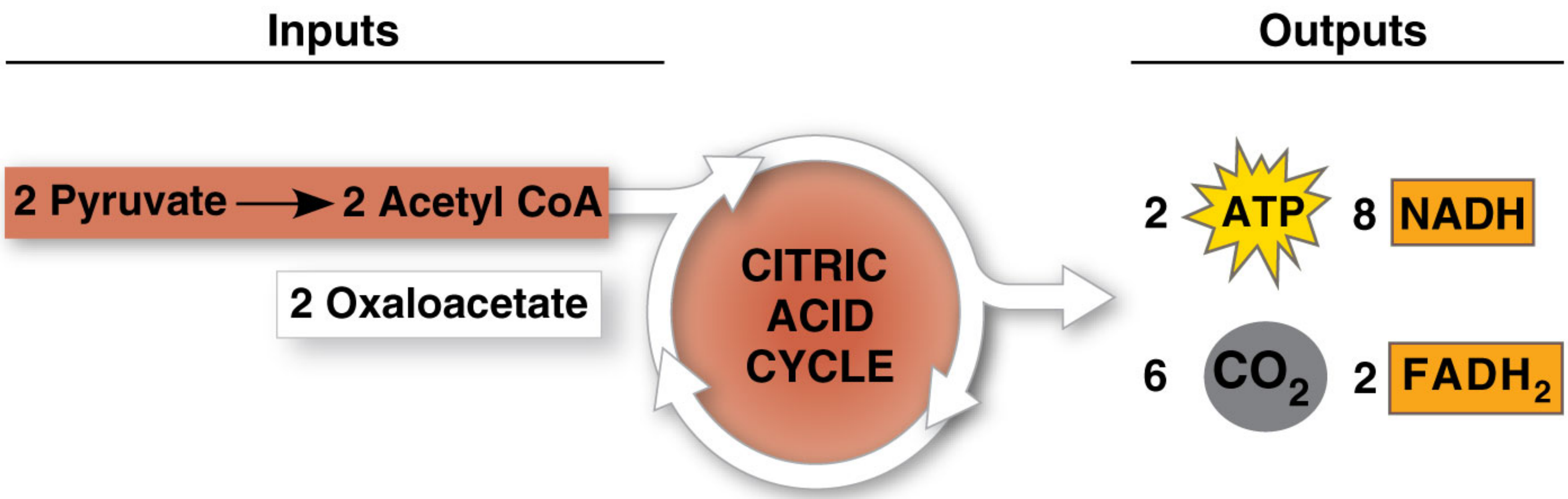
Citric Acid Cycle (Krebs)

- 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



S-CoA
C=O
CH3
Acetyl CoA
CoA-SH
1
Oxaloacetate
Citrate
H2O
2
Isocitrate
NAD+
NADH
+ H+
3
CO2
α-Ketoglutarate
CoA-SH
4
NAD+
NADH
+ H+
CO2
Succinyl CoA
S-CoA
5
CoA-SH
Pi
GTP GDP
ADP
ATP
Succinate
6
FAD
FADH2
Fumarate
7
H2O
Malate
8
NAD+
NADH
+ H+
CITRIC ACID CYCLE

Summary of Citric Acid Cycle

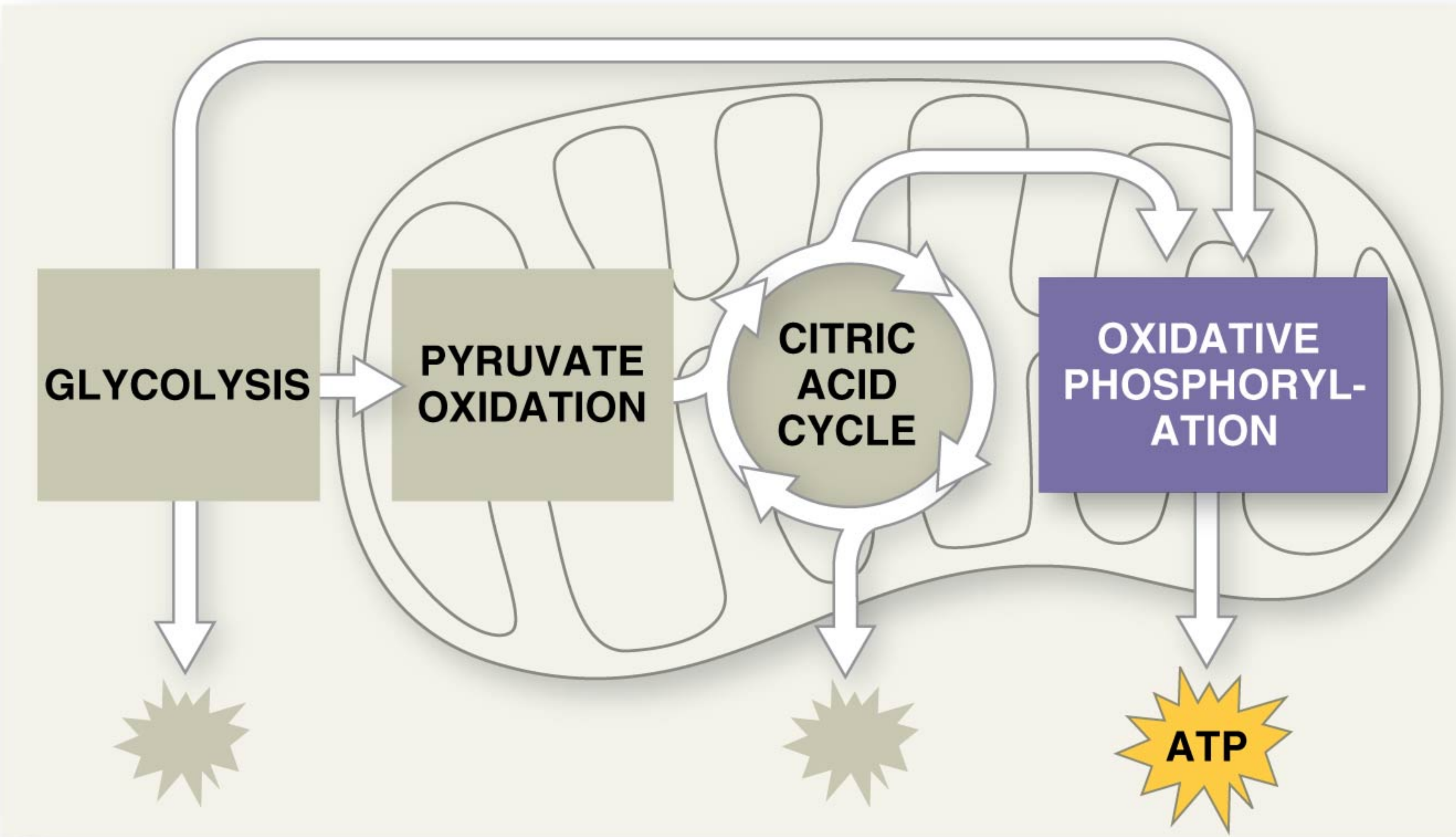


http://multimedia.mcb.harvard.edu/anim_mitochondria.html

BioVisions at Harvard: The Mitochondria

Cellular Respiration

Stage 3: Oxidative Phosphorylation

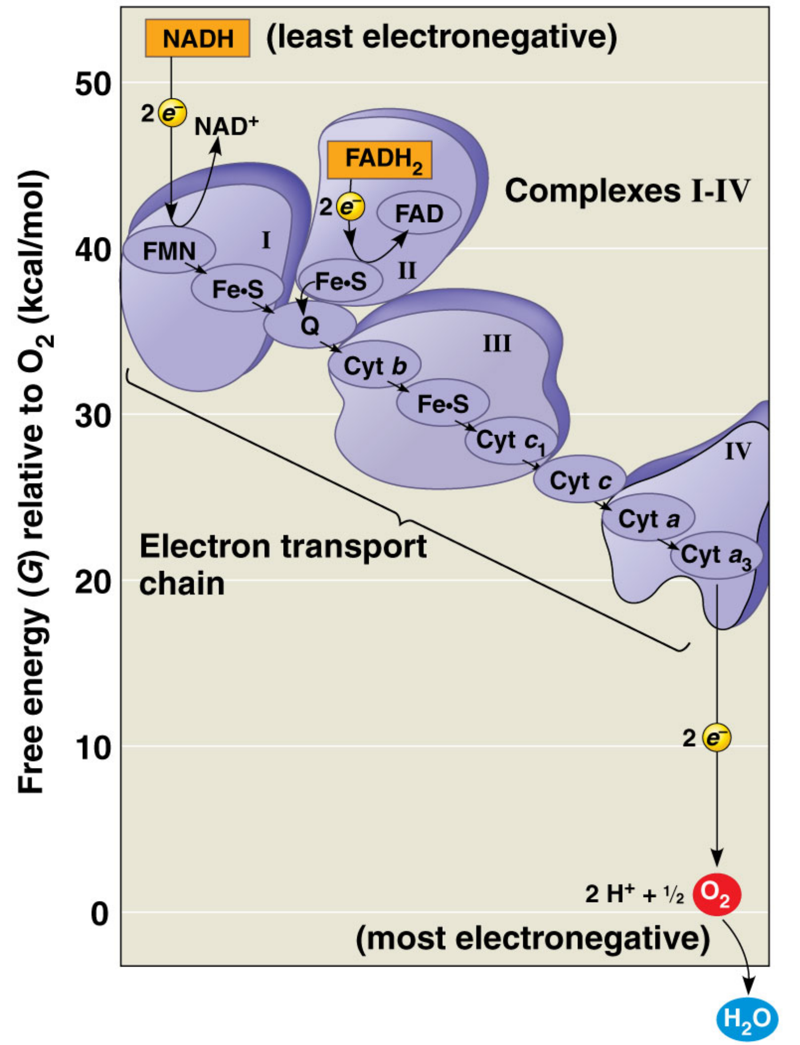

GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL- ATION
ATP

Oxidative Phosphorylation

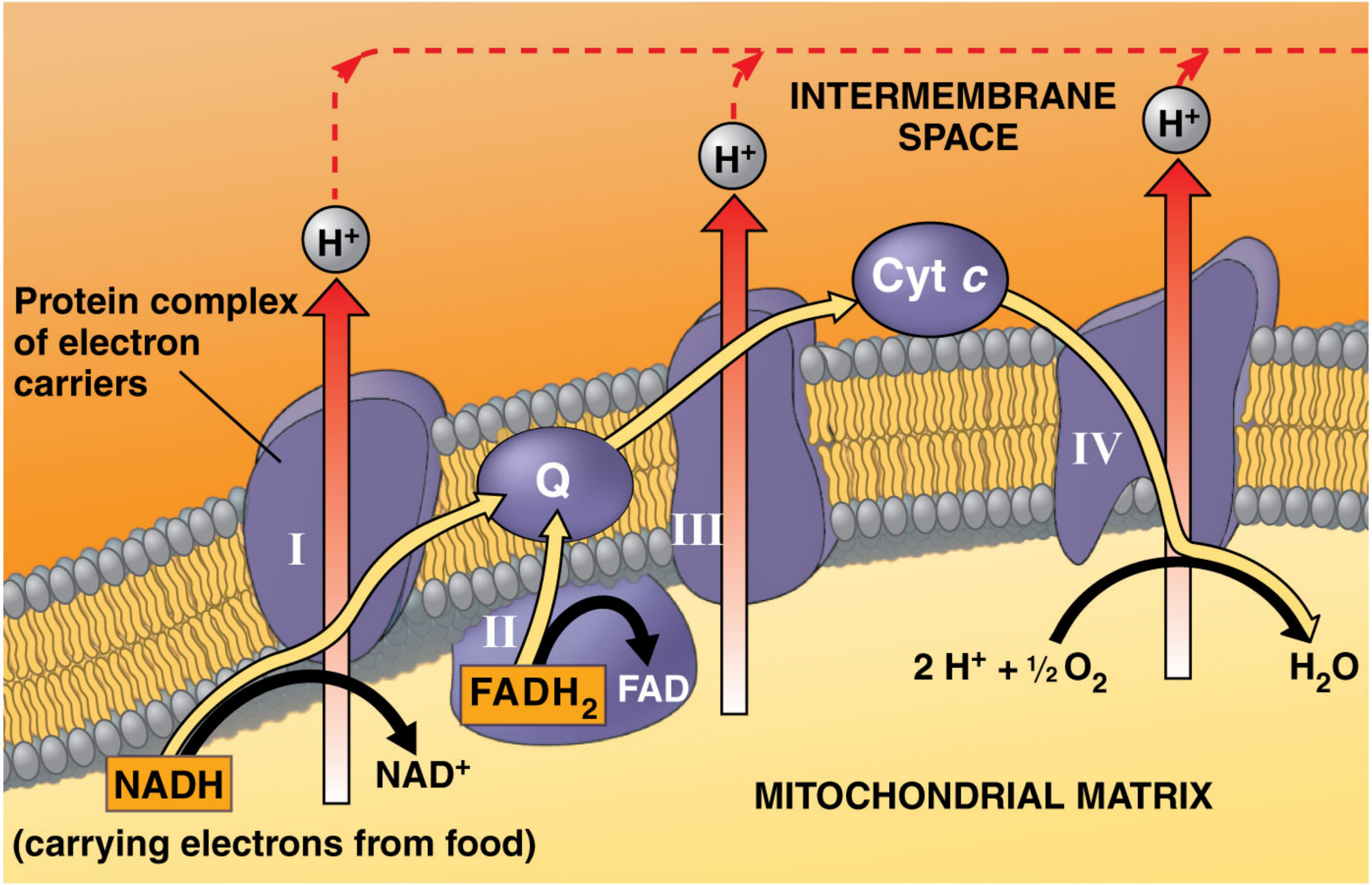
ELECTRON TRANSPORT CHAIN	CHEMIOSMOSIS
- Occurs in inner membrane of mitochondria - Produces **26-28 ATP** by oxidative phosphorylation via chemiosmosis	- H^+ ions pumped across inner mitochondrial membrane - H^+ diffuse through ATP synthase (ADP → ATP)

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 not make ATP directly
- Ease fall of e- from food to O_2
- $2H^+ + \frac{1}{2} O_2 \rightarrow$ H_2O



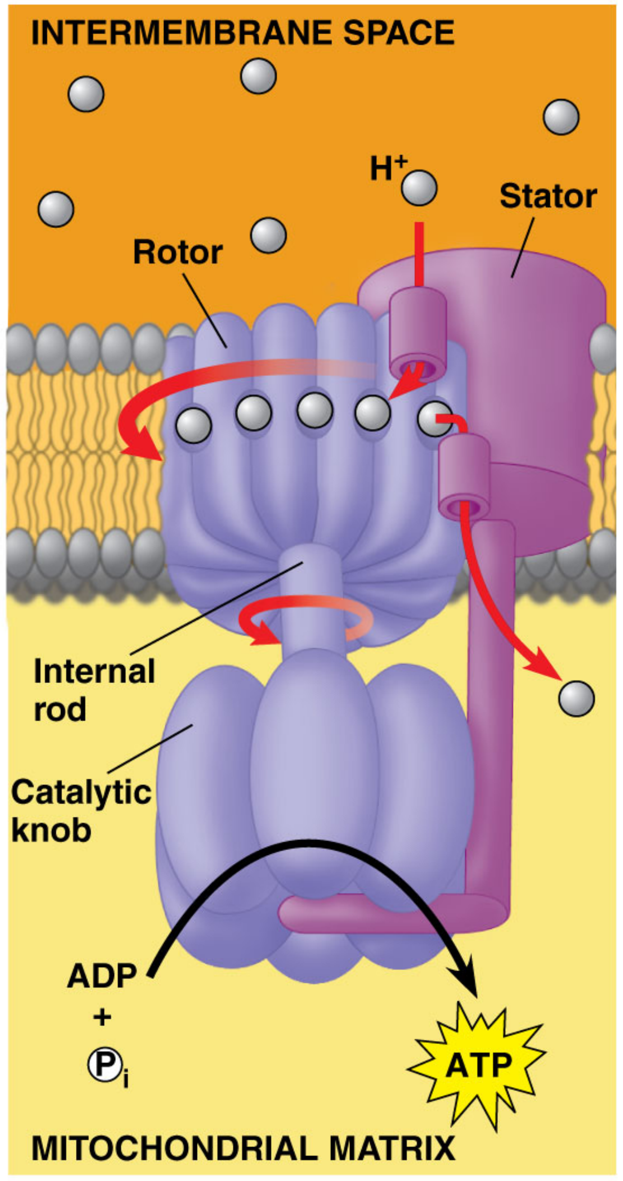
As electrons move through the ETC, proton pumps move H^+ across inner mitochondrial membrane



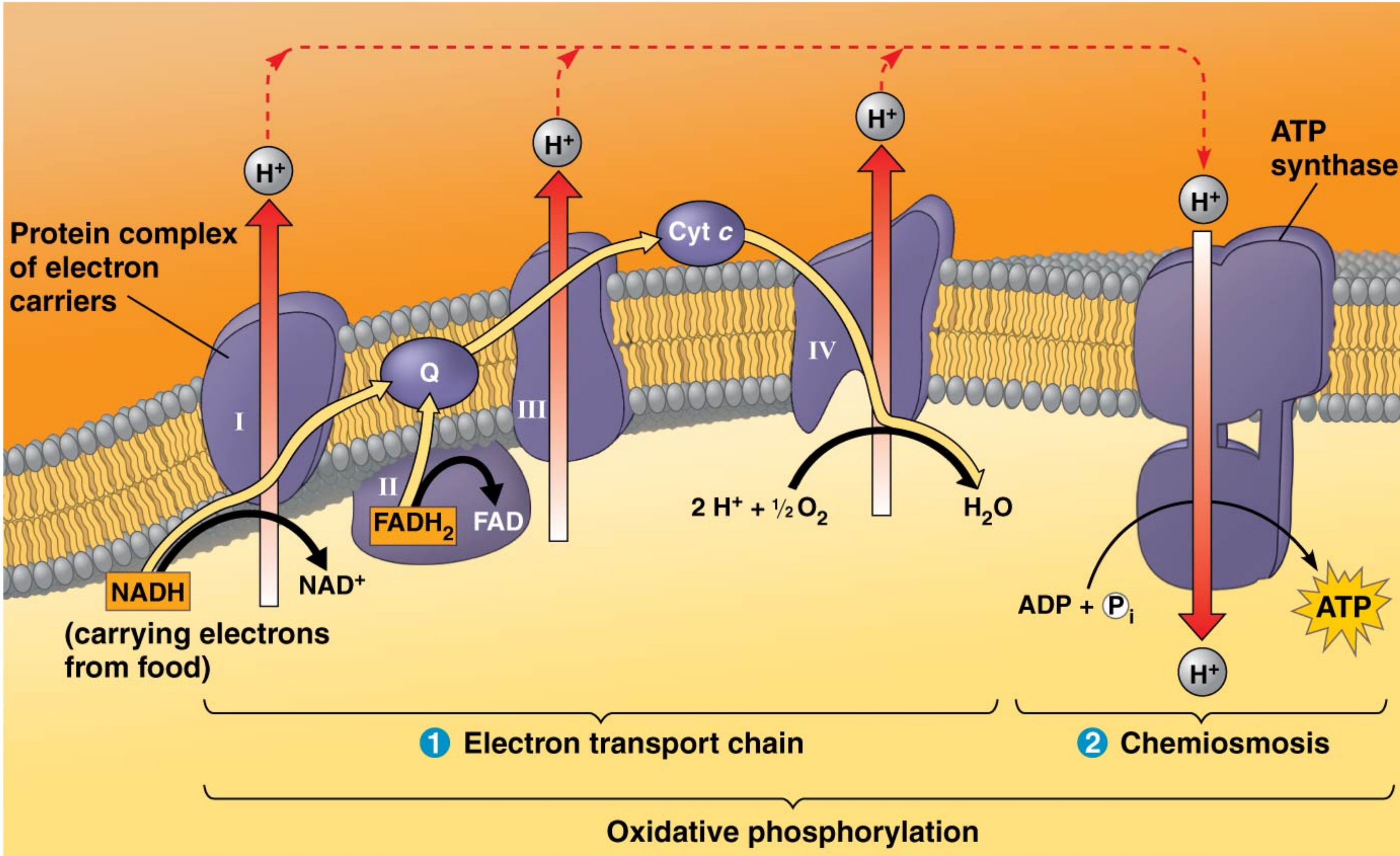
Chemiosmosis: Energy-Coupling Mechanism

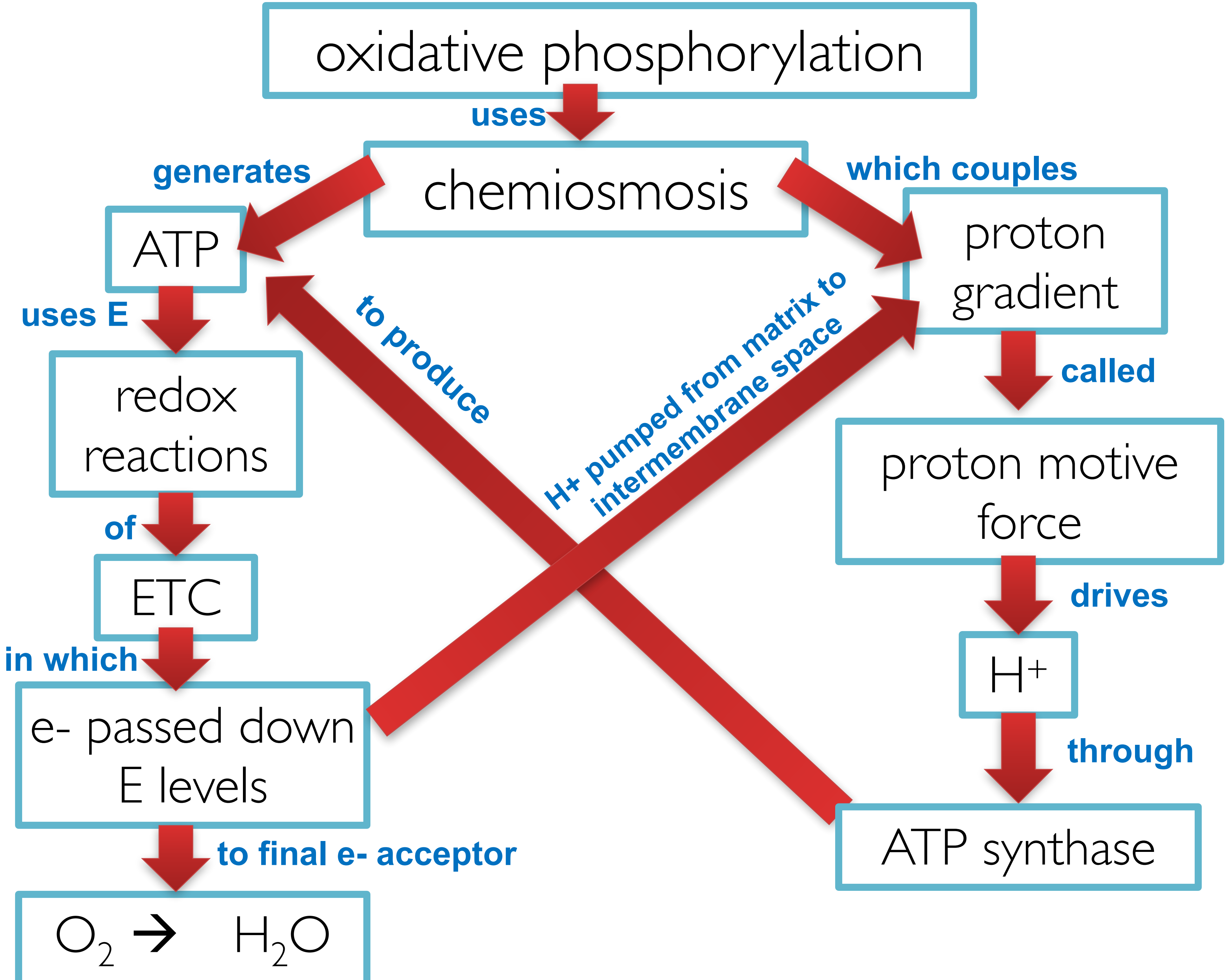
- **Chemiosmosis** = H^+ gradient across membrane drives cellular work
- **Proton-motive force**: use proton (H^+) gradient to perform work

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



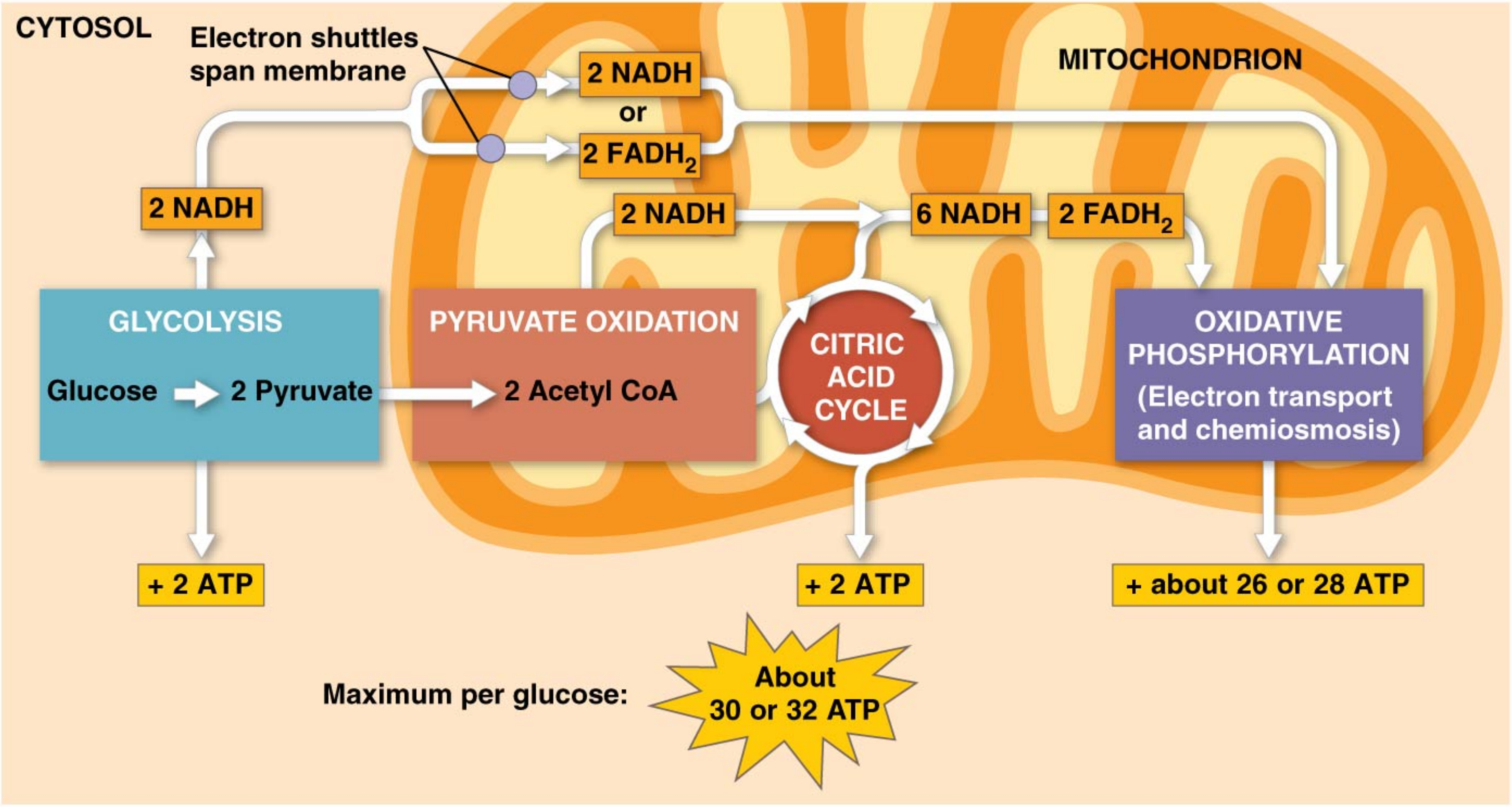
Chemiosmosis couples the ETC to ATP synthesis





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

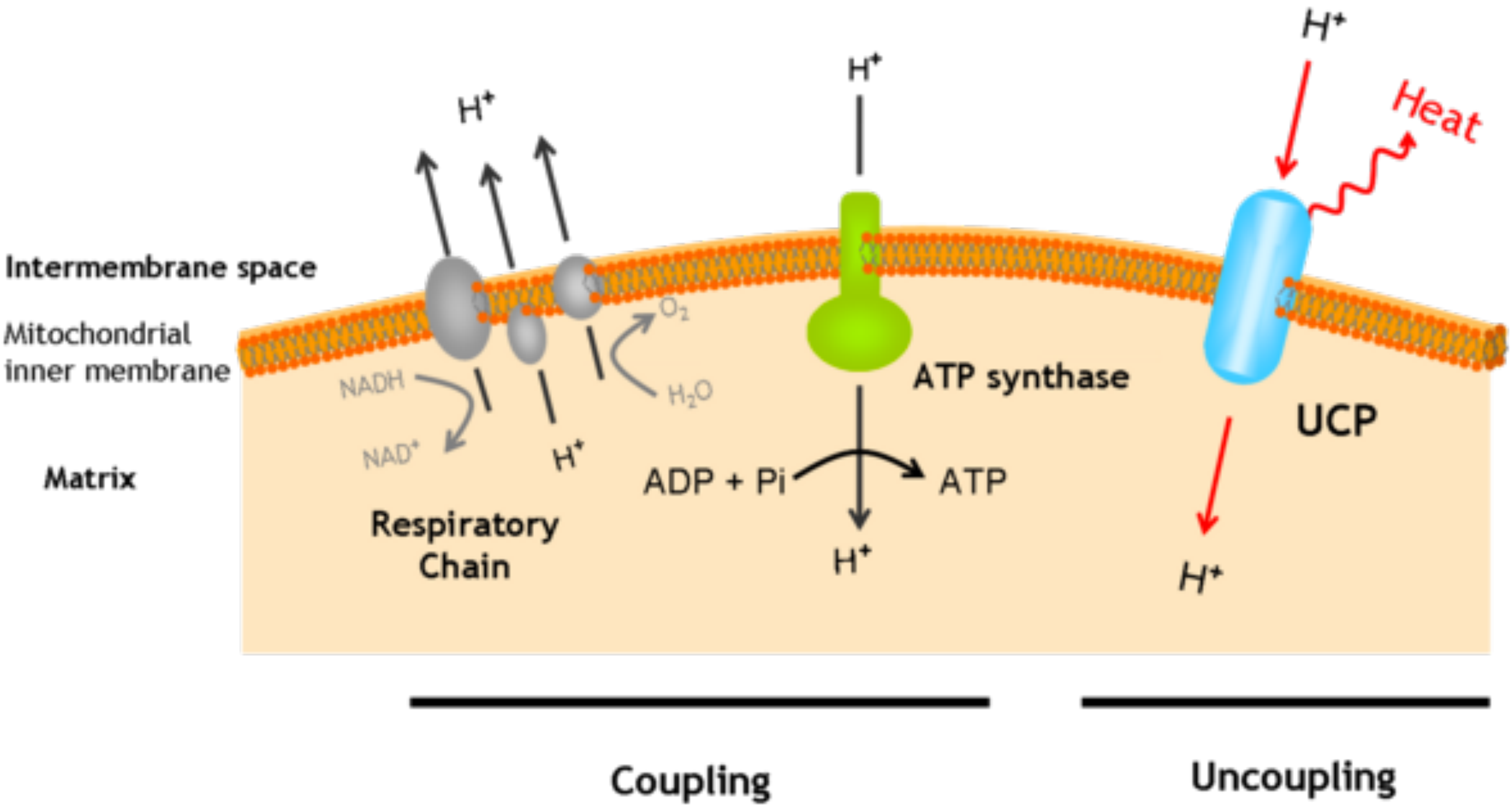


BioFlix: Cellular Respiration

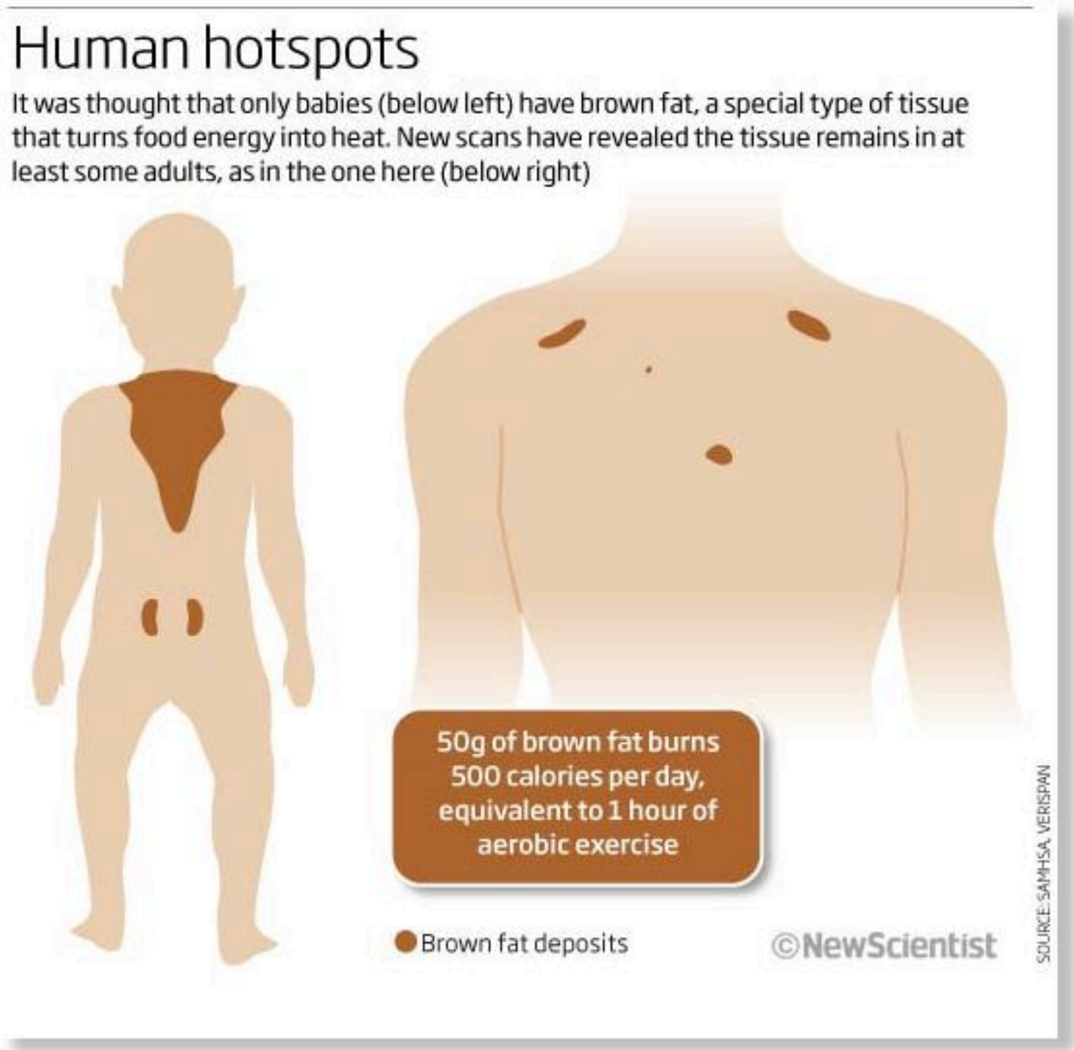
Non-Shivering Thermogenesis

- Allows **endotherms** to generate a lot of ***HEAT***
- **Thermogenin (UCP1)**: uncoupling protein found in mitochondria of **brown adipose (fat) tissue**
  - Decreases proton gradient – allows protons that were pumped into the intermembrane space to return to mitochondrial matrix
  - Fast substrate oxidation, but low ATP production
- Brown adipose tissue abundant in newborns and hibernating animals

Decoupling oxidative phosphorylation from electron transport generates heat



Brown Adipose Tissue

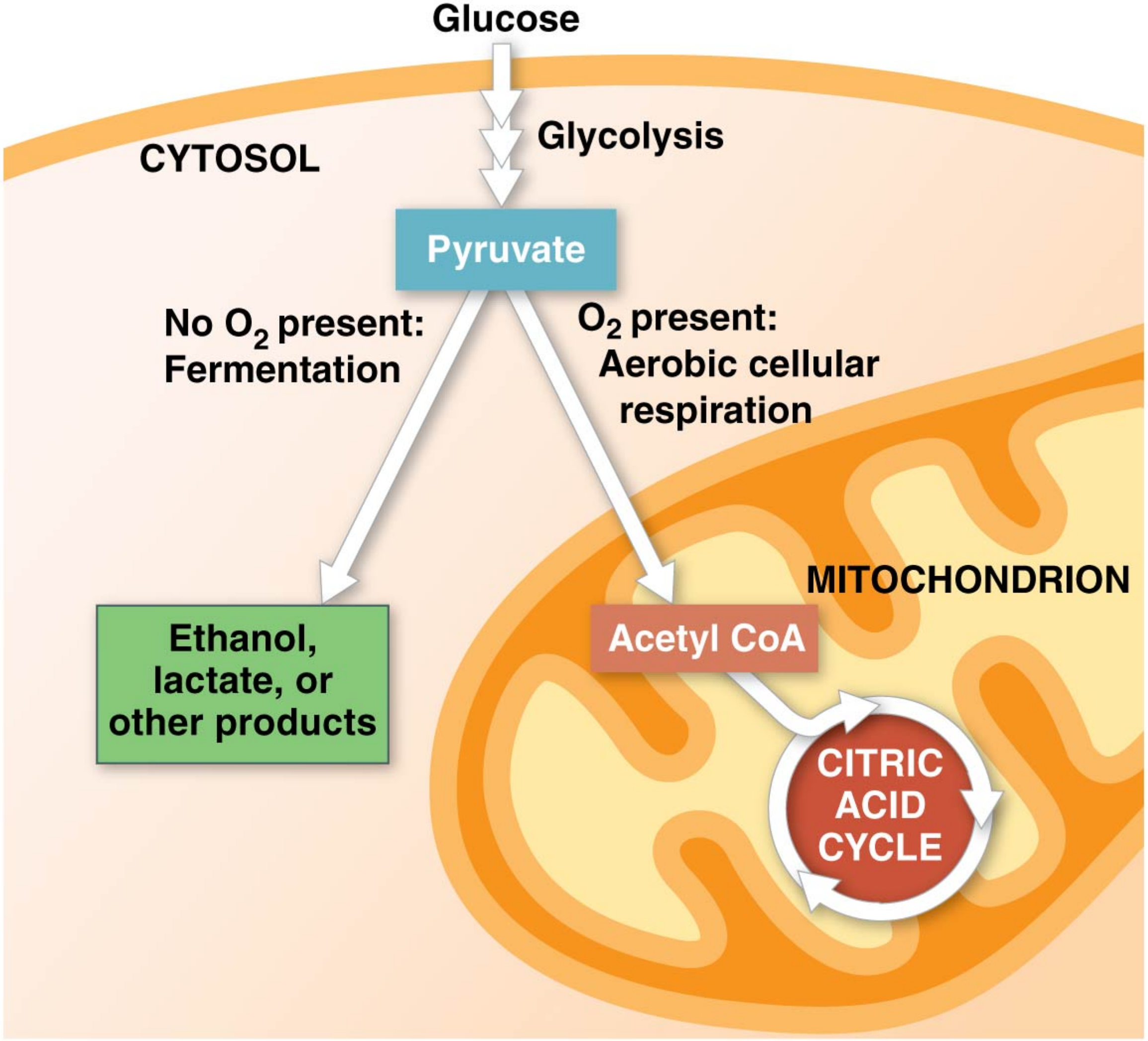


Anaerobic Respiration

- **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 → **FERMENTATION**

O_2 present → **RESPIRATION**

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**

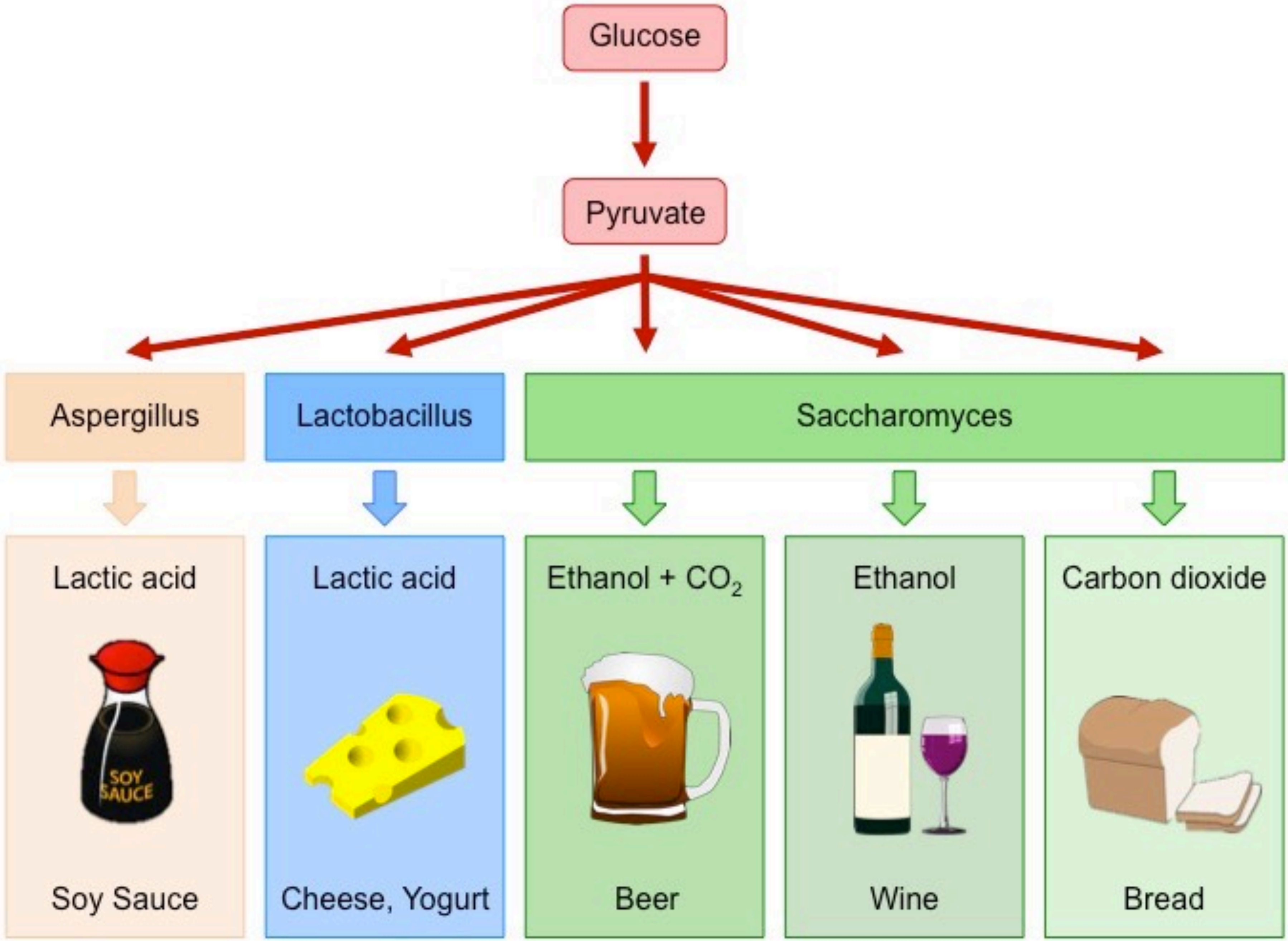
Types of Fermentation

ALCOHOL FERMENTATION

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

LACTIC ACID FERMENTATION

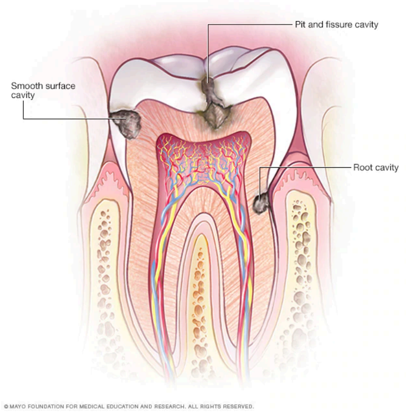
- Pyruvate → Lactate
- Ex. fungi, bacteria, human muscle cells
- Used to make cheese, yogurt, acetone, methanol
- Note: Lactate build-up does NOT causes muscle fatigue and pain (old idea)


Glucose
Pyruvate
Aspergillus
Lactobacillus
Saccharomyces
Lactic acid
Soy Sauce
Lactic acid
Cheese, Yogurt
Ethanol + CO_2
Beer
Ethanol
Wine
Carbon dioxide
Bread
SOY SAUCE

Fermentation at Work

Decomposition: Bloat stage (H_2 and CO_2 gases from anaerobic fermentation of gut bacteria)

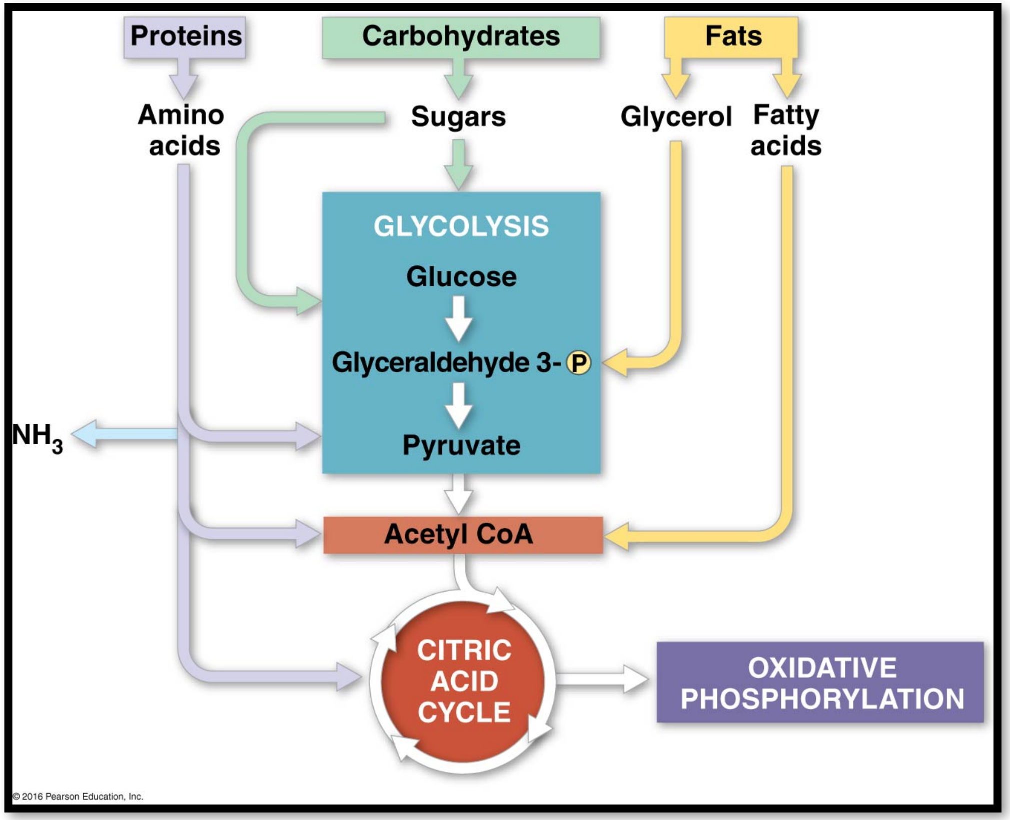
Sugar + Bacteria = Plaque
Bacterial fermentation →
Lactic Acid → Cavities



H_2 and CO_2 gases from anaerobic fermentation of gut bacteria

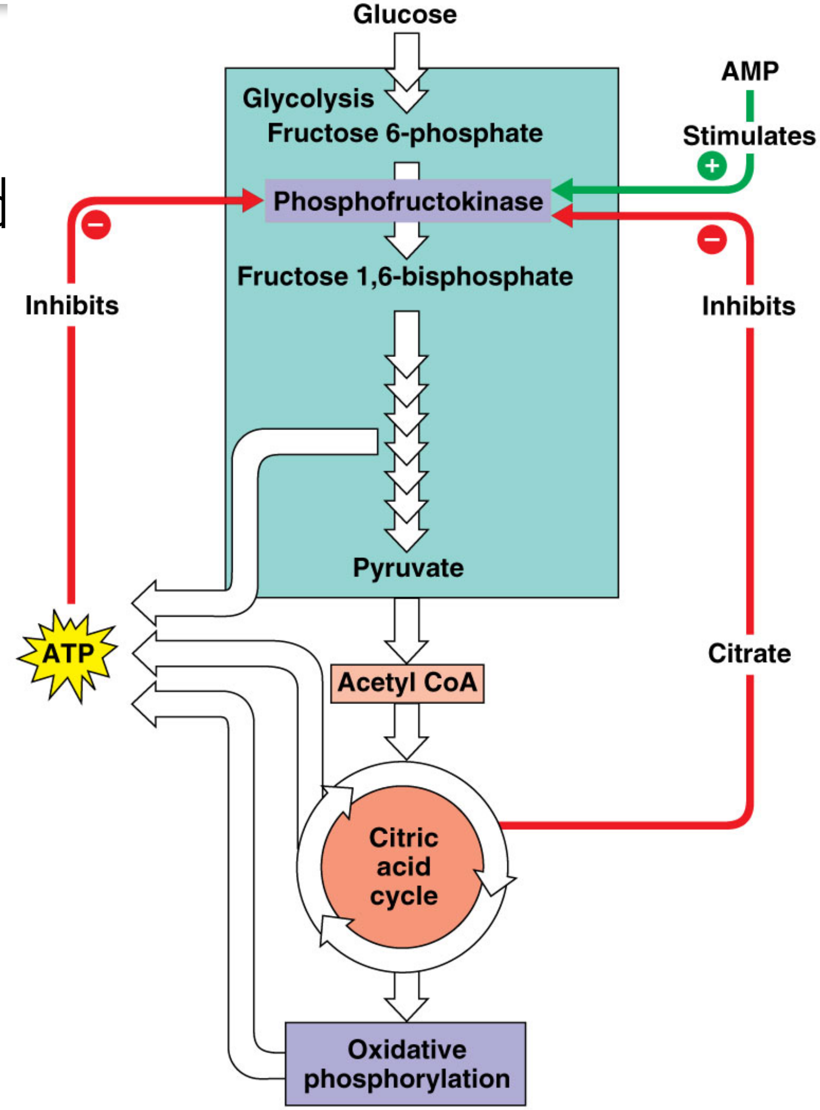
Various sources of fuel

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

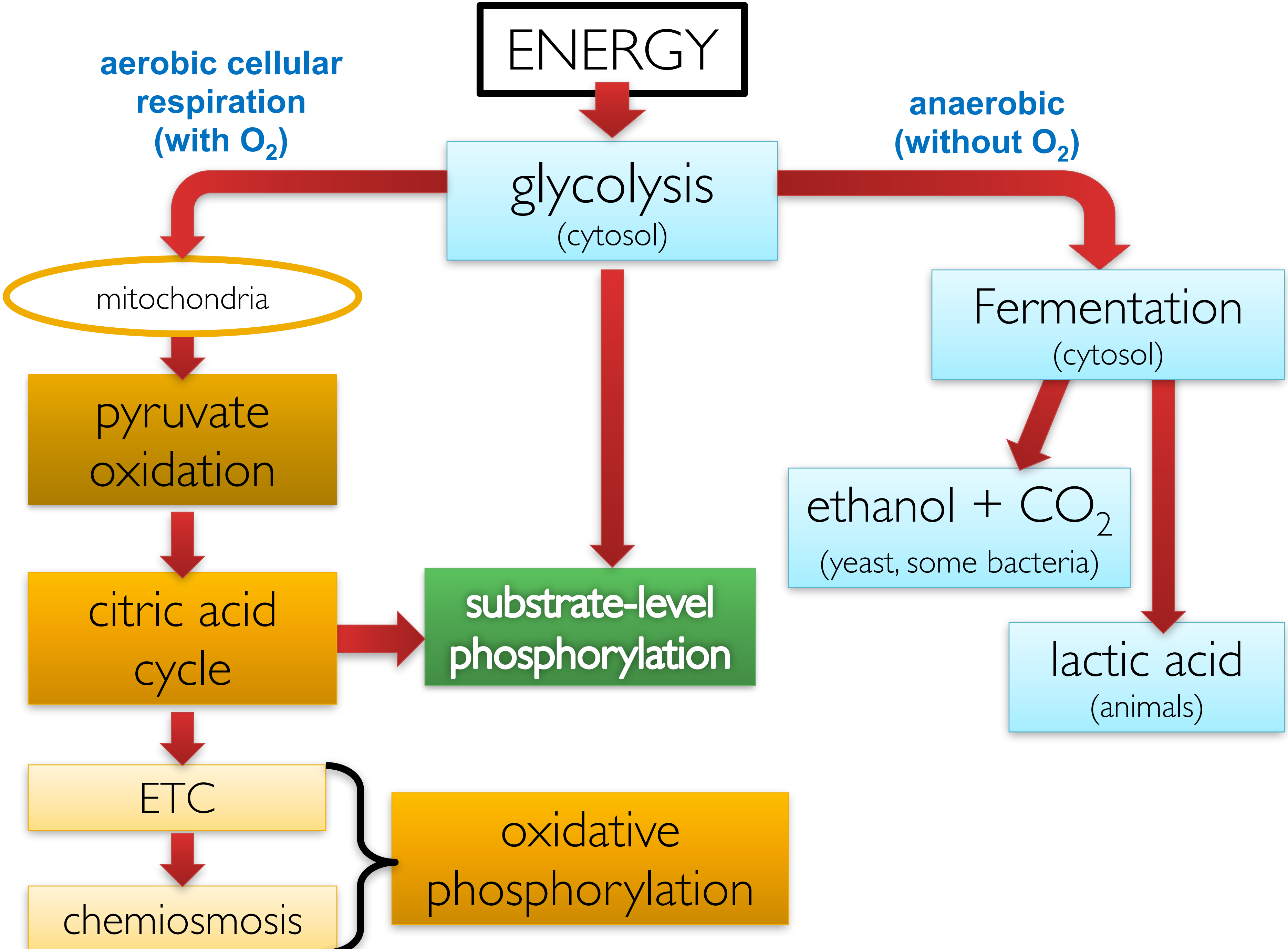


Phosphofructokinase (PFK)

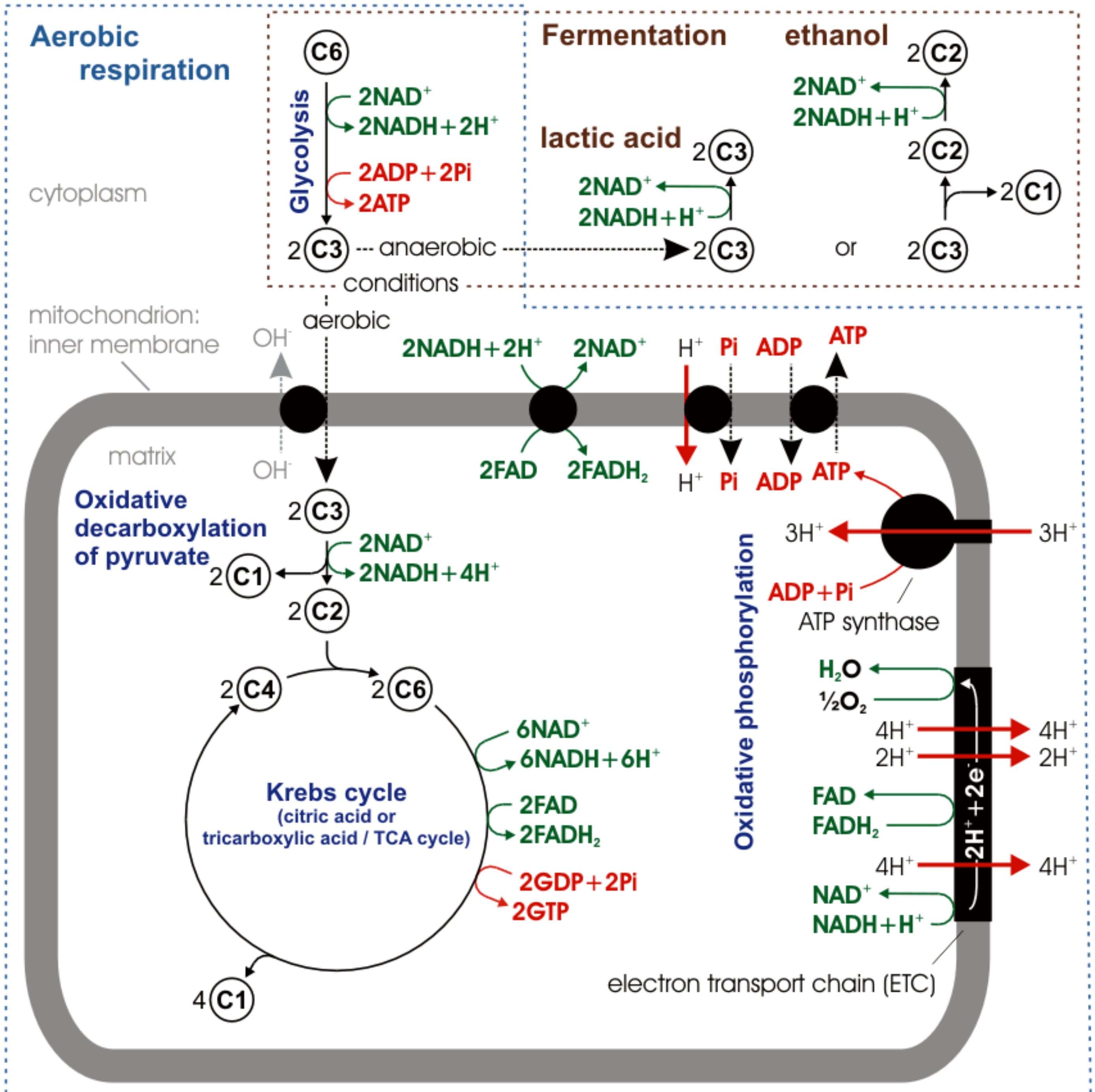
- Allosteric enzyme that controls rate of glycolysis and citric acid cycle
- Inhibited by ATP, citrate
- Stimulated by AMP
  - AMP+ P + P → ATP



Respiration: Big Picture

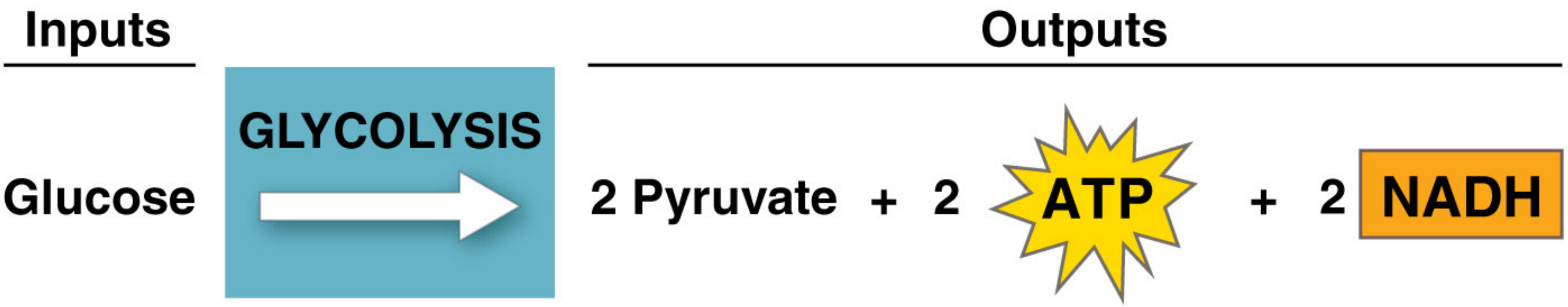


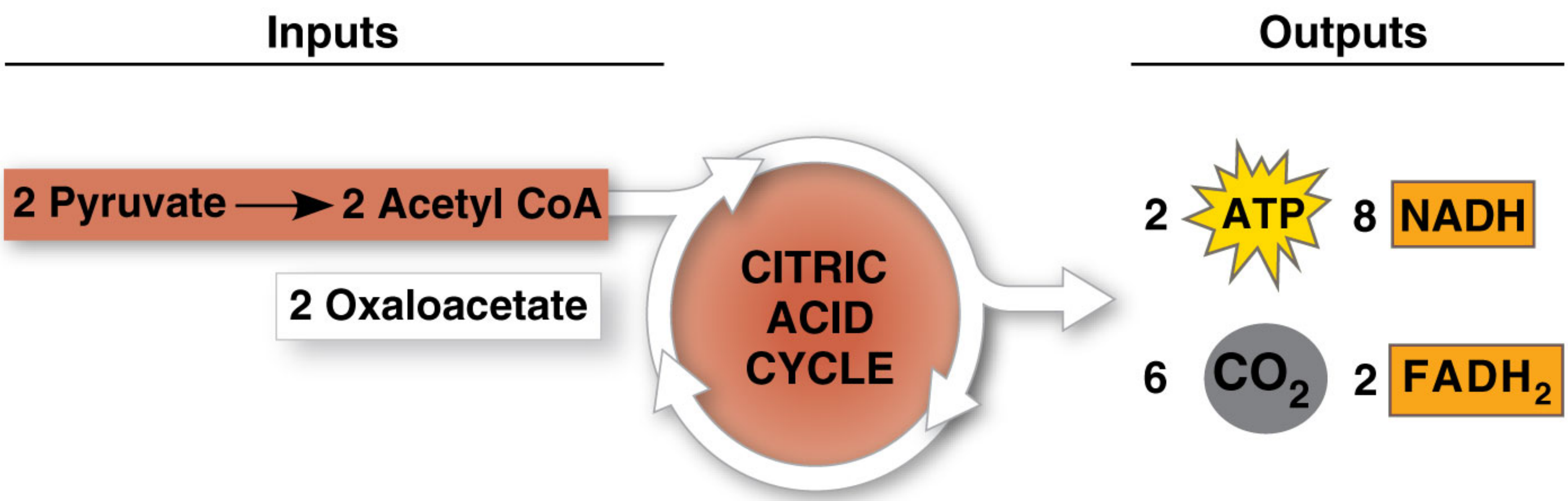
ENERGY
aerobic cellular respiration (with O_2)
anaerobic (without O_2)
glycolysis
(cytosol)
mitochondria
pyruvate oxidation
citric acid cycle
substrate-level phosphorylation
ETC
chemiosmosis
oxidative phosphorylation
Fermentation
(cytosol)
ethanol + CO_2
(yeast, some bacteria)
lactic acid
(animals)



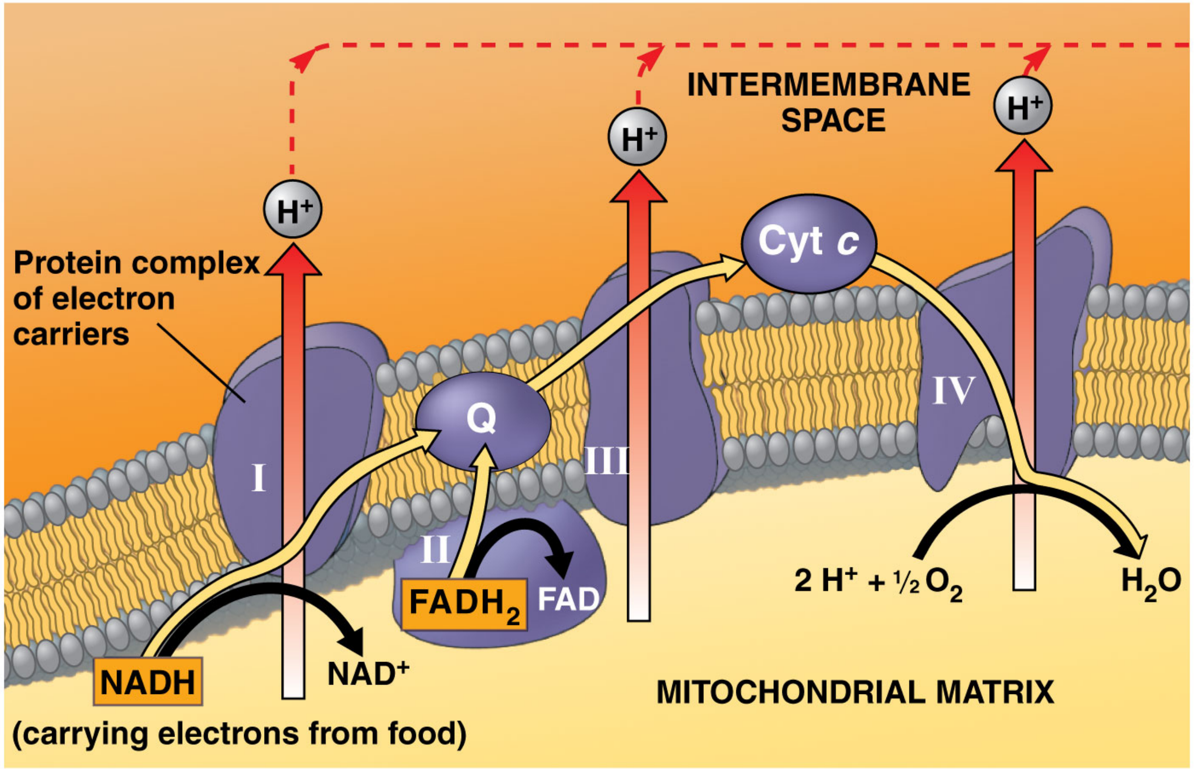
Aerobic respiration
cytoplasm
C6
Glycolysis
2NAD+
2NADH+2H+
2ADP+2Pi
2ATP
2 C3
anaerobic conditions
Fermentation
lactic acid
2 C3
2NAD+
2NADH+H+
2 C3
ethanol
2 C2
2NAD+
2NADH+H+
2 C2
2 C1
or
2 C3
mitochondrion: inner membrane
aerobic
OH-
2NADH+2H+
2NAD+
2FAD
2FADH2
H+
Pi
ADP
ATP
H+
Pi
ADP
ATP
matrix
OH-
Oxidative decarboxylation of pyruvate
2 C3
2NAD+
2NADH+4H+
2 C1
2 C2
3H+
3H+
ADP+Pi
ATP synthase
Oxidative phosphorylation
2 C4
2 C6
6NAD+
6NADH+6H+
Krebs cycle
(citric acid or tricarboxylic acid / TCA cycle)
2FAD
2FADH2
2GDP+2Pi
2GTP
4 C1
H2O
½O2
4H+
4H+
2H+
2H+
FAD
FADH2
2H+ +2e-
4H+
4H+
NAD+
NADH+H+
electron transport chain (ETC)

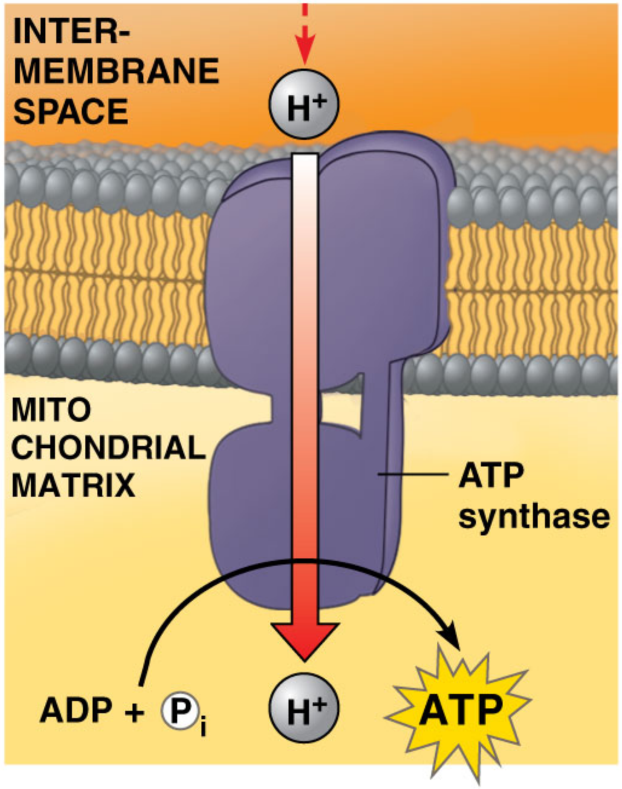
Glycolysis & Citric Acid Cycle



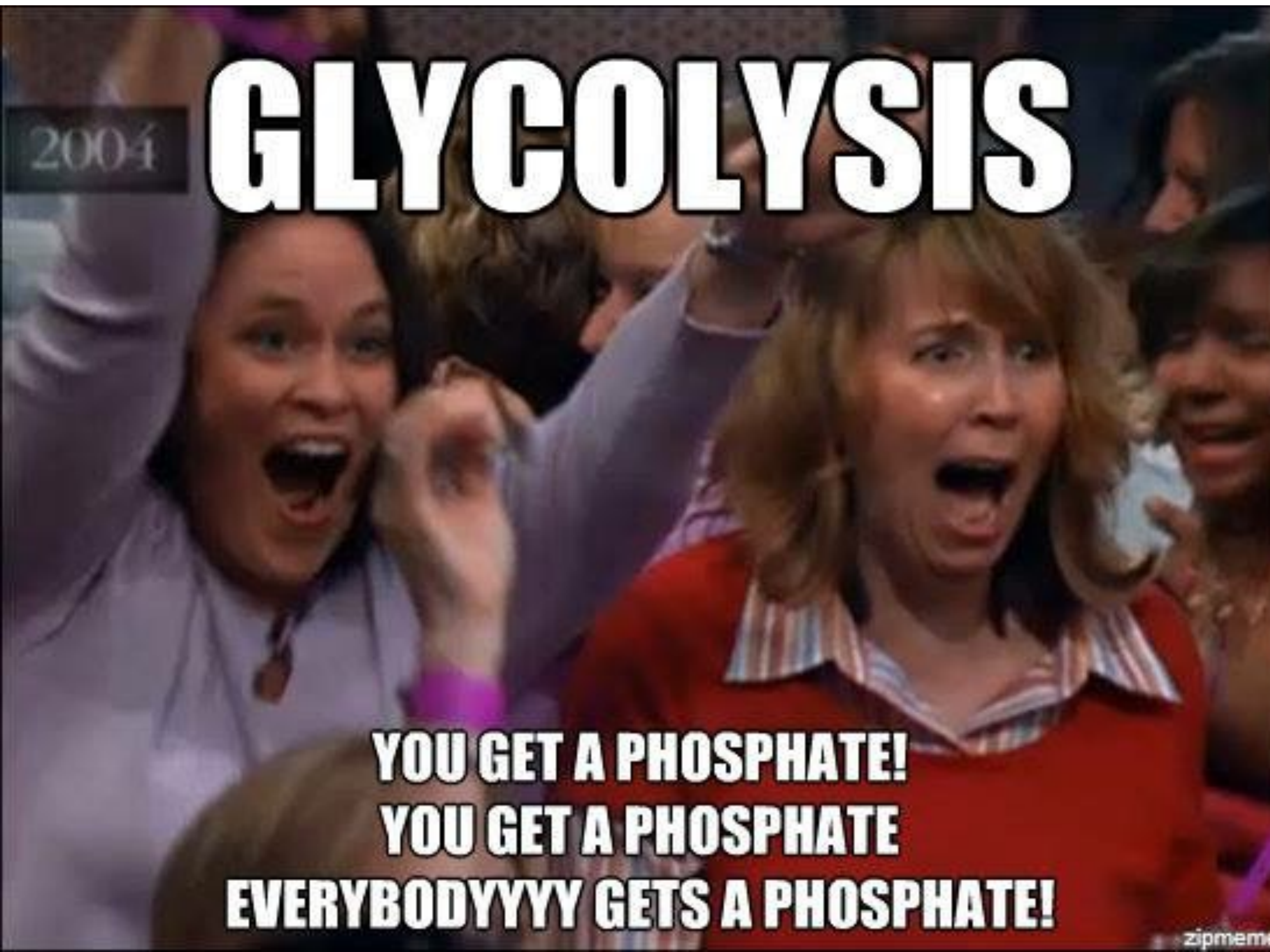


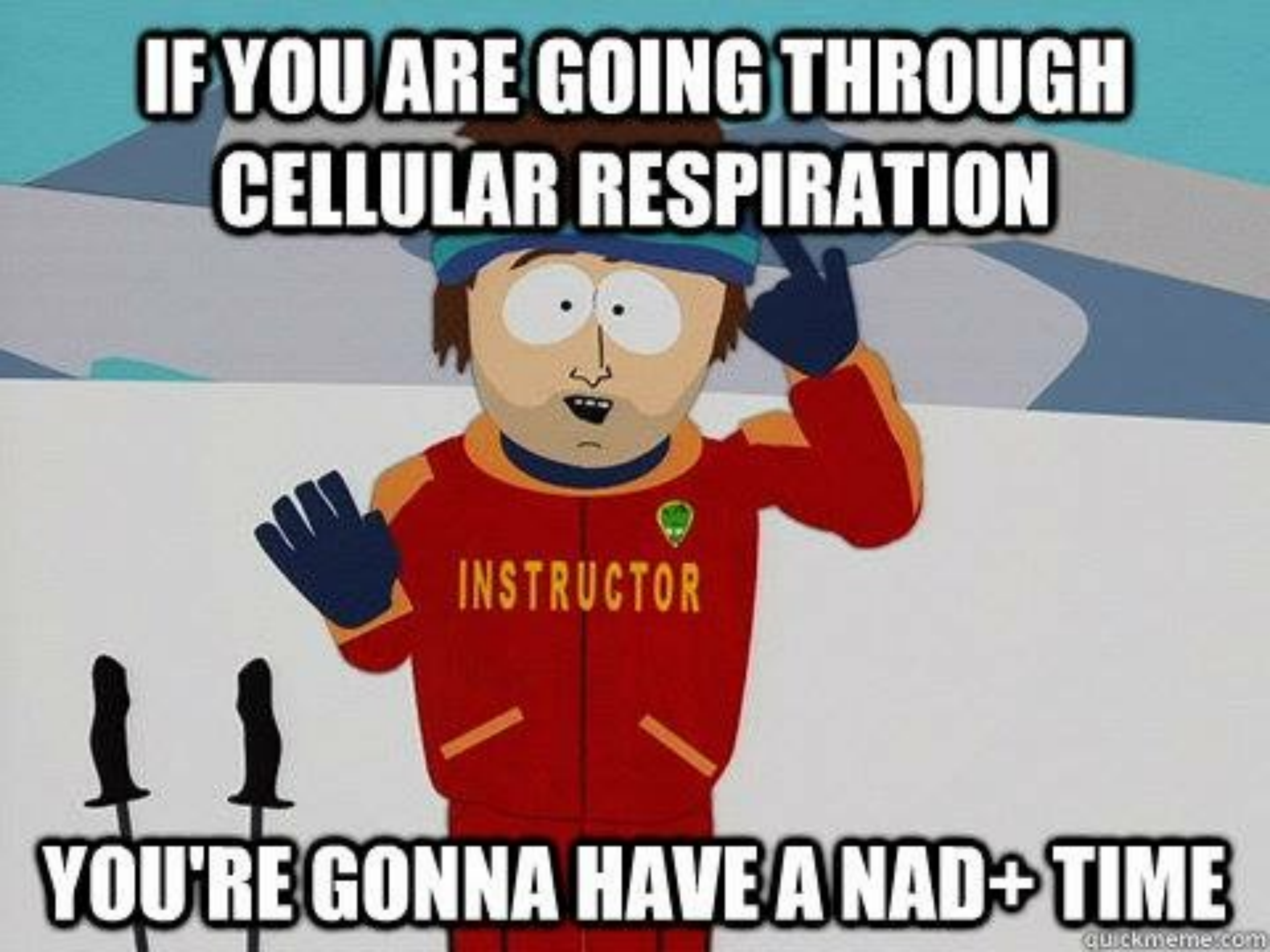
Oxidative Phosphorylation





Electron Transport Chain **Chemiosmosis**


2004
GLYCOLYSIS
YOU GET A PHOSPHATE!
YOU GET A PHOSPHATE
EVERYBODYYYY GETS A PHOSPHATE!
zipmeme


IF YOU ARE GOING THROUGH CELLULAR RESPIRATION
INSTRUCTOR
YOU'RE GONNA HAVE A NAD+ TIME
quickmeme.com