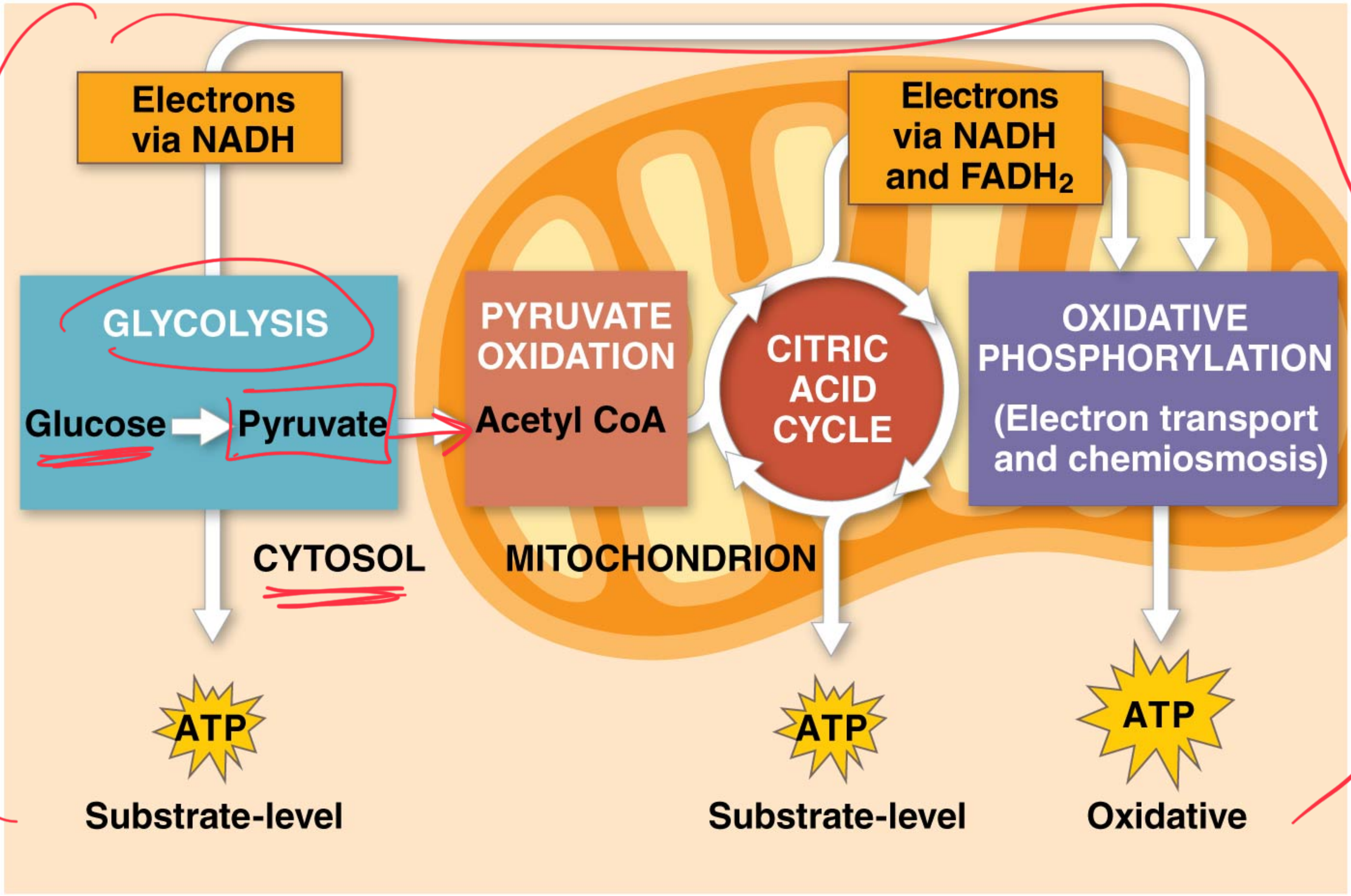
Stages of Cellular Respiration

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

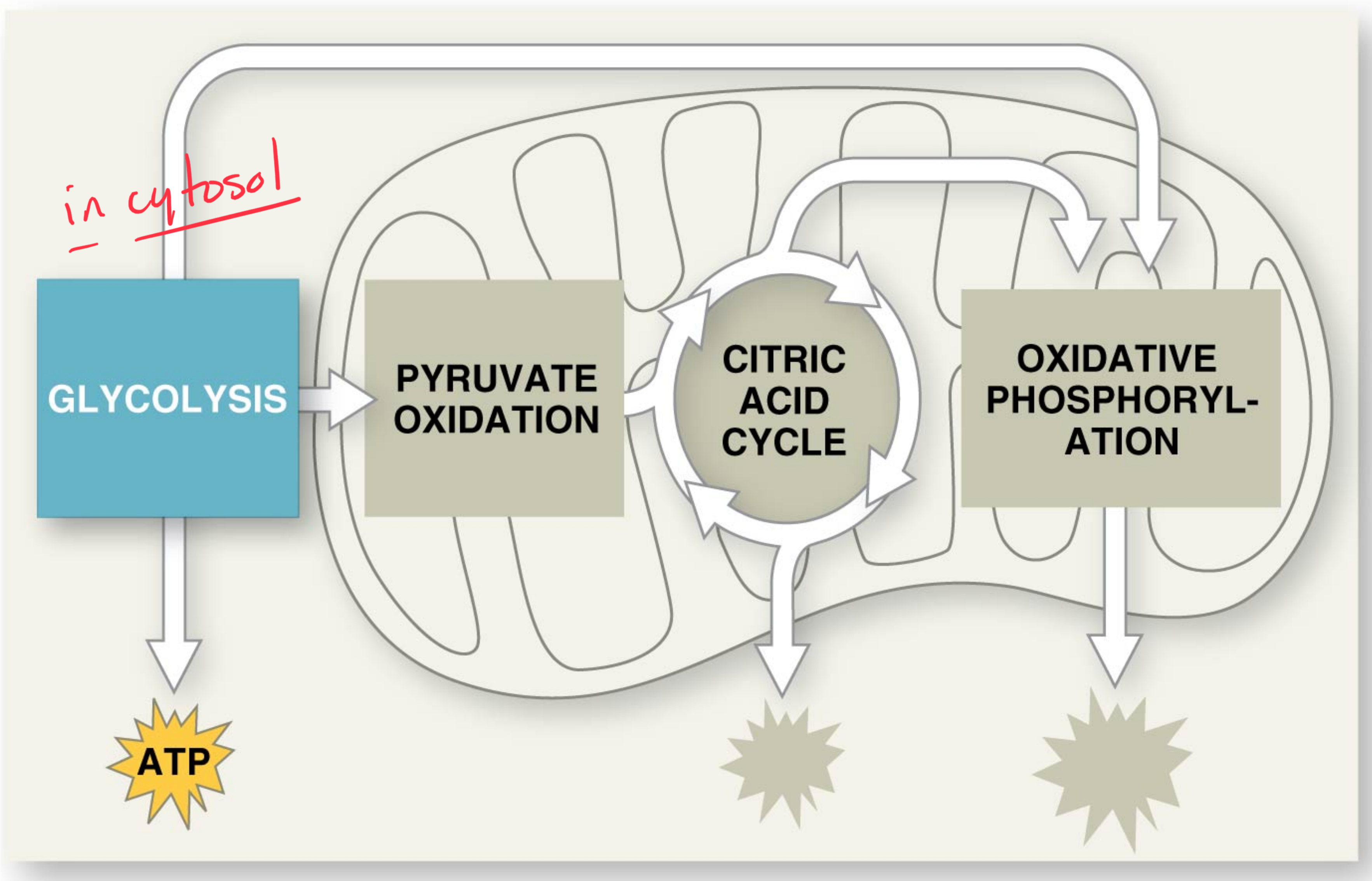
mitochondria

Overview of Cellular Respiration



Cellular Respiration

Stage 1: Glycolysis


in cytosol
GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Glycolysis

aerobic & anaerobic

with O_2 — without O_2

- "sugar splitting"

used only glycolysis before mitochondria

- Believed to be ancient (early prokaryotes - no O_2 available)

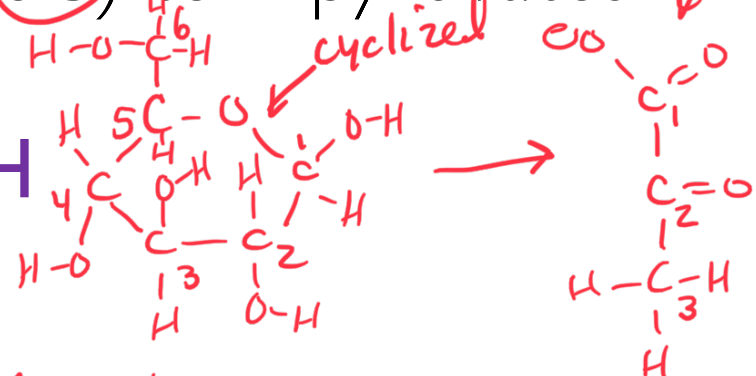
no dependency on oxygen

- Occurs in cytosol
- Partially oxidizes glucose (6C) to 2 pyruvates (3C)
- Net gain: $\boxed{2\ ATP}$ + 2NADH
- Also makes $2H_2O$
- No O_2 required

electron

cyclized

linear



glucose

uber

2 x pyruvate

Glycolysis

Stage 1: Energy Investment Stage

- Cell uses ATP to phosphorylate compounds of glucose

Invest 2 ATP → get 4 ATP

net production of 2 ATP

Stage 2: Energy Payoff Stage

- Two 3-C compounds oxidized
- For each glucose molecule:
  - 2 Net **ATP** produced by substrate-level phosphorylation

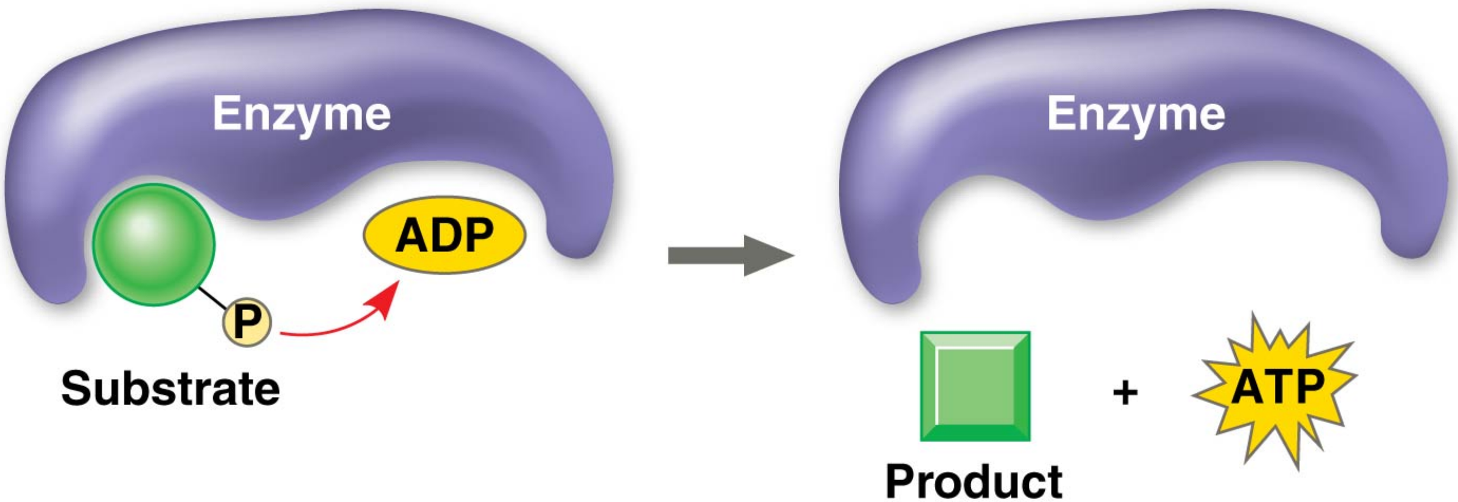
    ATP made within the reaction
  - 2 molecules of NAD^+ → NADH

Substrate-Level Phosphorylation

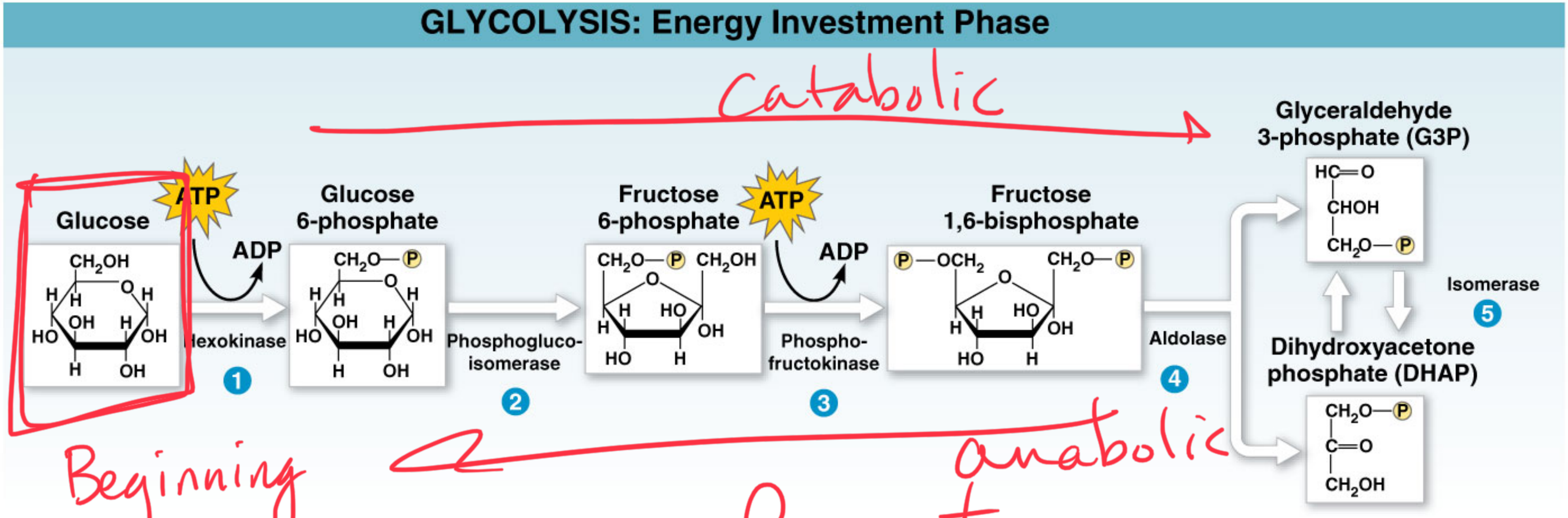
- Generate small amount of ATP
- <u>Phosphorylation:</u> enzyme transfers a phosphate to other compounds

P + compound

- ADP + P_i → ATP



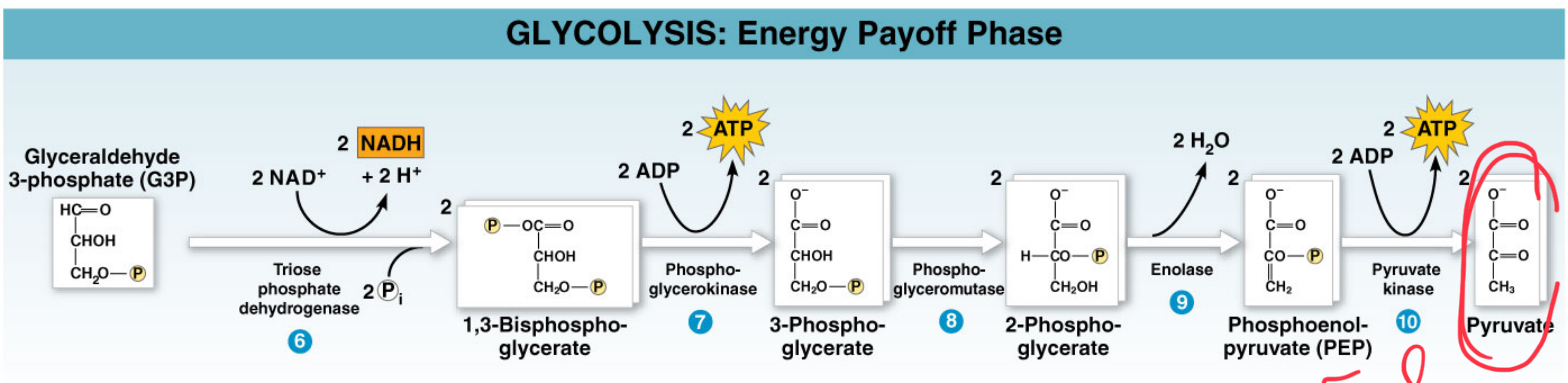
catabolic



Beginning

anabolic

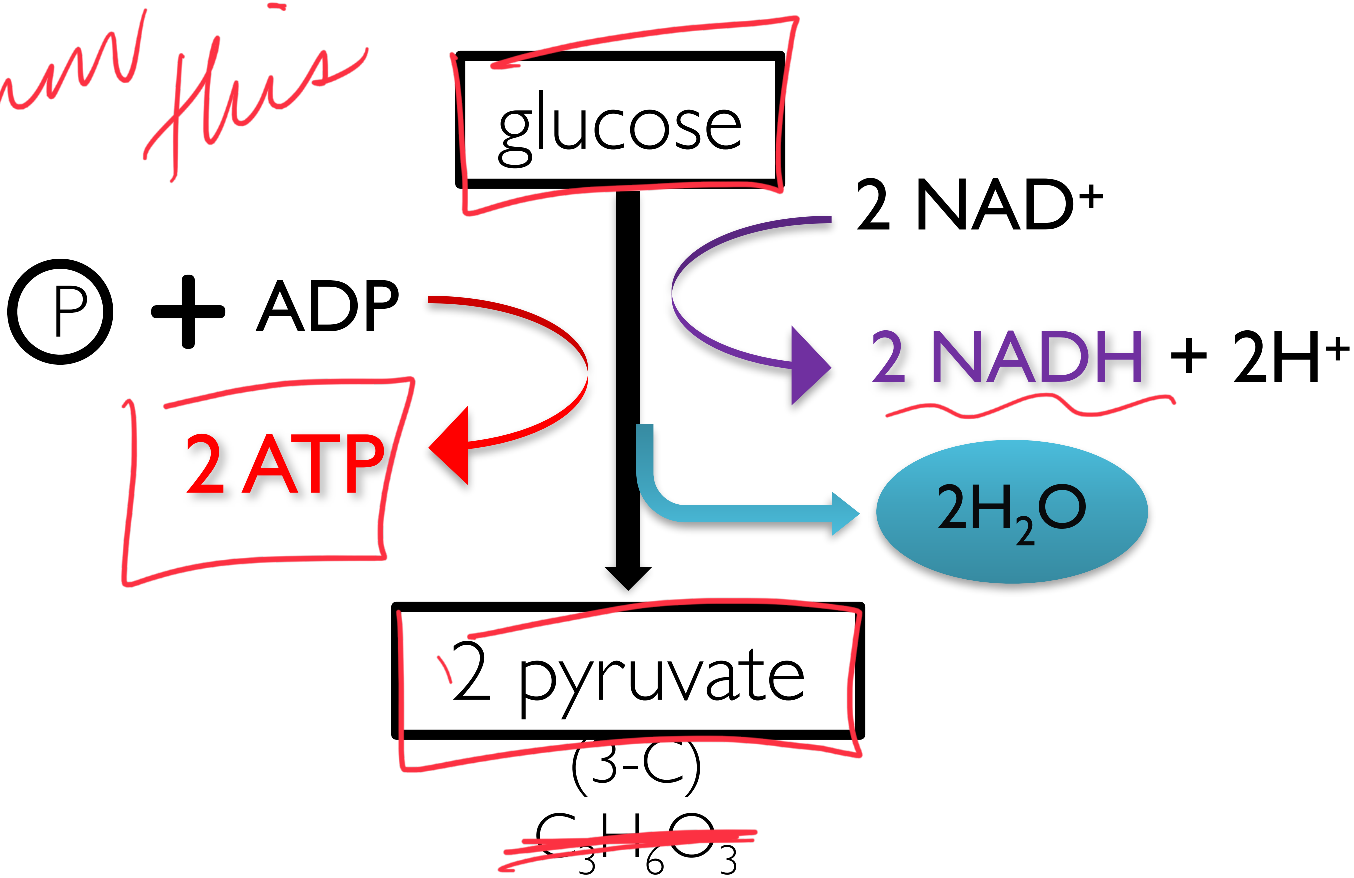
Glucose → Pyruvate



End

Glycolysis (Summary)

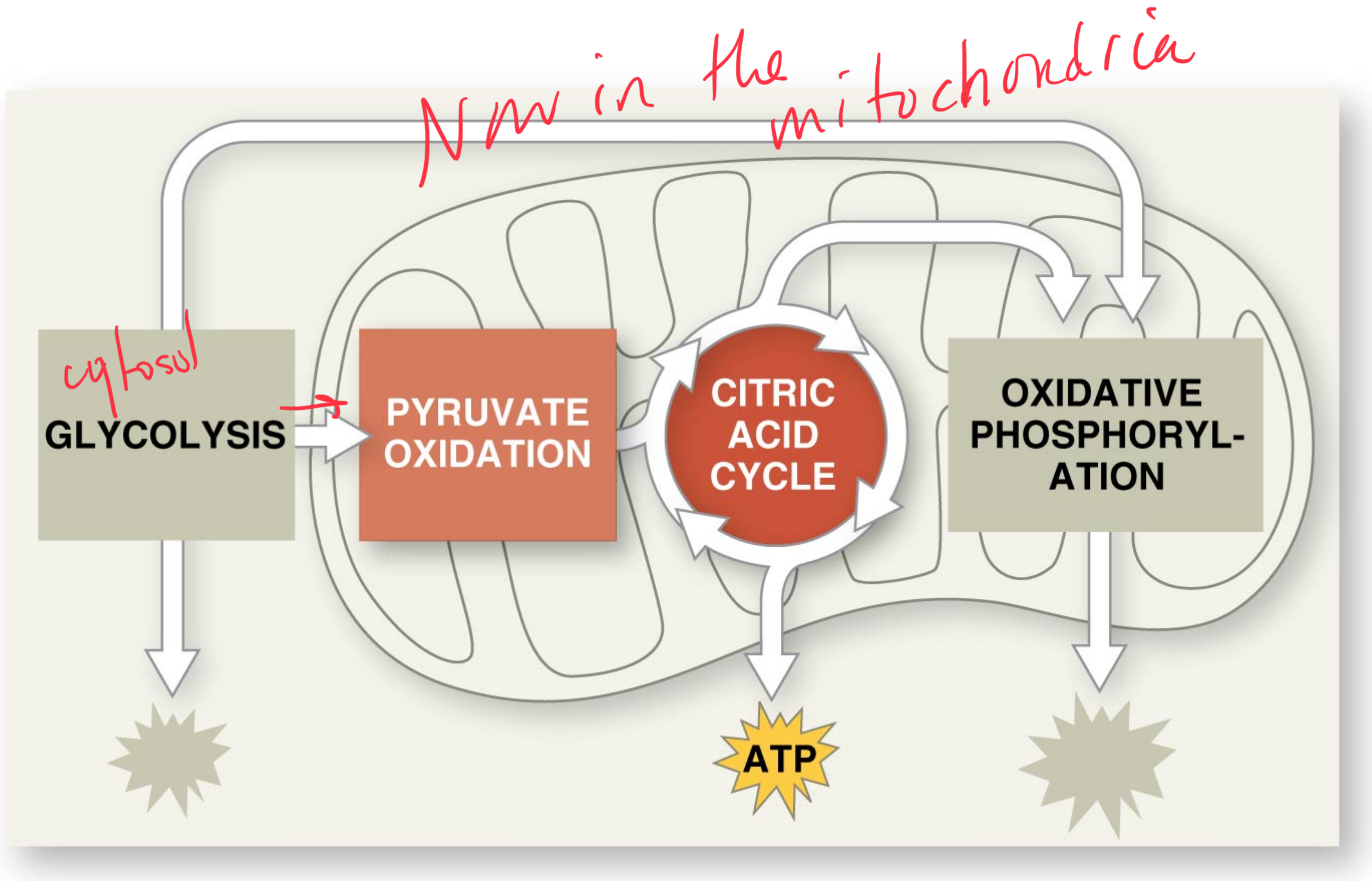
Know this



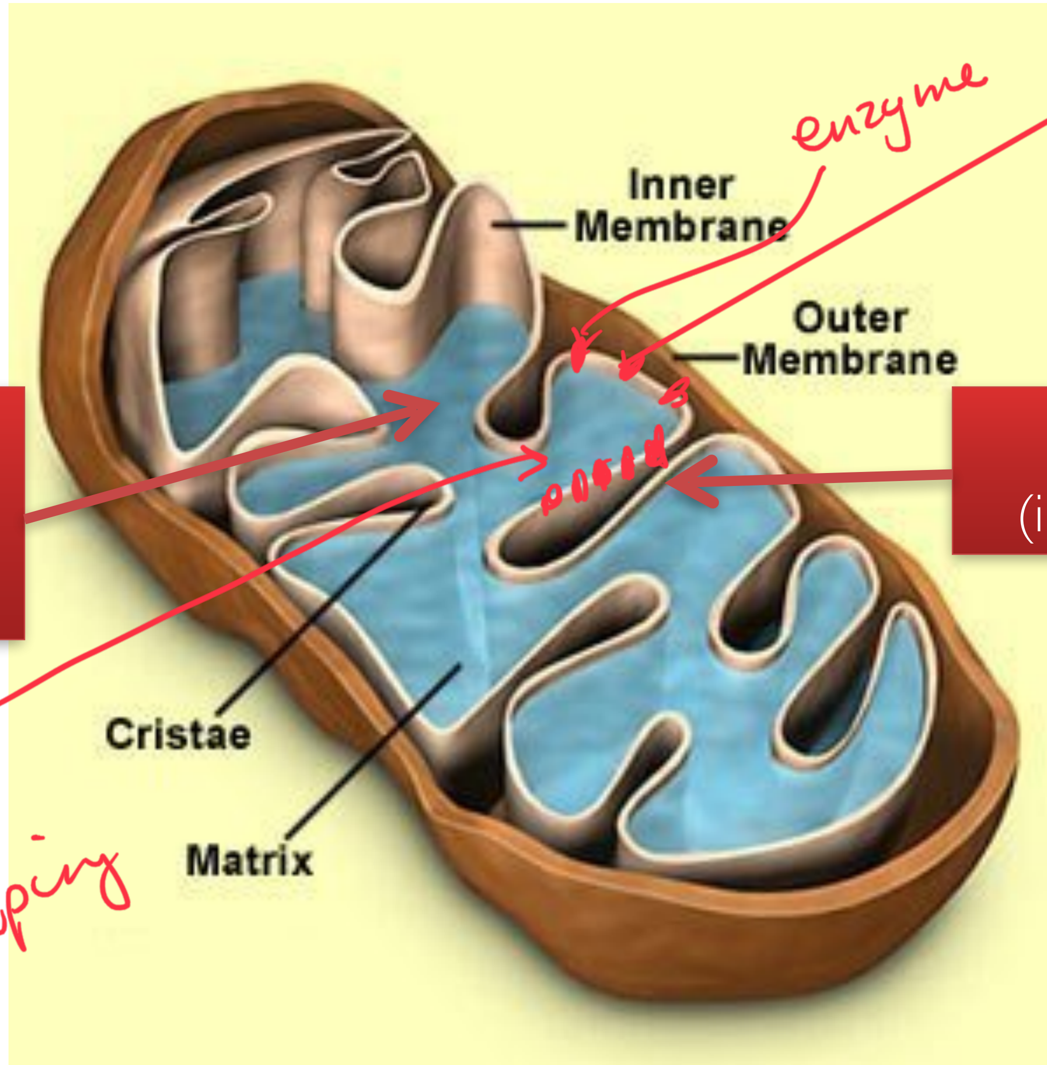
Cellular Respiration

Stage 2: Pyruvate Oxidation + Citric Acid Cycle

Krebs Cycle


Now in the mitochondria
cytosol
GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Mitochondrion Structure

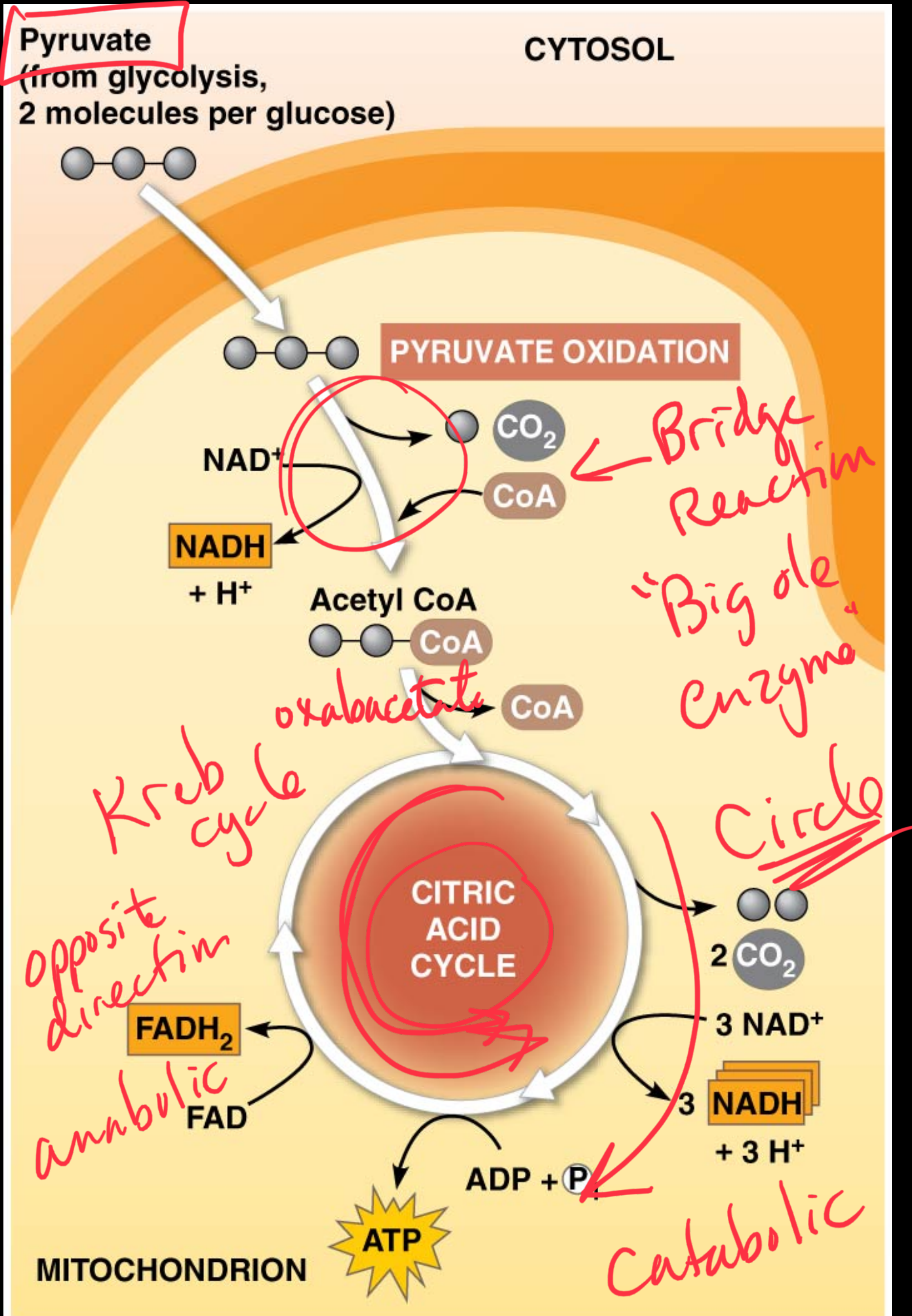


folds allow for more surface area

Citric Acid Cycle
(matrix)

ETC
(inner membrane)

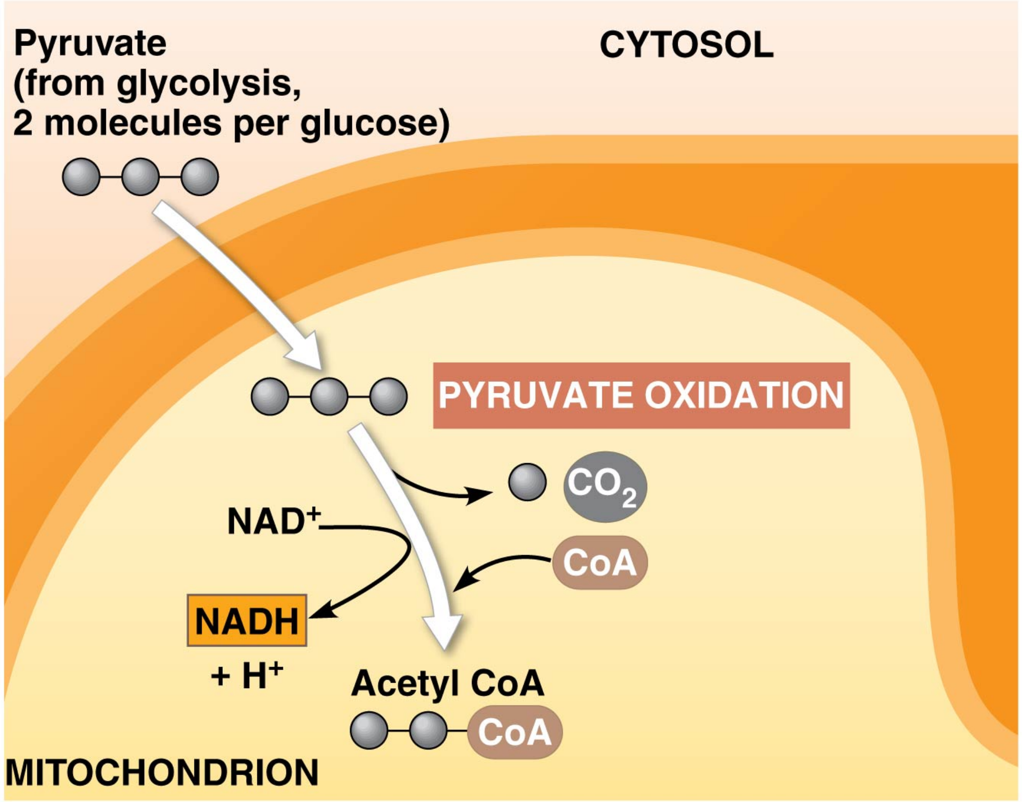
proximity effect
enzyme grouping

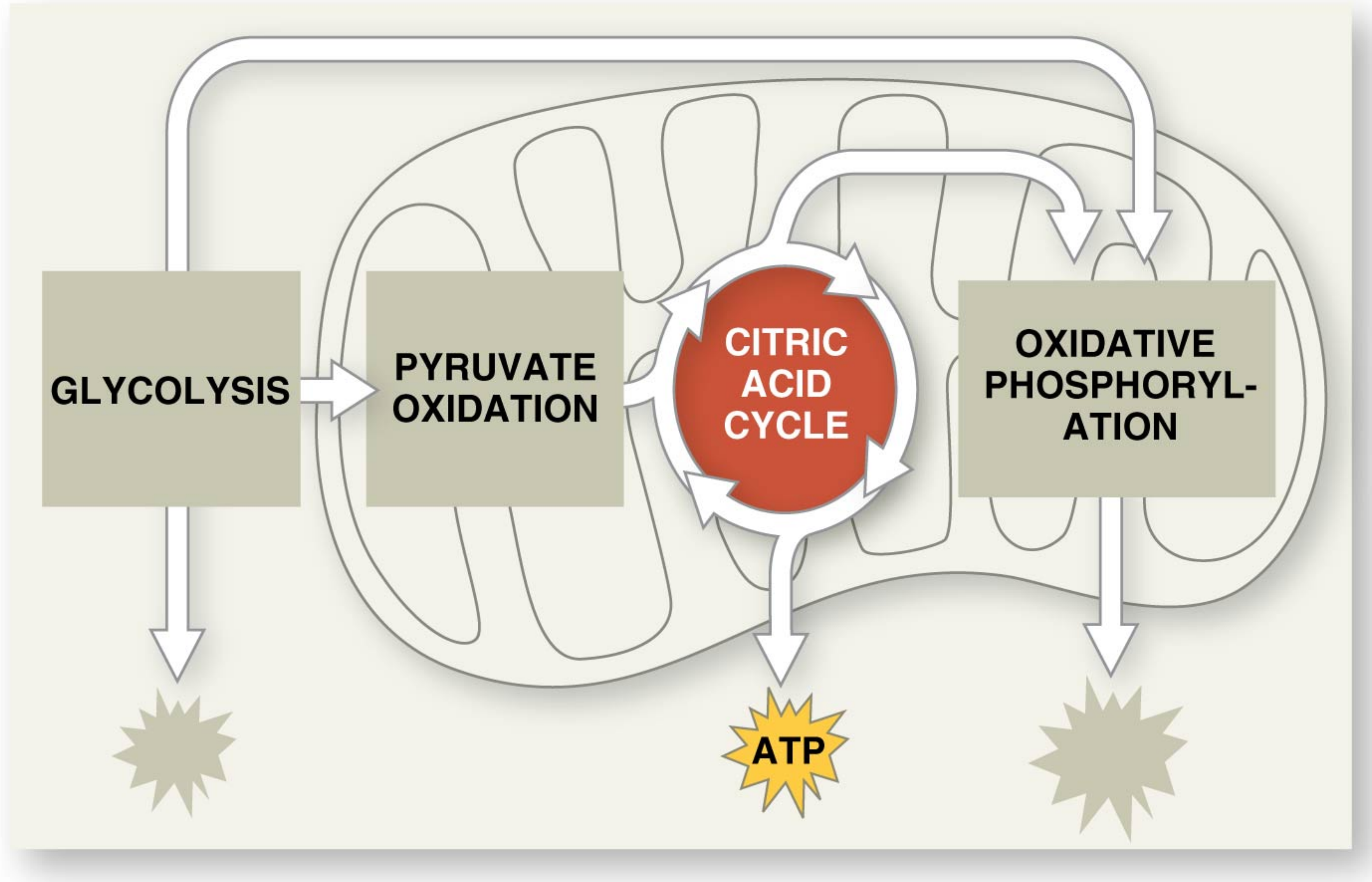


Pyruvate
(from glycolysis,
2 molecules per glucose)
CYTOSOL
PYRUVATE OXIDATION
CO_2
CoA
Bridge Reaction
NAD+
NADH
+ H+
Acetyl CoA
CoA
"Big ole" enzyme
oxaloacetate
CoA
Kreb cycle
Circle
CITRIC ACID CYCLE
2 CO_2
opposite direction
3 NAD+
FADH2
3 NADH
+ 3 H+
anabolic
FAD
ADP + P
ATP
Catabolic
MITOCHONDRION

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)

Didn't include Bridge Rxn

Glucose → 2 pyruvate
6C 6C

- Occurs in mitochondrial matrix
- Acetyl CoA → Citrate → CO_2 released

Pyruvate

"citric acid"

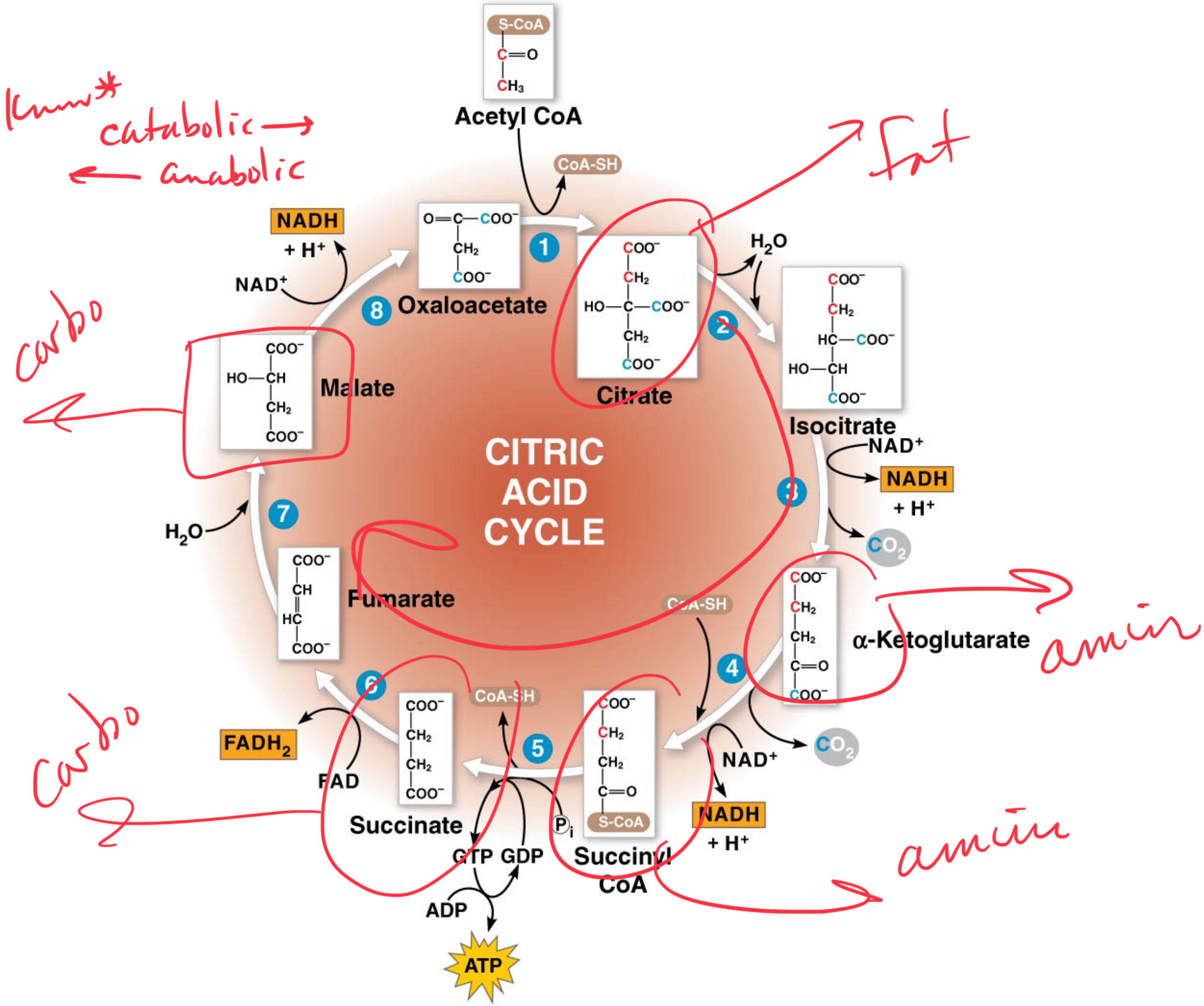
carbons ↳ CO_2

- Net gain: $\boxed{\text{2 ATP}}$, $\boxed{\text{6 NADH, 2 FADH}_2}$ (electron carrier)

substrate-level

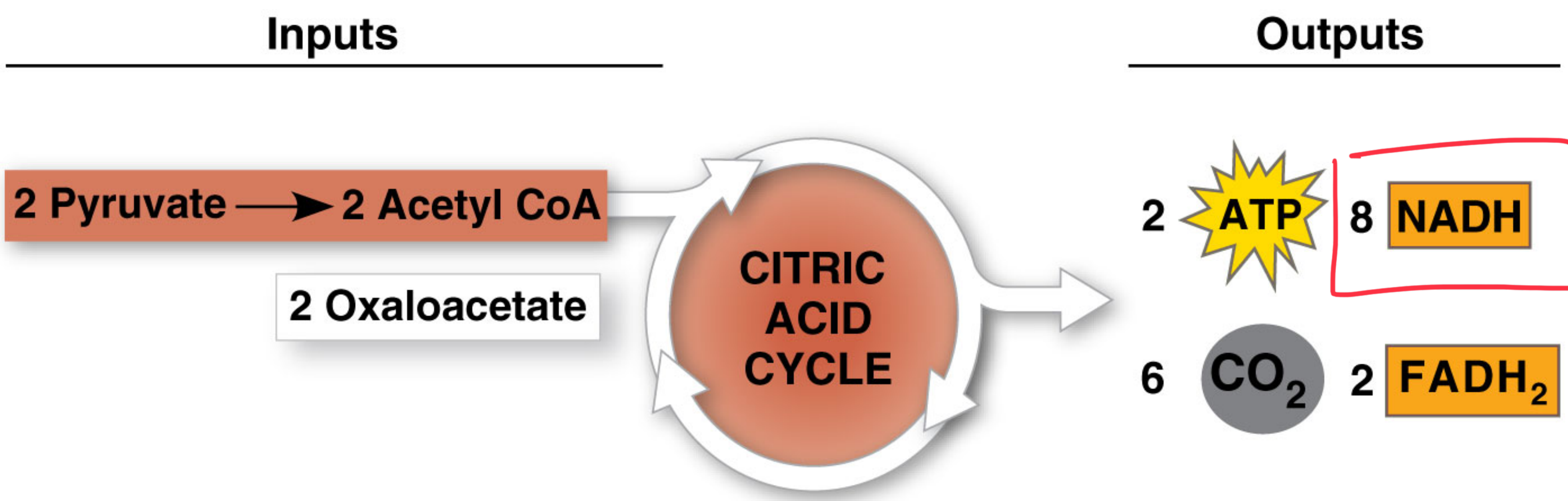
makes all these ubers ↓ shuttle electrons into electron transport chain (ETC)

- **ATP** produced by substrate-level phosphorylation


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

Summary of Citric Acid Cycle

including Bridge Rxn.

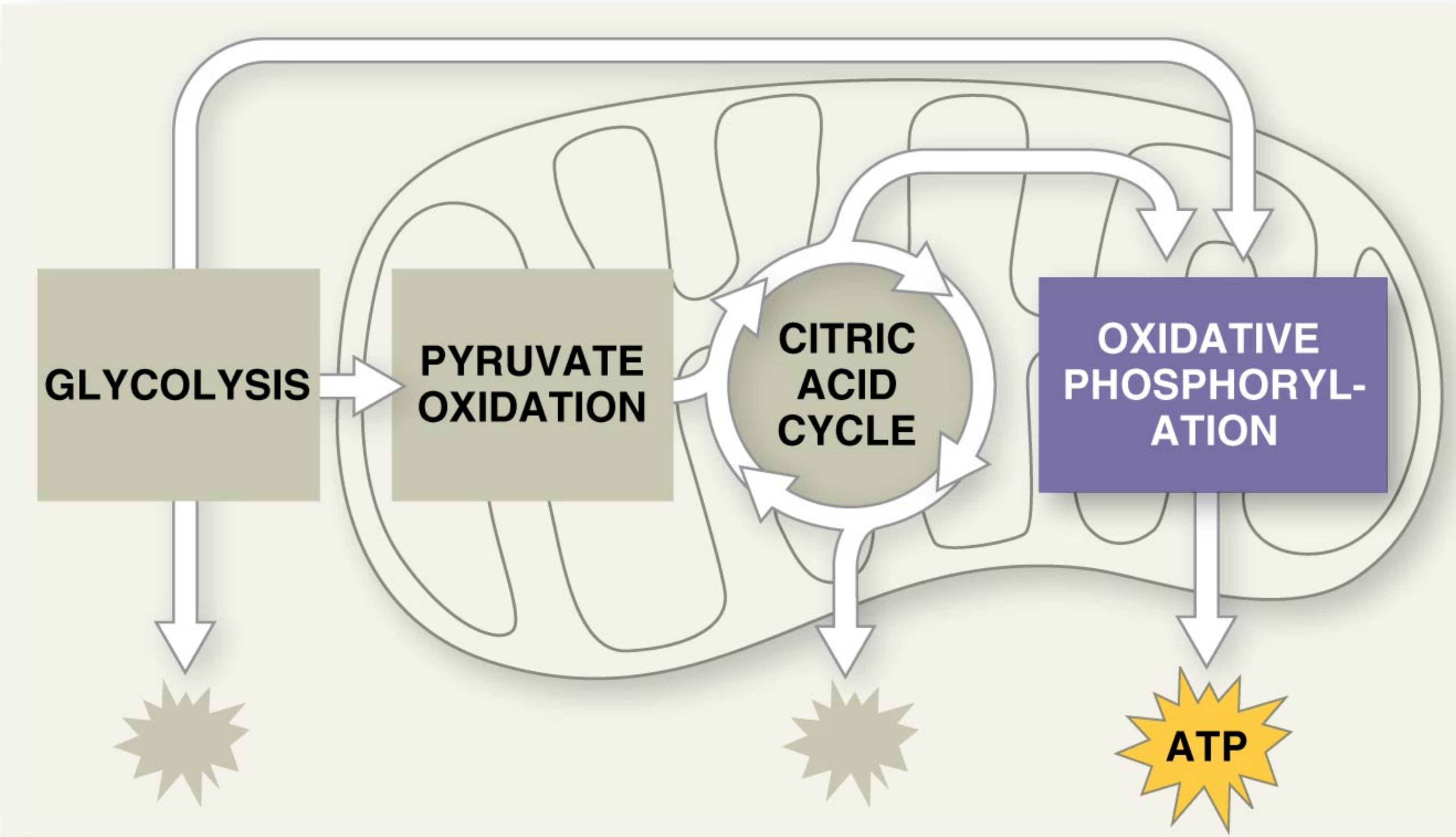


http://multimedia.mcb.harvard.edu/anim_mitochondria.html

BioVisions at Harvard: The Mitochondria

Cellular Respiration

Stage 3: Oxidative Phosphorylation


GLYCOLYSIS
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ATP

Oxidative Phosphorylation

ELECTRON TRANSPORT CHAIN (ETC)	Diffusion 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)

majority of ATP

dependent on oxygen

Electron Transport Chain (ETC)

- Collection of molecules embedded in inner membrane of mitochondria

electron uber

enzymes

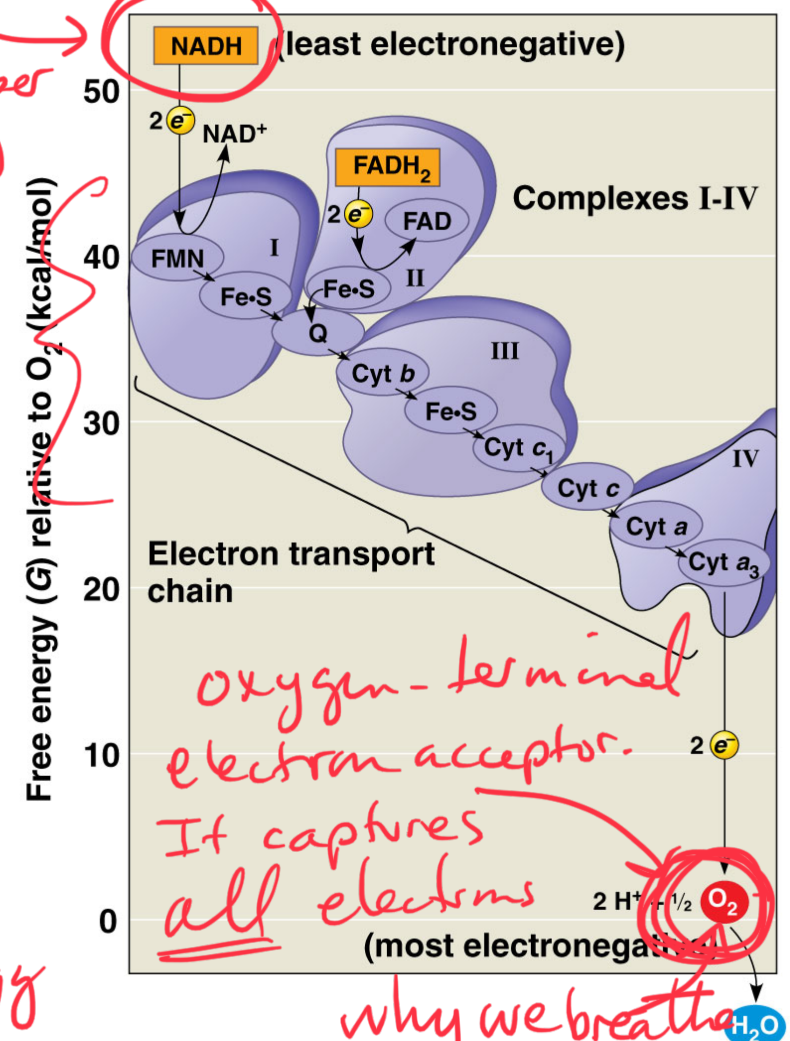
26-28 ATP

- Tightly bound protein + non-protein components
- Alternate between reduced/ oxidized states as accept/donate e-

redox reaction

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

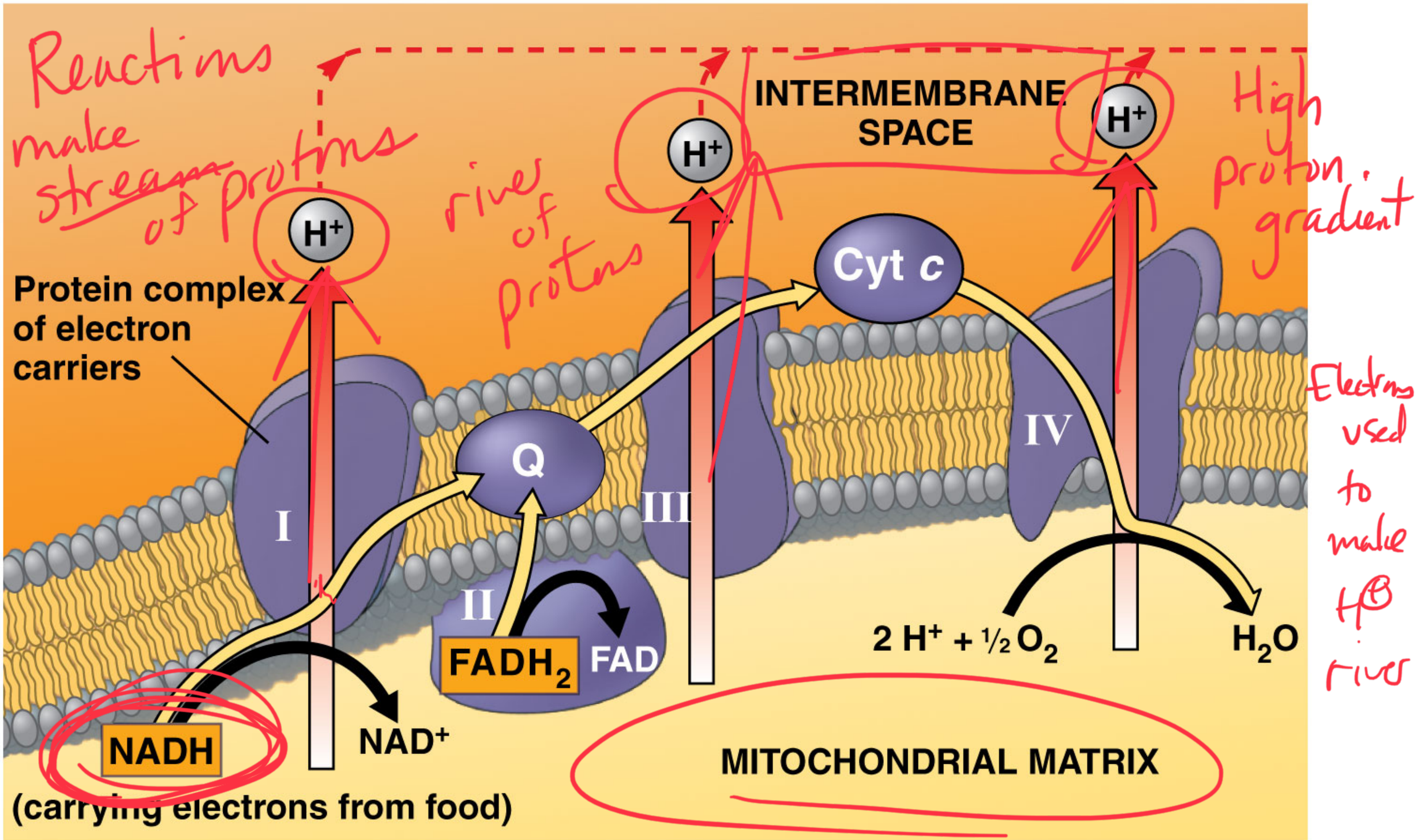
incrementally releases energy



oxygen - terminal electron acceptor. If captures all electrons

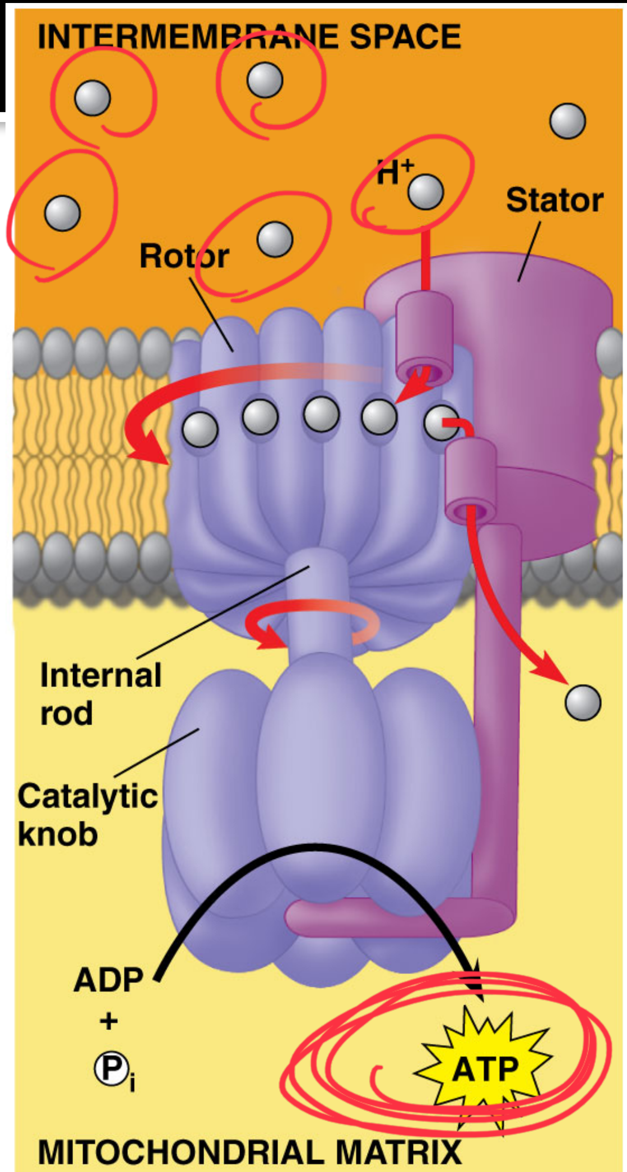
why we breathe

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

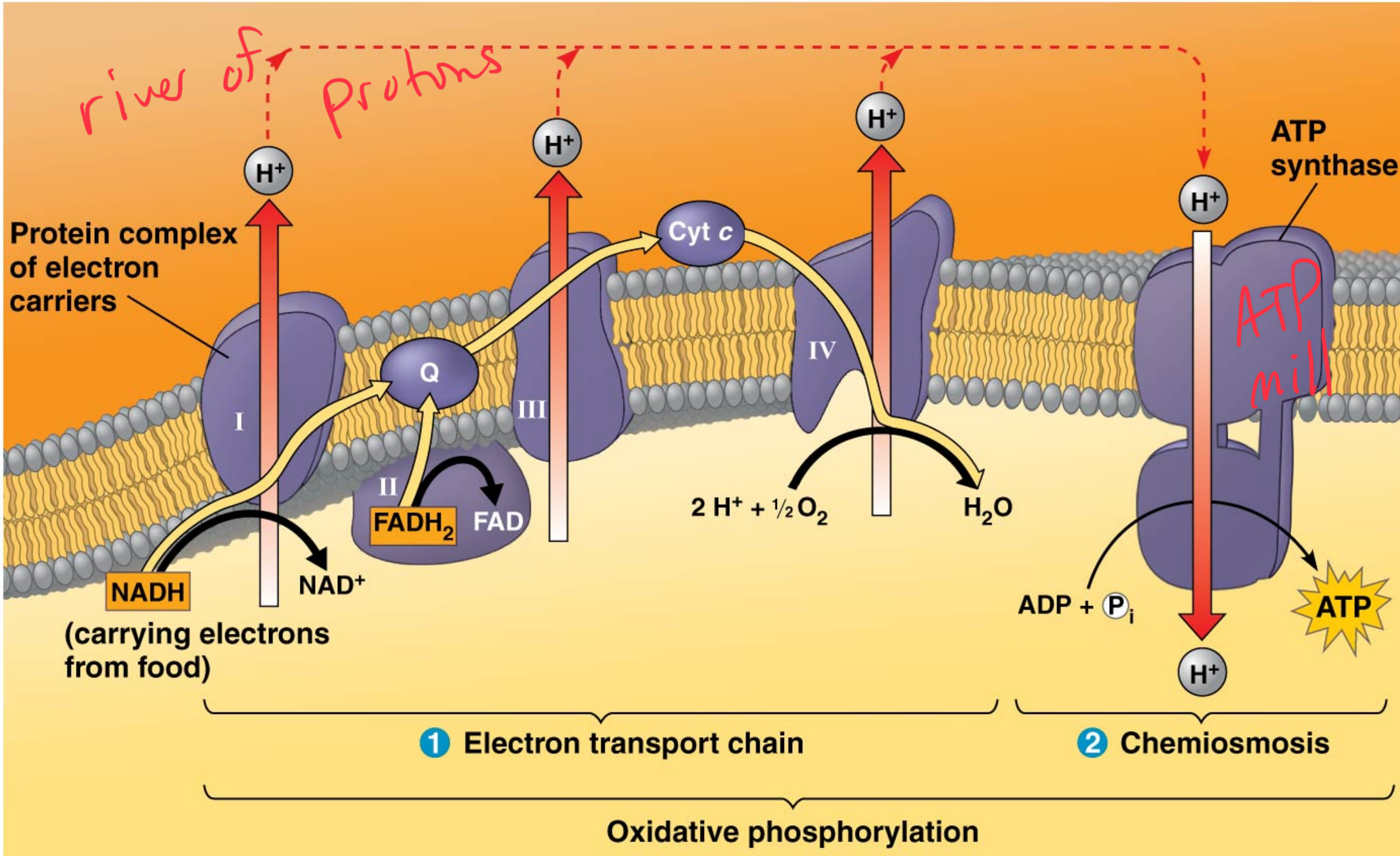


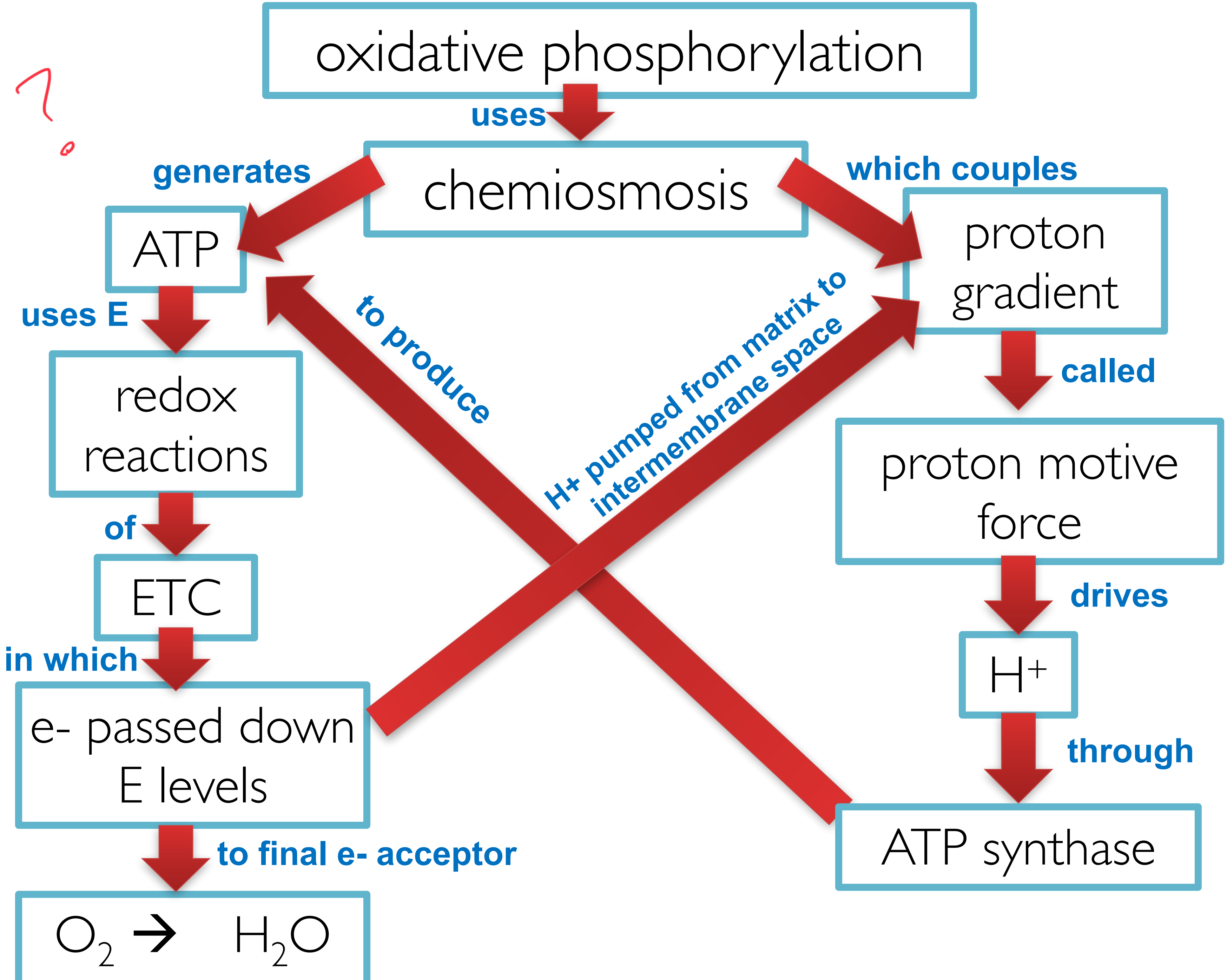
Chemiosmosis: Energy-Coupling Mechanism

- **Chemiosmosis** = H^+ gradient across membrane drives cellular work
  water wheel
- **Proton-motive force**: use proton (H^+) gradient to perform work
- **ATP synthase**: enzyme that makes ATP
  ↳ ATP mill
- Use E from proton (H^+) gradient – flow of H^+ back across membrane



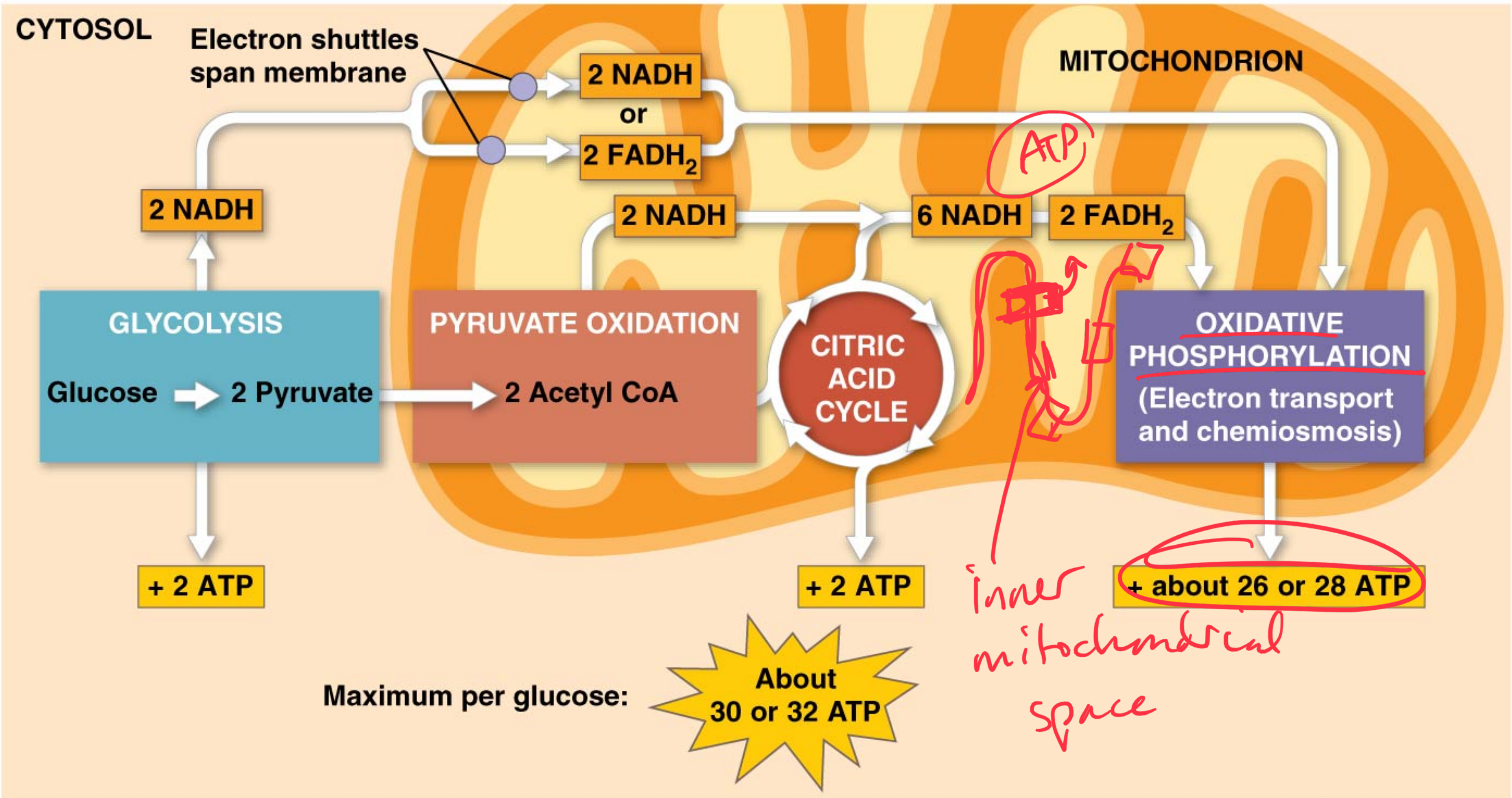
Chemiosmosis couples the ETC to ATP synthesis





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

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

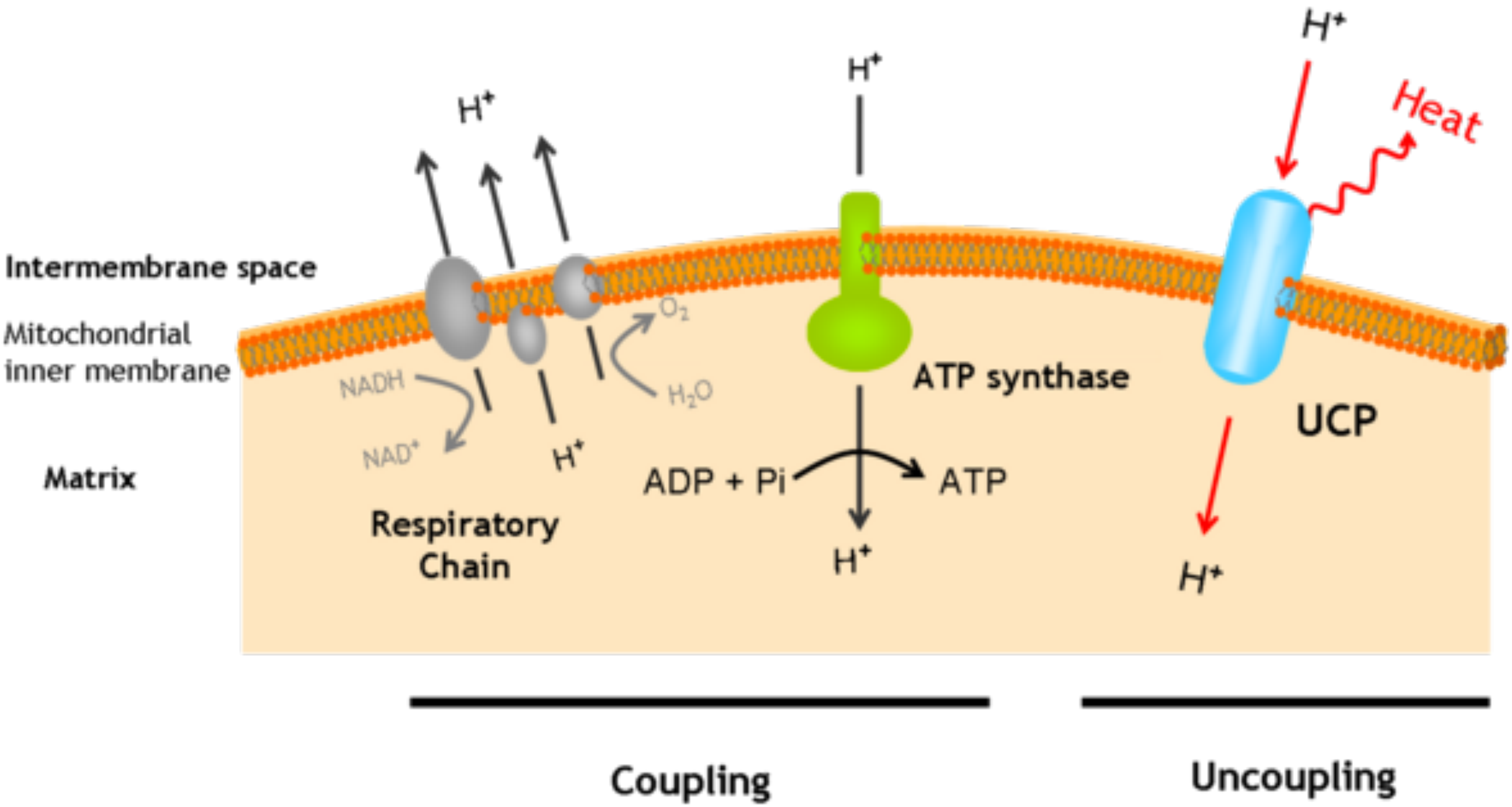


BioFlix: Cellular Respiration

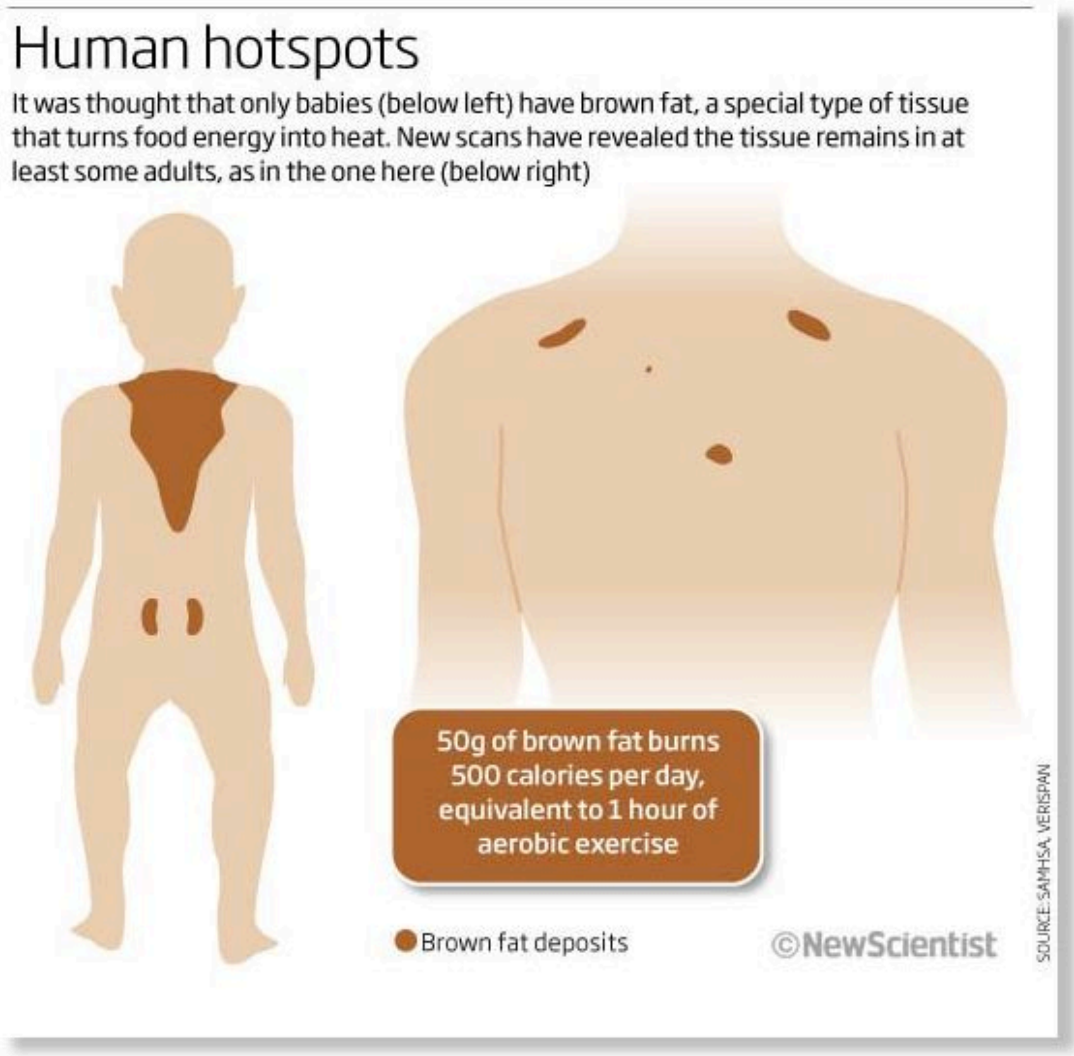
Non-Shivering Thermogenesis

- 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

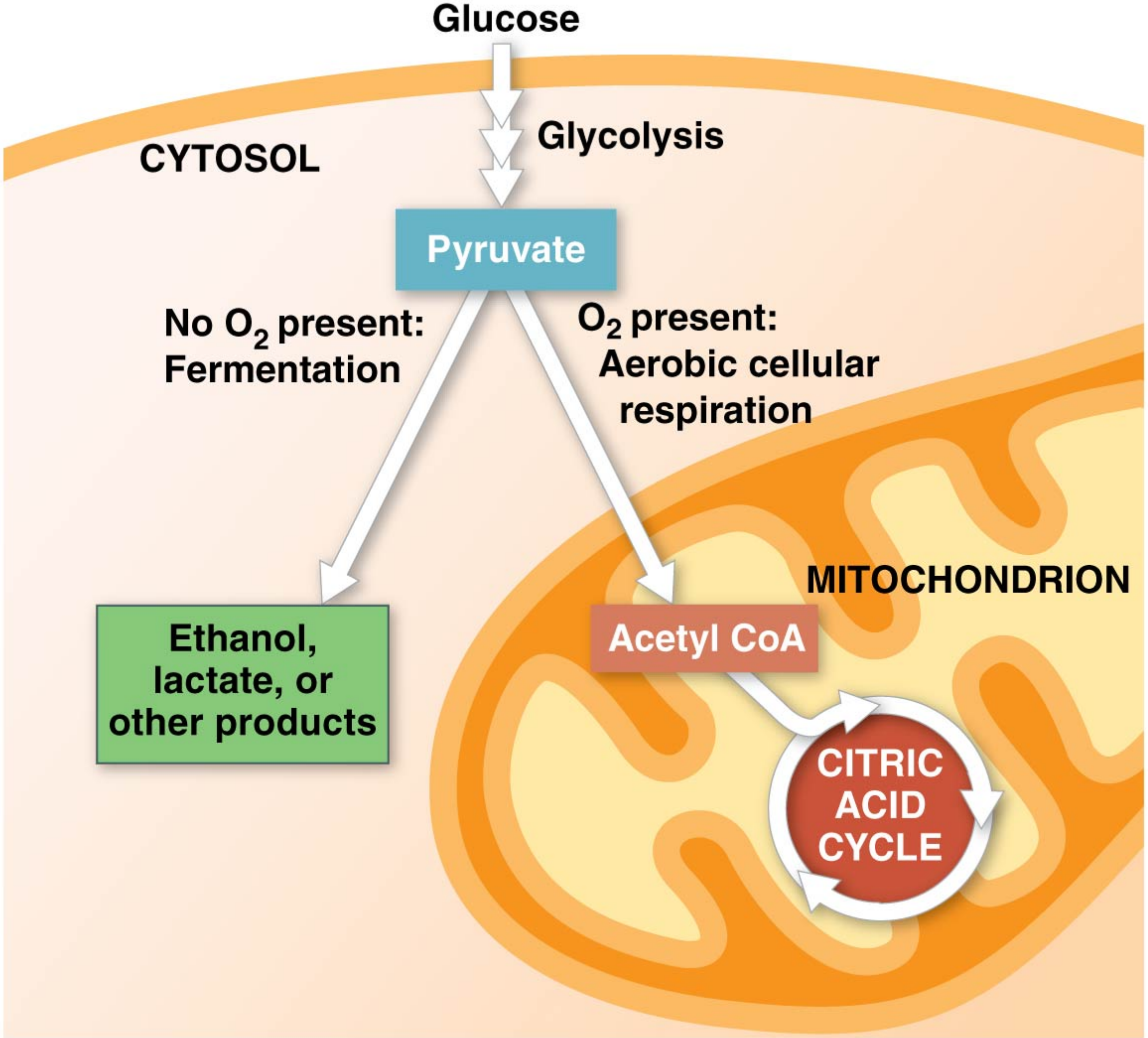


Anaerobic Respiration

- **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 | 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)

yeast

we

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)

occurs when no O_2 → therefore no access to mitochondria

Bacteria

Oxygen deprived environment