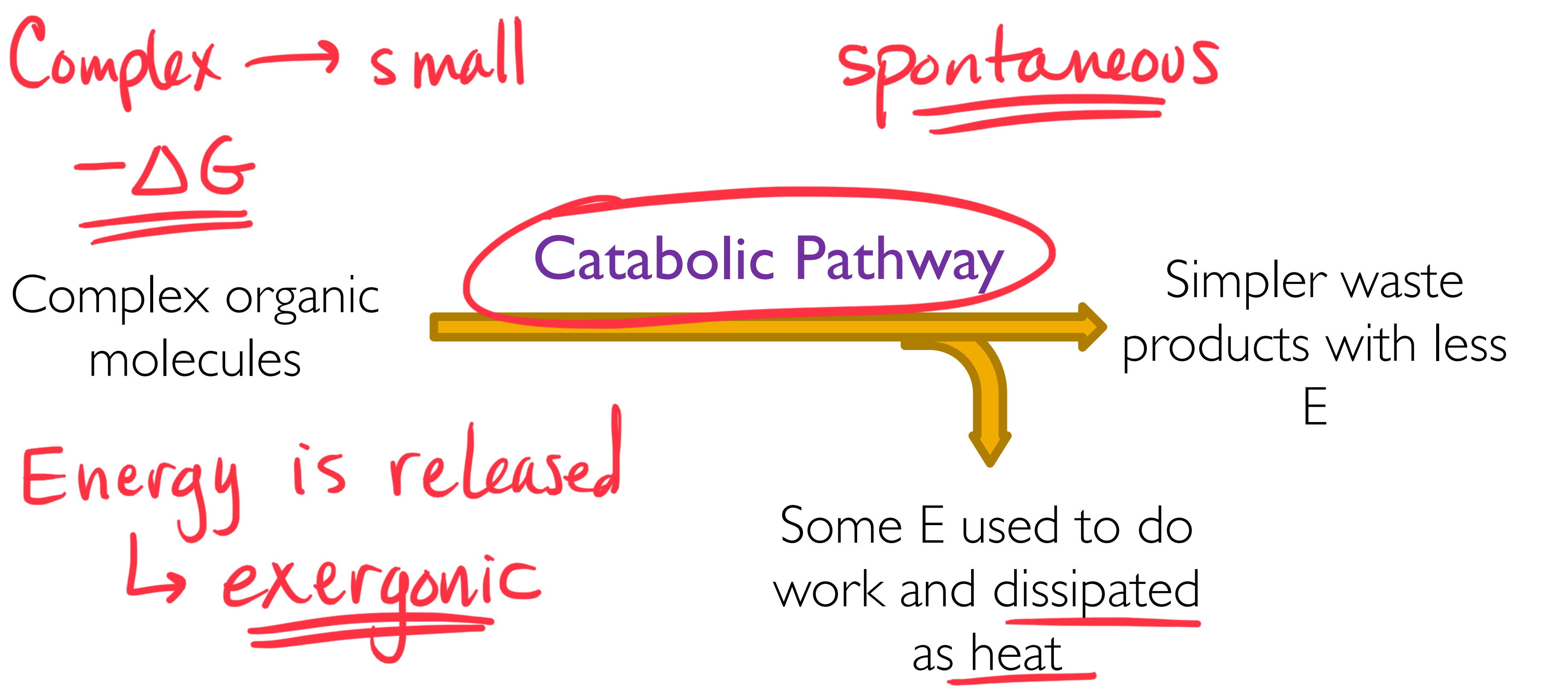

Complex → small
$-\Delta G$
spontaneous
Catabolic Pathway
Complex organic molecules
Simpler waste products with less E
Some E used to do work and dissipated as heat
Energy is released
↳ exergonic

Glucose → carbohydrate CH_2O

energy of the cell

Respiration: exergonic (releases E)

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

(+ heat)

32

Digestion of Glucose → cellular respiration

in oxygen

out carbon dioxide

Catabolic

Photosynthesis: endergonic (requires E)

Reverse

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

anabolic

ATP 48

producing glucose

Redox Reactions (oxidation-reduction)

oxidation (donor) lose e-

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

reduction (acceptor) gain e-

Reduced → more energy

Oxidized → less energy

- Oxidation = lose e- → is Loss of e⊖
- Reduction = gain e- → is Gain e⊖

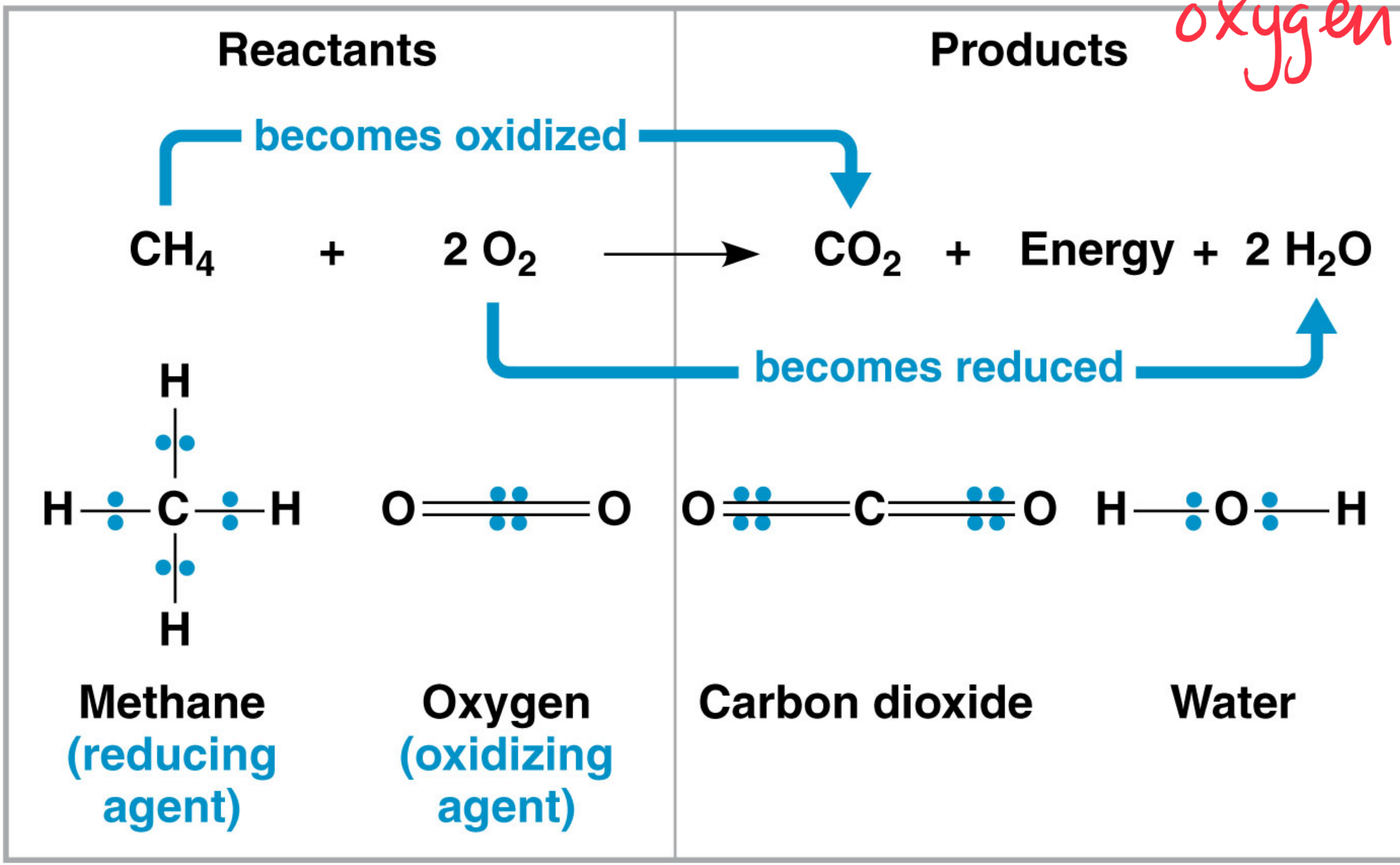
OiLRiG or ~~LeoGer~~

oxidation

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

reduction

oxidized → more bonds to oxygen



Energy Harvest

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

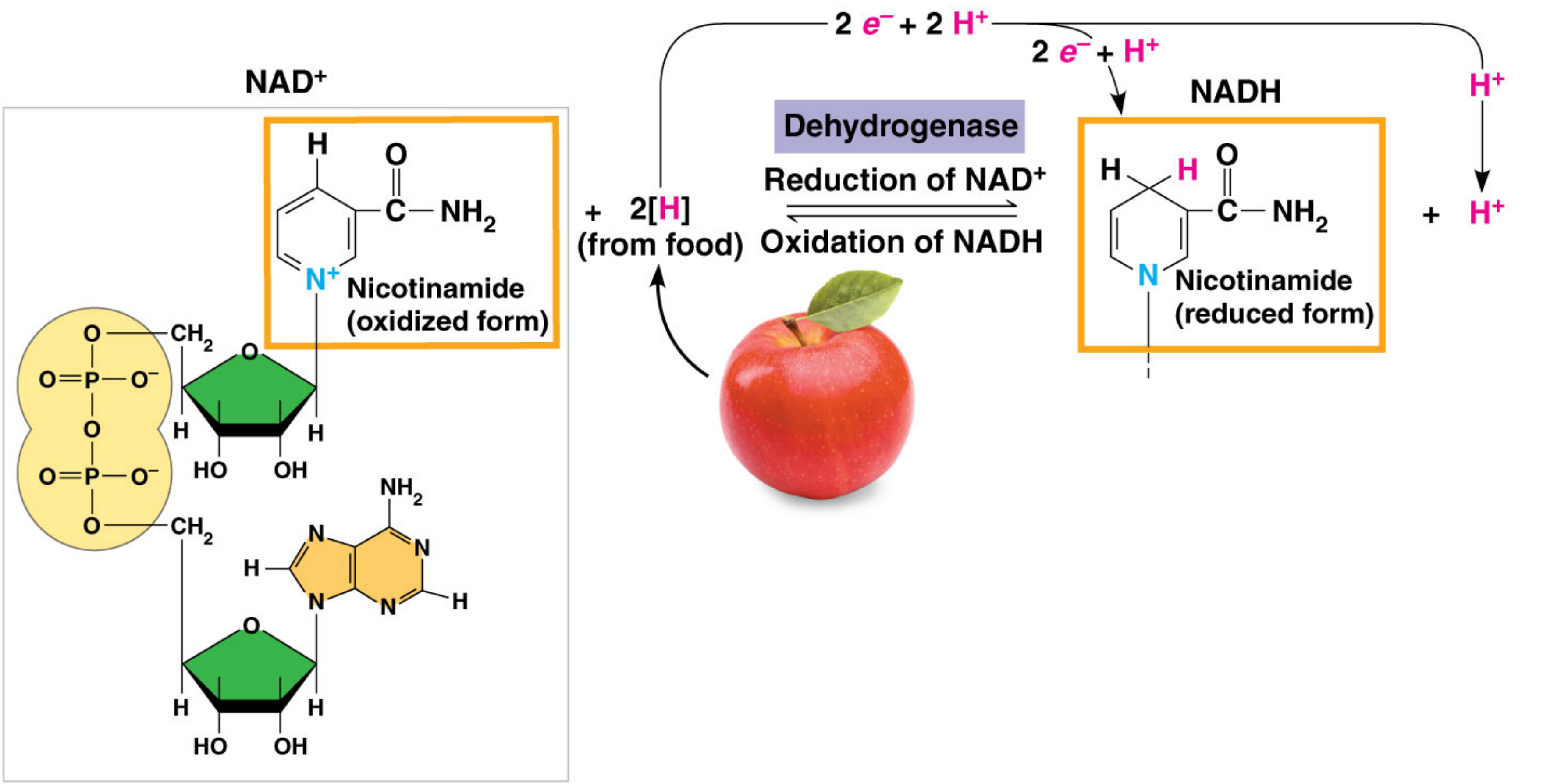
Food (Glucose) → NADH → ETC → O_2

electron uber

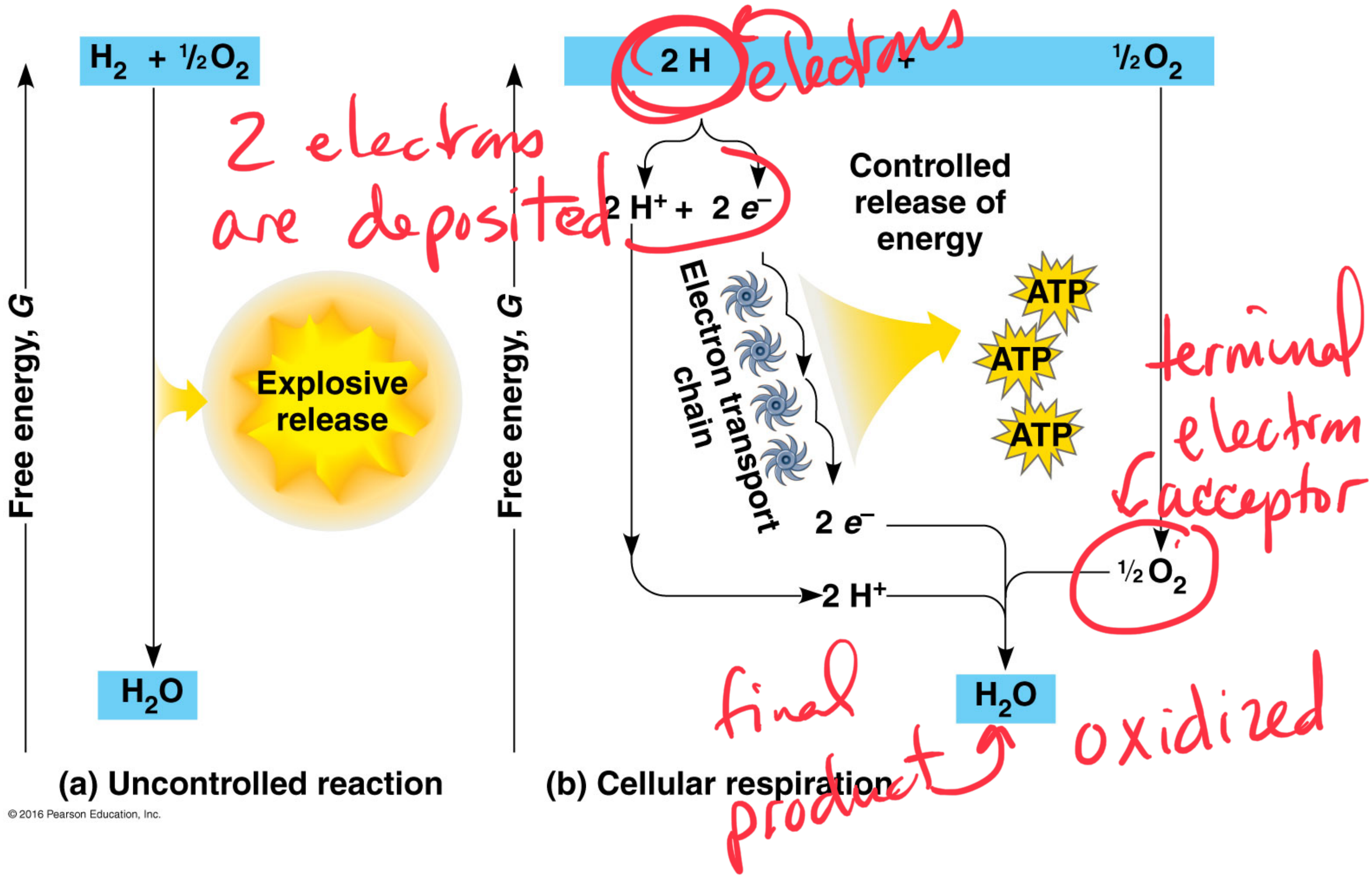
  - Coenzyme NAD^+ = electron acceptor
  - NAD^+ picks up $2e^-$ and $2H^+$ → NADH (stores E)
  - NADH carries electrons to the electron transport chain (ETC)
  - ETC: transfers e^- to O_2 to make H_2O ; releases energy

↳ Electron Transport Chain

NAD+ as an electron shuttle



Electron Transport Chain



Stages of Cellular Respiration

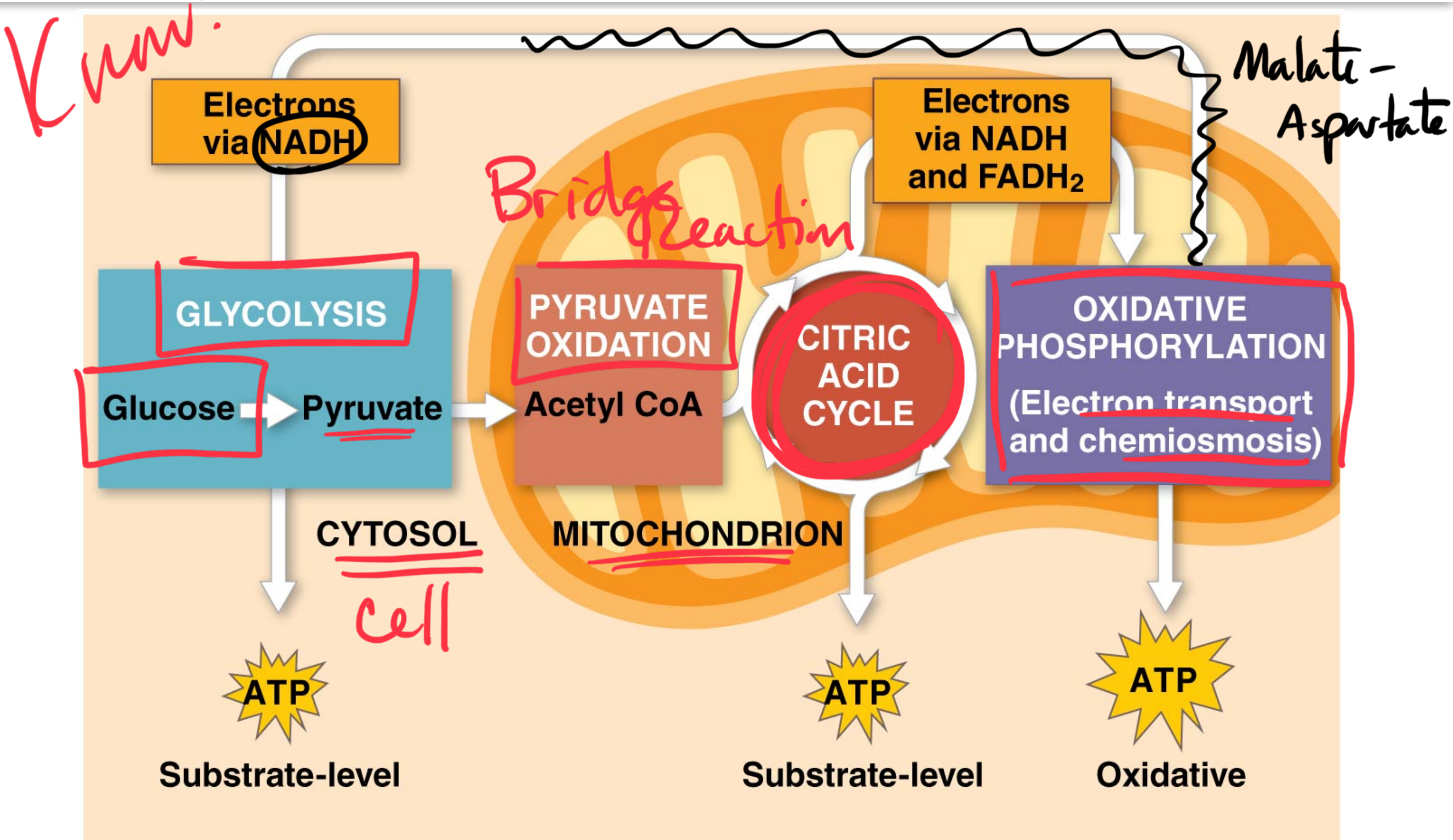
Catabolic Reactions

1. Glycolysis [10]
2. Pyruvate Oxidation [5] + Citric Acid Cycle (Krebs Cycle) [8]
3. Oxidative Phosphorylation (electron transport chain (ETC) & chemiosmosis)

Movement of electrons {Electron transport}
↓ leads to
Movement of protons {chemiosmosis}
↓
ATP

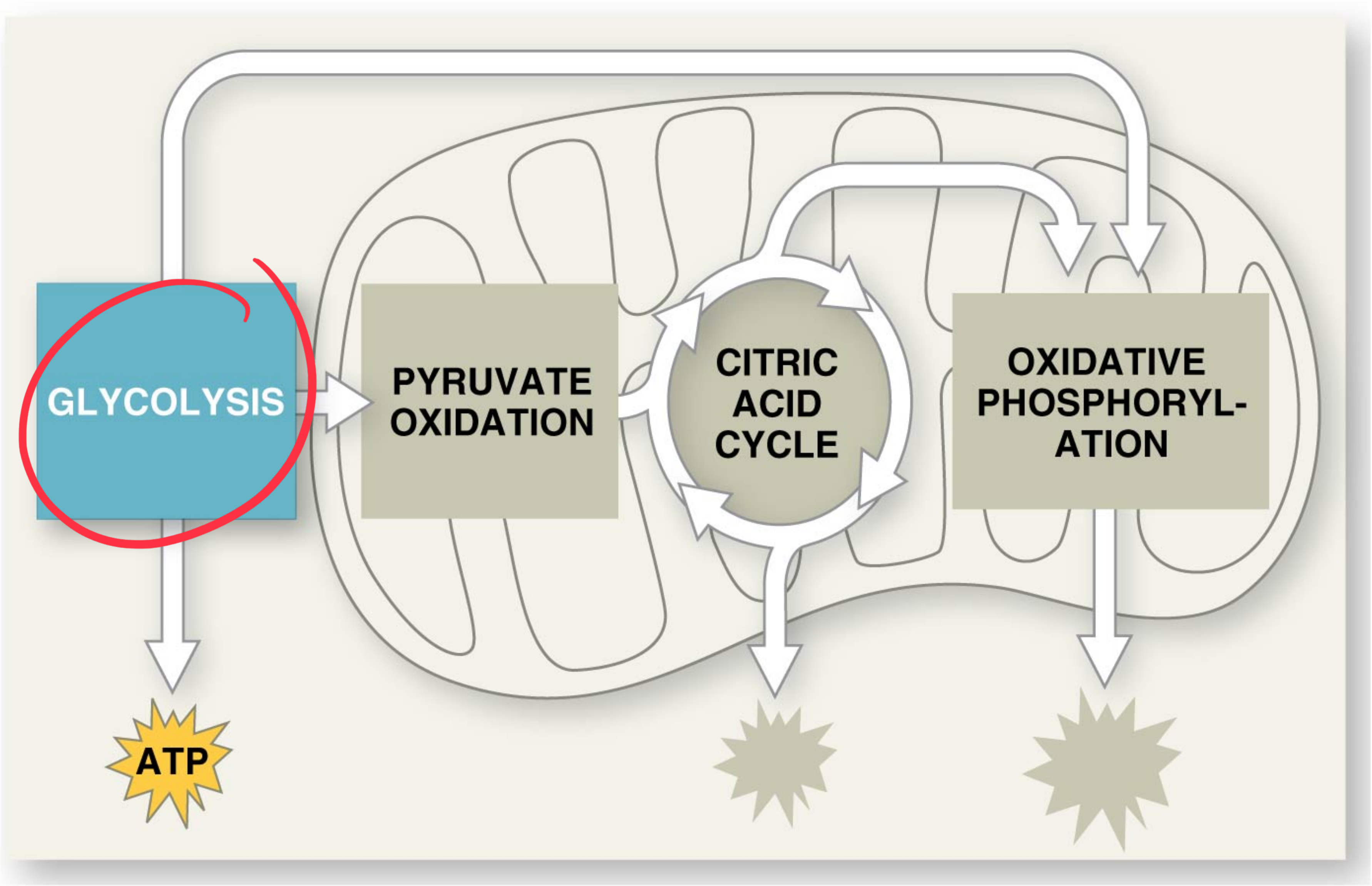
movement of protons from high → low

Overview of Cellular Respiration



Cellular Respiration

Stage 1: Glycolysis


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Glycolysis → to cut sugar (Glucose)

sugar to cut

outside the mitochondria

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

No O_2 millions and millions of years ago before mitochondria

- Occurs in cytosol
- Partially oxidizes glucose (6C) to 2 pyruvates (3C)

glucose → pyruvate (2)

- Net gain: 2 ATP + 2NADH
- Also makes $2H_2O$

2 out of 32

- No O_2 required

Glycolysis

[Gluc] → [Gluc]
Gluc-P_i
Not glucose

Stage 1: Energy Investment Stage

- Cell uses ATP to phosphorylate compounds of glucose

Use 2 ATP

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**

Make 4 ATP

$4 + (-2) = 2$

net 2 ATP

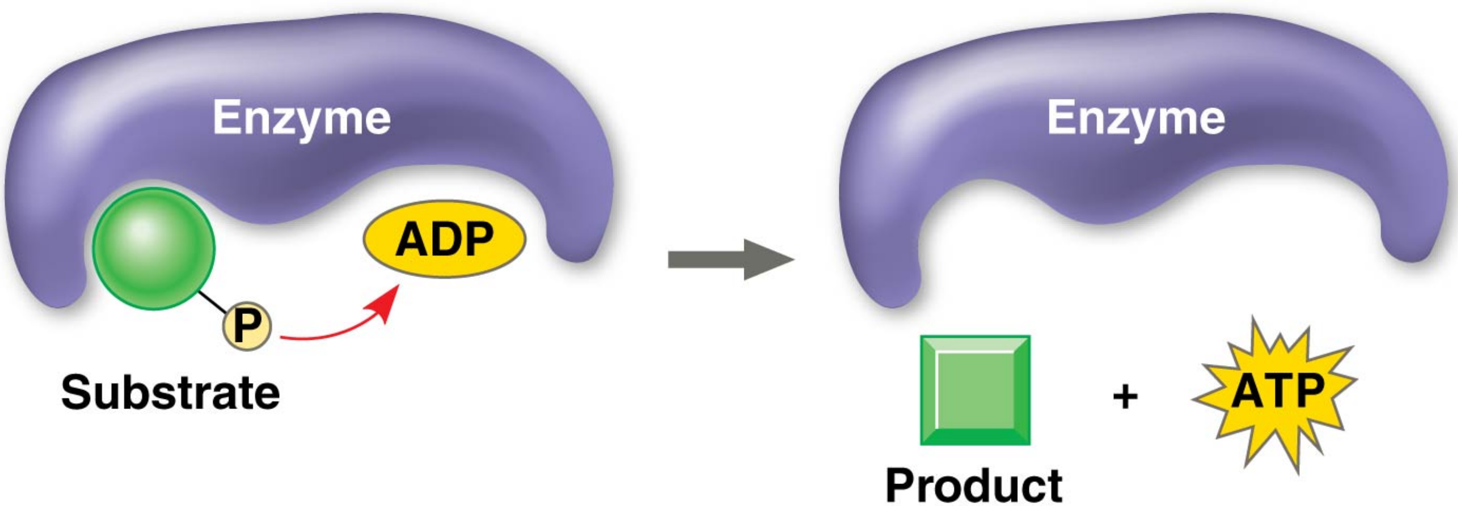
Substrate-Level Phosphorylation

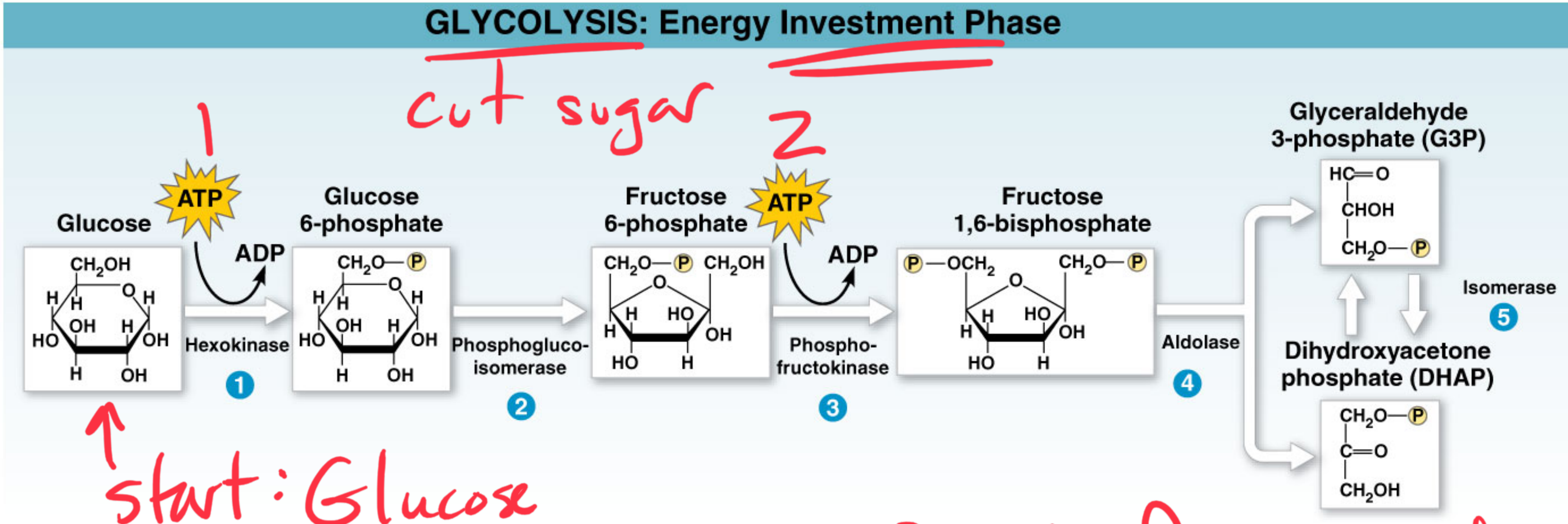
ATP is made in the reaction

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

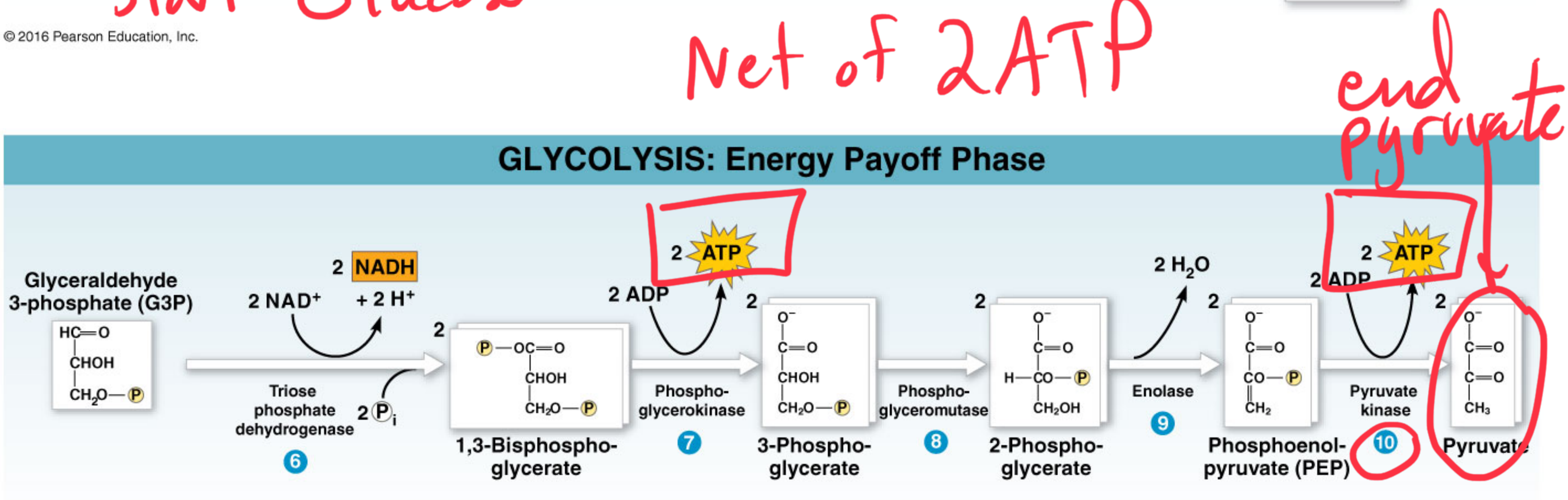
Ⓟ + compound

- ADP + P_i → ATP

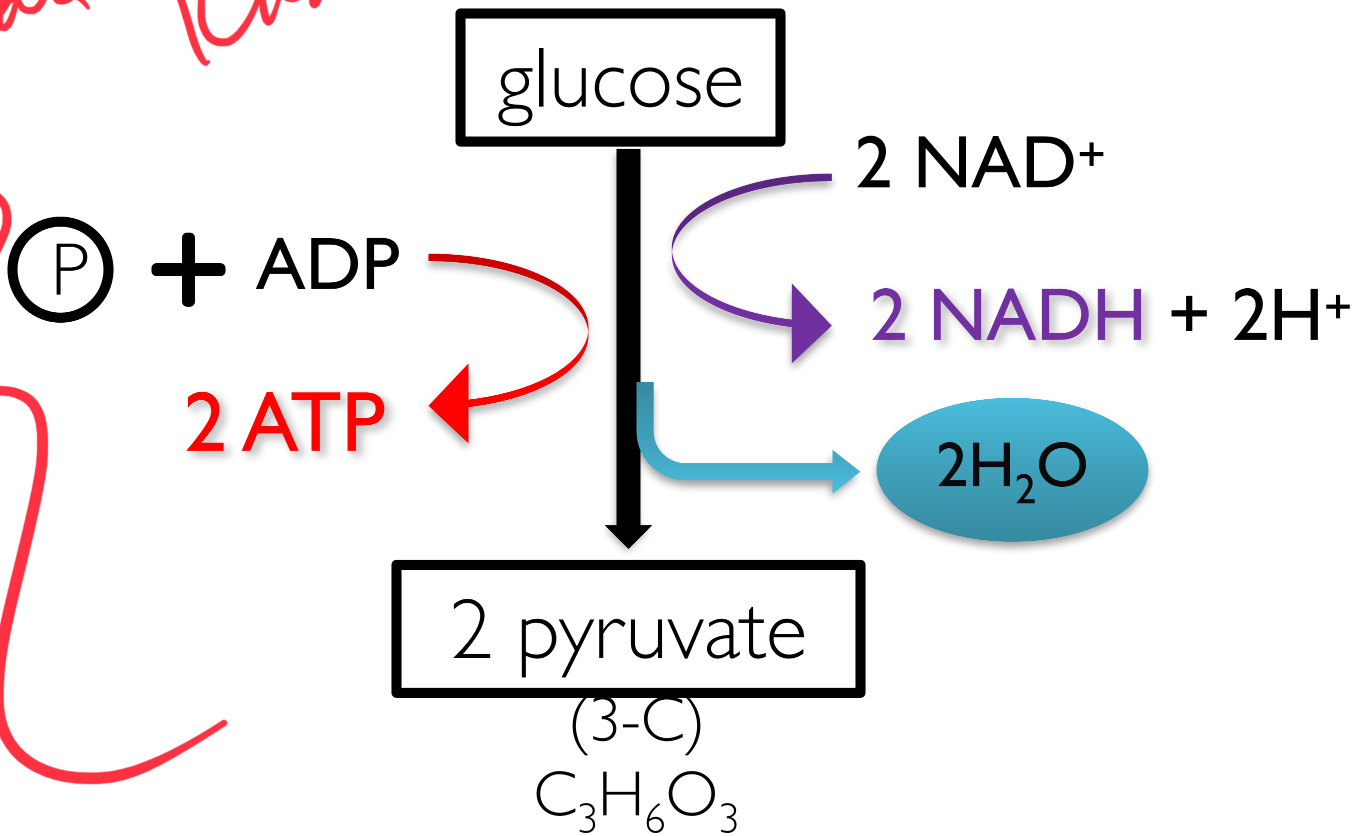



GLYCOLYSIS: Energy Investment Phase
cut sugar
1
2
Glucose
ATP
ADP
Hexokinase
1
Glucose 6-phosphate
Phosphogluco-isomerase
2
Fructose 6-phosphate
ATP
ADP
Phospho-fructokinase
3
Fructose 1,6-bisphosphate
Aldolase
4
Glyceraldehyde 3-phosphate (G3P)
Isomerase
5
Dihydroxyacetone phosphate (DHAP)
start: Glucose

Net of 2ATP

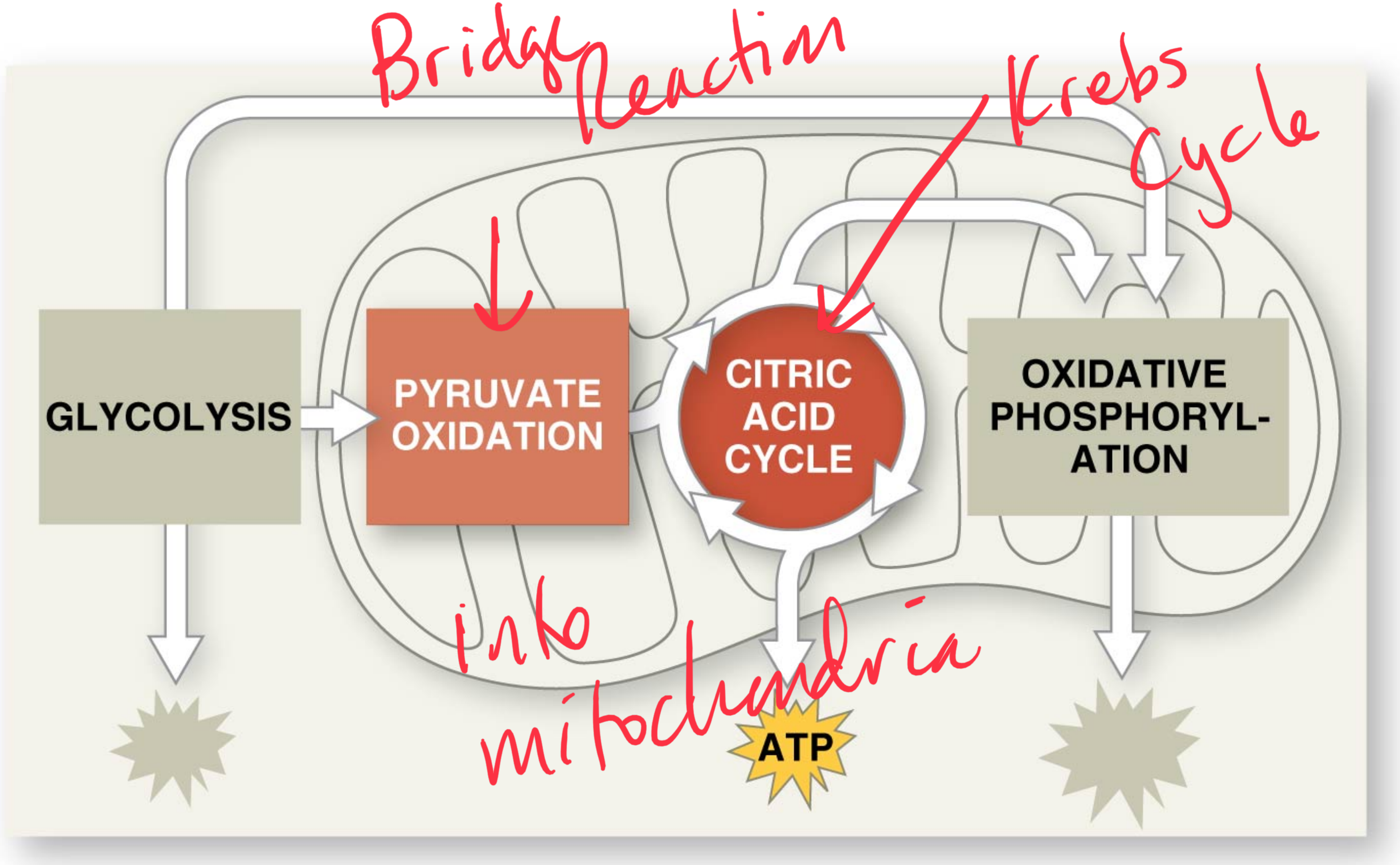

GLYCOLYSIS: Energy Payoff Phase
end pyruvate
Glyceraldehyde 3-phosphate (G3P)
2 NADH
2 NAD+
+ 2 H+
Triose phosphate dehydrogenase
2 Pi
6
2
1,3-Bisphospho-glycerate
2 ATP
2 ADP
Phospho-glycerokinase
7
2
3-Phospho-glycerate
Phospho-glyceromutase
8
2
2-Phospho-glycerate
2 H2O
Enolase
9
2
Phosphoenol-pyruvate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

Glycolysis (Summary)



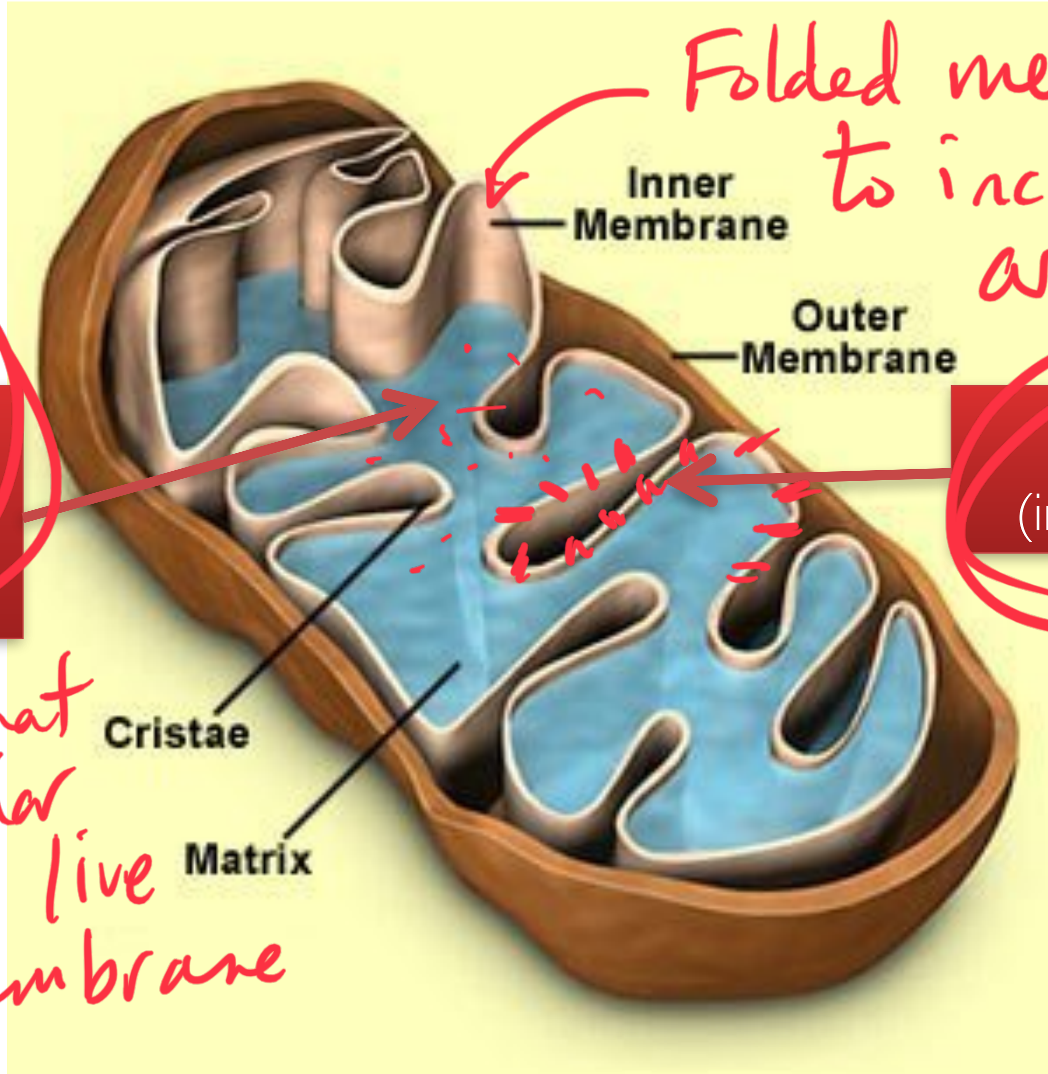
Cellular Respiration

Stage 2: Pyruvate Oxidation + Citric Acid Cycle


Bridge Reaction
Krebs Cycle
GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
into mitochondria
ATP

Mitochondrion Structure

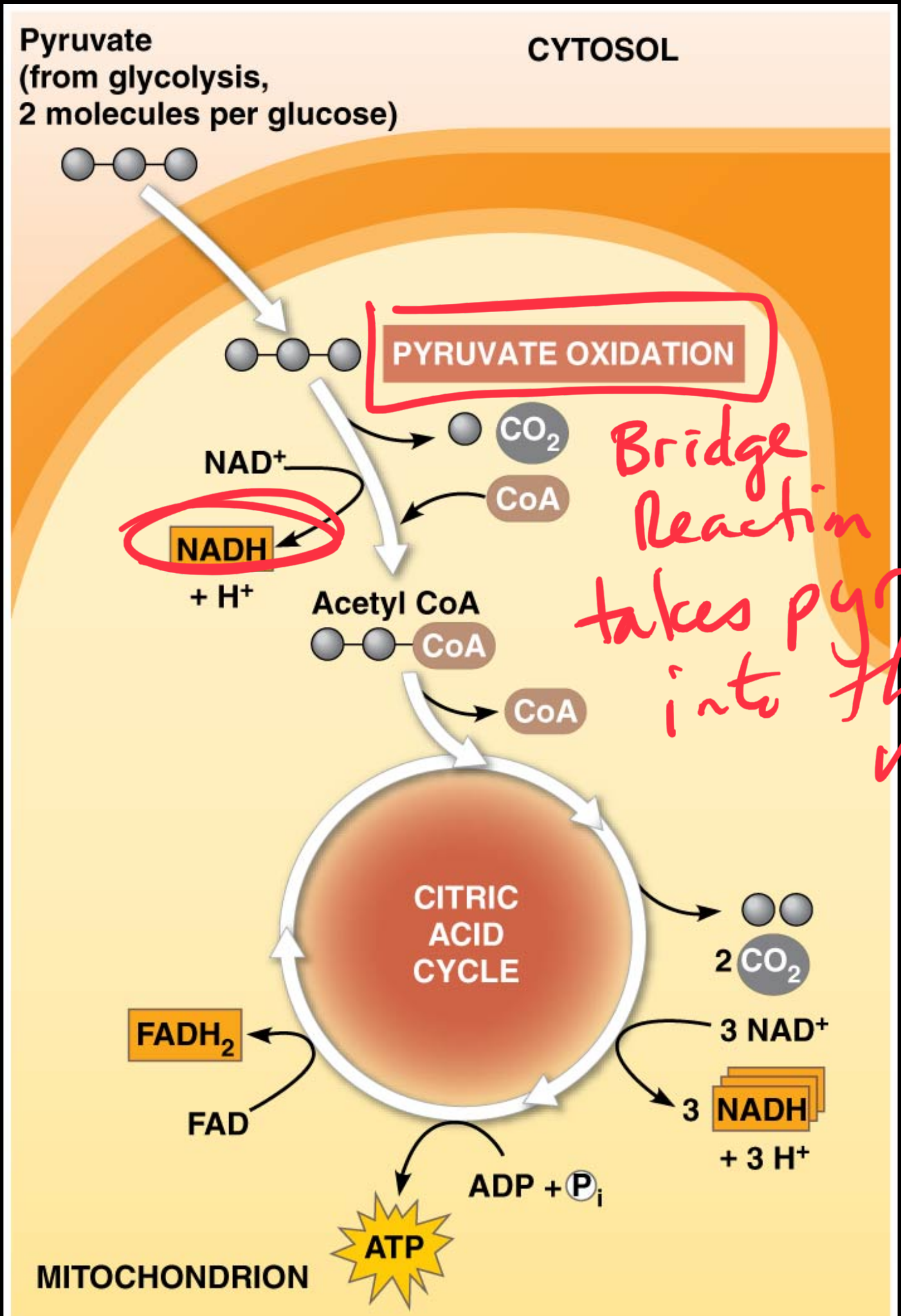
Citric Acid Cycle
(matrix)



ETC
(inner membrane)

Folded membrane? to increase surface area

Enzymes that drive cellular respiration live in the membrane

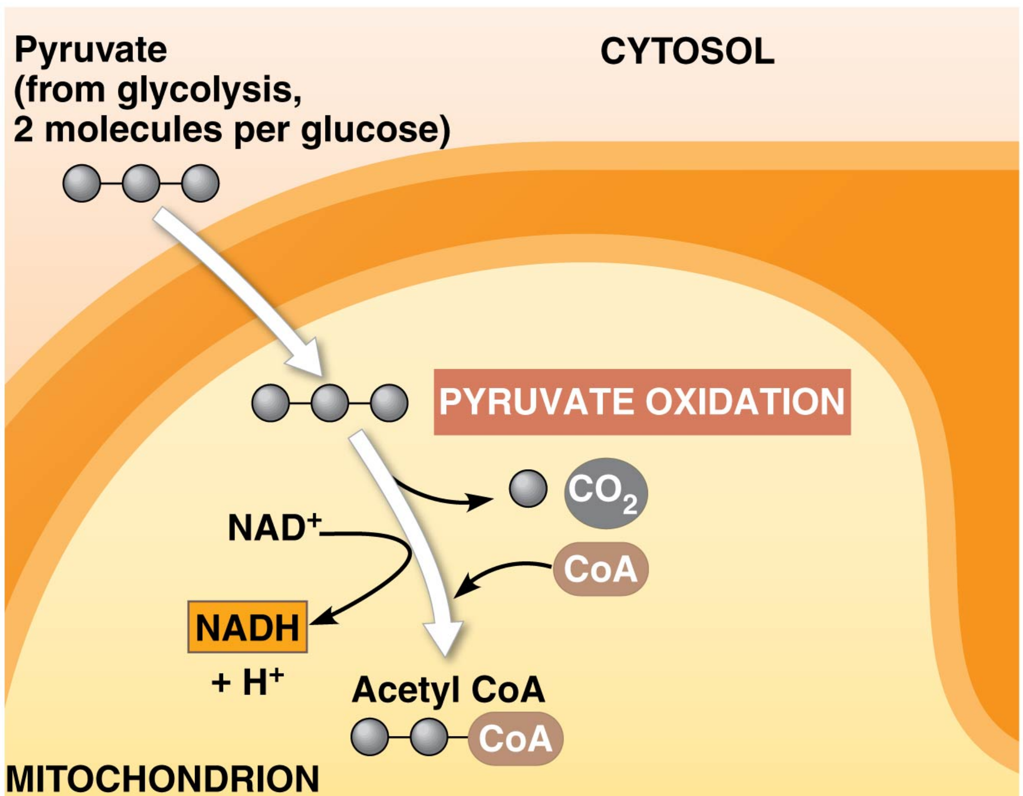


Bridge Reaction
takes pyruvate into the mitochondria

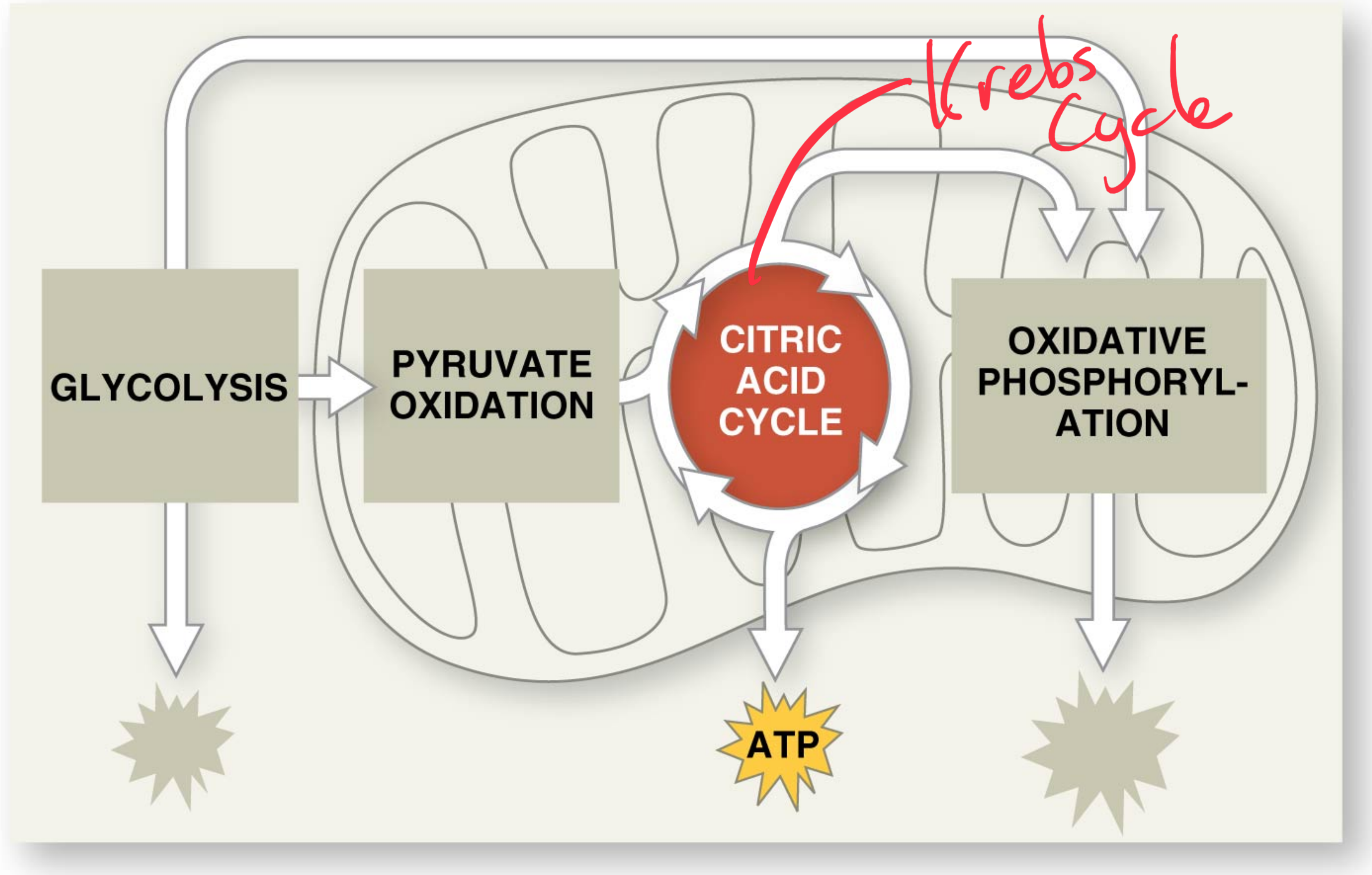
Pyruvate Oxidation

Bridge Reaction

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



In mito


Krebs Cycle
GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Citric Acid Cycle (Krebs)

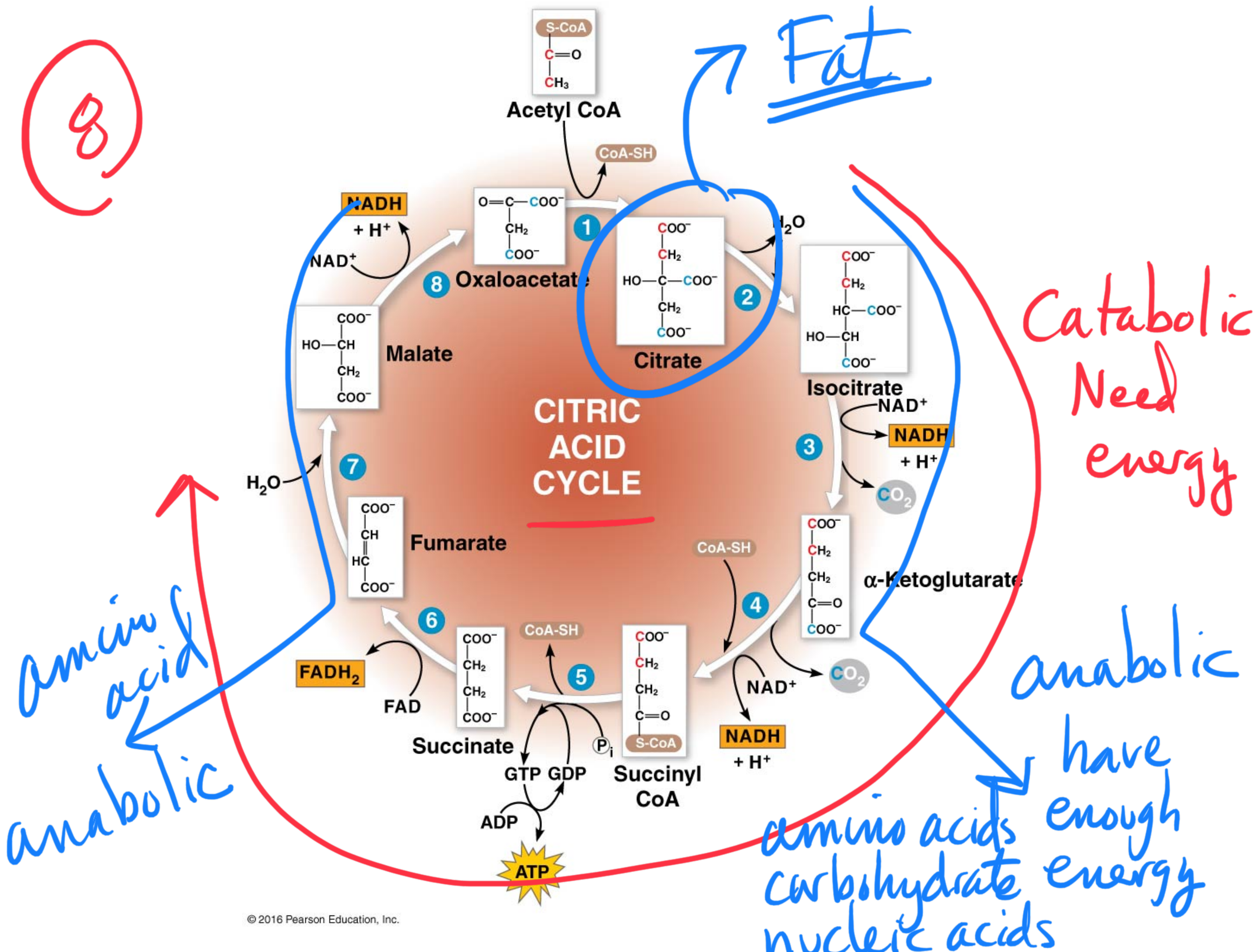
- Occurs in mitochondrial matrix
- Acetyl CoA → Citrate → CO_2 released
- Net gain: 2 ATP, 6 NADH, 2 $FADH_2$ (electron carrier)
- ATP produced by substrate-level phosphorylation

Cellular respiration is a combustion reaction

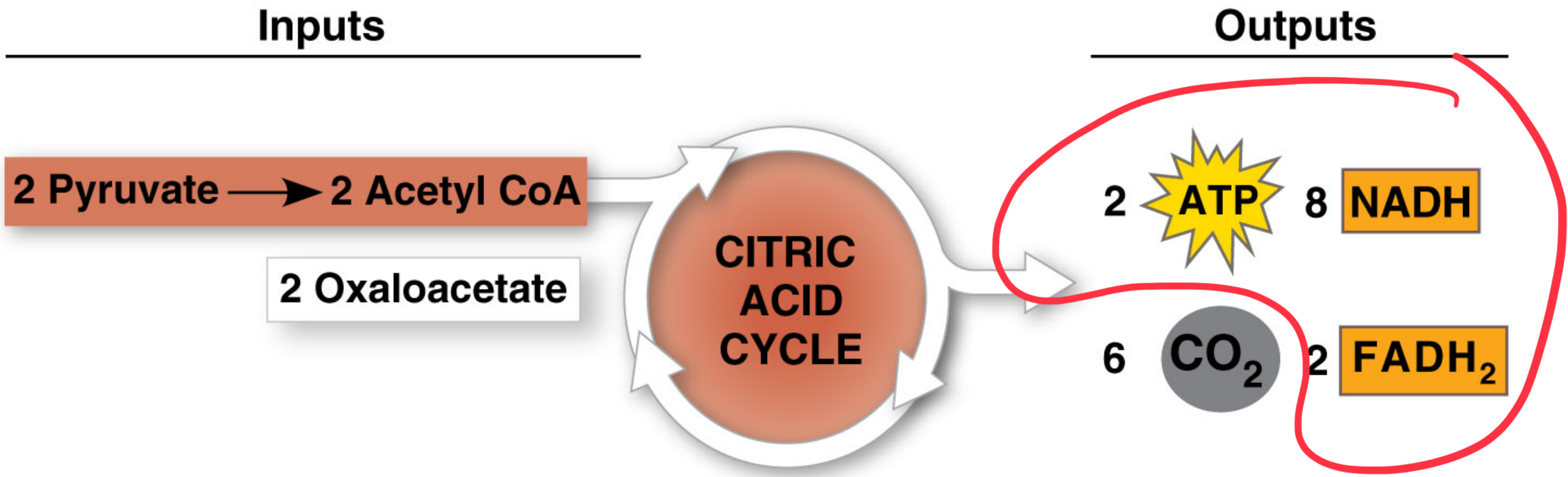
Glucose

$C_6H_{12}O_6 \rightarrow 6\,CO_2$

→ oxidative phosphorylation

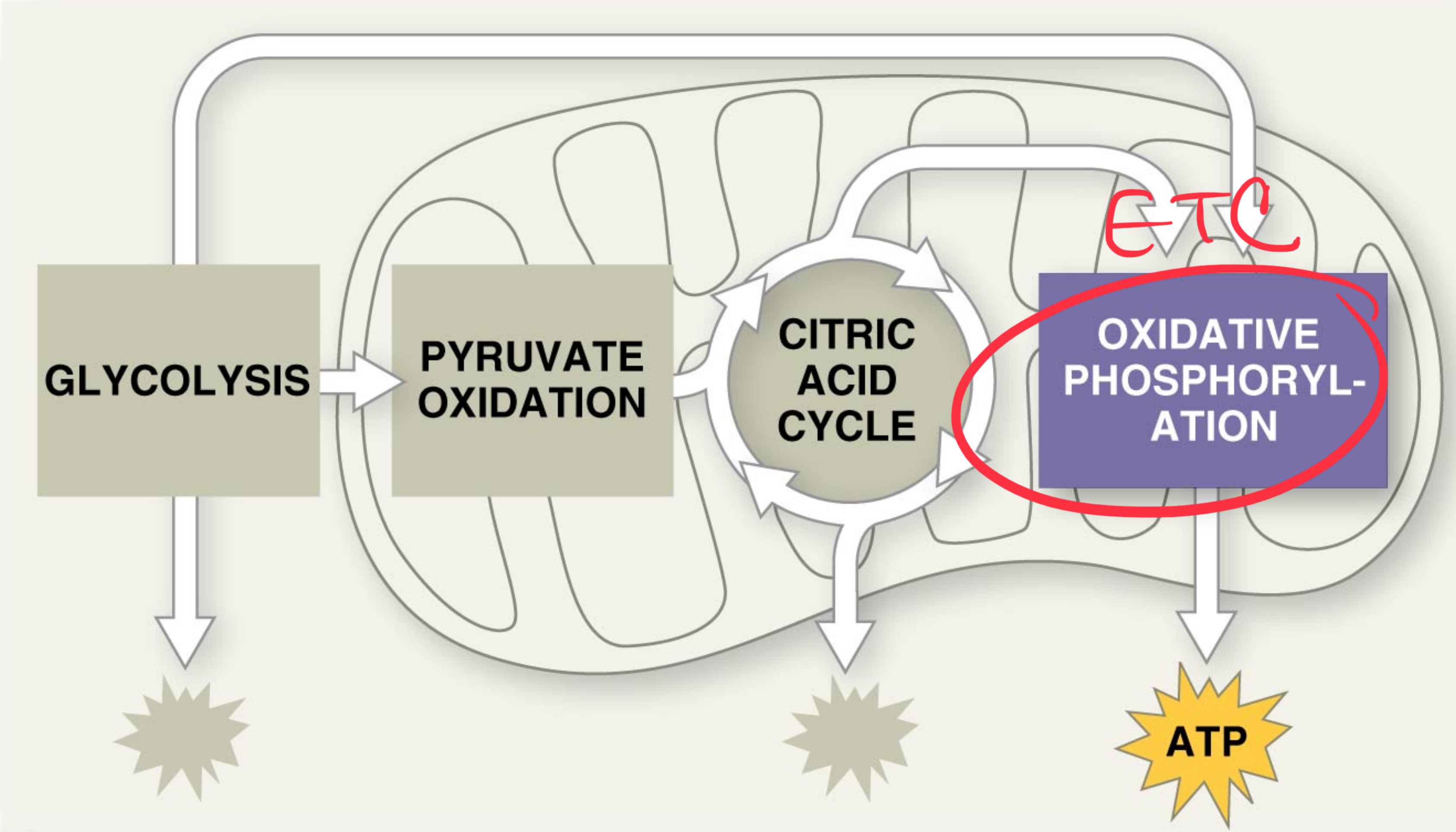

8
Fat
Acetyl CoA
S-CoA
CoA-SH
NADH + H+
NAD+
Oxaloacetate
Citrate
H_2O
Isocitrate
NAD+
NADH + H+
CO_2
α-Ketoglutarate
CoA-SH
NAD+
NADH + H+
CO_2
Succinyl CoA
S-CoA
Pi
GTP GDP
ADP
ATP
CoA-SH
Succinate
FAD
$FADH_2$
Fumarate
H_2O
Malate
CITRIC ACID CYCLE
Catabolic
Need energy
anabolic
have enough energy
amino acids
carbohydrate
nucleic acids
amino acid
anabolic

Summary of Citric Acid Cycle



Cellular Respiration

Stage 3: Oxidative Phosphorylation



ETC
GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
OXIDATIVE PHOSPHORYL-ATION
ATP

Oxidative Phosphorylation

ELECTRON TRANSPORT CHAIN

Movement of electrons

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

4 ATP produced through substrate-level phosphorylation
2-Glycolysis
2-Krebs

CHEMIOSMOSIS

Movement of protons

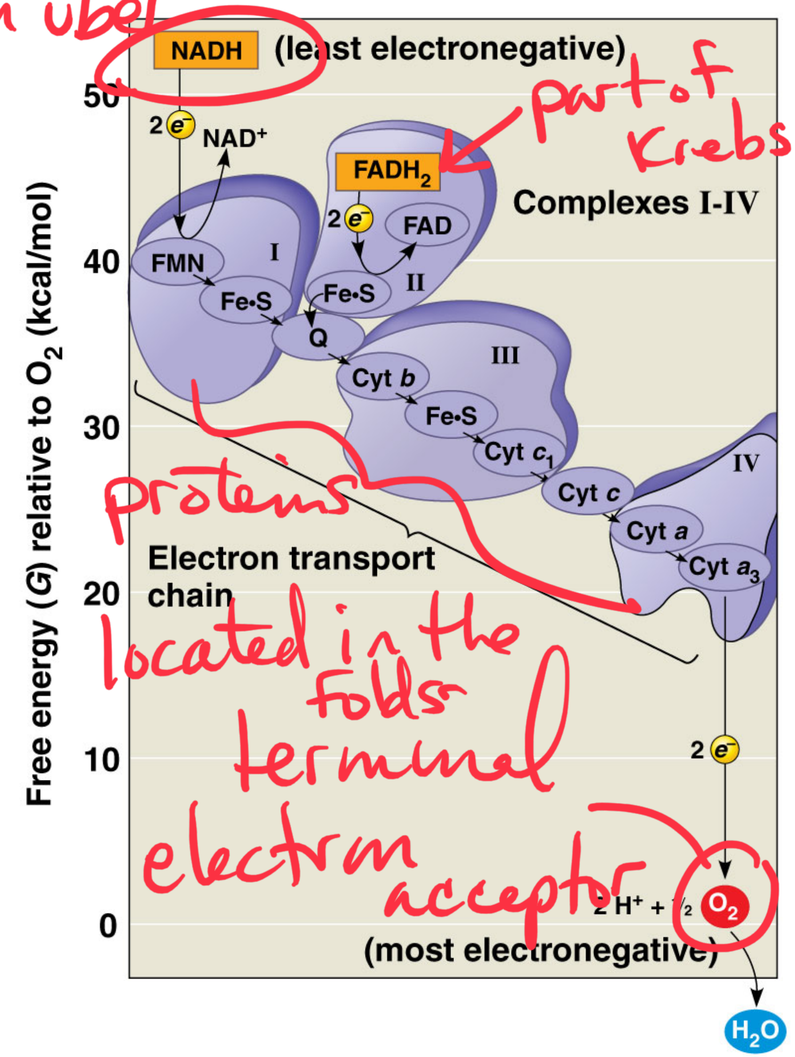
- H^+ ions pumped across inner mitochondrial membrane (proton)
- H^+ diffuse through ATP synthase (ADP → ATP)

Total 32 ATP

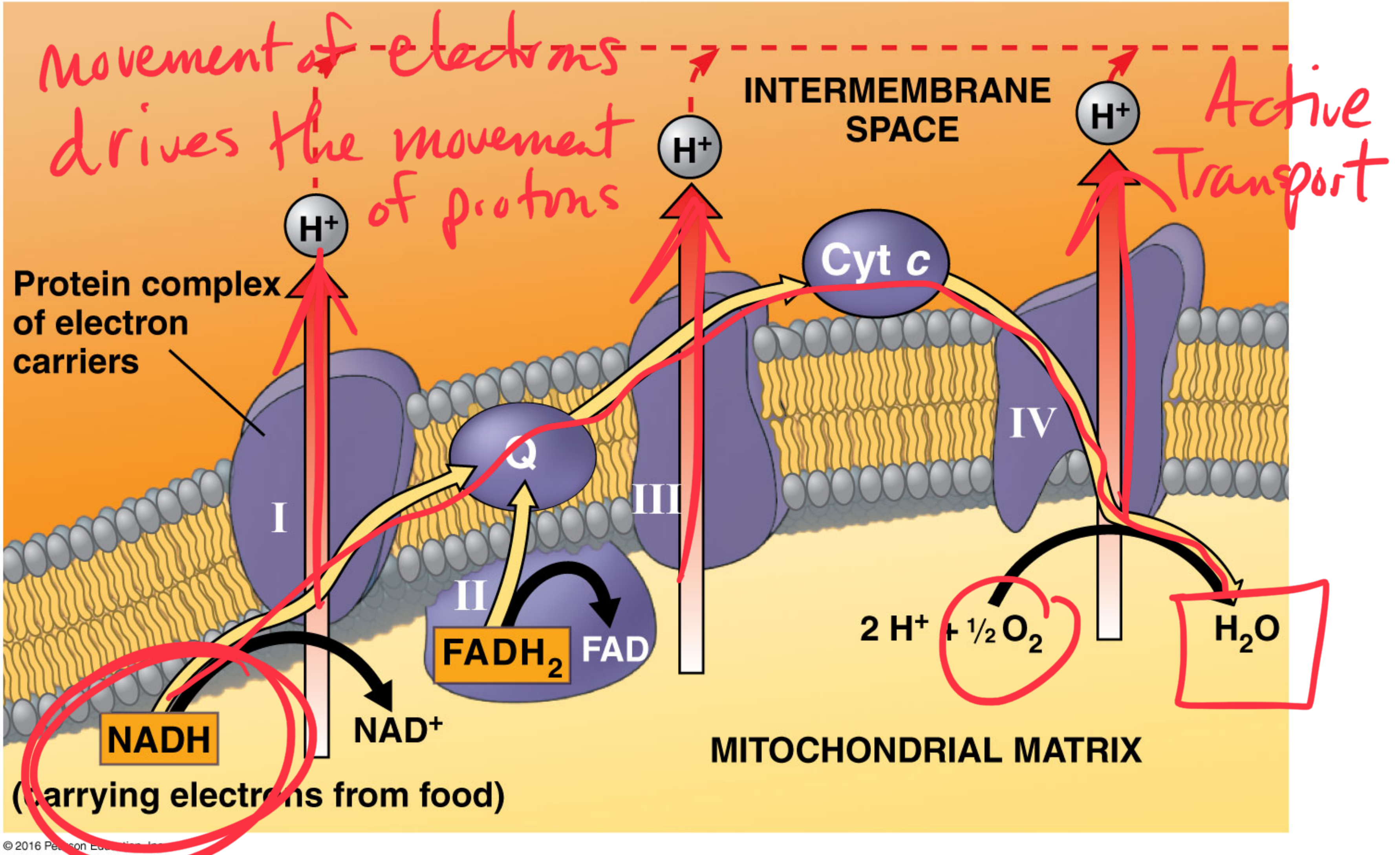
Electron Transport Chain (ETC)

- 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
- $2H^+ + \frac{1}{2} O_2 \rightarrow H_2O$

electron uber



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



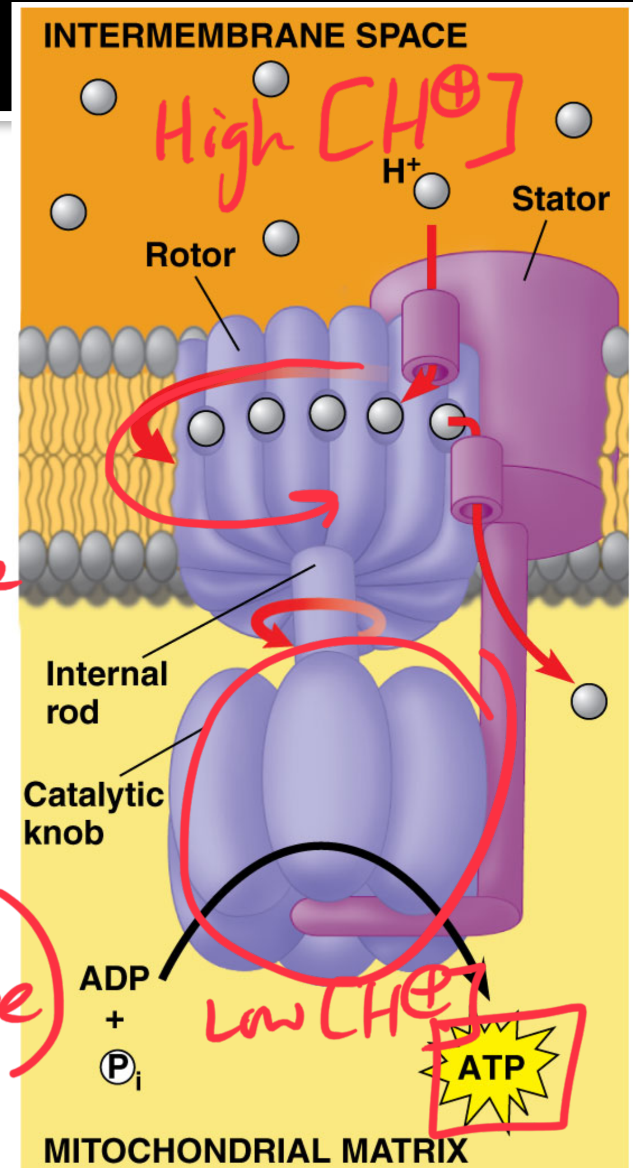
Chemiosmosis: Energy-Coupling Mechanism

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

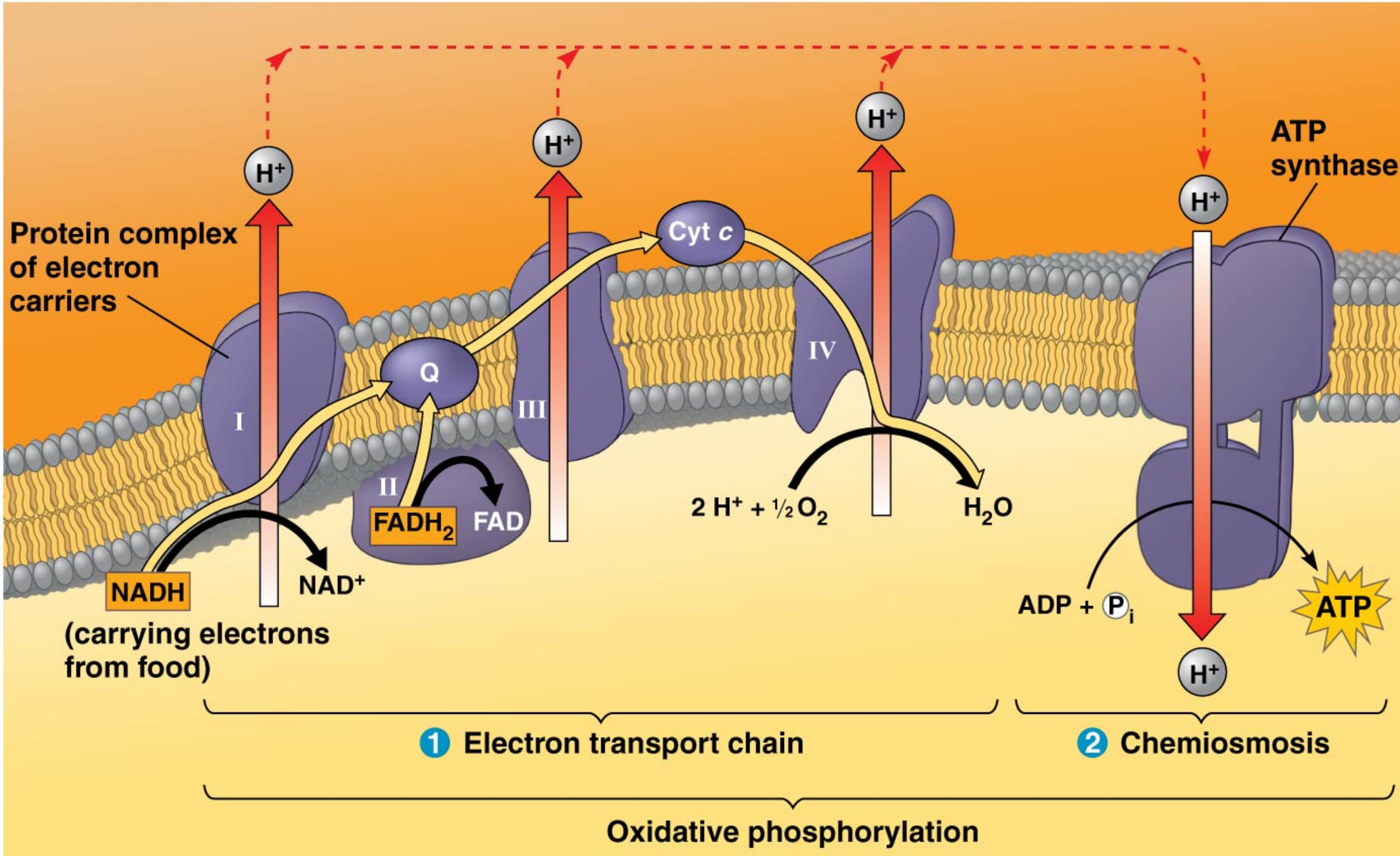
water wheel/turbine

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

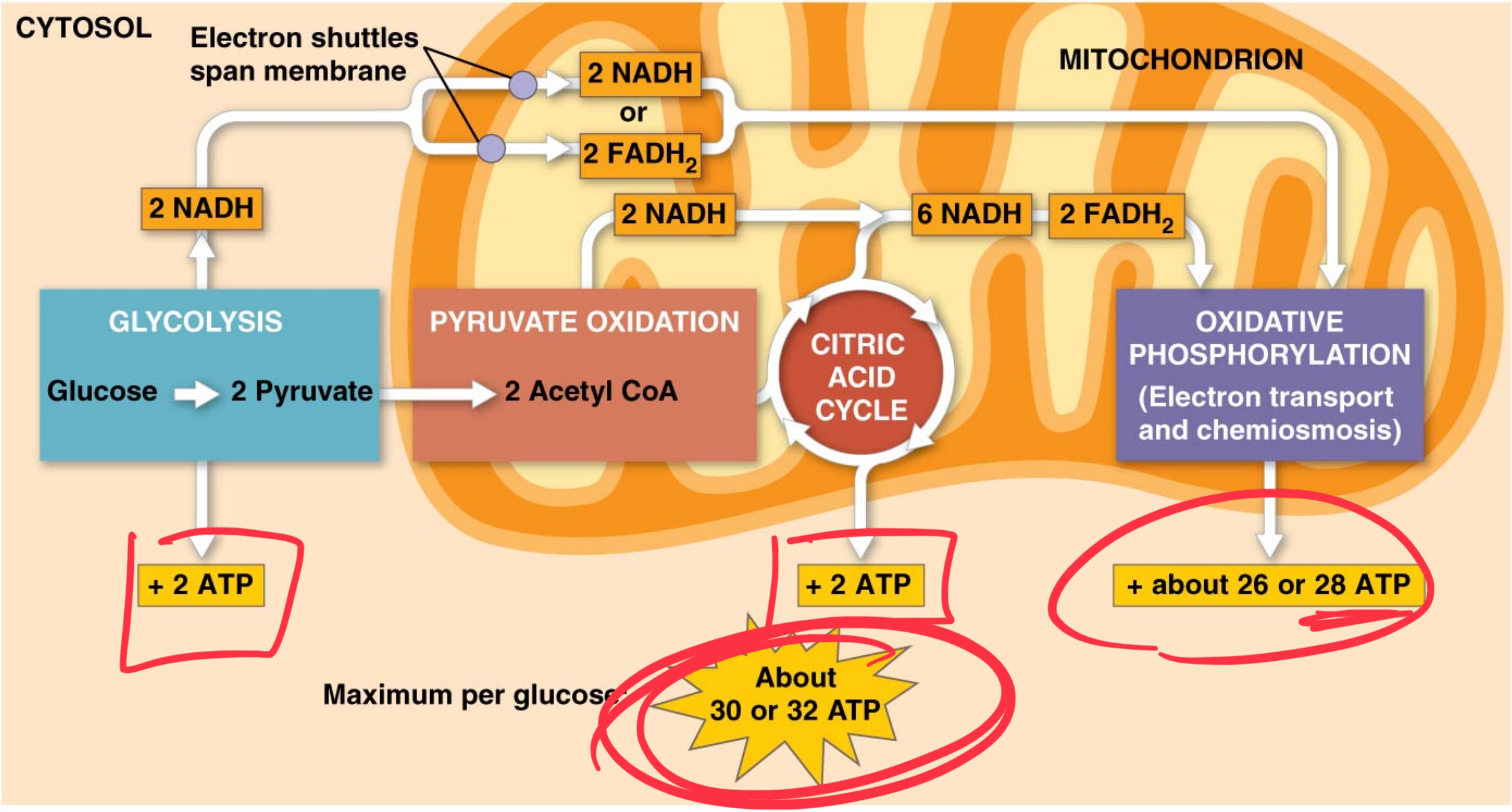
protein turbine (ATP synthase) that produces ATP



Chemiosmosis couples the ETC to ATP synthesis



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

Bears when they hibernate