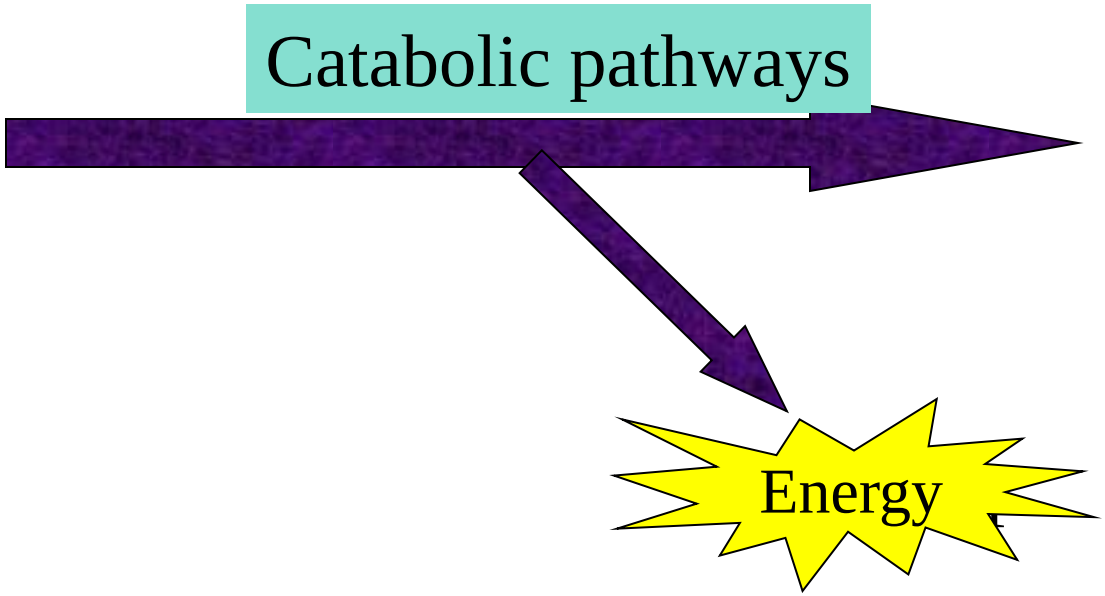
ENERGY PRODUCTION & STORAGE IN OXIDATIVE PHOSPHORYLATION

COMPILED BY
Prof. Sudhir K Awasthi
Dept. Of Life Sciences
CSJMU Kanpur

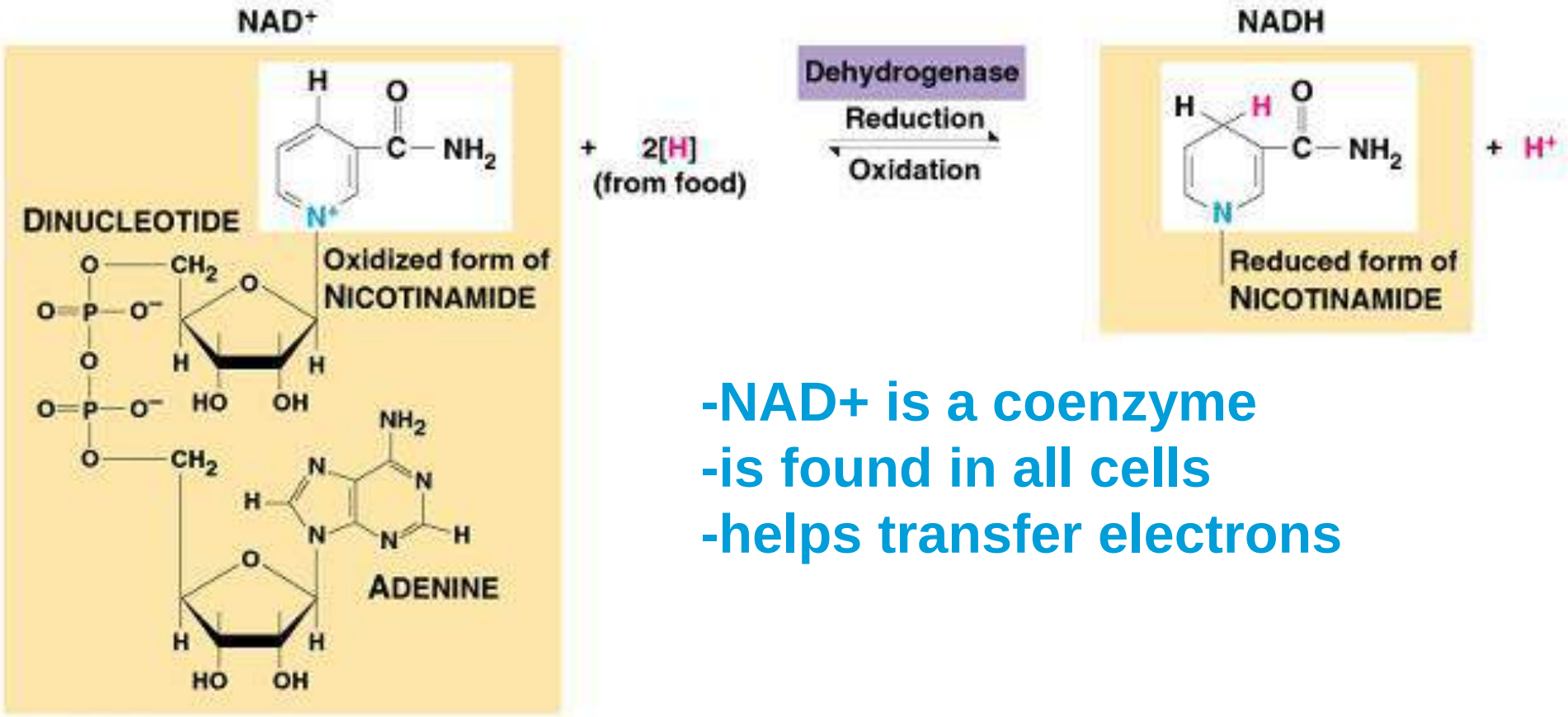
Complex Organic Molecules



Simpler waste Products w/ Less Energy

For work

Lost as heat



-NAD+ is a coenzyme
-is found in all cells
-helps transfer electrons

Overview of respiration

-glucose is **oxidized**

-electrons (hydrogen atoms) leave the carbon atoms and combine w/ O_2

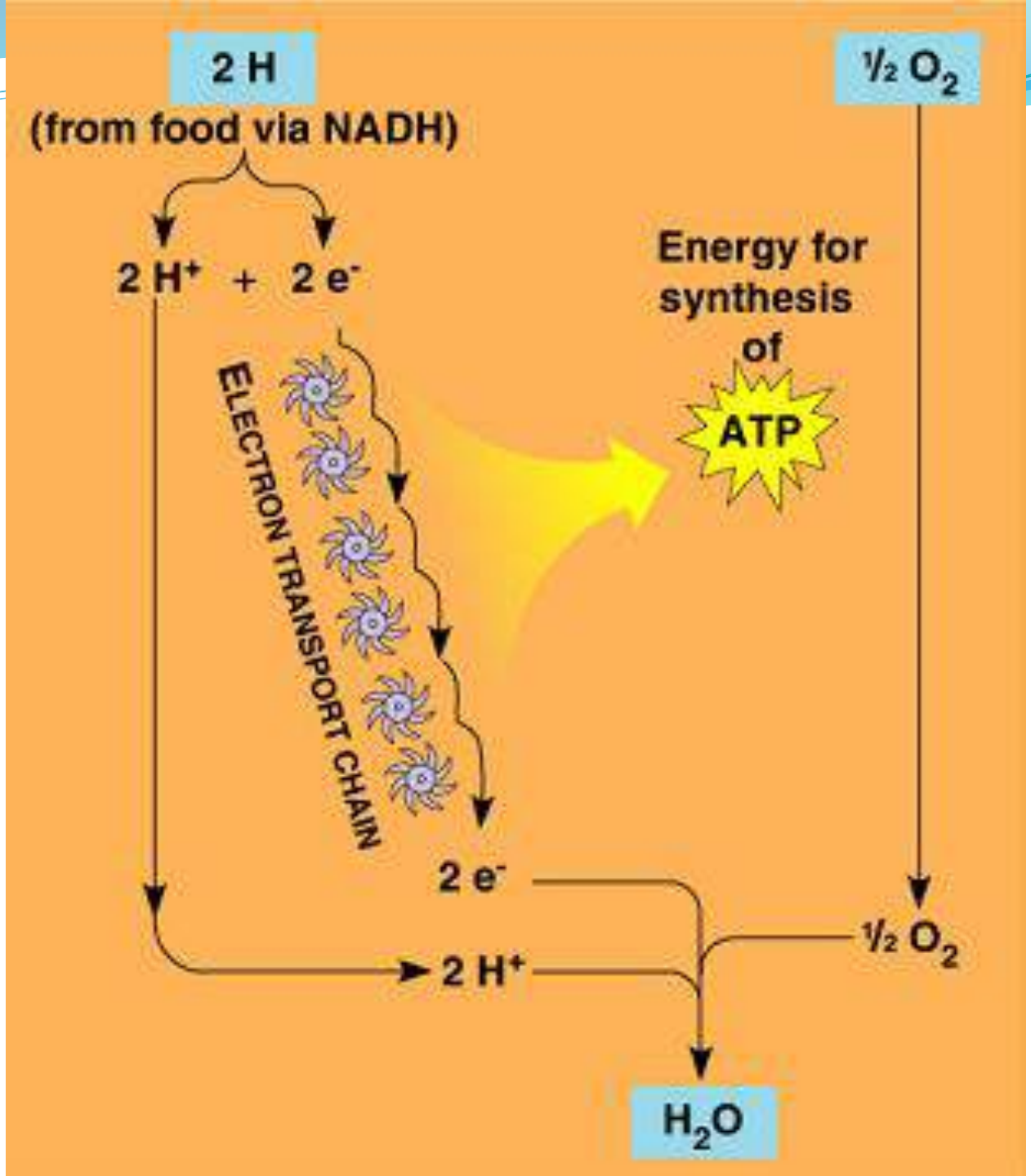
-this happens by a series of steps via **NAD+** and an electron transport chain

-During this process ATP is produced

Two ways to get ATP

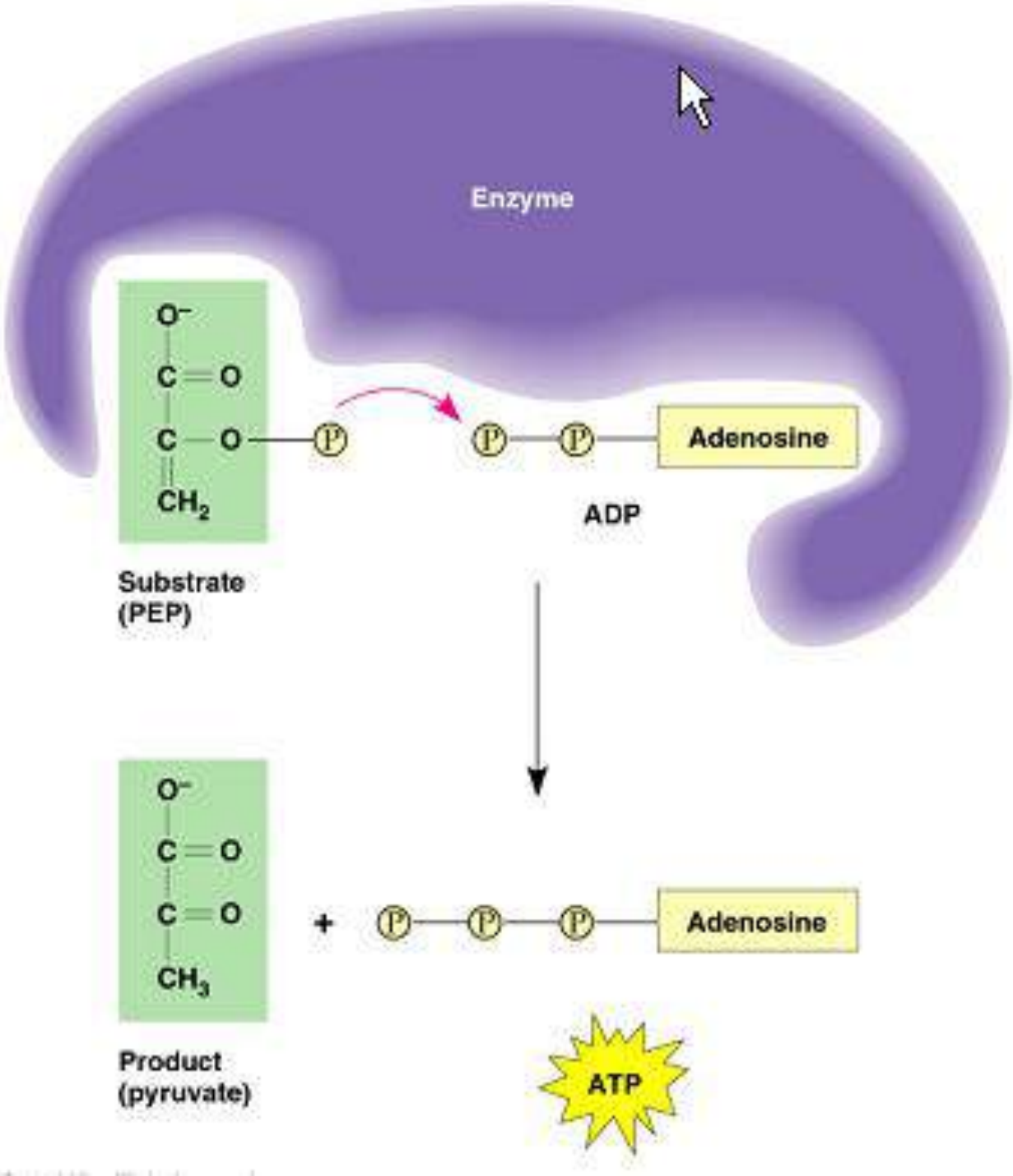
1 **Oxidative phosphorylation**

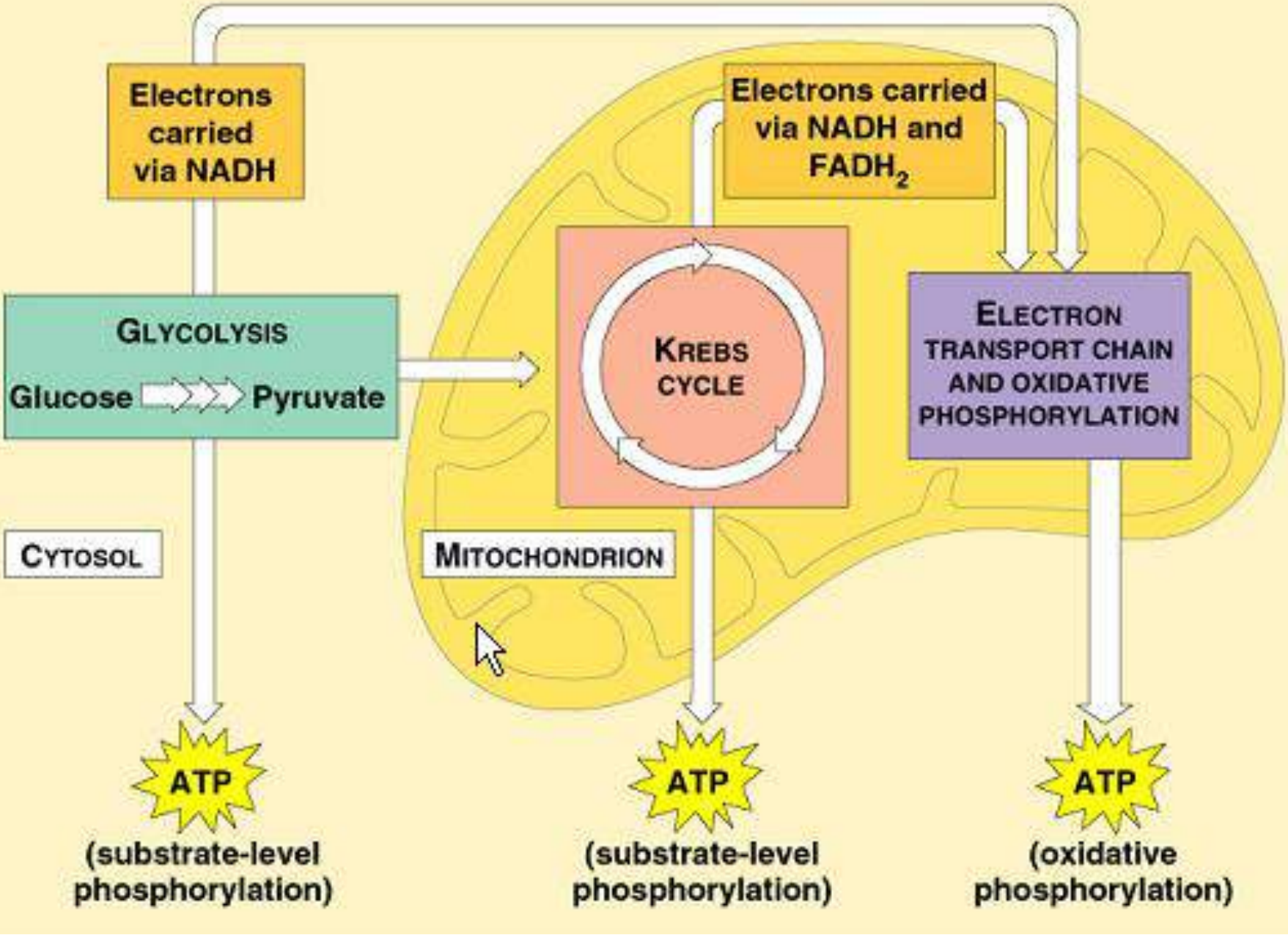
ATP production that is **coupled** to the **exergonic** transfer of electrons from food to oxygen


2 H
(from food via NADH)
½ O_2
2 H^+ + 2 e^-
Energy for synthesis of
ATP
ELECTRON TRANSPORT CHAIN
2 e^-
½ O_2
2 H^+
H_2O

2 Substrate level phosphorylation

ATP production by direct enzymatic transfer of phosphate from an intermediate substrate to ADP


Enzyme
O⁻
C
O
C
O
CH2
P
P
P
Adenosine
ADP
Substrate
(PEP)
O⁻
C
O
C
O
CH3
+
P
P
P
Adenosine
Product
(pyruvate)
ATP


Electrons carried via NADH
Electrons carried via NADH and $FADH_2$
GLYCOLYSIS
Glucose
Pyruvate
KREBS CYCLE
ELECTRON TRANSPORT CHAIN AND OXIDATIVE PHOSPHORYLATION
CYTOSOL
MITOCHONDRION
ATP
(substrate-level phosphorylation)
ATP
(substrate-level phosphorylation)
ATP
(oxidative phosphorylation)

Glycolysis overview

-glucose (contain 6 Carbons) is split into two 3-carbon sugars.

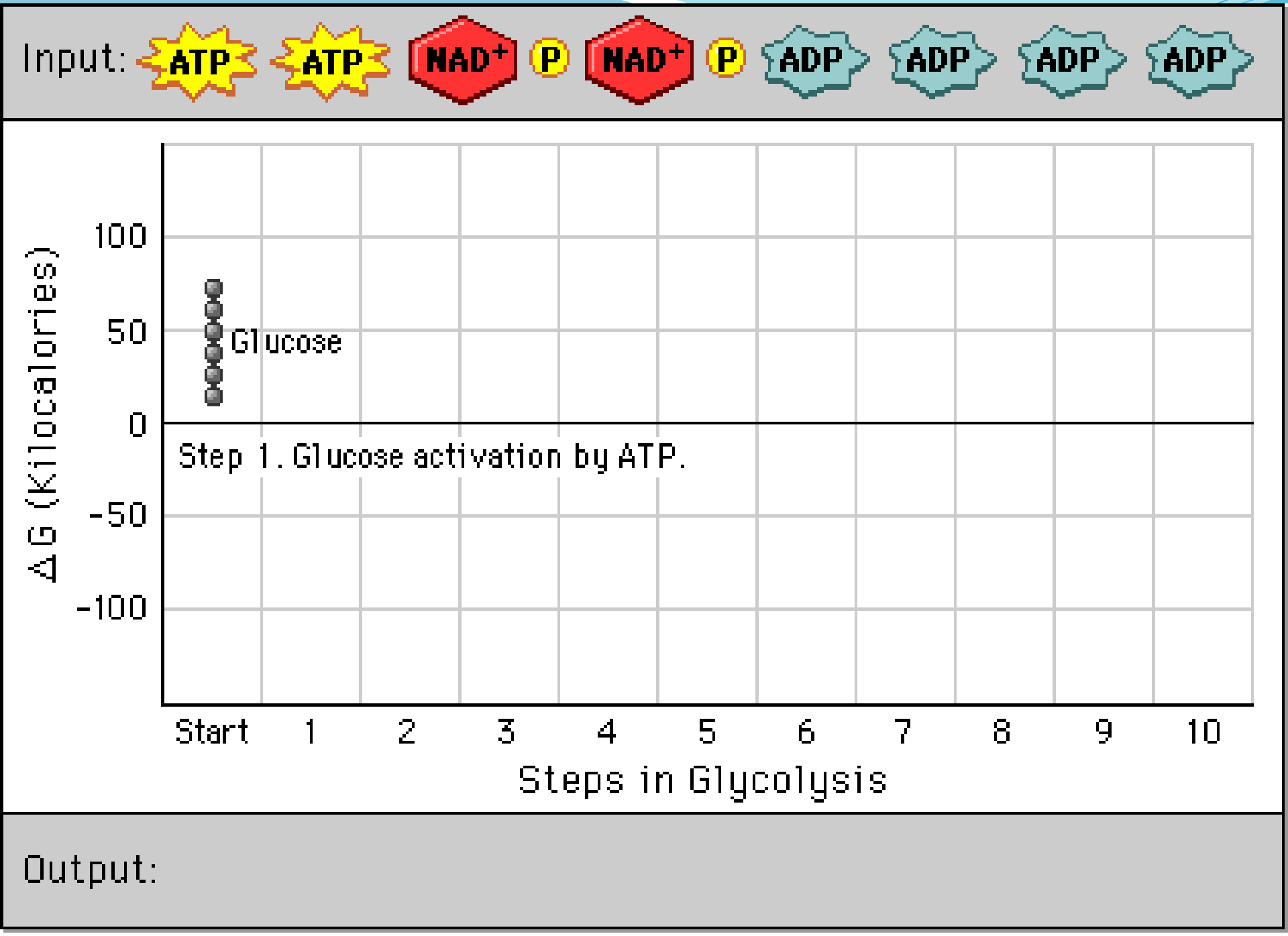
-these 3-carbon sugars are oxidized and rearranged to form 2 pyruvate molecules

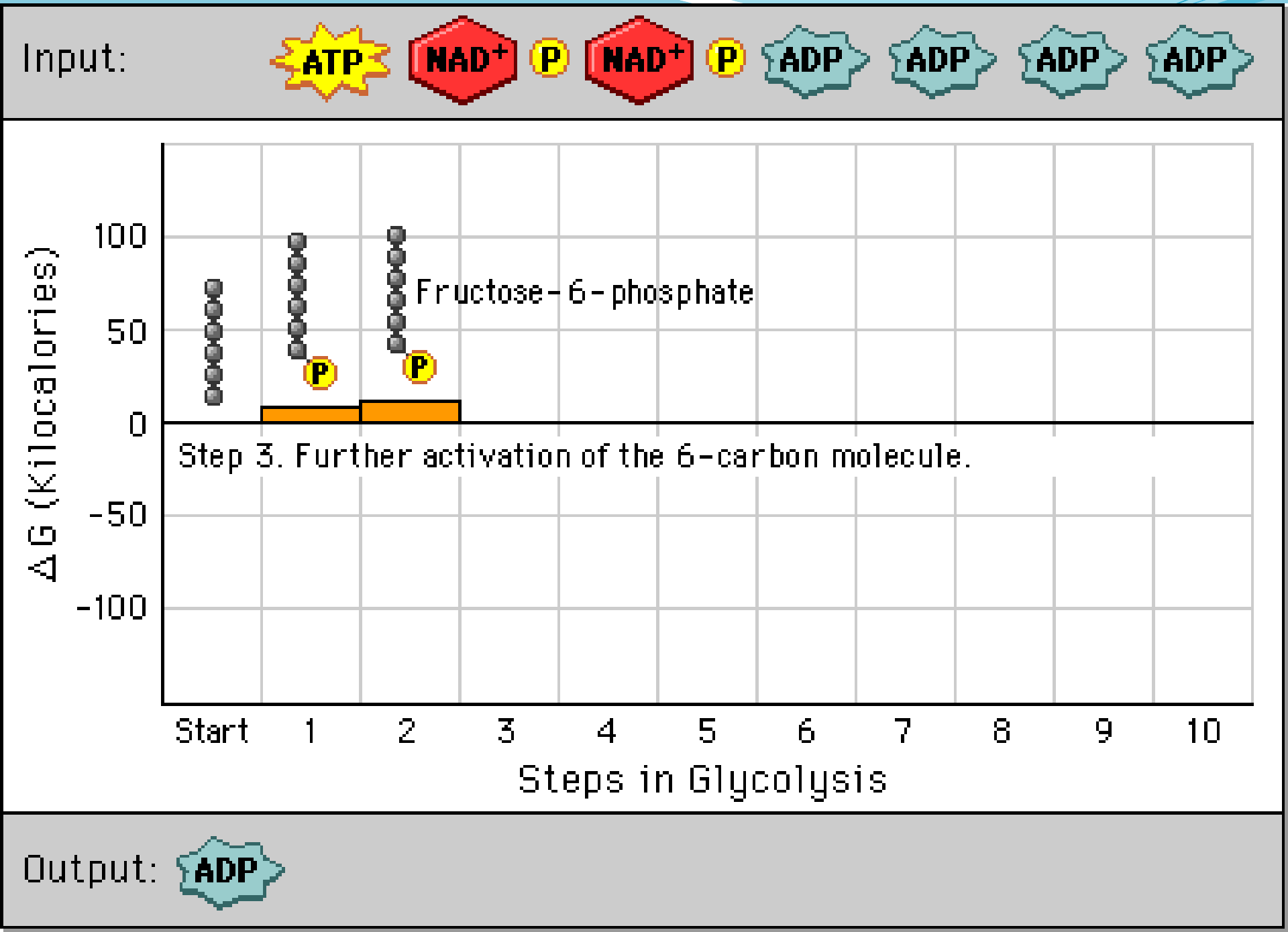
-occurs in the cytosol

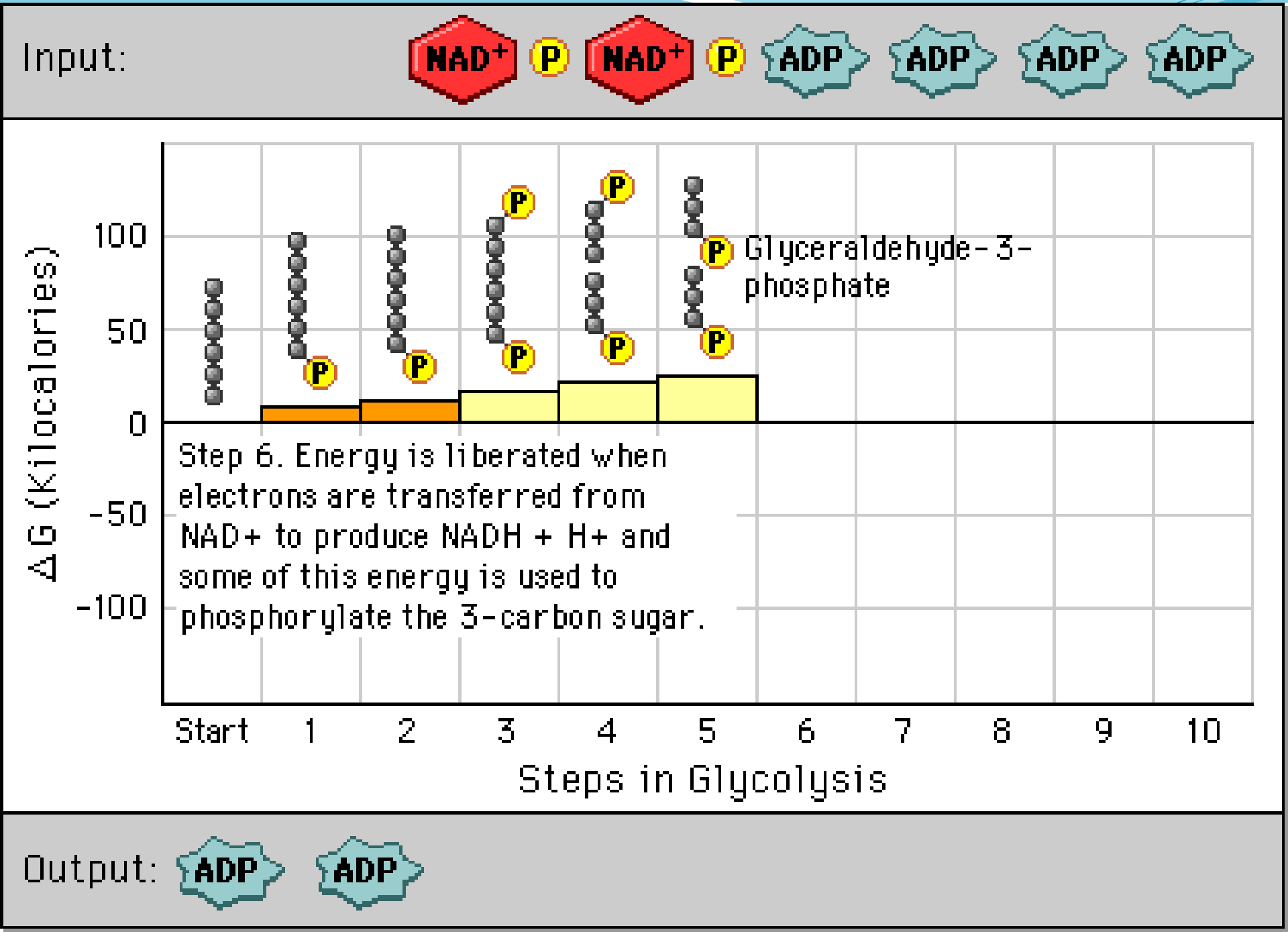
-no CO_2 released

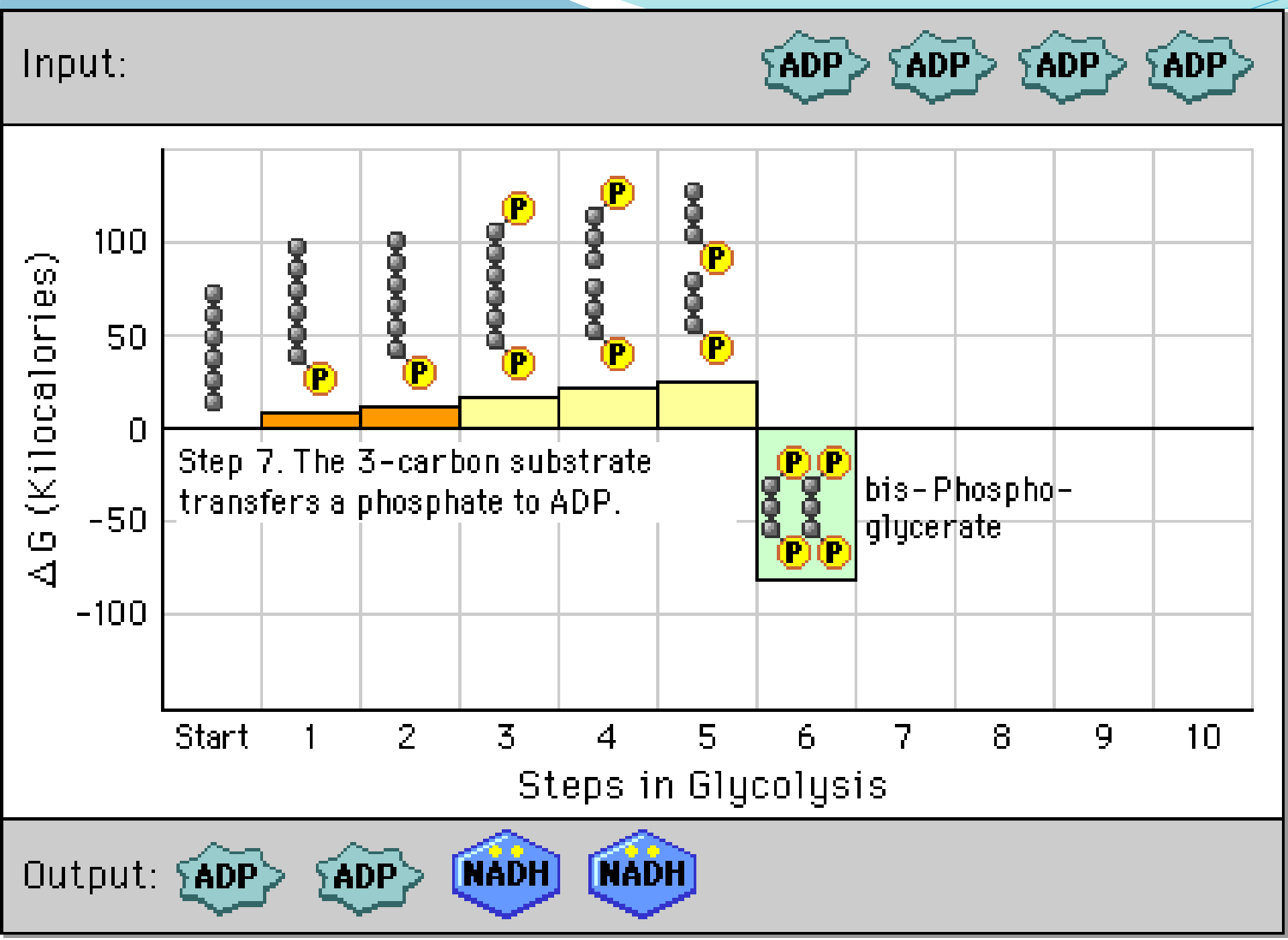
-occurs whether or not oxygen is present.

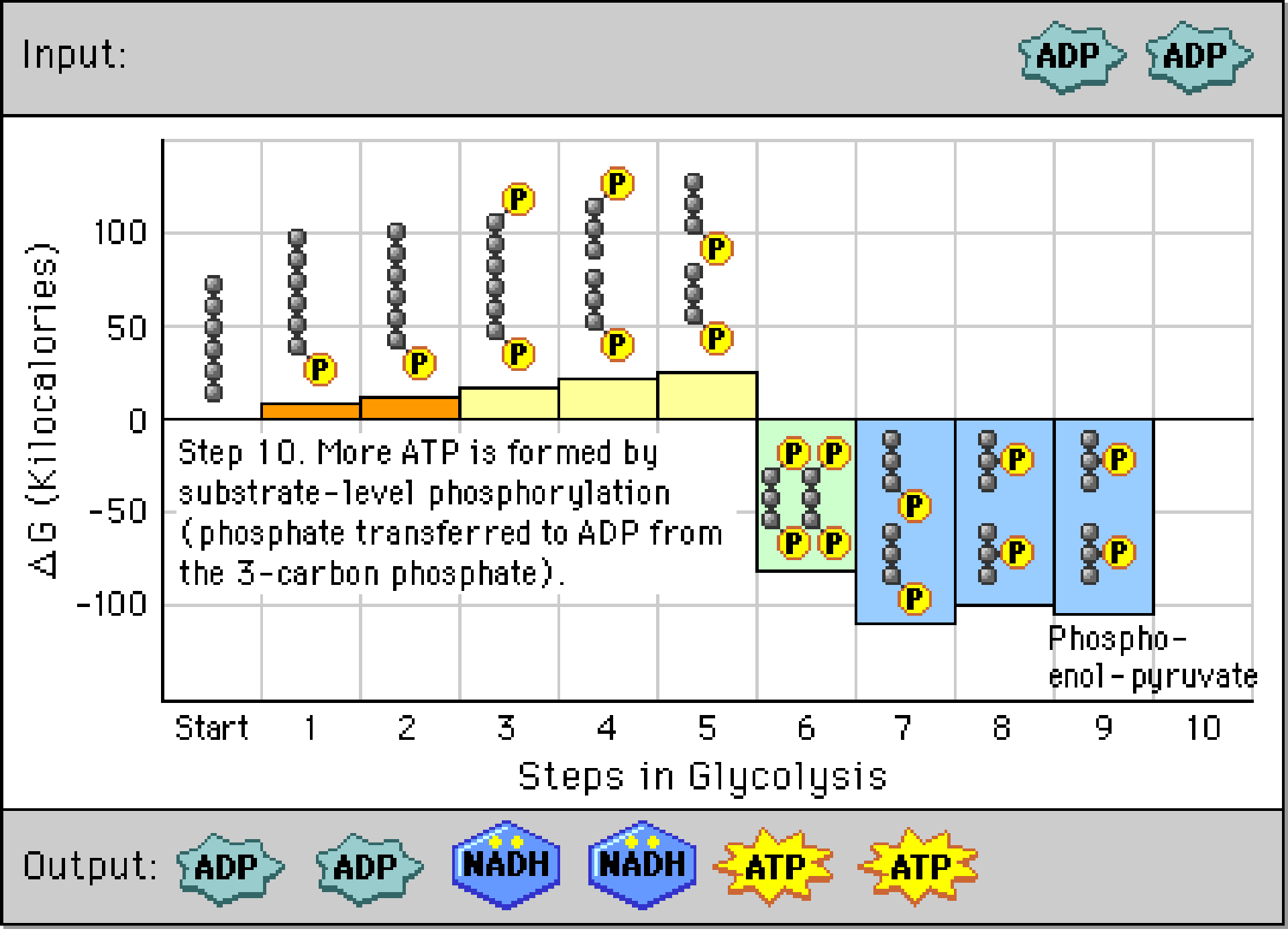
-2 net ATP produced


Input:
ATP
ATP
NAD+
P
NAD+
P
ADP
ADP
ADP
ADP
100
50
0
-50
-100
ΔG (kilocalories)
Glucose
Step 1. Glucose activation by ATP.
Start
1
2
3
4
5
6
7
8
9
10
Steps in Glycolysis
Output:

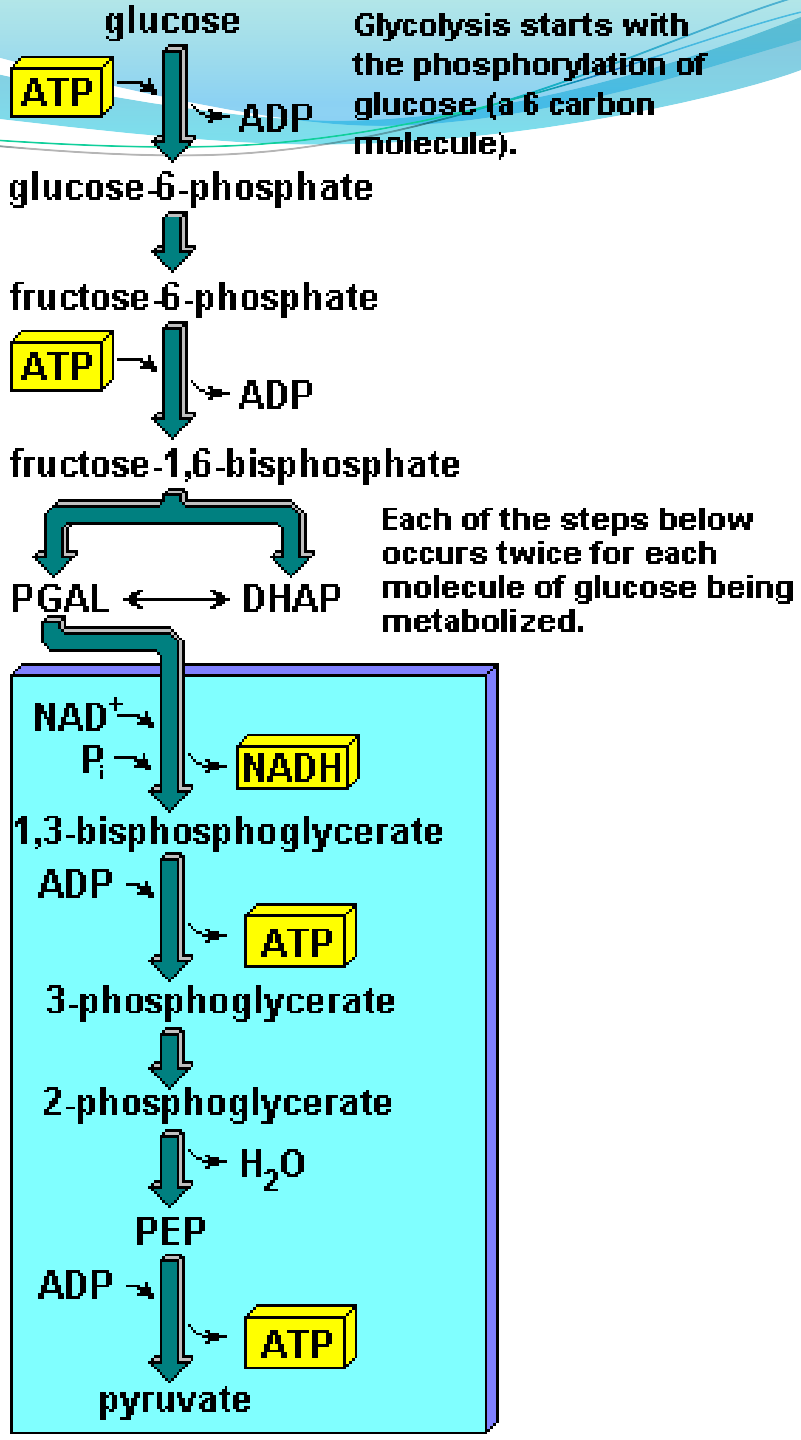

Input:
ATP
NAD+
P
NAD+
P
ADP
ADP
ADP
ADP
100
50
0
-50
-100
ΔG (Kilocalories)
Fructose-6-phosphate
P
P
Step 3. Further activation of the 6-carbon molecule.
Start
1
2
3
4
5
6
7
8
9
10
Steps in Glycolysis
Output:
ADP

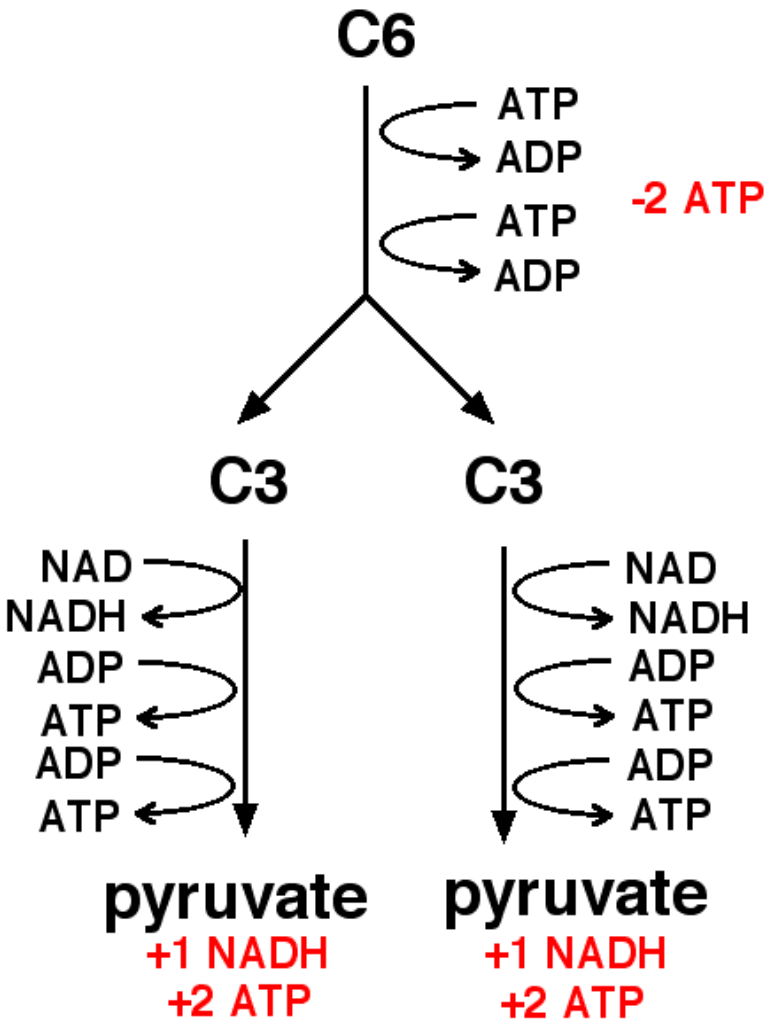

Input:
NAD+
P
NAD+
P
ADP
ADP
ADP
ADP
100
50
0
-50
-100
ΔG (Kilocalories)
Glyceraldehyde-3-phosphate
Step 6. Energy is liberated when electrons are transferred from NAD+ to produce NADH + H+ and some of this energy is used to phosphorylate the 3-carbon sugar.
Start
1
2
3
4
5
6
7
8
9
10
Steps in Glycolysis
Output:
ADP
ADP

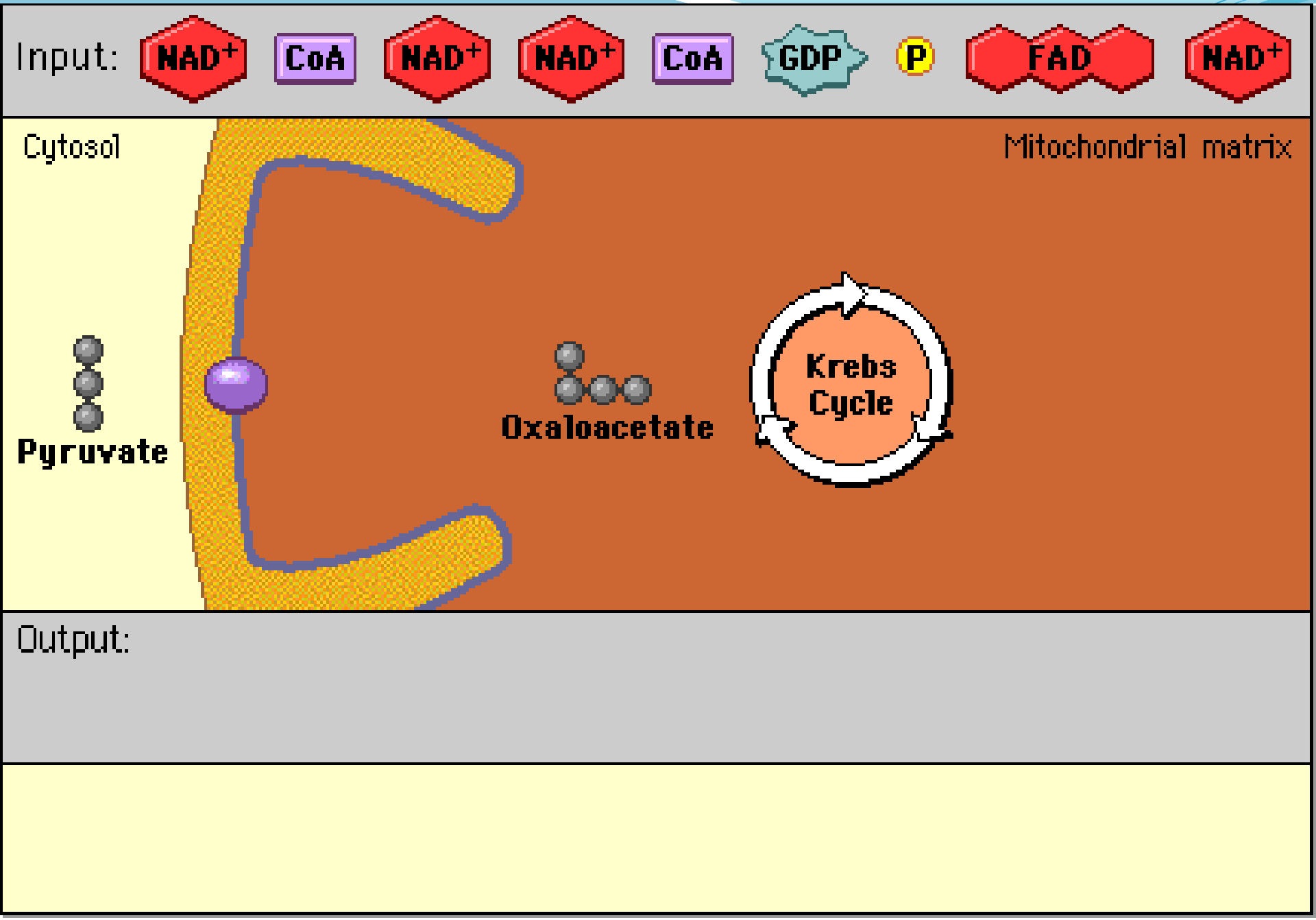

Input:
ADP
ADP
ADP
ADP
100
50
0
-50
-100
ΔG (Kilocalories)
P
Step 7. The 3-carbon substrate transfers a phosphate to ADP.
bis-Phospho-glycerate
Start
1
2
3
4
5
6
7
8
9
10
Steps in Glycolysis
Output:
ADP
ADP
NADH
NADH


Input:
ADP
ADP
100
50
0
-50
-100
ΔG (kilocalories)
P
Step 10. More ATP is formed by substrate-level phosphorylation (phosphate transferred to ADP from the 3-carbon phosphate).
Phospho-enol-pyruvate
Start
1
2
3
4
5
6
7
8
9
10
Steps in Glycolysis
Output:
ADP
ADP
NADH
NADH
ATP
ATP

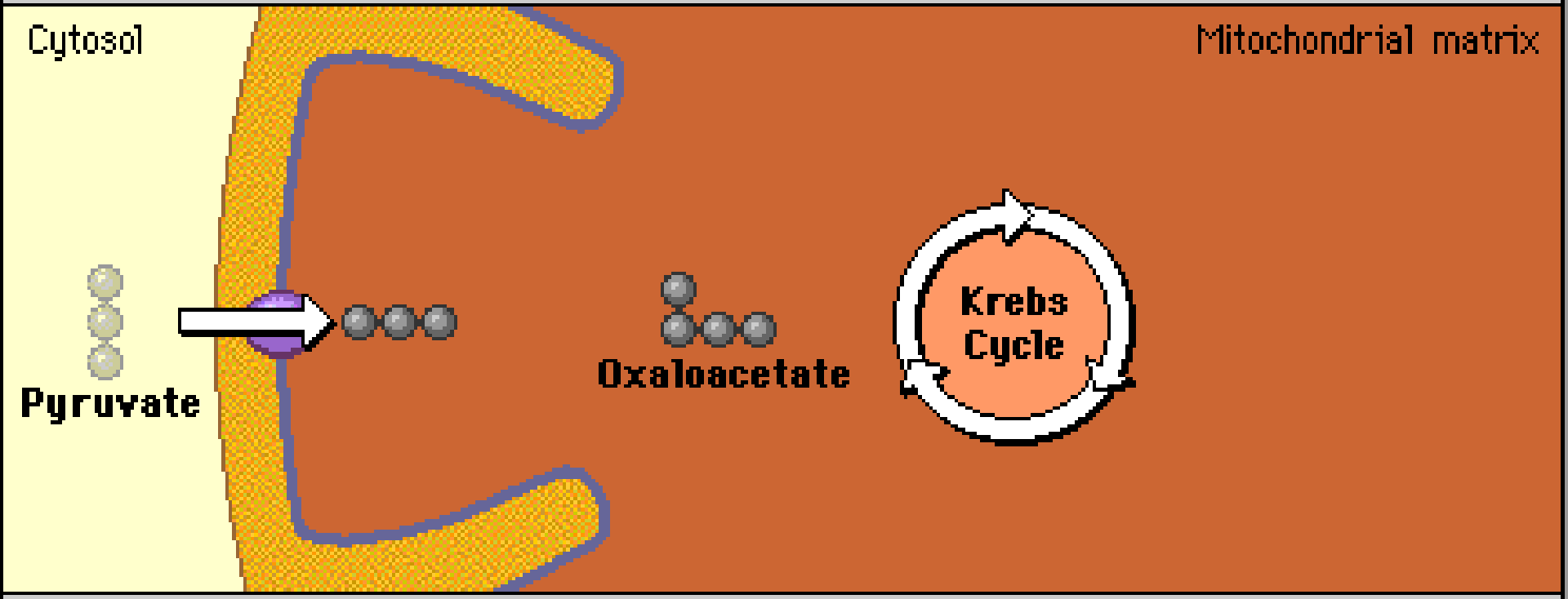
Glycolysis


glucose
ATP
ADP
Glycolysis starts with the phosphorylation of glucose (a 6 carbon molecule).
glucose-6-phosphate
fructose-6-phosphate
ATP
ADP
fructose-1,6-bisphosphate
PGAL ⟷ DHAP
Each of the steps below occurs twice for each molecule of glucose being metabolized.
NAD+
Pi
NADH
1,3-bisphosphoglycerate
ADP
ATP
3-phosphoglycerate
2-phosphoglycerate
H2O
PEP
ADP
ATP
pyruvate


C6
ATP
ADP
ATP
ADP
-2 ATP
C3
C3
NAD
NADH
ADP
ATP
ADP
ATP
NAD
NADH
ADP
ATP
ADP
ATP
pyruvate
+1 NADH
+2 ATP
pyruvate
+1 NADH
+2 ATP

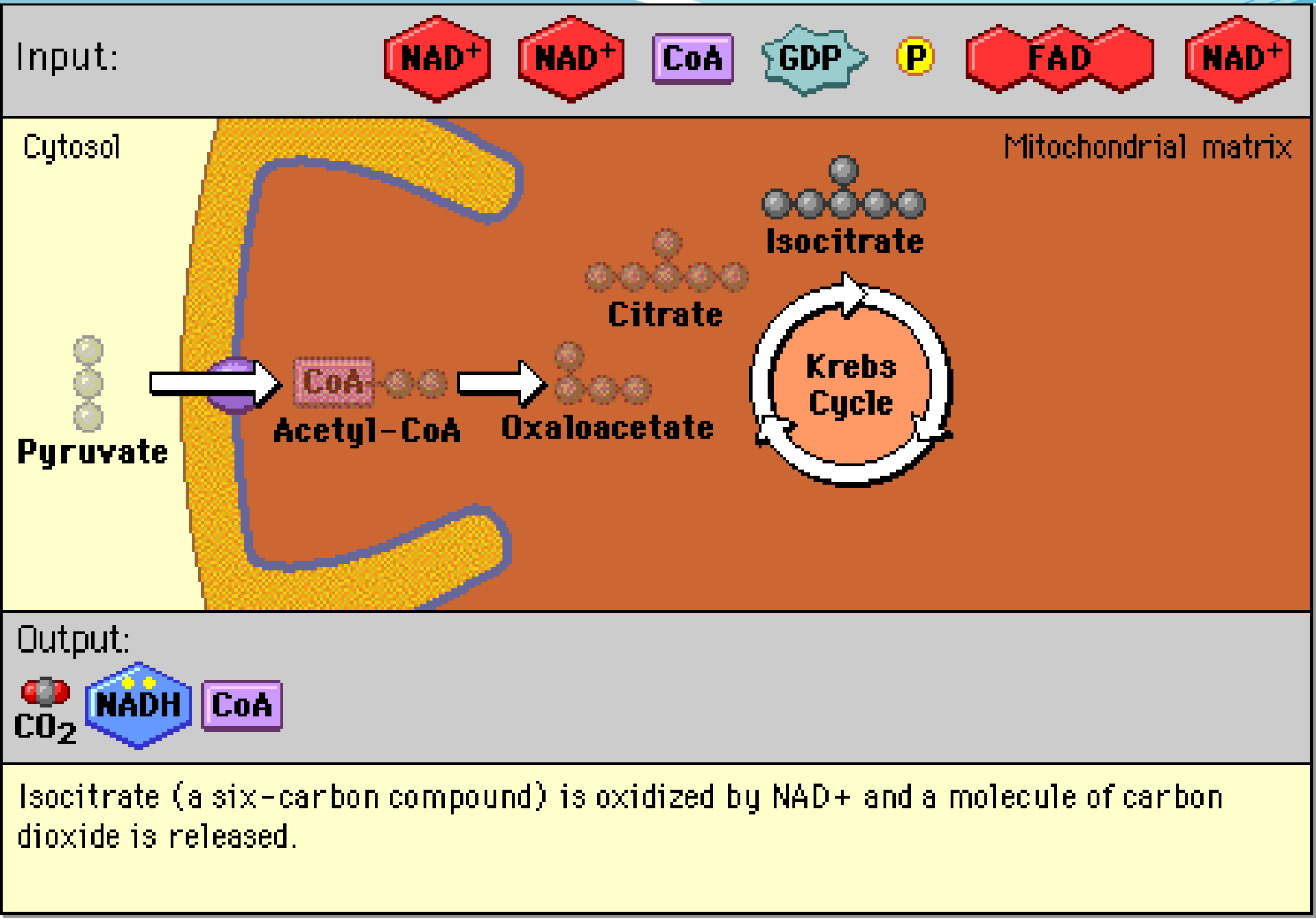

Input:
NAD+
CoA
NAD+
NAD+
CoA
GDP
P
FAD
NAD+
Cytosol
Mitochondrial matrix
Pyruvate
Oxaloacetate
Krebs Cycle
Output:

Input: NAD+ CoA NAD+ NAD+ CoA GDP P FAD NAD+

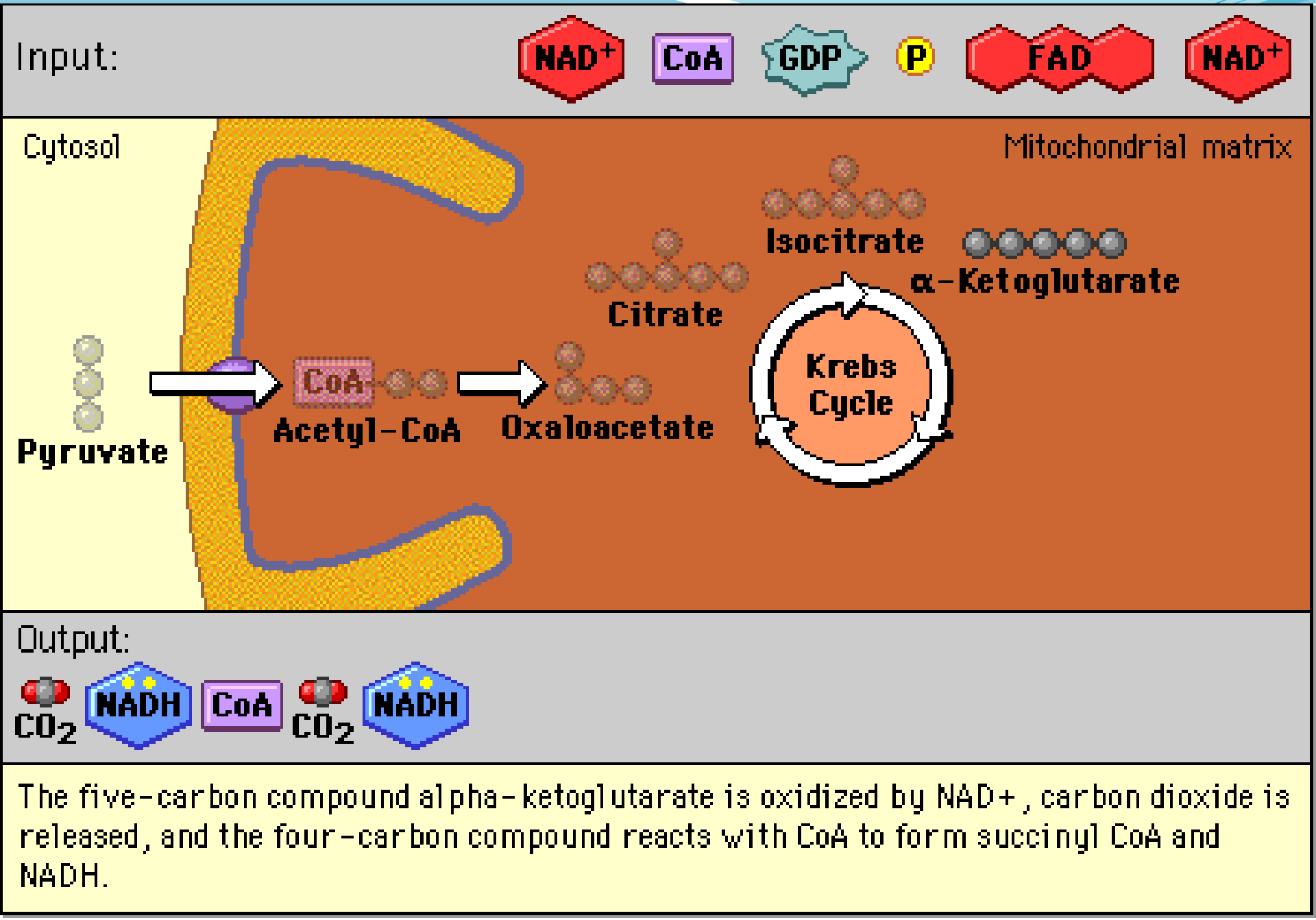


Output:

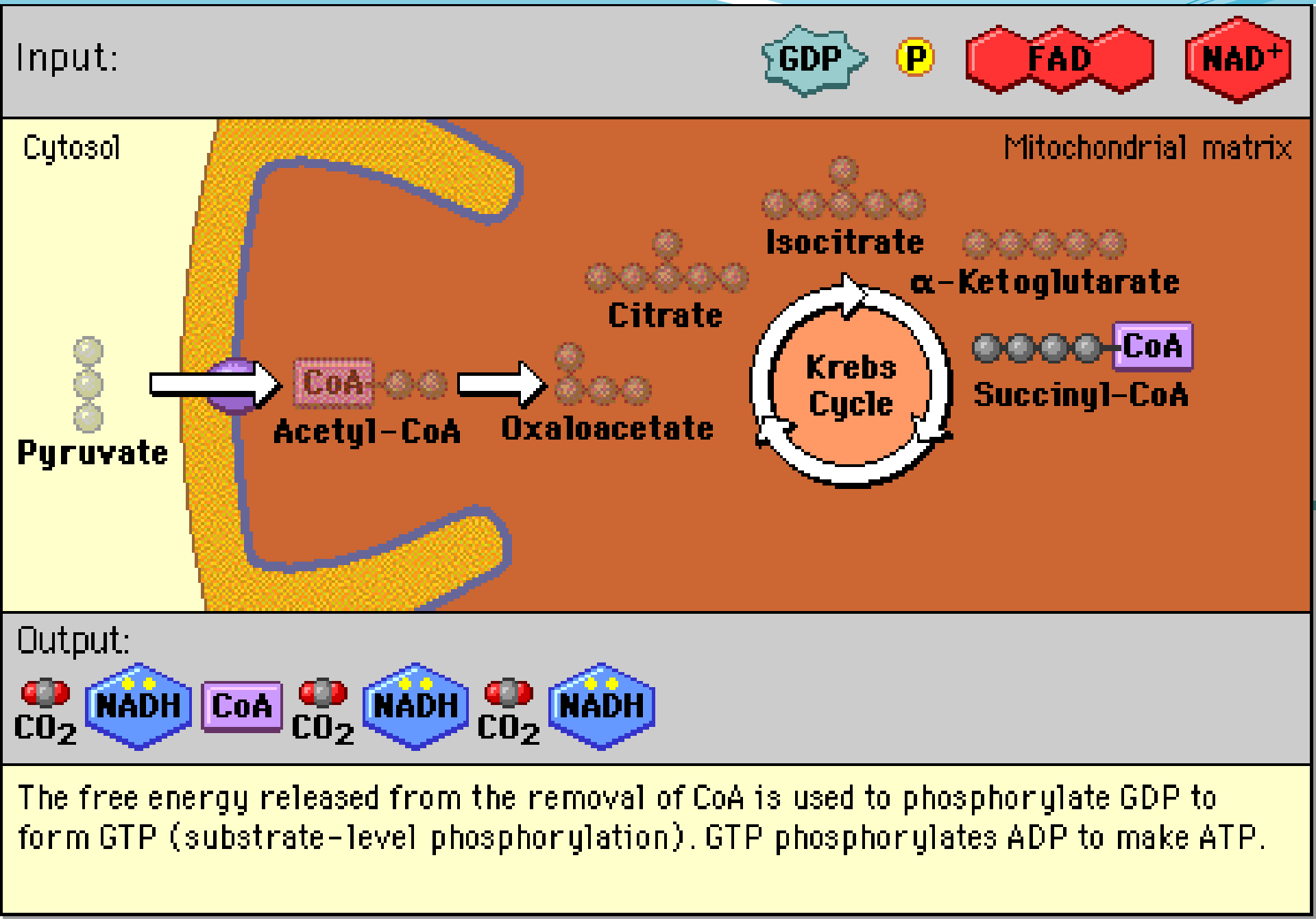
Pyruvate is oxidized to acetyl CoA (a two-carbon molecule) and carbon dioxide. NAD+ becomes reduced to NADH.



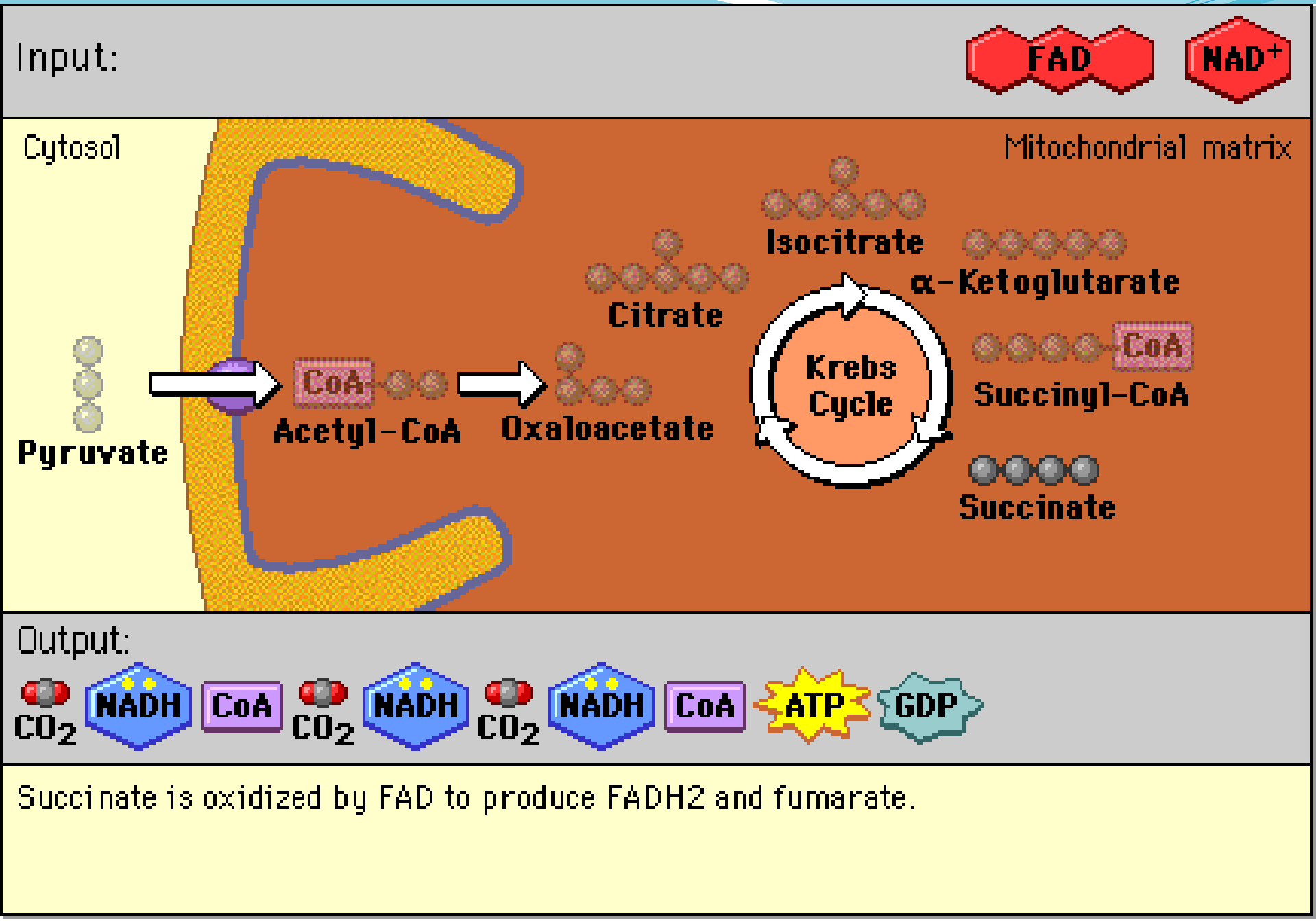
Isocitrate (a six-carbon compound) is oxidized by NAD+ and a molecule of carbon dioxide is released.



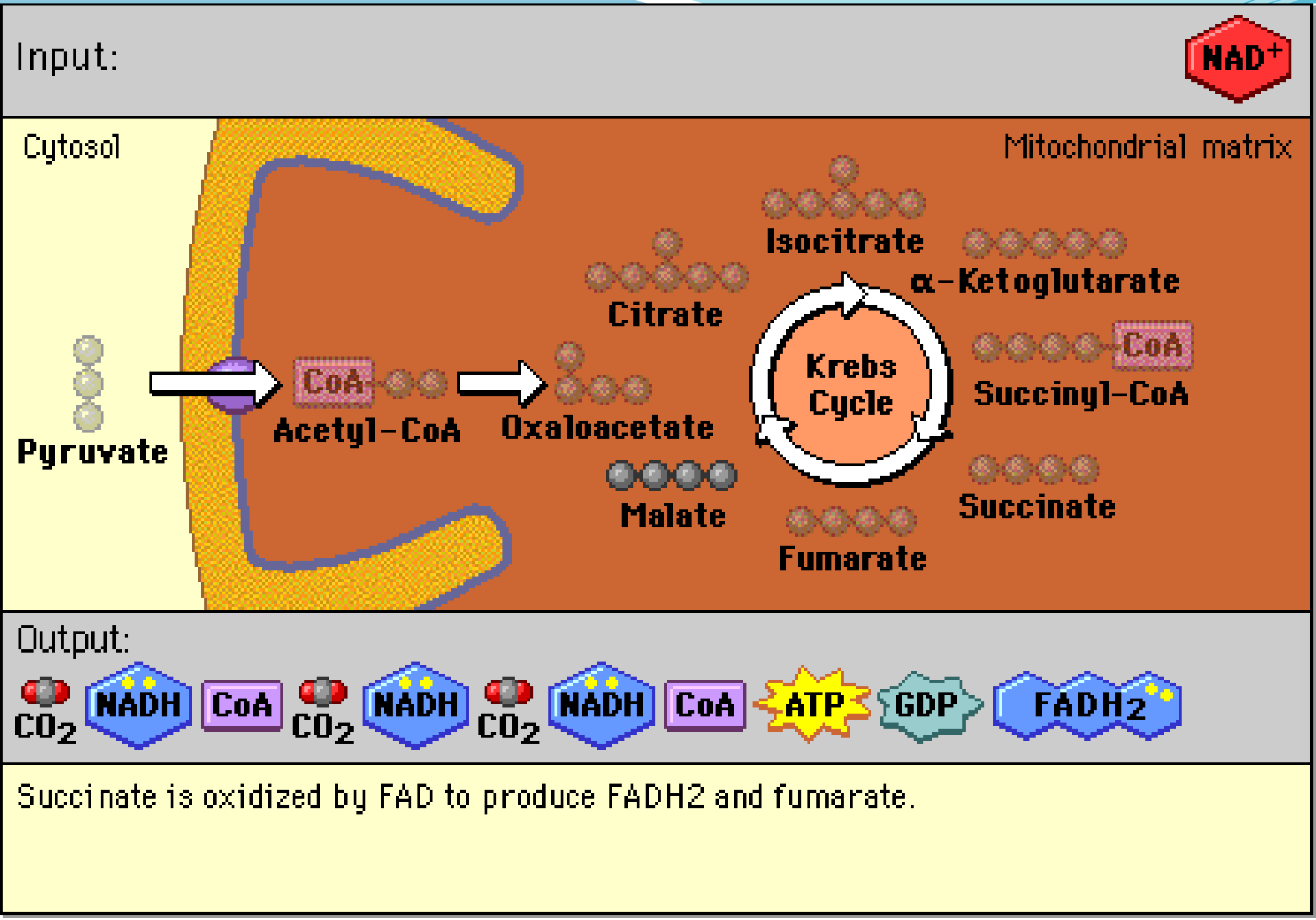
The five-carbon compound alpha-ketoglutarate is oxidized by NAD+, carbon dioxide is released, and the four-carbon compound reacts with CoA to form succinyl CoA and NADH.



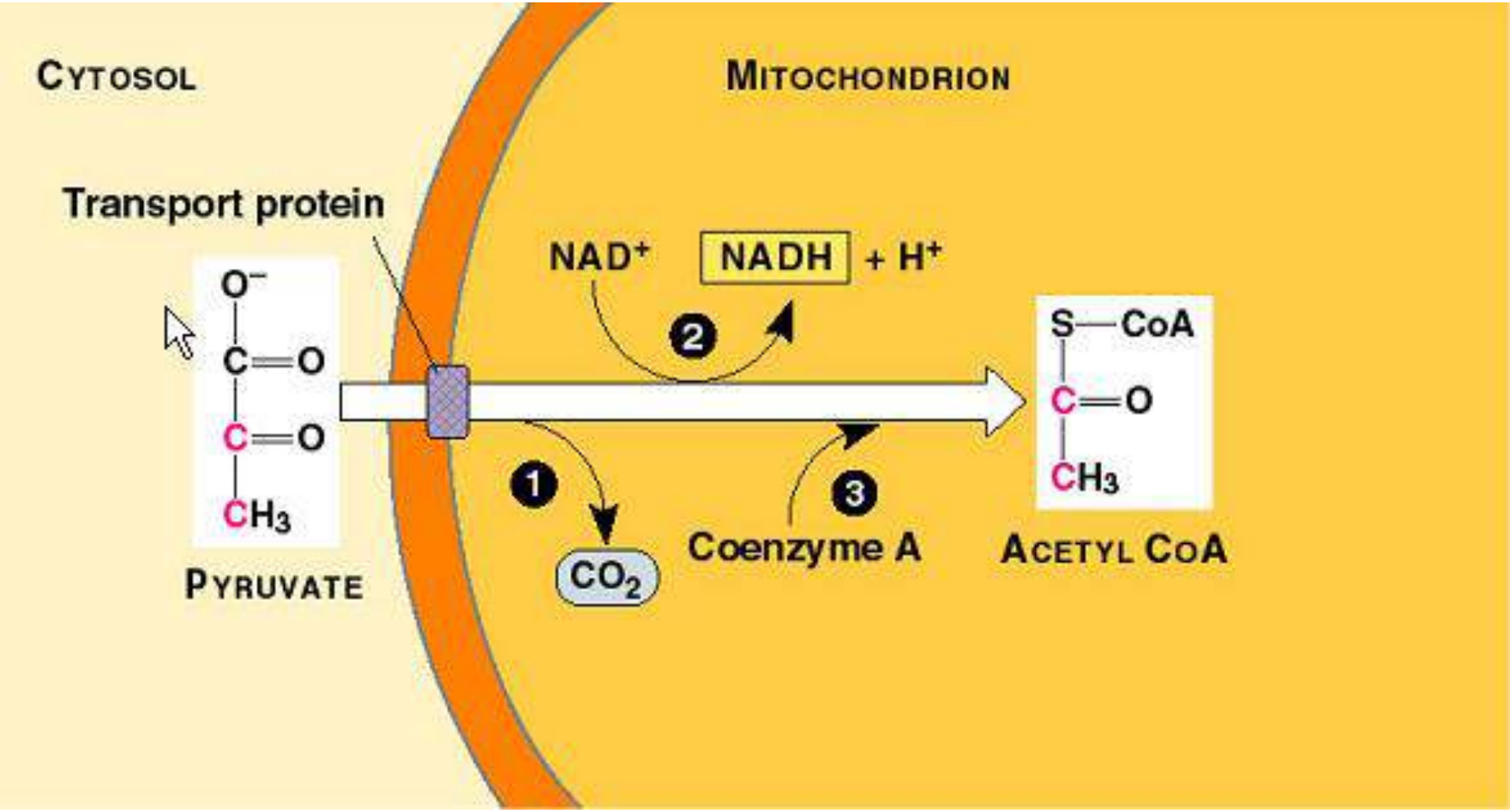
The free energy released from the removal of CoA is used to phosphorylate GDP to form GTP (substrate-level phosphorylation). GTP phosphorylates ADP to make ATP.

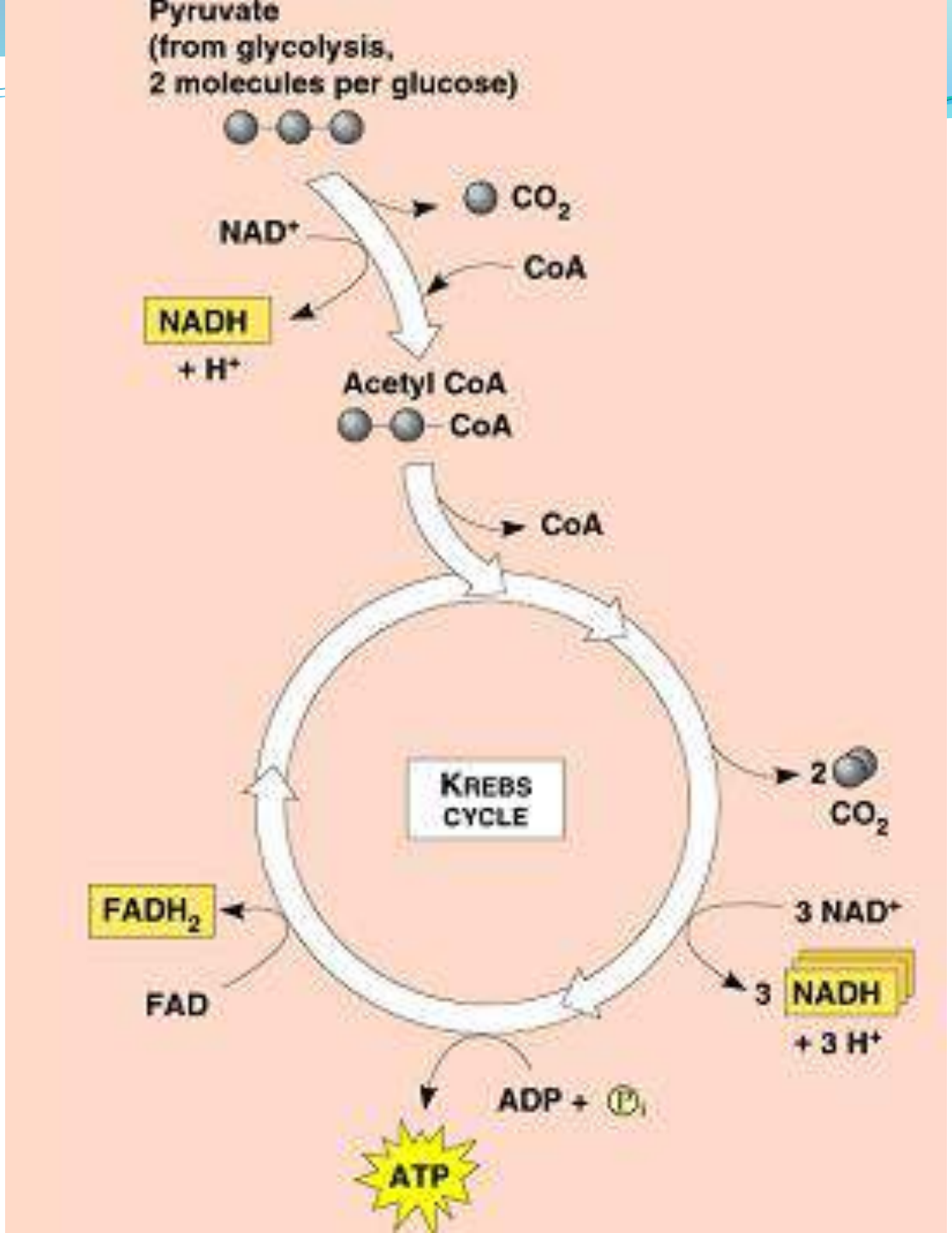


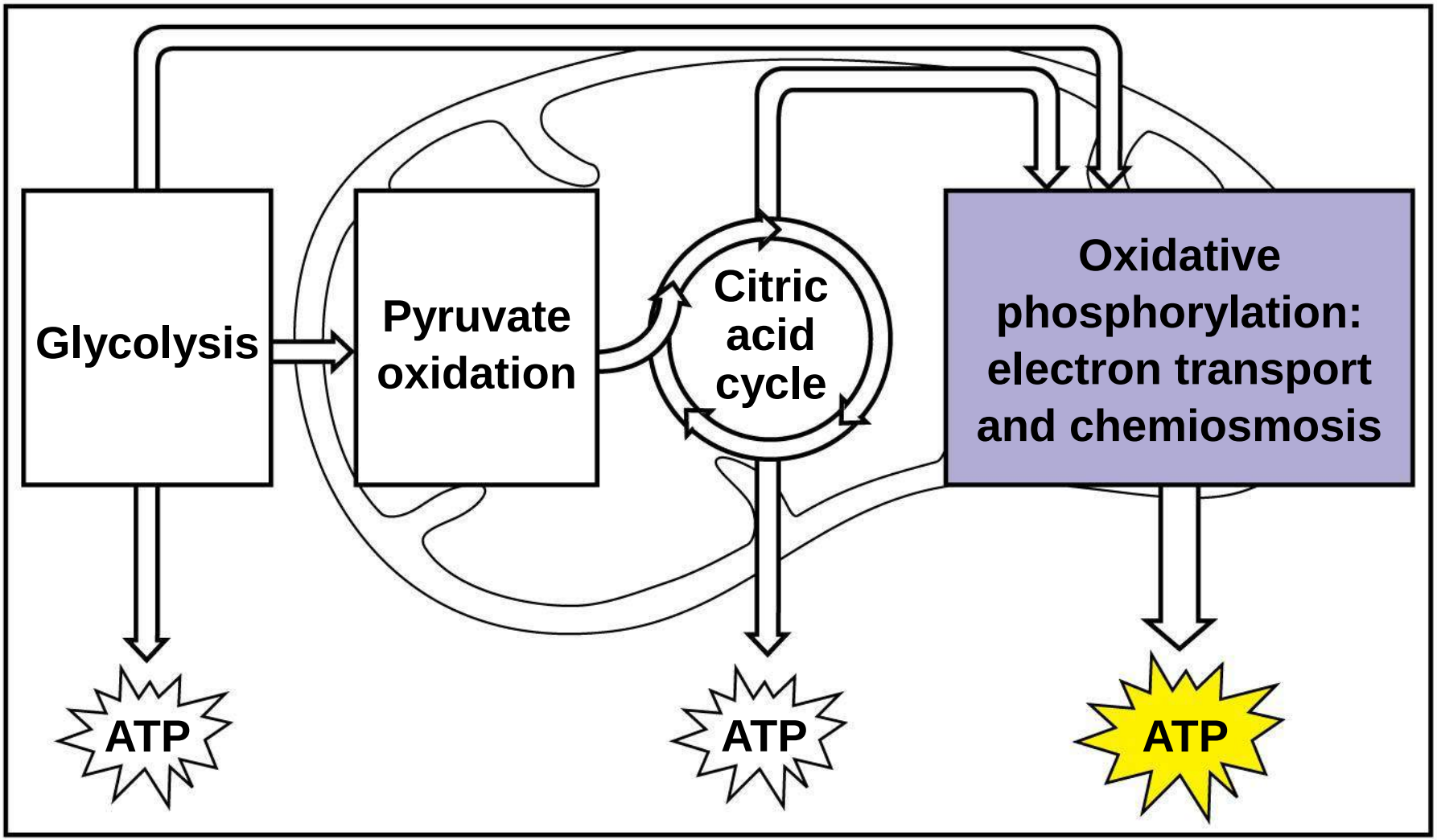
Succinate is oxidized by FAD to produce FADH2 and fumarate.

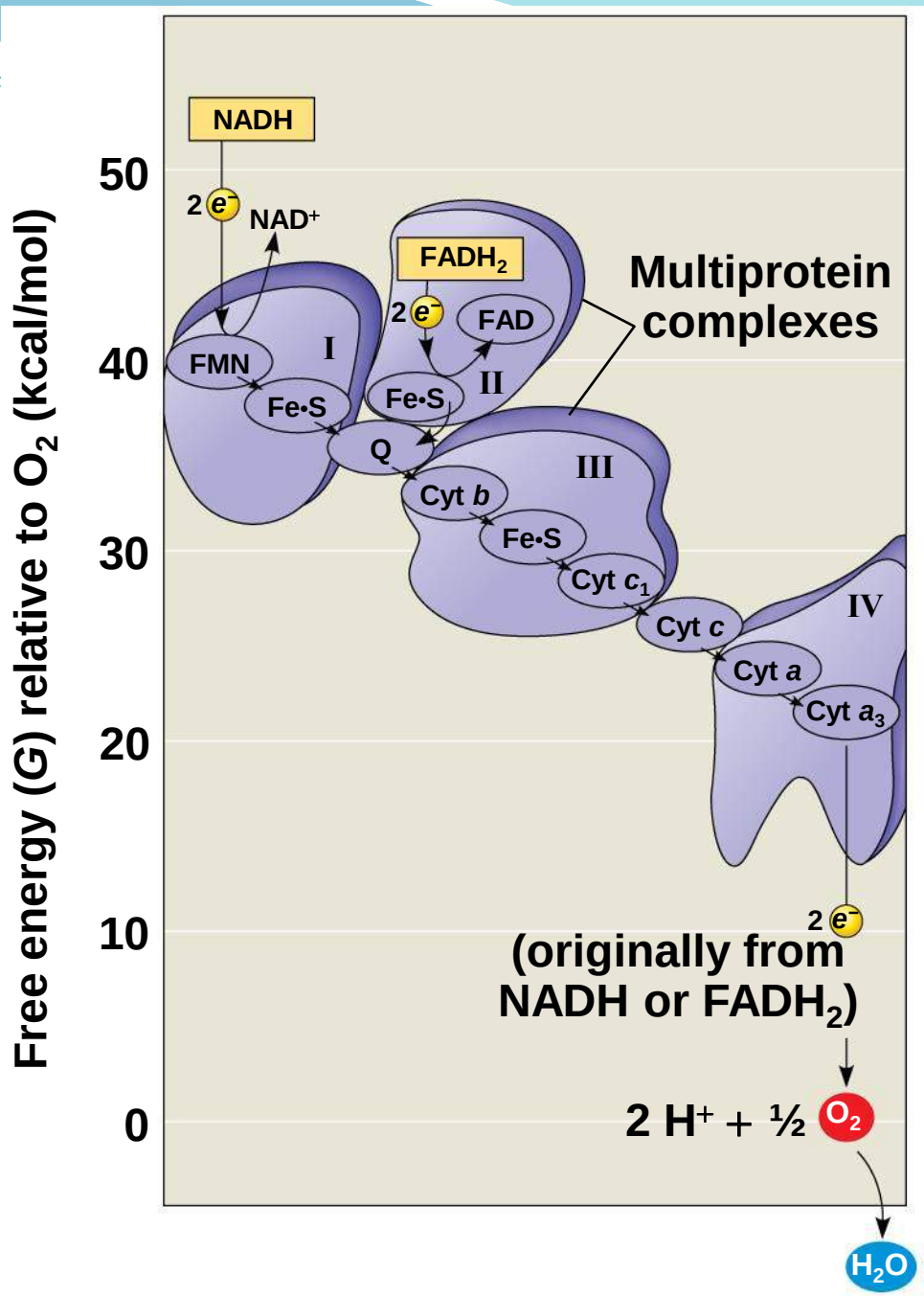


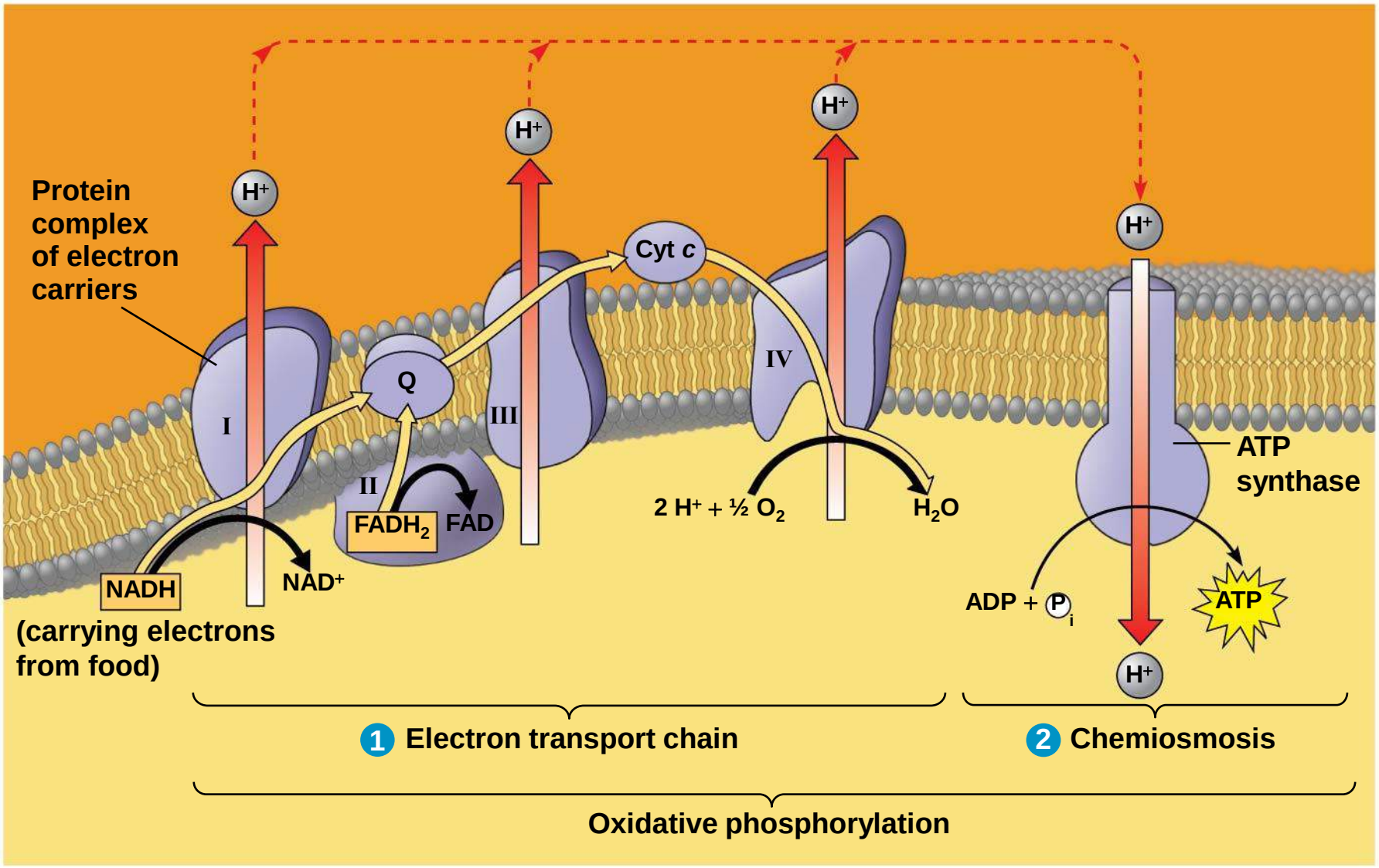
Succinate is oxidized by FAD to produce FADH2 and fumarate.

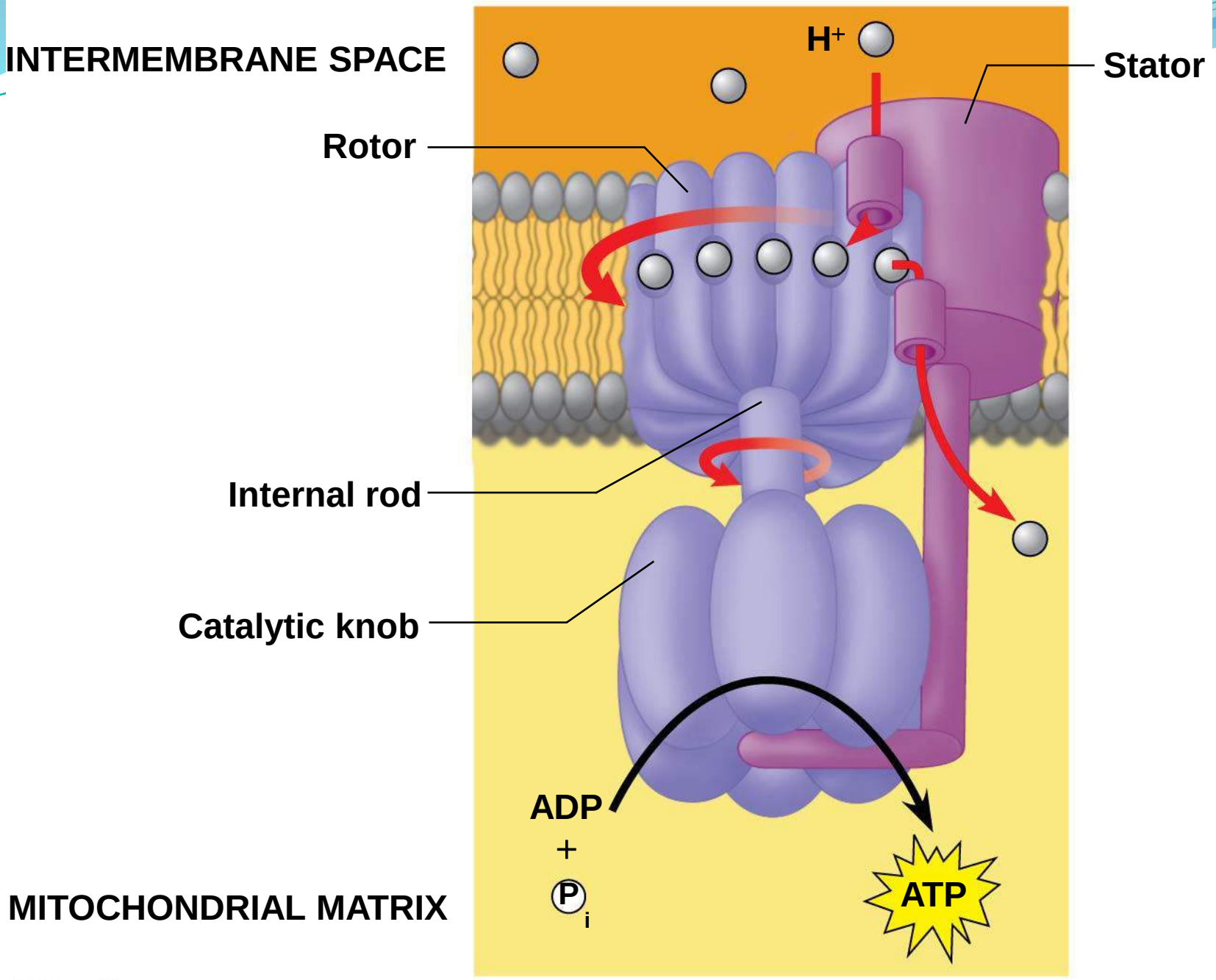

CYTOSOL
MITOCHONDRION
Transport protein
NAD+
NADH
+ H+
2
1
3
CO2
Coenzyme A
S—CoA
C=O
CH3
ACETYL COA
O−
C=O
C=O
CH3
PYRUVATE

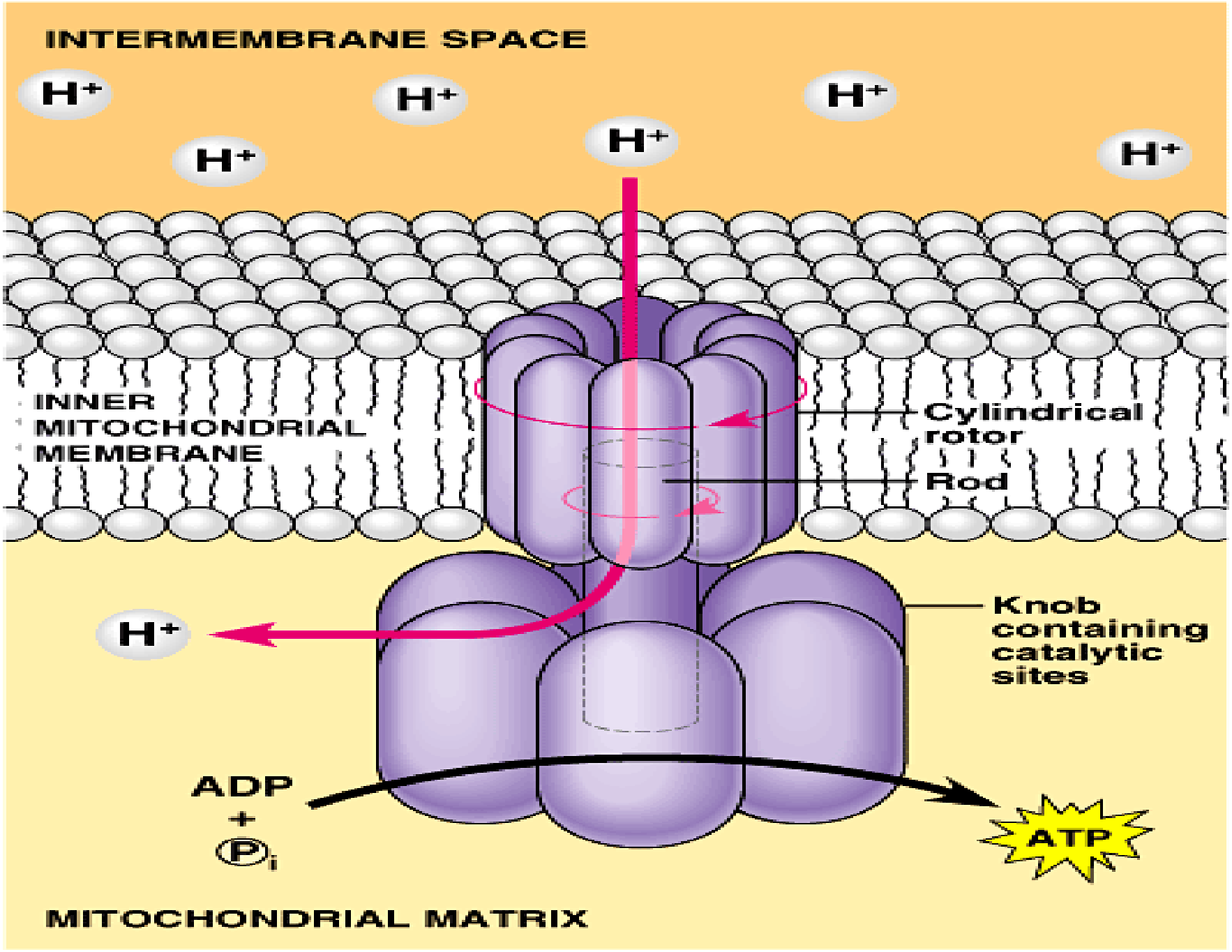

Pyruvate
(from glycolysis,
2 molecules per glucose)
CO2
NAD+
CoA
NADH
+ H+
Acetyl CoA
CoA
CoA
KREBS
CYCLE
2
CO2
FADH2
3 NAD+
FAD
3
NADH
+ 3 H+
ADP + P
ATP

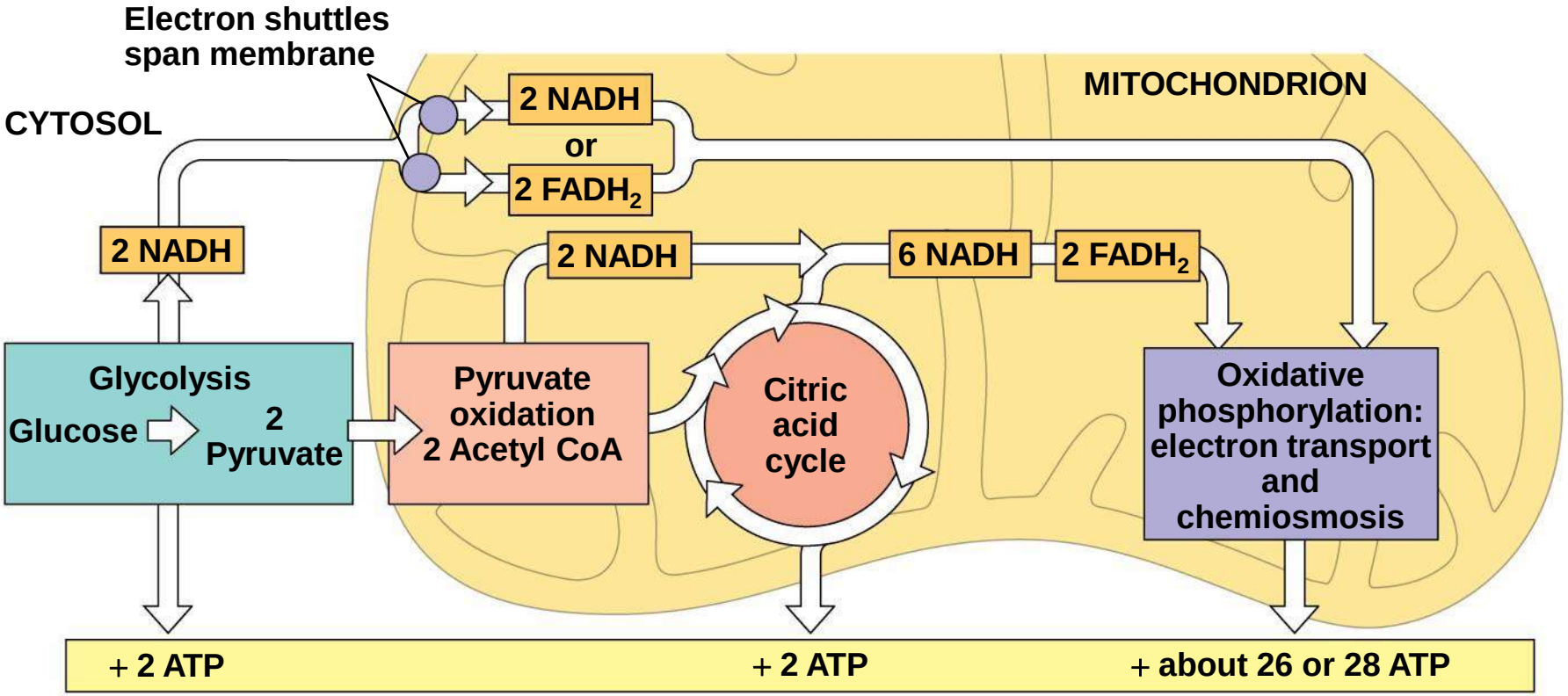

Glycolysis
Pyruvate oxidation
Citric acid cycle
Oxidative phosphorylation: electron transport and chemiosmosis
ATP
ATP
ATP


Free energy (G) relative to O2 (kcal/mol)
50
40
30
20
10
0
NADH
2 e⁻
NAD+
FADH2
2 e⁻
FAD
Multiprotein complexes
FMN
I
Fe•S
Fe•S
II
Q
III
Cyt b
Fe•S
Cyt c1
Cyt c
IV
Cyt a
Cyt a3
2 e⁻
(originally from NADH or FADH2)
2 H+ + ½ O2
H2O


Protein complex of electron carriers
H+
H+
H+
H+
Cyt c
I
II
III
IV
Q
FADH2
FAD
NADH
NAD+
(carrying electrons from food)
2 H+ + ½ O2
H2O
ATP synthase
ADP + Pi
ATP
H+
1 Electron transport chain
2 Chemiosmosis
Oxidative phosphorylation


INTERMEMBRANE SPACE
H+
Stator
Rotor
Internal rod
Catalytic knob
ADP
+
Pi
ATP
MITOCHONDRIAL MATRIX


INTERMEMBRANE SPACE
H+
H+
H+
H+
H+
H+
INNER MITOCHONDRIAL MEMBRANE
Cylindrical rotor
Rod
H+
Knob containing catalytic sites
ADP + Pi
ATP
MITOCHONDRIAL MATRIX



Maximum per glucose: About 30 or 32 ATP

Brown Fat in hibernating animals

Contain uncoupling protein that is a channel protein that allows diffusion of H+ NOT through ATP synthase

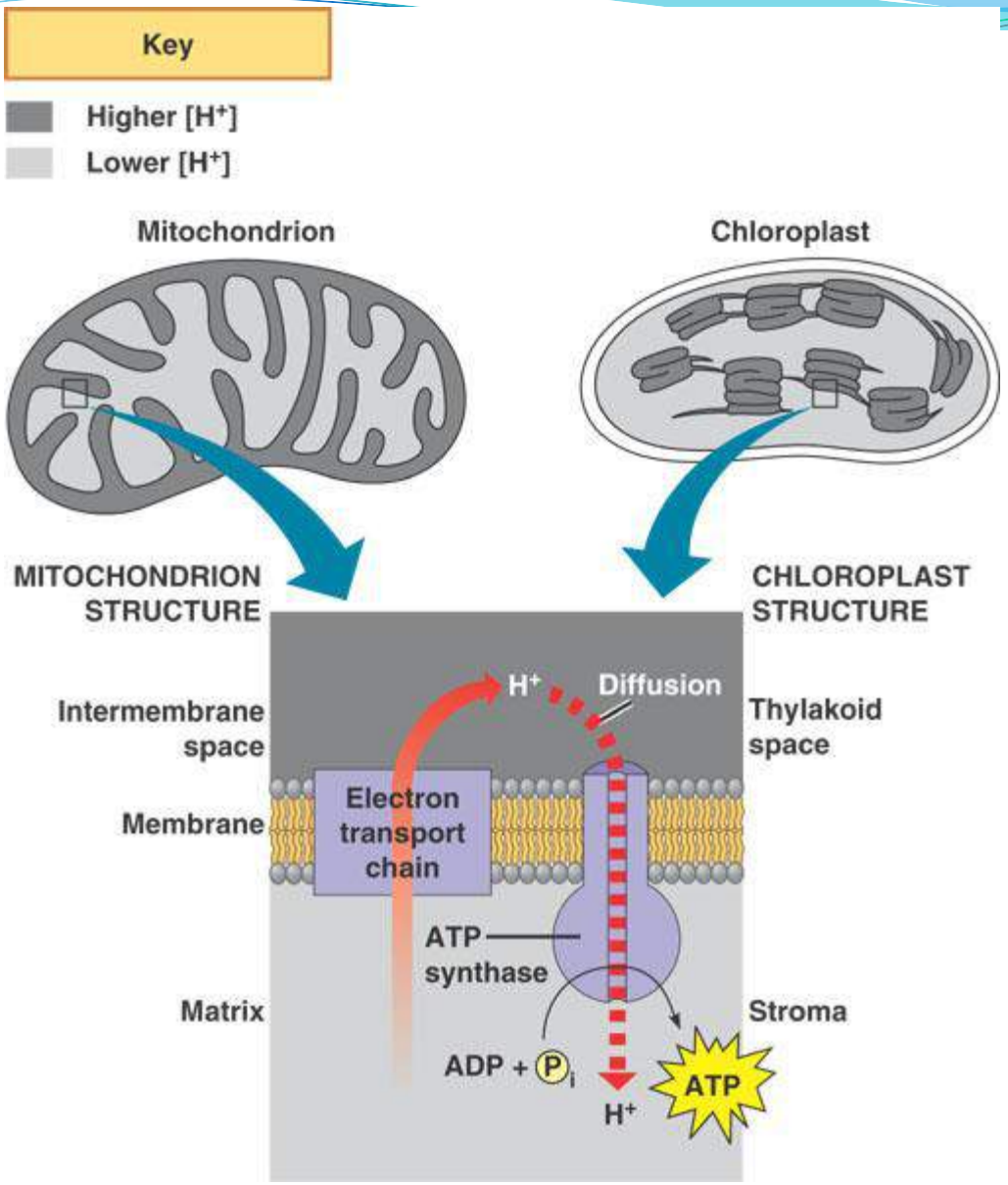
Comparison of chemiosmosis in chloroplasts and mitochondria

SIMILARITIES

An ETC in a membrane transports protons across a membrane

ATP synthase in membrane couples diffusion of protons with phosphorylation of ADP

ATP synthase and electron carriers (cytochromes) are very similar in both


Key
Higher [H+]
Lower [H+]
Mitochondrion
Chloroplast
MITOCHONDRION STRUCTURE
CHLOROPLAST STRUCTURE
Intermembrane space
Thylakoid space
H+
Diffusion
Membrane
Electron transport chain
ATP synthase
Matrix
Stroma
ADP + Pi
ATP
H+

DIFFERENCES

ETC

-mito transfer chemical E from food to ATP

-electrons are extracted from oxidation of food molecules

-chloroplasts transform light E into chemical E

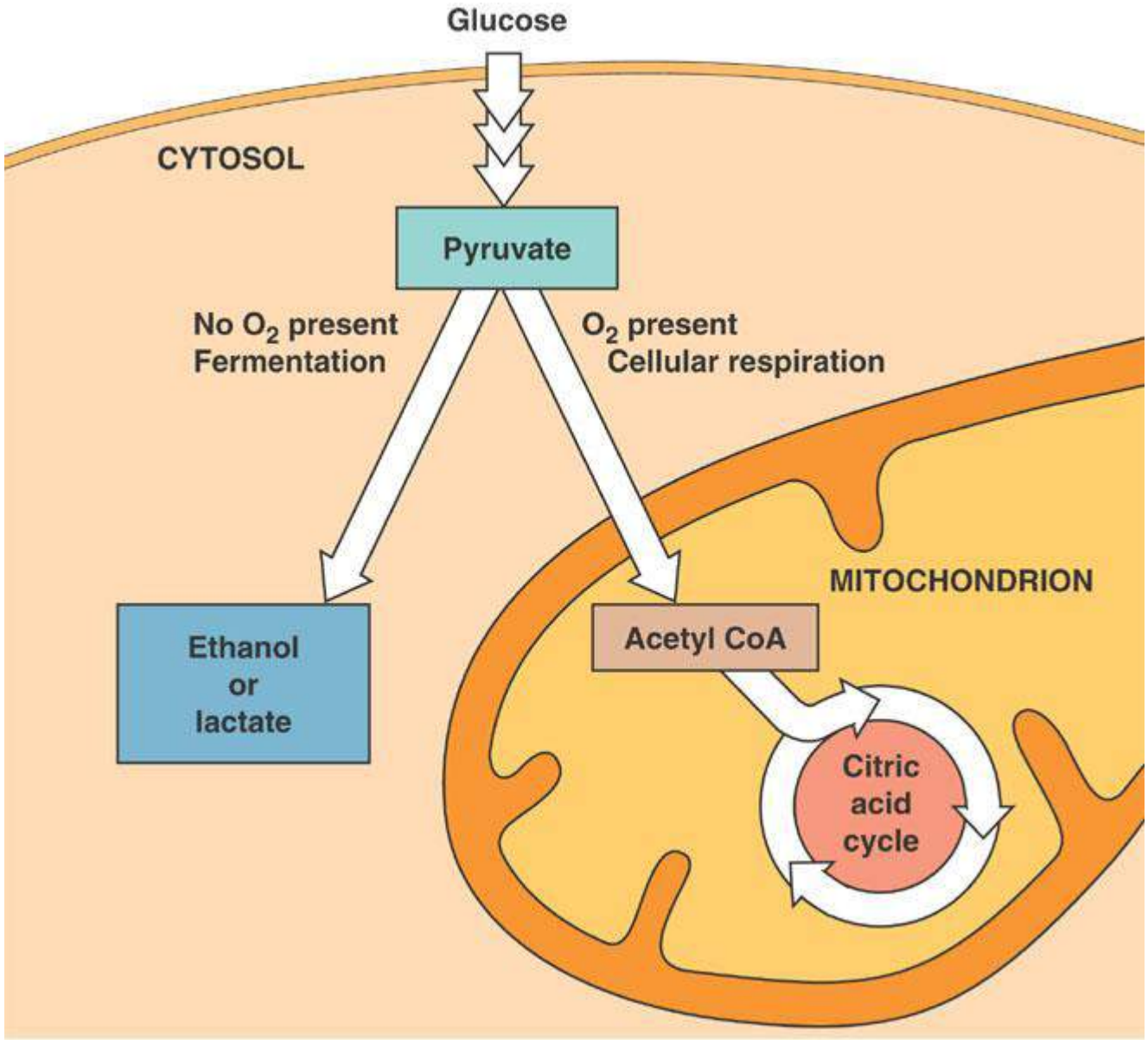
-uses light E to drive electrons to top of transport chain

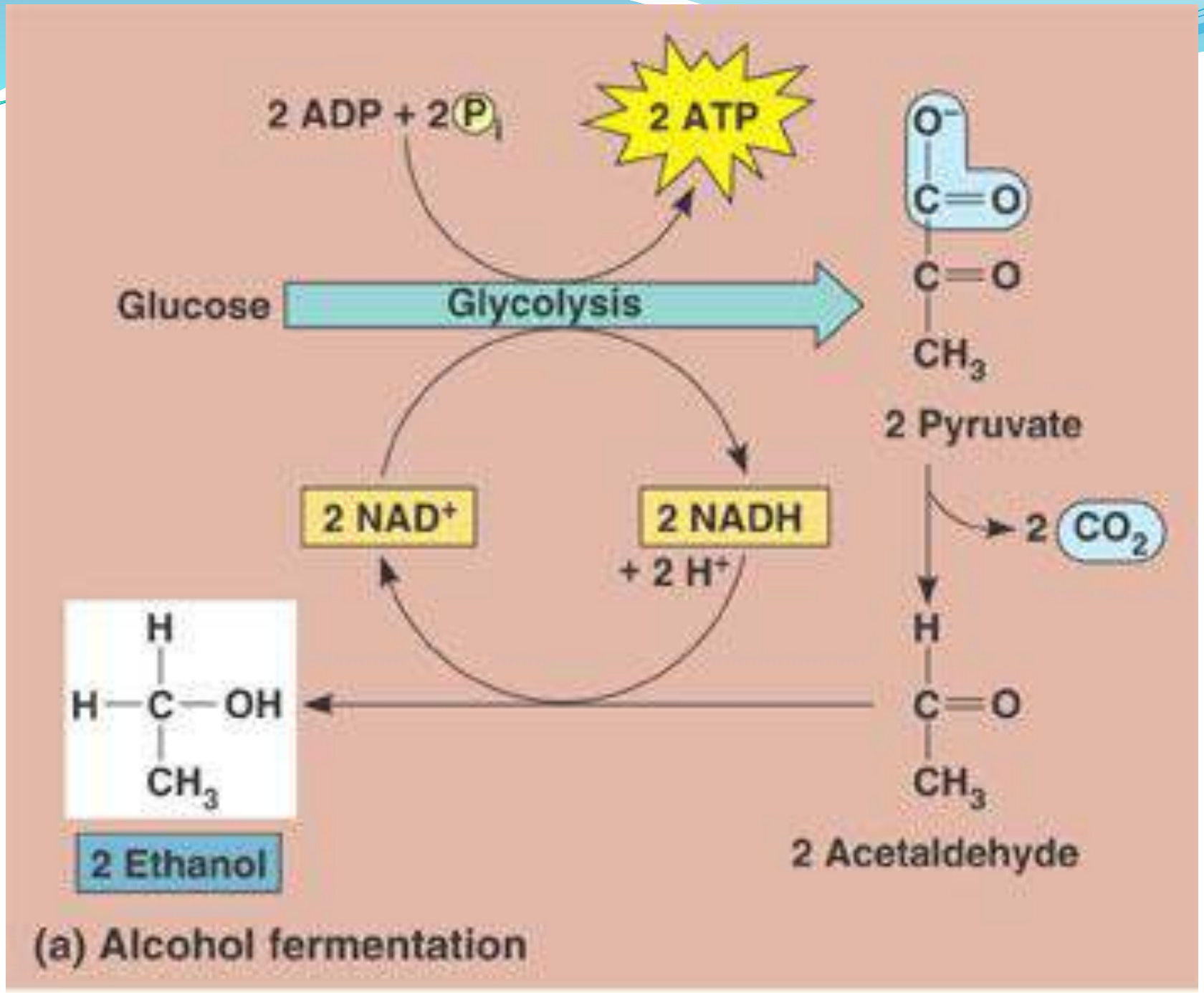
SPACIAL ORGANIZATION

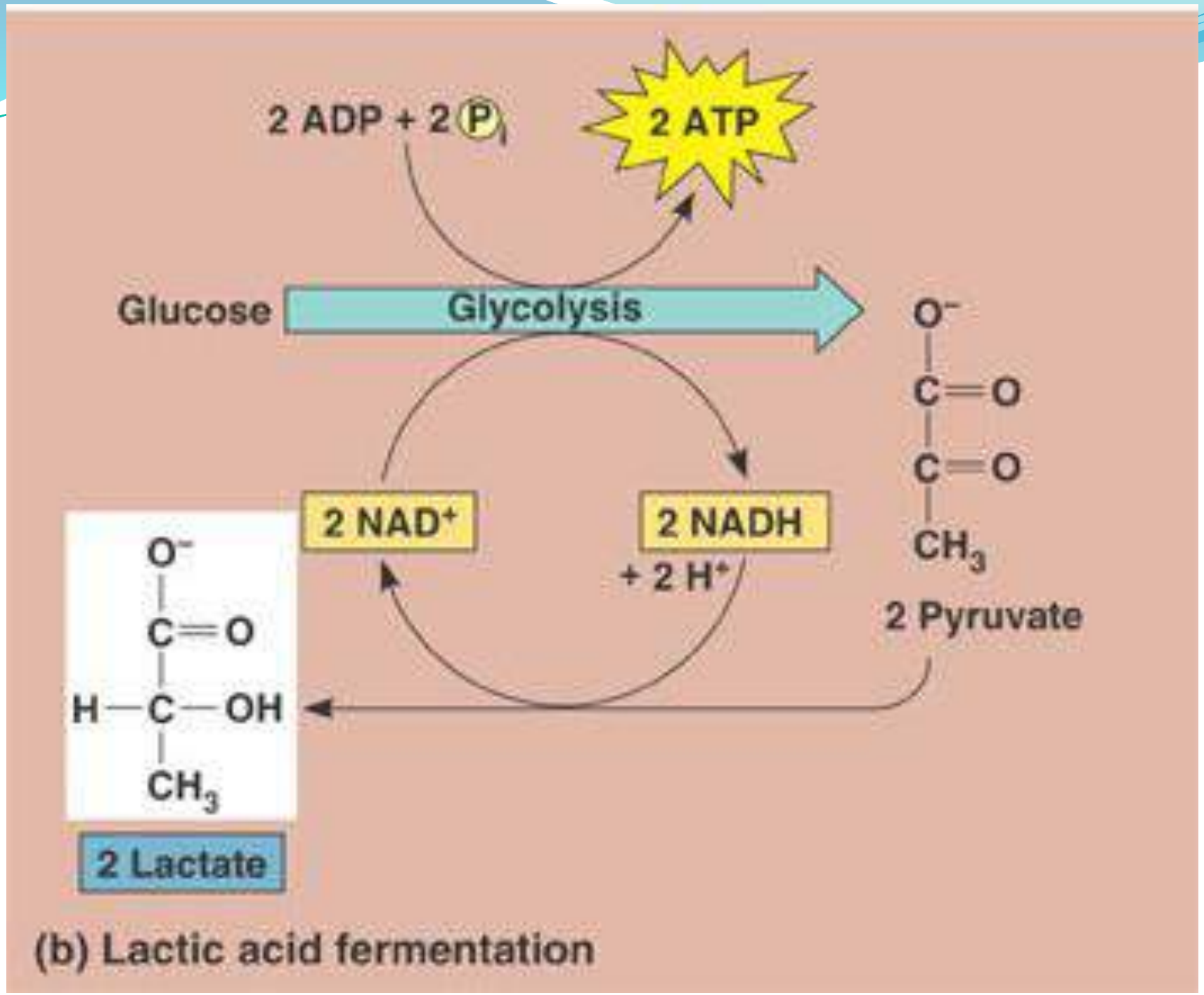
-mito pump protons from matrix out to the intermembrane space (which is a reservoir for protons)

-chloro. Thylakoid membrane pumps protons from stroma into thylakoid compartment (serve as a proton reservoir)

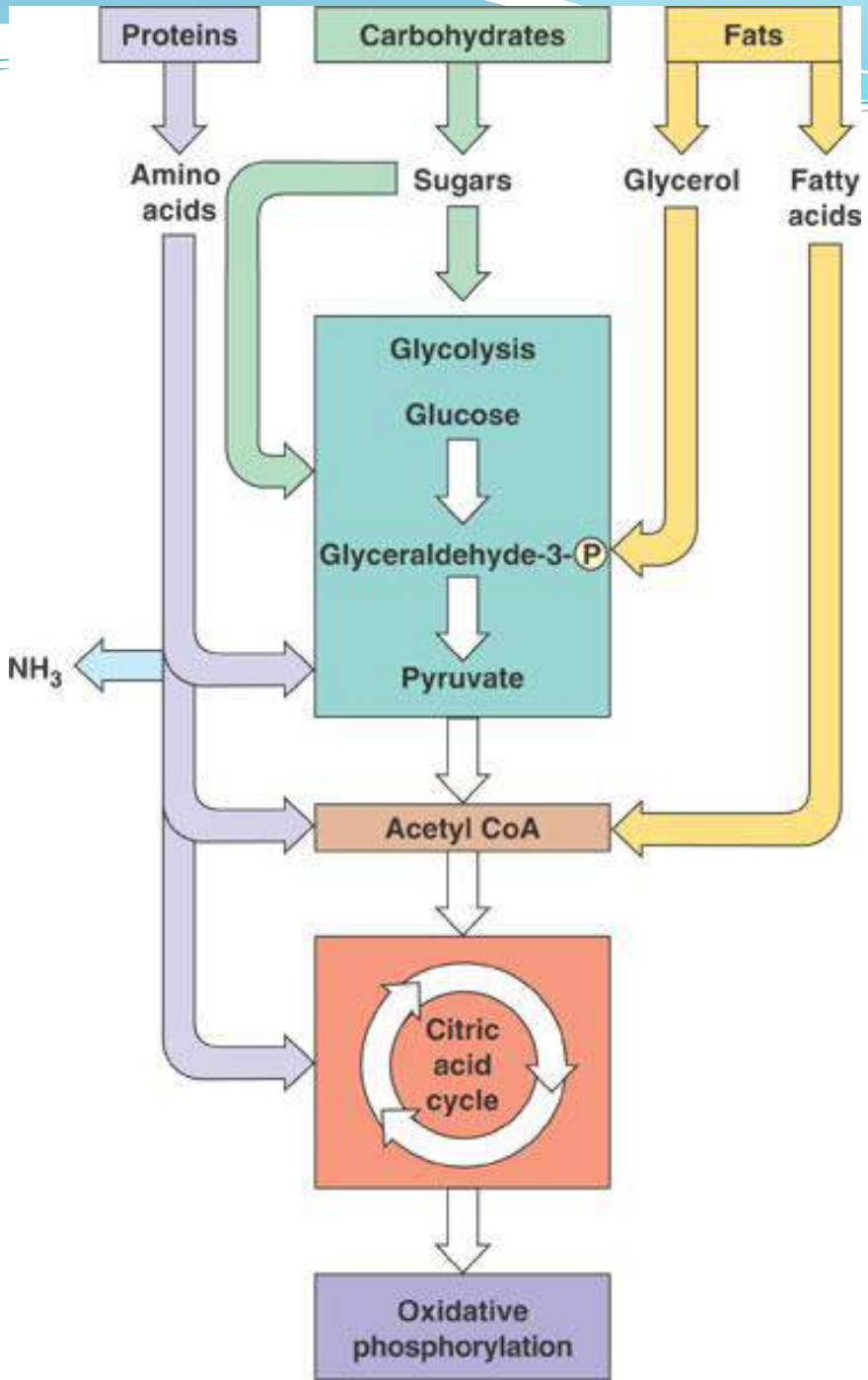
Fermentation




2 ADP + 2 P_i
2 ATP
Glucose
Glycolysis
2 Pyruvate
2 CO_2
2 NAD^+
2 NADH
+ 2 H^+
2 Ethanol
2 Acetaldehyde
(a) Alcohol fermentation



(b) Lactic acid fermentation


Proteins
Carbohydrates
Fats
Amino acids
Sugars
Glycerol
Fatty acids
Glycolysis
Glucose
Glyceraldehyde-3-P
Pyruvate
NH3
Acetyl CoA
Citric acid cycle
Oxidative phosphorylation

References

- Biochemistry by J.M Berg, J.L. Tymo Czko & Lubert Stryer(2011)
- Biochemistry by Voet & Voet (2016)
- Principles of Biochemistry by A.L. Lehninger , D.L. Nelson & M.M. Cox (2016)
- Basic Medical Biochemistry; A Clinical approach by Alisa Peet & Michael Lieberman (2017)
- Harper's Illustrated Biochemistry by V.W. Rodwell, D.A. Bender (2018)