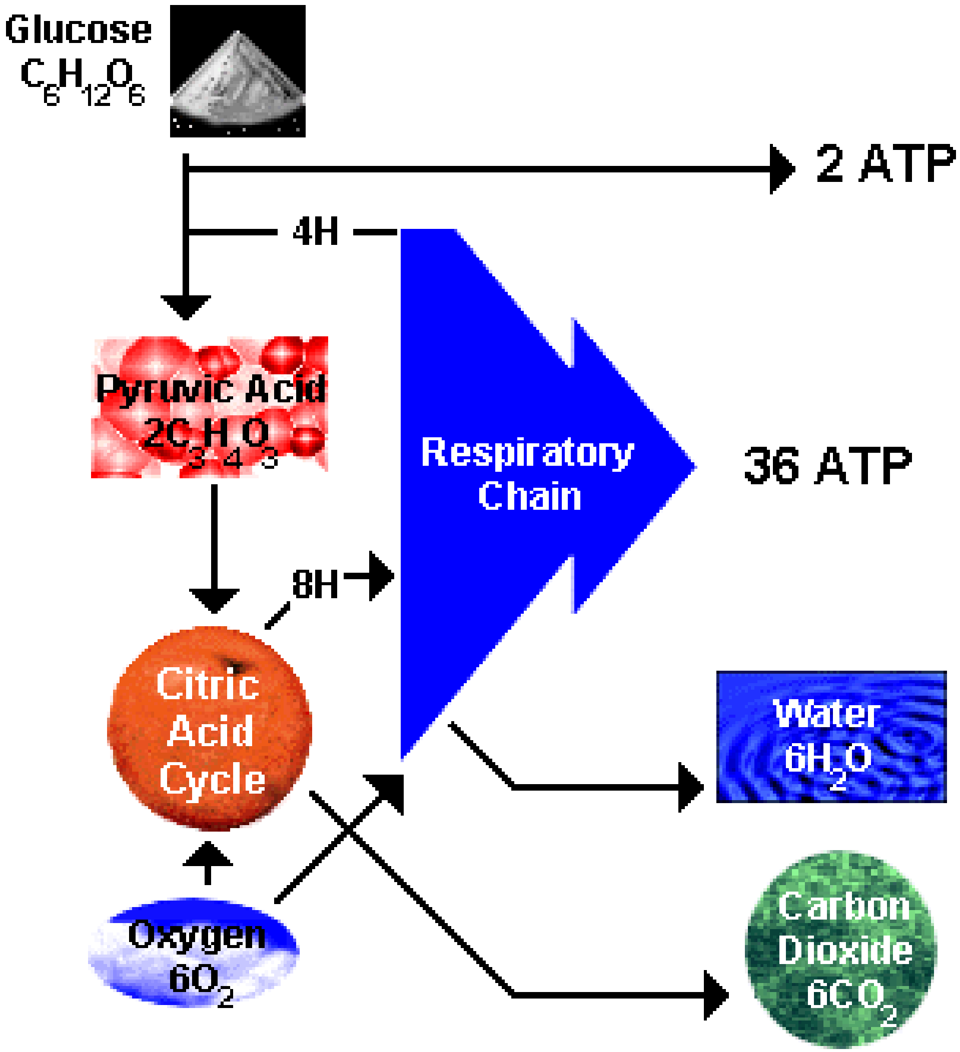
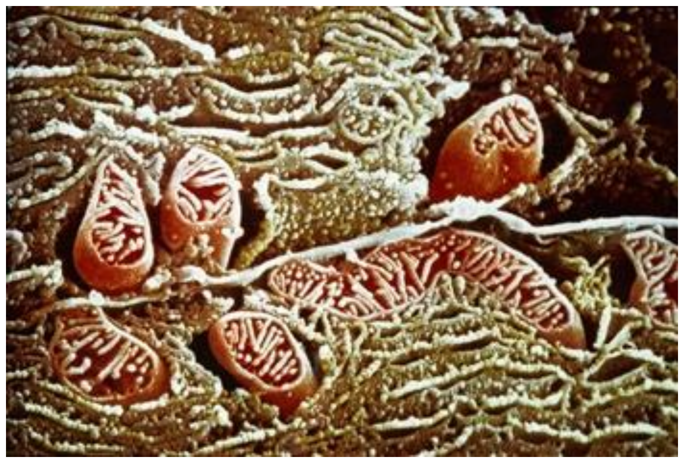


NOTES: Chapter 9 (Part 2): Glycolysis & Krebs Cycle (9.2 & 9.3)

● CELLULAR RESPIRATION:

reactions in living cells in which sugars are broken down and energy is released

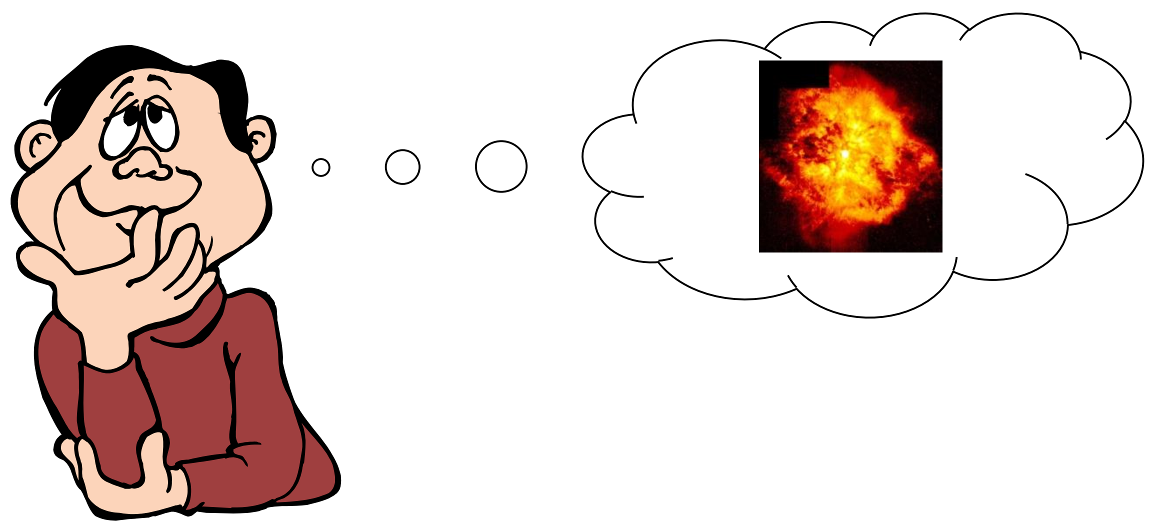


Mitochondria in a Liver Cell!!

Glucose + oxygen ➔ carbon dioxide + water + ENERGY

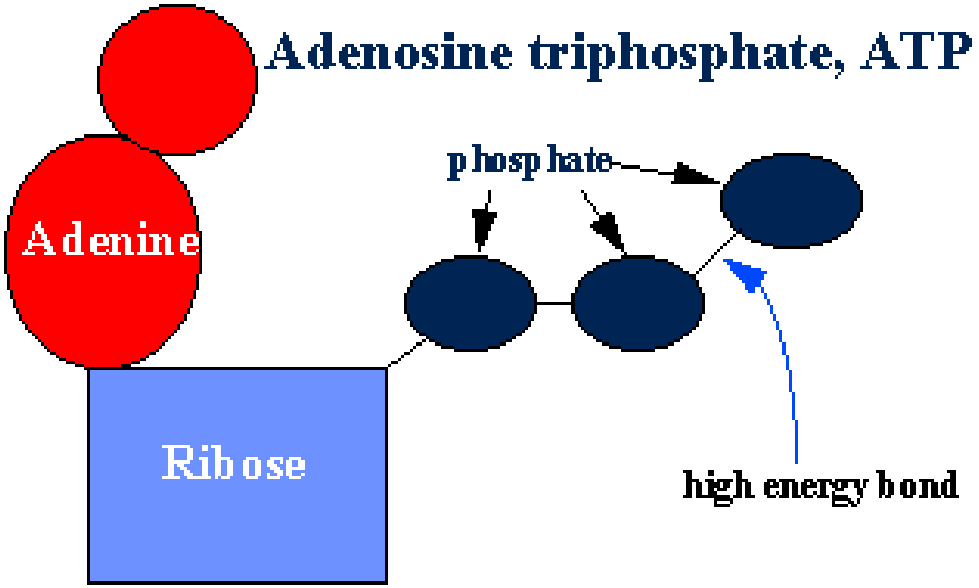
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + \text{energy}$$

- Food (glucose), like fuel, is “burned” by our cells for energy; however if it is burned all at once, too much energy is released.

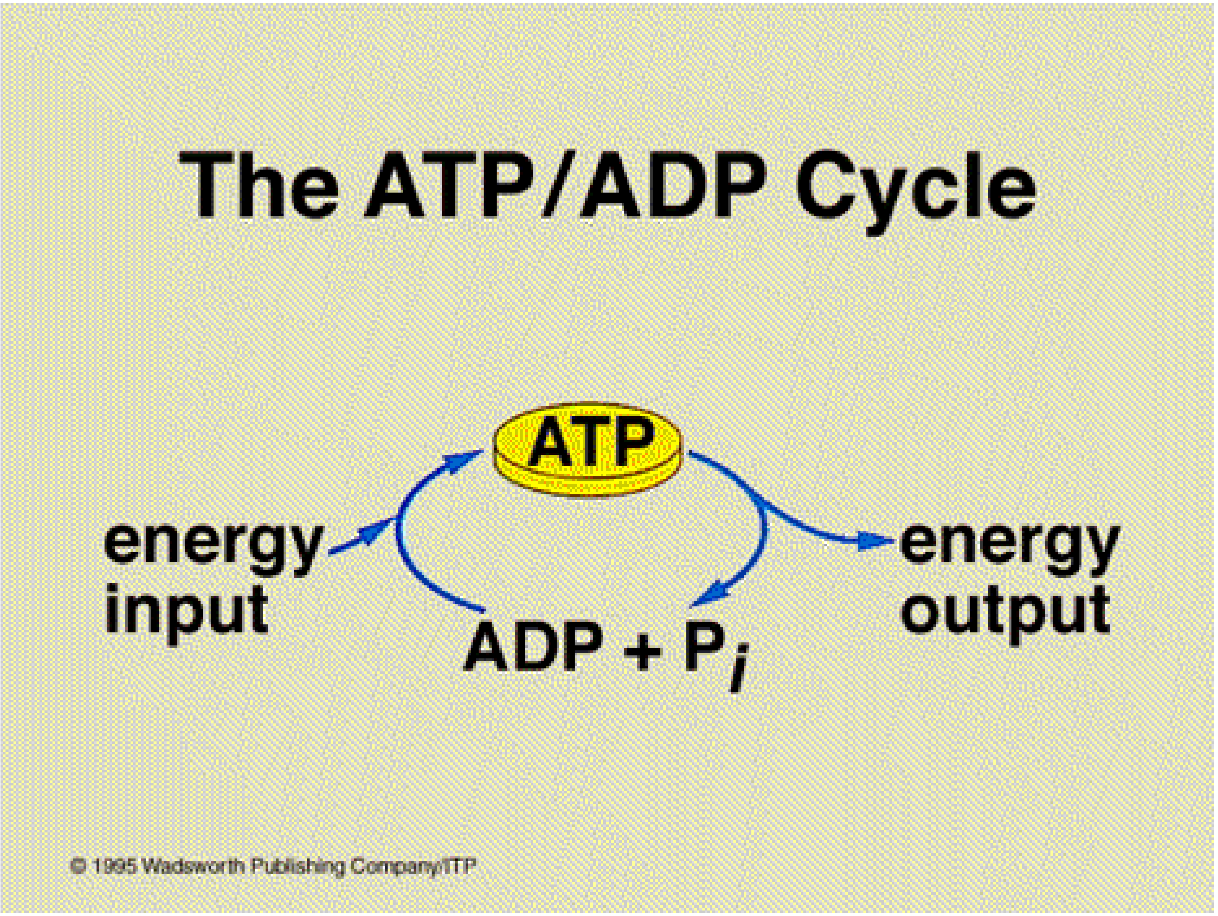


- So, the reaction is broken down into many small steps controlled by **ENZYMES**

- the energy is transferred to the bonds of **ATP** which stores and releases the energy in usable amounts (packets) to be used by the cell



Recall: the ATP cycle



-**Glucose** = "large denomination" ($100)

-**ATP** = "small change" ($1)

*For each molecule of glucose, the cell can make approximately **36-38 ATP**.

Steps of Cellular Respiration:

Phase of Resp.	Occurs where?	Starts with?	Ends with?	# of ATP made
Glycoly-sis	cyto-plasm	1 glucose	2 pyruvate; NADH	**2**
Krebs cycle (Citric Acid Cyc)				
E.T.C. (Resp Chain) & oxidative phosphor				

Steps of Cellular Respiration:

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Krebs cycle (Citric Acid Cyc)	inner matrix of mito-chondria	2 pyruvate	4 CO_2, NADH, $FADH_2$	**2**
E.T.C. (Resp Chain) & oxidative phosphor				

Steps of Cellular Respiration:

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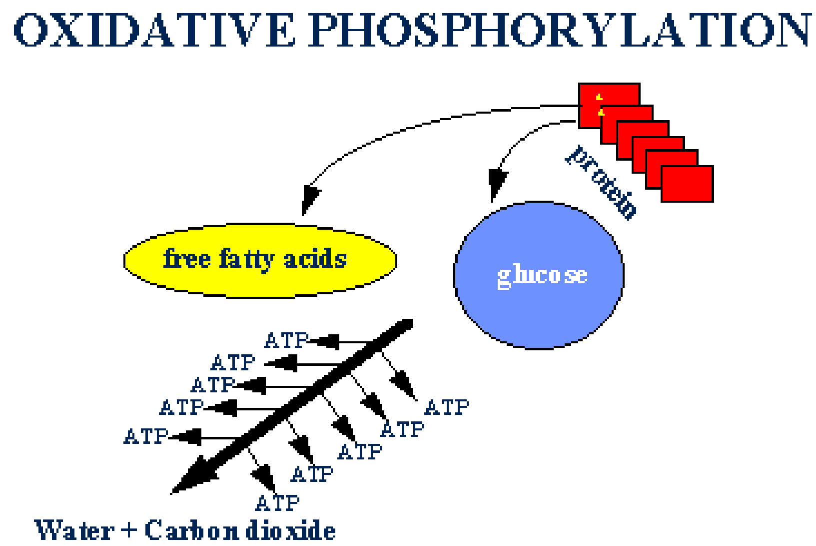
Krebs cycle (Citric Acid Cyc)	inner matrix of mito-chondria	2 pyruvate	4 CO_2, NADH, $FADH_2$	**2**
E.T.C. (Resp Chain) & oxidative phosphor	**cristae** (inner memb. of mito.)	NADH, $FADH_2$, O_2	H_2O, ATP	**32-34** (approx.)

2 Modes of ATP Synthesis

1) **oxidative phosphorylation**:

● mode of ATP synthesis powered by **redox reactions** which transfer electrons from **FOOD ➔ OXYGEN**

(occurs at the electron transport chain, or e.t.c.)



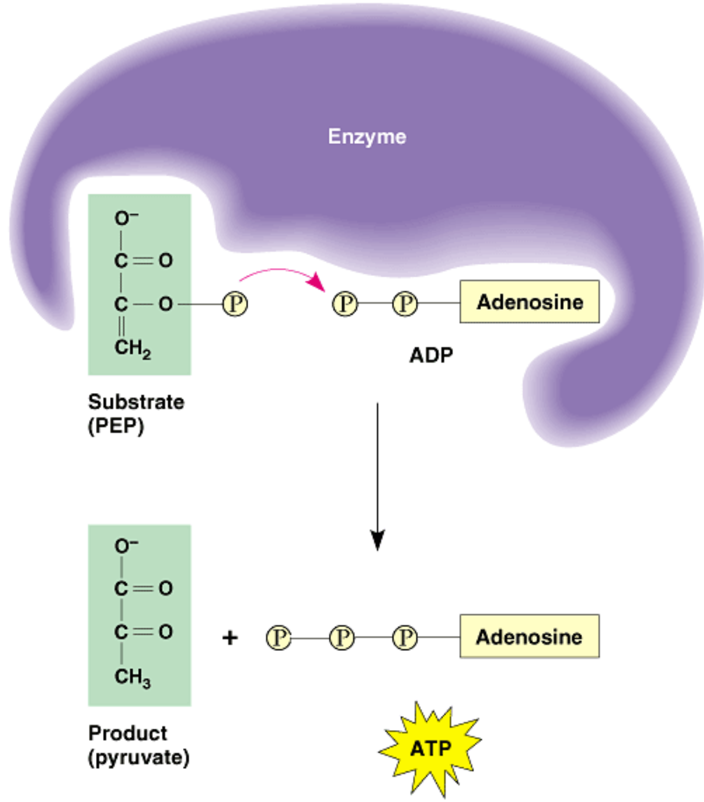
2) Substrate-level phosphorylation:

- involves the enzyme-catalyzed transfer of inorganic phosphate from a molecule to ADP to form ATP.
- mode of ATP

synthesis occurring in:

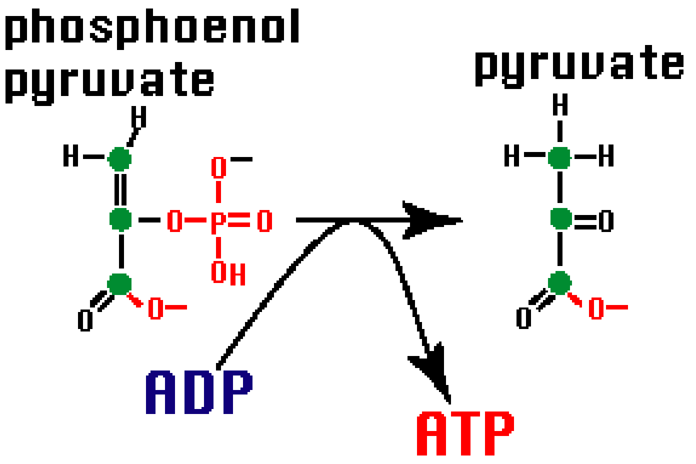
-**glycolysis (2 ATP)**

-**Krebs cycle (2 ATP)**



<u>GLYCOLYSIS</u>:

= "**<u>splitting of sugar</u>**"



<u>Summary of Glycolysis:</u>

1 Glucose ➔ **<u>2 pyruvate</u>**

2 ADP + 2 P_i ➔ **<u>2 ATP</u>**

(via substrate-level phosphorylation!)

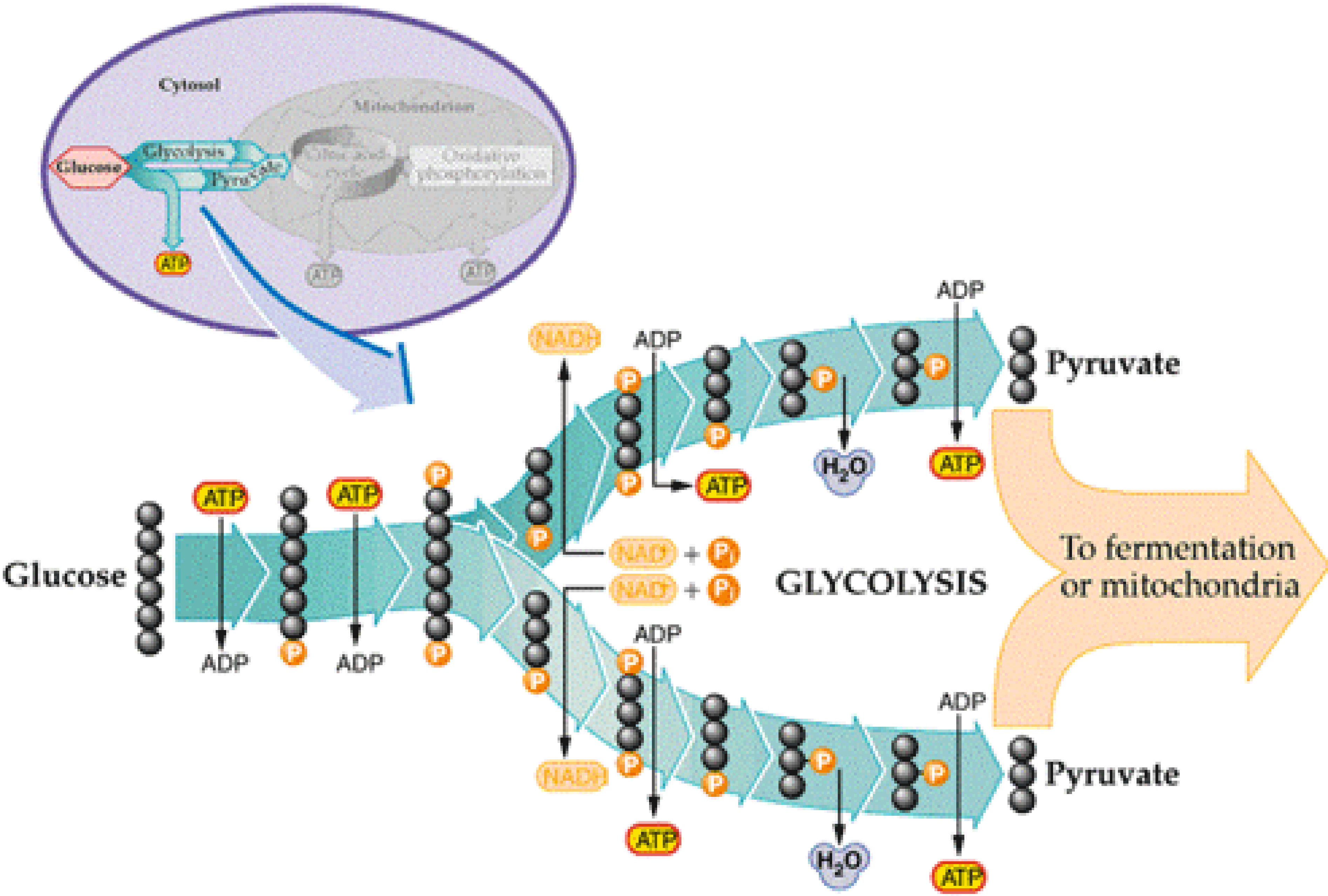
2 NAD^+ ➔ **<u>2 NADH</u>**

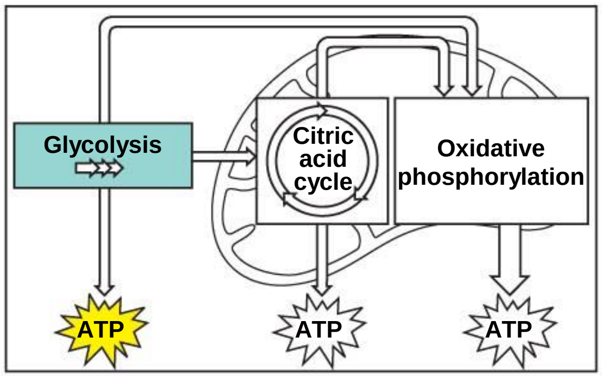
Glycolysis occurs in 10 steps:

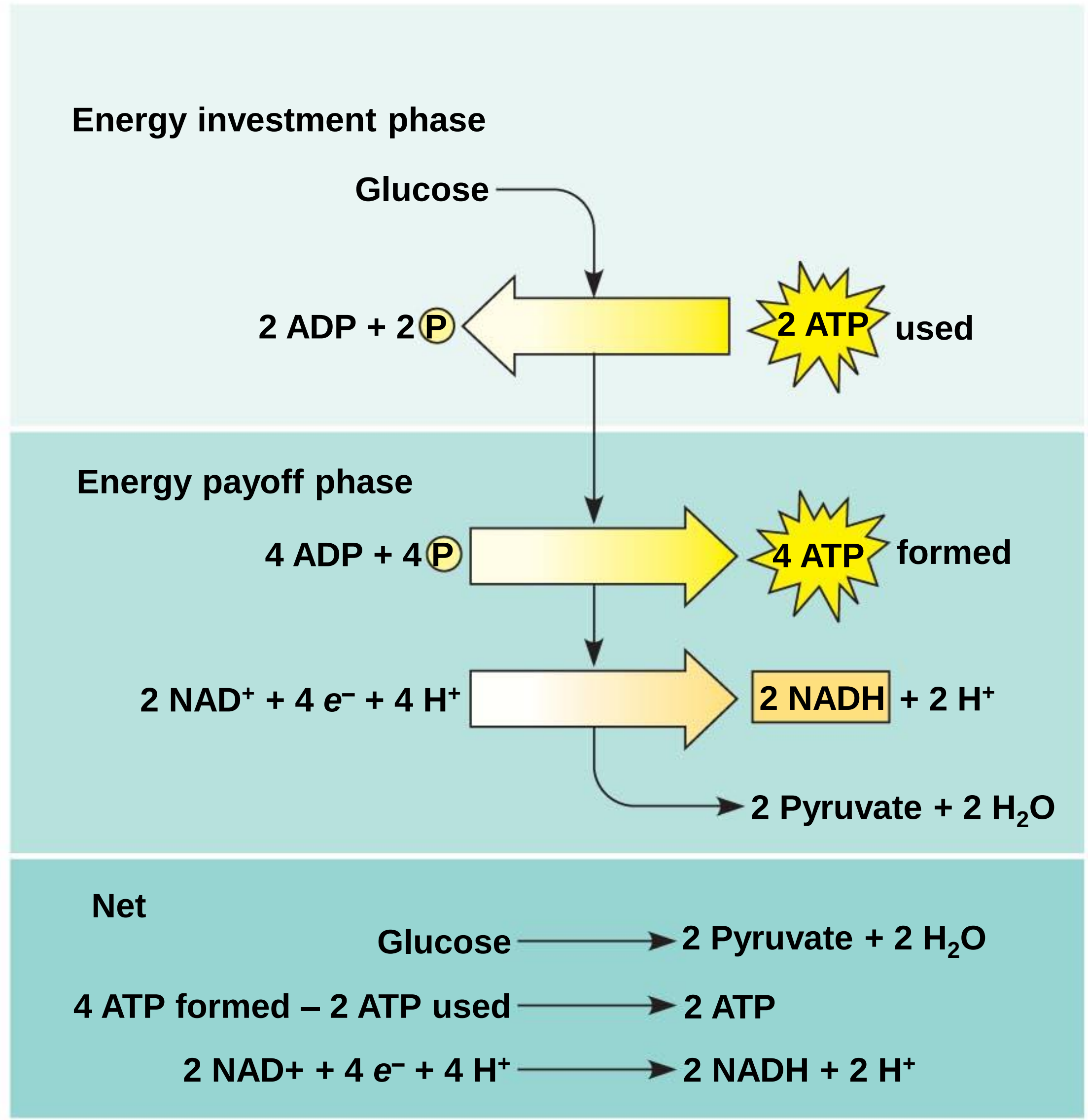
#1-5: energy-investment phase (2 ATP)

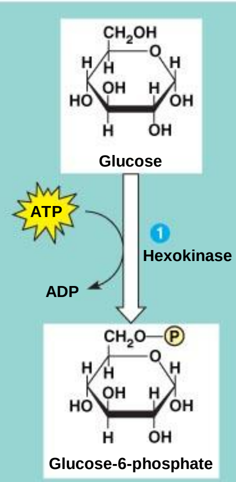
#6-10: energy-payoff phase (4 ATP)

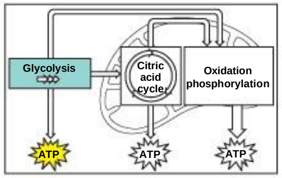
NET GAIN OF 2 ATP!

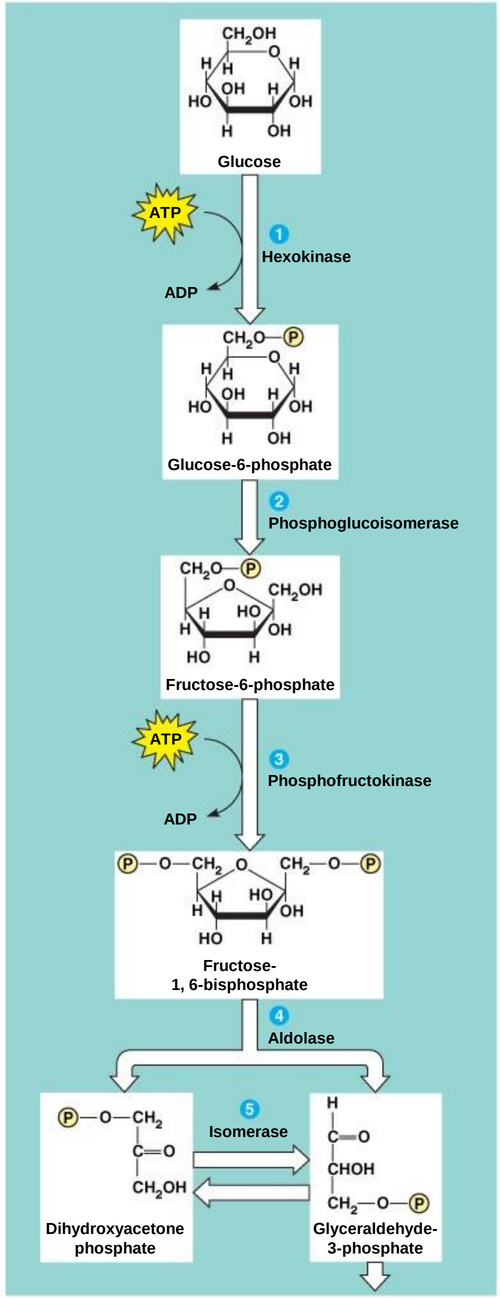

Cytosol
Mitochondrion
Glucose
Glycolysis
Pyruvate
Citric acid cycle
Oxidative phosphorylation
ATP
ATP
ATP
Glucose
ATP
ADP
ATP
ADP
P
P
P
P
NADH
ADP
ATP
ADP
H2O
ATP
Pyruvate
NAD+ + Pi
NAD+ + Pi
GLYCOLYSIS
To fermentation or mitochondria
NADH
ADP
ATP
H2O
ADP
ATP
Pyruvate

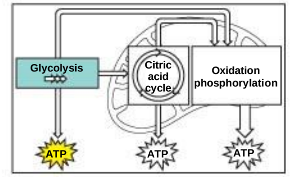

Glycolysis
Citric acid cycle
Oxidative phosphorylation
ATP
ATP
ATP

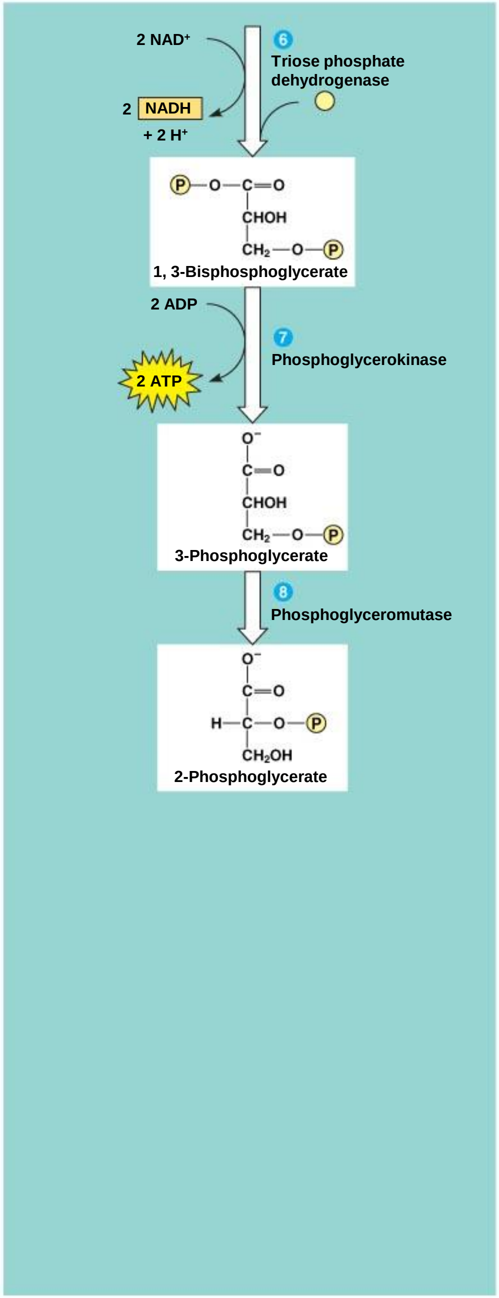

Energy investment phase
Glucose
2 ADP + 2 P
2 ATP used
Energy payoff phase
4 ADP + 4 P
4 ATP formed
2 NAD$^+$ + 4 e^- + 4 H$^+$
2 NADH + 2 H$^+$
2 Pyruvate + 2 H_2O
Net
Glucose → 2 Pyruvate + 2 H_2O
4 ATP formed – 2 ATP used → 2 ATP
2 NAD+ + 4 e^- + 4 H$^+$ → 2 NADH + 2 H$^+$

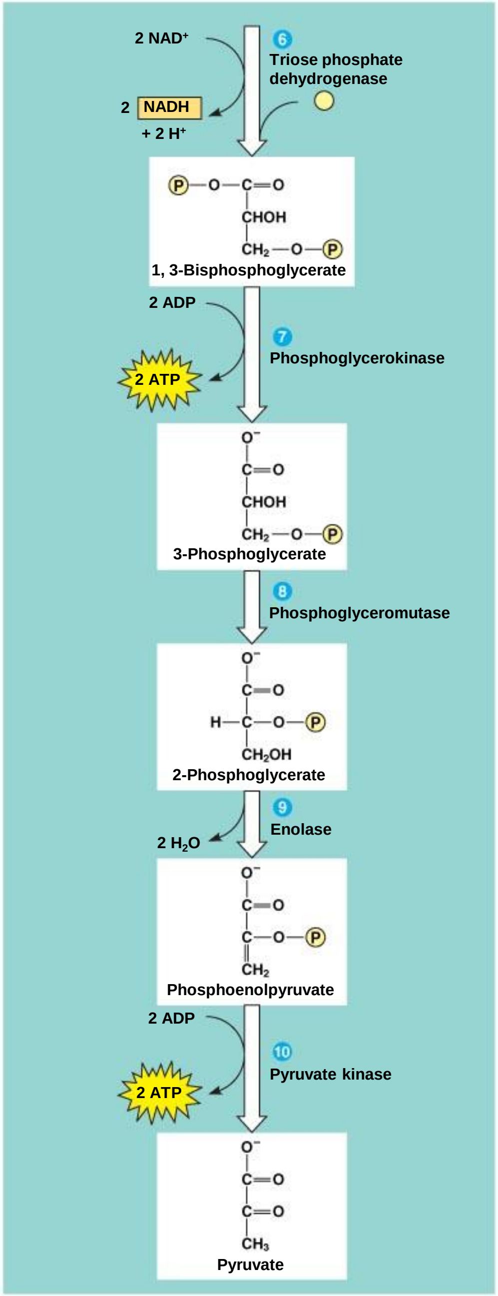

CH2OH
H
H
O
H
OH
H
HO
OH
H
OH
Glucose
ATP
1
Hexokinase
ADP
CH2O—P
H
H
O
H
OH
H
HO
OH
H
OH
Glucose-6-phosphate


Glycolysis
Citric acid cycle
Oxidation phosphorylation
ATP
ATP
ATP


Glucose
ATP
1
Hexokinase
ADP
Glucose-6-phosphate
2
Phosphoglucoisomerase
Fructose-6-phosphate
ATP
3
Phosphofructokinase
ADP
Fructose-
1, 6-bisphosphate
4
Aldolase
5
Isomerase
Dihydroxyacetone
phosphate
Glyceraldehyde-
3-phosphate


Glycolysis
Citric
acid
cycle
Oxidation
phosphorylation
ATP
ATP
ATP


2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
1, 3-Bisphosphoglycerate
2 ADP
7
Phosphoglycerokinase
2 ATP
3-Phosphoglycerate
8
Phosphoglyceromutase
2-Phosphoglycerate


2 NAD+
6
Triose phosphate dehydrogenase
2 NADH
+ 2 H+
1, 3-Bisphosphoglycerate
2 ADP
7
Phosphoglycerokinase
2 ATP
3-Phosphoglycerate
8
Phosphoglyceromutase
2-Phosphoglycerate
9
Enolase
2 H2O
Phosphoenolpyruvate
2 ADP
10
Pyruvate kinase
2 ATP
Pyruvate

GLYCOLYSIS ANIMATION!

<u>KREBS CYCLE:</u>

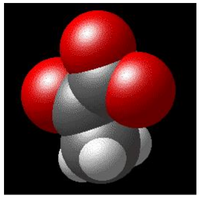
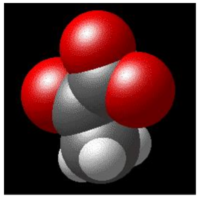
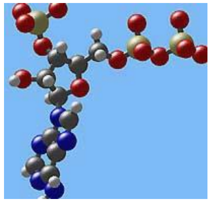
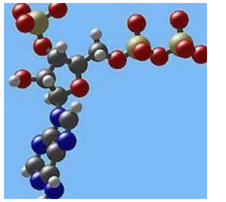
- glycolysis releases <u><1/4 of energy in glucose</u>

- the majority remains in the <u>2 pyruvate</u>

- <u>**IF**</u> molecular O_2 is present: pyruvate enters a mitochondrion, where enzymes of the <u>**KREBS CYCLE**</u> (a.k.a. the <u>**CITRIC ACID CYCLE**</u>) complete oxidation

BUT FIRST….

- Before the Krebs Cycle can begin, pyruvate must be converted to acetyl CoA, which <u>links the cycle to glycolysis</u>

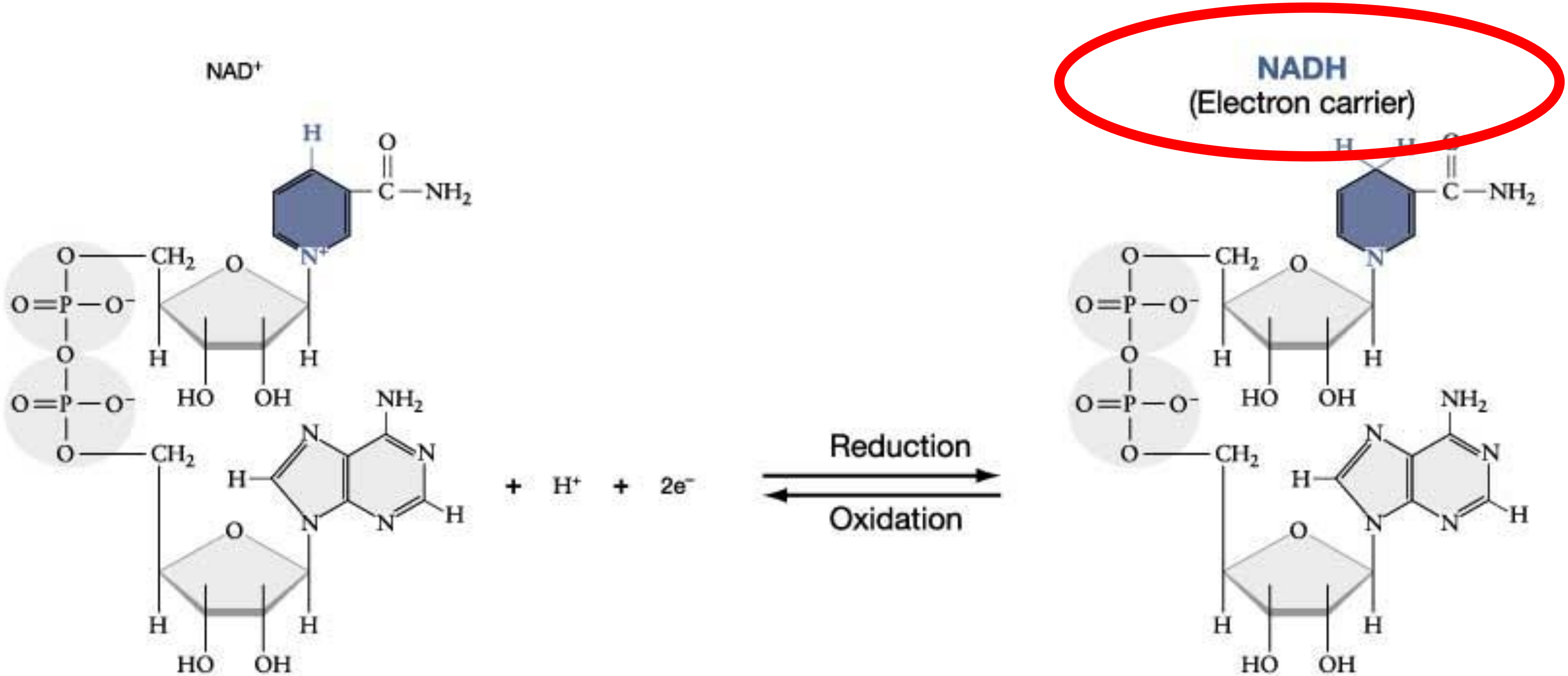
***But FIRST*:**    

2 Pyruvate ➔ 2 acetyl CoA

This conversion occurs in 3 steps:

1) carboxyl group removed & given off as CO_2 (2 CO_2 produced, 1 for each pyruvate)

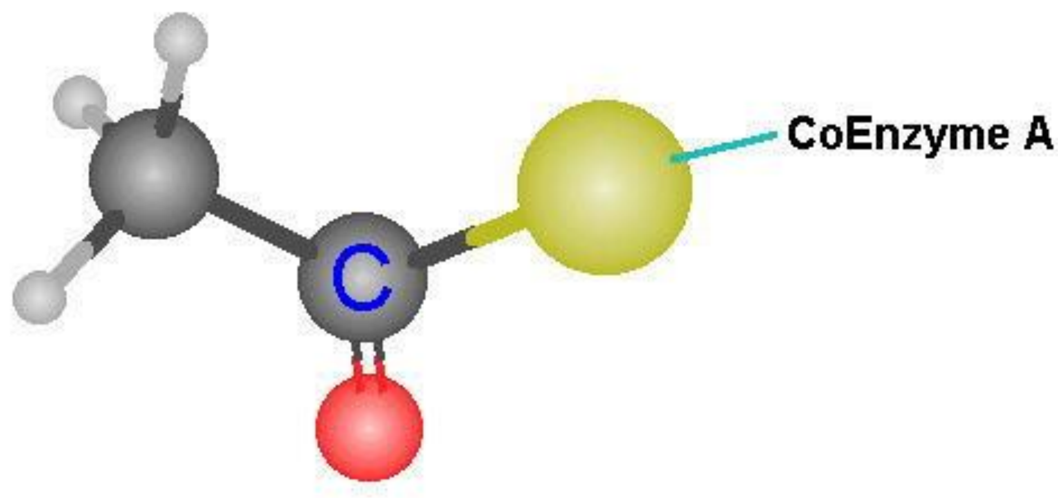
2) each remaining 2-C fragment is oxidized forming acetate; the extracted electrons are transferred to NAD^+, **forming NADH** (2 NADH produced, 1 for each fragment).

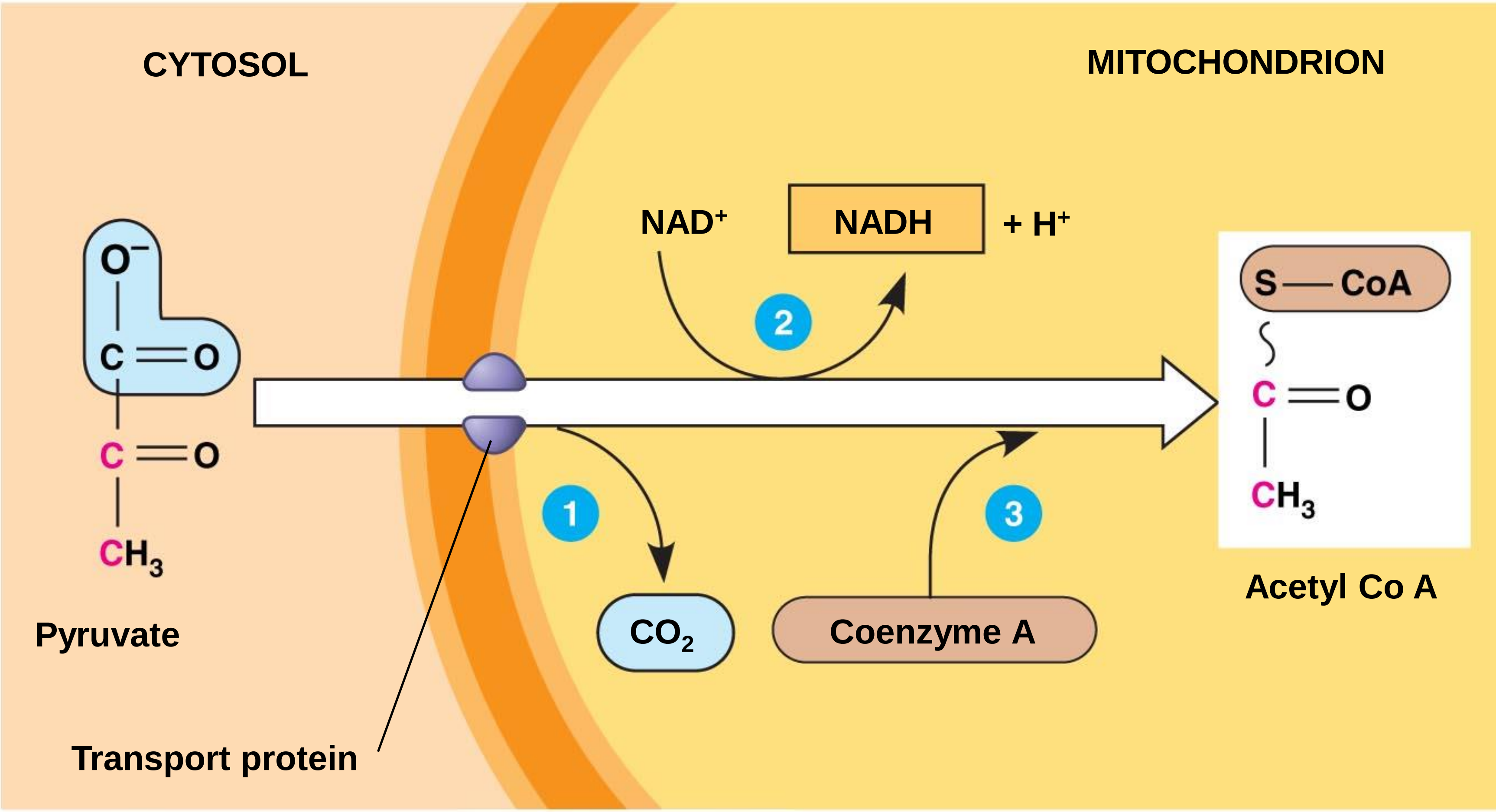

NAD⁺
NADH
(Electron carrier)
+ H⁺ + 2e⁻
Reduction
Oxidation

Final step of pyruvate ➔ acetyl CoA step:

3) Coenzyme A (from vitamin B) is attached to acetate ➔ **acetyl CoA**…

…on to the Krebs Cycle for further oxidation!

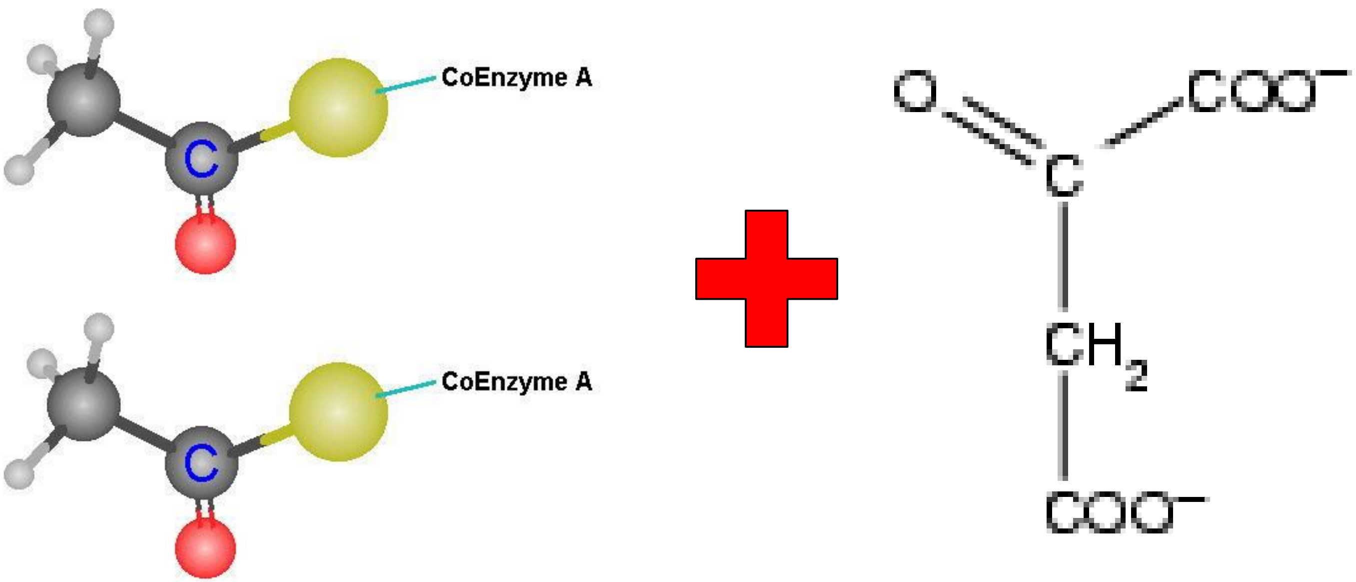




CYTOSOL
MITOCHONDRION
NAD+
NADH
+ H+
O−
C
O
C
O
CH3
S
CoA
C
O
CH3
2
1
3
CO2
Coenzyme A
Acetyl Co A
Pyruvate
Transport protein

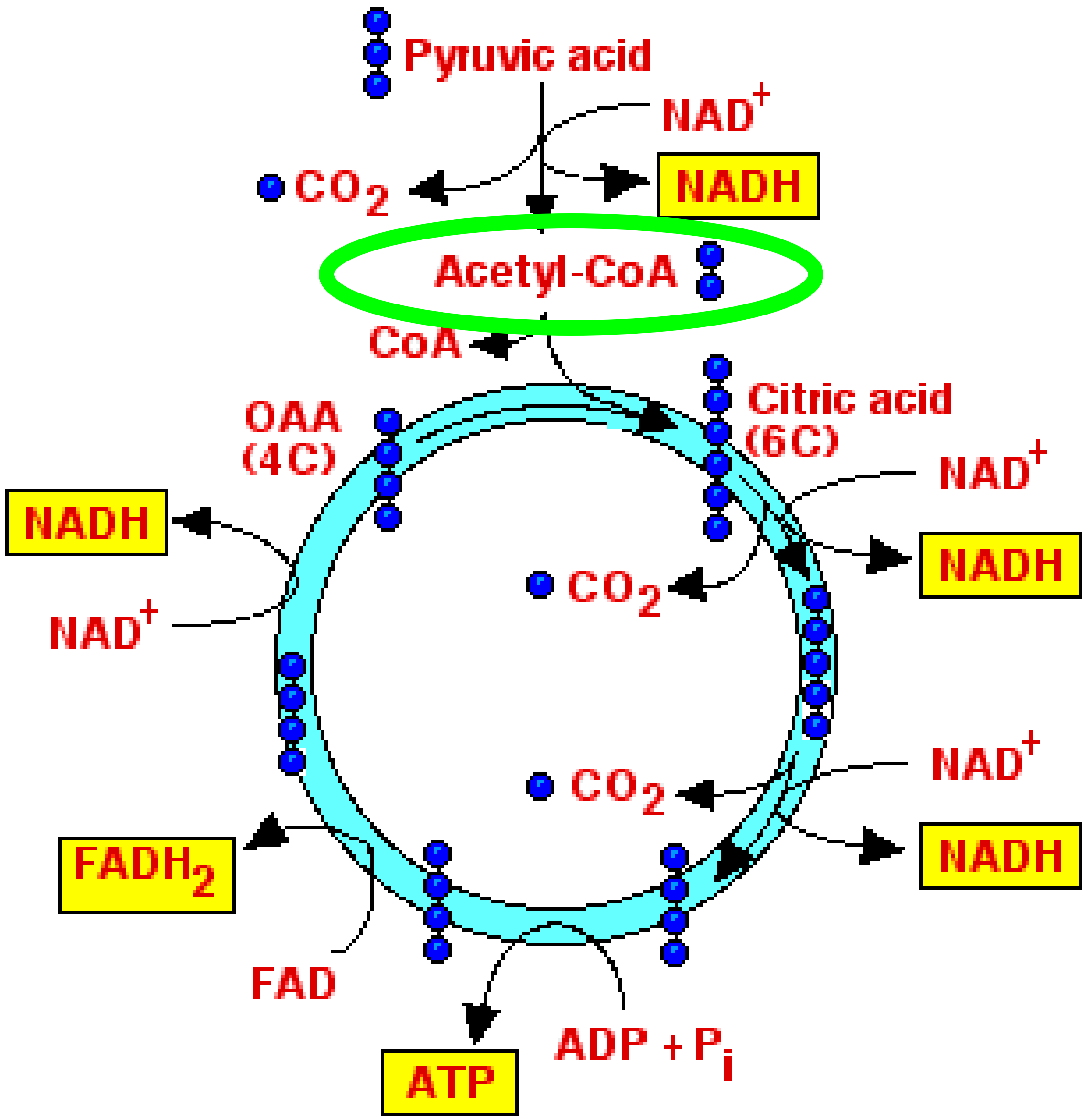
<u>Krebs Cycle (a.k.a. Citric Acid Cycle):</u>

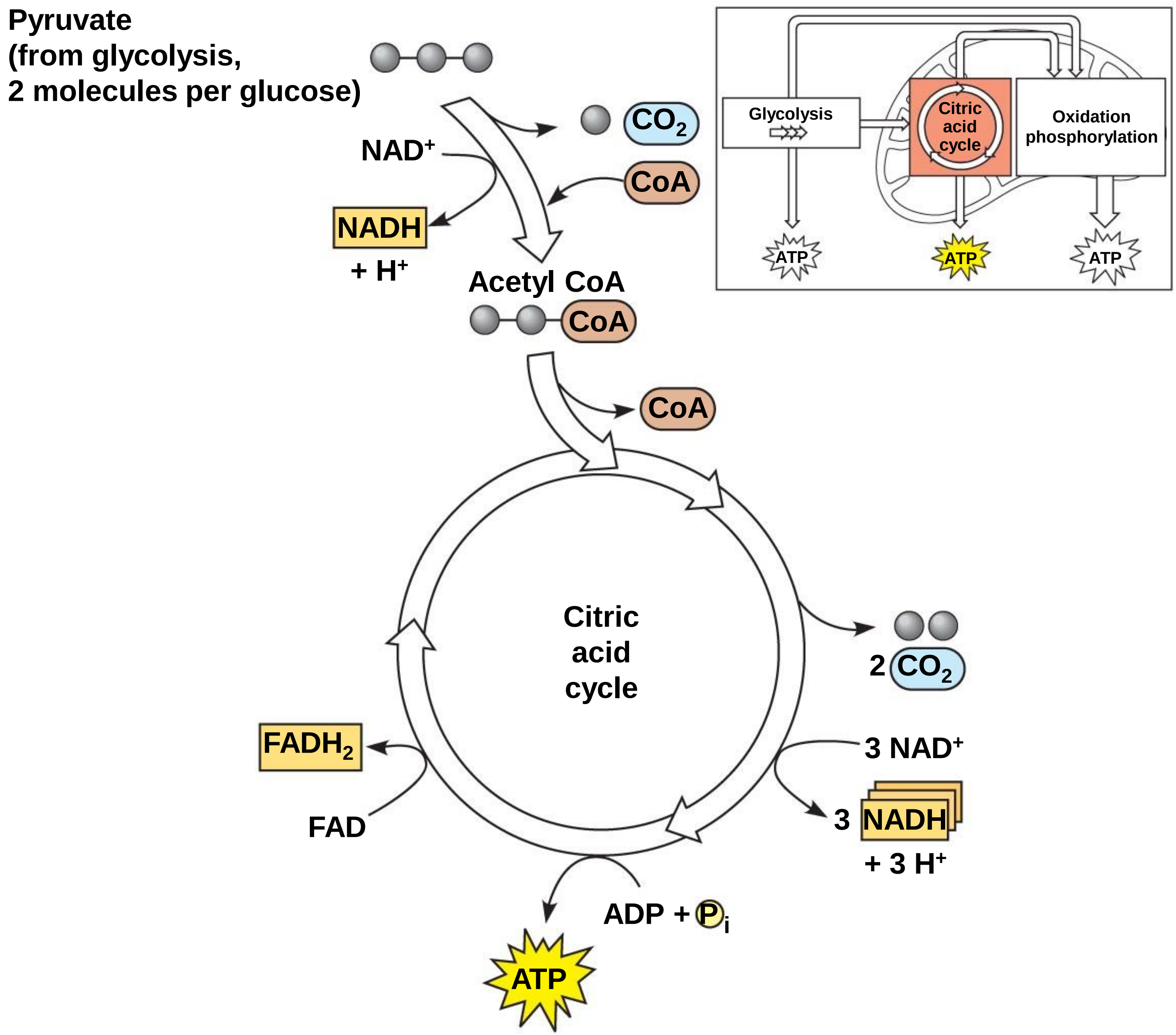
- 2 molecules of acetyl CoA enter the cycle (in the matrix of a mitochondrion) & each combine with a molecule of **<u>OXALOACETATE</u>**…



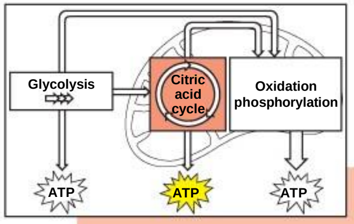
- For EACH molecule of acetyl CoA that enters:
  - ➔ 2 molecules of CO_2 are given off
  - ➔ 3 molecules of NADH are formed
  - ➔ 1 molecule of $FADH_2$ is formed
  - ➔ 1 molecule of ATP formed by substrate phosphorylation (direct transfer of P_i to ADP from an intermediate substrate)

Krebs Cycle
(Citric Acid Cycle)

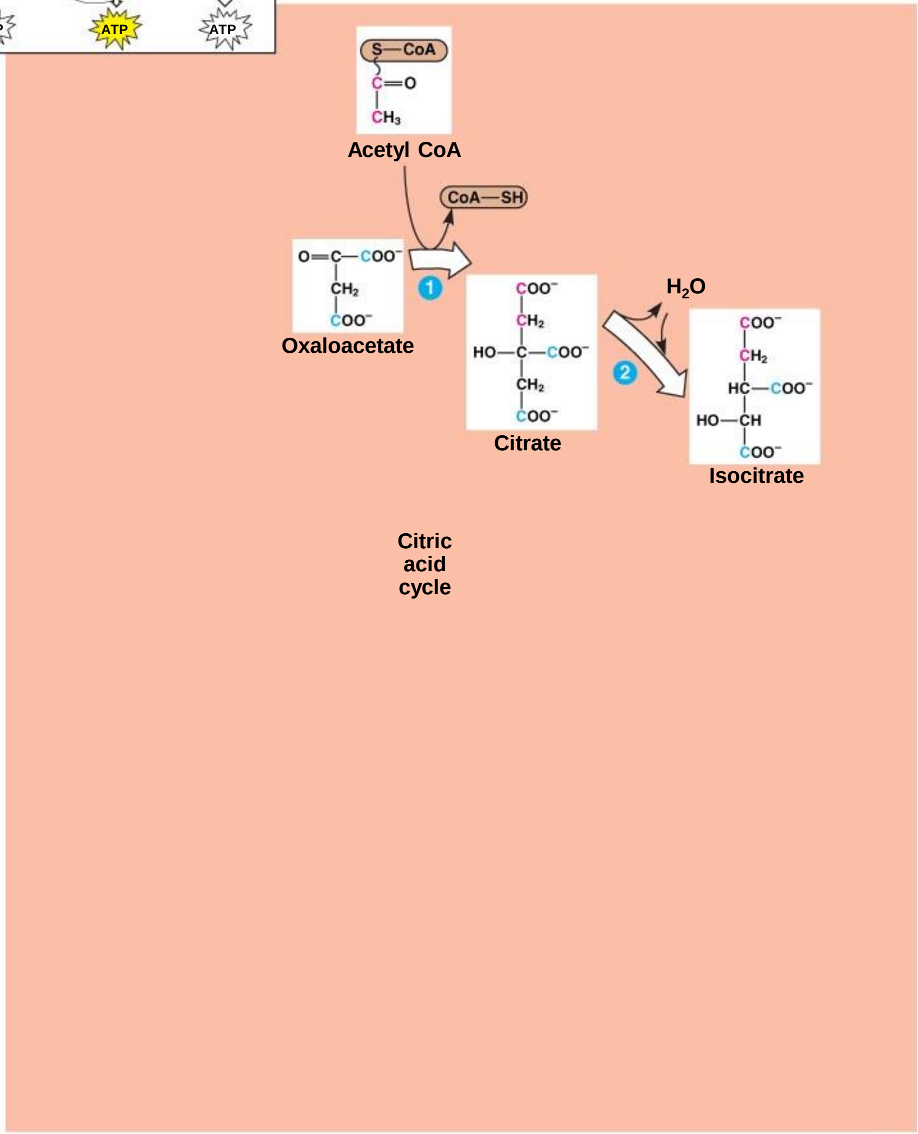



Pyruvate
(from glycolysis,
2 molecules per glucose)
CO2
NAD+
CoA
NADH
+ H+
Acetyl CoA
CoA
CoA
Citric
acid
cycle
2 CO2
3 NAD+
3 NADH
+ 3 H+
FADH2
FAD
ADP + P i
ATP
Glycolysis
Citric
acid
cycle
Oxidation
phosphorylation
ATP
ATP
ATP

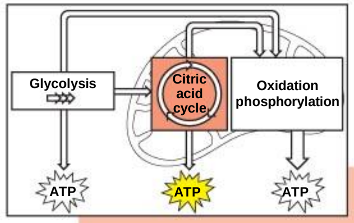
- The Krebs Cycle has eight steps, each catalyzed by a specific enzyme;
- The acetyl group of acetyl CoA joins the cycle by **combining with oxaloacetate**, forming citrate;
- The next seven steps decompose the citrate back to oxaloacetate, making the process a **cycle!**
- The NADH and $FADH_2$ produced by the cycle relay electrons extracted from food to the electron transport chain.

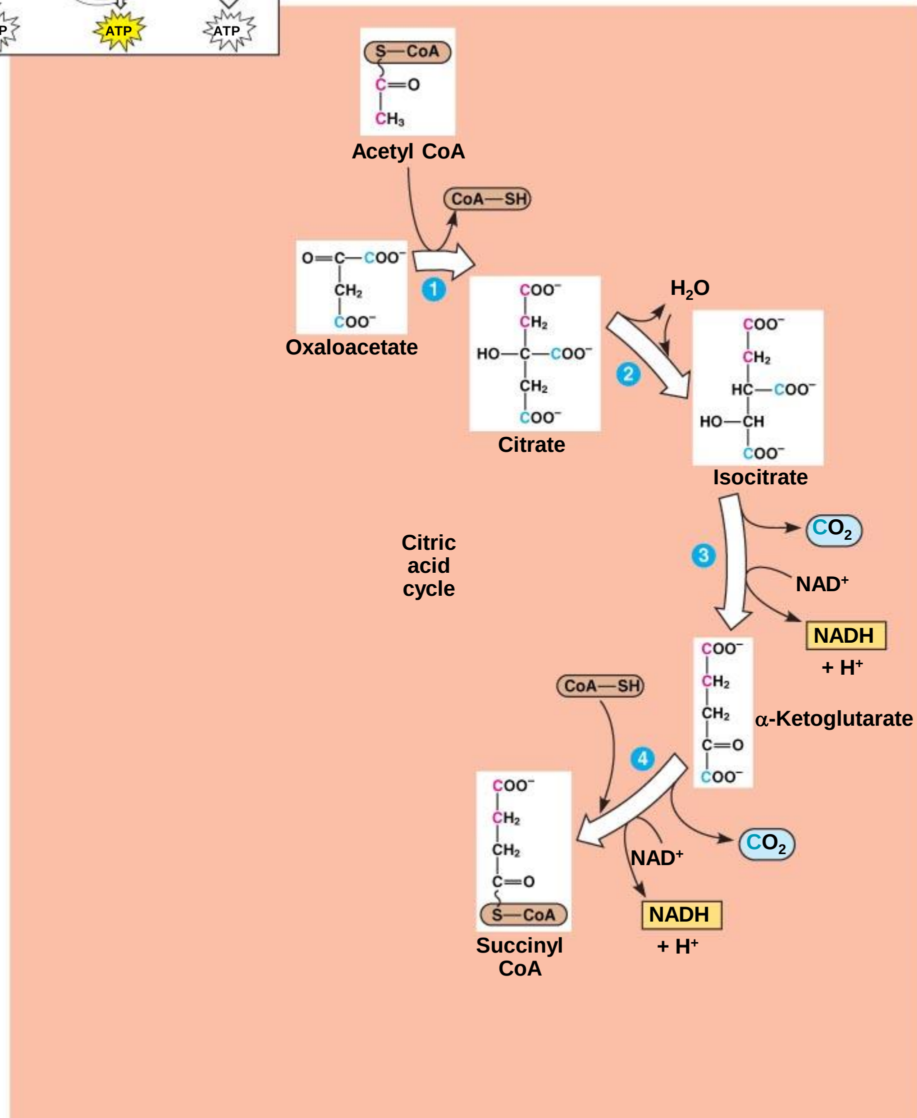


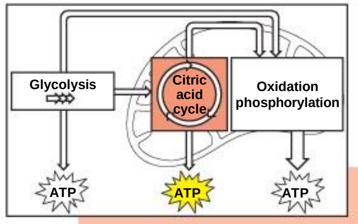
Glycolysis
Citric acid cycle
Oxidation phosphorylation
ATP
ATP
ATP

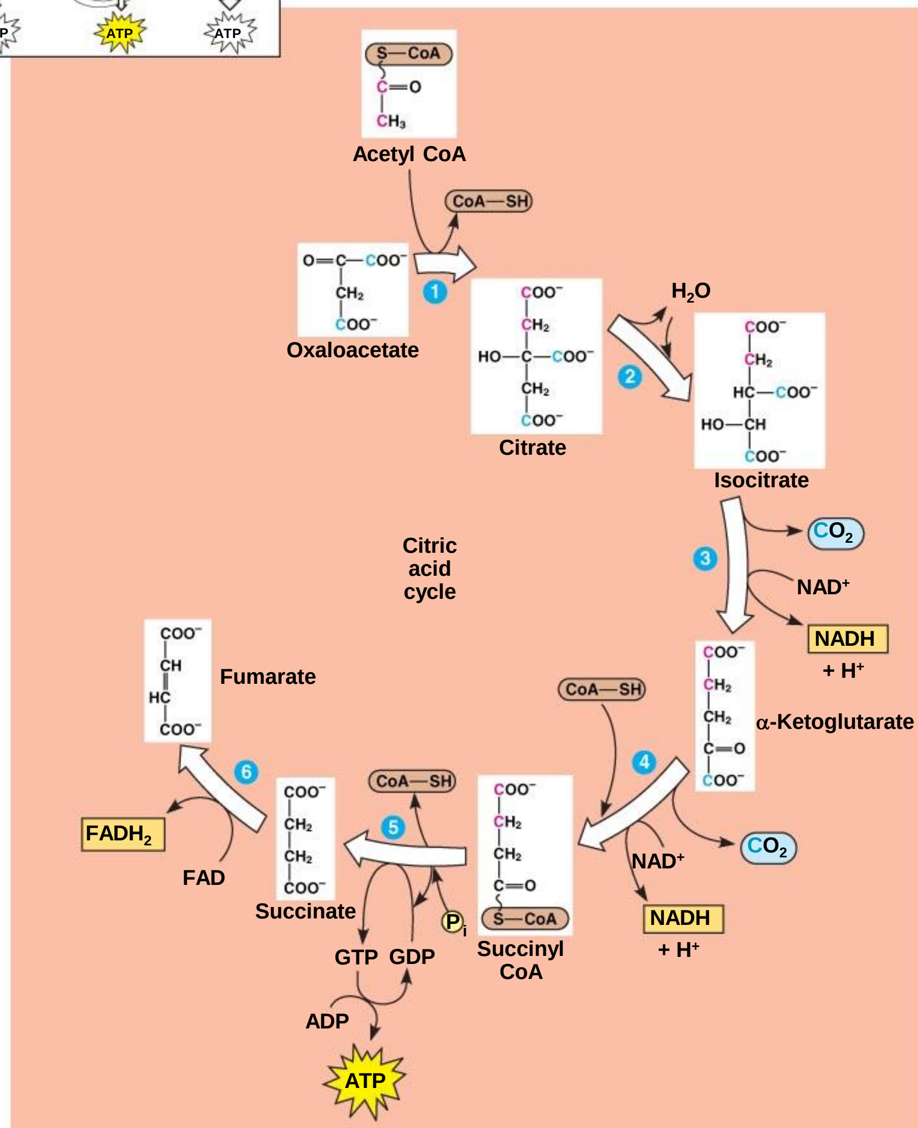


S—CoA
C=O
CH₃
Acetyl CoA
CoA—SH
O=C—COO⁻
CH₂
COO⁻
Oxaloacetate
1
COO⁻
CH₂
HO—C—COO⁻
CH₂
COO⁻
Citrate
H₂O
2
COO⁻
CH₂
HC—COO⁻
HO—CH
COO⁻
Isocitrate
Citric acid cycle

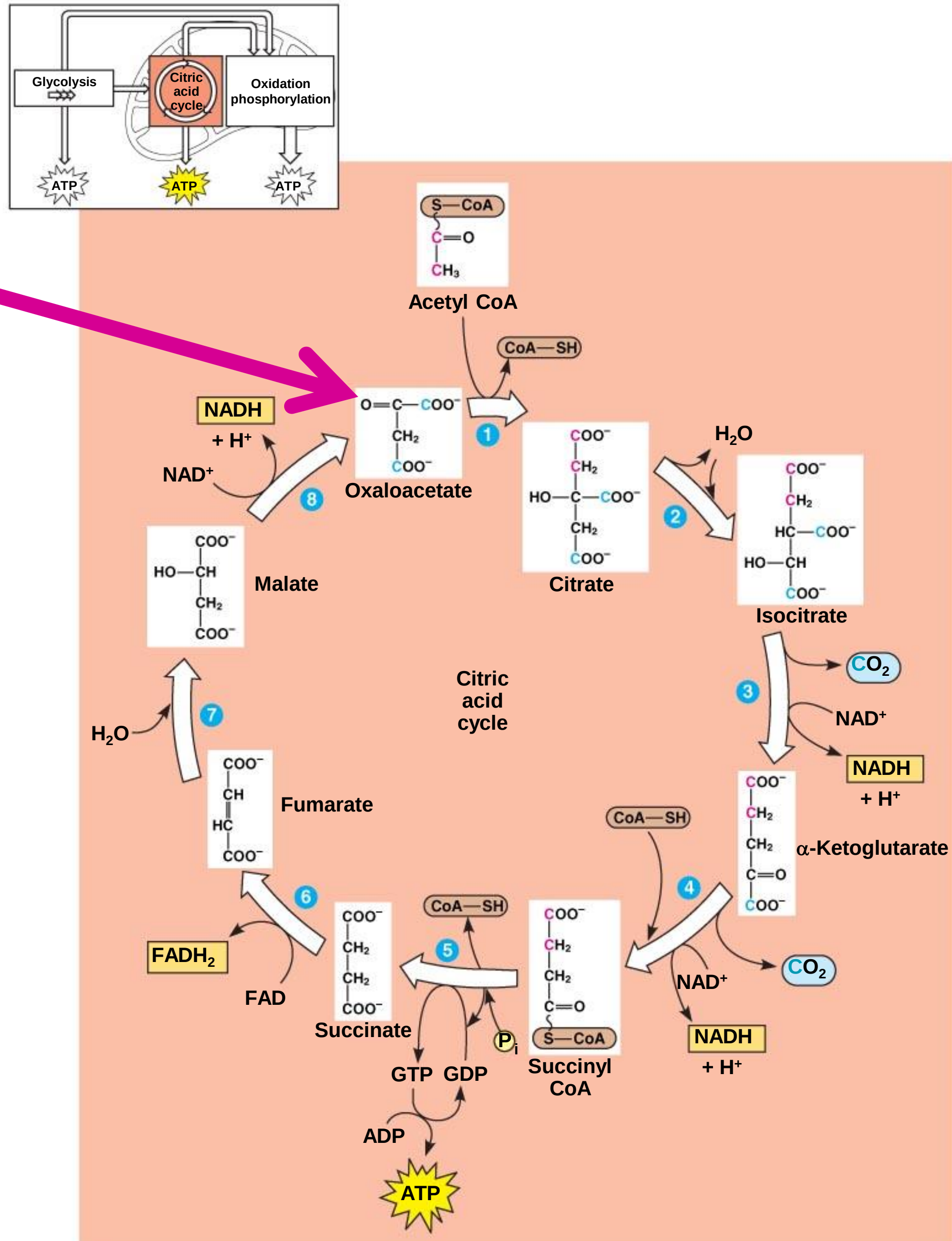

Glycolysis
Citric acid cycle
Oxidation phosphorylation
ATP
ATP
ATP


Acetyl CoA
CoA—SH
Oxaloacetate
Citrate
H_2O
Isocitrate
CO_2
NAD^+
NADH
$+ H^+$
α-Ketoglutarate
CoA—SH
CO_2
NAD^+
NADH
$+ H^+$
Succinyl CoA
Citric acid cycle
1
2
3
4


Glycolysis
Citric acid cycle
Oxidation phosphorylation
ATP
ATP
ATP


Acetyl CoA
CoA—SH
Oxaloacetate
Citrate
H_2O
Isocitrate
CO_2
NAD+
NADH
+ H+
α-Ketoglutarate
CoA—SH
CO_2
NAD+
NADH
+ H+
Succinyl CoA
CoA—SH
Pi
GTP
GDP
ADP
ATP
Succinate
FAD
$FADH_2$
Fumarate
Citric acid cycle

Oxaloacetate makes this a CYCLE! (&, P.S., it is my #7 most favorite term in bio!) ☺



- SO, since 2 molecules of acetyl CoA go through the cycle, the “totals” are:

➔ **$\underline{4\ CO_2}$**

➔ **<u>6 NADH</u>**

➔ **$\underline{2\ FADH_2}$**

➔ **<u>2 ATP formed</u>**

KREBS CYCLE ANIMATION!