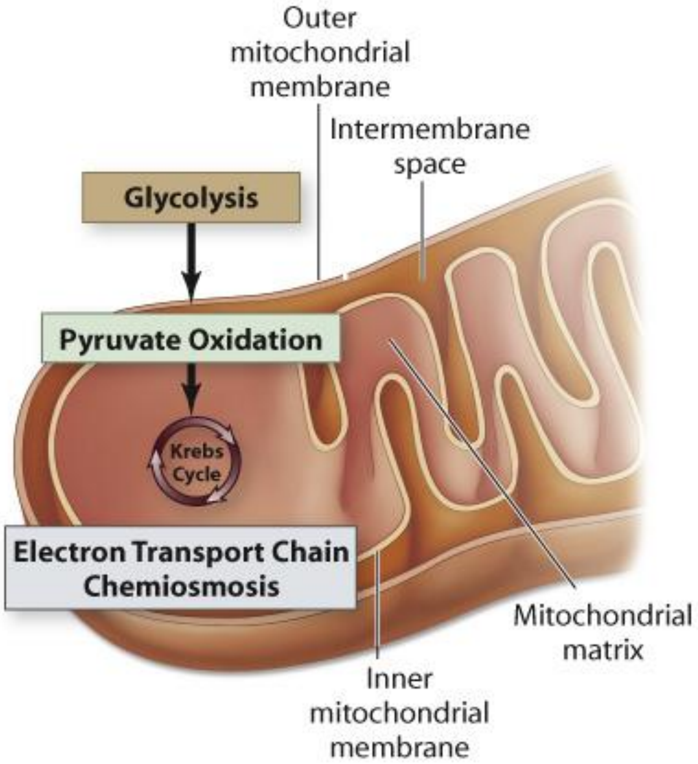
3.2 Aerobic Respiration

Aerobic Cellular Respiration

- Catabolic pathways
- Breaks down energy-rich compounds to make ATP
- Requires oxygen
- Occurs in different parts of the cell



$$C_6H_{12}O_6\ (s) + 6O_2(g) \rightarrow 6CO_2(g) + 6H_2O(l) + \text{energy}$$

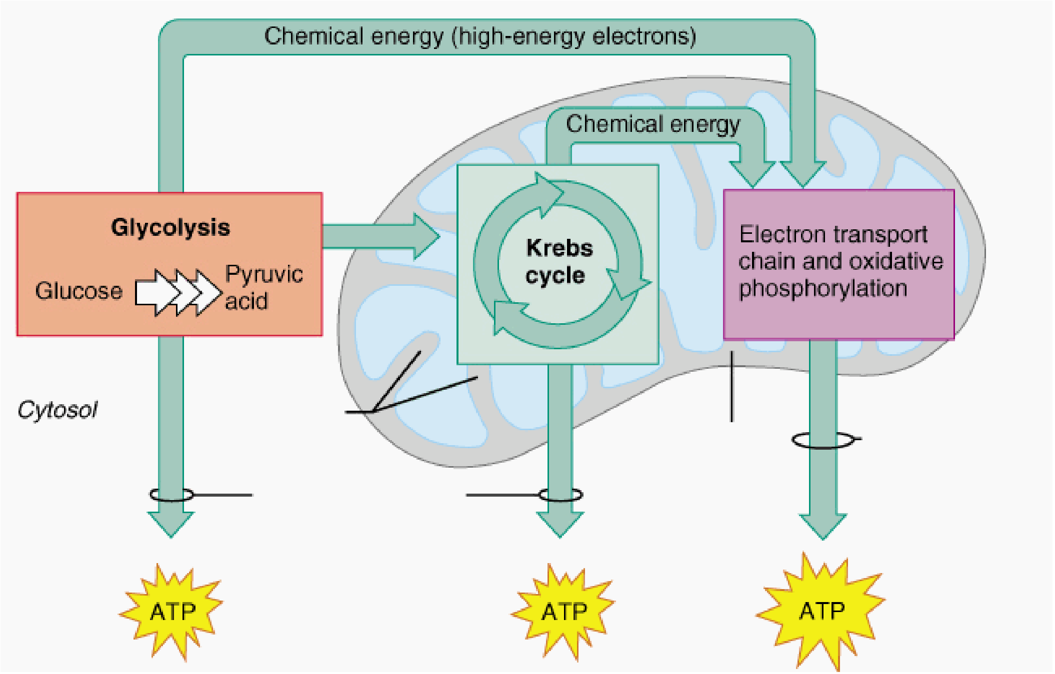
Metabolism of Glucose – ATP Yield

- Eukaryotes: 36 ATP molecules
  - 2+2+4+6+22
  - Yield from total glycolytic NADH – 4 ATP

- Prokaryotes: 38 ATP molecules
  - 2+2+6+6+22
  - Yield from total glycolytic NADH – 6 ATP

4 Main stages of aerobic cellular respiration

1. Glycolysis
2. Pyruvate Oxidation
3. Krebs Cycle
4. Electron Transport Chain and Chemiosmosis

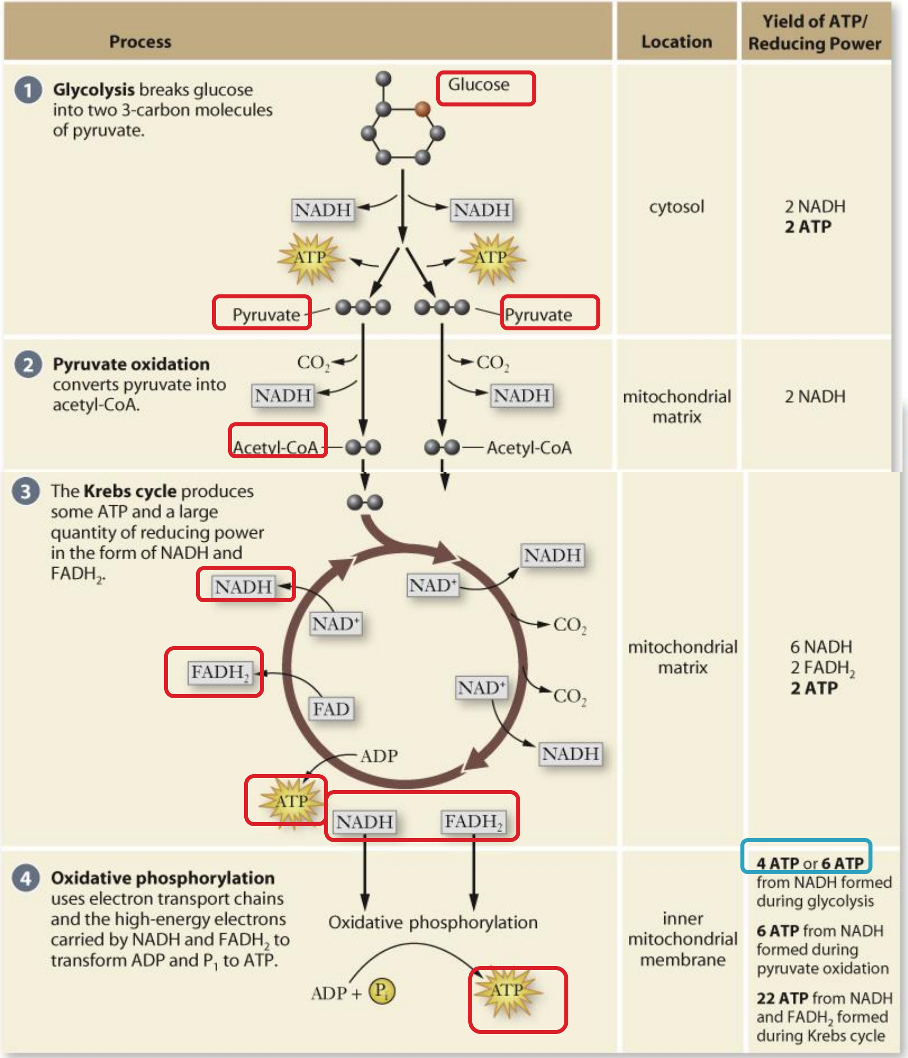


Substrate-level phosphorylation

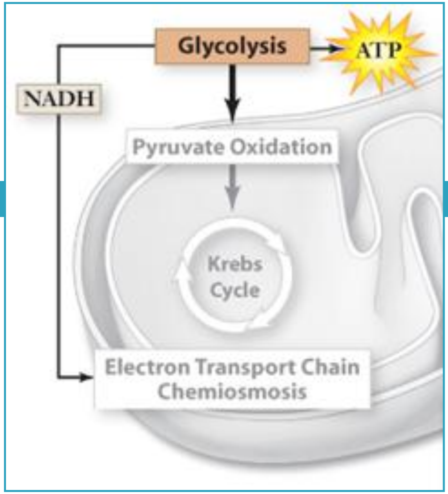
Substrate-level phosphorylation

Oxidative phosphorylation

1. Glycolysis
2. Pyruvate Oxidation
3. Krebs Cycle
4. Electron Transport Chain and Chemiosmosis



1. Glycolysis

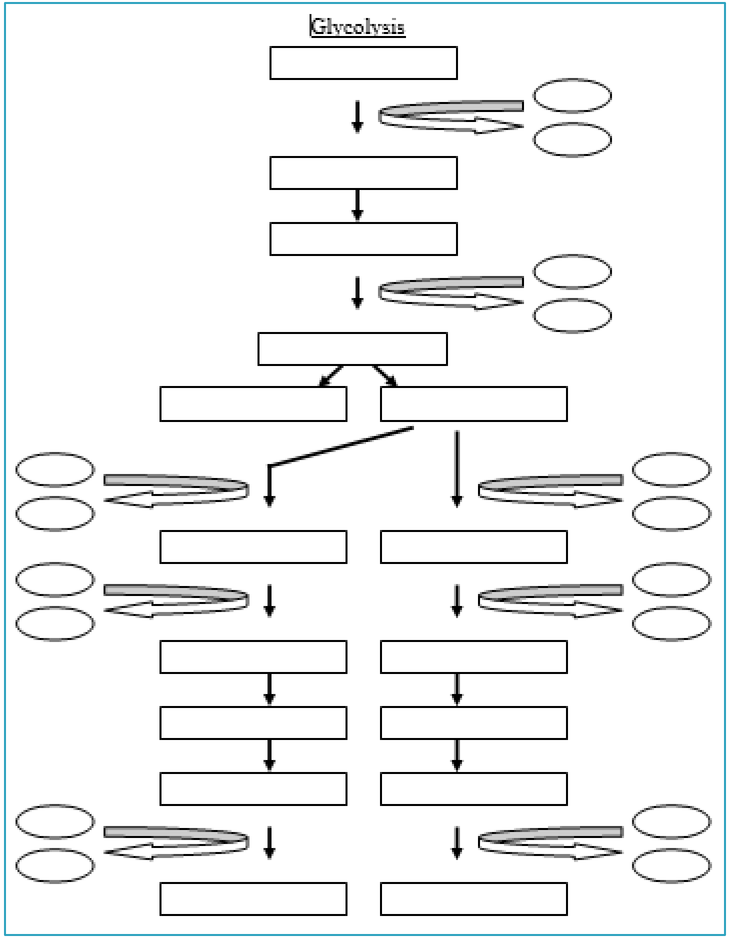


- 10 reactions
- Net reaction:

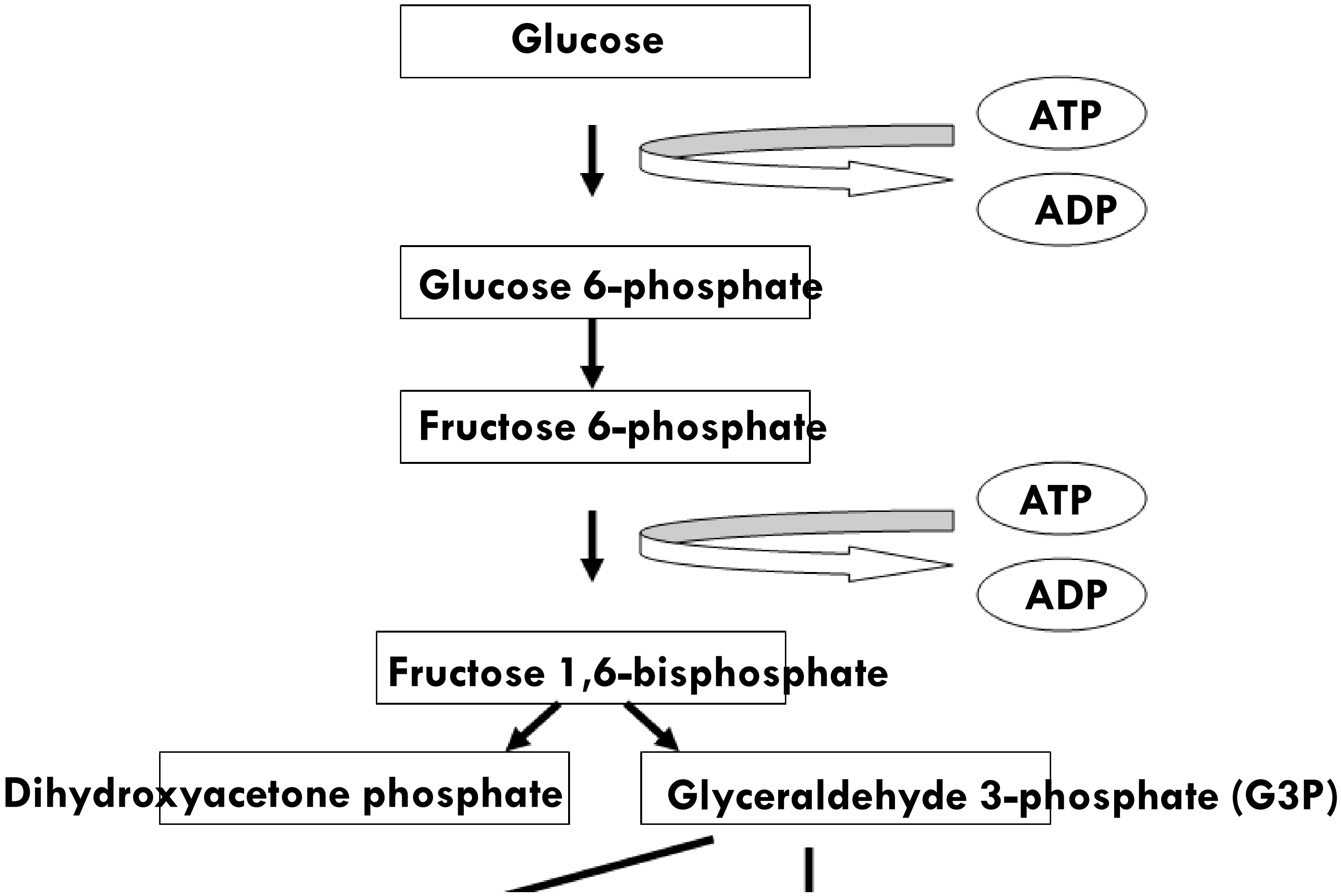
$$\text{glucose} + 2\ NAD^+ + 2\ ADP + 2\ P_i \rightarrow$$

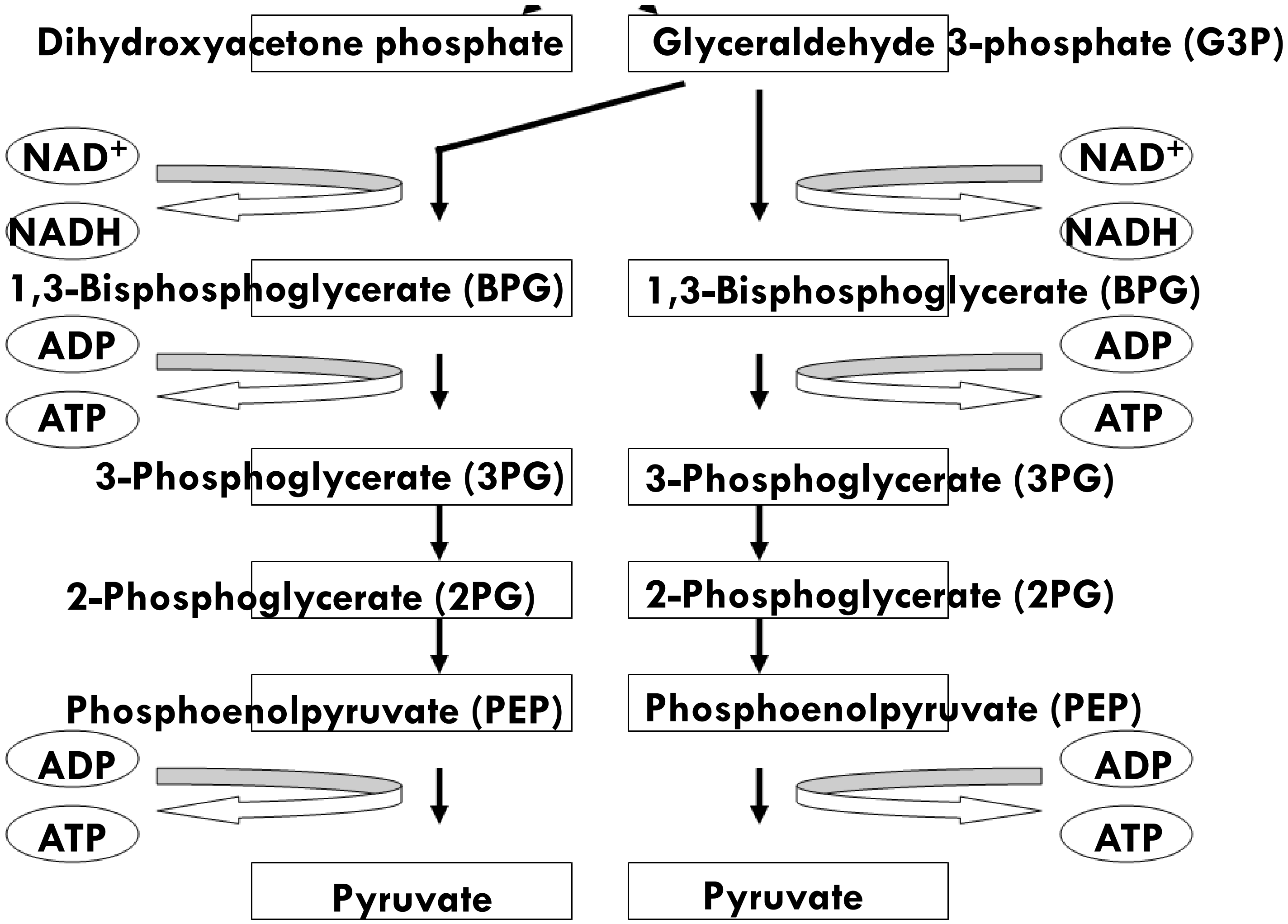
$$2\ \text{pyruvate} + 2H_2O + 2\ NADH + 2\ ATP$$

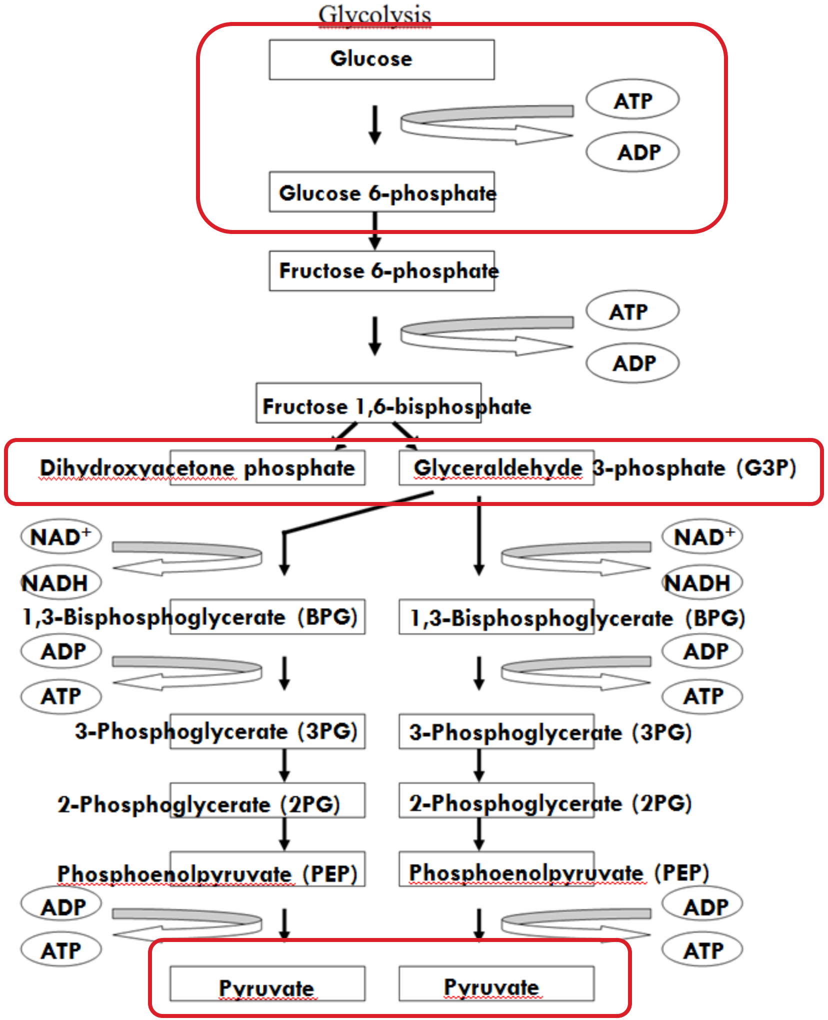
Glycolysis Overview


Glycolysis

Glycolysis


Glucose
ATP
ADP
Glucose 6-phosphate
Fructose 6-phosphate
ATP
ADP
Fructose 1,6-bisphosphate
Dihydroxyacetone phosphate
Glyceraldehyde 3-phosphate (G3P)


Dihydroxyacetone phosphate
Glyceraldehyde 3-phosphate (G3P)
NAD+
NADH
NAD+
NADH
1,3-Bisphosphoglycerate (BPG)
1,3-Bisphosphoglycerate (BPG)
ADP
ATP
ADP
ATP
3-Phosphoglycerate (3PG)
3-Phosphoglycerate (3PG)
2-Phosphoglycerate (2PG)
2-Phosphoglycerate (2PG)
Phosphoenolpyruvate (PEP)
Phosphoenolpyruvate (PEP)
ADP
ATP
ADP
ATP
Pyruvate
Pyruvate



Glycolysis
Glucose
ATP
ADP
Glucose 6-phosphate
Fructose 6-phosphate
ATP
ADP
Fructose 1,6-bisphosphate
Dihydroxyacetone phosphate
Glyceraldehyde 3-phosphate (G3P)
NAD+
NADH
NAD+
NADH
1,3-Bisphosphoglycerate (BPG)
1,3-Bisphosphoglycerate (BPG)
ADP
ATP
ADP
ATP
3-Phosphoglycerate (3PG)
3-Phosphoglycerate (3PG)
2-Phosphoglycerate (2PG)
2-Phosphoglycerate (2PG)
Phosphoenolpyruvate (PEP)
Phosphoenolpyruvate (PEP)
ADP
ATP
ADP
ATP
Pyruvate
Pyruvate

2. Pyruvate Oxidation

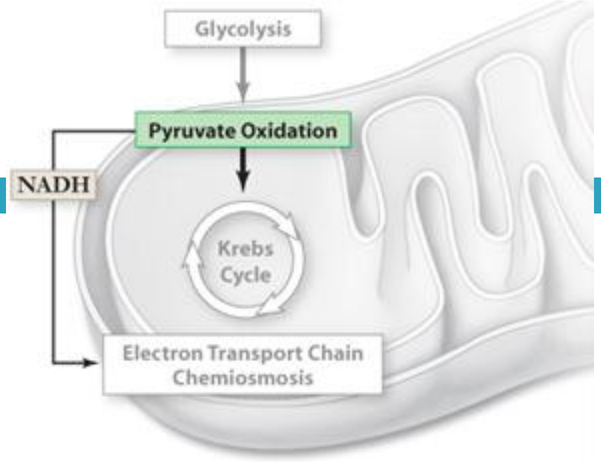
1 glucose

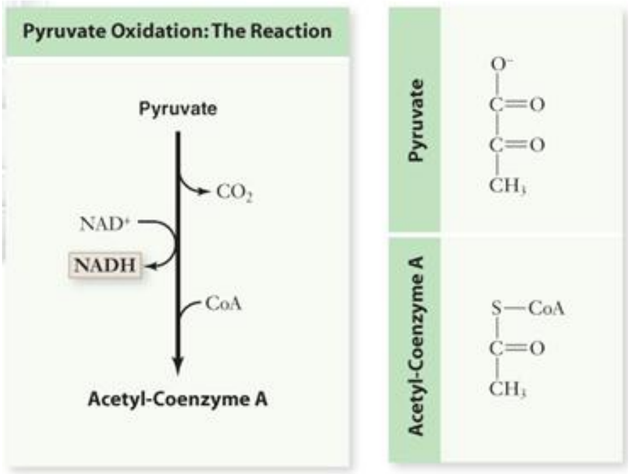
→ 2 pyruvate

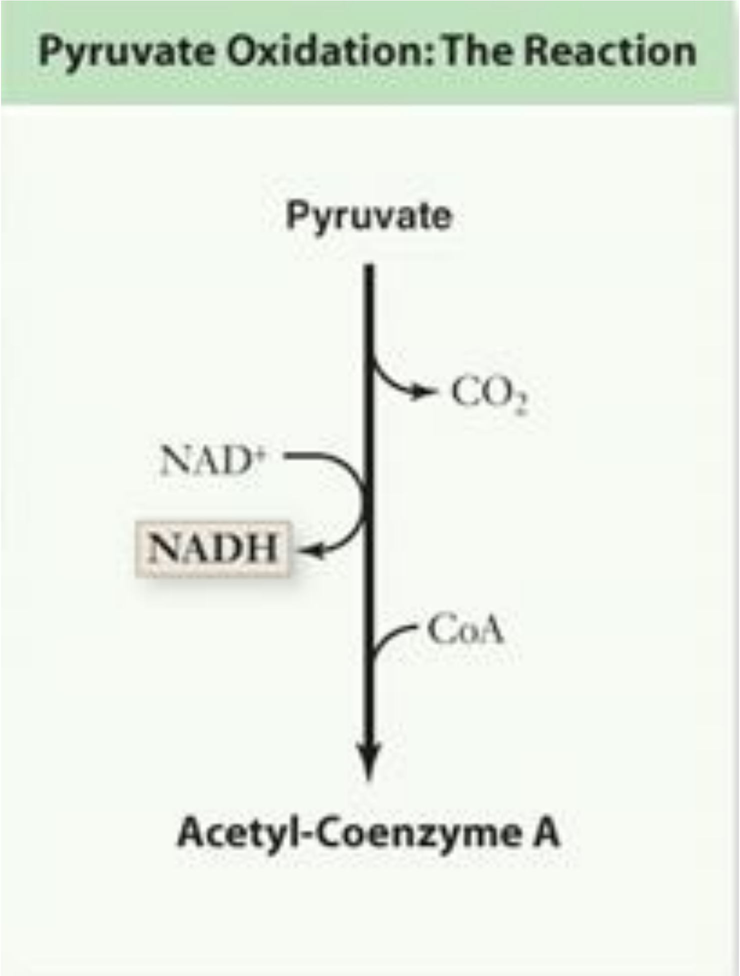
(transported into mitochondrial matrix)

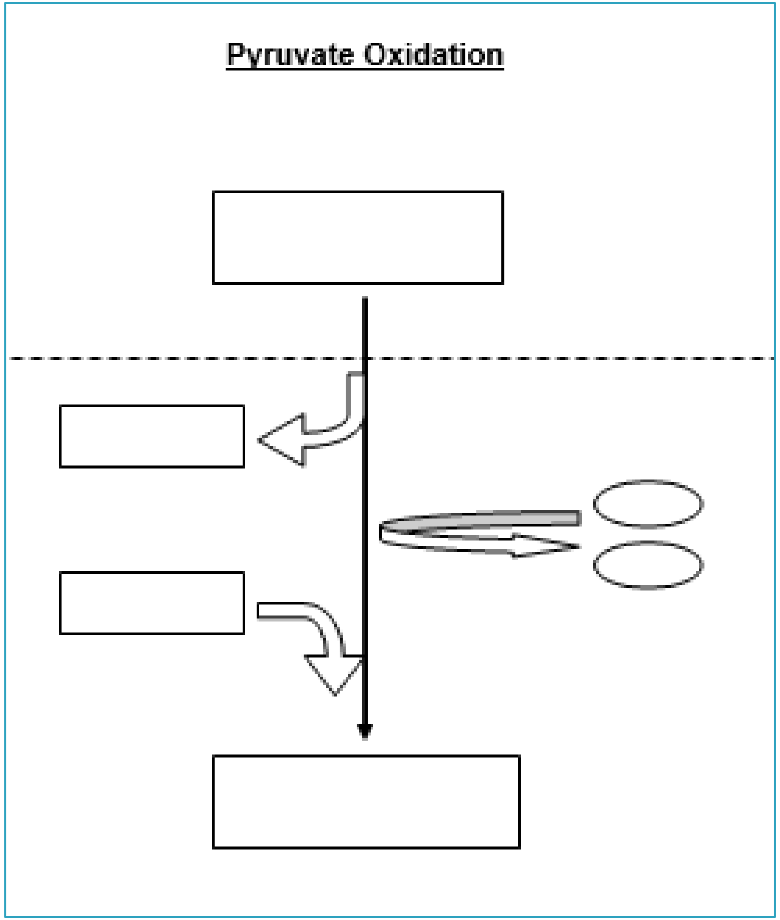
→ 2 acetyl-CoA + 2 NADH

- Only when oxygen is present

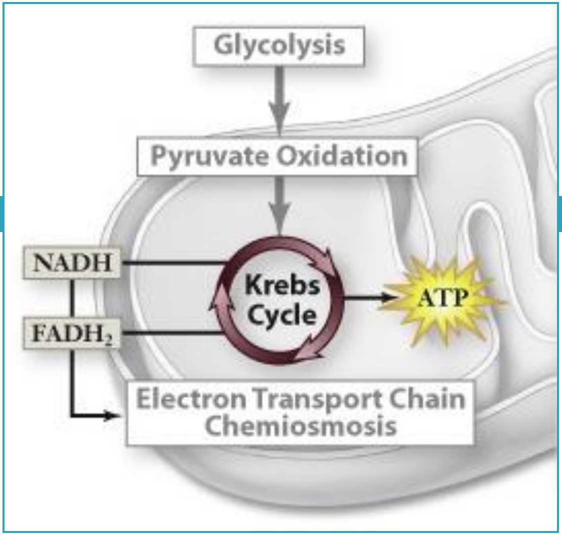





Pyruvate Oxidation: The Reaction
Pyruvate
CO_2
NAD^+
NADH
CoA
Acetyl-Coenzyme A

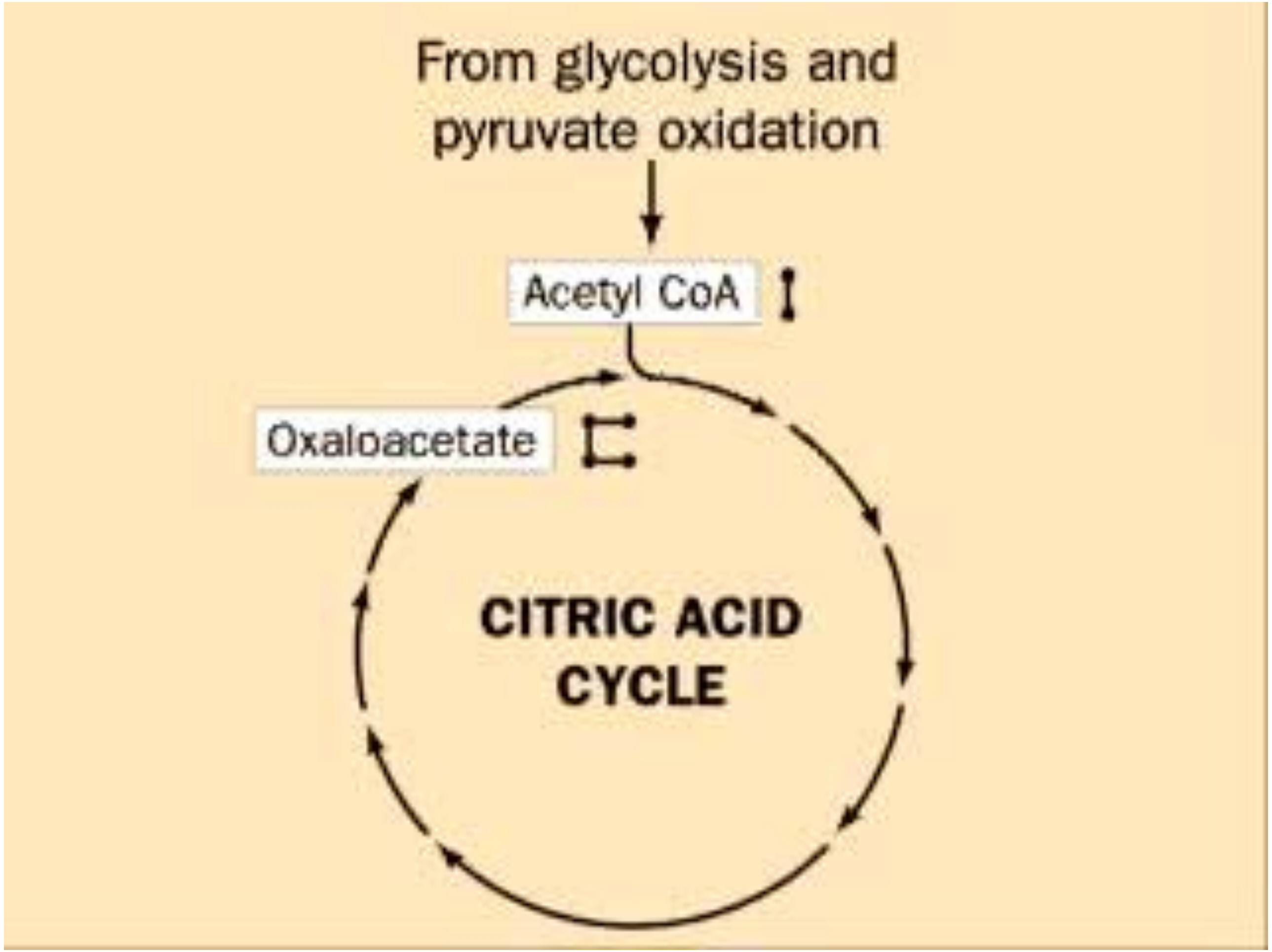

Pyruvate Oxidation

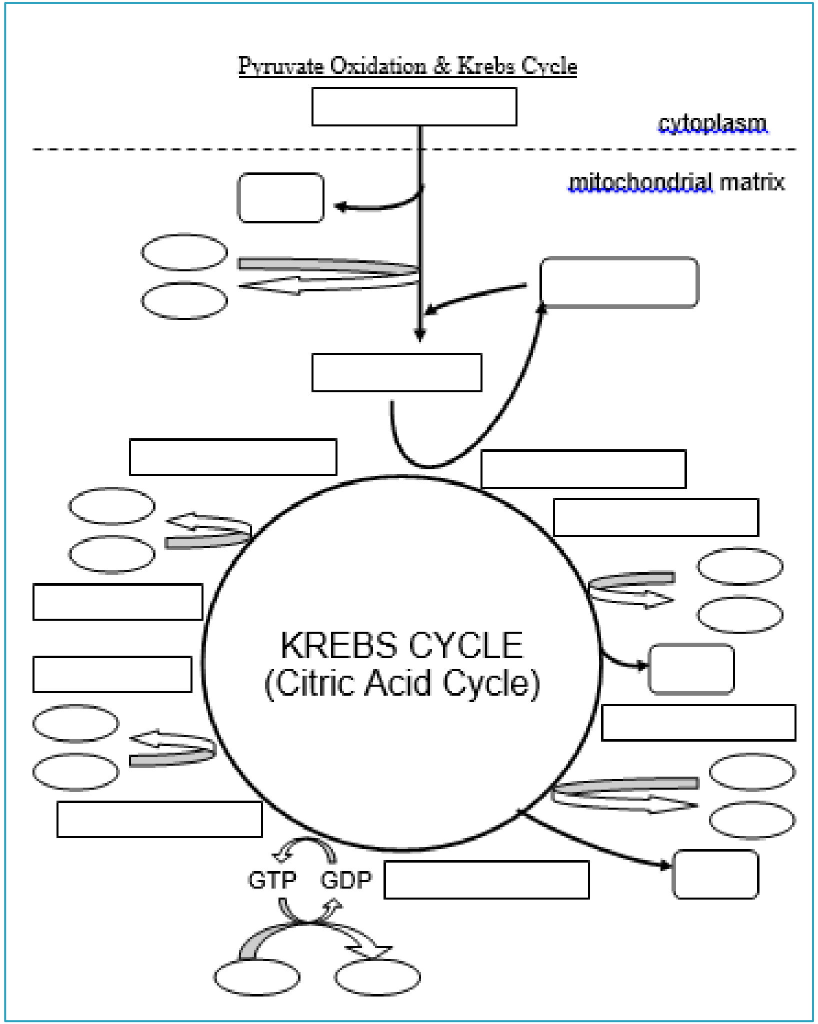
3. Krebs Cycle



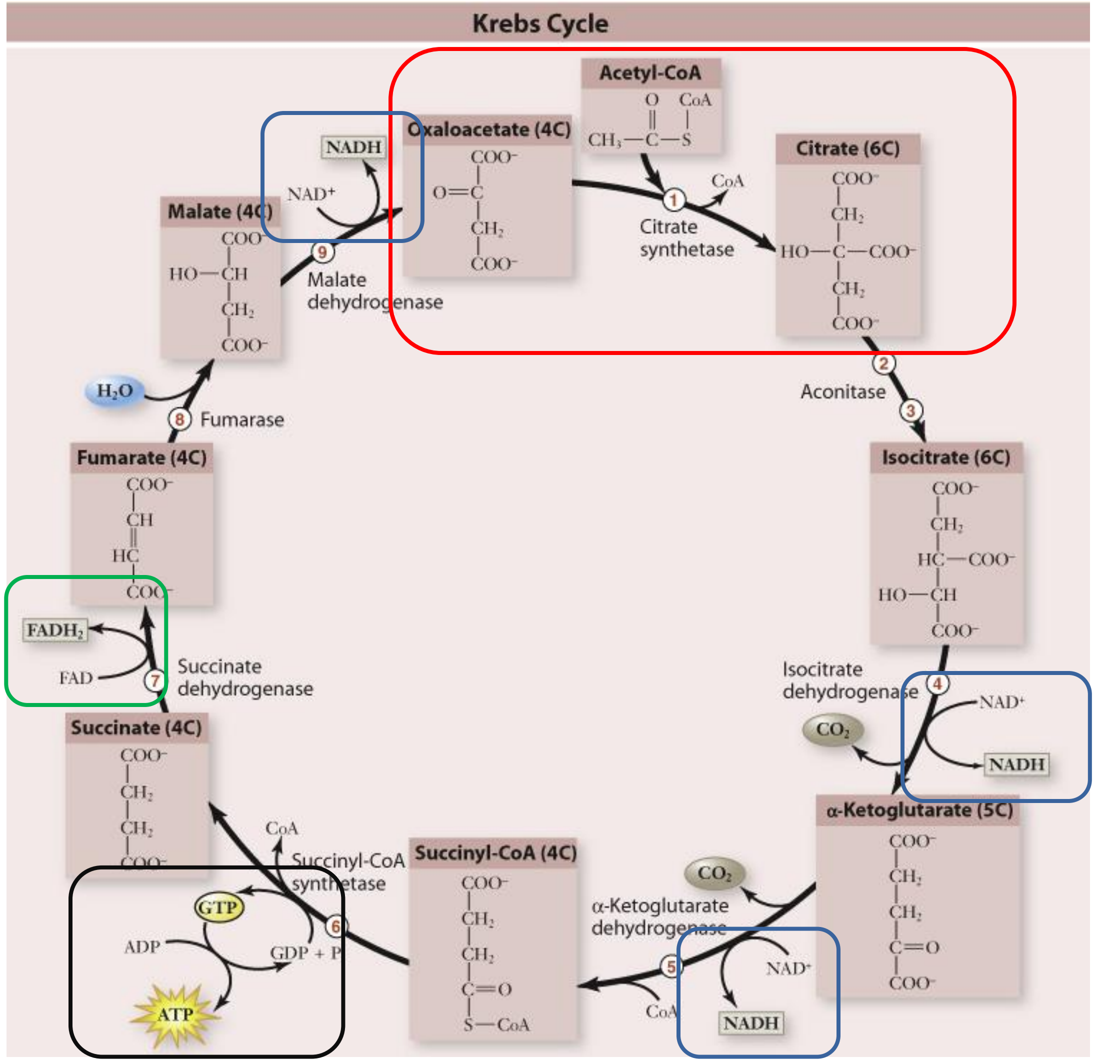
- Cyclical metabolic pathway
- 9 reactions
- Occurs in the mitochondrial matrix
- Completes breakdown of glucose to carbon dioxide
- 1 glucose → 2 acetyl Co-A → 2 Kreb cycles → total 4 CO_2

Krebs Cycle Overview





See textbook p.127



Krebs Cycle
Acetyl-CoA
Oxaloacetate (4C)
Citrate (6C)
CoA
Citrate synthetase
Aconitase
Isocitrate (6C)
Isocitrate dehydrogenase
NAD+
NADH
CO2
α-Ketoglutarate (5C)
α-Ketoglutarate dehydrogenase
NAD+
NADH
CO2
CoA
Succinyl-CoA (4C)
Succinyl-CoA synthetase
CoA
GTP
GDP + P
ADP
ATP
Succinate (4C)
Succinate dehydrogenase
FAD
FADH2
Fumarate (4C)
Fumarase
H2O
Malate (4C)
Malate dehydrogenase
NAD+
NADH

Kreb's Cycle – Net production

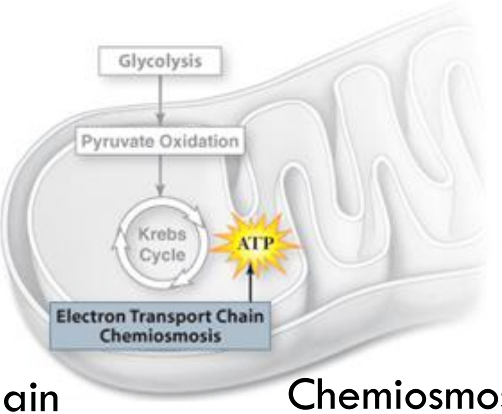
- The net production for **<u>each</u>** acetyl-CoA is:

  3 NADH, 1 $FADH_2$, and 1 ATP.

- NADH and $FADH_2$ will be used to produce ATP in the oxidative phosphorylation pathway.

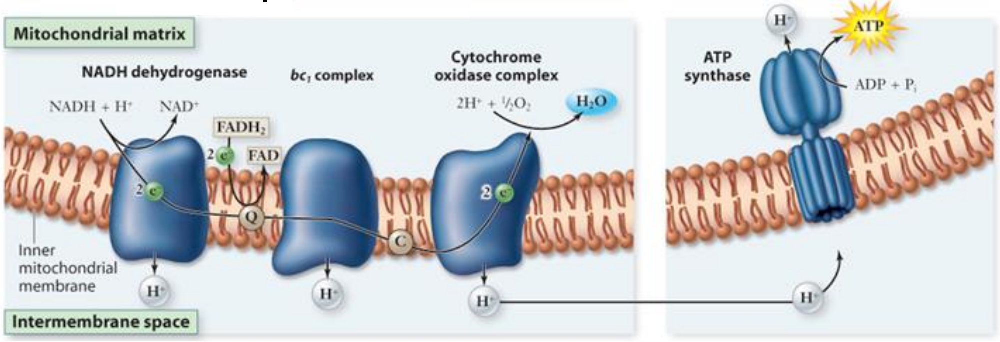
4. Oxidative Phosphorylation

- Oxidation of NADH and $FADH_2$ by electron transport chain
- Produces ATP in chemiosmosis
- Oxygen (electron acceptor) is converted to water
- Energy transferred from electron carriers to ATP



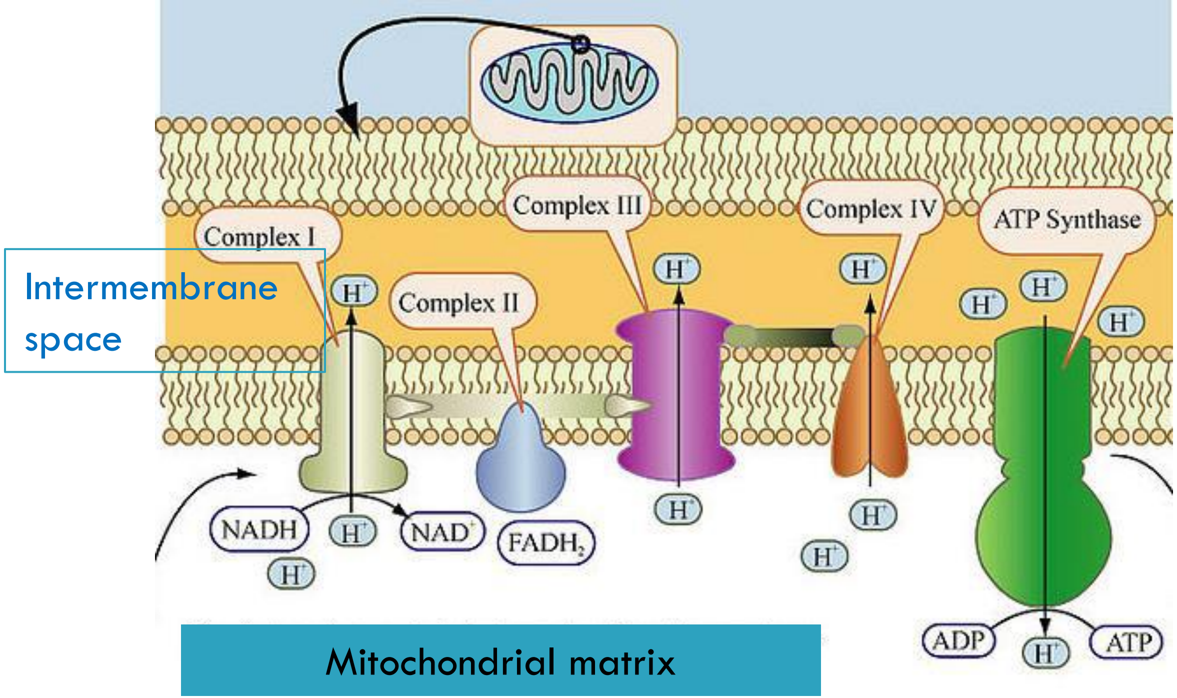
Electron transport chain

Chemiosmosis



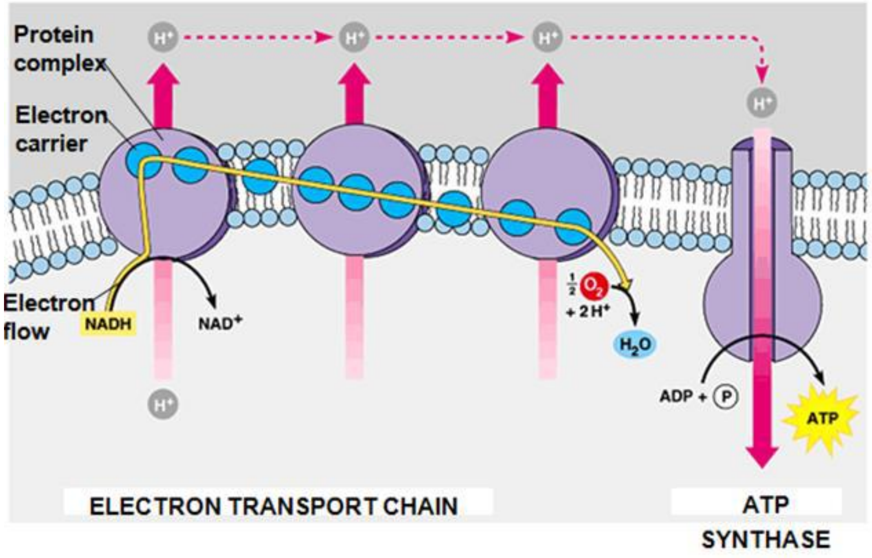
Electron Transport Chain

- A series of electron carriers and proteins
- Embedded in the inner membrane of mitochondrion
- Arranged in order of increasing electronegativity



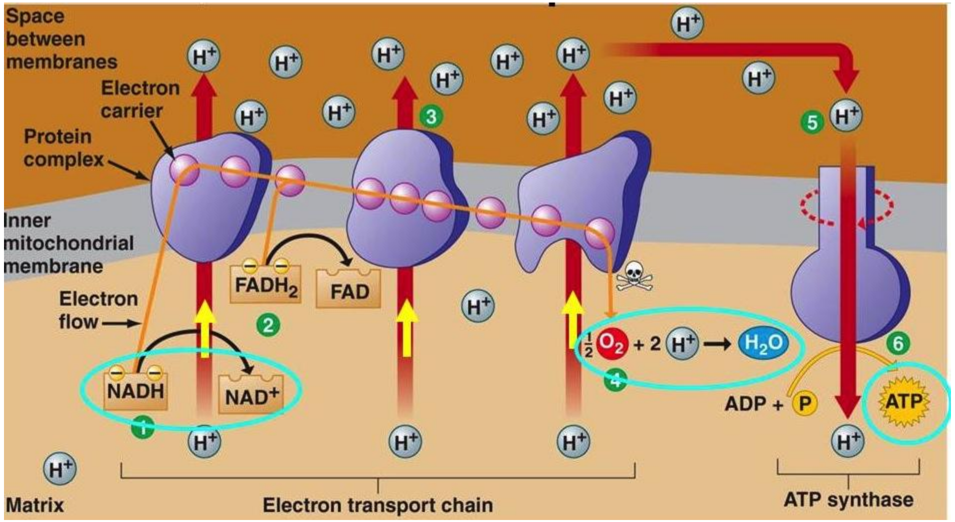
Electron Transport Chain

- A series of REDOX reactions occur between each protein complex to transfer electrons
- 2 electrons are transferred each time
- As electrons move down the ETC, energy is release and electrons become more stable



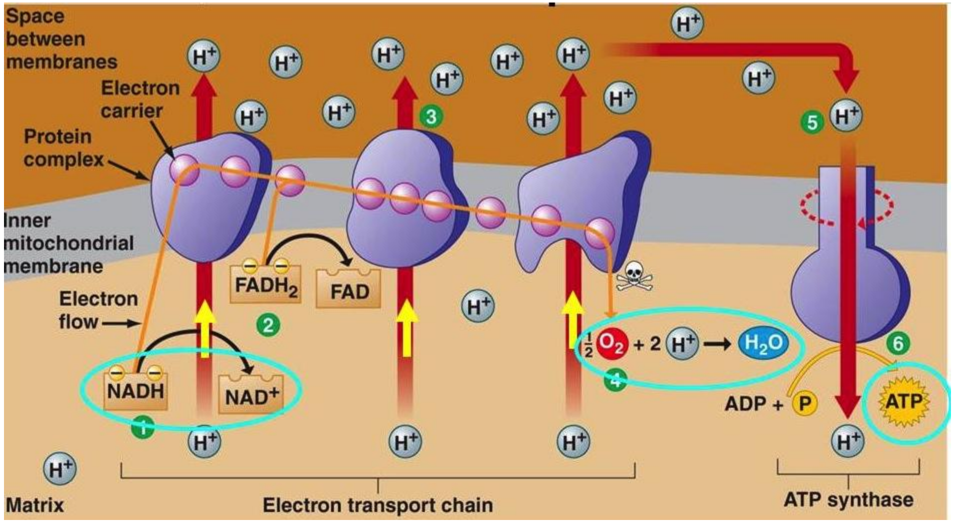
Step 1:

- NADH reduces (donate electrons to) NADH dehydrogenase (Complex I)
- Ubiquitone shuttle electrons to Complex II
- Energy released during the REDOX reaction pumps H+ into the intermembrane space



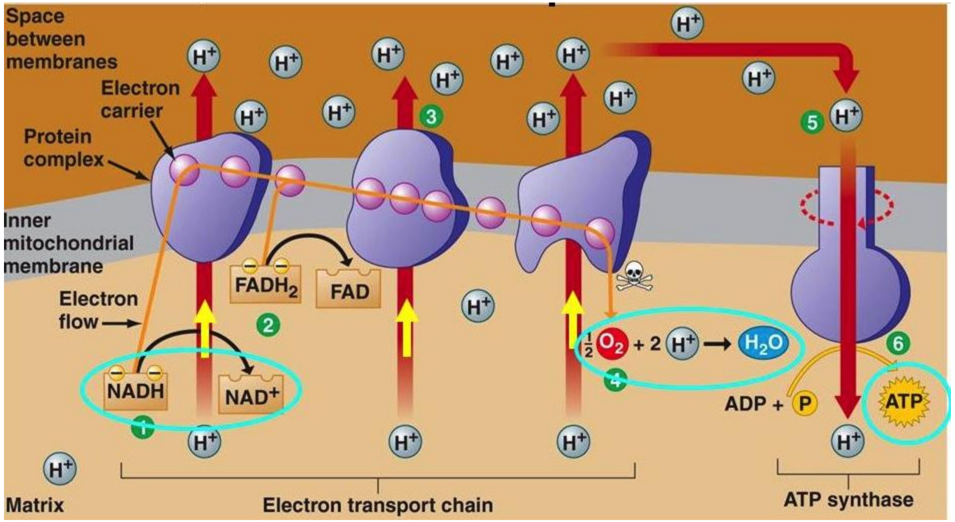
Step 2:

- Cytochrome b-c1 (Complex II) receives electrons from ubiquitone and is reduced
- Cytochrome C shuttle electrons to Complex II
- Energy released during the REDOX reaction pumps H+ into the intermembrane space



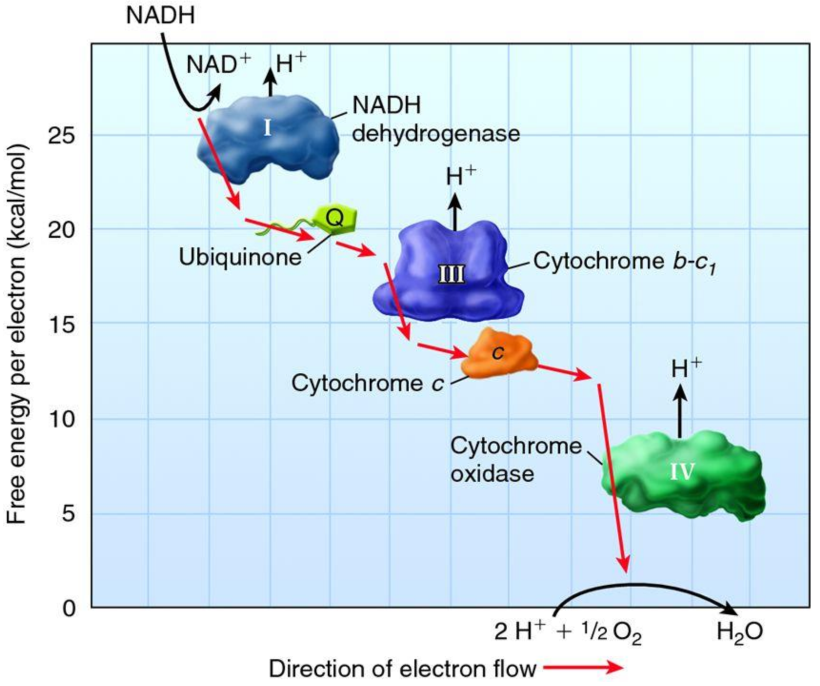
Step 3:

- Cytochrome C reduces Cytochrome oxidase complex (Complex III)
- Oxygen is very electronegative and plucks electrons away from Complex III
- O_2 combines with H^+ to form H_2O



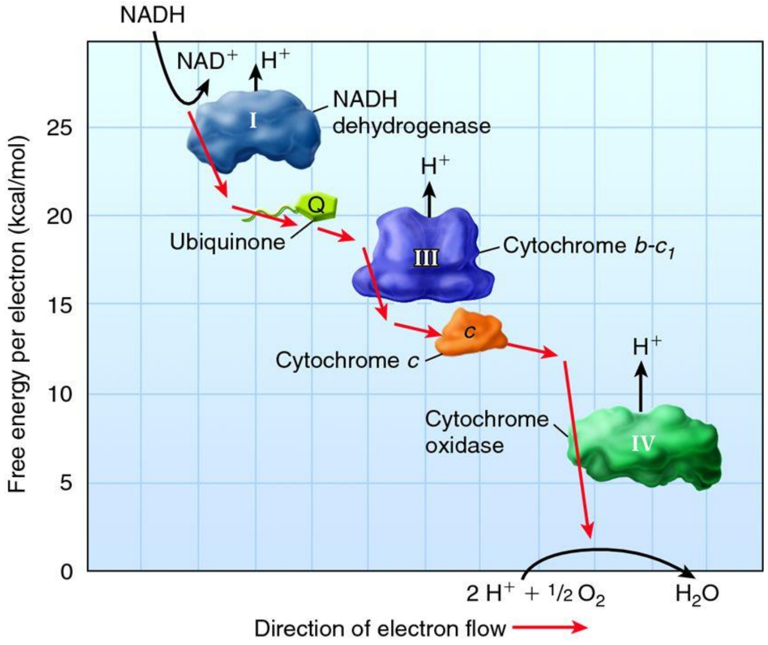
Electron Transport Chain - Energy

- Highly exergonic
- Free energy released is used to pump H^+ into the intermembrane space



Electron Transport Chain - Energy

- No substrates or products are involved in electron transport.
- The electron carriers continuously cycle between their reduced form and their oxidized form while passing electrons from one to the next and finally to oxygen

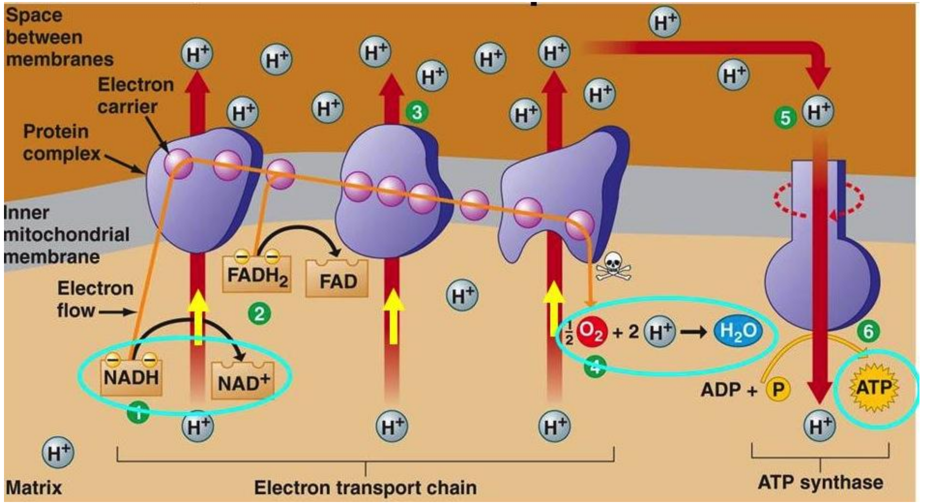


NADH vs $FADH_2$

NADH	$FADH_2$
Pumps out 3 H^+	Pumps out 2 H^+
Produces more ATP	Enter ETC at ubiquitone

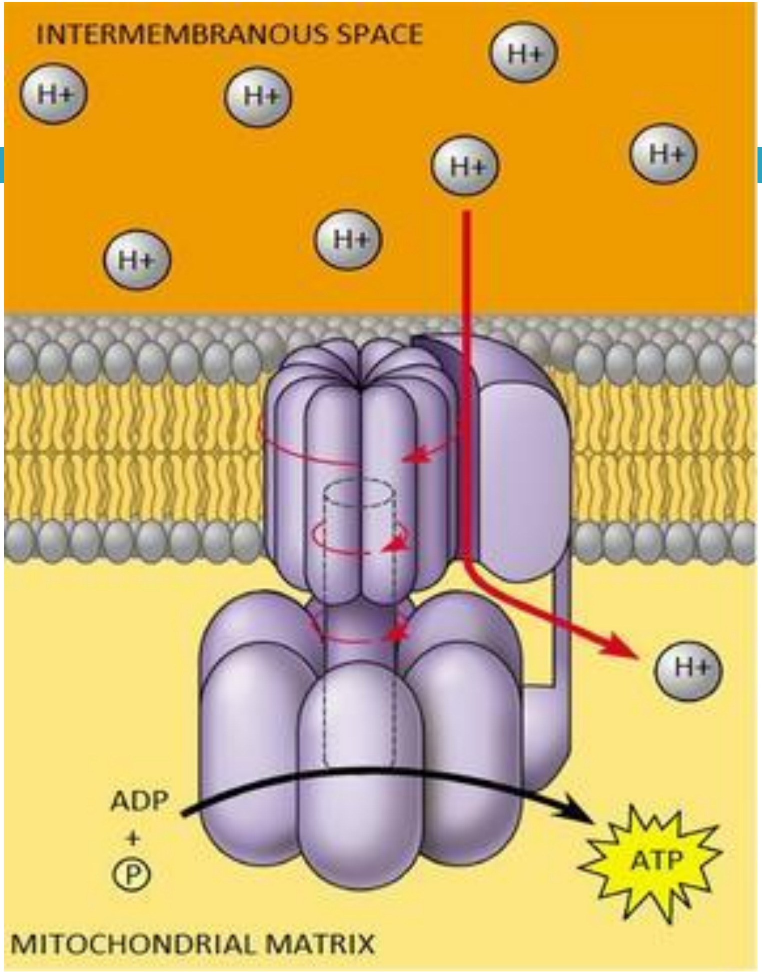
Electron Transport Chain & Chemiosmosis

- Inner mitochondrial membrane prevents H^+ from flowing back into the matrix
- Protons pumped into the intermembrane space during ETC creates an electrochemical gradient
- → drive the synthesis of ATP

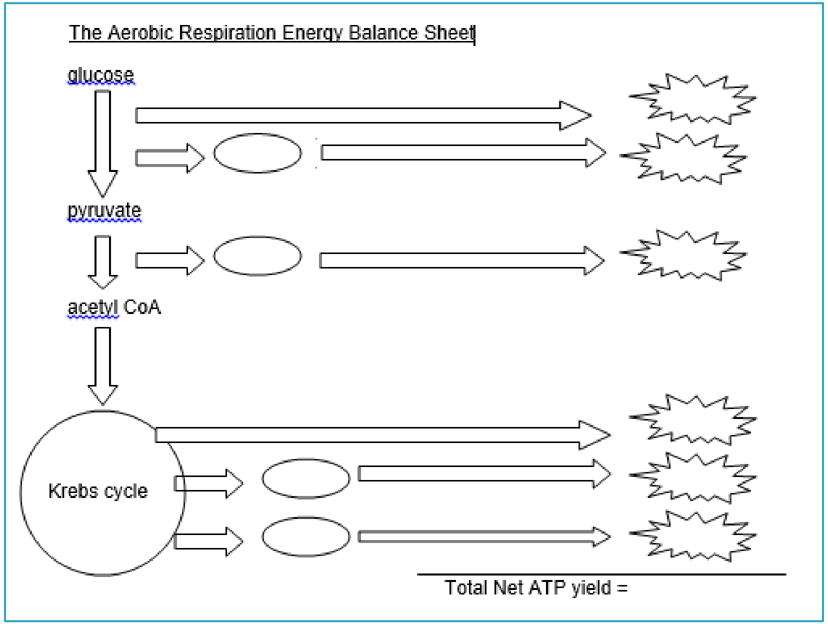


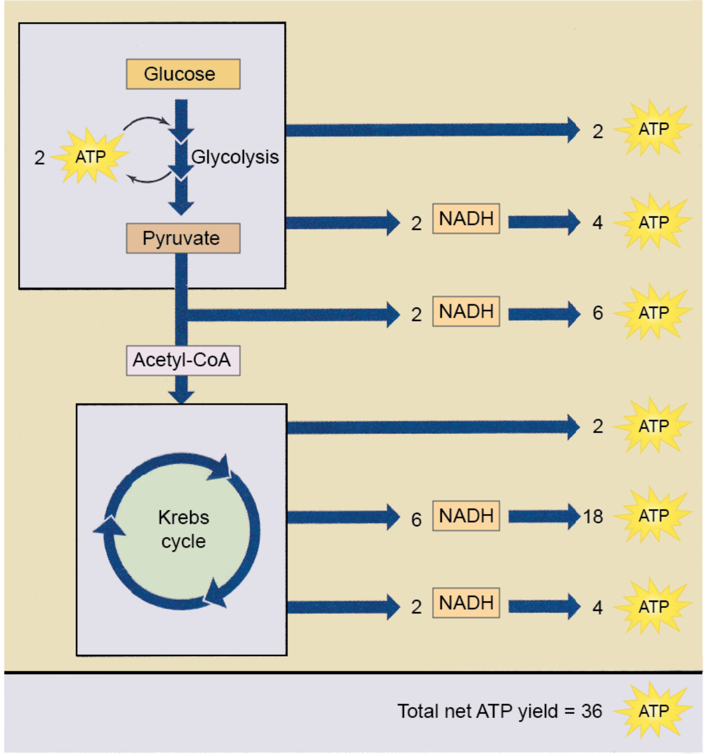
Chemiosmosis

- The process in which ATPase converts energy from the electrochemical gradient to synthesize ATP
- ADP + P_i → ATP



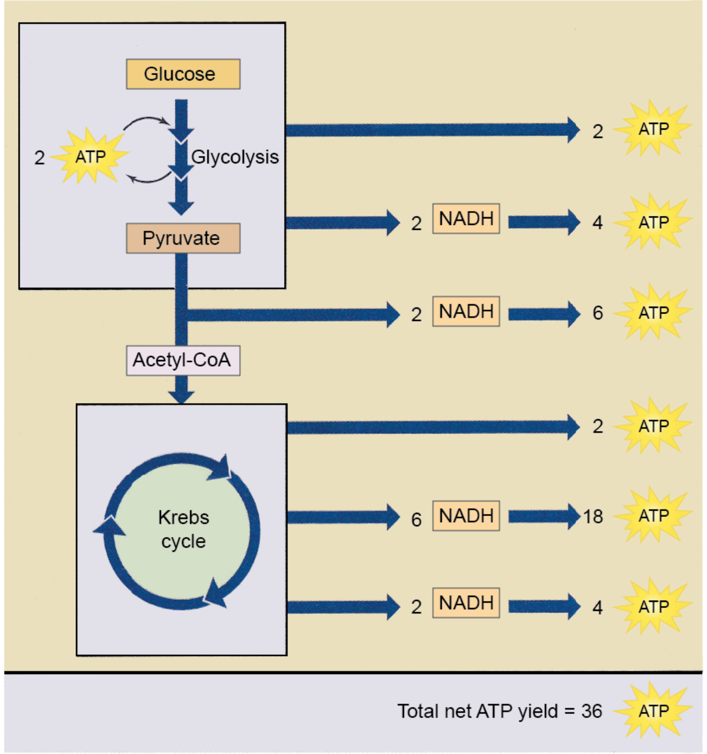
Aerobic Respiration – Energy Balance Sheet





Aerobic Respiration – Energy Balance Sheet

- Prokaryotes can generate 38 ATP
- they do not have to use up 2 ATP to transport NADH from glycolysis across the mitochondrial membranes

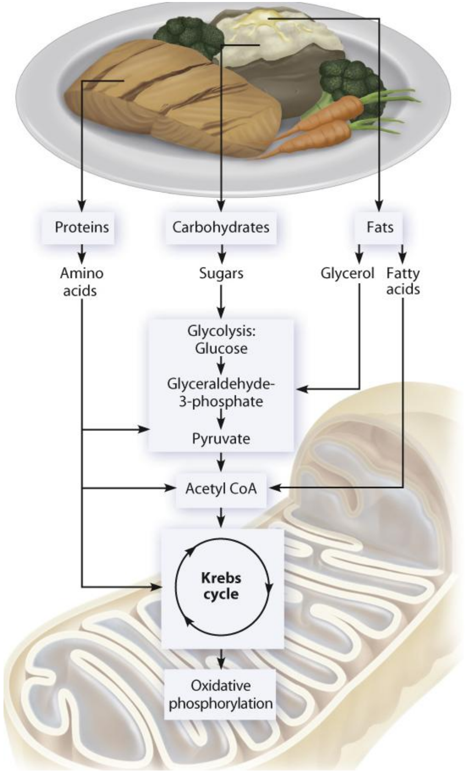


Aerobic Respiration – Energy Balance Sheet

- Experimental observations show only 30-32 ATP are produced. Because:
- Some protons leak through the inner mitochondrial membrane
- Some energy is used to transport pyruvate into the mitochondria
- Some energy is used to transport ATP into cytoplasm for use

Interconnections of Metabolic Pathways

- Compounds from the breakdown of all dietary nutrients can be converted into intermediates in glycolysis and the Kreb's cycle
- They can enter/leave at many different stages of the pathways



Regulation of Aerobic Catabolic Pathways

- Rate of ATP production is controlled by feedback mechanisms.
- Ratio of ATP to ADP remains constant
- Enzymes involved are:

1. Phosphofructokinase (in glycolysis)
2. Pyruvate dehydrogenase (in pyruvate oxidation)