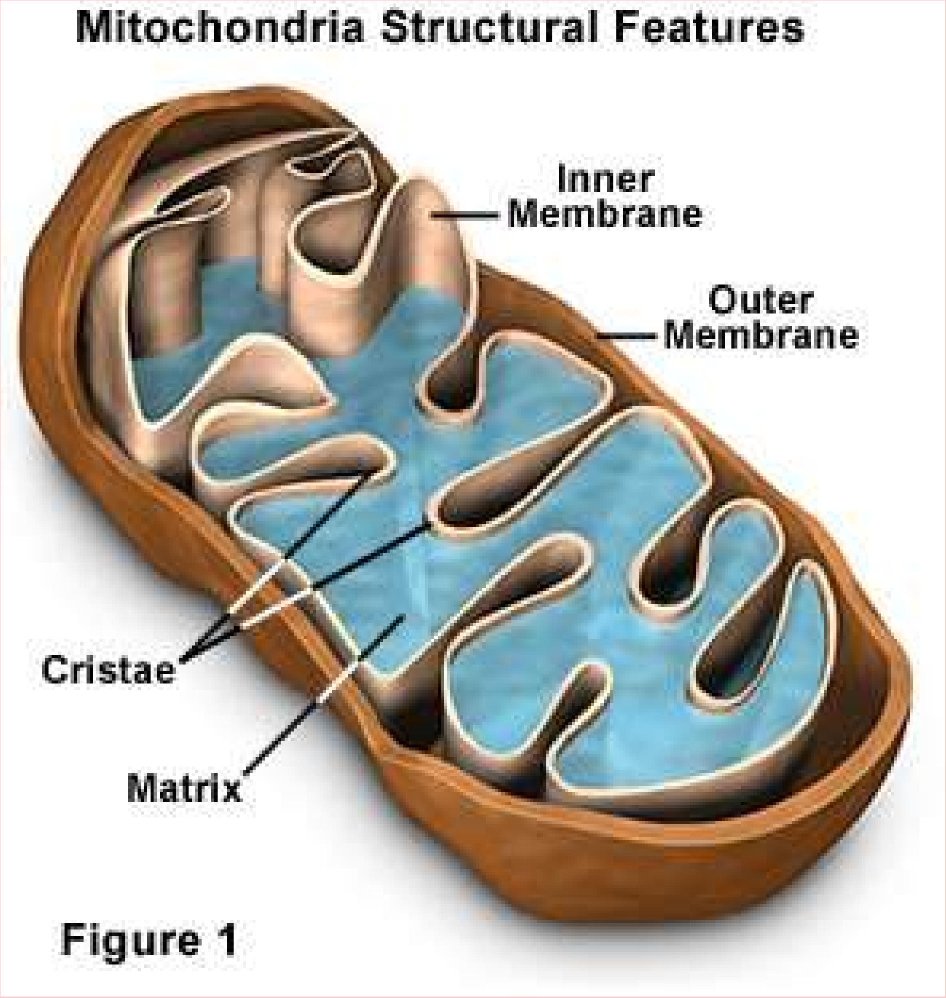
Cellular Respiration



Mitochondria Parts and Functions

Mitochondrial Parts	Functions in Cellular Respiration
Outer mitochondrial membrane	Separates the contents of the mitochondrion from the rest of the cell
Matrix	Internal cytosol-like area that contains the enzymes for the link reaction & Krebs Cycle
Cristae	Tubular regions surrounded by membranes increasing surface area for oxidative phosphorylation
Inner mitochondrial membrane	Contains the carriers for the ETC & ATP synthase for chemiosmosis
Space between inner & outer membranes	Reservoir for hydrogen ions (protons), the high concentration of hydrogen ions is necessary for chemiosmosis

Oxidation and reduction

- Cellular respiration involves the oxidation and reduction of compounds.
  - They occur together because they involve the transfer of electrons.
- Electron carriers are substances that can accept and give up electrons as required.
  - The main one for cellular respiration is NAD

Oxidation and Reduction

Oxidation	Reduction
Loss of electrons	Gain of electrons
Gain of oxygen	Loss of oxygen
Loss of hydrogen	Gain of hydrogen
Results in many C – O bonds	Results in many C – H bonds
Results in a compound with lower potential energy	Results in a compound with higher potential energy

A useful way to remember: OIL = Oxidation Is Loss (of electrons)

RIG= Reduction Is Gain (of electrons)

These two reactions occur together during chemical reactions= redox reactions. One compound's or element's loss is another compound's or element's gain.

becomes oxidized

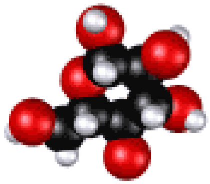
$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

becomes reduced

Cellular Respiration

- 3 Major stages
  - Glycolysis
  - The citric acid cycle (TCA or Krebbs)
  - Oxidative phosphorylation

$C_6H_{12}O_6$ + 6O_2 <----> 6 CO_2 + 6 $H_2$0 + e- ---> 36-38 ATP



Respiration

- Glycolysis
  - Rearranges the bonds in glucose releasing free energy in the form of ATP & producing two molecules of pyruvate
- The citric acid cycle (Krebs Cycle)
  - Completes the breakdown of glucose releasing carbon dioxide; synthesizing ATP & electrons are carried off by NADH & $FADH_2$
- Oxidative phosphorylation
  - Is driven by the electron transport chain
  - Generates ATP

Where does all the magic happen?

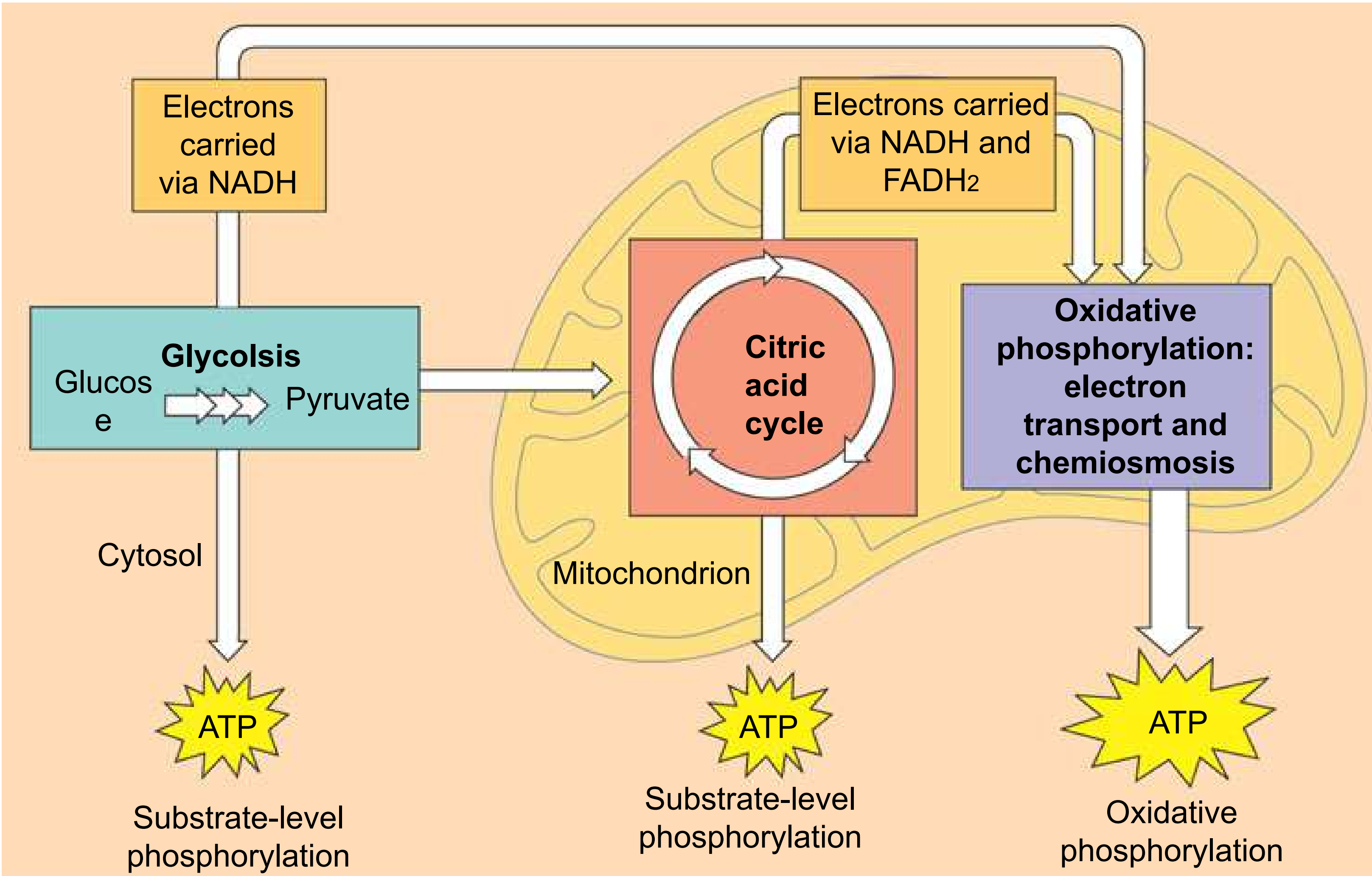
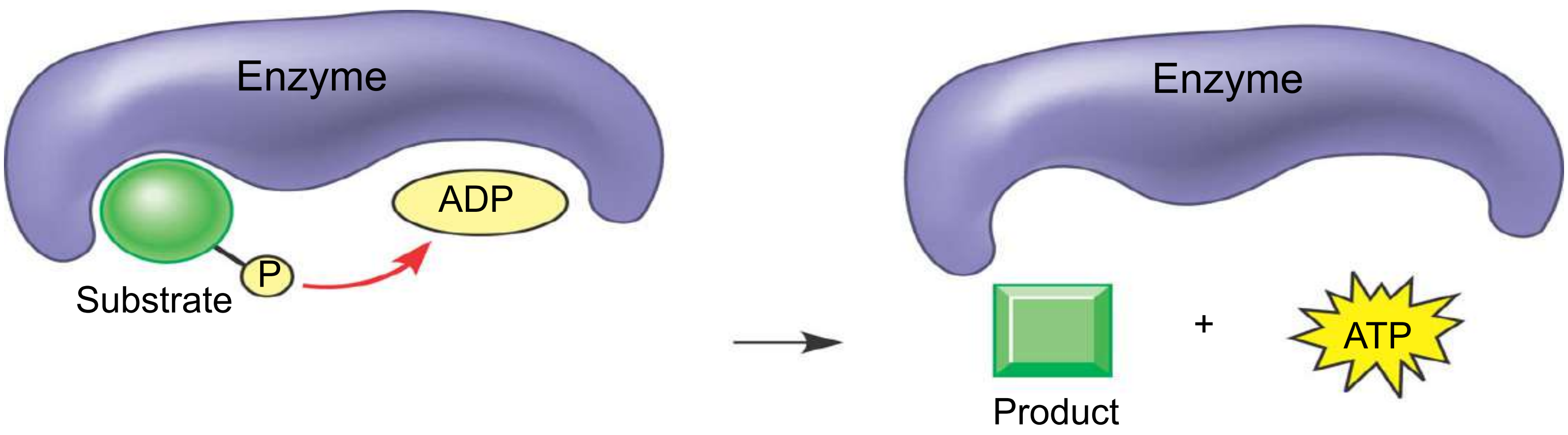


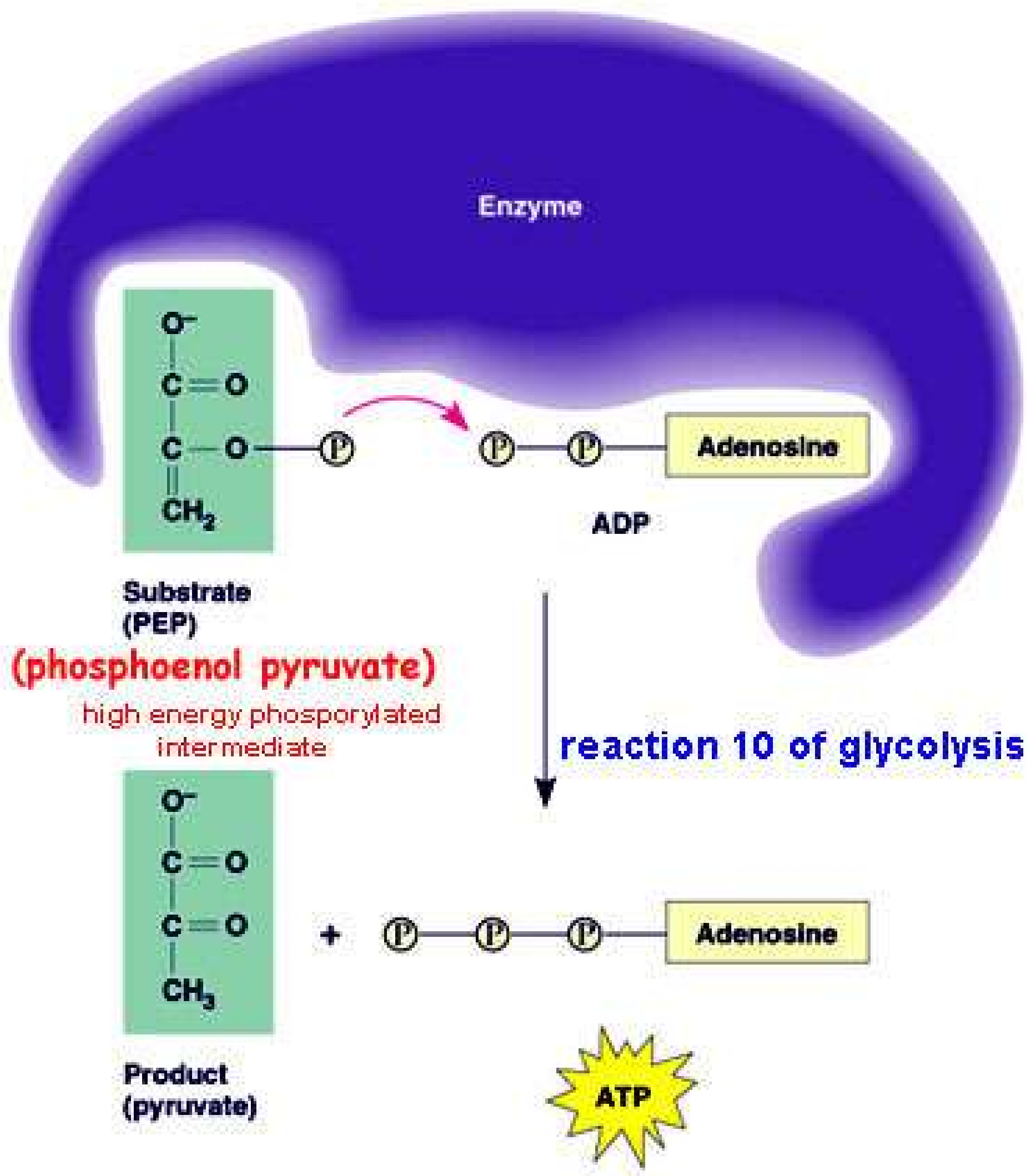
Figure 9.6

2 ATP 2 ATP 32-34 ATP

Substrate Level Phosphorylation

- Occurs in both glycolysis & the citric acid cycle
  - In order to make an adenosine triphosphate, a phosphate group is taken from an intermediate compound, referred to as a substrate, and given to an ADP molecule.




Enzyme
O⁻
C=O
C—O—P
CH2
P—P—Adenosine
ADP
Substrate (PEP)
(phosphoenol pyruvate)
high energy phosporylated intermediate
reaction 10 of glycolysis
O⁻
C=O
C=O
CH3
+ P—P—P—Adenosine
Product (pyruvate)
ATP

1) Which of the following statements concerning the metabolic degradation of glucose ($C_6H_{12}O_6$) to carbon dioxide (CO_2) and water is (are) *true*?

A) The breakdown of glucose to carbon dioxide and water is exergonic.
B) The breakdown of glucose to carbon dioxide and water has a free energy change of -686 kcal/mol.
C) The breakdown of glucose to carbon dioxide and water involves oxidation-reduction or redox reactions.
D) Only A and B are correct.
A, B, and C are correct.

2) Which of the following statements is (are) correct about an oxidation-reduction (or redox) reaction?

A) The molecule that is reduced gains electrons.
B) The molecule that is oxidized loses electrons.
C) The molecule that is reduced loses electrons.
D) The molecule that is oxidized gains electrons.
Both A and B are correct.

3) Which of the following statements describes the results of this reaction?

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

) $C_6H_{12}O_6$ is oxidized and O_2 is reduced.
B) O_2 is oxidized and H_2O is reduced.
C) CO_2 is reduced and O_2 is oxidized.
D) $C_6H_{12}O_6$is reduced and CO_2 is oxidized.
E) O_2 is reduced and CO_2 is oxidized.

4) Which process in eukaryotic cells will proceed normally whether oxygen (O_2) is present or absent?
A) electron transport
glycolysis
C) the citric acid cycle
D) oxidative phosphorylation
E) chemiosmosis

5) Which of the following statements about glycolysis *false*?
A) Glycolysis has steps involving oxidation-reduction reactions.
B) The enzymes of glycolysis are located in the cytosol of the cell.
C) Glycolysis can operate in the complete absence of O2.
) The end products of glycolysis are CO2 and H2O.
E) Glycolysis makes ATP exclusively through substrate-level phosphorylation.

Major Stages of Cellular Respiration

Stages	Starting molecule	End Product	Location	Substrate level phosphorylation	Energy shuttled to oxidative phosphorylation
Glycolysis	1 glucose	2 pyruvate	cytosol	2 ATP	2 NADH
Linkage Reaction	2 pyruvate	Acetyl Co-A, 2 CO_2	Matrix of mitochondria	None	2 NADH
Krebs Cycle (CAC)	2 acetyl-CoA	4 CO_2	Matrix of mitochondria	2 ATP	6 NADH 2 $FADH_2$
ETC and oxidative phosphorylation	electrons	ATP	Inner membrane of mitochondria	none	none

By oxidative phosphorylation
32-34 ATP's are produced

Glycolysis

- Harvests energy by oxidizing glucose to pyruvate

- Glycolysis
  - Means "splitting of sugar"
  - Breaks down glucose into pyruvate
  - Occurs in the cytosol of the cell

- Two major phases
  - Energy investment phase
  - Energy payoff phase

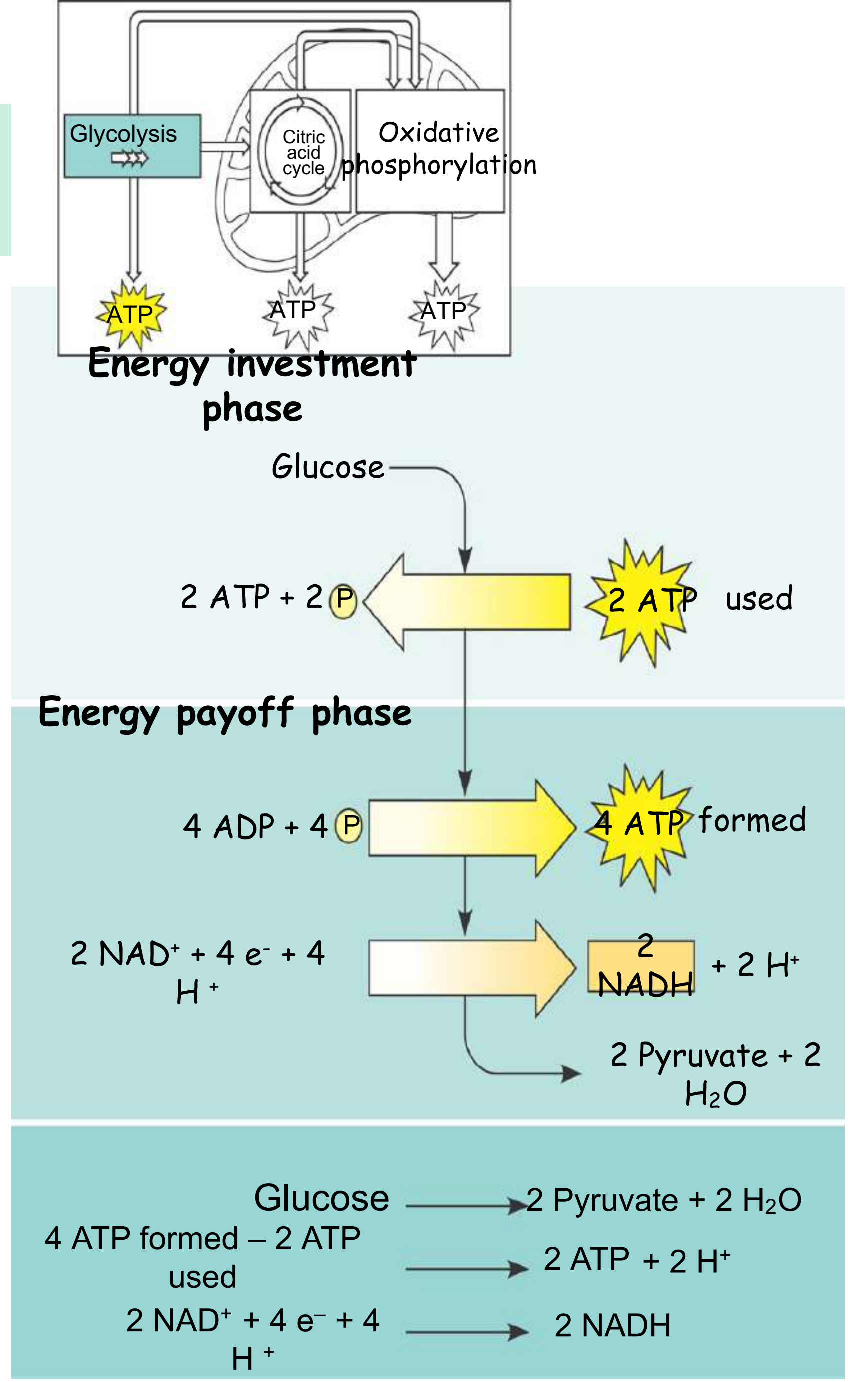
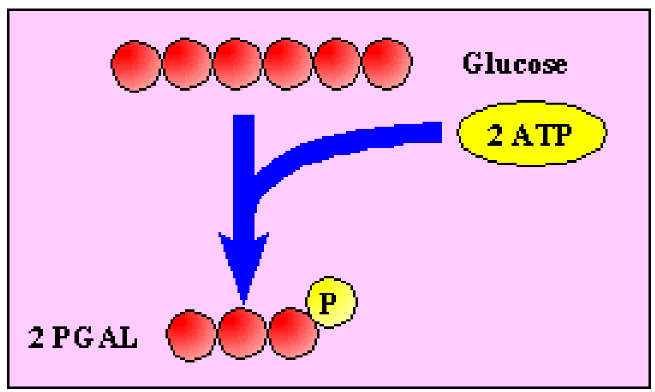


Figure 9.8

The First Stage of Glycolysis

Glucose (6C) is broken down into 2 PGAL's (3C sugar)
This requires two ATP's



ENERGY INVESTMENT STAGE

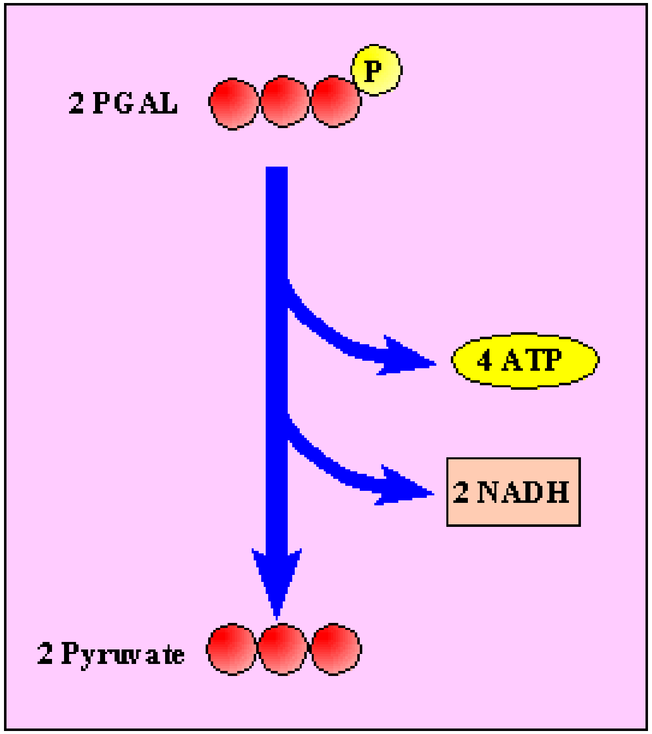
The Second Stage of Glycolysis

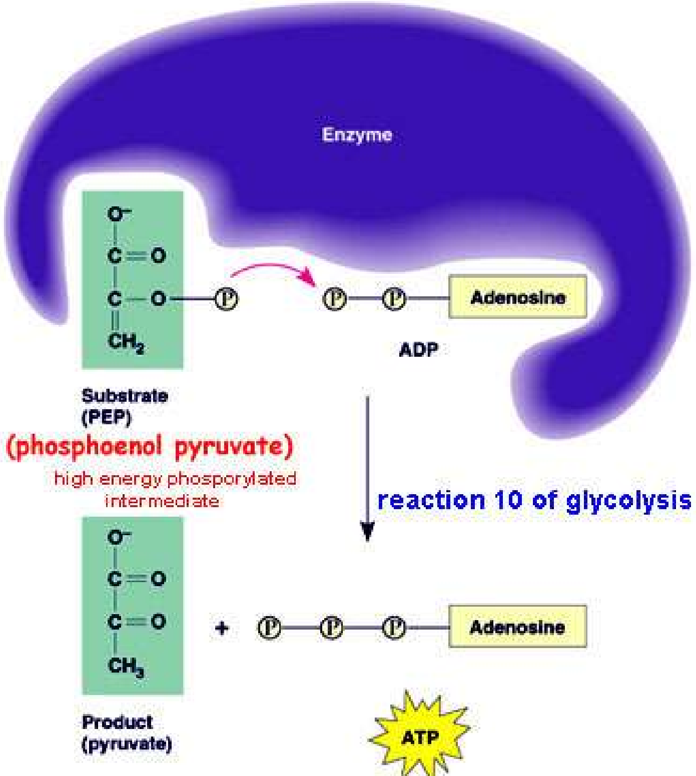
2 PGAL's (3C) are converted to 2 pyruvates

This creates 4 ATP's and 2 NADH's (electron shuttlers)

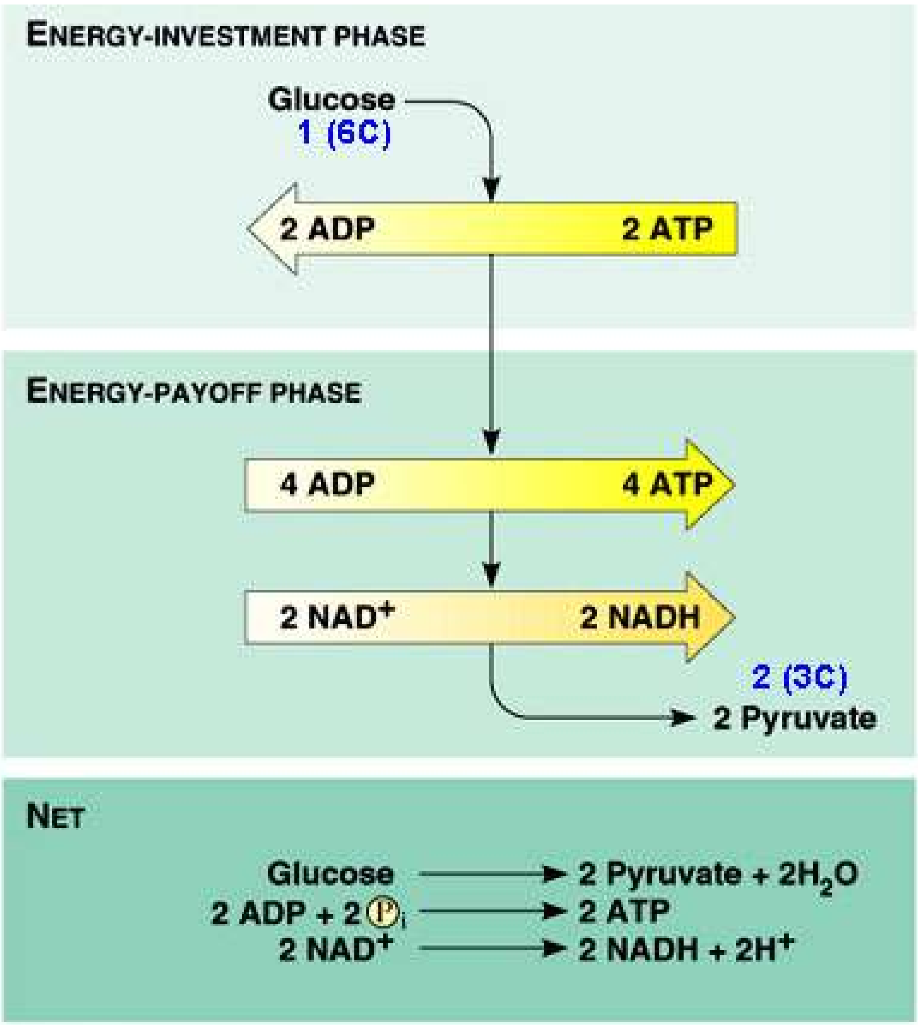
The **net** ATP production of Glycolysis is 2 ATP's

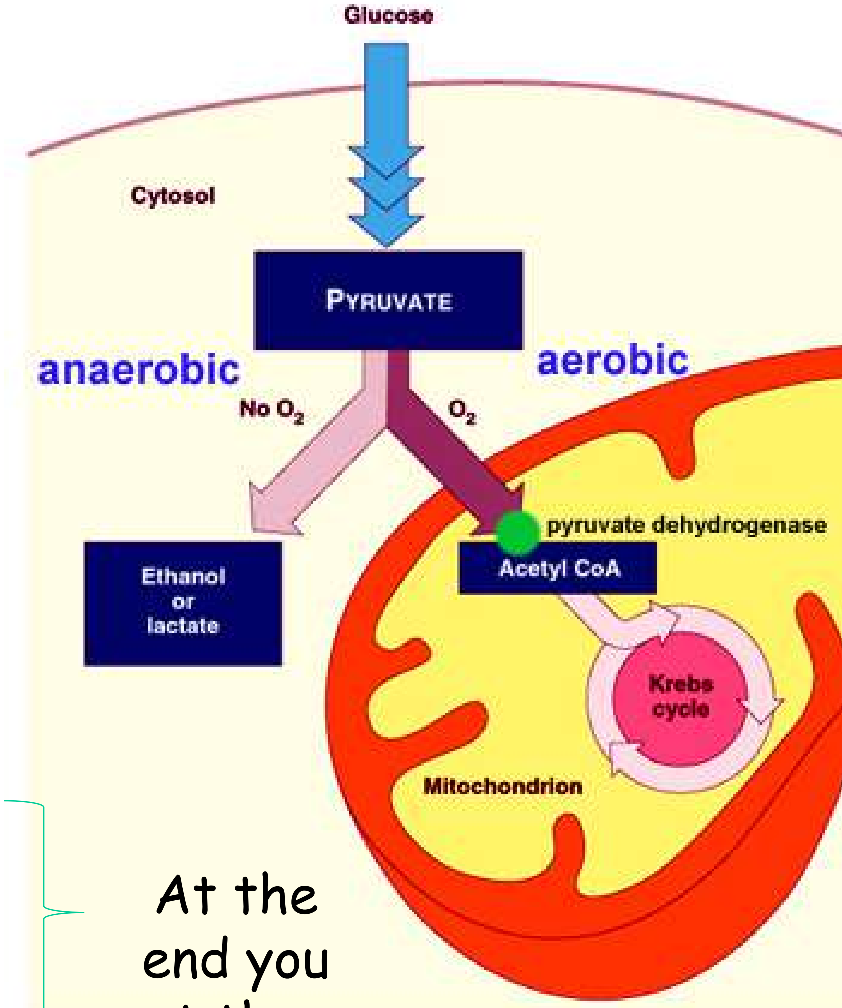
ENERGY PAY-OFF STAGE





Glycolysis Summary





At the end you get these

- Glycolysis
  - Occurs in nearly all organisms
  - Probably evolved in ancient prokaryotes before there was oxygen in the atmosphere

Feedback inhibition

- Cellular respiration
  - Is controlled by allosteric enzymes at key points in glycolysis and the citric acid cycle
  - If ATP levels get too high feedback inhibition will block the 1st enzyme of the pathway.

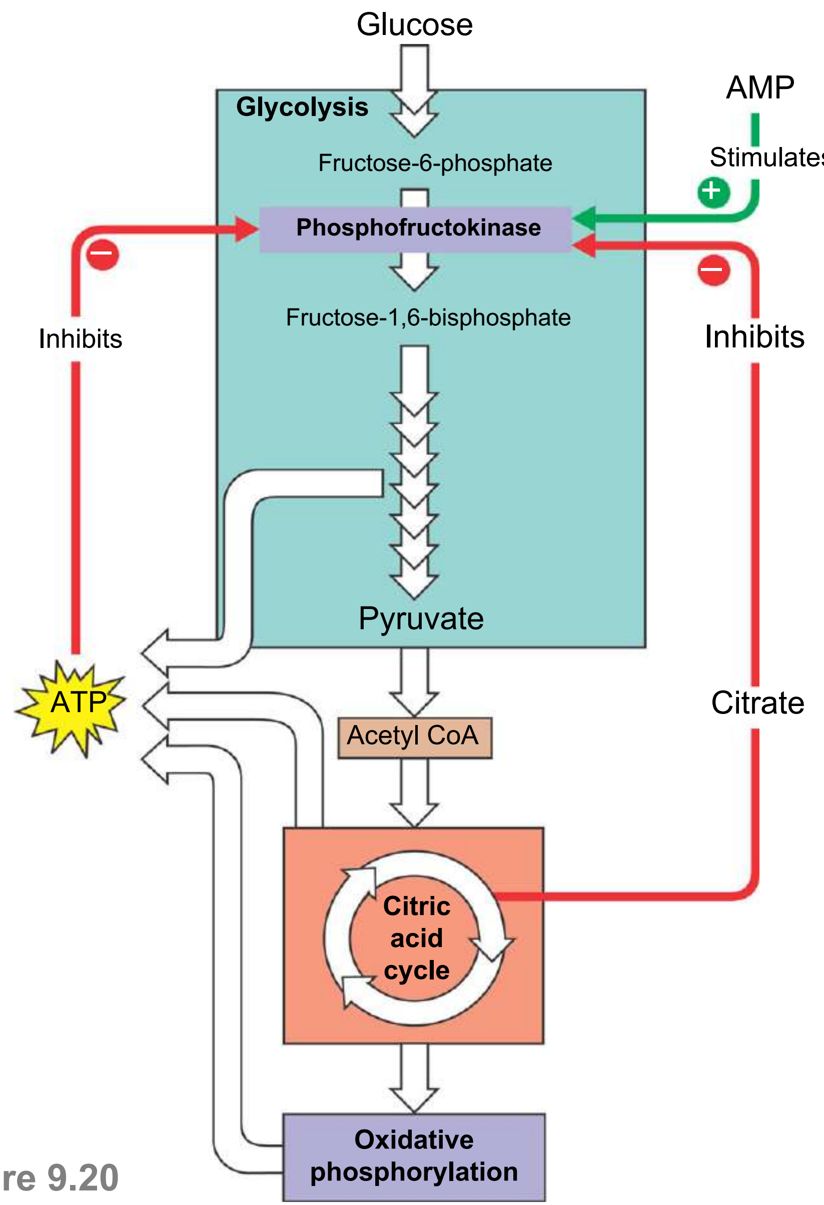


Figure 9.20

Before the Krebs cycle can begin….we have the link reaction

- Pyruvate must first be converted to acetyl CoA, which links the cycle to glycolysis

What is lost or gained during this process?

One carbon atom is lost as CO_2 , an electron is given to NADH & a different 2-carbon chain is the result.

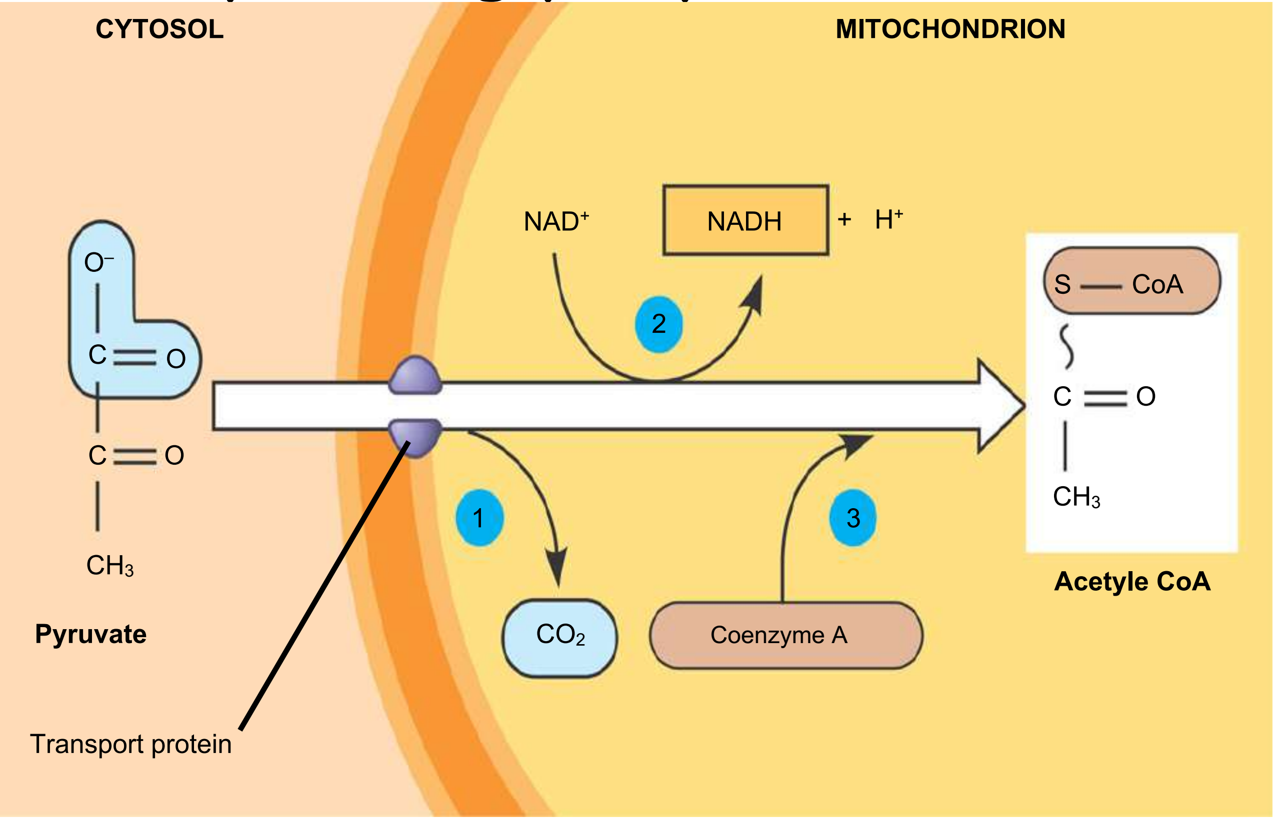
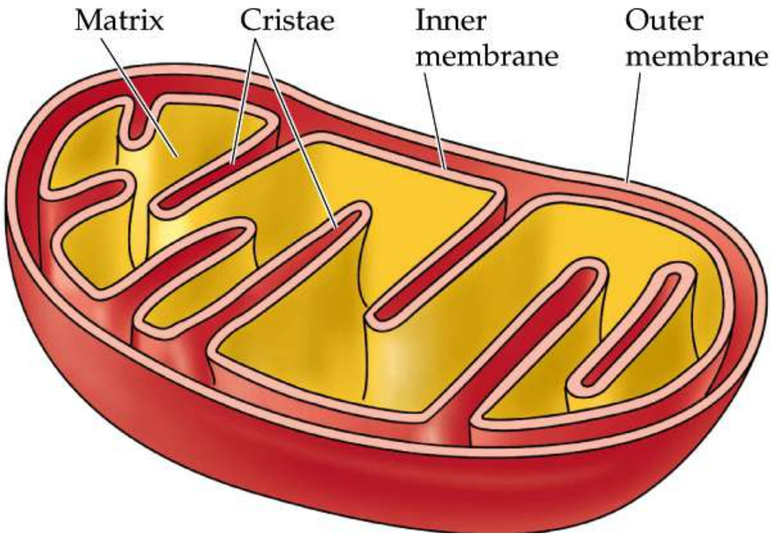


Figure 9.10

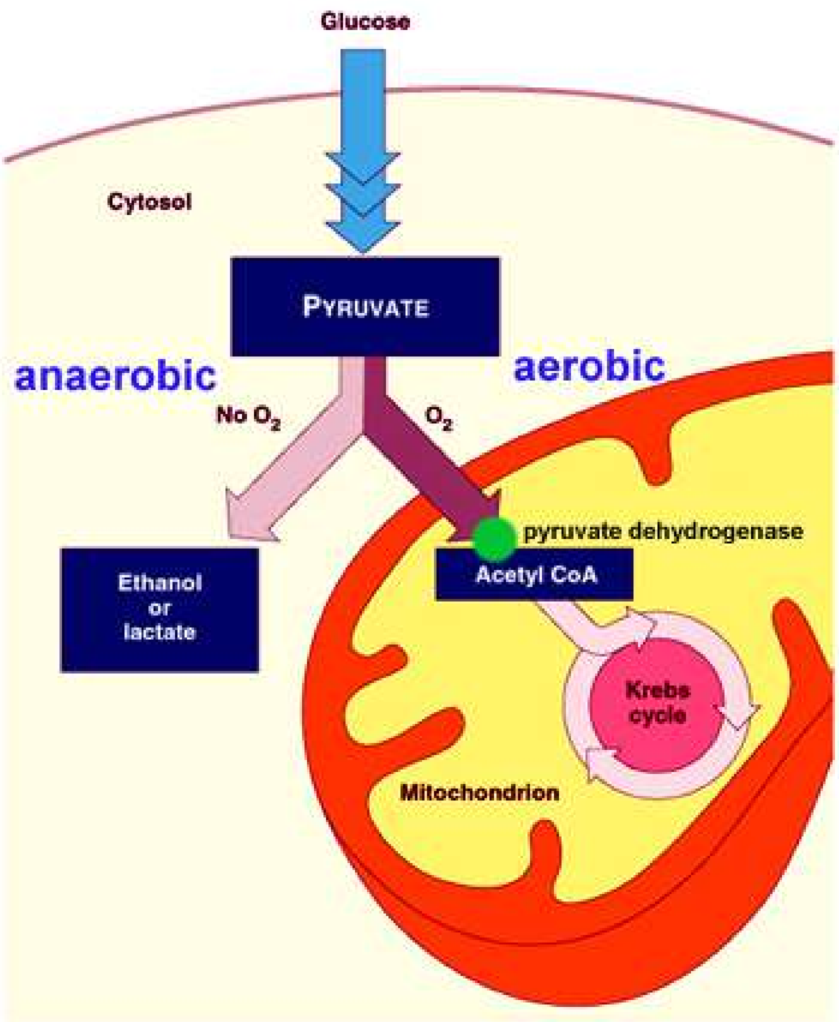
Citric Acid Cycle
a.k.a. Krebs Cycle

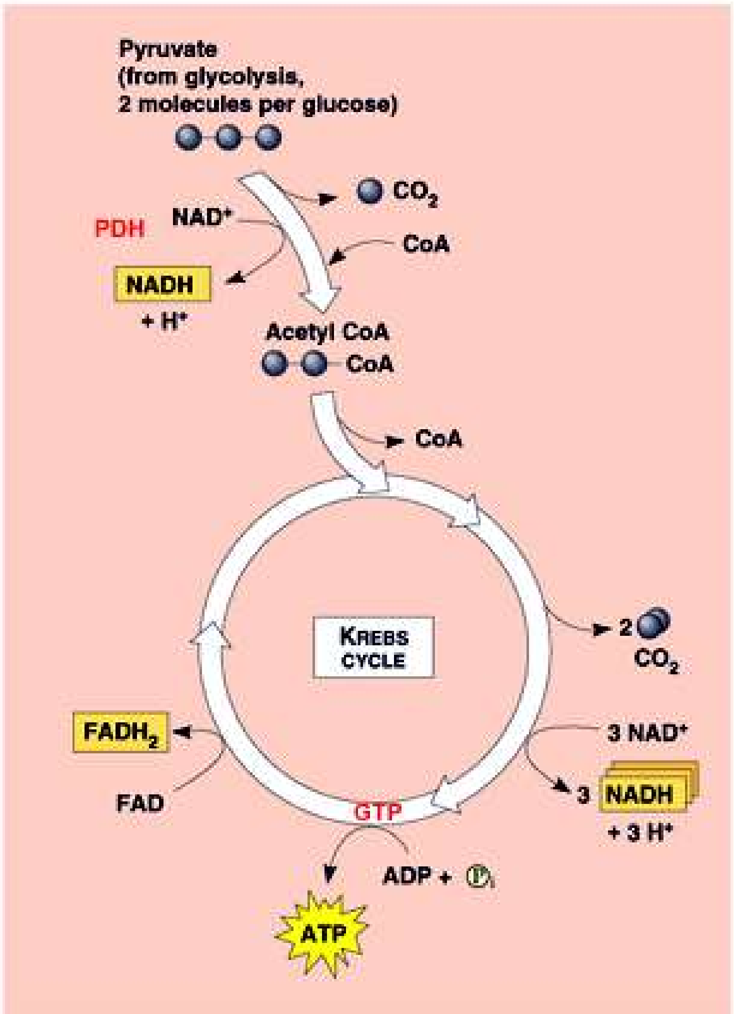
- Completes the energy-yielding oxidation of organic molecules

- The citric acid cycle
  - Takes place in the matrix of the mitochondrion

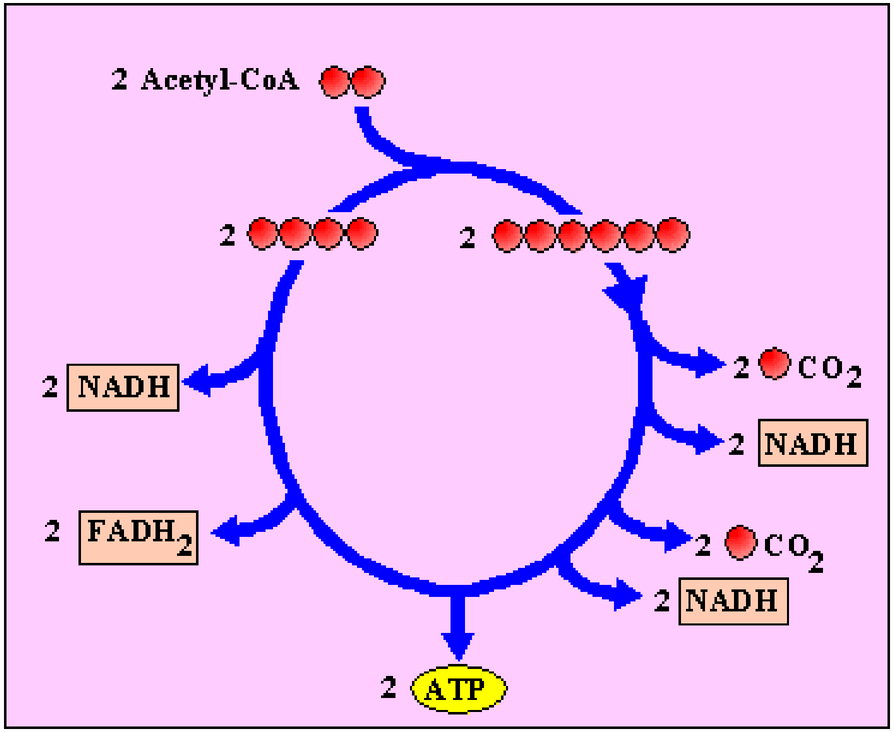


FATE OF PYRUVATE





The Krebs Cycle



6 NADH's are generated
2 $FADH_2$ is generated
2 ATP are generated
4 CO_2's are released

Two turns for each molecule of glucose because each glucose is converted to 2 molecules of acetyl CoA.

Linkage reaction & Krebs's Cycle (citric acid cycle, TCA cycle)

Goal: take pyruvate and put it into the Krebs's cycle, producing $FADH_2$ and more NADH

Where: the mitochondria matrix

There are two steps

- The Conversion of Pyruvate to Acetyl CoA
- The Kreb's Cycle proper

In the Krebs's cycle, all of Carbons, Hydrogens, and Oxygen in pyruvate end up as CO_2 and H_2O

The Krebs's cycle produces 2 ATP's, 6 NADH's, and 2$FADH_2$'s per glucose molecule

If the main purpose of cell respiration is to produce ATP, why do glycolysis & the Krebs cycle only make 4 molecules of ATP total by the time glucose has been converted to carbon dioxide?

Although glycolysis & the Krebs cycle only produce 4 ATP molecules when glucose is converted to CO_2 , these reactions produce 12 shuttle molecules of NADH & $FADH_2$ which will eventually generate 90% of the total ATP production during the final phase of cell respiration.

The free energy for the oxidation of glucose to CO_2 and water is -686 kcal/mole and the free energy for the reduction of NAD^+ to NADH is +53 kcal/mole. Why are only two molecules of NADH formed during glycolysis when it appears that as many as a dozen could be formed?

A)Most of the free energy available from the oxidation of glucose is used in the production of ATP in glycolysis.

B) Glycolysis is a very inefficient reaction, with much of the energy of glucose released as heat.

Most of the free energy available from the oxidation of glucose remains in pyruvate, one of the products of glycolysis

.

D) There is no CO_2 or water produced as products of glycolysis.

E) Glycolysis consists of many enzymatic reactions, each of which extracts some energy from the glucose molecule.

In the presence of oxygen, the three-carbon compound pyruvate can be catabolized in the citric acid cycle. First, however, the pyruvate 1) loses a carbon, which is given off as a molecule of CO_2, 2) is oxidized to form a two-carbon compound called acetate, and 3) is bonded to coenzyme A. These three steps result in the formation of:

A)acetyl CoA, O_2, and ATP.

B) acetyl CoA, $FADH_2$, and CO_2.

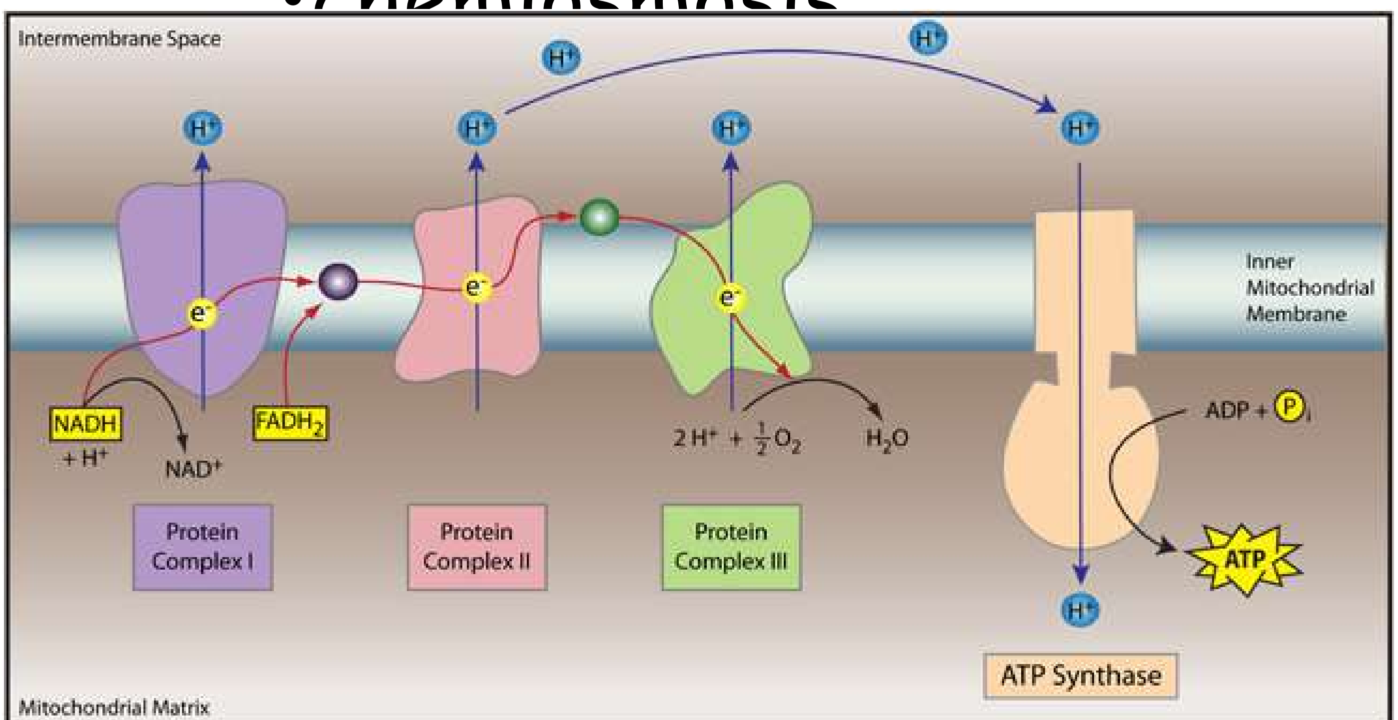
C) acetyl CoA, FAD, H_2, and CO_2.

acetyl CoA, NADH, H^+, and CO_2.

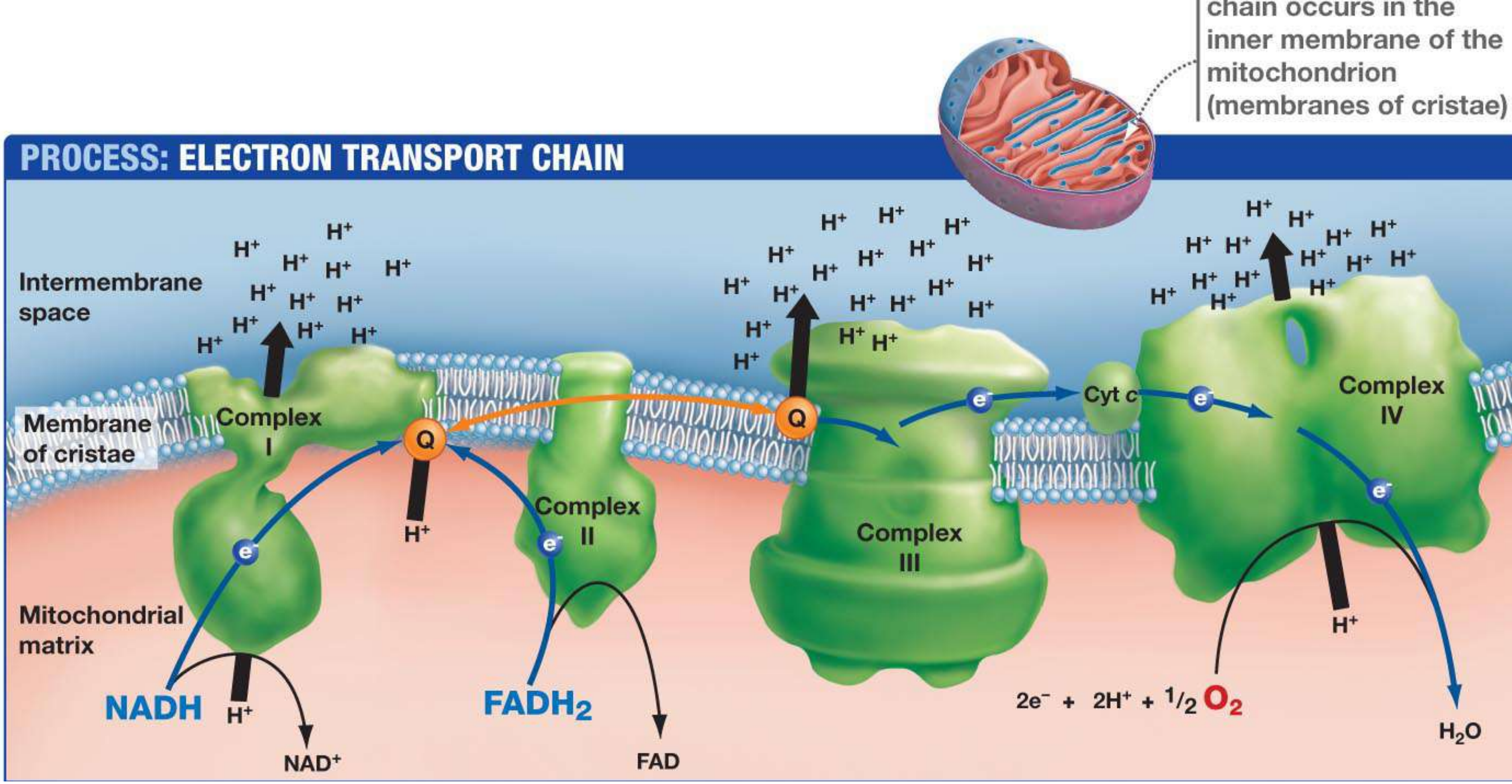
E) acetyl CoA, NAD^+, ATP, and CO_2.

After the Krebs Cycle…

- **Oxidative phosphorylation=**
  - electron transport
  - chemiosmosis



Electron Transport Chain



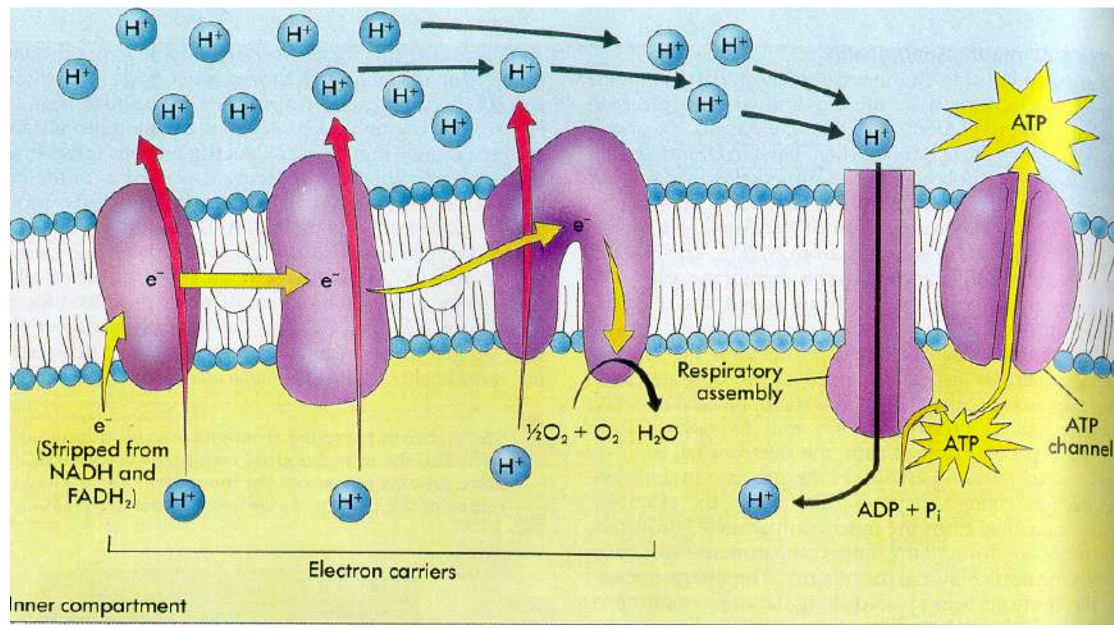
-Electrons from NADH and $FADH_2$ lose energy in several steps

-At the end of the chain electrons are passed to oxygen, forming water

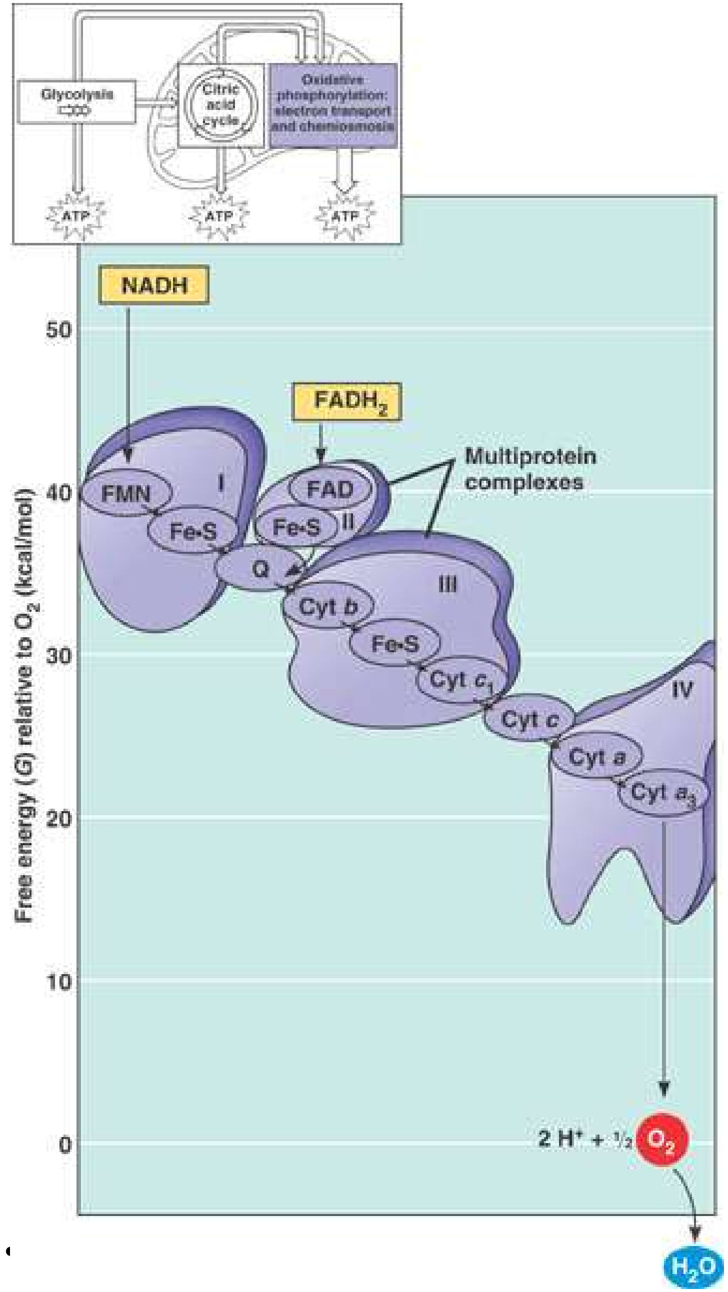
ETC

- Electron transfer causes protein complexes to pump H^+ from the mitochondrial matrix to the intermembrane space

The resulting H^+ gradient
- Stores energy
- Drives chemiosmosis in ATP synthase
- Is referred to as a proton-motive force



- $FADH_2$ enters the ETC at a lower free energy level than the NADH.
  - Results in $FADH_2$ produces 2 ATP's to NADH's 3
- Oxygen is the final electron acceptor
  - The electrons + oxygen + 2 hydrogen ions = H_2O
- Important to note that low amounts of energy is lost at each exchange along the ETC.



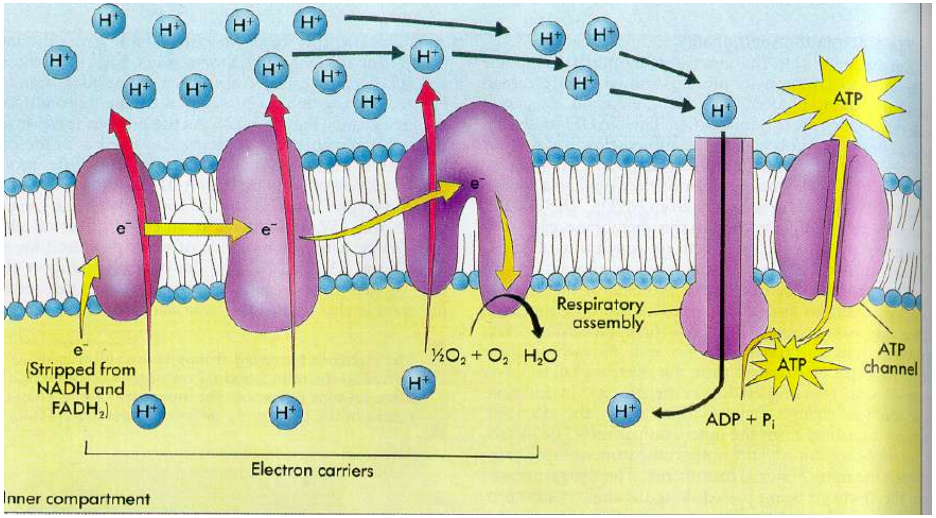
Chemiosmosis

- NADH + H^+ supplies pairs of hydrogen atoms to the 1^{st} carrier. (NAD^+ returns to matrix)
- Hydrogen ions are split into 2 electrons which pass from carrier to carrier in the chain.
- Energy is released as the electrons pass from carrier to carrier and they are able to transfer protons (H^+)across the inner membrane.
- A concentration of protons build up in the inner-membrane space results in a store of potential energy.

Chemiosmosis

- To allow electrons to continue to flow, they must be transferred to a terminal electron acceptor at the end of the chain.
  - Aerobic respiration = oxygen

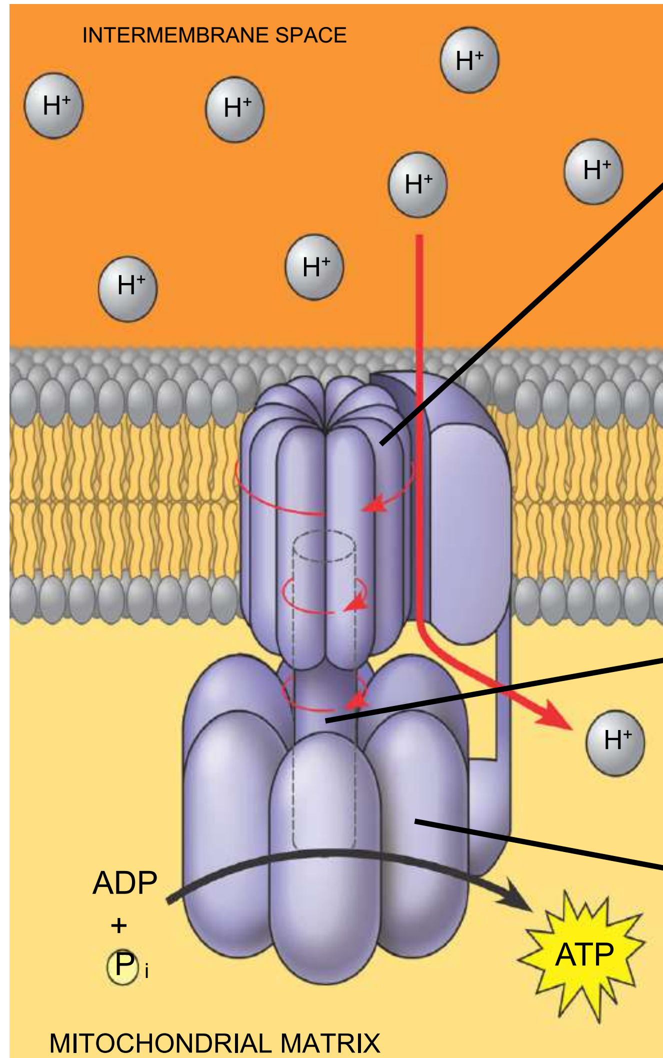
- Protons pass back through the ATP synthase into the matrix by way of diffusion and as they pass through energy is release allowing for the phosphorylation of ATP.



Chemiosmosis:
The Energy-Coupling Mechanism

- ATP synthase
  - Is the enzyme that actually makes ATP

32-34 ATP



A **rotor** within the membrane spins clockwise when H^+ flows past it down the H^+ gradient.

A **stator** anchored in the membrane holds the knob stationary.

A **rod** (for “stalk”) extending into the knob also spins, activating catalytic sites in the knob.

Three catalytic sites in the stationary **knob** join inorganic Phosphate to ADP to make ATP.

Figure 9.14

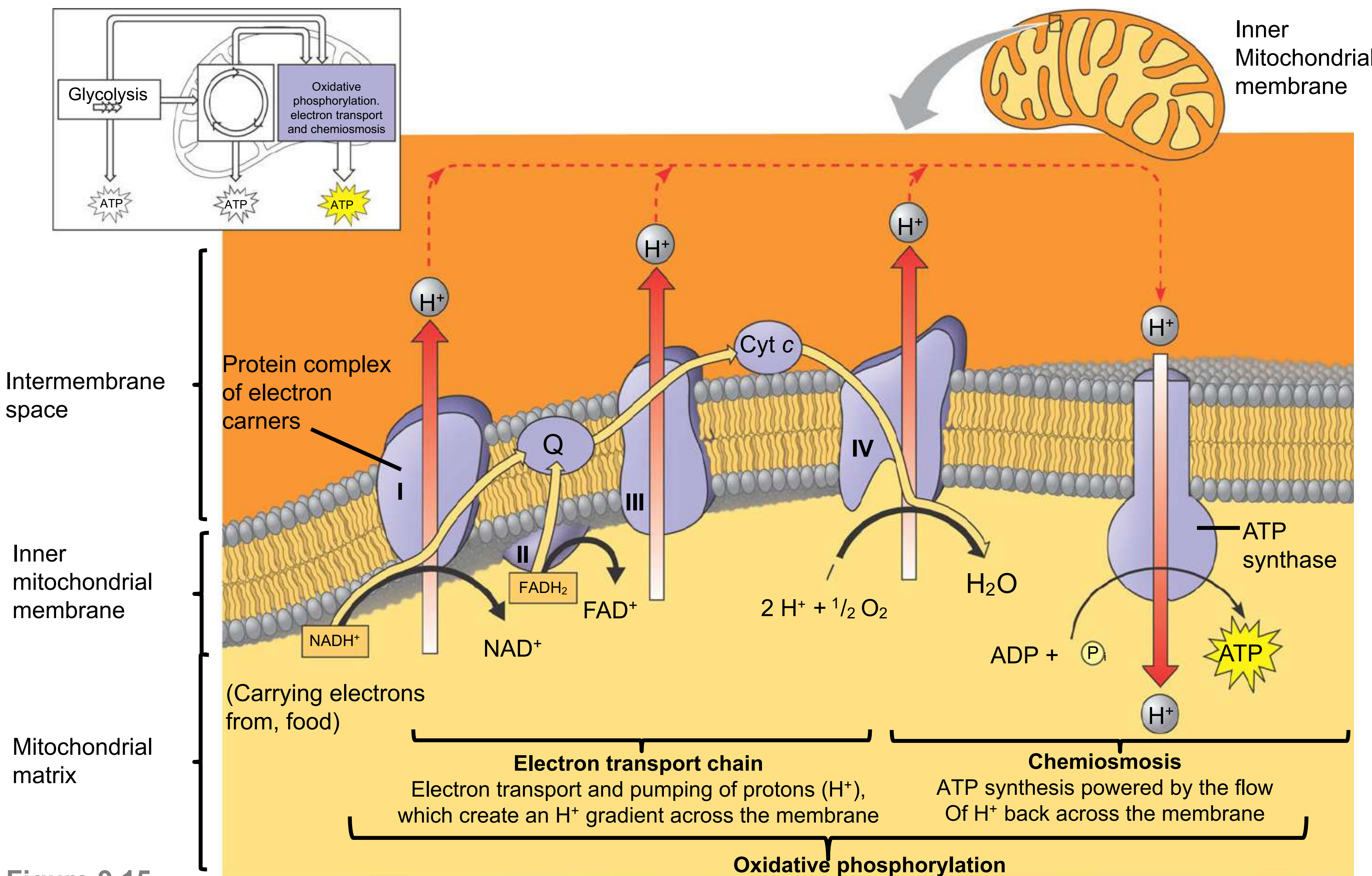

Glycolysis
Oxidative phosphorylation. electron transport and chemiosmosis
ATP
ATP
ATP
Inner Mitochondrial membrane
Intermembrane space
Inner mitochondrial membrane
Mitochondrial matrix
Protein complex of electron carners
H+
H+
H+
H+
H+
Cyt c
Q
I
II
III
IV
NADH+
NAD+
FADH2
FAD+
2 H+ + 1/2 O2
H2O
ATP synthase
ADP + P i
ATP
(Carrying electrons from, food)
Electron transport chain
Electron transport and pumping of protons (H+), which create an H+ gradient across the membrane
Chemiosmosis
ATP synthesis powered by the flow Of H+ back across the membrane
Oxidative phosphorylation

Figure 9.15

How does electronegativity play a part in the electron transport chain?

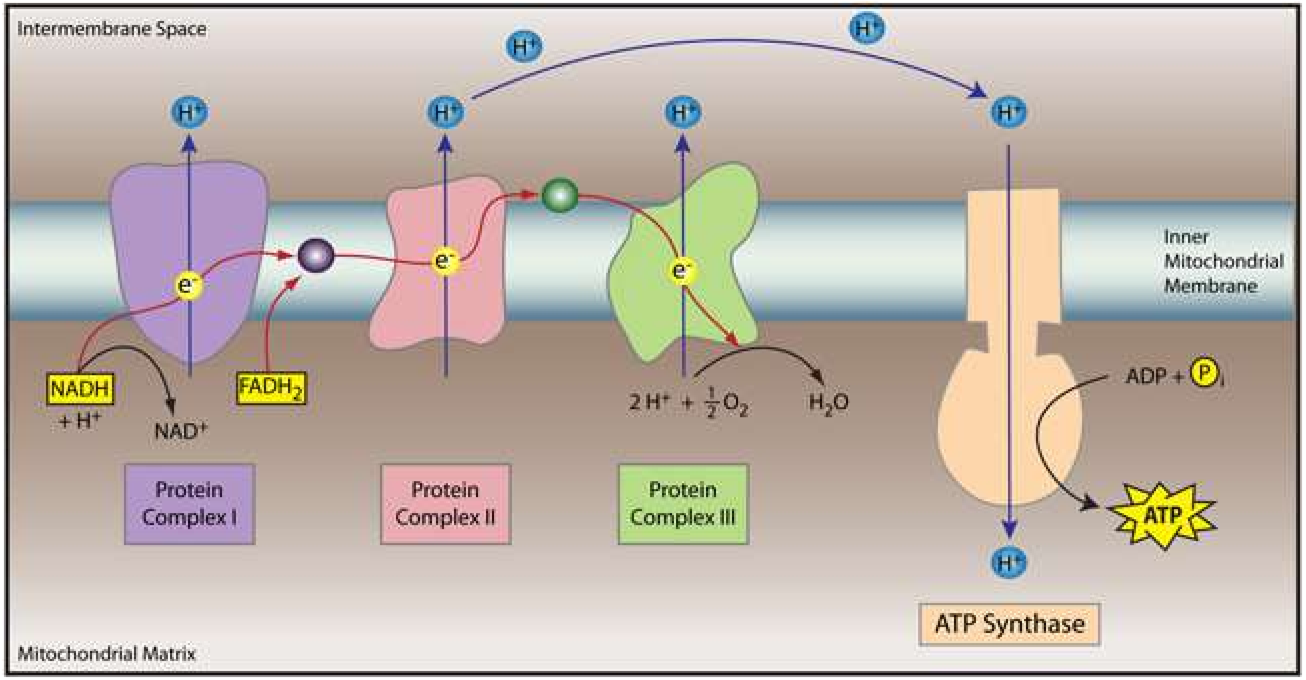
Because each electron acceptor in the chain is more electronegative than the previous, the electron will move from one electron transport chain molecule to the next, falling closer and closer to the nucleus of the last electron acceptor.

Where do the electrons for the ETC come from?

NADH and $FADH_2$ which got theirs from glucose.

What molecule is the final acceptor of the electron?

Oxygen, from splitting O_2 molecule & grabbing 2 H^+ .

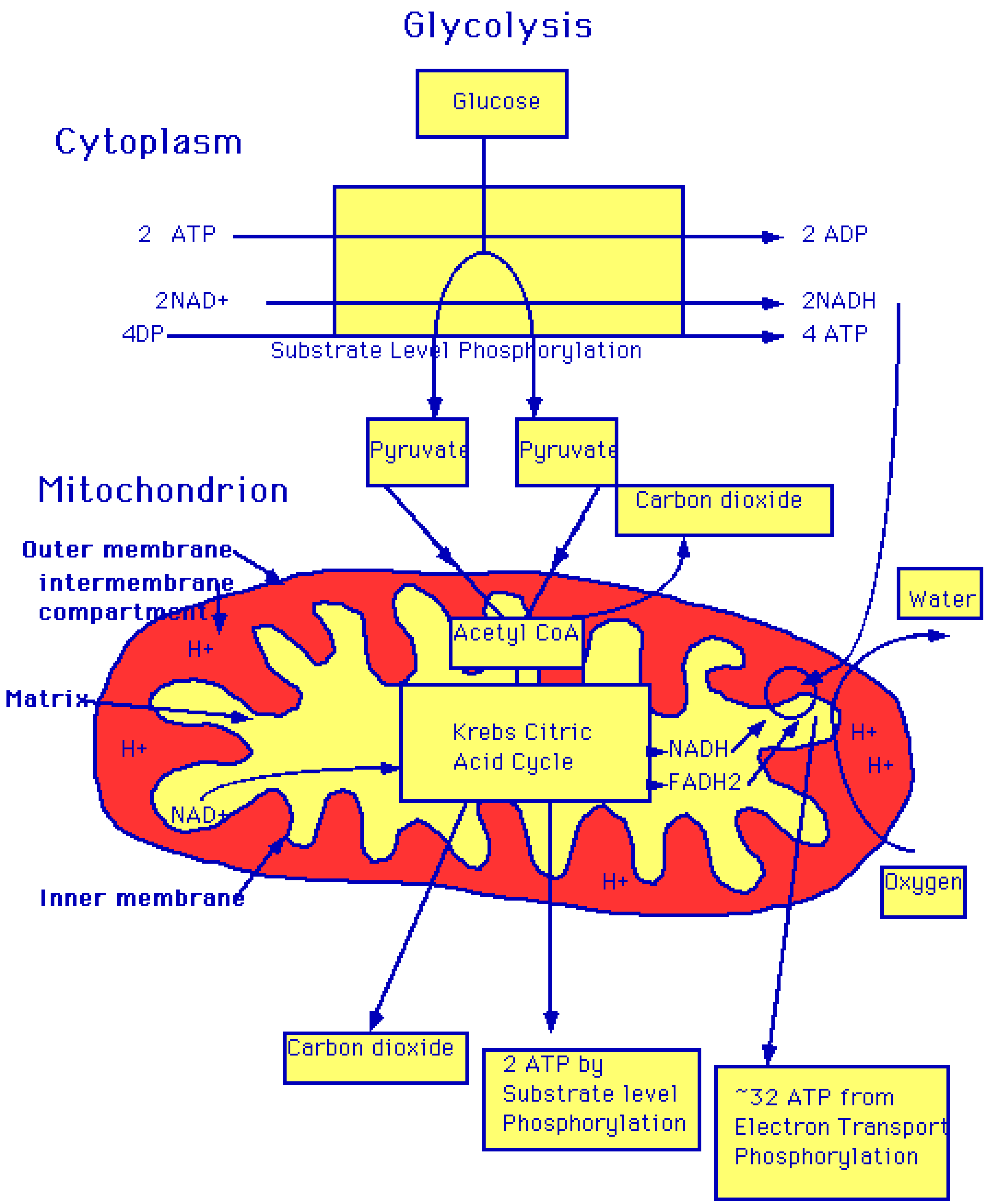


What's consumed during this process?

O_2

What's gained by this process?

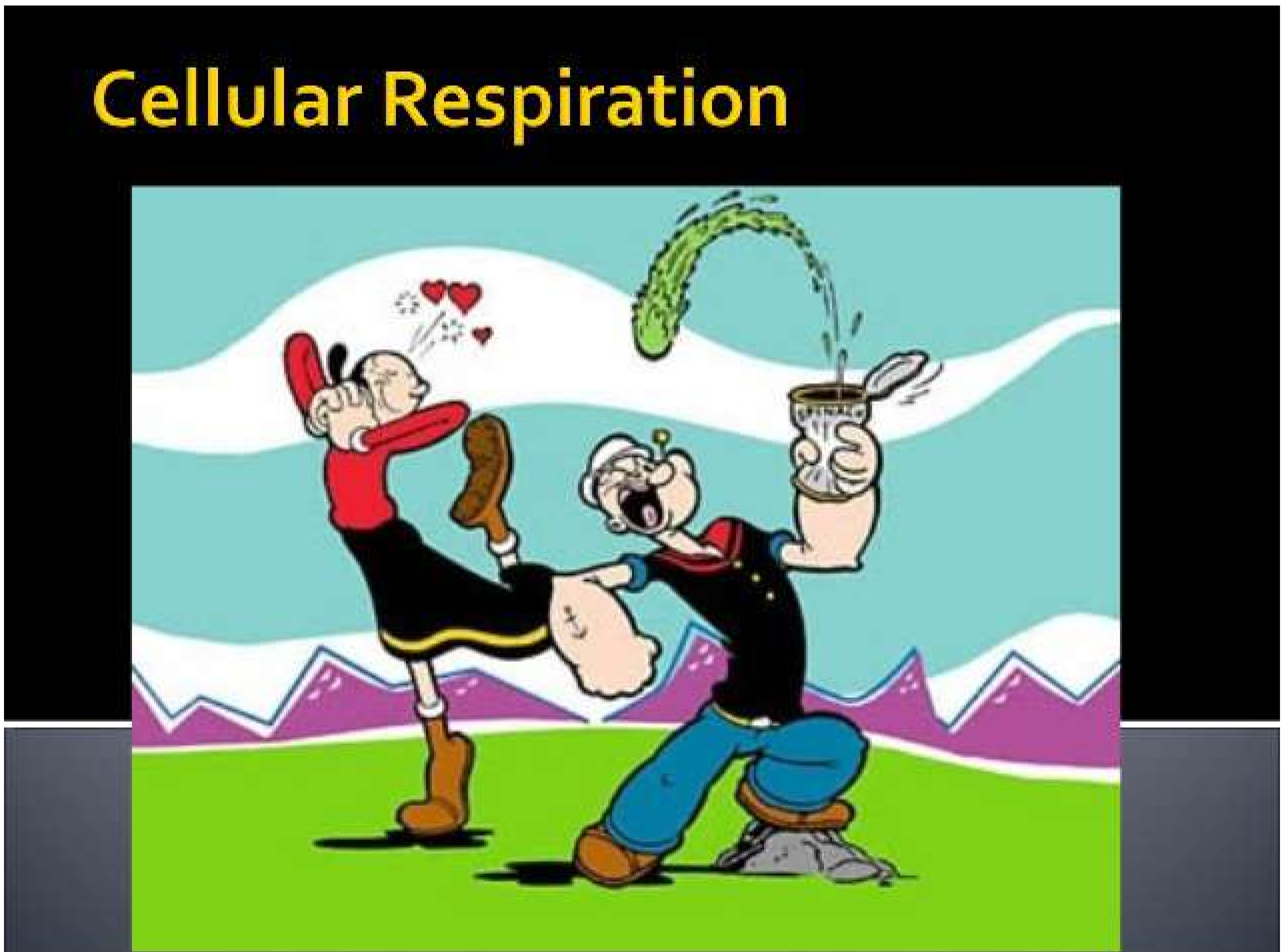
H^+ inside the inner membrane space


Glycolysis
Glucose
Cytoplasm
2 ATP
2 ADP
2NAD+
2NADH
4DP
4 ATP
Substrate Level Phosphorylation
Pyruvate
Pyruvate
Mitochondrion
Carbon dioxide
Outer membrane
intermembrane
compartment
Water
Acetyl CoA
H+
Matrix
Krebs Citric
Acid Cycle
NADH
FADH2
H+
H+
H+
NAD+
H+
Oxygen
Inner membrane
Carbon dioxide
2 ATP by
Substrate level
Phosphorylation
~32 ATP from
Electron Transport
Phosphorylation

The Case of…

The Seven Deaths

Let's do a simulation!!



Net Energy Production from Aerobic Respiration

Glycolysis: 2 ATP (4 produced but 2 are net gain)
Kreb's Cycle: 2 ATP
Electron Transport Phosphorylation: 32 ATP

- Each NADH produced in Glycolysis is worth 2 ATP (2 x 2 = 4) - the NADH is worth 3 ATP, but it costs an ATP to transport the NADH into the mitochondria, so there is a net gain of 2 ATP for each NADH produced in gylcolysis
- Each NADH produced in the conversion of pyruvate to acetyl COA and Kreb's Cycle is worth 3 ATP (8 x 3 = 24)
- Each $FADH_2$ is worth 2 ATP (2 x 2 = 4)
- 4 + 24 + 4 = 32

Net Energy Production: 36-38 ATP

Is cellular respiration endergonic or exergonic

Is it a catabolic or anabolic process?

If one ATP molecule holds 7.3kcal of potential energy, how much potential energy does 1 glucose molecule produce in cell respiration?

At its maximum output, 38 x 7.3kcal = 277.4kcal

One molecule of glucose actually contains 686 kcal/mol of potential energy. Where does the remaining energy go when glucose is reduced?

It's lost as heat-which is why our bodies are warm right now.

What is the net efficiency of cell respiration if glucose contains 686kcal and only 277.4kcal are produced?

277.4/ 686 x 100 = 40% energy recovered from aerobic respiration

Is 40% net efficiency of cellular respiration good or not?

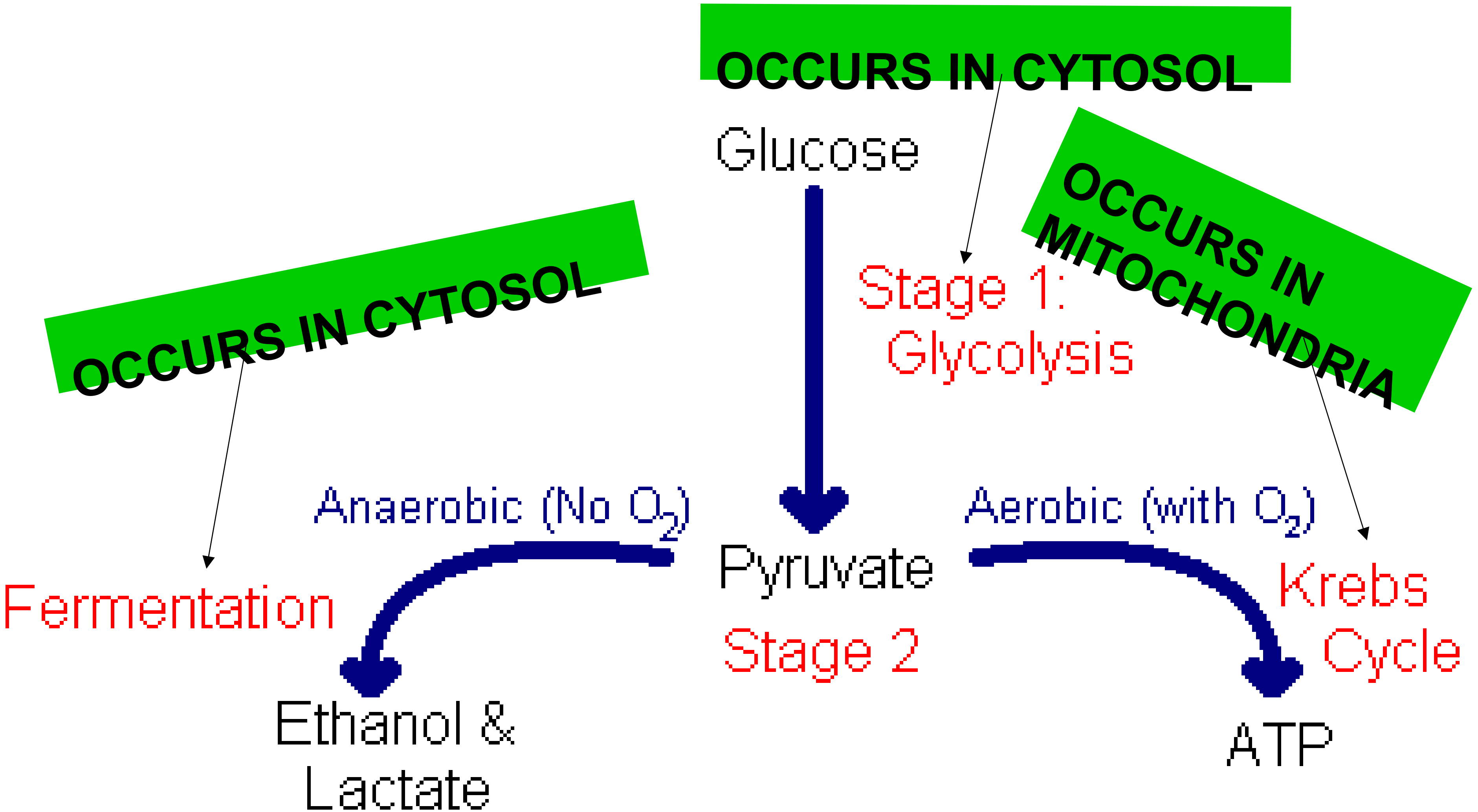
- Let’s first look at the following energy capturing processes that you see in everyday life.

An incandescent light bulb is about 5% efficient

Electricity generated from coal is about 21% efficient

The most efficient gasoline combustion engine in cars is about 23% efficient.

So…now what do you think?


OCCURS IN CYTOSOL
Glucose
Stage 1:
Glycolysis
OCCURS IN MITOCHONDRIA
OCCURS IN CYTOSOL
Anaerobic (No O_2)
Aerobic (with O_2)
Fermentation
Pyruvate
Stage 2
Krebs Cycle
Ethanol &
Lactate
ATP

Anaerobic Respiration

- Fermentation enables some cells to produce ATP without the use of oxygen

- Glycolysis
  - Can produce ATP with or without oxygen, in aerobic or anaerobic conditions
  - Couples with fermentation to produce ATP

Anaerobic Respiration

- Fermentation consists of

– Glycolysis plus reactions that regenerate NAD^+, which can be reused by glyocolysis

- Alcohol fermentation

– Pyruvate is converted to ethanol in two steps, one of which releases CO_2

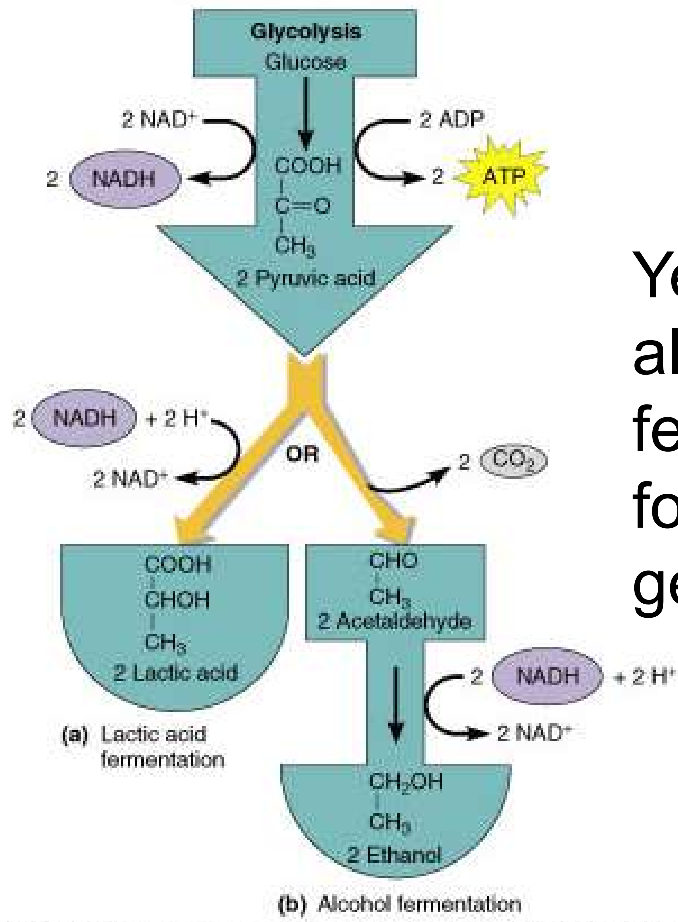
- Lactic acid fermentation

– Pyruvate is reduced directly to NADH to form lactate as a waste product

Stage 2: If oxygen is absent- Fermentation

-Produces organic molecules, including alcohol and lactic acid, and it occurs in the absence of oxygen.

Cells not getting enough oxygen, excess pyruvate molecules are converted into lactic acid molecules, raising the pH in the cells



Yeast uses alcoholic fermentation for ATP generation.

Wine producers traditionally used their feet to soften and grind the grapes before leaving the mixture to stand in buckets. In so doing, they transferred microorganisms from their feet into the mixture. At the time, no one knew that the alcohol produced during fermentation was produced because of one of these microorganisms — a tiny, one-celled eukaryotic fungus that is invisible to the naked eye: **yeast**.

Red Blood Cells Have No Mitochondria…How Do They Produce Energy

- By fermentation, via anaerobic glycolysis of glucose followed by lactic acid production.
- As the cells do not own any protein coding DNA they cannot produce new structural or repair proteins or enzymes and their lifespan is limited.

Comparing Chemiosmosis in Respiration vs Photosynthesis

Respiration Chemiosmosis	Photosynthesis Chemiosmosis
Involves an ETC embedded in the membranes of the cristae	Involves ETC embedded in the membranes of the thylakoids
Energy is released when electrons are exchanged from one carrier to another	Energy is released when electrons are exchanged from one carrier to another
Released energy is used to actively pump hydrogen ions into the intermembrane space	Released energy is used to actively pump hydrogen ions into the thylakoid space
Hydrogen ions come from the matrix	Hydrogen ions come from the stroma
Hydrogen ions diffuse back into the matrix through the channels of ATP synthase	Hydrogen ions diffuse back into the stroma through the channels of ATP synthase
ATP synthase catalyses the oxidative phosphorylation of ADP to ATP	ATP synthase catalyses the photophosphorylation of ADP to form ATP