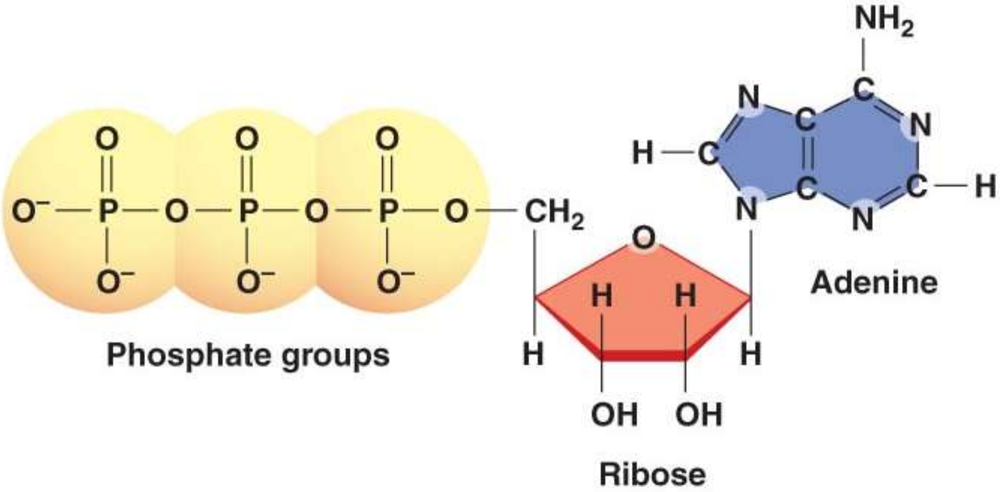
ATP:
Energy Source of the cell

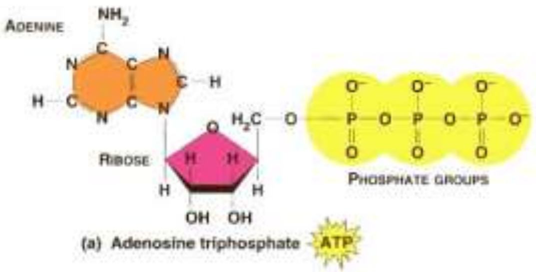
ATP:
Energy Source of the cell

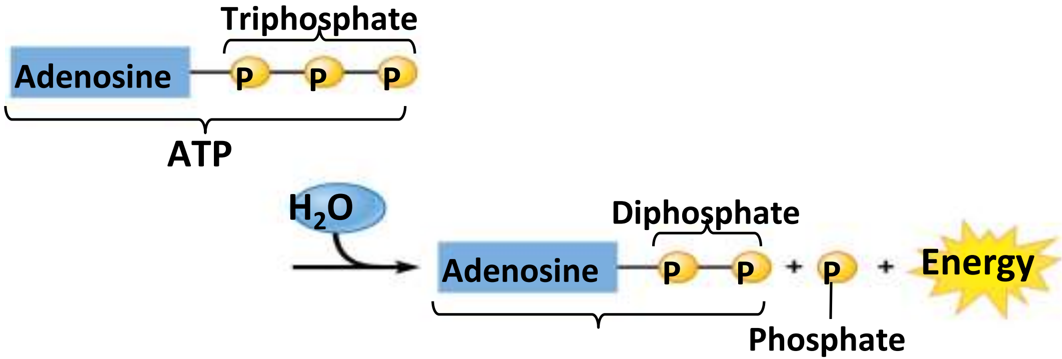
- What is ATP?



ATP drives cellular work by coupling exergonic and endergonic reactions

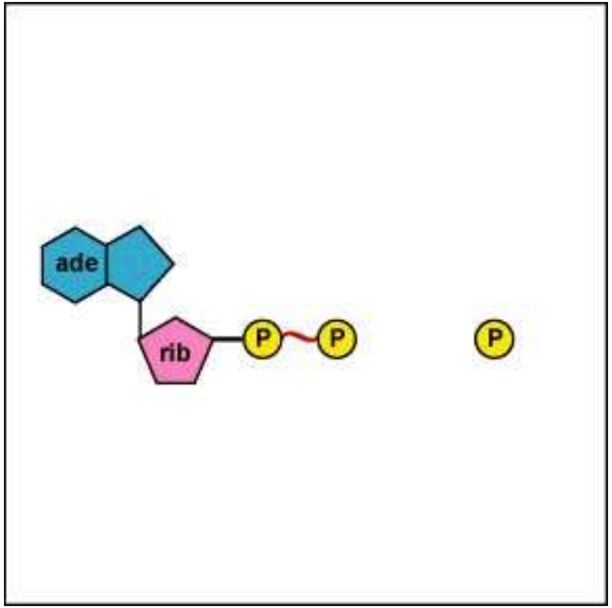
- **ATP**, adenosine triphosphate, powers nearly all forms of cellular work.
- ATP consists of ___adenosine____and a __triphosphate_ tail (3 phosphates)
- ____hydrolysis_______of ATP releases energy by transferring its third phosphate from ATP to some other molecule in a process called __**phosphorylation**.____





ATP drives cellular work by coupling exergonic and endergonic reactions

- A cell uses and ___regenerates______ ATP continuously.
- In the ATP cycle, energy released in an exergonic reaction, such as the breakdown of glucose during cellular respiration, is used in an endergonic reaction to generate ATP from ADP.

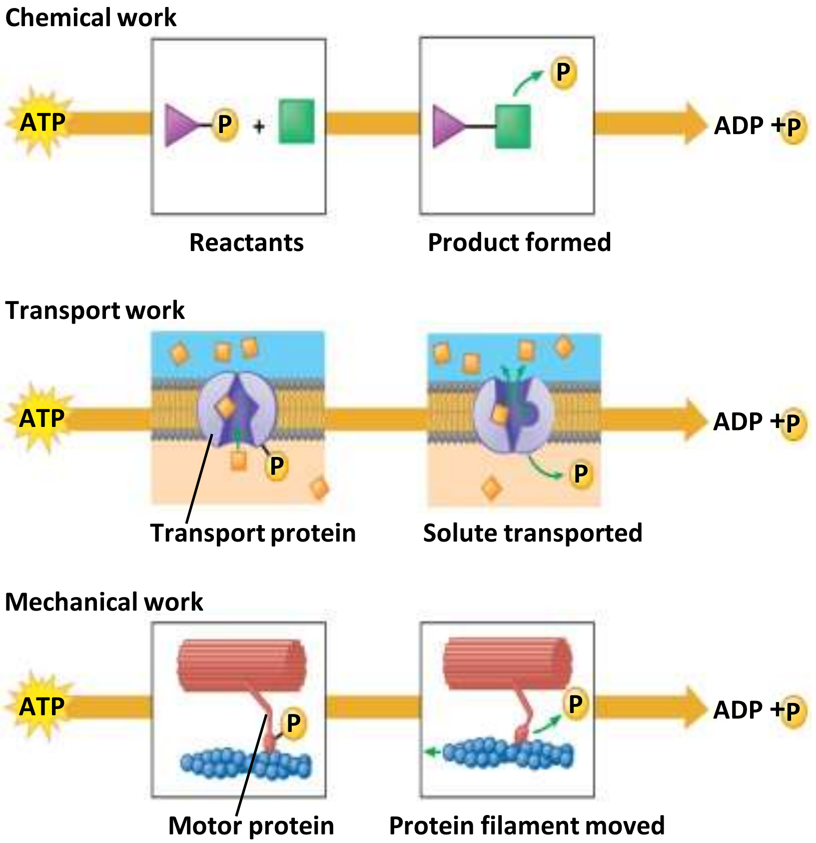


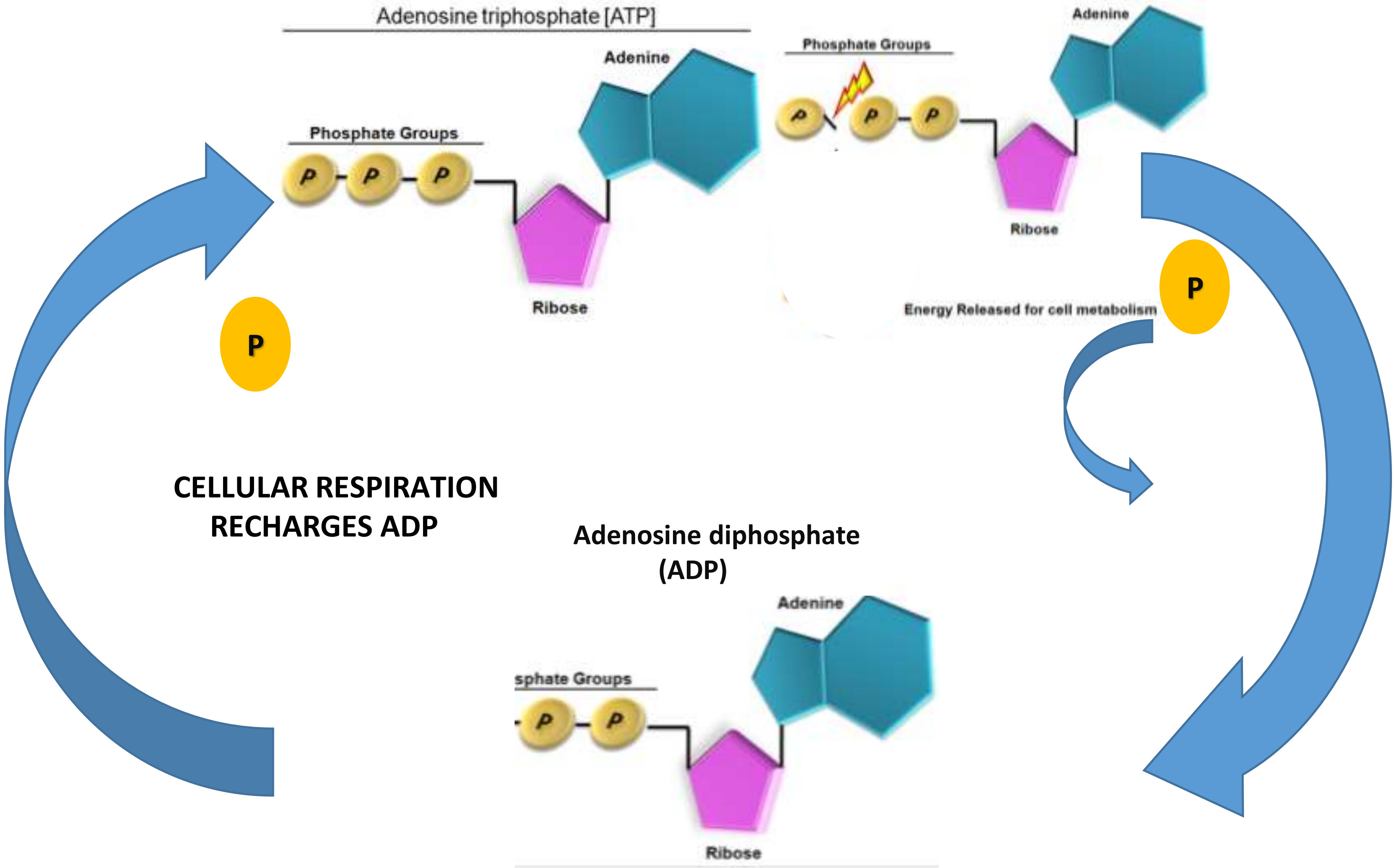
ATP drives cellular work by coupling exergonic and endergonic reactions

There are three main types of cellular work:

1. __chemical______
2. __transport_____
3. _mechanical_____

- ATP drives all three of these types of work.

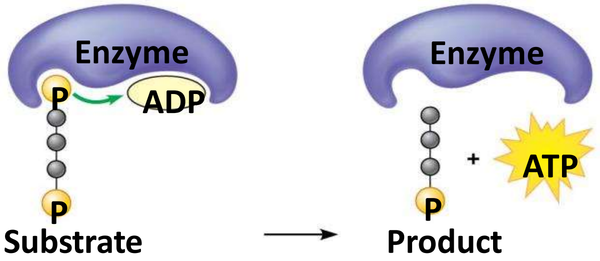




Adenosine triphosphate [ATP]
Adenine
Phosphate Groups
P P P
Ribose
Phosphate Groups
Adenine
P P P
Ribose
Energy Released for cell metabolism
P
P
CELLULAR RESPIRATION
RECHARGES ADP
Adenosine diphosphate
(ADP)
Adenine
sphate Groups
P P
Ribose

Substrate Level Phosphorylation

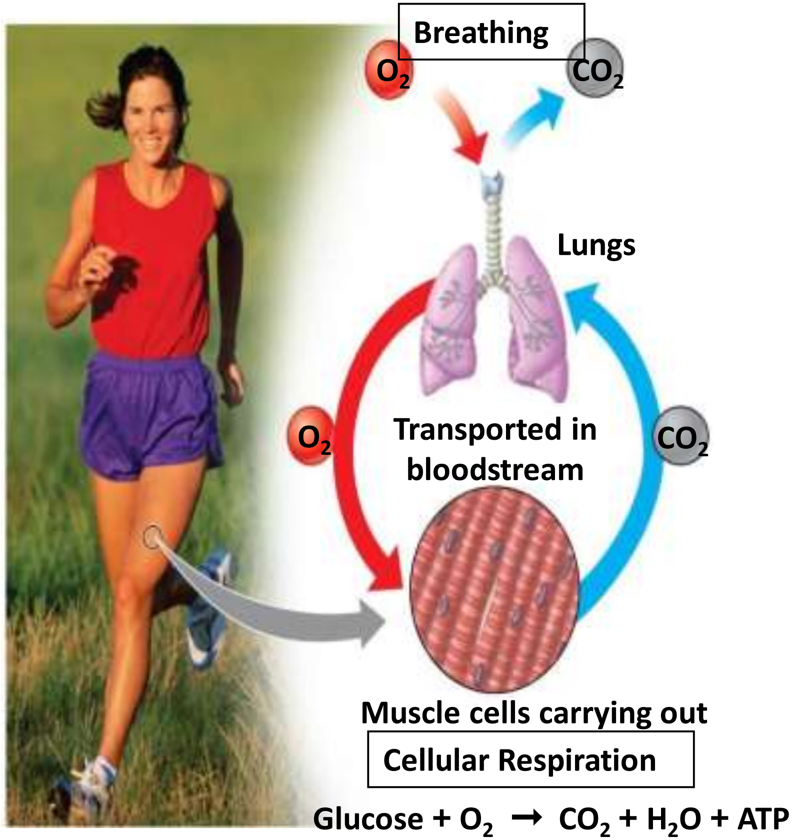
- ATP is formed during cellular respiration, but also can be formed by **substrate-level phosphorylation** during which an **enzyme** transfers a phosphate group from a **substrate** molecule to ADP and ATP is formed.



Cellular Respiration:
Aerobic Harvesting of Energy

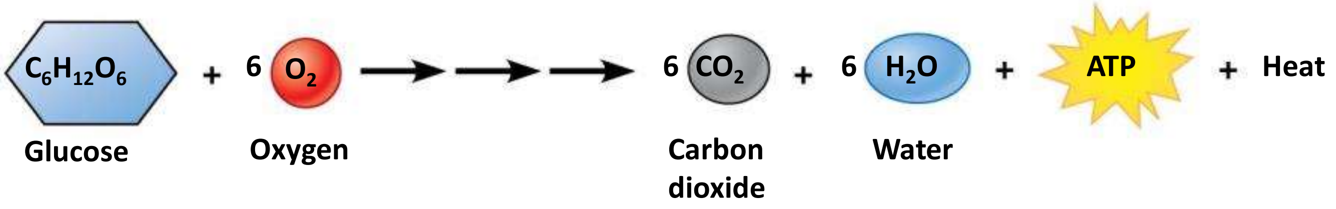
Breathing supplies O_2 and removes CO_2 in cellular respiration

- Respiration,(as it relates to breathing), and cellular respiration are not the same.
- Respiration, in the breathing sense, refers to an exchange of gases. Usually an organism brings in oxygen from the environment and releases waste CO_2.
- **Cellular respiration** is the aerobic (oxygen-requiring) harvesting of energy from food molecules by cells.



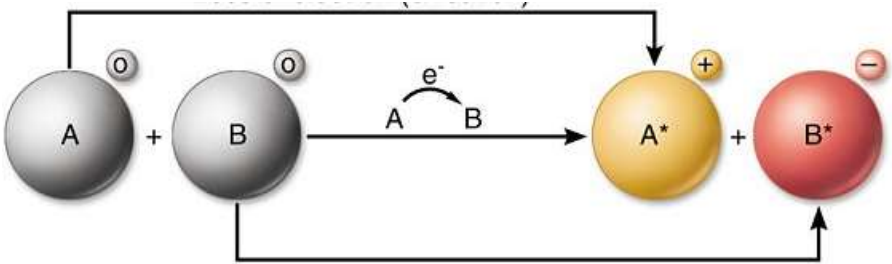
Cellular respiration banks energy in ATP molecules

- Cellular respiration is an exergonic (energy- releasing) process that transfers energy from the bonds in __glucose__ to form __ATP.__
- Cellular respiration can produce up to __32 ATP__ molecules for __one__ glucose molecule and use about __34%__ of the energy originally stored in glucose, releasing the other 66% as __heat__
- This energy conversion efficiency is better than most energy conversion systems compared to only **25% of the energy** in gasoline produces the kinetic energy of movement.



Cells capture energy from electrons "falling" from organic fuels to oxygen

- **Oxidation-reduction reaction, or redox reaction.**
  - The movement of ____**electrons**_____from one molecule to another.
  - the loss of electrons from one substance is called _**oxidation**_ and the **addition** of electrons to another substance is called _**reduction**____
  - a molecule is __**oxidized**__when it loses one or more electrons, and a molecule is ___reduced___when it gains one or more electrons.



Cells capture energy from electrons "falling" from organic fuels to oxygen

- A cellular respiration equation is helpful to show the changes in hydrogen atom distribution.
  - Glucose __**loses**__ its hydrogen atoms and becomes __**oxidized**__ to CO_2.
  - Oxygen __**gains**__ hydrogen atoms and becomes __**reduced**__ to H_2O.

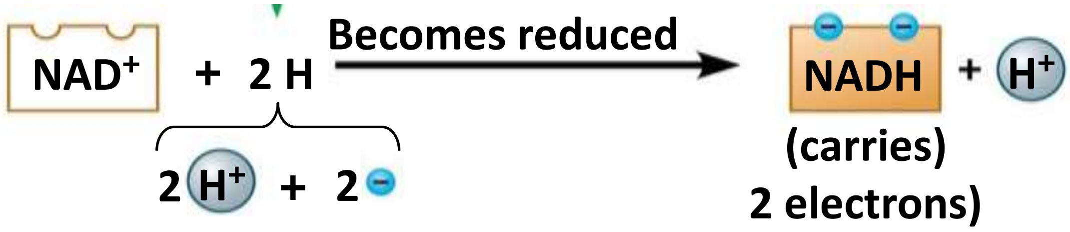
Loss of hydrogen atoms (becomes oxidized)

$$\underset{\text{(Glucose)}}{C_6H_{12}O_6} + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O + \text{ATP} + \text{Heat}$$

Gain of hydrogen atoms (becomes reduced)

Cells capture energy from electrons "falling" from organic fuels to oxygen

- An important player in the process of oxidizing glucose is a coenzyme called __**NAD$^+$**,_ which accepts electrons and becomes reduced to__**NADH**_____. (electron acceptors)



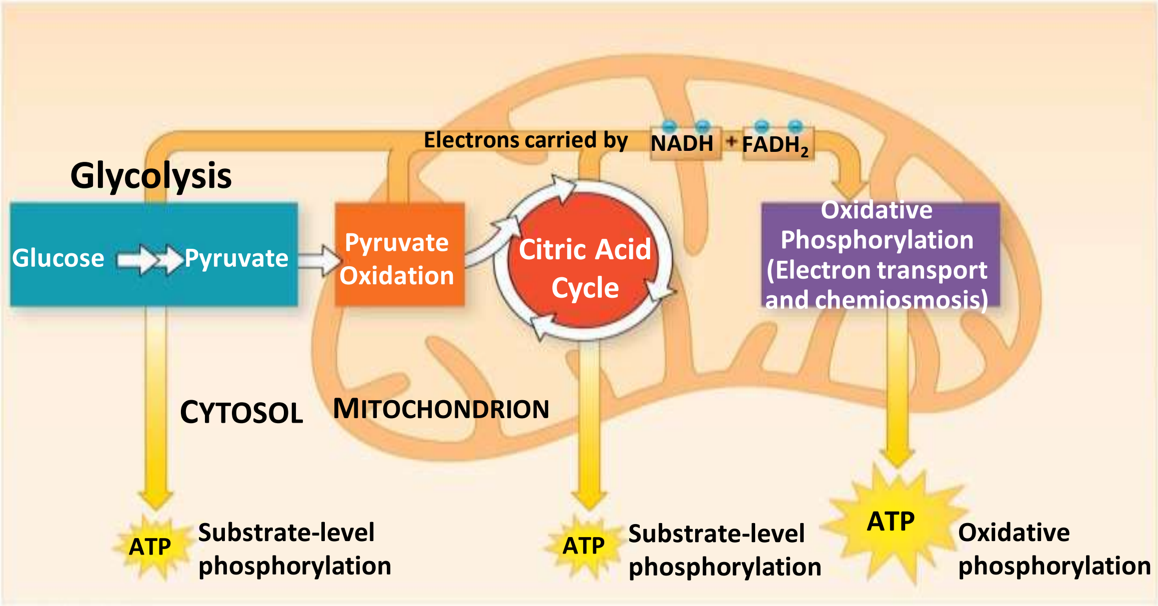
$$NAD^+ + 2e^- + H \longrightarrow NADH$$

Stages of Cellular Respiration

Overview: Cellular respiration occurs in three main stages

- Cellular respiration consists of a sequence of steps that can be divided into three stages.
  - Stage 1: Glycolysis (occurs in cytosol)
  - Stage 2: Pyruvate oxidation and the citric acid cycle
  - Stage 3: Oxidative phosphorylation or ETC

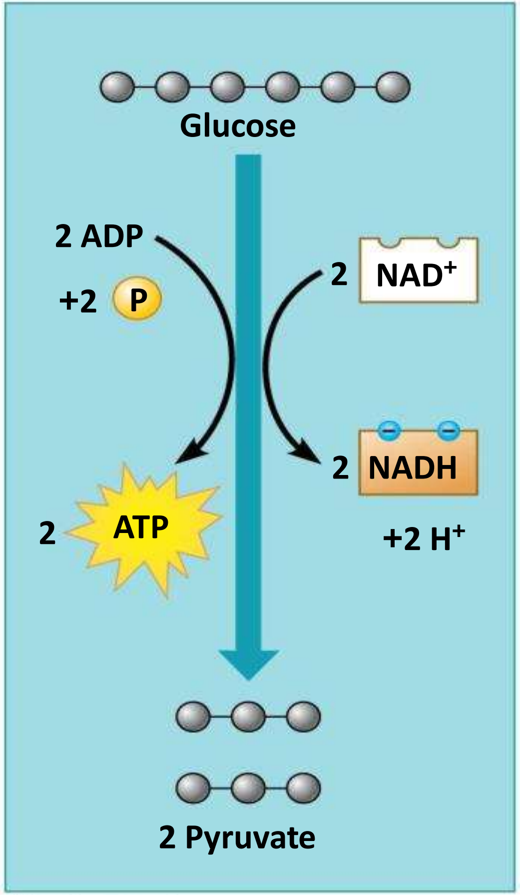
occurs in mitochondria



Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

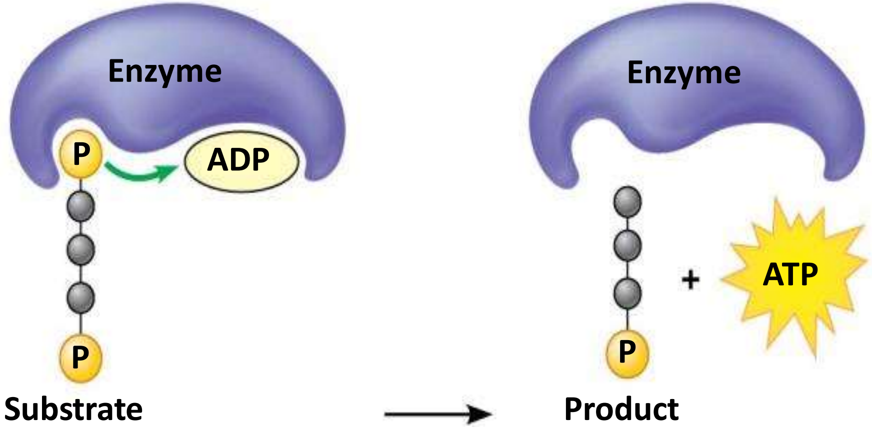
In **glycolysis**:

- a single molecule of glucose is enzymatically __split__ in half through a series of steps
- two molecules of ___pyruvate___ are produced
- two molecules of NAD^+ are ___reduced___ to two molecules of __NADH___
- there is a _NET_ gain of ___two___ molecules of ATP (produced by substrate level phosphorylation).



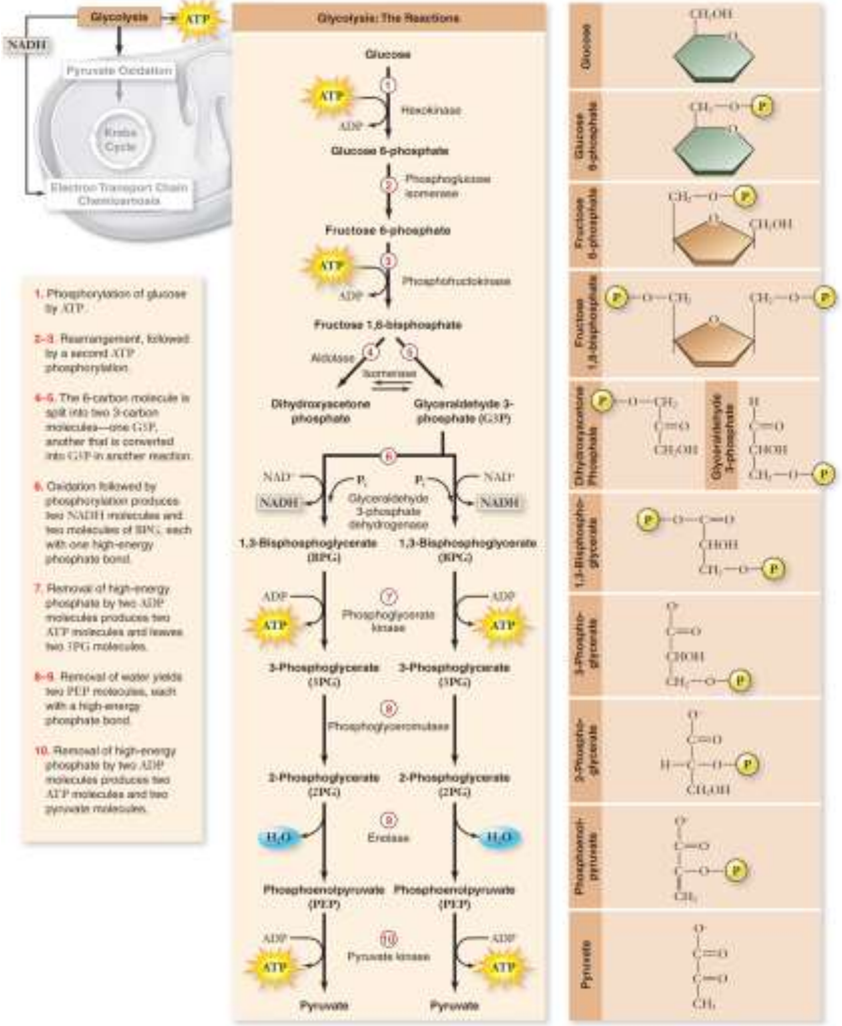
Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

ATP is formed in glycolysis by **substrate-level phosphorylation** during which an enzyme transfers a phosphate group from a substrate molecule to ADP and ATP is formed.



Glycolysis harvests chemical energy by oxidizing glucose to pyruvate

- The steps of glycolysis have two main phases.
  - the energy investment phase and the energy payoff phase

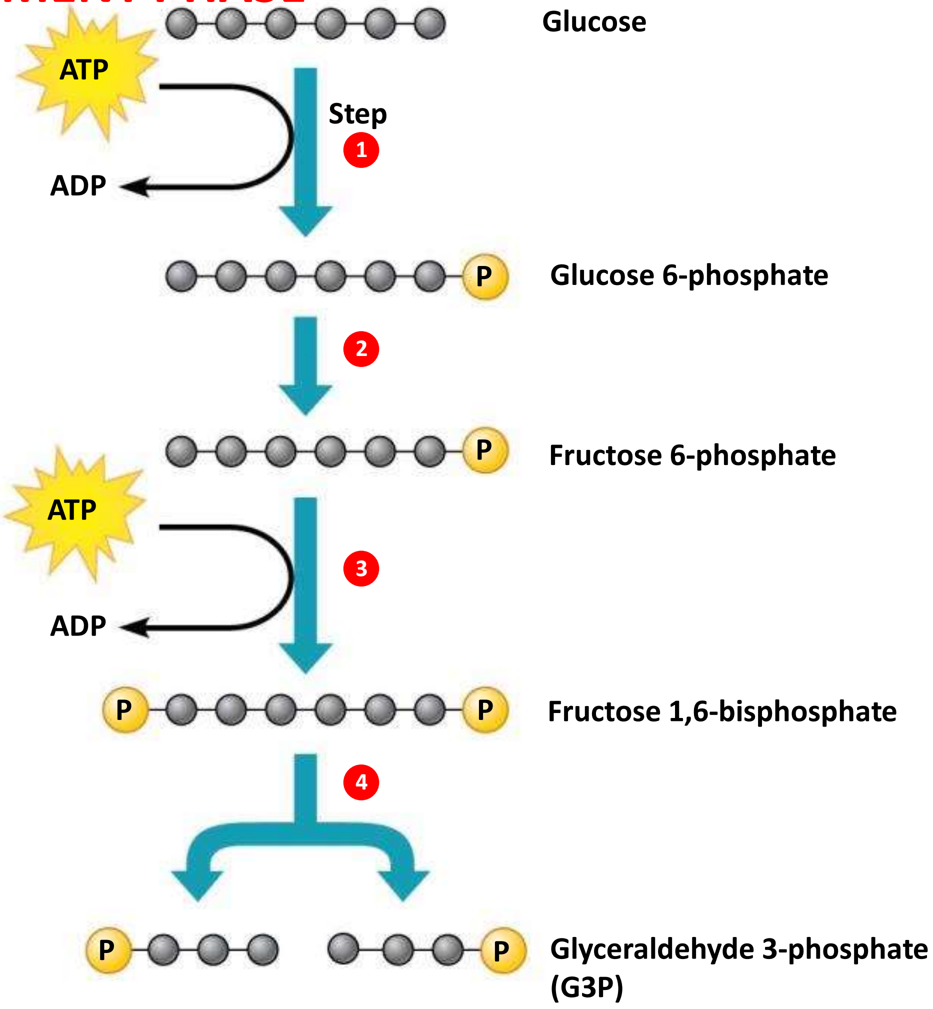


Glycolysis
ATP
NADH
Pyruvate Oxidation
Krebs Cycle
Electron Transport Chain Chemiosmosis
1. Phosphorylation of glucose by ATP.
2–3. Rearrangement, followed by a second ATP phosphorylation.
4–5. The 6-carbon molecule is split into two 3-carbon molecules—one G3P, another that is converted into G3P in another reaction.
6. Oxidation followed by phosphorylation produces two NADH molecules and two molecules of BPG, each with one high-energy phosphate bond.
7. Removal of high-energy phosphate by two ADP molecules produces two ATP molecules and leaves two 3PG molecules.
8–9. Removal of water yields two PEP molecules, each with a high-energy phosphate bond.
10. Removal of high-energy phosphate by two ADP molecules produces two ATP molecules and two pyruvate molecules.
Glycolysis: The Reactions
Glucose
ATP
ADP
Hexokinase
Glucose 6-phosphate
Phosphoglucose isomerase
Fructose 6-phosphate
Phosphofructokinase
Fructose 1,6-bisphosphate
Aldolase
Isomerase
Dihydroxyacetone phosphate
Glyceraldehyde 3-phosphate (G3P)
NAD+
NADH
Pi
Glyceraldehyde 3-phosphate dehydrogenase
1,3-Bisphosphoglycerate (BPG)
Phosphoglycerate kinase
3-Phosphoglycerate (3PG)
Phosphoglyceromutase
2-Phosphoglycerate (2PG)
H2O
Enolase
Phosphoenolpyruvate (PEP)
Pyruvate kinase
Pyruvate
Glucose
Glucose 6-phosphate
Fructose 6-phosphate
Fructose 1,6-bisphosphate
Dihydroxyacetone Phosphate
Glyceraldehyde 3-phosphate
1,3-Bisphosphoglycerate
3-Phosphoglycerate
2-Phosphoglycerate
Phosphoenolpyruvate
Pyruvate

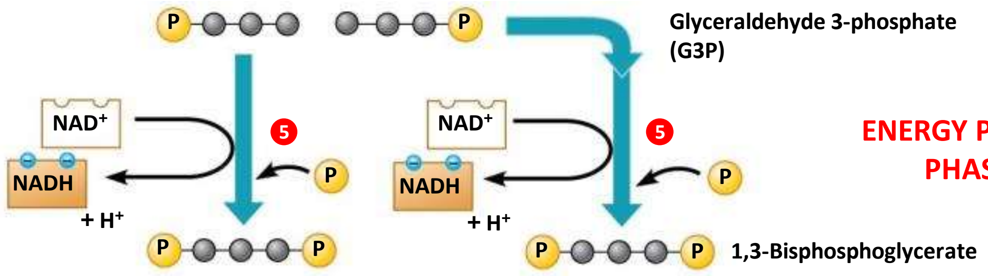
ENERGY INVESTMENT PHASE

Steps 1 – 3 Glucose is energized, using ATP.

Step 4 A six-carbon intermediate splits into two three-carbon intermediates.



Step 5 A redox reaction generates NADH.

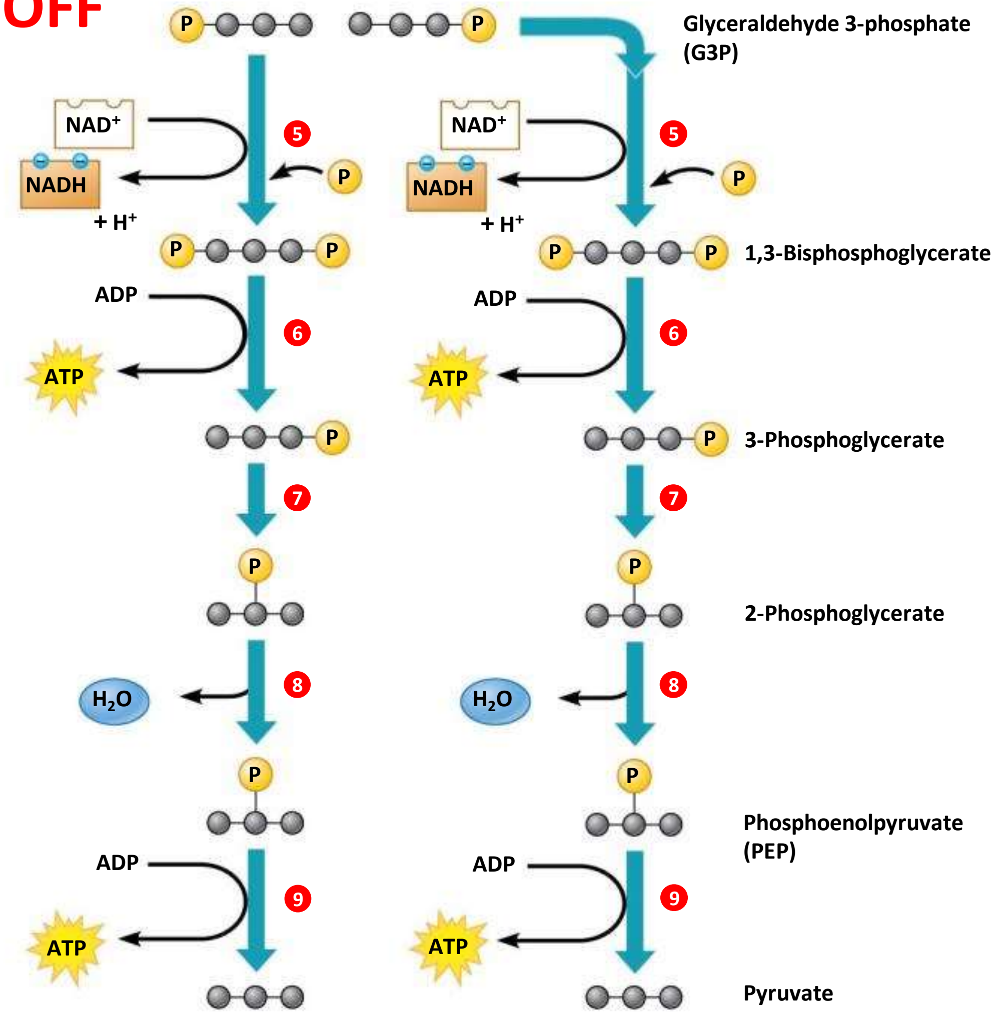


ENERGY PAYOFF PHASE

ENERGY PAYOFF PHASE

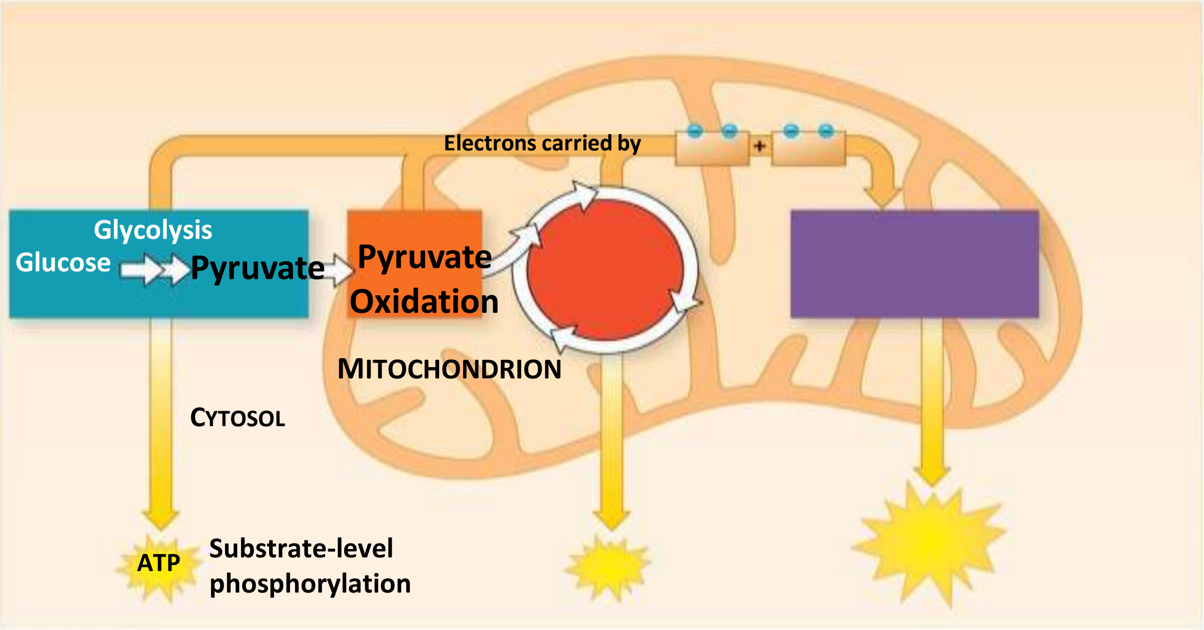
Step 5 A redox reaction generates NADH.

Steps 6 – 9 ATP and pyruvate are produced.

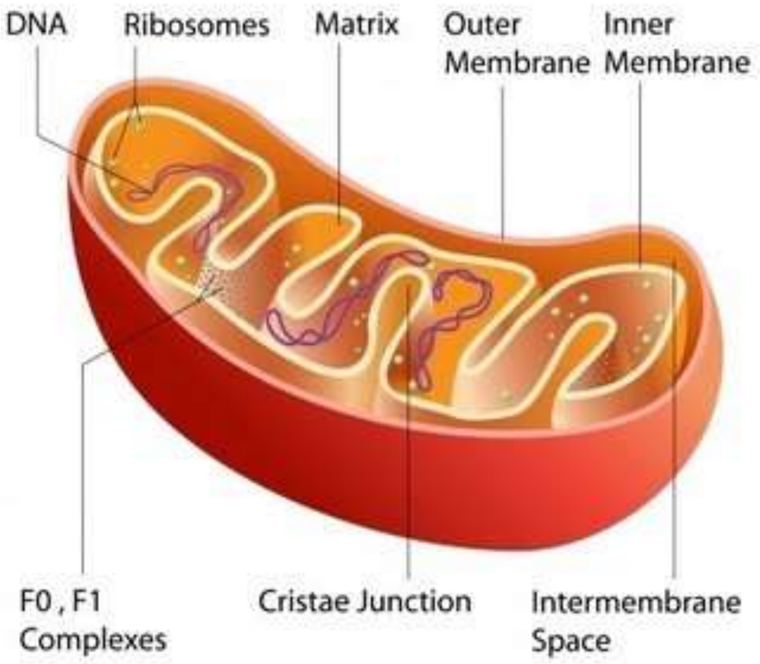


Pyruvate is oxidized in preparation for the citric acid cycle

- At the finish of glycolysis, ________ of the stored energy still remains in the pyruvate molecules
  90%
- Pyruvate molecules are then transported from the _______________ into a _______________ where the citric acid cycle and oxidative phosphorylation will occur.
  cytosol
  mitochondria



Anatomy of Mitochondria

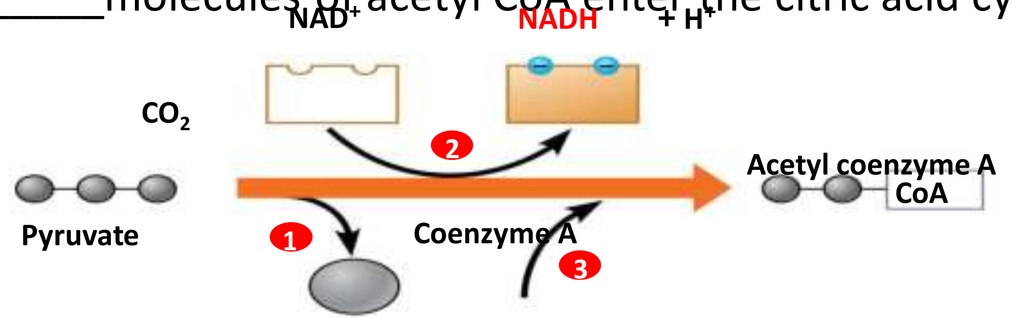


Pyruvate is oxidized in preparation for the citric acid cycle

Pyruvate does not enter the citric acid cycle but undergoes some chemical grooming in which

- a carboxyl group is removed and given off as CO_2 ________
- the two-carbon compound remaining is oxidized ________________ while a molecule NADH of NAD^+ is reduced to ________
- acetyl CoA
  coenzyme A joins with the two-carbon group to form acetyl two coenzyme A, abbreviated as ______________.

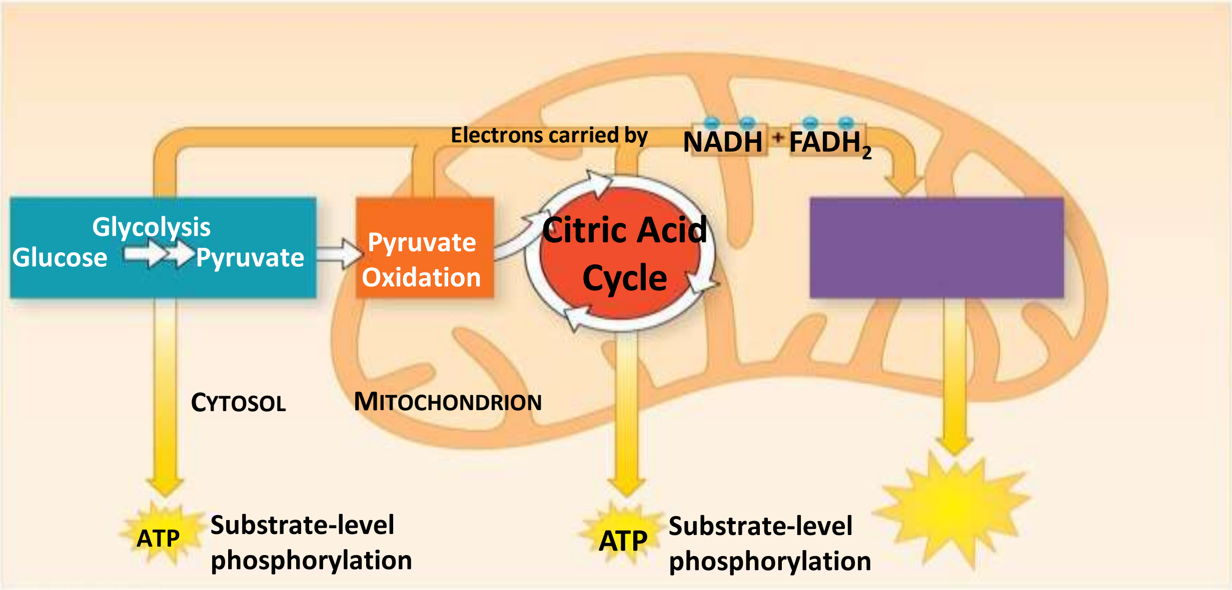
- Then ________ molecules of acetyl CoA enter the citric acid cycle.

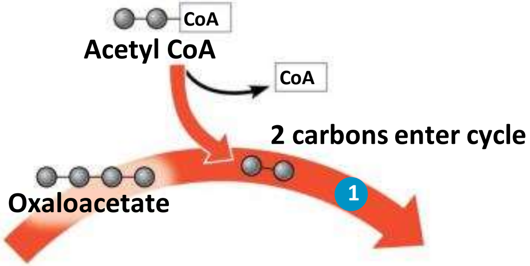


The citric acid cycle completes oxidation of organic molecules

The citric acid cycle (also called the Krebs cycle after the German-British researcher Hans Krebs) completes the oxidation of organic molecules, and generates many _NADH___ and _$FADH_2$_molecules.

- Occurs in the __Mitochondria____

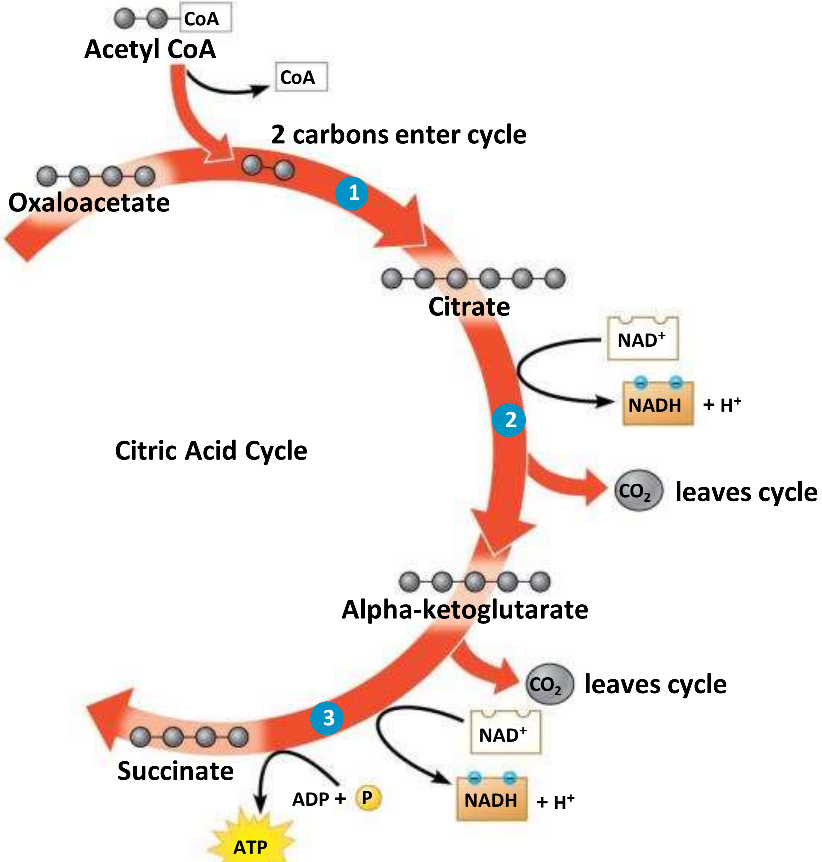




Citric Acid Cycle

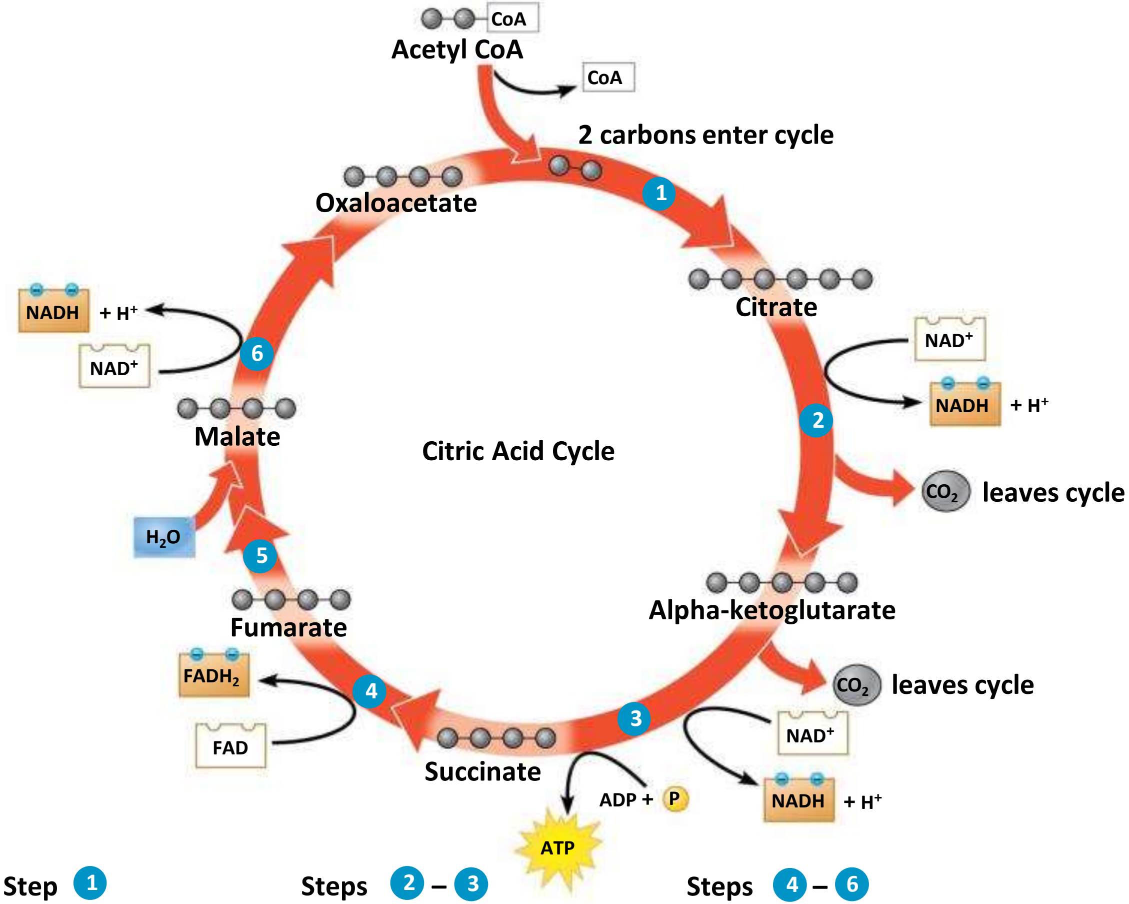
Step 1

Acetyl CoA stokes the furnace.



Step 1
Acetyl CoA stokes the furnace.

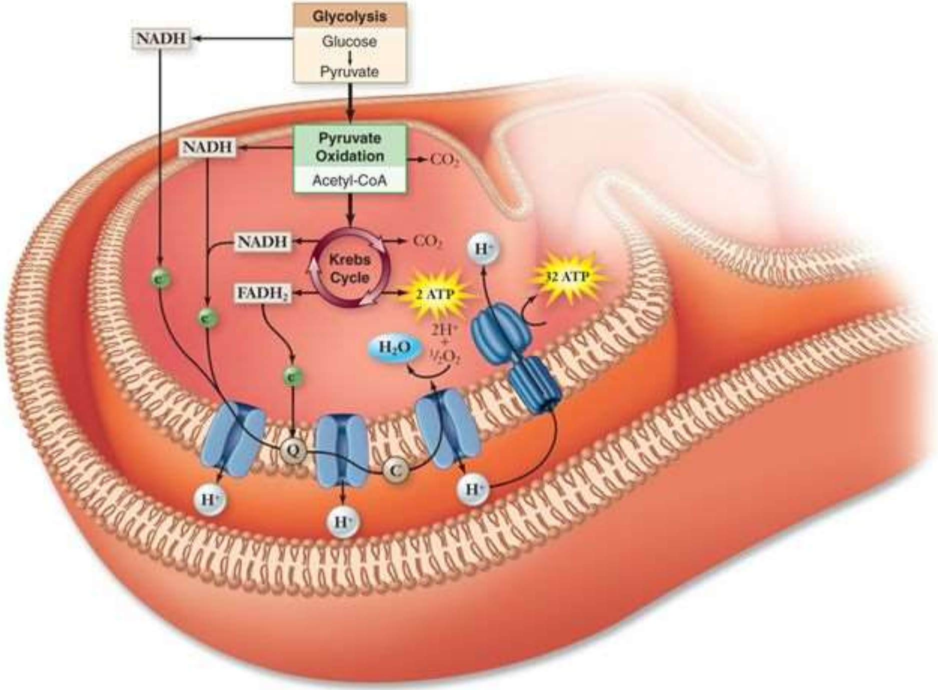
Steps 2 – 3
NADH, ATP, and CO_2 are generated during redox reactions.



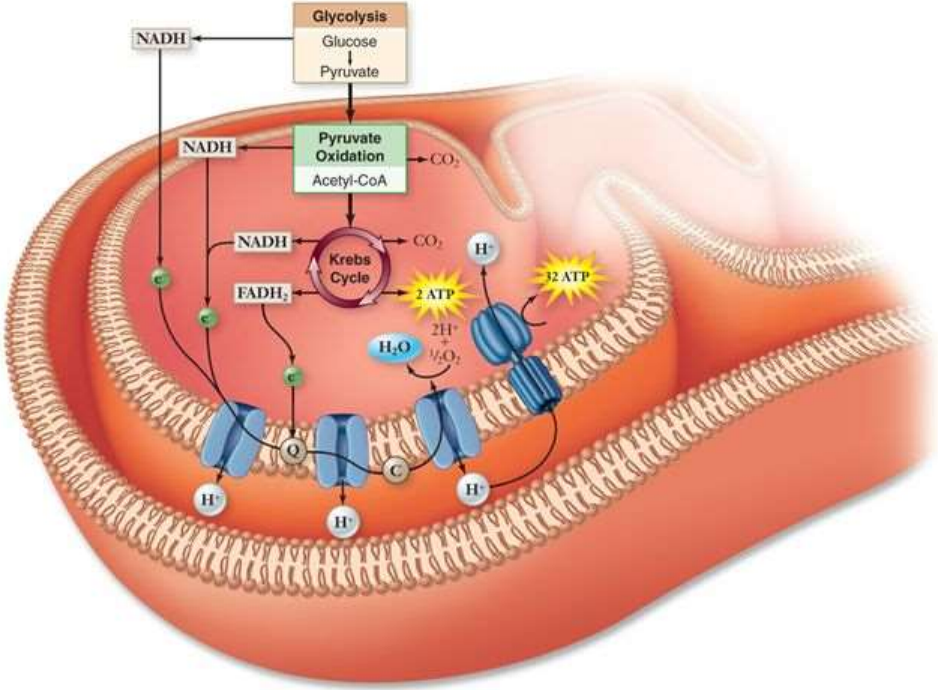
Step 1
Acetyl CoA stokes the furnace.

Steps 2 – 3
NADH, ATP, and CO_2 are generated during redox reactions.

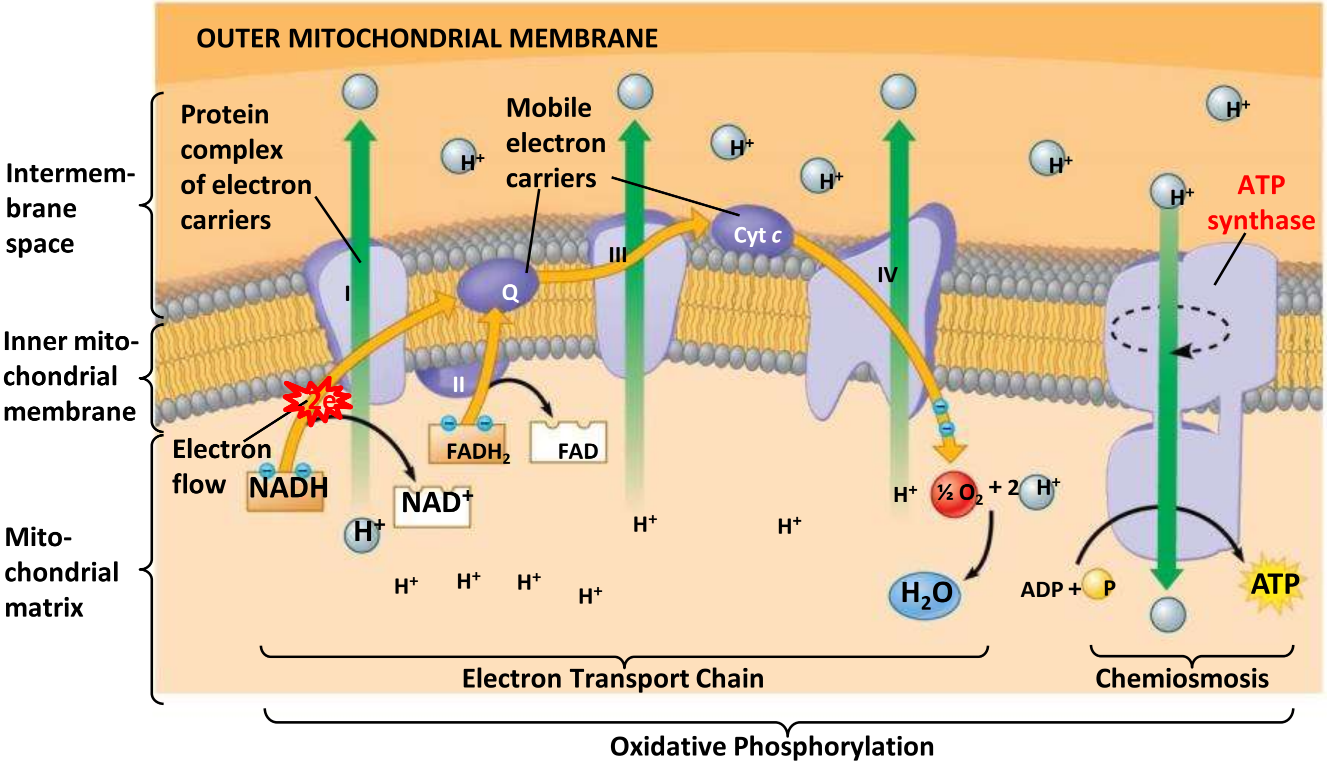
Steps 4 – 6
Further redox reactions generate $FADH_2$ and more NADH.



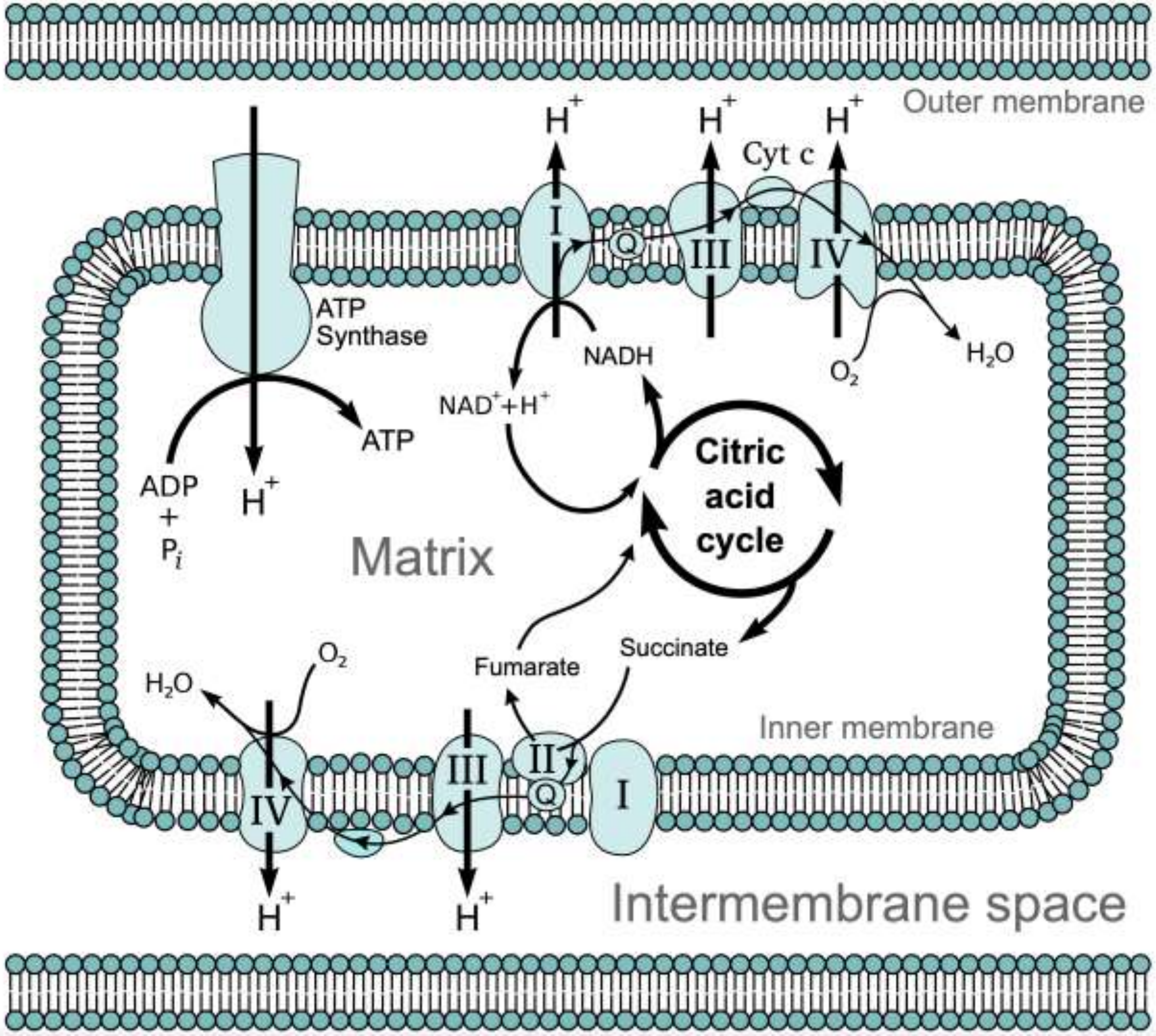
Glycolysis
Glucose
Pyruvate
NADH
Pyruvate Oxidation
Acetyl-CoA
NADH
CO_2
NADH
Krebs Cycle
CO_2
$FADH_2$
2 ATP
32 ATP
H^+
H_2O
$2H^+ + \frac{1}{2}O_2$
Q
C
H^+
H^+
H^+


Glycolysis
Glucose
Pyruvate
NADH
Pyruvate Oxidation
Acetyl-CoA
NADH
CO_2
NADH
Krebs Cycle
CO_2
$FADH_2$
2 ATP
H^+
32 ATP
$2H^+$
+
$\frac{1}{2}O_2$
H_2O
Q
C
H^+
H^+
H^+

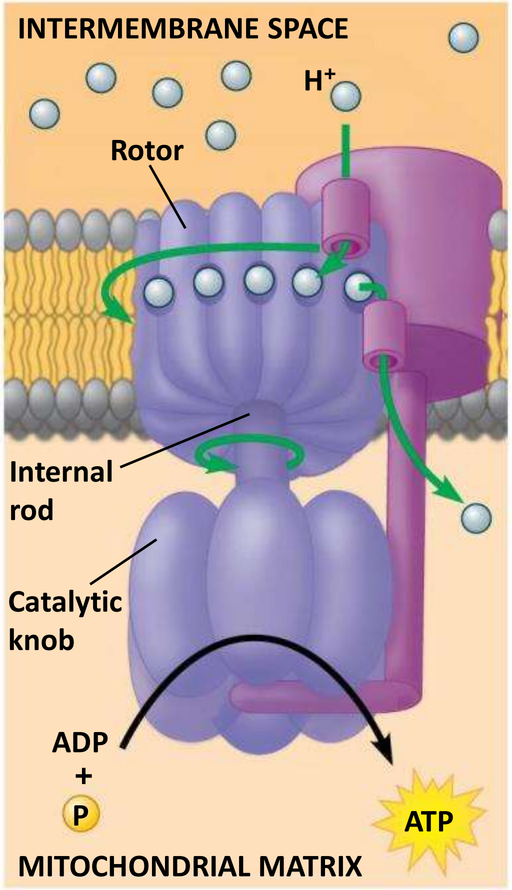
Most ATP production occurs by oxidative phosphorylation (The Electron Transport Chain)



The Electron Transport Chai



Most ATP production occurs by oxidative phosphorylation (The Electron Transport Chain)



Most ATP production occurs by oxidative phosphorylation (The Electron Transport Chain)

Thus, after glycolysis and the citric acid cycle, the cell has gained

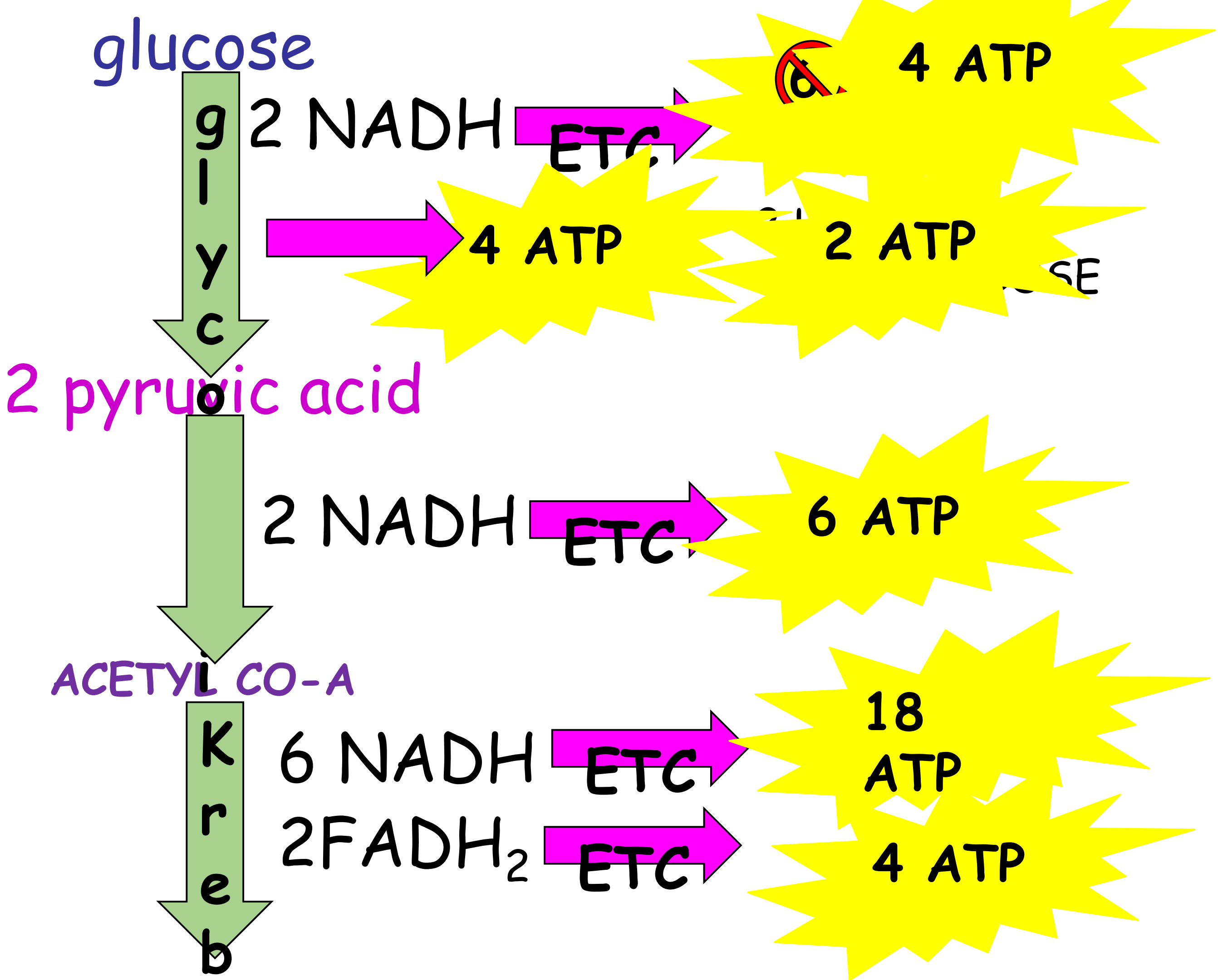
- 4 ATP
- 10 NADH
- 2 $FADH_2$

- To harvest the energy banked in NADH and $FADH_2$, these molecules must shuttle their high-energy _______________to an electron transport chain for oxidative phosphorylation

electrons

- This occurs in the ____________ of mitochondria

membranes

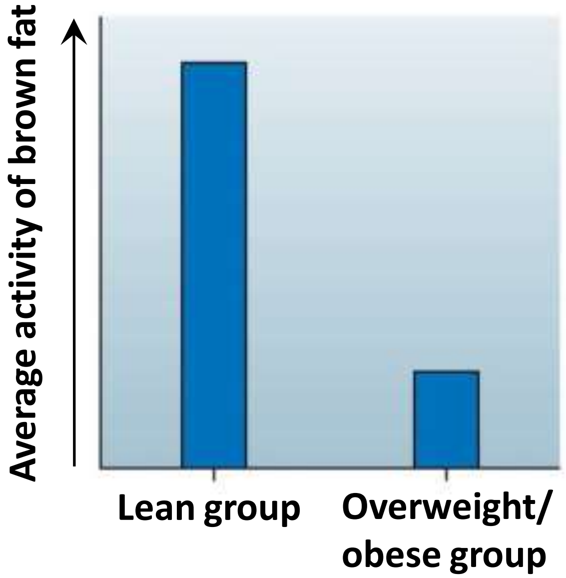

glucose
2 NADH
ETC
4 ATP
4 ATP
2 ATP
2 pyruvic acid
2 NADH
ETC
6 ATP
ACETYL CO-A
6 NADH
ETC
18 ATP
$2FADH_2$
ETC
4 ATP

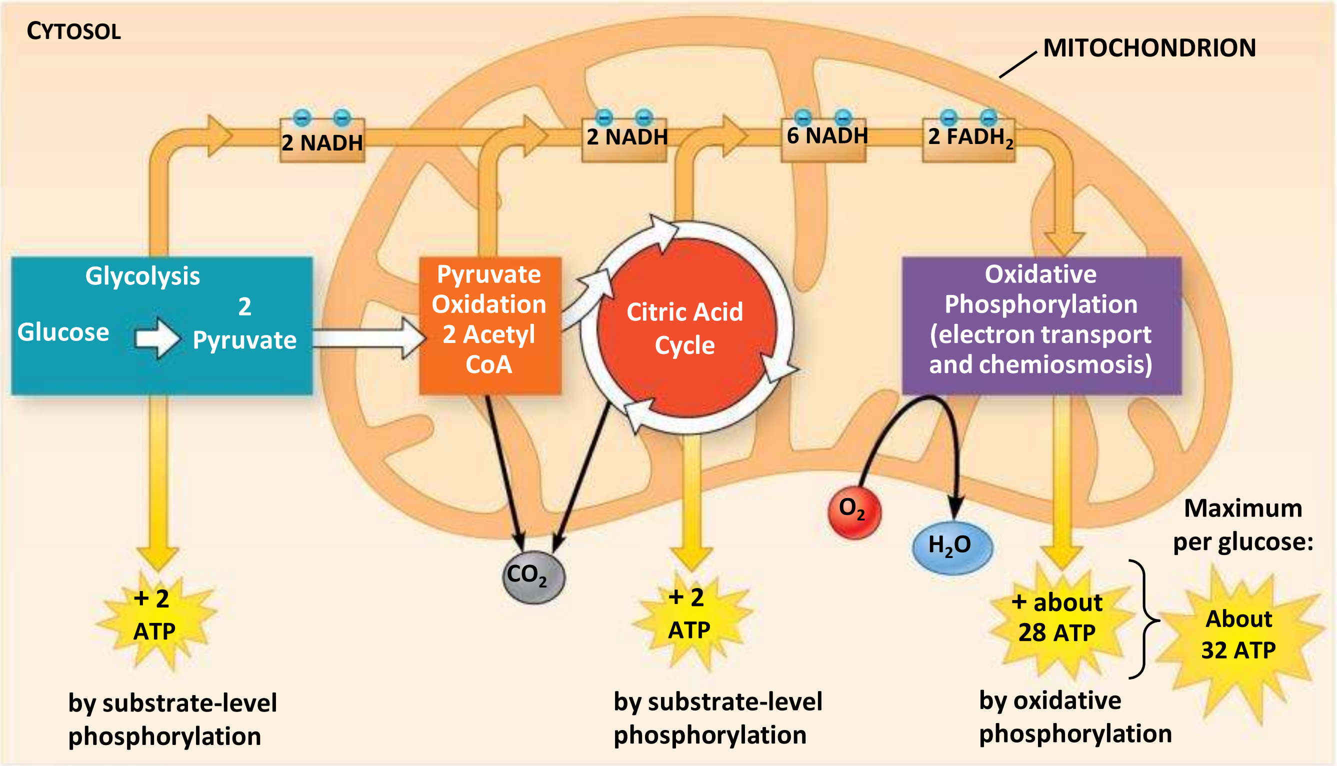
Overview: Oxidative phosphorylation

- The final stage of cellular respiration is oxidative phosphorylation (ETC), which involves electron transport and chemiosmosis and requires an adequate supply of__oxygen__.
- The electron transport chain is a series of __proteins__(electron carriers) built into a membrane that accept __electrons__from high energy NADH and $FADH_2$
- The proteins create an H^+ __concentration gradient__across the membrane and then use the energy of that gradient to drive ATP synthesis.
- When the electrons reach the bottom of the ETC they are picked up by the **final electron acceptor** __O_2__to form__water__.
- In **chemiosmosis,** the H^+ diffuses back across the inner membrane, through **ATP synthase** complexes, driving the synthesis of ATP.

SCIENTIFIC THINKING: Scientists have discovered heat-producing, calorie-burning brown fat in adults

- Mitochondria in brown fat can burn fuel and produce heat without making ATP.
- Ion channels spanning the inner mitochondrial membrane
  - allow H^+ to flow freely across the membrane
  - dissipate the H^+ gradient that the electron transport chain produced, which does not allow ATP synthase to make ATP.
- Scientific studies of humans indicate that brown fat may be present in most people when activated by cold environments, the brown fat of lean individuals is more active.





$$GTP+ADP \xrightarrow{\text{Nucleoside diphosphate kinase}} ATP+GDP$$

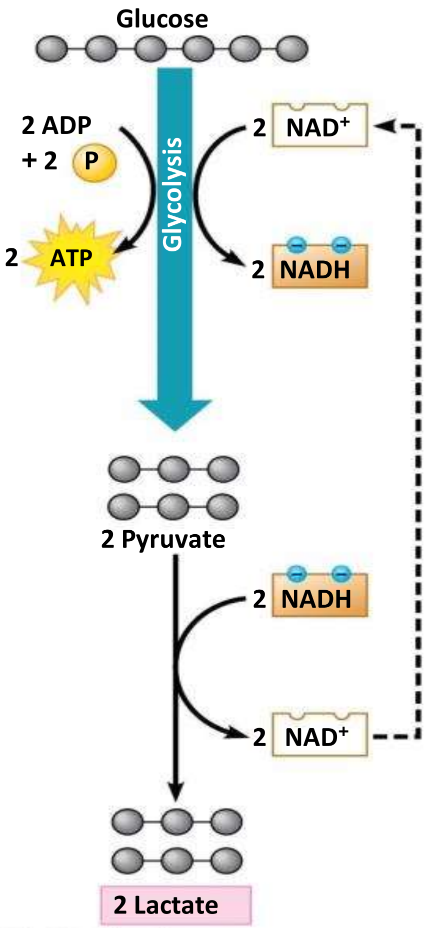
Fermentation: Anaerobic Harvesting of Energy

Fermentation enables cells to produce ATP without oxygen

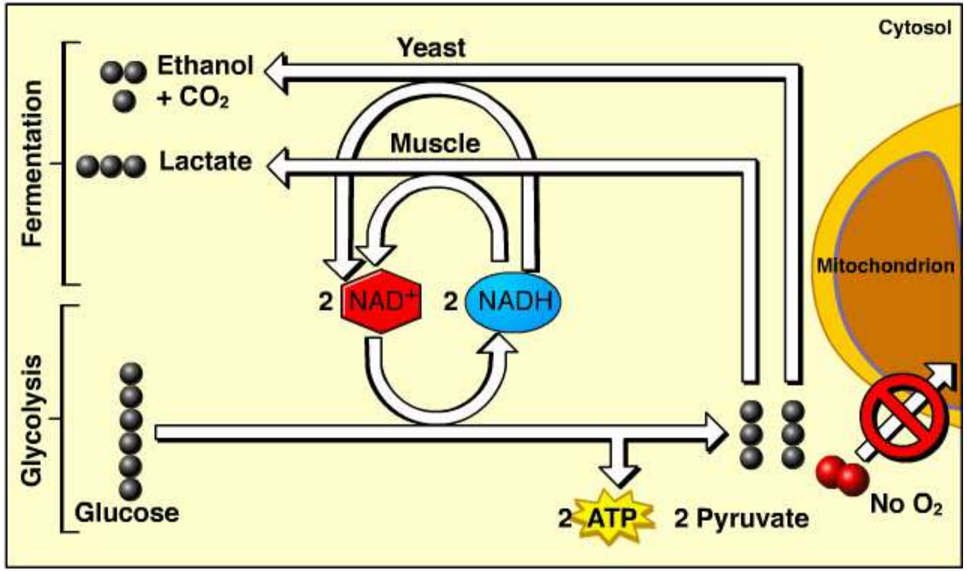
- Fermentation is a way of harvesting chemical energy that does not require oxygen.
- Fermentation uses glycolysis, produces two ATP molecules per glucose, and reduces NAD^+ to NADH.
- Fermentation also provides an anaerobic path for recycling NADH back to NAD^+.

Lactic Acid Fermentation

- Your muscle cells and certain bacteria can regenerate NAD^+ through **lactic acid fermentation**, in which NADH is oxidized back to NAD^+ and pyruvate is reduced to lactate.
- Lactate is carried by the blood to the liver, where it is converted back to pyruvate and oxidized in the mitochondria of liver cells.
- The dairy industry uses lactic acid fermentation by bacteria to make cheese and yogurt.
- Other types of microbial fermentation turn soybeans into soy sauce and cabbage into sauerkraut.

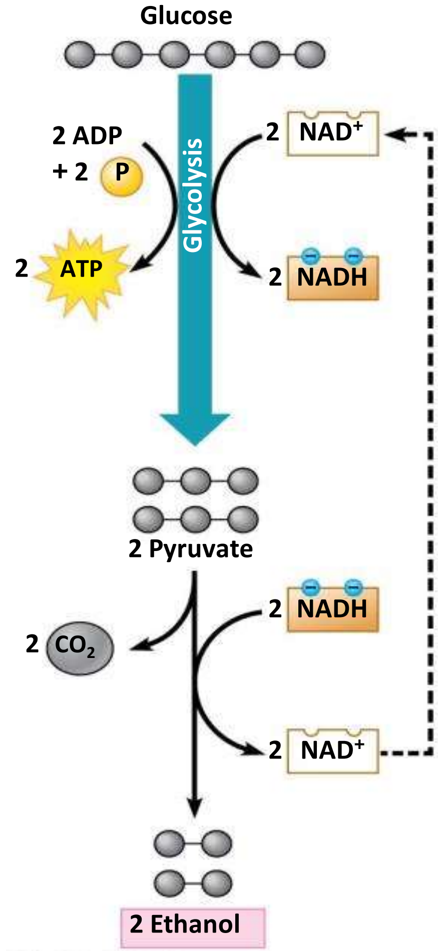


Fermentation Overview



Alcohol Fermentation

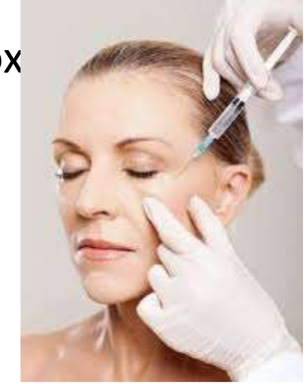
- The baking and winemaking industries have used **alcohol fermentation** for thousands of years.
- In this process, yeast (single-celled fungi) oxidize NADH back to NAD^+ and convert pyruvate to CO_2 and ethanol.



Fermentation enables cells to produce ATP without oxygen

- Obligate anaerobes (bacterial cells) require anaerobic conditions, are poisoned by oxygen, and live in stagnant ponds and deep soils. Ex. *Clostridium botulinum,* causes botulism.

Botox



- Facultative anaerobes can make ATP by fermentation or oxidative phosphorylation and include yeasts and many bacteria.

EVOLUTION CONNECTION: Glycolysis evolved early in the history of life on Earth

- Glycolysis is the universal energy-harvesting process of life. The role of glycolysis in fermentation and respiration dates back to life long before oxygen was present, when only prokaryotes inhabited the Earth, about 3.5 billion years ago.
- The ancient history of glycolysis is supported by its occurrence in all the domains of life and location within the cell, using pathways that do not involve any membrane-enclosed organelles of the eukaryotic cell.

Connections Between Metabolic Pathways

Cells use many kinds of organic molecules as fuel for cellular respiration

- Although glucose is considered to be the primary source of sugar for respiration and fermentation, ATP is generated using carbohydrates, fats, and proteins.
- Fats make excellent cellular fuel because they contain many hydrogen atoms and thus many energy-rich electrons and yield more than twice as much ATP per gram as compared to a gram of carbohydrate.
- Proteins can also be used for fuel, although your body preferentially burns sugars and fats first.