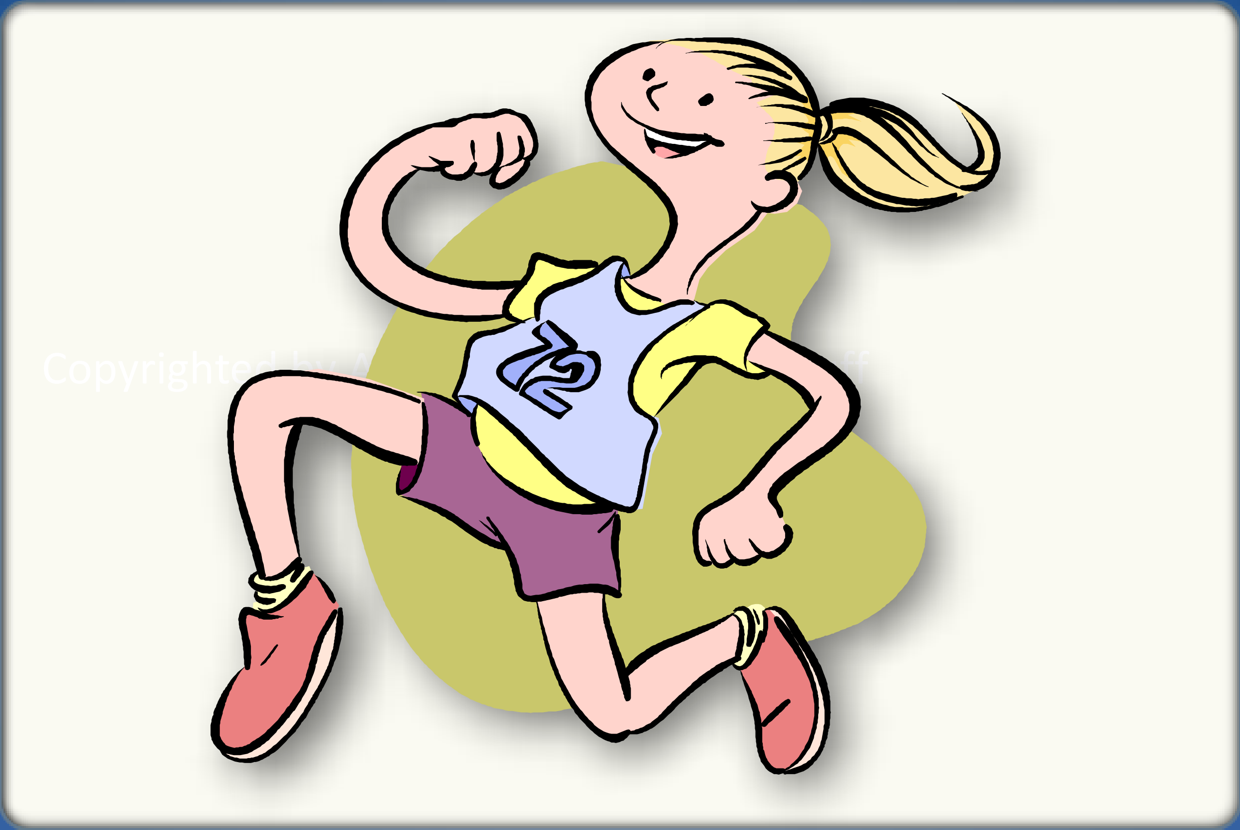


Cellular Respiration

Let's get energized!

THE IMPORTANCE OF FOOD

Food provides living things with the: chemical building blocks they need to grow and reproduce.

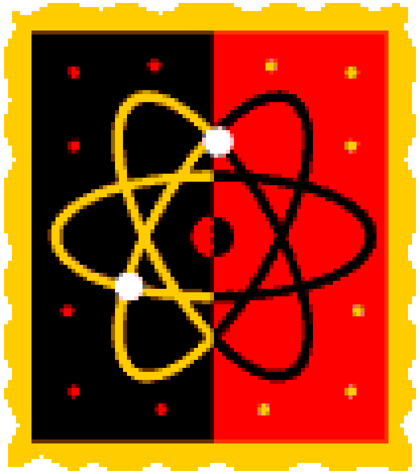
Food serves as a source of…

…raw materials for the cells of the body.

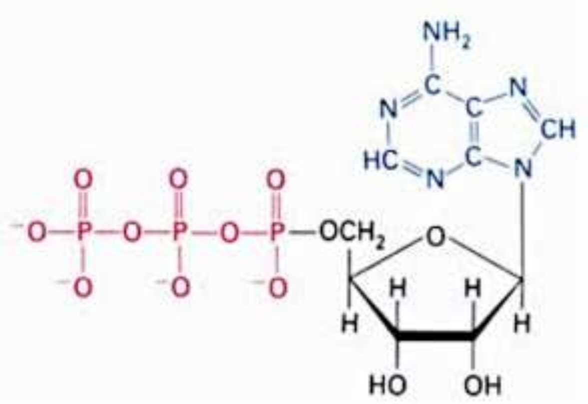
Food serves as a source of _energy_.

Chemical Energy and ATP

Inside living cells, energy can be stored in chemical compounds.



One of the principal chemical compounds that cells use to store and release energy is:



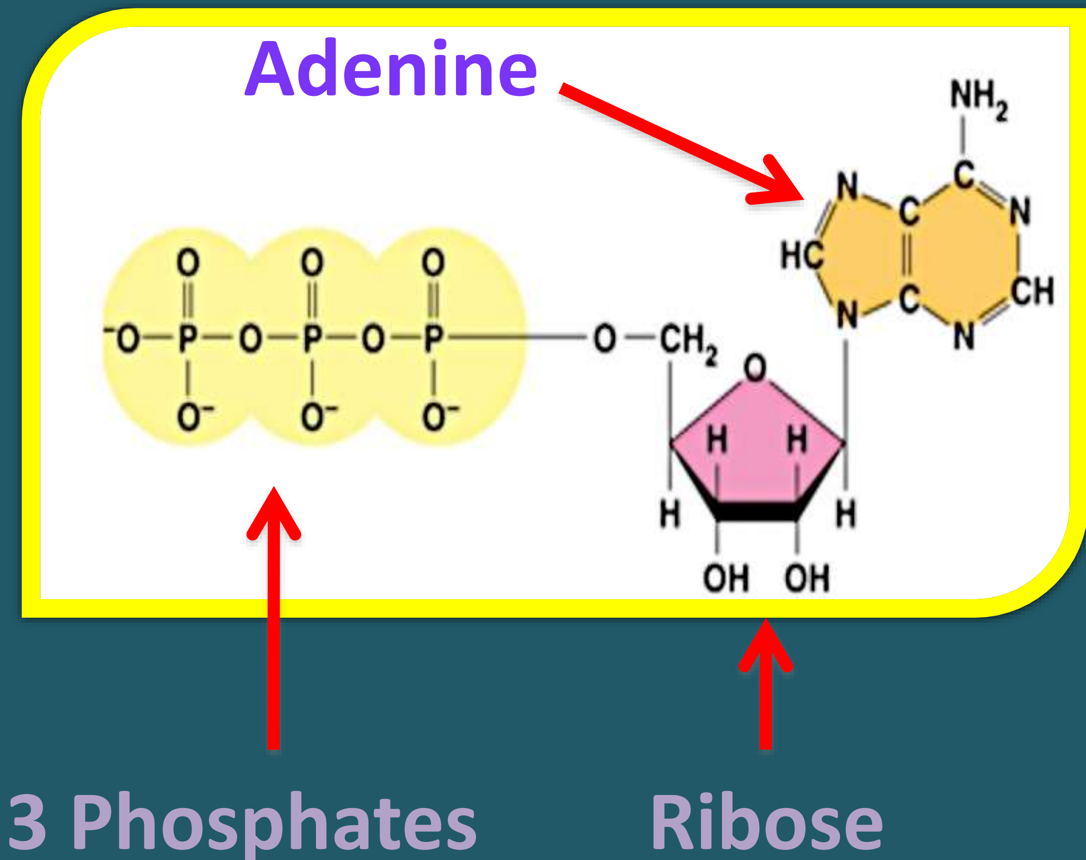
ADP and ATP

ATP -- Adenosine Triphosphate

ADP – Adenosine Diphosphate

ADP is energy poor (like a dead battery.)	ATP is energy rich (like a charged battery.)

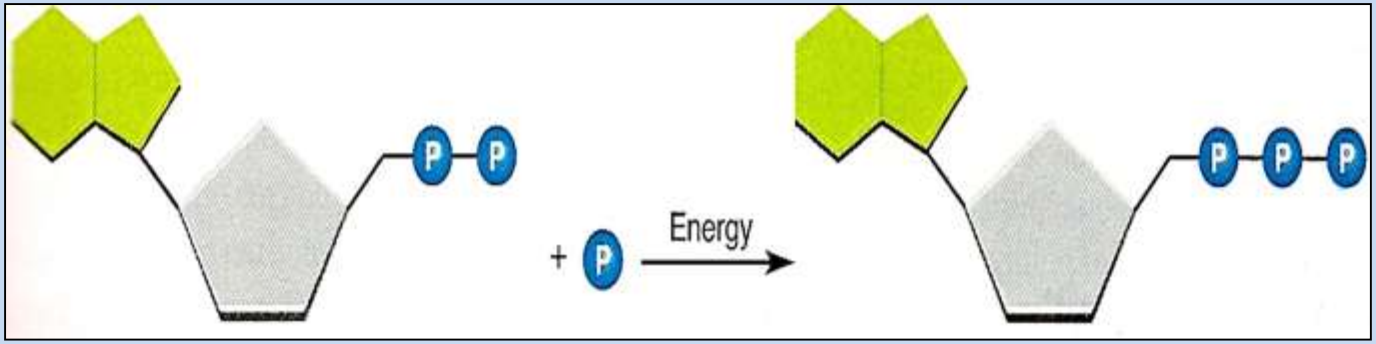
Structure of ATP



Consists of:

1) Adenine, a nitrogen base
2) Ribose, a five-carbon sugar
3) A chain of three phosphate groups

How ADP Becomes ATP



ADP is a compound that looks almost like ATP. The difference is that….

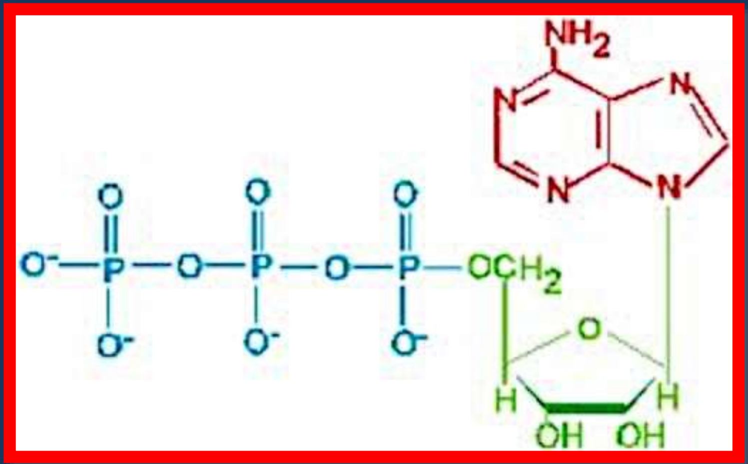
…ADP has 2 phosphate groups and ATP has three phosphate groups.

When a cell has energy available, it can store small amounts of it by adding a phosphate group to ADP.

Adding a phosphate to ADP forms a molecule of ATP. The addition of the third phosphate stores energy.

When a cell needs energy, the third phosphate will be removed. This releases energy.

ATP has enough stored energy to power a variety of cellular activities such as.....



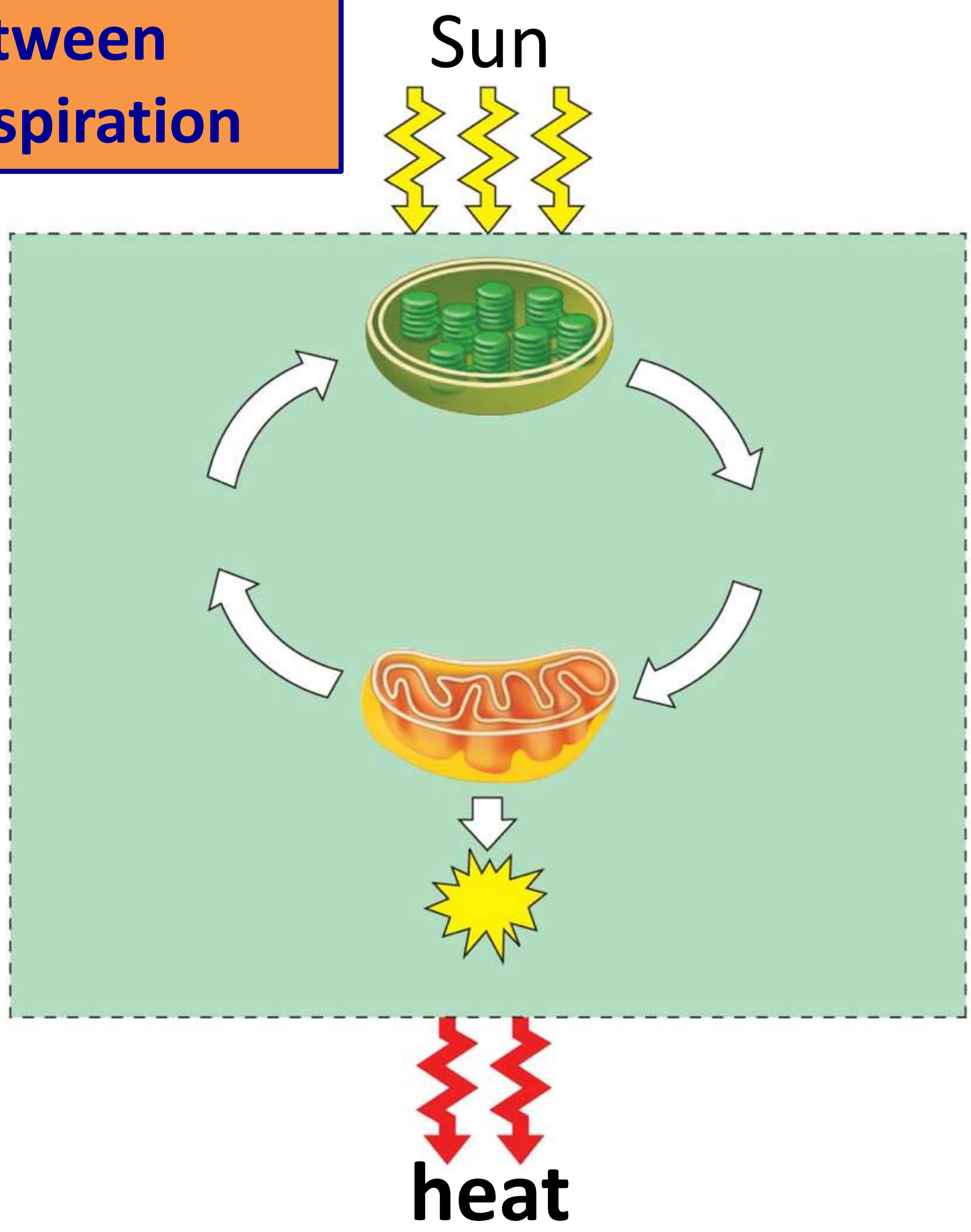
1. Photosynthesis
2. Protein synthesis
3. Muscle contraction
4. Active transport across the cell membrane

The ATP molecule is the _basic energy source_ of all living cells.

In a cell, ATP is used continuously and must be regenerated continuously. In a working muscle cell, 10 million ATP are consumed and regenerated per sec.

The Relationship Between Photosynthesis and Respiration

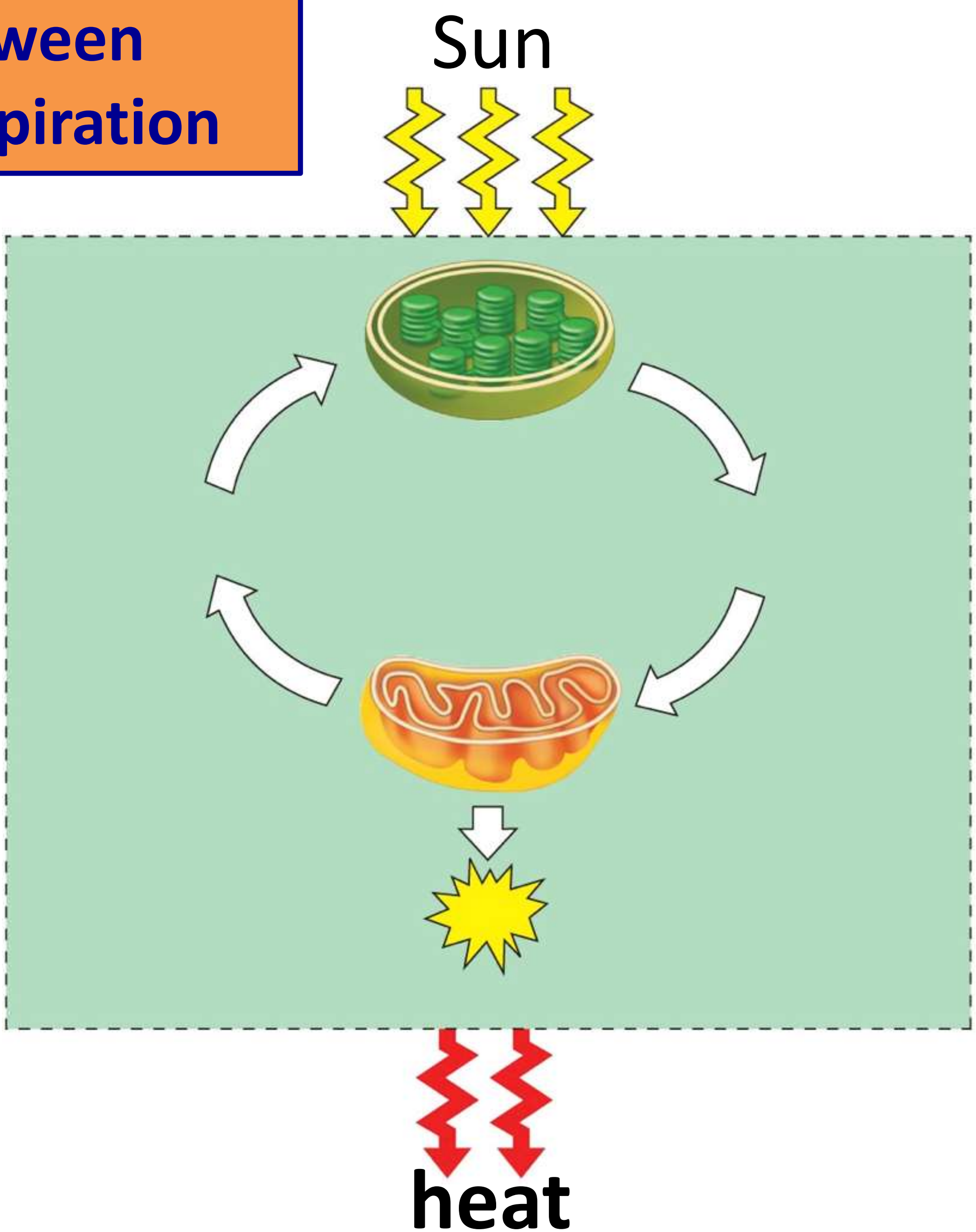
Energy flows into an ecosystem as __sunlight__ and leaves as __heat__. Energy is not __recycled__. Energy follows a one-way path through our ecosystem.



The Relationship Between Photosynthesis and Respiration

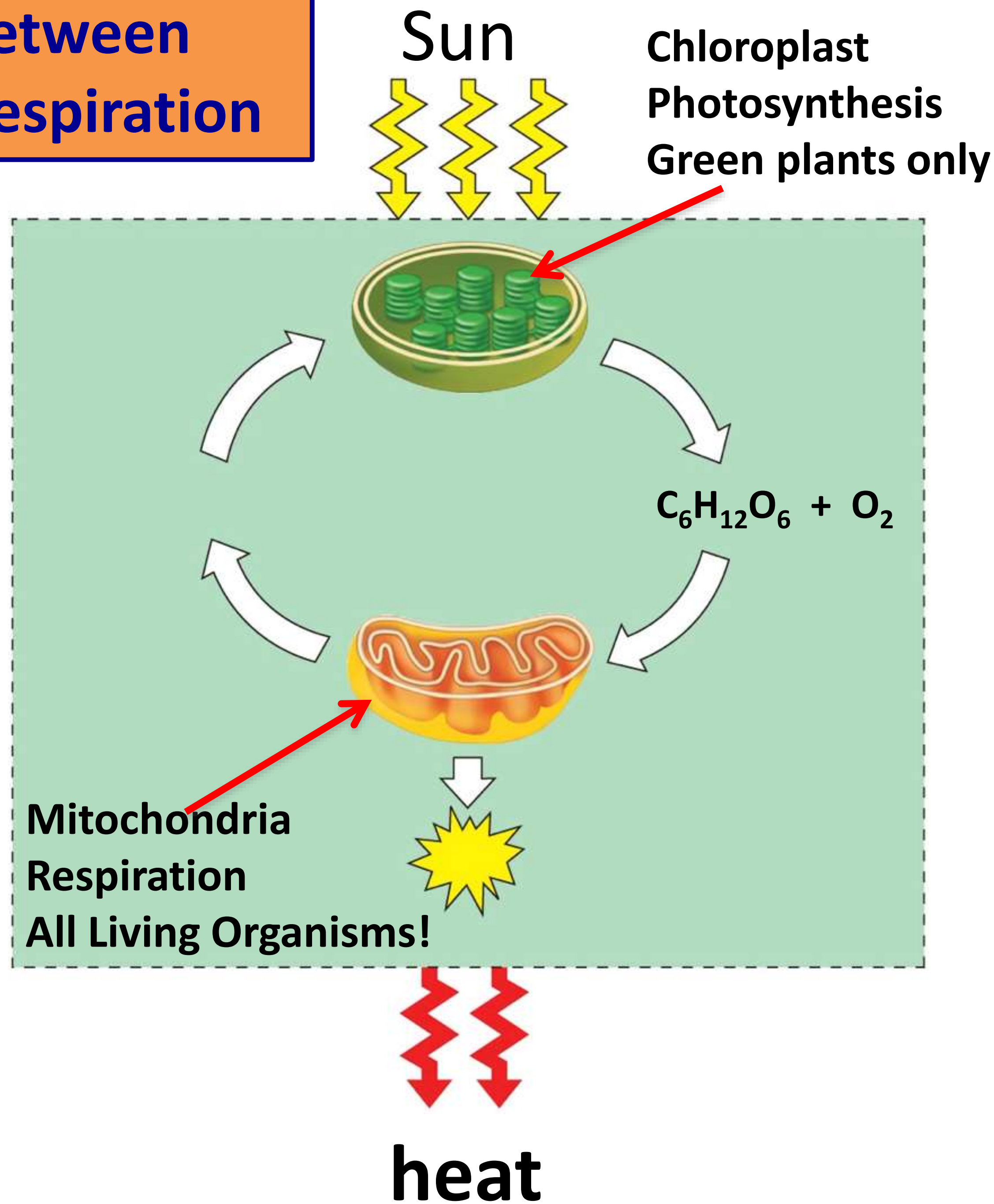
However, the chemical elements essential to life are recycled.

Photosynthesis converts light energy from the sun into chemical energy, which is stored in carbohydrates and other organic compounds.



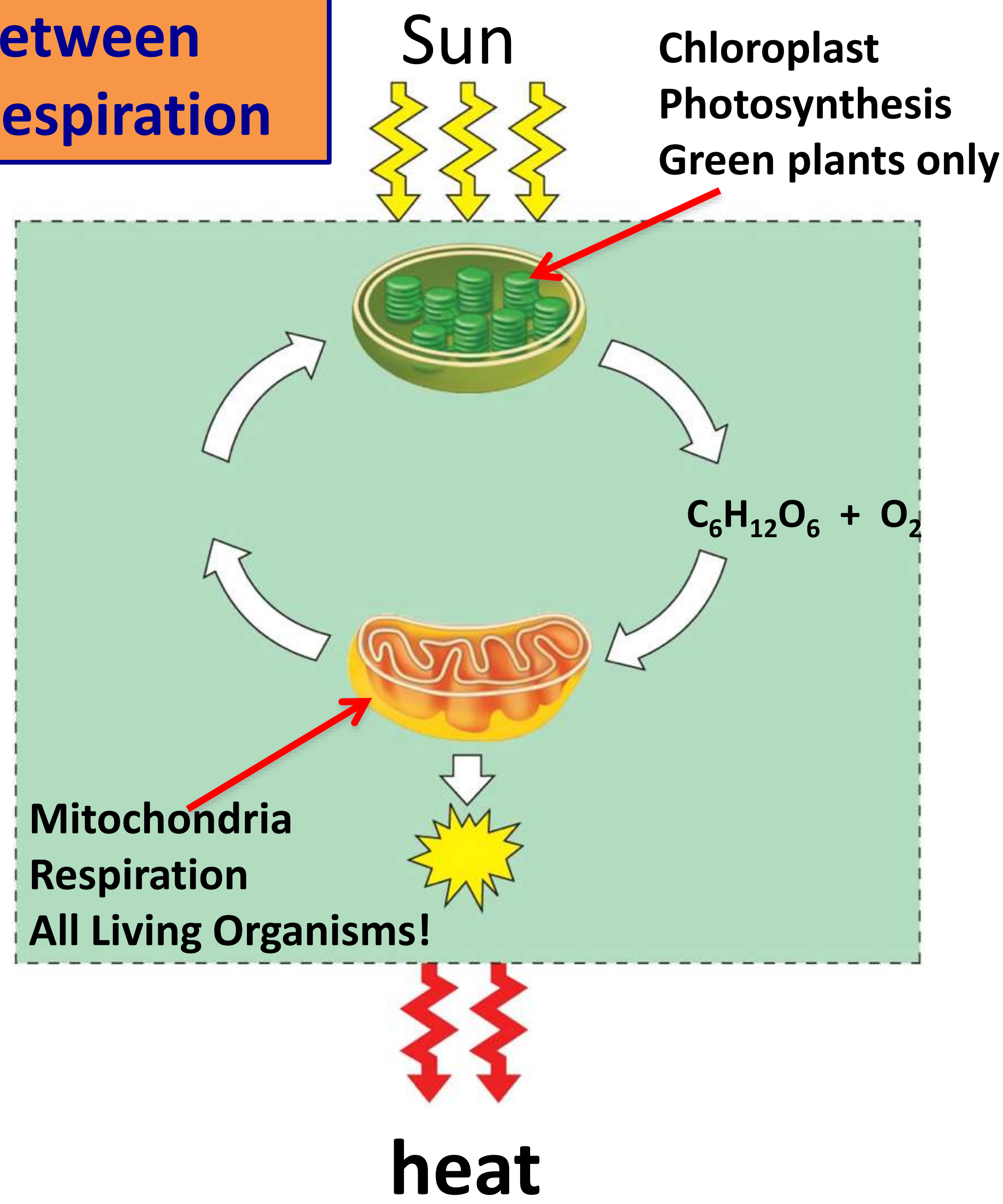
The Relationship Between Photosynthesis and Respiration

Photosynthesis generates the oxygen____ and glucose____ used by the mitochondria of eukaryotes as fuel for: cellular respiration.



The Relationship Between Photosynthesis and Respiration

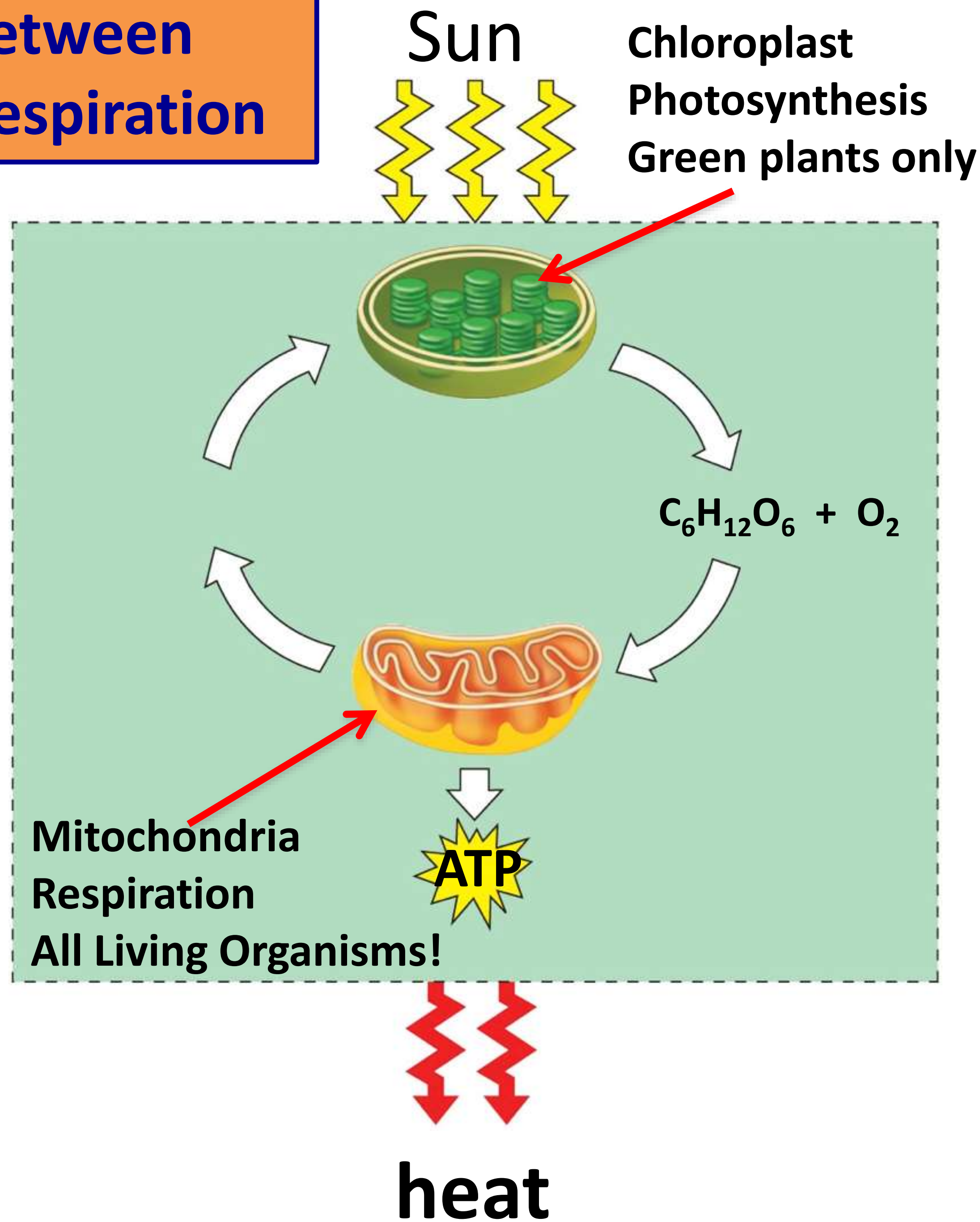
Cellular respiration breaks down ___glucose___ into simpler substances and releases the stored ___energy___.



The Relationship Between Photosynthesis and Respiration

Some of this energy is used to make _ATP_ from ADP.

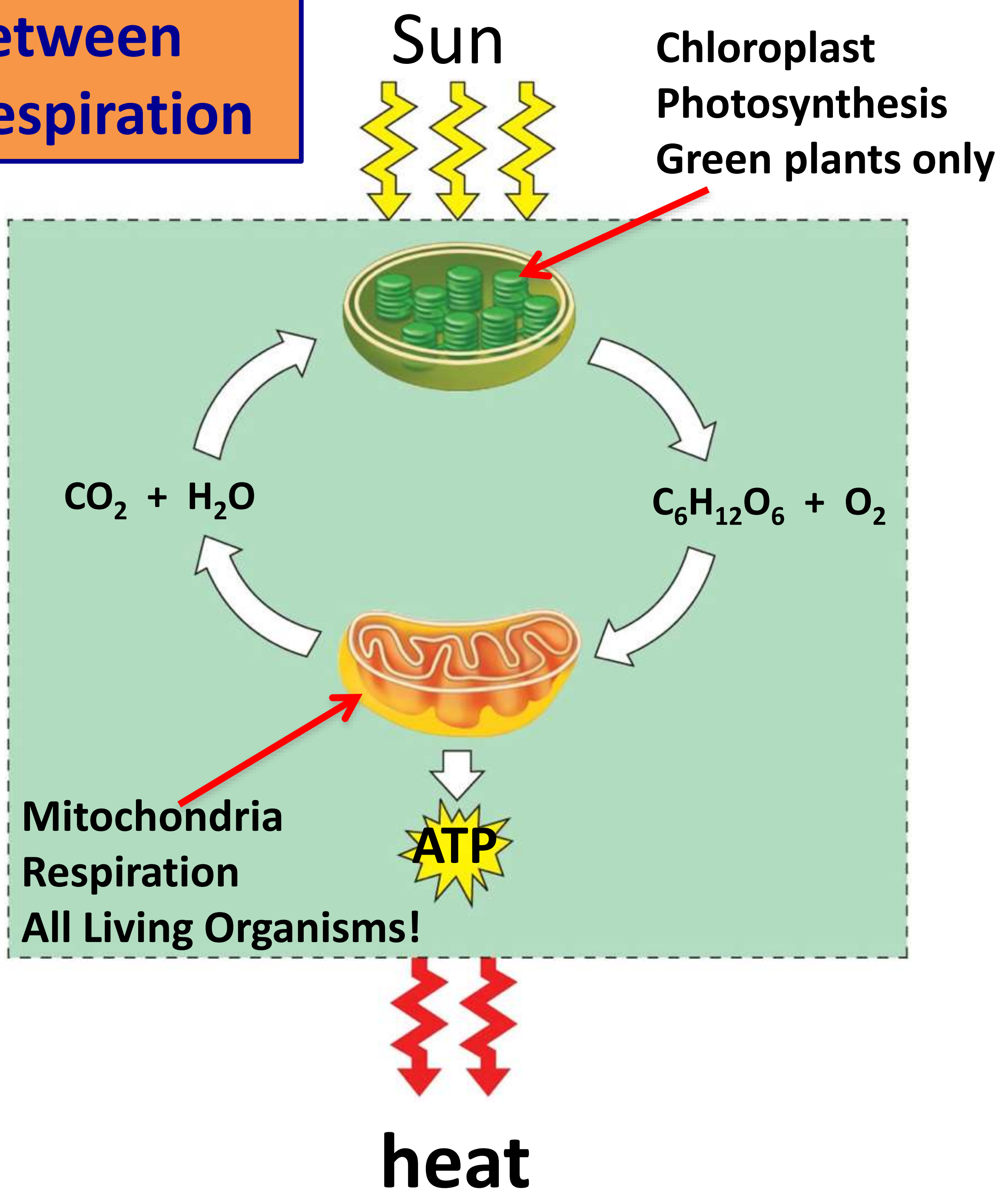
Some of this energy is lost as _heat_.



The Relationship Between Photosynthesis and Respiration

The waste products of respiration, __CO_2 and H_2O__, are the raw materials for __photosynthesis__.

IMPORTANT NOTE: While only green plants carry out __photosynthesis__, ALL living things carry out __respiration__.



OVERVIEW OF RESPIRATION

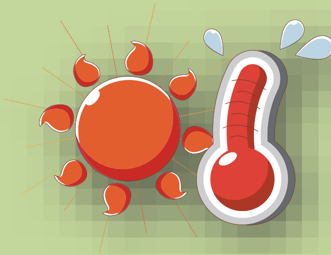
Cellular respiration is the process that **releases energy by breaking down glucose and other food molecules in the presence of oxygen.**

It is the process of converting **glucose to ATP**.

Equation for respiration:

$$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O + 36\ ATP$$

There is much _**energy**_ stored in this molecule of _**glucose**_. This energy must be released in _**small, controlled**_ steps. If all the energy from glucose were released at once, most of it would be lost as _**heat and light**_.



The energy stored in glucose will be released bit by bit and this energy will be used to produce _**ATP**_.

The energy cannot be released from the glucose all at once. It would be the equivalent of the gas tank in your car exploding in one single reaction, rather than in the small controlled combustions that drive your car.

THERE ARE 2 TYPES OF RESPIRATION:

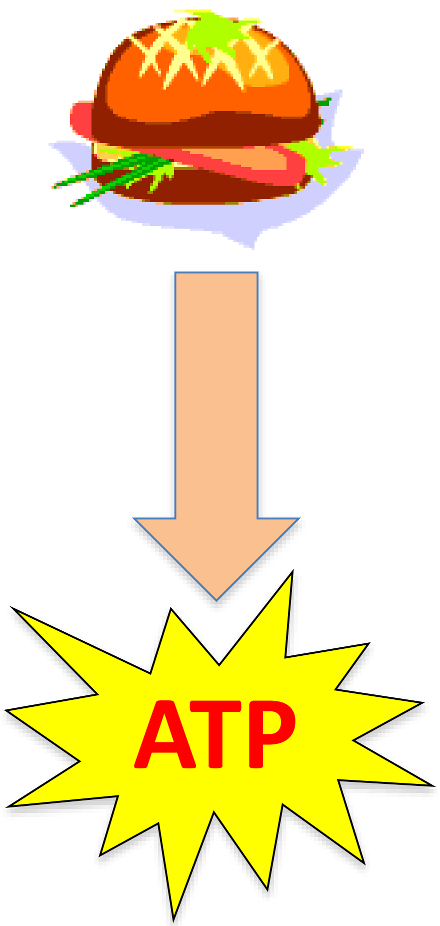
Aerobic Respiration: Requires oxygen

Anaerobic Respiration: Does NOT require oxygen

Respiration takes place in three main stages:

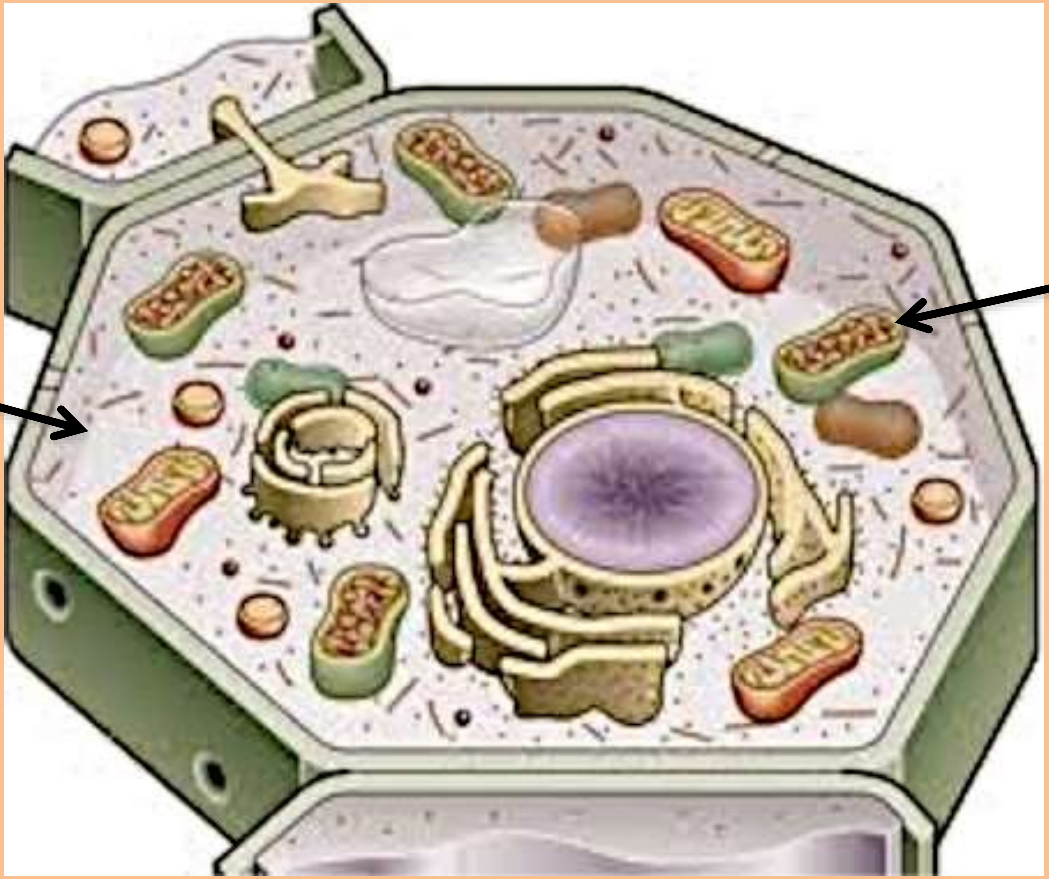
Respiration

- Glycolysis (anaerobic)
- Krebs cycle (aerobic)
- Electron Transport Chain (aerobic)



Glycolysis occurs in the _cytoplasm_, but the Krebs cycle, and electron transport chain occurs in the _mitochondria_.

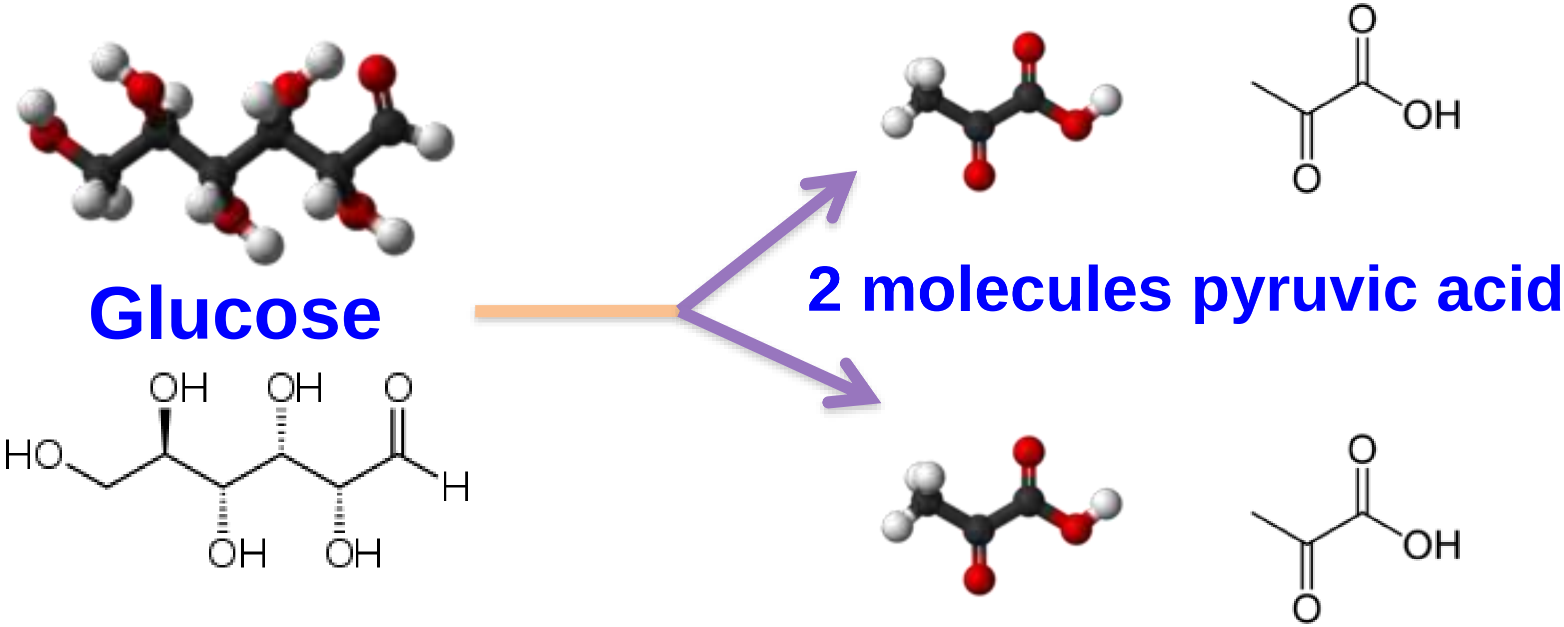
Glycolysis occurs in the cytoplasm.



The Krebs cycle and the electron transport chain occur in the mitochondria.

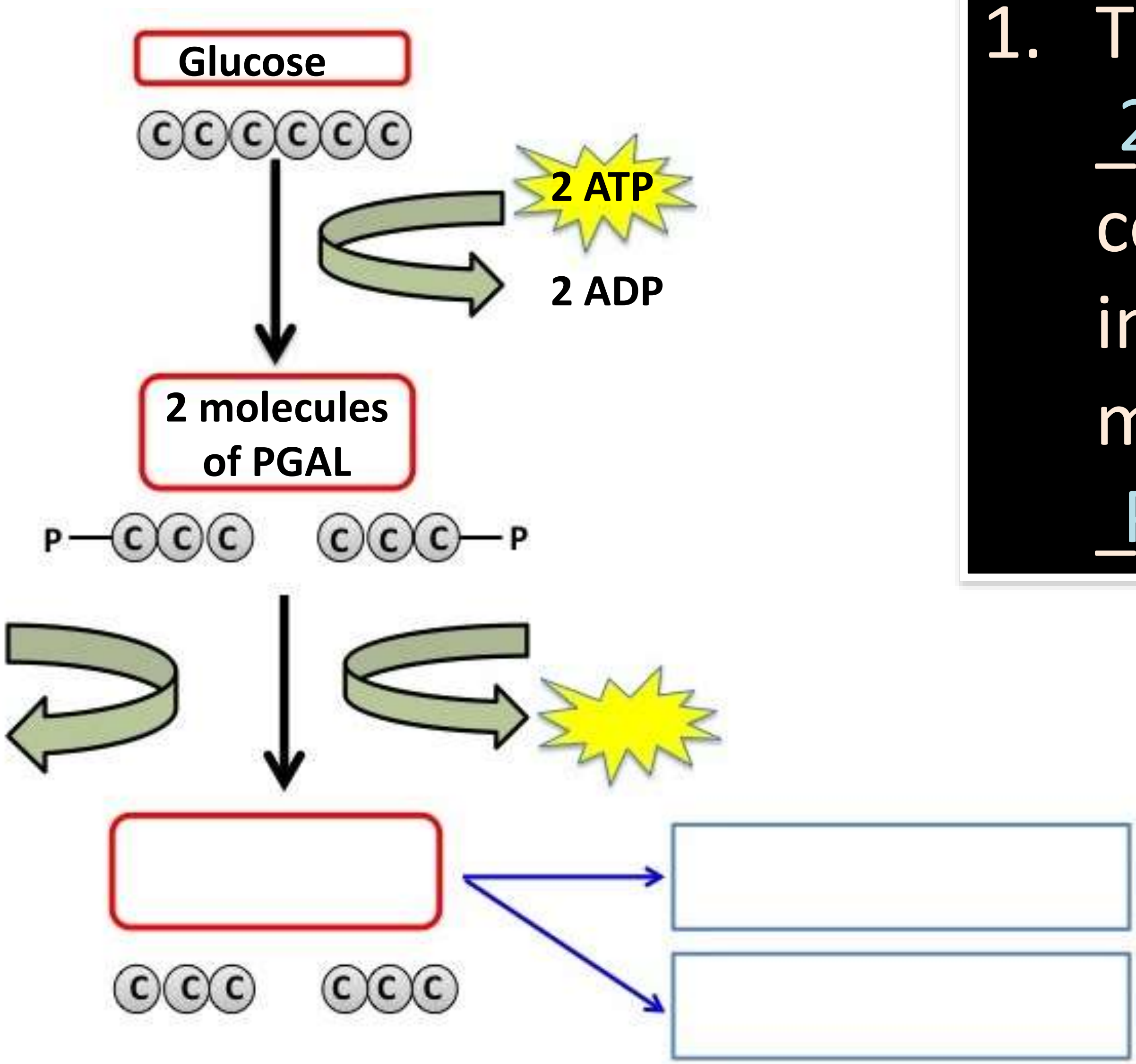
Definition:

Glycolysis is the process in which one molecule of glucose is oxidized to produce two molecules of pyruvic acid.



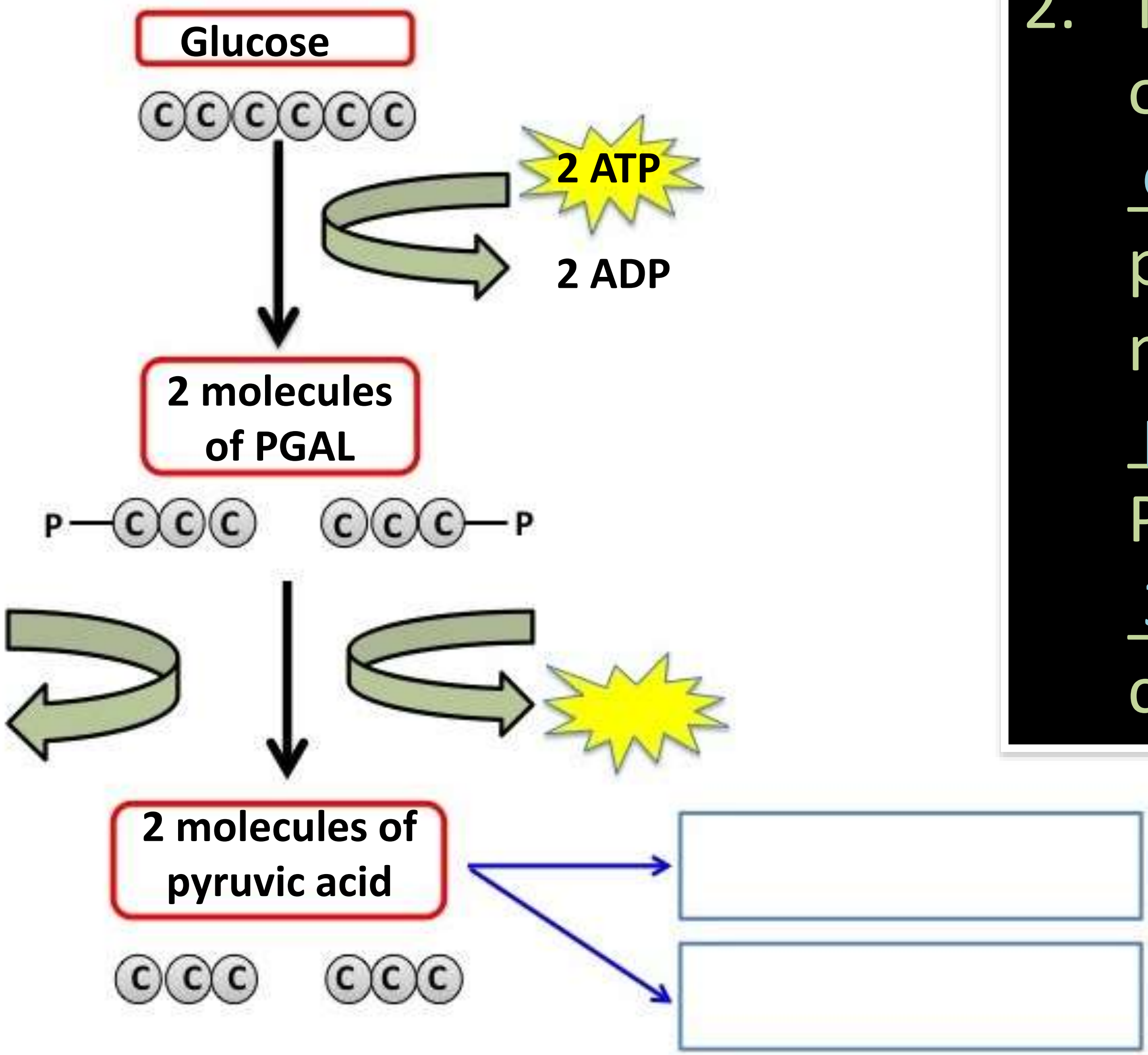
GLYCOLYSIS

Steps in Glycolysis



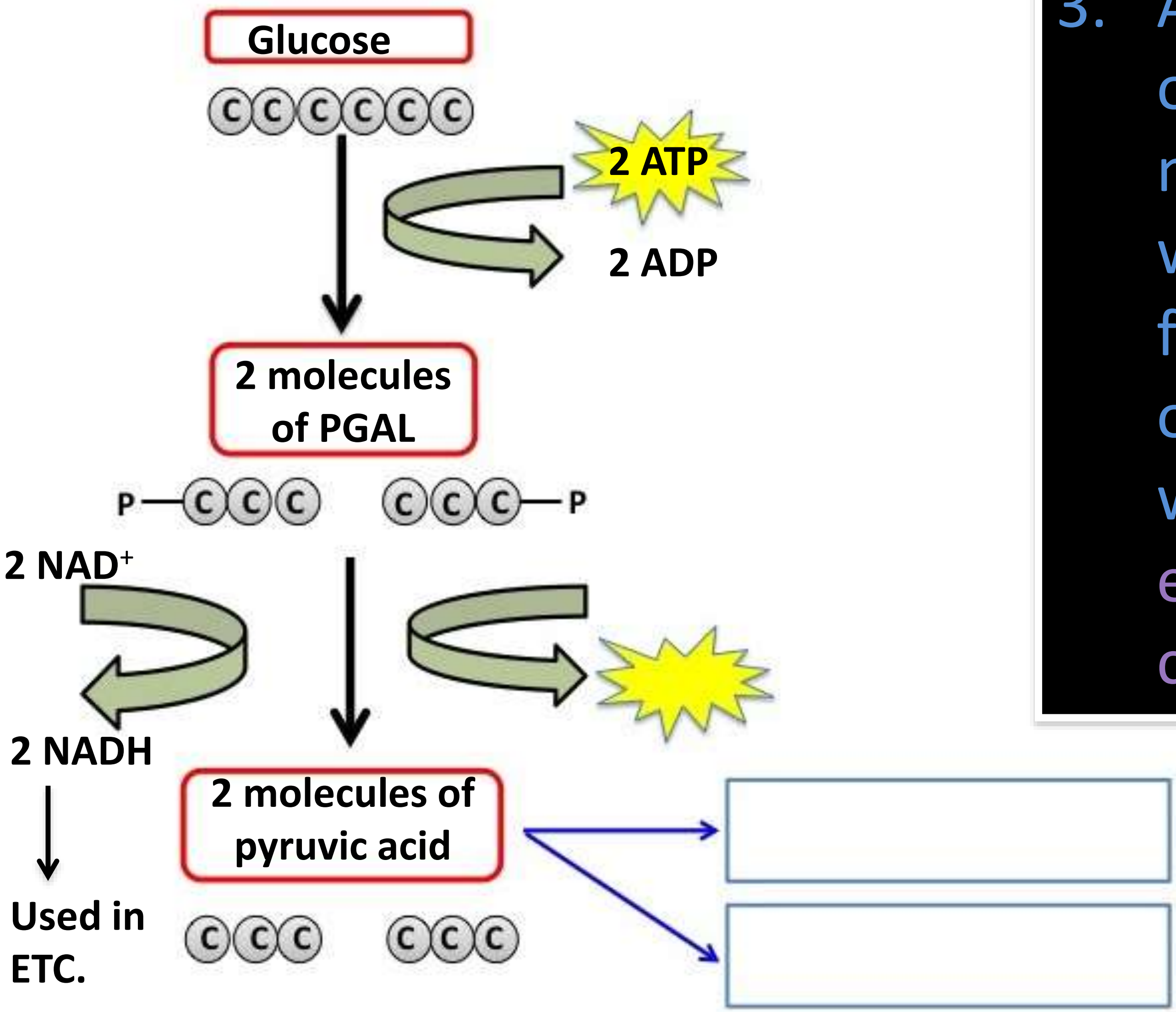
1. The energy of _2 ATP_ is used to convert _glucose_ into two molecules of _PGAL_.

Steps in Glycolysis



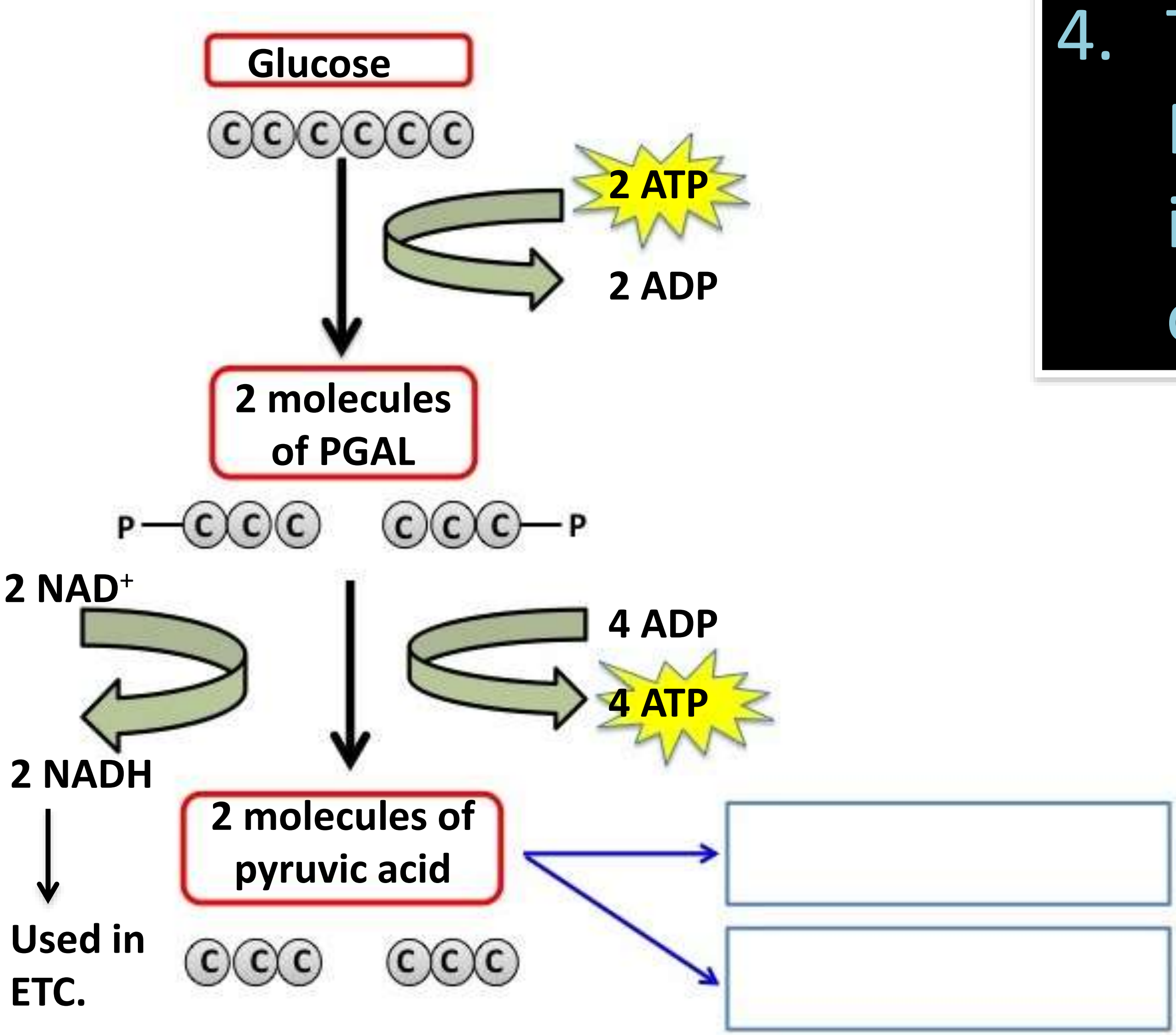
2. The two molecules of _PGAL_ will be _oxidized_ to produce two molecules of _pyruvic acid_. Pyruvic acid is a _3-carbon_ compound.

Steps in Glycolysis



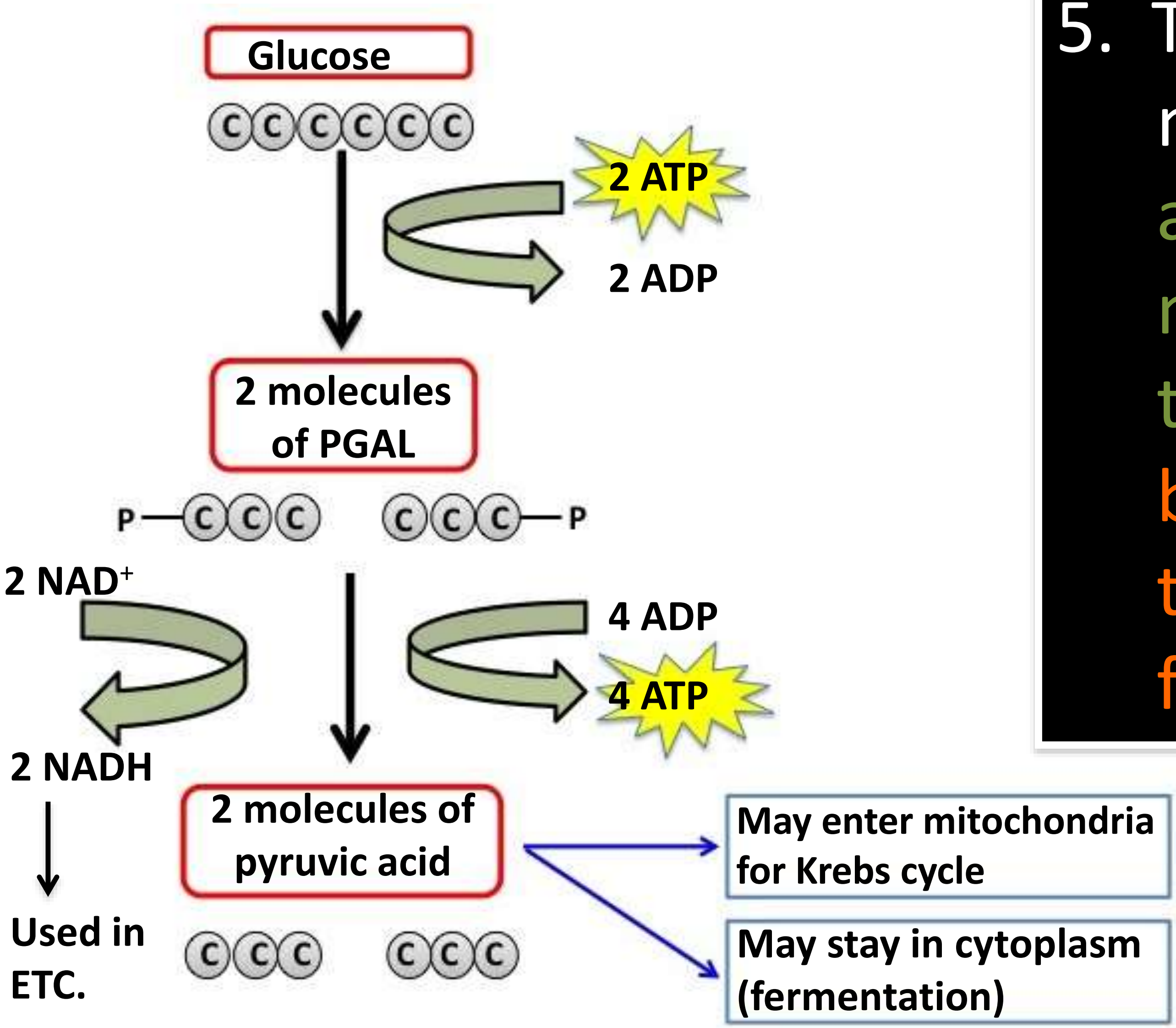
3. As the PGAL is oxidized, two molecules of NAD^+ will be reduced to form two molecules of NADH. These will be used in the: electron transport chain.

Steps in Glycolysis



4. The oxidation of PGAL also results in the production of __4 ATP__.

Steps in Glycolysis



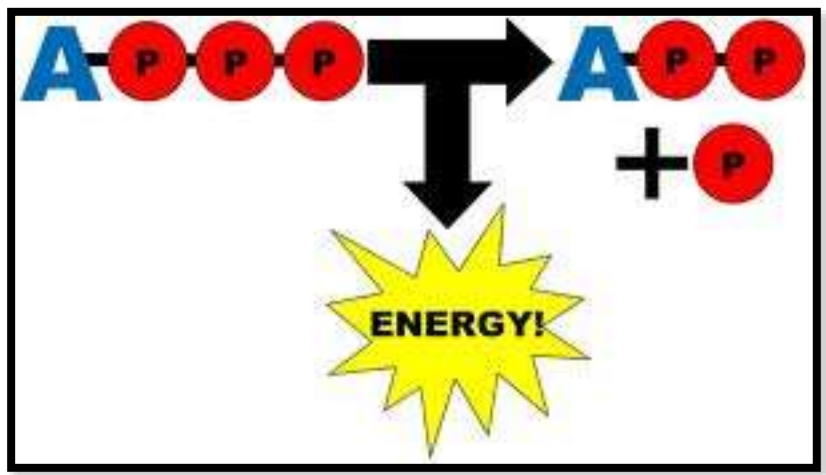
5. The pyruvic acid may:
   a) enter the mitochondria for the Krebs cycle
   b) may remain in the cytoplasm for fermentation.

ATP Production:

Two molecules of ATP are consumed at the beginning, but four molecules of ATP are produced by the end of glycolysis.

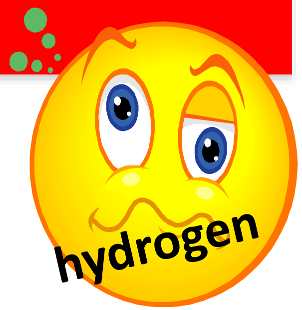
Glycolysis has a gain of 2 ATP.

Even though cellular respiration is an energy releasing process, the cell must invest a small amount of energy to get the reaction going.



NADH Production:

I'm NAD$^+$, the hydrogen acceptor. My job is to carry hydrogen to the electron transport chain.



1. During this reaction, two high-energy electrons are removed from each PGAL . These electrons are passed to the electron acceptor NAD$^+$.
2. NAD$^+$ in respiration is similar to NADP$^+$ in photosynthesis.
3. Each NAD$^+$ accepts a pair of electrons to form NADH.
4. This NADH holds the electrons until they can be transferred to other molecules.
5. NAD$^+$ helps to pass the energy from glucose to other pathways in the cells.

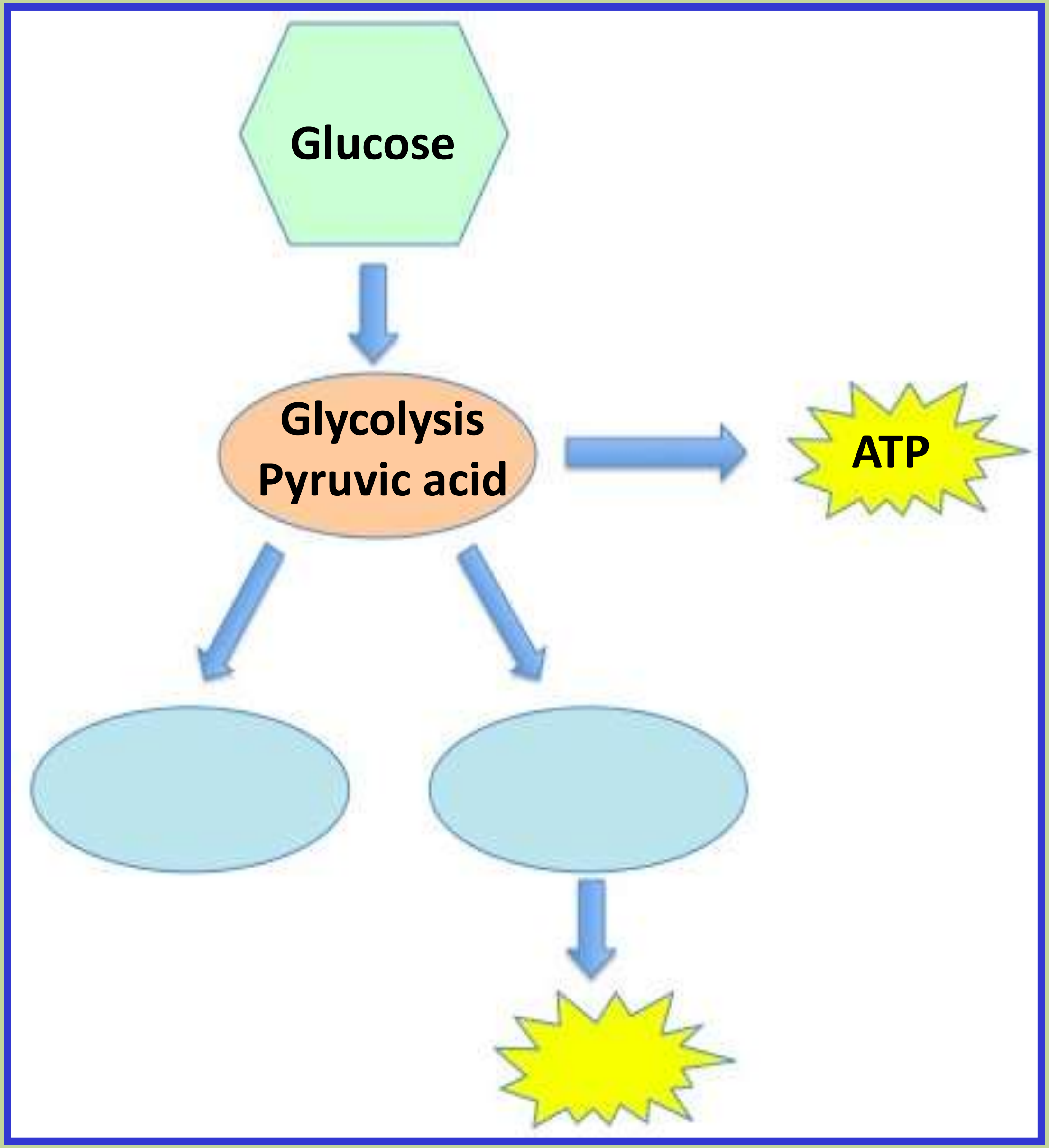
Advantages and Disadvantages of Glycolysis

1. Glycolysis only produces a gain of 2 ATP per molecule of glucose, but the process is so fast that 1000's of ATP are produced in just a few milliseconds.
2. Another advantage is that glycolysis does not require oxygen. Energy can be produced for the cell even if no oxygen is present.

3. Disadvantage: If the cell relied only on glycolysis for ATP production, the cell would quickly run out of NAD^+ to accept the hydrogen electrons. Without NAD^+, the cell cannot keep glycolysis going and ATP production would stop. To keep glycolysis going, the NADH must deliver their high-energy cargo of electrons to another pathway, and then return to glycolysis to be used again.

The Fate of Pyruvic Acid – What happens to it?

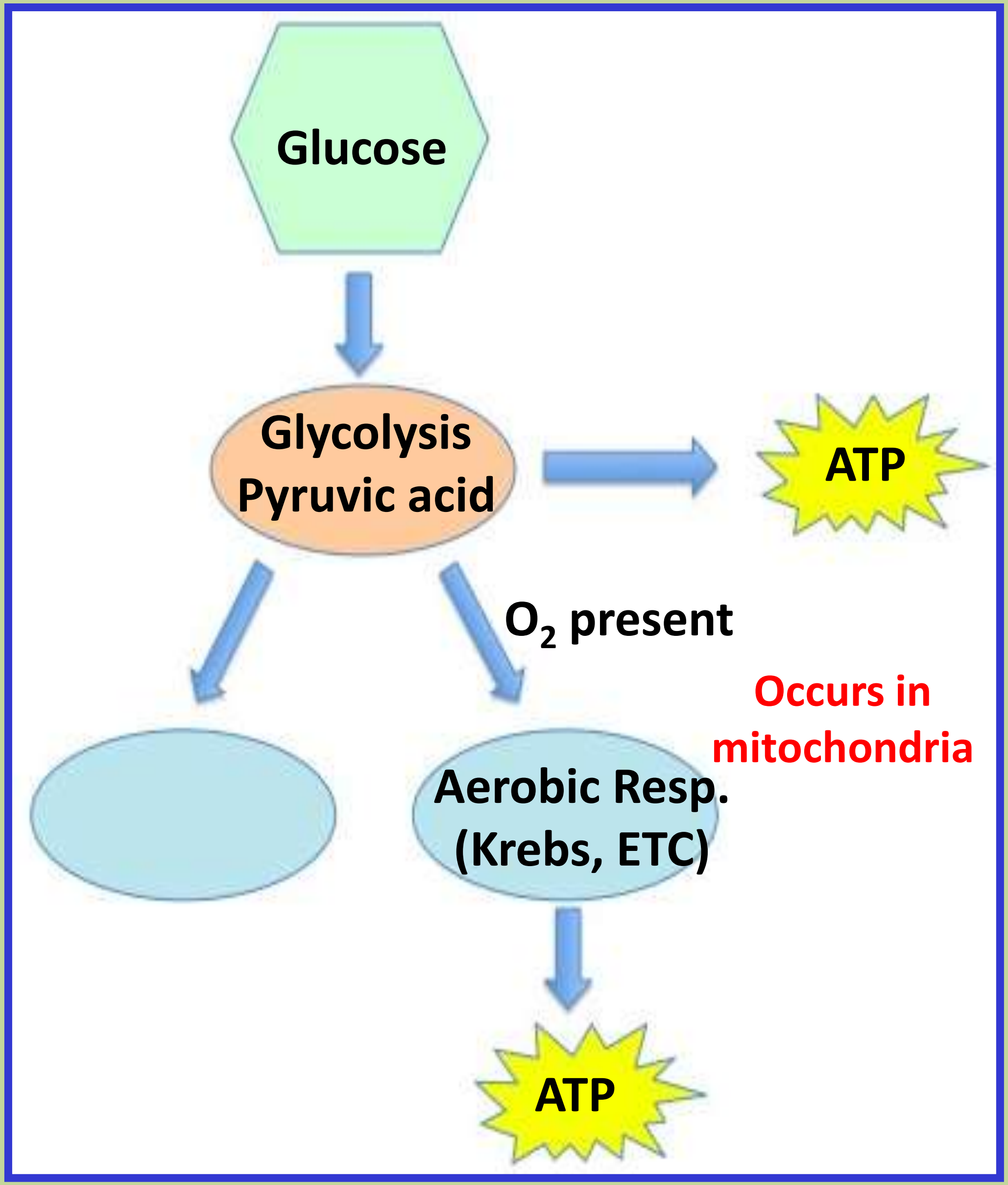
There are _two_ possibilities for the path that _pyruvic acid_ will now take.
It depends on whether or not _oxygen_ is present.



The Fate of Pyruvic Acid – What happens to it?

If oxygen is present:

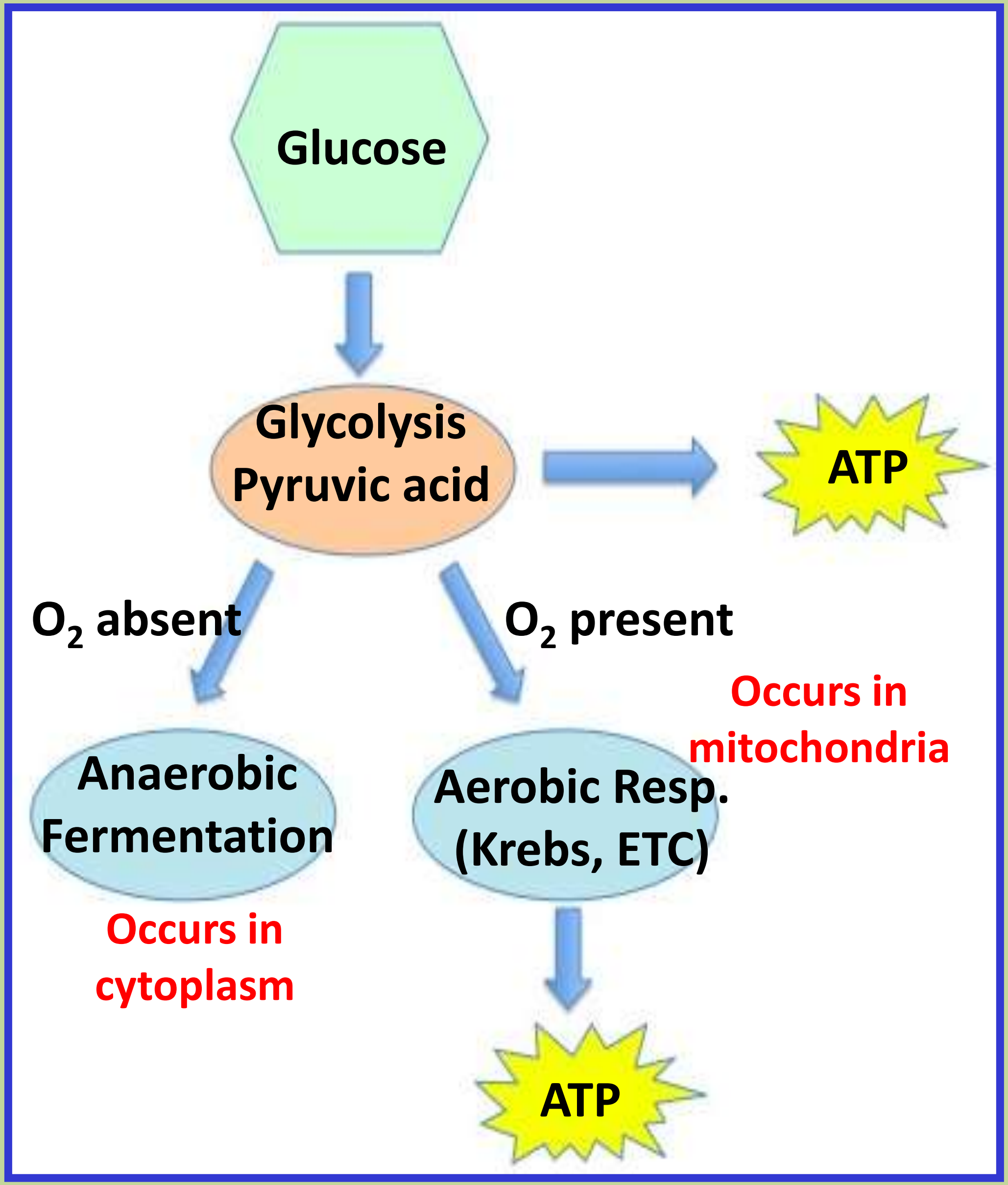
1. In the presence of oxygen, the pyruvic acid will enter the <u>mitochondria</u> and undergo <u>aerobic</u> respiration.
2. Aerobic respiration includes the stages known as the <u>Krebs cycle</u> and the <u>electron transport chain</u>.
3. Aerobic respiration will yield many more <u>ATP</u> than <u>glycolysis</u>.



The Fate of Pyruvic Acid – What happens to it?

If no oxygen is present:

1. In the absence of oxygen, the pyruvic acid will enter the __anaerobic__ pathways of __fermentation__.
2. Fermentation yields no additional __ATP__.
3. Occurs in the __cytoplasm__.



What are the two major stages of aerobic respiration?

Aerobic respiration has two major stages:

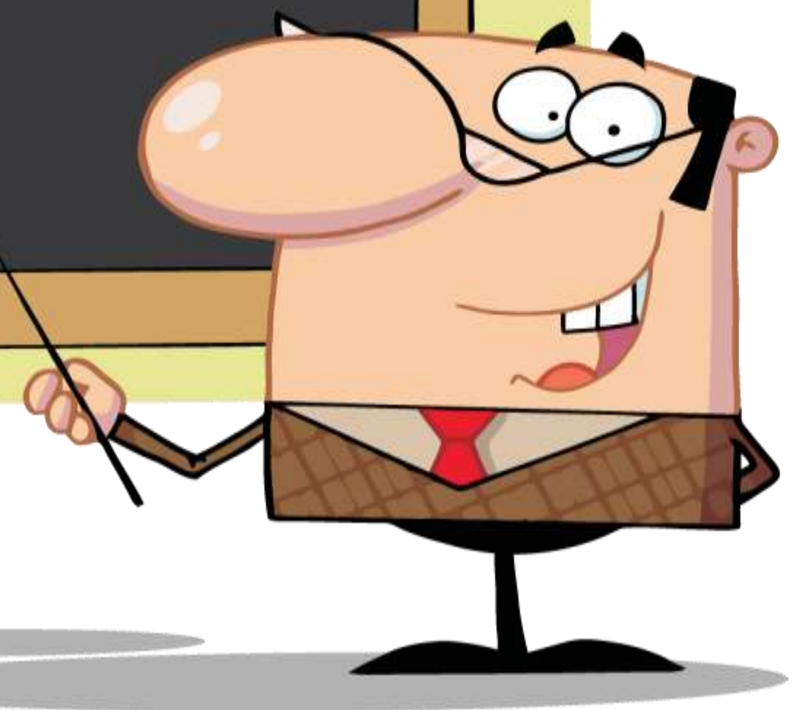
1. The Krebs cycle
2. The electron transport chain

What are the main points of the Krebs cycle?

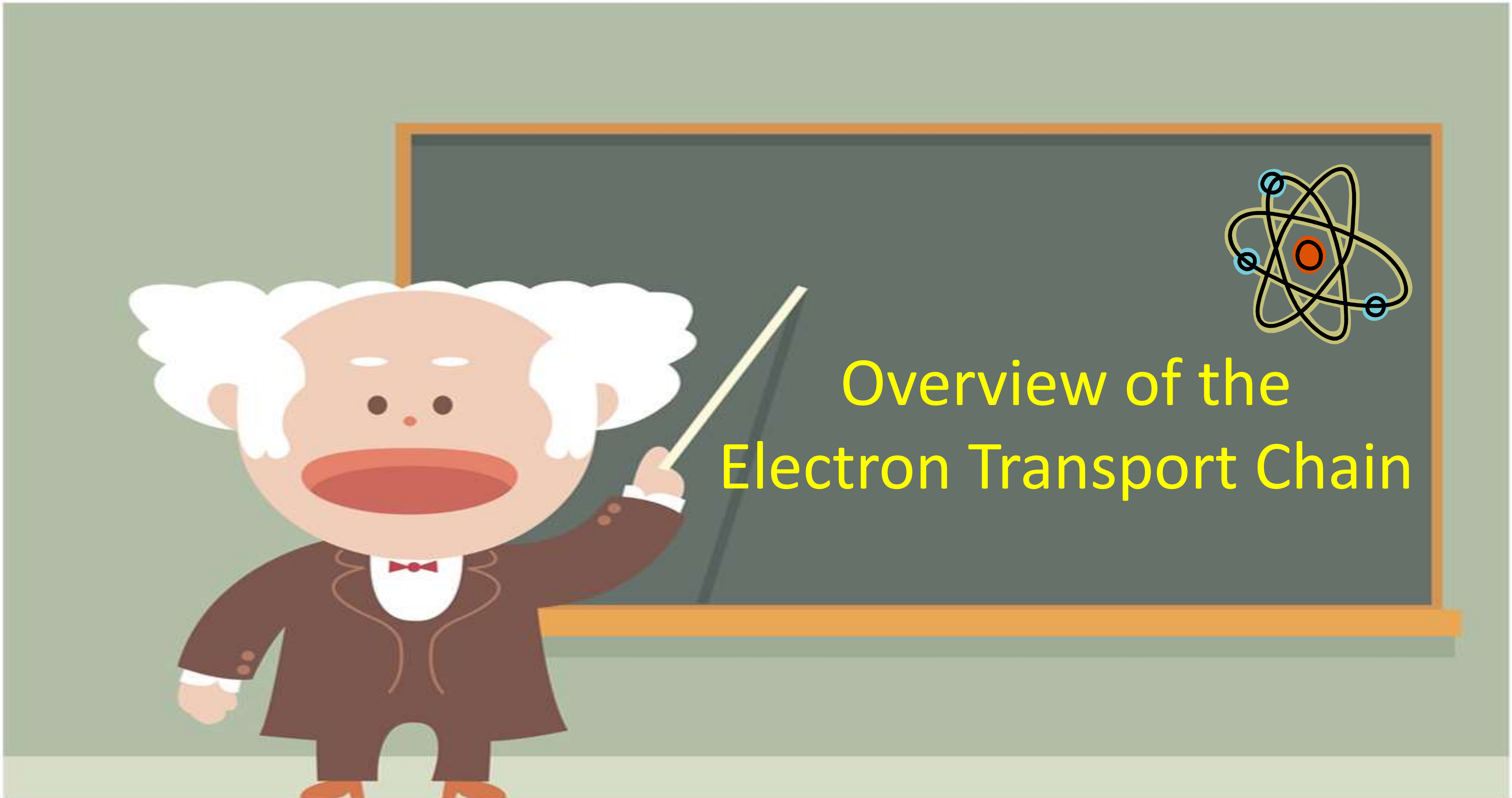
Krebs cycle:

1. The oxidation of glucose is completed.
2. The _hydrogen_ that is removed from pyruvic acid will be accepted by _NAD^+_ to form _NADH_.
3. There will be:

   a small yield of ATP.



Overview of the Electron Transport Chain

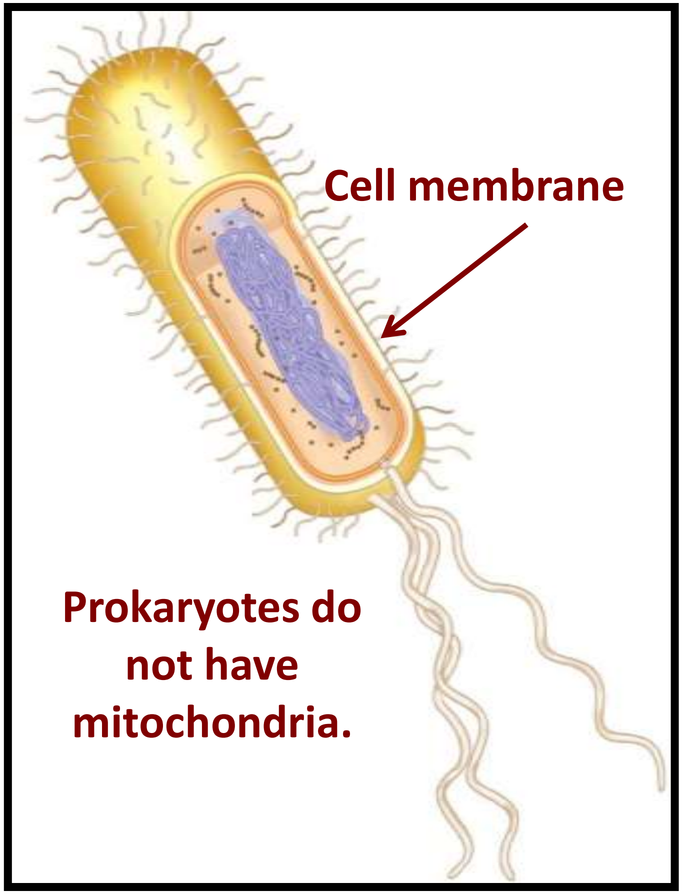


1. The _NADH_ that has been produced during _glycolysis_ and the _Krebs cycle_ will be used to produce _ATP_.
2. Most of the ATP produced during aerobic respiration is produced by _the electron transport chain_.

How does respiration compare in prokaryotic and eukaryotic cells?

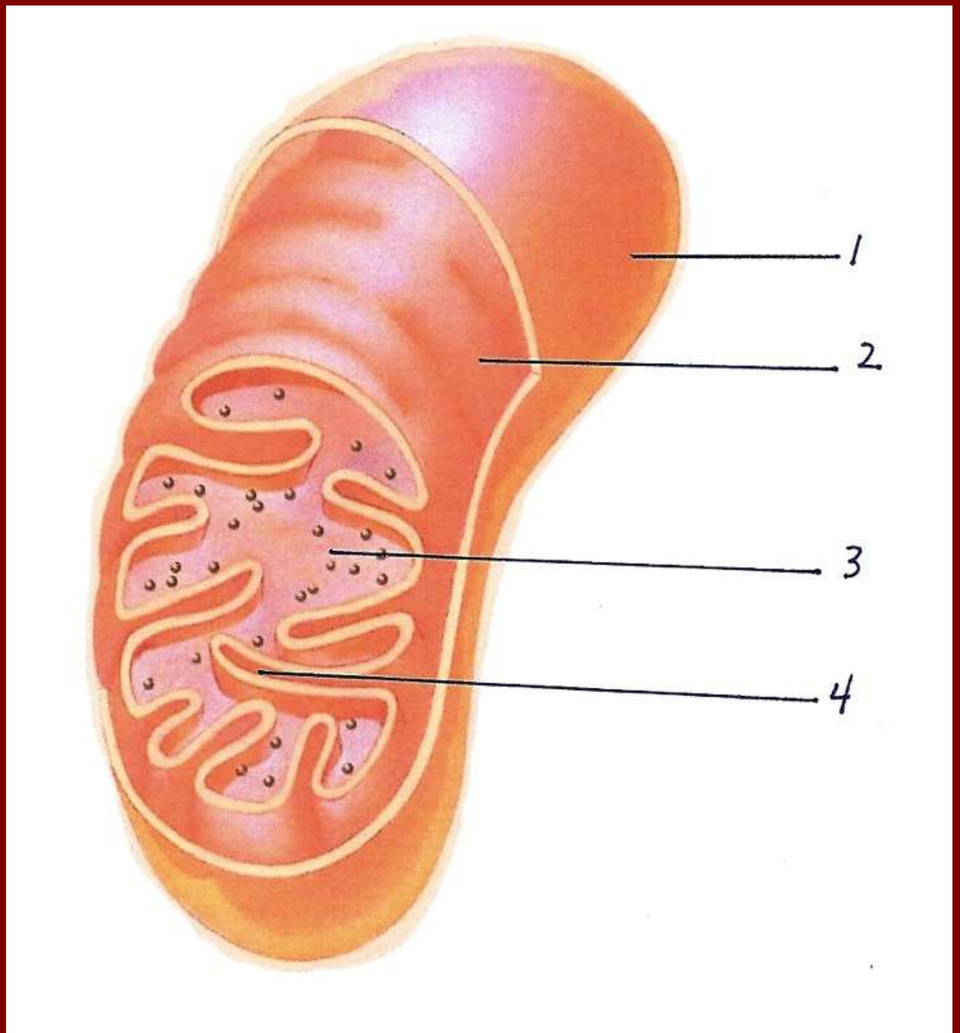
In prokaryotic cells, the Krebs cycle and the electron transport chain occur in the _cytoplasm_ and along special structures of the _cell membrane_.

In eukaryotic cells, these reactions occur inside the _mitochondria_. If oxygen is available, the pyruvic acid that was produced during glycolysis will enter the mitochondria for aerobic respiration.



STRUCTURE OF THE MITOCHONDRIA

Label the following structures found in the mitochondria.



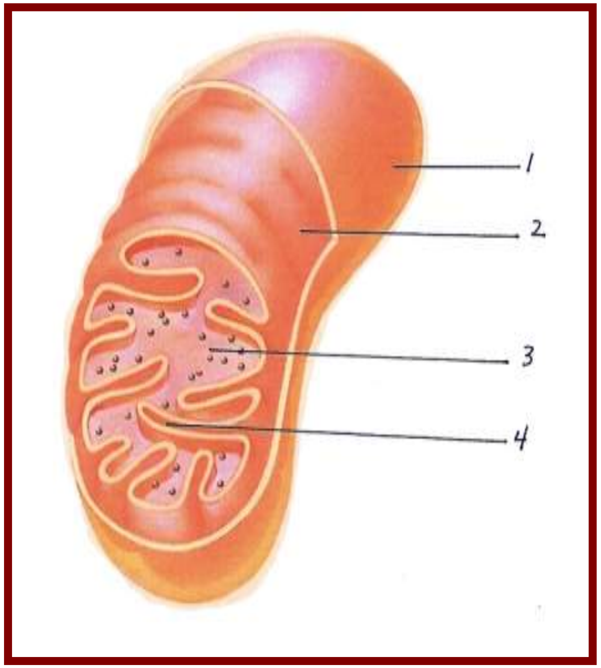
1 – Outer membrane

2 – Inner Membrane

3 – Matrix

4 – Cristae

STRUCTURE OF THE MITOCHONDRIA



The Krebs cycle occurs in the matrix of the mitochondria and the electron transport chain occurs along the cristae membranes.

The _matrix_ is the space inside the inner membrane.
It contains…
…the enzymes that are needed for the reactions of the Krebs cycle as well as mitochondrial DNA and ribosomes.

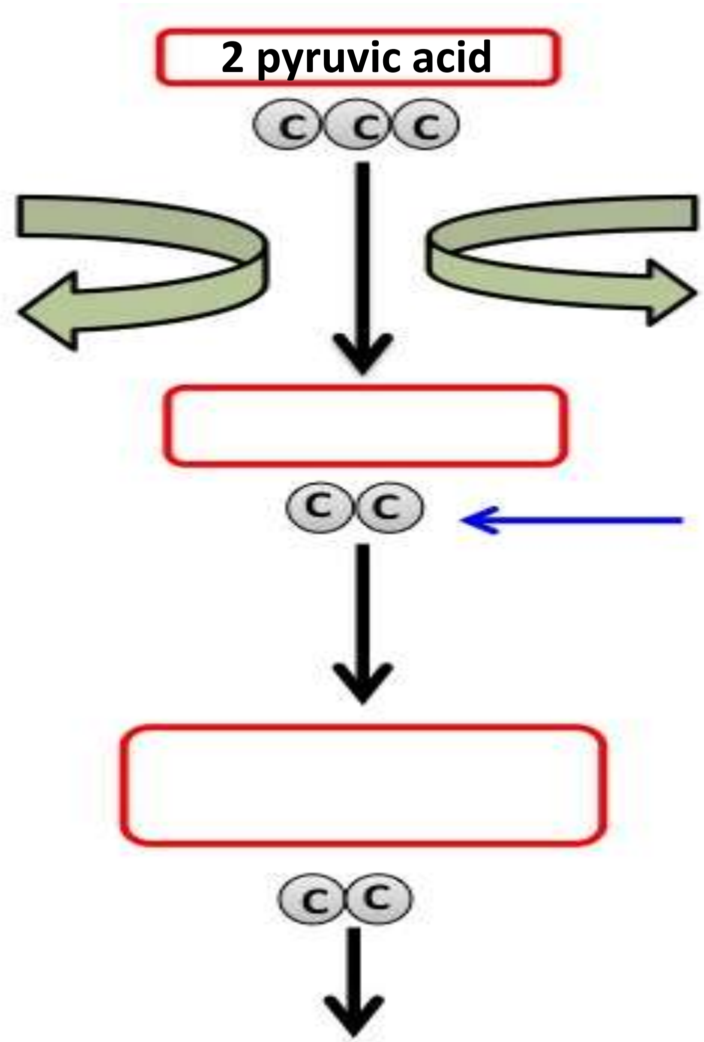
The inner membrane has folds and loops called _cristae_.
The cristae:
increase the surface area for the reactions of the respiration process.

At the end of glycolysis, about 90% of the chemical energy that was available in the glucose molecule is still unused. This energy is locked in:
the high-energy electrons of pyruvic acid.

The Bridge Reactions:
As the pyruvic acid enters the mitochondria, the following reaction occurs.

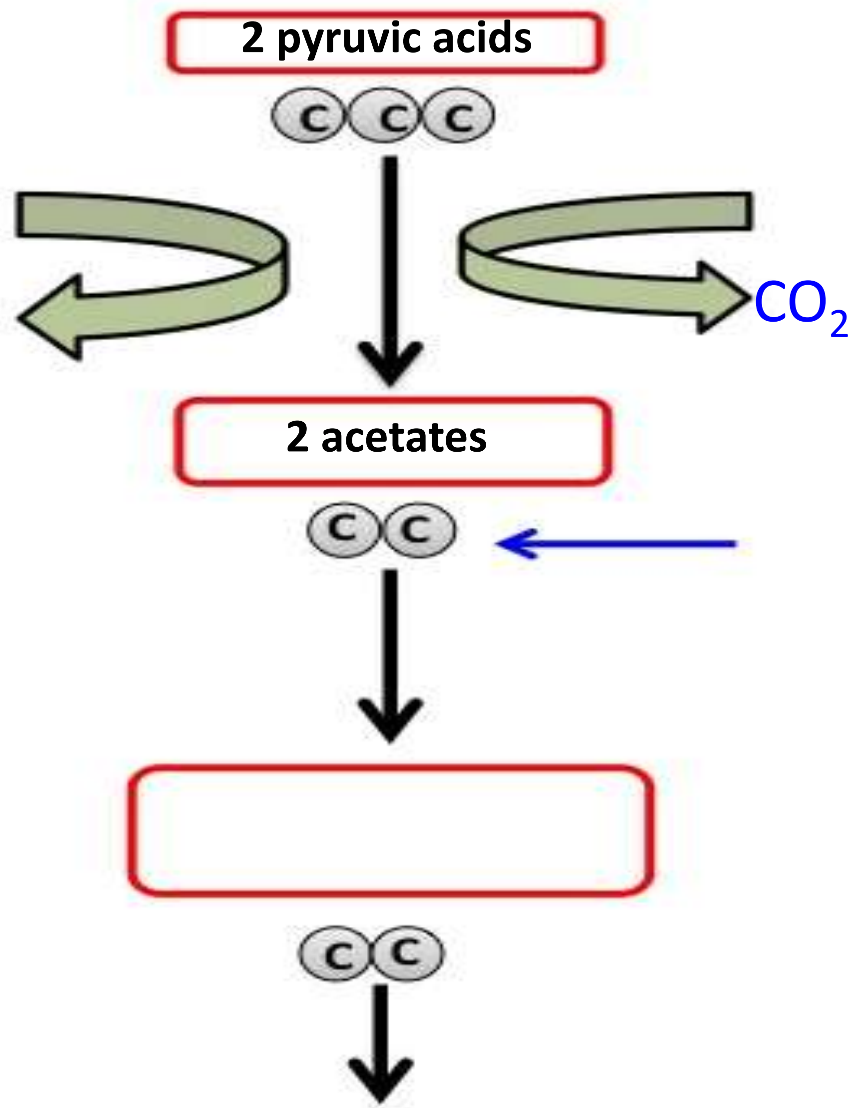
Steps in the Bridge Reaction:

1. Pyruvic acid enters the mitochondria.



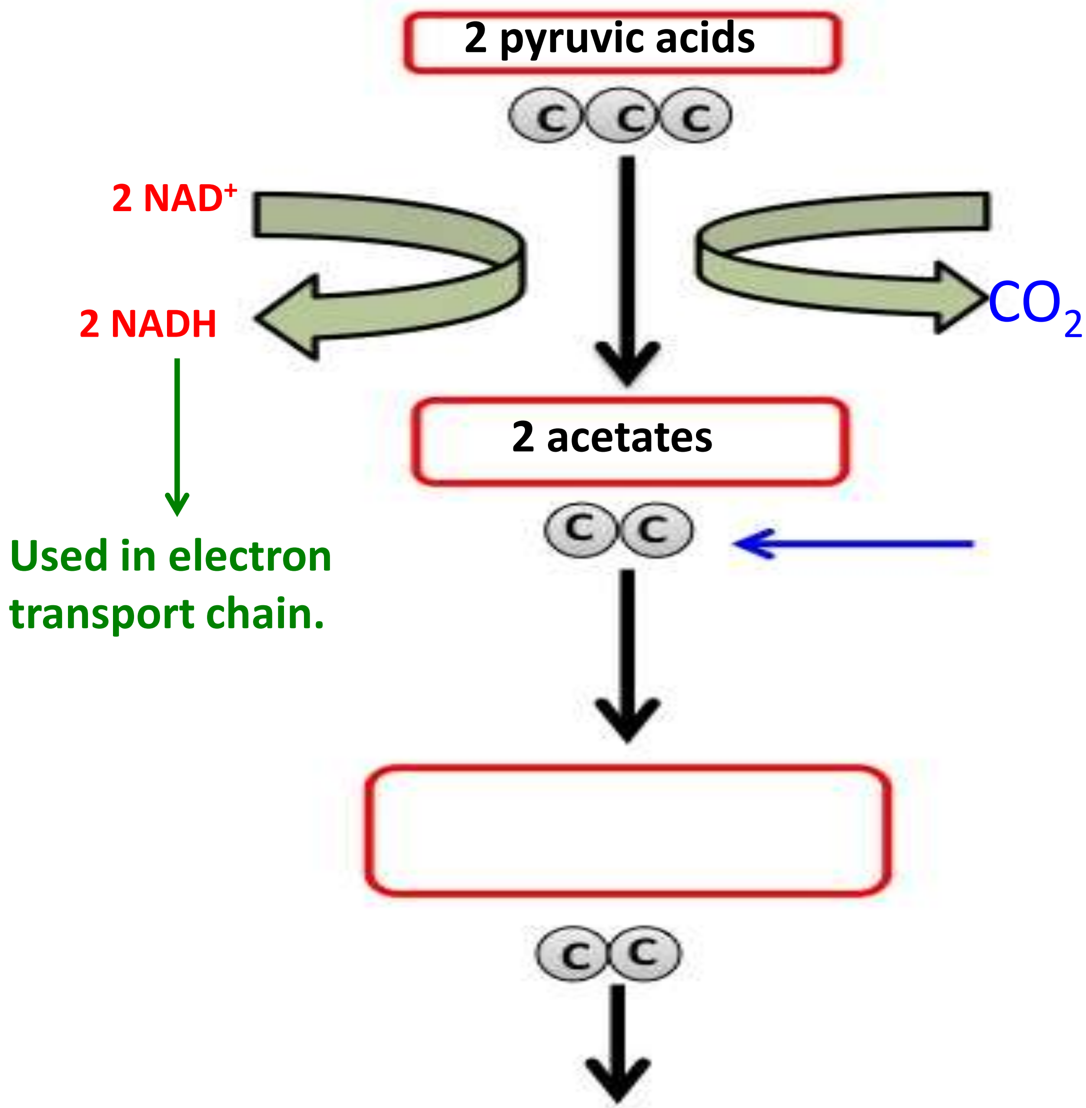
Steps in the Bridge Reaction:

2. The 3-C pyruvic acid is converted to 2-C acetate. This is accomplished by removing a molecule of CO_2 from each molecule of pyruvic acid. The carbon dioxide is: released into the air.



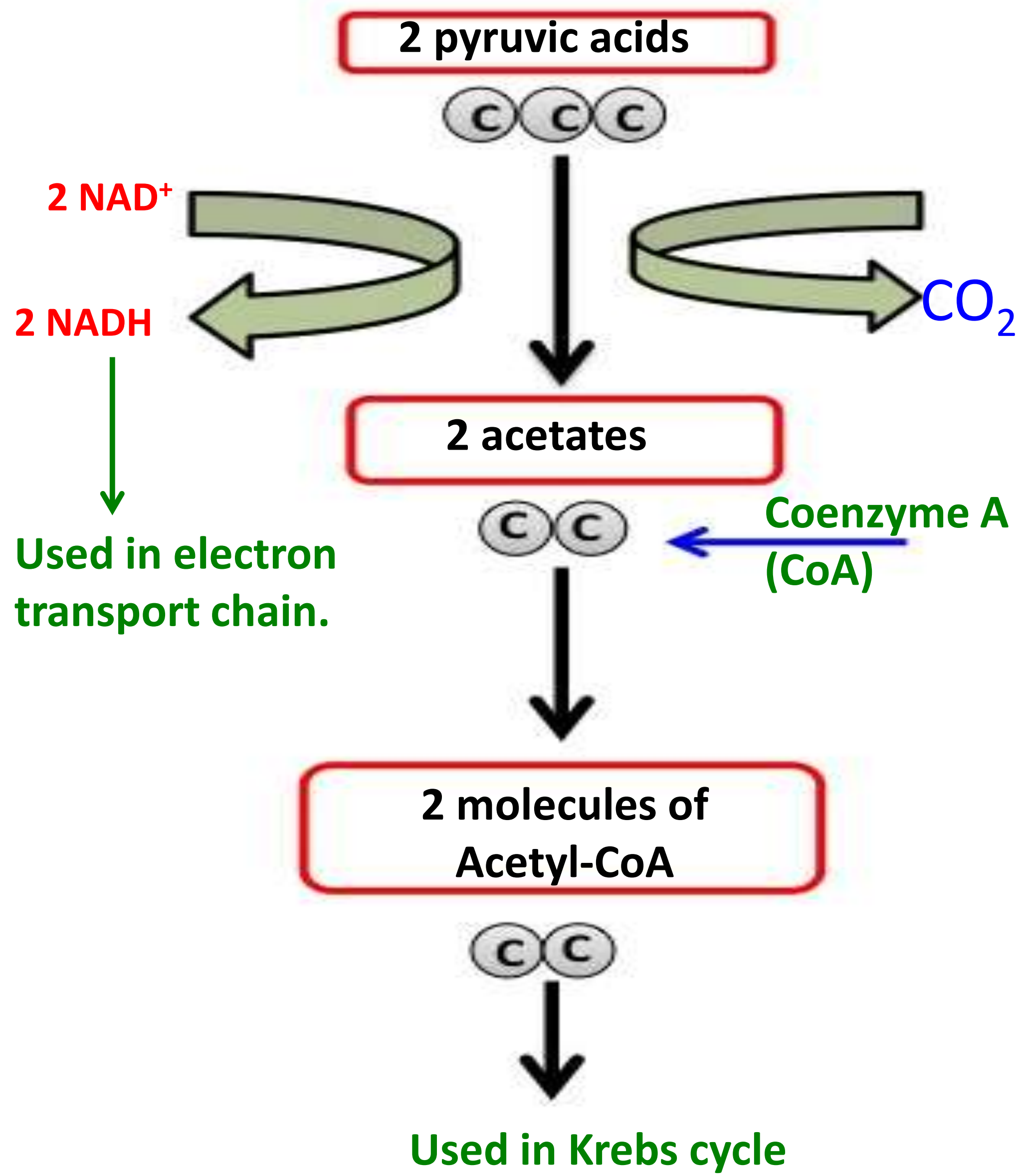
Steps in the Bridge Reaction:

3. For each pyruvic acid that is converted to _acetate_, one molecule of _NAD⁺___ is converted to _NADH__.



Steps in the Bridge Reaction:

4. Coenzyme A___________ attaches to the acetate to form acetyl CoA________. The acetyl-CoA will be used in the Kreb's cycle__________.



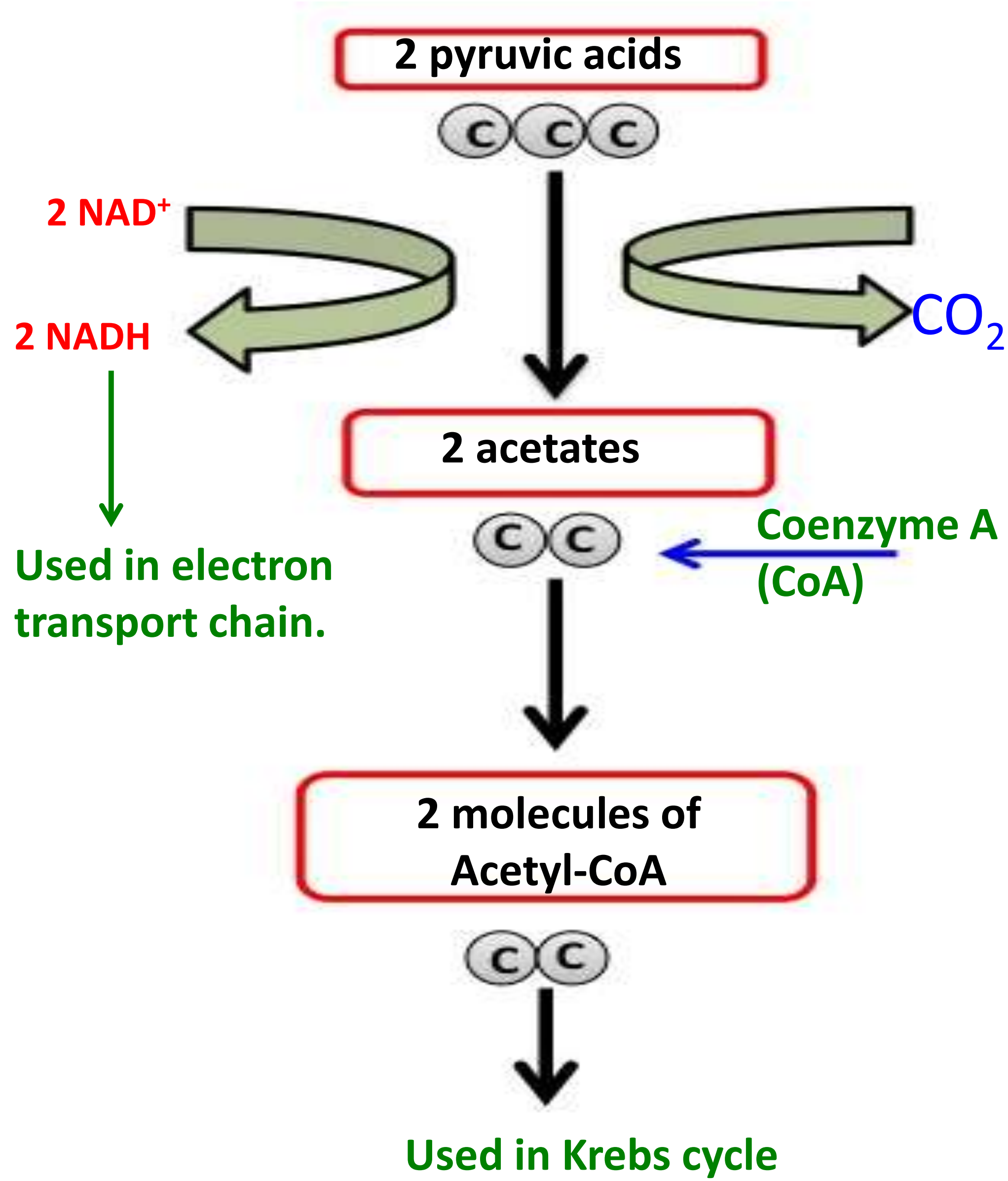
Steps in the Bridge Reaction:

5. This reaction is often referred to as "_The Bridge Reaction__". It is the bridge between:

a) the cytoplasm and the mitochondria

b) anaerobic and aerobic respiration

c) glycolysis and the Krebs cycle.



The Krebs Cycle

The Krebs cycle is a biochemical pathway that uses the _acetyl-CoA_ molecules from the _bridge reactions_ to produce:

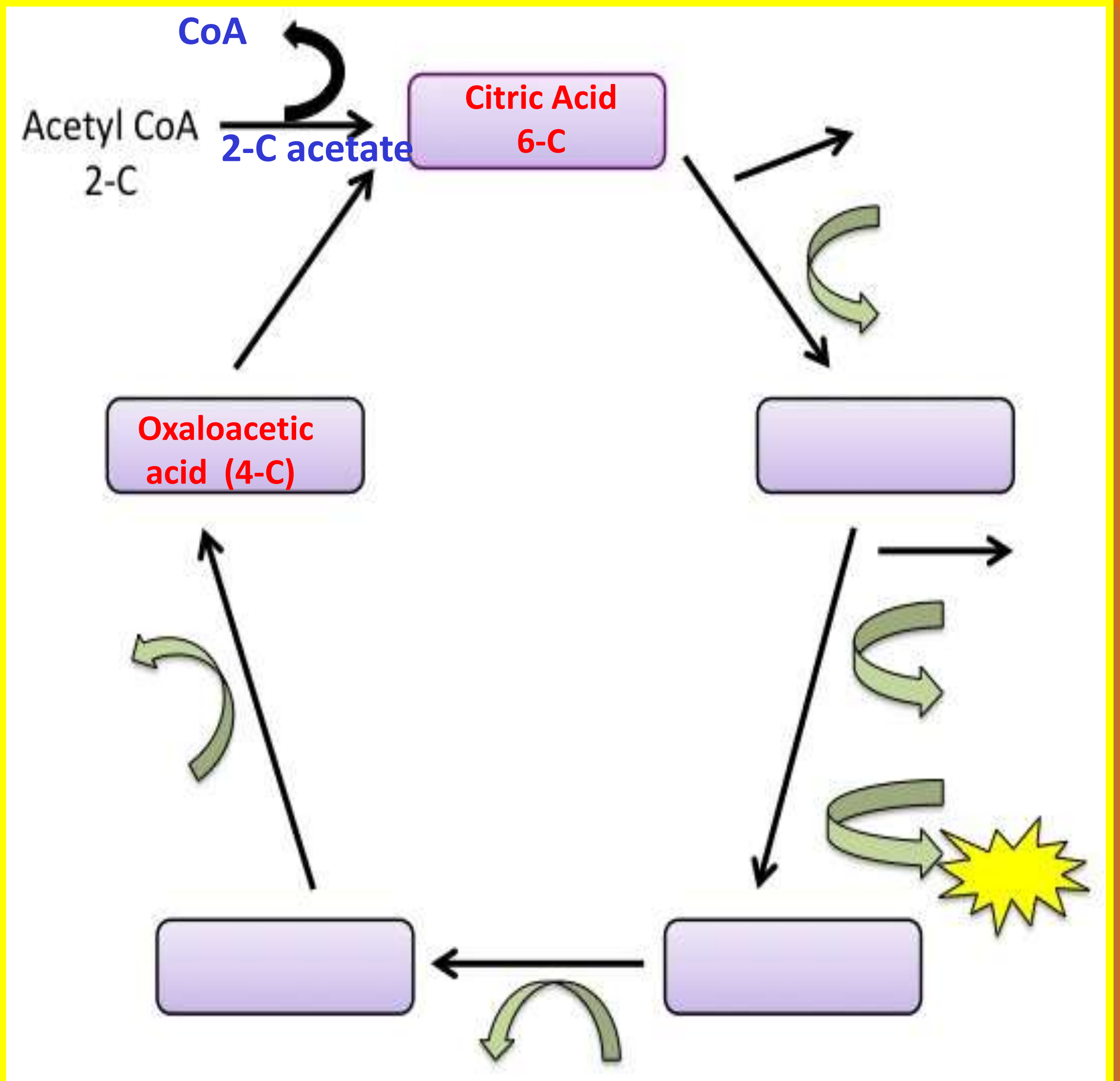
- hydrogen atoms
- ATP
- carbon dioxide.

This set of reactions occurs in the _matrix_ of the _mitochondria_.

The Krebs cycle is so named to honor Hans Krebs. He was a German – British scientist who was largely responsible for working out the pathway in the 1930's.

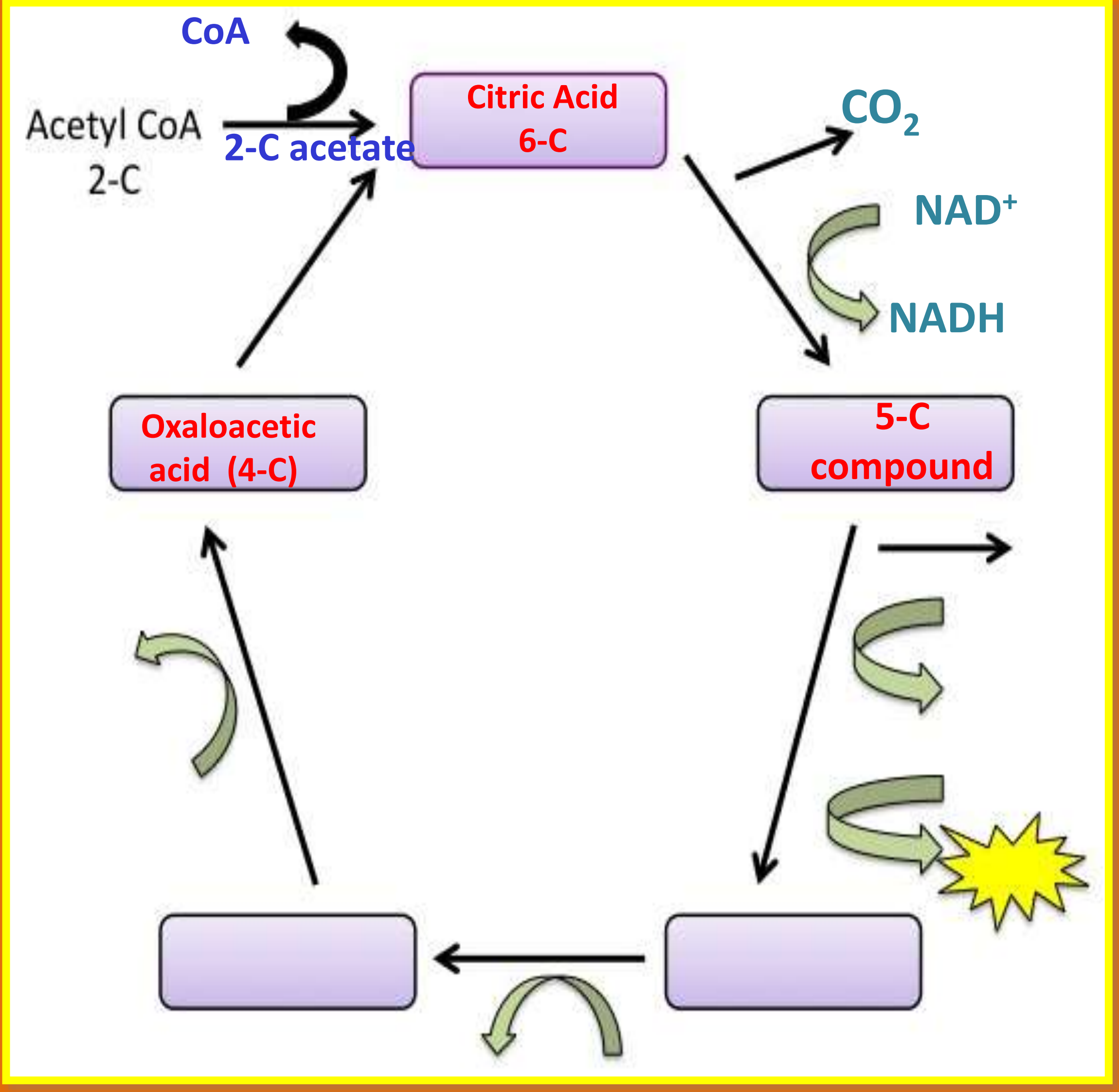
The Steps of the Krebs Cycle

1. CoA attaches the 2-C acetate to the 4-C oxaloacetic acid to produce the 6C compound called citric acid. The CoA is regenerated to be used again.



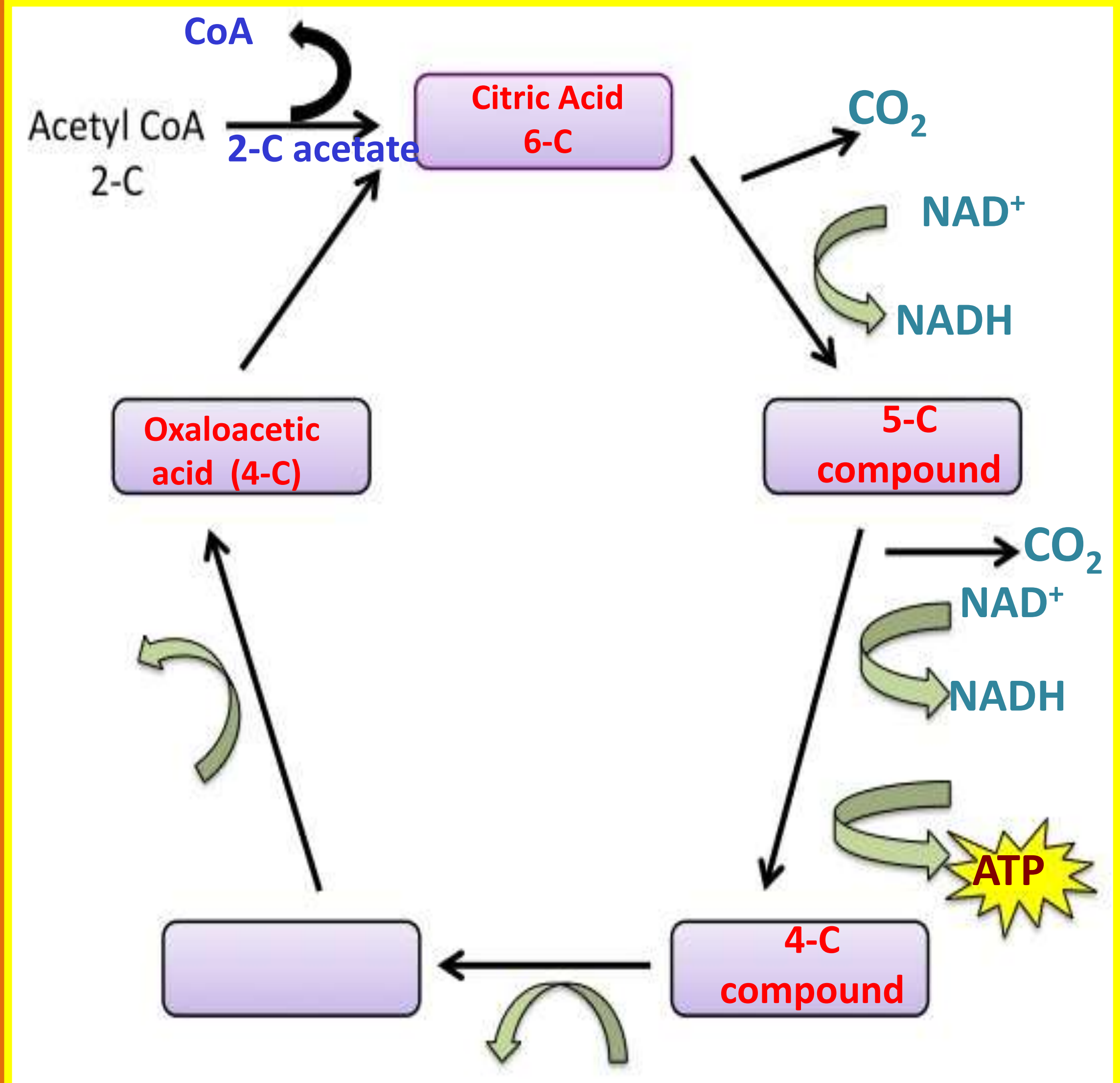
The Steps of the Krebs Cycle

2. The 6-C citric acid releases a molecule of CO_2 to form a 5-C compound. As citric acid is oxidized, the hydrogen is transferred to NAD^+ to form NADH.



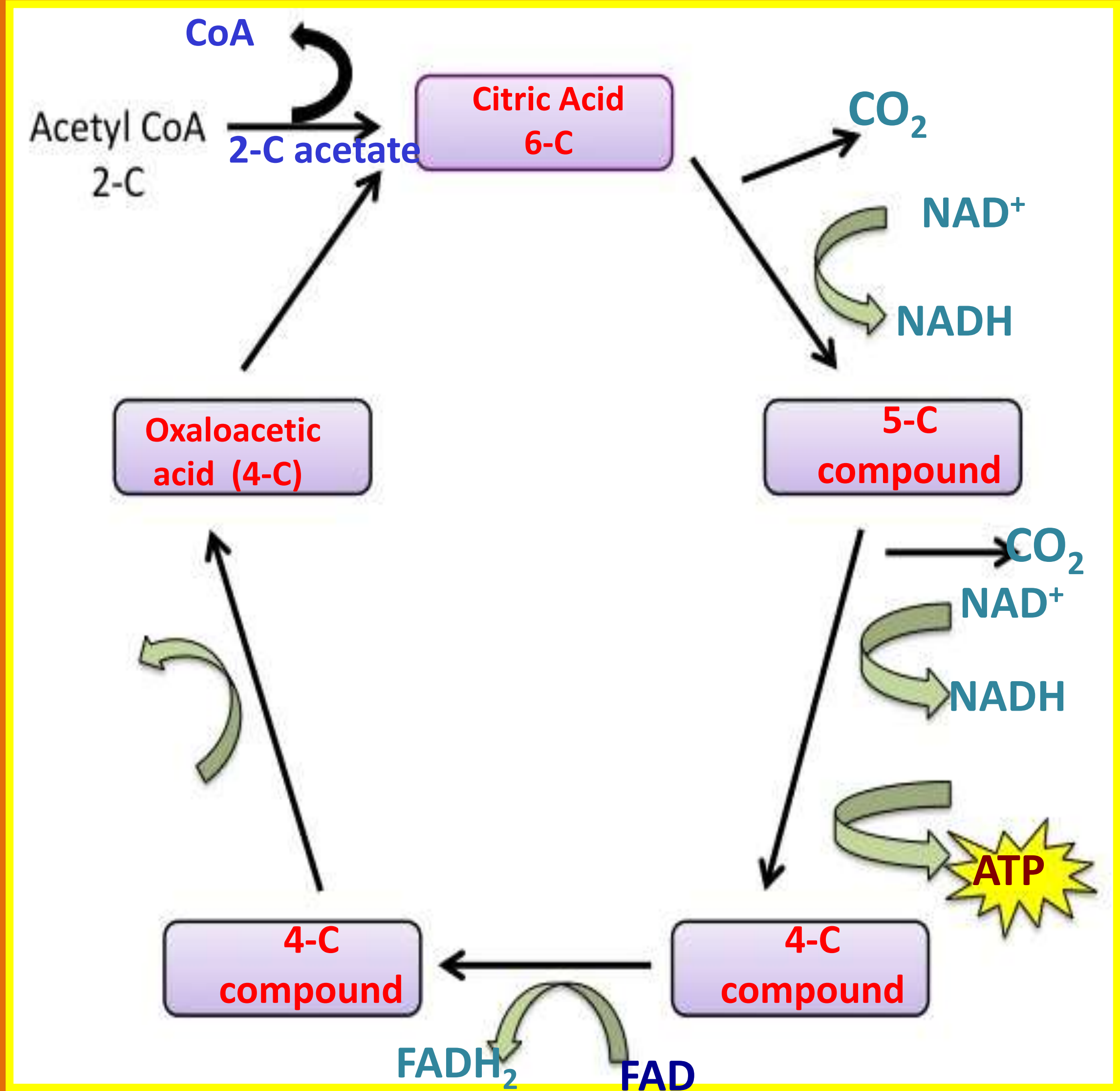
The Steps of the Krebs Cycle

3. The 5-C compound releases $\underline{\ CO_2\ }$ and a _hydrogen_ atom forming a 4-C compound. _NAD+_ is reduced to form _NADH_ and one molecule of _ATP_ is produced.



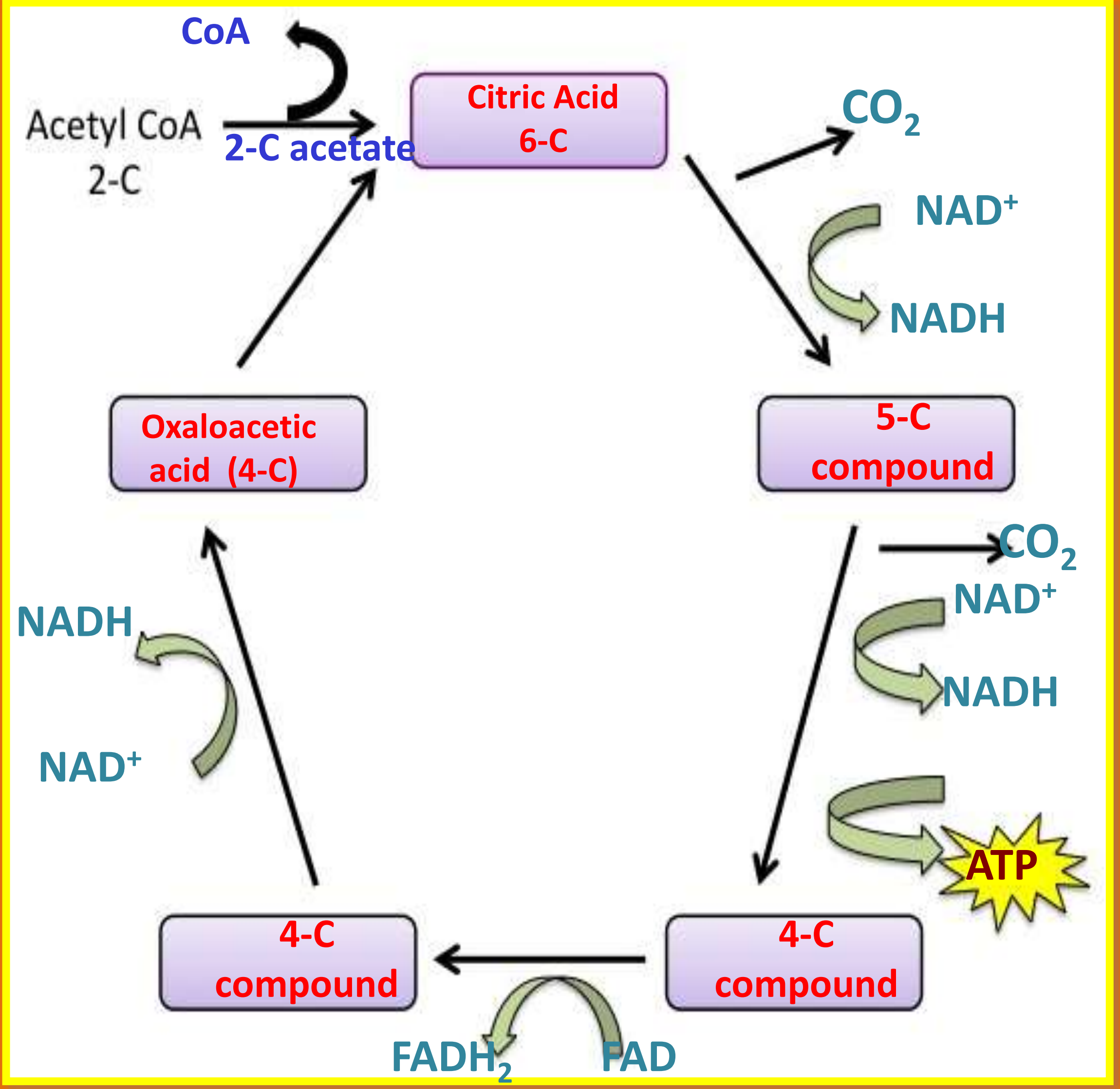
The Steps of the Krebs Cycle

4. This 4-C compound releases a _hydrogen__ to form another 4-C compound. This time, the hydrogen is used to reduce _FAD_ to _$FADH_2$___.



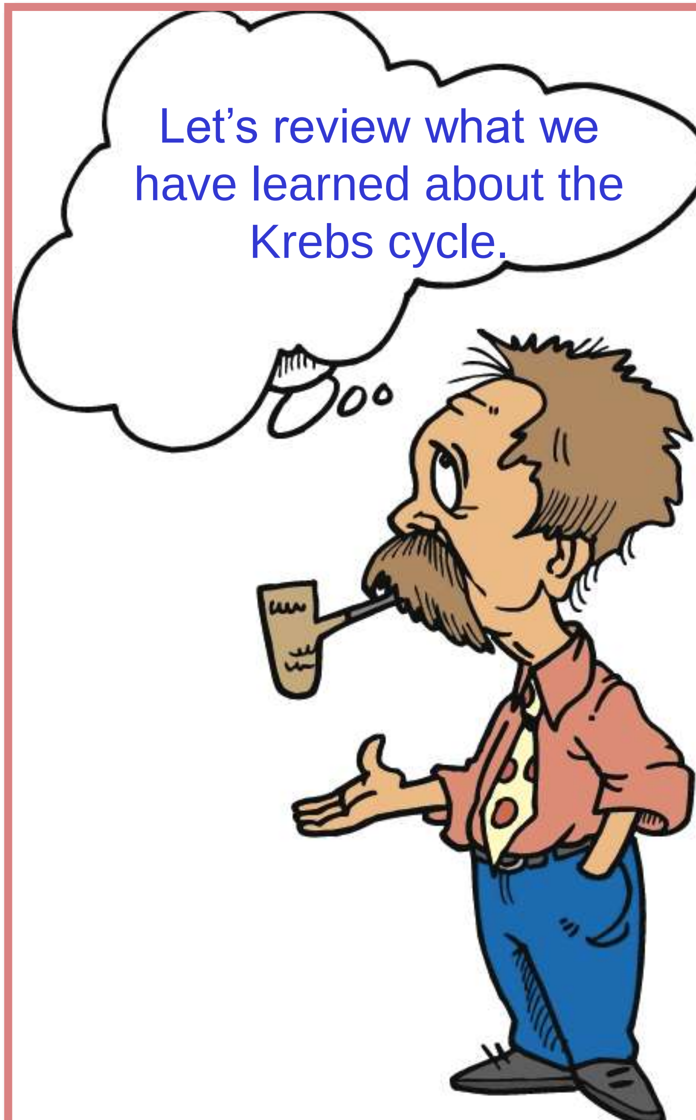
The Steps of the Krebs Cycle

5. In the last step, the 4-C _oxaloacetic acid_ is regenerated which keeps the _Krebs cycle_ going. The hydrogen that is released is used to form a final _NADH_.



Summary of the Krebs Cycle

_NAD$^+$ and FAD__ are electron carriers very similar to the NADP$^+$ that was used in photosynthesis. NAD$^+$ and FAD will deliver the _high-energy electrons__ of hydrogen to the _electron transport chain_.



Summary of the Krebs Cycle

What is the total amount of CO_2, ATP, NADH, and $FADH_2$ that is produced during one turn of the Krebs cycle?

a) 2 CO_2
b) 1 ATP
c) 3 NADH
d) 1 $FADH_2$

The above totals are for one molecule of pyruvic acid.

Summary of the Krebs Cycle

Now remember that during glycolysis, glucose was broken down into two molecules of pyruvic acid. Therefore, one glucose molecule causes two turns of the Krebs cycle.

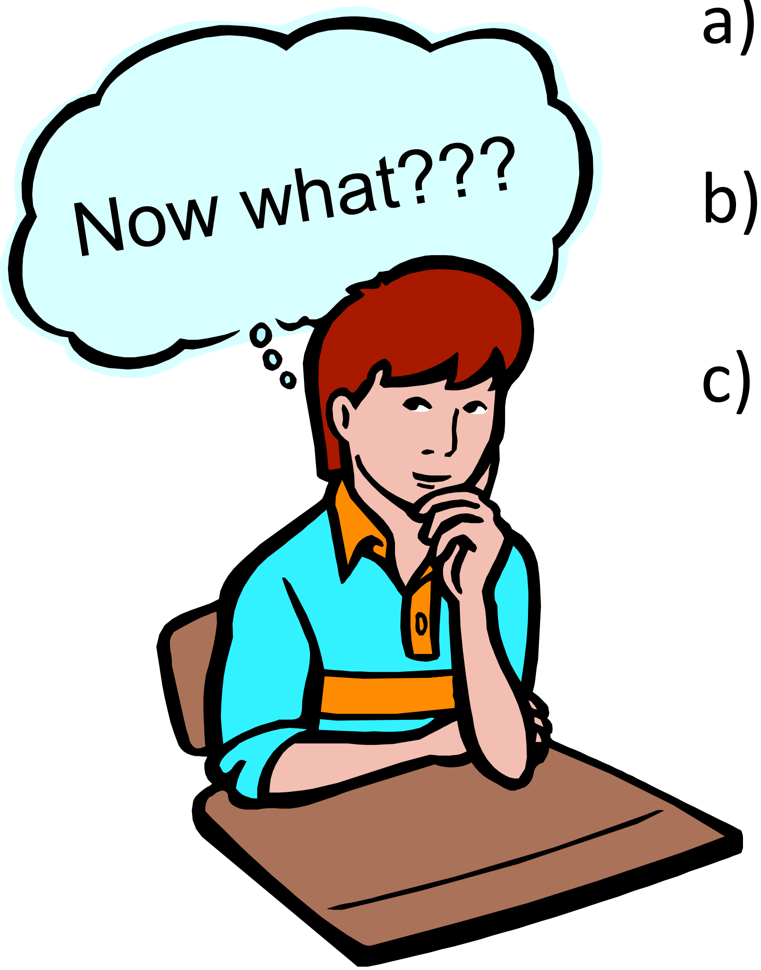
What is the total amount of CO_2, ATP, NADH, and $FADH_2$ that is produced per molecule of glucose in the Krebs cycle?

a) 4 CO_2

b) 2 ATP

c) 6 NADH

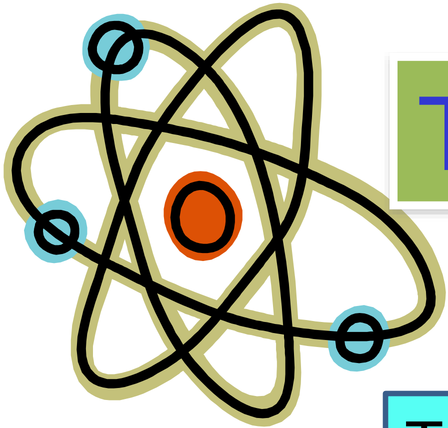
d) 2 $FADH_2$



What happens to each of these products?

a) The carbon dioxide is released when you exhale.
b) The ATP is used for cellular activities.
c) The NADH and the $FADH_2$ will be used in the next stage to generate huge amounts of ATP.

Most of the energy contained in the original _glucose_ molecule still has not been transferred to _ATP_. This transfer of energy will occur in the next step, the electron transport chain.



The Electron Transport Chain

The electron transport chain consists of a series of ___proteins___ that are embedded in the ___inner membranes (cristae)___ of the mitochondria in eukaryotic cells.

In prokaryotic cells, the electron transport chain lies along the ___cell membrane___.

In this last stage of aerobic respiration, NADH and $FADH_2$ will:

release hydrogen atoms, generating energy to produce ATP.

The Electron Transport Chain

What is the total number of NADH and $FADH_2$ that has been produced so far?

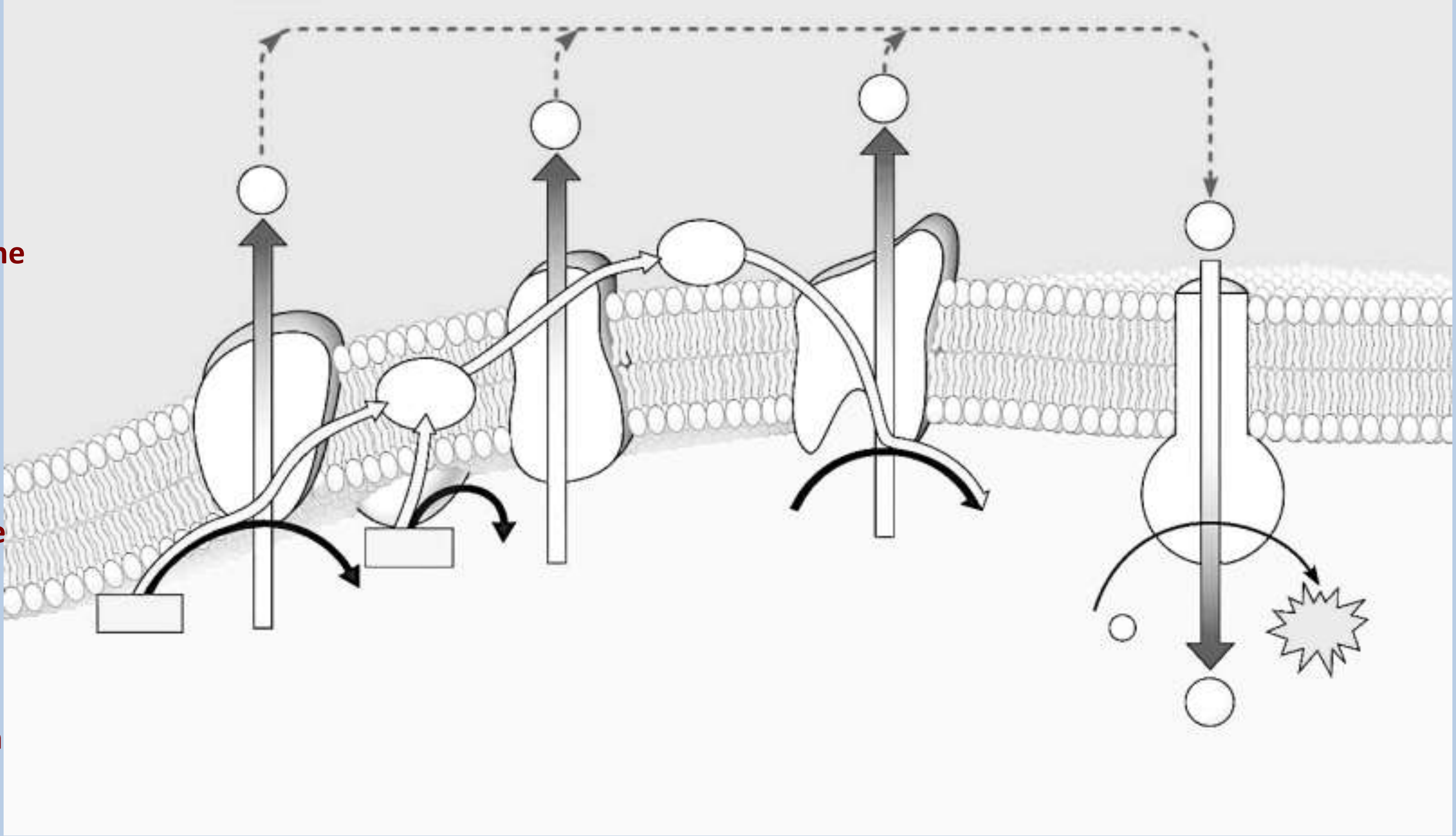
a) 10 NADH (2 from glycolysis, 2 from the bridge reactions and 6 from the Krebs cycle)
b) 2 $FADH_2$ (from the Krebs cycle)
c) The purpose of NADH and $FADH_2$ is to: carry high-energy electrons to the electron transport chain.
d) The electron transport chain uses these high-energy electrons to convert ADP to ATP.

Steps of the Electron Transport Chain

Inner membrane space

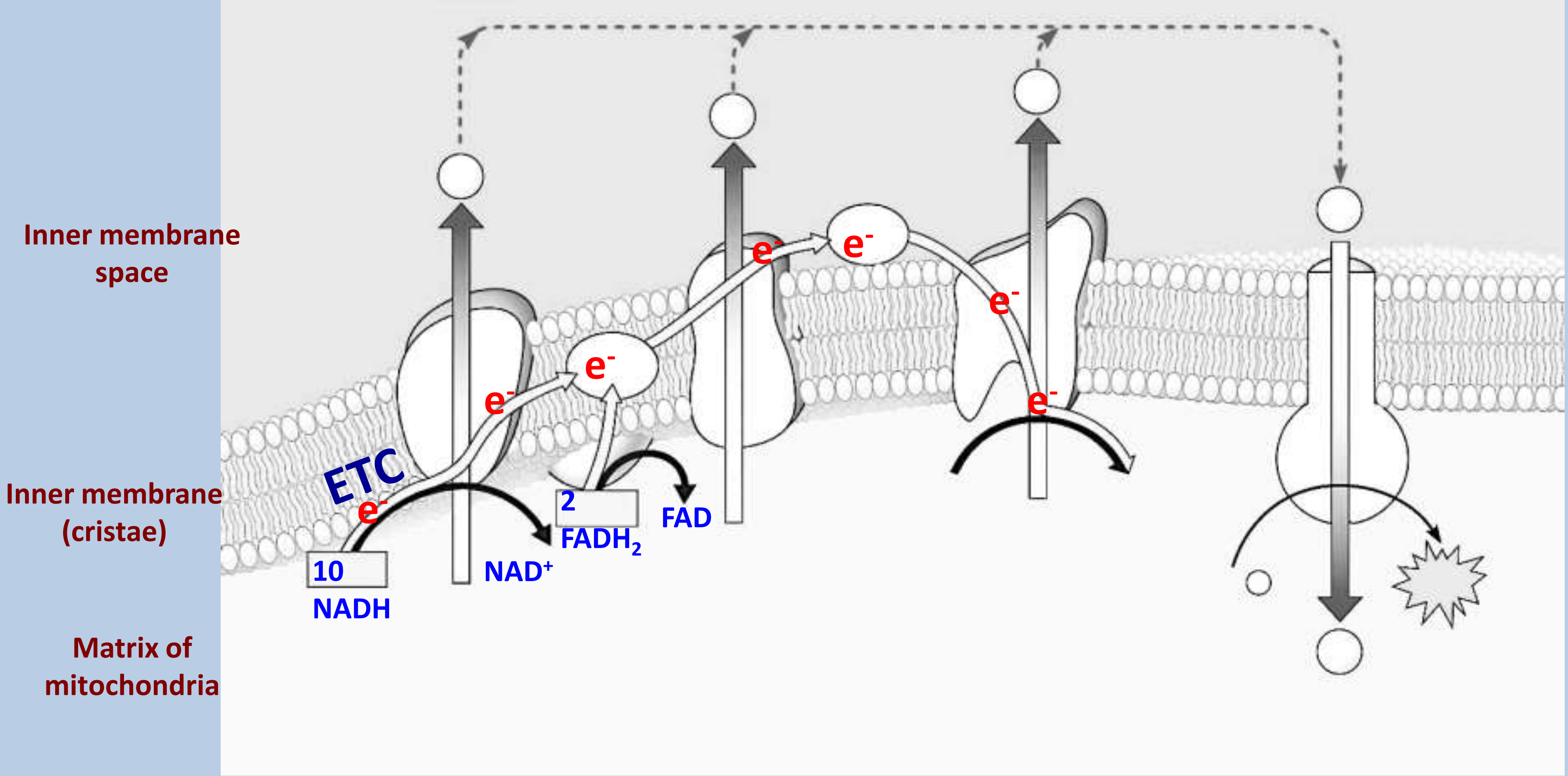
Inner membrane (cristae)

Matrix of mitochondria



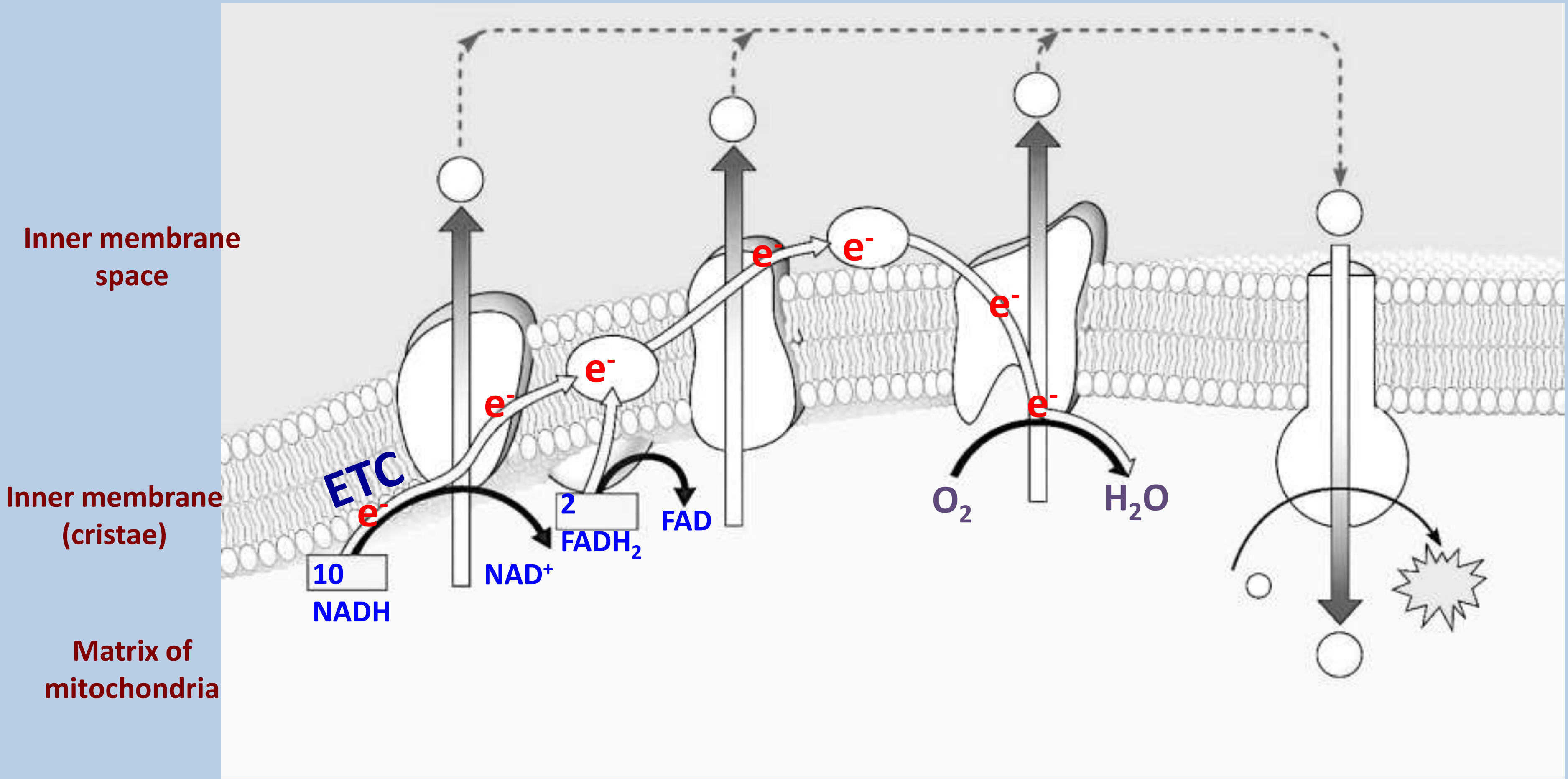
First, let's label a few sections of the diagram.

Steps of the Electron Transport Chain



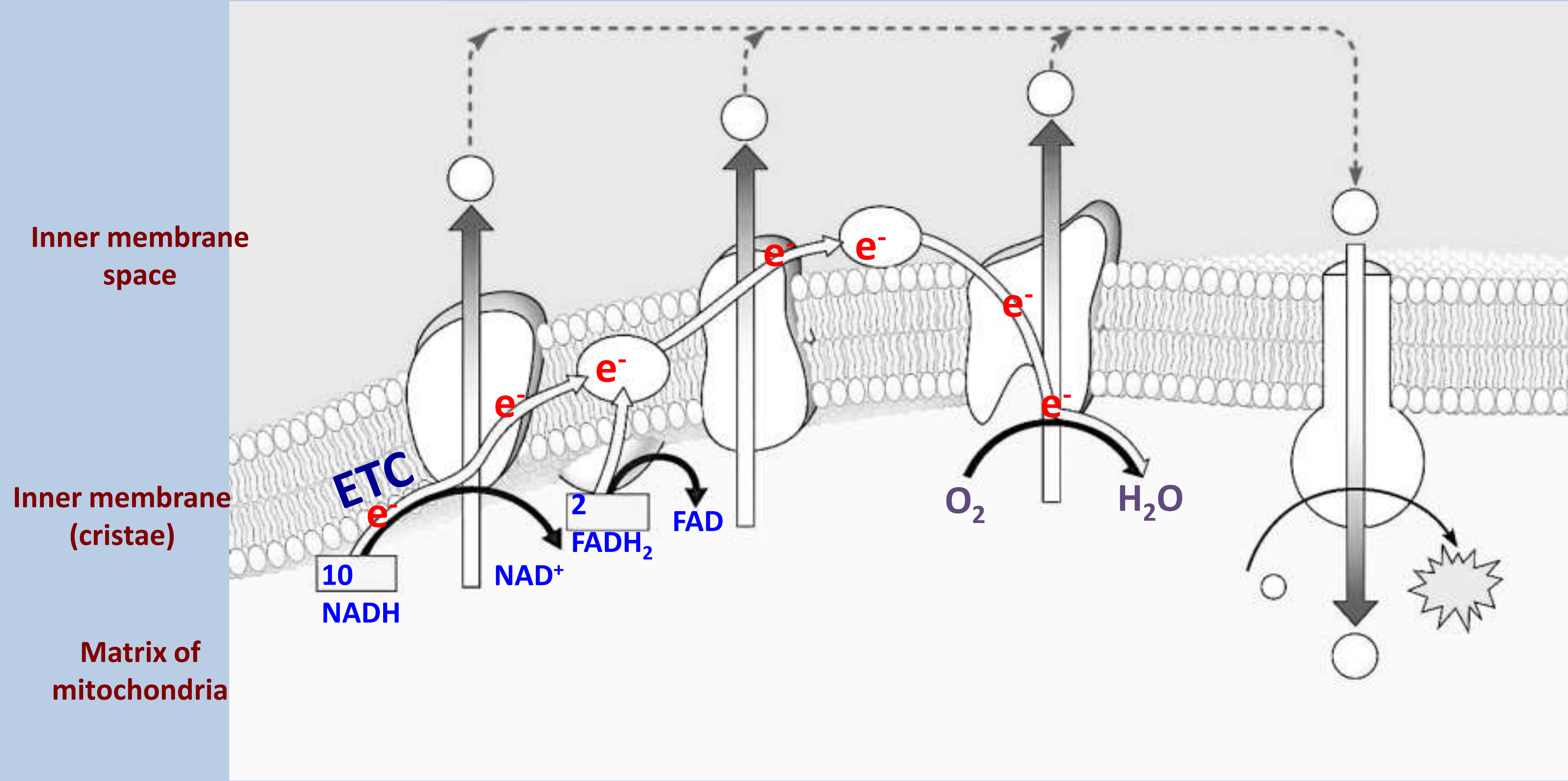
1. The high-energy electrons from _NADH and FADH$_2$__ are passed along the electron transport chain, from one protein to the next.

Steps of the Electron Transport Chain



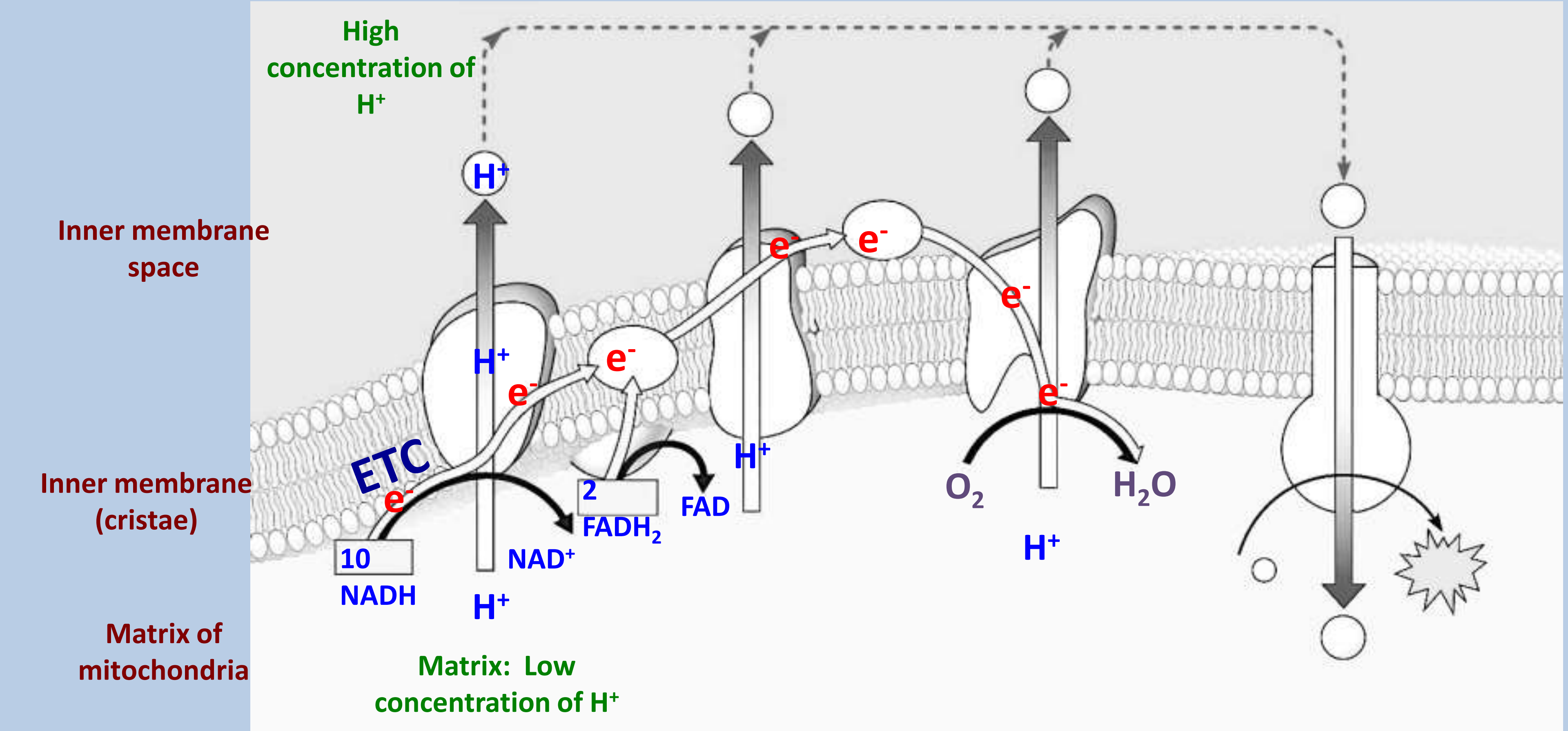
2. At the end of the electron transport chain, the _electrons and hydrogen__ will be combined with _oxygen__ to form _water.

Steps of the Electron Transport Chain



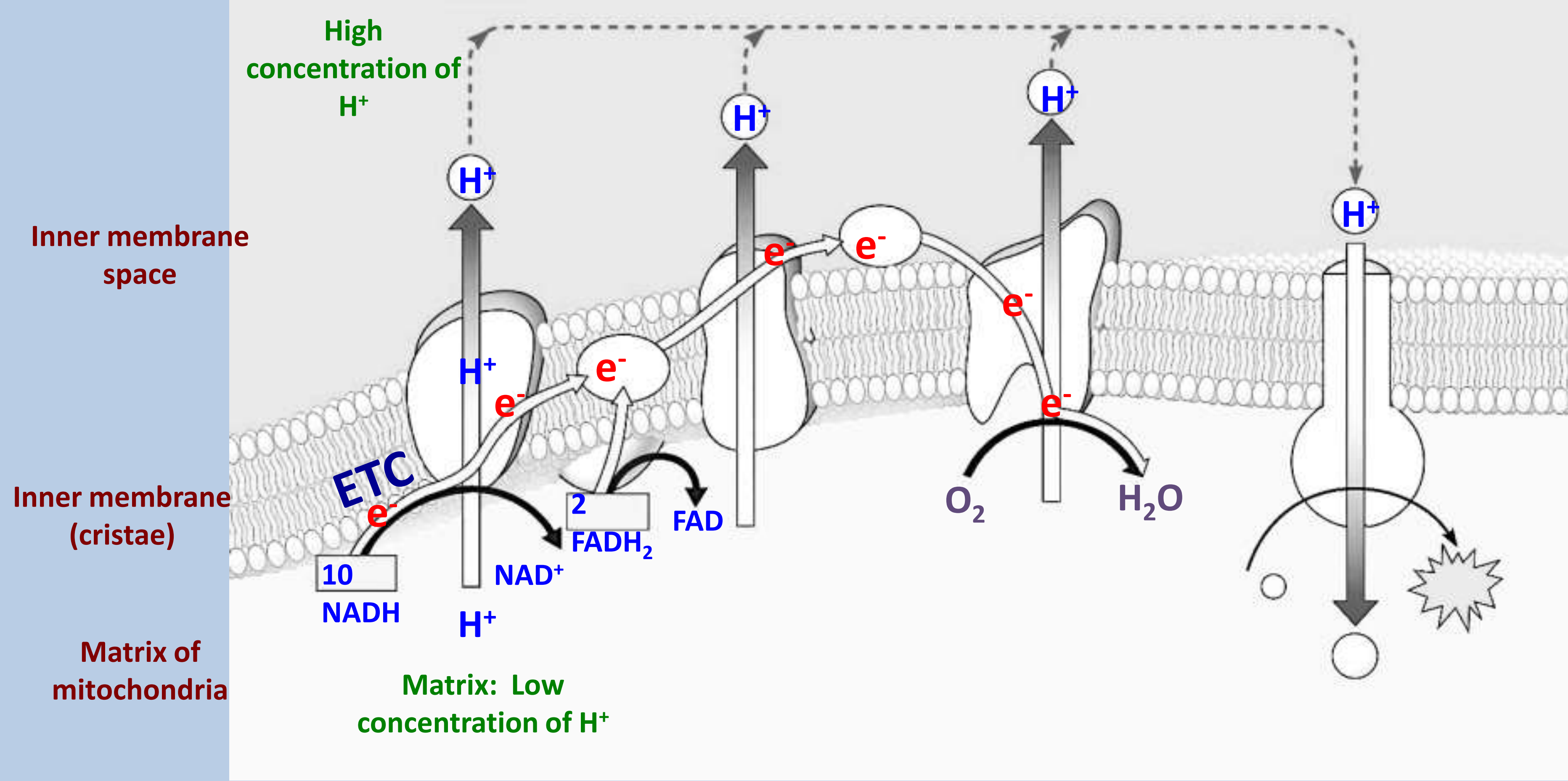
3. Oxygen is the final electron acceptor. Oxygen is essential for getting rid of:
low energy electrons and hydrogen ions.

Steps of the Electron Transport Chain



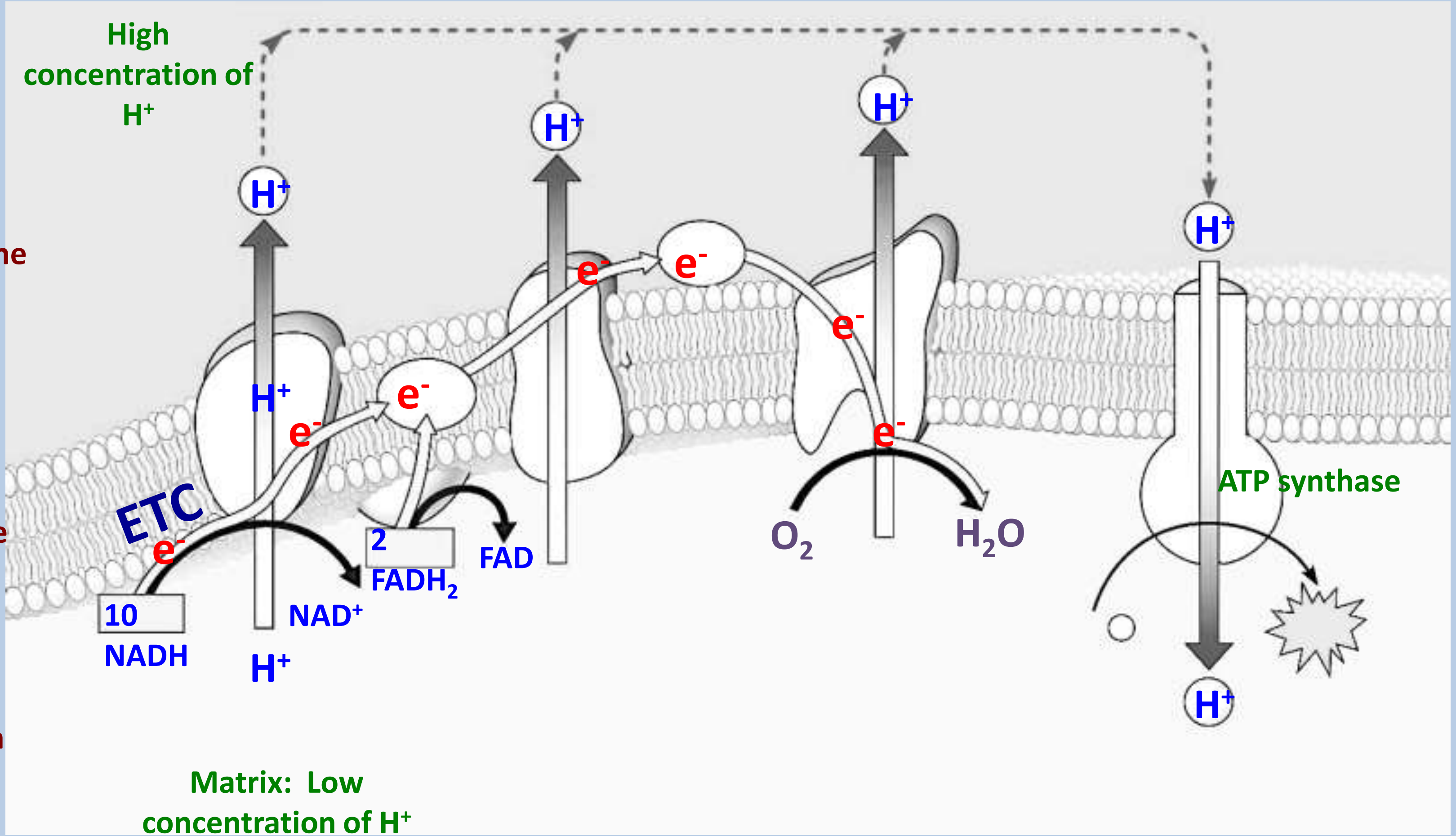
4. As these electrons move down the electron transport chain, they release _energy__. This energy is used to pump _hydrogen protons (H^+)__ across the membrane from the _matrix__ to the _inner membrane space__. The hydrogen protons are pumped _against__ the concentration gradient from an area of _low_ concentration in the matrix to an area of _high_ concentration in the inner membrane space.

Steps of the Electron Transport Chain



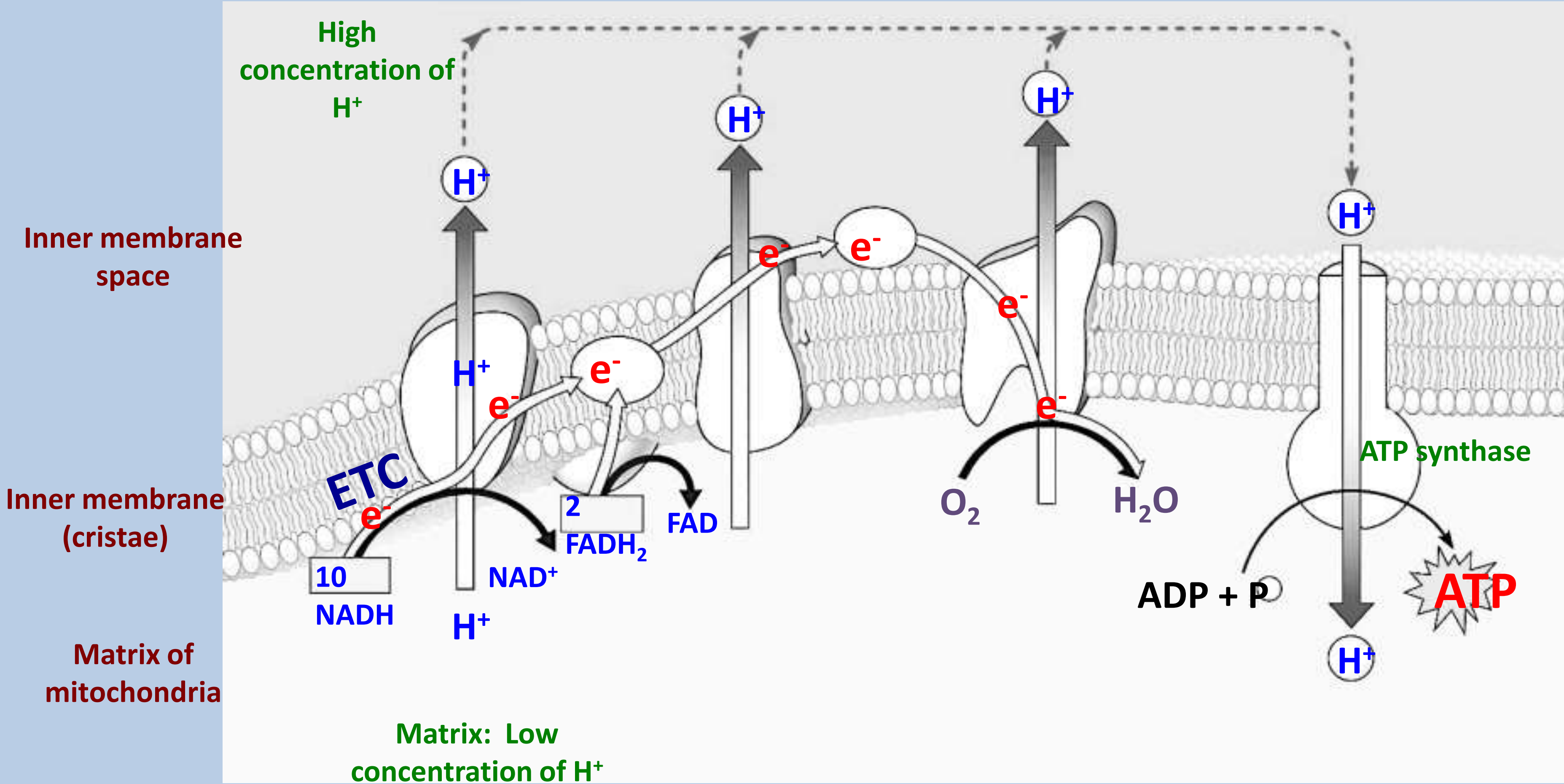
5. A concentration __gradient__ has now been established. There is a high concentration of hydrogen in the _inner membrane_ space and a low concentration in the _matrix__.

Steps of the Electron Transport Chain



6. Also embedded in the mitochondrial membranes are enzymes called __ATP synthases__. Hydrogen ions flow through __ATP synthase__ back to the __matrix__, the area of __low__ concentration.

Steps of the Electron Transport Chain



7. As the hydrogen flows through ATP synthase, it spins a rotor. Each time it rotates, a phosphate is attached to ADP to form ATP.

Recap of Electron Transport

a) This system couples the movement of high-energy electrons with the production of ATP.
b) As the high-energy electrons move down the electron transport chain, they release _energy_.
c) This energy is used to move _hydrogen protons (H^+)_ across the membrane.
d) These ions then rush back across the membrane, producing: enough force to spin the ATP synthase and generate enormous amounts of ATP.

ATP Accounting

Let's summarize what has happened prior to the electron transport chain:

Glycolysis → Gain of 2 ATP. Produces 2 NADH.

Bridge Reaction → Produces 2 NADH.

Krebs cycle → Produces 2 ATP, 6 NADH and 2 $FADH_2$

ATP Accounting

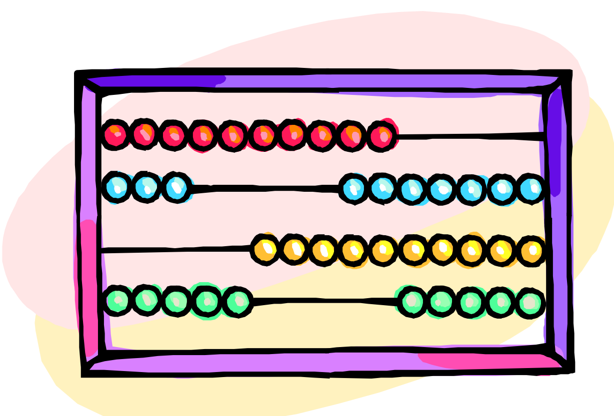
Each NADH has enough energy to produce __3 ATP__.
Each $FADH_2$ has enough energy to produce __2 ATP__.

10 NADH = __30 ATP__

2 $FADH_2$ = __4 ATP__

Glycolysis → __2 ATP__
Krebs cycle → __2 ATP__
Electron Transport Chain → __34 ATP__

One molecule of glucose has produced __38 ATP__.



Only about 40% of the energy contained in the glucose molecule has been converted to __ATP__. The remaining 60% is given off as __heat__.

FERMENTATION

Fermentation occurs when: oxygen is not present.

Since no oxygen is required, fermentation is an **anaerobic** process.

The anaerobic pathways are not very efficient in transferring energy from **glucose** to **ATP**.

Fermentation will yield only a gain of **2 ATP** per molecule of **glucose**.

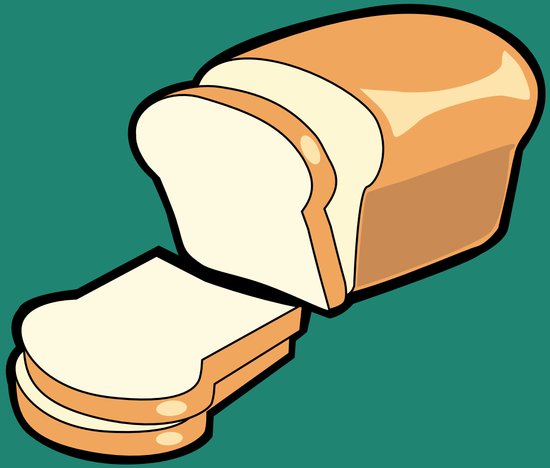
There are two main types of fermentation:

Alcoholic fermentation →

←Lactic acid fermentation

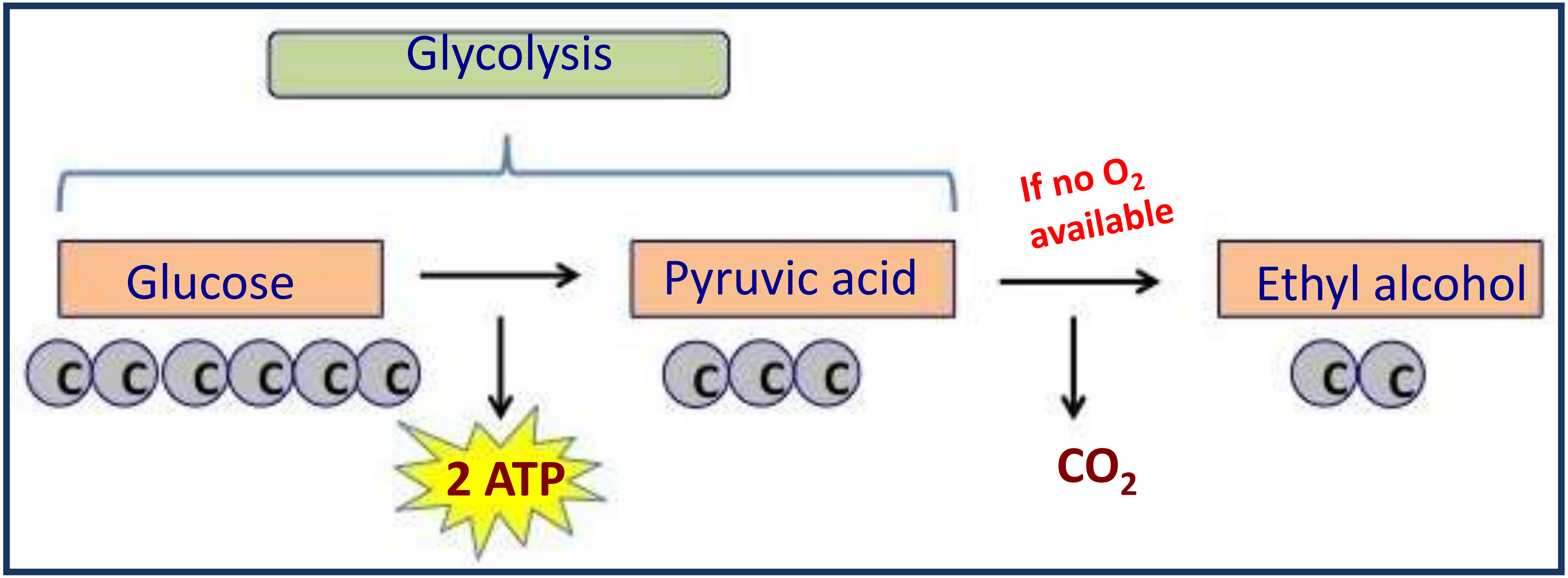
Alcoholic Fermentation

Yeasts perform alcoholic fermentation. Yeasts convert _pyruvic acid_ into _ethyl alcohol_ when they run out of _oxygen_.



Yeasts are used to make breads and alcohol.

The Steps of Alcoholic Fermentation



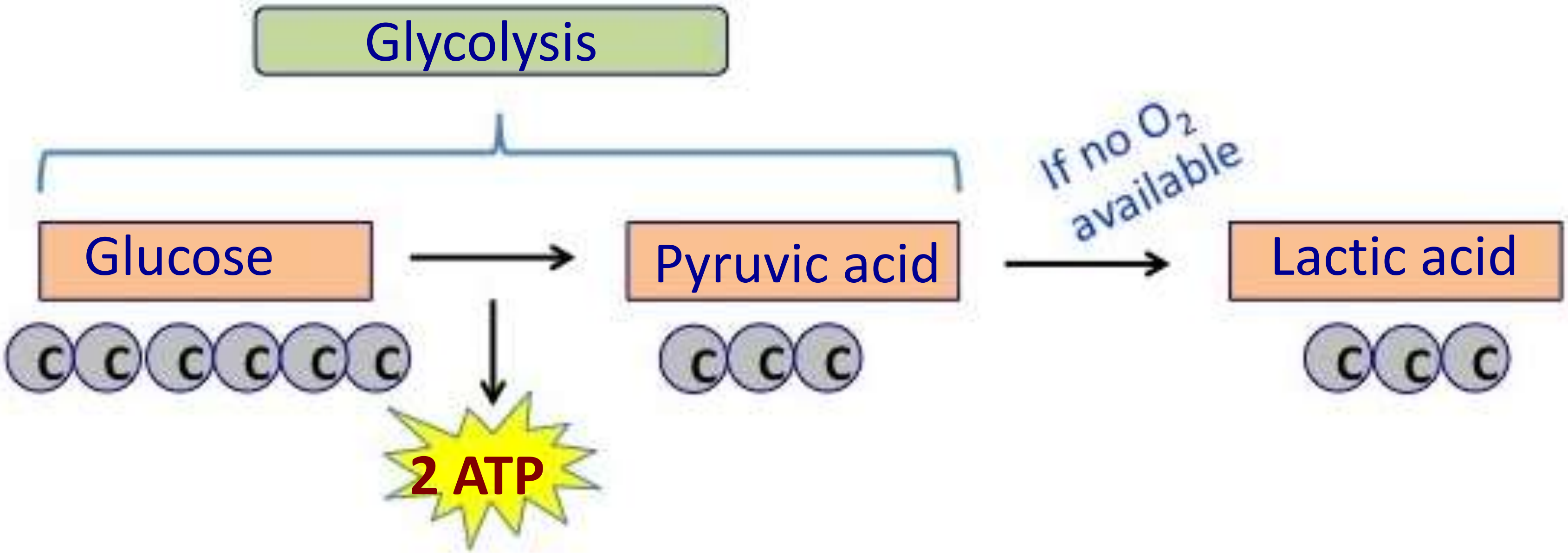
Yeasts are used in this way in both the _alcohol_ and the _baking_ industries.

The alcohol makes alcoholic beverages.

The _carbon dioxide_ that is given off causes bread dough to _rise_.

Small bubbles are formed in the dough, making the bread rise. (The alcohol evaporates during the baking process.)

The Steps of Lactic Acid Fermentation



Pyruvic acid____ is converted to lactic acid_ by muscle_ cells when there is a shortage of __oxygen_.
It is produced in muscle cells during strenuous exercise because the muscles are using up the _oxygen that is present and the body is not supplying the muscle tissue with enough additional oxygen.

This causes severe cramps because it lowers the pH of the muscle and reduces the muscle's ability to contract.

When oxygen returns to the muscles, the lactic acid will be converted back to pyruvic acid. The pyruvic acid will then go into aerobic respiration.

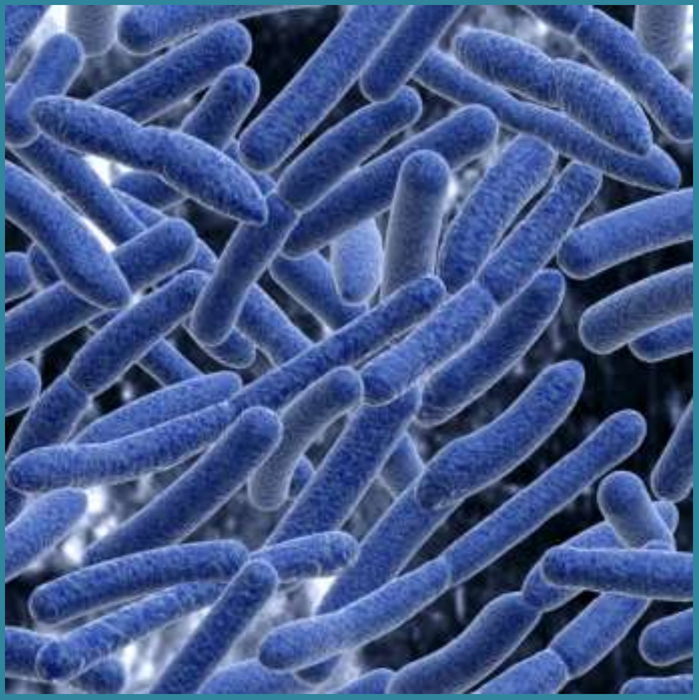
A wide variety of foods are produced by bacteria using lactic acid fermentation: cheese, yogurt, buttermilk, sour cream, pickles, sauerkraut.

Evolution of Anaerobic Pathways

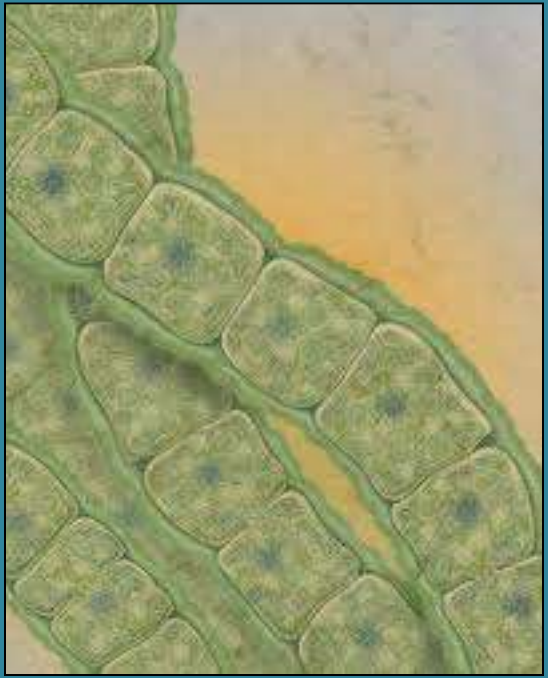
The __anaerobic__ pathways probably evolved very early in the history of life on Earth.

The first organisms were _bacteria_ and they produced all of their _ATP_ through _glycolysis_.

It took over a _billion_ years for the first _photosynthetic_ organisms to appear on Earth.

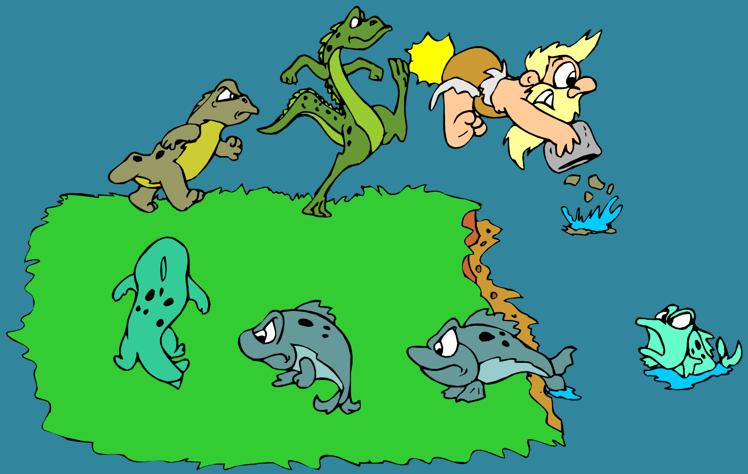


These photosynthetic organisms began to fill the atmosphere with oxygen, which stimulated the evolution of organisms that use aerobic respiration.



The anaerobic pathways provide enough energy for only:

small, unicellular organisms.



Larger organisms have much greater energy requirements that cannot be satisfied by anaerobic respiration alone. Larger organisms rely on the more energy efficient pathways of aerobic respiration.

Comparing Photosynthesis to Respiration

	Photosynthesis	Respiration
Function	Energy capture.	Energy release.
Location	Chloroplasts	Mitochondria
Reactants	CO_2 and H_2O	$C_6H_{12}O_6$ and O_2
Products	$C_6H_{12}O_6$ and O_2	CO_2 and H_2O
Equation	$CO_2 + H_2O + \text{sun} \rightarrow C_6H_{12}O_6$ and O_2	$C_6H_{12}O_6 + O_2 \rightarrow CO_2 + H_2O +$ 38 ATP