

CHAPTER 04

CELLULAR METABOLISM

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CELL METABOLISM OVERVIEW

Keep the “big picture” in mind as we discuss the particulars!

1. **Cellular respiration and fermentation are catabolic (energy – yielding) pathways.**
2. **Cells must recycle the ATP they use for work.**
3. **REDOX reactions release energy when electrons move closer to electronegative atoms.**
4. **Electrons “fall” from organic molecules to oxygen during cellular respiration.**

OVERVIEW

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5. The “fall” of electrons during respiration is stepwise via-
NAD⁺
Electron transport chain
6. **Respiration** *cumulative function of:*
Glycolysis: harvests chemical energy by **oxidizing glucose to pyruvate**
Krebs cycle: completes the energy – yielding **oxidation of organic molecules**
Electron transport: chain of molecules transferring electrons whose energy powers ATP synthesis.

OVERVIEW

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7. **Inner mitochondrial membrane** couples electron transport to ATP synthesis.
Electron transport pathway
Chemiosmosis (the energy - coupling mechanism)
Oxidative phosphorylation
8. **Cellular respiration** generates ***many* ATP** for **each** sugar molecule it oxidizes.
9. **Fermentation** enables some cells to produce ATP **without oxygen**. (but relatively inefficient !)
10. Glycolysis and the Krebs cycle connect to many other metabolic pathways.

OVERVIEW

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Always remember that the underlying concept of this topic is related to the fact that electron transfers to lower energy states result in the RELEASE of energy. How that occurs and what the resulting energy is used for is the basis of metabolism.

Cellular respiration and fermentation:
are catabolic pathways
-(energy – yielding)-

Each results in ATP formation

OVERVIEW

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FERMENTATION:

- **anaerobic** conditions.
- BOTH **electron donors** and **electron acceptors** are **organic compounds**.
- result: **partial** degradation of sugars.

RESPIRATION:

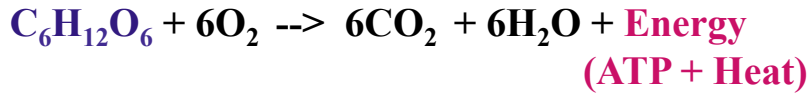
- **The ultimate electron acceptor is an inorganic compound (i.e., oxygen).**
- Most common and **efficient**.
- **Exergonic (energy - releasing) process:**
 $\text{Organics} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} + \text{Energy (food)}$
Source of fuel:
may be carbohydrates, fats or proteins.

OVERVIEW

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RESPIRATION:

Cellular respiration, however, usually refers to the **oxidation of glucose (Dextrose)** as the fuel.

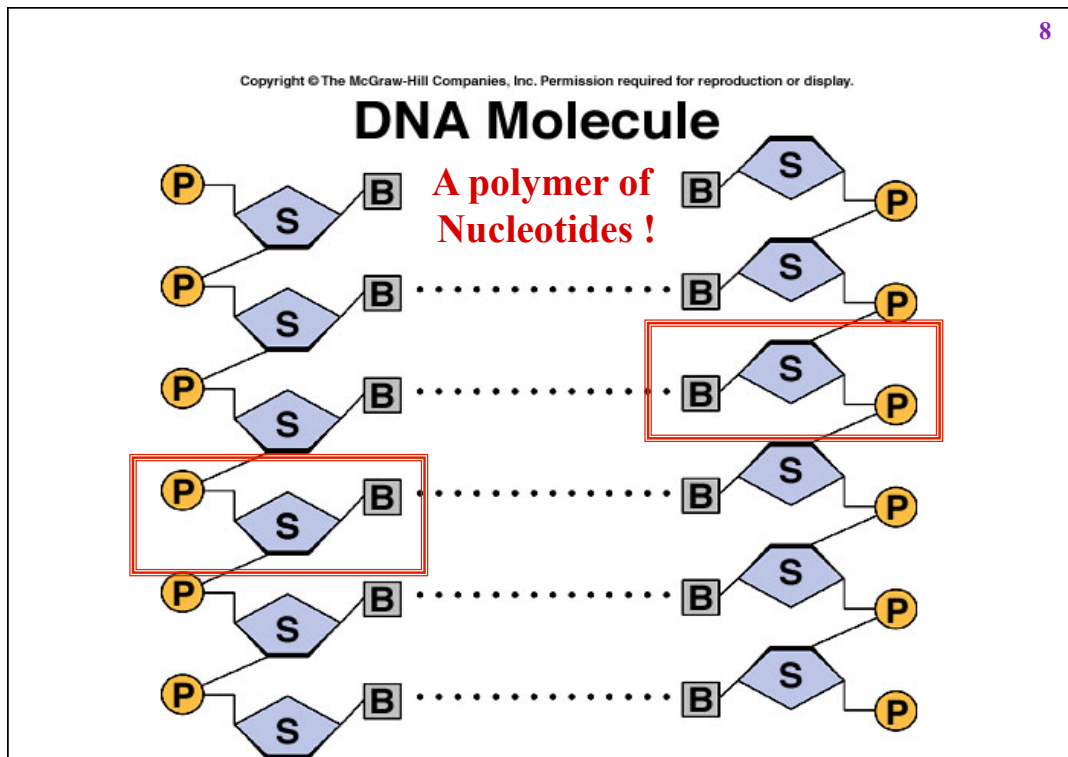


CELLS RECYCLE the ATP they use for work.

Respiration transfers ENERGY **from food to ATP.**

ATP is a **NUCLEOTIDE**; recall the definition:

Sugar, phosphates and a nitrogenous Base; i.e., DNA, also.



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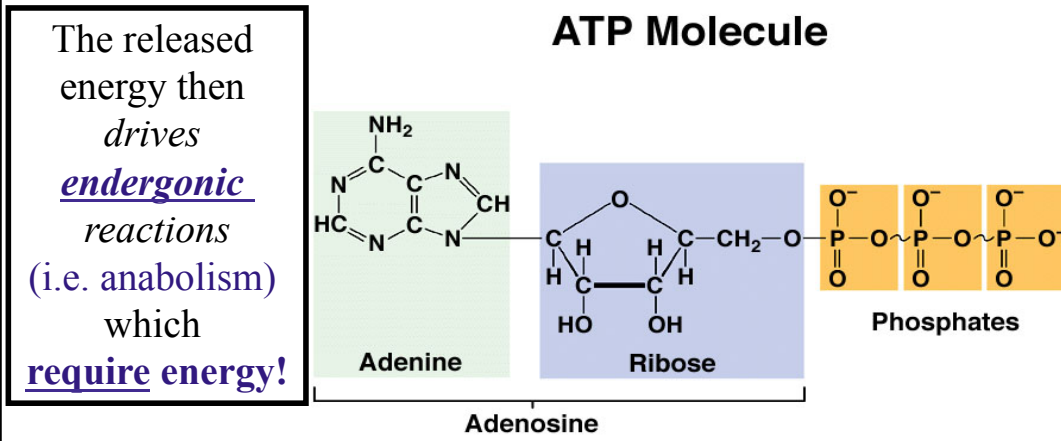
CELLS RECYCLE the ATP they use for work.

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Cells hydrolyze these bonds. Reaction is-

exergonic: products possess less free energy since energy is released.

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CELLS RECYCLE the ATP they use for work.

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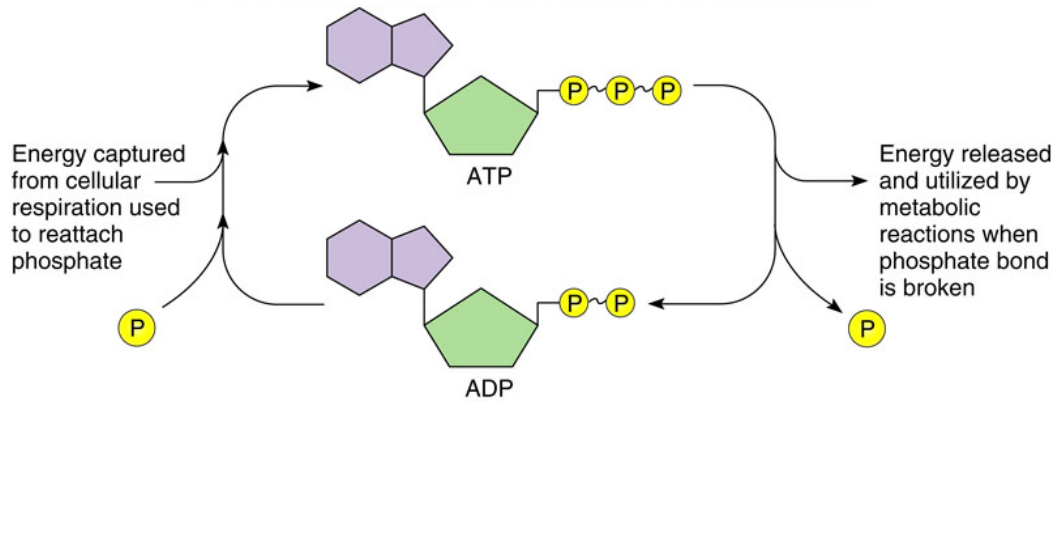
Mechanism: Cells enzymatically (not by hydrolysis- otherwise some energy would be lost as heat) transfer a **terminal phosphate** (with its **energy**) from ATP to another compound.

Recall: $ATP \rightarrow ADP + P_i + \text{energy}$

That compound is then referred to as **phosphorylated** (now more “reactive”)

Eventually, the compound “pays the bill” to perform cellular work by losing its phosphate group (releasing the stored energy within the bond) which, as we have seen, came from the original ATP molecule!

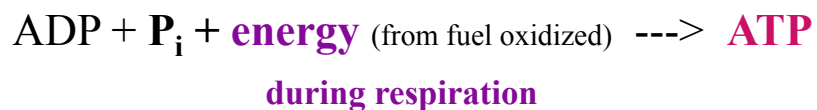
ATP Regeneration



CELLS RECYCLE the ATP they use for work.

Of course, cells must **replenish** their ATP supply in order to continue to do work.

Respiration provides the energy here:



**Read the above until you comprehend
before attempting to continue.**

REDOX Reactions.

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REDOX reactions

release energy when electrons move closer to electronegative atoms.

Redox reaction is a short reference to:

oxidation – reduction reactions

involves the partial or complete transfer of electrons from one reactant to another.

oxidation
reduction

partial or complete **loss of electrons**
partial or complete **gain of electrons**

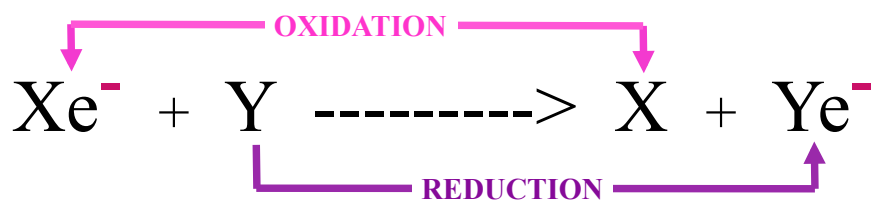
LEO the lion says GER!

REDOX Reactions.

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A Generalized REDOX reaction:

Electron transfer requires both a donor and an acceptor; so, when one is oxidized, the other is reduced.



ABOVE: X = Substance being oxidized; acts as a *reducing agent* because it *reduces* Y.

Y = Substance being reduced; acts as an *oxidizing agent* because it *oxidizes* X.

REDOX Reactions.

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IMPORTANT:

Electrons LOSE potential energy as they move towards more electronegative atoms.

Oxygen is **VERY electronegative** (a powerful **oxidizing agent**).

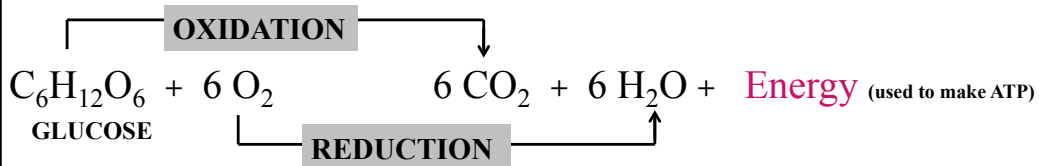
Therefore, redox reactions that move electrons closer to oxygen **release energy**.

Cellular : a **REDOX** process that transfers hydrogen **respiration** (with its electron) from sugar (called **dehydrogenation**) to oxygen.

Here's
how.....

REDOX Reactions.

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Electrons "fall" from organic molecules to oxygen during cellular respiration.

Valence electrons of carbon and hydrogen **LOSE** potential energy as they **shift toward the electronegative oxygen**.

The energy released is used to make **ATP !!!**

Note: Carbohydrates and fats are excellent energy sources since they are so rich in C to H bonds.

Electrons “fall” from organic molecules to oxygen during cellular respiration.

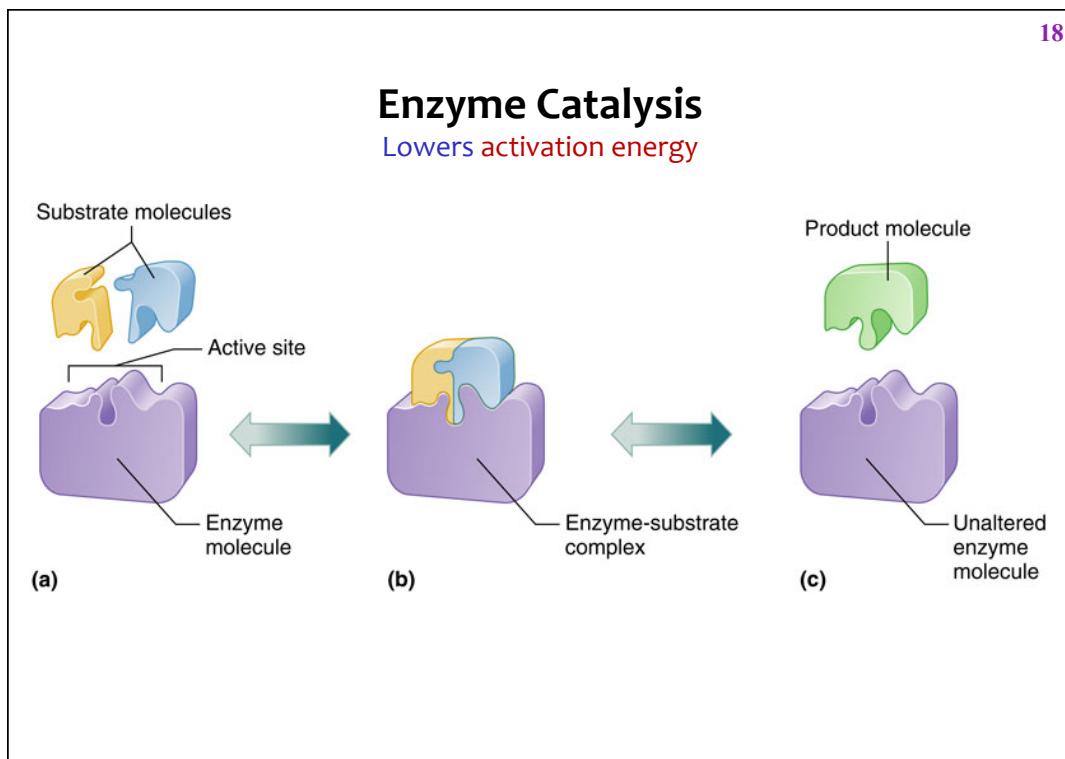
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Even the preceding reaction must overcome the **activation energy** necessary to “ignite” the glucose.

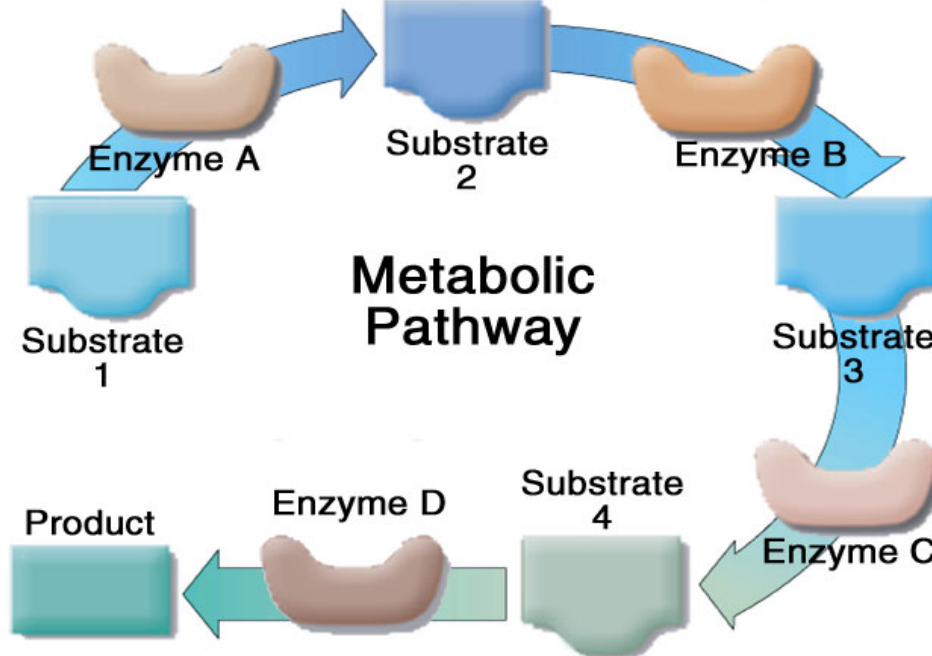
The sugar, in reality, is burned (oxidized) **slowly**, not in one explosive step.

Actually, this is a good thing since a spontaneous burst (release) of energy would proceed so quickly that **little time would exist to capture all of the energy released!**

Naturally, **enzymes lower the activation energy** so that the slowly oxidized glucose may pass through **glycolysis** and the **Krebs cycle** (to be discussed shortly) in a stepwise fashion.

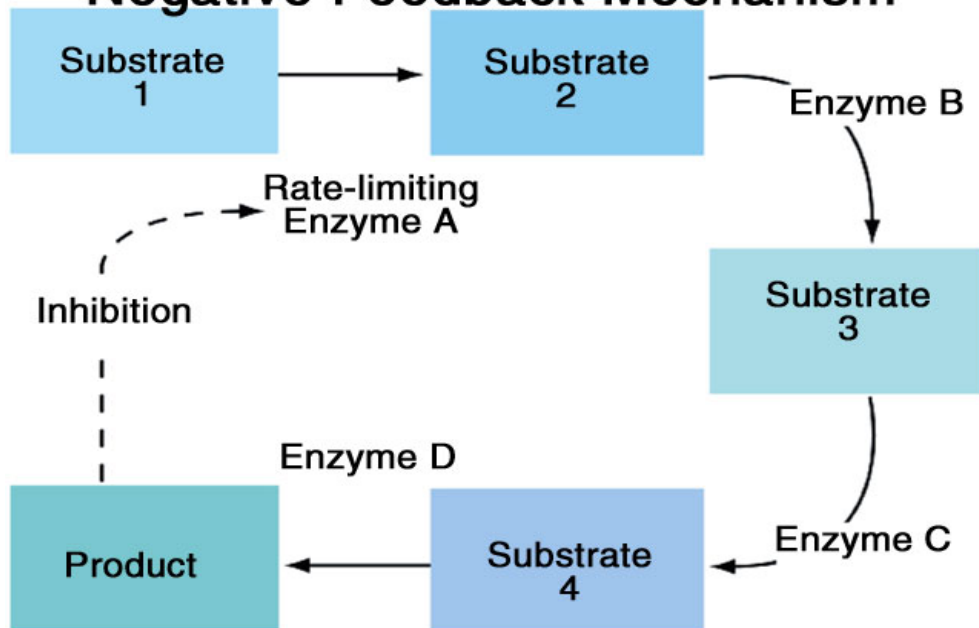


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Negative Feedback Mechanism



The “fall” of electrons during respiration is stepwise via NAD^+ and an Electron Transport Chain (ETC).

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Hydrogen atoms stripped from glucose are **NOT transferred directly to oxygen !**
They are first passed to a special electron acceptor (NAD^+)

NAD^+ = Nicotinamide Adenine Dinucleotide
(is a **coenzyme** found in all cells)

Recall: *Coenzyme is a small non-protein molecule that is required for certain enzymes to function*

NAD^+ **assists** enzymes in electron transfers during metabolic redox reactions.

The “fall” of electrons during respiration is stepwise via NAD^+ and an Electron Transport Chain (ETC).

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During glucose oxidation, NAD^+ functions as an oxidizing reagent:

NAD^+ traps energy – rich electrons from glucose or food.

The enzymes that NAD^+ assists are dehydrogenases which:

- remove a pair of hydrogen atoms (2 protons, 2 electrons) from the substrate
- deliver the **two electrons** and **one proton** to NAD^+
- release the **remaining proton** into the surrounding medium.

AFTERWARDS

The “fall” of electrons during respiration is stepwise via NAD^+ and an **Electron Transport Chain (ETC)**.



These **high energy electrons** (transferred from the substrate to NAD^+) are then **passed down the ELECTRON TRANSPORT CHAIN to oxygen**, powering the synthesis of ATP. Referred to as an-***Oxidative phosphorylation***.

So what is the ELECTRON TRANSPORT CHAIN (ETC) and what does it do ???.

Basically, it is composed of **a series of electron-carrier molecules** built in to the mitochondrial **inner membrane** .

These molecules **accept energy-rich electrons** from reduced **NADH** (and also **FADH_2**) and pass them along the chain to the **final electron acceptor (oxygen)**.

The electronegative oxygen accepts these electrons, along with hydrogen nuclei (recall dehydrogenation at the start) to form **water**.

Again, the stepwise nature of this **allows for the relatively slow release of energy**, thereby allowing the cell to capture the energy.

Since energy is **released** along the way, this reaction is **exergonic**. ($\Delta G = -53 \text{ kcal/mole}$).

RESPIRATION is a cumulative function of:

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- 1. Glycolysis** A catabolic pathway that occurs in the **cytosol**.
Partially oxidizes **glucose (6C) into 2 pyruvate (3C)** molecules.
- 2. Krebs cycle** (also called the **citric acid cycle**)
Occurs in the **mitochondrial matrix**.
Completes glucose oxidation by breaking a **pyruvate derivative (acetyl CoA)** into **CO₂**.

Glycolysis and the Krebs cycle produce:

A small amount of **ATP** by **substrate – level phosphorylation**.
NADH (by transferring electrons from the substrate to **NADH⁺**)

(The Krebs cycle also produces **FADH₂** by transferring electrons to **FAD**).

RESPIRATION is a cumulative function of:

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- 3. Electron Transport Chain**
 - Located at the **inner membrane of the mitochondrion**.
 - Accepts **energized electrons from reduced coenzymes (NADH and FADH₂)**, that are harvested during glycolysis and the Krebs cycle.

Oxygen (electronegative!) pulls these electrons **down the electron transport chain**: lower energy state.

Couples this exergonic slide of electrons to **ATP synthesis (aka oxidative phosphorylation, here)**.
This produces most (90%) of the ATP.

Oxidative phosphorylation : ATP production that is coupled to the exergonic transfer of electrons from **food to oxygen**. This occurs while electrons pass down the electron transport chain.

RESPIRATION is a cumulative function of:

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A **small amount of ATP** is produced **directly** by the reactions of **glycolysis** and the **Krebs cycle**.

This mechanism of producing ATP (from **glycolysis** **and** the **Krebs cycle**) is called **substrate – level phosphorylation**.

Substrate – level phosphorylation =
ATP production by direct **enzymatic transfer of phosphate** from an **intermediate substrate** in catabolism to **ADP**. (to make ATP)

GLYCOLYSIS harvests chemical energy by oxidizing glucose (6C) to two pyruvate (3C) molecules

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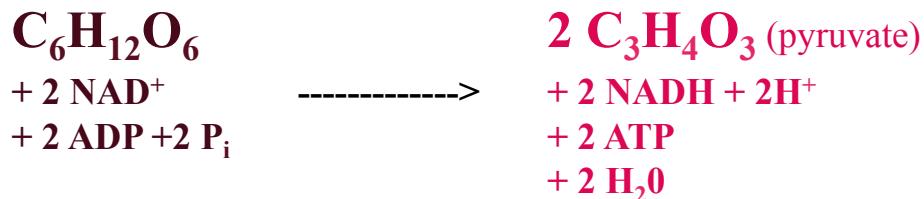
ANAEROBIC. Occurs whether or not oxygen is present.

Each reaction is catalyzed by specific **enzymes dissolved in the cytosol**.

No carbon dioxide is released as **glucose** is oxidized to **pyruvate**;

all carbon in glucose can be accounted for
in the two molecules of pyruvate.

SUMMARY REACTION for GLYCOLYSIS

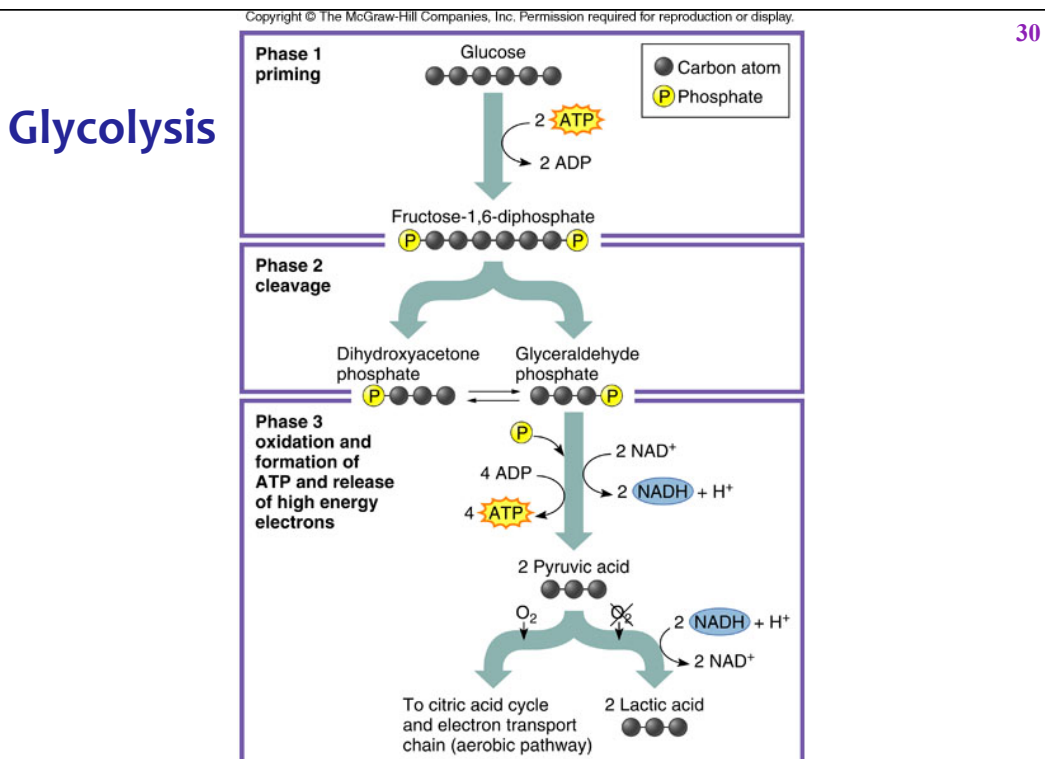


The KREBS CYCLE completes the energy – yielding oxidation of organic molecules.

Most of the chemical energy originally stored in glucose still resides in the two pyruvate molecules produced by glycolysis. **The fate of pyruvate depends upon the presence/absence of O₂.**

If **oxygen** is **present**, pyruvate enters the mitochondrion where it is completely oxidized by a series of enzyme – controlled reactions.

The **junction between** glycolysis and the Krebs cycle is the **oxidation of pyruvate to acetyl CoA.**



KREBS CYCLE reactions

Krebs cycle reactions:

oxidize the remaining acetyl fragments of **acetyl CoA to CO₂**.

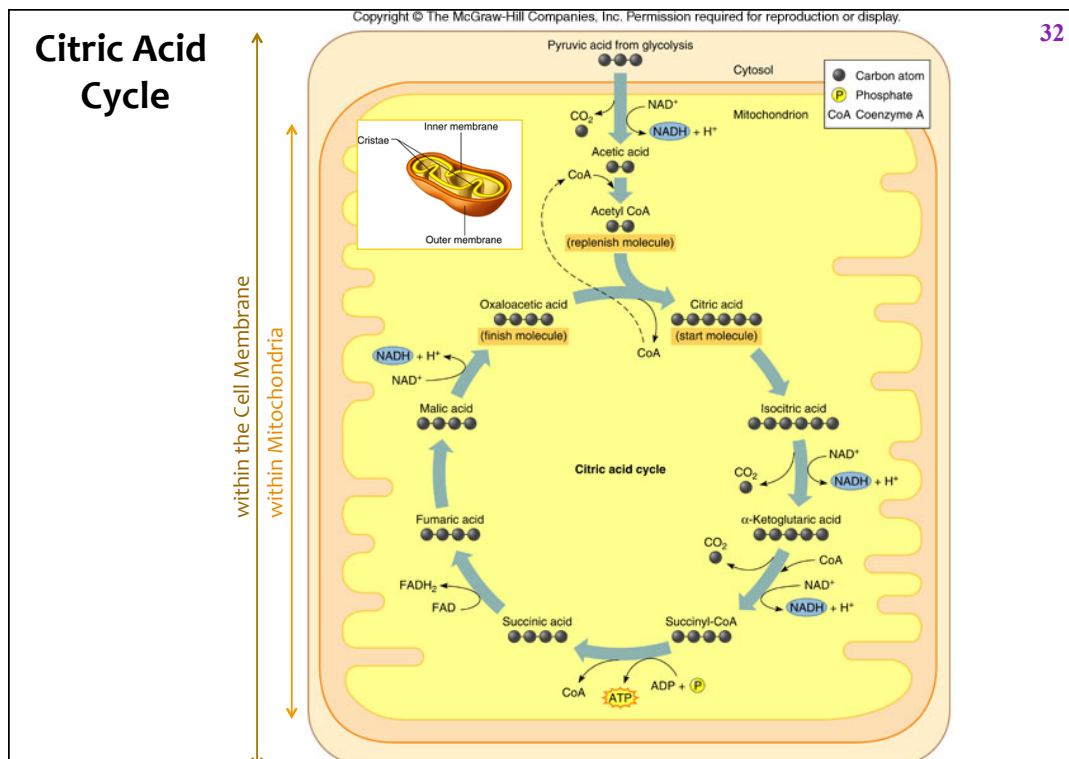
Energy released from this exergonic process is used to **reduce coenzymes (NAD⁺ and FAD)** and to **phosphorylate ADP (substrate – level phosphorylation)**.

The Krebs cycle has eight enzyme – controlled steps.

the first step: **Acetyl CoA (2C)** joins **oxaloacetate (4C)** to form **citrate (6C)**

the last step: **regeneration of oxaloacetate (4C)**; becomes available for the first step.

Each turn through the Krebs cycle occurs twice for an original molecule of glucose. (each turn: 1 ATP produced; total: 2 ATP)



The INNER MITOCHONDRIAL MEMBRANE
couples electron transport to ATP synthesis.

*Only a few molecules of ATP are produced
 by **substrate – level phosphorylation**:
 2 net ATPs per glucose from *glycolysis*.
 2 ATPs per glucose from *the Krebs cycle*.*

**Most molecules of ATP are produced by
 the ETC and oxidative phosphorylation:**

At the end of the Krebs cycle, most of the energy extracted
 from glucose is in molecules of **NADH and FADH₂**.

These reduced **coenzymes link glycolysis and the Krebs cycle to
 oxidative phosphorylation** by passing their **electrons down the
 electron transport chain (ETC) to oxygen.**

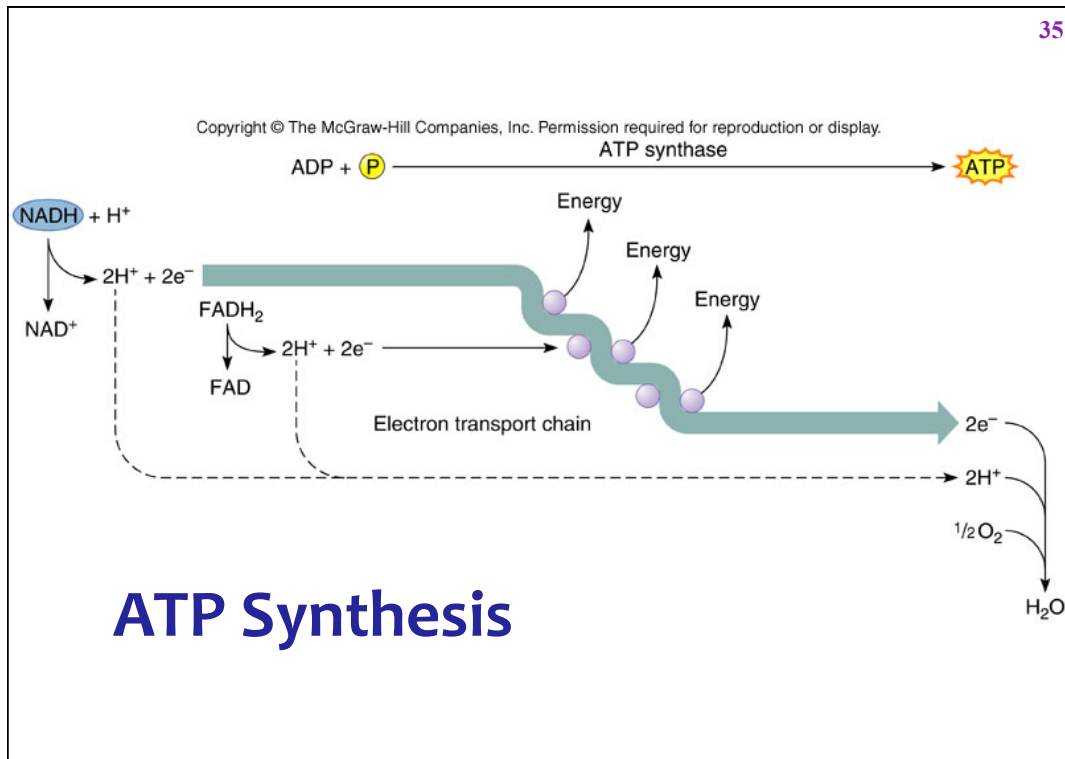
The INNER MITOCHONDRIAL MEMBRANE
couples electron transport to ATP synthesis.

Note: Though the Krebs cycle occurs only under
 aerobic conditions, **it does not use oxygen directly.**
 It is the **ETC** and **oxidative phosphorylation** which
require oxygen as the final electron acceptor.

This **exergonic** transfer of electrons **down the ETC**
 is **coupled to ATP synthesis.**

Some of the carrier molecules that act as electron
 carriers in the ETC: called **cytochromes**.

You will use these molecules for identification in Microbiology !



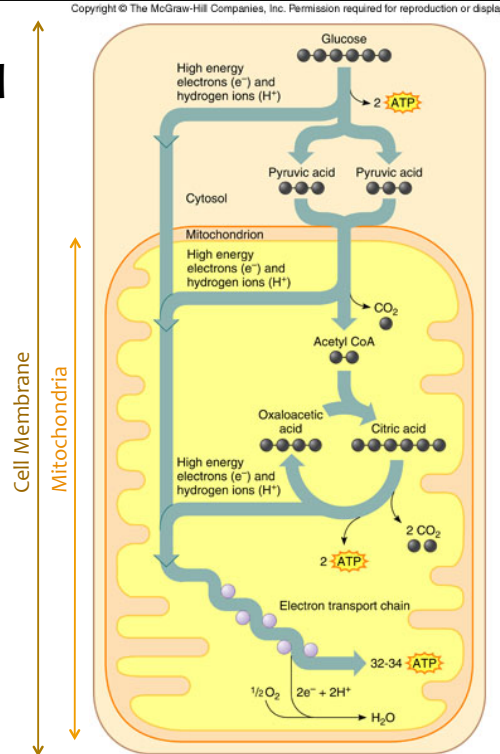
CHEMIOSMOSIS: The Energy – Coupling mechanism.

*The mechanism for coupling **exergonic** electron flow from the oxidation of food to the **endergonic process of oxidative phosphorylation** is called **CHEMIOSMOSIS**.*

ATP Synthetase: protein complex containing-

1. **Enzyme which makes ATP**
2. **Uses a proton gradient across the inner mitochondrial membrane. (powers ATP synthesis)**

Glycolysis and Aerobic Respiration



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FERMENTATION: allows some cells to produce ATP without the help of Oxygen

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FERMENTATION = The anaerobic catabolism of organic nutrients.

Remember, glycolysis produces 2 pyruvate molecules from glucose whether oxygen is present or not ! Then what ?

Recall:

Aerobic conditions: pyruvate is **oxidized further** and more ATP is made as **NADH passes electrons removed from glucose to the ETC**. **NAD⁺ is regenerated** in the process.

But fermentation occurs under- Anaerobic conditions -->

FERMENTATION: allows some cells to produce ATP without the help of Oxygen

But fermentation occurs under-

Anaerobic conditions:

pyruvate is **reduced** and NAD^+ is regenerated.

This prevents the cell from depleting (using up) the pool of NAD^+ , which is the oxidizing agent for glycolysis to continue. No additional ATP is produced.

FERMENTATION is NOT very efficient;

Far **less ATP produced** than by **aerobic** respiration !

Also note that the **final electron acceptor** is **not oxygen** but an **organic molecule!**

FERMENTATION: allows some cells to produce ATP without the help of Oxygen

Two common types of fermentation:

01. **Alcohol Fermentation.** Pyruvate -----> **ethanol.**
often performed by yeast and some bacteria.

02. **Lactic Acid Fermentation.** Pyruvate -----> **Lactic Acid.**
often performed by yeast and some bacteria.

Also, **low oxygen** conditions;
strenuous muscle activity-
Lactate accumulates: carried back to the liver where it is converted back to pyruvate when oxygen becomes available.

commercial importance:
yogurt and cheese production

MICROBIOLOGY PREVIEW: Some organisms (i.e., bacteria) can be classified based on the effect oxygen has on growth & metabolism.

Very important!

Strict (obligate) aerobes

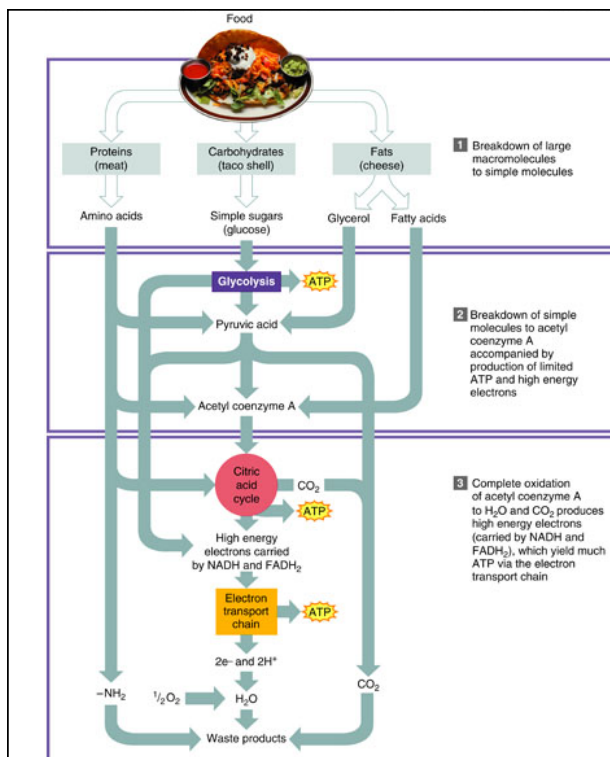
organisms that **require oxygen** as the final electron acceptor for growth.

Strict (obligate) anaerobes

organisms that live **ONLY** in the **absence of oxygen**.

Facultative anaerobes

make their ATP by **either** fermentation **OR** respiration.



Catabolism Summary

Proteins, Fats and Carbohydrates are ALL capable of being used in Cellular Respiration !!

Proteins: **Deamination** of amino acids allows entry into cellular respiration.

Fats: Products enter cellular respiration at the **glycolysis level (as glutaraldehyde) from glycerol.**
or as....
Acetyl CoA
(beta oxidation of fatty acids)

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Metabolic Pathways

Last Slide

