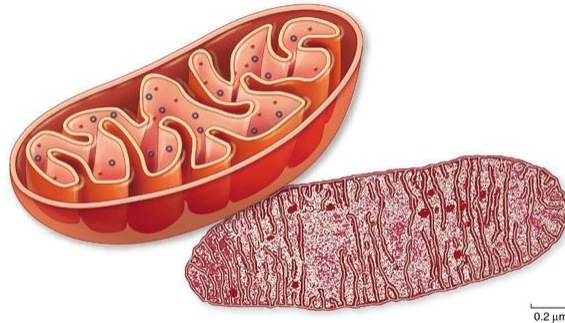


# How Cells Harvest Energy

## Chapter 7



# Respiration

Organisms classified on how they obtain energy:

**autotrophs**: produce their own organic molecules through photosynthesis

**heterotrophs**: live on organic compounds produced by other organisms

All organisms use **cellular respiration** to extract energy from organic molecules

# Respiration

Cellular respiration: series of reactions that are:

- oxidations – loss of electrons
- also **dehydrogenations** – lost electrons accompanied by hydrogen

Actually lost: hydrogen atom ( $1 e^-$  &  $1 p^+$ )

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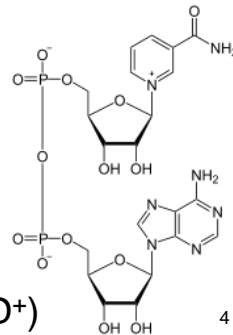
# Respiration

Redox reactions,  $e^-$  carry energy from 1 molecule to another

**NAD<sup>+</sup>** electron carrier

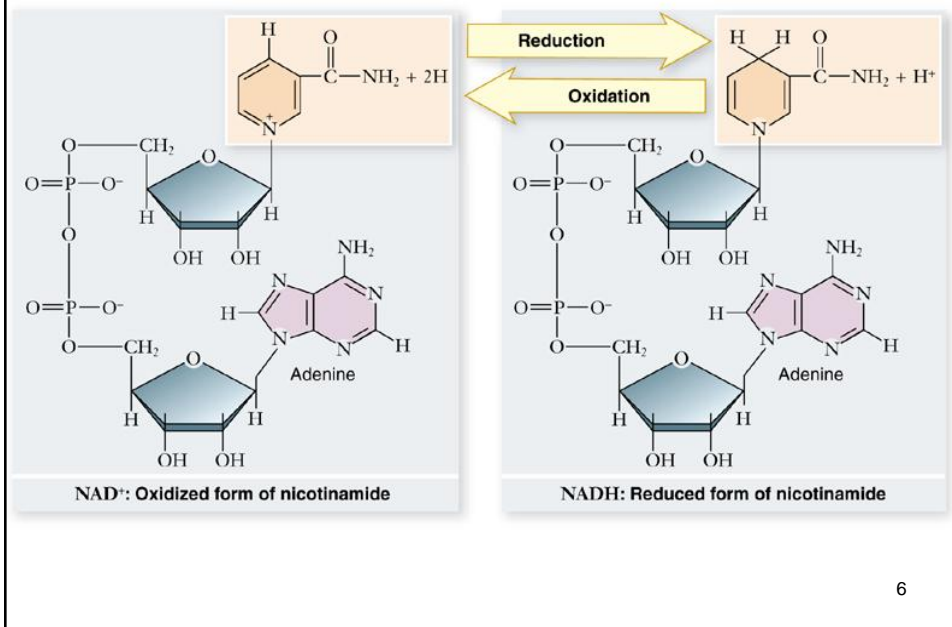
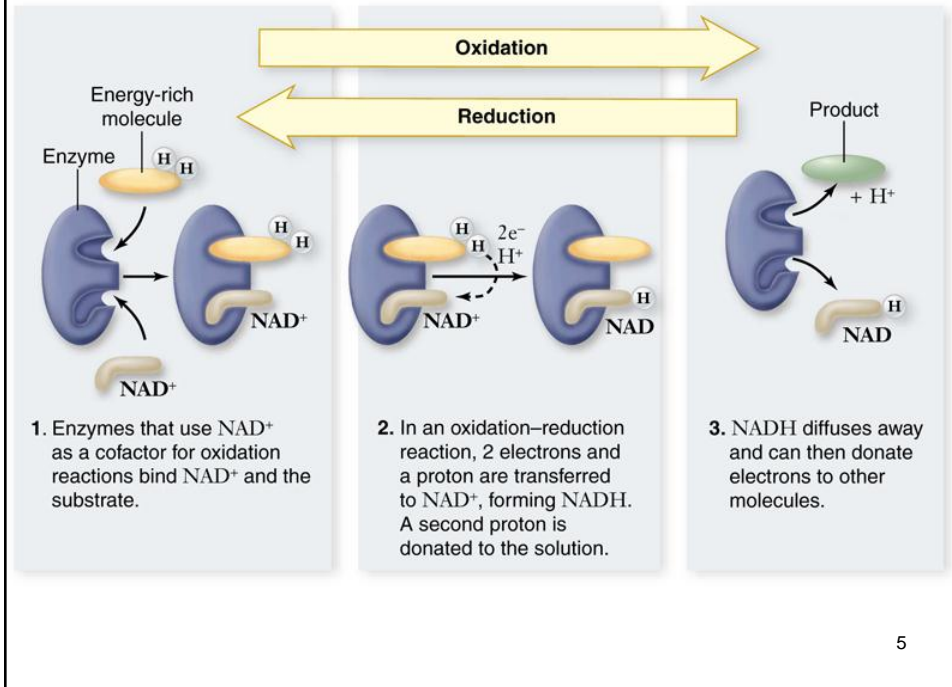
-NAD accepts  $2 e^-$  &  $1 p^+$  → **NADH**

-reaction reversible



*Nicotinamide adenine dinucleotide (NAD<sup>+</sup>)*

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# Respiration

During respiration, electrons shuttled through electron carriers to a final electron acceptor

**aerobic respiration:**

final electron acceptor: **oxygen ( $O_2$ )**

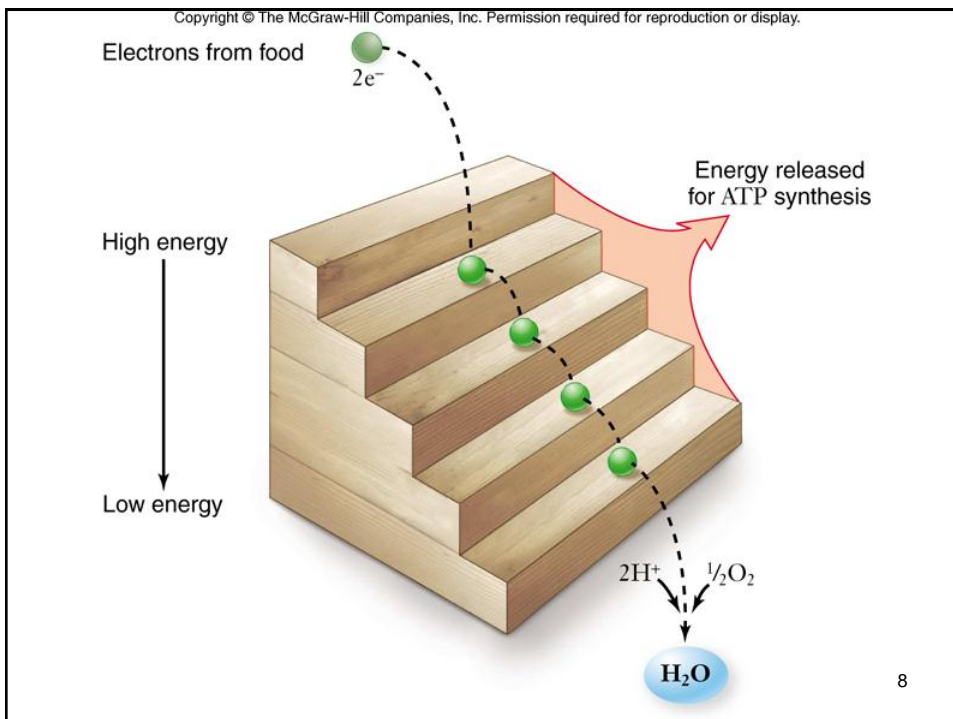
**anaerobic respiration:**

final electron acceptor: inorganic molecule (not  $O_2$ )

**fermentation:**

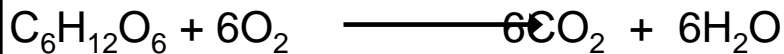
final electron acceptor: organic molecule

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# Respiration

Aerobic respiration:



$\Delta G = -686\text{kcal/mol}$  of glucose

$\Delta G$  can be even higher than this in a cell

This large amount of energy must be released in small steps rather than all at once

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# Respiration

Goal of respiration → produce ATP

- energy released from oxidation reaction in form of electrons
- electrons shuttled by electron carriers (e.g.  $\text{NAD}^+$ ) to an **electron transport chain**
- electron energy converted to ATP at electron transport chain

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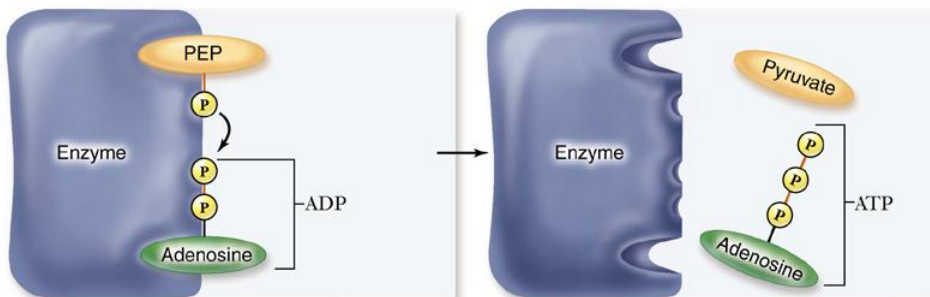
# Oxidation of Glucose

Cells able to make ATP via:

1. **substrate-level phosphorylation** – transferring a phosphate directly to ADP from another molecule
2. **oxidative phosphorylation** – use of **ATP synthase** & **energy derived from a proton ( $H^+$ ) gradient** to make ATP

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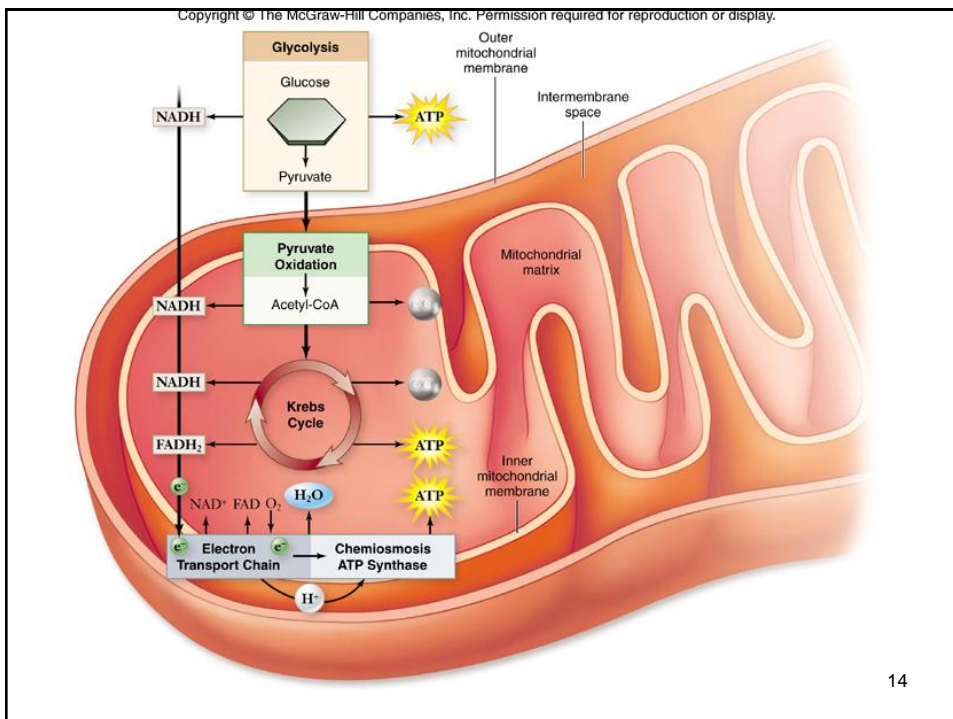
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# Oxidation of Glucose

complete oxidation of glucose proceeds in stages:

1. glycolysis
2. pyruvate oxidation
3. Krebs cycle
4. electron transport chain & chemiosmosis

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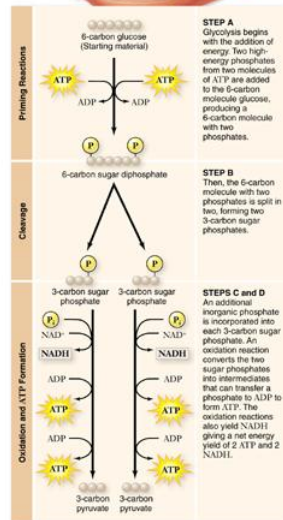
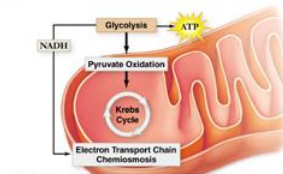
# Glycolysis

**Glycolysis** converts glucose to pyruvate

- a 10-step biochemical pathway
- occurs in cytoplasm
- 2 molecules of pyruvate formed
- net production of 2 ATP molecules by substrate-level phosphorylation
- 2 NADH produced by reduction of  $\text{NAD}^+$

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## Glycolysis

For glycolysis to continue, NADH must be recycled to NAD<sup>+</sup> by either:

1. aerobic respiration – occurs when oxygen available as final electron acceptor
2. fermentation – occurs when oxygen is not available; an organic molecule final electron acceptor

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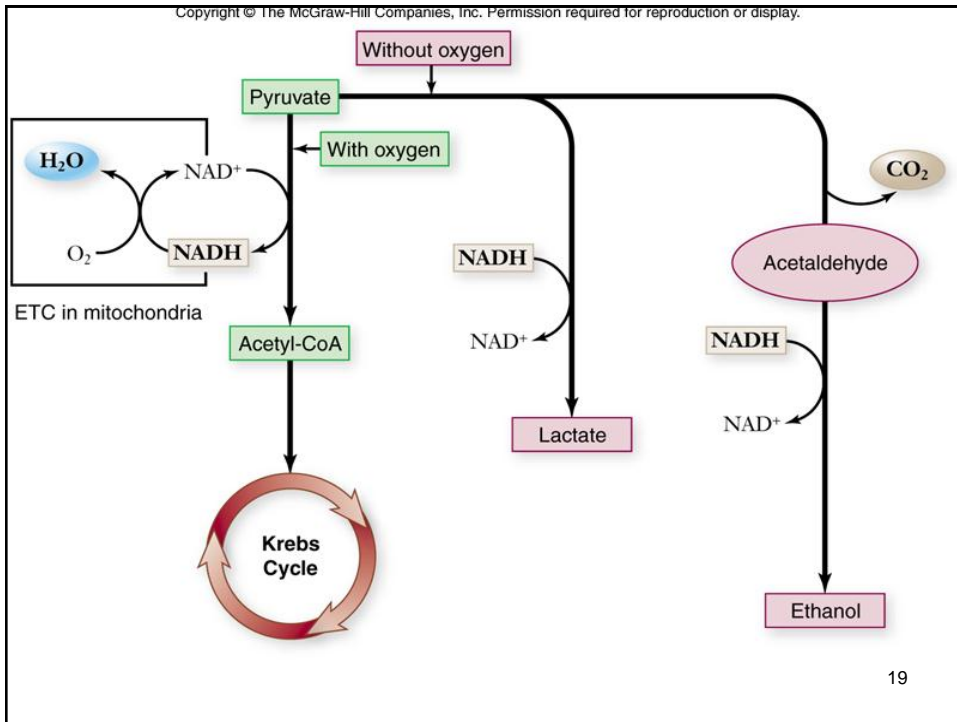
## Glycolysis

Fate of pyruvate depends on oxygen availability

When oxygen present, pyruvate oxidized to acetyl-CoA which enters Krebs cycle

Without oxygen, pyruvate is reduced in order to oxidize NADH back to NAD<sup>+</sup>

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## Pyruvate Oxidation

- In presence of oxygen, pyruvate oxidized
- occurs in mitochondria in eukaryotes
- occurs at plasma membrane in prokaryotes
- in mitochondria, a multienzyme complex (**pyruvate dehydrogenase**) catalyzes reaction

# Pyruvate Oxidation

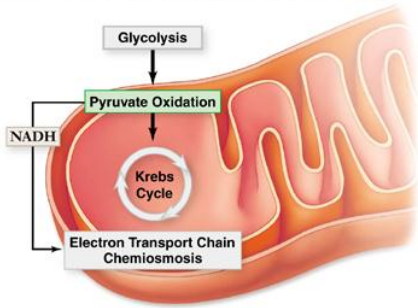
Products of pyruvate oxidation include:

- 1  $\text{CO}_2$
- 1 NADH
- 1 **acetyl-CoA** which consists of 2 carbons from pyruvate attached to coenzyme A

Acetyl-CoA proceeds to Krebs cycle

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**Pyruvate Oxidation: The Reaction**

Pyruvate

$\text{NAD}^+ \rightarrow \text{NADH}$

$\text{CO}_2$

CoA

Acetyl Coenzyme A

**Pyruvate**

$$\begin{array}{c} \text{O}^- \\ | \\ \text{C}=\text{O} \\ | \\ \text{C}=\text{O} \\ | \\ \text{CH}_3 \end{array}$$

**Acetyl Coenzyme A**

$$\begin{array}{c} \text{S}-\text{CoA} \\ | \\ \text{C}=\text{O} \\ | \\ \text{CH}_3 \end{array}$$

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## Krebs Cycle

**Krebs cycle** oxidizes acetyl group from pyruvate

-occurs in matrix of mitochondria

-biochemical pathway of 9 steps

-first step:

acetyl group + oxaloacetate  $\longrightarrow$  citrate  
(2 carbons)      (4 carbons)      (6 carbons)

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## Krebs Cycle

Remaining steps of Krebs cycle:

-release 2 molecules of  $\text{CO}_2$

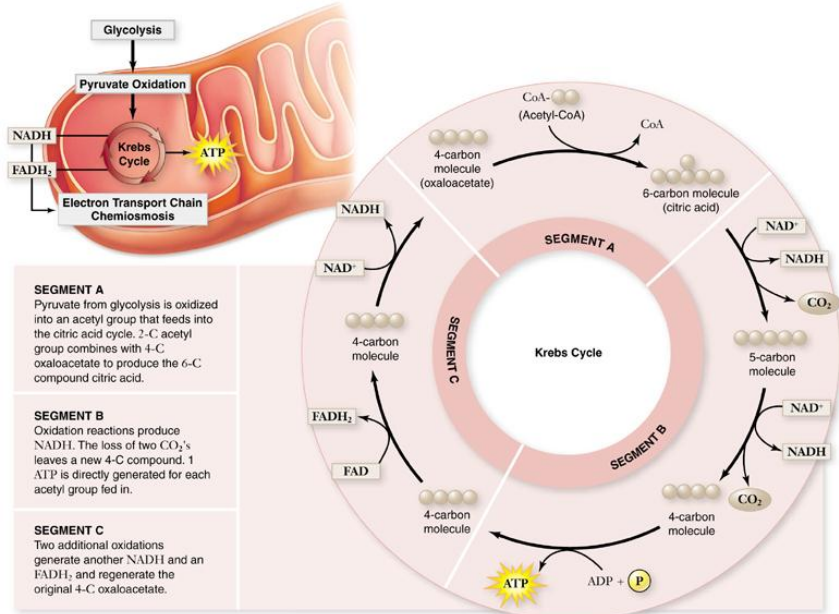
-reduce 3  $\text{NAD}^+$  to 3  $\text{NADH}$

-reduce 1  $\text{FAD}$  (electron carrier) to  $\text{FADH}_2$

-produce 1  $\text{ATP}$

-regenerate oxaloacetate

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## Krebs Cycle

After glycolysis, pyruvate oxidation & Krebs cycle, glucose oxidized to:

- 6  $\text{CO}_2$
  - 4  $\text{ATP}$
  - 10  $\text{NADH}$
  - 2  $\text{FADH}_2$
- } These electron carriers proceed to electron transport chain

## Electron Transport Chain

**Electron transport chain (ETC):** a series of membrane-bound electron carriers

- embedded in mitochondrial inner membrane
- electrons from NADH & FADH<sub>2</sub> transferred to complexes of ETC
- each complex transfers electrons to next complex in chain

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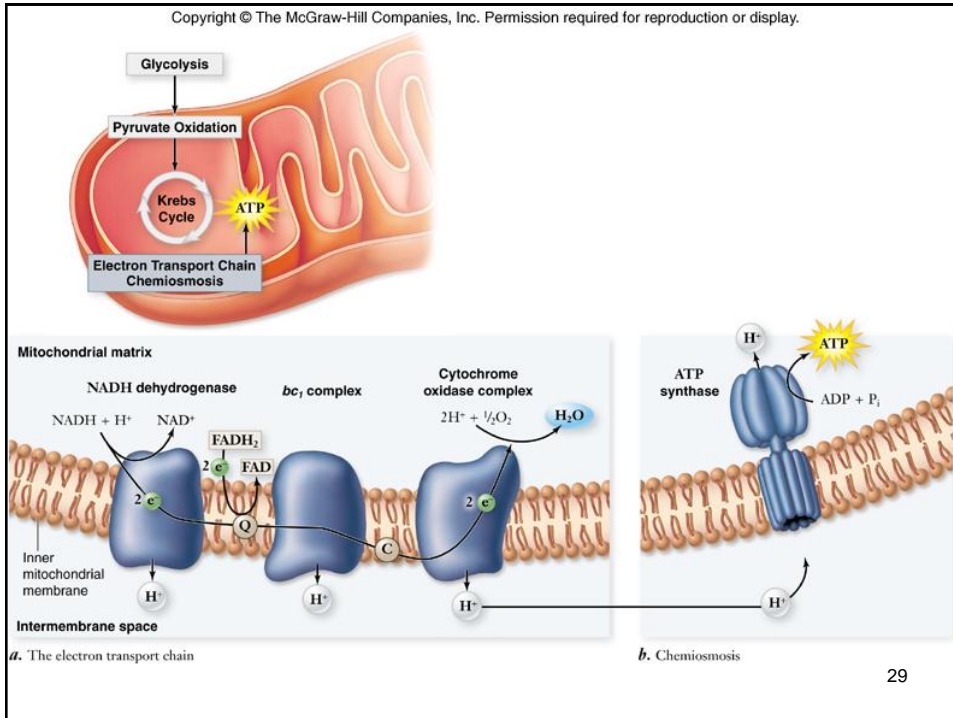
## Electron Transport Chain

As electrons transferred, some electron energy lost with each transfer

Energy used to pump protons (H<sup>+</sup>) across membrane from matrix to inner membrane space

A **proton gradient** established

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## Electron Transport Chain

Higher negative charge in matrix attracts protons (H<sup>+</sup>) back from intermembrane space to matrix.

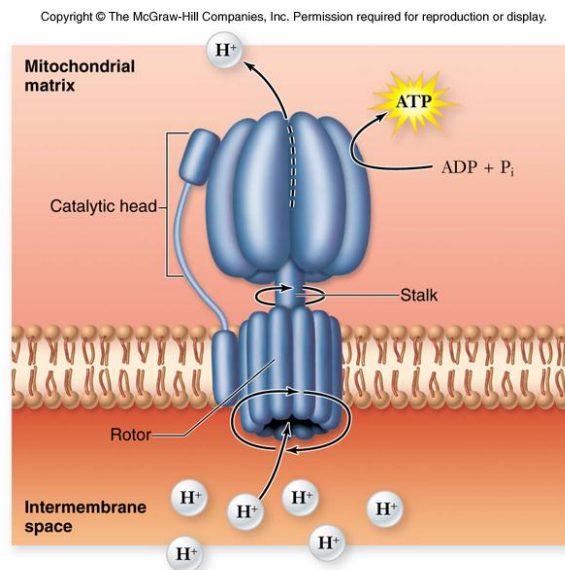
Accumulation of protons in intermembrane space drives protons into matrix via diffusion

# Electron Transport Chain

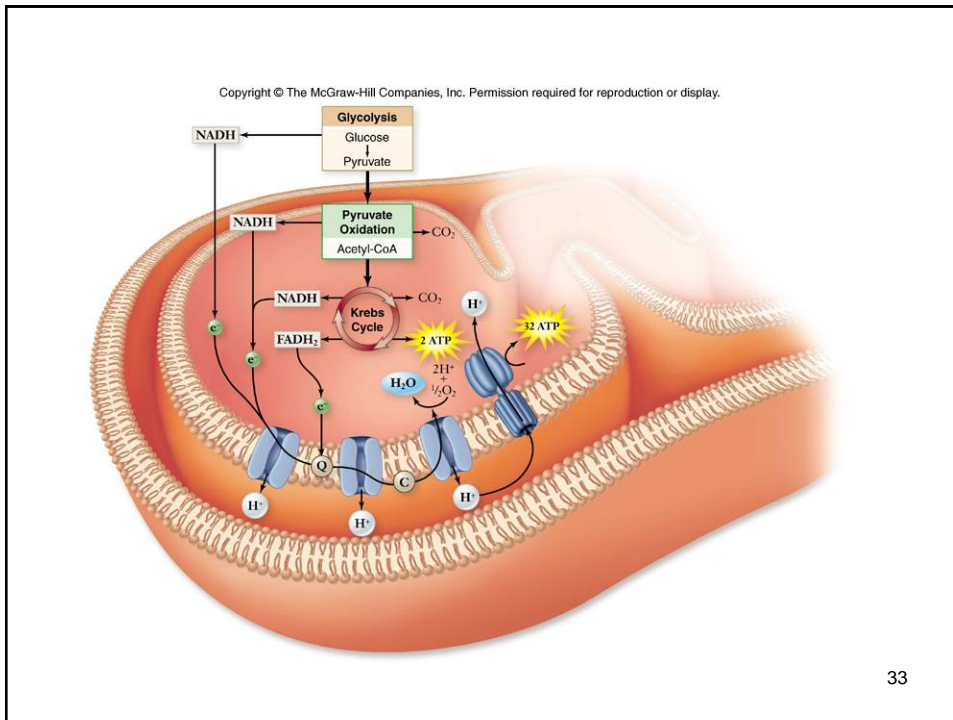
Most protons move back to matrix through **ATP synthase**

ATP synthase: membrane-bound enzyme uses energy of proton gradient to synthesize ATP from ADP + P<sub>i</sub>.

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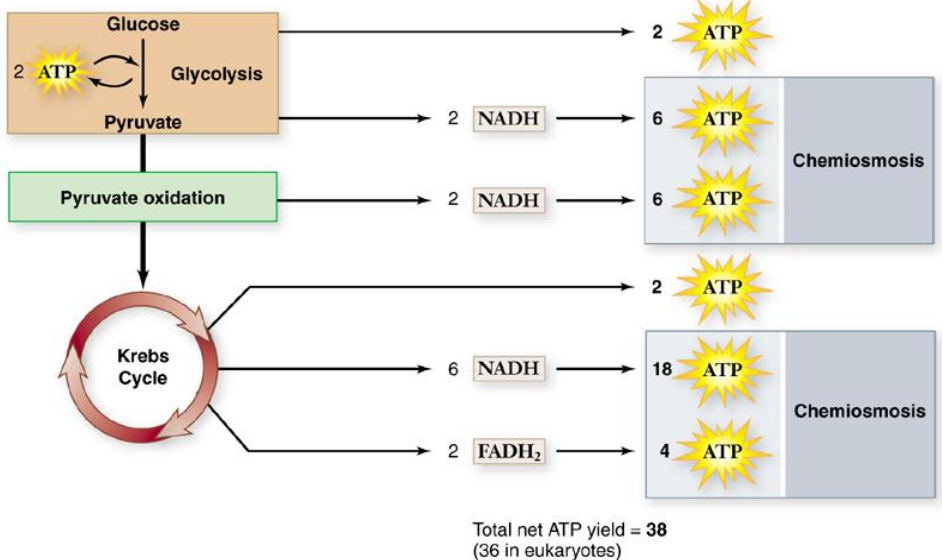
## Energy Yield of Respiration

theoretical energy yields

- 38 ATP/glucose for bacteria
- **36 ATP/glucose for eukaryotes**

actual energy yield

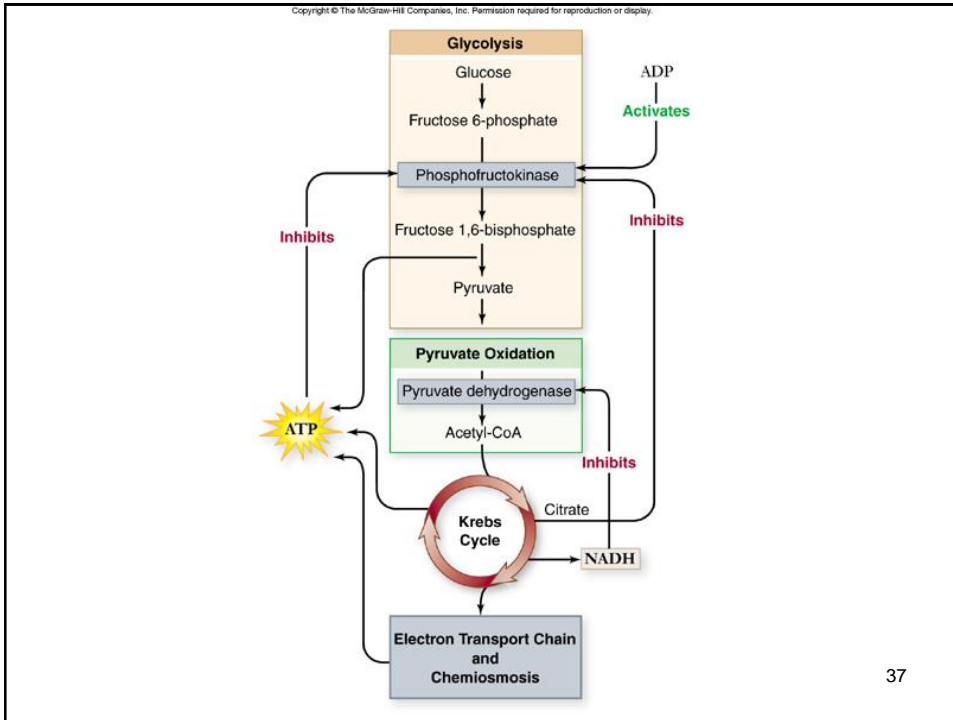
- 30 ATP/glucose for eukaryotes
- reduced yield due to “leaky” inner membrane & use of proton gradient for purposes other than ATP synthesis



## Regulation of Respiration

Regulation of aerobic respiration is by feedback inhibition

- a step within glycolysis is allosterically inhibited by ATP & by citrate
- high levels of NADH inhibit pyruvate dehydrogenase
- high levels of ATP inhibit citrate synthetase



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## Oxidation Without O<sub>2</sub>

Respiration occurs without O<sub>2</sub> via either:

1. **anaerobic respiration**
  - use of inorganic molecules (other than O<sub>2</sub>) as final electron acceptor
2. **fermentation**
  - use of organic molecules as final electron acceptor

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## Oxidation Without O<sub>2</sub>

Anaerobic respiration by methanogens

- methanogens use CO<sub>2</sub>
- CO<sub>2</sub> reduced to CH<sub>4</sub> (methane)

Anaerobic respiration by sulfur bacteria

- inorganic sulphate (SO<sub>4</sub>) reduced to hydrogen sulfide (H<sub>2</sub>S)

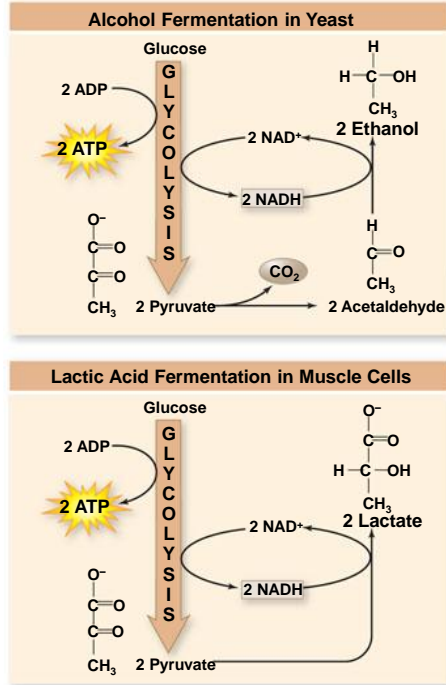
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## Oxidation Without O<sub>2</sub>

**Fermentation** reduces organic molecules in order to regenerate NAD<sup>+</sup>

1. **ethanol fermentation** occurs in yeast
  - CO<sub>2</sub>, ethanol & NAD<sup>+</sup> produced
2. **lactic acid fermentation**
  - occurs in animal cells (especially muscles)
  - electrons transferred from NADH to pyruvate to produce lactic acid

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## Catabolism of Protein & Fat

Catabolism of proteins:

- amino acids undergo **deamination** to remove amino group
- remainder of amino acid converted to a molecule that enters glycolysis or Krebs cycle
- for example:
  - alanine is converted to pyruvate
  - aspartate is converted to oxaloacetate

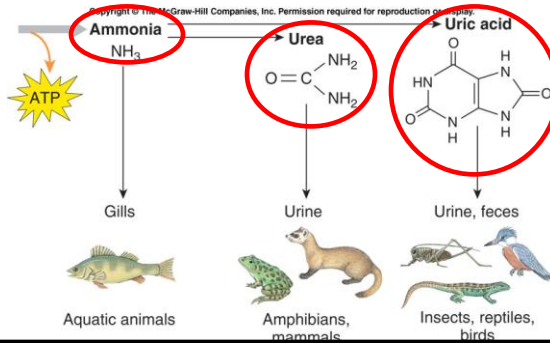
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# Catabolism of Protein & Fat

Catabolism of fats:

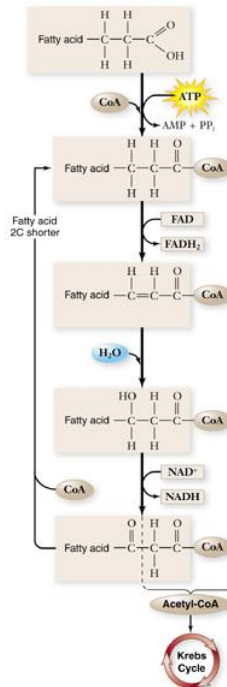
- fats broken down to fatty acids & glycerol
- fatty acids converted to acetyl groups by  $\beta$ -oxidation

Respiration of a 6-carbon fatty acid yields 20% more energy than glucose

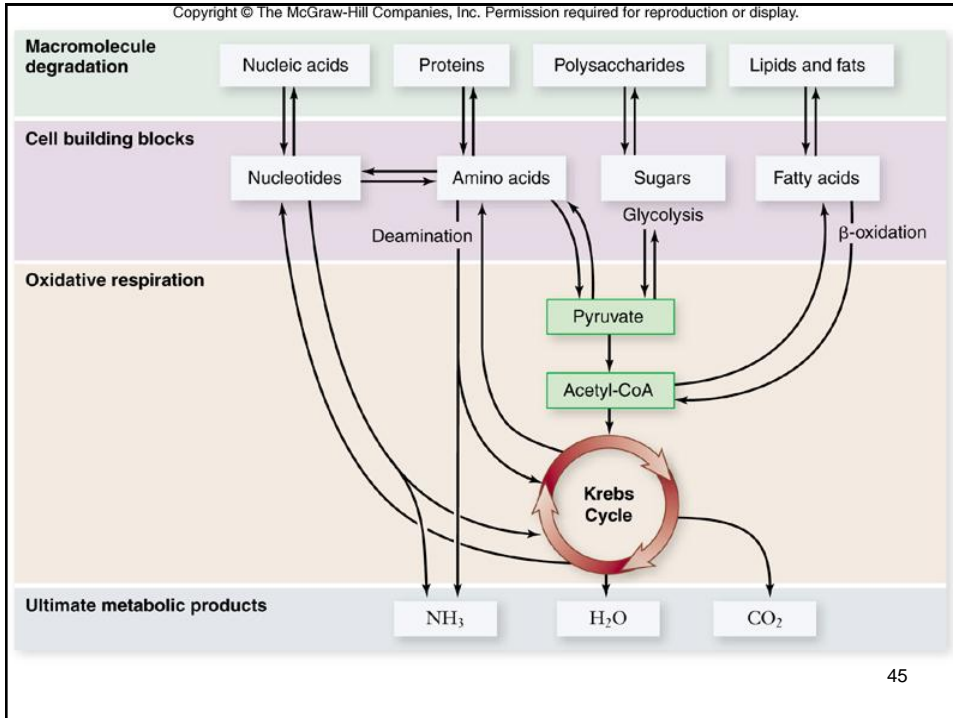


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## Evolution of Metabolism

Hypothetical timeline for evolution of metabolism:

1. ability to store chemical energy in ATP
2. evolution of glycolysis
3. anaerobic photosynthesis (using  $\text{H}_2\text{S}$ )
4. use  $\text{H}_2\text{O}$  in photosynthesis (not  $\text{H}_2\text{S}$ )
5. evolution of nitrogen fixation
6. aerobic respiration evolved most recently