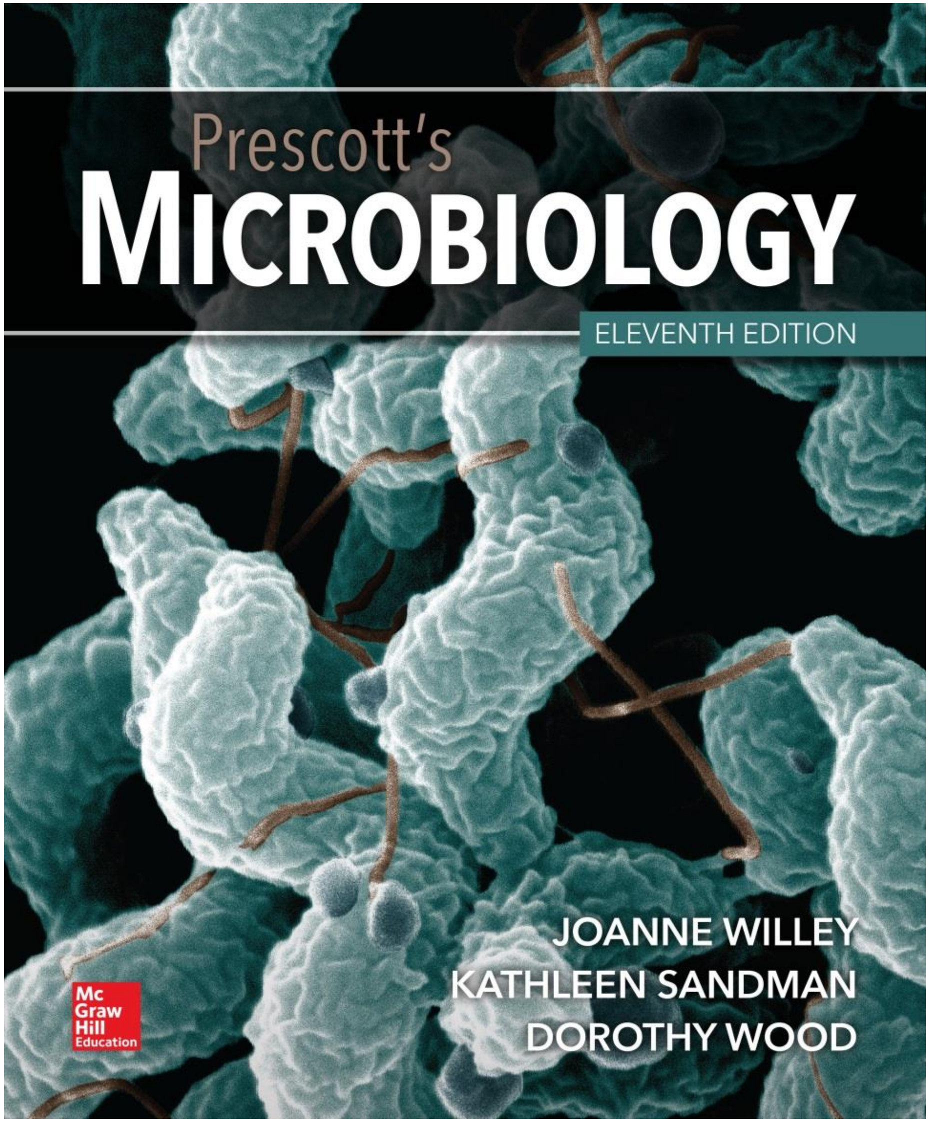


Prescott's

MICROBIOLOGY

ELEVENTH EDITION

JOANNE WILLEY
KATHLEEN SANDMAN
DOROTHY WOOD

Chapter 11

Catabolism: Energy Release and Conservation

Requirements for Carbon, Hydrogen, and Oxygen

Often satisfied together.

- Carbon source often provides H, O, and electrons.

Heterotrophs.

- Use organic molecules as carbon sources which often also serve as energy source.
- Can use a variety of carbon sources.

Autotrophs.

- Use carbon dioxide as their sole or principal carbon source.
- Must obtain energy from other sources.

Nutritional Types of Organisms

Based on energy source:

- **Phototrophs** use light.
- **Chemotrophs** obtain energy from oxidation of chemical compounds.

Based on electron source:

- **Lithotrophs** use reduced inorganic substances.
- **Organotrophs** obtain electrons from organic compounds.

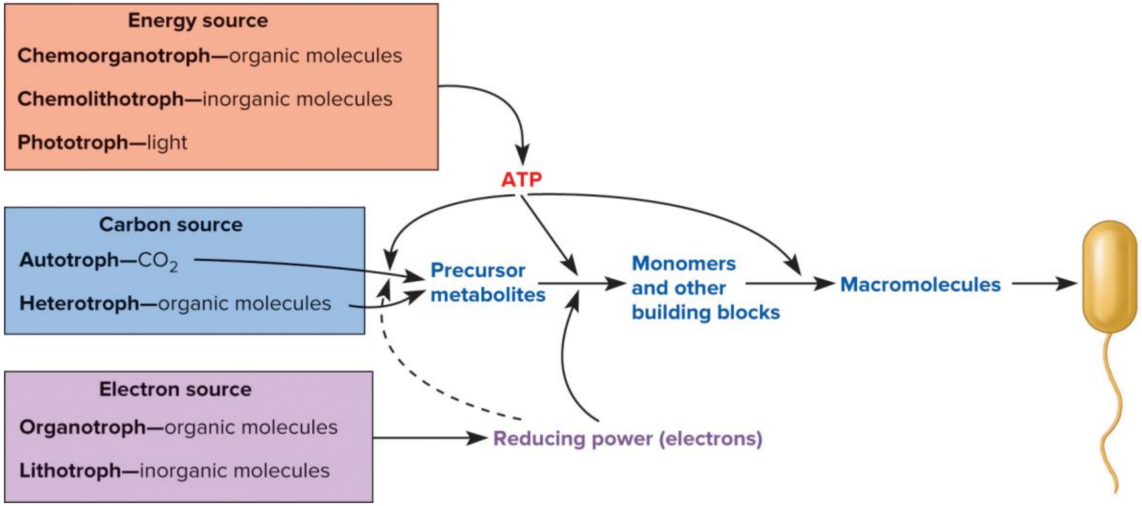
Major Nutritional Types

Nutritional Type	Carbon Source	Energy Source	Electron Source	Representative Microorganisms
Photolithoautotroph	CO_2	Light	Inorganic e^- donor	Purple and green sulfur bacteria, cyanobacteria, diatoms
Photoorganoheterotroph	Organic carbon	Light	Organic e^- donor	Purple nonsulfur bacteria, green nonsulfur bacteria
Chemolithoautotroph	CO_2	Inorganic chemicals	Inorganic e^- donor	Sulfur-oxidizing bacteria, hydrogen-oxidizing bacteria, methanogens, nitrifying bacteria, iron-oxidizing bacteria
Chemolithoheterotroph	Organic carbon	Inorganic chemicals	Inorganic e^- donor	Some sulfur-oxidizing bacteria (For example, *Beggiatoa*)
Chemoorganoheterotroph	Organic carbon	Organic chemicals, often same as C source	Organic e– donor, often same as C source	Most nonphotosynthetic microbes, including most pathogens, fungi, and many protists and archaea

Fueling Reactions

Despite diversity of energy, electron, and carbon sources used by organisms, they all have the same basic needs:

- **ATP as an energy currency.**
- **Reducing power to supply electrons for chemical reactions.**
- **Precursor metabolites for biosynthesis.**



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Chemoorganotrophic Fueling Processes

Also called chemoheterotrophs.

Processes used to catabolize energy source:

- Aerobic respiration.
- Anaerobic respiration.
- Fermentation.

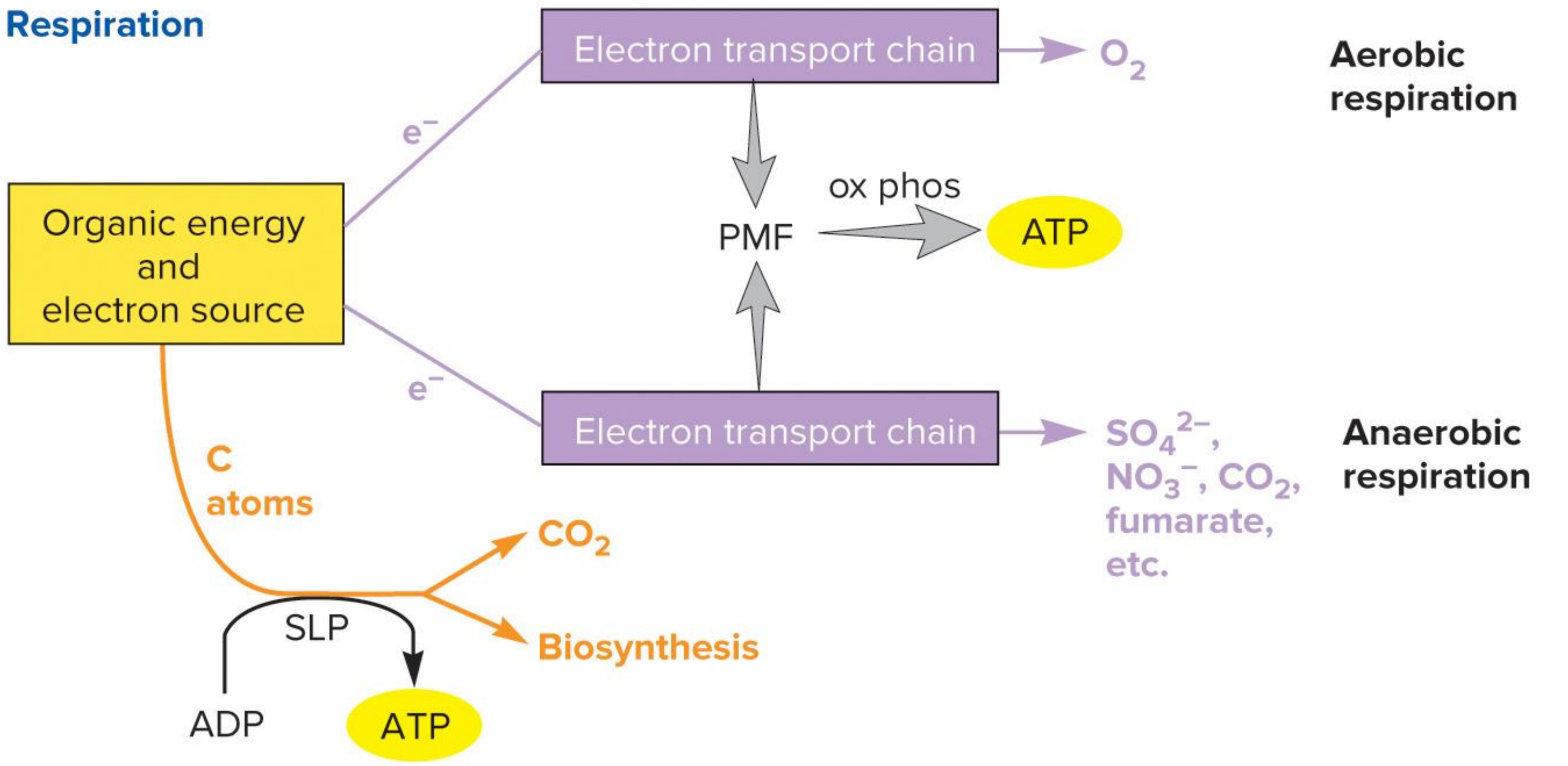
Respiration 1

Most respiration involves use of an electron transport chain.

- **Aerobic respiration**—final electron acceptor is oxygen.
- **Anaerobic respiration**—final electron acceptor is different exogenous acceptor such as NO_3^-, SO_4^{2-}, CO_2, Fe^{3+}, or SeO_4^{2-}
- As electrons pass through the electron transport chain to the final electron acceptor, a proton motive force (PMF) is generated and used to synthesize ATP.

Respiration 2

Chemoorganotrophic Fueling Processes



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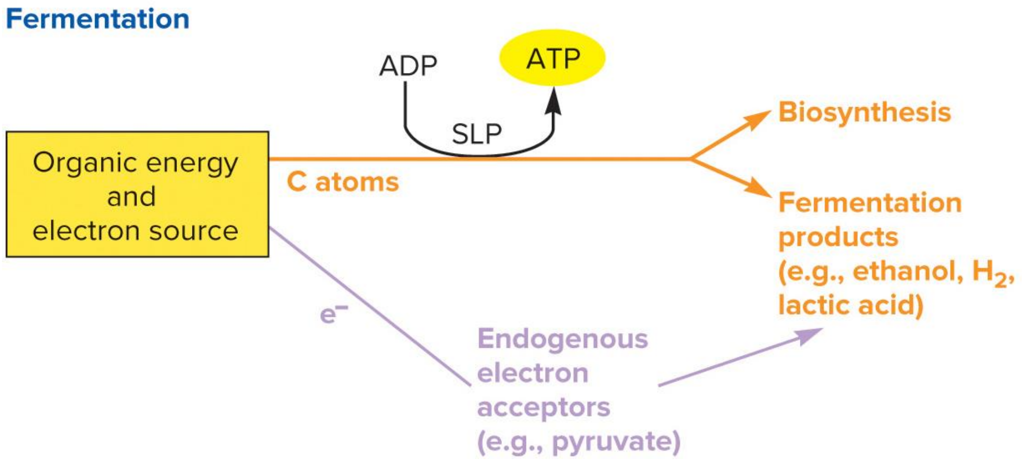
Fermentation 1



Uses an endogenous electron acceptor.

- Usually an intermediate of the pathway used to oxidize the organic energy source, For example, pyruvate.

Does not involve the use of an electron transport chain nor the generation of a proton motive force.

ATP synthesized only by substrate-level phosphorylation.

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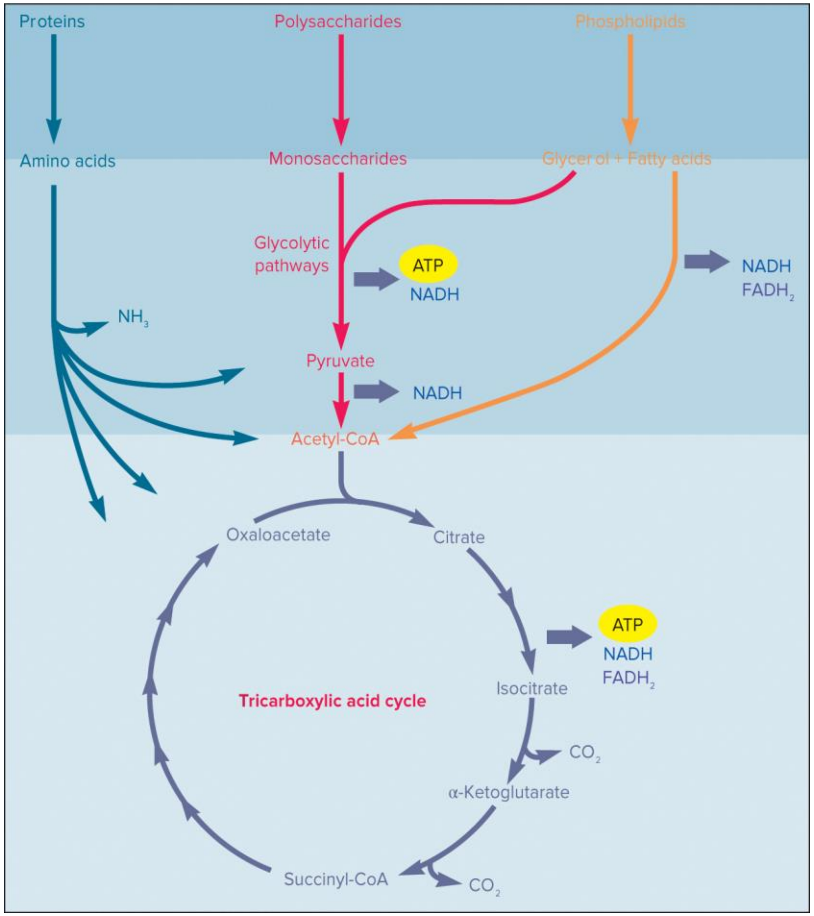
Energy Sources[1]

Many different energy sources are funneled into common degradative pathways.

Most pathways generate glucose or intermediates of the pathways used in glucose metabolism.

Few pathways greatly increase metabolic efficiency.



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Catabolic/Amphibolic Pathways

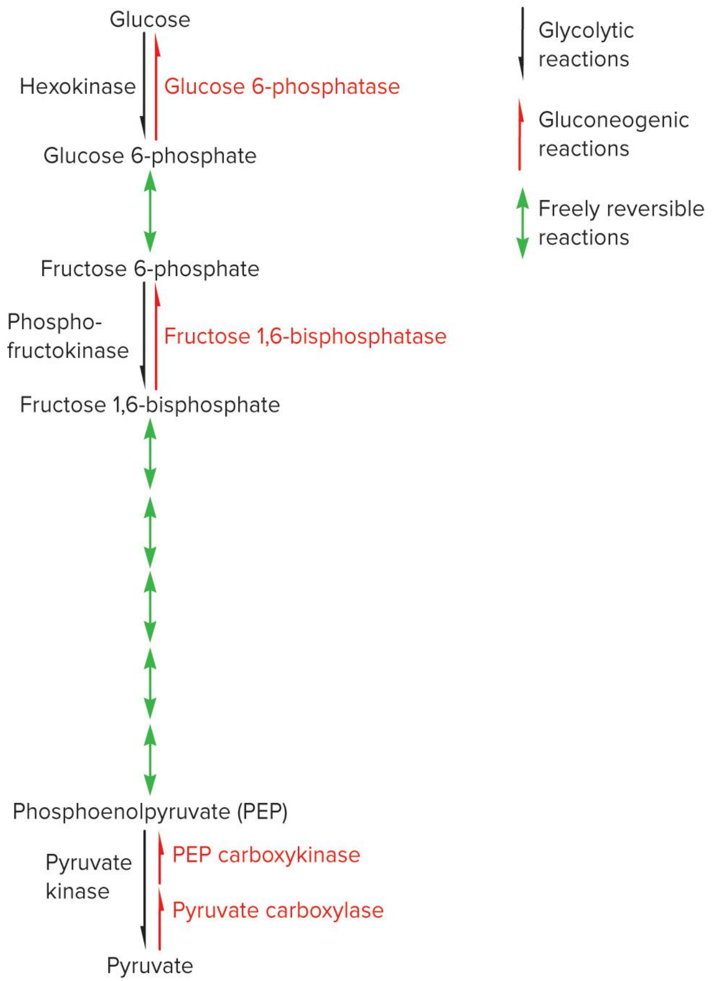
Enzyme catalyzed reactions **whereby the product of one reaction serves as the substrate for the next.**

Pathways also provide materials for biosynthesis.

Amphibolic pathways.

- Function both as catabolic and anabolic pathways.
- For example, Embden–Meyerhof pathway.

The Embden–Meyerhof Pathway



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Aerobic Respiration

Process that can completely catabolize an organic energy source to CO_2 using.

- **Glycolytic pathways (glycolysis).**
- **TCA cycle with oxygen as the final electron acceptor.**

Produces ATP (most of it indirectly via the activity of the **electron transport chain**) and high energy electron carriers.

11.4 Glucose to Pyruvate: The First Step 1

a. List the three major pathways that catabolize glucose to pyruvate.
b. Describe substrate-level phosphorylation.
c. Diagram the major changes made to glucose as it is catabolized by the Embden–Meyerhof, Entner–Doudoroff, and pentose phosphate pathways.
d. Identify those reactions of the Embden–Meyerhof, Entner–Doudoroff, and pentose phosphate pathways that consume ATP, produce ATP and NAD(P)H, generate precursor metabolites, or are redox reactions.

11.4 Glucose to Pyruvate: The First Step 2

e. Calculate the yields of ATP and NAD(P)H by the Embden–Meyerhof, Entner–Doudoroff, and pentose phosphate pathways.

f. Summarize the function of the Embden–Meyerhof, Entner–Doudoroff, and pentose phosphate pathways.

g. Draw a simple diagram that shows the connection between the Entner–Doudoroff pathway and the Embden–Meyerhof pathway and the connection between the pentose phosphate pathway and the Embden–Meyerhof pathway.

h. Create a table that shows which types of organisms use each of the glycolytic pathways.

Breakdown of Glucose to Pyruvate

Three common routes:

- Embden–Meyerhof pathway.
- Entner–Doudoroff pathway.
- Pentose phosphate pathway.

Embden–Meyerhof Pathway

Occurs in cytoplasmic matrix of most microorganisms, plants, and animals.

The most common pathway for glucose degradation to pyruvate in stage two of aerobic respiration.

Function in presence or absence of O_2

Two phases:

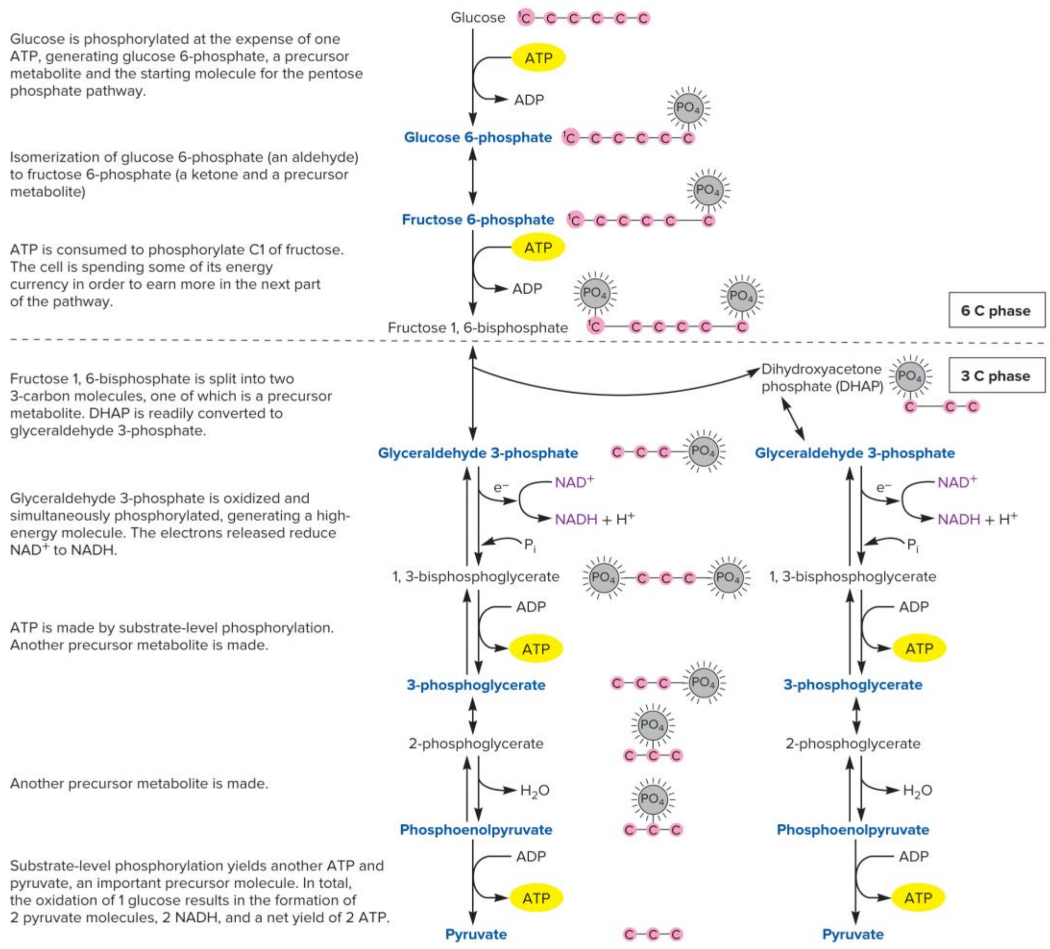
- Six-carbon phase.
- Three-carbon phase.

$$\text{glucose} + 2\text{ADP} + 2\text{P}_i + 2\text{NAD}^+$$
$$\downarrow$$
$$2\text{ pyruvate} + 2\text{ATP} + 2\text{NADH} + 2\text{H}^+$$

Specifics of Embden–Meyerhof Pathway

Addition of phosphates “primes the pump”.

Oxidation step—generates NADH, **high-energy molecules used to synthesize ATP by substrate-level phosphorylation**.



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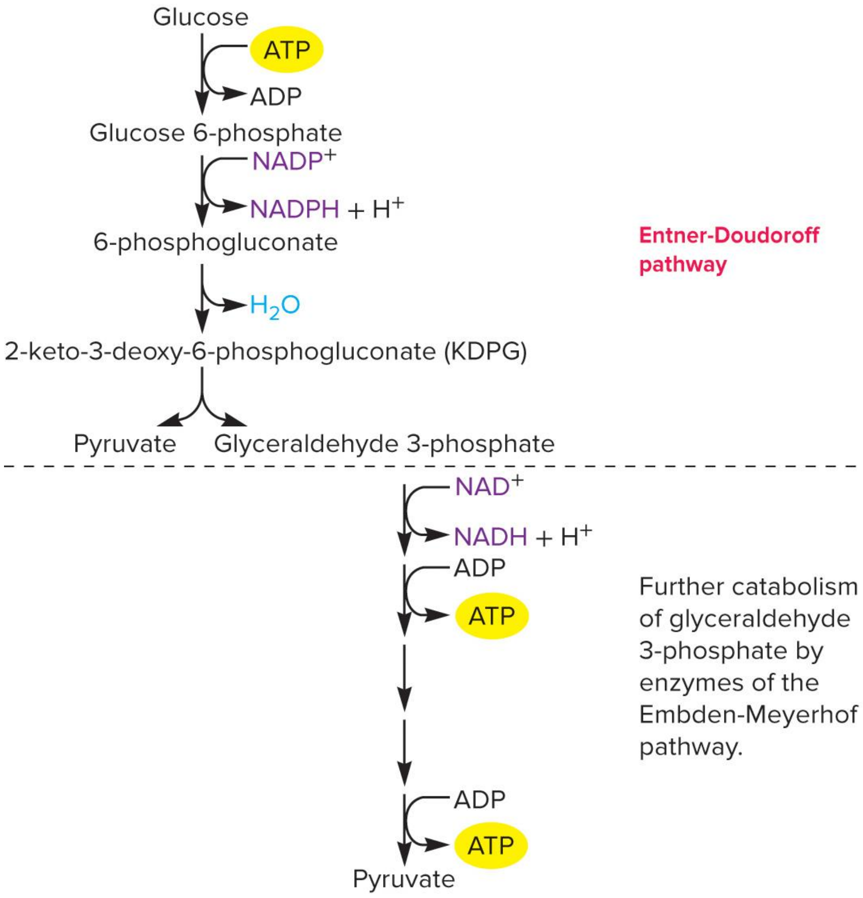
The Entner–Doudoroff Pathway

Used by some Gram-negative bacteria, especially those found in soil.

Replaces the 6-carbon phase of the Embden–Meyerhof pathway.

Yield per glucose molecule:

- 1 ATP.
- 1 NADPH.
- 1 NADH.



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The Pentose Phosphate Pathway

Also called **hexose monophosphate pathway**.

Can operate at same time as glycolytic pathway or Entner–Doudoroff pathway.

Can operate aerobically or anaerobically.

An amphibolic pathway:

$$\text{glucose-6-P} + 12NADP^+ + 7H_2O$$

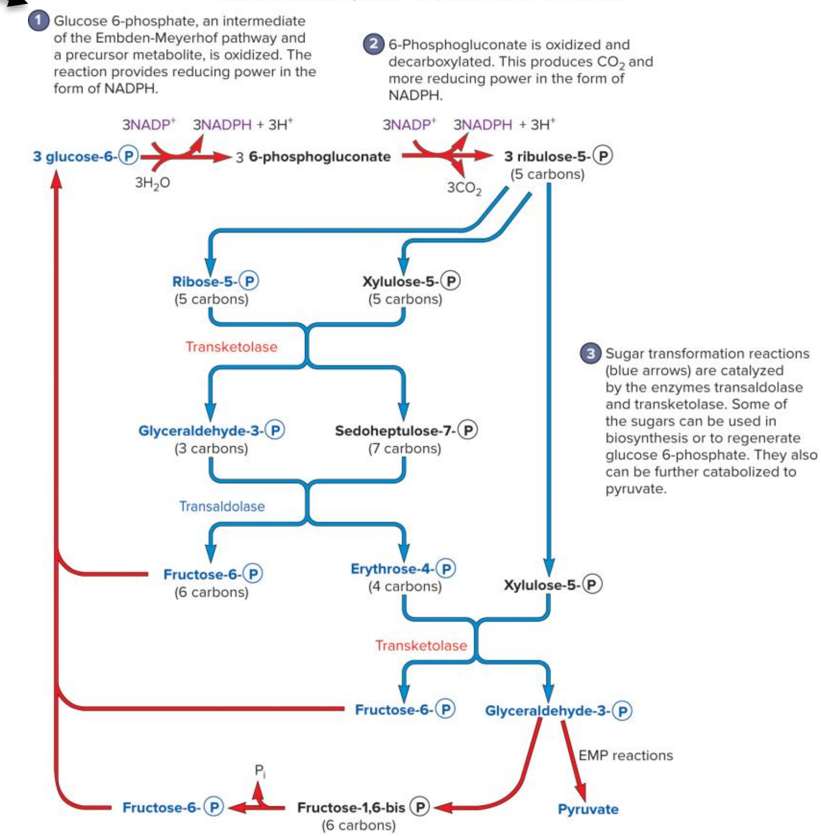
$$\downarrow$$

$$6CO_2 + 12NADPH + 12H^+\ P_i$$

Pentose Phosphate Pathway Specifics

Oxidation steps

Produce NADPH, which is needed for biosynthesis



Sugar trans- formation reactions

Produce sugars needed for biosynthesis

Sugars can also be further degraded

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The Tricarboxylic Acid Cycle

Also called **citric acid cycle and Krebs cycle.**

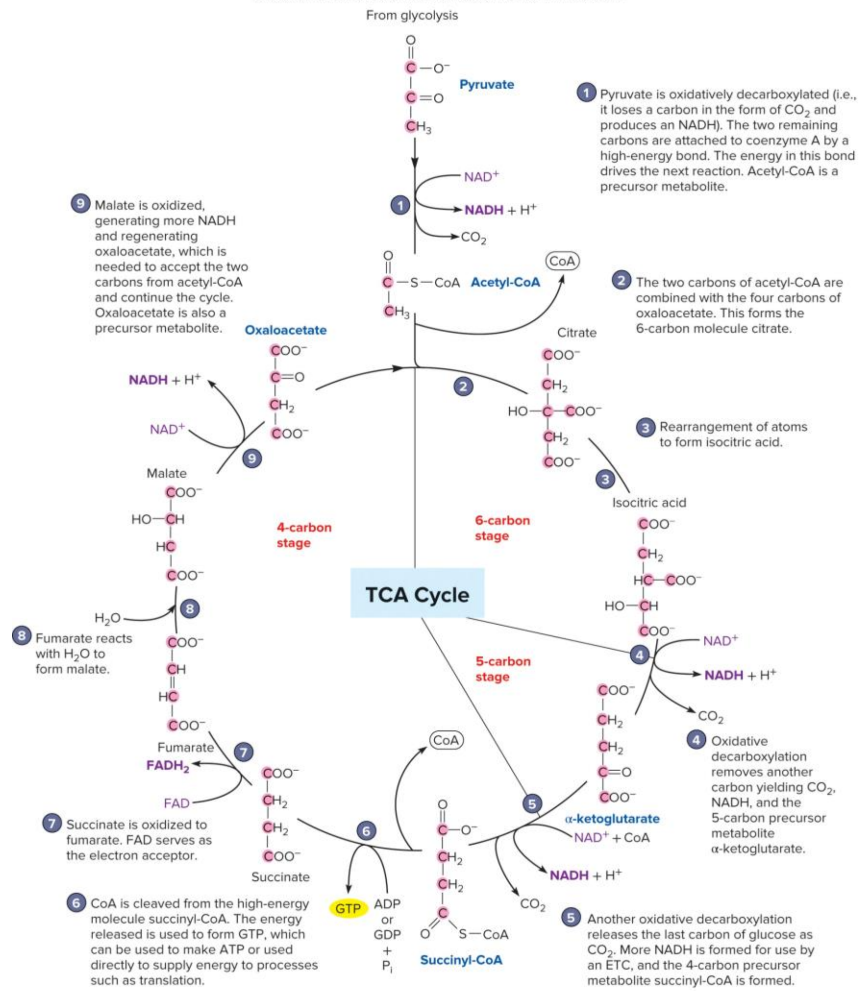
Common in aerobic bacteria, archaea, free-living protists, and fungi.

Major role is as a source of precursor metabolites for use in biosynthesis.

Summary TCA Cycle

For each acetyl-CoA molecule oxidized, TCA cycle. generates:

- 2 molecules of CO_2
- 3 molecules of NADH.
- One $FADH_2$
- One GTP.



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Electron Transport and Oxidative Phosphorylation

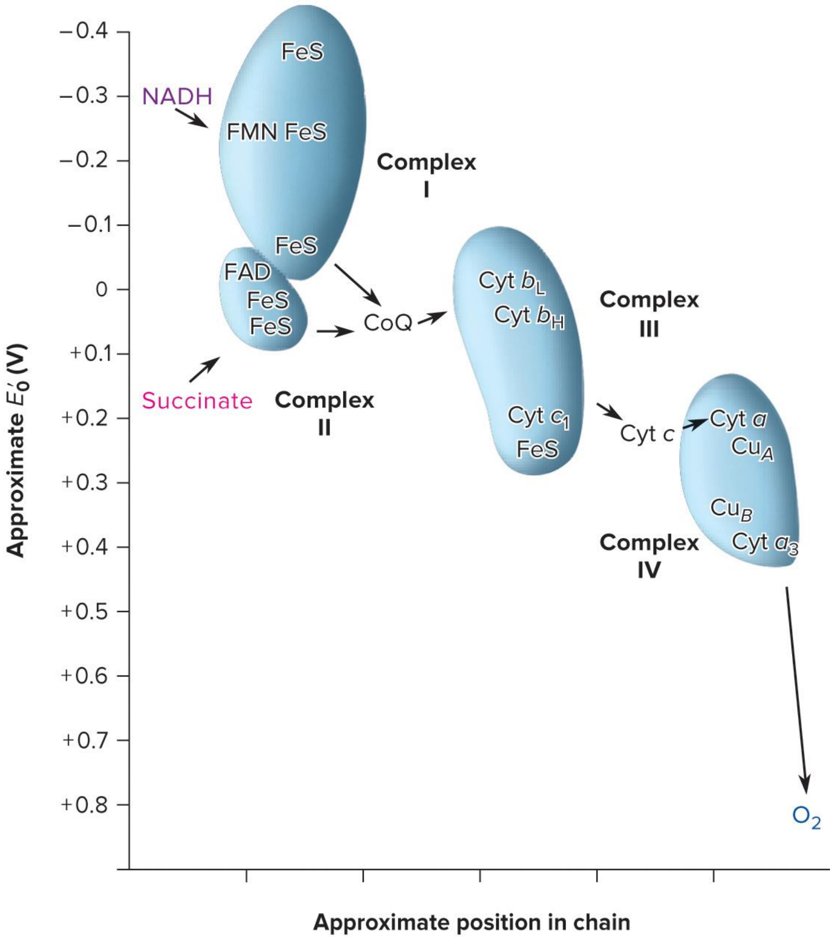
Only 4 ATP molecules synthesized directly from oxidation of glucose to CO_2.

Most ATP made when NADH and $FADH_2$ (formed as glucose degraded) are oxidized in electron transport chain (ETC).

Electron Transport Chains

The mitochondrial electron transport chain **(ETC) = a series of e^- carriers, operating together to transfer e^- from NADH and $FADH_2$ to a terminal e^- acceptor, O_2.**

e^- flow from carriers with more *negative reduction potentials (E_0) to carriers with more positive E_0.*



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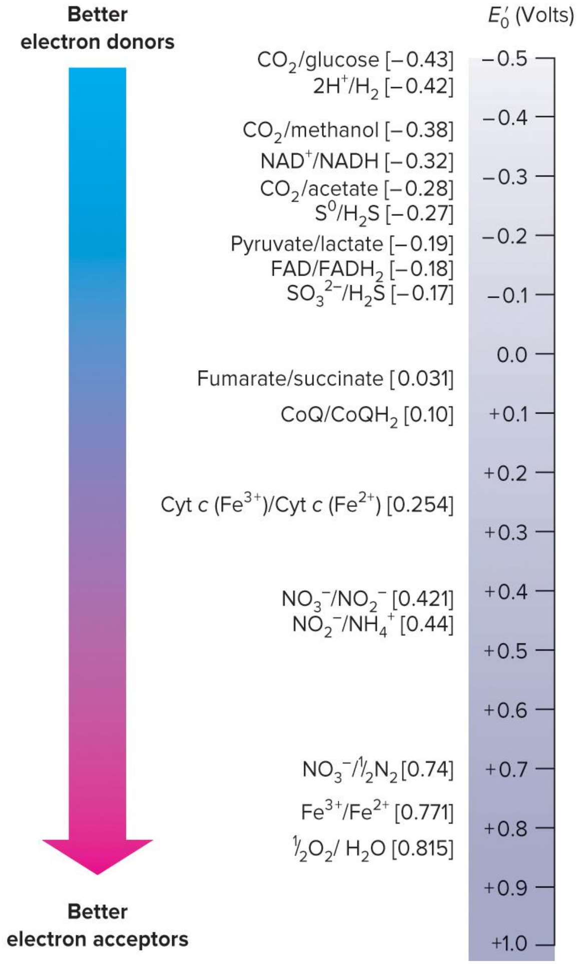
Electron Transport Chain—Redox Pairs

Each carrier is reduced and then reoxidized.

Carriers are constantly recycled.

The difference in reduction potentials electron carriers, NADH and O_2 is large, resulting in release of great deal of energy.



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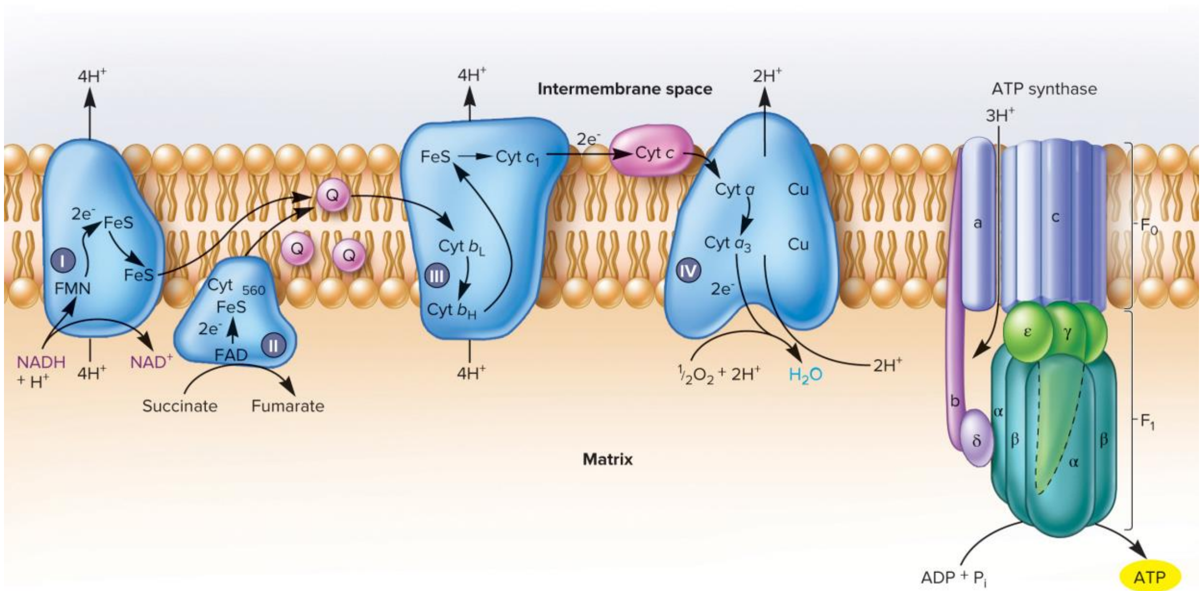
Electron Transport Chain Creates a Proton Gradient

In eukaryotes the e^- transport chain carriers are in the inner mitochondrial membrane, connected by coenzyme Q and cytochrome c.

e^- transfer accompanied by proton movement across inner mitochondrial membrane.



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Bacterial and Archaeal ETCs

Located in plasma membrane.

Some resemble mitochondrial ETC, but many are different:

- Different electron carriers.
- Different terminal oxidases.
- May be branched.
- May be shorter—fewer protons and therefore less energy.

Paracoccus denitrificans [1]

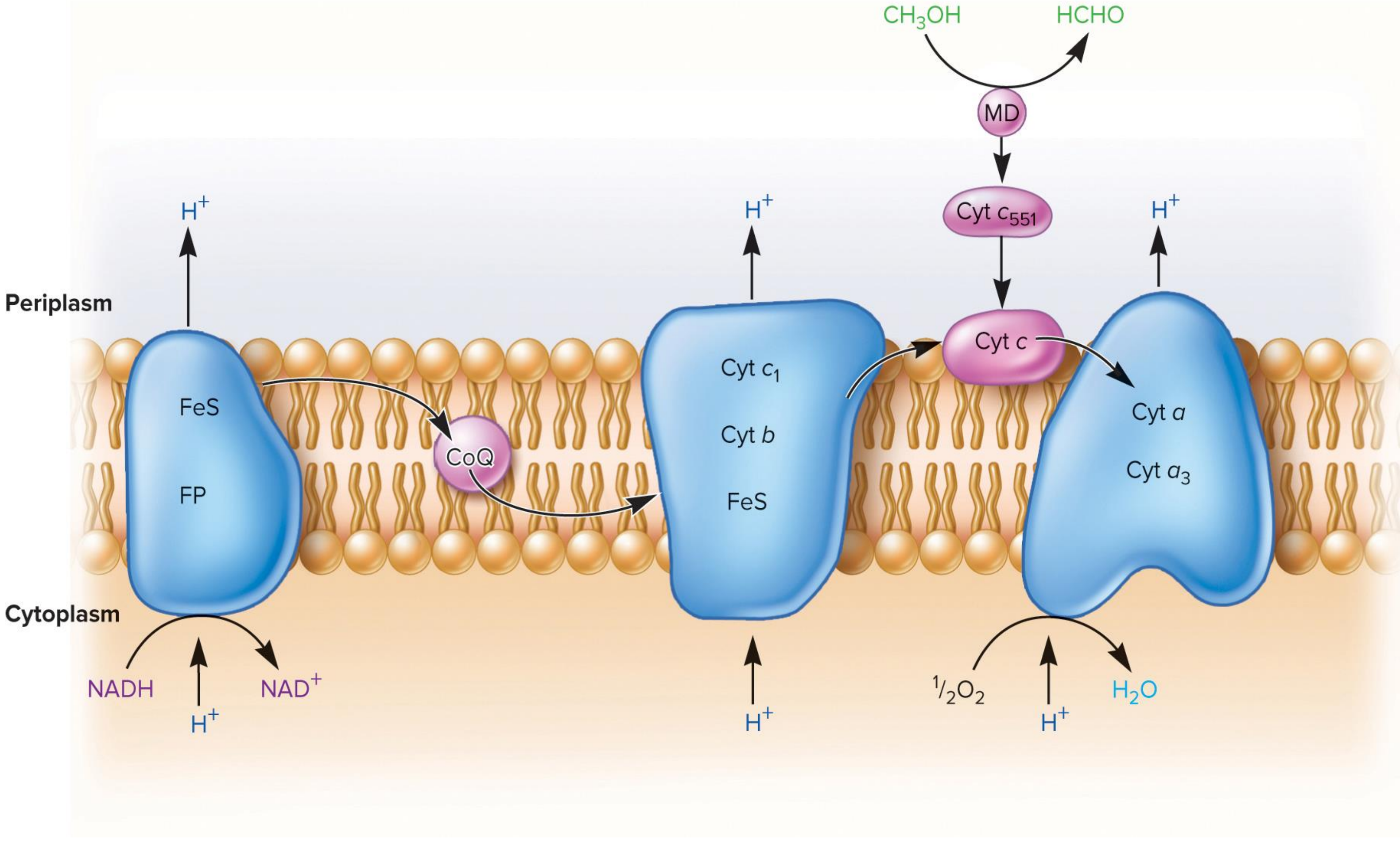
Gram-negative, facultative anaerobe, soil bacterium.

Extremely versatile metabolically.

Under oxic conditions, uses aerobic respiration.

- Similar electron carriers and transport mechanism as mitochondria.
- Protons transported to periplasmic space rather than inner mitochondrial membrane.
- Can use one-carbon molecules instead of glucose as a source of energy and electrons.

Paracoccus denitrificans 2



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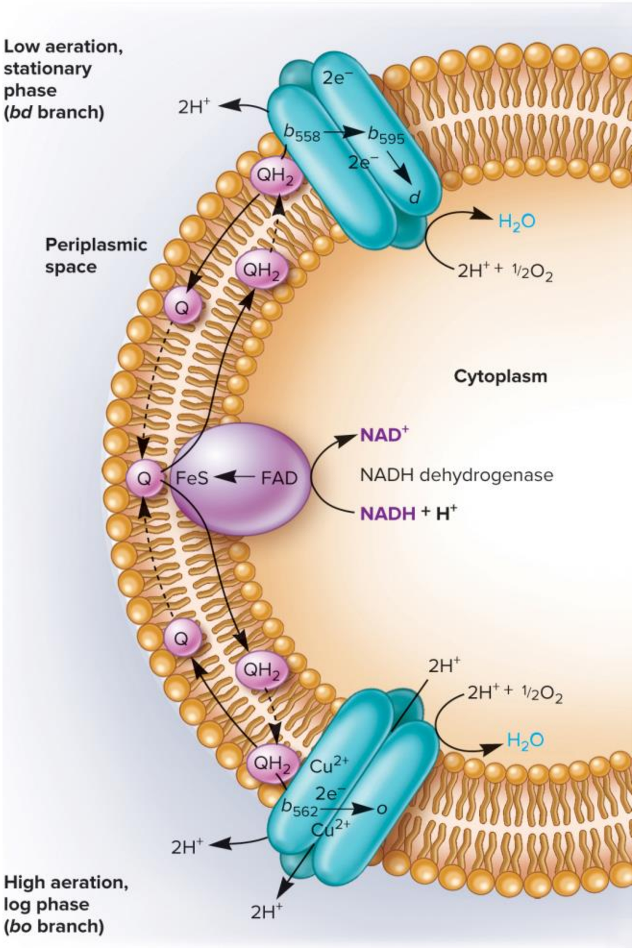
Electron Transport Chain of *E. coli*

Different array of cytochromes used than in mitochondrial



Branched pathway

Upper branch—stationary phase and low aeration

Lower branch—log phase and high aeration

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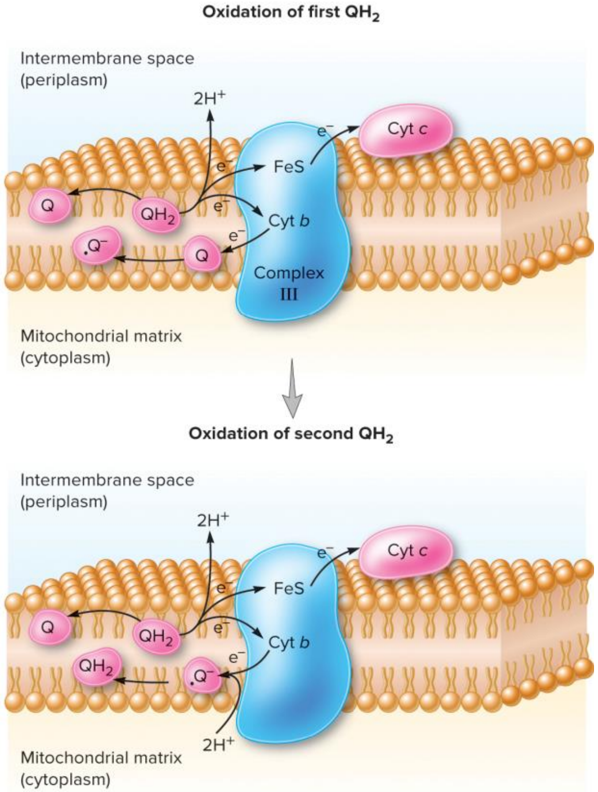
Oxidative Phosphorylation

Process by which ATP is synthesized as the result of electron transport driven by the oxidation of a chemical energy source.



Net reaction:

QH_2 + 2Cyt *c* (oxidized) + $2H^+$ (matrix side)

$\downarrow$

Q + 2Cyt *c* (reduced) + $4H^+$ (intermembrane space side)

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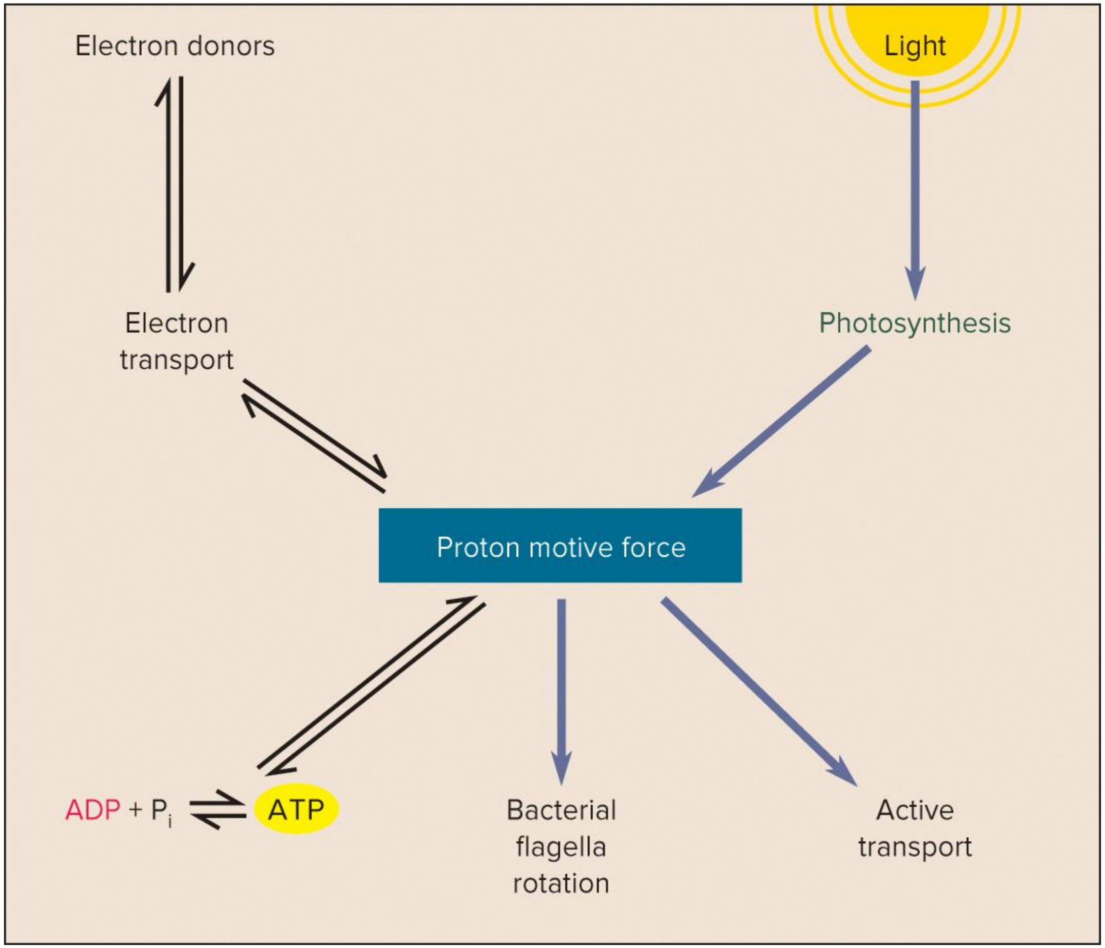
Chemiosmotic Hypothesis

The most widely accepted hypothesis to explain oxidative phosphorylation.

- Protons move outward from the mitochondrial matrix as e^- are transported down the chain.
- Proton expulsion during e^- transport results in the formation of a concentration gradient of protons and a charge gradient.
- **The combined chemical and electrical potential** difference make up the proton motive force **(PMF).**

The Central Role of Proton Motive Force



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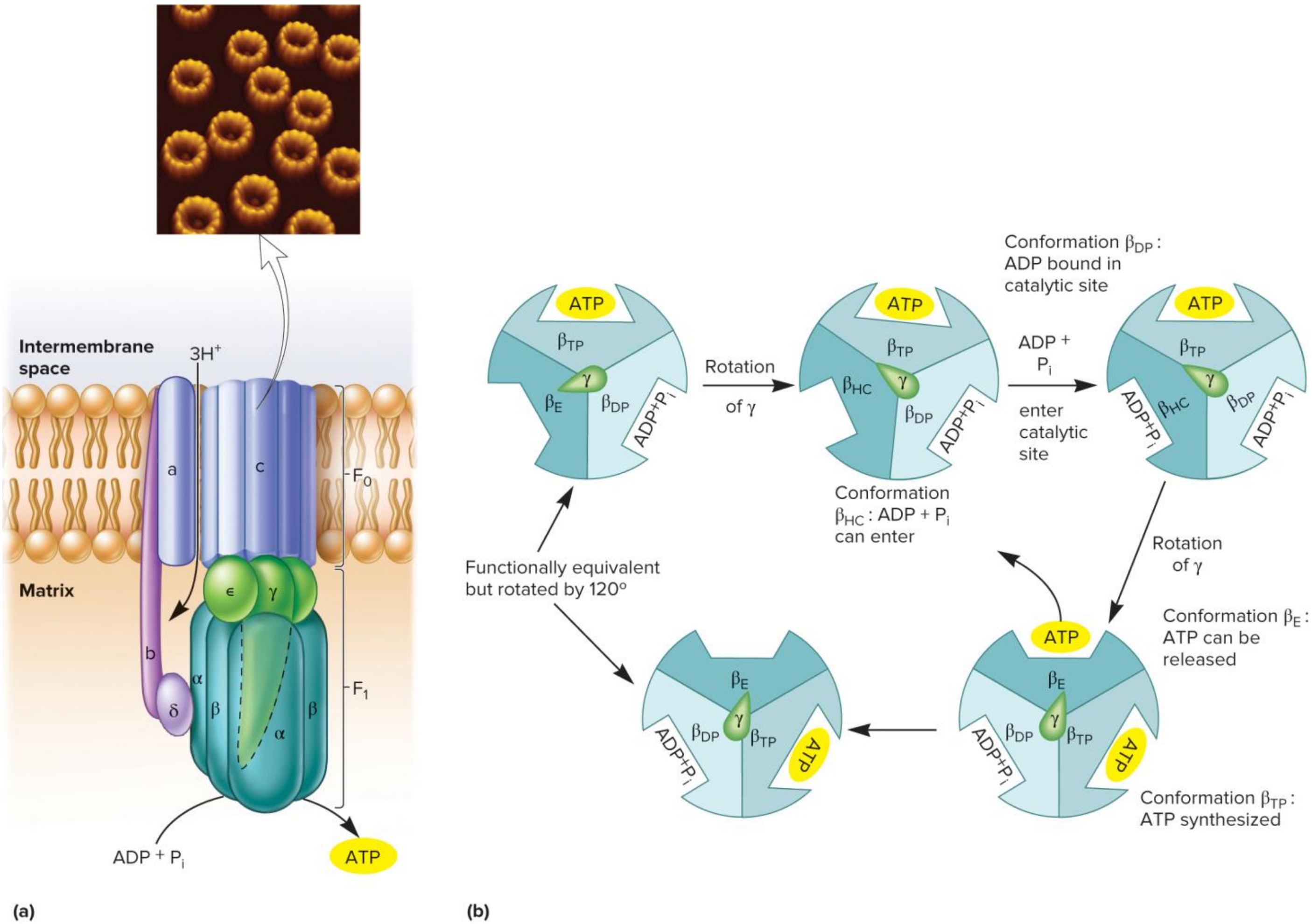
PMF Drives ATP Synthesis

Diffusion of protons back across membrane (down gradient) drives formation of ATP.

ATP synthase.

- Uses PMF down gradient to catalyze ATP synthesis.
- Functions like rotary engine (conformational changes).

ATP Synthase Structure and Function



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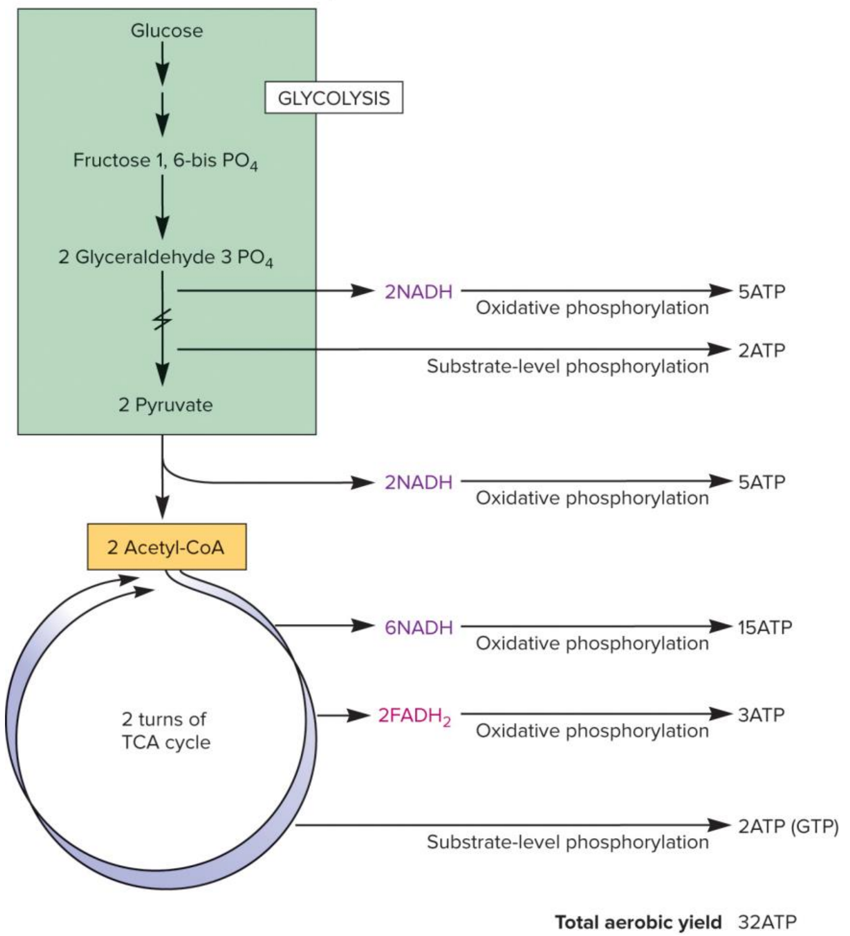
ATP Yield During Aerobic Respiration

Maximum ATP yield can be calculated.

- Includes phosphorus to oxygen (P/O) ratios of NADH and $FADH_2$
- ATP produced by substrate-level phosphorylation.

The maximum total yield of ATP during aerobic respiration by eukaryotes is 32.



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Theoretical vs. Actual Yield of ATP

Amount of ATP produced during aerobic respiration **varies depending on growth conditions and nature of ETC.**

Under anaerobic conditions, glycolysis only yields 2 ATP molecules.

Factors affecting ATP yield.

- Bacterial ETCs are shorter and have lower P/O ratios.
- ATP production may vary with environmental conditions.
- PMF in bacteria and archaea is used for other purposes than ATP production (flagella rotation).
- Precursor metabolite may be used for biosynthesis.

11.7 Anaerobic Respiration Uses the Same Three Steps as Aerobic Respiration

a. Compare and contrast aerobic respiration and anaerobic respiration using glucose as carbon source.

b. List examples of terminal electron acceptors used during anaerobic respiration.

c. Explain why the use of nitrate (NO_3^-) as a terminal electron acceptor is dissimilatory nitrate reduction.

d. Explain why less energy is conserved during anaerobic respiration, as compared to aerobic respiration.

e. Discuss three examples of the importance of anaerobic respiration.

Anaerobic Respiration

Uses electron carriers other than O_2.

Generally yields less energy because E_0 of electron acceptor is less positive than E_0 of O_2.

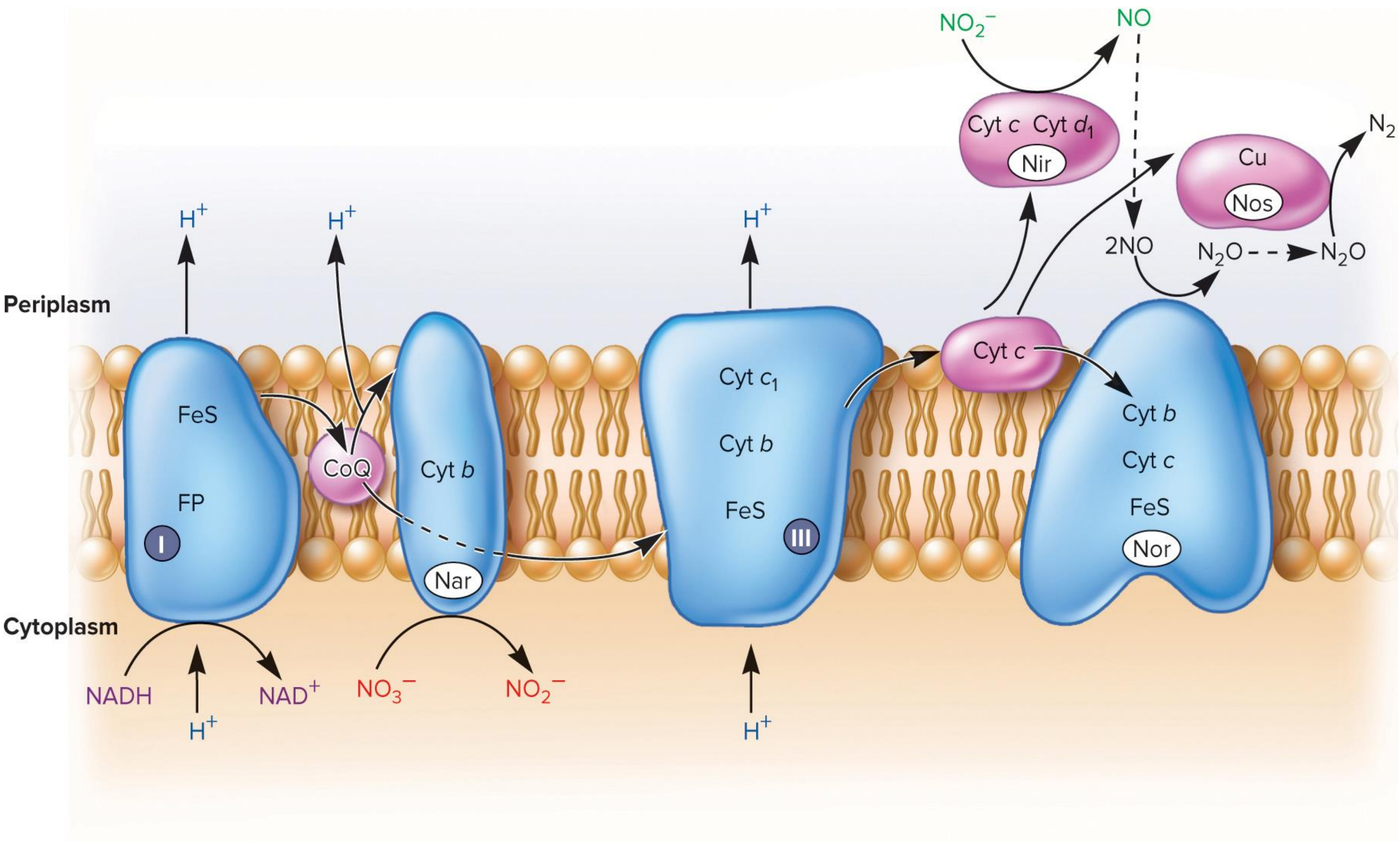
Dissimilatory nitrate reduction.

- Use of nitrate as terminal electron acceptor, making it unavailable to cell for assimilation or uptake.

Denitrification.

- Reduction of nitrate to nitrogen gas.
- In soil, causes loss of soil fertility.

Example of Anaerobic Respiration



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11.8 Fermentation Does Not Involve an Electron Transport Chain

a. Compare and contrast the importance of oxidative phosphorylation and substrate level phosphorylation in aerobic respiration, anaerobic respiration, and fermentation.
b. List the pathways that may function during fermentation if glucose is the organism's carbon and energy source.
c. Create a table that lists some of the common fermentation pathways and their products and examples of their importance.
d. Compare the use of ATP synthase during respiration and fermentation.

Fermentation[2]

Oxidation of NADH produced by glycolysis.

Pyruvate or derivative used as endogenous electron acceptor.

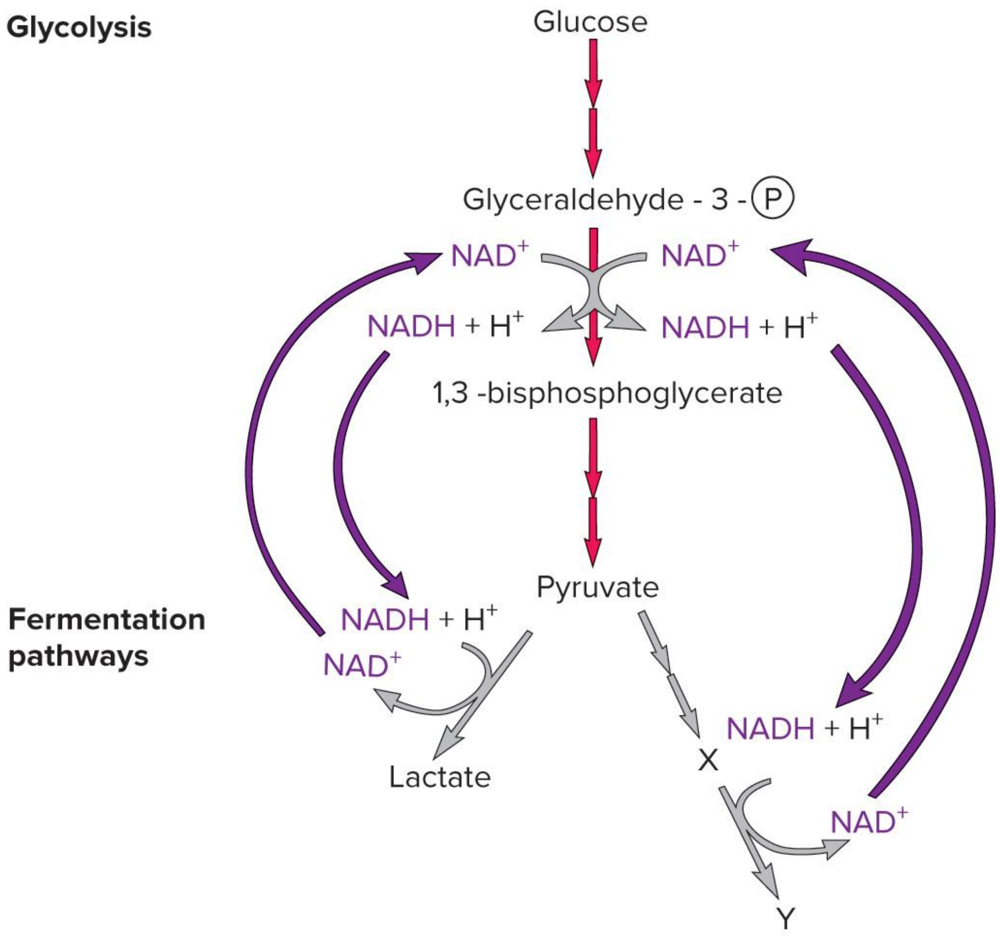
Substrate only partially oxidized.

Oxygen not needed.

Oxidative phosphorylation does not occur.

- **ATP formed by substrate-level phosphorylation.**

Reoxidation of NADH During Fermentation



Common Microbial Fermentations

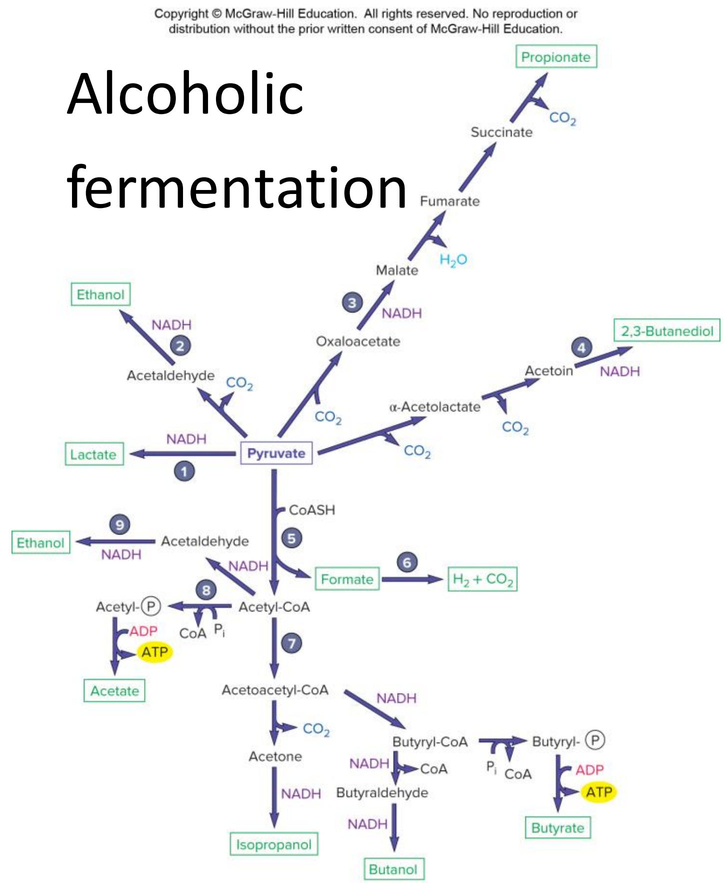
Alcoholic fermentation

Homolactic fermenters

Heterolactic fermenters

Food spoilage

Yogurt, sauerkraut, pickles, etc.



1. Lactic acid bacteria (*Streptococcus, Lactobacillus* species), *Bacillus* spp., enteric bacteria
2. Yeast, *Zymomonas* spp.
3. Propionic acid bacteria (*Propionibacterium* spp.)
4. *Enterobacter, Serratia, Bacillus* species
5. Enteric bacteria
6. Enteric bacteria
7. *Clostridium* spp.
8. Enteric bacteria
9. Enteric bacteria

Alcoholic beverages, bread, etc.

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Fermentation Balance is Affected by Environment

	Fermentation Balance (µM Product/100 µM Glucose)	
	Acid Growth (pH 6.0)	**Alkaline Growth (pH 8.0)**
Ethanol	50	50
Formic acid	2	86
Acetic acid	36	39
Lactic acid	80	70
Succinic acid	11	15
Carbon dioxide	88	2
Hydrogen gas	75	0.5

Catabolism of Other Carbohydrates

Many different carbohydrates can serve as energy source.

Carbohydrates can be supplied externally or internally (from internal reserves).

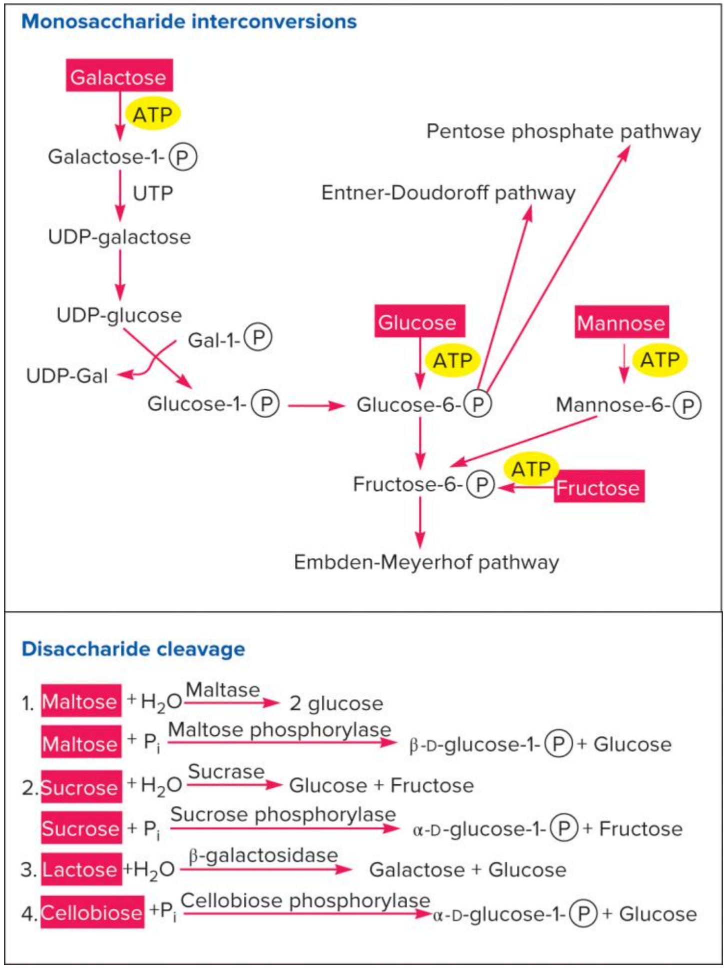
Carbohydrates

Monosaccharides.

- Converted to other sugars that enter glycolytic pathway.

Disaccharides and polysaccharides.

- Cleaved by hydrolases or phosphorylases.



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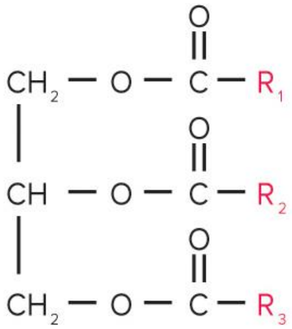
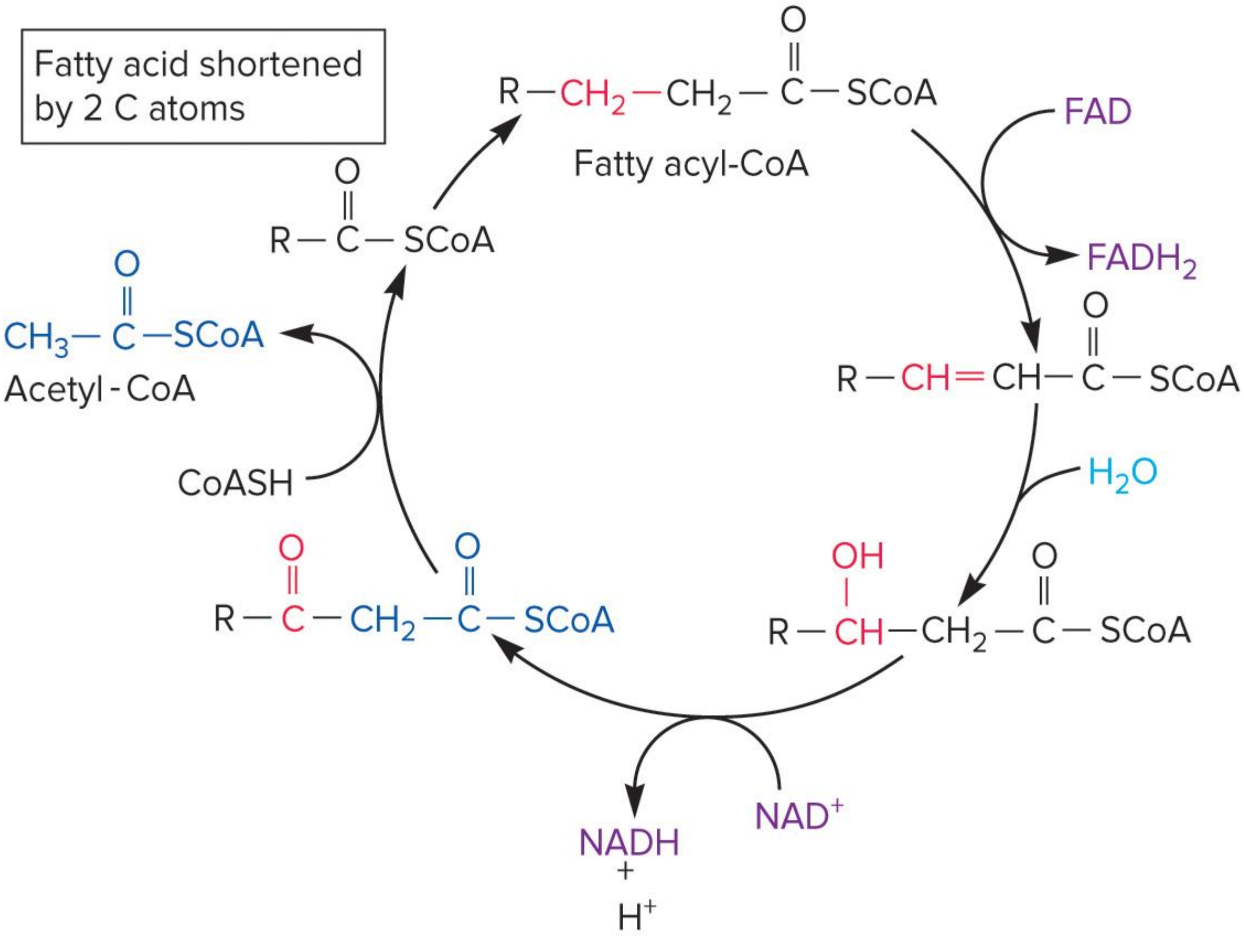
Lipid Catabolism

Triglycerides are common energy sources.

- Hydrolyzed to glycerol and fatty acids by lipases.
- Glycerol degraded via glycolytic pathway.
- Fatty acids often oxidized via β-oxidation pathway.



Fatty Acid β Oxidation



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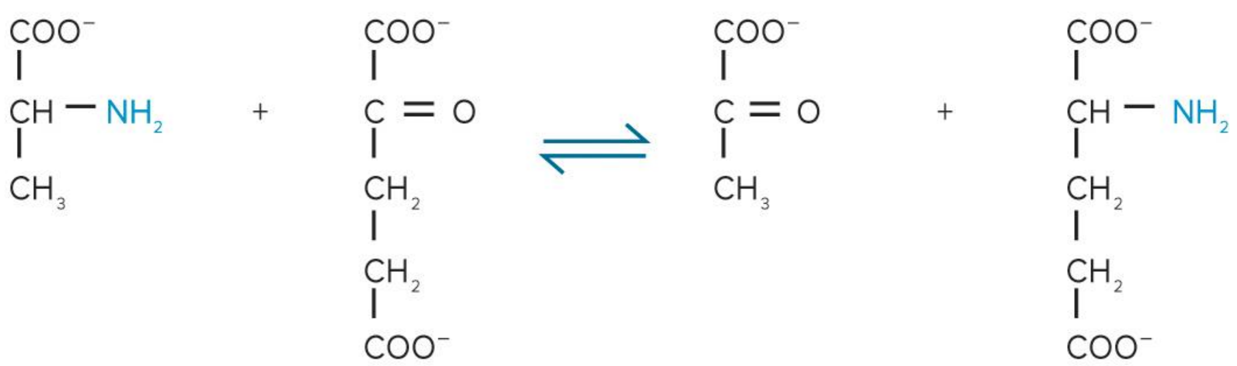
Protein and Amino Acid Catabolism

Protease: hydrolyzes protein to amino acids.

Deamination: removal of amino group from amino acid.

- Resulting organic acids converted to pyruvate, acetyl-CoA, or TCA cycle intermediate.
- Can occur through transamination.



Alanine α-Ketoglutarate Pyruvate Glutamate

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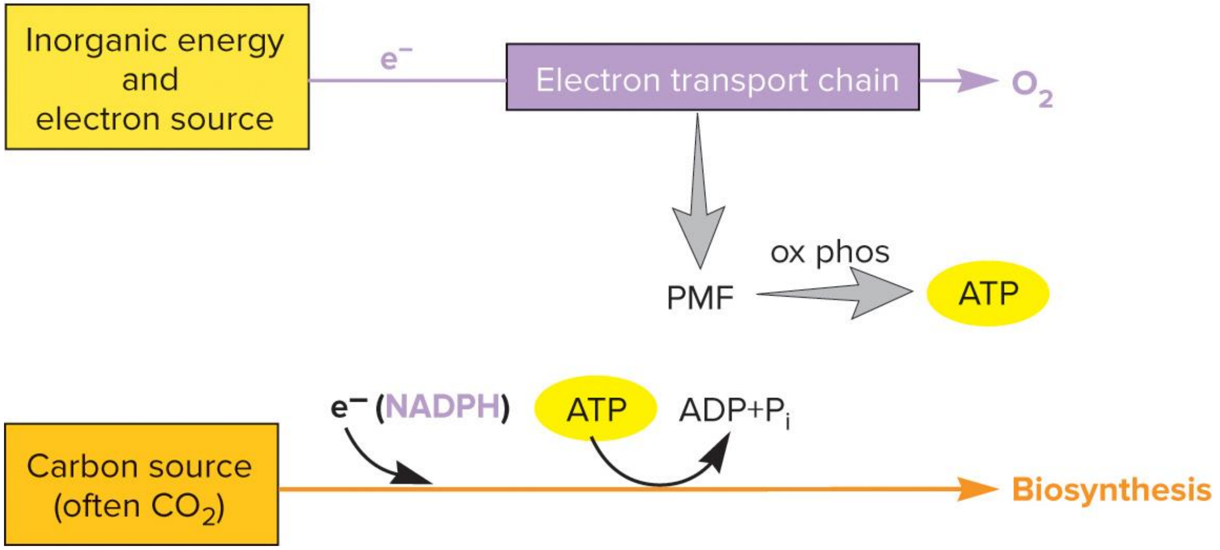
Chemolithotrophy

Carried out by certain bacteria and archaea.

e^- released from inorganic molecule energy source.

- Transferred to terminal e^- acceptor by ETC.

ATP synthesized by ETC and oxidative phosphorylation.



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Energy Sources₂

Bacterial and archaeal species have specific electron donor/acceptor preferences.

Much less energy is available from oxidation of inorganic molecules than glucose due to more positive redox potentials.

Three Major Groups of Chemolithotrophs

Have significant ecological impact.

Several bacteria and archaea oxidize hydrogen.

Nitrifying bacteria oxidize ammonia to nitrate.

Sulfur-oxidizing microbes.

- Hydrogen sulfide (H_2S), sulfur (S^0), thiosulfate ($S_2O_3^{2-}$).

Sulfur-Oxidizing Bacteria

ATP can be synthesized by both oxidative phosphorylation and substrate-level phosphorylation.

(a) Direct oxidation of sulfite

$$SO_3^{2-} \xrightarrow{\text{sulfite oxidase}} SO_4^{2-} + 2e^-$$

(b) Formation of adenosine 5′-phosphosulfate

$$2SO_3^{2-} + 2AMP \longrightarrow 2APS + 4e^-$$

$$2APS + 2P_i \longrightarrow 2ADP + 2SO_4^{2-}$$

$$2ADP \longrightarrow AMP + ATP$$

$$2SO_3^{2-} + AMP + 2P_i \longrightarrow 2SO_4^{2-} + ATP + 4e^-$$

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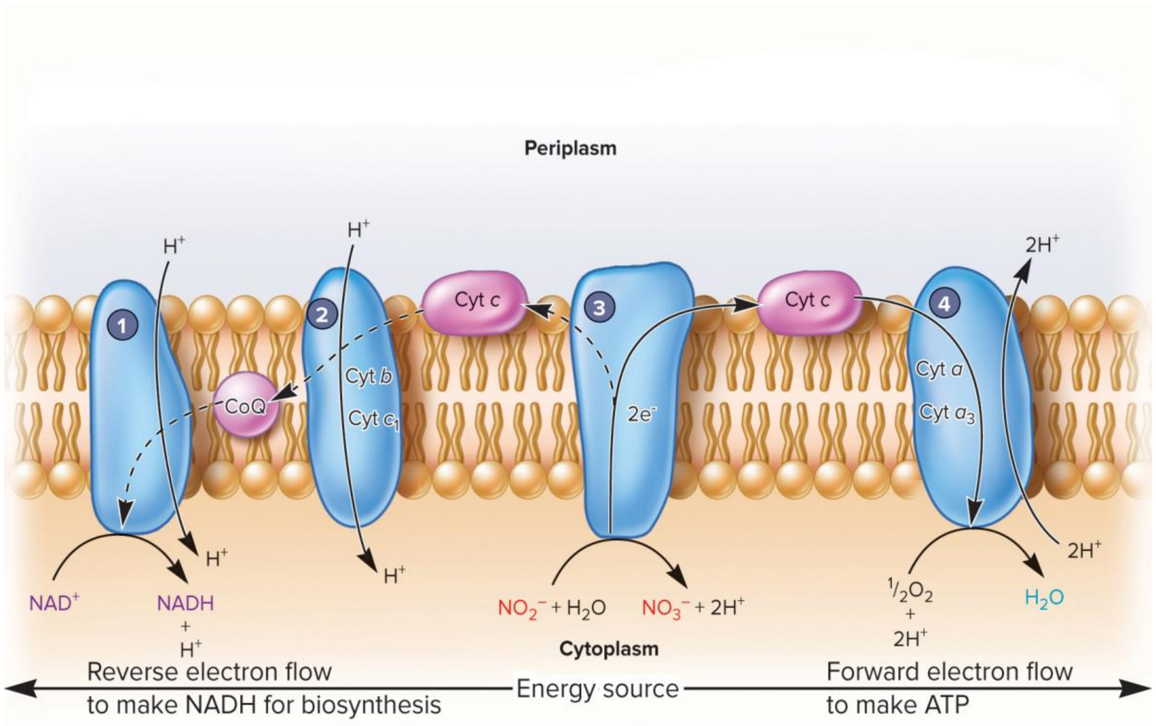
Reverse Electron Flow by Chemolithotrophs [1]

Calvin cycle requires NAD(P)H as e^- source for fixing CO_2.

Many energy sources used by chemolithotrophs have E_0 more positive than $NAD^+(P)/NAD(P)H$.

- Use reverse electron flow to generate NAD(P)H.

Reverse Electron Flow by Chemolithotrophs 2



When a *Nitrobacter* sp. needs to make more NADH, reverse electron flow is used. This is done at the expense of the PMF. Notice that protons are moving from the periplasm to the cytoplasm.

When a *Nitrobacter* sp. needs to synthesize ATP, electrons flow in a forward direction and generate PMF. Notice that protons are being moved across the membrane by the cytochrome aa_3 oxidase.

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Diversity of Phototrophic Microorganisms

Eukaryotes	Multicellular green, brown, and red algae; unicellular protists (For example, euglenoids, dinoflagellates, diatoms)
Bacteria	Cyanobacteria, green sulfur bacteria, green nonsulfur bacteria, purple sulfur bacteria, purple nonsulfur bacteria, heliobacteria, acidobacteria
Archaea	Halophiles

Photosynthesis

Energy from light trapped and converted to chemical energy.

A two-part process.

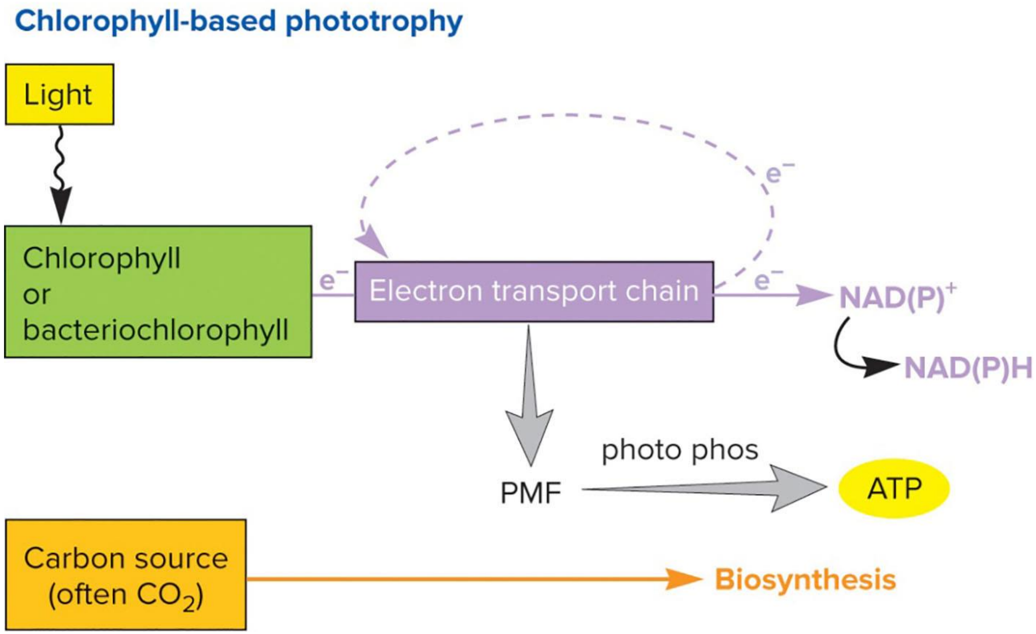
- ***Light reactions:*** light energy is trapped and converted to chemical energy.
- **Dark reactions**: energy produced in the light reactions is used to reduce CO_2 and synthesize cell constituents.

Light Reactions in Oxygenic Photosynthesis

Photosynthetic eukaryotes and cyanobacteria

Oxygen is generated and released into the environment

Most important pigments are chlorophylls



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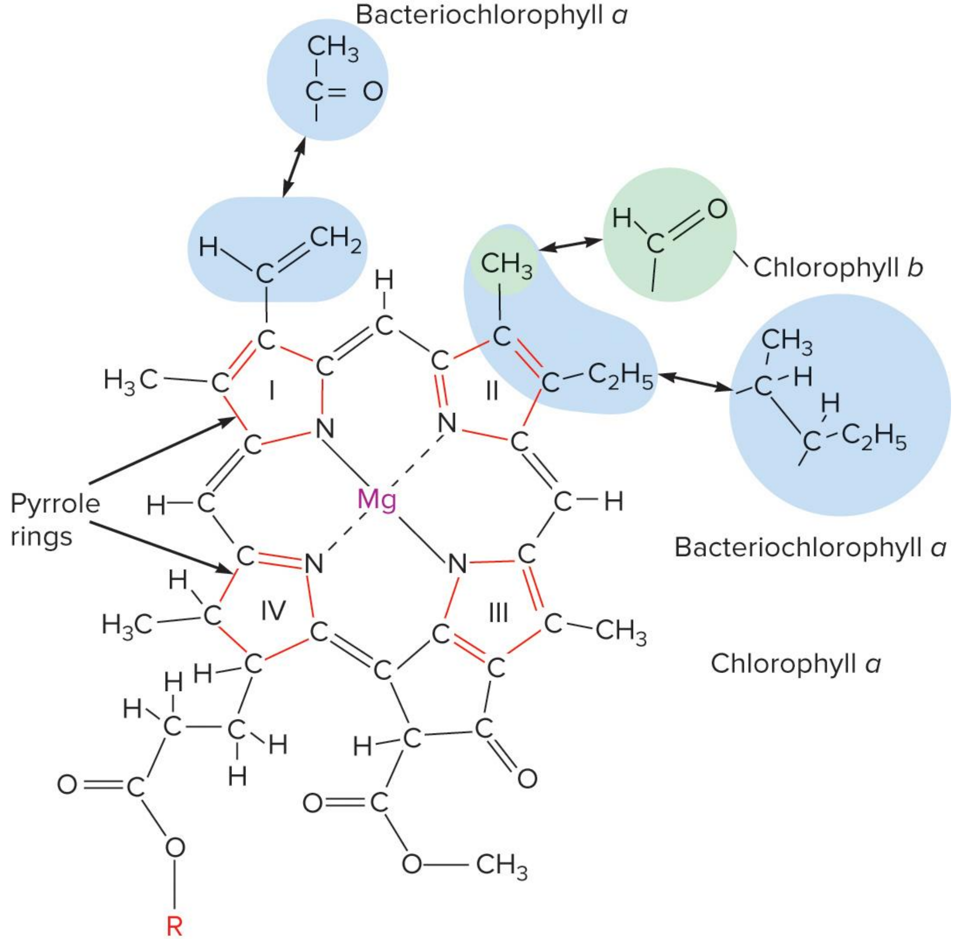
Chlorophyll

Major light-absorbing pigments.

Different chlorophylls have different absorption peaks.



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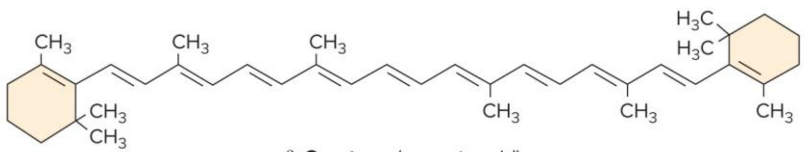
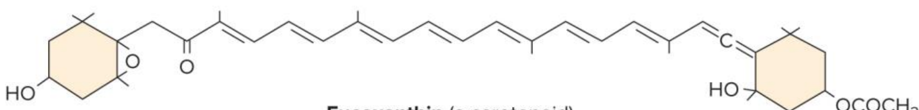
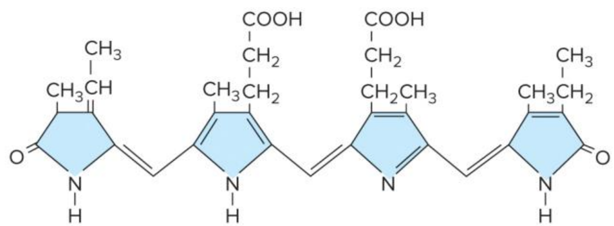
The Light Reaction in Oxygenic Photosynthesis—Accessory Pigments



β-**Carotene** (a carotenoid)



Fucoxanthin (a carotenoid)



Phycocyanobilin

Accessory pigments (For example, carotenoids and phycobiliproteins).

- Transfer light energy to chlorophylls.
- Absorb different wavelengths of light than chlorophylls.

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Organization of Pigments

Antennas.

- Highly organized arrays of chlorophylls and accessory pigments.
- Captured light transferred to special reaction-center chlorophyll.

Photosystems.

- Antenna and its associated reaction-center chlorophyll.

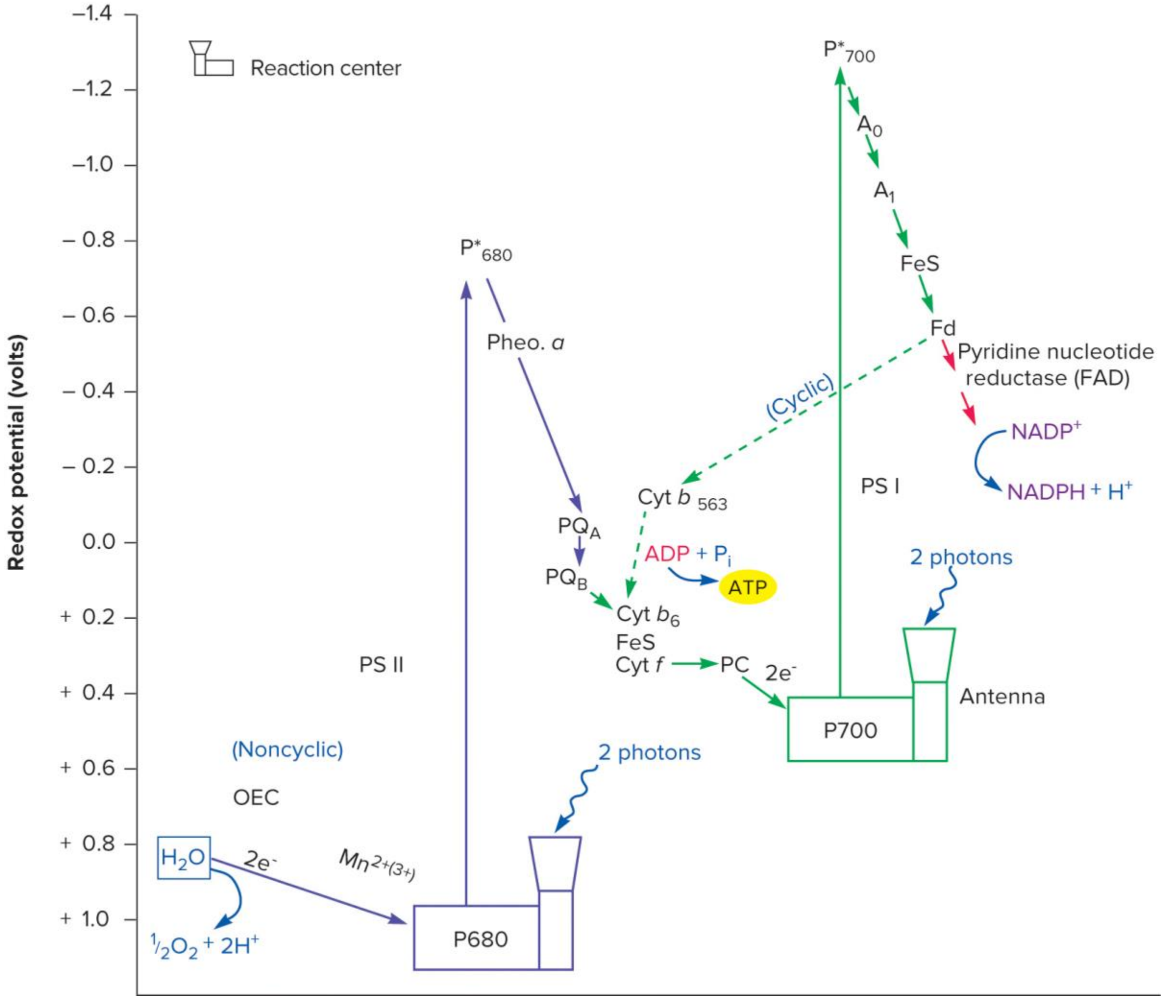
Electron flow $\rightarrow$ PMF $\rightarrow$ ATP.

Oxygenic Photosynthesis 1

Noncyclic electron flow—ATP + NADPH made (noncyclic photophosphorylation).

Cyclic electron flow—ATP made (cyclic photophosphorylation).

Oxygenic Photosynthesis 2



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Light Reaction in Anoxygenic Photosynthesis

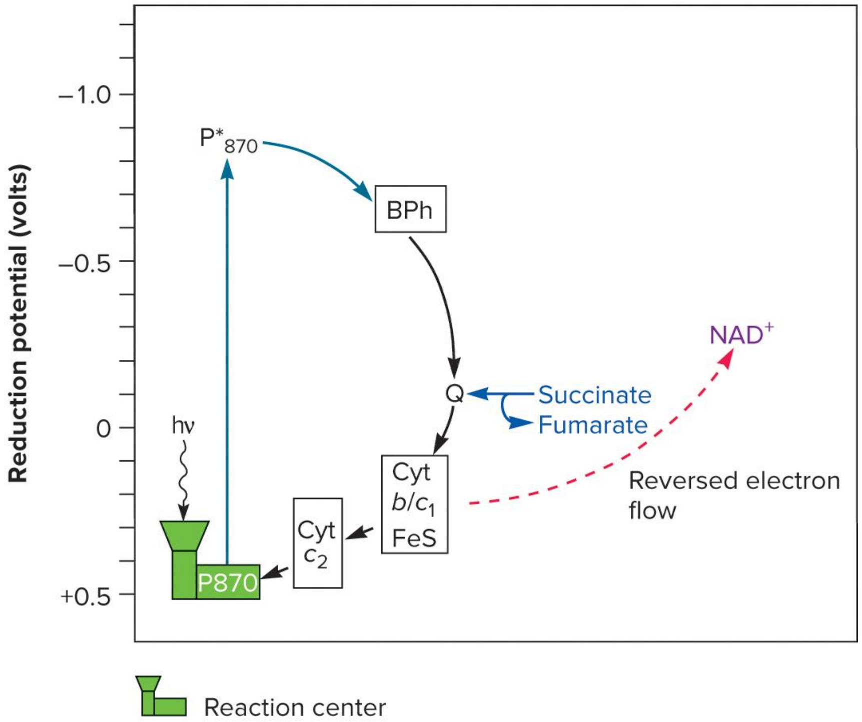
H_2O not used as an electron source; therefore O_2 is not produced.

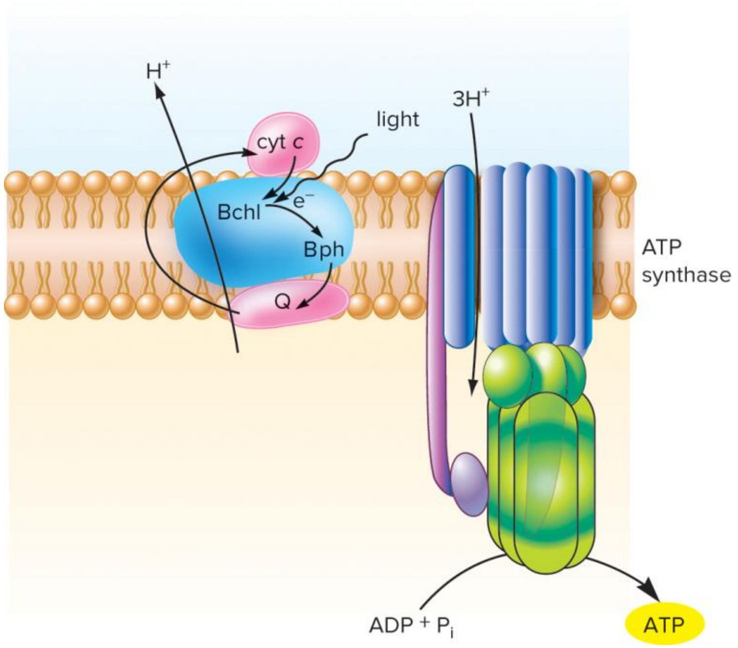
Only one photosystem involved.

Uses bacteriochlorophylls and mechanisms to generate reducing power.

Carried out by phototrophic green bacteria, phototrophic purple bacteria, and heliobacteria.

An Example of Bacterial Anoxygenic Photosynthesis





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Archaerhodopsin-Based Phototrophy 1

Some archaea use a type of phototrophy that involves archaerhodopsin.

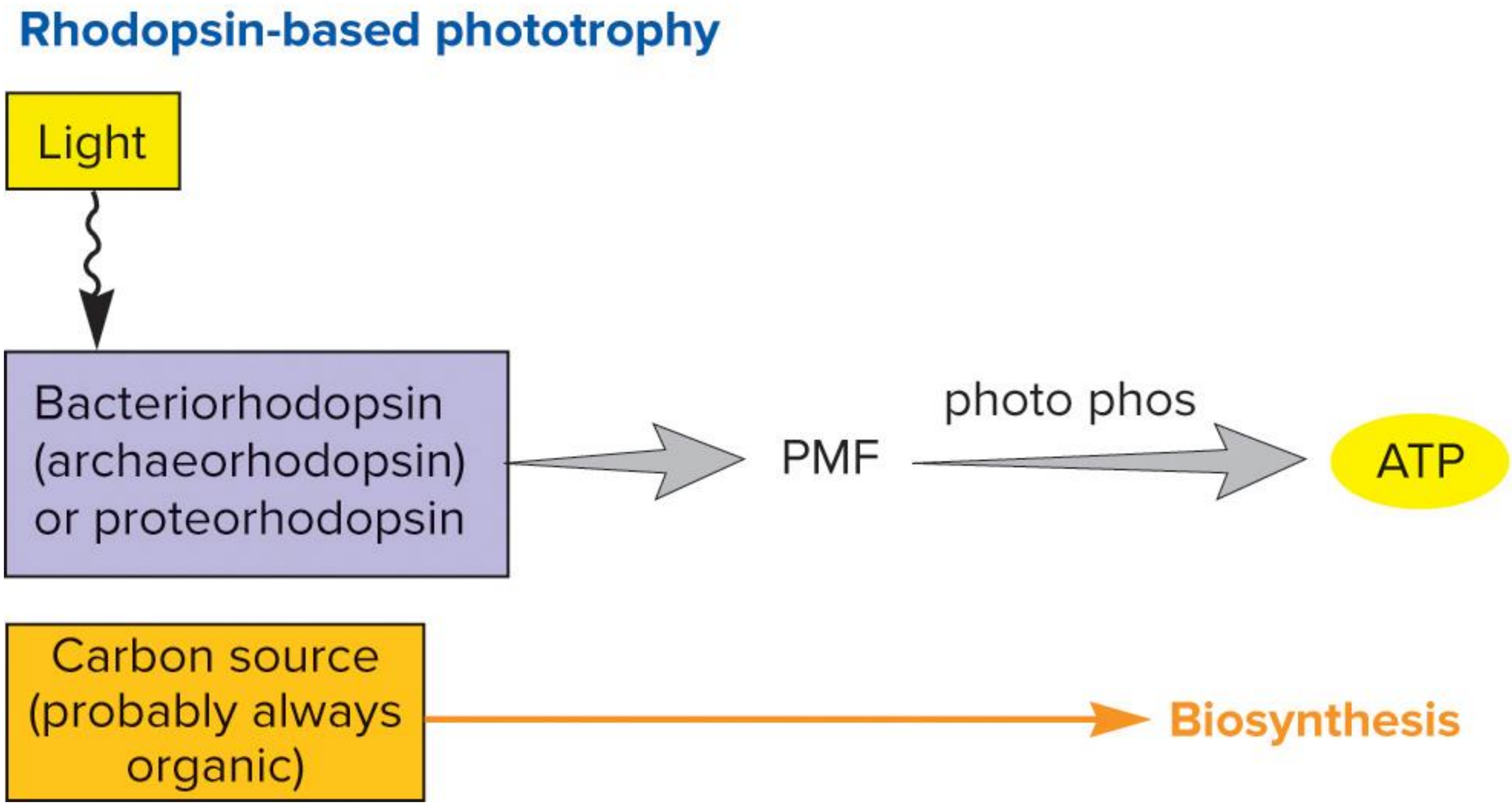
- A membrane protein.
- Functions as a light-driven proton pump.

Similar molecules/methods are found in some bacteria and eukaryotic microbes, as well.

A proton motive force is generated.

An electron transport chain is NOT involved.

Archaerhodopsin-Based Phototrophy 2



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