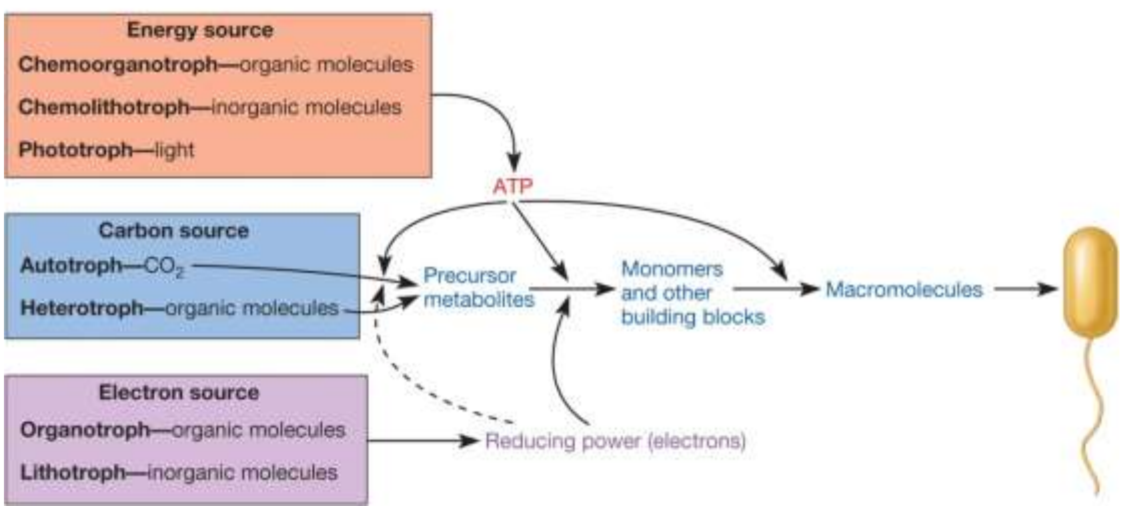
11

Catabolism: Energy Release and Conservation

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



Microorganisms May Change Nutritional Type

- Some have great metabolic flexibility based on environmental requirements
- Provides distinct advantage if environmental conditions change frequently

Chemoorganotrophic Fueling Processes

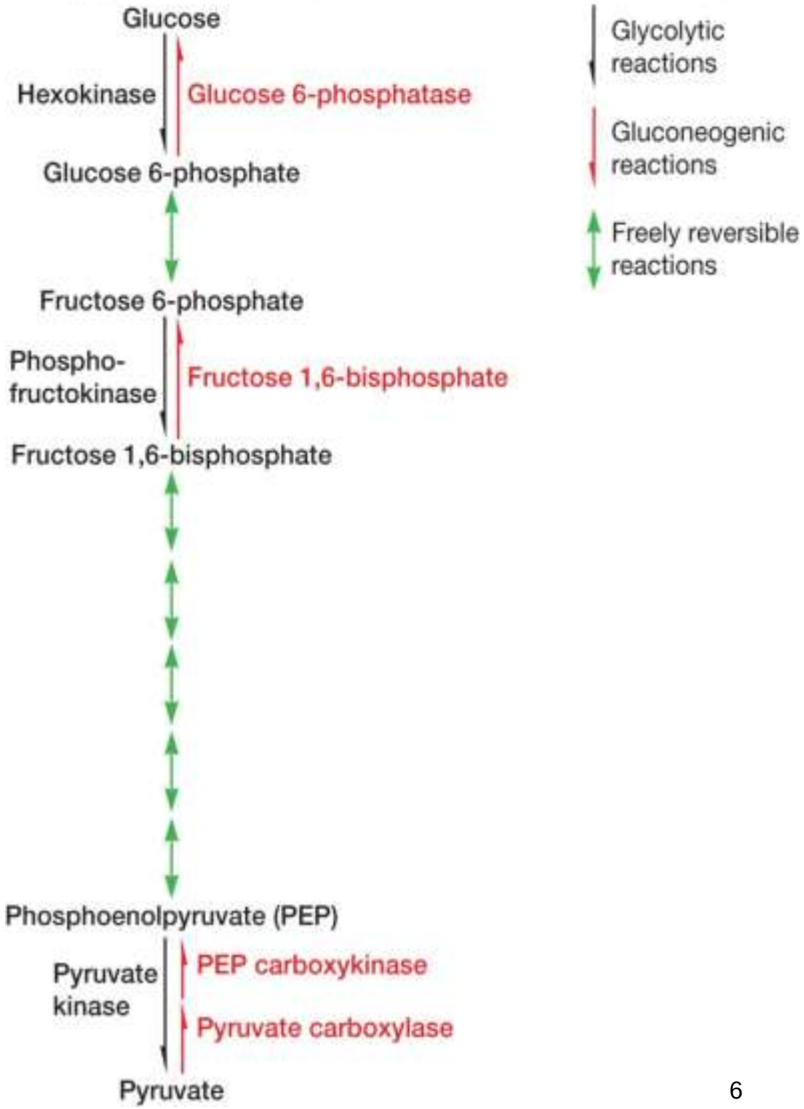
- Also called chemoheterotrophs
- Processes
  - aerobic respiration
  - anaerobic respiration
  - fermentation

Catabolic(الهدم) Pathways

- Enzyme catalyzed reactions whereby(بواسطة) the product of one reaction serves as the substrate for the next
- Pathways also provide materials for biosynthesis
- Amphibolic pathways

Amphibolic Pathways

- Function both as catabolic and anabolic pathways
- Important ones
  - Embden-Meyerhof pathway
  - pentose phosphate pathway
  - tricarboxylic acid (TCA) cycle



Aerobic Respiration

- Process that can completely catabolize an organic energy source to CO_2 using
  - glycolytic pathways (glycolysis)
  - TCA cycle
  - electron transport chain 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

The Breakdown of Glucose to Pyruvate

- Three common routes
  - – Embden-Meyerhof pathway
  - – pentose phosphate pathway
  - – Entner-Duodoroff pathway

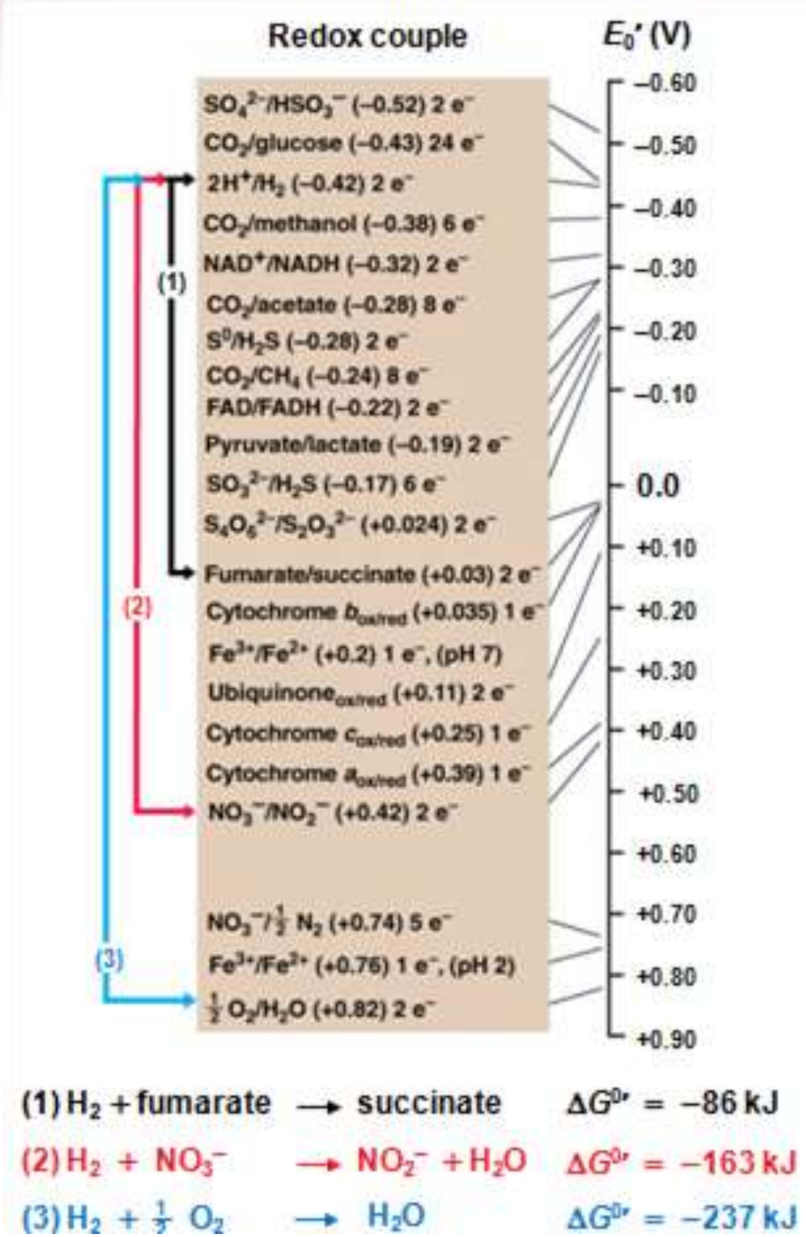
The Embden-Meyerhof Pathway

- 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

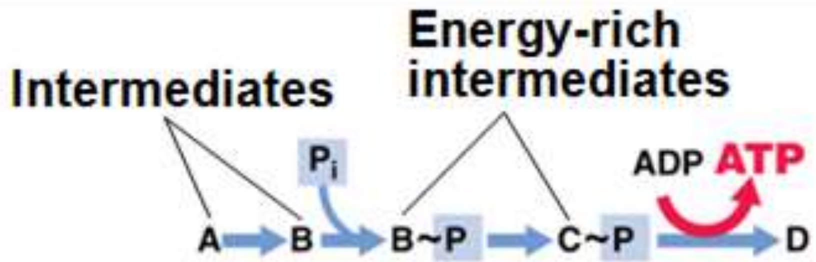
Oxidation-Reduction Reactions

- **Oxidation-reduction reactions (redox)-** Reactions in which electrons move from an electron donor to an electron acceptor
- As an electron moves from the donor to the acceptor, the donor become less energy rich and the acceptor becomes more energy rich
- Acceptor + ne^- donor
- Standard equilibrium potential (E0)- It is the measure of the tendency of the donor to lose electrons

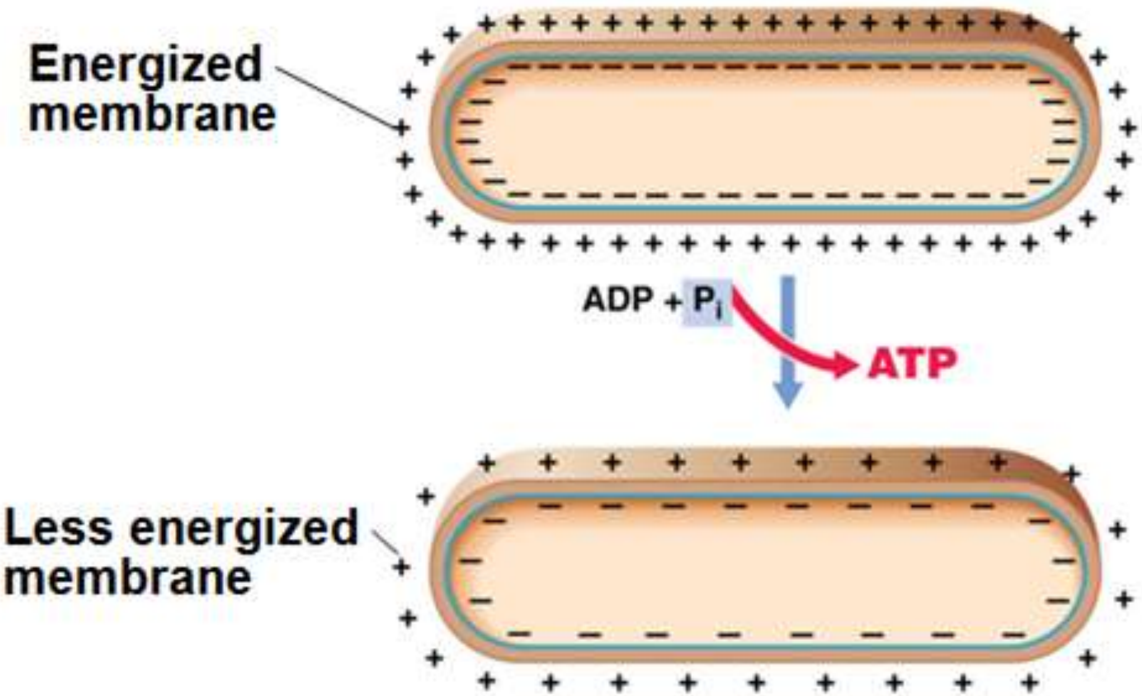
The reduction oxidation couples



Energy conservation in fermentation and respiration



(a) Substrate-level phosphorylation

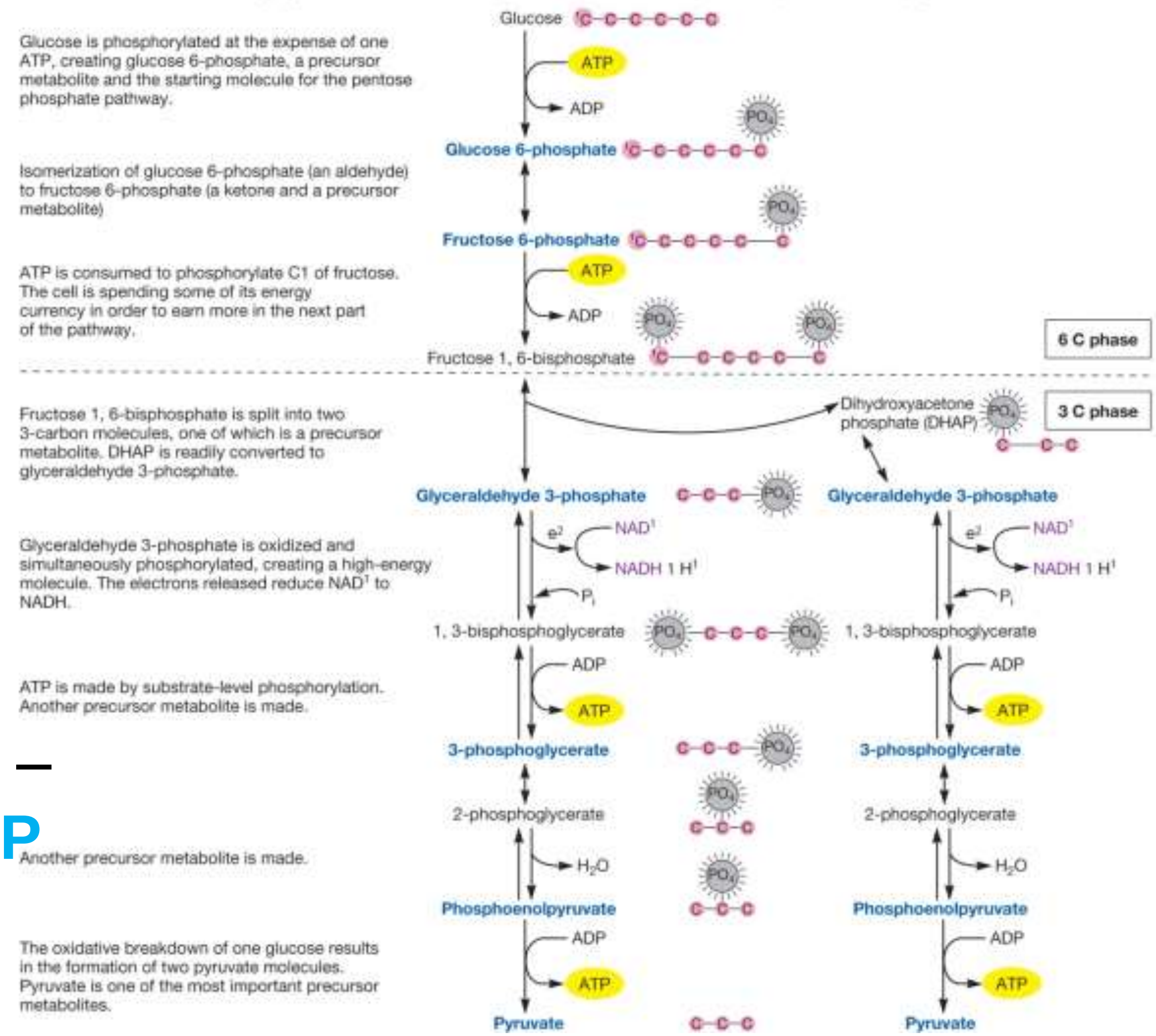


(b) Oxidative phosphorylation

Addition of phosphates “primes the pump”

Oxidation step – generates NADH

High-energy molecules – used to **synthesize ATP by substrate-level phosphorylation**



Summary of Glycolysis

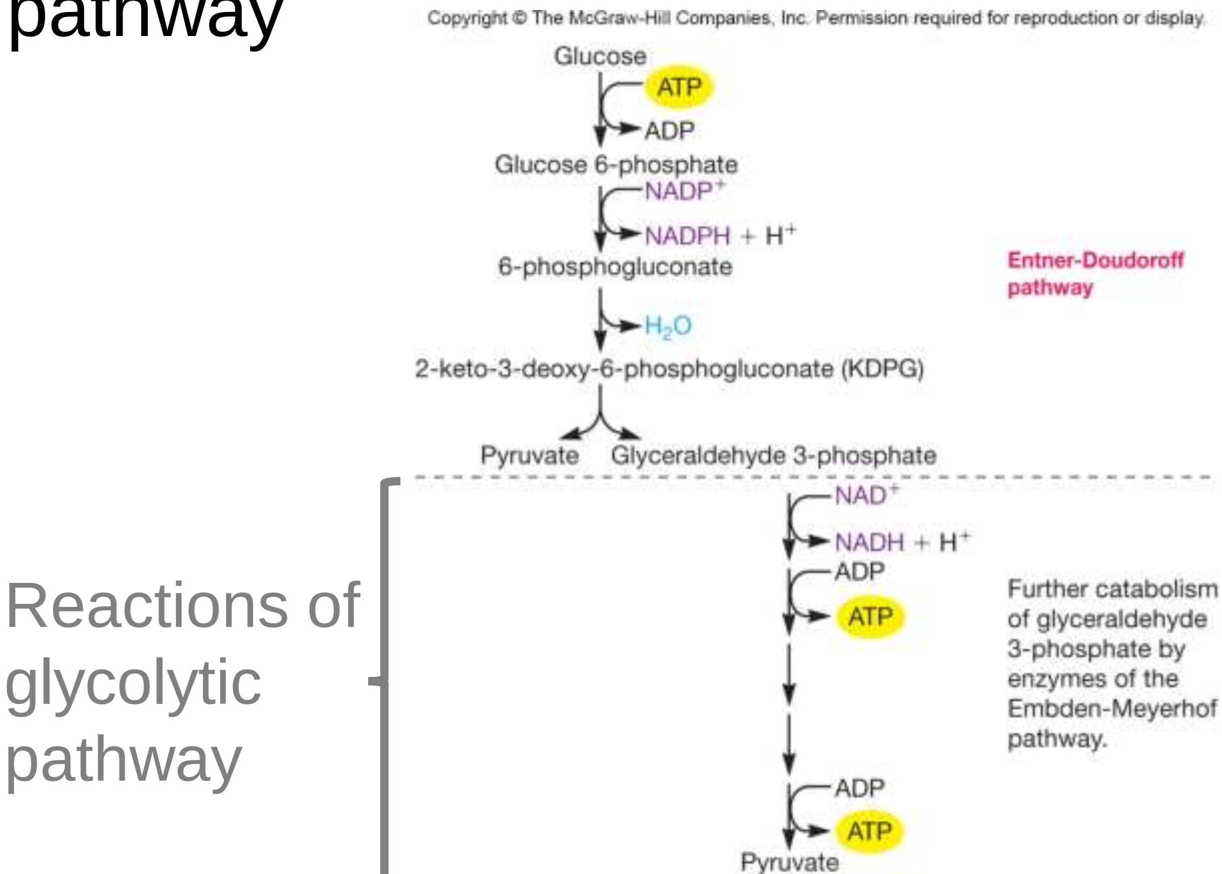
$$\text{glucose} + 2\text{ADP} + 2\text{P}_i + 2\text{NAD}^+$$

$$\downarrow$$

$$2\ \text{pyruvate} + 2\text{ATP} + 2\text{NADH} + 2\text{H}^+$$

The Entner-Duodoroff Pathway

- Used by soil bacteria and a few gram-negative bacteria
- Replaces the first phase of the Embden-Meyerhof pathway



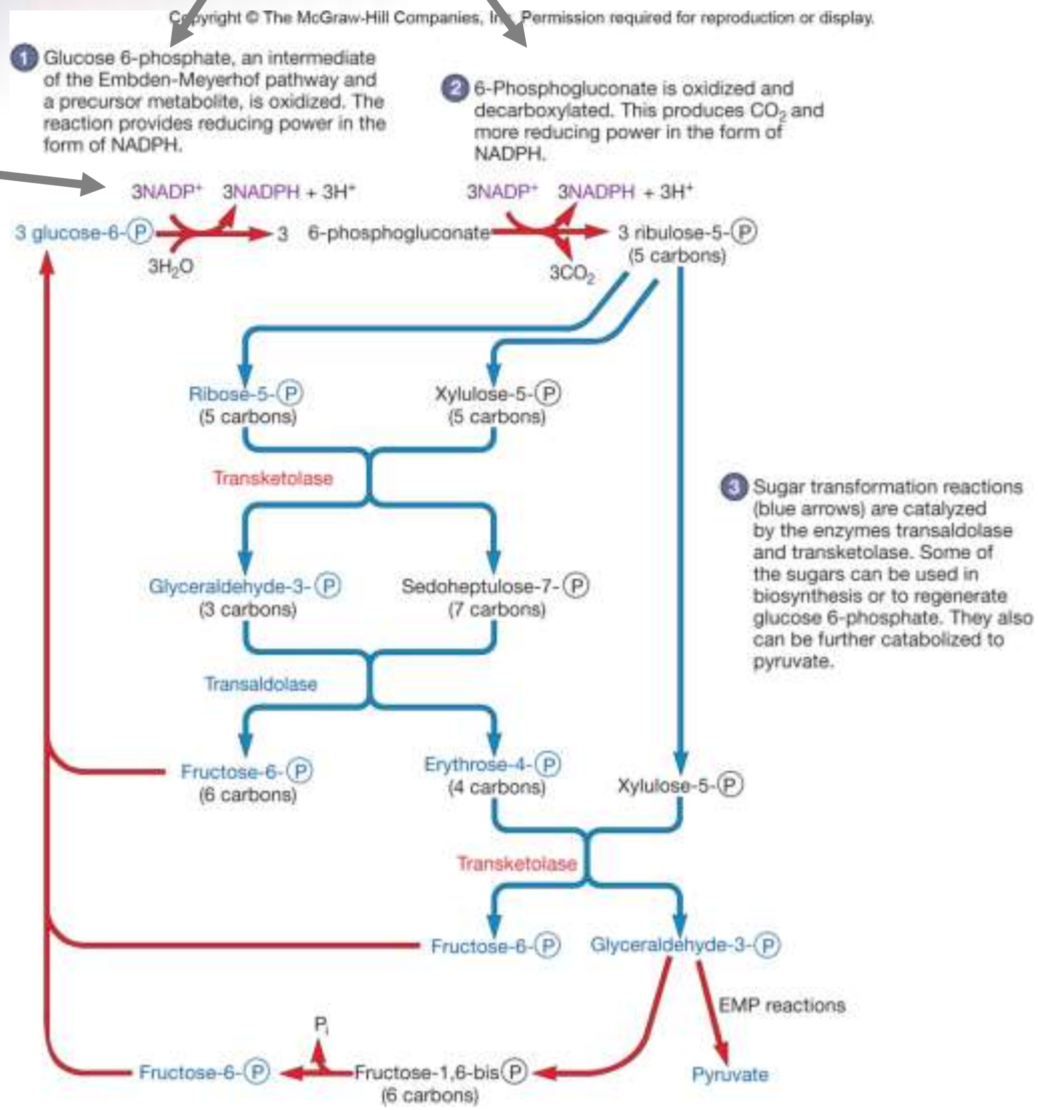
- Yield per glucose molecule:
  - 1 ATP
  - 1 NADPH
  - 1 NADH

The Pentose Phosphate Pathway

- Also called hexose monophosphate pathway
- Can operate at same time as glycolytic pathway or Entner-Duodoroff pathway
- Can operate aerobically or anaerobically
- An amphibolic pathway

Oxidation steps

Produce NADPH, which is needed for biosynthesis



Sugar trans-formation reactions

Produce sugars needed for biosynthesis

Sugars can also be further degraded

Summary of Pentose Phosphate Pathway

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

$$\downarrow$$

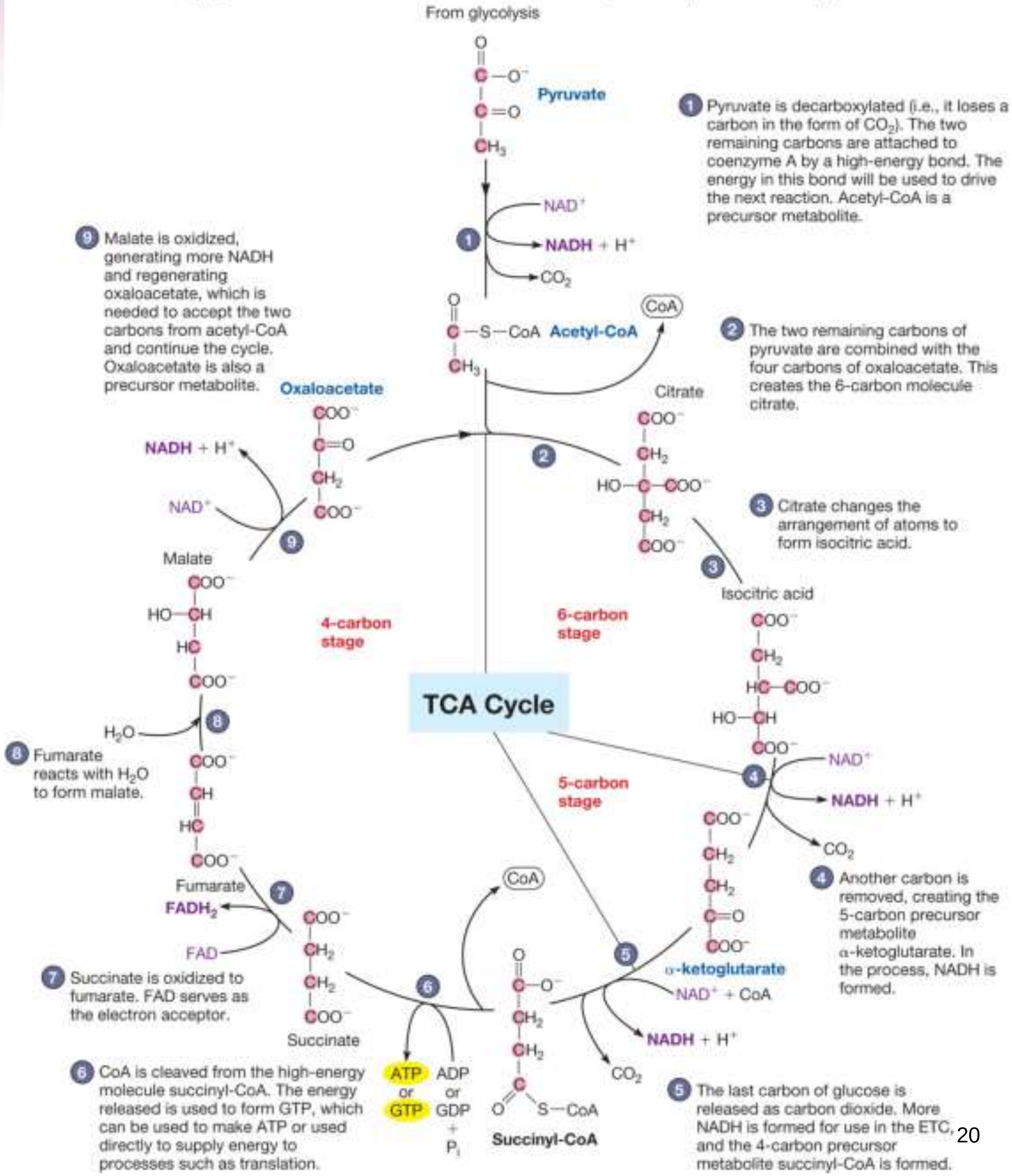
$$6CO_2 + 12NADPH + 12H^+ \; P_i$$

The Tricarboxylic Acid Cycle

- Also called citric acid cycle and Kreb's cycle
- Common in **aerobic bacteria, free-living protozoa, most algae, and fungi**
- Major role is as a source of carbon skeletons 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



Electron Transport and Oxidative Phosphorylation

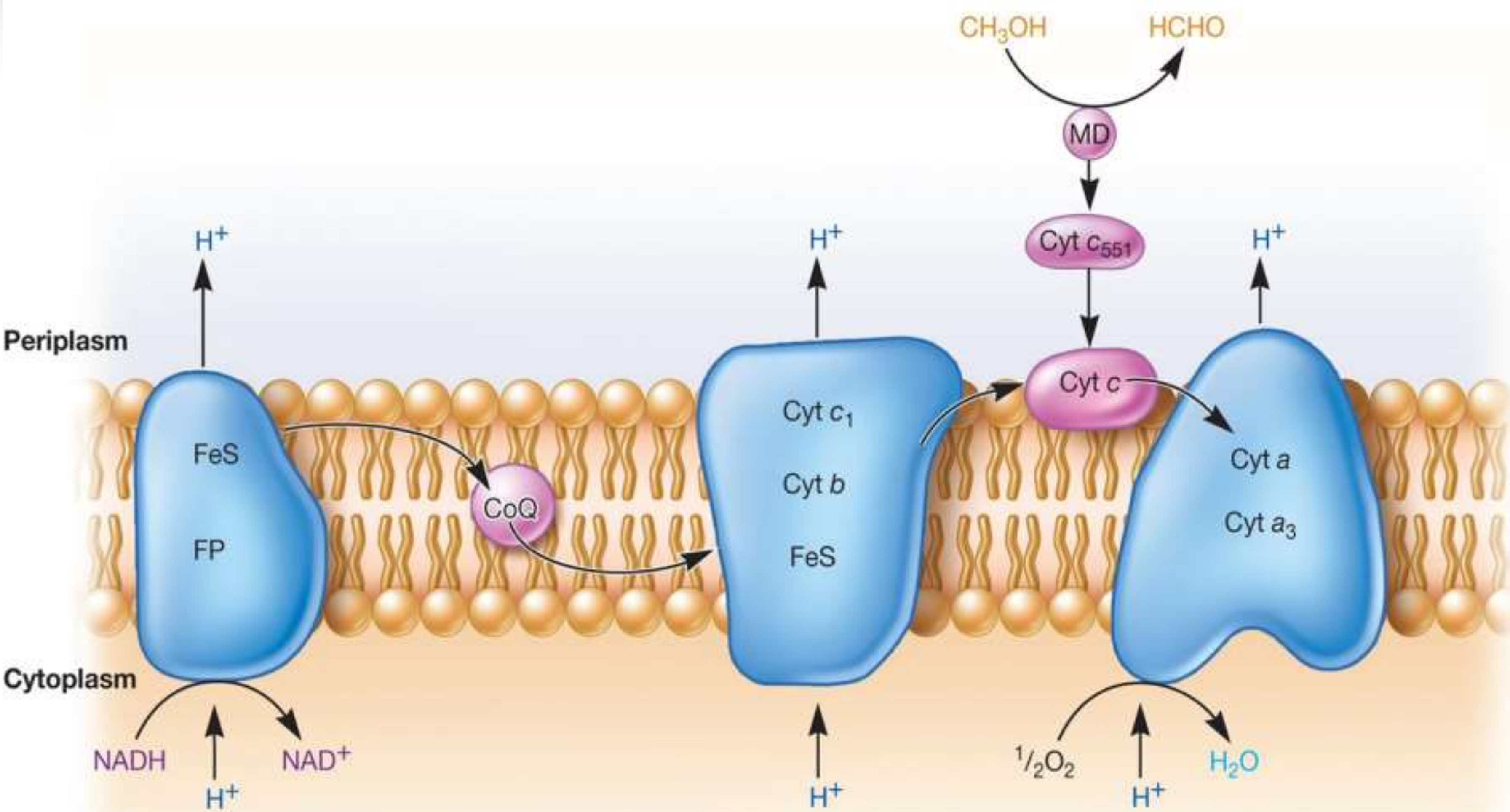
- Only **4 ATP molecules synthesized** directly from oxidation of glucose to CO_2
- Most ATP made when **NADH and $FADH_2$** (formed as glucose degraded) are oxidized in electron transport chain (ETC)

Bacterial and Archaeal ETCs

- Located in **plasma membrane**
- Some <u>resemble</u>(يشبه) mitochondrial ETC, but many are different
  - **different electron carriers**
  - **may be branched**
  - **may be shorter**

Paracoccus denitrificans

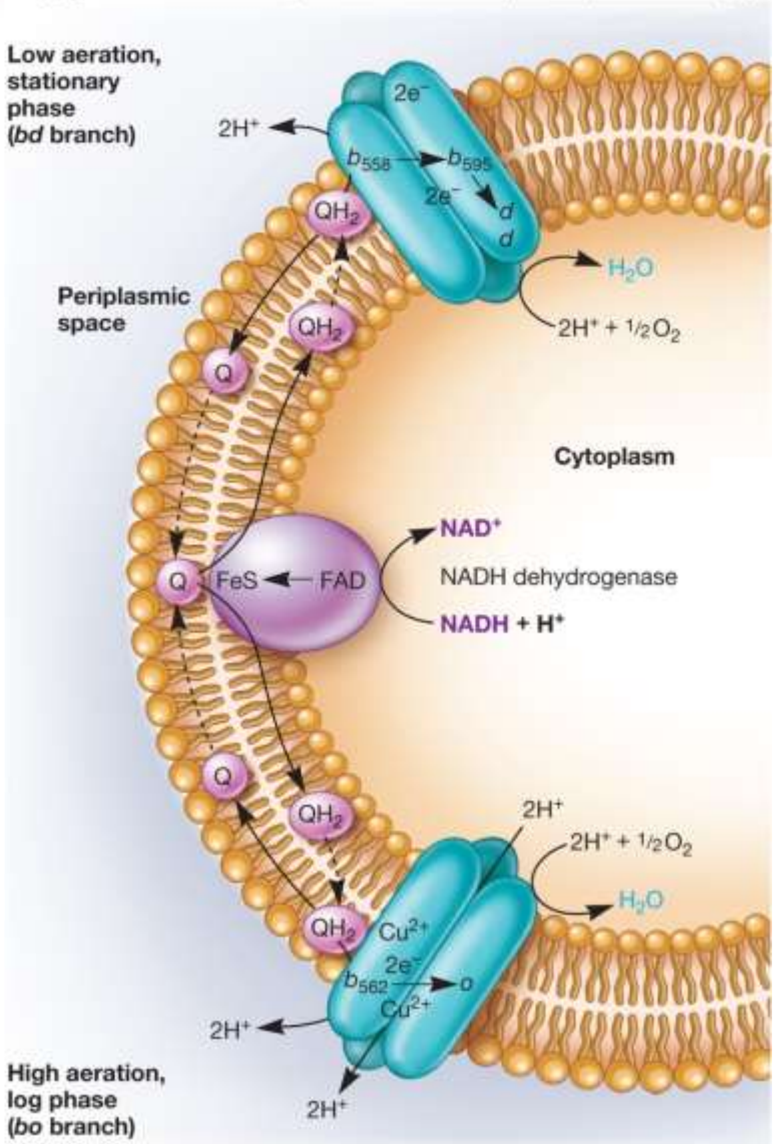
- **Facultative**, soil bacterium
- Extremely versatile metabolically
- **Under oxic conditions, uses aerobic respiration**
  - similar electron carriers and transport mechanism as mitochondria
  - protons transported to periplasmic space rather than inner mitochondrial membrane
  - can use one carbon molecules instead of glucose



CH3OH
HCHO
MD
H+
H+
Cyt c551
H+
Periplasm
Cyt c
Cyt c1
FeS
Cyt a
Cyt b
CoQ
Cyt a3
FP
FeS
Cytoplasm
NADH
NAD+
1/2O2
H2O
H+
H+
H+

Electron Transport Chain of *E. coli*

Different array of cytochromes used than in mitochondrial



Branched pathway

Upper branch – stationary phase and low aeration

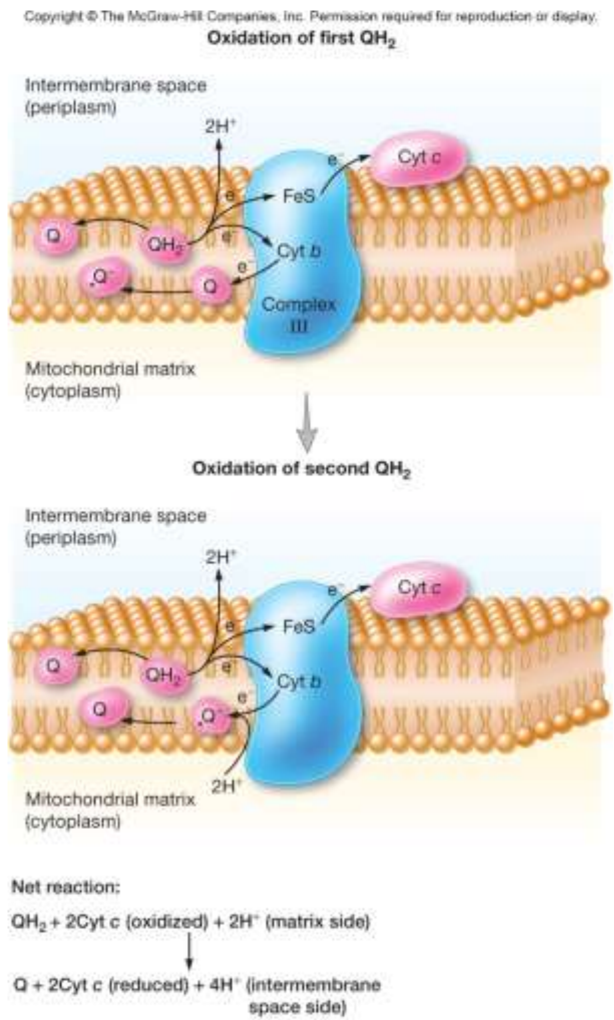
Lower branch – log phase and high aeration

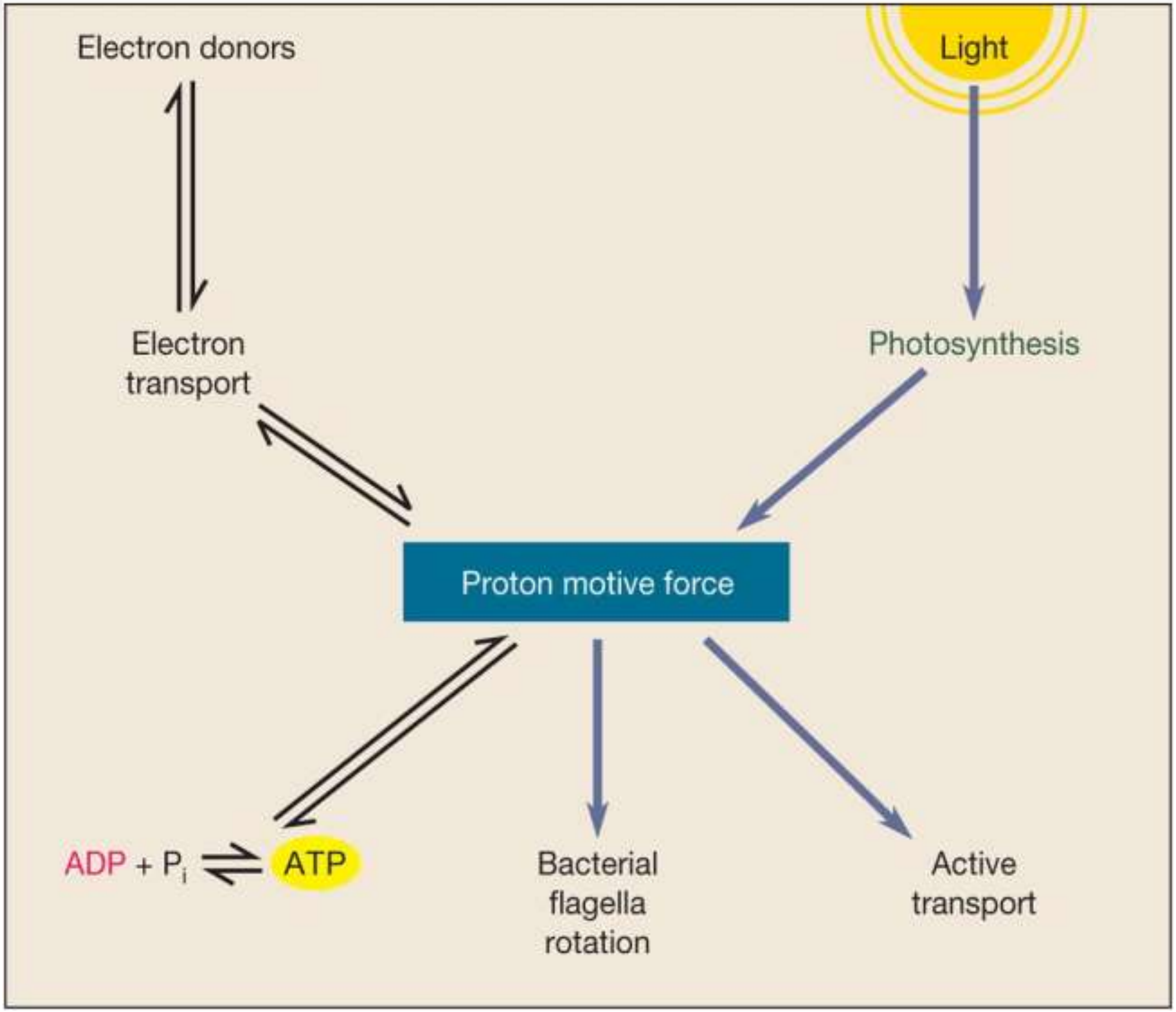
Oxidative Phosphorylation

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

Chemiosmotic Hypothesis

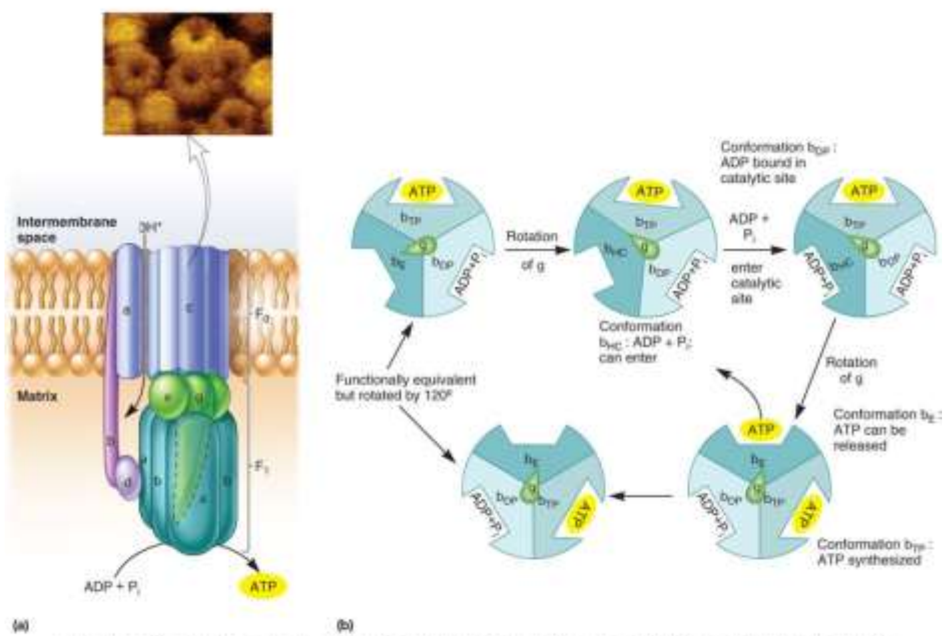
- The most widely accepted hypothesis to explain oxidative phosphorylation
  - protons move outward from the mitochondrial matrix as e^- are transported down the chain
  - proton expulsion(يطرد) during e^- transport results in the formation of a concentration gradient of protons and a charge gradient
  - the combined chemical and electrical potential difference make up the proton motive force (PMF)



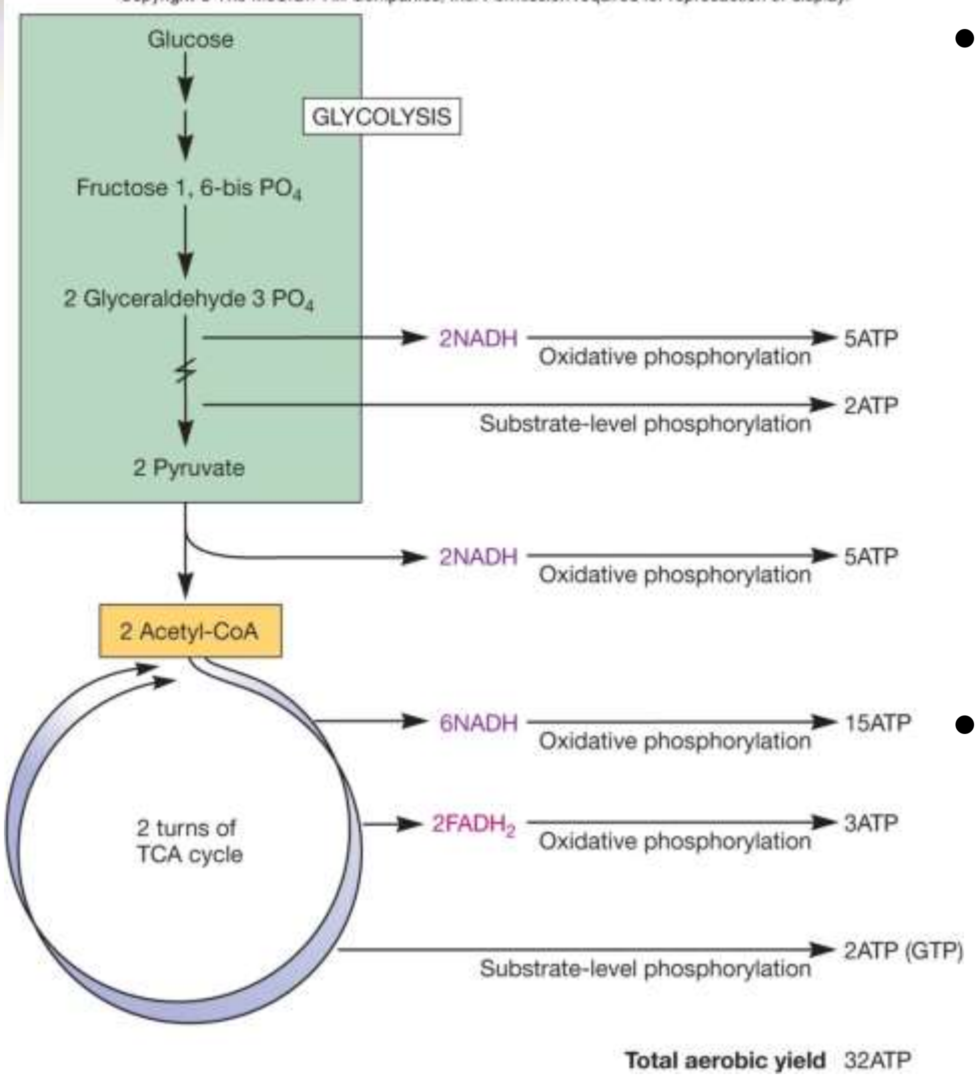

Electron donors
Light
Electron transport
Photosynthesis
Proton motive force
ADP + P_i ⇌ ATP
Bacterial flagella rotation
Active transport

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 Yield During Aerobic Respiration



- Maximum ATP yield can be calculated
  - includes P/O ratios of NADH and $FADH_2$
  - ATP produced by substrate level phosphorylation
- The theoretical maximum total yield of ATP during aerobic respiration is 38
  - the actual number closer to **30 than 38**

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

Anaerobic Respiration

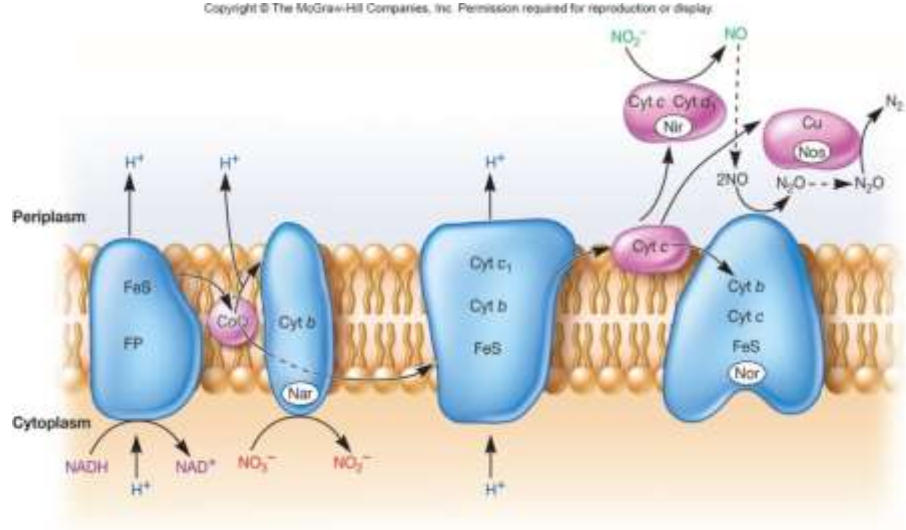
- Uses electron acceptors (carriers خطأ)other than O_2
- Generally yields less energy because E_0 of electron acceptor is less positive than E_0 of O_2

Table 11.3 Some Electron Acceptors Used in Respiration

	Electron Acceptor	Reduced Products	Examples of Microorganisms
Aerobic	O_2	H_2O	All aerobic bacteria, fungi, and protists
Anaerobic	NO_3^-	NO_2^-	Enteric bacteria
	NO_3^-	NO_2^-, N_2O, N_2	*Pseudomonas*, *Bacillus*, and *Paracoccus*
	SO_4^{2-}	H_2S	*Desulfovibrio* and *Desulfotomaculum*
	CO_2	CH_4	Methanogens
	CO_2	Acetate	Acetogens
	S^0	H_2S	*Desulfuromonas* and *Thermoproteus*
	Fe^{3+}	Fe^{2+}	*Pseudomonas*, *Bacillus*, and *Geobacter*
	$HAsO_4^{2-}$	$HAsO_2$	*Bacillus*, *Desulfotomaculum*, *Sulfurospirillum*
	SeO_4^{2-}	Se, $HSeO_3^-$	*Aeromonas*, *Bacillus*, *Thauera*
	Fumarate	Succinate	*Wolinella*

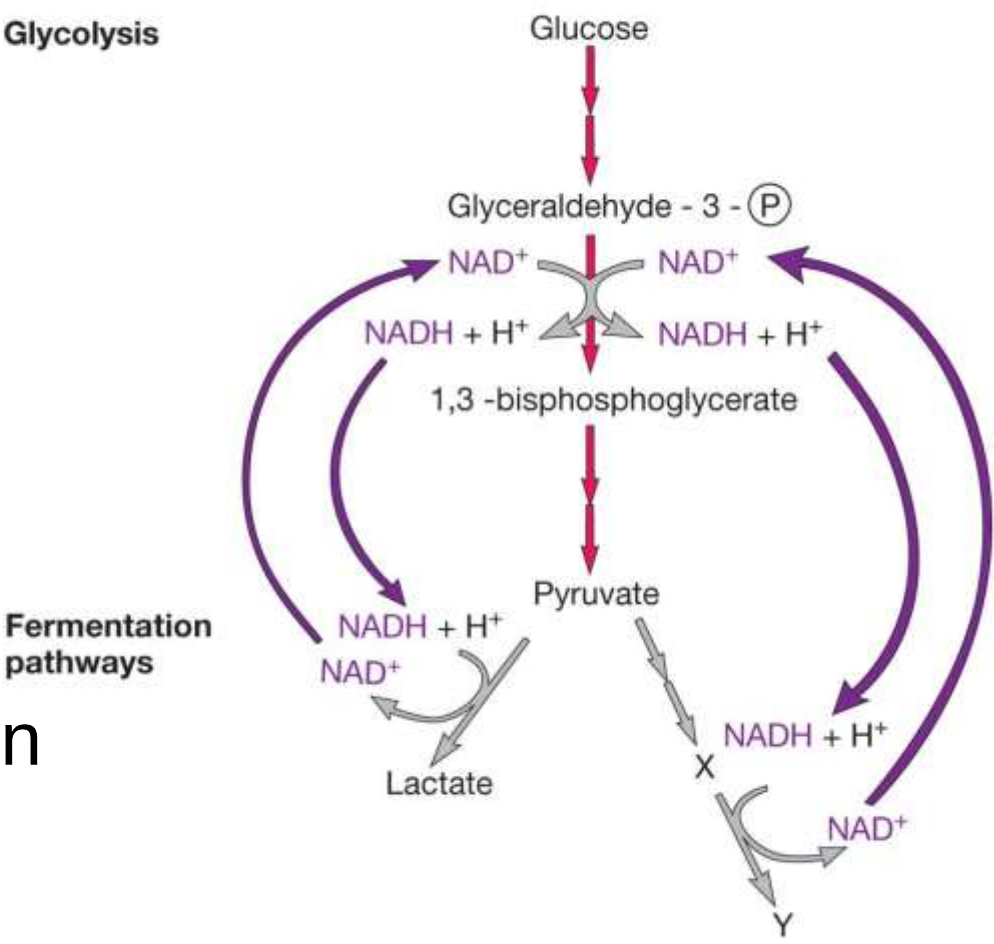
An Example…

- **Dissimilatory nitrate reduction**
  – use of nitrate as terminal electron acceptor, making it unavailable to cell for <u>assimilation</u>(للاستيعاب) or uptake
- **Denitrification**
  – reduction of nitrate to nitrogen gas
  – in soil, causes loss of soil fertility(خصوبة التربة)



Fermentation

- 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**



Homolactic fermenters

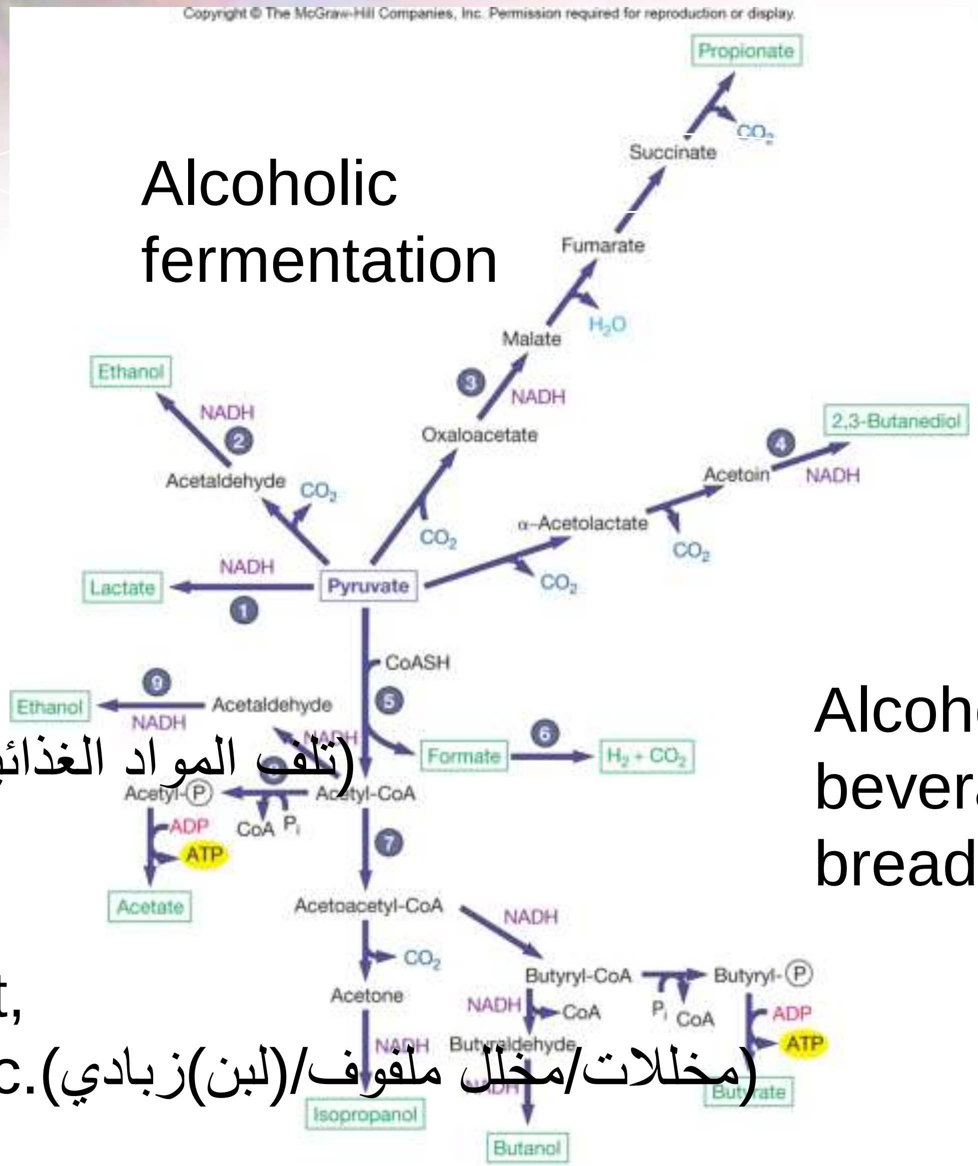
Heterolactic fermenters

Food Spoilage(تلف المواد الغذائية)

Yogurt, sauerkraut, pickles, etc.(مخللات/مخلل ملفوف/(لبن)زبادي)

Alcoholic fermentation

Alcoholic beverages, bread, etc.



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

Table 11.4 Mixed Acid Fermentation Products of *Escherichia coli*

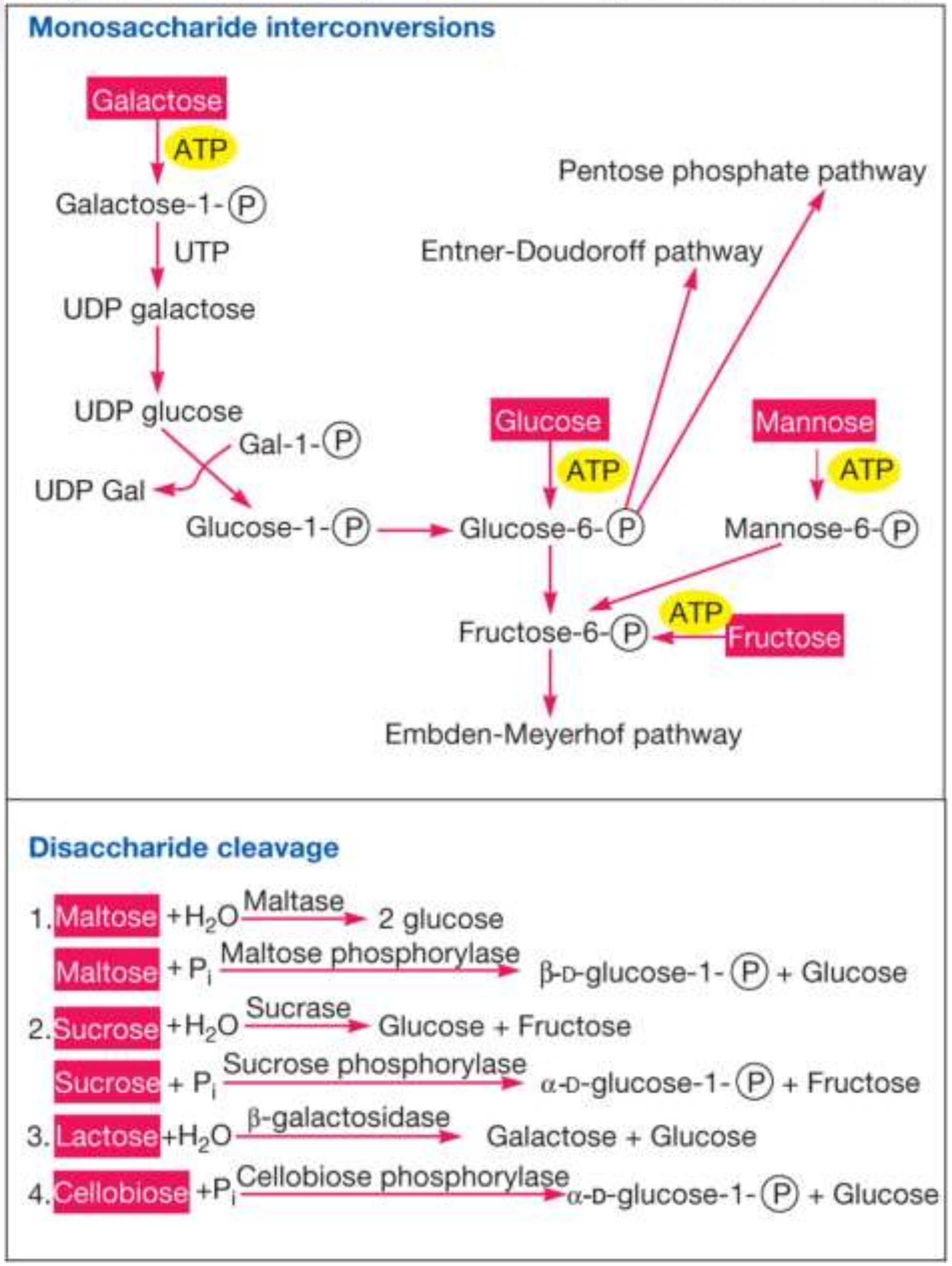
	FERMENTATION BALANCE (μM PRODUCT/100 μM GLUCOSE)	
	Acid Growth (pH 6.0)	Alkaline Growth (pH 8.0)
Ethanol	50	50
Formic acid	2	86
Acetic acid	36	39
Lactic acid	80	70
Succinic acid	11	15
Carbon dioxide	88	2
Hydrogen gas	75	0.5

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**



Reserve Polymers

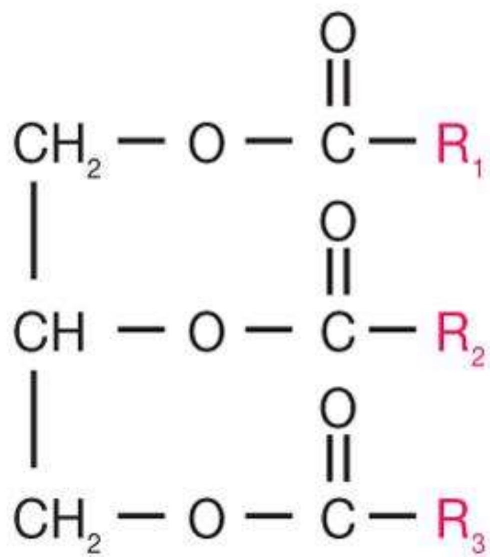
- Used as energy sources in absence of external nutrients
  - e.g., **glycogen and starch**
    - **cleaved by phosphorylases**

      $(\text{glucose})_n + P_i \rightarrow (\text{glucose})_{n-1} + \text{glucose-1-P}$
    - glucose-1-P enters glycolytic pathway
  - e.g., poly-hydroxybutyrate

    PHB → → → acetyl-CoA
    - acetyl-CoA enters TCA cycle

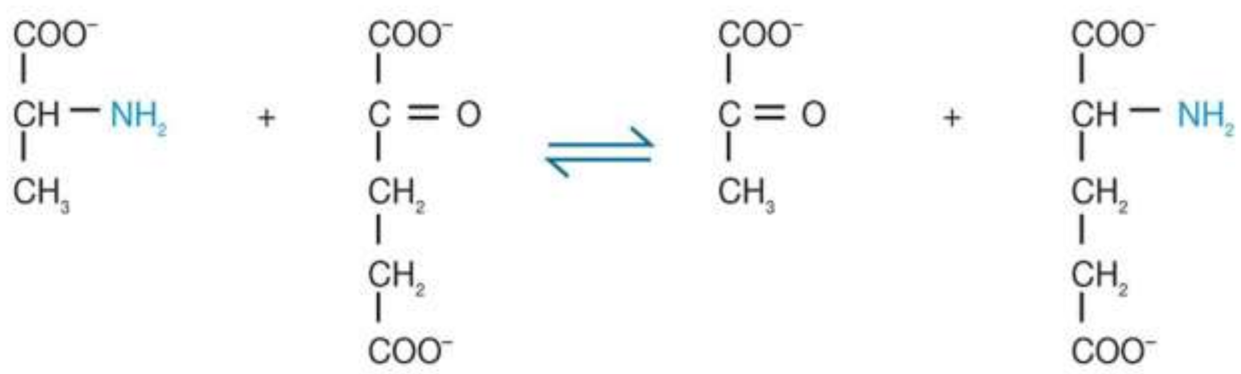
Lipid Catabolism

- Triglycerides
  - common energy sources
  - hydrolyzed to **glycerol and fatty acids by lipases**
    - **glycerol degraded via glycolytic pathway**
    - **fatty acids often oxidized via β-oxidation pathway**



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 be oxidized via TCA cycle
    - can be used for biosynthesis
  - can occur through transamination



Alanine α-Ketoglutarate Pyruvate Glutamate

Chemolithotrophy

- Carried out by chemolithotrophs
- E^- released from energy source which is an **inorganic molecule**
  - transferred to terminal e^- acceptor by ETC
- ATP synthesized by oxidative phosphorylation

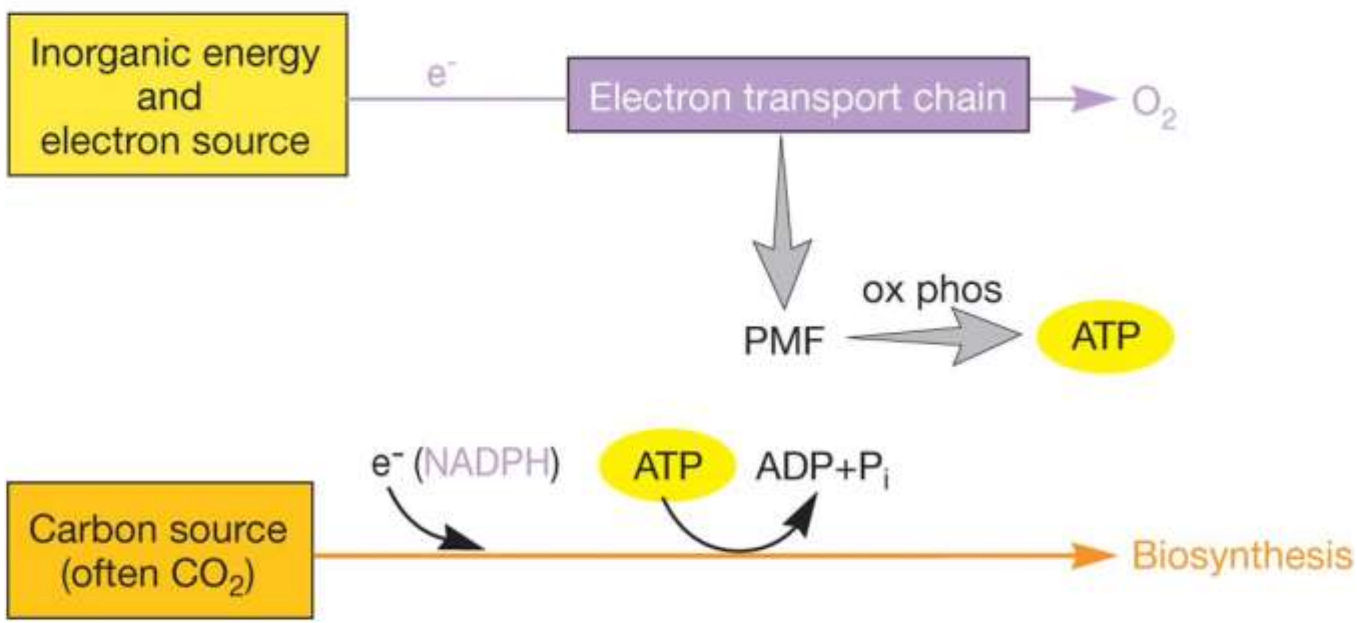


Table 11.5 Representative Chemolithotrophs and Their Energy Sources

Bacteria	Electron Donor	Electron Acceptor	Products
Alcaligenes, *Hydrogenophaga*, and *Pseudomonas* spp.	H_2	O_2	H_2O
Nitrobacter	NO_2^-	O_2	NO_3^-, H_2O
Nitrosomonas	NH_4^+	O_2	NO_2^-, H_2O
Thiobacillus denitrificans	S^0, H_2S	NO_3^-	SO_4^{2-}, N_2
Acidithiobacillus ferrooxidans	Fe^{2+}, S^0, H_2S	O_2	Fe^{3+}, H_2O, H_2SO_4

Energy Sources

Table 11.6 Energy Yields from Oxidations Used by Chemolithotrophs

Reaction	$\Delta G^{\circ\prime}$ (kcal/mole)[1]
$H_2 + \frac{1}{2}O_2 \rightarrow H_2O$	−56.6
$NO_2^- + \frac{1}{2}O_2 \rightarrow NO_3^-$	−17.4
$NH_4^+ + 1\frac{1}{2}O_2 \rightarrow NO_2^- + H_2O + 2H^+$	−65.0
$S^0 + 1\frac{1}{2}O_2 + H_2O \rightarrow H_2SO_4$	−118.5
$S_2O_3^{2-} + 2O_2 + H_2O \rightarrow 2SO_4^{2-} + 2H^+$	−223.7
$2Fe^{2+} + 2H^+ + \frac{1}{2}O_2 \rightarrow 2Fe^{3+} + H_2O$	−11.2

1 The $\Delta G^{\circ\prime}$ for complete oxidation of glucose to CO_2 is −686 kcal/mole. A kcal is equivalent to 4.184 kJ.

- Bacterial and archaeal species have specific electron donor/acceptor preferences
- Much less energy is available from oxidation of inorganic molecules than glucose oxidation due to more positive redox potentials

Three Major Groups of Chemolithotrophs

- Have ecological importance
- **Several bacteria and archaea oxidize hydrogen**
- **Sulfur-oxidizing microbes**
  - hydrogen sulfide (H_2S), sulfur (S^0), thiosulfate ($S_2O_3^{2-}$)
- **Nitrifying bacteria** oxidize ammonia to nitrate

Sulfur-Oxidizing Bacteria

(a) Direct oxidation of sulfite

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

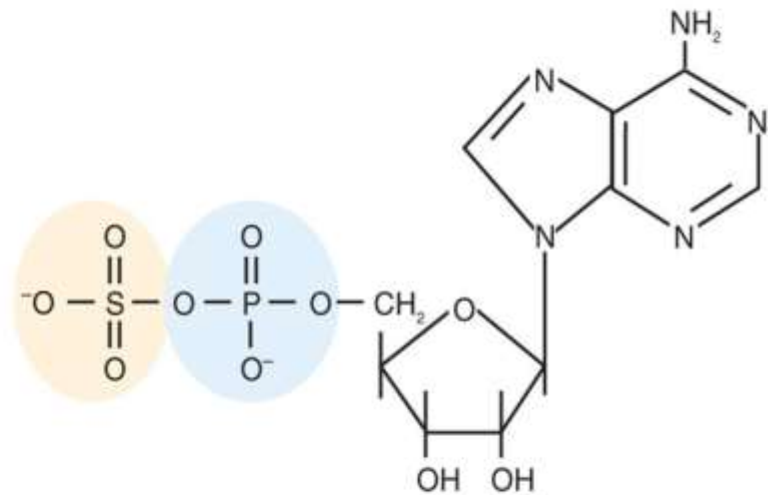
(b) Formation of adenosine 5′-phosphosulfate

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

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

$$2ADP \longrightarrow AMP + ATP$$

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

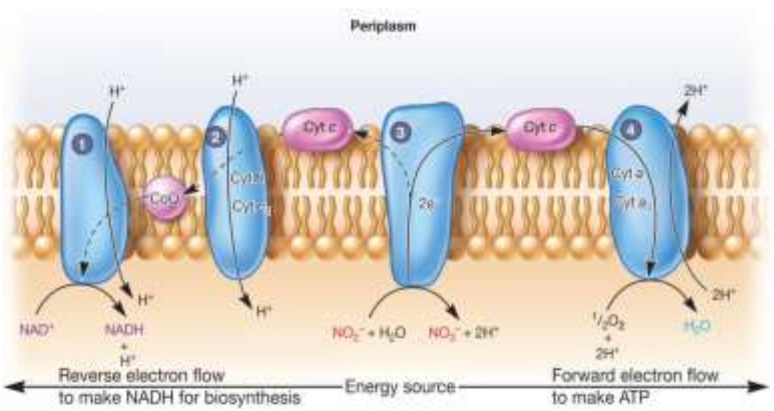


(c) Adenosine 5′-phosphosulfate

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

Reverse Electron Flow by Chemolithotrophs

- 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



When *Nitrobacter* 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.

Cytoplasm

When *Nitrobacter* 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.

Metabolic Flexibility of Chemolithotrophs

- Many switch from **chemolithotrophic metabolism to chemoorganotrophic metabolism**
- **Many switch from autotrophic metabolism (via Calvin cycle) to heterotrophic metabolism**

Phototrophy

Table 11.7	Diversity of Phototrophic Microorganisms
Eukaryotes	Multicellular green, brown, and red algae; unicellular protists (e.g., 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**

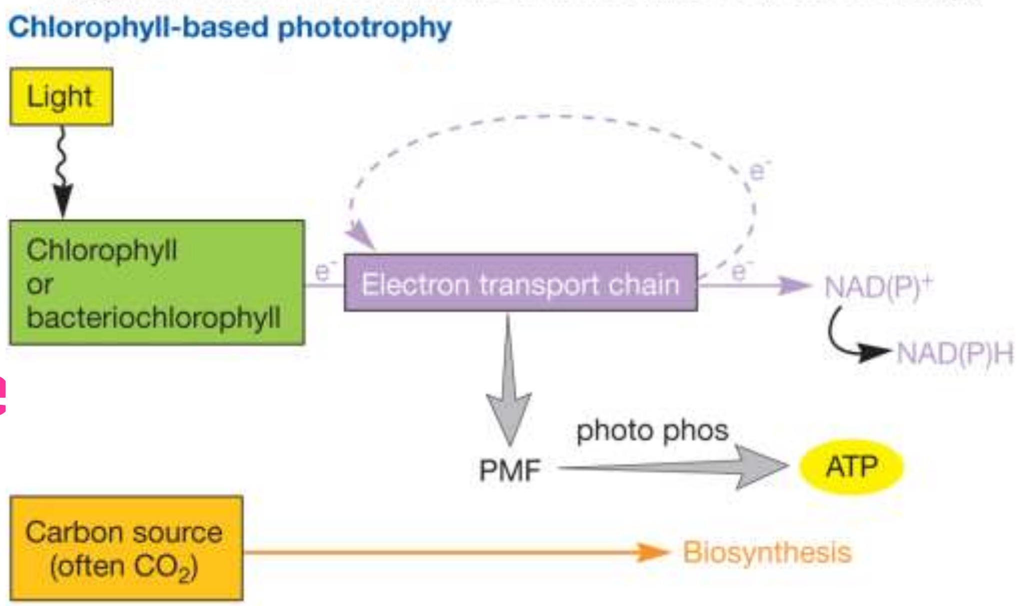


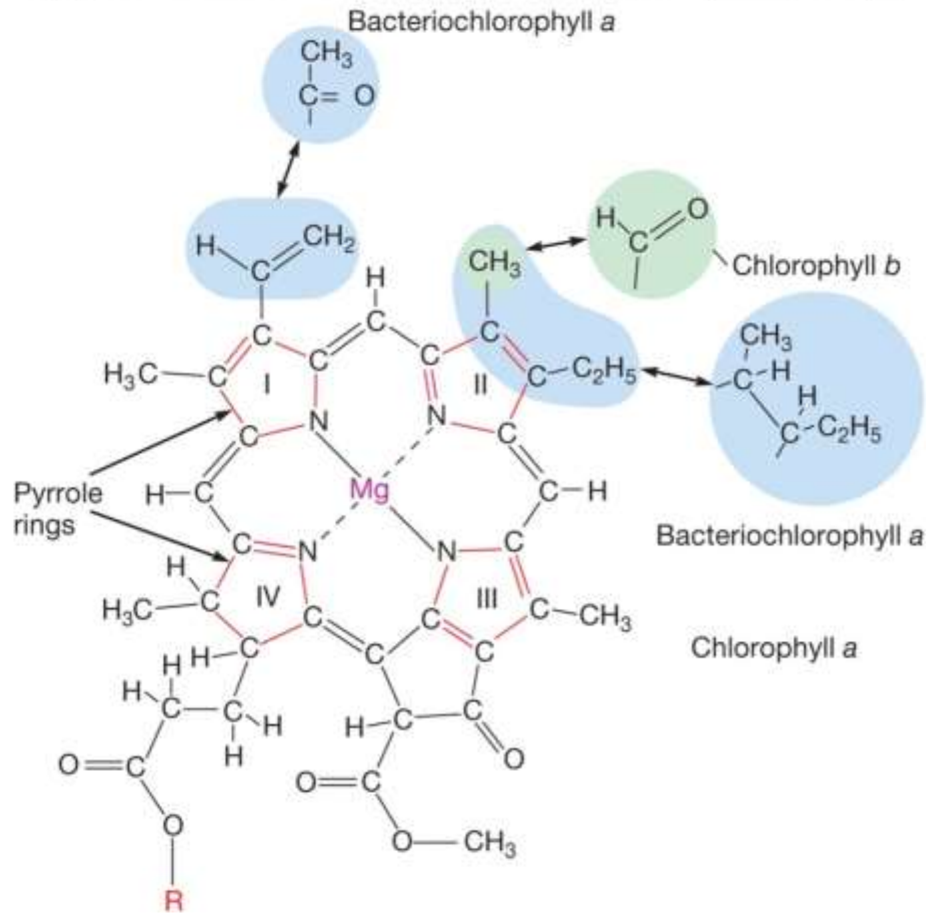
Table 11.8 Properties of Chlorophyll-Based Photosynthetic Systems

Property	Eukaryotes	Cyanobacteria	Green Bacteria, Purple Bacteria, Heliobacteria, and Acidobacteria
Photosynthetic pigment	Chlorophyll *a*	Chlorophyll *a*[1]	Bacteriochlorophyll
Number of photosystems	2	2[2]	1
Photosynthetic electron donors	H_2O	H_2O	H_2, H_2S, S, organic matter
O_2 production pattern	Oxygenic	Oxygenic[3]	Anoxygenic
Primary products of energy conversion	ATP + NADPH	ATP + NADPH	ATP
Carbon source	CO_2	CO_2	Organic or CO_2

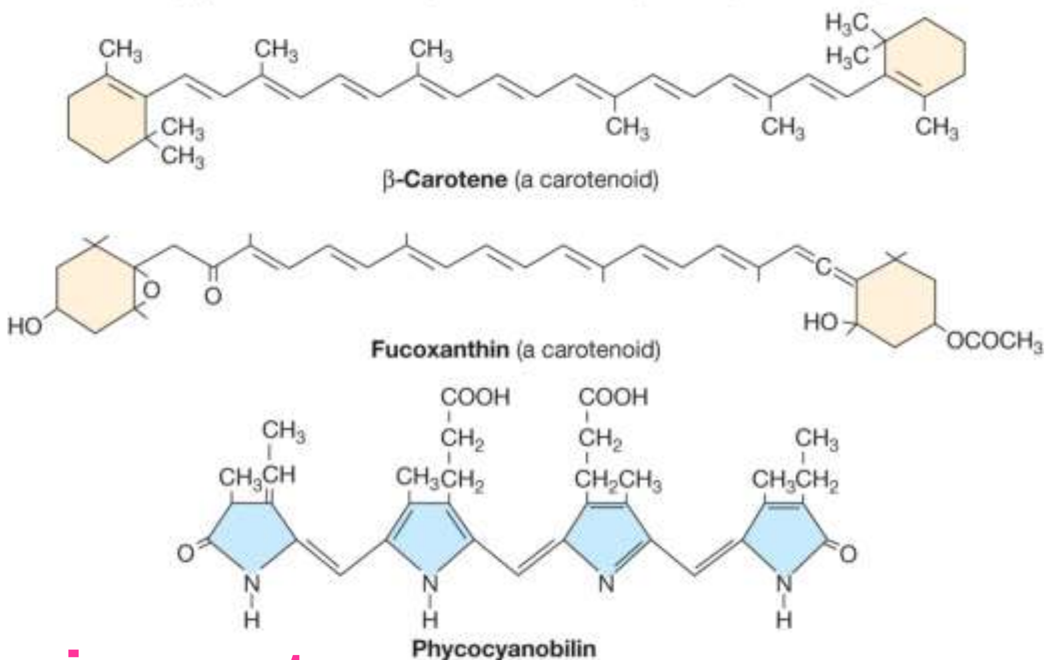
1 Members of the cyanobacterial genus *Prochlorococcus* have divinyl chlorophyll *a* and *b*.
2 A recently discovered cyanobacterium lacks photosystem II.
3 Some cyanobacteria can function anoxygenically under certain conditions. For example, *Oscillatoria* can use H_2S as an electron donor instead of H_2O.

The Light Reaction in Oxygenic Photosynthesis

- **Chlorophylls**
  - major light-absorbing pigments
  - **different chlorophylls have different absorption peaks**



The Light Reaction in Oxygenic Photosynthesis



- **Accessory pigments**
  - transfer light energy to chlorophylls
  - e.g., **carotenoids and phycobiliproteins**
  - accessory pigments absorb different wavelengths of light than chlorophylls

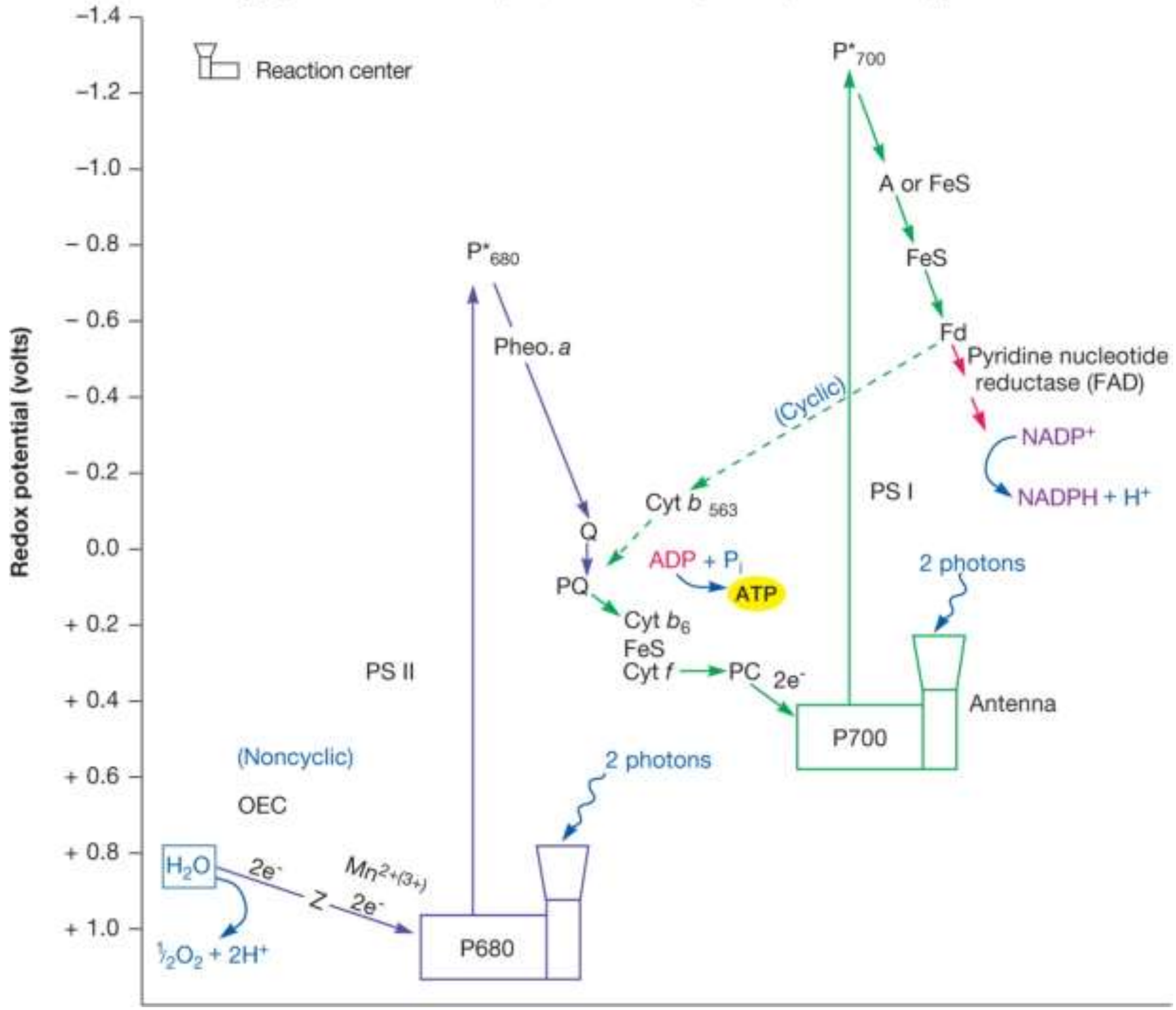
Organization of Pigments

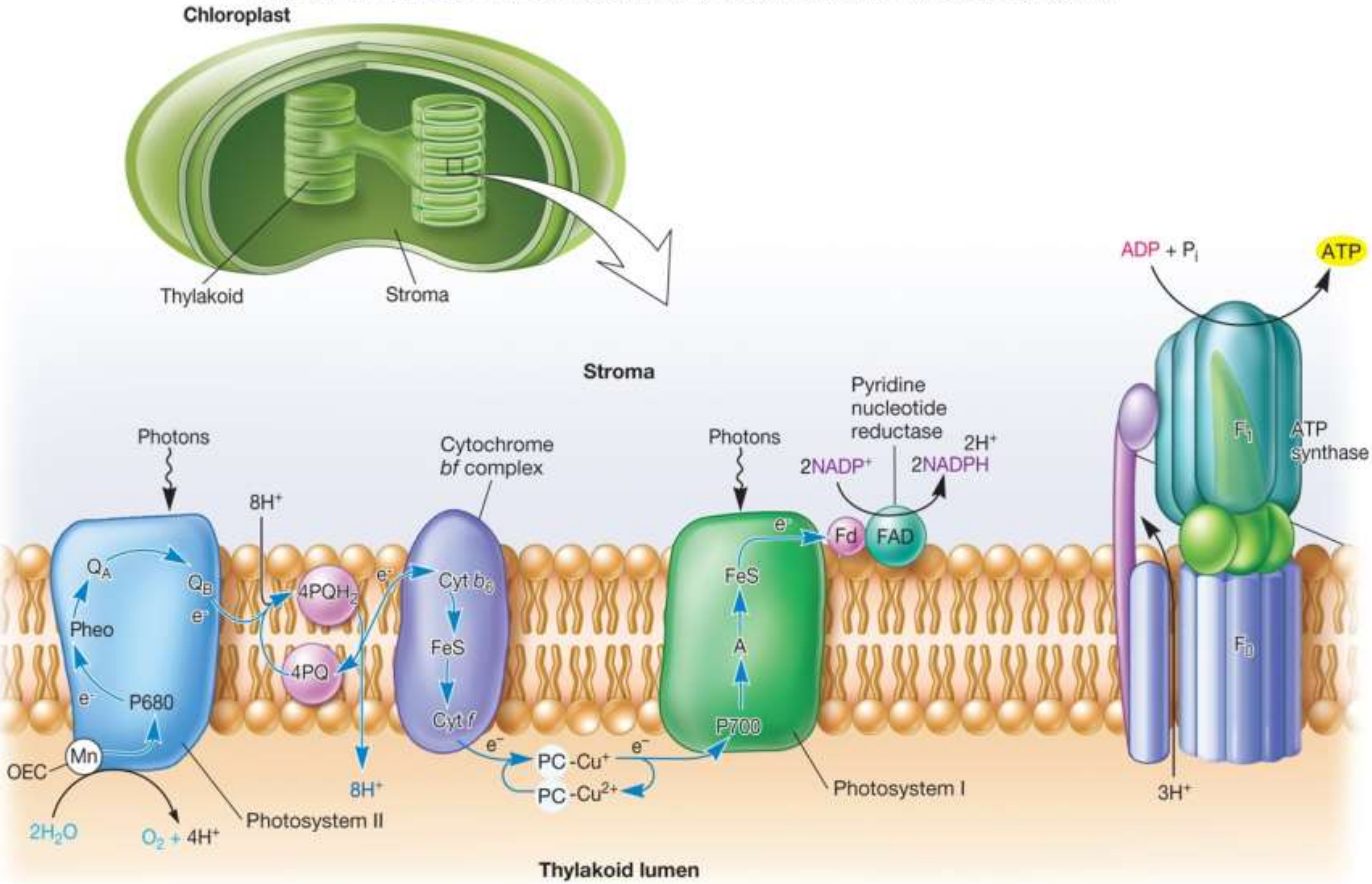
- **Antennas**
  - highly organized arrays of chlorophylls and accessory pigments
  - **captured light transferred to special reaction-center chlorophyll**
    - directly involved in photosynthetic electron transport
- **Photosystems**
  - **antenna and its associated reaction-center chlorophyll**
- Electron flow → PMF → ATP

Oxygenic Photosynthesis

Noncyclic electron flow – ATP + NADPH made (noncyclic photophos-phorylation)

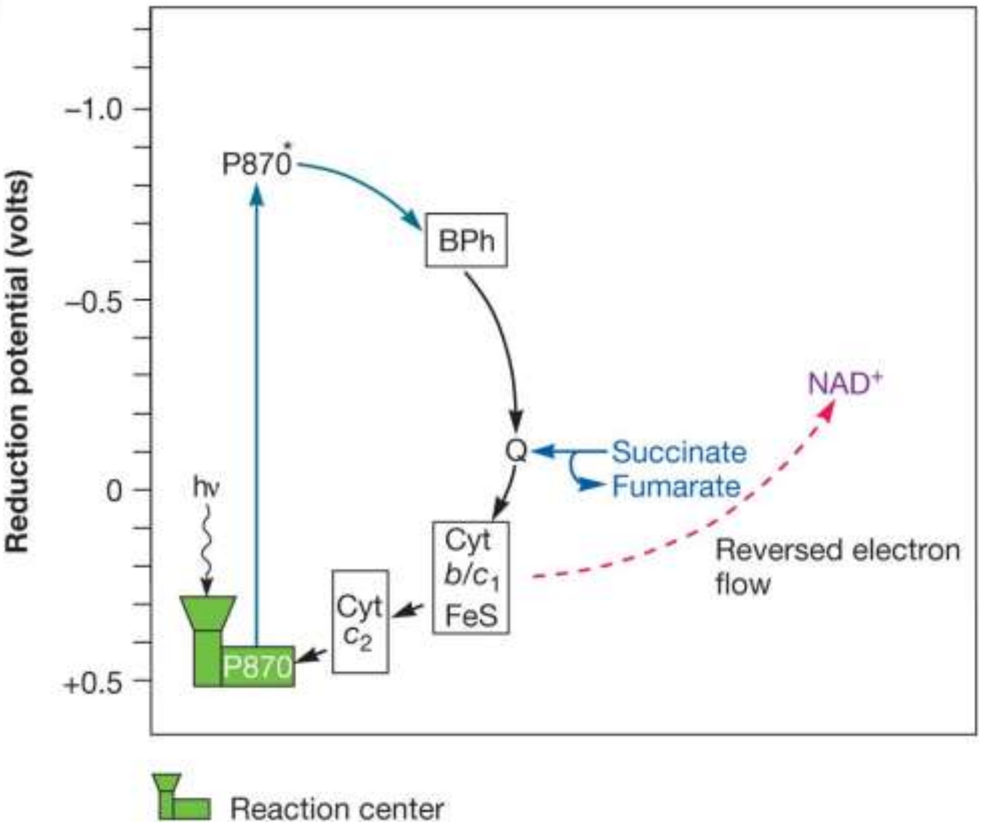
Cyclic electron flow – ATP made (cyclic photophos-phorylation)

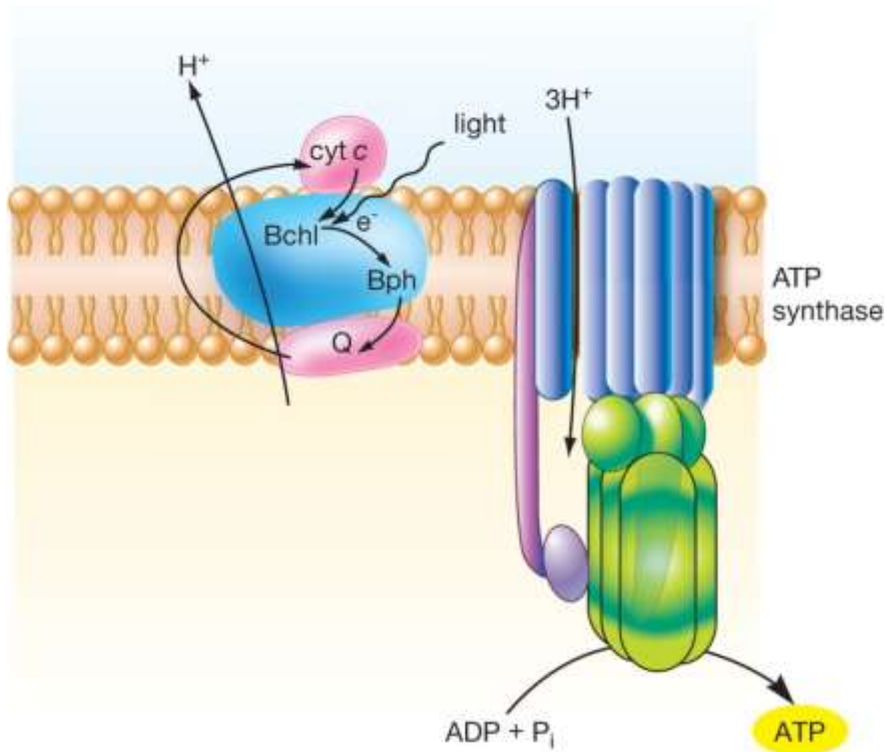



Chloroplast
Thylakoid
Stroma
Stroma
Photons
Photons
Cytochrome
bf complex
8H+
Pyridine
nucleotide
reductase
2H+
2NADP+
2NADPH
ADP + Pi
ATP
F1
ATP
synthase
Fo
QA
QB
Pheo
P680
Mn
OEC
4PQH2
4PQ
Cyt b6
FeS
Cyt f
8H+
PC-Cu+
PC-Cu2+
FeS
A
P700
Fd
FAD
3H+
2H2O
O2 + 4H+
Photosystem II
Photosystem I
Thylakoid lumen

The 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**


Reduction potential (volts)
−1.0
−0.5
0
+0.5
P870*
BPh
Q
Succinate
Fumarate
NAD+
Cyt b/c1 FeS
Cyt c2
hv
P870
Reversed electron flow
Reaction center


H+
3H+
light
cyt c
Bchl
e-
Bph
Q
ATP synthase
ADP + Pi
ATP

Bacteriorhodopsin-Based Phototrophy

- Some archaea use a type of phototrophy that involves bacteriorhodopsin
  - a membrane protein
  - functions as a light-driven proton pump
- A proton motive force is generated
- An electron transport chain is not involved