Microbes as Energy Transducers

- The Metabolic Menu
- Metabolic Strategies
- Respiration & Fermentation
- Chemolithotrophy
- Photoautotrophy
- Biogeochemical Cycles
- Metabolism in Primitive Organisms

All major types of nutrition and metabolism evolved among prokaryotes: they are the ultimate biochemists

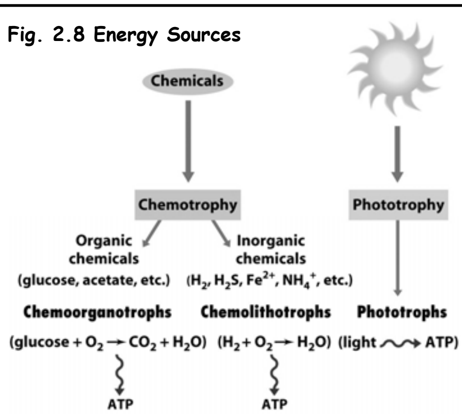
The prokaryotes exhibit some unique modes of nutrition as well as **every type** of nutrition found in eukaryotes.

Major Modes of Nutrition:

Prokaryotes exhibit a great diversity in how they obtain the necessary resources **(energy and carbon)** to synthesize organic compounds.

- Some obtain energy from light **(phototrophs)**, while others use chemicals taken from the environment **(chemotrophs)**.
- Many can utilized CO_2 as a carbon source **(autotrophs)** and others require at least one organic nutrient as a carbon source **(heterotrophs)**.

Fig. 2.8 Energy Sources



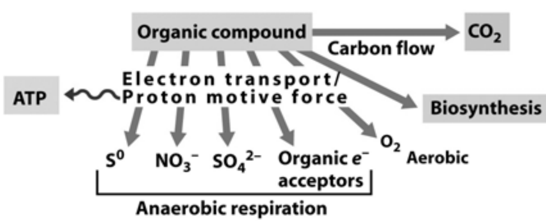
Depending upon the energy source **AND** the carbon source, prokaryotes have **four** possible nutritional modes:

1. Photoautotrophs: Use light energy to synthesize organic compounds from CO_2 – Includes the cyanobacteria. (Actually all photosynthetic eukaryotes fit in this category.)

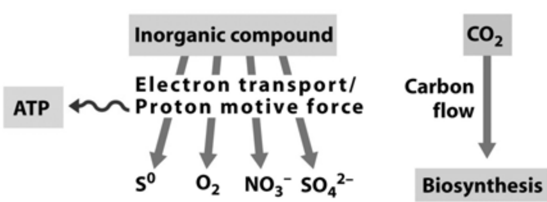
2. Chemoautotrophs: Require only CO_2 as a carbon source and obtain energy by oxidizing inorganic compounds. This mode of nutrition is unique only to certain prokaryotes.

3. Photoheterotrophs: Use light to generate ATP from an organic carbon source. This mode of nutrition is unique only to certain prokaryotes.

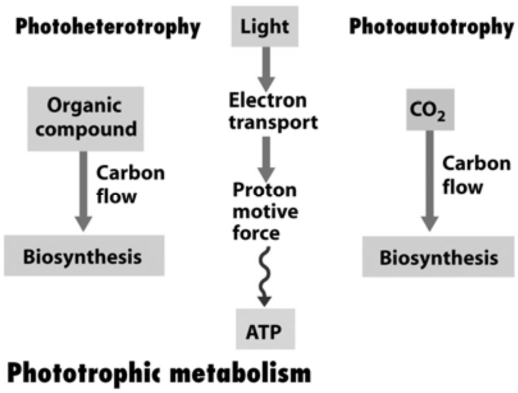
4. Chemoheterotrophs: Must obtain organic molecules for energy and as a source of carbon. Found in many bacteria as well as most eukaryotes.



Chemoorganotrophic metabolism



Chemolithotrophic metabolism

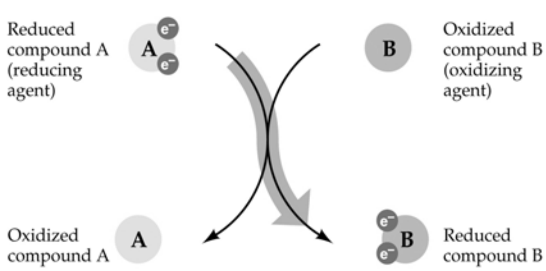


Metabolic Menu
For Chemotrophs

Potential Microbial Metabolic Processes:

	e- donor	e- acceptor	C source	Organisms
Autolithotrophy				
	H_2	O_2	CO_2	Hydrogen oxidizers
	$HS^-, S^0, S_2O_3^{-2}$	O_2	CO_2	Sulfur oxidizers
	Fe^{+2}	O_2	CO_2	Iron oxidizers
	Mn^{+2}	O_2	CO_2	Manganese oxidizers
	NH_4^+, NO_2^-	O_2	CO_2	Nitrifiers
	$HS^-, S^0, S_2O_3^{-2}$	NO_3^-	CO_2	Denitrifying/S-oxidizers
	H_2	NO_3	CO_2	Hydrogen oxidizers
	H_2	S^0, SO_4^{-2}	CO_2	Sulfate Reducers (SRBs)
	H_2	CO_2	CO_2	Methanogens & Acetogens
Heteroorganotrophy				
	Org.C	O_2	Org.C	Aerobic Heterotrophy
	Org.C	NO_3^-	Org.C	Denitrifyers
	Org.C	S^0, SO_4^{-2}	Org.C	Sulfate Reducers (SRBs)
	Org.C	Org.C	Org.C	Fermenters
Methylotrophy				
	CH_4,(C-1's)	O_2, SO_4^{-2}	CH_4, CO_2, CO	Methane (C-1) oxidizers

Oxidation and Reduction are Coupled Reactions



A is oxidized, losing electrons

B is reduced, gaining electrons

Redox Rxns:

$H_2 \rightarrow 2\ e^- + 2\ H^+$

Electron-donating half reaction

$\frac{1}{2} O_2 + 2\ e^- \rightarrow O^{2-}$

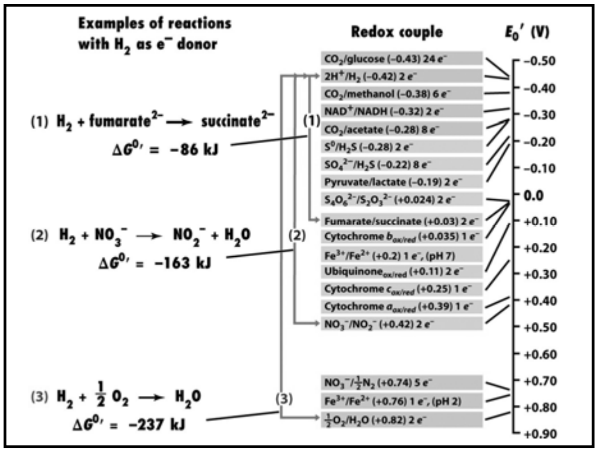
Electron-accepting half reaction

$2\ H^+ + O^{2-} \rightarrow H_2O$

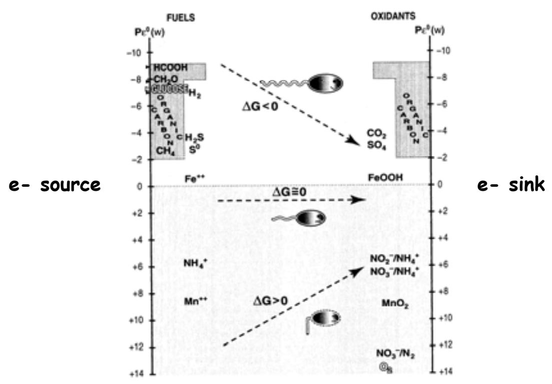
Formation of water

Electron donor — $H_2 + \frac{1}{2} O_2 \rightarrow H_2O$ — Electron acceptor

Net reaction

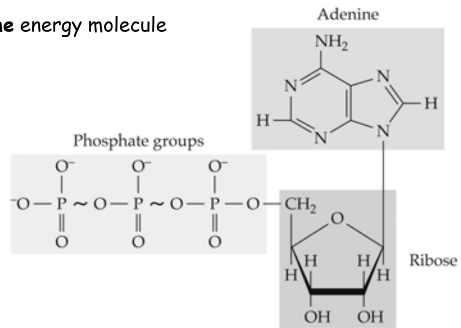


Thermodynamics: The Chemical Fuels and Oxidants of Life



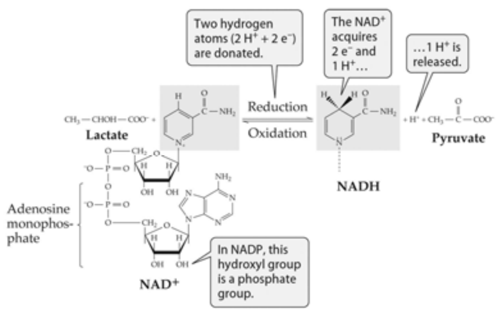
Adenosine-5′-triphosphate (ATP)

The energy molecule



Adenosine triphosphate

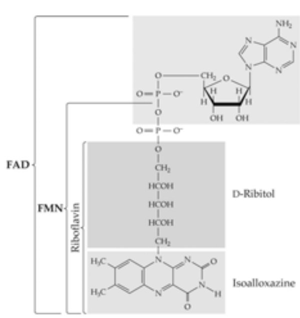
Nicotinamide adenine dinucleotide (NAD)



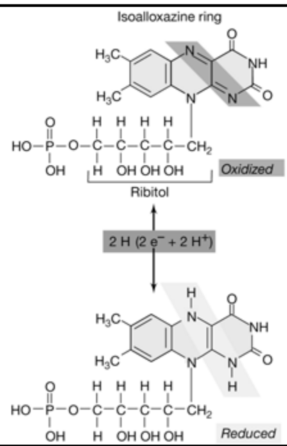
The redox molecule

Flavin nucleotides, components of flavoproteins

Specialty redox molecule

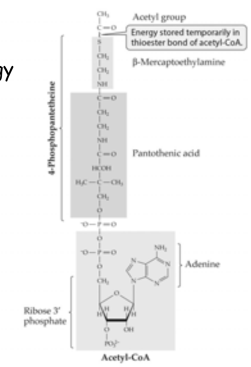


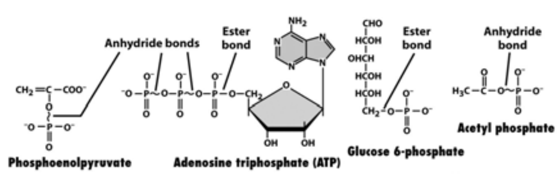
Flavin nucleotides

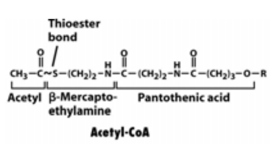


Acetyl-coenzyme A (acetyl-CoA)

Specialty energy molecule

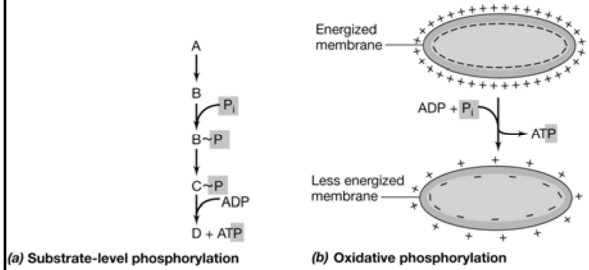






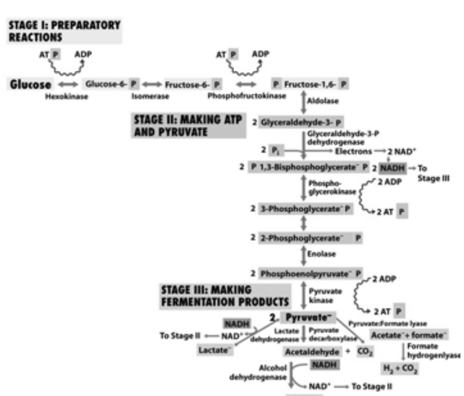
Compound	$G^{0'}$ kJ/mol
$\Delta G^{0'} > 30$kJ	
Phosphoenolpyruvate	−51.6
1,3-Bisphosphoglycerate	−52.0
Acetyl phosphate	−44.8
ATP	−31.8
ADP	−31.8
Acetyl CoA	−31
$\Delta G^{0'} < 30$kJ	
AMP	−14.2
Glucose 6-phosphate	−13.8

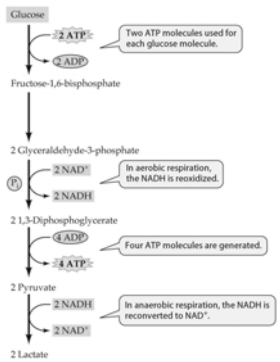
Two Ways to Make ATP: Quick & Dirty or Turbo-Charged



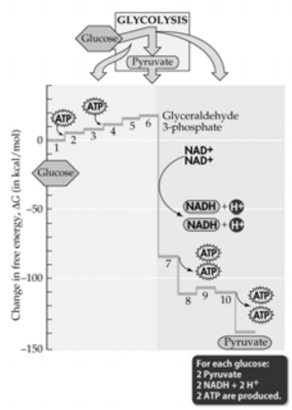
7.1 *Cellular Locations for Energy Pathways in Eukaryotes and Prokaryotes*

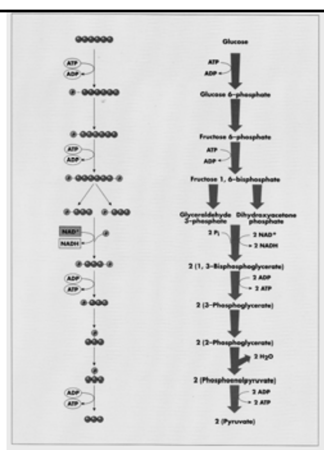
EUKARYOTES	PROKARYOTES
External to mitochondrion	**In cytoplasm**
Glycolysis	Glycolysis
Fermentation	Fermentation
	Citric acid cycle
Inside mitochondrion	**On inner face of plasma membrane**
Inner membrane	Pyruvate oxidation
Pyruvate oxidation	Respiratory chain
Respiratory chain	
Matrix	
Citric acid cycle	





Glycolysis: Short Form

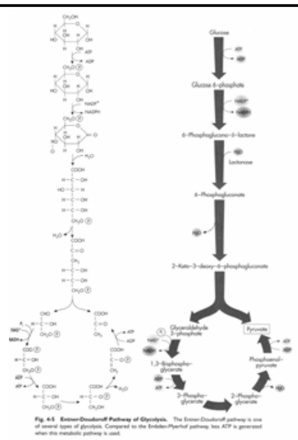




Glycolysis aka Embden-Meyerhof

The short form!

4 ATP / 2 Net
2 NADH+H

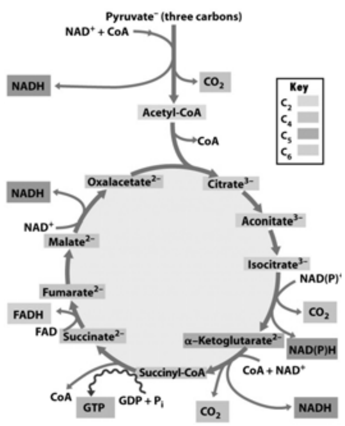


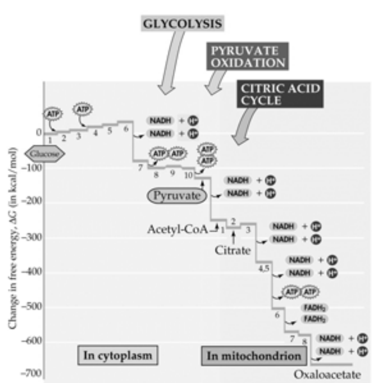
Entner-Doudoroff

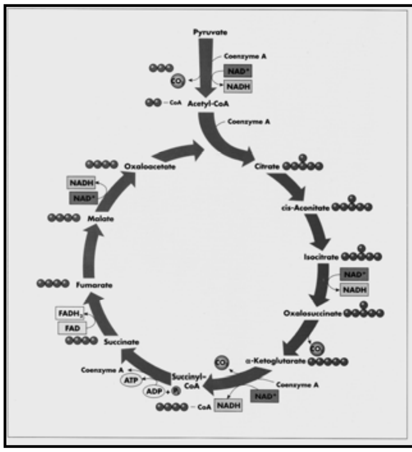
2 ATP / only 1 Net
2 NADH+H

No PFK!!!

Many Gram negatives use this pathway







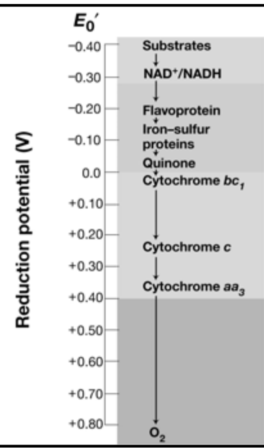
Citric Acid Cycle aka TCA cycle

The short form!

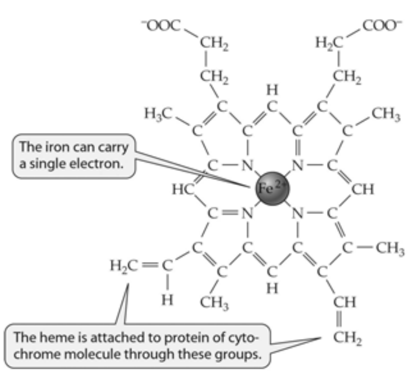
2 ATP (via GTP)
8 NADH+H
2 $FADH_2$

All Carbon to CO_2

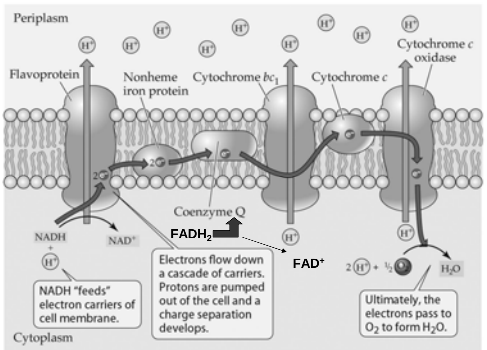
Electron Transport Chains and their Relative Potential



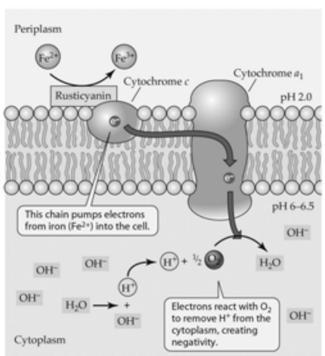
The heme part of a cytochrome, the elegant porphyrin ring!



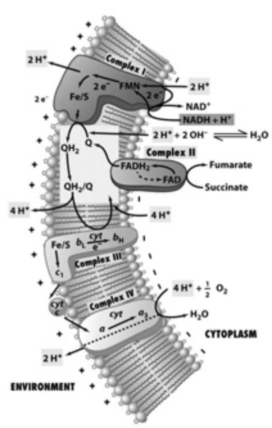
Electron transport chain in aerobic bacterium



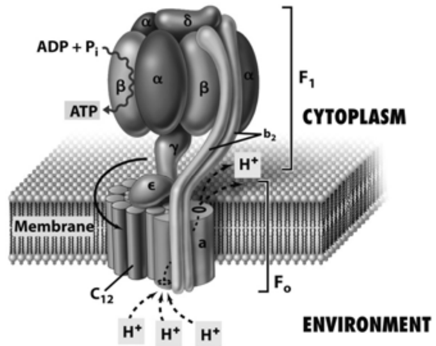
Abbreviated electron transport chain of an iron-oxidizing bacterium

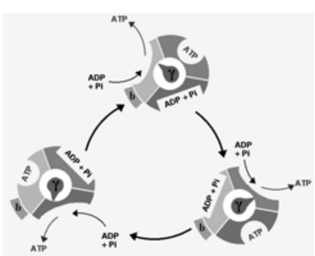


Generation of PMF



ATP Synthase
Structure & Function





F1 Subunit Topview

ATP Synthase acts as a rotary motor turning in 120 degree steps.

Energetics Balance Sheet for Aerobic Respiration

(1) **Glycolysis:** Glucose + $2NAD^+$ + 2 ATP → 2 $Pyruvate^-$ + 4 ATP + 2 NADH
+ 4 ADP ↓ to CAC; 2 NADH ↓ to Complex I

(a) Substrate-level phosphorylation
2 ADP + Pi → 2 ATP (× 2)
(b) Oxidative phosphorylation
2 NADH → 6 ATP
} 8 ATP

(2) **CAC:** $Pyruvate^-$ + $4NAD^+$ + GDP + FAD → 3 CO_2 + 4 NADH + FADH+ GTP
4 NADH ↓ to Complex I; FADH ↓ to Complex II

(a) Substrate-level phosphorylation
1 GDP + Pi → 1 GTP
1 GTP + 1 ADP → 1 ATP + 1 GDP
(b) Oxidative phosphorylation
4 NADH → 12 ATP
1 FADH → 2 ATP
} 15 ATP (×2)

(3) **Sum: Glycolysis plus CAC → 38 ATP per glucose**

Fermentation – Key Features

(1) Substrate-level phosphorylation is the rule*.

(2) Always anaerobic (even when some O_2 might be around).

(3) No externally supplied terminal electron acceptor.

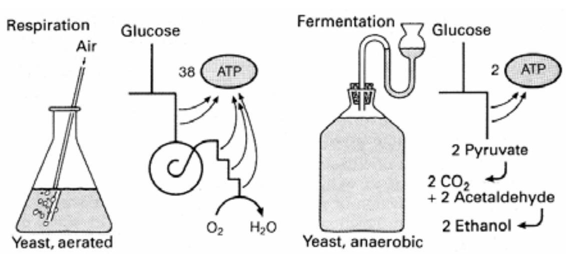
Many types.... 2 major themes

(1) $NADH+H^+$ gets oxidized to NAD^+

(2) Electron acceptor is usually **Pyruvate** or its derivative.

*Rules are always meant to be broken!

Pasteur Effect: ~20X more biomass when aerated



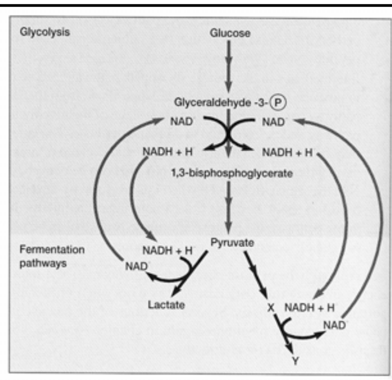
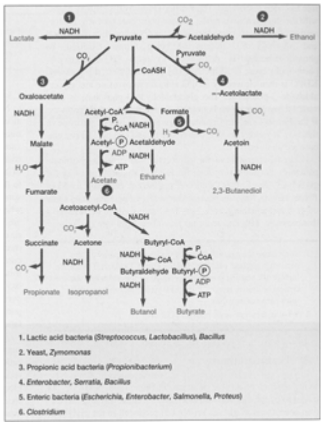
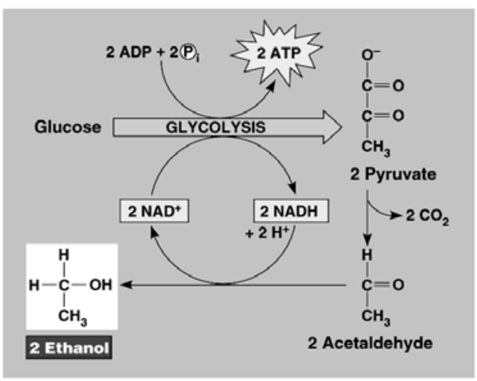


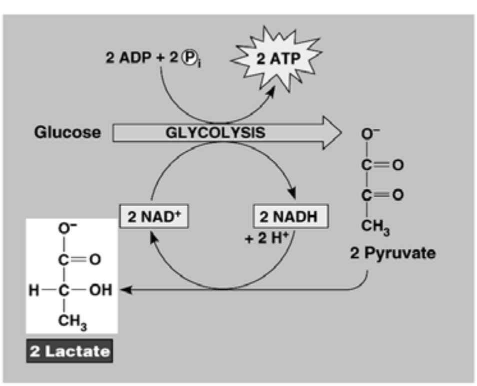
Figure 9.9 Reoxidation of NADH During Fermentation. NADH from glycolysis is reoxidized by being used to reduce pyruvate or a pyruvate derivative (X). Either lactate or reduced product Y result.

Figure 9.10 Some Common Microbial Fermentations. Only pyruvate fermentations are shown for the sake of simplicity; many other organic molecules can be fermented. Most of these pathways have been simplified by deletion of one or more steps and intermediates. Pyruvate and major end products are shown in color.





(a) Alcohol fermentation



(b) Lactic acid fermentation

Propionic Acid Fermentation

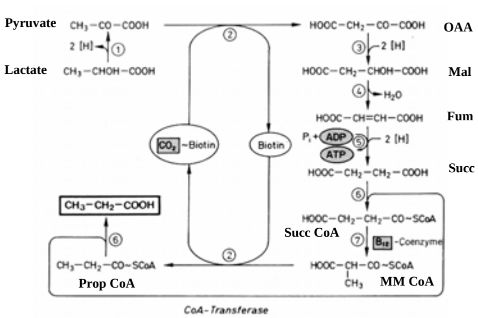
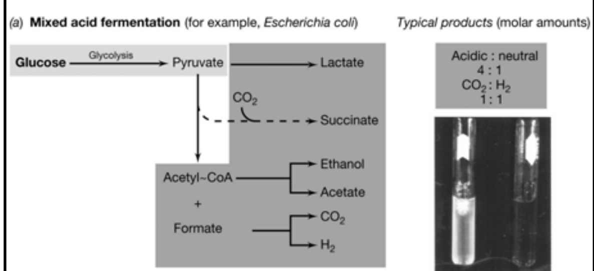
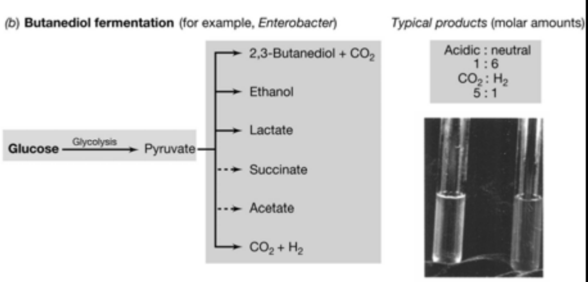


Fig. 8.3. *Methylmalonyl-CoA pathway of propionate formation.*

Enzymes: (1) lactate dehydrogenase; (2) methylmalonyl-CoA carboxy-transferase; (3) malate dehydrogenase; (4) fumarase; (5) fumarate reductase (leading to regeneration of ATP by proton translocation); (6) CoA transferase; (7) methylmalonyl-CoA mutase.



Methyl Red Test



Voges-Proskauer Test

Clostridial Fermentations

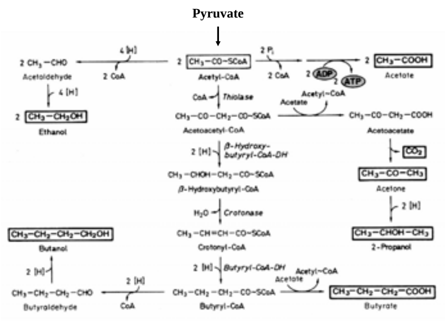


Fig. 8.4. *The formation of acetate, ethanol,* n*-butanol, butyrate, acetone, and 2-propanol during clostridial fermentations.*

Table 17.7 Examples of common bacterial fermentations and some of the organisms carrying them out

Type	Overall reaction[a]	Organisms
Alcoholic	Hexose → 2 Ethanol + 2 CO_2	Yeast *Zymomonas*
Homolactic	Hexose → 2 $Lactate^-$ + 2 H^+	*Streptococcus* Some *Lactobacillus*
Heterolactic	Hexose → $Lactate^-$ + Ethanol + CO_2 + H^+	*Leuconostoc* Some *Lactobacillus*
Propionic acid	$Lactate^-$ → $Propionate^-$ + $Acetate^-$ + CO_2	*Propionibacterium* *Clostridium propionicum*
Mixed acid	Hexose → Ethanol + 2, 3-Butanediol + $Succinate^{2-}$ + $Lactate^-$ + $Acetate^-$ + $Formate^-$ + H_2 + CO_2	Enteric bacteria[b] *Escherichia* *Salmonella* *Shigella* *Klebsiella* *Enterobacter*
Butyric acid	Hexose → $Butyrate^-$ + $Acetate^-$ + H_2 + CO_2	*Clostridium butyricum*
Butanol	Hexose → Butanol + $Acetate^-$ + Acetone + Ethanol + H_2 + CO_2	*Clostridium acetobutylicum*
Caproate	Ethanol + $Acetate^-$ + CO_2 → $Caproate^-$ + $Butyrate^-$ + H_2	*Clostridium kluyveri*
Homoacetogenic	Fructose → 3 $Acetate^-$ + 3 H^+ 2 H_2O 4 H_2 + 2 CO_2 + H^+ → $Acetate^-$ +	*Clostridium aceticum* *Acetobacterium*
Methanogenic	$Acetate^-$ + H_2O → CH_4 + HCO_3^-	*Methanosaeta* *Methanosarcina*

[a] Reactions are intended as an overview of the process and are not necessarily balanced.
[b] Not all organisms produce all products. In particular, butanediol production is limited to only certain enteric bacteria.

Table 8.2 Examples of products generated during fermentation of glucose and the microorganism involved

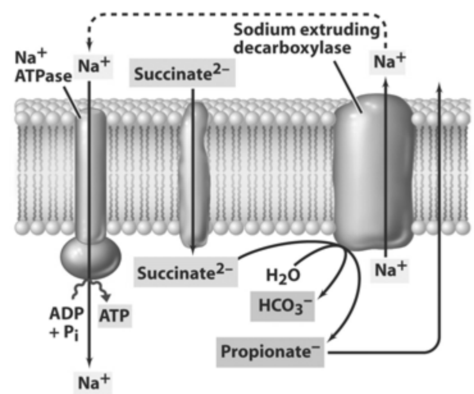
Type	Nongaseous Product	Micro-organism
Mixed acid	ethanol + acetate + lactate	*Escherichia coli*
Butanediol (neutral)	2,3-butanediol + ethanol	*Enterobacter aerogenes*
Alcoholic	ethanol	*Zymomonas mobilis*
Homolactic	lactate	*Lactobacillus acidophilus*
Heterolactic	lactate + ethanol	*Lactobacillus brevis*
Butanol/ acetone	acetone + butanol	*Clostridium butyricum*

The short list

Table 17.8 Some unusual bacterial fermentations

Type	Overall balanced reaction	Organisms
Acetylene	$2\,C_2H_2 + 3\,H_2O \rightarrow$ Ethanol + Acetate$^-$ + H^+	*Pelobacter acetylenicus*
Glycerol	4 Glycerol + $2\,HCO_3^- \rightarrow$ 7 Acetate$^-$ + $5\,H^+ + 4\,H_2O$	*Acetobacterium* sp.
Resorcinol (an aromatic compound)	$2\,C_6H_4(OH)_2 + 6\,H_2O \rightarrow$ 4 Acetate$^-$ + Butyrate$^-$ + $5\,H^+$	*Clostridium* sp.
Phloroglucinol (an aromatic compound)	$C_6H_6O_3 + 3\,H_2O \rightarrow$ 3 Acetate$^-$ + $3\,H^+$	*Pelobacter massiliensis* *Pelobacter acidigallici*
Putrescine	$10\,C_4H_{12}N_2 + 26\,H_2O \rightarrow$ 6 Acetate$^-$ + 7 Butyrate$^-$ + $20\,NH_4^+ + 16\,H_2 + 13\,H^+$	Unclassified gram-positive nonsporing anaerobes
Citrate	Citrate^{3-} + $2\,H_2O \rightarrow$ Formate$^-$ + 2 Acetate$^-$ + $HCO_3^- + H^+$	*Bacteroides* sp.
Aconitate	Aconitate^{3-} + $H^+ + 2\,H_2O \rightarrow 2\,CO_2$ + 2 Acetate$^-$ + H_2	*Acidaminococcus fermentans*
Glyoxylate	4 Glyoxylate$^-$ + $3\,H^+ + 3\,H_2O \rightarrow 6\,CO_2 + 5\,H_2$ + Glycolate$^-$	Unclassified gram-negative bacterium
Succinate	Succinate^{2-} + $H_2O \rightarrow$ Propionate$^-$ + HCO_3^-	*Propionigenium modestum*
Oxalate	Oxalate^{2-} + $H_2O \rightarrow$ Formate$^-$ + HCO_3^-	*Oxalobacter formigenes*
Malonate	Malonate^{2-} + $H_2O \rightarrow$ Acetate$^-$ + HCO_3^-	*Malonomonas rubra* *Sporomusa malonica*
Benzoate	2 Benzoate$^-$ $\rightarrow$ Cyclohexane carboxylate$^-$ + 3 Acetate$^-$ + HCO_3^- + $3H^+$	*Syntrophus aciditrophicus*

The unusual fermentations of succinate and oxalate



The unusual fermentations of succinate and oxalate