Microbes as Energy Transducers

- The Metabolic Menu
- Metabolic Strategies
- Respiration & Fermentation
- Chemolithotrophy
- Photoautotrophy
- Biogeochemical Cycles
- Metabolism in Early Microbes

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

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

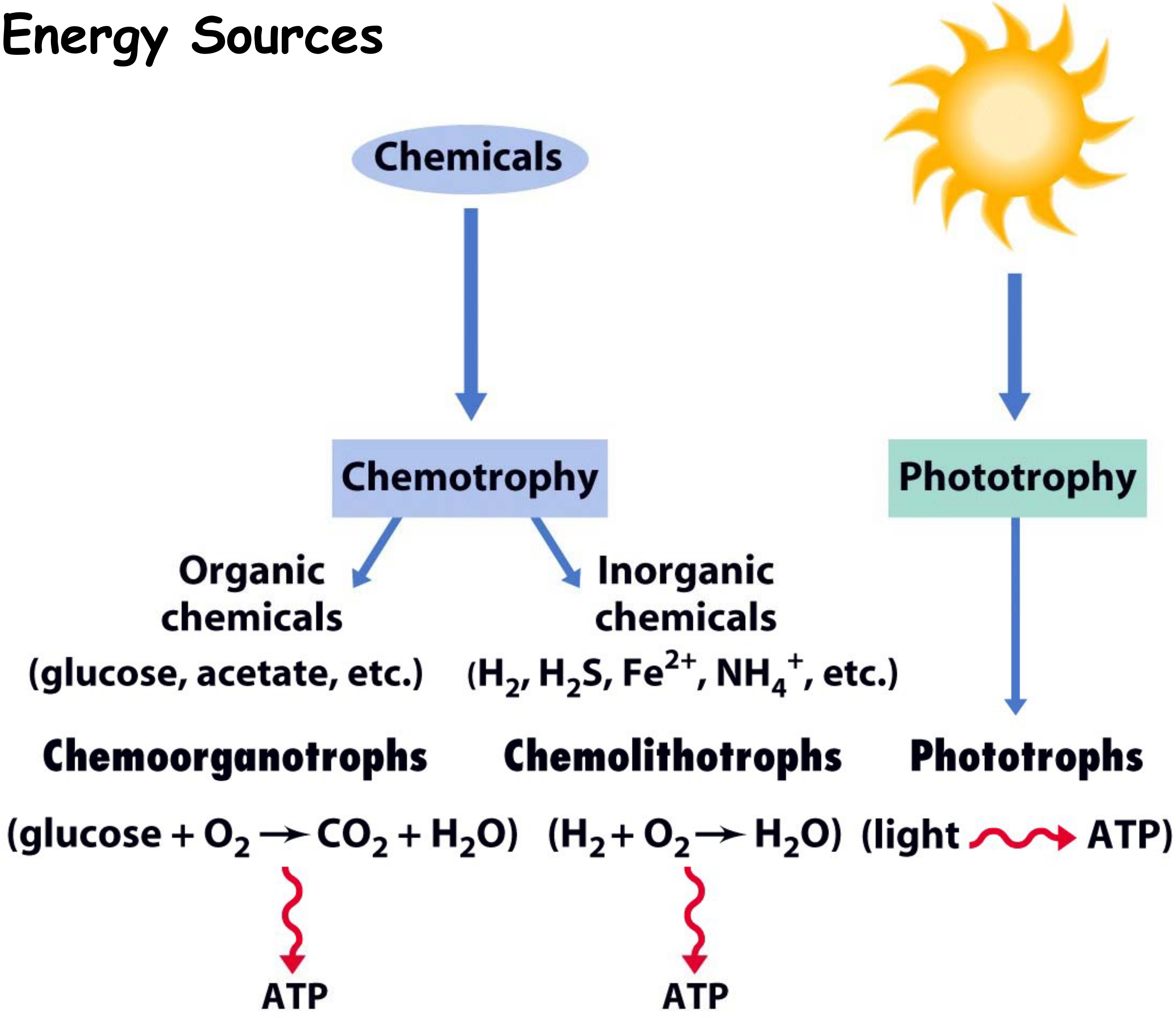
Major Modes of Nutrition:

Microbes 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)**.

Energy Sources



Chemicals

Chemotrophy

Organic chemicals (glucose, acetate, etc.)

Inorganic chemicals (H_2, H_2S, Fe^{2+}, NH_4^+, etc.)

Chemoorganotrophs

($glucose + O_2 \rightarrow CO_2 + H_2O$)

ATP

Chemolithotrophs

($H_2 + O_2 \rightarrow H_2O$)

ATP

Phototrophy

Phototrophs

(light $\rightsquigarrow$ ATP)

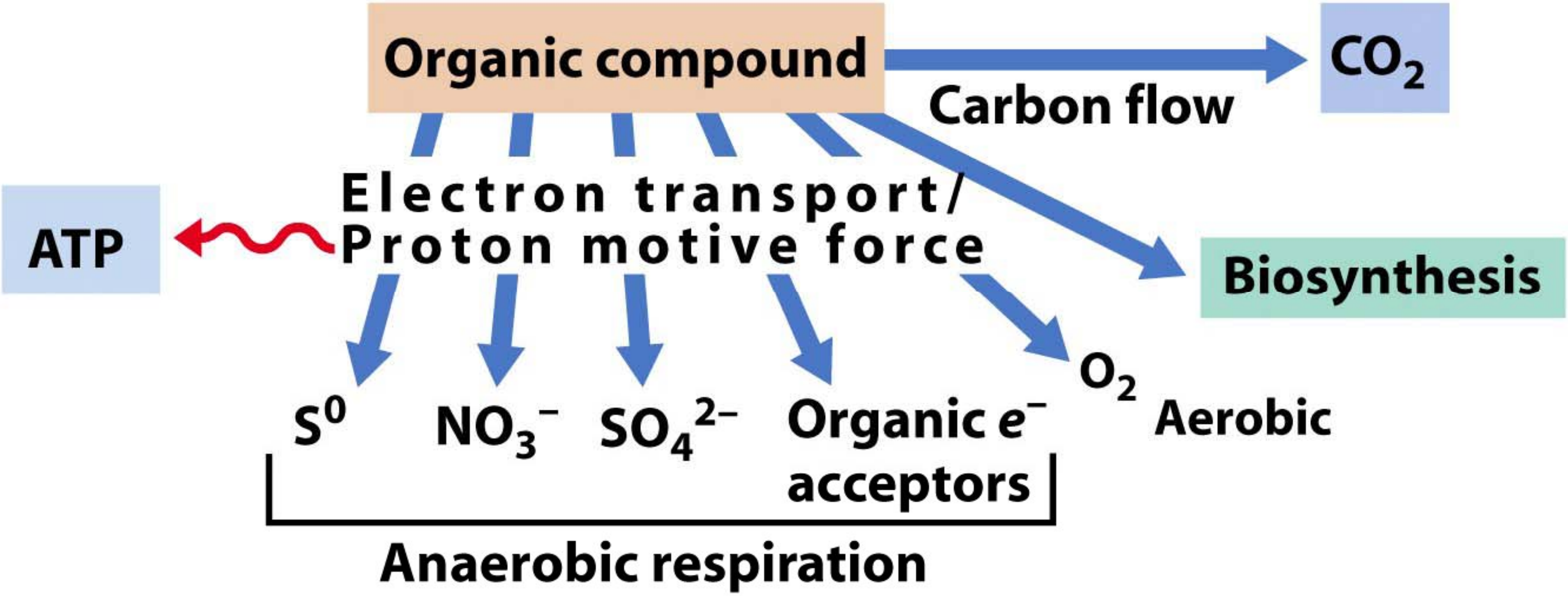
Depending upon the energy source **AND** the carbon source, microbes have **four** possible nutritional modes:

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 microbes.

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

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



Organic compound

Carbon flow

CO_2

Biosynthesis

ATP

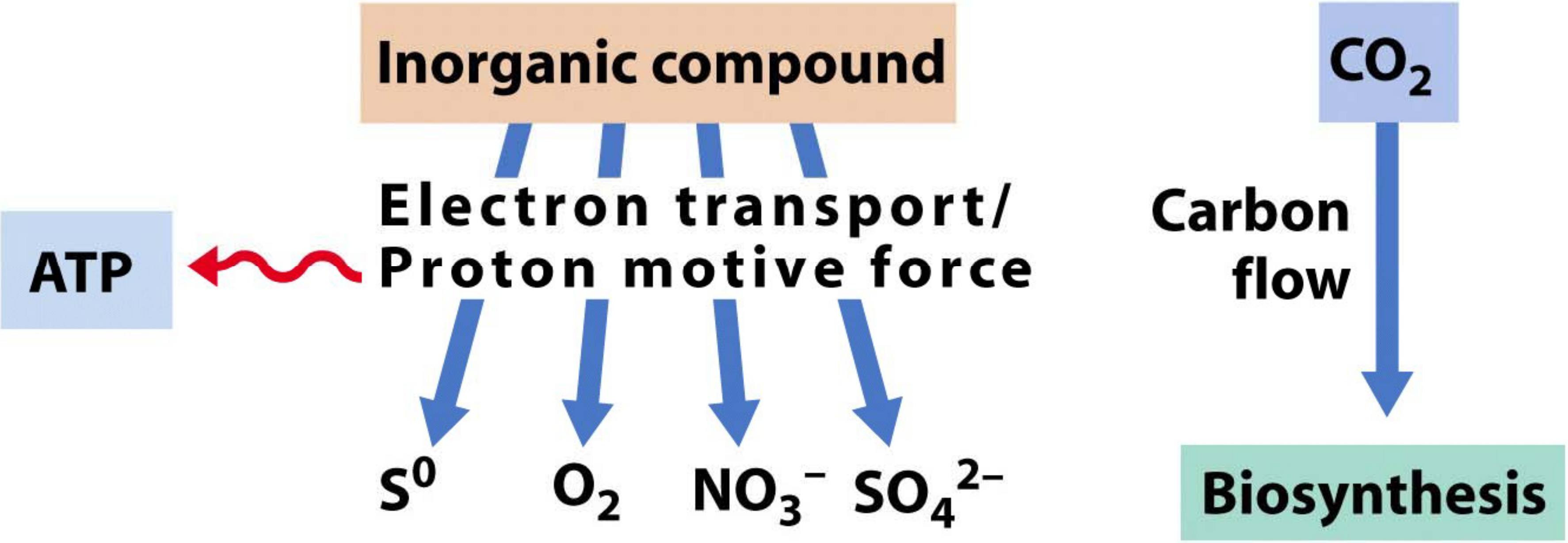
Electron transport/Proton motive force

S^0 NO_3^- SO_4^{2-} Organic e^- acceptors

Anaerobic respiration

O_2 Aerobic

Chemoorganotrophic metabolism



Inorganic compound

Electron transport/ Proton motive force

ATP

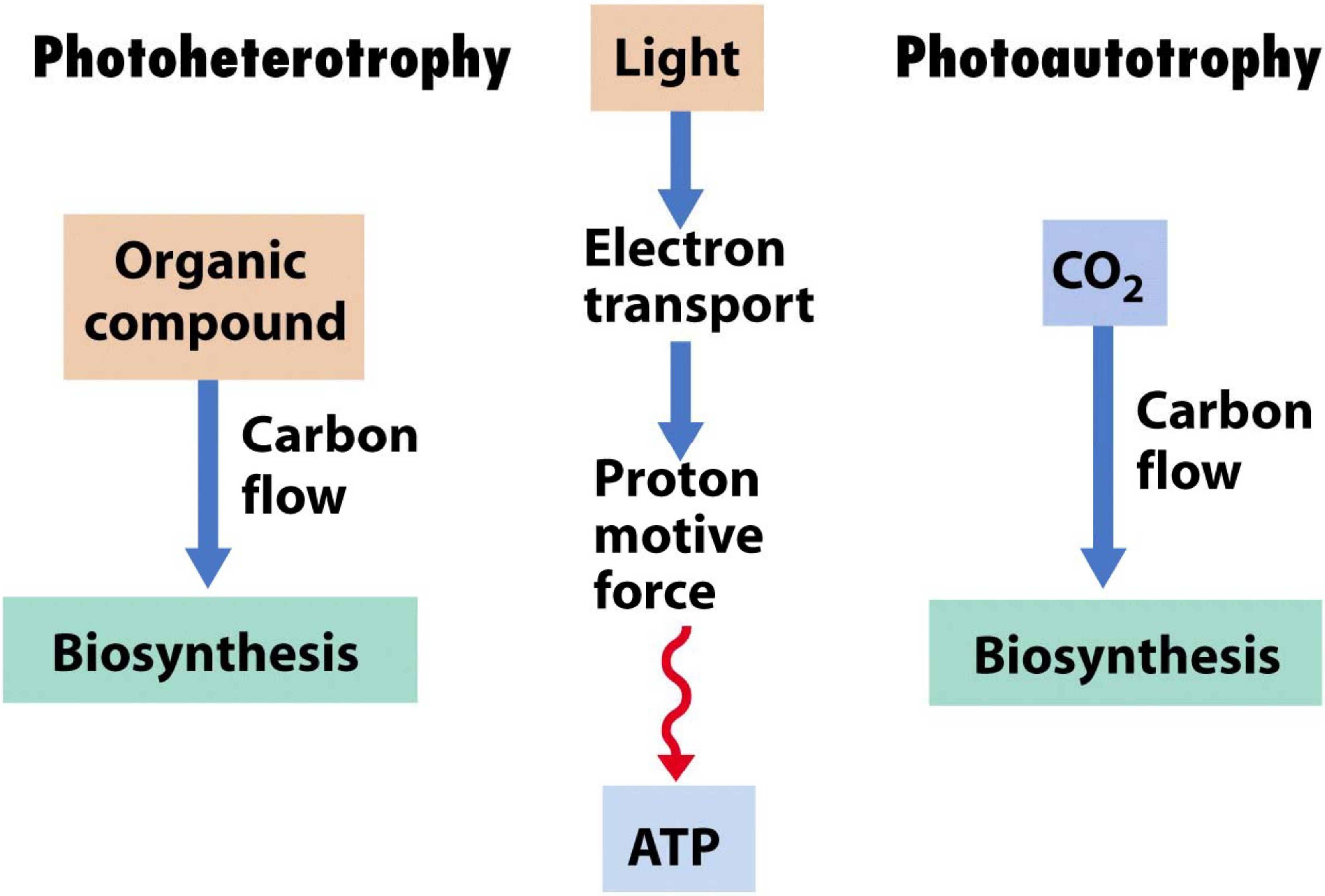
S^0 O_2 NO_3^- SO_4^{2-}

CO_2

Carbon flow

Biosynthesis

Chemolithotrophic metabolism



Photoheterotrophy

Light

Photoautotrophy

Organic compound

Carbon flow

Biosynthesis

Electron transport

Proton motive force

ATP

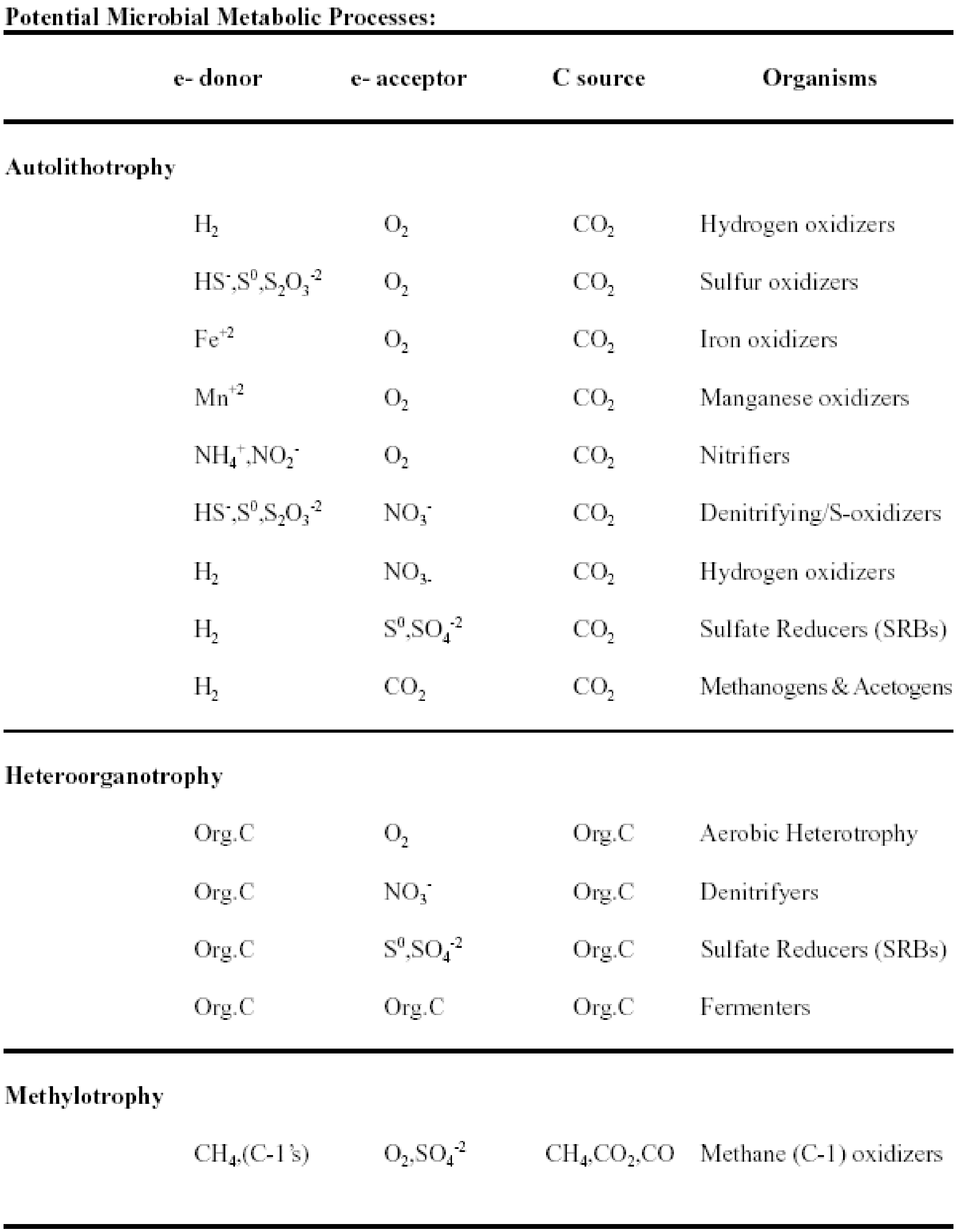
CO_2

Carbon flow

Biosynthesis

Phototrophic metabolism

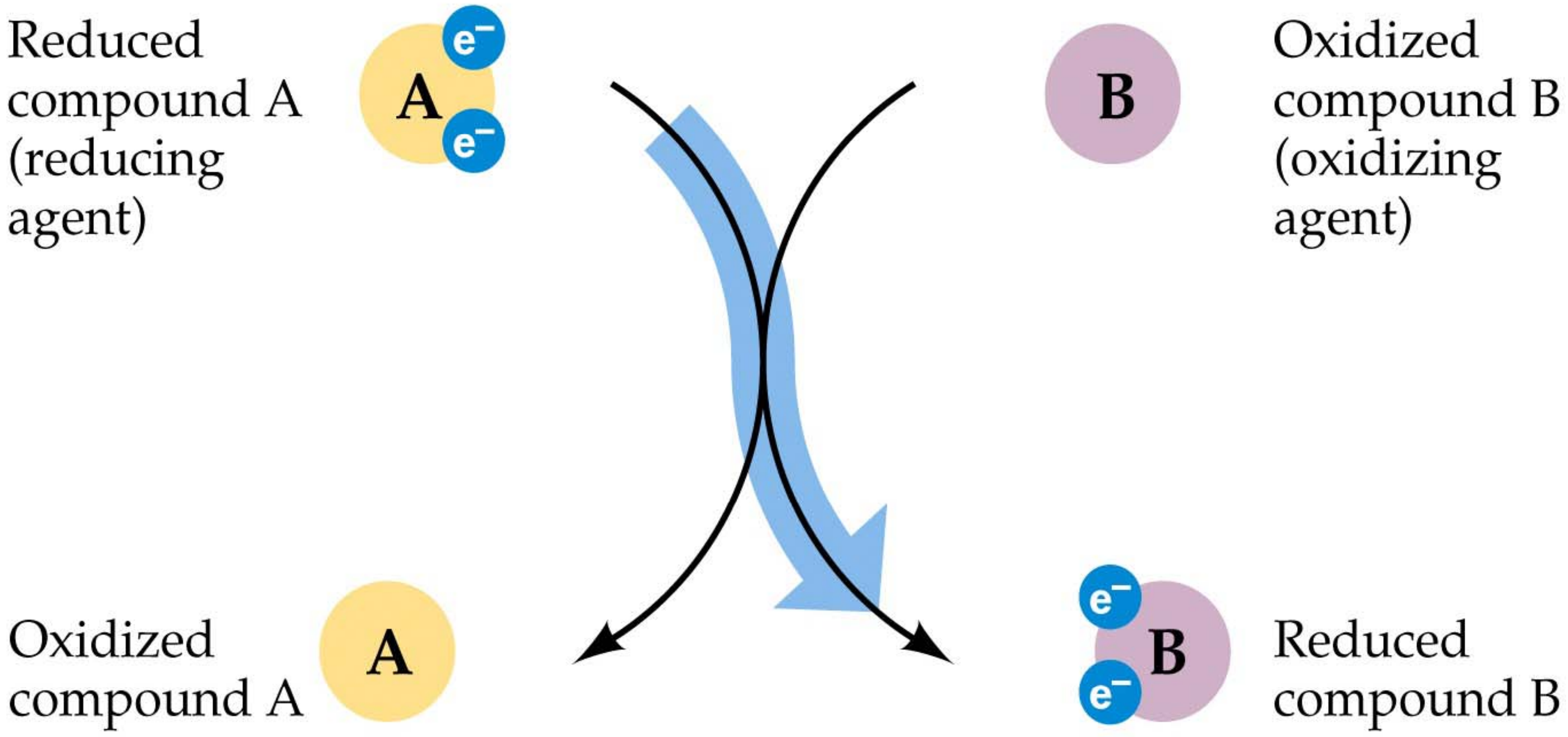
Metabolic Menu For Chemotrophs



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

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

Electron-accepting half reaction

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

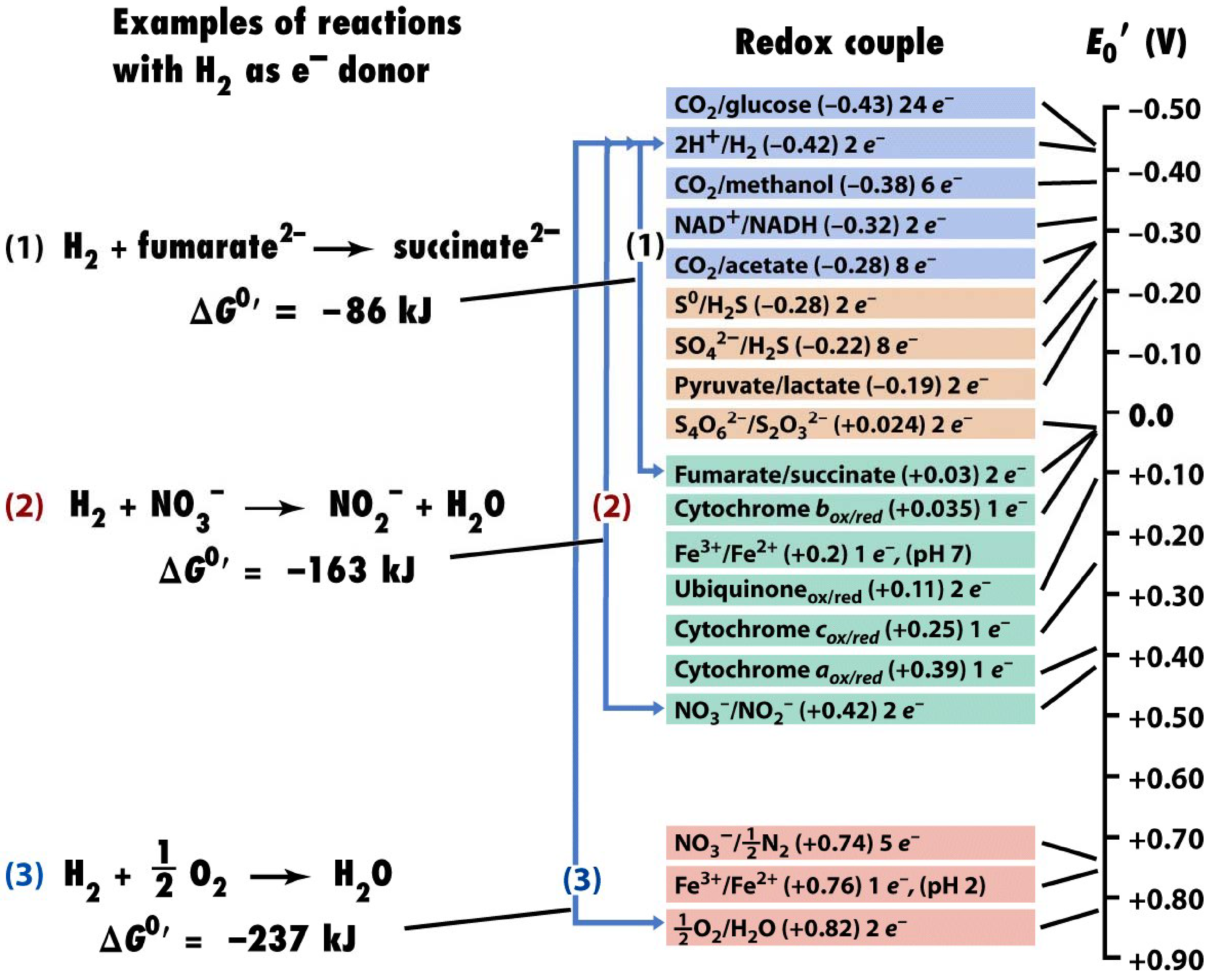
Formation of water

Electron donor

$$H_2 + \tfrac{1}{2}O_2 \rightarrow H_2O$$

Electron acceptor

Net reaction



Examples of reactions with H_2 as e^- donor

(1) $H_2 + \text{fumarate}^{2-} \longrightarrow \text{succinate}^{2-}$

$\Delta G^{0\prime} = -86$ kJ

(2) $H_2 + NO_3^- \longrightarrow NO_2^- + H_2O$

$\Delta G^{0\prime} = -163$ kJ

(3) $H_2 + \frac{1}{2} O_2 \longrightarrow H_2O$

$\Delta G^{0\prime} = -237$ kJ

Redox couple

CO_2/glucose (−0.43) 24 e^-

$2H^+/H_2$ (−0.42) 2 e^-

CO_2/methanol (−0.38) 6 e^-

NAD^+/NADH (−0.32) 2 e^-

CO_2/acetate (−0.28) 8 e^-

S^0/H_2S (−0.28) 2 e^-

SO_4^{2-}/H_2S (−0.22) 8 e^-

Pyruvate/lactate (−0.19) 2 e^-

$S_4O_6^{2-}/S_2O_3^{2-}$ (+0.024) 2 e^-

Fumarate/succinate (+0.03) 2 e^-

Cytochrome $b_{ox/red}$ (+0.035) 1 e^-

Fe^{3+}/Fe^{2+} (+0.2) 1 e^-, (pH 7)

Ubiquinone$_{ox/red}$ (+0.11) 2 e^-

Cytochrome $c_{ox/red}$ (+0.25) 1 e^-

Cytochrome $a_{ox/red}$ (+0.39) 1 e^-

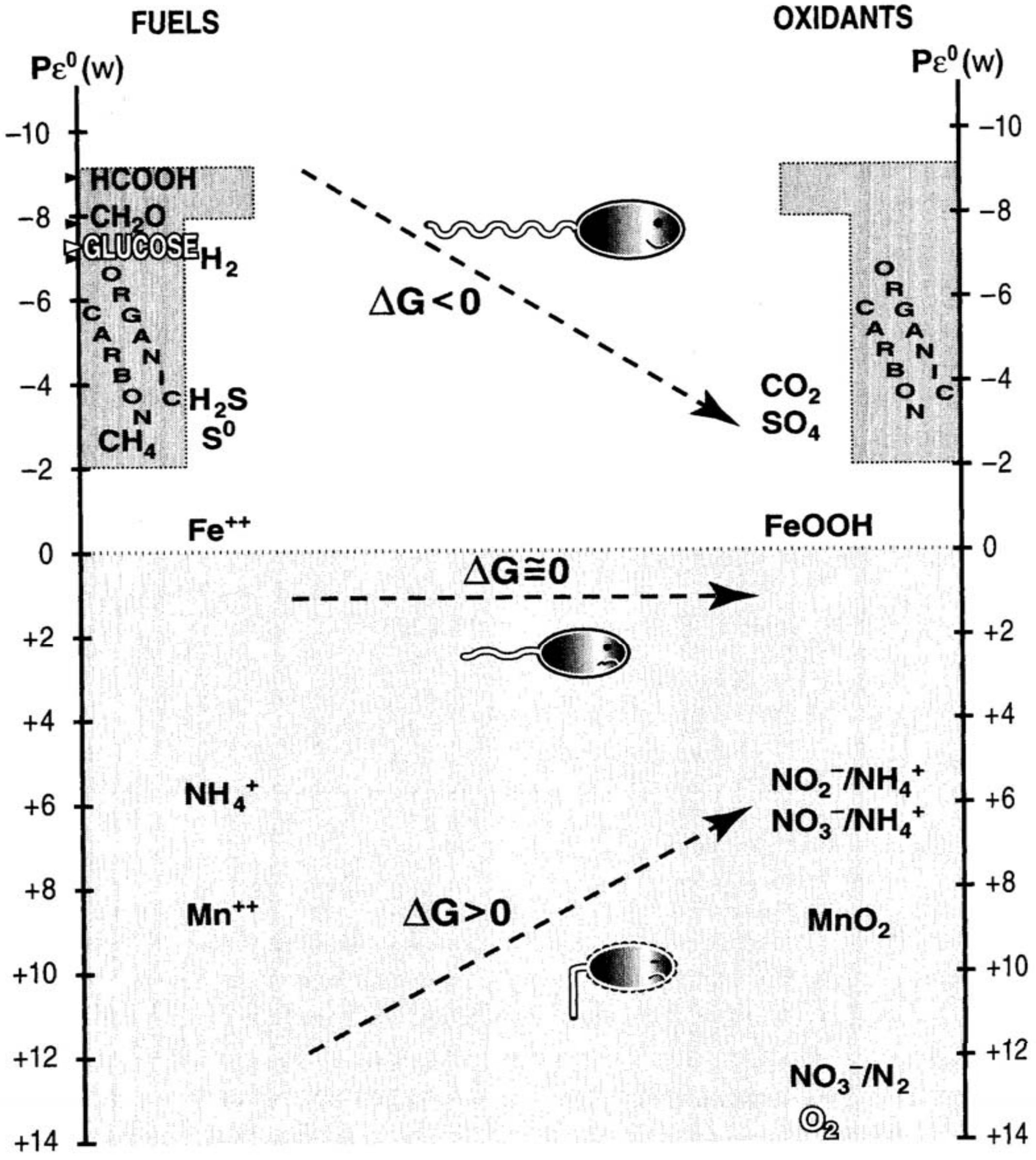
NO_3^-/NO_2^- (+0.42) 2 e^-

$NO_3^-/\frac{1}{2}N_2$ (+0.74) 5 e^-

Fe^{3+}/Fe^{2+} (+0.76) 1 e^-, (pH 2)

$\frac{1}{2}O_2/H_2O$ (+0.82) 2 e^-

Thermodynamics: The Chemical Fuels and Oxidants of Life

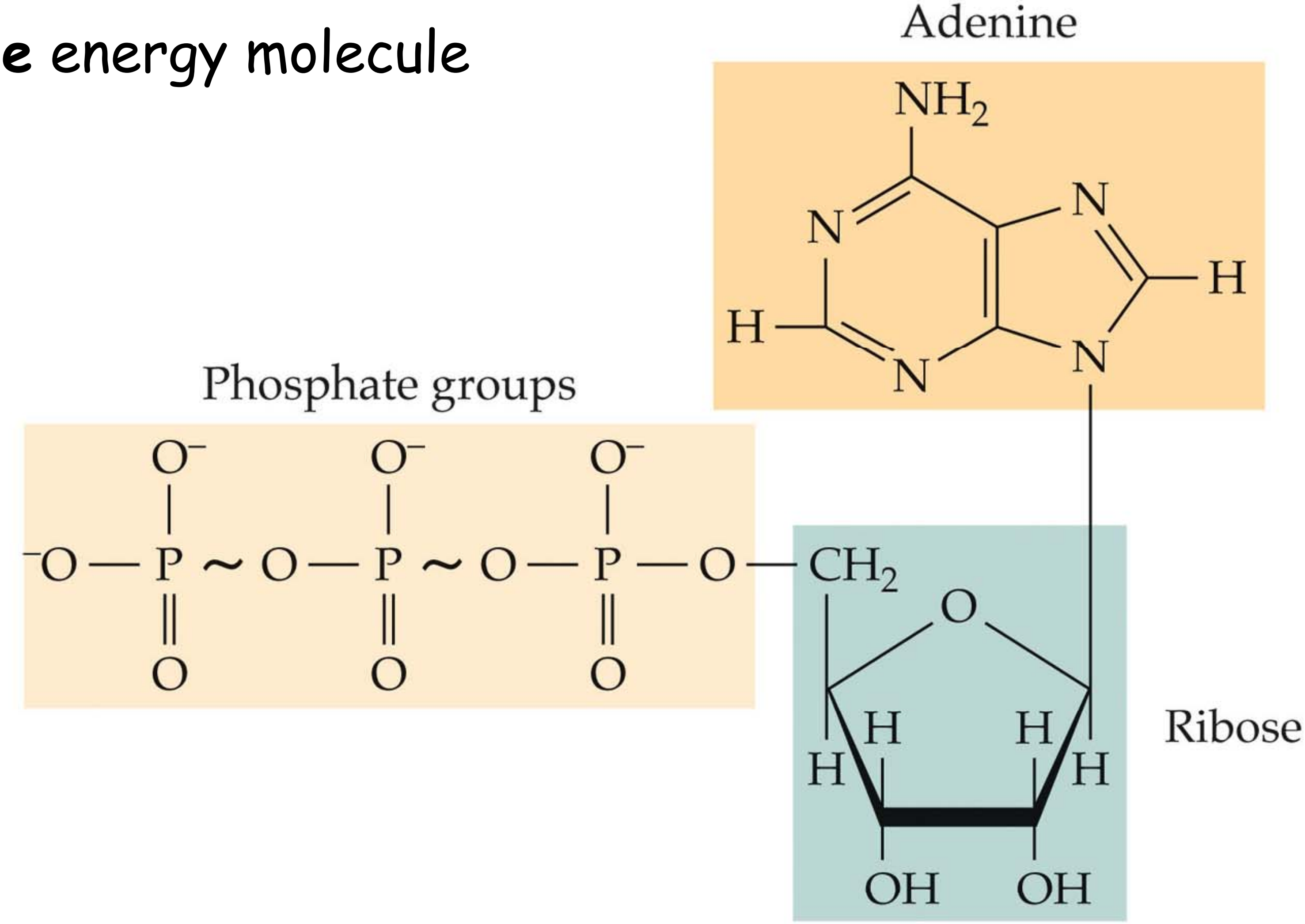


e- source

e- sink

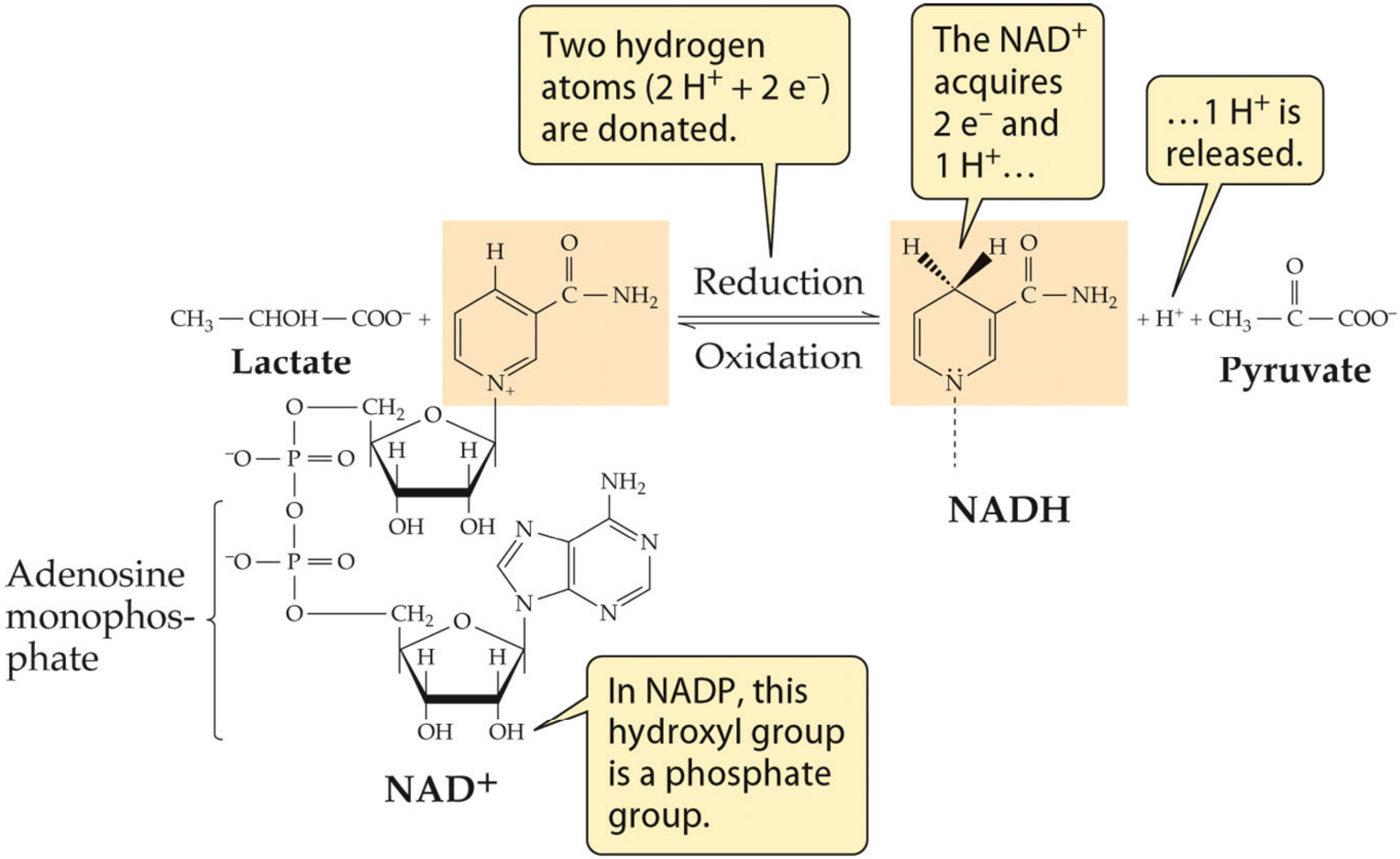
Adenosine-5'-triphosphate (ATP)

The energy molecule



Adenosine triphosphate

Nicotinamide adenine dinucleotide (NAD)


Two hydrogen atoms (2 H^+ + 2 e^-) are donated.

The NAD^+ acquires 2 e^- and 1 H^+…

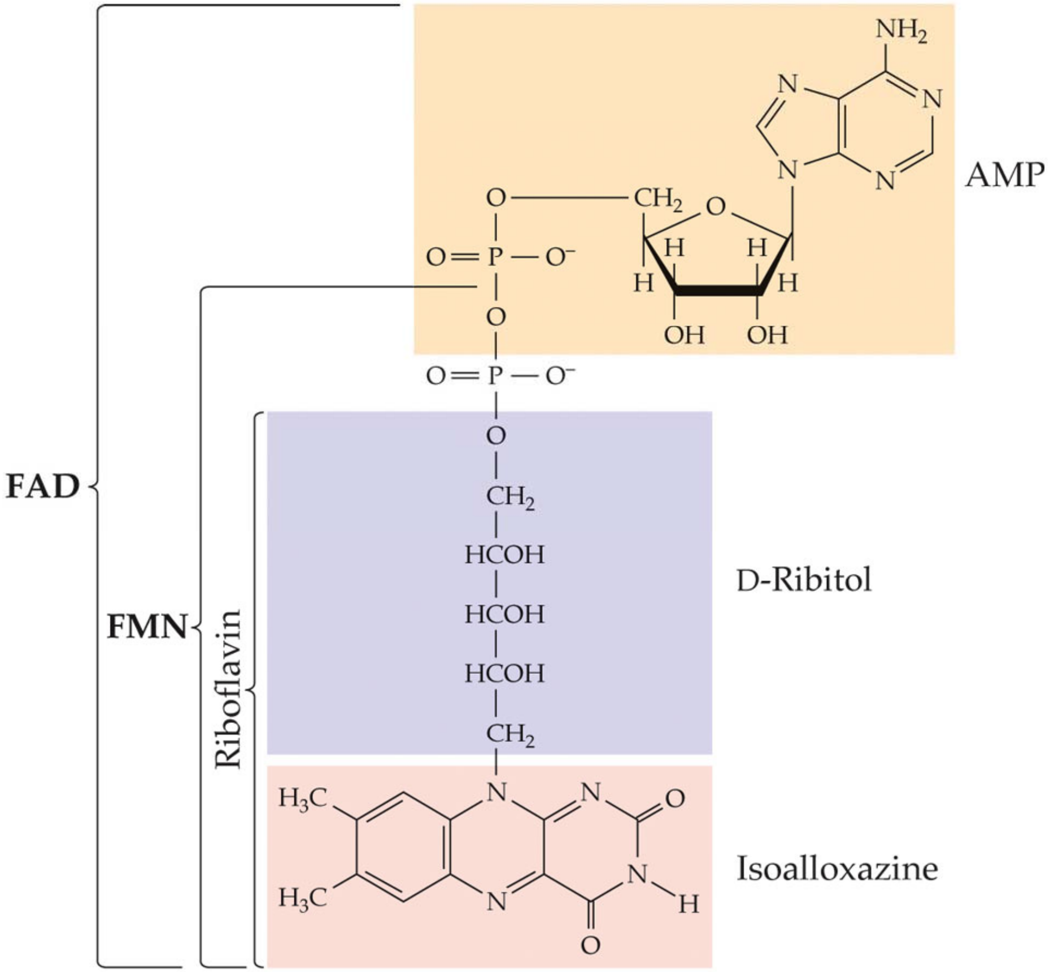
…1 H^+ is released.

In NADP, this hydroxyl group is a phosphate group.

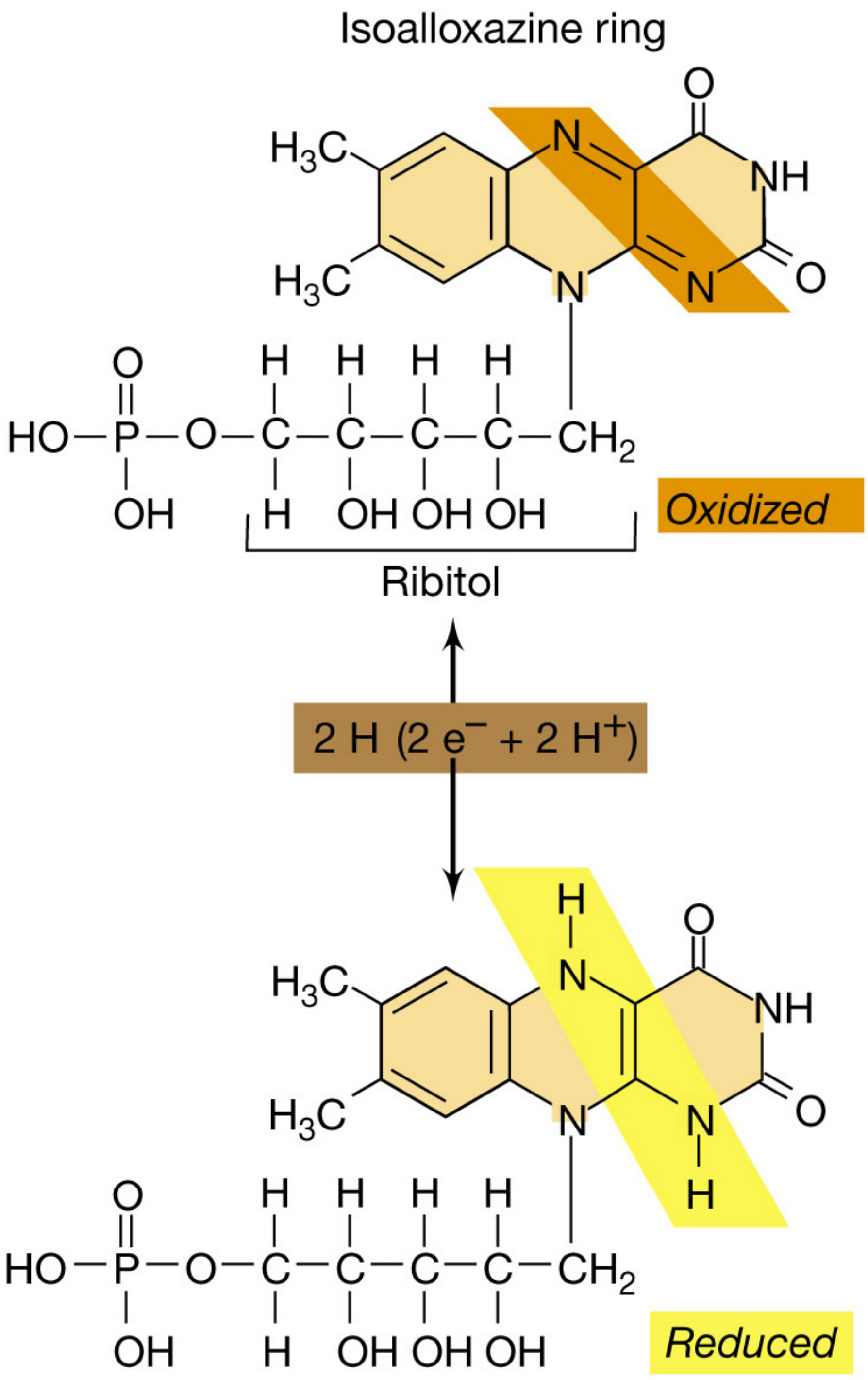
The redox molecule

Flavin nucleotides, components of flavoproteins

Specialty redox molecule

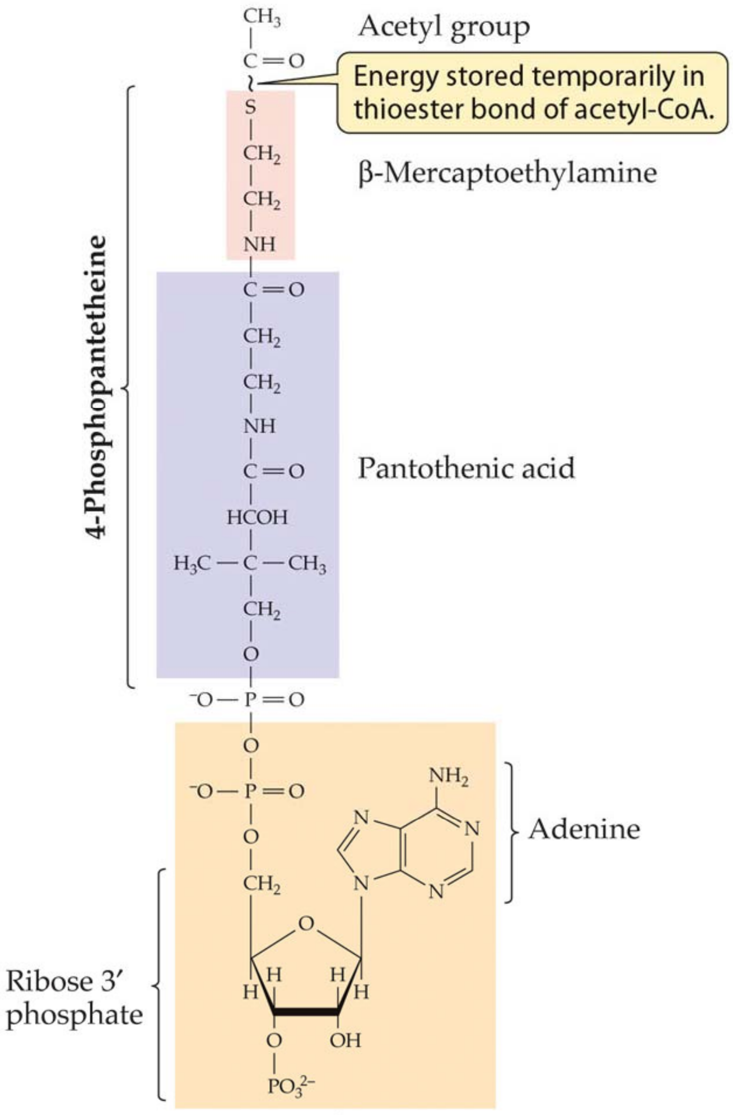


Flavin nucleotides


Isoalloxazine ring
Ribitol
Oxidized
2 H (2 e⁻ + 2 H⁺)
Reduced

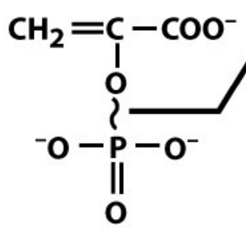
Acetyl-coenzyme A (acetyl-CoA)

Specialty energy molecule

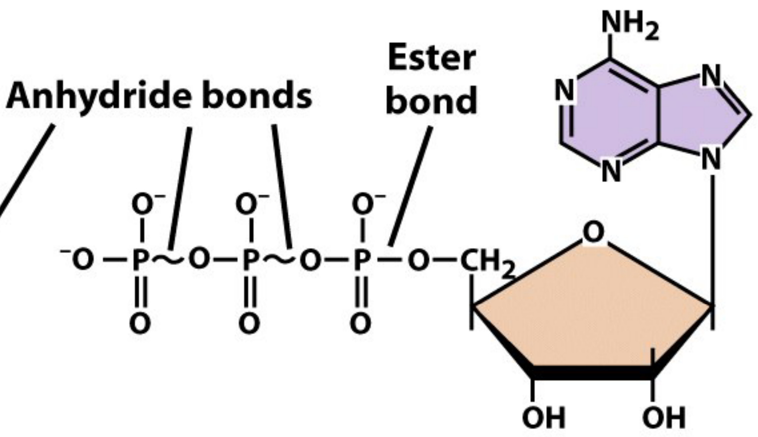


Energy stored temporarily in thioester bond of acetyl-CoA.

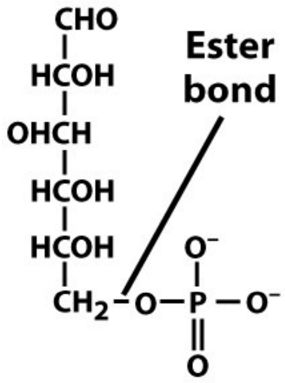
Acetyl-CoA



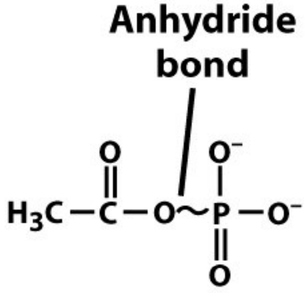
Phosphoenolpyruvate



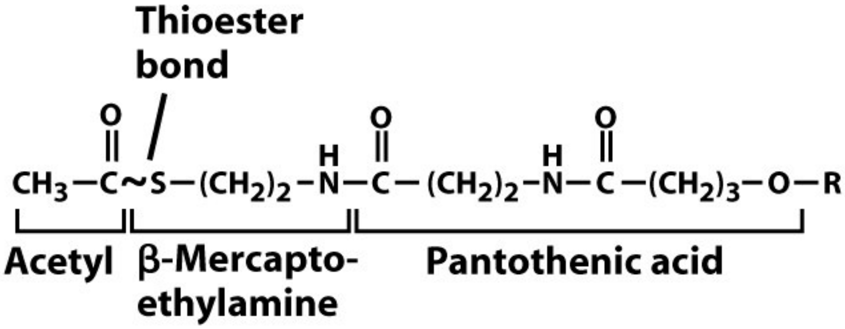
Adenosine triphosphate (ATP)



Glucose 6-phosphate



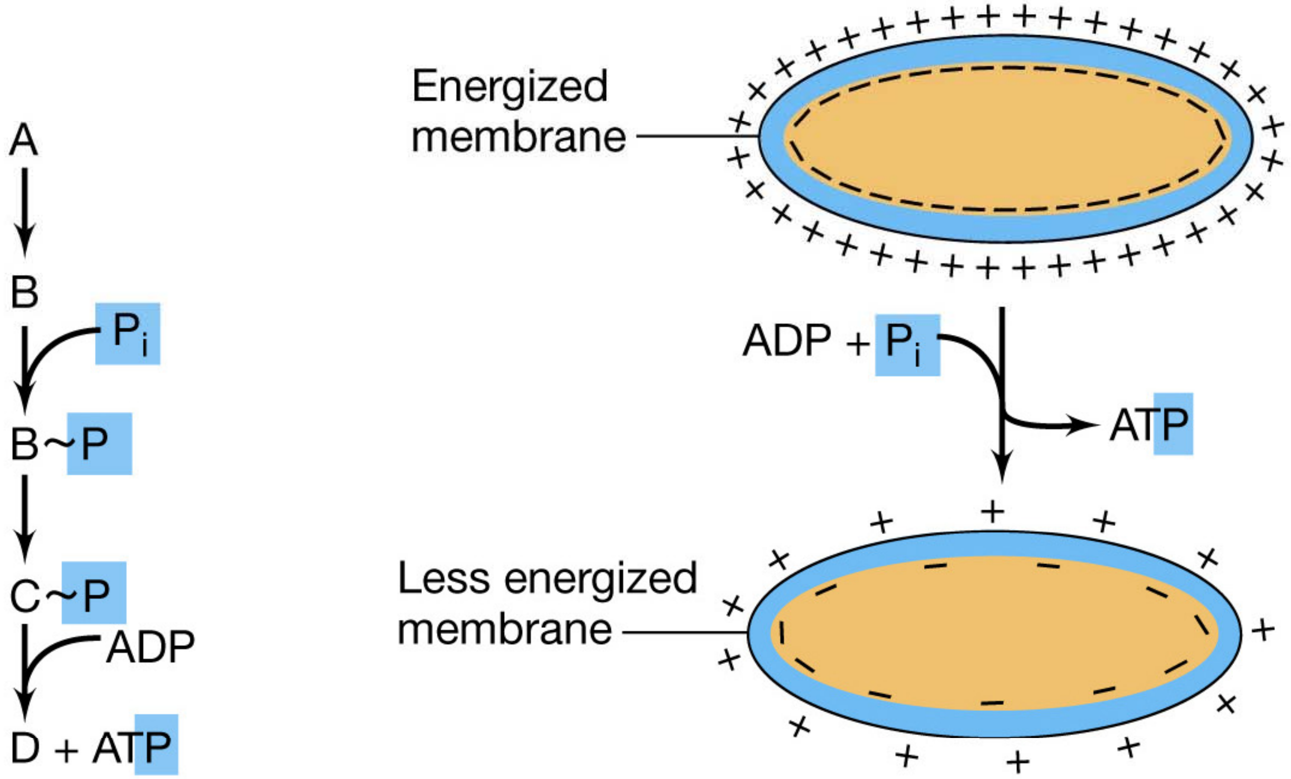
Acetyl phosphate



Acetyl-CoA

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

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

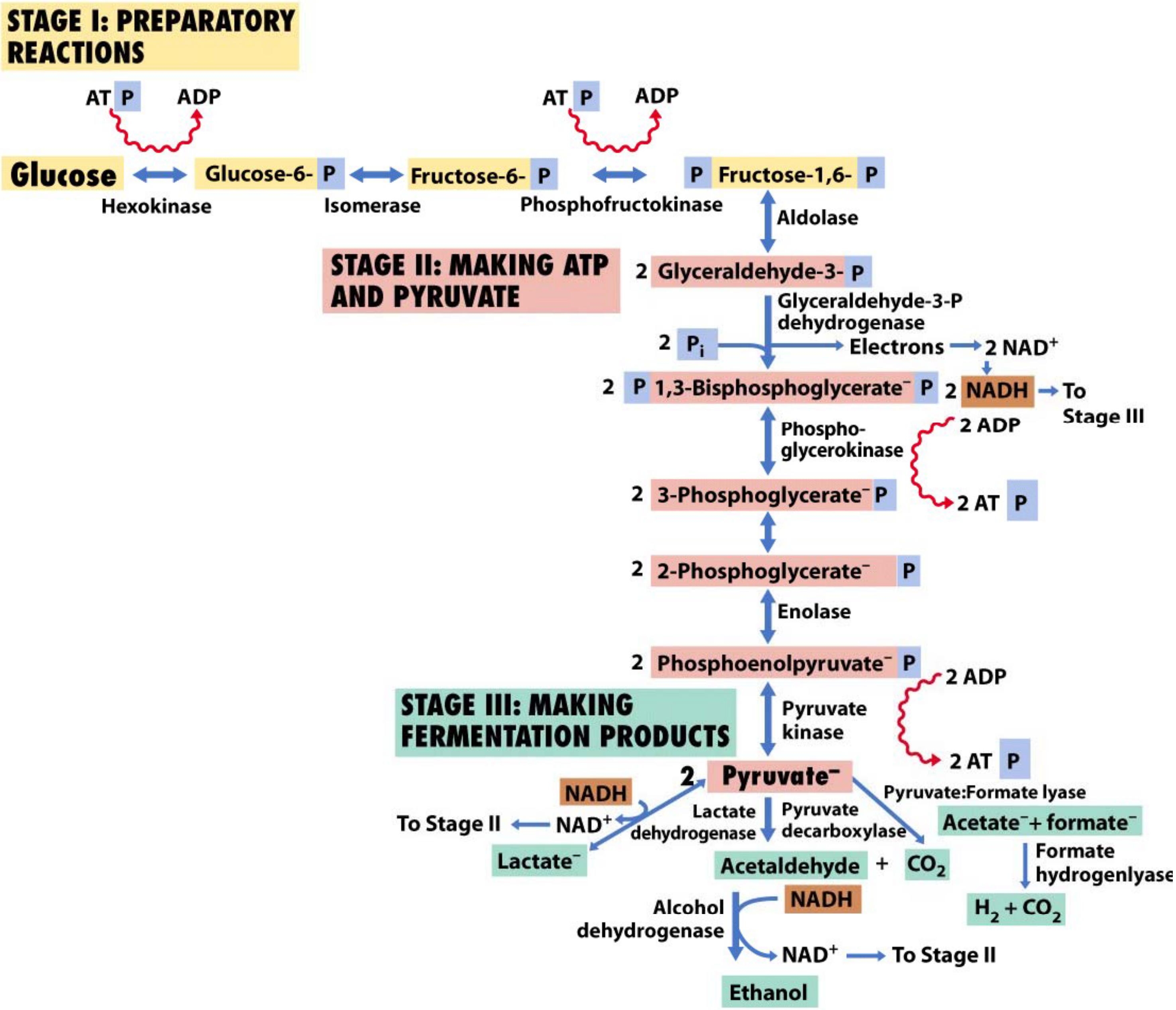


***(a)* Substrate-level phosphorylation**

***(b)* Oxidative phosphorylation**

7.1 Cellular Locations for Energy Pathways in Eukaryotes and Prokaryotes

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



STAGE I: PREPARATORY REACTIONS

ATP → ADP

Glucose ⟷ Glucose-6-P ⟷ Fructose-6-P ⟷ P Fructose-1,6-P

Hexokinase

Isomerase

ATP → ADP

Phosphofructokinase

Aldolase

STAGE II: MAKING ATP AND PYRUVATE

2 Glyceraldehyde-3-P

Glyceraldehyde-3-P dehydrogenase

2 P_i

Electrons → 2 NAD^+

2 P 1,3-Bisphosphoglycerate$^-$ P

2 NADH → To Stage III

Phosphoglycerokinase

2 ADP → 2 ATP

2 3-Phosphoglycerate$^-$ P

2 2-Phosphoglycerate$^-$ P

Enolase

2 Phosphoenolpyruvate$^-$ P

Pyruvate kinase

2 ADP → 2 ATP

STAGE III: MAKING FERMENTATION PRODUCTS

2 Pyruvate$^-$

NADH

To Stage II ← NAD^+

Lactate dehydrogenase

Lactate$^-$

Pyruvate decarboxylase

Acetaldehyde + CO_2

Alcohol dehydrogenase

NADH

NAD^+ → To Stage II

Ethanol

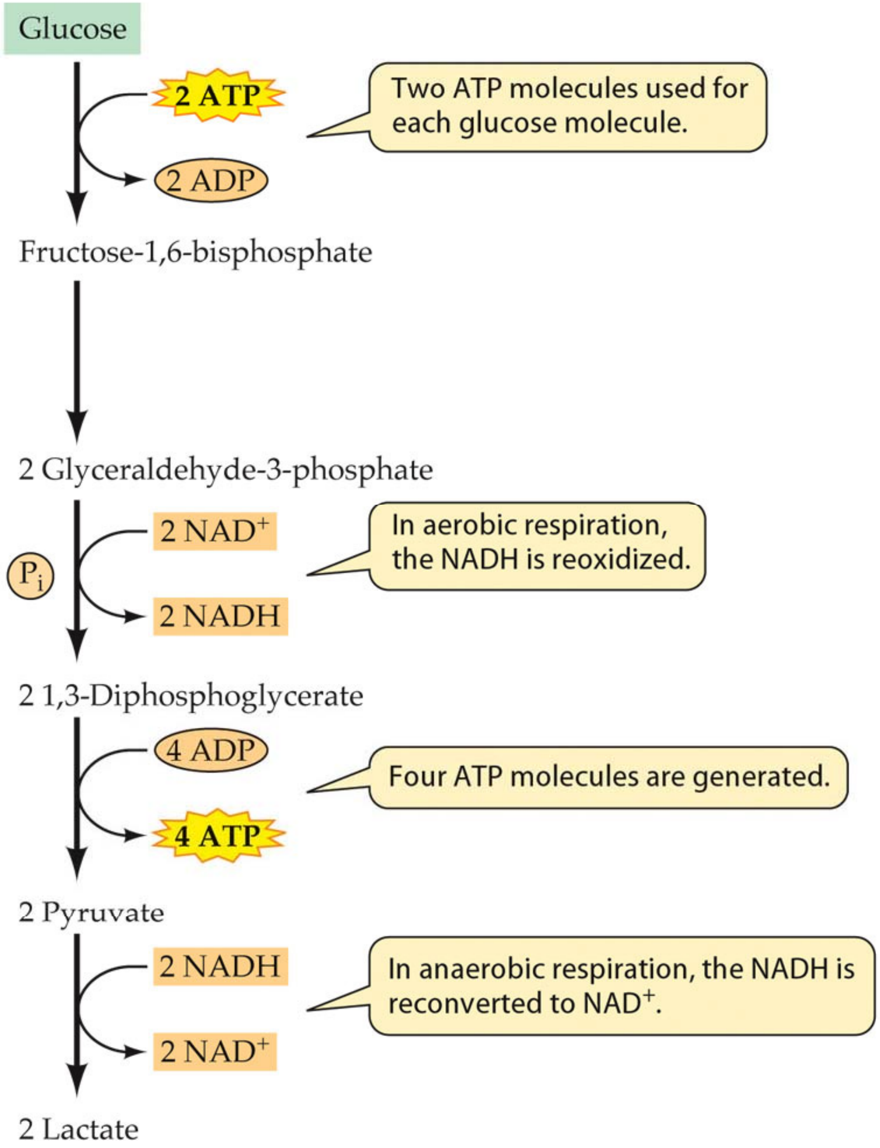
Pyruvate:Formate lyase

Acetate$^-$ + formate$^-$

Formate hydrogenlyase

$H_2 + CO_2$

Glycolysis: Short Form



Glucose

2 ATP

2 ADP

Two ATP molecules used for each glucose molecule.

Fructose-1,6-bisphosphate

2 Glyceraldehyde-3-phosphate

P_i

2 NAD^+

2 NADH

In aerobic respiration, the NADH is reoxidized.

2 1,3-Diphosphoglycerate

4 ADP

4 ATP

Four ATP molecules are generated.

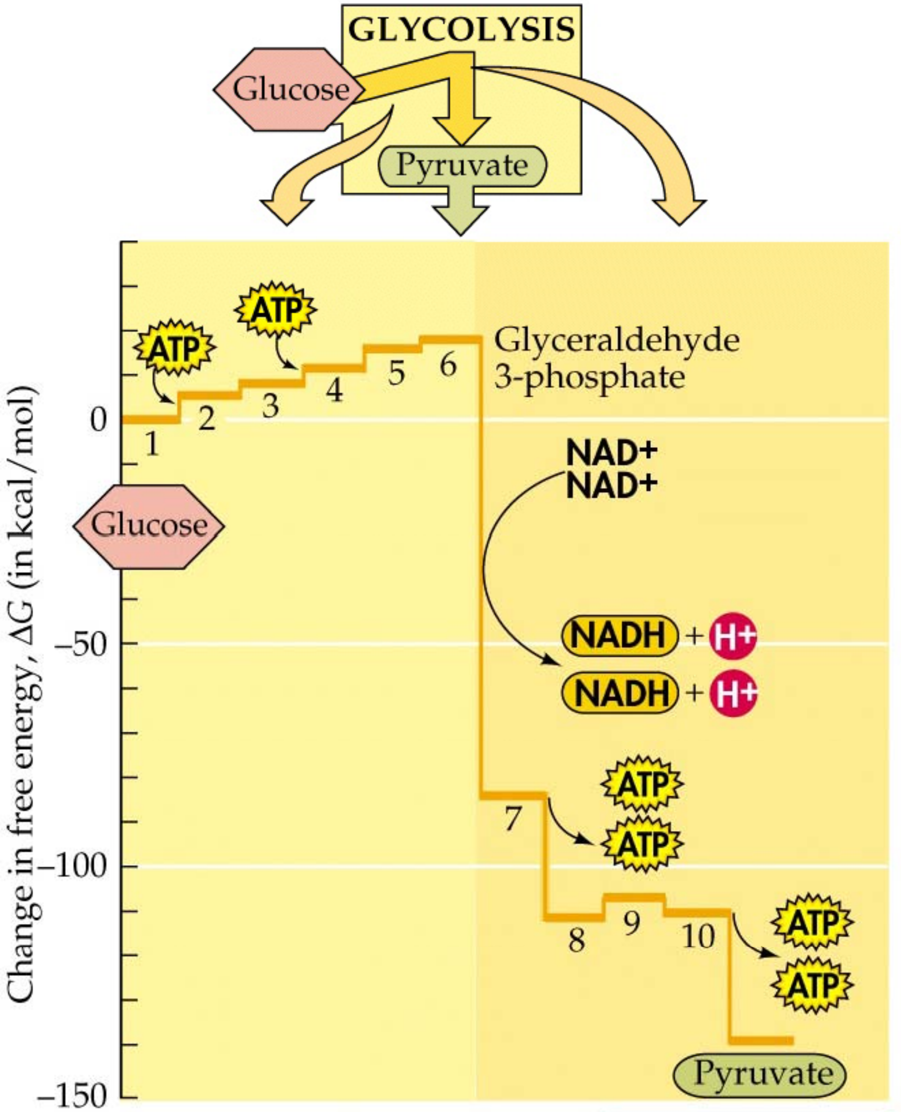
2 Pyruvate

2 NADH

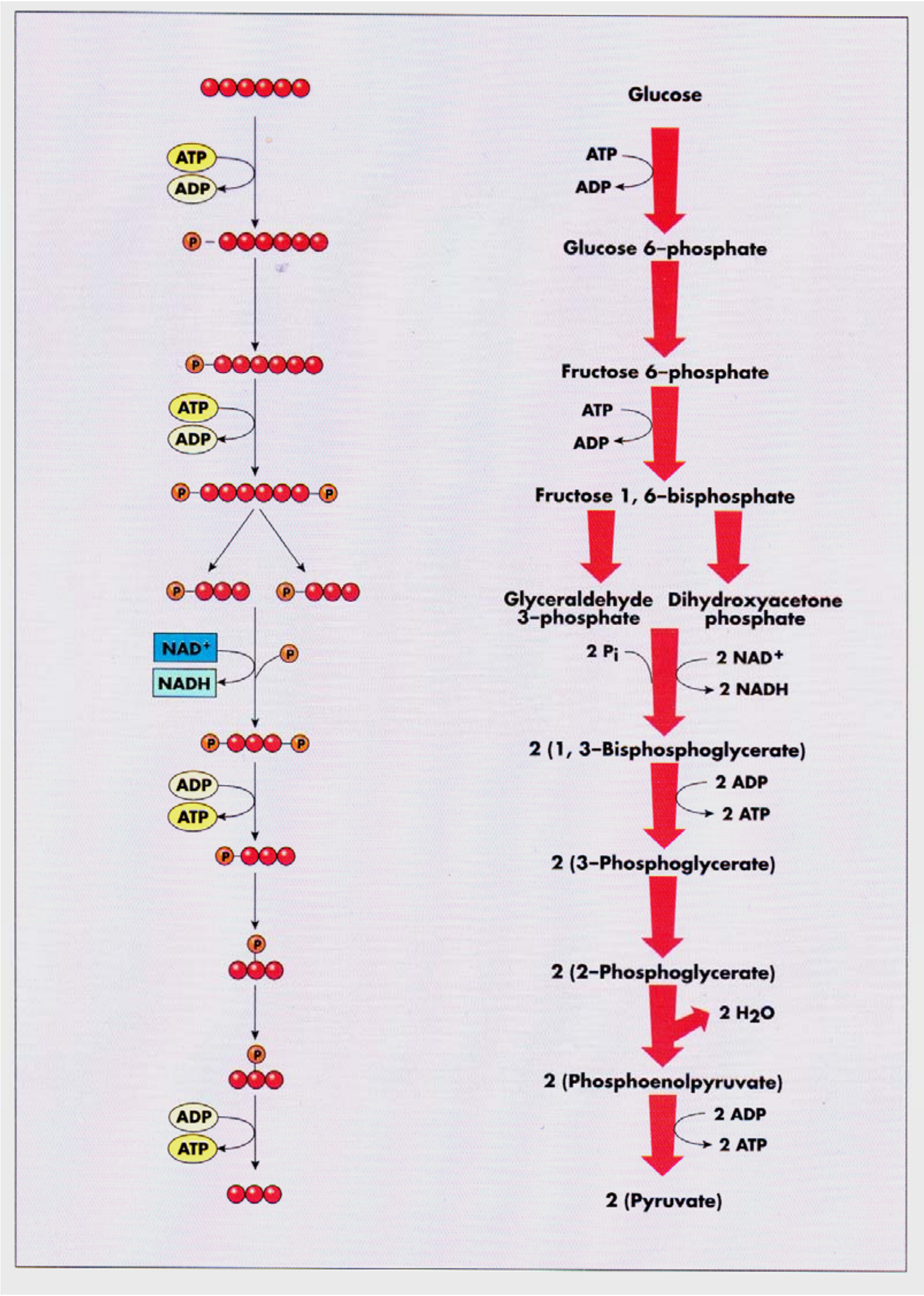
2 NAD^+

In anaerobic respiration, the NADH is reconverted to NAD^+.

2 Lactate



For each glucose:
2 Pyruvate
2 NADH + 2 H^+
2 ATP are produced.



Glycolysis aka Embden-Meyerhof

The short form!

4 ATP / 2 Net
2 NADH+H

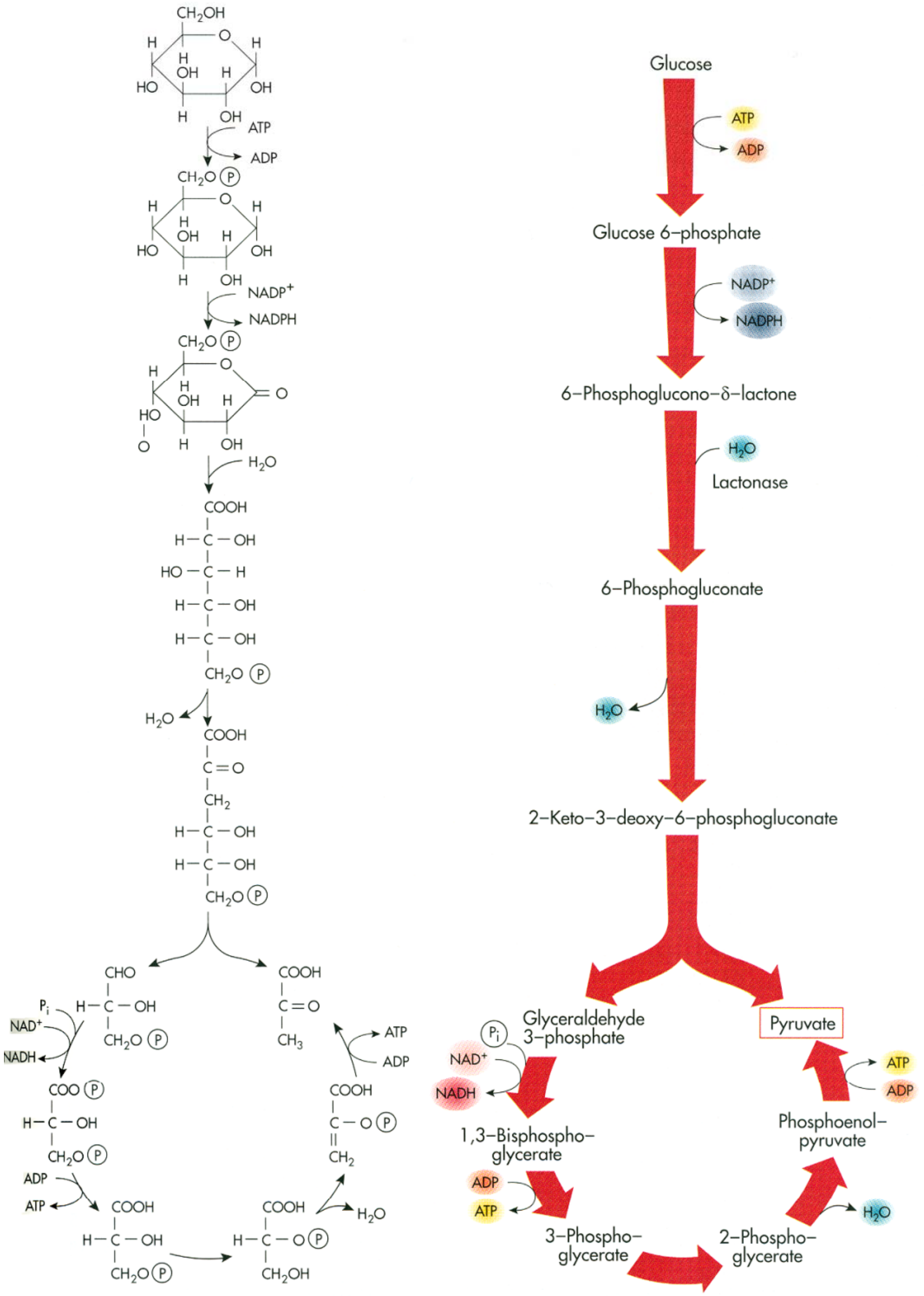


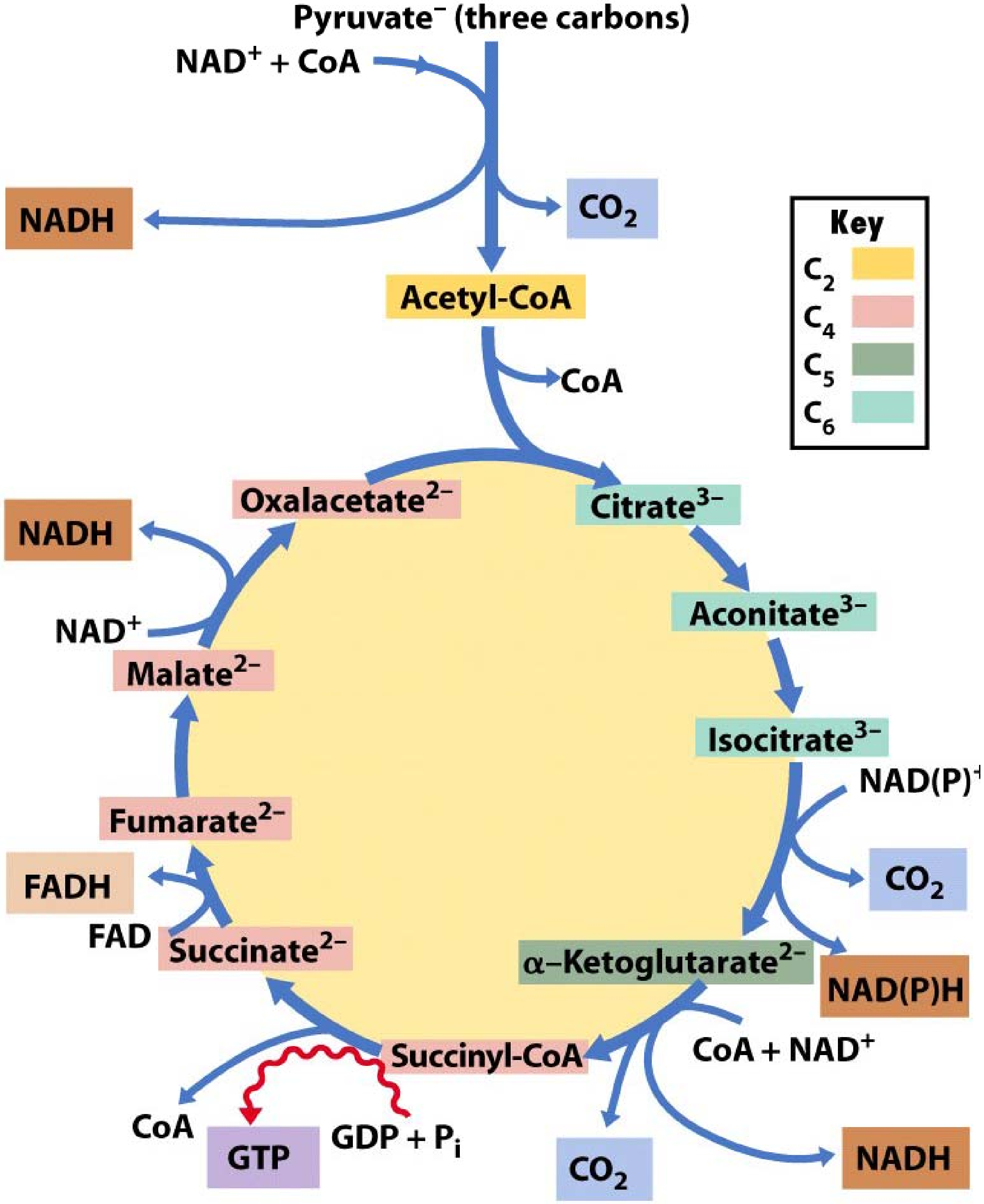
Fig. 4-5 Entner-Doudoroff Pathway of Glycolysis. The Entner-Doudoroff pathway is one of several types of glycolysis. Compared to the Embden-Myerhof pathway, less ATP is generated when this metabolic pathway is used.

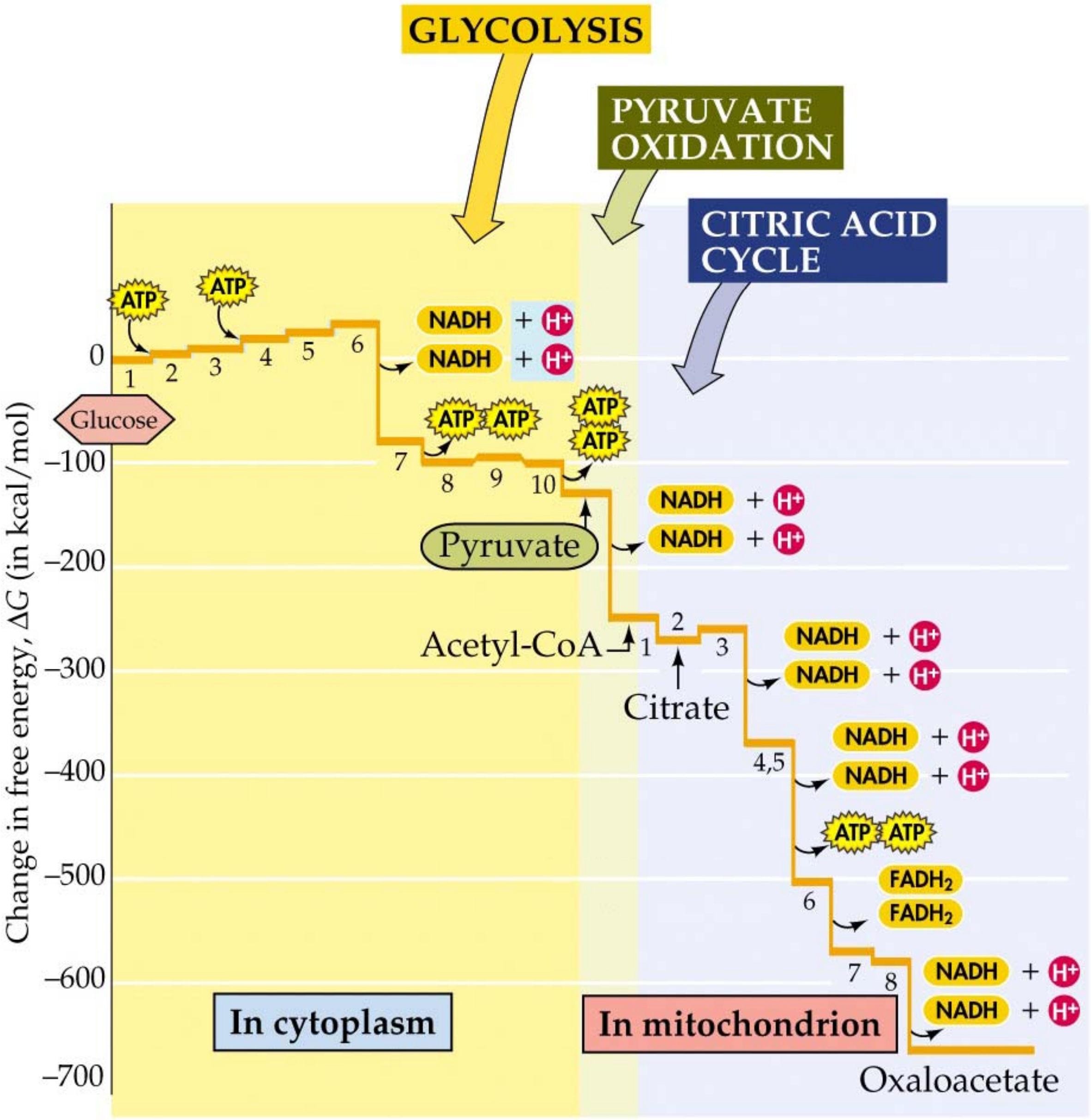
Entner-Doudoroff

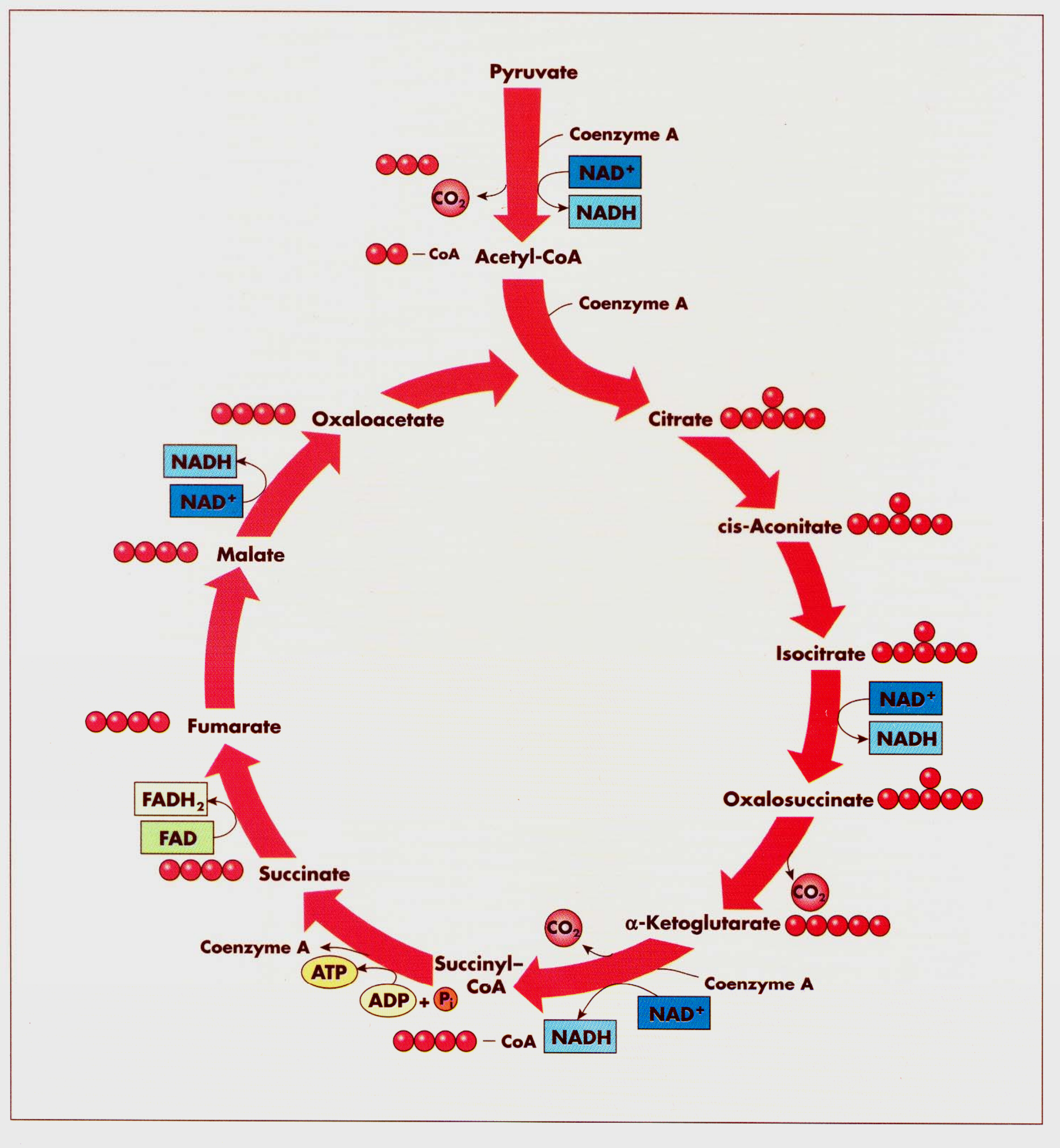
2 ATP / only 1 Net
2 NADH+H

No PFK!!!

Many Gram negatives use this pathway


Pyruvate$^-$ (three carbons)
NAD$^+$ + CoA
NADH
CO_2
Acetyl-CoA
CoA
Key
C_2 🟨
C_4 🟥
C_5 🟩
C_6 🟦
Oxalacetate^{2-}
Citrate^{3-}
NADH
NAD$^+$
Aconitate^{3-}
Malate^{2-}
Isocitrate^{3-}
NAD(P)$^+$
Fumarate^{2-}
CO_2
FADH
FAD
Succinate^{2-}
α–Ketoglutarate^{2-}
NAD(P)H
Succinyl-CoA
CoA + NAD$^+$
CoA
GTP
GDP + P_i
CO_2
NADH


GLYCOLYSIS
PYRUVATE OXIDATION
CITRIC ACID CYCLE
Change in free energy, ΔG (in kcal/mol)
0
–100
–200
–300
–400
–500
–600
–700
Glucose
ATP
ATP
1
2
3
4
5
6
NADH + H+
NADH + H+
7
ATP
ATP
8
9
10
ATP
ATP
Pyruvate
NADH + H+
NADH + H+
Acetyl-CoA
1
2
3
Citrate
NADH + H+
NADH + H+
4,5
NADH + H+
NADH + H+
ATP
ATP
6
FADH2
FADH2
7
8
NADH + H+
NADH + H+
Oxaloacetate
In cytoplasm
In mitochondrion



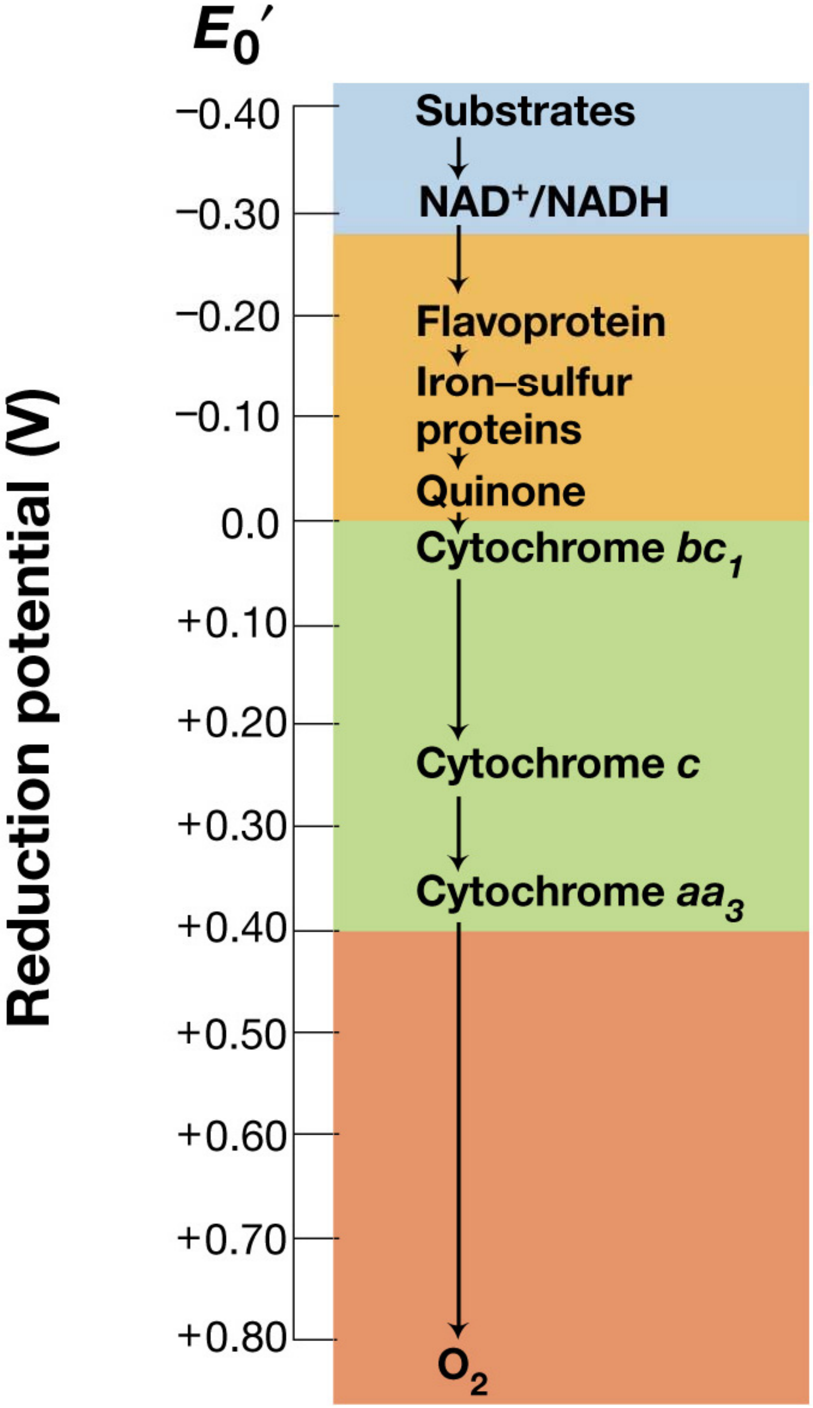
Citric Acid Cycle
aka TCA cycle

The short form!

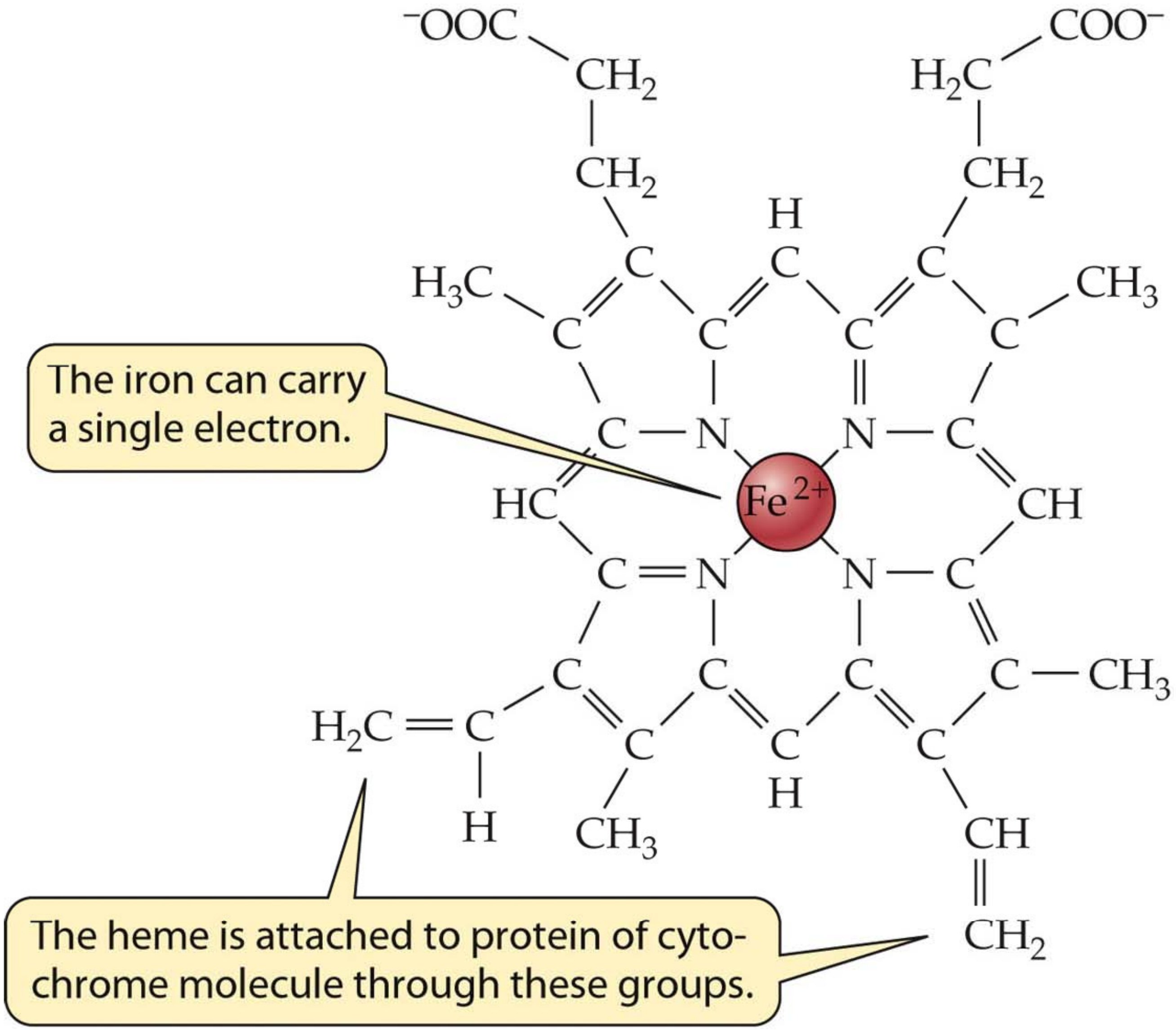
2 ATP (via GTP)
8 NADH+H
2 $FADH_2$

All Carbon to CO_2

Electron Transport Chains and their Relative Potential



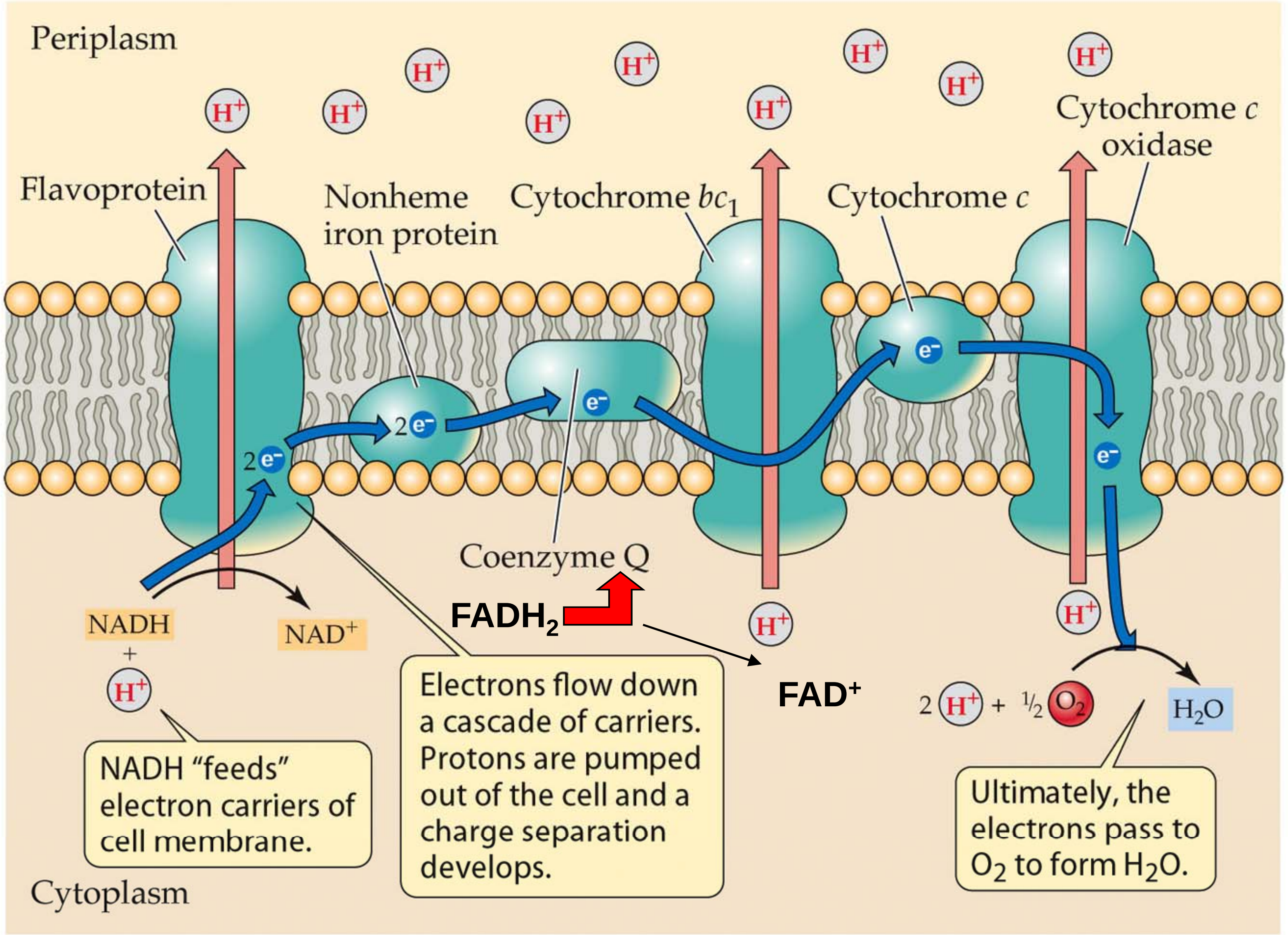
The heme part of a cytochrome, the elegant porphyrin ring!



The iron can carry a single electron.

The heme is attached to protein of cytochrome molecule through these groups.

Electron transport chain in aerobic bacterium

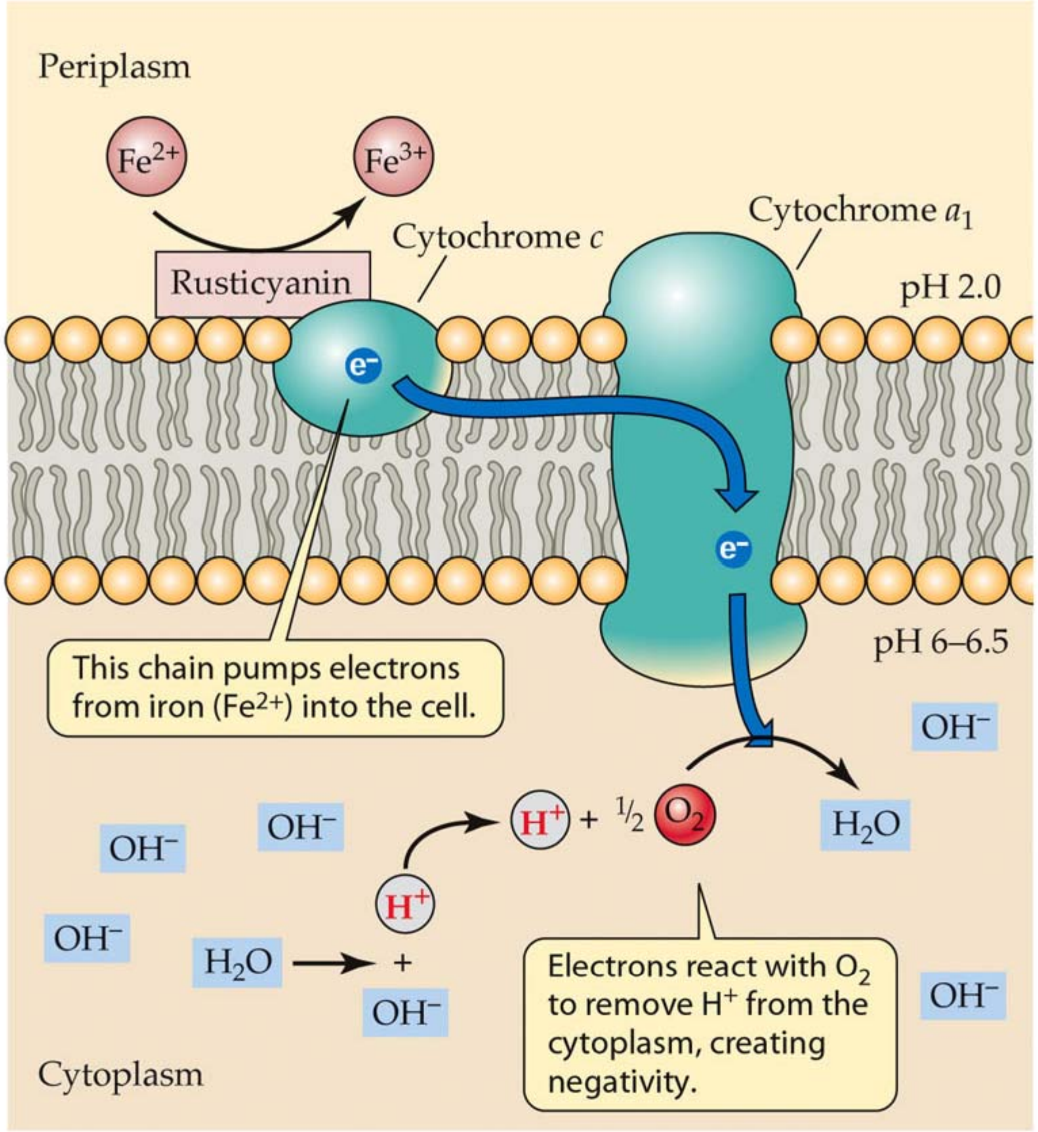


NADH “feeds” electron carriers of cell membrane.

Electrons flow down a cascade of carriers. Protons are pumped out of the cell and a charge separation develops.

Ultimately, the electrons pass to O_2 to form H_2O.

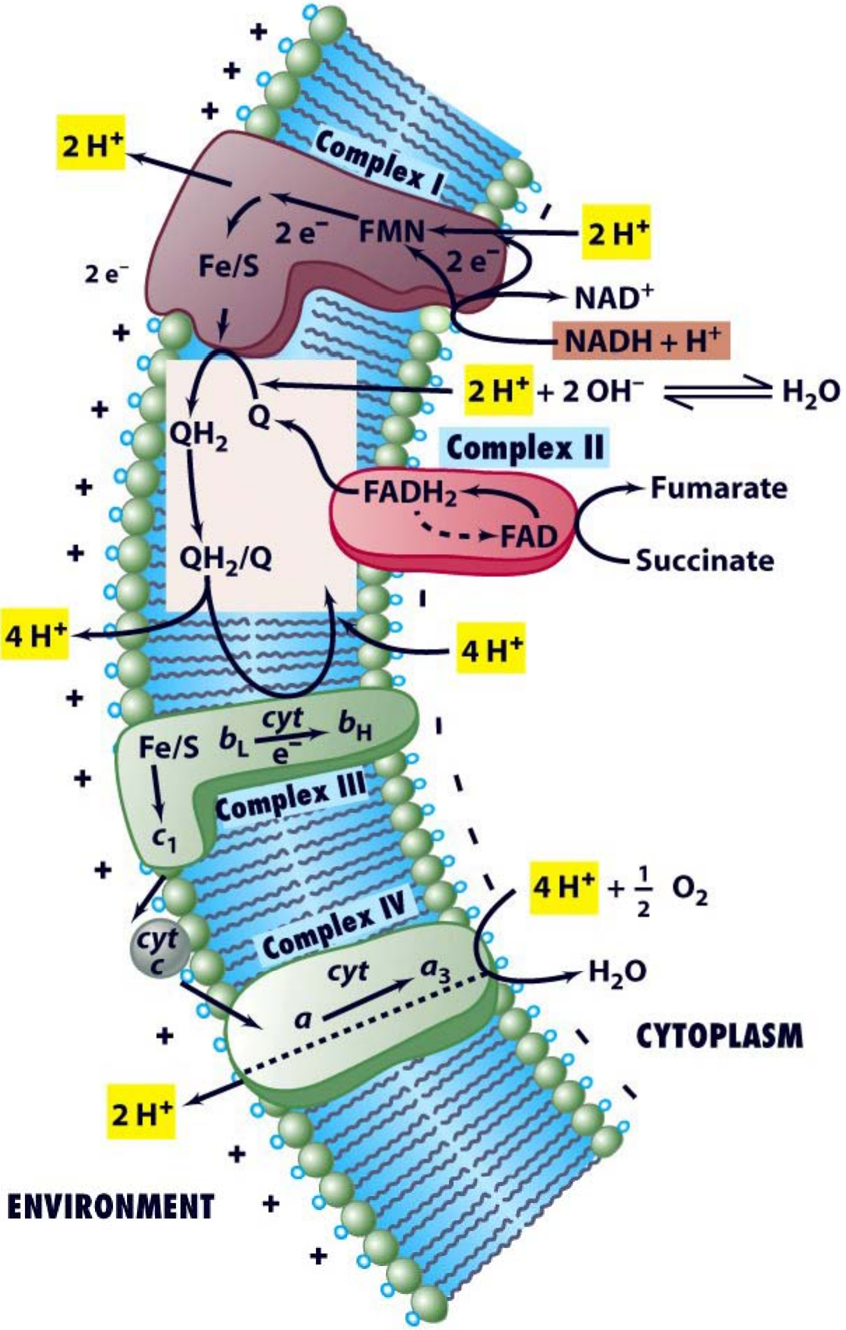
Abbreviated electron transport chain of an iron-oxidizing bacterium



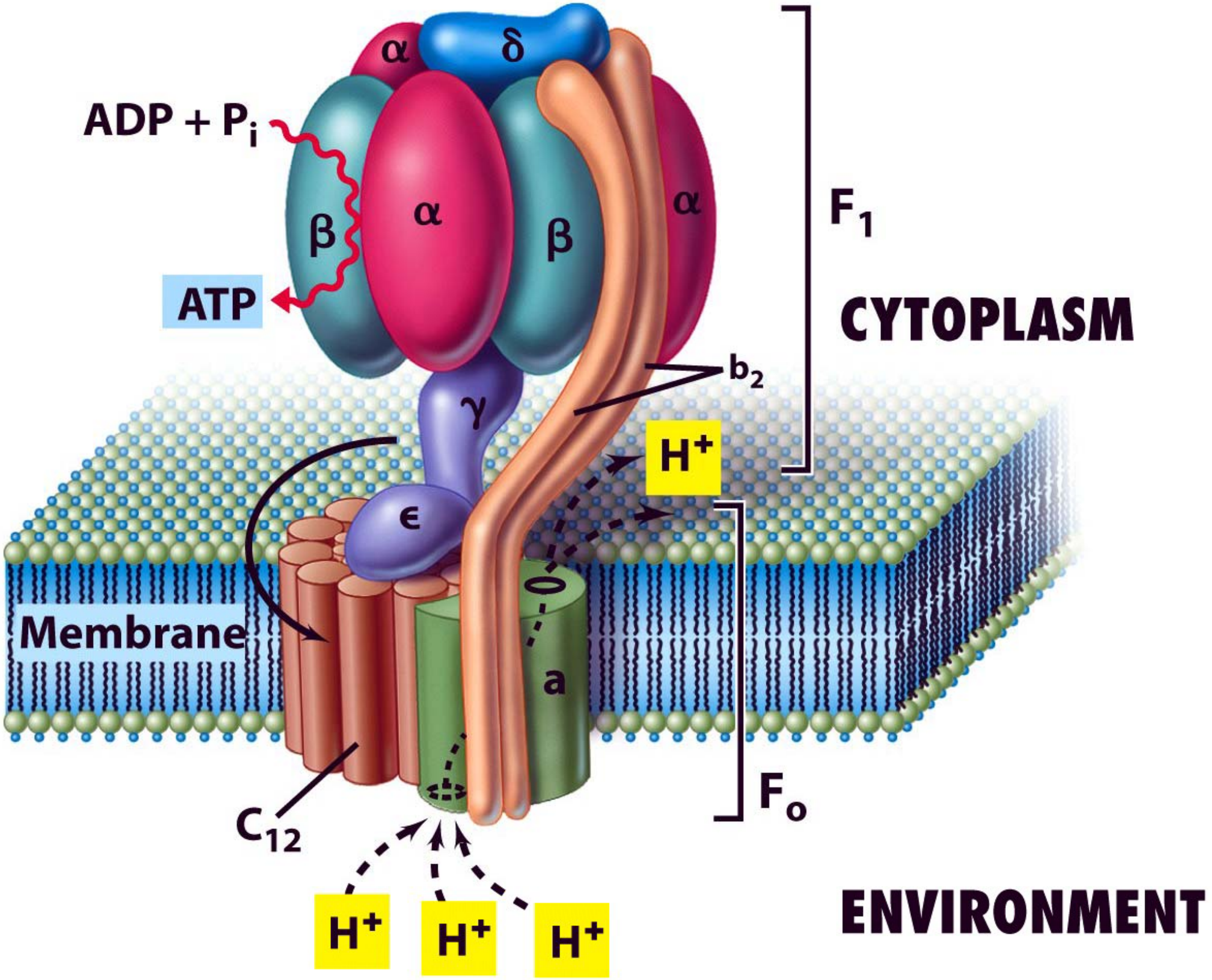
This chain pumps electrons from iron (Fe^{2+}) into the cell.

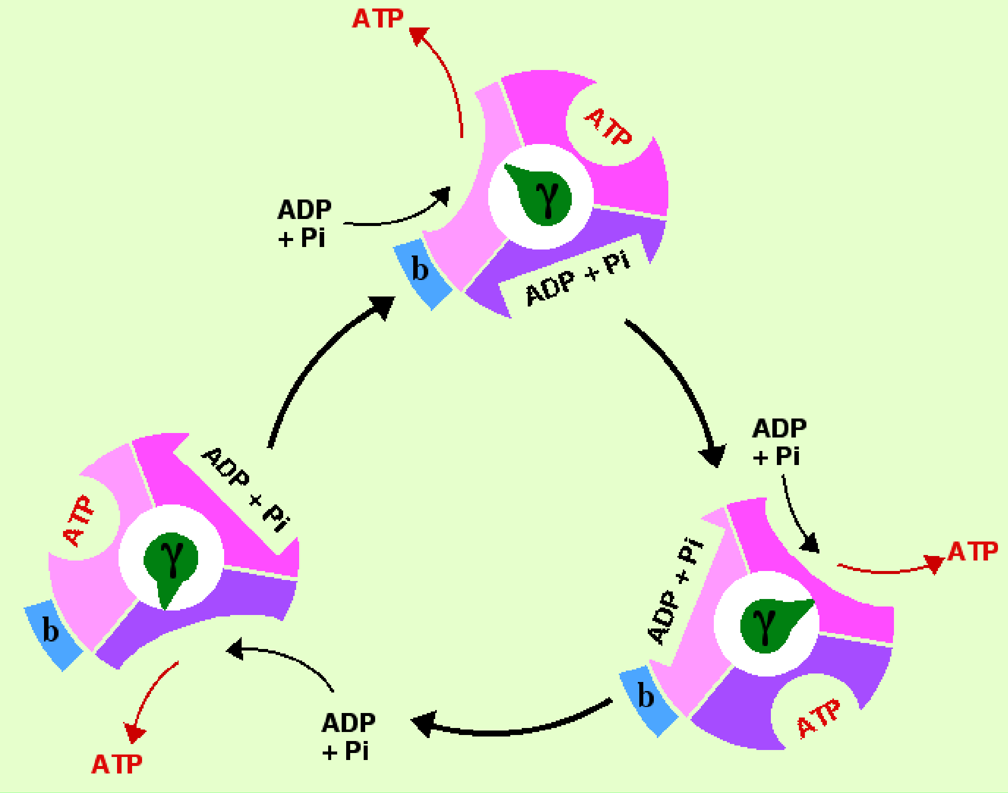
Electrons react with O_2 to remove H^+ from the cytoplasm, creating negativity.

Generation of PMF



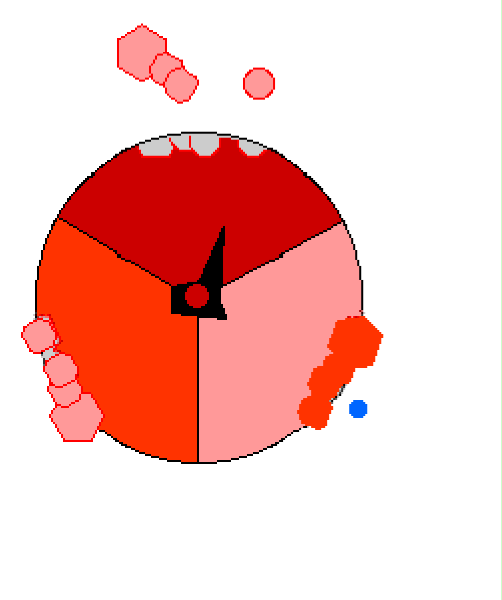
ATP Synthase
Structure & Function





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
↓ 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
↓ to Complex I
↓ 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.

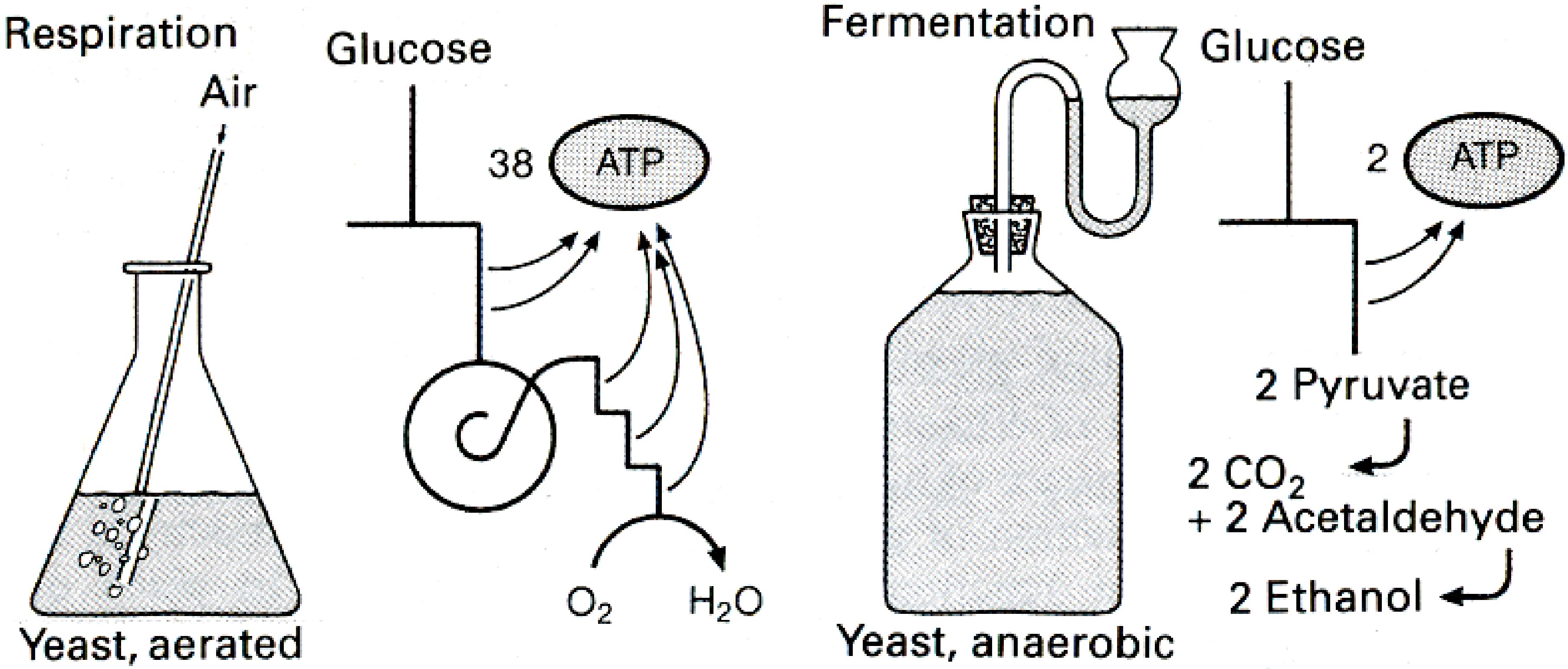
Many types.... 2 major themes

(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



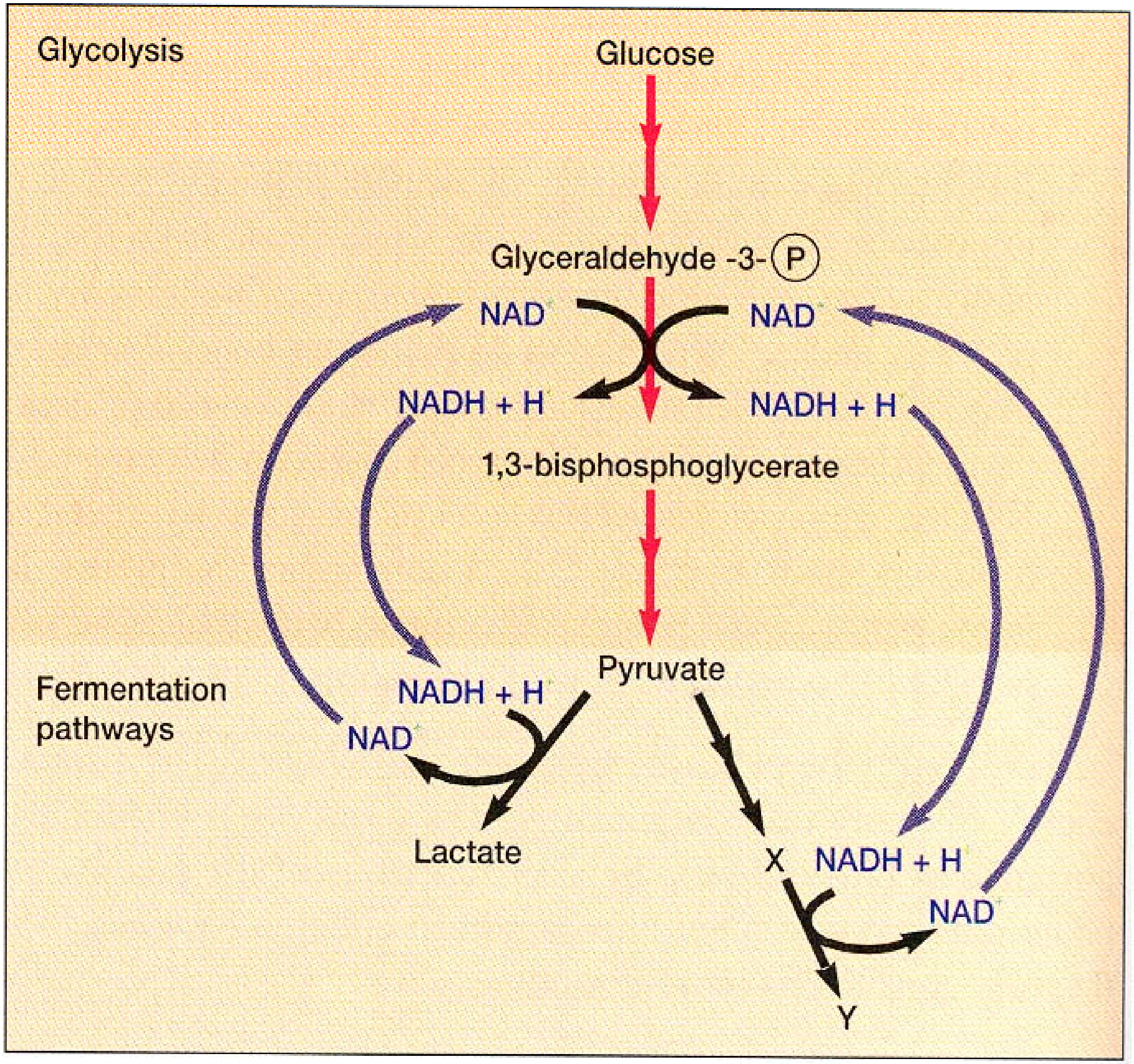


Figure 9.9 Reoxidation of NADH During Fermentation. NADH from glycolysis is reoxidized by being used to reduce pyruvate or a pyruvate derivative (X). Either lactate or reduced product Y result.

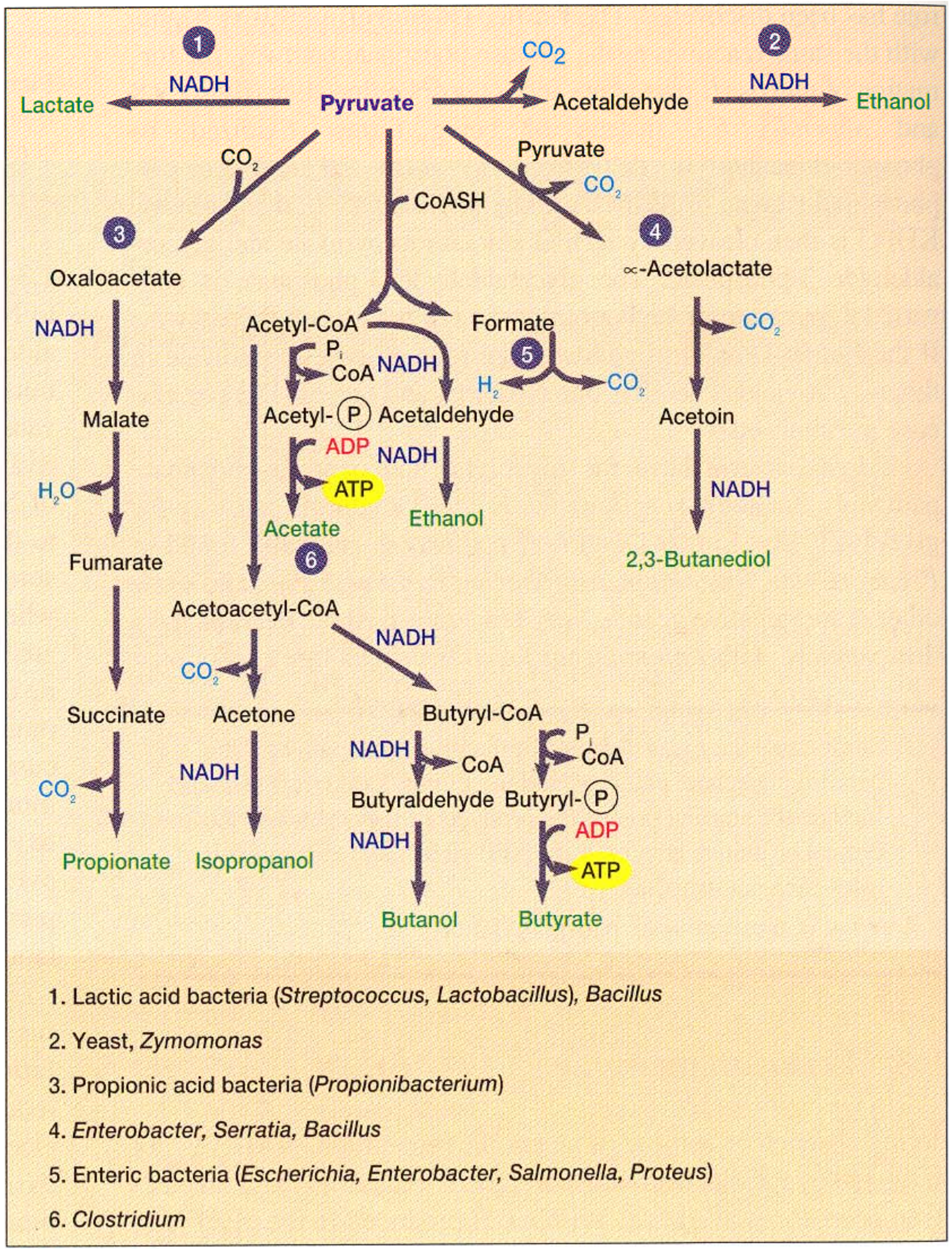
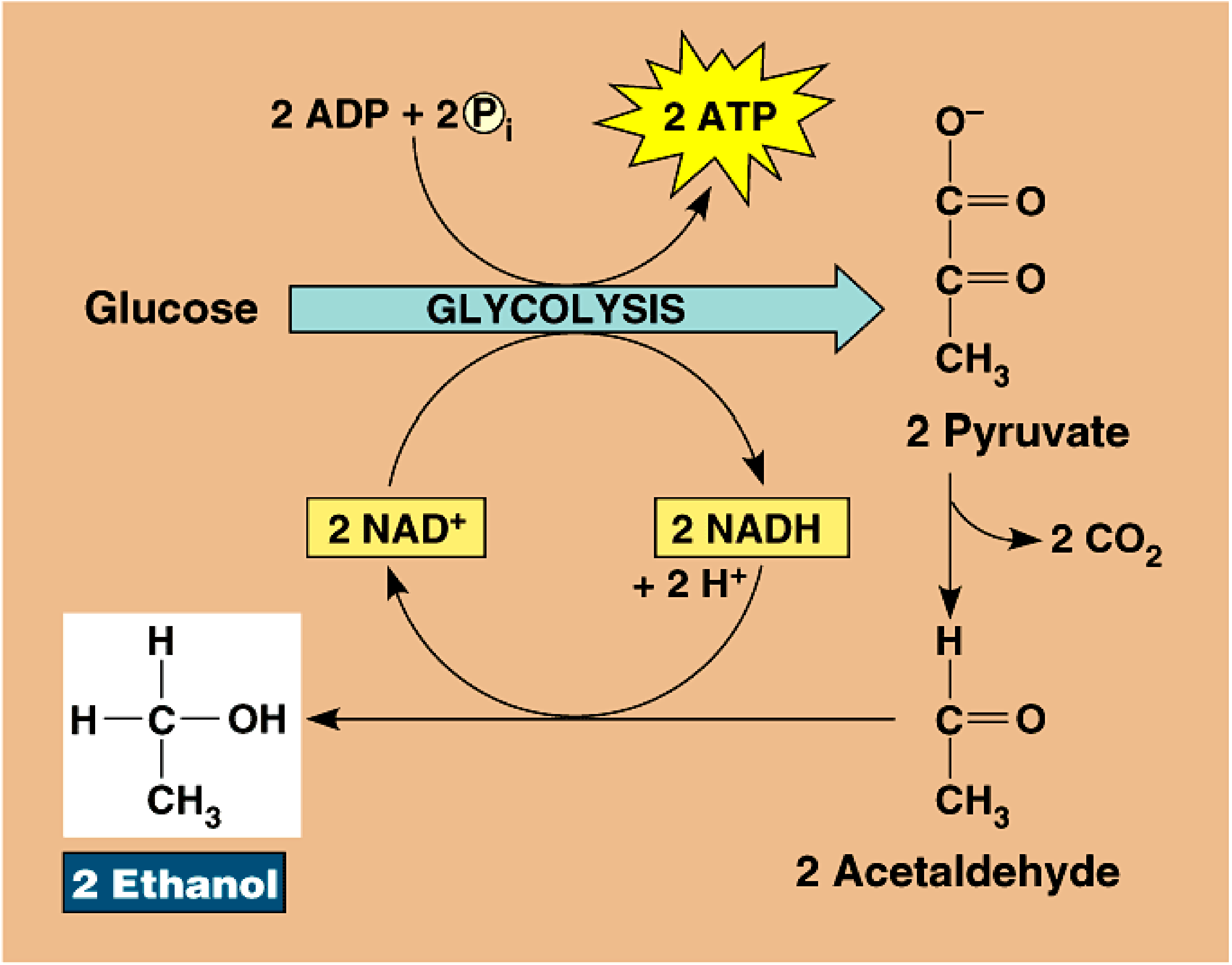
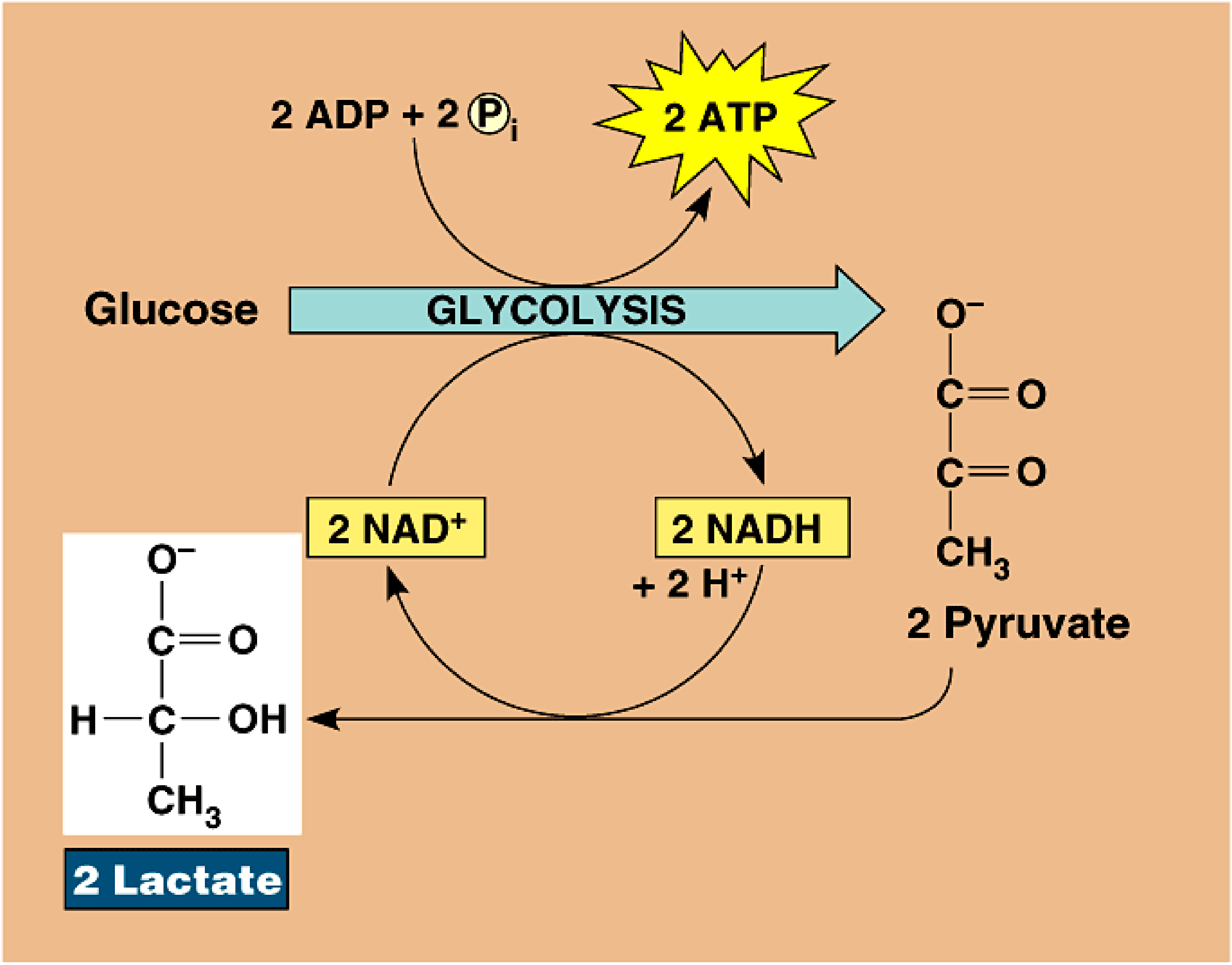


Figure 9.10 **Some Common Microbial Fermentations.** Only pyruvate fermentations are shown for the sake of simplicity; many other organic molecules can be fermented. Most of these pathways have been simplified by deletion of one or more steps and intermediates. Pyruvate and major end products are shown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



(a) Alcohol fermentation



(b) Lactic acid fermentation

Propionic Acid Fermentation

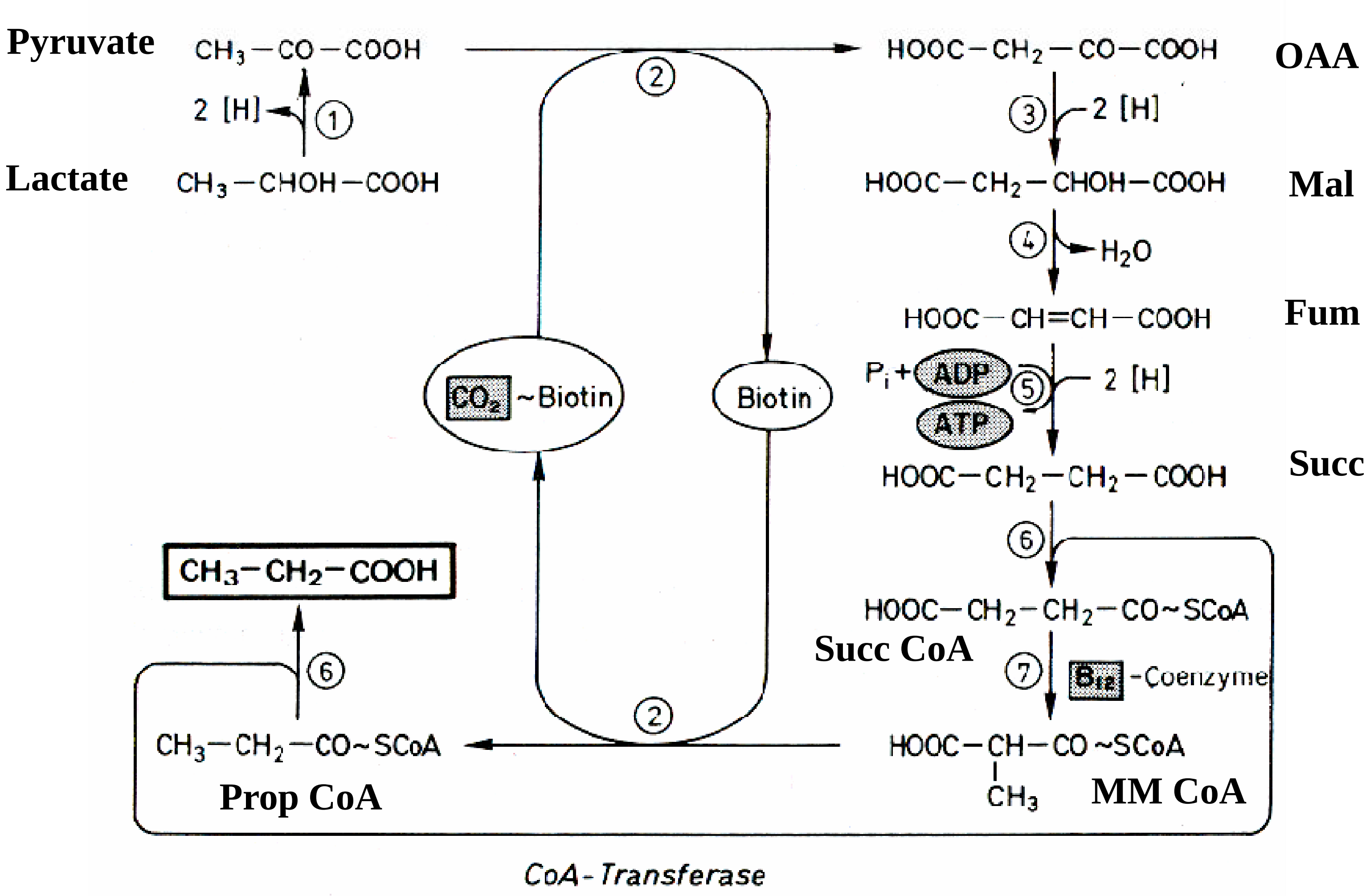
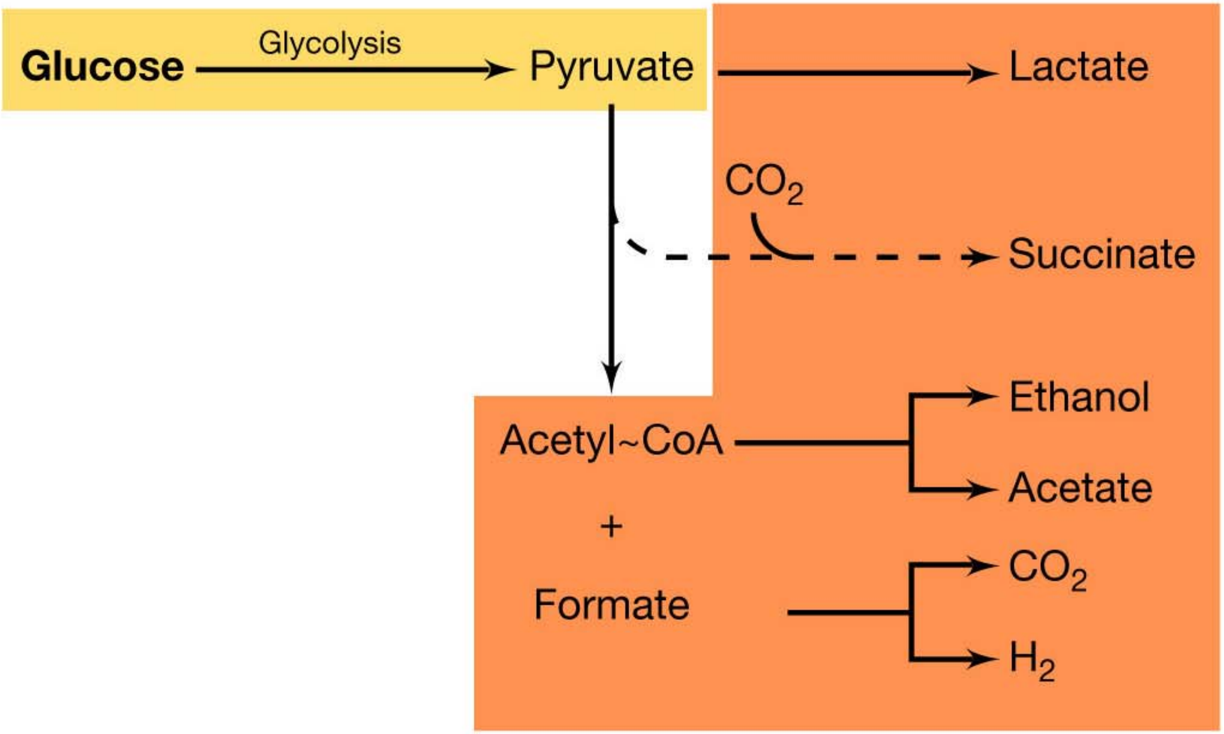


Fig. 8.3. *Methylmalonyl-CoA pathway of propionate formation.*

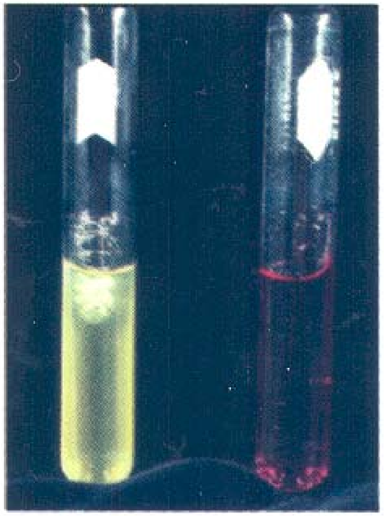
Enzymes: (1) lactate dehydrogenase; (2) methylmalonyl-CoA carboxytransferase; (3) malate dehydrogenase; (4) fumarase; (5) fumarate reductase (leading to regeneration of ATP by proton translocation); (6) CoA transferase; (7) methylmalonyl-CoA mutase.

(*a*) **Mixed acid fermentation** (for example, *Escherichia coli*)


Glucose
Glycolysis
Pyruvate
Lactate
CO_2
Succinate
Acetyl~CoA
+
Formate
Ethanol
Acetate
CO_2
H_2

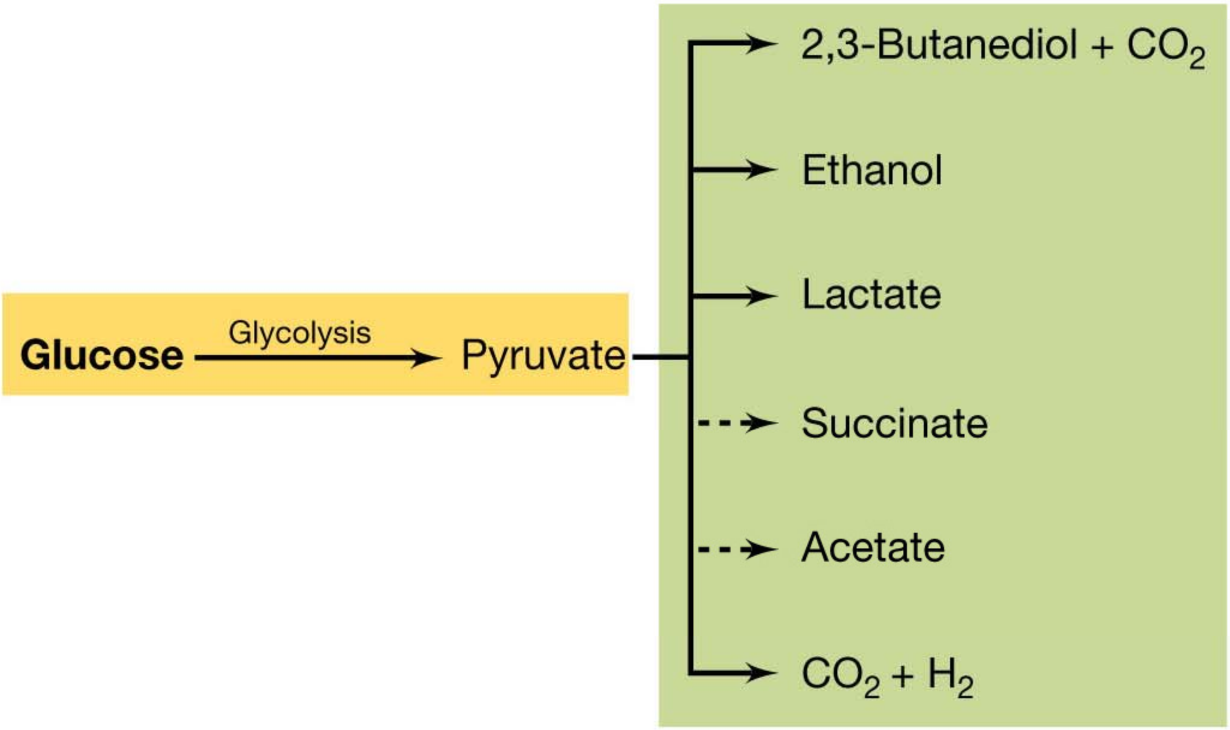
Typical products (molar amounts)

Acidic : neutral
4 : 1
$CO_2 : H_2$
1 : 1



Methyl Red Test

(*b*) **Butanediol fermentation** (for example, *Enterobacter*)

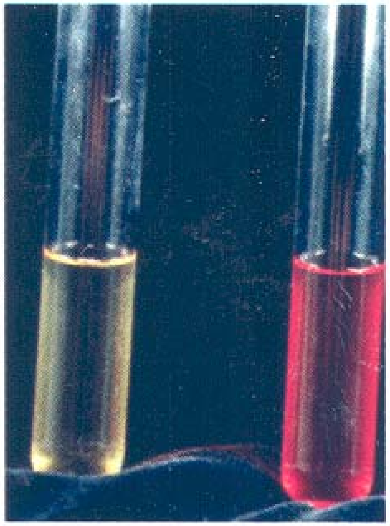


Glucose $\xrightarrow{\text{Glycolysis}}$ Pyruvate

- 2,3-Butanediol + CO_2
- Ethanol
- Lactate
- Succinate
- Acetate
- CO_2 + H_2

Typical products (molar amounts)

Acidic : neutral
1 : 6
CO_2 : H_2
5 : 1



Voges-Proskauer Test

Clostridial Fermentations

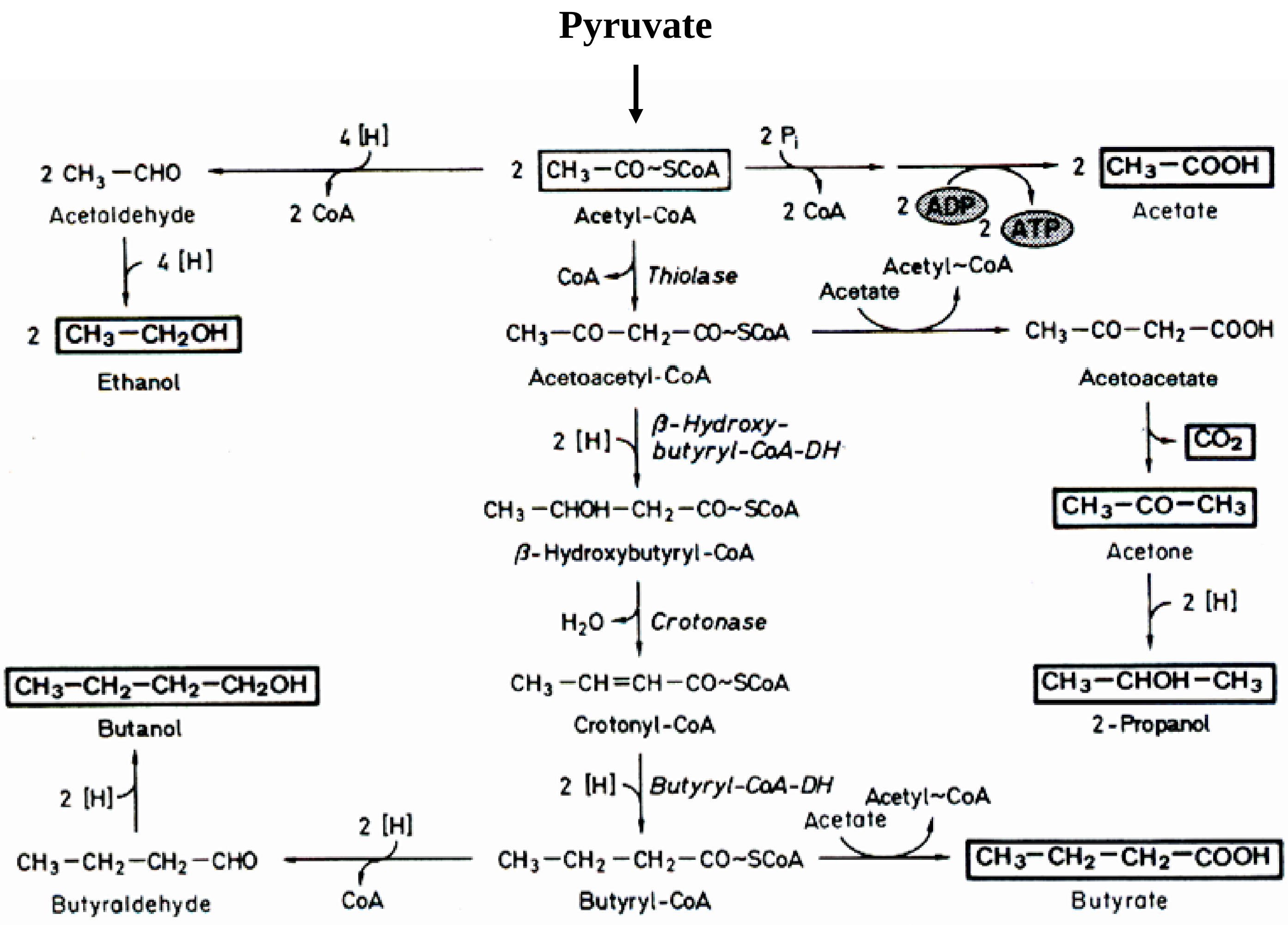


Fig. 8.4. *The formation of acetate, ethanol,* n*-butanol, butyrate, acetone, and 2-propanol during clostridial fermentations.*

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

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

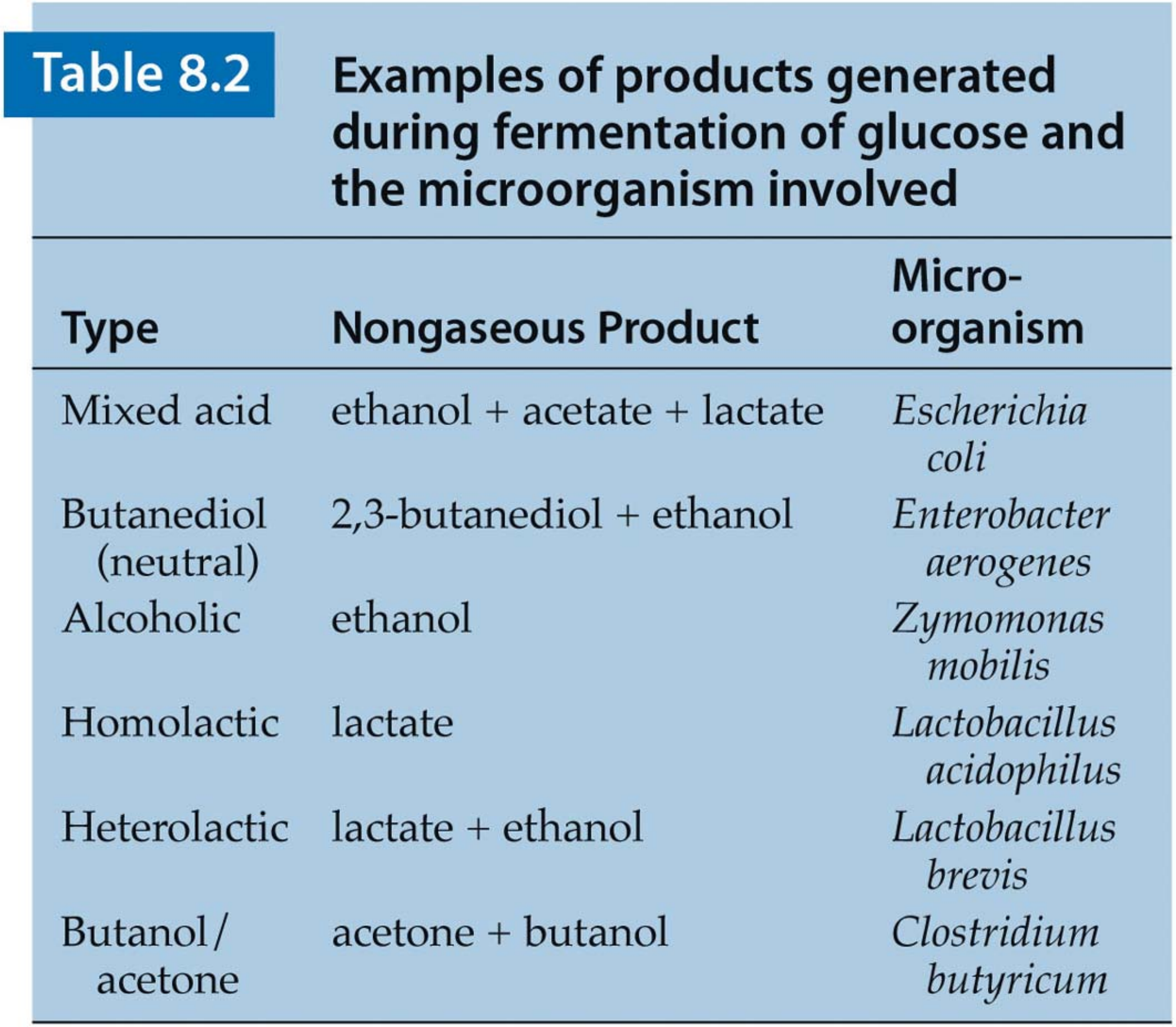


Table 8.2 Examples of products generated during fermentation of glucose and the microorganism involved

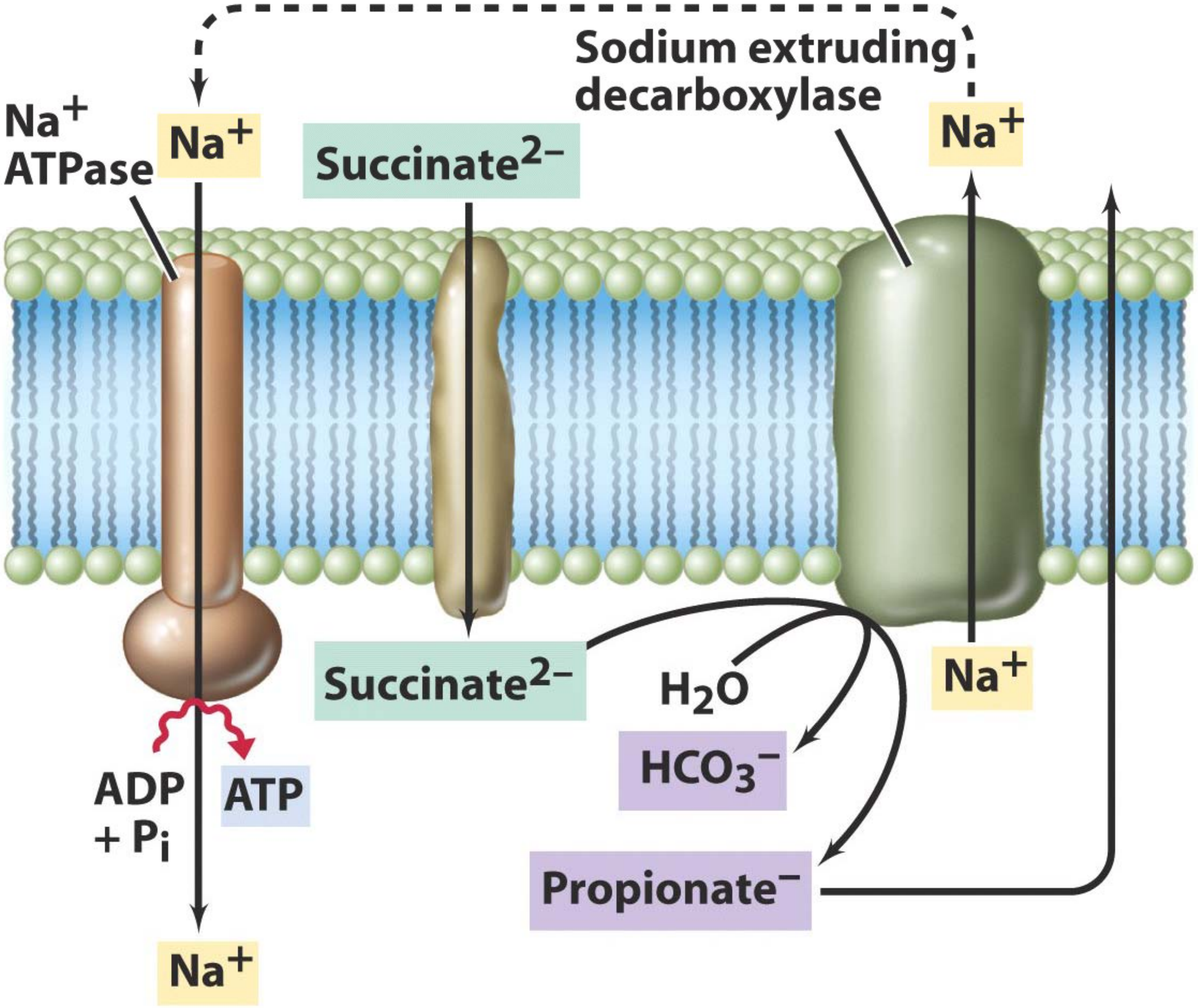
Type	Nongaseous Product	Microorganism
Mixed acid	ethanol + acetate + lactate	*Escherichia coli*
Butanediol (neutral)	2,3-butanediol + ethanol	*Enterobacter aerogenes*
Alcoholic	ethanol	*Zymomonas mobilis*
Homolactic	lactate	*Lactobacillus acidophilus*
Heterolactic	lactate + ethanol	*Lactobacillus brevis*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

The short list

Table 17.8 Some unusual bacterial fermentations

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

The unusual fermentations of succinate and oxalate



The unusual fermentations of succinate and oxalate