Program

1. **Introduction**

   Microbial physiology: problems and prospects

2. **Metabolic diversity. Metabolic processes of energy transduction**

   Diversity and adaptability: the energetic basis of microbial life

3. **Overview of central pathways of heterotrophic metabolism**

   Glycolysis, pentose phosphate pathway, Entner-Doudoroff pathway, glyoxylate cycle, the citric acid cycle and its modifications

4. **Physiology of growth in extreme environments**

   Adaptations to extreme conditions. Temperature, pH and osmotic homeostasis

5. **Membranes and solutes transport**

   Diversity of transport mechanisms

   A functional-phylogenetic classification system for transmembrane solute transporters

6. **Metabolic regulation**

   Transcription in Prokaryotes

   Enzyme induction

   Repression by catabolite

   Repression and attenuation by final metabolites

   Termination and anti-termination

7. **Physiological adaptation and homeostasis**

   General introduction to the systems of signal transduction

   Redox control and oxidative stress

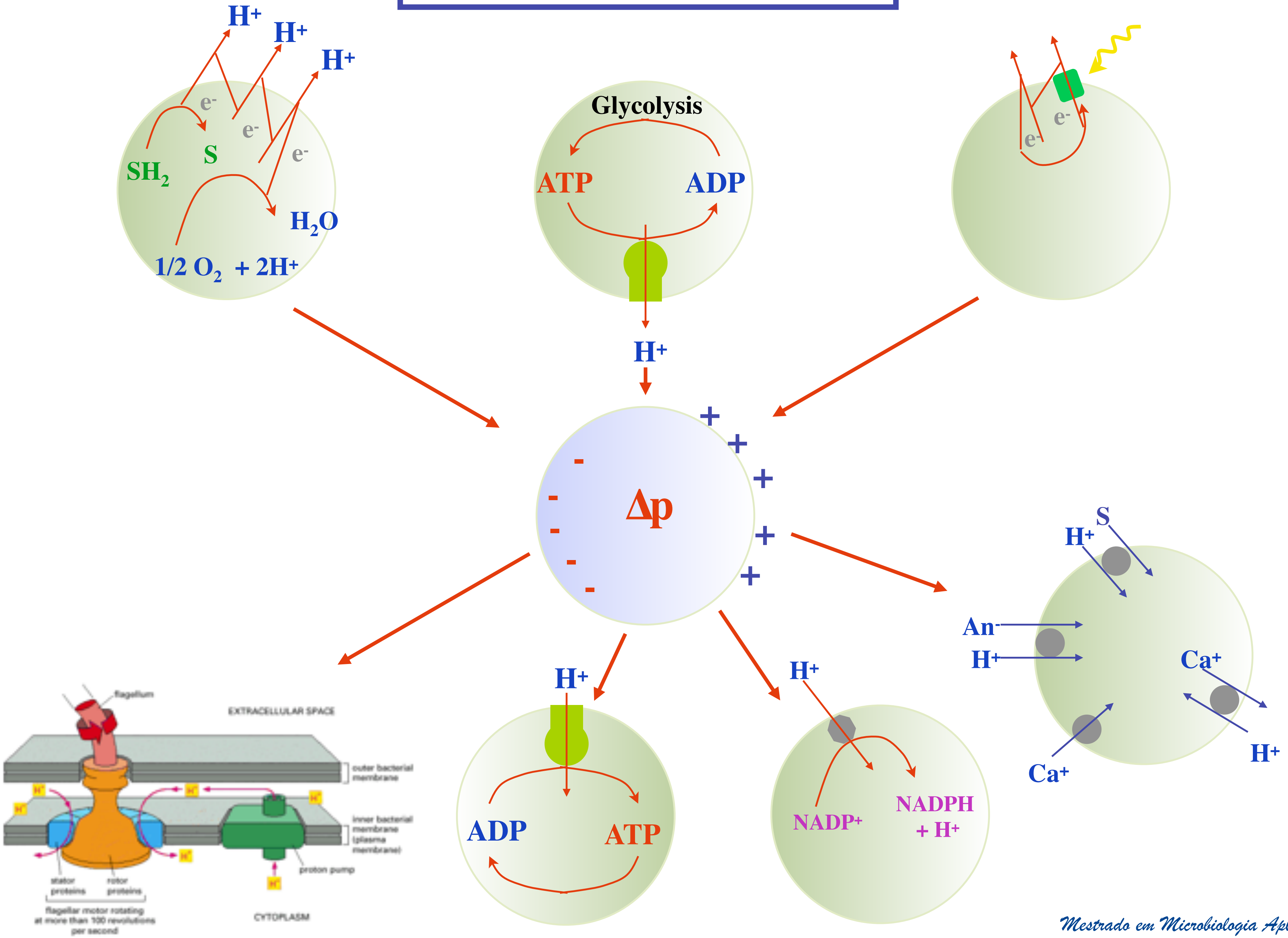
   Hierarchical regulation of transport and utilization of carbon sources

   Regulation of gene expression associated with transition aerobic / anaerobic

   Photo-regulation in prokaryotes

8. **Nitrate reduction and nitrogen cycle in archaea**
9. **Methanogenic archaea, methane and carbon cycle**
10. **"Omics" technology and Systems Microbiology**

Nutrients and energy production



Energy Transduction

Gibbs-Helmholtz equation

$$\Delta G = \Delta H - T\Delta S$$

ΔG: *Gibbs energy changes* (free energy changes)

ΔH: enthalpy change

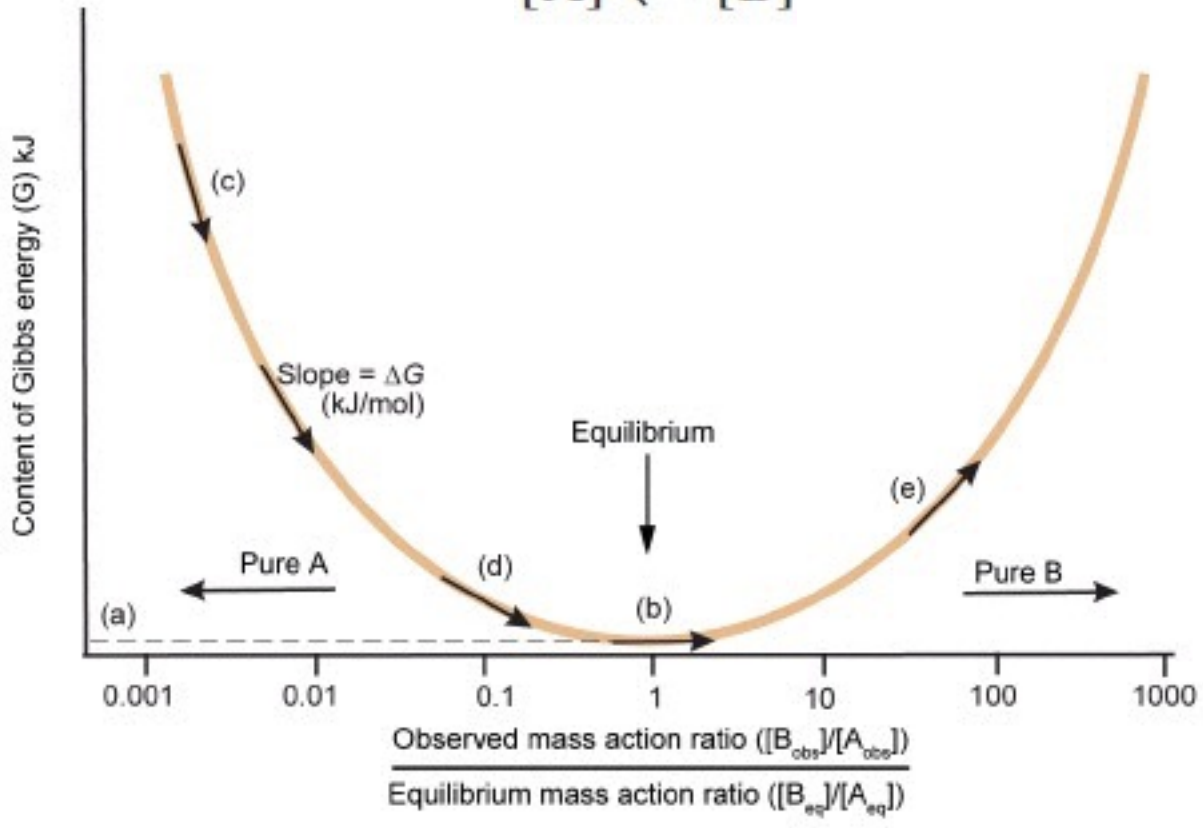
ΔS: entropy change

* **Manifestations of Gibbs energy are interconverted**

- ✓ **ΔG: used in the description of metabolic reactions and its displacement from equilibrium**
- ✓ **ΔE: redox potential changes, in the oxidation-reduction reactions occurring in the electron transfer pathways in respiration and photosynthesis**
- ✓ **$\Delta\tilde{\mu}_{H^+}$: the available energy in the ion electrochemical gradient**
- ✓ **$Nh\nu$: the energy available from the absorption of quanta of light in photosynthetic systems**

ΔG: used in the description of metabolic reactions and its displacement from equilibrium

$$[\mathrm{A}] \rightleftharpoons [\mathrm{B}]$$



$$aA + bB \rightleftharpoons cC + dD$$

$$K = \frac{[\mathrm{C}]_{eq}^{c}[\mathrm{D}]_{eq}^{d}}{[\mathrm{A}]_{eq}^{a}[\mathrm{B}]_{eq}^{b}}\,\mathrm{Molar}^{(c+d-a-b)}$$

$$\Gamma = \frac{[\mathrm{C}]_{\mathrm{obs}}^{c}[\mathrm{D}]_{\mathrm{obs}}^{d}}{[\mathrm{A}]_{\mathrm{obs}}^{a}[\mathrm{B}]_{\mathrm{obs}}^{b}}\,\mathrm{Molar}^{(c+d-a-b)}$$

$$\boxed{\Delta G = -2.3RT\log_{10}\left\{\frac{K}{\Gamma}\right\}}$$

$$\Delta G^{\circ} = -2.3RT\log_{10}K$$

$$\boxed{\Delta G = \Delta G^{\circ} + 2.3RT\log_{10}\left\{\frac{[C]_{\mathrm{obs}}^{c}[D]_{\mathrm{obs}}^{d}}{[A]_{\mathrm{obs}}^{a}[B]_{\mathrm{obs}}^{b}}\right\}}$$

$$observed\ mass\ action\ ratio \quad \Gamma = \frac{[B]_{obs}}{[A]_{obs}}$$

$$equilibrium\ constant \quad K = \frac{[B]_{eq}}{[A]_{eq}}$$

Energy Transduction

* Δ*G* and the redox potential

Biological oxidation-reduction reactions

1. Direct electron transfer

$2Fe(II) + 1/2\ O_2 + 2H^+ \Rightarrow 2Fe(III) + H_2O$

2. *Hydrogen transfer* (2e⁻ reduction followed by de addition of 2H+)

$AH_2 + B \Rightarrow A + BH_2$

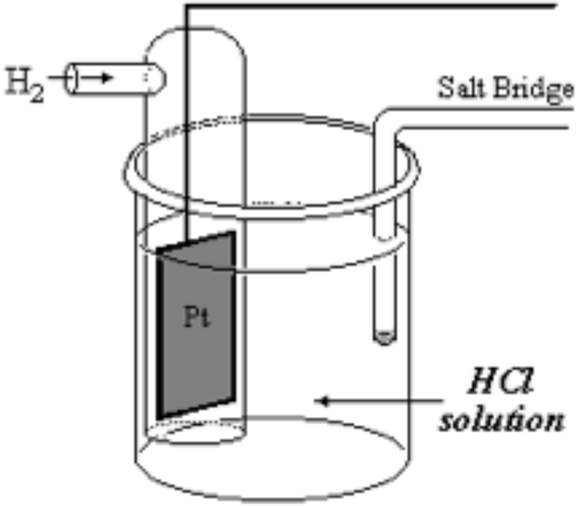
3. Transfer of hydride ion (:H⁻ 2e- reduction followed by de addition of 1H+)

$NAD^+ + SH_2 \Rightarrow NADH + H^+ + S$

4. Direct incorporation of oxygen

$R\text{-}CH_3 + 1/2\ O_2 \Rightarrow R\text{-}CH_2OH$

E_h redox potential



standard hydrogen electrode : H_2
E = 0 V at 25ºC

E_h redox potential is a mesure of the tendency of a chemical species to acquire electrons and be reduced. Reduction potential is measured in volts (V), or millivolts (mV).

Reducing equivalent (redox equivalent): generic term refers to any number of chemical species which transfer the equivalent of one electron in redox reactions

Energy Transduction

E: a measure of affinity for e$^-$

$$2Fe(II) + 1/2\ O_2 + 2H^+ \Rightarrow 2Fe(III) + H_2O$$

reduced oxidized oxidized reduced

$$2Fe(III) + 2e^- \Rightarrow 2Fe(II) \qquad E^o = +770\ mV$$

$$1/2\ O_2 + 2e^- + 2H^+ \Rightarrow H_2O \qquad E^o = +820\ mV$$

$$\boxed{E = E^o + 2{,}3\ \frac{RT}{nF} \left(\frac{[e^-\ \text{acceptor - oxidized}]}{[e^-\ \text{donor - reduced}]} \right)}$$

n: number of electrons transferred

F: Faraday constant (9,6485 x 10^4 C)

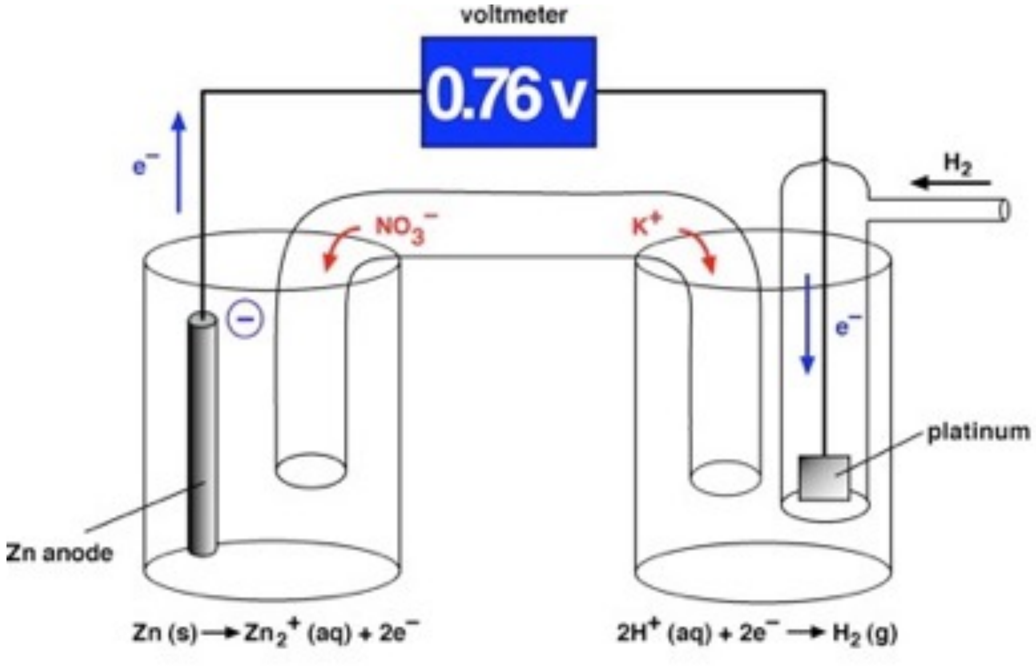
O_2 - oxidizing agent - relatively + redox potential E

2Fe(II) - reducing agent - relatively - redox potential E

$$\boxed{\Delta G = -nF\ \Delta E_h}$$

E is a measure of ΔG in electrochemical units

$$\Delta E_h = E\ (\text{acceptor couple}) - E\ (\text{donor couple})$$



Energy Transduction

* $\Delta\tilde{\mu}_X{}^{m+}$ Electrochemical potential

Ion electrochemical potential across a membrane

✓ **Ion concentration gradient**

ΔG associated to the transfer of 1 mol of solute across a membrane from a concentration $[X]_A$ to a concentration $[X]_B$.

In the absence of a membrane potential

$$\boxed{\Delta G\ (\text{Jmol}^{-1}) = 2{,}3RT\log_{10}\frac{[X]_B}{[X]_A}}$$

✓ **Electric potential difference - $\Delta\psi$ membrane potential**

ΔG associated to the transfer of 1 mol of cation X^{m+}, transported down an electrical potential of $\Delta\psi$ (mV)

$$\boxed{\Delta G\ (\text{Jmol}^{-1}) = -mF\Delta\psi}$$

m: valence of the ion

***F*: Faraday constant 9,6485 x 10^4 C**

✓ **$\Delta\tilde{\mu}_H{}^{+}$ Electrochemical gradient**

ΔG associated to the transfer of 1 mole do catião X^{m+}, of cation X^{m+}, transported down an electrical potential of $\Delta\psi$ (mV), from a concentration $[X]_A$ to a concentration $[X]_B$

$$\boxed{\Delta G\ (\text{Jmol}^{-1}) = -mF\Delta\psi + 2{,}3RT\log_{10}\frac{[X^{m+}]_B}{[X^{m+}]_A}}$$

Energy Transduction

* $\Delta\tilde{\mu}_{H^+}$ Proton electrochemical gradient

$$\boxed{\Delta\tilde{\mu}_{H^+}\,(\text{Jmol}^{-1}) = -F\Delta\psi + 2{,}3\;RT\;\log_{10}\frac{[H^+]_e}{[H^+]_i}}$$

$$\text{Log}\;([H^+]_e\,/\,[H^+]_i) = \log[H^+]_e - \log[H^+]_i \Leftrightarrow -\log[H^+]_i - (-\log[H^+]_e\,) = \text{pH}_i - \text{pH}_e = \Delta\text{pH}$$

$$\boxed{\Delta\tilde{\mu}_{H^+}\,(\text{Jmol}^{-1}) = -F\Delta\psi + 2{,}3RT\,\Delta\text{pH}}$$

The electrochemical gradient that is established when a proton cross the membrane is function of the electrical potential (membrane potential - $\Delta\psi$) and the difference of $[H^+]$ between two phases separated by the membrane (ΔpH)

* Protonmotive force or protonic potential (Δp) in units of voltage

$$\Delta p\,(\text{mV}) = -(\Delta\tilde{\mu}_{H^+}/F) \qquad\qquad \Delta p\,(\text{mV}) = \Delta\psi - \frac{2{,}3RT}{F}\,\Delta\text{pH}$$

By convention $\Delta\psi$ is negative when the inner surface of the membrane is negative

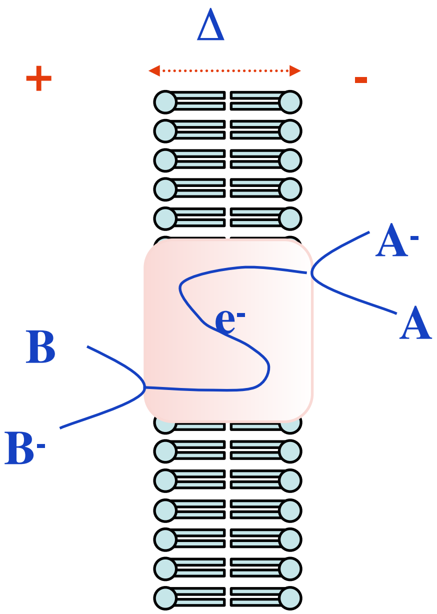
$$\boxed{\Delta\tilde{\mu}_{H^+} = 1\;\text{kJmol}^{-1} \Leftrightarrow \Delta\text{p} = -10.4\;\text{mV} \qquad\qquad \Delta\text{p} = -200\;\text{mV} \Leftrightarrow \Delta\mu_{H^+} = 19\;\text{kJmol}^{-1}}$$

$$\boxed{\text{a}\;\;25^{o}\text{C}\;\;\Delta p\,(\text{mV}) = \Delta\psi - 59\,\Delta\text{pH}}$$

Energy Transduction

* ΔE_h and ΔG for an electron transfer between redox couples located on opposite sites of a membrane sustaining a membrane potential

$$\boxed{\Delta G = -nF\ \Delta E_h}$$



$\Delta E_h = E$ (acceptor couple) - E (donor couple)

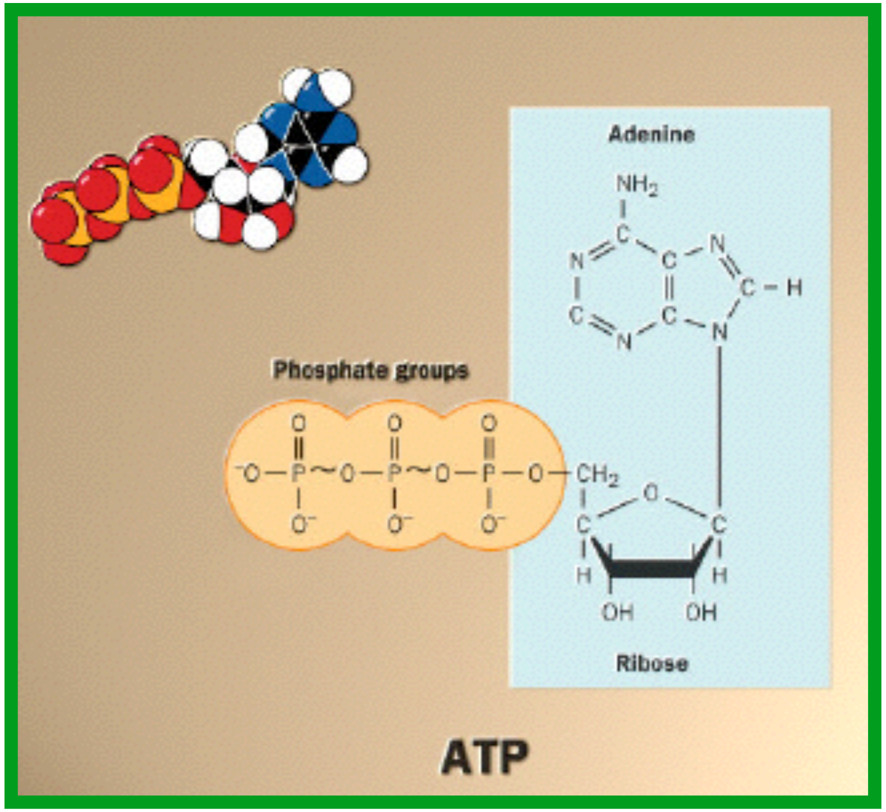
$$\Delta E = E_{\mathrm{B}} - E_{\mathrm{A}}$$

$$\boxed{\Delta G = -nF\ (\Delta E + \Delta\psi)}$$

The value of the membrane potential must be added to the redox potential difference to calculate the effective Gibbs energy change ΔG

Energy Transduction

* **Phosphorylation potential**



*In the cytoplasm the chemical energy available for endergonic reactions: ATP, PEP, nucleotide derivatives, acyl-phosphates and acyl-CoA

* ~ bond with a high free energy of hydrolysis

* The energy input required to break a bond is known as bond energy.

P - O : bond energy = + 413 kJ

ΔG = -35 kJ

* Bonds with high energy hydrolysis ⇔ high potential for group transfer

✓ Under physiological conditions (physiological [ ]s of ATP, ADP and Pi), the energy hydrolysis or ΔG for ATP synthesis is designated as phosphorylation potential(ΔG_p).

$$\boxed{\Delta G_p = \Delta G^o + 2{,}3RT\log_{10}\left(\frac{[ATP]}{[ADP]\,[Pi]}\right)}$$

near the equilibrium: $\Delta G_p / F = y\,\Delta p$

ΔG_p = -50 kJ (518 mV) e y = 3

Under these conditions the hydrolysis of 1 ATP ⇔ Δp = -173 mV

The chemiosmotic hypothesis

* **Energy coupling - energy-transducing membranes**

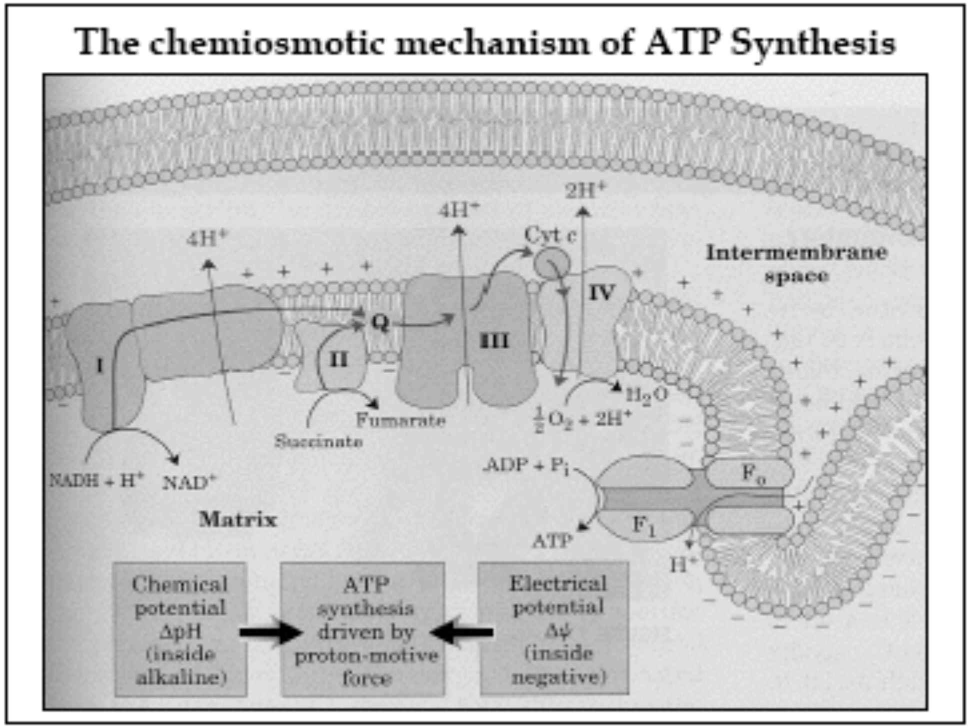
The ATP synthetase complex is associated with energy-transducing membranes:

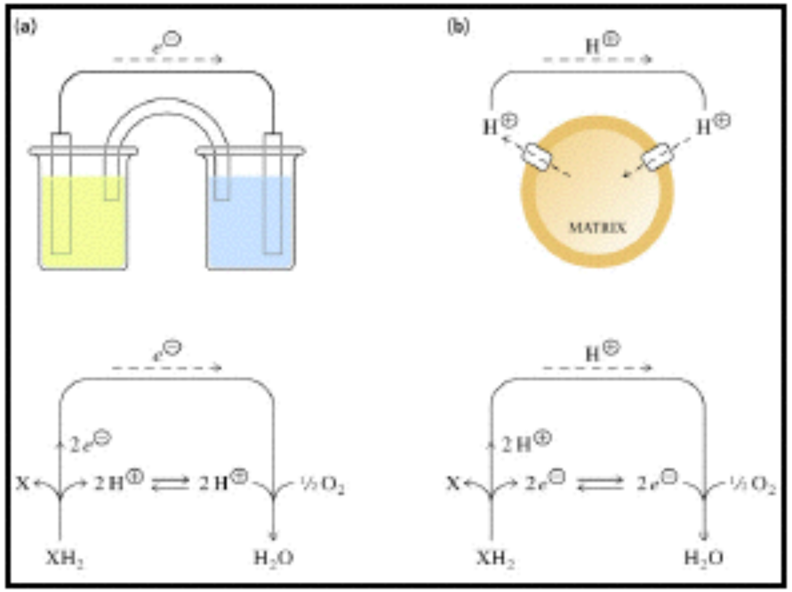
- ✓ **Plasma membrane of prokaryotic cells**
- ✓ **Inner membrane of mitochondria**
- ✓ **Plasma membrane of photosynthetic bacteria**
- ✓ **Thylakoid membrane of chloroplasts**

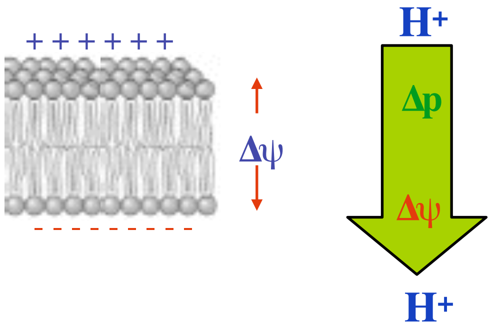
* **Energy-transducing membranes features**

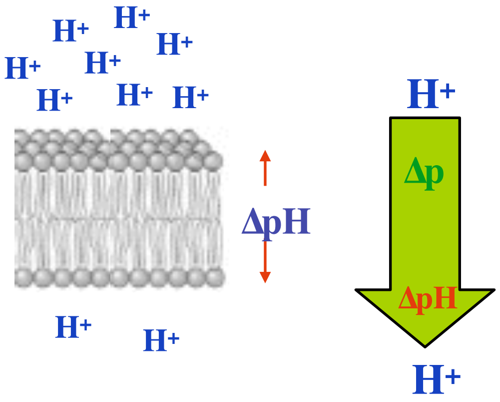
- **A low proton permeability (a low effective proton conductance)**
- **Contains two proton pumps: primary and secondary pumps**
- **The nature of the primary proton pump depends on the energy source**
- **Secondary pump = ATP synthase**
- **The primary and secondary pumps are coupled through translocation of protons ($\Delta\tilde{\mu}_{H^+}$)**

The chemiosmotic hypothesis









The chemiosmotic hypothesis

* **Dissipation of Δp**

✓ **Solute transport**

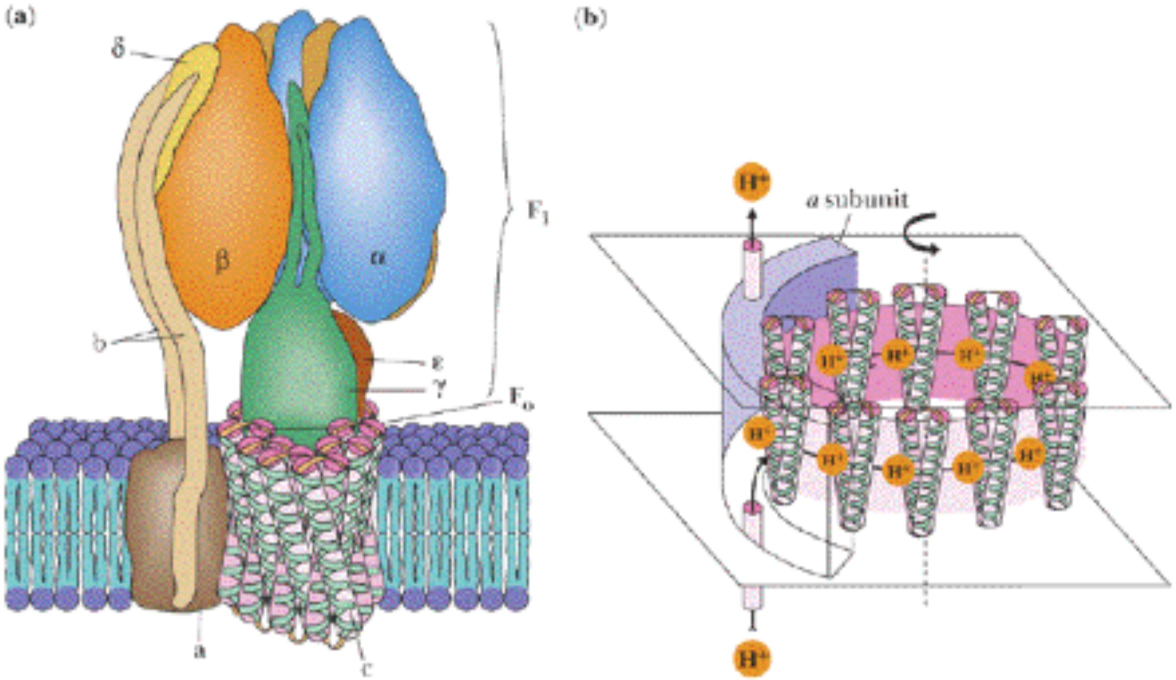
$H^+_i + \text{energy} \Leftrightarrow H^+_o$ **primary transport**

$H^+_o + S_o \Leftrightarrow H^+_i + S_i$ **secondary transport**

✓ **ADP phosphorylation**

- **F_0 and F_1 complexes**
- **F_0: united integrated in the membrane (ab_2c_{12})**

F_1: catalytic unit ($\alpha_3\beta_3\gamma\delta\varepsilon$)



Proton flux ⇒ rotation of unit c ⇒ rotation of unit γ ⇒ conformational change

✓ **Reversed electron transfer**

O **Electron transfer to more negative redox potentials**

O **ATP hydrolysis**

The laws of cell energetics

The first law

The living cell avoids direct utilization of external energy sources in the performance of useful work. It transforms energy of these sources to a convertible energy currency, i.e. ATP, $\Delta\tilde{\mu}_{H^+}$ or $\Delta\tilde{\mu}_{Na^+}$, which is then spent to support various types of energy-consuming processes

The cell prefers to deal with energy in a money-type circulation rather than with barter

A célula prefere negociar com a "energia em circulação" (dinheiro) em vez de negociar por "câmbio"

The second law

Any living cell always possesses at least two energy currencies, one water-soluble (ATP) and the other membrane-linked ($\Delta\tilde{\mu}_{H^+}$ and/or $\Delta\tilde{\mu}_{Na^+}$)

The cell always has some currency in cash and some in cheques

A célula tem sempre alguma energia "em caixa" e alguma em "cheques"

The third law

All the energy requirements of the living cell can be satisfied if at least one of three convertible energy currencies is produced at the expense of external energy sources. The cell is always competent in the ATP → $\Delta\tilde{\mu}_{H^+}$ and/or ATP → $\Delta\tilde{\mu}_{Na^+}$ interconversions due to reversibility of H^+-ATP e Na^+-ATP synthases

It does not matter how an income is received, in cash or in cheques, as long as they are interconvertible

Não *interessa como é recebido o salário, em dinheiro ou em cheque, visto que eles são convertíveis*

Skulachev, V.P. (1992) - The laws of cell energetics - Eur. J. Biochem. 208, 203-209

Energy classes of microorganisms

✓ **Carbon source**
- Autotrophs - CO_2
- Heterotrophs - organic substrates

✓ **Energy source**
- Phototrophs - light
- Chemotrophs - organic / inorganic compounds

✓ **Nature of electron donor**
- Lithotrophs - inorganic compounds
- Organotrophs - organic compounds

o **Photolithotrophy**
- ✓ Light - energy source
- ✓ CO_2 - carbon source
- ✓ inorganic compound - e^- donor

o **Photoorganotrophy**
- ✓ Light - energy source
- ✓ organic substratos - C source
- ✓ organic substratos - e^- donor

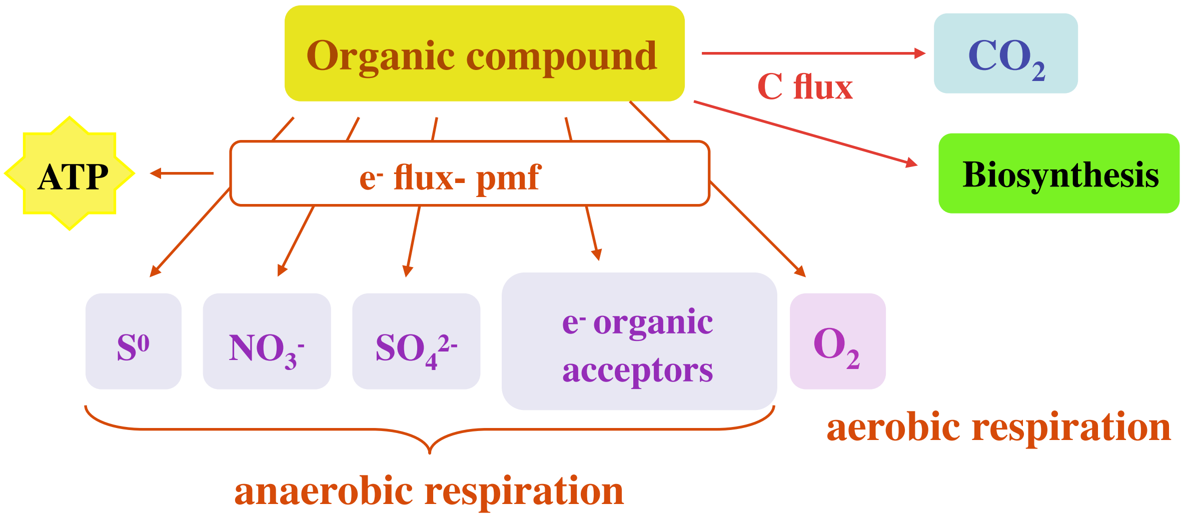
o **Chemolithotrophs**
- ✓ inorganic compound - energy
- ✓ CO_2 - carbon source
- ✓ inorganic compound - e^- donor

o **Chemoorganotrophy**
- ✓ organic substratos - energy
- ✓ organic substratos - C source
- ✓ organic substratos - e^- donor

o **Mixotrophy** - inorganic compound - energy source; organic substrates - C source

Energy classes of microorganisms

- ✓ **Chemoorganotrophic metabolism**



Organic compound

C flux

CO_2

Biosynthesis

ATP

e^- flux- pmf

S^0

NO_3^-

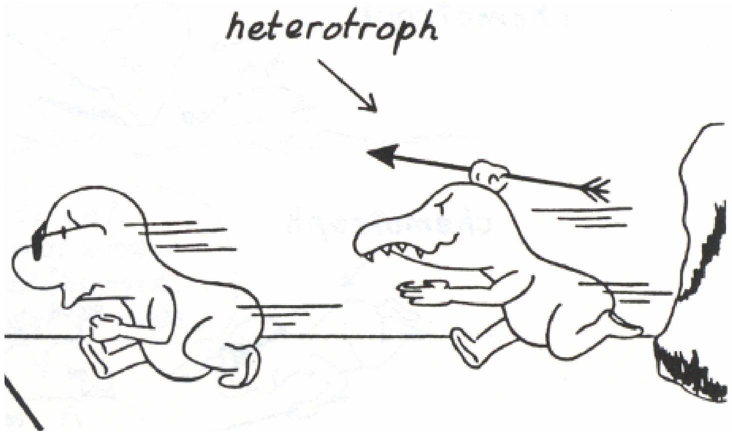
SO_4^{2-}

e^- organic acceptors

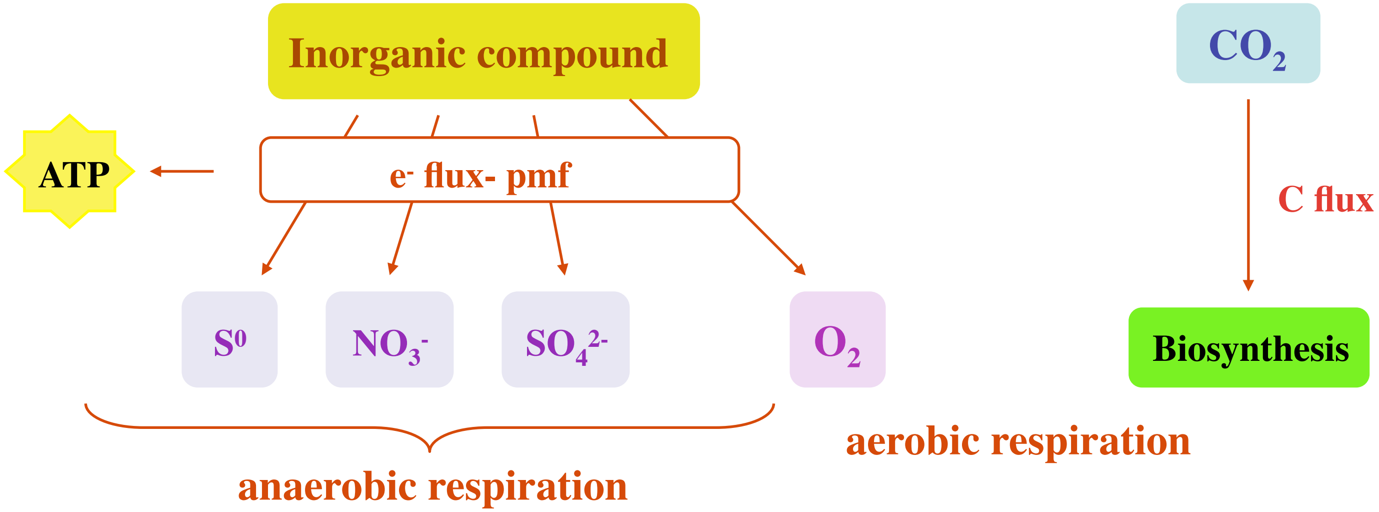
O_2

aerobic respiration

anaerobic respiration



- ✓ **Chemolithotrophic metabolism**



Inorganic compound

ATP

e^- flux- pmf

S^0

NO_3^-

SO_4^{2-}

O_2

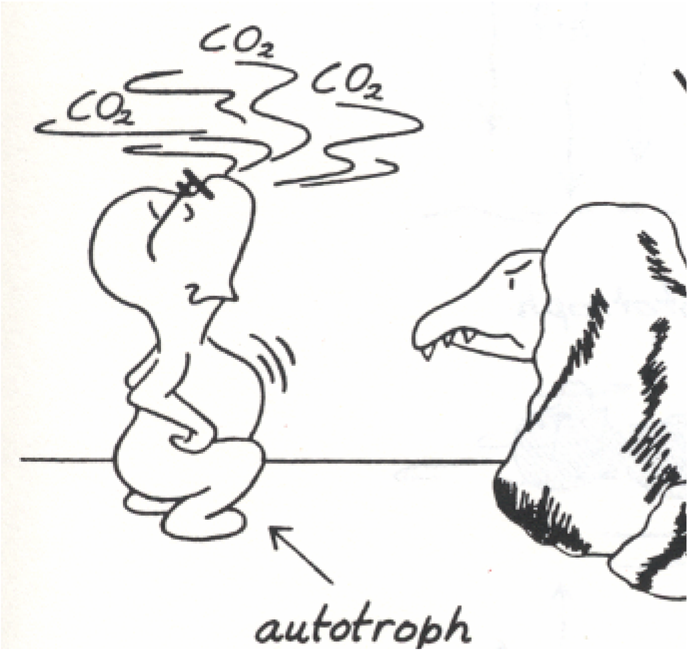
anaerobic respiration

aerobic respiration

CO_2

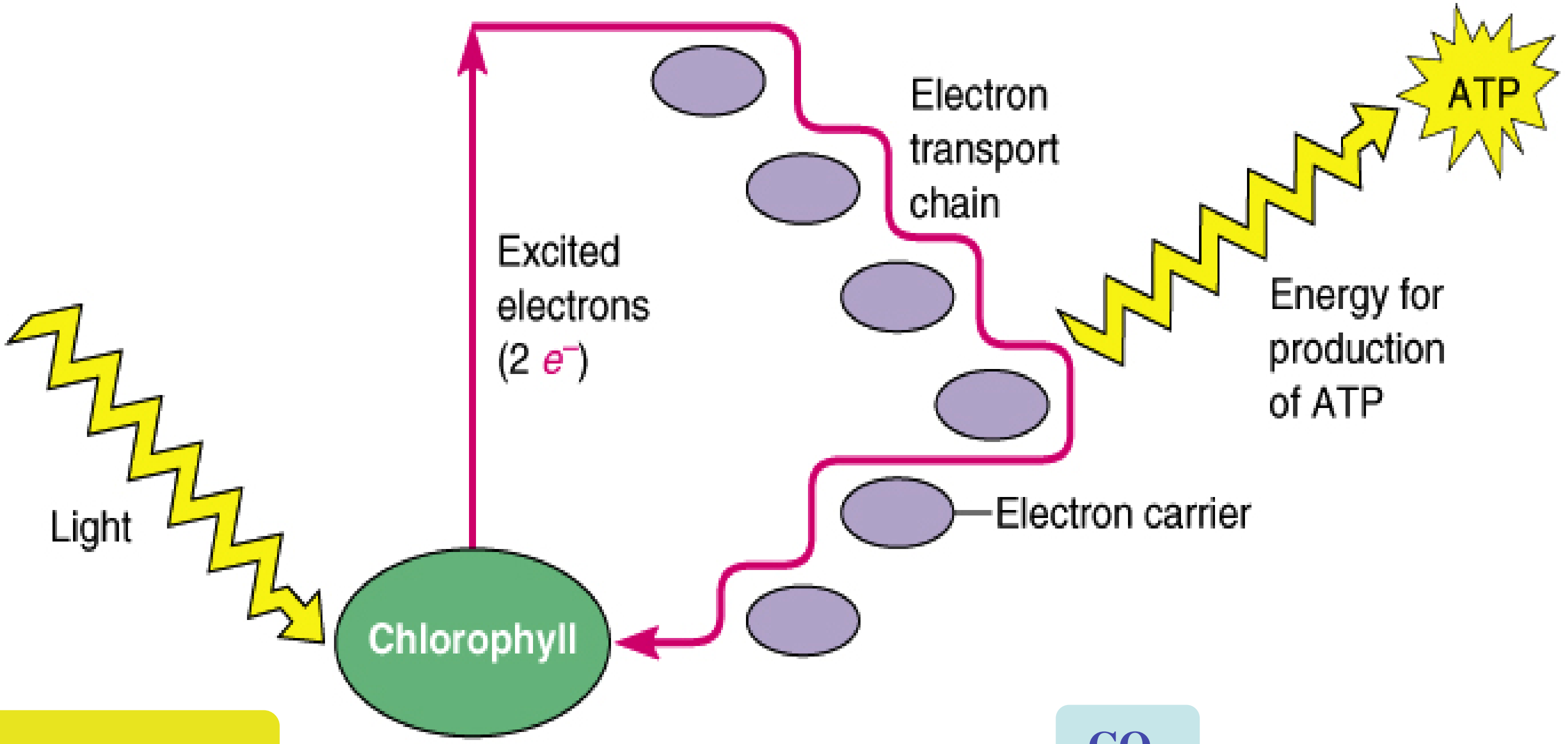
C flux

Biosynthesis



Energy classes of microorganisms

✓ **Phototrophic metabolism**



organic compound

C flux

Biosynthesis

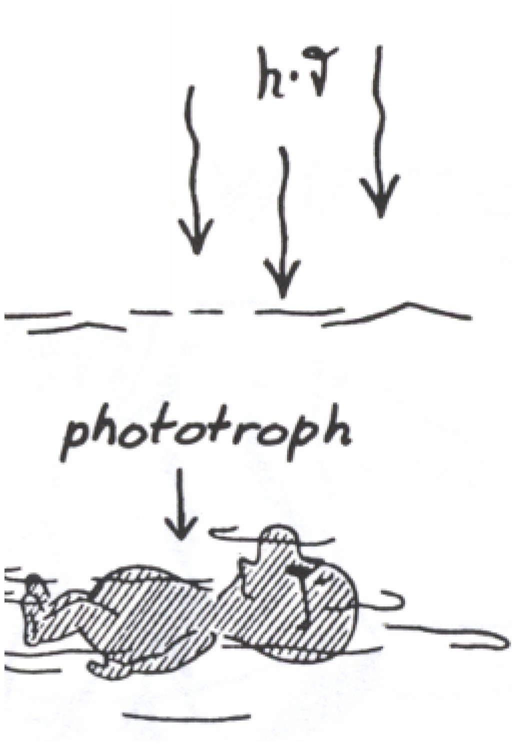
Photoheterotrophy

CO_2

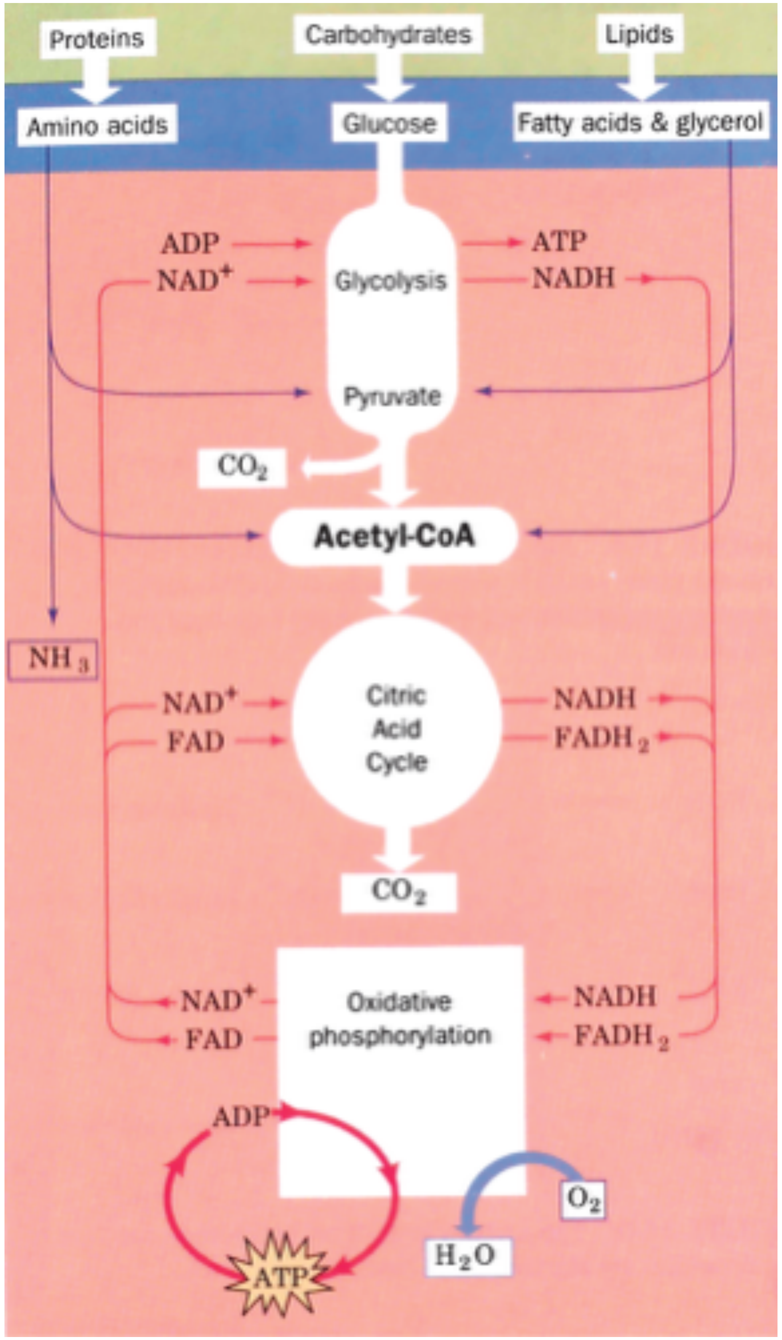
C flux

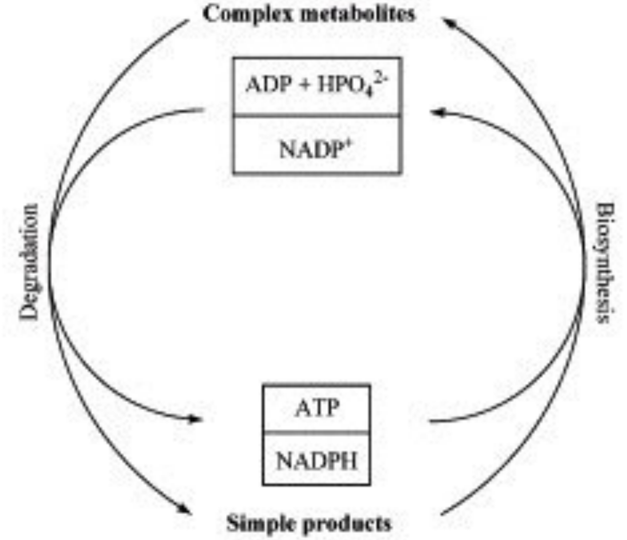
Biosynthesis

Photoautotrophy



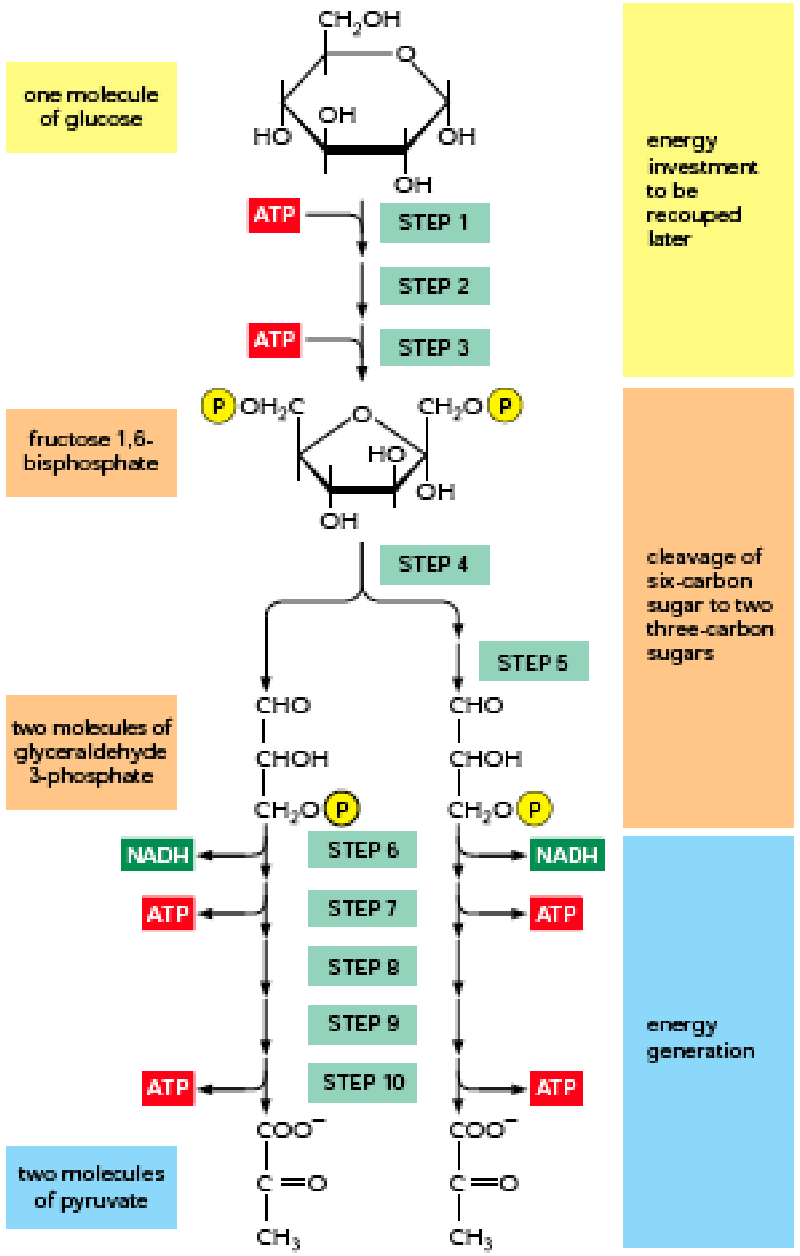
3. Overview of central pathways of heterotrophic metabolism





3. Overview of central pathways of heterotrophic metabolism

Glicólise



one molecule of glucose

fructose 1,6-bisphosphate

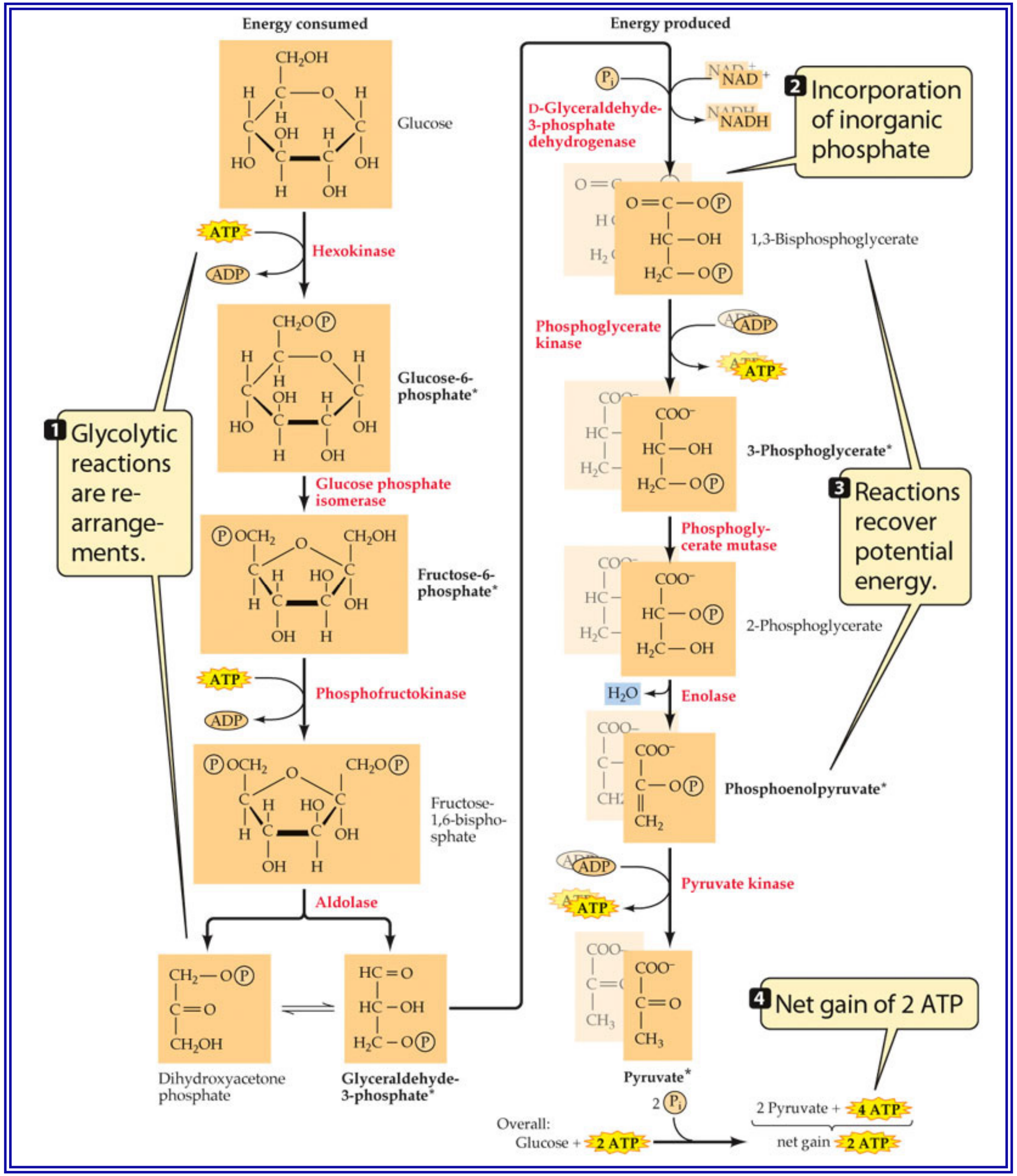
two molecules of glyceraldehyde 3-phosphate

two molecules of pyruvate

energy investment to be recouped later

cleavage of six-carbon sugar to two three-carbon sugars

energy generation



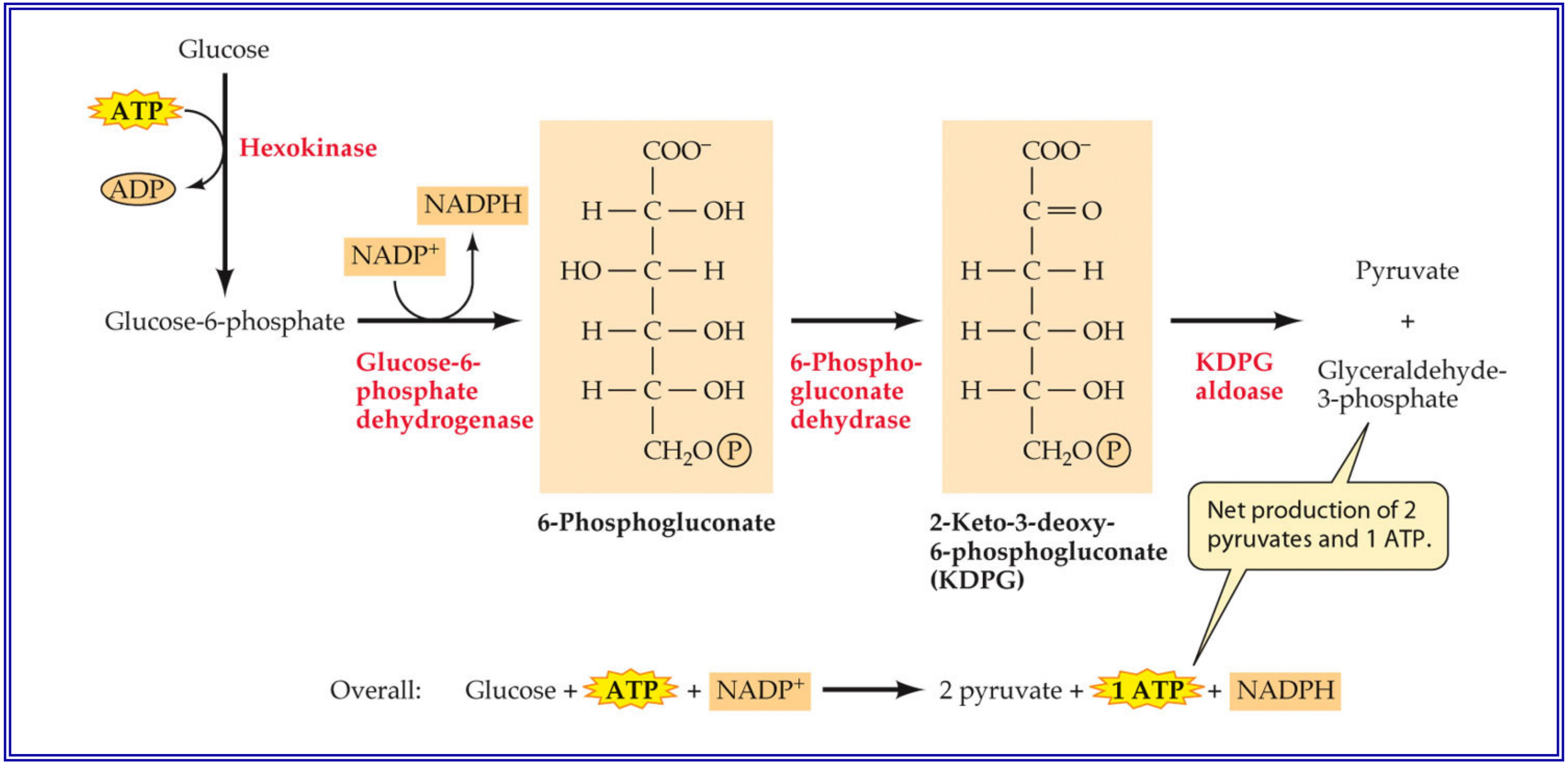
❶ Glycolytic reactions are re-arrange-ments.

❷ Incorporation of inorganic phosphate

❸ Reactions recover potential energy.

❹ Net gain of 2 ATP

Via de Entner-Doudoroff



Net production of 2 pyruvates and 1 ATP.

Overall: Glucose + ATP + $NADP^+$ ⟶ 2 pyruvate + 1 ATP + NADPH

3. Overview of central pathways of heterotrophic metabolism

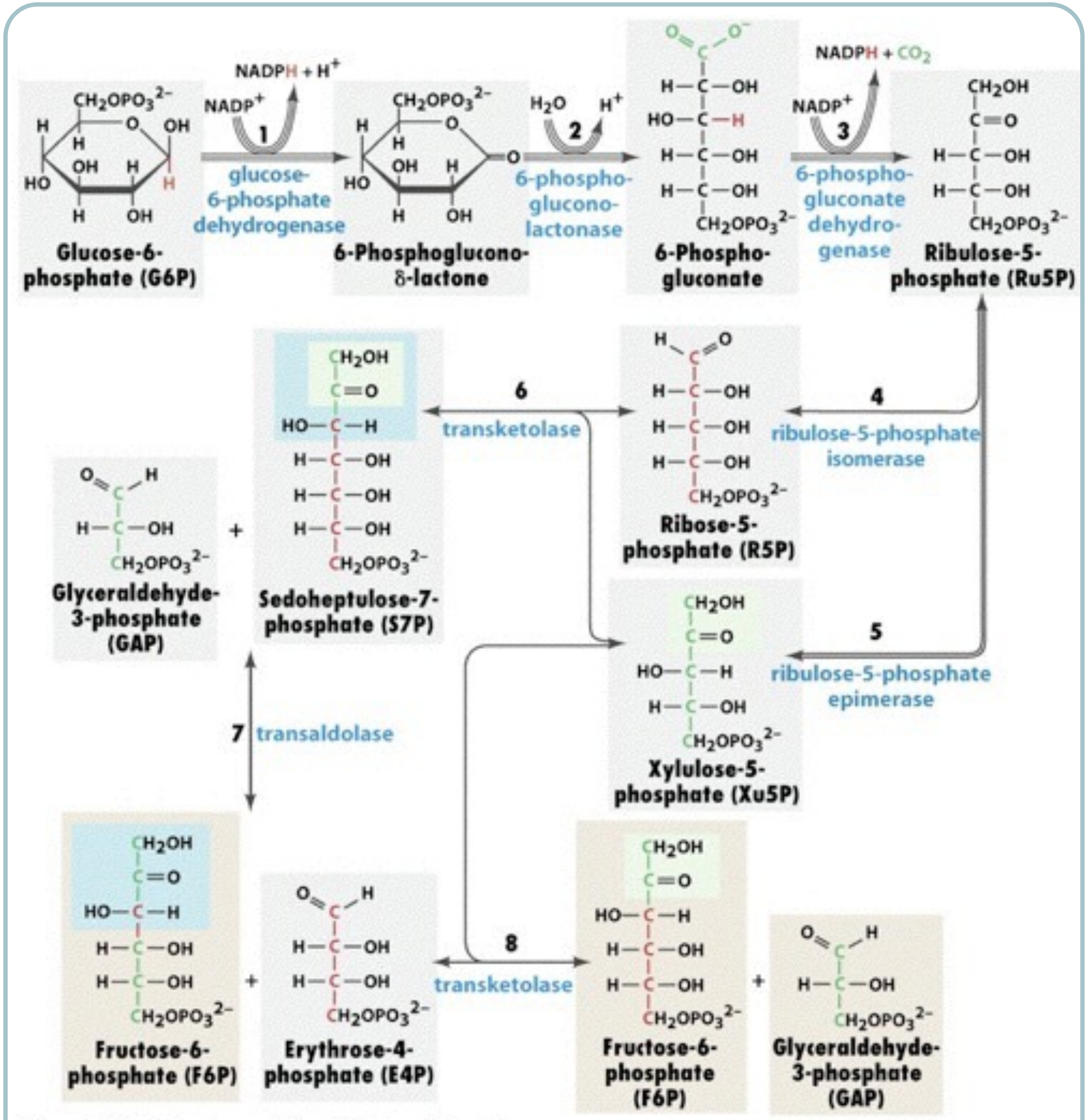
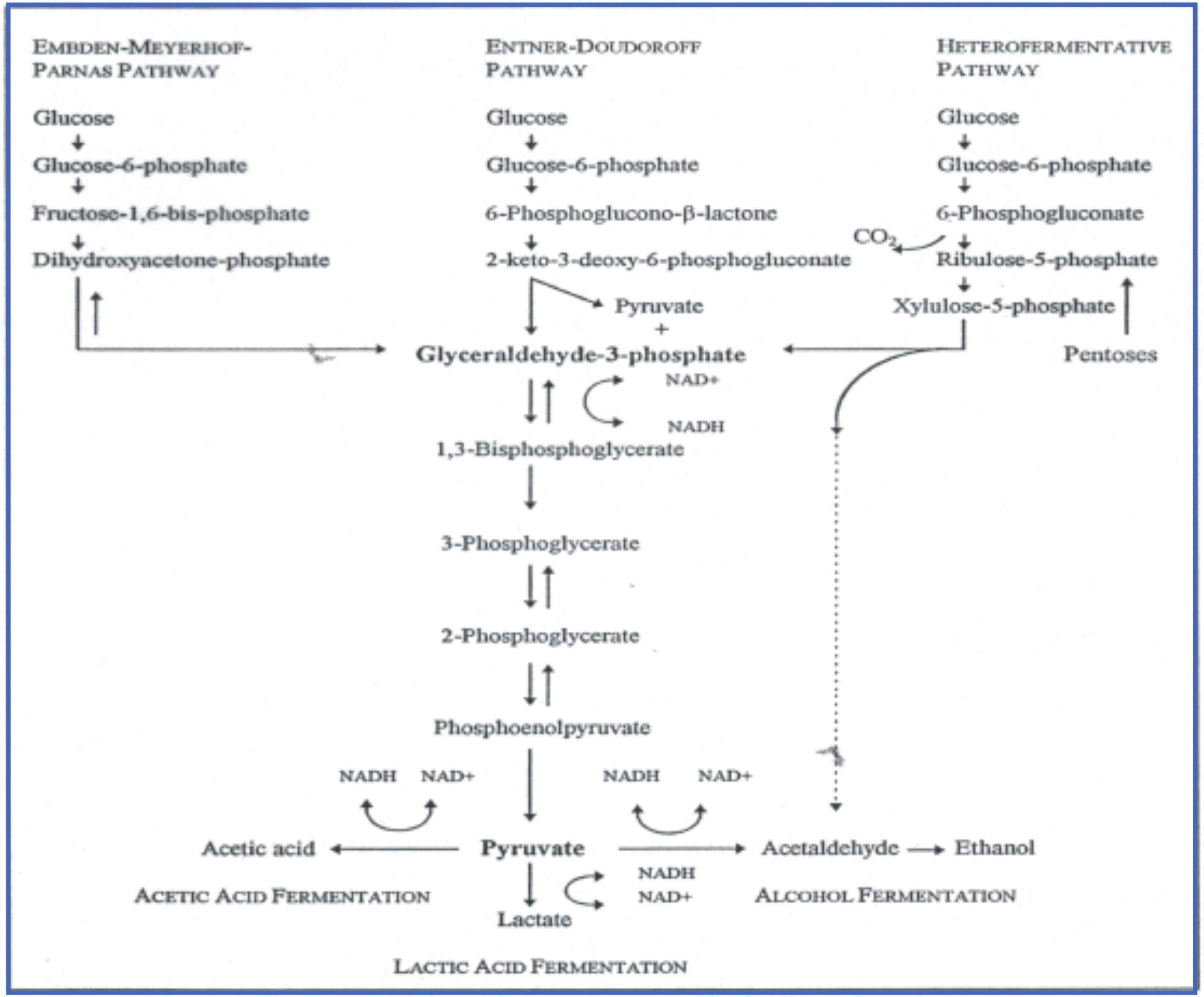


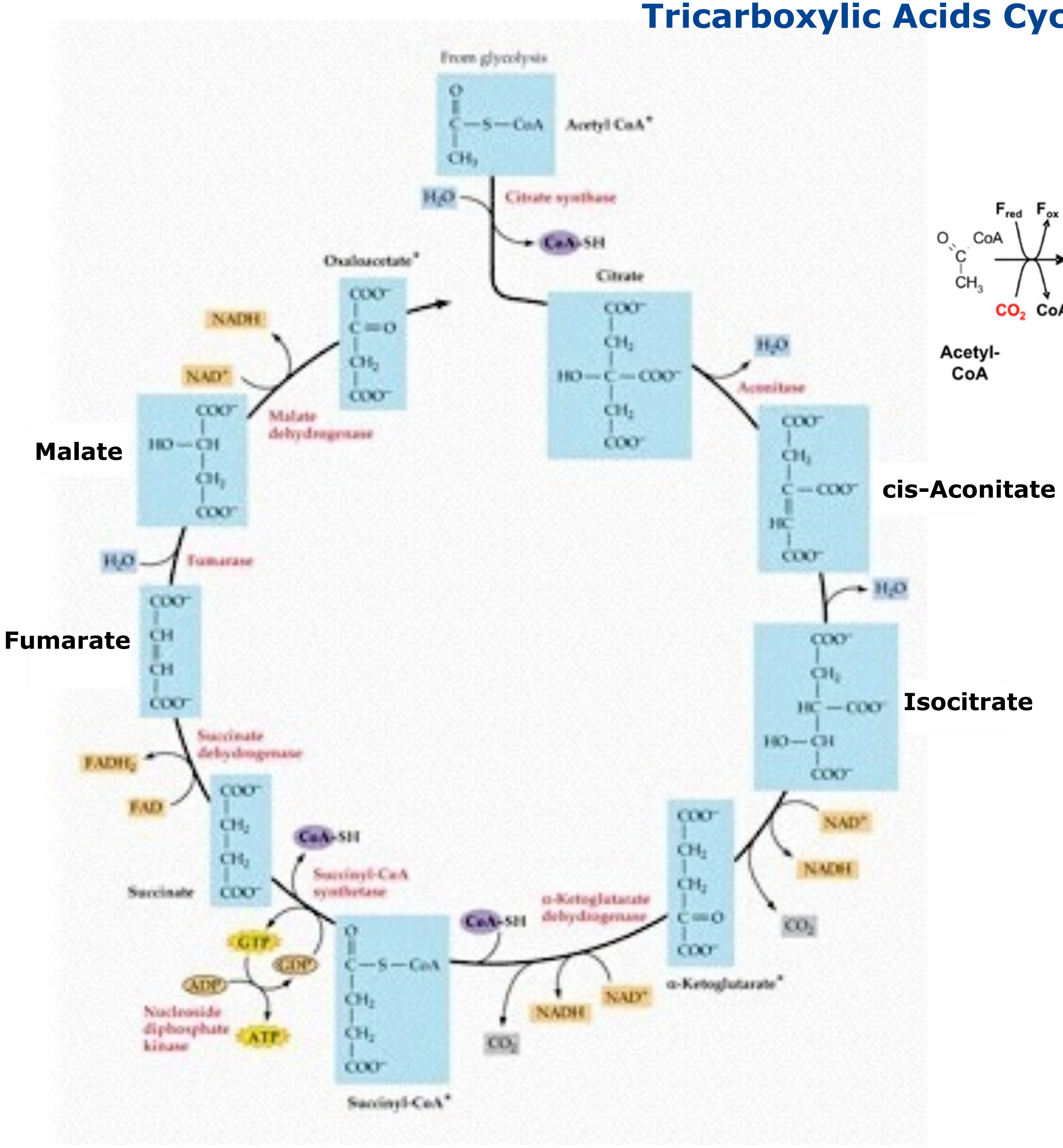
Figure 14-30 Fundamentals of Biochemistry, 2/e

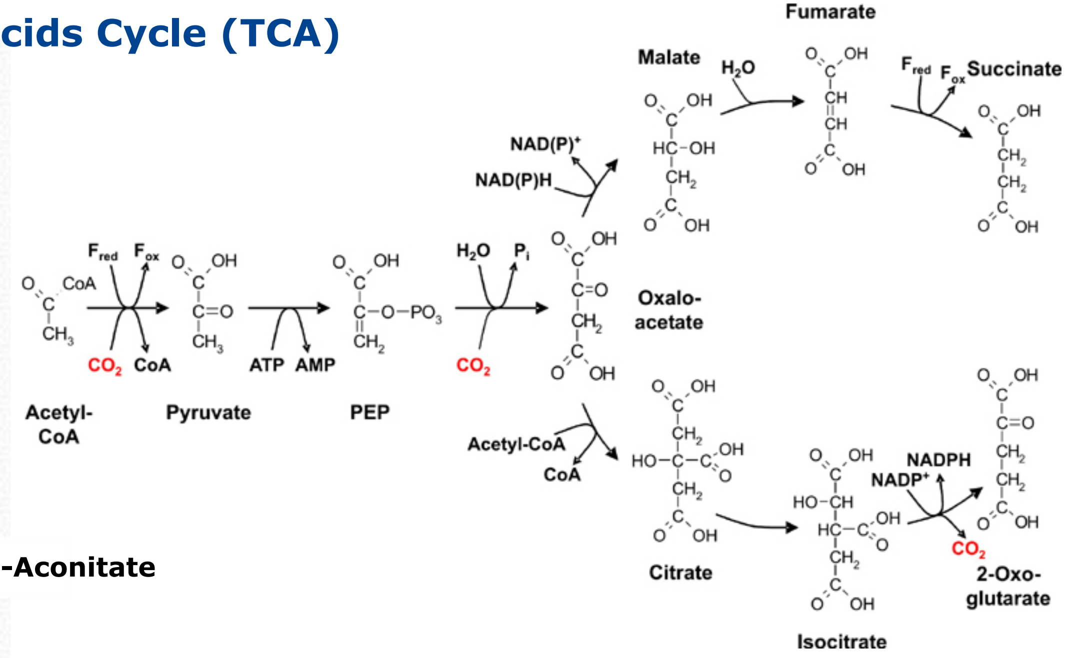
Via das pentoses fosfato

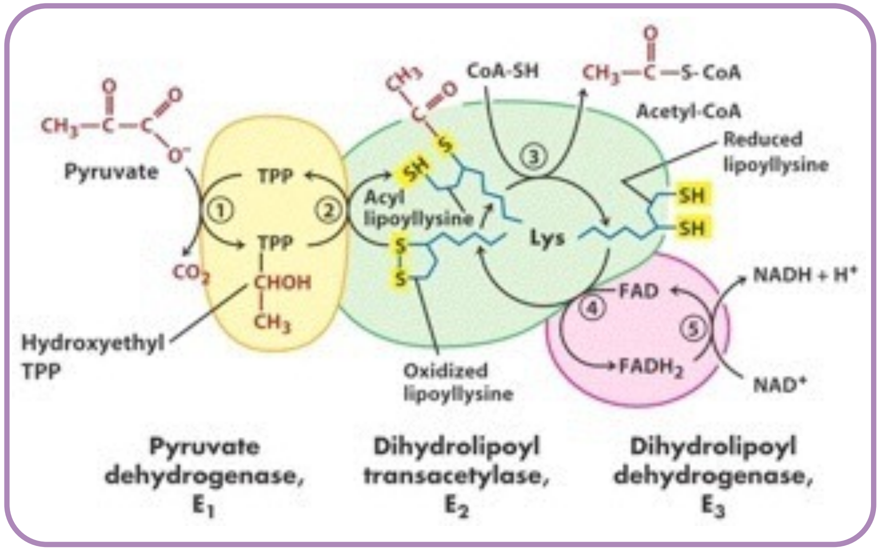
3. Overview of central pathways of heterotrophic metabolism



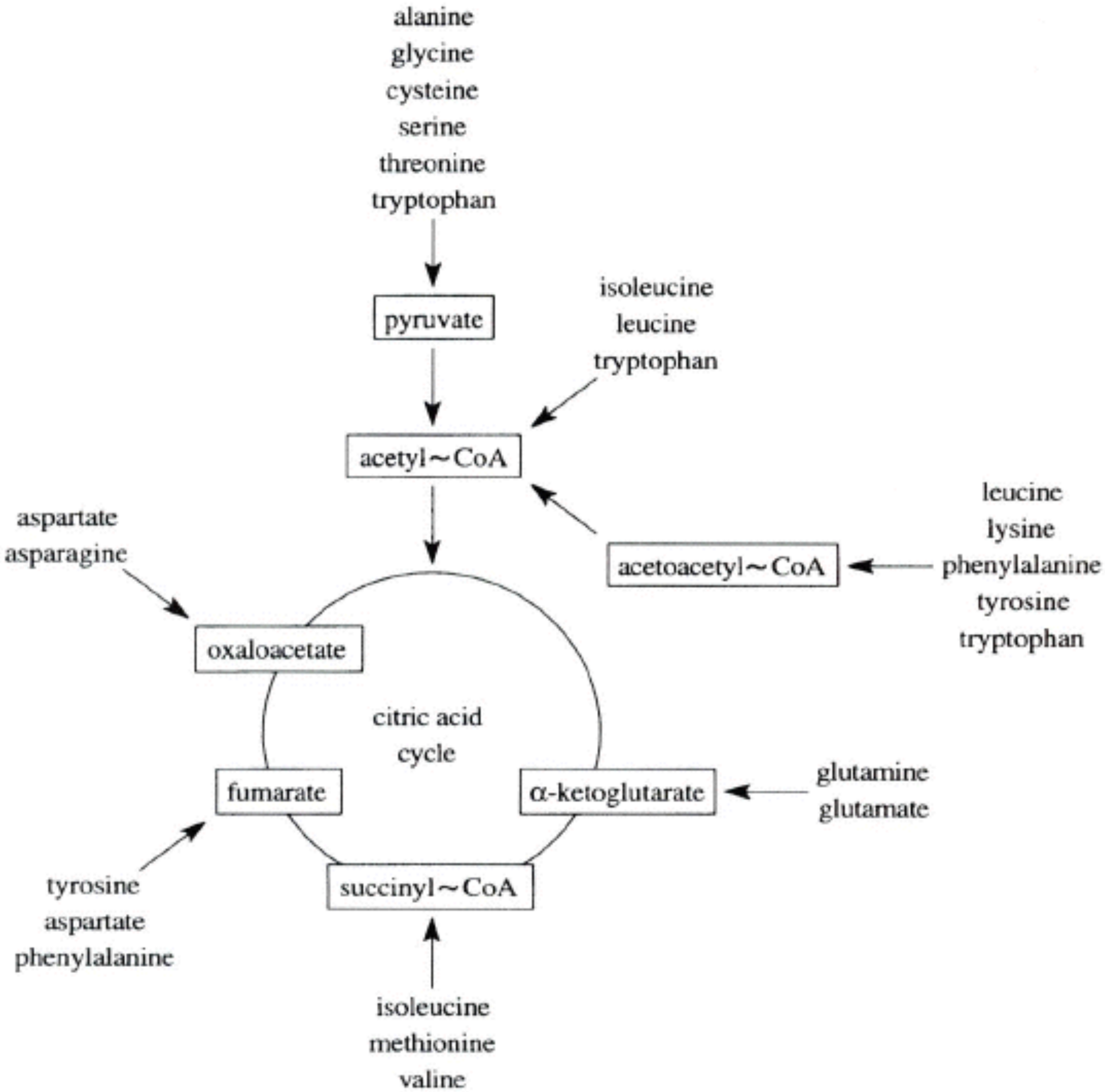
Tricarboxylic Acids Cycle (TCA)



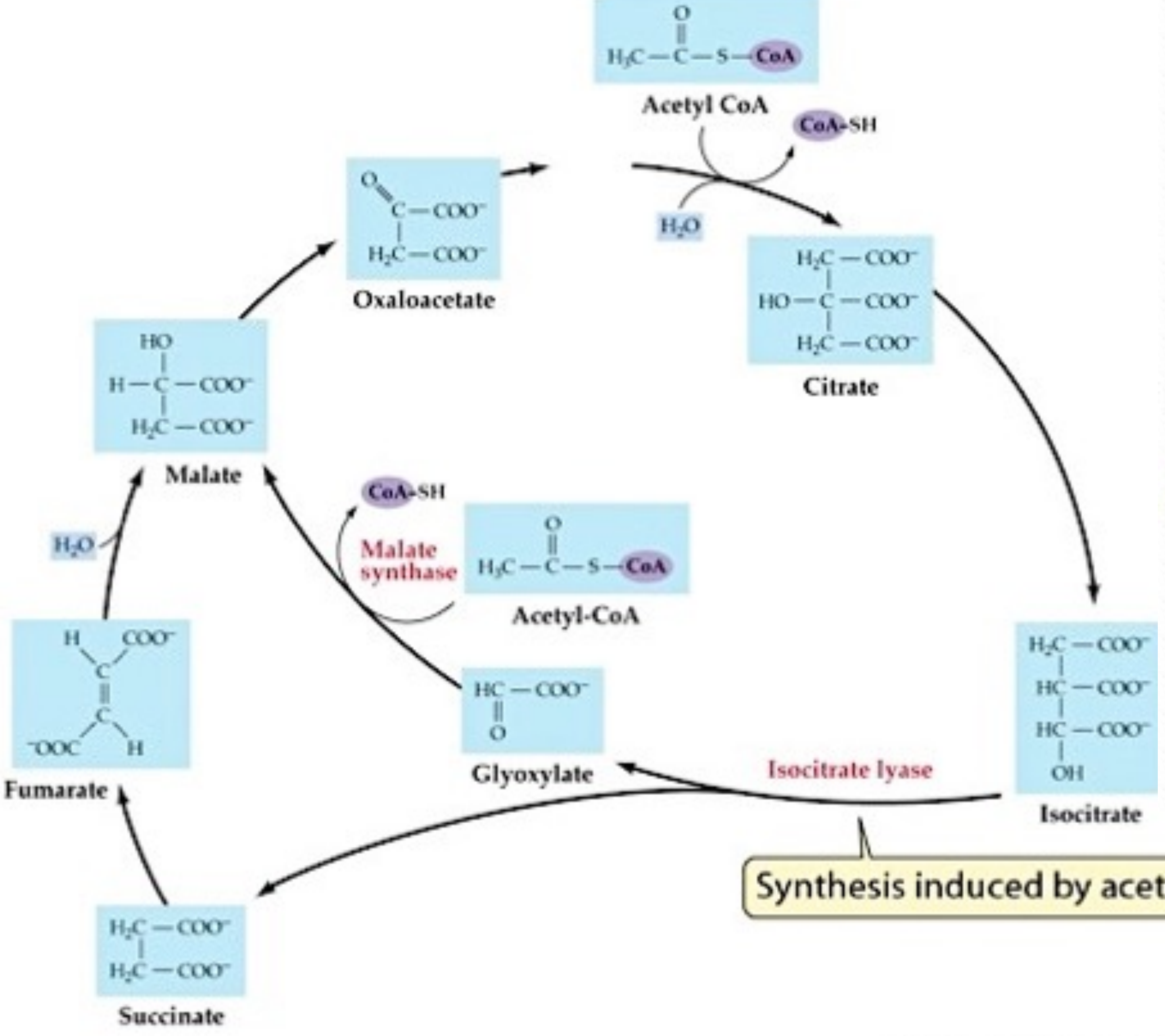




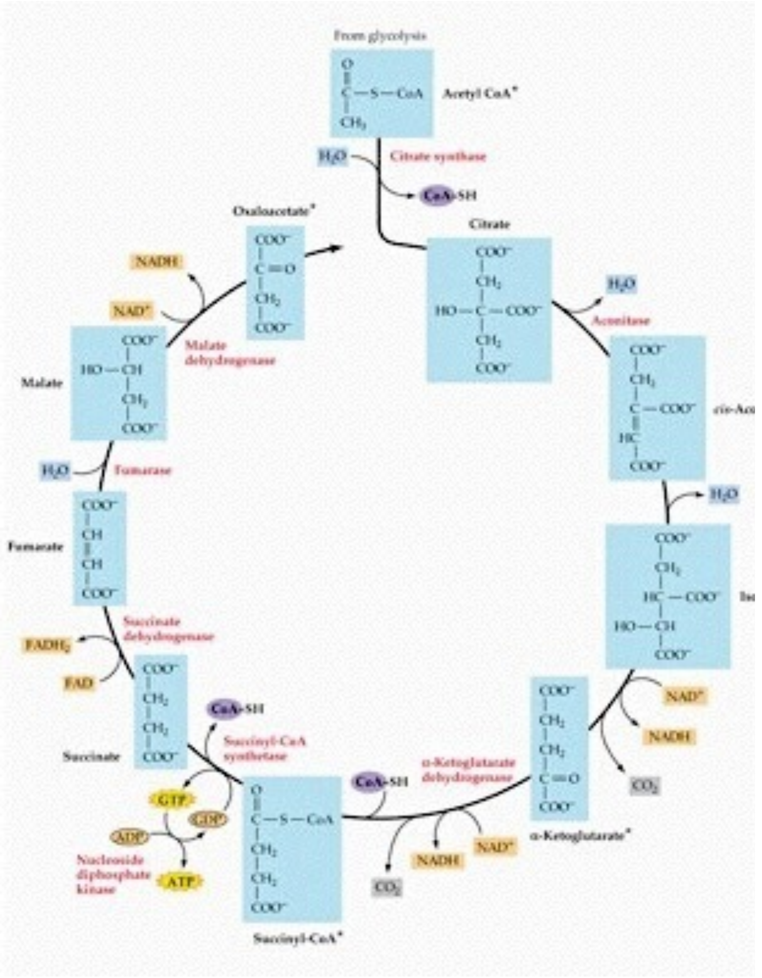
3. Overview of central pathways of heterotrophic metabolism



Glyoxylate Cycle



Synthesis induced by acetate



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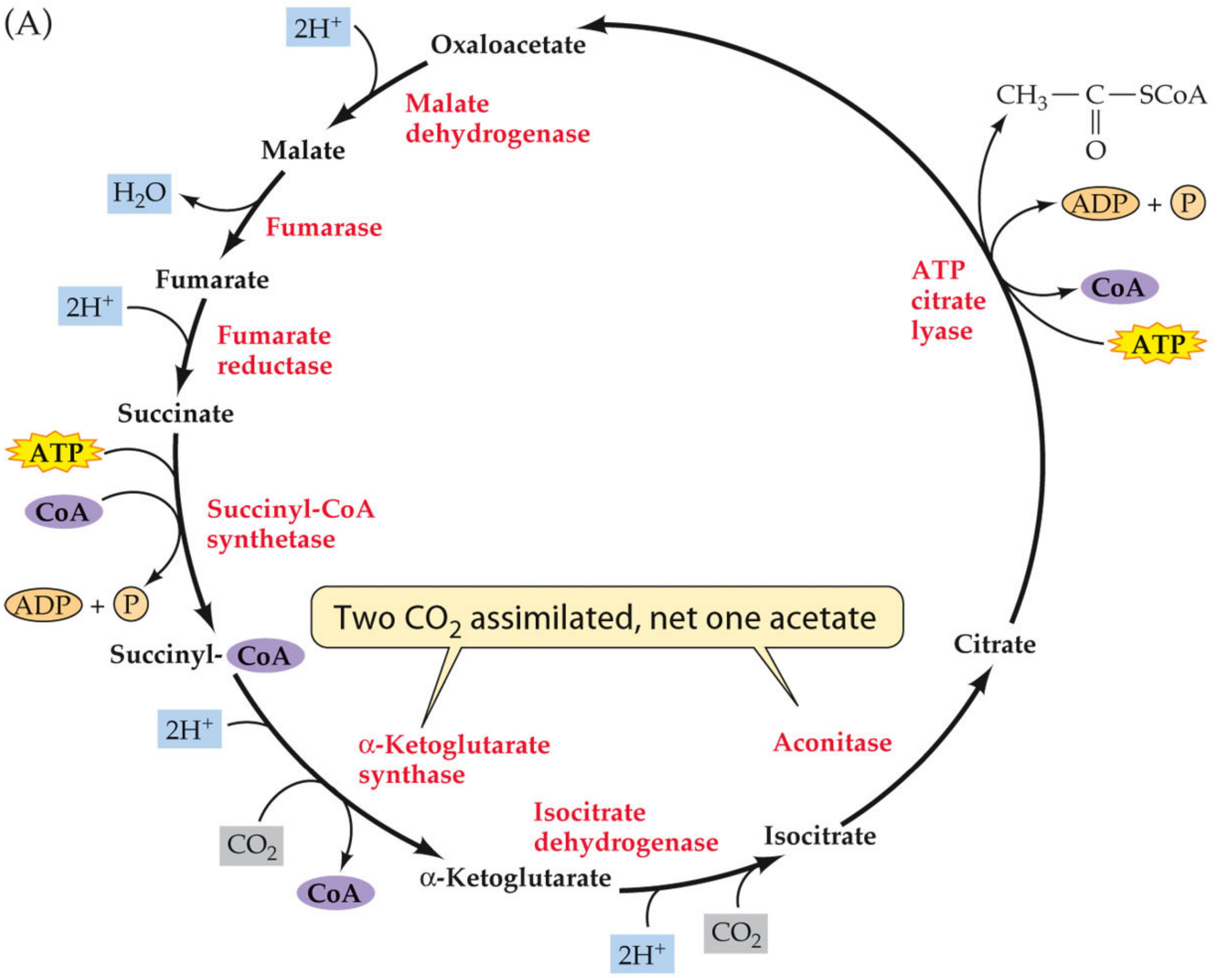
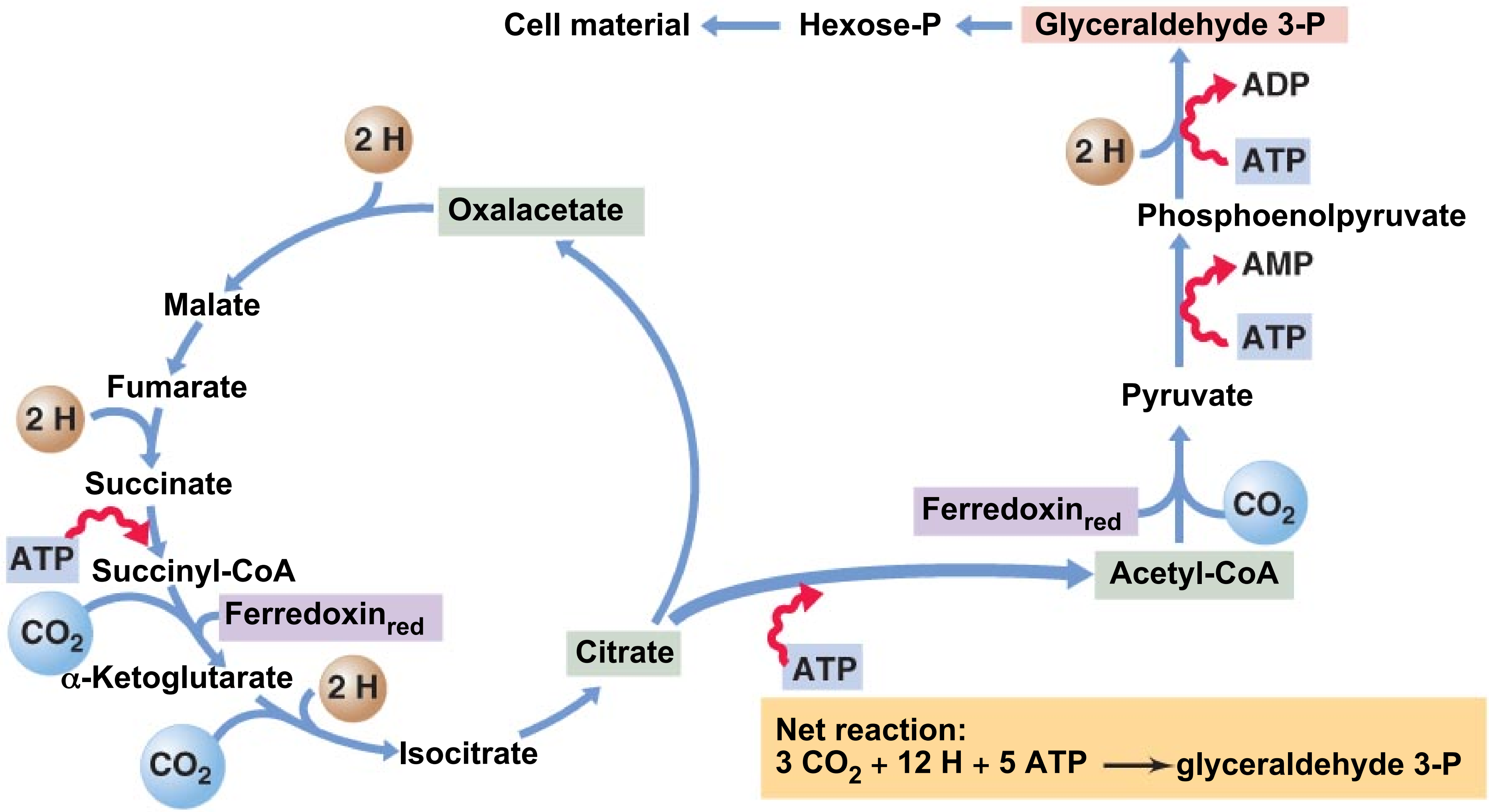
Reverse TCA



MICROBIAL LIFE, **Figure 10.8 (Part 1)** © 2002 Sinauer Associates, Inc.

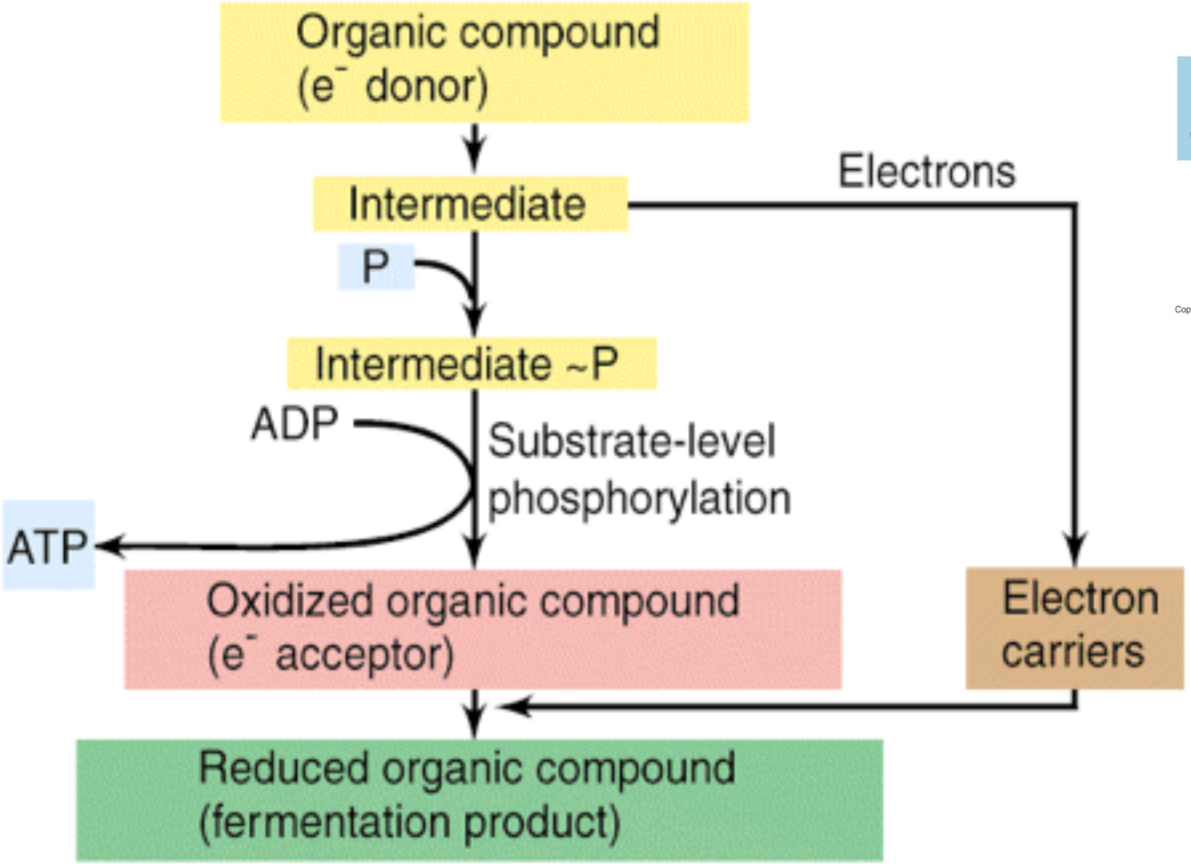
Reverse TCA

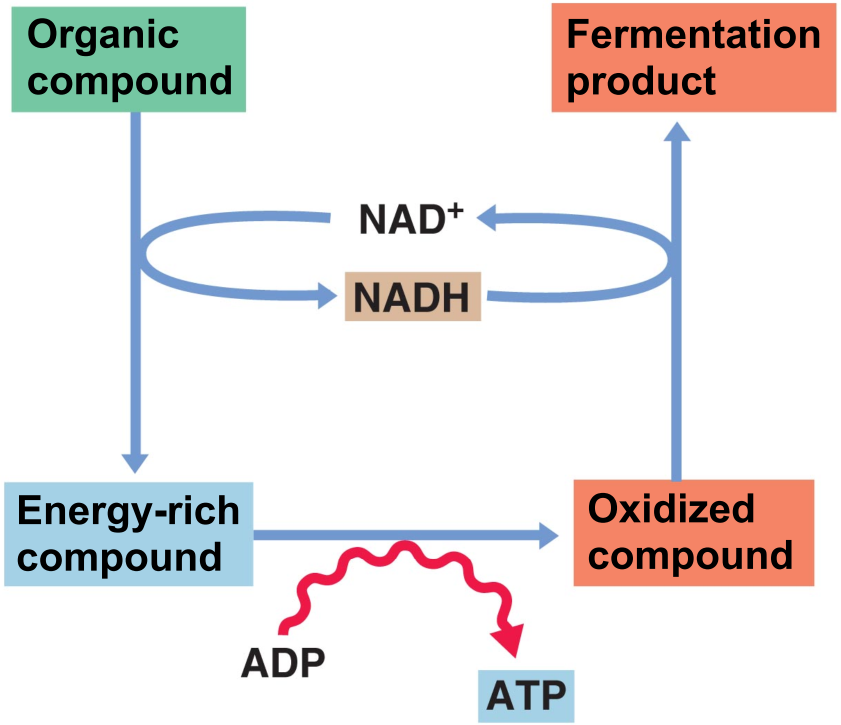


Net reaction:
$3\ CO_2 + 12\ H + 5\ ATP \longrightarrow$ glyceraldehyde 3-P

3. Overview of central pathways of heterotrophic metabolism

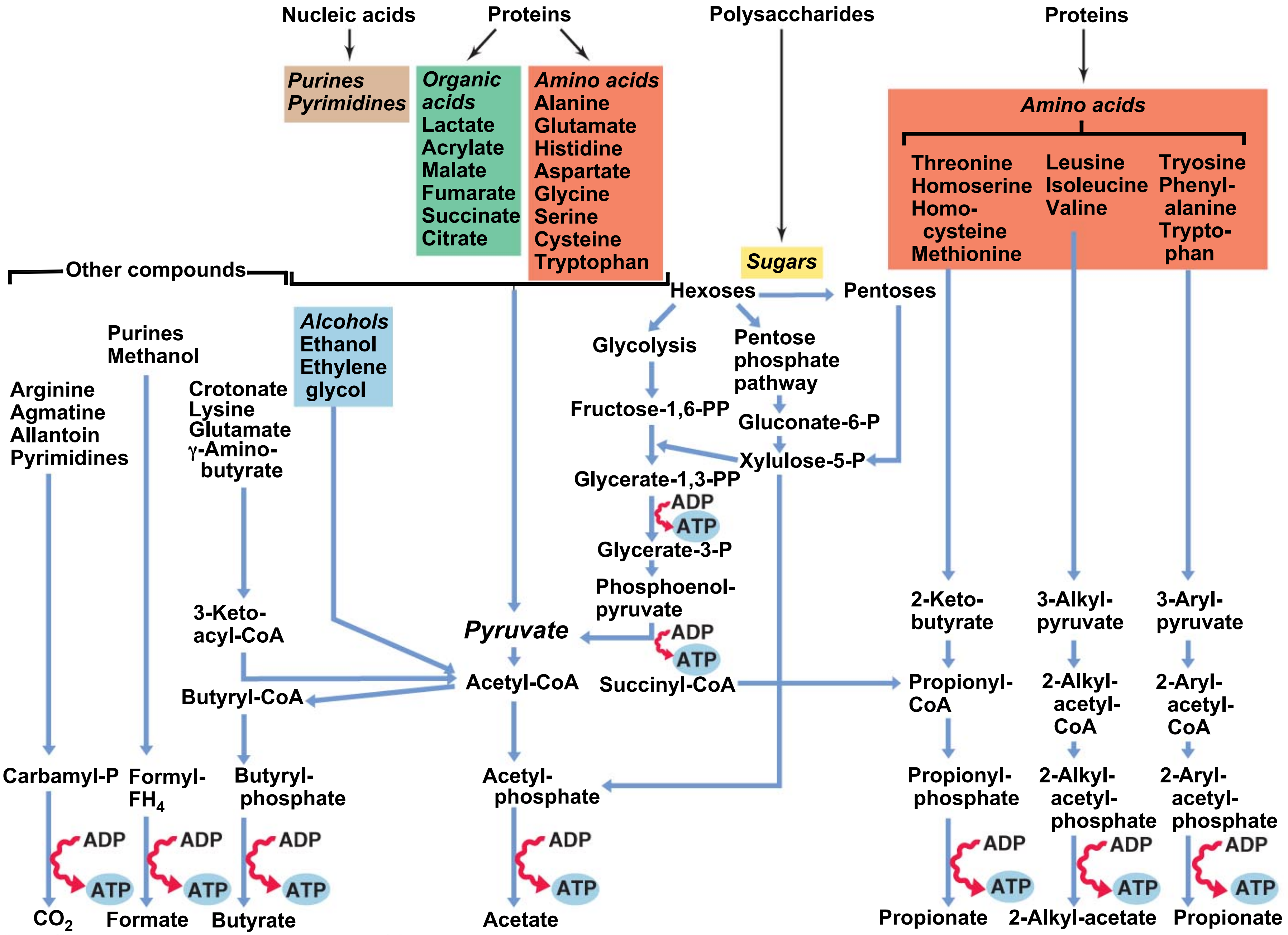
Fermentation and substrate level phosphorylation





3. Overview of central pathways of heterotrophic metabolism

Fermentations



Nucleic acids

Proteins

Polysaccharides

Proteins

Purines
Pyrimidines

Organic acids
Lactate
Acrylate
Malate
Fumarate
Succinate
Citrate

Amino acids
Alanine
Glutamate
Histidine
Aspartate
Glycine
Serine
Cysteine
Tryptophan

Sugars

Amino acids

Threonine
Homoserine
Homo-cysteine
Methionine

Leusine
Isoleucine
Valine

Tryosine
Phenyl-alanine
Trypto-phan

Other compounds

Arginine
Agmatine
Allantoin
Pyrimidines

Purines
Methanol

Crotonate
Lysine
Glutamate
γ-Amino-butyrate

Alcohols
Ethanol
Ethylene glycol

Hexoses

Pentoses

Glycolysis

Pentose phosphate pathway

Fructose-1,6-PP

Gluconate-6-P

Xylulose-5-P

Glycerate-1,3-PP

ADP

ATP

Glycerate-3-P

Phosphoenol-pyruvate

ADP

ATP

Pyruvate

Acetyl-CoA

Succinyl-CoA

3-Keto-acyl-CoA

Butyryl-CoA

2-Keto-butyrate

3-Alkyl-pyruvate

3-Aryl-pyruvate

Propionyl-CoA

2-Alkyl-acetyl-CoA

2-Aryl-acetyl-CoA

Carbamyl-P

Formyl-FH_4

Butyryl-phosphate

Acetyl-phosphate

Propionyl-phosphate

2-Alkyl-acetyl-phosphate

2-Aryl-acetyl-phosphate

ADP

ATP

CO_2

Formate

Butyrate

Acetate

Propionate

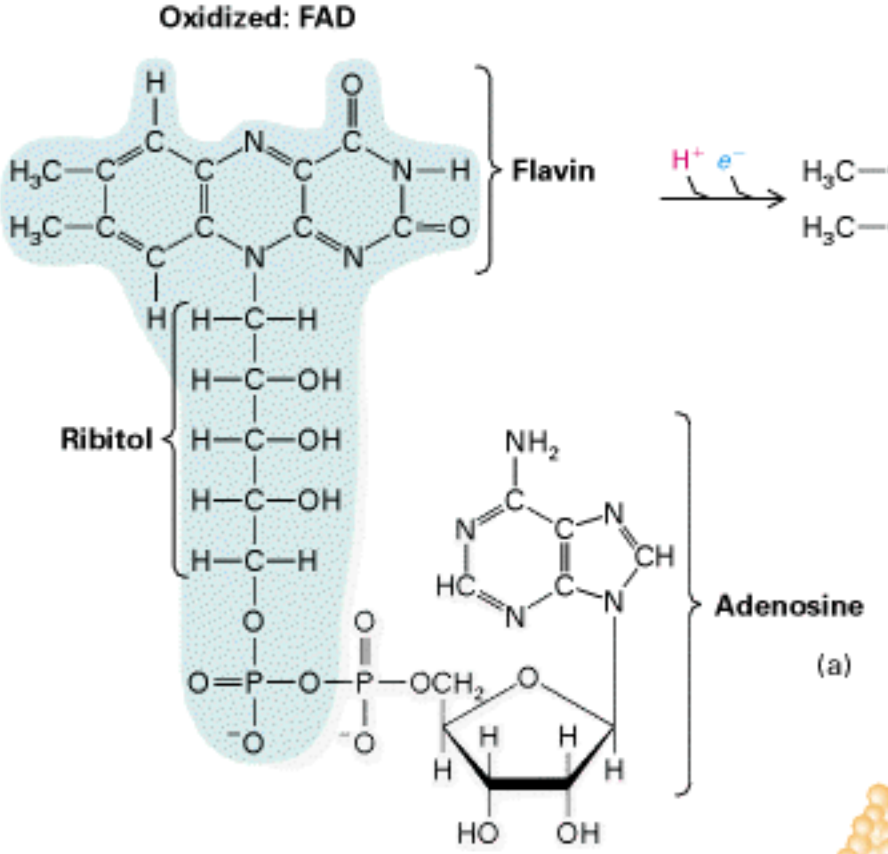
2-Alkyl-acetate

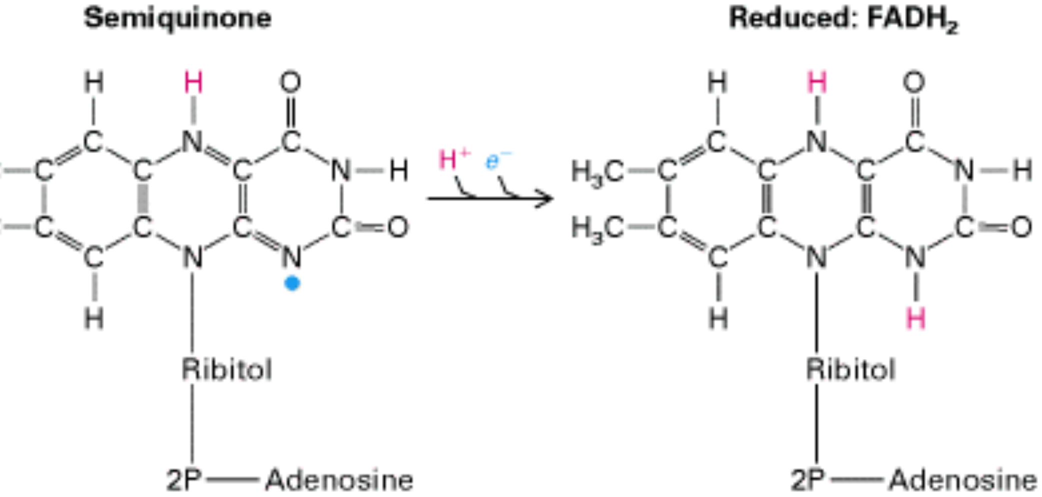
Propionate

Electron Transport in Prokaryotes

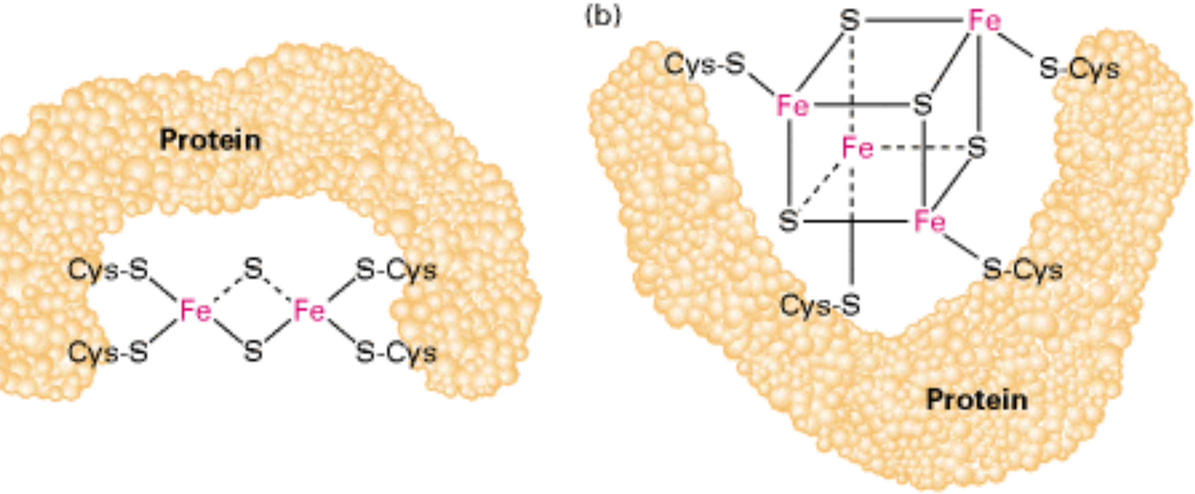
Electron Transporters

Flavoproteins





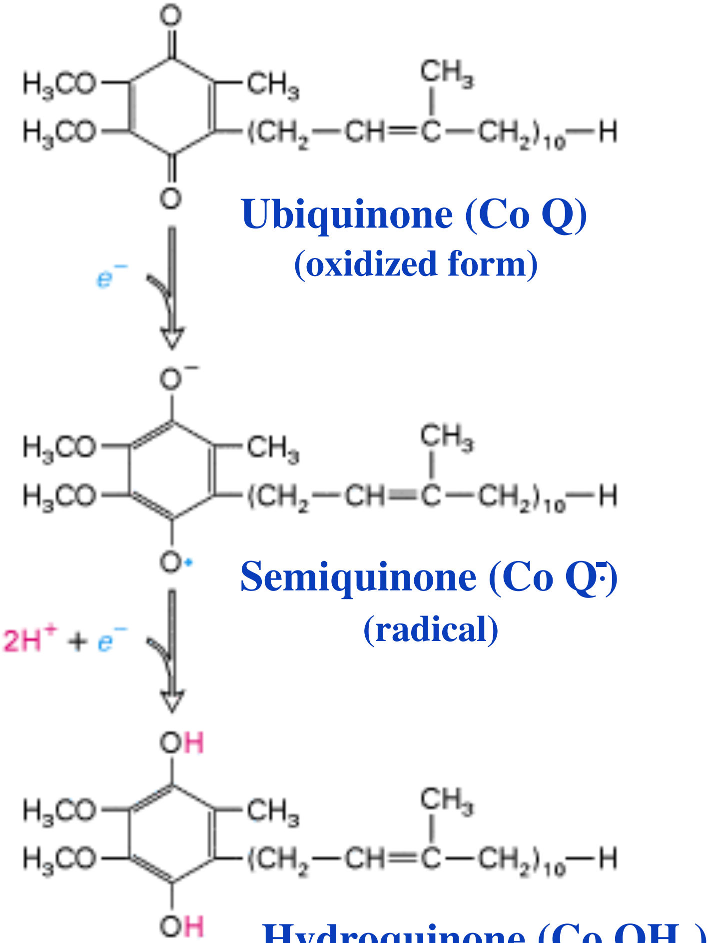
Fe-S Proteins



Electron Transport in Prokaryotes

Electron Transporters

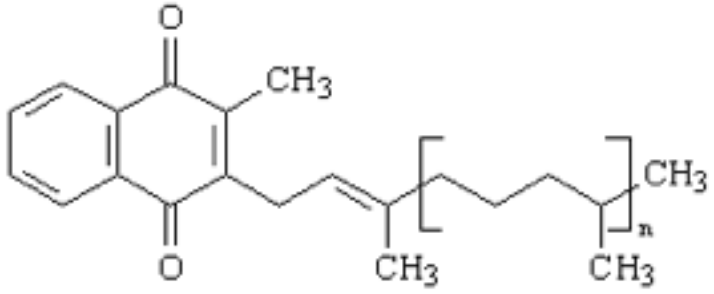
Quinones



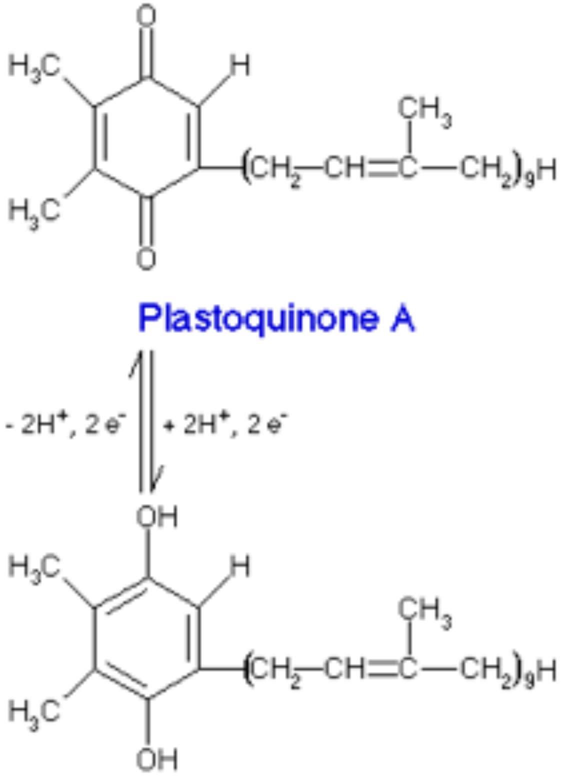
Ubiquinone (Co Q)
(oxidized form)

Semiquinone (Co Q$^{\cdot}$)
(radical)

Hydroquinone (Co QH$_2$)
(reduced form)



Menaquinone (vitamine K1)



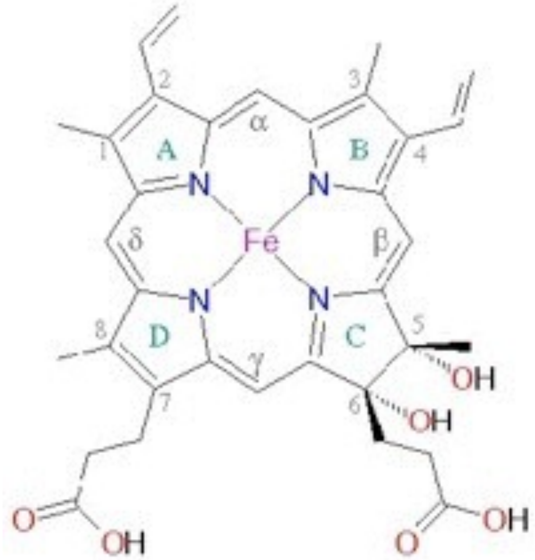
Plastoquinone A

Plastohydroquinone A

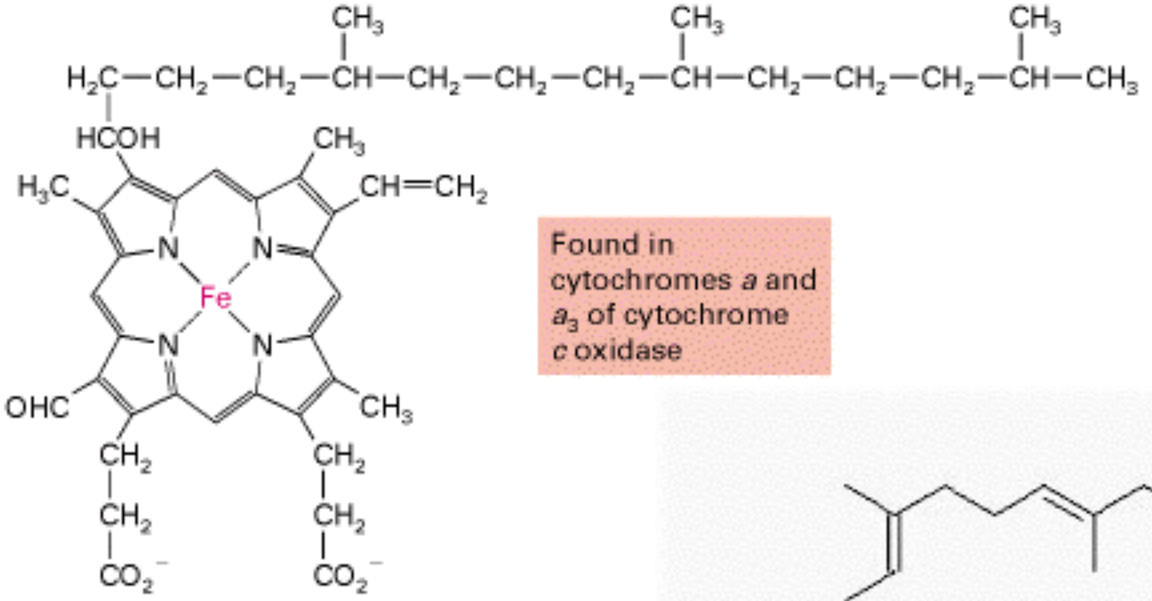
Electron Transport in Prokaryotes

Electron Transporters

Cytochromes

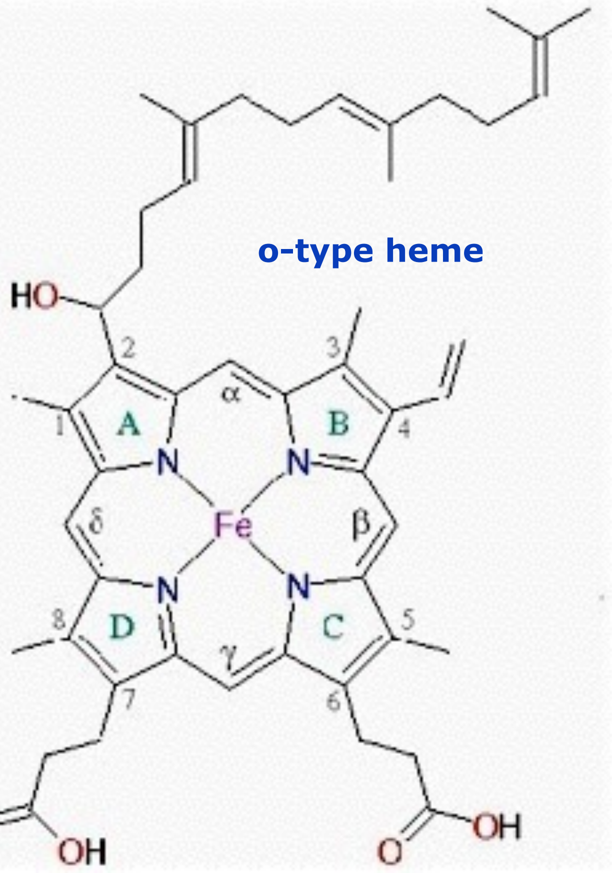


d-type heme

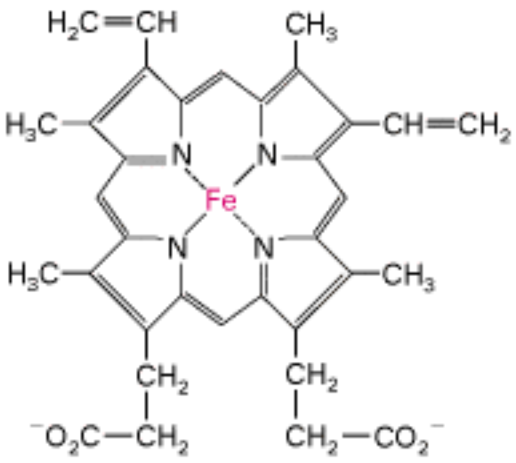


a-type heme

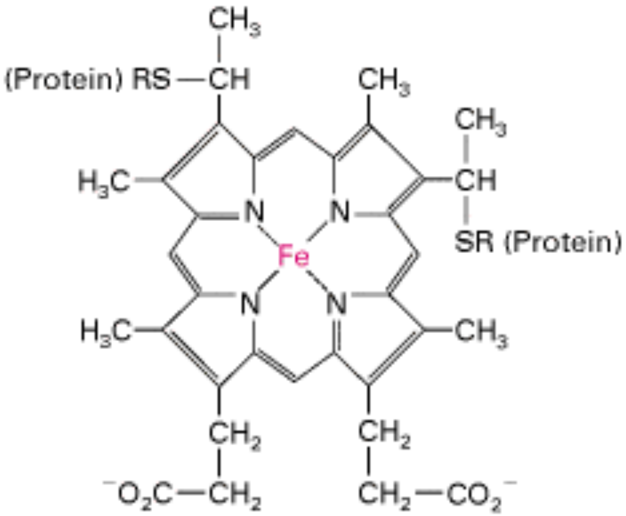
Found in cytochromes *a* and a_3 of cytochrome *c* oxidase



o-type heme

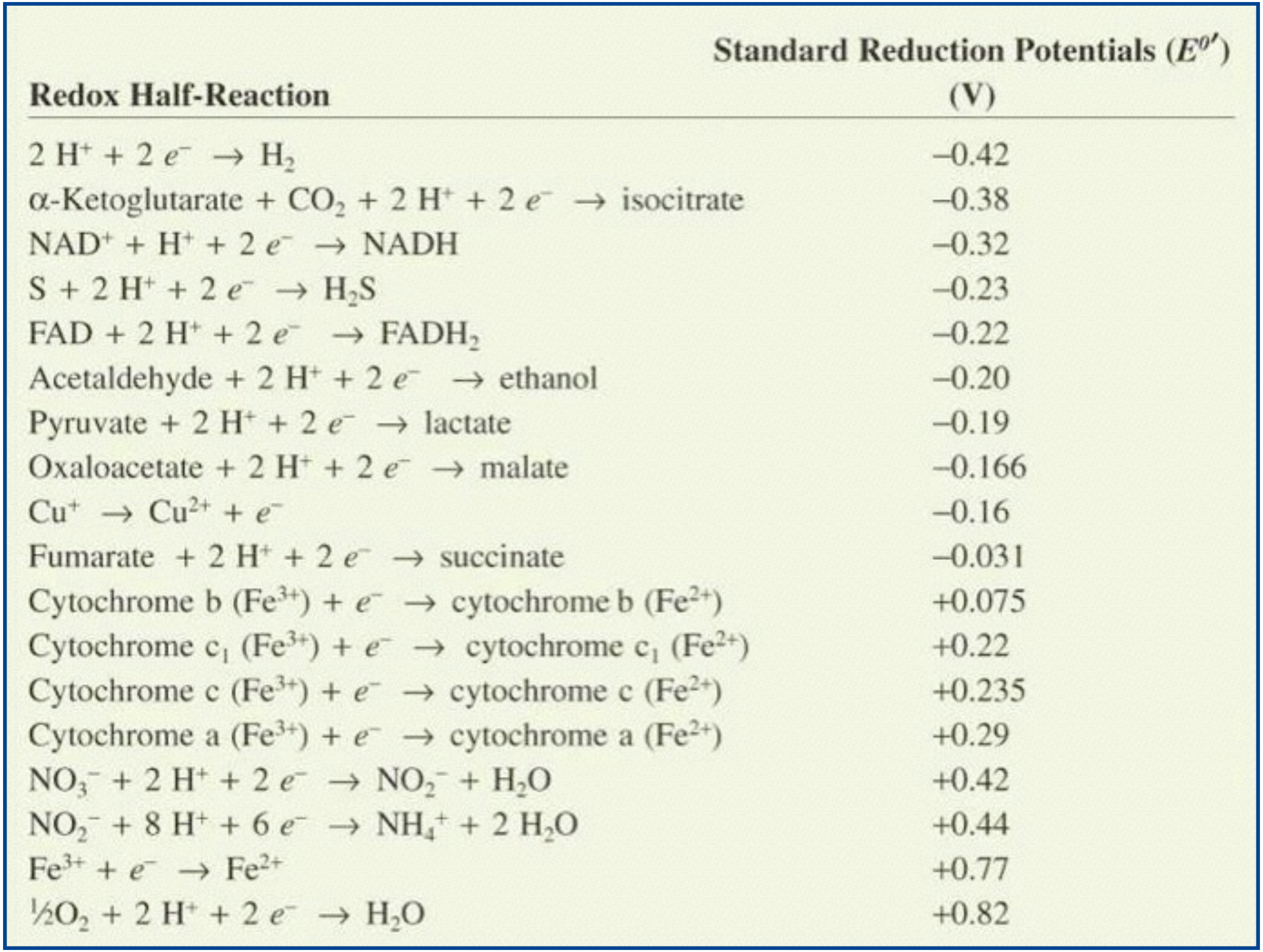


b-type heme



c-type heme

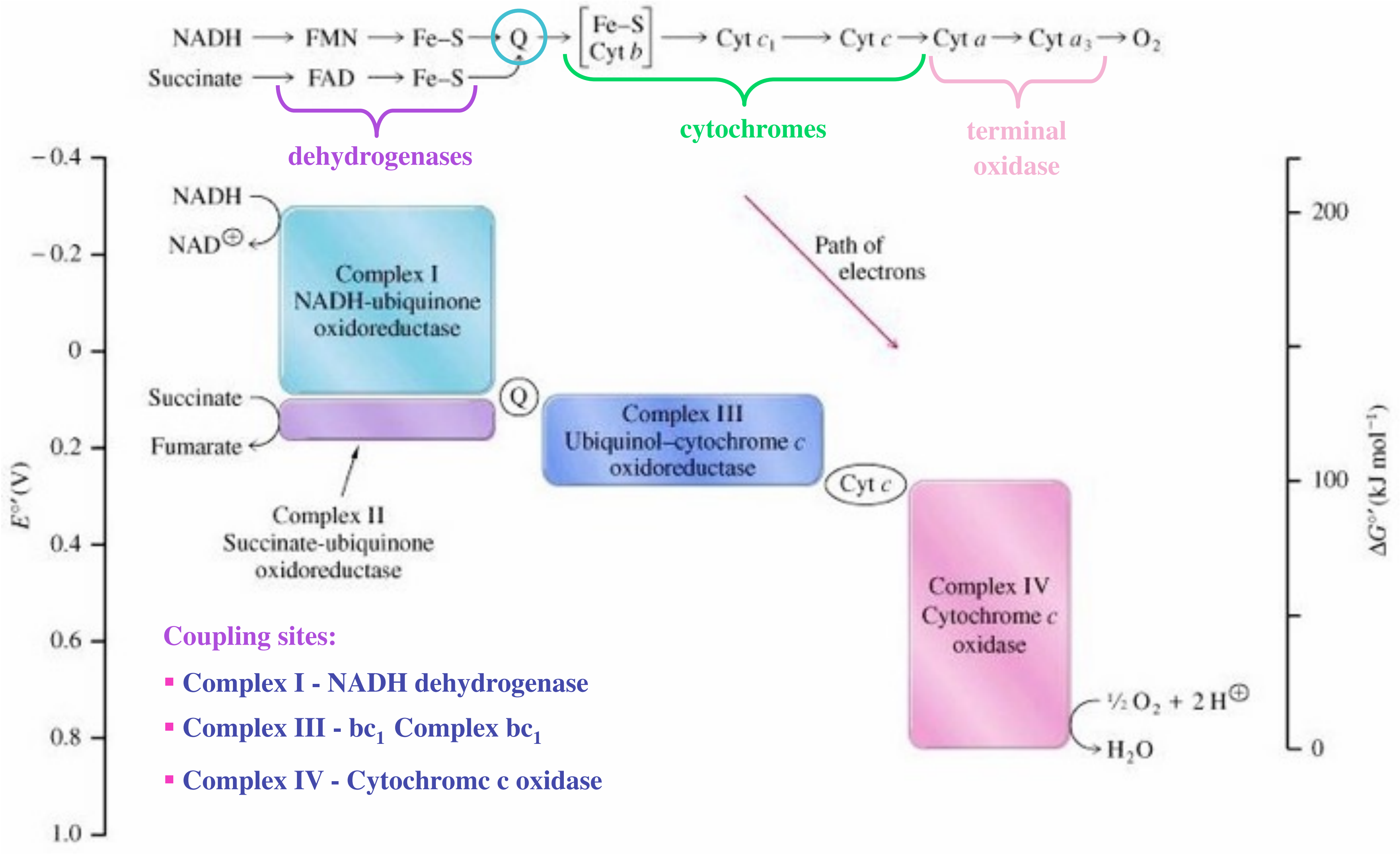
3. Overview of central pathways of heterotrophic metabolism



Redox Half-Reaction	Standard Reduction Potentials ($E^{0\prime}$) (V)
$2\ H^+ + 2\ e^- \rightarrow H_2$	–0.42
α-Ketoglutarate + $CO_2 + 2\ H^+ + 2\ e^- \rightarrow$ isocitrate	–0.38
$NAD^+ + H^+ + 2\ e^- \rightarrow NADH$	–0.32
$S + 2\ H^+ + 2\ e^- \rightarrow H_2S$	–0.23
$FAD + 2\ H^+ + 2\ e^- \rightarrow FADH_2$	–0.22
Acetaldehyde + $2\ H^+ + 2\ e^- \rightarrow$ ethanol	–0.20
Pyruvate + $2\ H^+ + 2\ e^- \rightarrow$ lactate	–0.19
Oxaloacetate + $2\ H^+ + 2\ e^- \rightarrow$ malate	–0.166
$Cu^+ \rightarrow Cu^{2+} + e^-$	–0.16
Fumarate + $2\ H^+ + 2\ e^- \rightarrow$ succinate	–0.031
Cytochrome b (Fe^{3+}) + $e^- \rightarrow$ cytochrome b (Fe^{2+})	+0.075
Cytochrome c_1 (Fe^{3+}) + $e^- \rightarrow$ cytochrome c_1 (Fe^{2+})	+0.22
Cytochrome c (Fe^{3+}) + $e^- \rightarrow$ cytochrome c (Fe^{2+})	+0.235
Cytochrome a (Fe^{3+}) + $e^- \rightarrow$ cytochrome a (Fe^{2+})	+0.29
$NO_3^- + 2\ H^+ + 2\ e^- \rightarrow NO_2^- + H_2O$	+0.42
$NO_2^- + 8\ H^+ + 6\ e^- \rightarrow NH_4^+ + 2\ H_2O$	+0.44
$Fe^{3+} + e^- \rightarrow Fe^{2+}$	+0.77
$\frac{1}{2}O_2 + 2\ H^+ + 2\ e^- \rightarrow H_2O$	+0.82

Electron Transport Organization

Mitochondrial standard



Coupling sites:

- Complex I - NADH dehydrogenase
- Complex III - bc_1 Complex bc_1
- Complex IV - Cytochromc c oxidase

Electron Transport Organization

Energy transduction parameters

✓ $H^+ / 2e^-$ (H^+ / O) : number of translocated protons / 2 electrons transferred

NADH → O_2 $H^+ / 2e^- = 10$
Complex I and III $H^+ / 2e^- = 4$
Complex IV $H^+ / 2e^- = 2$

✓ P/O (P/ $2e^-$) : number of ATP formed / 2 electrons transferred

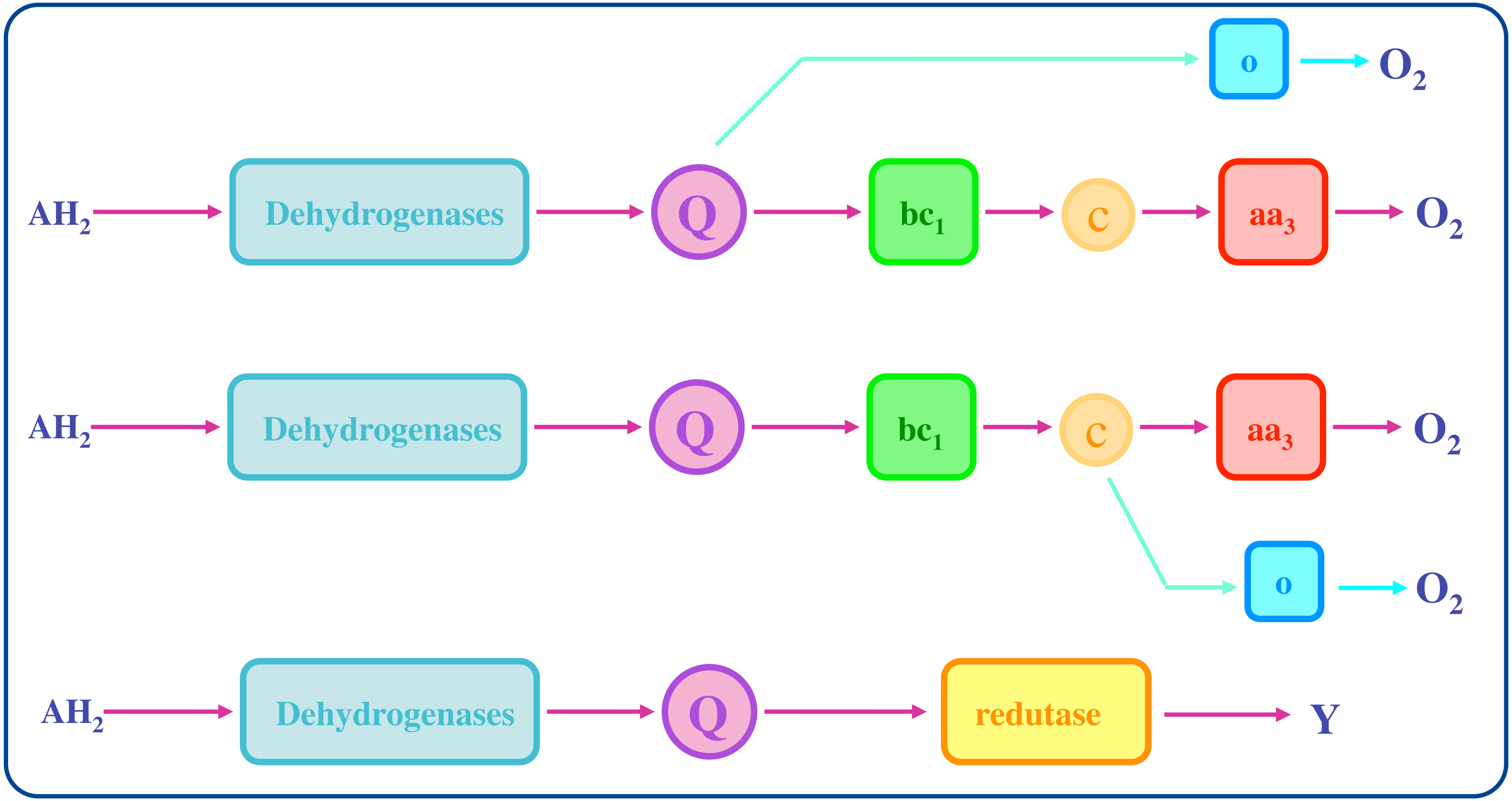
NADH → O_2 P/O = 3 ⇔ 3 coupling sites
succinato → O_2 P/O = 2 ⇔ 2 coupling sites
citocromo c → O_2 P/O = 1 ⇔ 1 coupling site

✓ H^+ / ATP : number of protons that enter the cell via ATP sintase
Mitochondria: H^+ / ATP = 3 + 1
Bacteria: H^+ / ATP = 3

✓ In the mitochondria if H^+ / ATP = 4 and $H^+ / 2e^- = 10$ ⇔ maximum value of P/O = 2,5

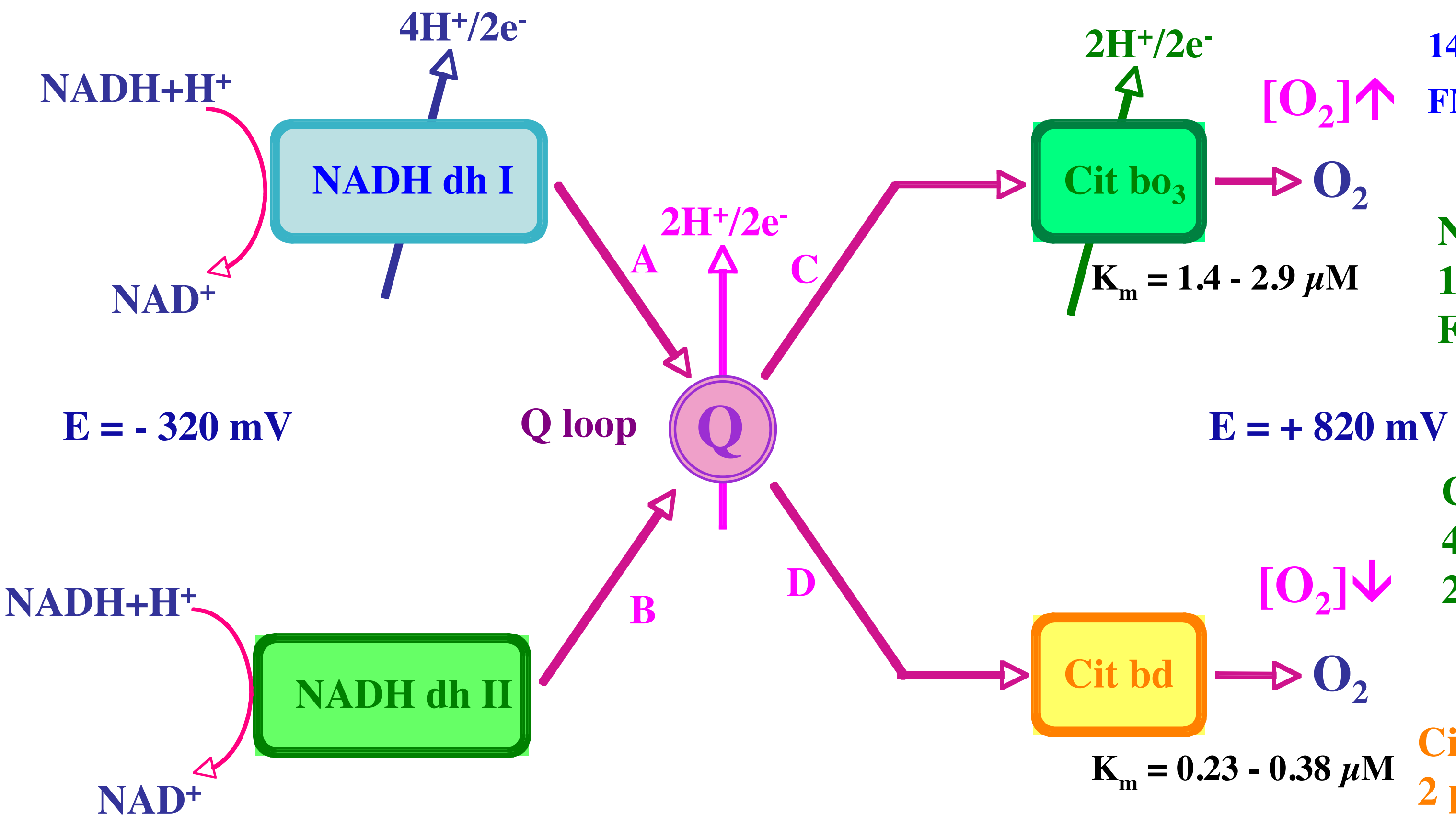
Electron Transport Organization

Bacterial standard



Electronic flow patterns in bacteria

Escherichia coli ➡ **Aerobiose**



NADH dh I
14 polipéptidos *nuo*
FMN, FeS

NADH dh II *ndh*
1 polipéptido
FAD

Cit bo *cyoABCD*
4 polipéptidos
2Cu, 2 hemes tipo b

Cit bd *cydAB*
2 polipéptidos
2 hemes b + 1 heme d

A - C: $8H^+/2e^- \Rightarrow 8/3$ ATP/ $2e^- \approx 2{,}7$ ATP / $2e^-$

A - D: $6H^+/2e^- \Rightarrow 6/3$ ATP/ $2e^- \approx 2$ ATP / $2e^-$

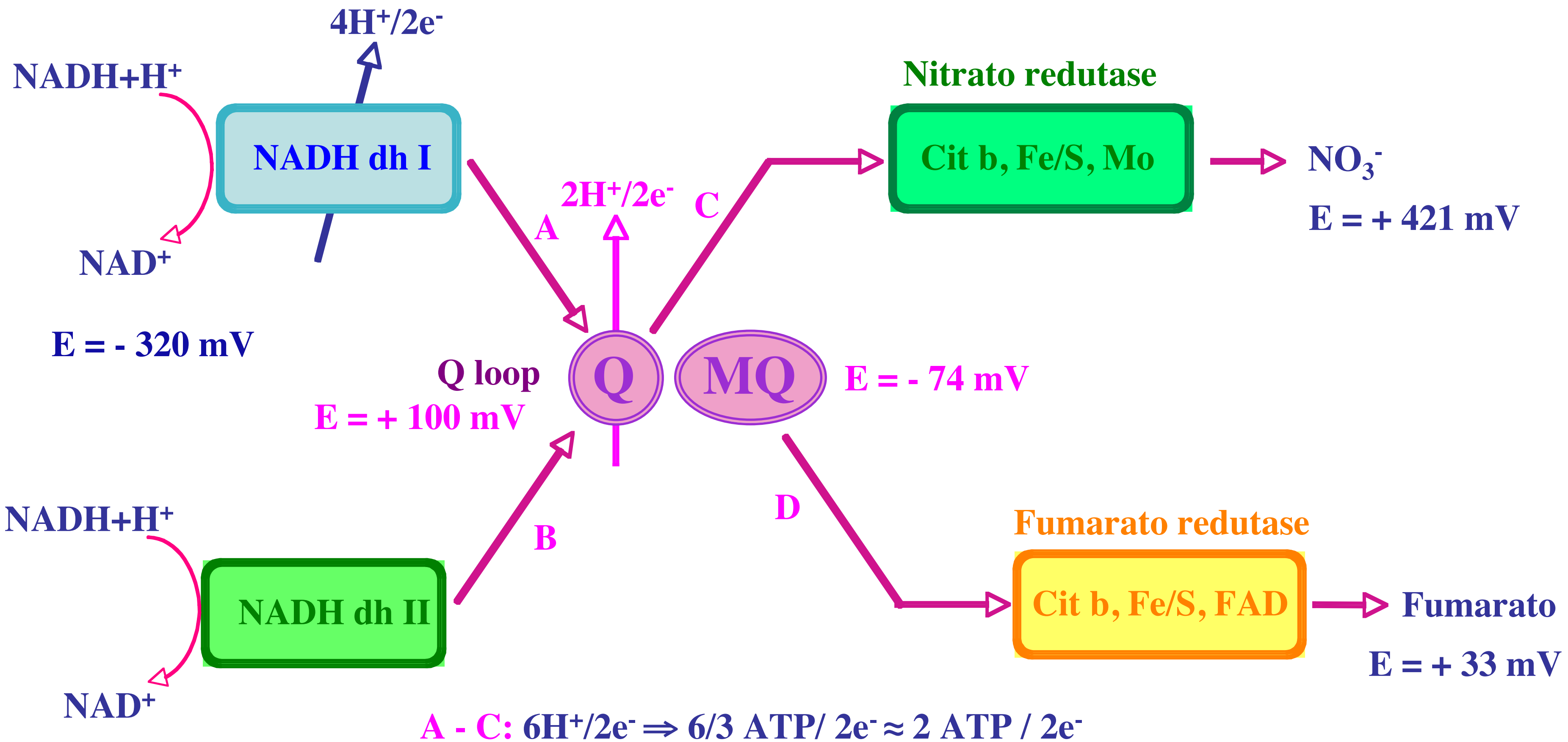
B - C: $4H^+/2e^- \Rightarrow 4/3$ ATP/ $2e^- \approx 1{,}3$ ATP / $2e^-$

B - D: $2H^+/2e^- \Rightarrow 2/3$ ATP/ $2e^- \approx 0{,}67$ ATP / $2e^-$

Electronic flow patterns in bacteria

Escherichia coli

Anaerobiose



A - C: $6H^+/2e^- \Rightarrow 6/3\ ATP/\ 2e^- \approx 2\ ATP\ /\ 2e^-$

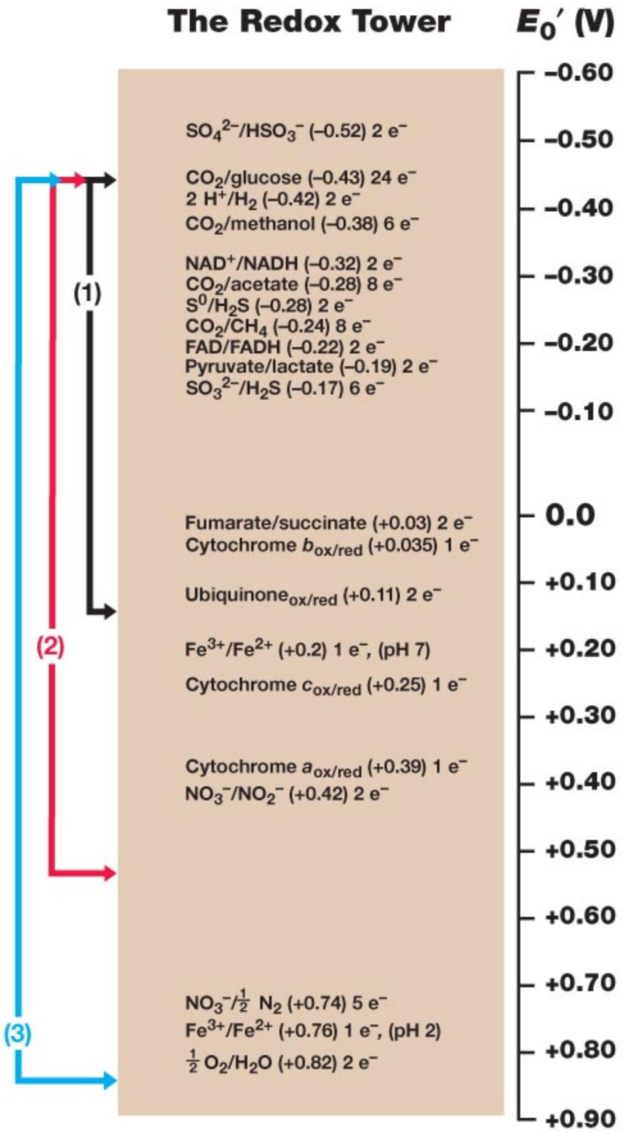
A - D: $6H^+/2e^- \Rightarrow 6/3\ ATP/\ 2e^- \approx 2\ ATP\ /\ 2e^-$

B - C: $2H^+/2e^- \Rightarrow 2/3\ ATP/\ 2e^- \approx 0{,}67\ ATP\ /\ 2e^-$

B - D: $2H^+/2e^- \Rightarrow 2/3\ ATP/\ 2e^- \approx 0{,}67\ ATP\ /\ 2e^-$

Electronic flow patterns in bacteria

- ***Escherichia coli***



The Redox Tower

SO_4^{2-}/HSO_3^- (−0.52) 2 e^-
CO_2/glucose (−0.43) 24 e^-
2 H^+/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^-
CO_2/CH_4 (−0.24) 8 e^-
FAD/FADH (−0.22) 2 e^-
Pyruvate/lactate (−0.19) 2 e^-
SO_3^{2-}/H_2S (−0.17) 6 e^-
Fumarate/succinate (+0.03) 2 e^-
Cytochrome $b_{ox/red}$ (+0.035) 1 e^-
Ubiquinone$_{ox/red}$ (+0.11) 2 e^-
Fe^{3+}/Fe^{2+} (+0.2) 1 e^-, (pH 7)
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^-

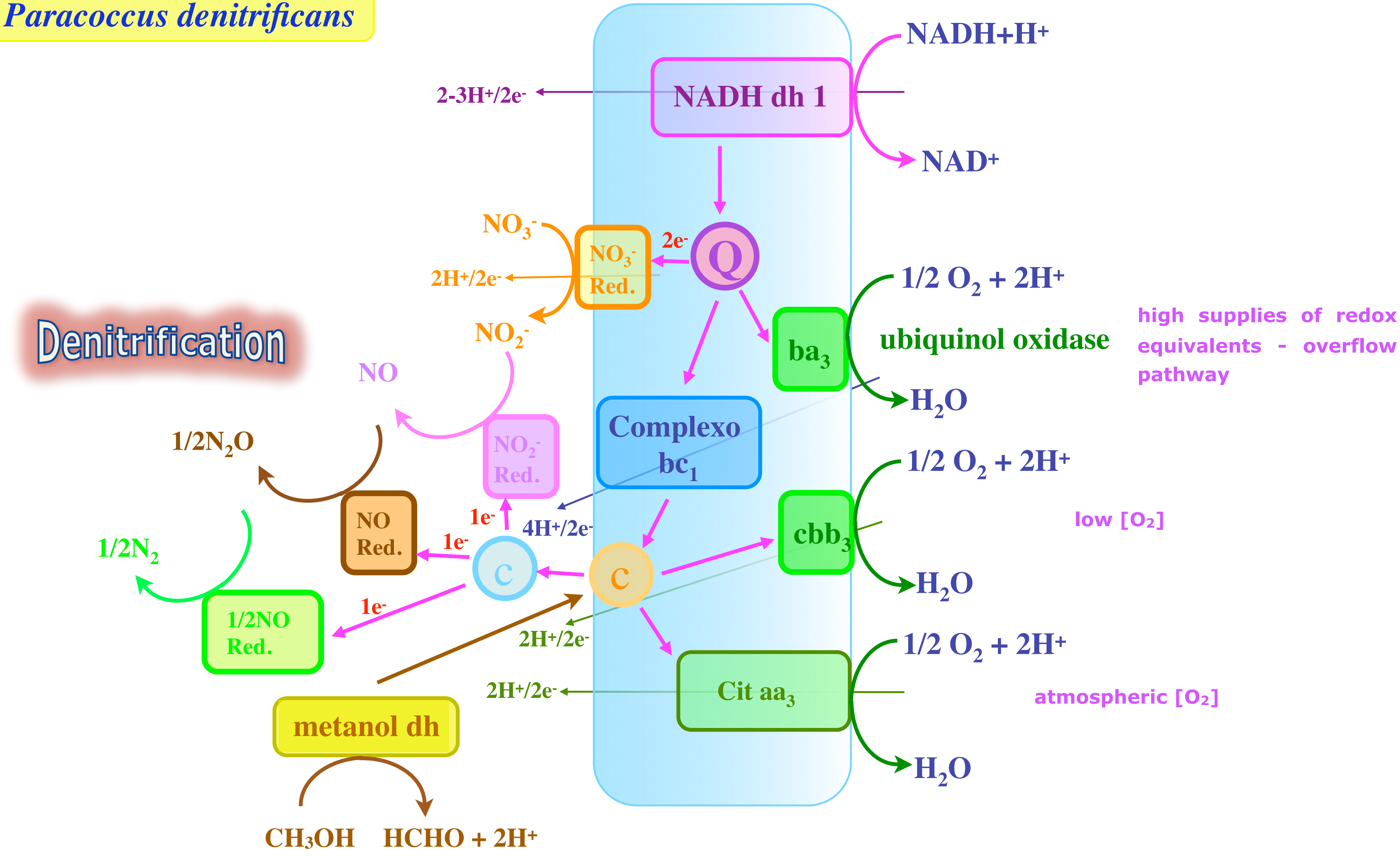
(1) H_2 + fumarate $\longrightarrow$ succinate $\Delta G^{0\prime} = -86$ kJ

(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

Electronic flow patterns in bacteria

Paracoccus denitrificans

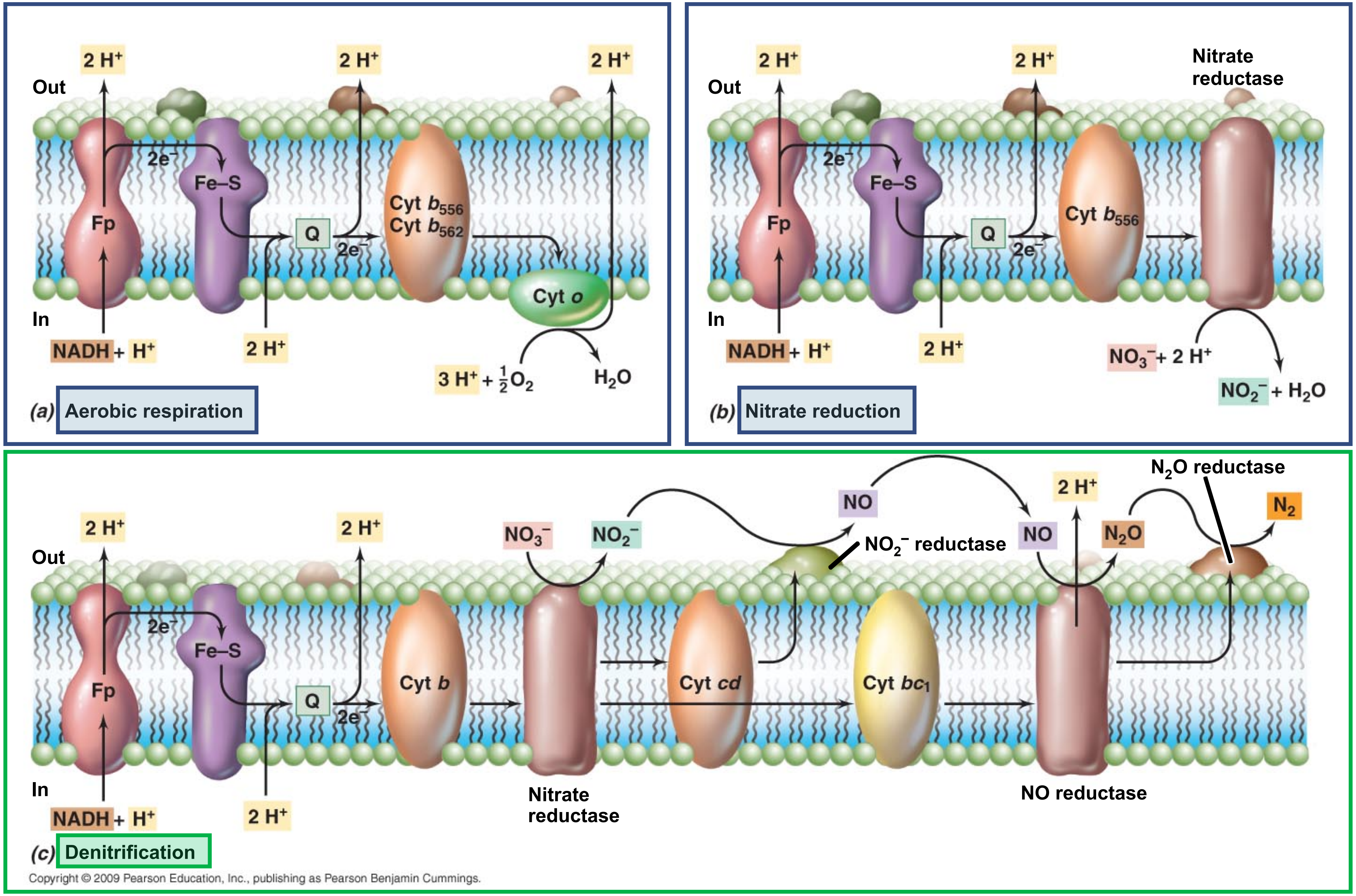


high supplies of redox equivalents - overflow pathway

low [O_2]

atmospheric [O_2]

Escherichia coli



Paracoccus denitrificans