ENERGY METABOLISM

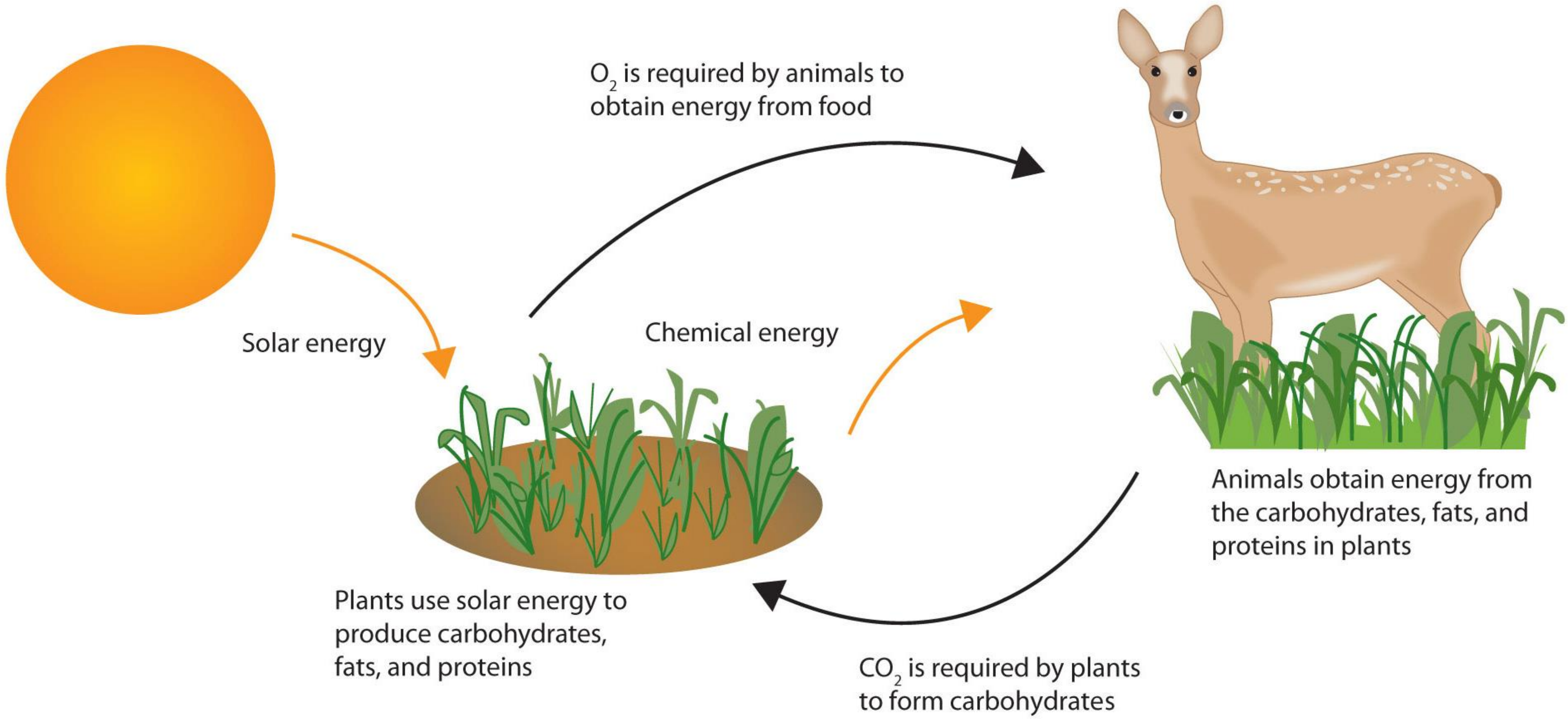
Lecture 1

Living cells and organisms must perform work to stay alive, to grow, and to reproduce

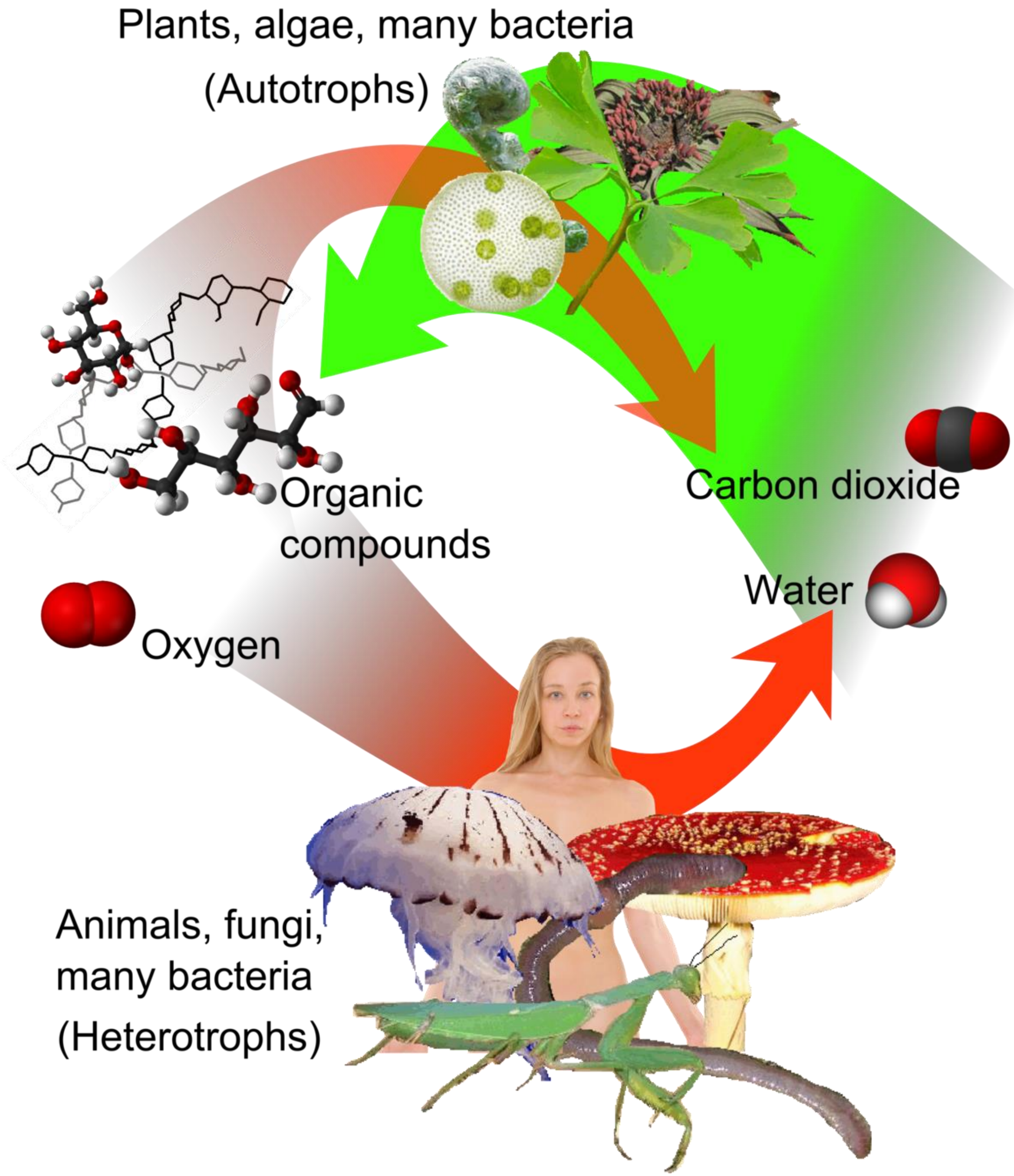
they require energy for

- **maintaining their highly organized structures;**
- **synthesizing cellular components,**
- **generation of a concentration and electrical gradients**
- **motion, heat production and many other processes.**

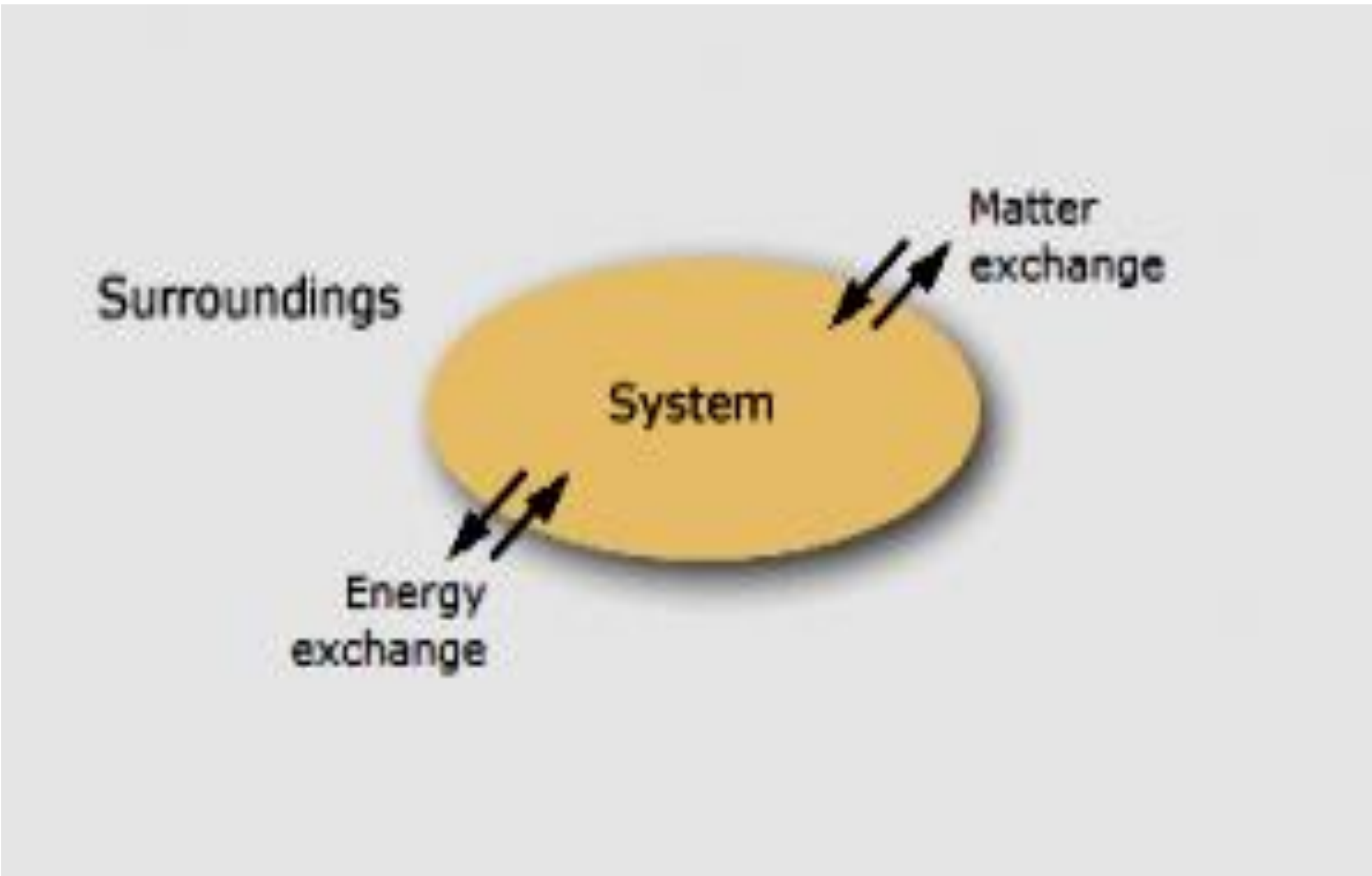
Bioenergetics is the quantitative study of energy relationships and energy conversions in biological systems

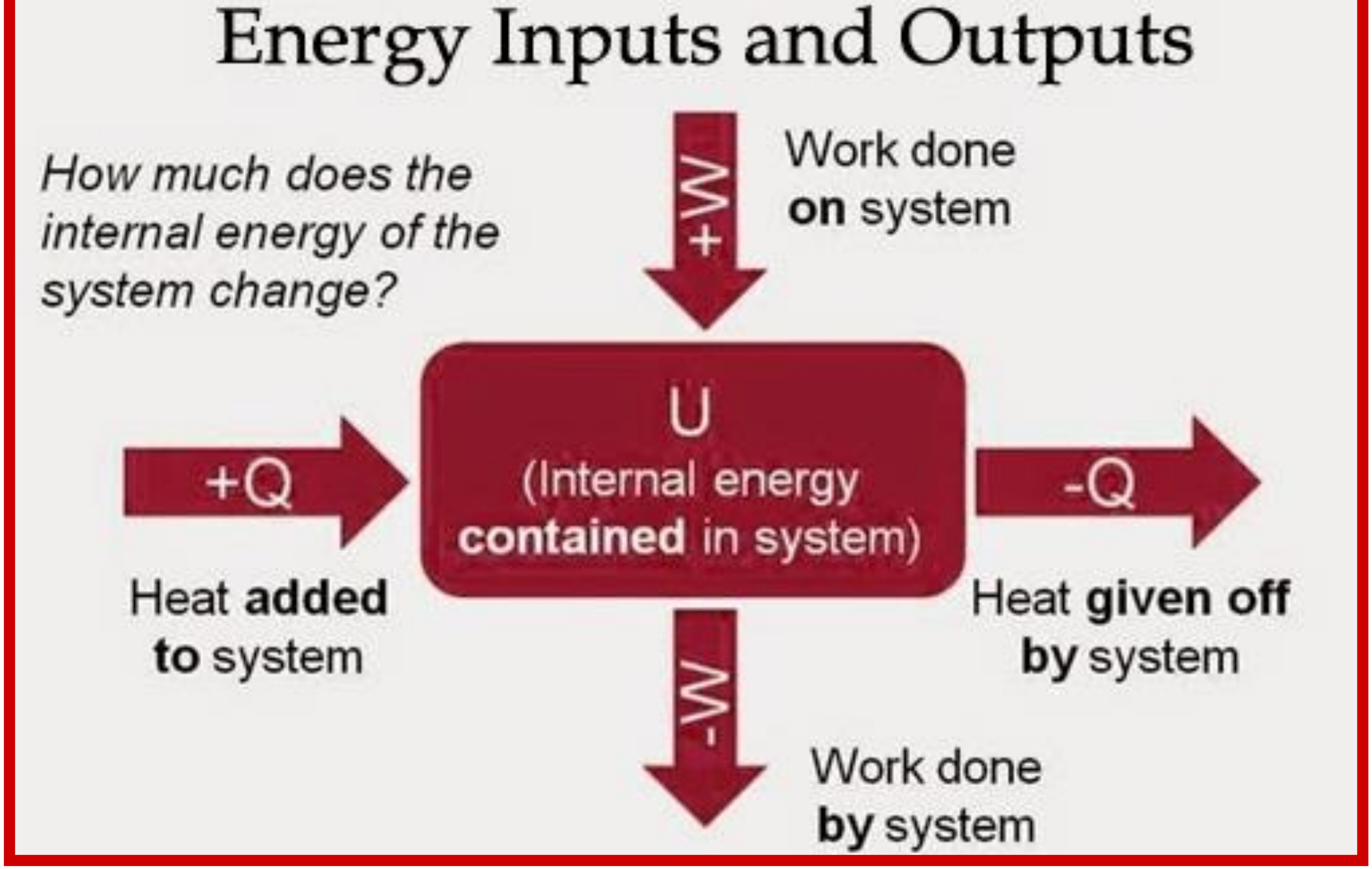


O_2 is required by animals to obtain energy from food
Solar energy
Chemical energy
Animals obtain energy from the carbohydrates, fats, and proteins in plants
Plants use solar energy to produce carbohydrates, fats, and proteins
CO_2 is required by plants to form carbohydrates


Plants, algae, many bacteria
(Autotrophs)
Organic
compounds
Carbon dioxide
Oxygen
Water
Animals, fungi,
many bacteria
(Heterotrophs)

Living cells and organism are open systems exchanging both material and energy with their surroundings





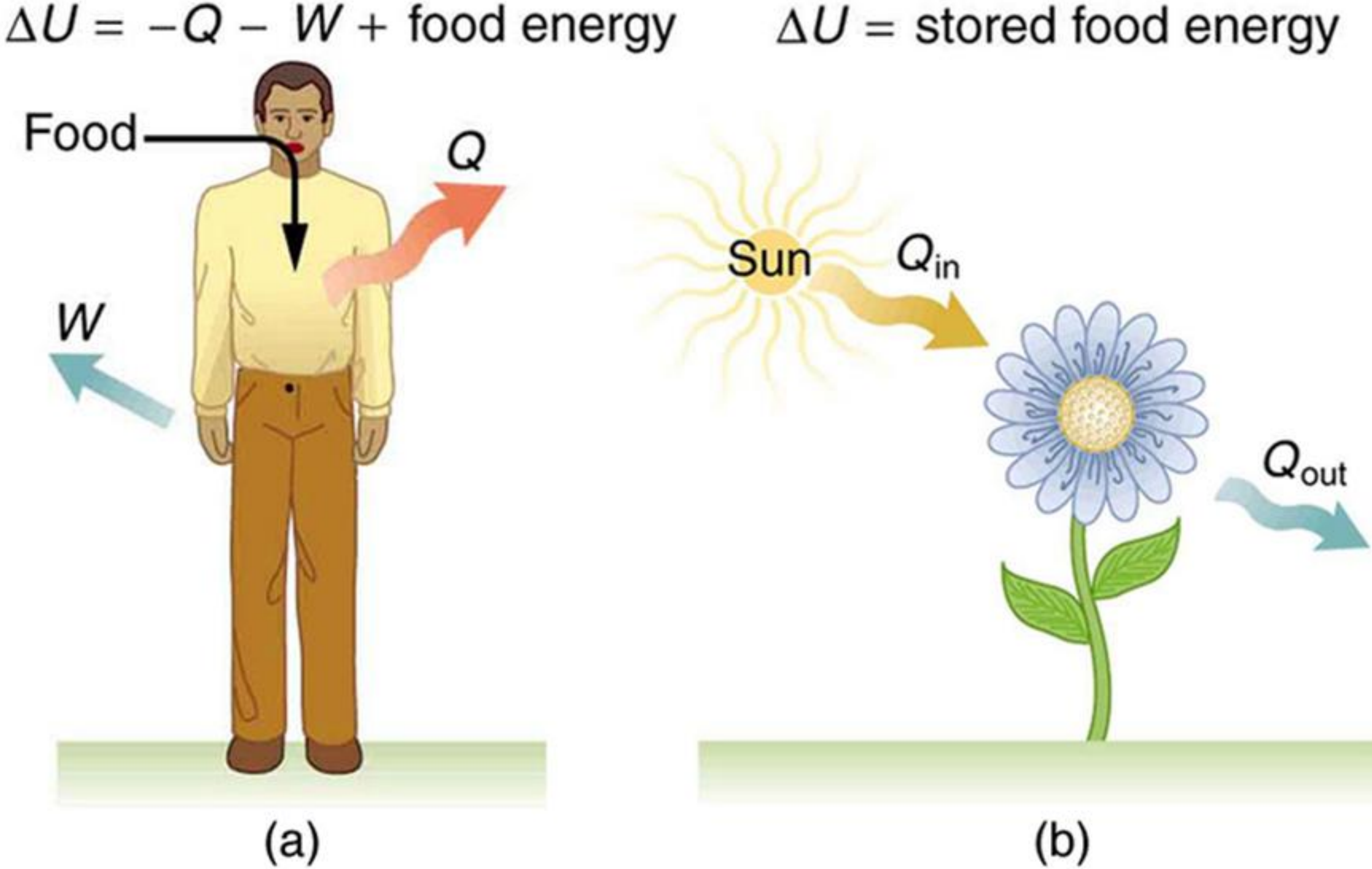
The change in internal energy of a system is equal to the heat added to the system minus the work done by the system.

$$\Delta U = Q - W$$

Change in internal energy

Heat added to the system

Work done by the system



ΔU = −Q − W + food energy
ΔU = stored food energy
Food
Q
W
Sun
Q_in
Q_out
(a)
(b)

The energy changes occurring in a chemical reaction are described by three thermodynamic quantities

- **Gibbs' free energy, (ΔG), expresses the amount of energy which can be used to perform work at the constant temperature and pressure.**

- **Enthalpy (ΔH), is the total energy (or heat content) which may be available from any system, or molecule, or chemical reaction.**

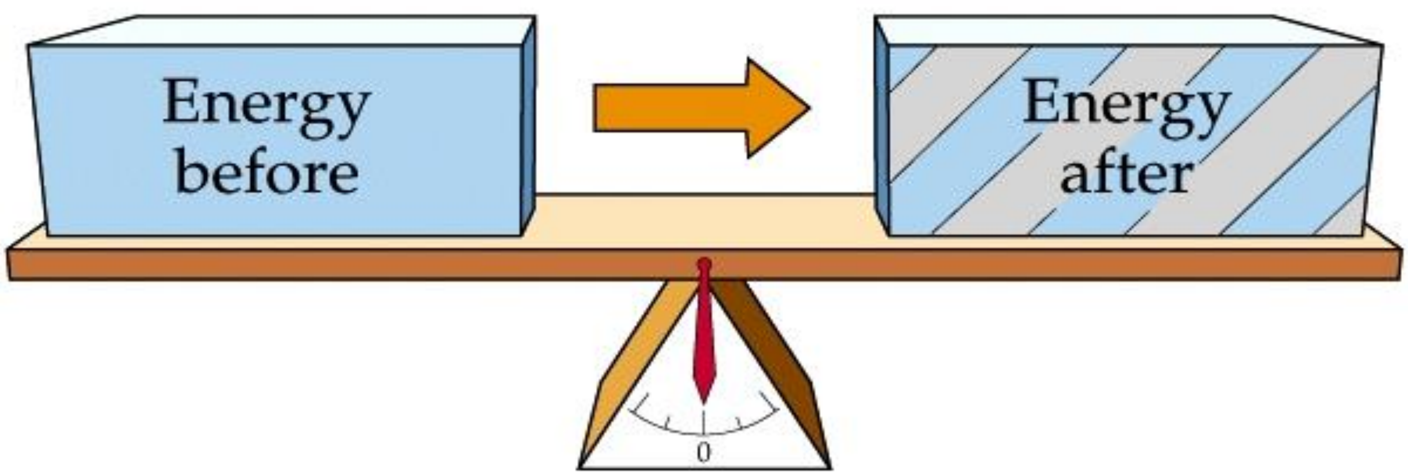
- **Entropy, (ΔS), is a quantitative expression for disorder in a system**

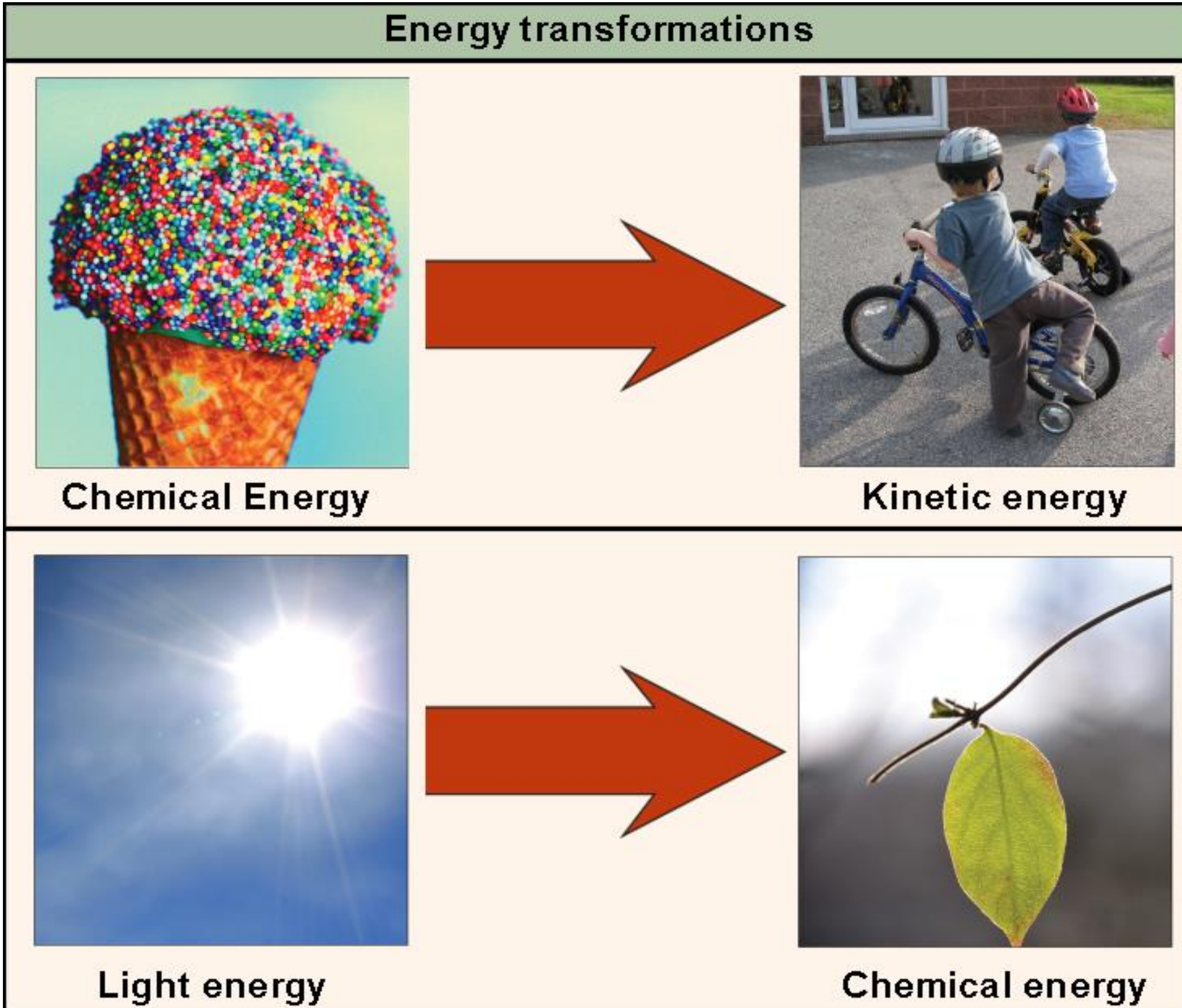
The portion of energy which cannot be converted to work is called bound energy (TΔS)

Biological energy transformations obey the laws of thermodynamics.

The first law is **the principle of the conservation of energy**:

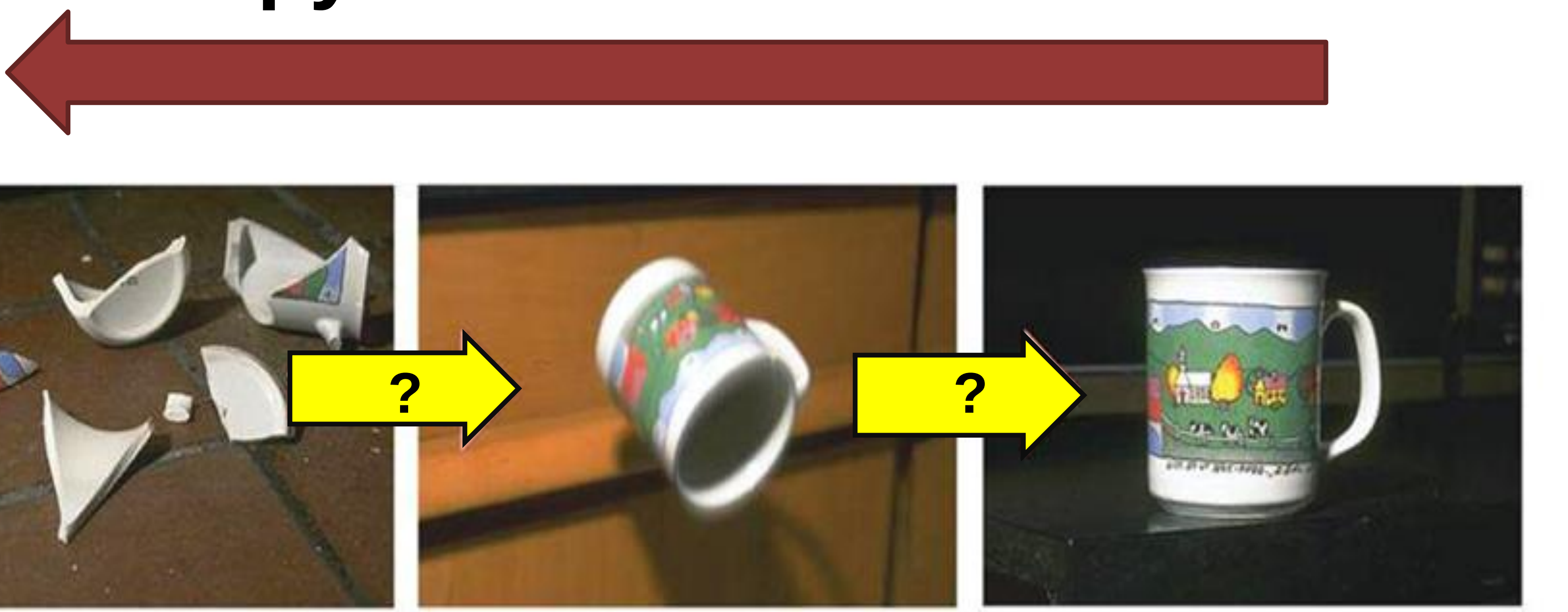
for any physical or chemical change, the total amount of energy in the universe remains constant; energy may change form or it may be transported from one region to another; but it cannot be created or destroyed.




Energy transformations
Chemical Energy
Kinetic energy
Light energy
Chemical energy

The second law of thermodynamics says that the universe always tends toward increasing disorder:

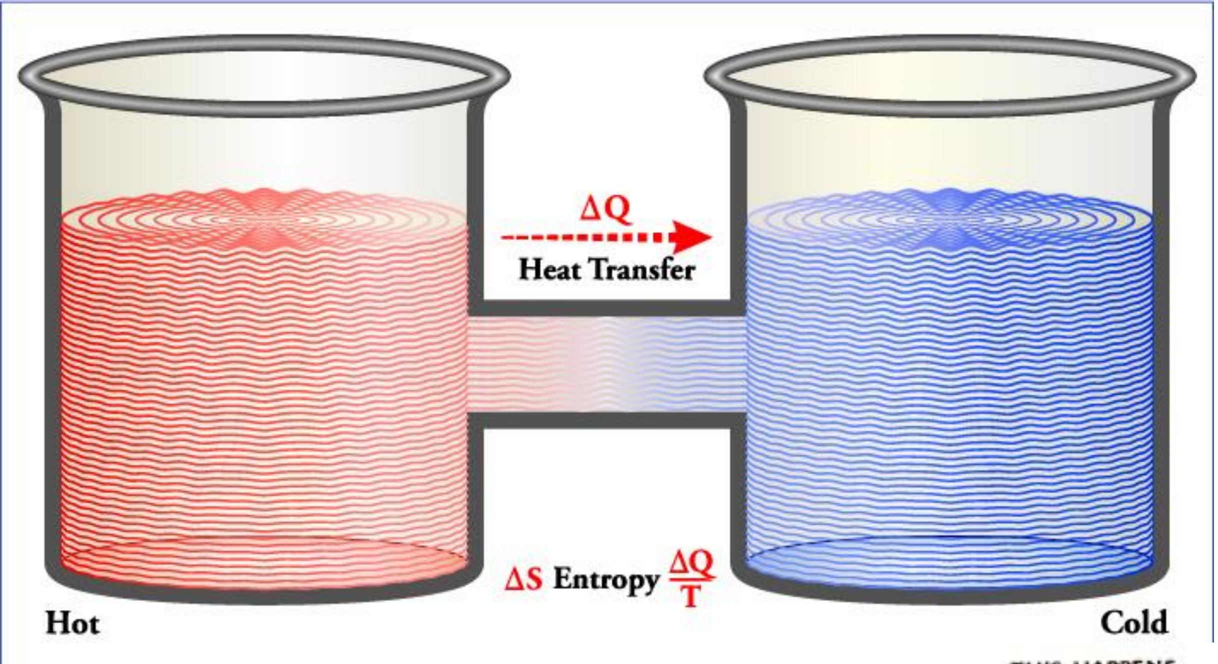
in all natural processes, the entropy of the universe increases.



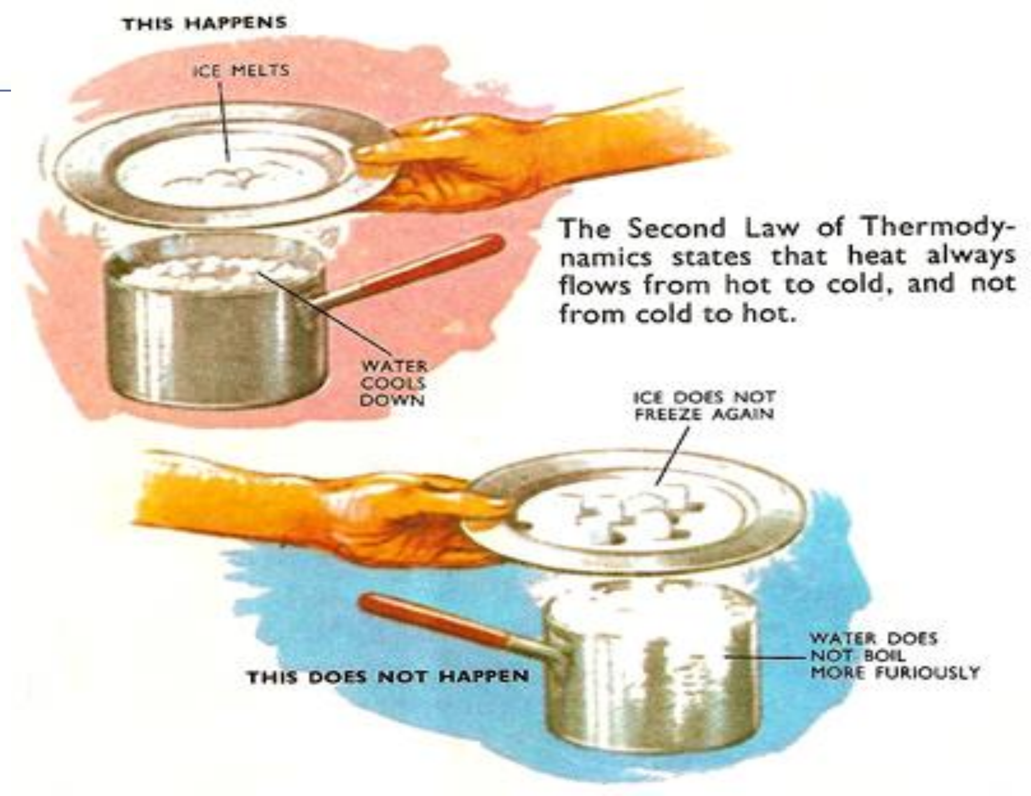
Initial state.

Later: cup reassembles and rises up.

Later still: cup lands on table.



Second Law of Thermodynamics

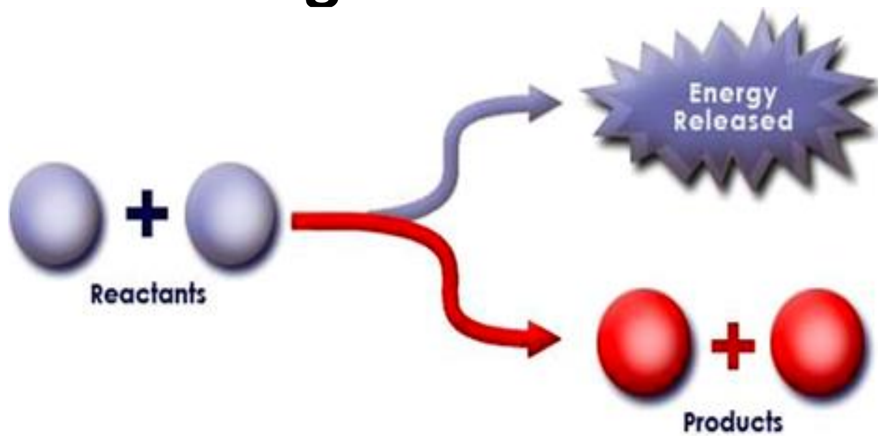


The Second Law of Thermodynamics states that heat always flows from hot to cold, and not from cold to hot.

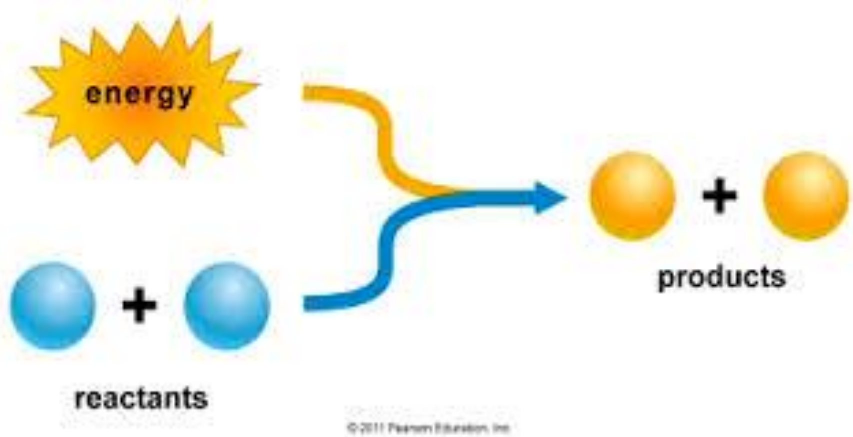
Under the conditions existing in biological systems (including constant temperature and pressure), changes in free energy, enthalpy, and entropy are related to each other quantitatively by the equation:

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

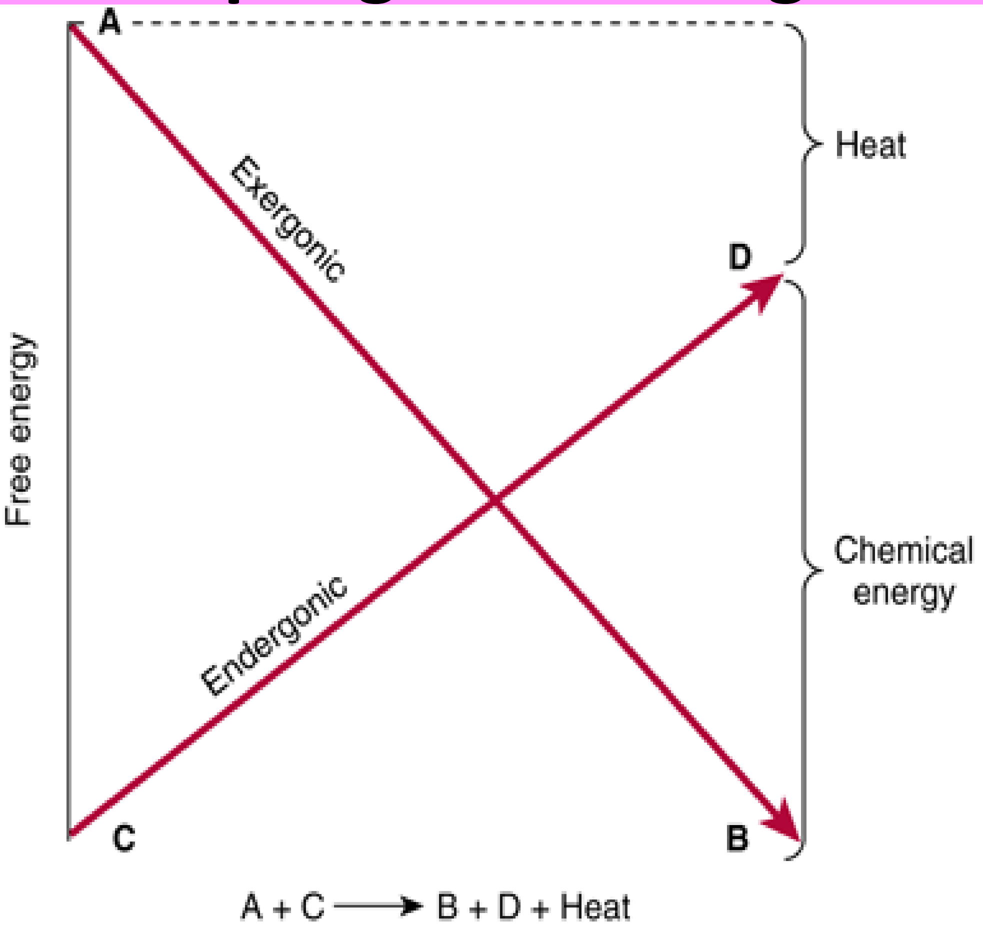
- If ΔG is **negative** (–ΔG), the reaction will proceed spontaneously with the release of energy, and the reaction is called **exergonic** reaction.



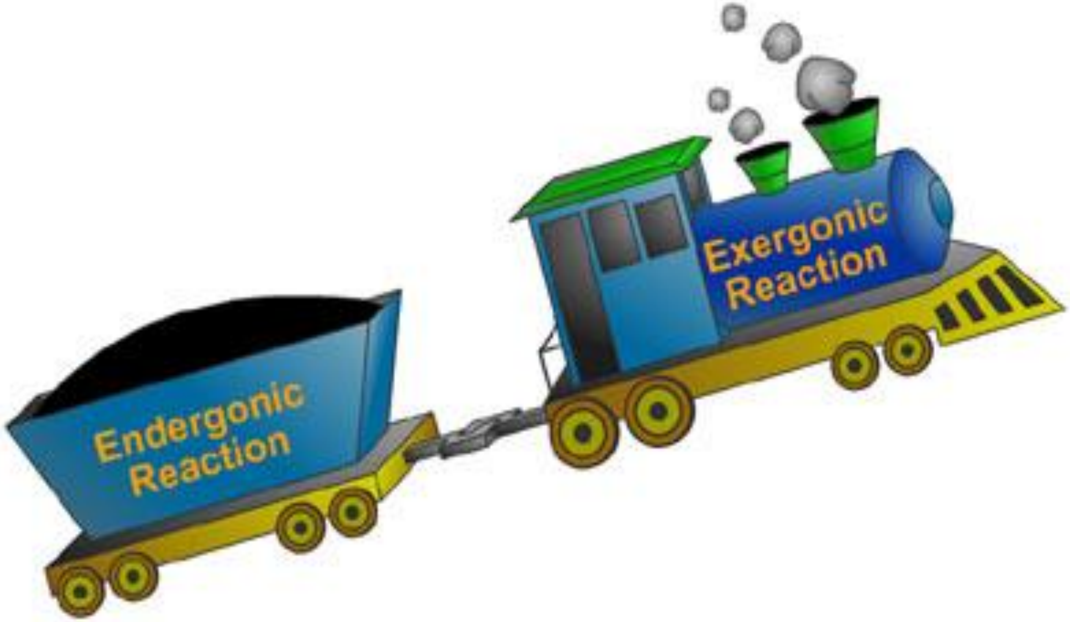
- If ΔG is **positive** (+ΔG), the reaction will not proceed spontaneously and has to be supplied with energy from outside; such a reaction is called **endergonic** reaction.



Coupling of an exergonic and endergonic reaction

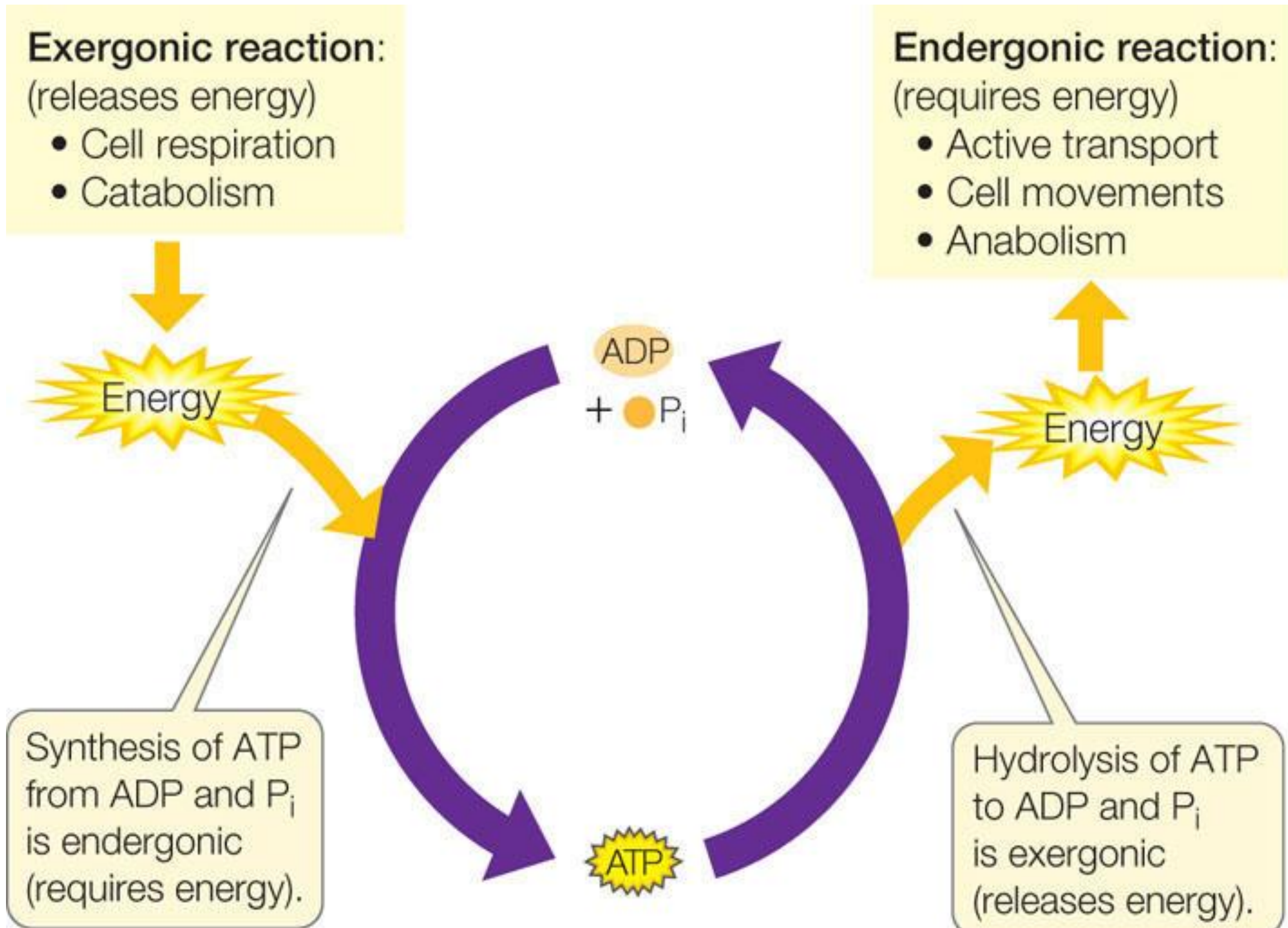


Source: Murray RK, Bender DA, Botham KM, Kennelly PJ, Rodwe
Illustrated Biochemistry, 29th Edition: www.accessmedicine.con



Living systems must transfer energy from one molecule to another without losing all of it as heat.

Some of the energy must be conserved in a chemical form in order to drive nonspontaneous biosynthetic reactions.


Exergonic reaction:
(releases energy)
• Cell respiration
• Catabolism
Endergonic reaction:
(requires energy)
• Active transport
• Cell movements
• Anabolism
Energy
ADP
+ Pi
Energy
ATP
Synthesis of ATP from ADP and Pi is endergonic (requires energy).
Hydrolysis of ATP to ADP and Pi is exergonic (releases energy).

High-energy compounds (macroergic compounds)

Macroergic compounds contain energy-rich chemical bond, or macroergic bond. Macroergic bond is the bond which hydrolysis is accompanied by the release of free energy ($-\Delta G$) greater than 5 kcal/mol (21 kJ/mol).

High-energy bond is designated as the sign

“ ~ “ (tilda).

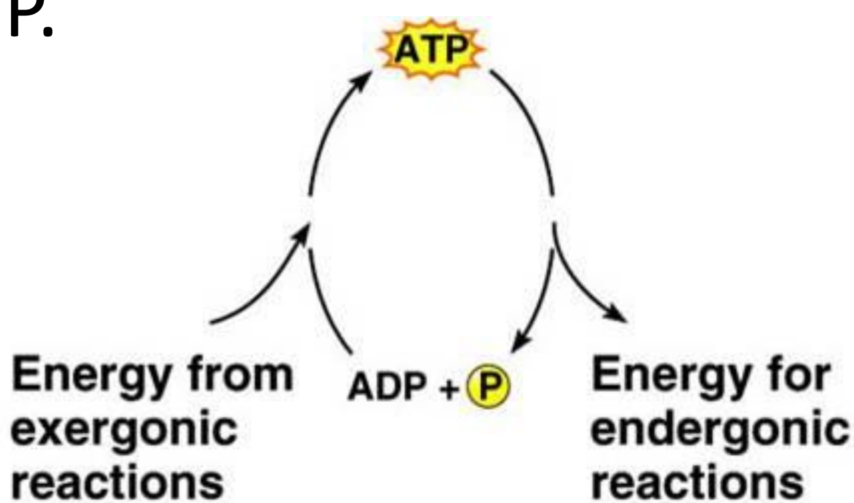
There are two types of macroergic compounds.

- **Phosphate-containing macroergic compounds:** creatine phosphate, 1,3-bisphosphoglycerate, phosphoenolpyruvate, carbamoyl phosphate, ATP.
- **Sulfur-containing macroergic compounds** (thioesters): acetyl CoA, acyl CoA, succinyl CoA

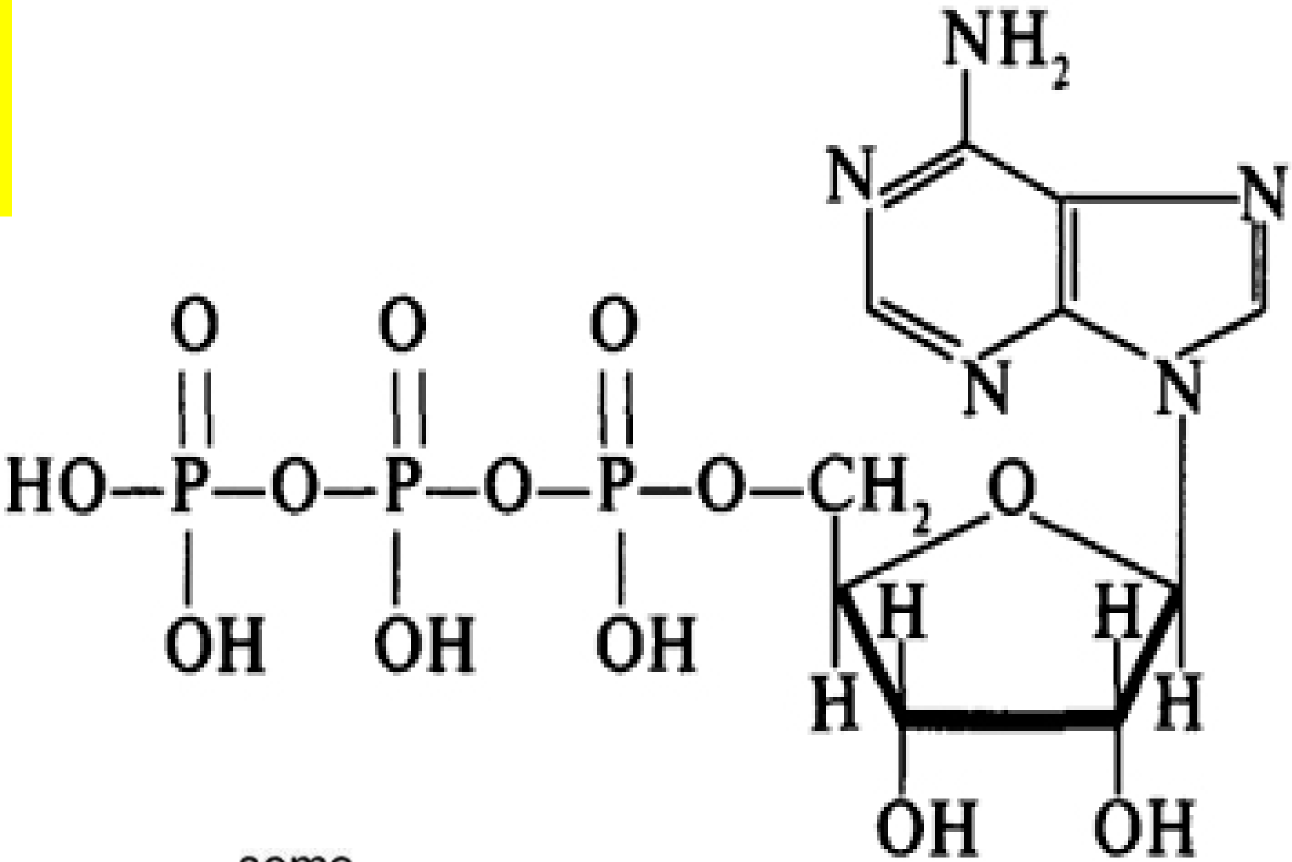
ATP

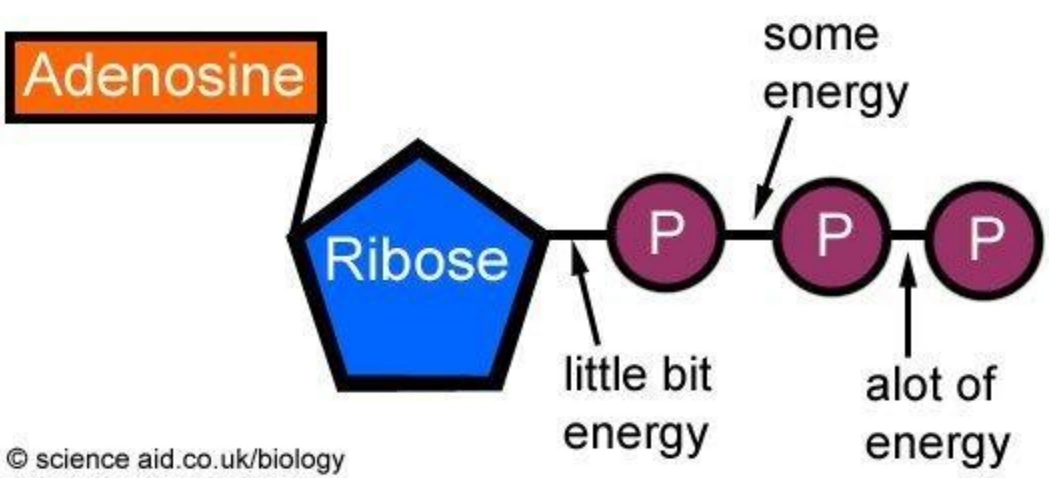
ATP is universal energy currency because only this compound can immediately give its energy (accumulated in the macroergic bond) for the performing any type of work in the living cell.

When ATP is used for metabolic work, high-energy bonds are broken and it is converted to ADP or to AMP.

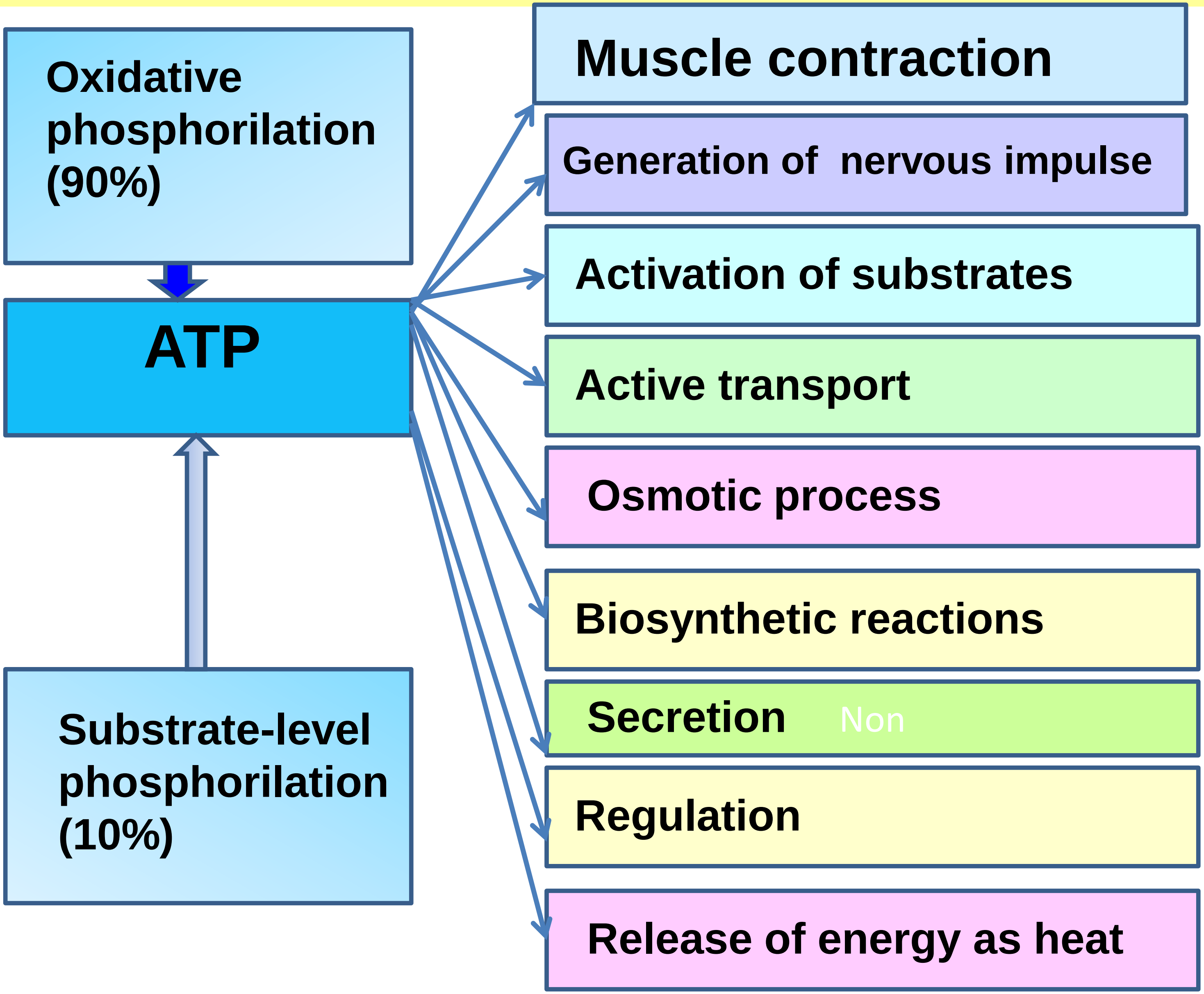


ATP


NH2
N
N
N
N
O
O
O
HO
P
O
P
O
P
O
CH2
O
OH
OH
OH
H
H
H
H
OH
OH


Adenosine
Ribose
P
P
P
some energy
little bit energy
alot of energy
© science aid.co.uk/biology

Ways of the ATP formation and its use



Biological oxidation

is the cellular process in which the organic substances release energy (ATP),

produce CO_2 and H_2O

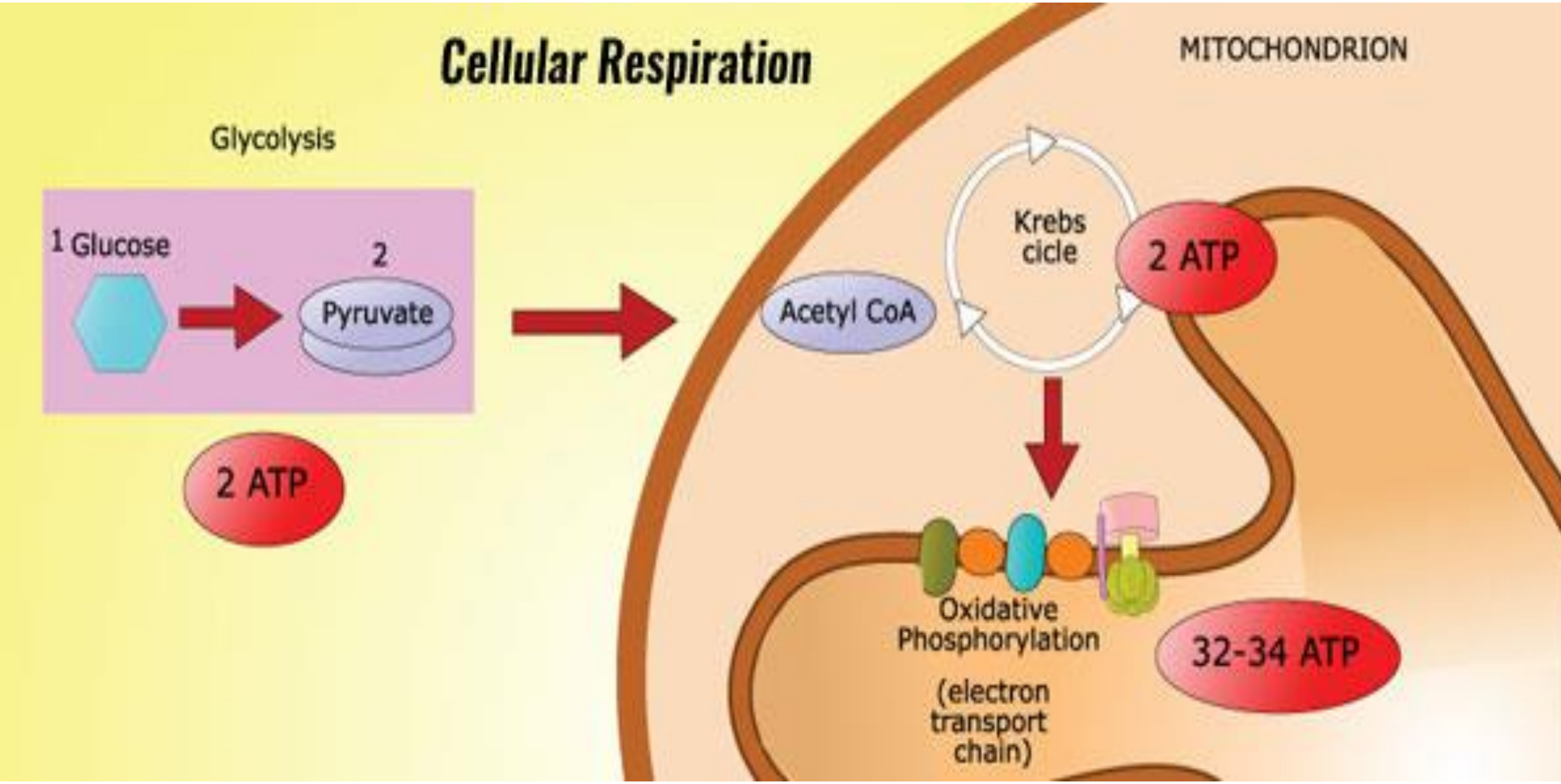
through oxidative-reductive reactions

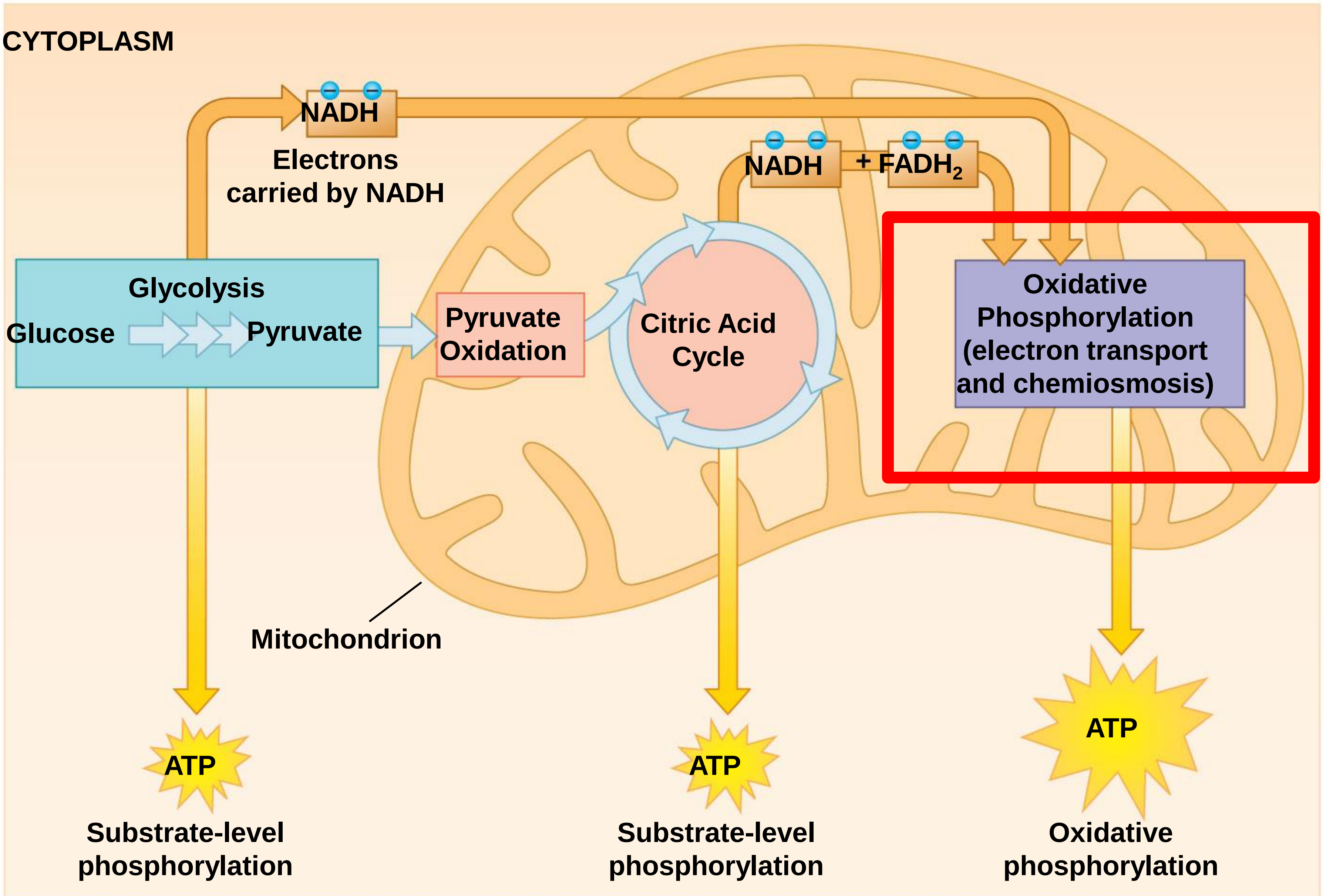
Biological oxidation

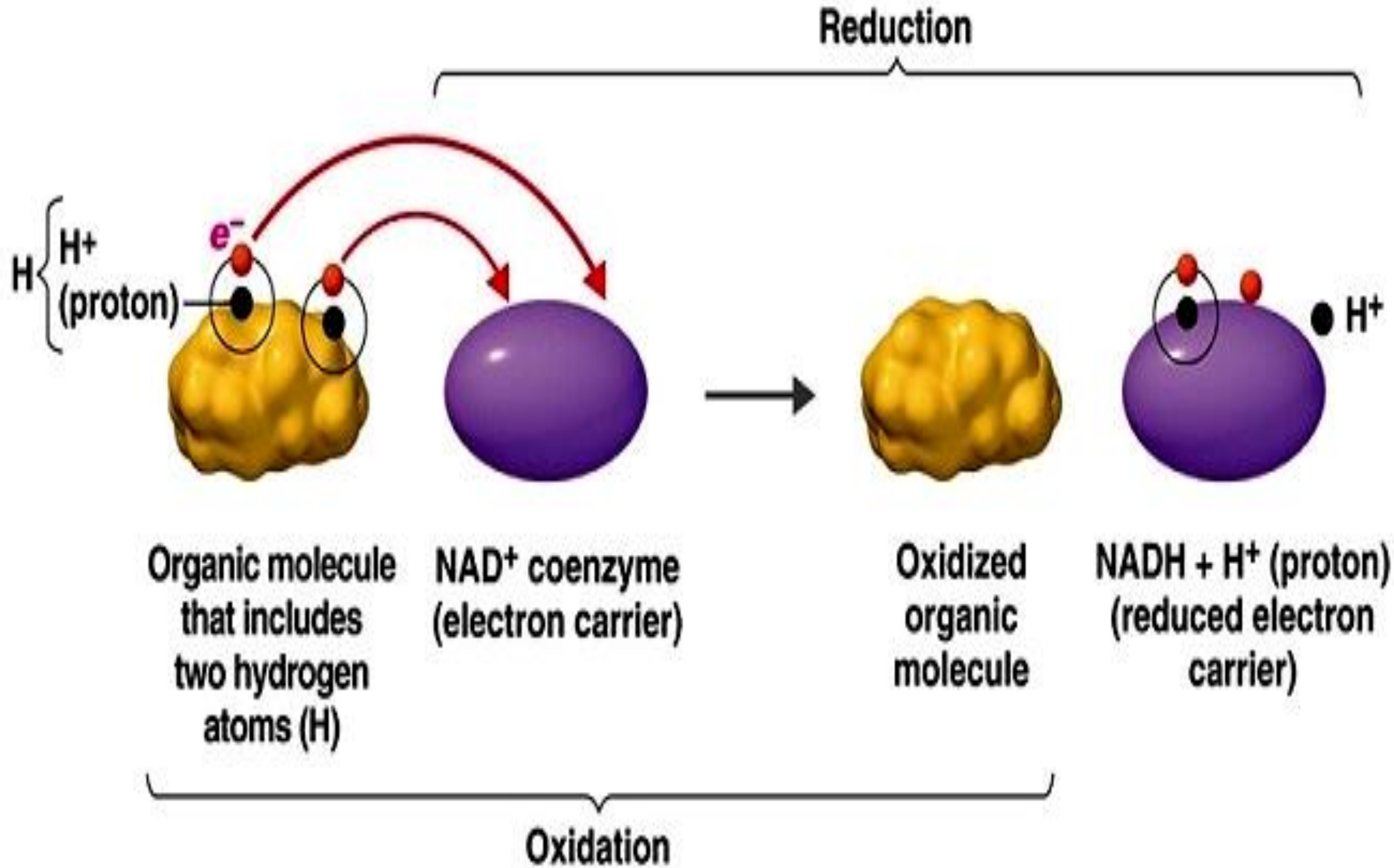
- It refers to cellular oxidation of various metabolic fuels by
  - addition of oxygen
  - removal of electrons
  - removal of hydrogen
- Usually takes place with the help of enzymes

Cellular respiration

- **is a set of metabolic reactions that take place in the cells to convert chemical energy from nutrients into ATP, and then release waste products.**
- **oxidizing agent (electron acceptor) is oxygen**
- **last stage occurs in mitochondria**


Cellular Respiration
MITOCHONDRION
Glycolysis
1 Glucose
2
Pyruvate
2 ATP
Acetyl CoA
Krebs
cicle
2 ATP
Oxidative
Phosphorylation
(electron
transport
chain)
32-34 ATP

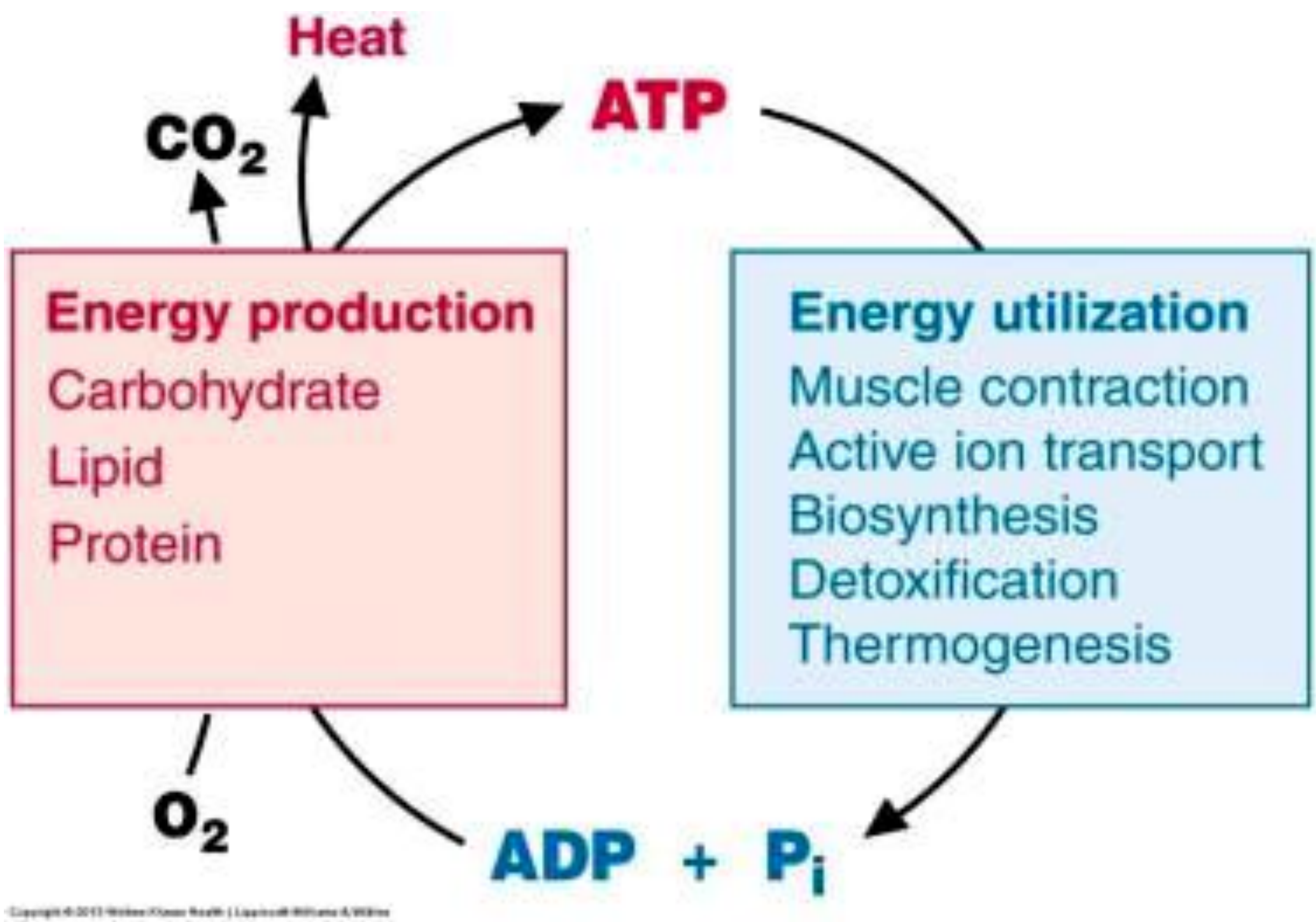

CYTOPLASM
NADH
Electrons carried by NADH
NADH
+ FADH2
Glycolysis
Glucose
Pyruvate
Pyruvate Oxidation
Citric Acid Cycle
Oxidative Phosphorylation (electron transport and chemiosmosis)
Mitochondrion
ATP
ATP
ATP
Substrate-level phosphorylation
Substrate-level phosphorylation
Oxidative phosphorylation

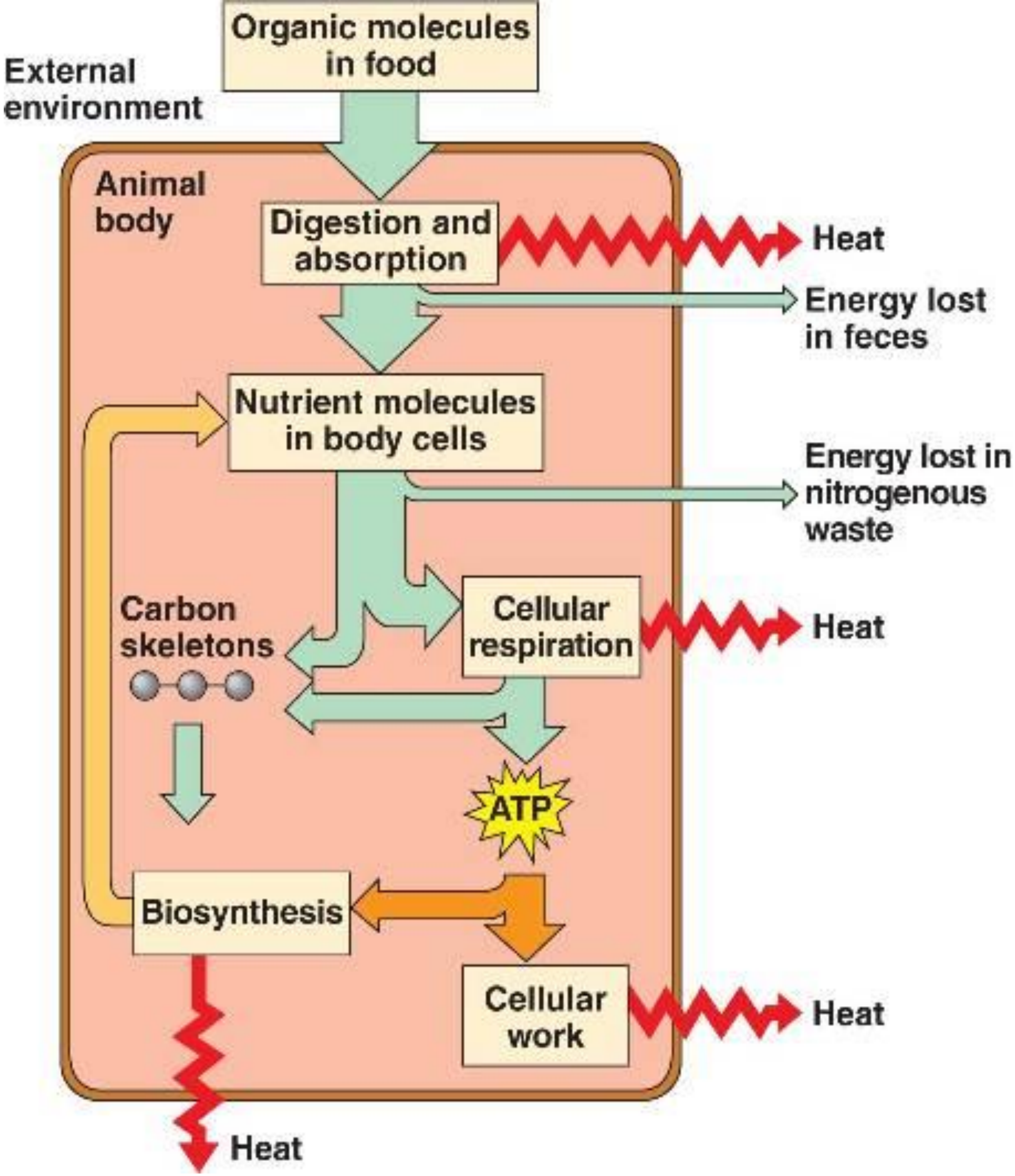


Oxidation is the loss of two electrons or two hydrogen atoms; reduction is the gain of them

Oxidation of metabolic fuels is essential to life

In higher organisms, fuels, such as carbohydrates and lipids are metabolized to carbon dioxide and water.



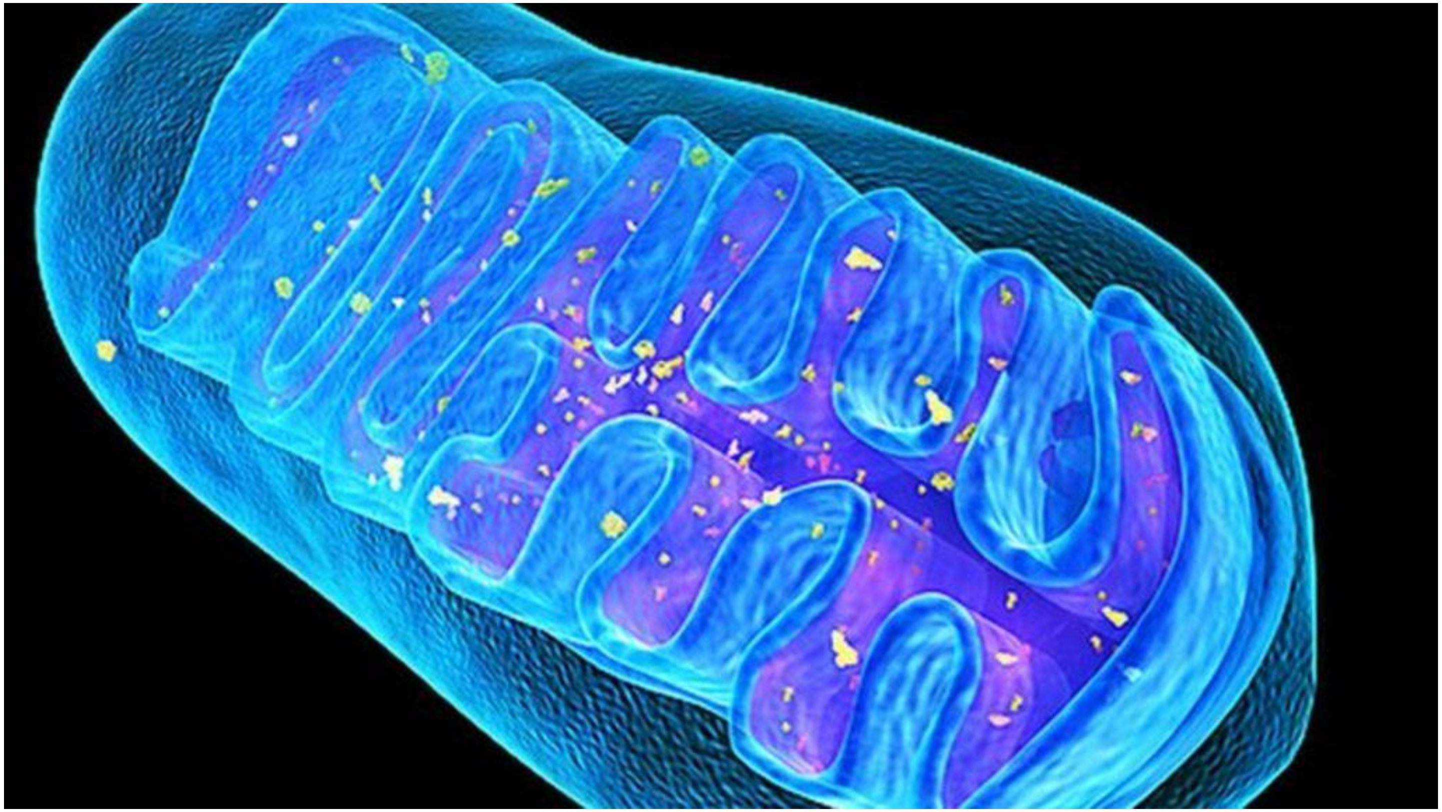


About 40% of food energy is conserved as ATP, and the remaining 60% is liberated as heat.

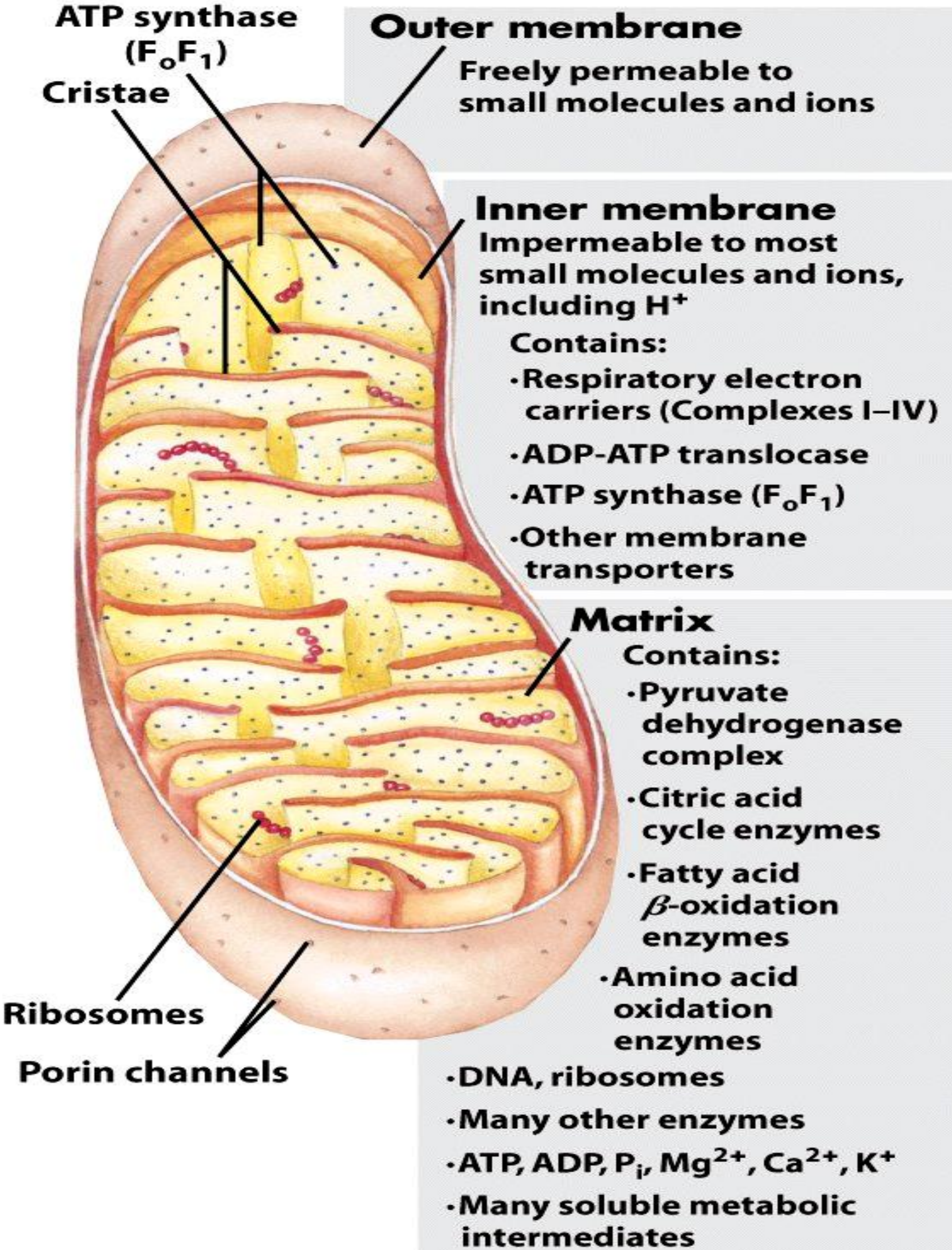
Most metabolic energy is provided by oxidation-reduction reactions in mitochondria

Mitochondria

Mitochondria are subcellular organelles, about the size of bacteria. They are essential for aerobic metabolism in eukaryotes. Their main function is to oxidize metabolic fuels and conserve free energy by synthesizing ATP



Mitochondrion



Double membrane, with inner membrane very impermeable

TCA occurs in the matrix

ETC in the inner membrane

The ETC consists of several components (carriers) which follow one another in the definite sequence.

Electron Transport Chain

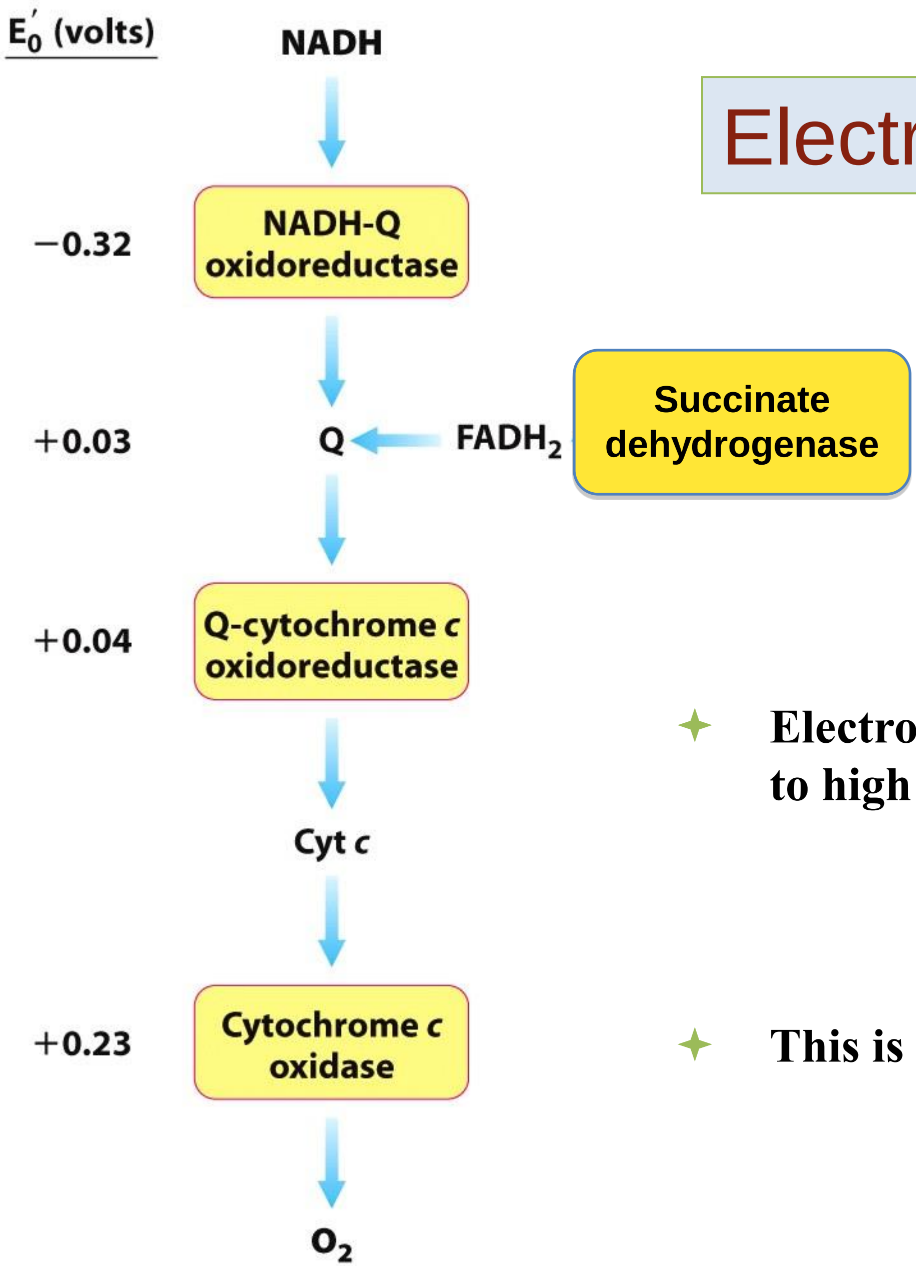


Figure 20.10
Biochemistry: A Short Course, Second Edition

- **Electrons flow from carriers with low to high reduction potential.**
- **This is energetically downhill**.

The components of the ETC transfer protons and electrons (or only electrons) from reduced substrates (SH_2) or from reduced coenzymes (such as NADH or $FADH_2$) to oxygen (O_2) with the resultant formation of water.

Electron transport chain

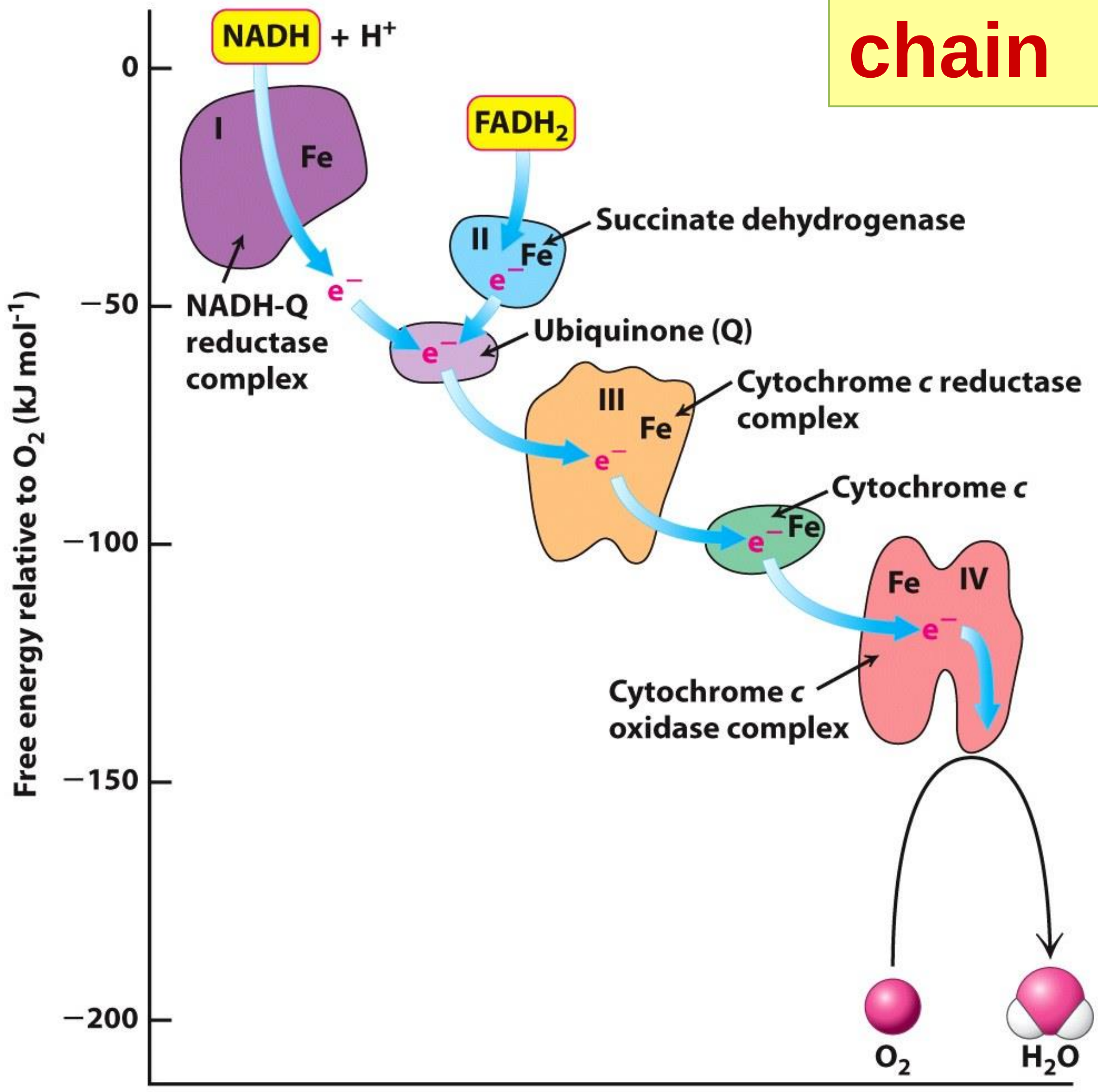


Figure 20.6
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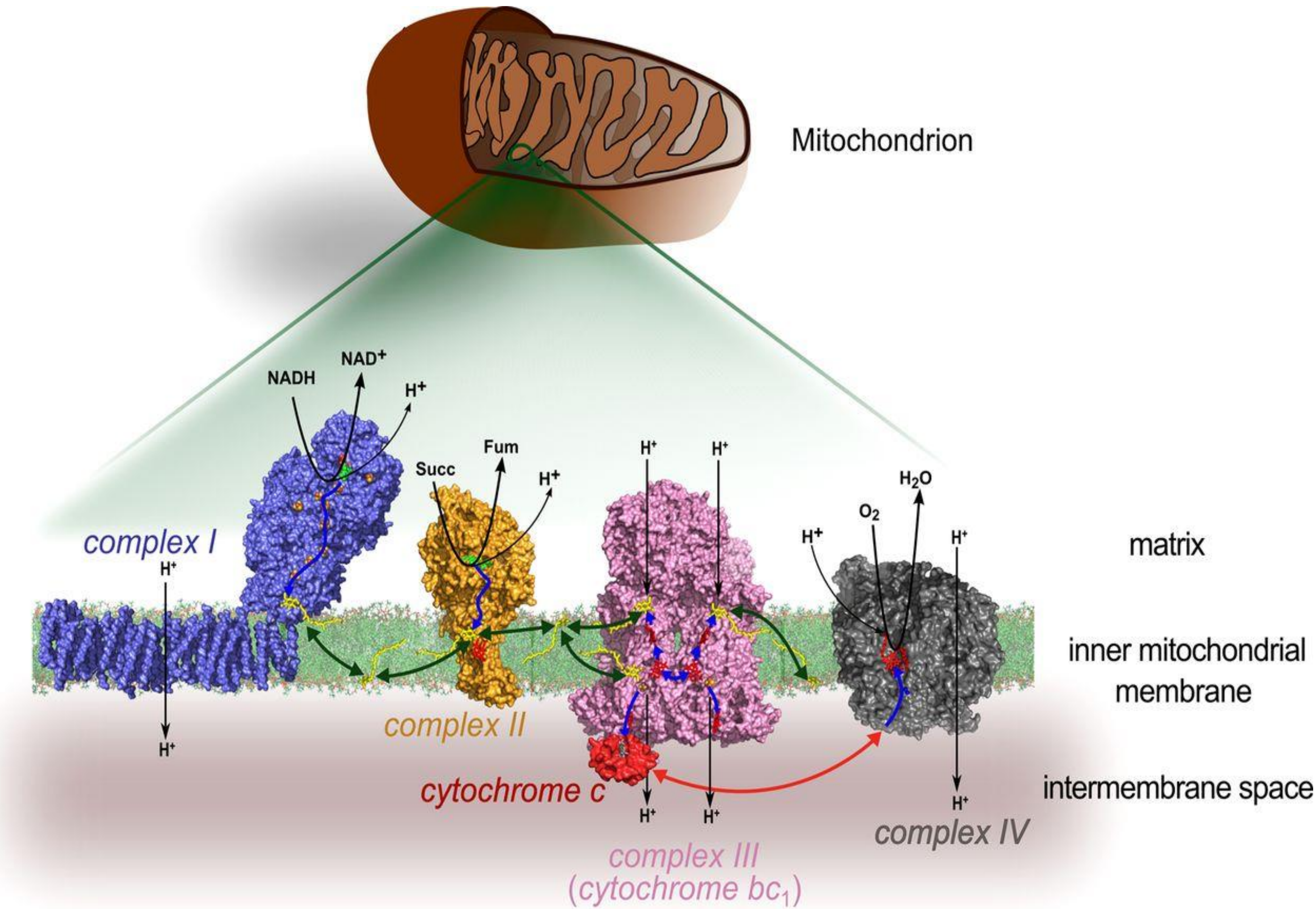
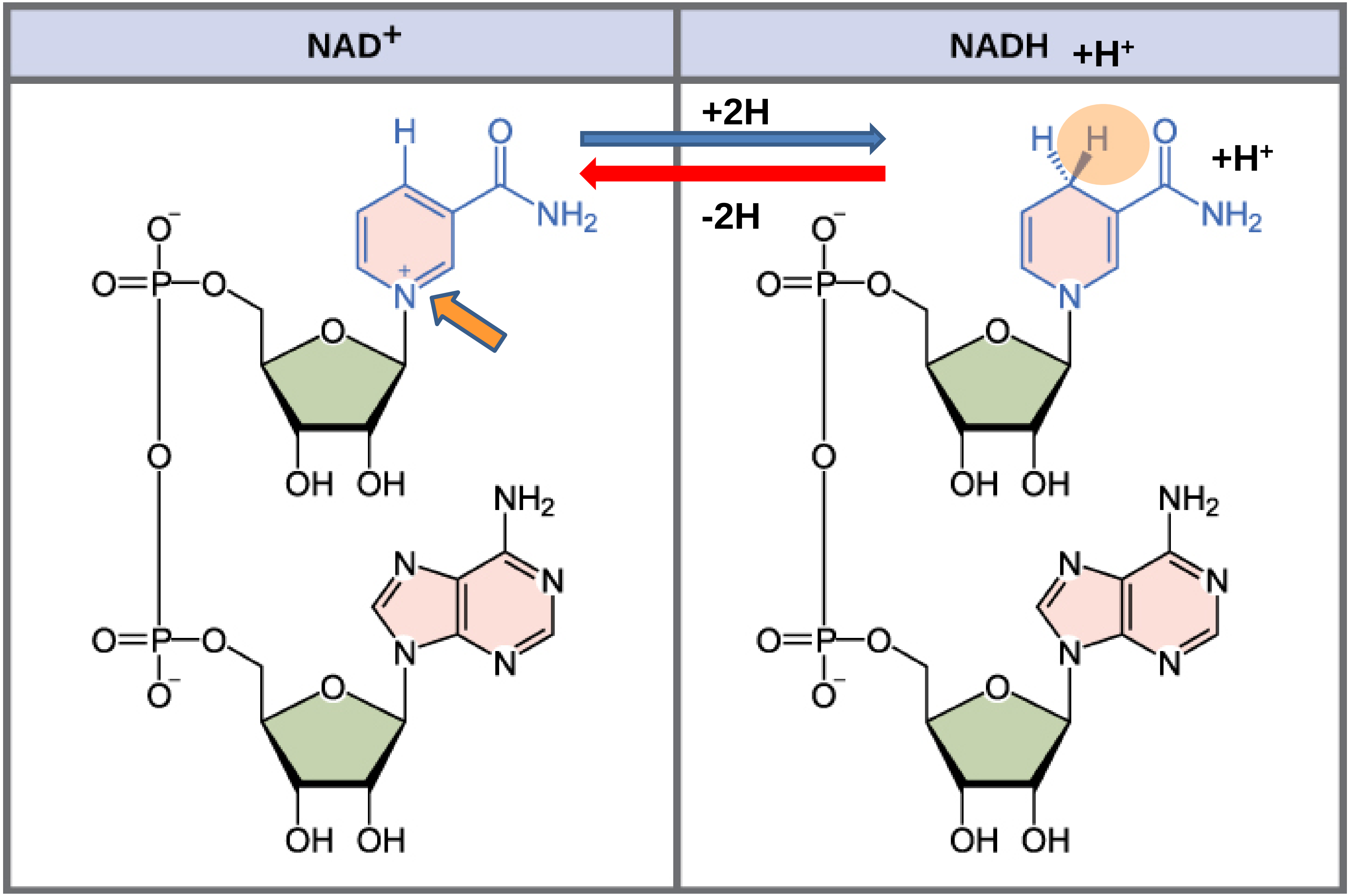
Thus, in the ETC, a number of oxidative-reduction reactions take place. (Oxidation is the loss of two electrons or two hydrogen atoms; reduction is the gain of them). Due to consecutive oxidation-reduction reactions in the ETC, free energy is produced. A portion of this energy (about 50-75%) is accumulated in the phosphate bonds of ATP, and the other portion of the free energy is released as heat.



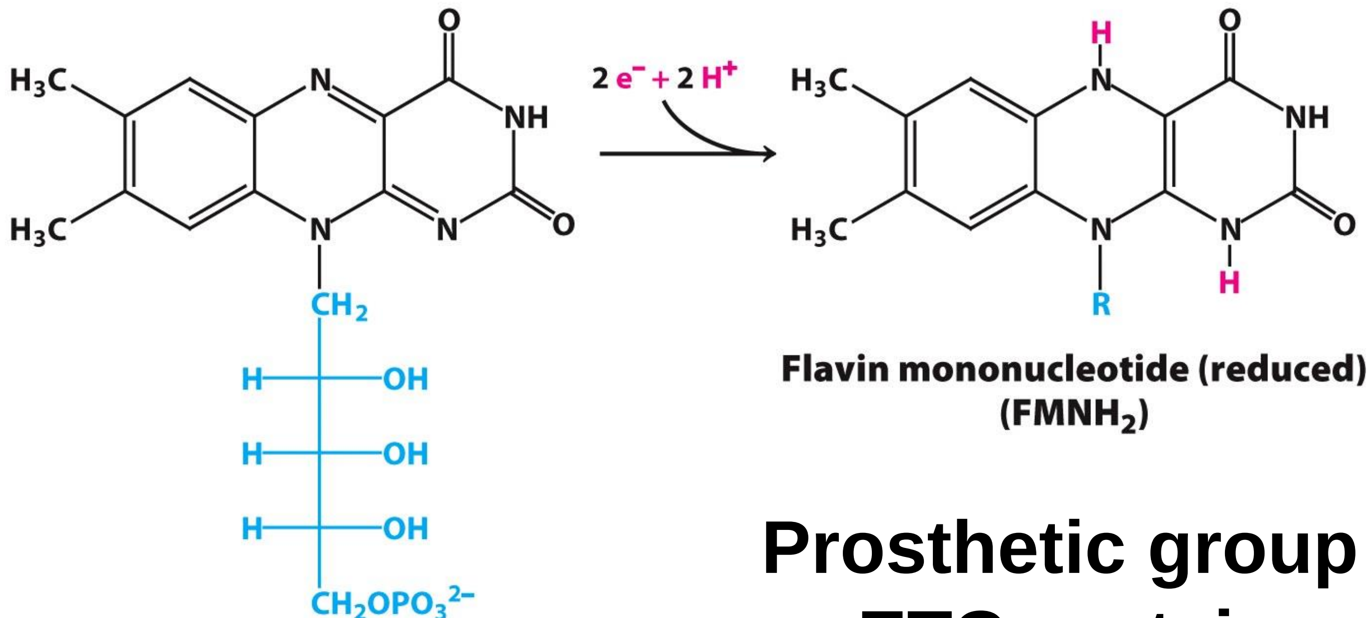
Mitochondrion
NADH
NAD+
H+
Fum
Succ
H+
H+
H+
H2O
O2
H+
H+
complex I
H+
matrix
inner mitochondrial
membrane
H+
complex II
cytochrome c
intermembrane space
H+
H+
H+
complex IV
complex III
(cytochrome bc1)

ETC carriers: NAD



NAD (nicotinamide adenine dinucleotide)

ETC carriers: FMN



Flavin mononucleotide (reduced) ($FMNH_2$)

Flavin mononucleotide (oxidized) (FMN)

Figure 20.5
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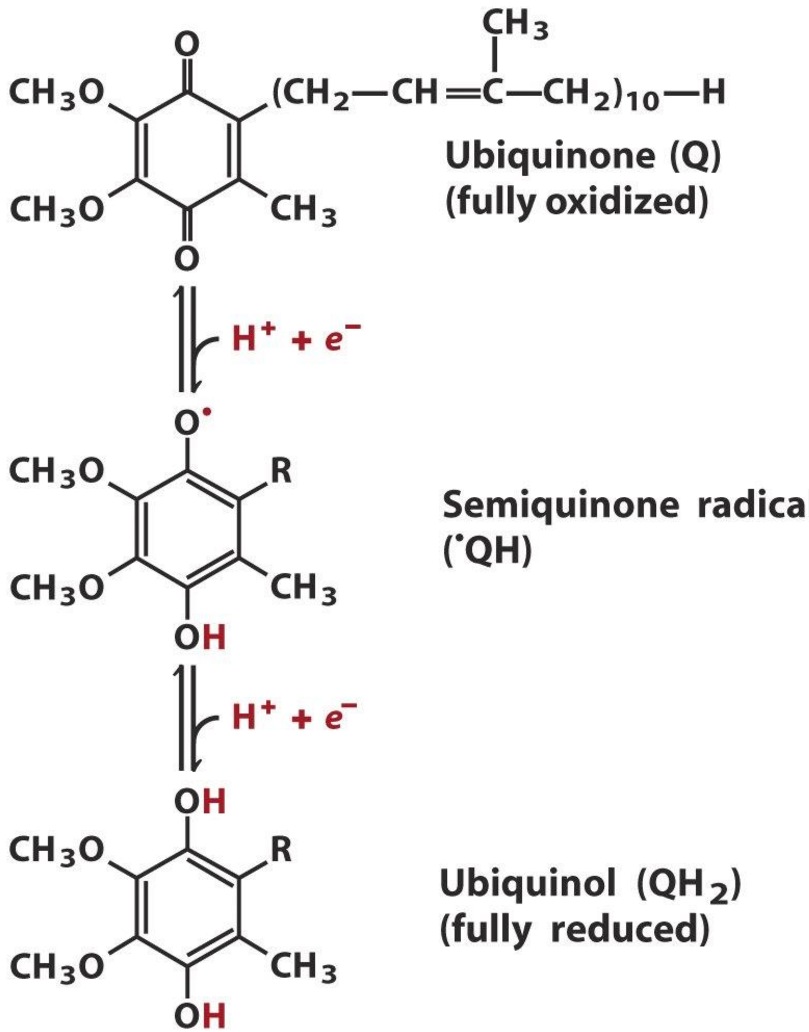
Prosthetic group of ETC protein (complex I)

1- or 2-electron acceptor

ETC carriers: Coenzyme Q

Mobile electron carrier within the bilayer

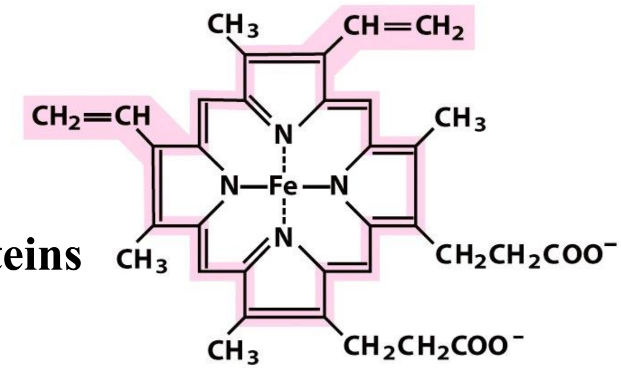
1- or 2-electron acceptor



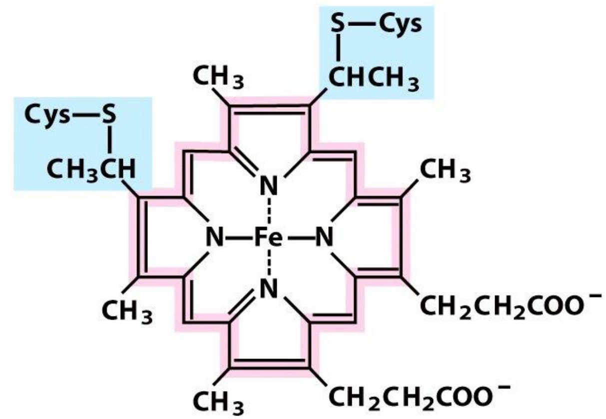
ETC carriers: Cytochromes

Heme proteins

Most are integral proteins

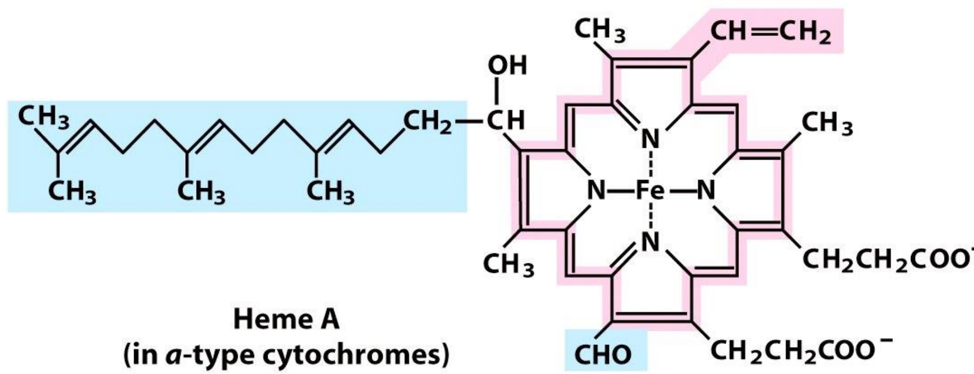


Iron protoporphyrin IX
(in *b*-type cytochromes)



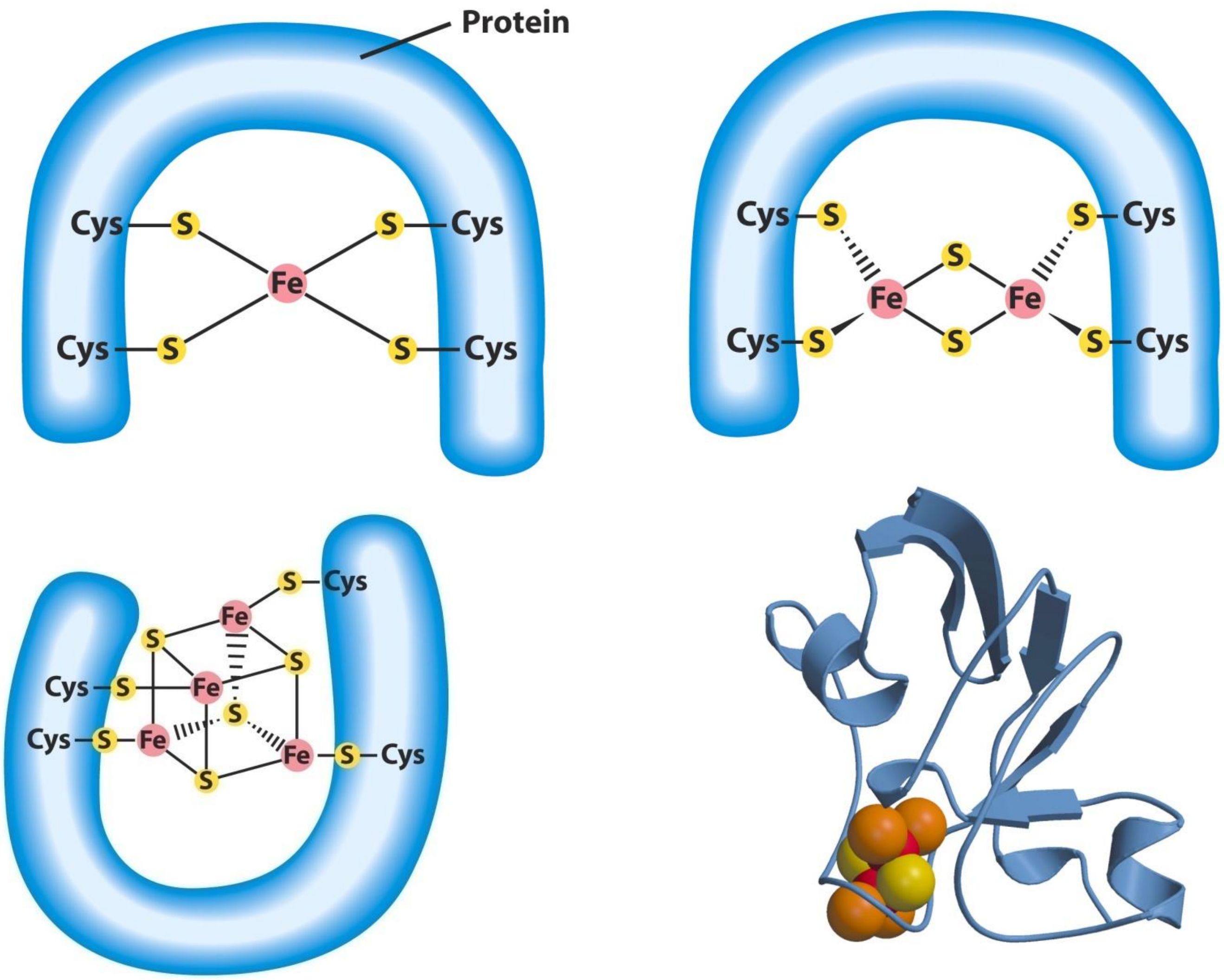
Heme C
(in *c*-type cytochromes)

Cytochrome c is a soluble peripheral protein

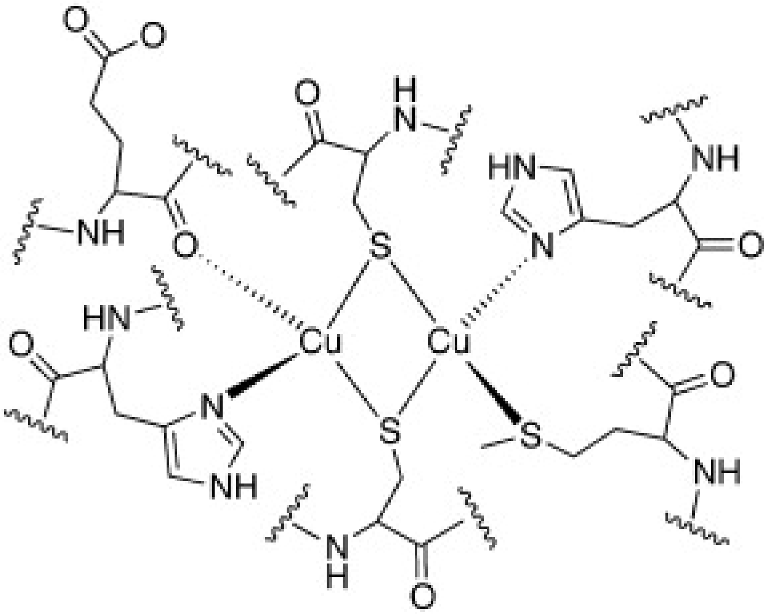


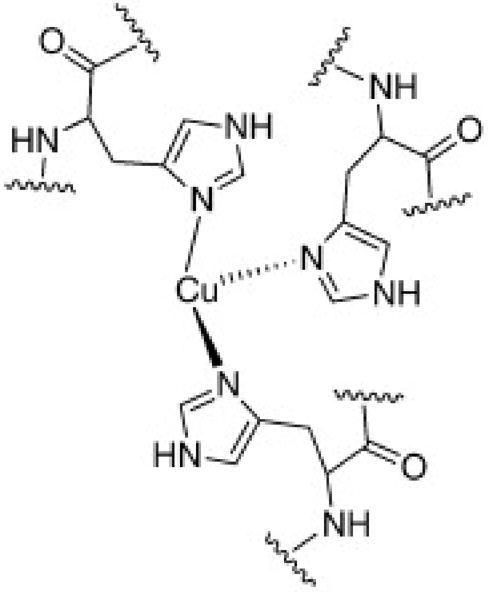
Heme A
(in *a*-type cytochromes)

ETC carriers: Iron-sulfur proteins



ETC carriers: Copper centers





- Cu_A center
- Cu_B center

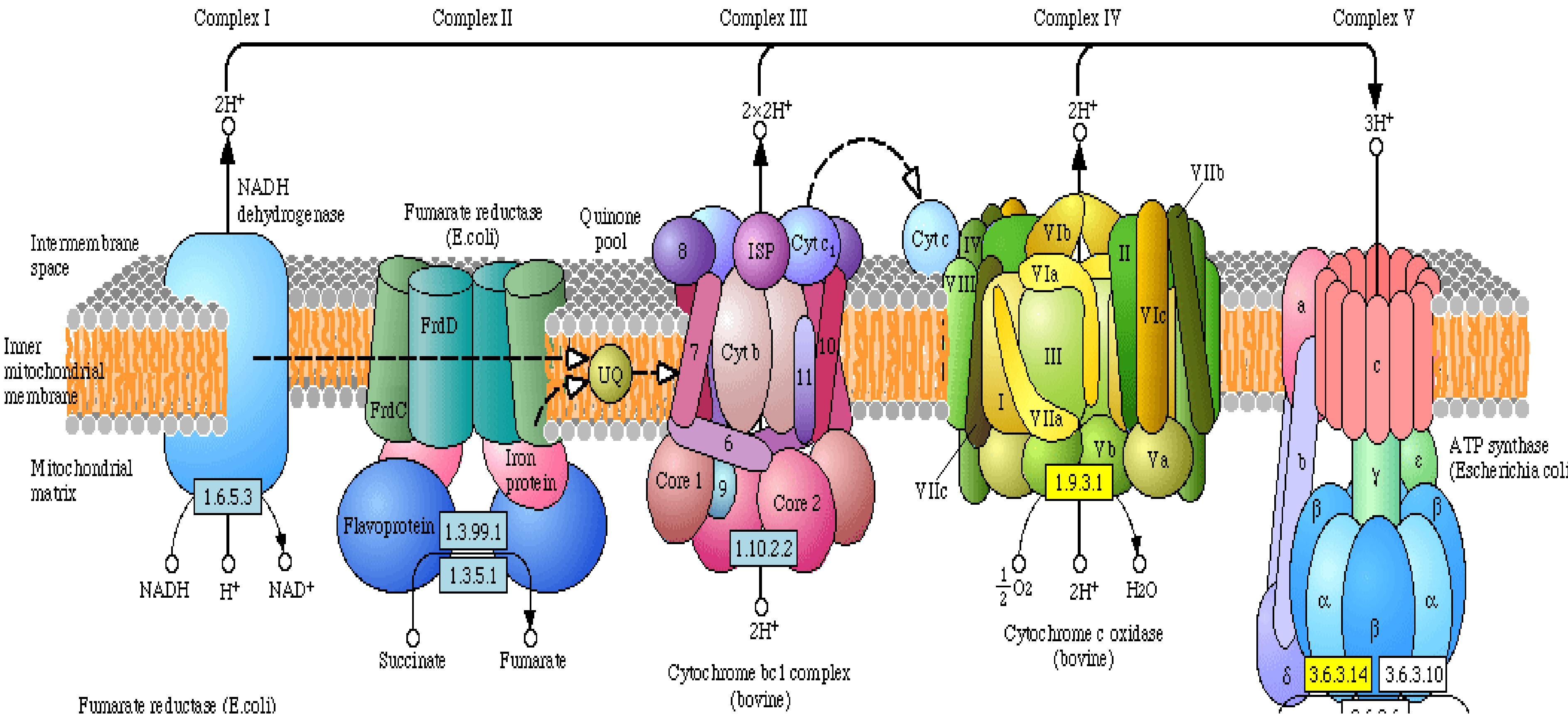
Electron Transport Chain: Proteins

TABLE 19–3 The Protein Components of the Mitochondrial Electron-Transfer Chain

Enzyme complex/protein	*Mass (kDa)*	*Number of subunits*[*]	*Prosthetic group(s)*
I NADH dehydrogenase	850	43 (14)	FMN, Fe-S
II Succinate dehydrogenase	140	4	FAD, Fe-S
III Ubiquinone cytochrome *c* oxidoreductase	250	11	Hemes, Fe-S
Cytochrome *c*[†]	13	1	Heme
IV Cytochrome oxidase	160	13 (3–4)	Hemes; Cu_A, Cu_B

[*]Numbers of subunits in the bacterial equivalents in parentheses.

[†]Cytochrome *c* is not part of an enzyme complex; it moves between Complexes III and IV as a freely soluble protein.



Complex I
Complex II
Complex III
Complex IV
Complex V
2H+
2×2H+
2H+
3H+
NADH dehydrogenase
Fumarate reductase (E.coli)
Quinone pool
Intermembrane space
Inner mitochondrial membrane
Mitochondrial matrix
FrdD
FrdC
Iron protein
Flavoprotein
UQ
8
ISP
Cyt c1
7
Cyt b
10
11
6
Core 1
9
Core 2
Cyt c
IV
VIII
VIb
VIa
II
VIc
III
I
VIIa
Vb
Va
VIIb
VIIc
a
b
c
ε
γ
β
α
δ
ATP synthase (Escherichia coli)
1.6.5.3
1.3.99.1
1.3.5.1
1.10.2.2
1.9.3.1
3.6.3.14
3.6.3.10
NADH
H+
NAD+
Succinate
Fumarate
2H+
1/2 O2
2H+
H2O
Cytochrome bc1 complex (bovine)
Cytochrome c oxidase (bovine)
Fumarate reductase (E.coli)

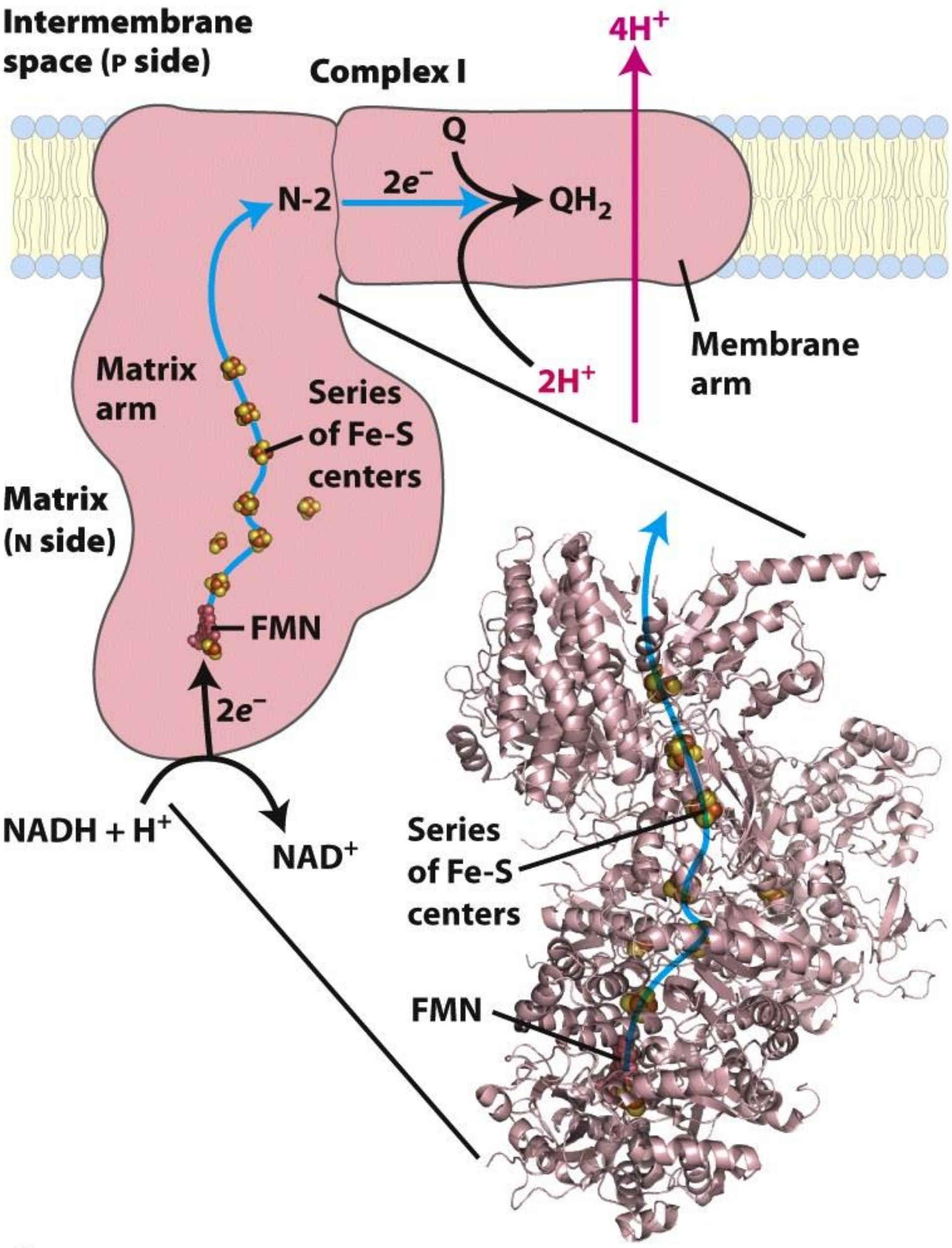


Figure 19-9
Lehninger Principles of Biochemistry, Fifth Edition

Complex I

NADH-CoQ oxidoreductase

Complex II: succinate-CoQ oxidoreductase

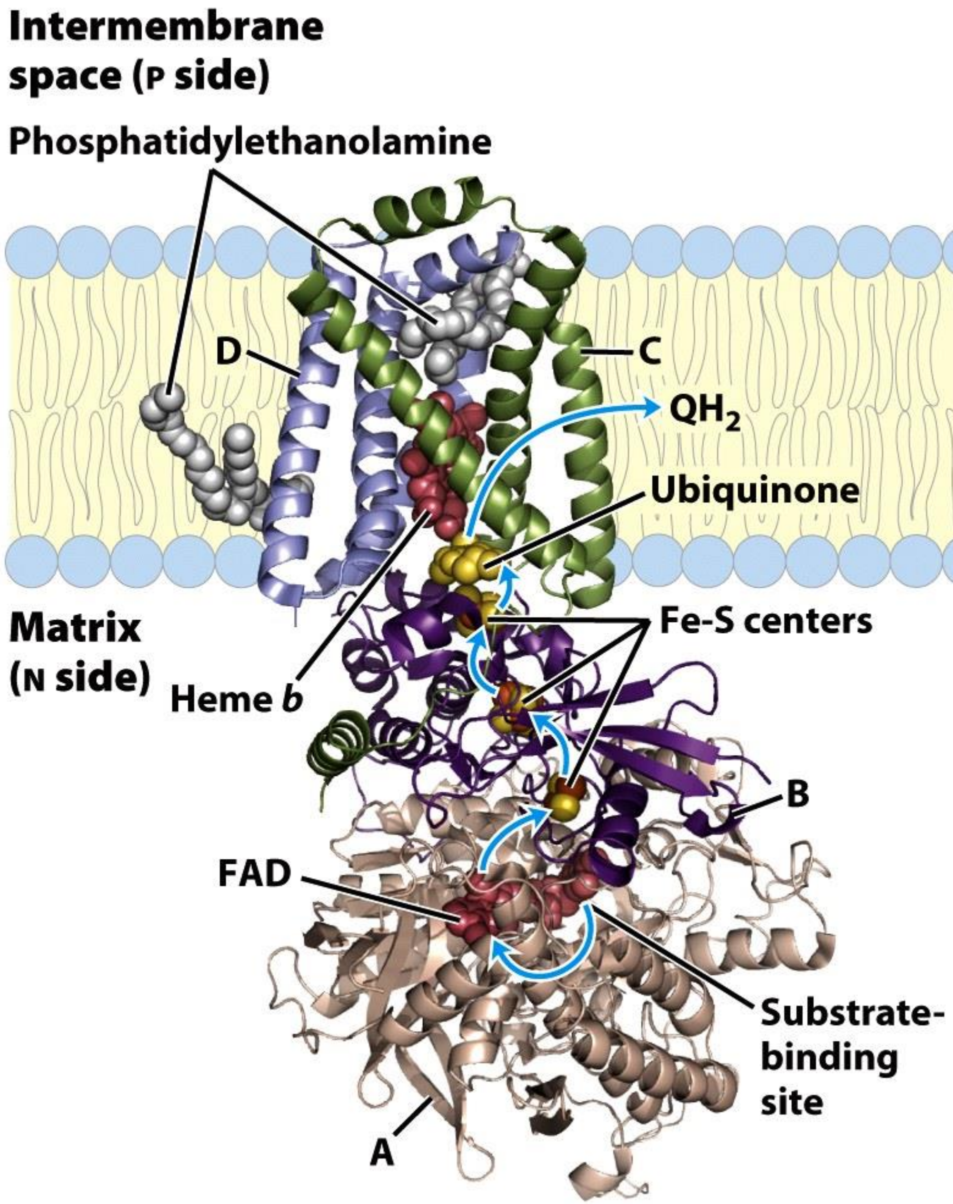


Figure 19-10
Lehninger Principles of Biochemistry, Fifth Edition

- Complex II (succinate dehydrogenase)

Complex III: $CoQH_2$-cyt c oxidoreductase

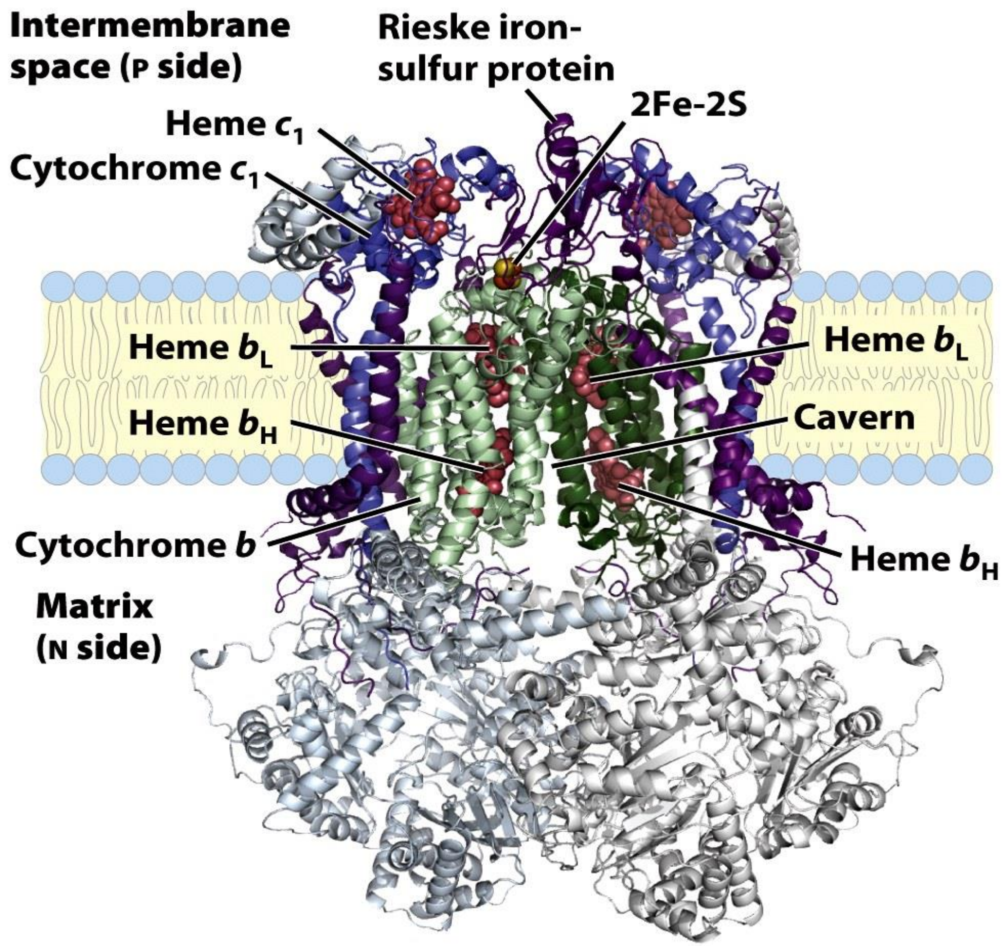
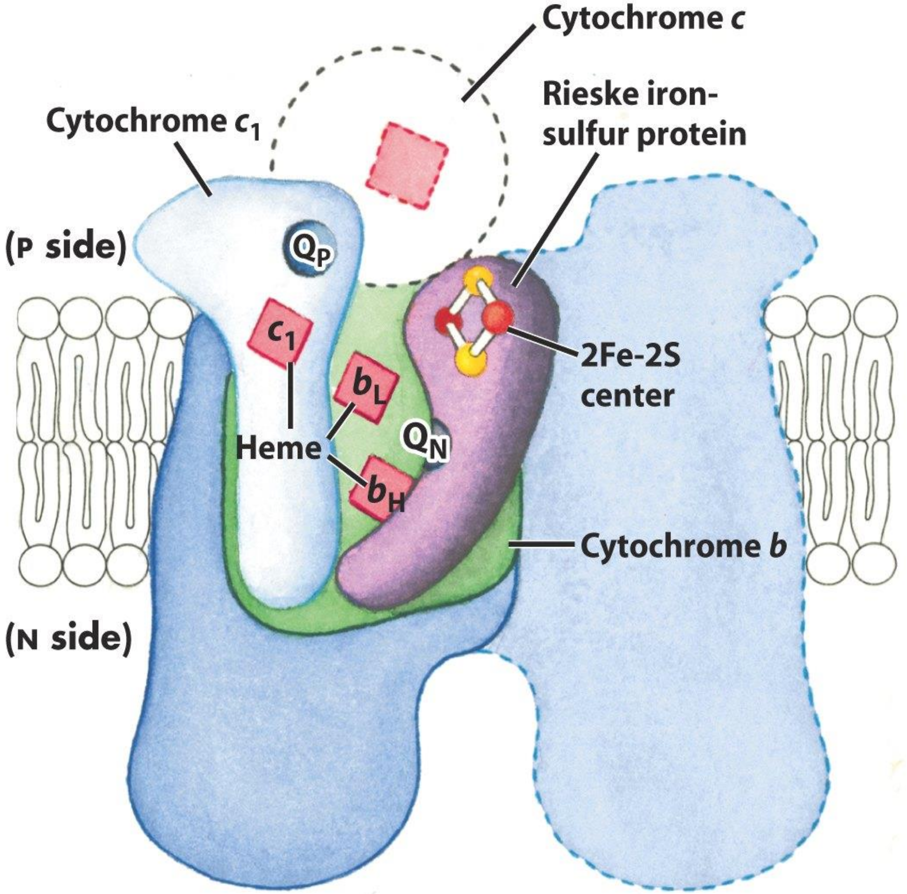
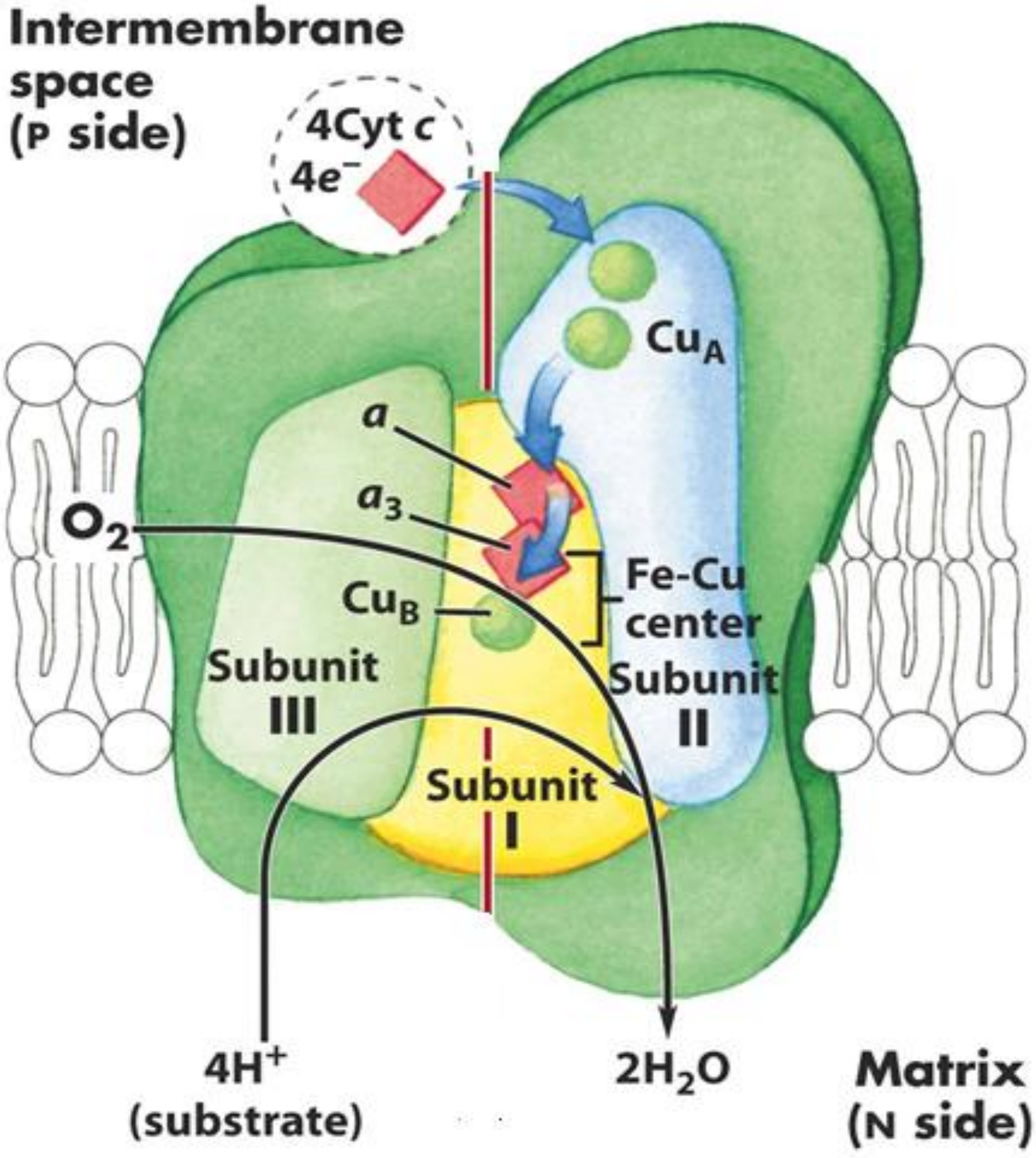


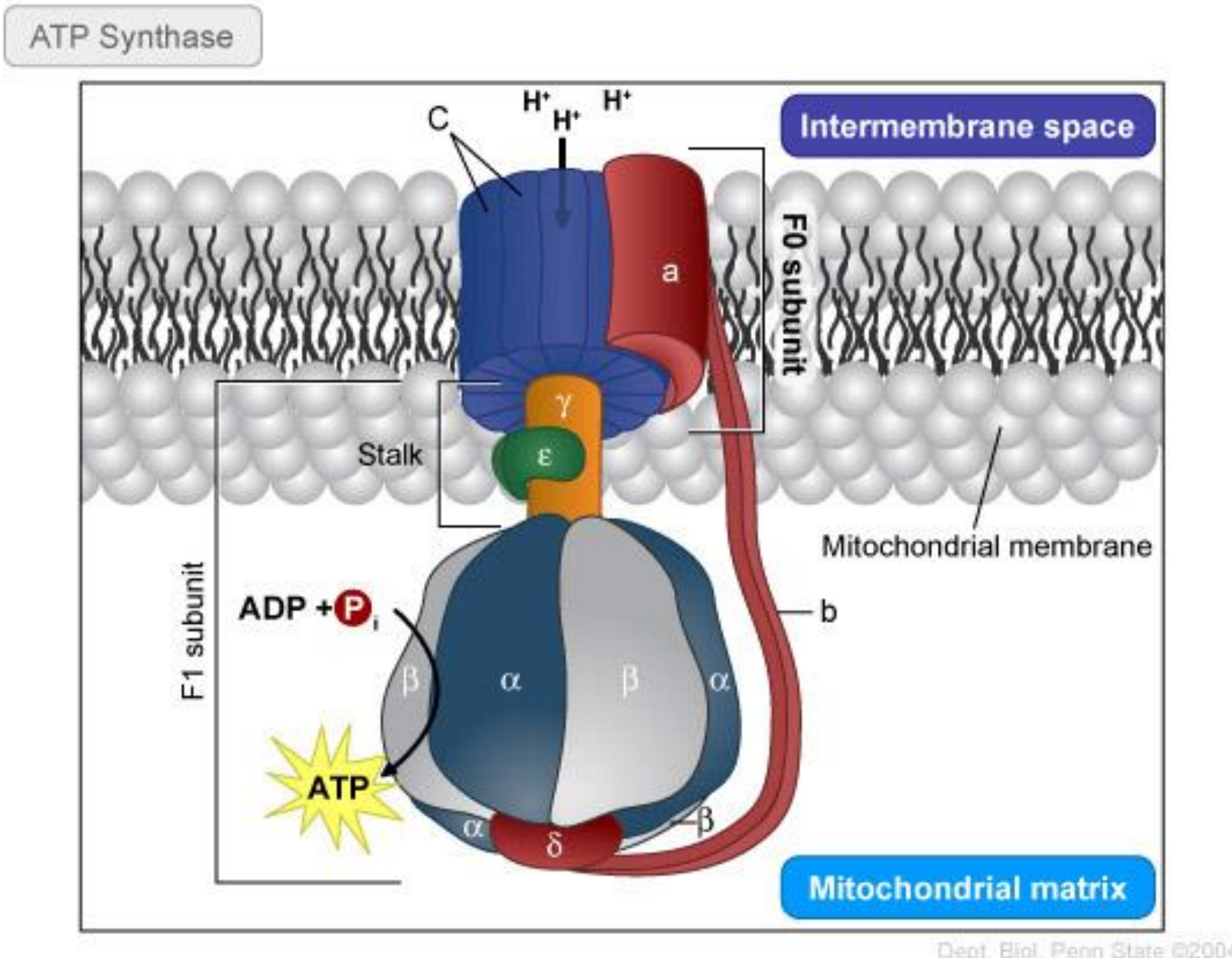
Figure 19-11a
Lehninger Principles of Biochemistry, Fifth Edition

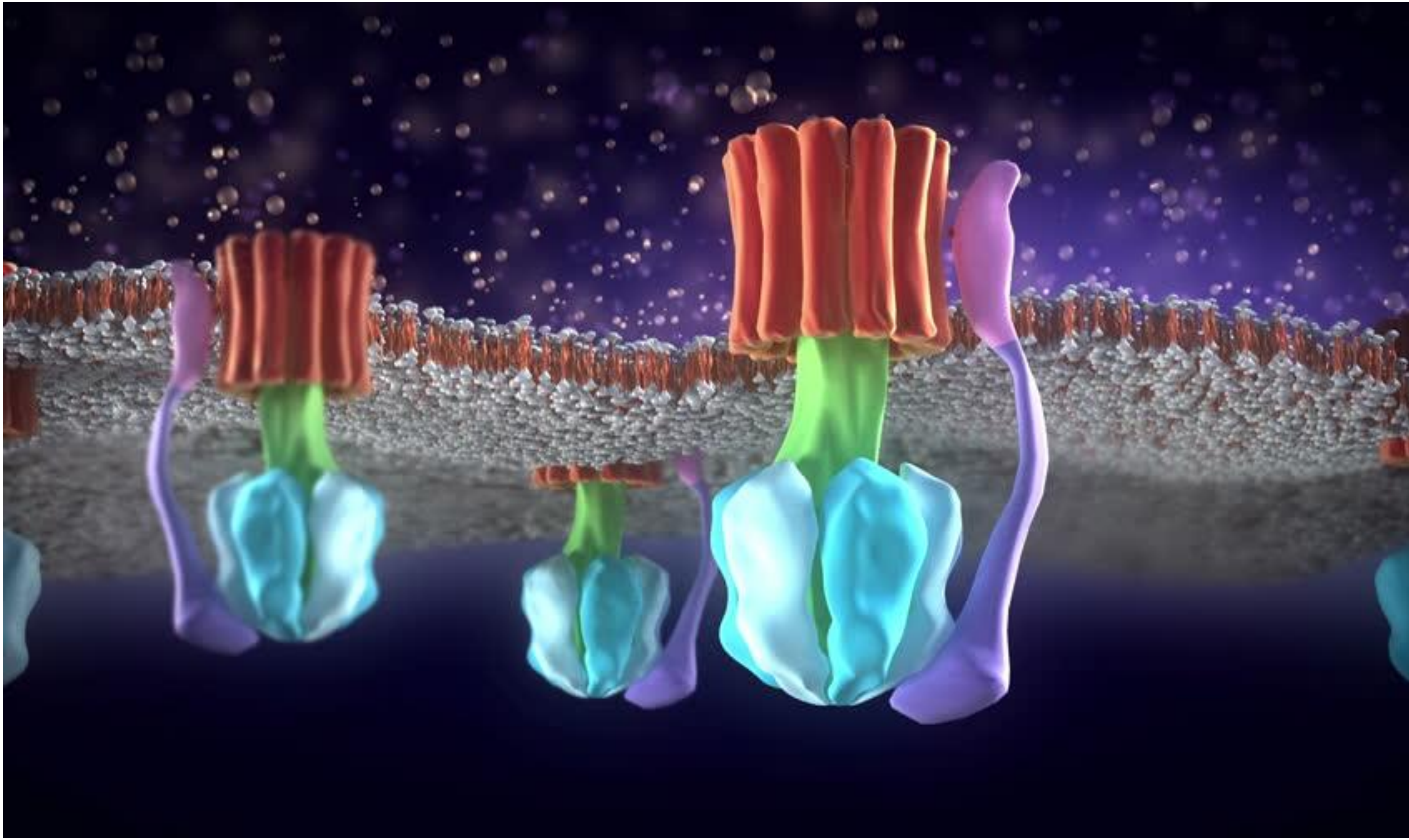


Complex IV: cyt c oxidase

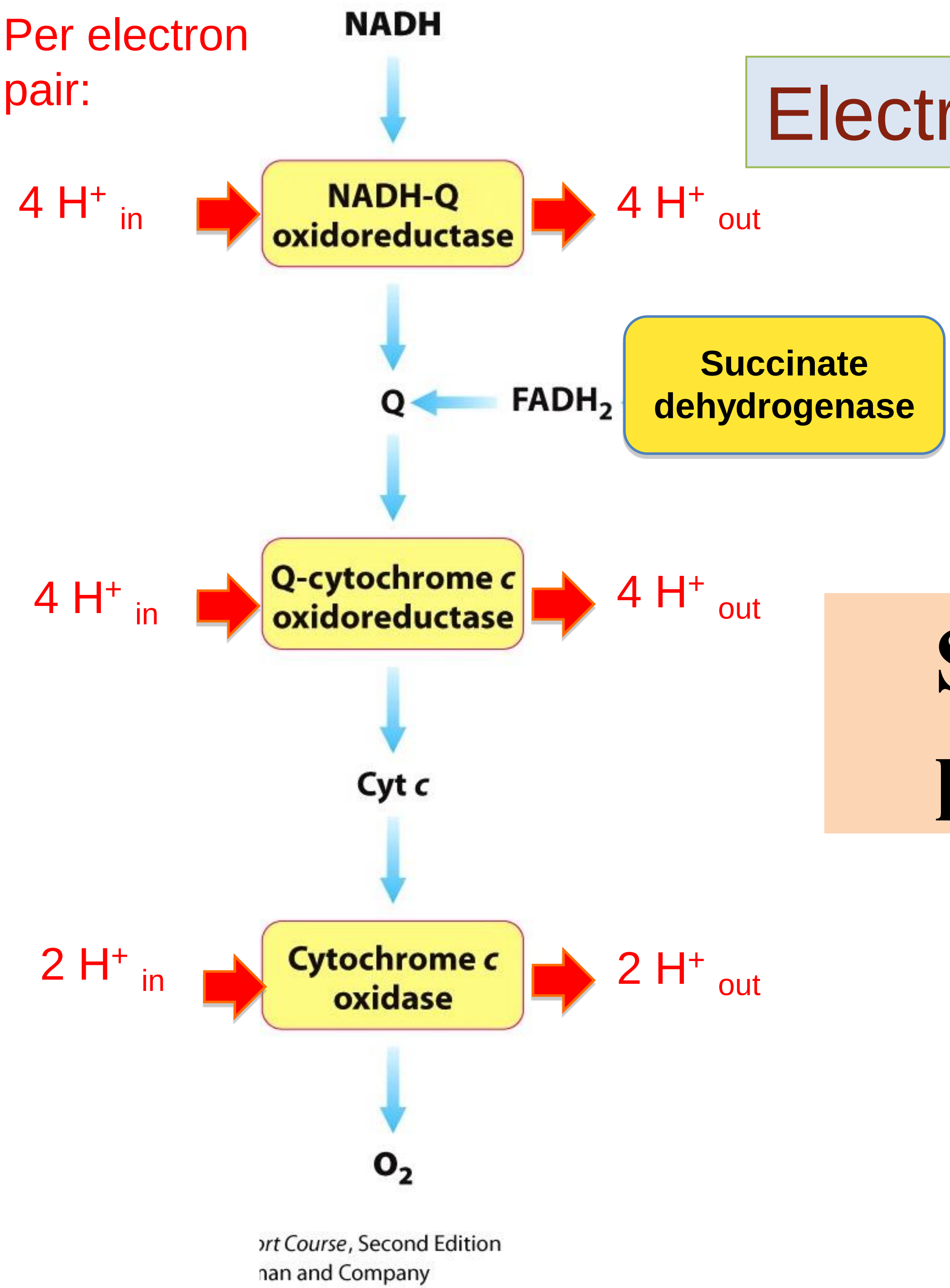


Complex V: ATP synthase

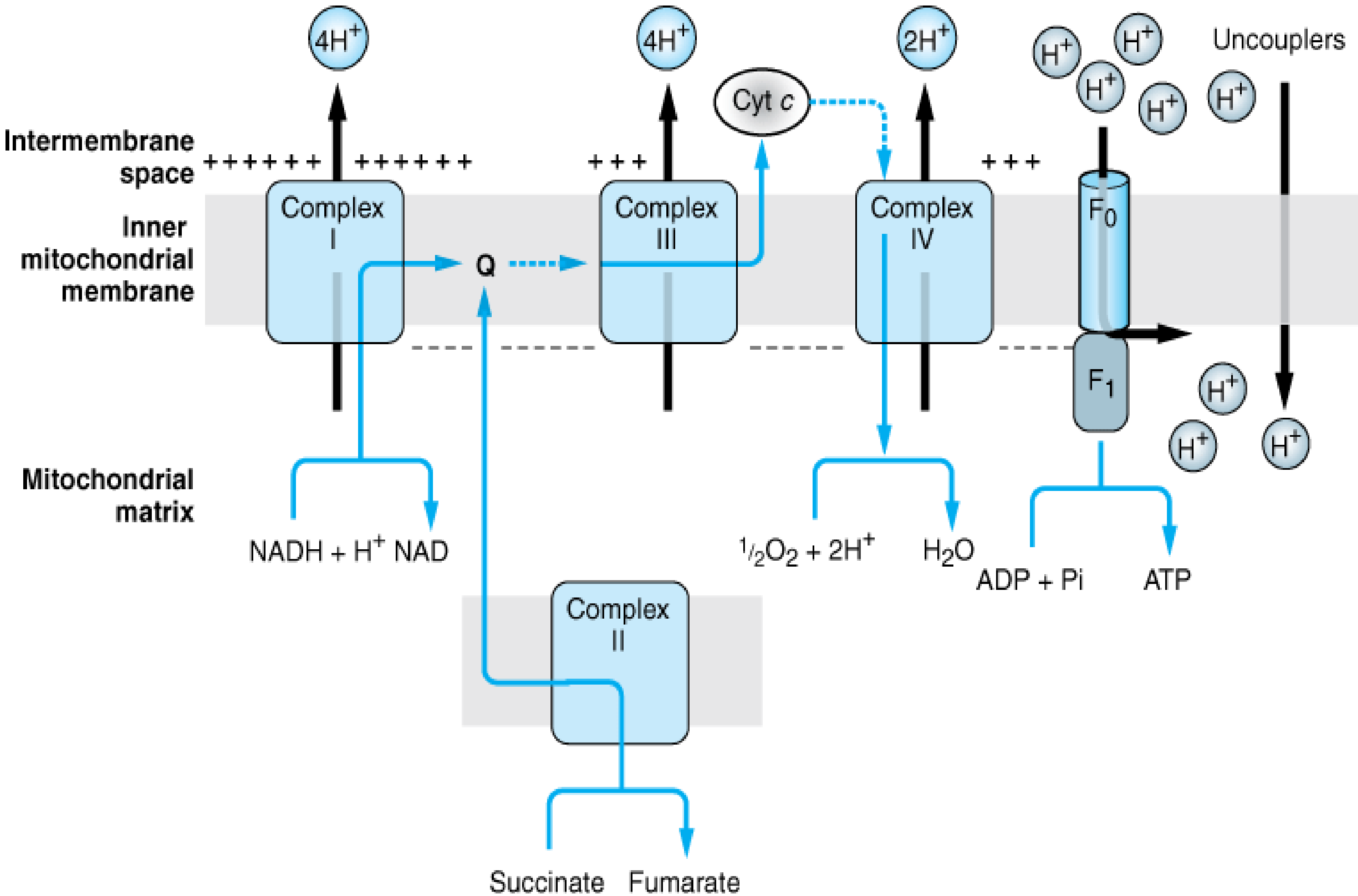




Electron Transport Chain



Some carriers pump protons


4H+
4H+
2H+
Cyt c
Uncouplers
Intermembrane space
++++++ ++++++
+++
+++
Inner mitochondrial membrane
Complex I
Q
Complex III
Complex IV
F0
F1
Mitochondrial matrix
NADH + H+ NAD
1/2O2 + 2H+
H2O
ADP + Pi
ATP
H+
Complex II
Succinate
Fumarate

Chemiosmotic Mechanism

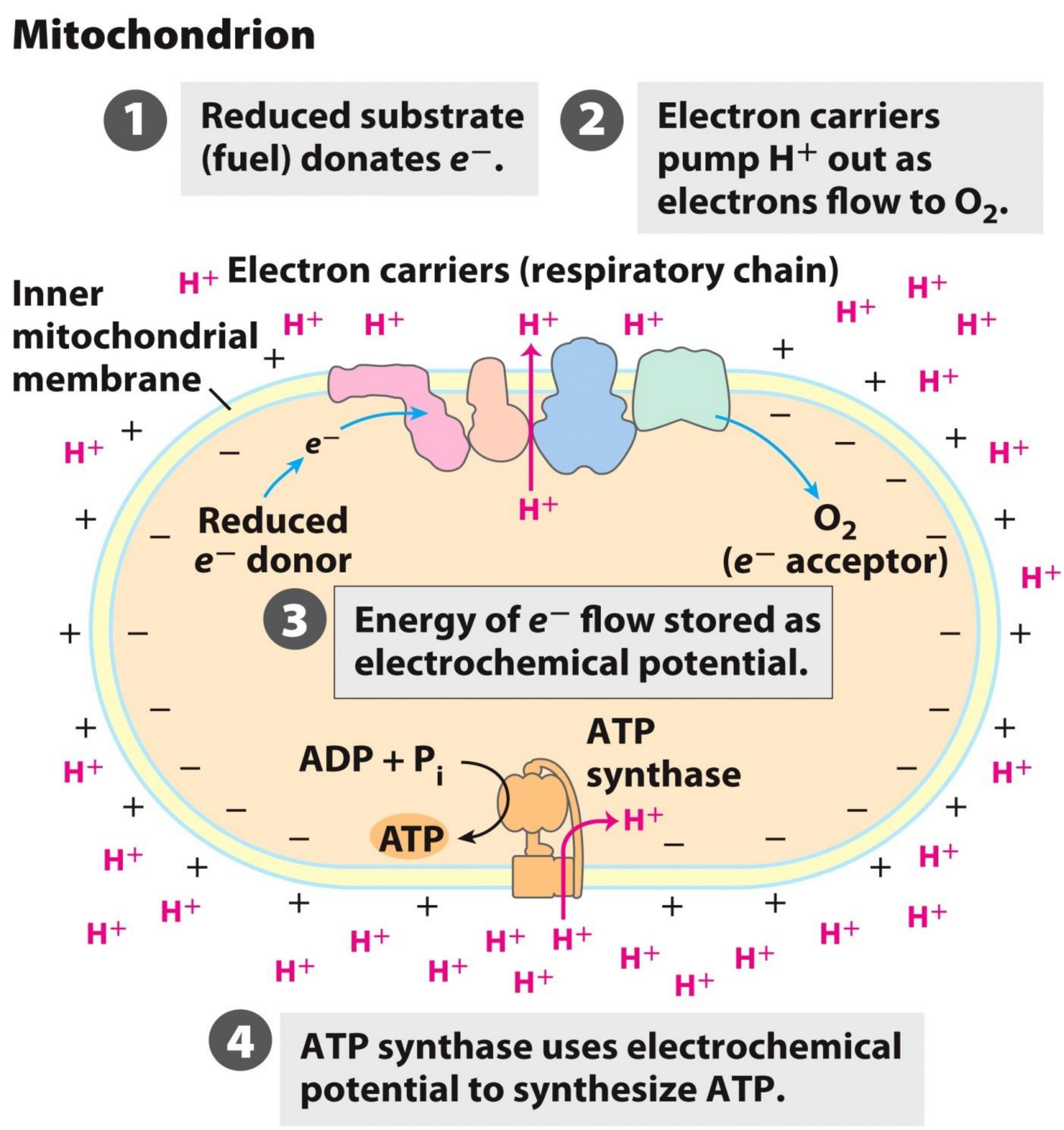


Figure 19-1a
Lehninger Principles of Biochemistry, Sixth Edition

Electron transport chain sets up an H^+ gradient (proton motive force).

Energy of the pmf is harnessed to make ATP.