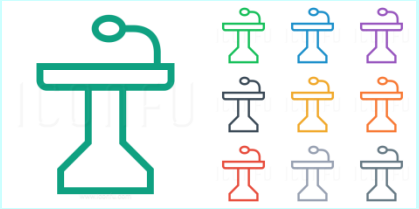
Biological Chemistry Department

Biological Chemistry

Introduction into Metabolism.
Electron transport chain (ETC).
Oxidative Phosphorylation.
Inhibitors of ETC and Uncouples.
Microsomal oxidation.
Non-enzymatic oxidation.

Speciality: Pharmacy for foreign students (Language of instructions – English)

Lecturer: ass. prof. Kravchenko G.B.



Lecture Plan

1. Introduction into Metabolism.
1.1. The biosynthesis of ATP.
1.2. The Pathways of Catabolism .
1.3. High-energy bond compounds.
1.4. The Tricarboxylic Acid Cycle.
2. Electron transport chain (ETC). Oxidative Phosphorylation.
2.1. Biochemical anatomy of a mitochondrion.
2.2. The electron transport chain.
2.3. Oxidative phosphorilation.
3. Inhibitors of ETC and Uncouples. Microsomal oxidation.

Individual work

1. Non-enzymatic oxidation.

Information Resources

1. Biological Chemistry: Textbook / A.L. Zagayko, L.M. Voronina, G.B. Kravchenko, K.V. Strel`chenko. – Kharkiv: NUPh; Original, 2011. – 73-87 p.

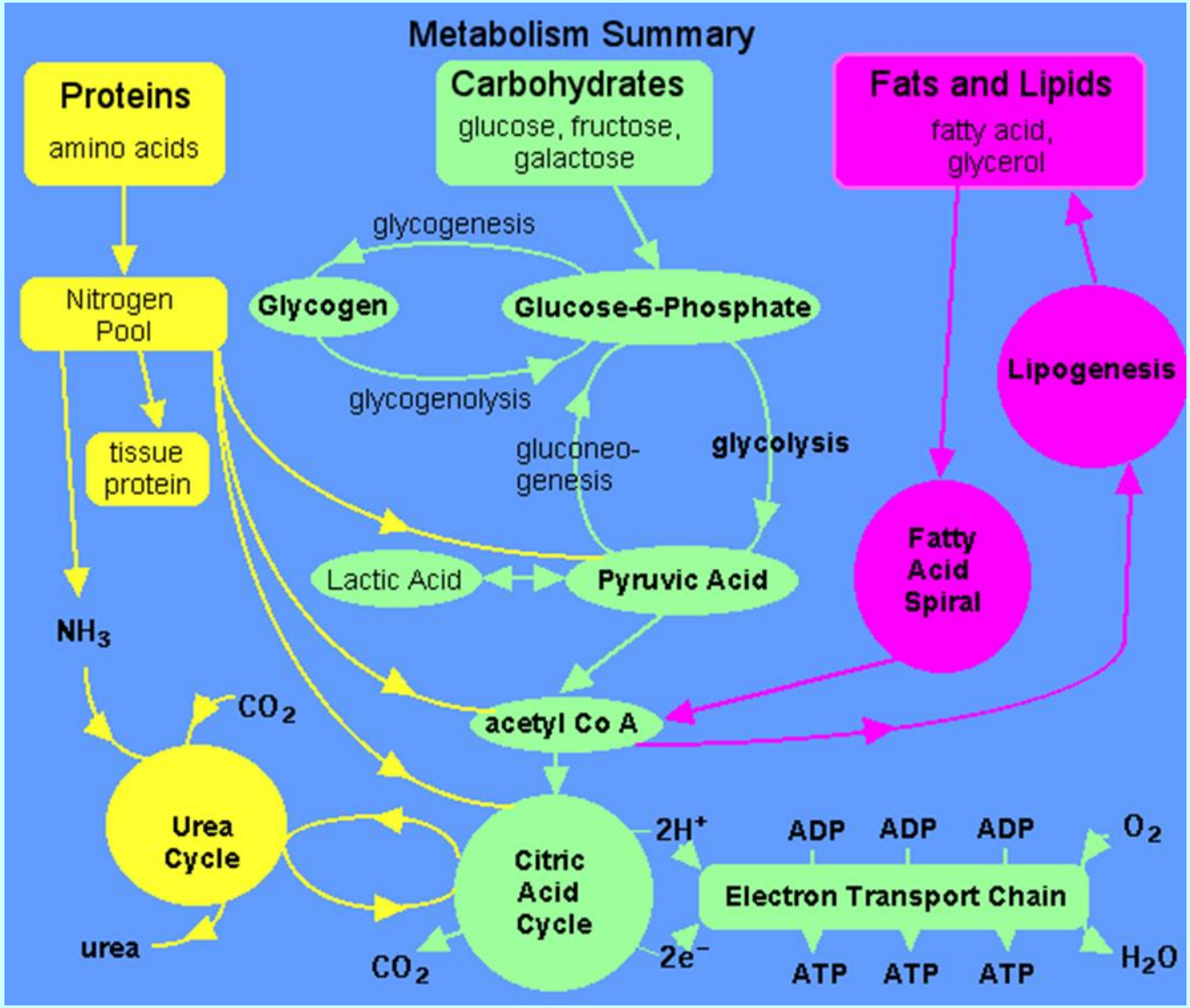
2. Training Journal for Licensed Exam "KROK-1": Study Material in Biological Chemistry. – Kharkiv: NUPh, 2017. – 41-49 p.

3. Laboratory Manual on Biochemistry. Kharkiv: NUPh, 2017. - 43-46 p.

4. Mitochondria: Biogenesis, Functions, and Disease: The Medical Biochemistry Page. Available on: **https://themedicalbiochemistrypage.org/mitochondria.php.**

5. Introduction to Pyruvate Metabolism and the TCA Cycle: The Medical Biochemistry Page. Available on: **https://themedicalbiochemistrypage.org/tca-cycle.php.**

6. Mitochondrial Functions and Biological Oxidations: The Medical Biochemistry Page. Available on: **https://themedicalbiochemistrypage.org/oxidative-phosphorylation.php.**



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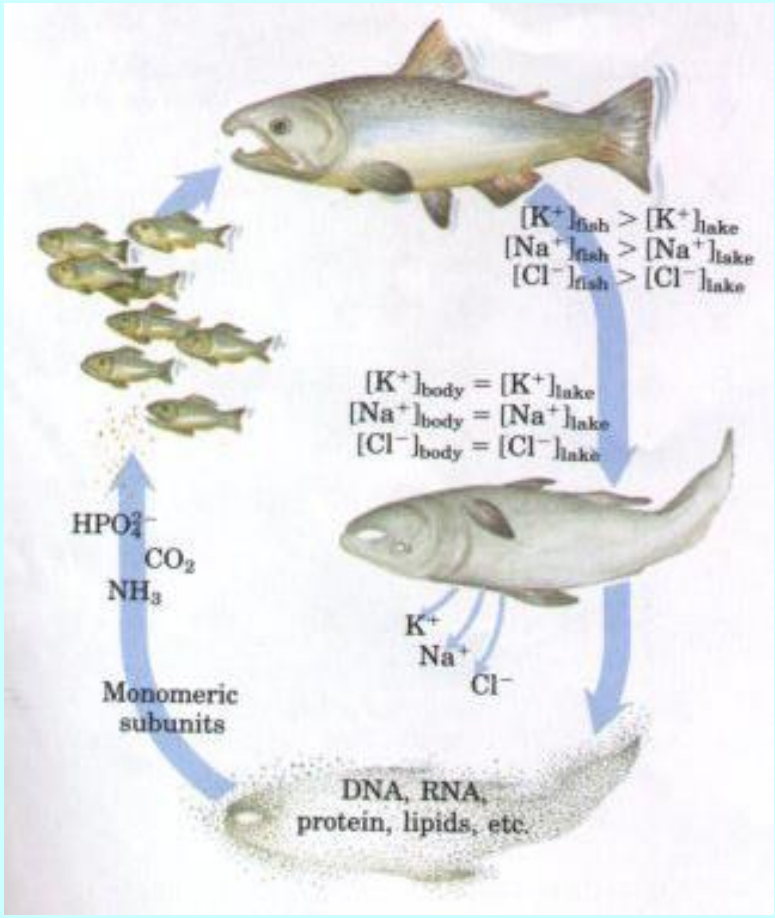
Metabolism is the sum total of all the enzyme-catalyzed reactions that occur in a living organism is a dynamic, coordinated activity. Many of these reactions are organized into pathways.

Metabolism serves two fundamentally different purposes:

the generation of energy to drive vital functions and

the synthesis of biological molecules.



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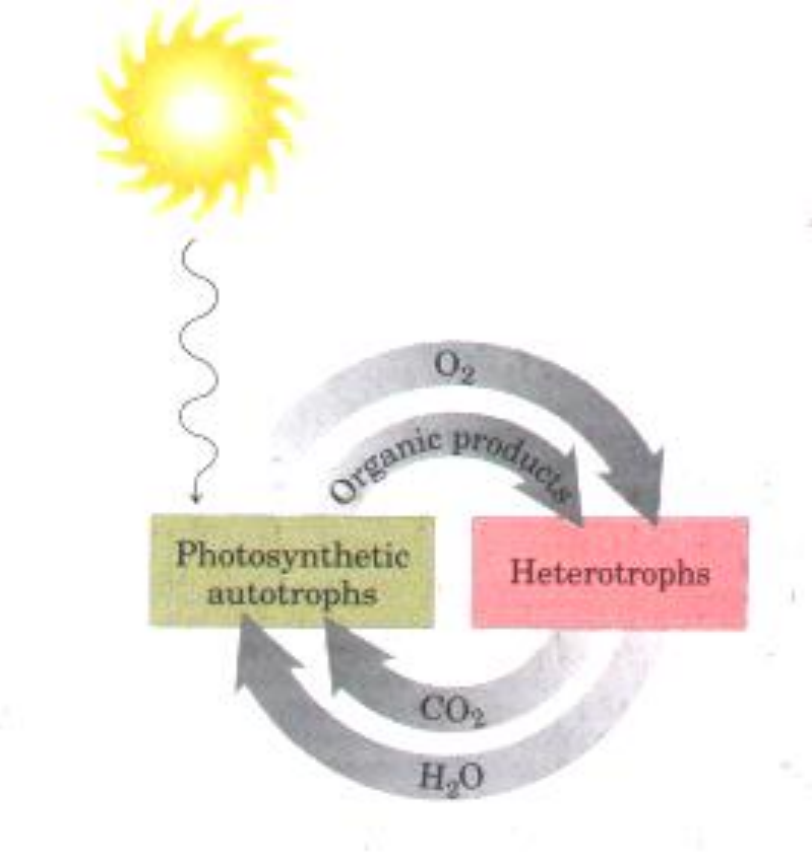
Organisms are often classified according to the major metabolic pathways they exploit to obtain carbon or energy.

Classification based on carbon requirements defines two major groups: autotrophs and heterotrophs.

A further metabolic distinction among organisms is whether or not they can use oxygen as an electron acceptor in energy-producing pathways. Those that can are called aerobes or aerobic organisms; others, termed anaerobes, can subsist without O_2.



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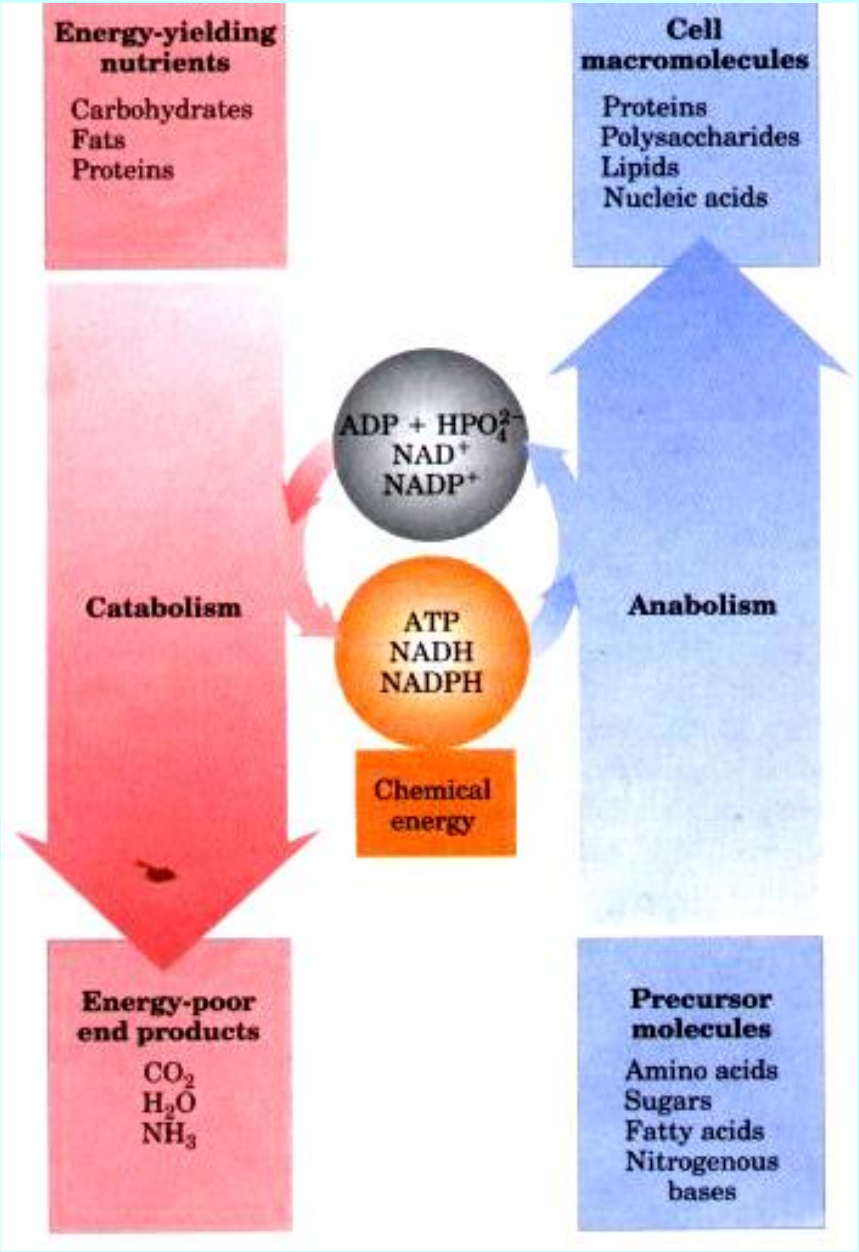
In general metabolism may be divided into two categories:

catabolism or the break down of molecules to obtain energy;

and anabolism or the synthesis of all compounds needed by the cells (examples are DNA, RNA, an protein synthesis).



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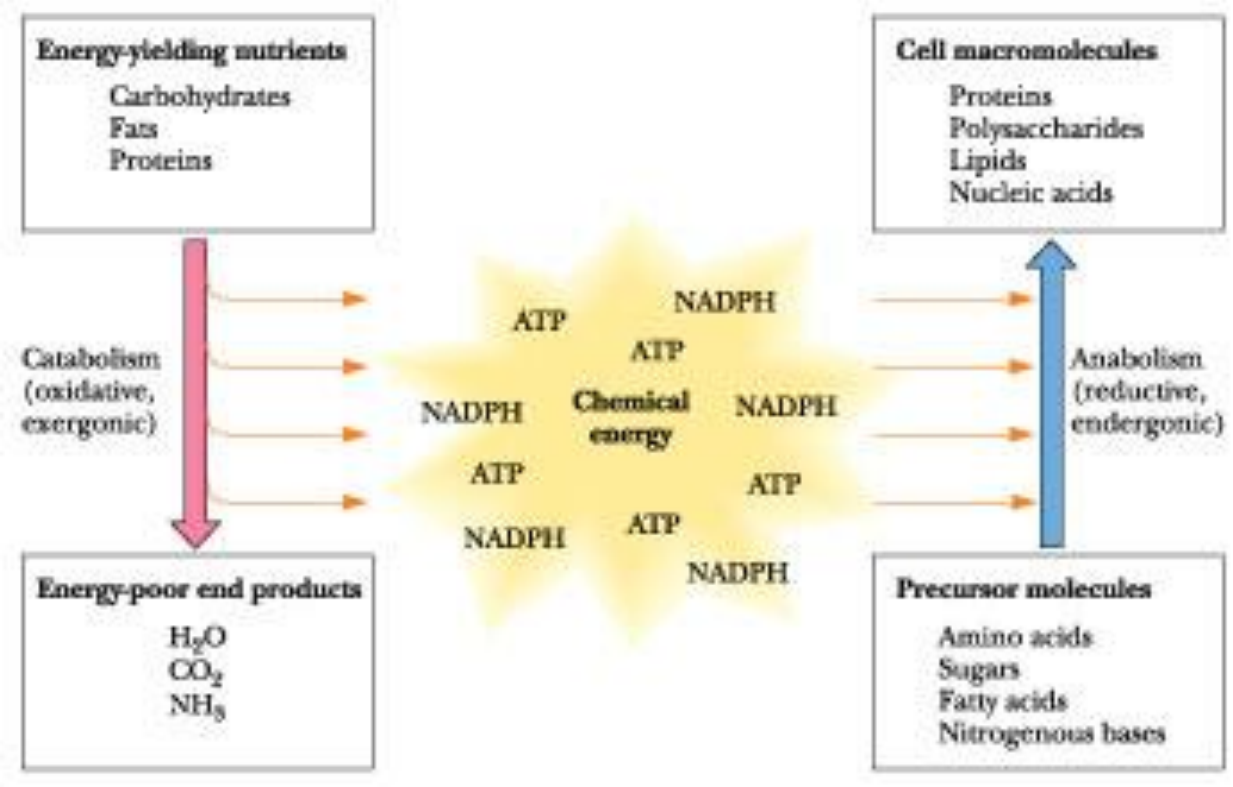
Anabolism and Catabolism Are Not Mutually Exclusive

Oxidative, exergonic pathways of catabolism release free energy and reducing power that are captured in the form of ATP and NADPH, respectively. Anabolic processes are endergonic, consuming chemical energy in the form of ATP and using NADPH as a source of high-energy electrons for reductive purposes.



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Living cells conserve energy in a biologically useful form

Living cells have an energy source in molecule, Adenosine triphosphate (ATP). ATP can be generated by oxidizing several metabolic fuels, although carbohydrates and fats are especially important. ATP is used in innumerable vital metabolic reactions and physiological functions.

The primary objective of intermediary metabolism is to maintain a steady supply of ATP so that living cells can grow, reproduce, and respond to the stress and strains imposed by starvation, exercise, overeating, etc.

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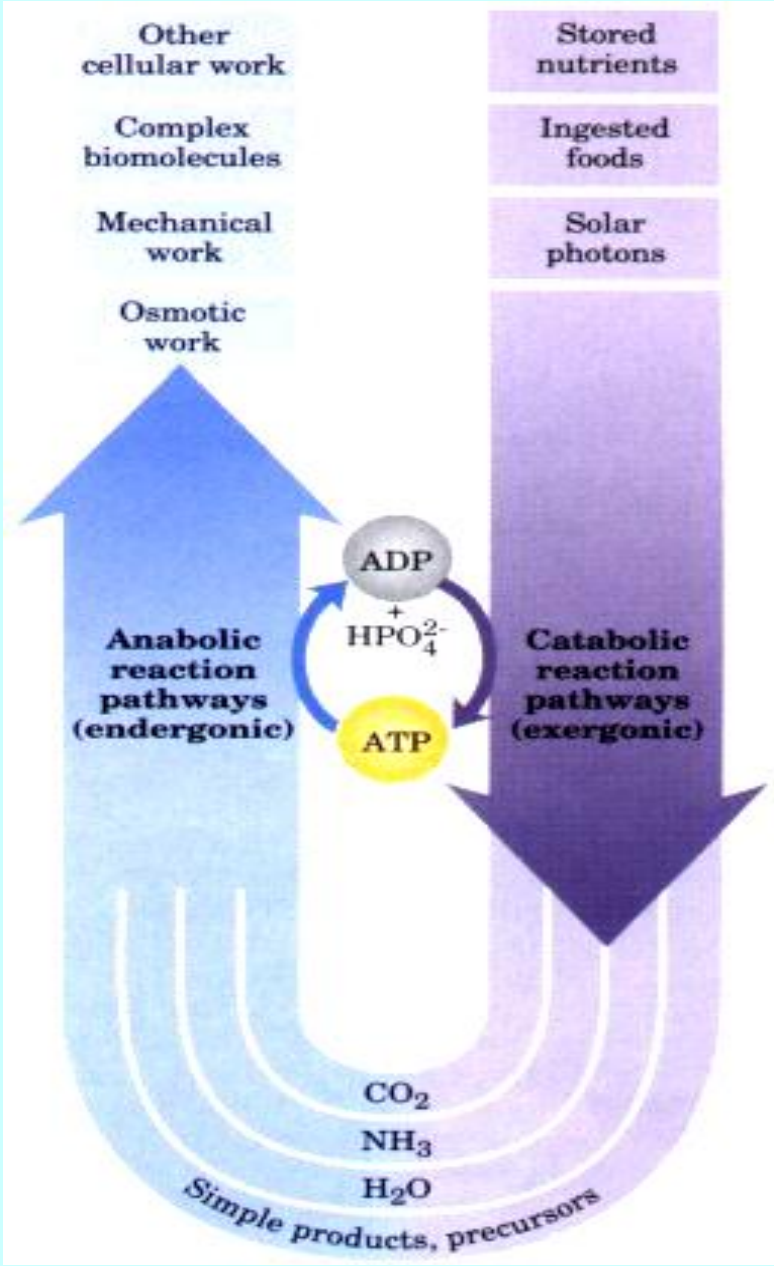

The biosynthesis of ATP

ATP can be synthesized by phosphorylation of adenosine diphosphate (ADP) by two types of process. One does not need oxygen and is known as substrate-level phosphorylation. The other requires oxygen and is known as oxidative phosphorylation.

Two reactions of glycolysis, namely the phosphoglycerate kinase and pyruvate kinase reactions, produce ATP by direct phosphorylation of ADP. This is substrate-level phosphorylation and is especially important for generating ATP if the tissues are inadequately supplied with oxygen.

ATP can also be made anaerobically from the phosphagen phosphocreatine. Another example – the reaction catalyzed by succinyl CoA synthetase, produces GTP (guanosine triphosphate) in Krebs cycle.

Oxidative phosphorylation

In the presence of oxygen, oxidative phosphorylation is by far the most important mechanism for synthesizing ATP. This process is coupled to the oxidation of the reduced "electron carriers" $NADH+H^+$ and $FADH_2$ via the respiratory chain.

The Pathways of Catabolism Converge to a Few End Products

If we survey the catabolism of the principal energy-yielding nutrients (carbohydrates, lipids, and proteins) in a typical heterotrophic cell, we see that the degradation of these substances involves a succession of enzymatic reactions. In the presence of oxygen (aerobic catabolism), these molecules are degraded ultimately to carbon dioxide, water, and ammonia. Aerobic catabolism consists of three distinct stages.

Stage 1, the nutrient macromolecules are broken down into their respective building blocks. Given the great diversity of macromolecules, these building blocks represent a rather limited number of products. Proteins yield up their 20 component amino acids, polysaccharides give rise to carbohydrate units that are convertible to glucose, and lipids are broken down into glycerol and fatty acids .

Stages of Catabolism

Stage 1

Stage 2

Stage 3

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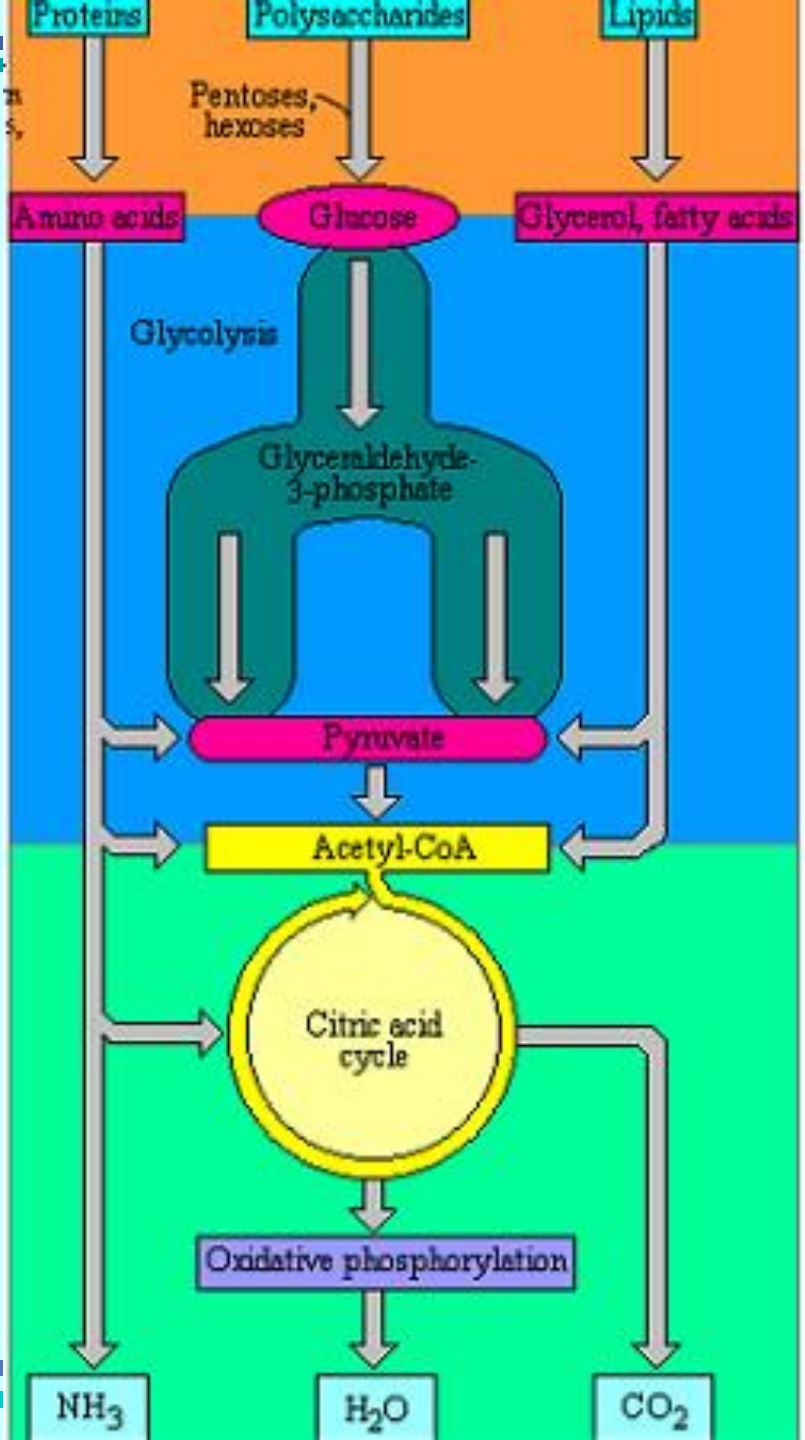
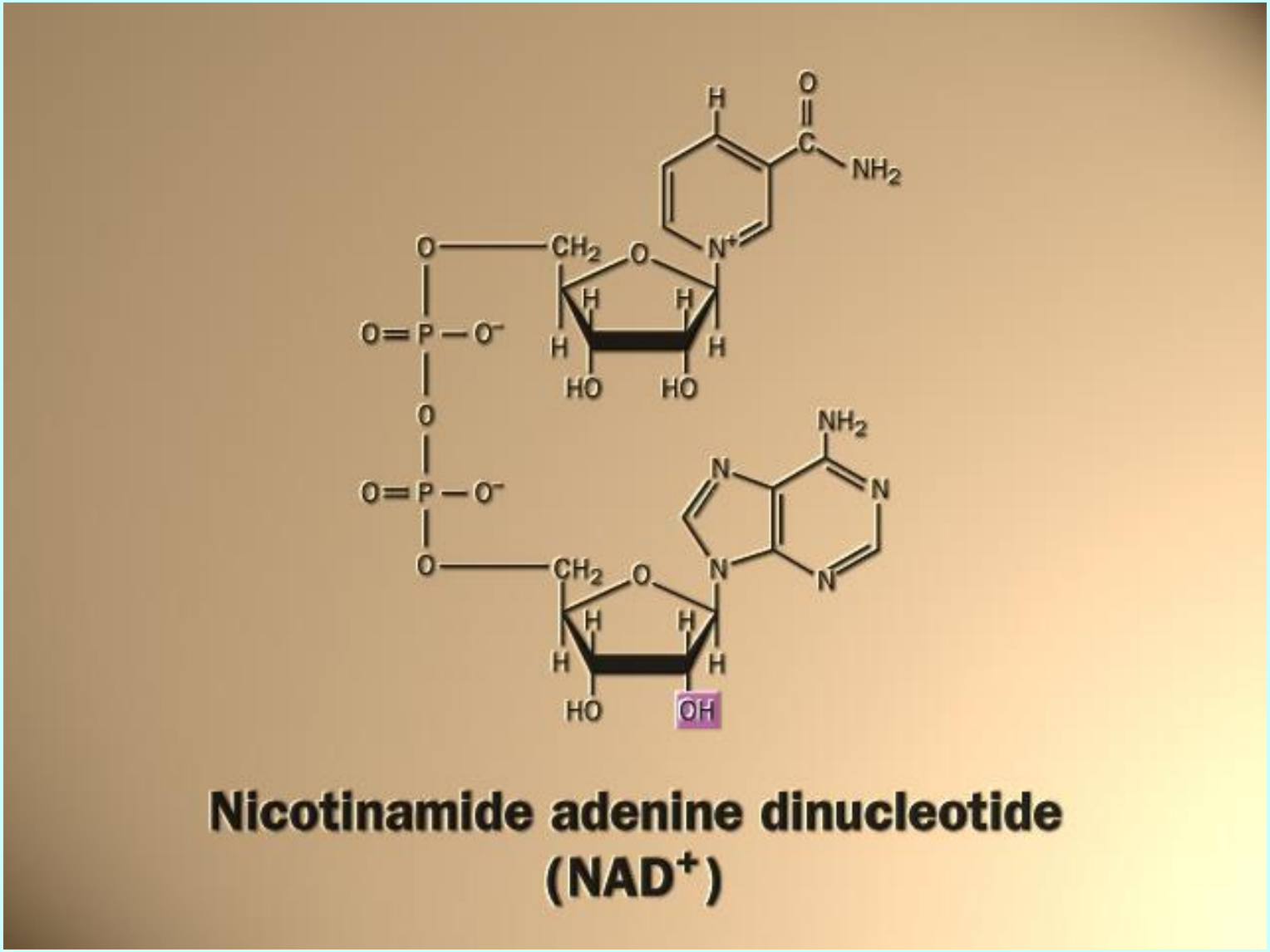


In stage 2, the collection of product building blocks generated in stage 1 is further degraded to yield an even more limited set of simpler metabolic intermediates. The deamination of amino acids leaves α- keto acid carbon skeletons. Several of these α- keto acids are citric acid cycle intermediates and are fed directly into stage 3 catabolism via this cycle. Others are converted either to the three-carbon α-keto acid pyruvate or to the acetyl groups of acetyl-coenzyme A (acetyl-CoA). Glucose and the glycerol from lipids also generate pyruvate , whereas the fatty-acids are broken into two-carbon units that appear as acetyl-CoA . Because pyruvate also gives rise to acetyl-CoA , we see that the degradation of macromolecular nutrients converges to a common end product, acetyl-CoA.

The combustion of the acetyl groups of acetyl-CoA by the citric acid cycle and oxidative phosphorylation to produce CO_2 and H_2O represents stage 3 of catabolism. The end products of the citric acid cycle, CO_2 and H_2O, are the ultimate waste products of aerobic catabolism. The oxidation of acetyl-CoA during stage 3 metabolism generates most of the energy produced by the cell.

Amphibolic Intermediates

Certain of the central pathways of intermediary metabolism, such as the citric acid cycle, and many metabolites of other pathways have dual purposes—they serve in both catabolism and anabolism. This dual nature is reflected in the designation of such pathways as amphibolic rather than solely catabolic or anabolic. In any event, in contrast to catabolism—which converges to the common intermediate, acetyl-CoA — the pathways of anabolism diverge from a small group of simple metabolic intermediates to yield a spectacular variety of cellular constituents.



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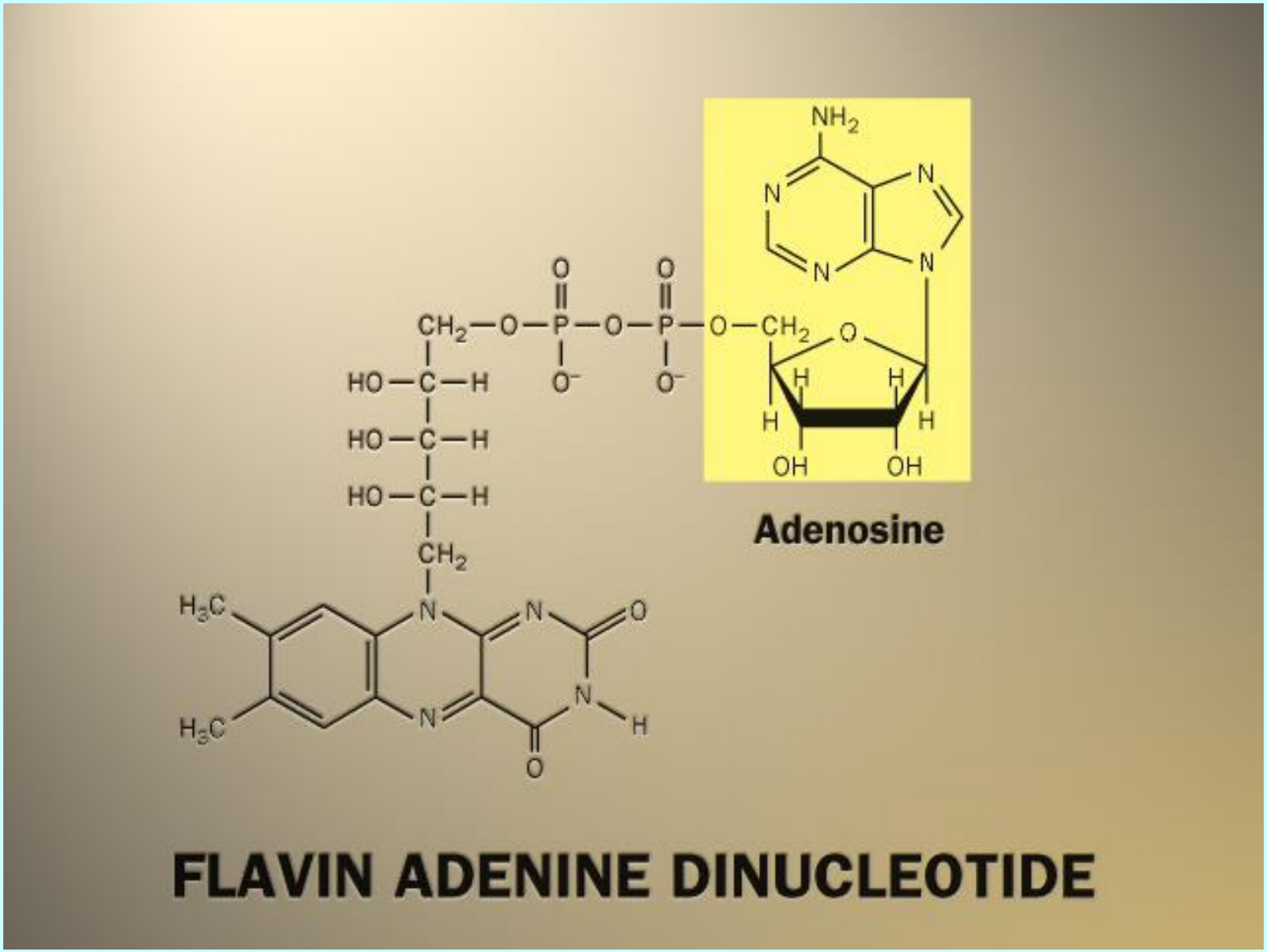

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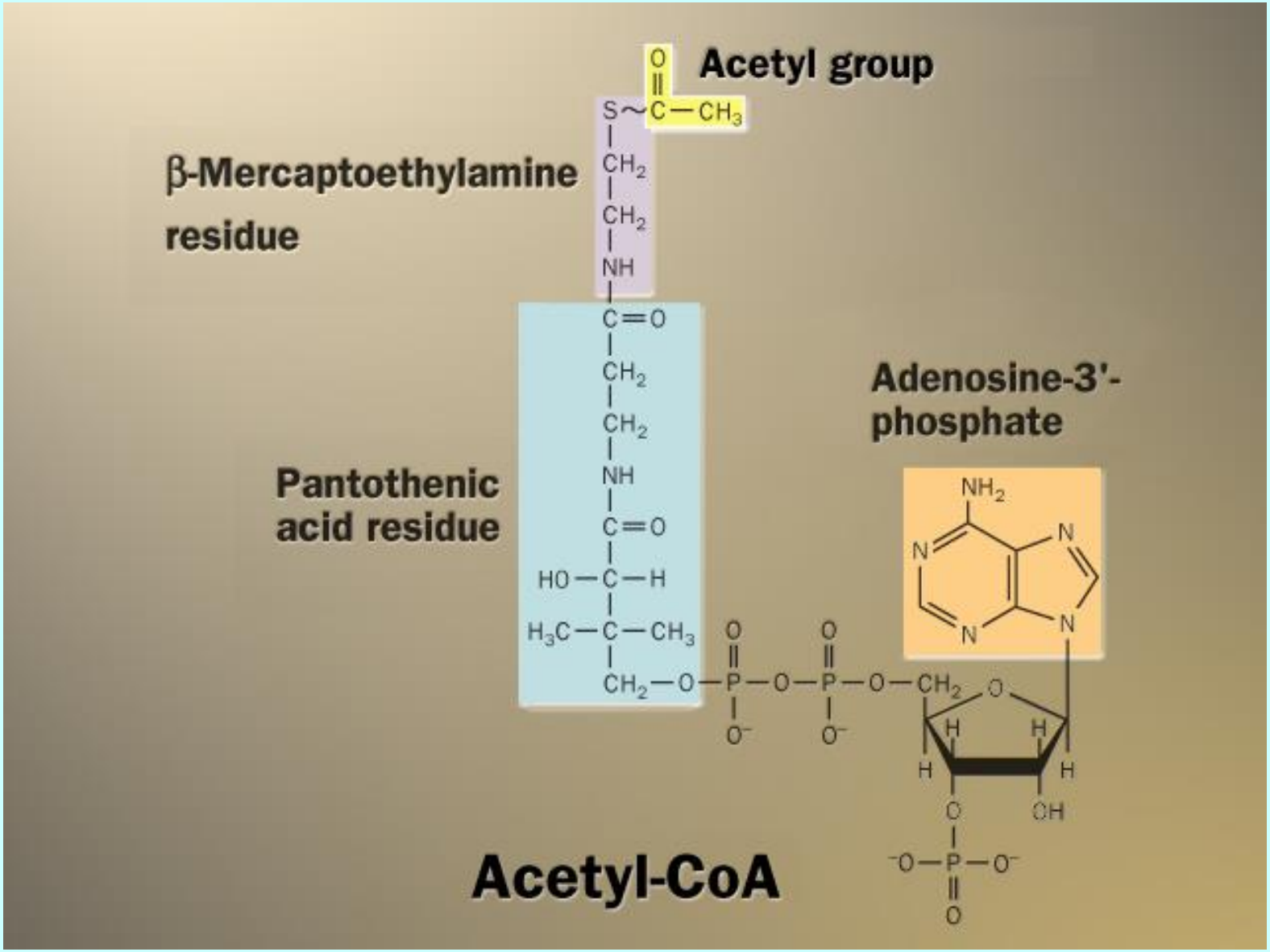

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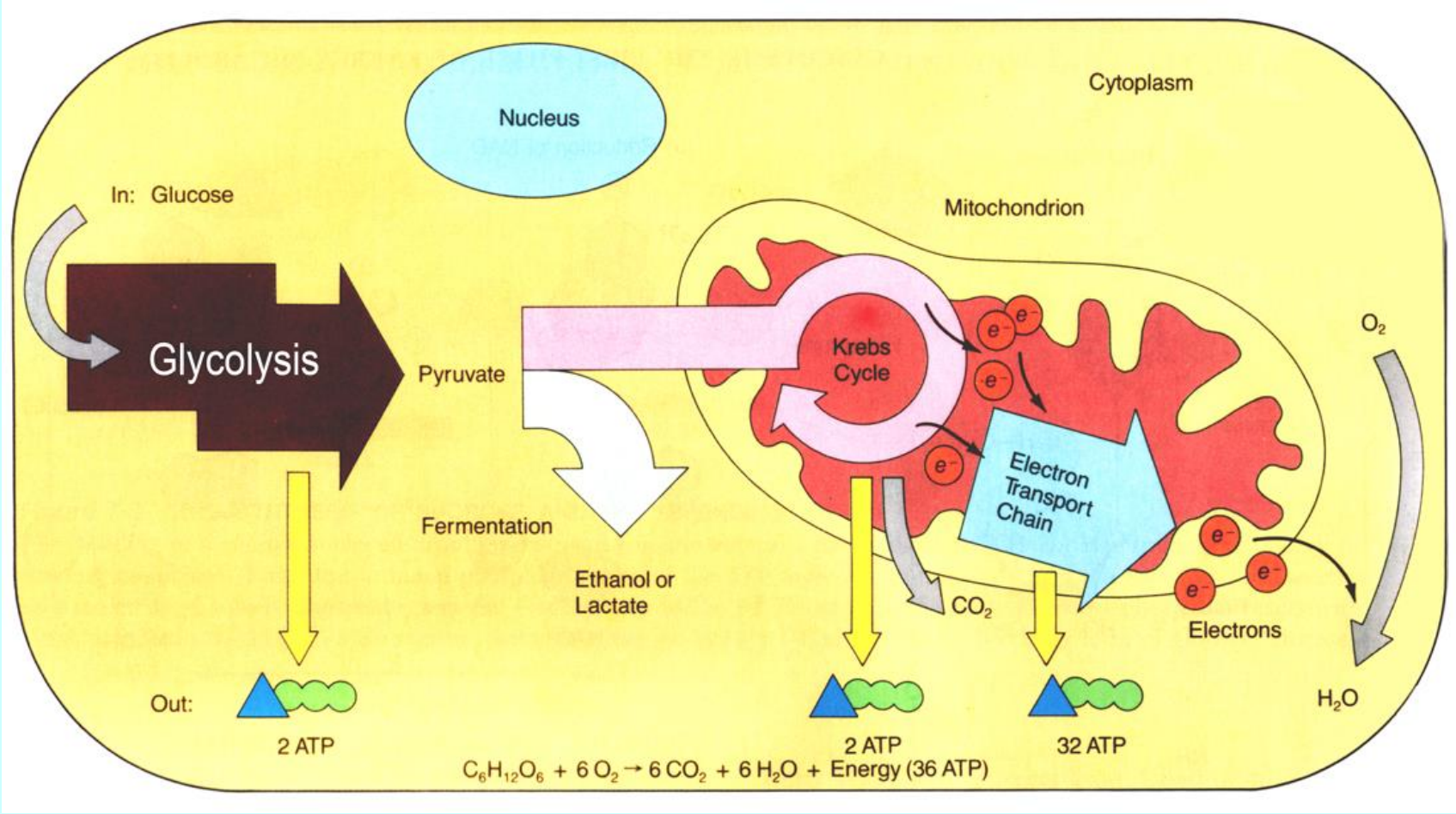
Metabolic Pathways Are Compartmentalized Within Cells – each compartment is dedicated to specialized metabolic functions, and the enzymes appropriate to these specialized functions are confined together within the organelle.



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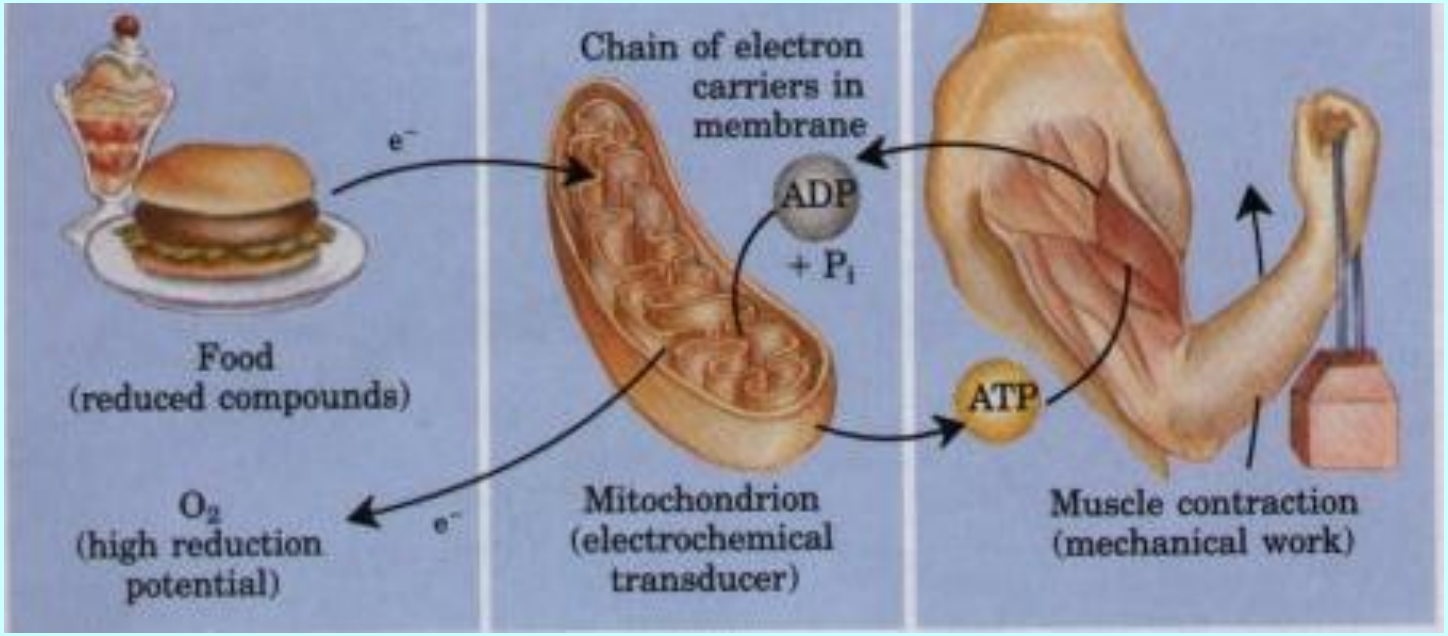
Bioenergetics is a term which describes the biochemical or metabolic pathways by which the cell ultimately obtains energy.

Living cells constantly perform work and thus require energy for the maintenance of highly organized structures, for the synthesis of cellular components, for movement, for the generation of electrical currents, for the production of light, and for many other processes. Bioenergetics is the quantitative study of energy relationships and energy conversions in biological systems.



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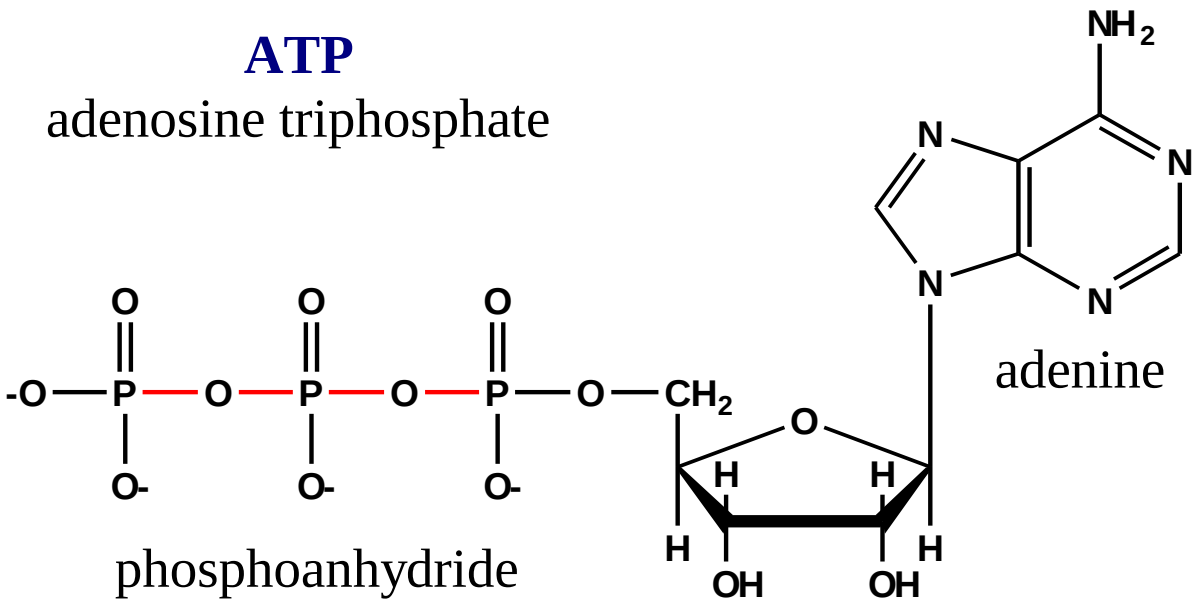
“High energy” bonds

ATP
adenosine triphosphate



Phosphoanhydride bonds (formed by splitting out H_2O between 2 phosphoric acids or between carboxylic & phosphoric acids) have a **large negative ΔG of hydrolysis**.

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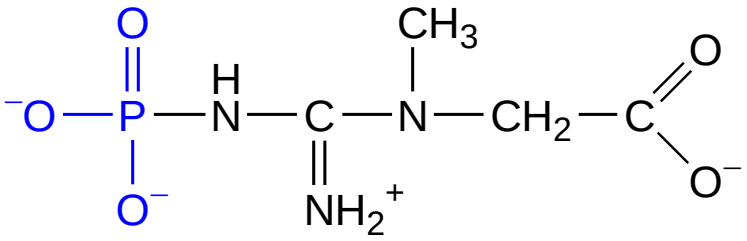
- **ATP** often serves as an **energy source**.

Hydrolytic **cleavage** of one or both of the "high energy" bonds of ATP is **coupled** to an energy-requiring (non-spontaneous) reaction.

- **AMP** functions as an **energy sensor** & **regulator** of metabolism.

Phosphocreatine (creatine phosphate), another compound with a "high energy" phosphate linkage, is used in nerve & muscle for **storage of ~P bonds**.



phosphocreatine

Creatine Kinase catalyzes:

Phosphocreatine + ADP ↔ ATP + creatine

This is a **reversible** reaction, though the equilibrium constant slightly favors phosphocreatine formation.

- Phosphocreatine is produced when ATP levels are high.
- When ATP is depleted during **exercise** in muscle, phosphate is transferred from phosphocreatine to ADP, to **replenish ATP**.

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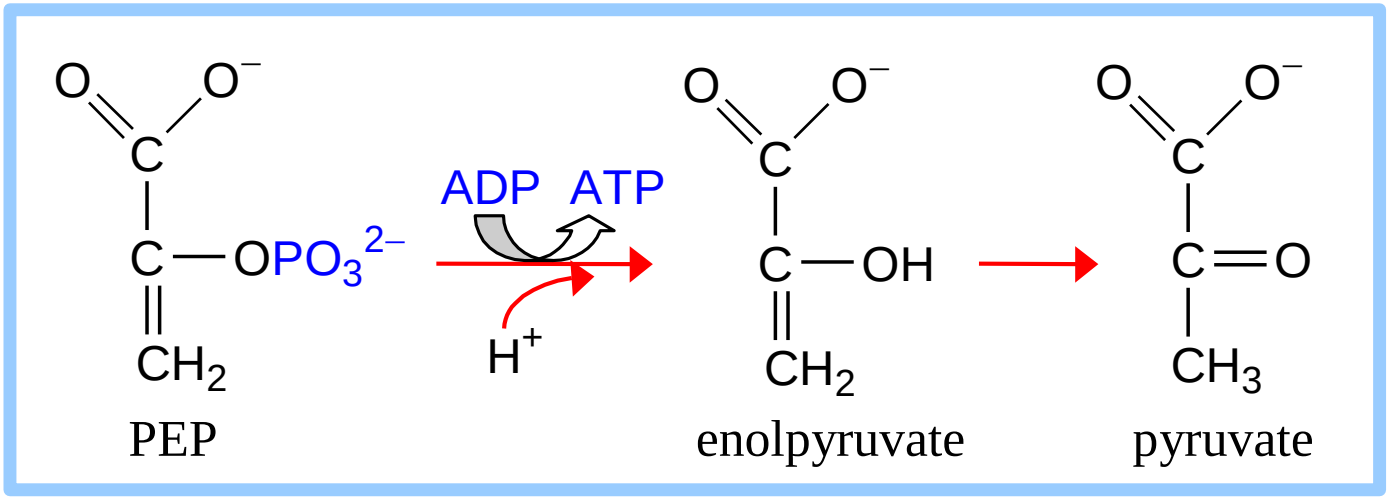

Phosphoenolpyruvate (PEP), involved in ATP synthesis in Glycolysis, has a very high ΔG of P_i hydrolysis.

Removal of P_i from ester linkage in PEP is spontaneous because the enol spontaneously converts to a ketone.

The ester linkage in PEP is an exception.

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ATP has special roles in energy coupling & P_i transfer.

ΔG of phosphate hydrolysis from ATP is **intermediate** among examples below.

ATP can thus act as a P_i donor, & ATP can be synthesized by P_i transfer, e.g., from PEP.

Compound	$\Delta G^{o'}$ of phosphate hydrolysis, kJ/mol
Phosphoenolpyruvate (PEP)	– 61.9
Phosphocreatine	– 43.1
Pyrophosphate	– 33.5
ATP (to ADP)	– 30.5
Glucose-6-phosphate	– 13.8
Glycerol-3-phosphate	– 9.2

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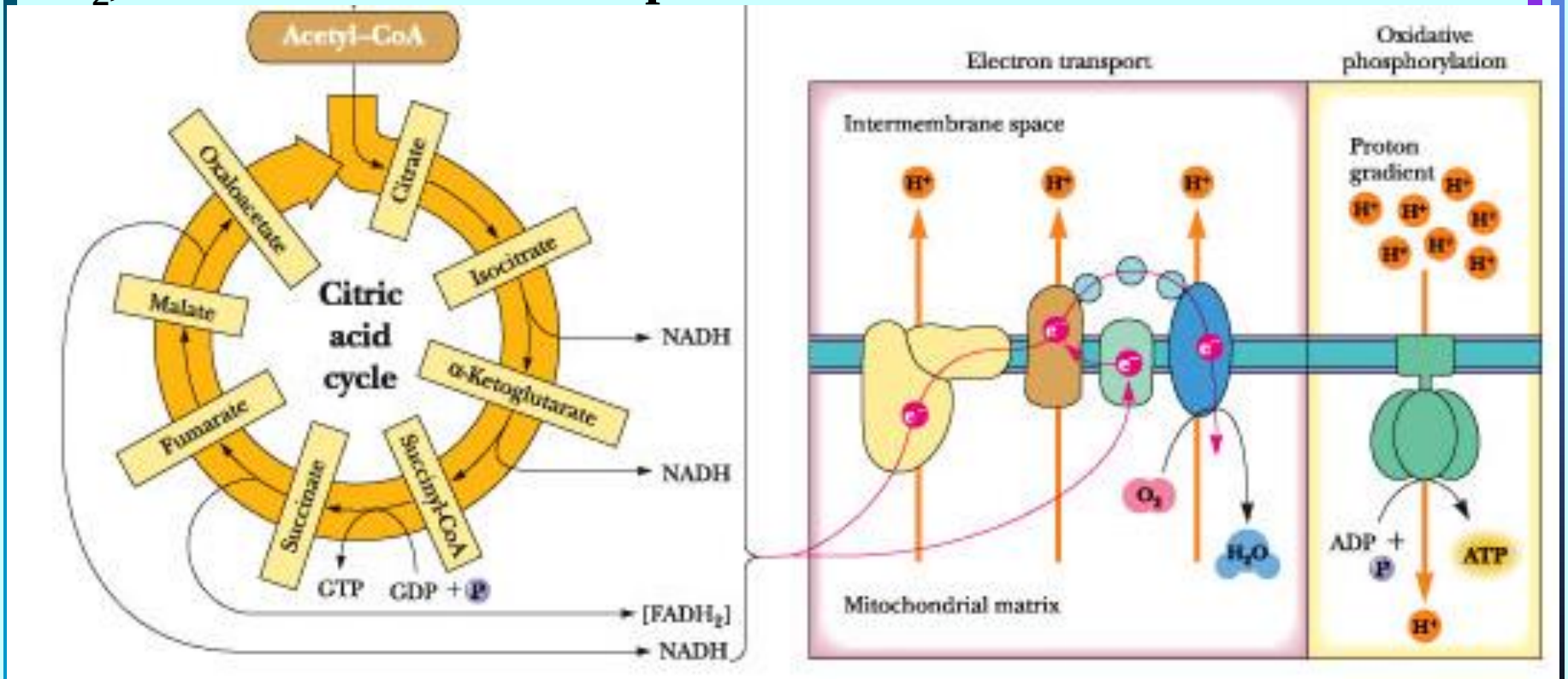
The Tricarboxylic Acid Cycle

Acetyl-coenzyme A is oxidized to CO_2 in the tricarboxylic acid (TCA) cycle (also called the citric acid cycle). The electrons liberated by this oxidative process are then passed through an elaborate, membrane-associated electron transport pathway to O_2, the final electron acceptor.



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Hans Krebs Discovered of the TCA Cycle

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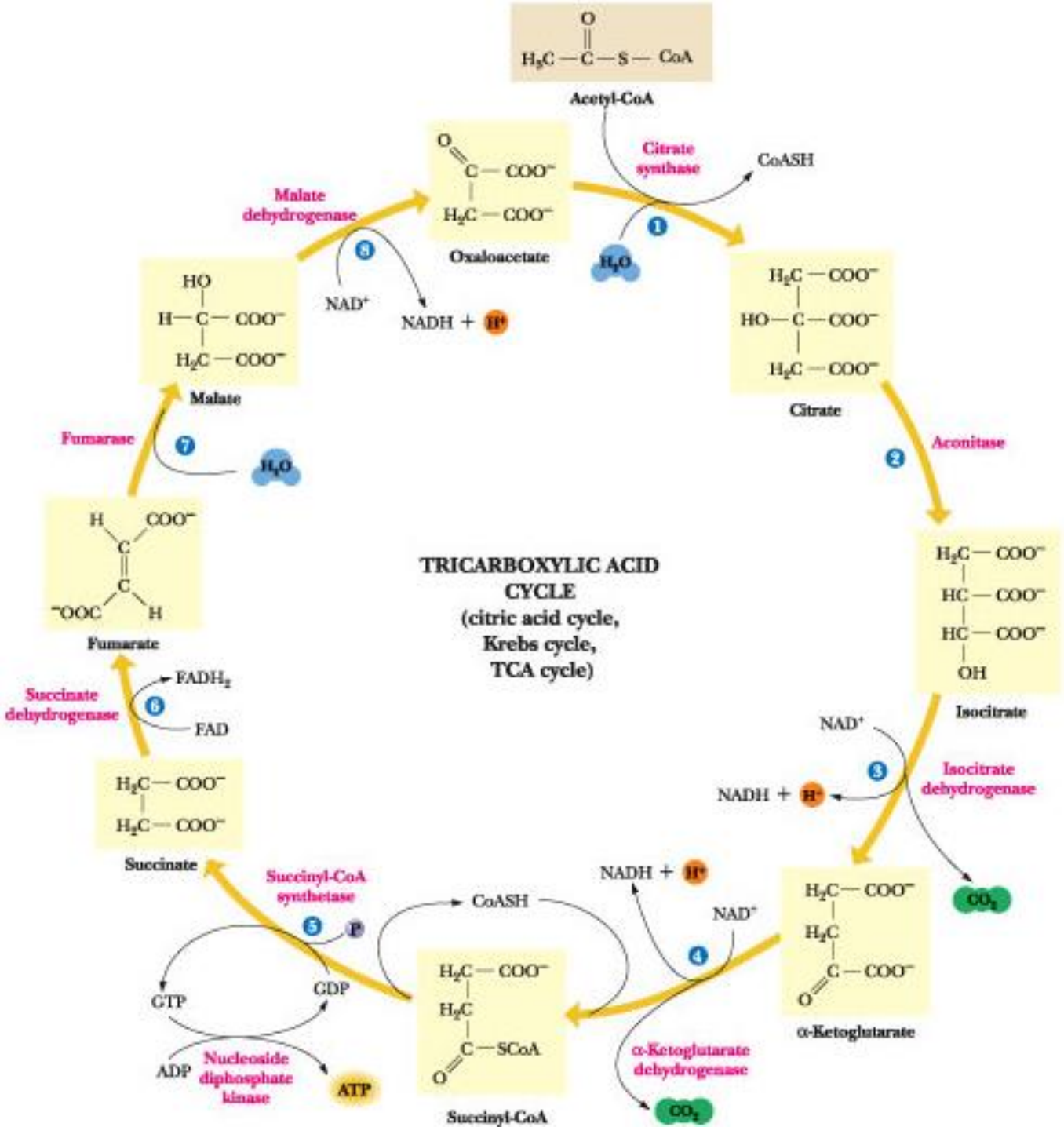

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A Summary of the Cycle

The net reaction accomplished by the TCA cycle, as follows, shows two molecules of CO_2, one ATP, and four reduced coenzymes produced per acetate group oxidized. The cycle is exergonic, with a net DG°' for one pass around the cycle of approximately -40kJ/mol.

$$\text{Acetyl-CoA} + 3\,NAD^+ + [FAD] + ADP + P_i + 2\,H_2O \rightleftharpoons$$
$$2\,CO_2 + 3\,NADH + 3\,H^+ + [FADH_2] + ATP + CoASH$$
$$\Delta G^{\circ\prime} = -40\ \text{kJ/mol}$$

BIOLOGICAL OXIDATION

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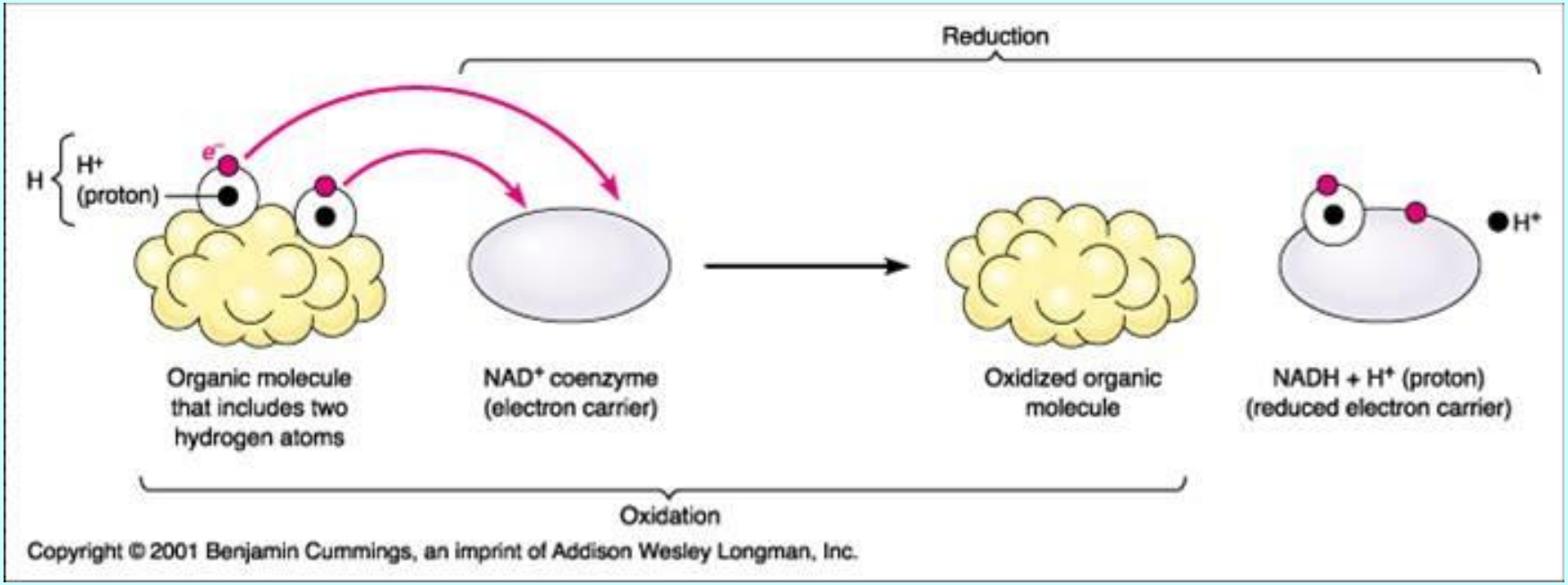
Biological oxidation - energy-producing reactions in living cells involving the transfer of hydrogen atoms or electrons from one molecule to another.

In many cases this is accomplished by the transfer of hydrogen atoms or electrons from one molecule (hydrogen or electron donor) to another (the acceptor).



The discovery in 1948 by Eugene Kennedy and Albert Lehninger that mitochondria are the site of oxidative phosphorylation in eukaryotes marked the beginning of the modern phase of studies of biological energy transductions.

Albert L. Lehninger
1917 - 1986

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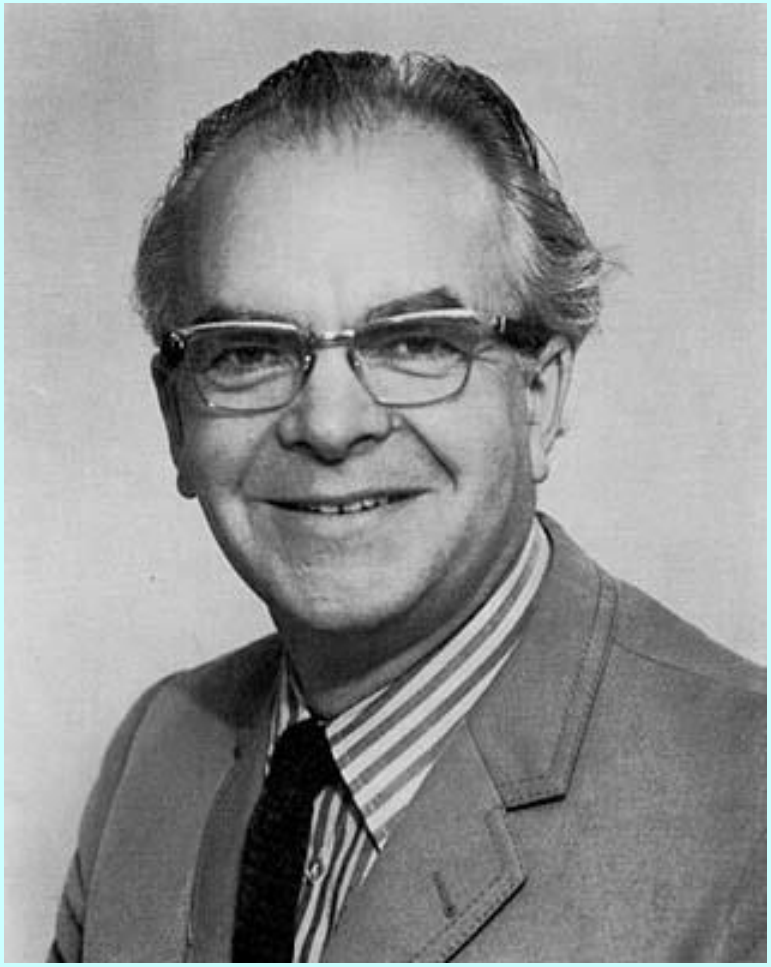
In the early 1960s Peter Mitchell suggested a new paradigm that has become central to current thinking and research on biological energy transductions.



Peter Mitchell
1920-1992

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The Nobel prize (Chemistry in 1997) for the determination of the detailed mechanism by which ATP shuttles energy was shared by:

Dr John Walker
(Cambridge)

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Dr Paul Boyer
(University of California)

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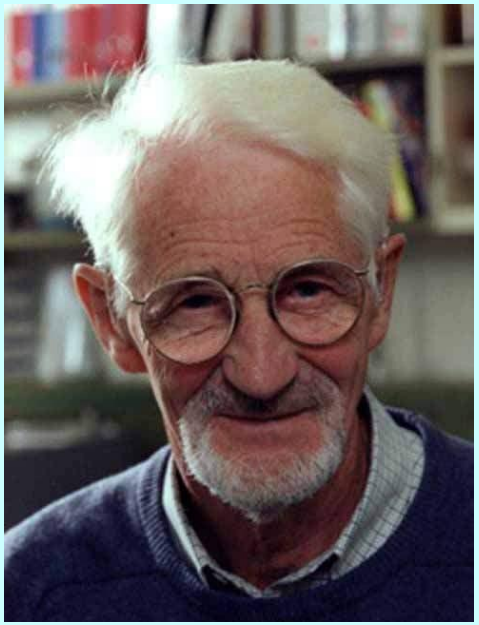
Dr Jens Skou
(Aarhus University)



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The enzyme which makes ATP is called ATP synthase, or ATPase, and sits on the mitochondria in animal cells or chloroplasts in plant cells.

Walker first determined the amino acid sequence of this enzyme, and then elaborated its 3 dimensional structure.

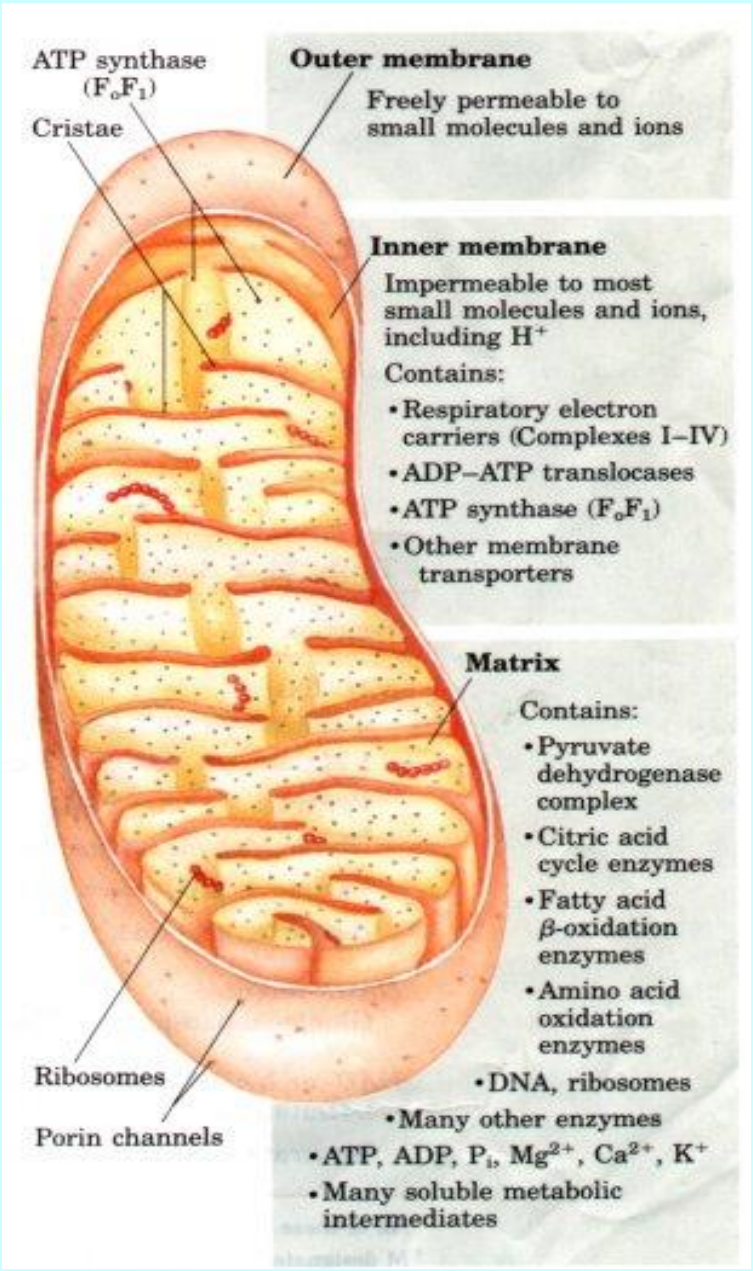
Boyer showed that contrary to the previously accepted belief, the energy requiring step in making ATP is not the synthesis from ADP and phosphate, but the initial binding of the ADP and the phosphate to the enzyme.

Skou was the first to show that this enzyme promoted ion transport through membranes, giving an explanation for nerve cell ion transport as well as fundamental properties of all living cells. He later showed that the phosphate group that is ripped from ATP binds to the enzyme directly. This enzyme is capable of transporting sodium ions when phosphorylated like this, but potassium ions when it is not.

Biochemical anatomy of a mitochondrion

The convolutions (cristae) of the inner membrane give it a very large surface area.

The mitochondrial pool of coenzymes and intermediates is functionally separate from the cytosolic pool. The mitochondria of invertebrates, plants, and microbial eukaryotes are similar to those shown here, althougl there is much variation in size, shape, and degree of convolution of the inner membrane.



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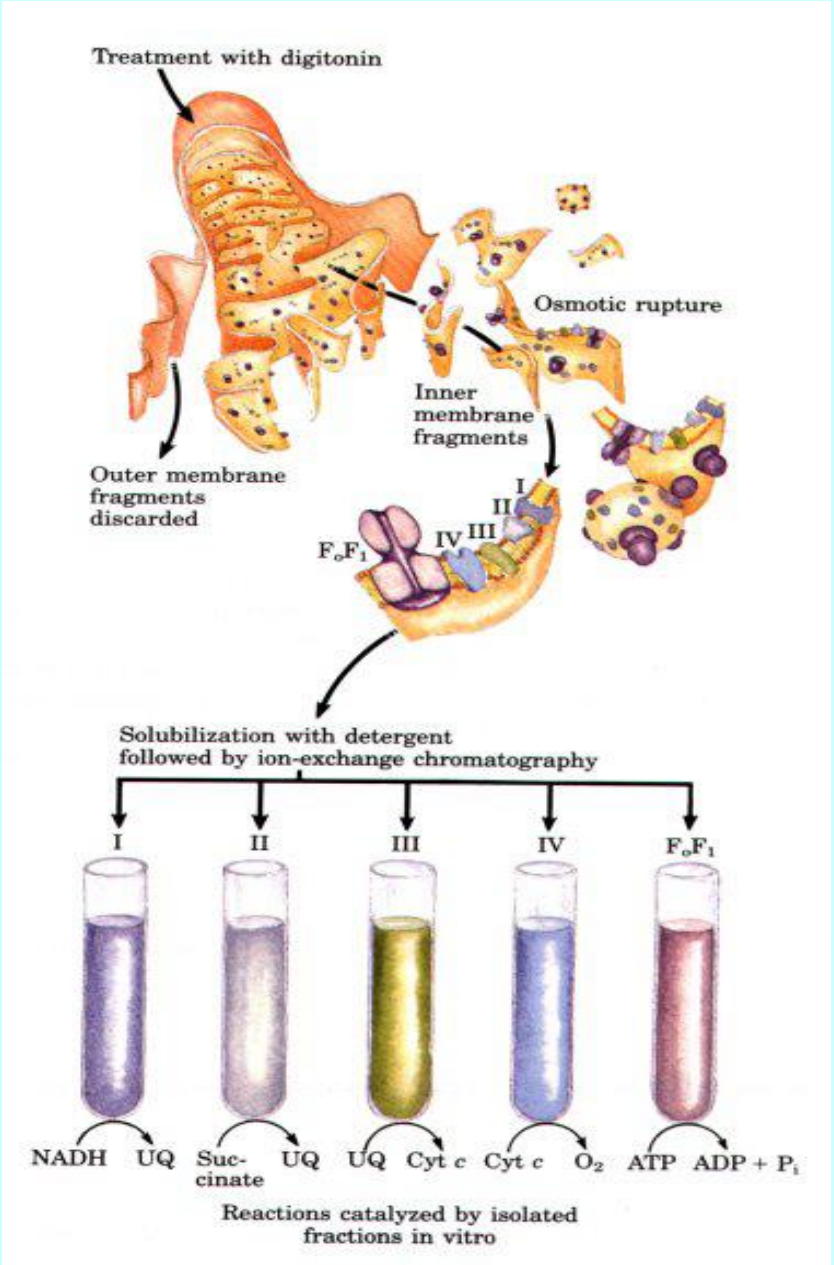
The resulting mixture of inner membrane proteins is resolved by ion-exchange chromatography into different complexes (I througl IV) of the respiratory chain, each with its unique protein composition , and the enzyme ATP synthase (sometimes called Complex V).



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The electron transport chain

(ETC, or respiratory chain, or electron transfer chain) - a sequence of electron-carrying proteins that transfer electrons from substrates to molecular oxygen in aerobic cells.

The metabolic energy from oxidation of food materials: sugars, fats, and amino acids is funneled into formation of reduced coenzymes (NADH) and reduced flavoproteins ($FADH_2$). The electron transport chain reoxidizes the coenzymes, and channels the free energy obtained from these reactions into the synthesis of ATP. This reoxidation process involves the removal of both protons and electrons from the coenzymes. Electrons move from NADH and [$FADH_2$] to molecular oxygen, O_2, which is the terminal acceptor of electrons in the chain.

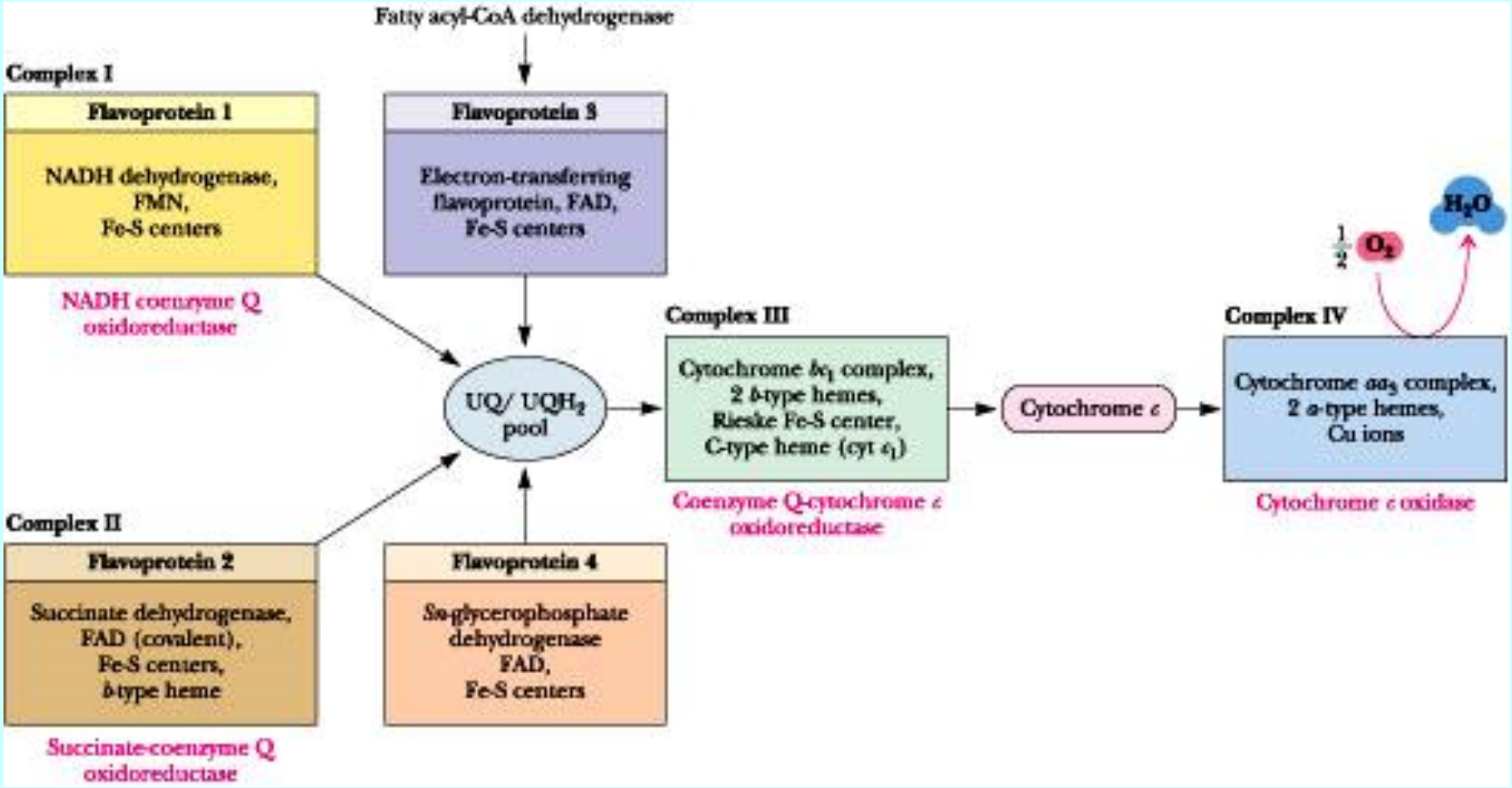
Solubilization of the membranes containing the electron transport chain results in the isolation of four distinct protein complexes, and the complete chain can thus be considered to be composed of four parts:

(I) NADH-coenzyme Q reductase,

(II) succinate-coenzyme Q reductase,

(III) coenzyme Q-cytochrome *c* reductase, and

(IV) cytochrome *c* oxidase.



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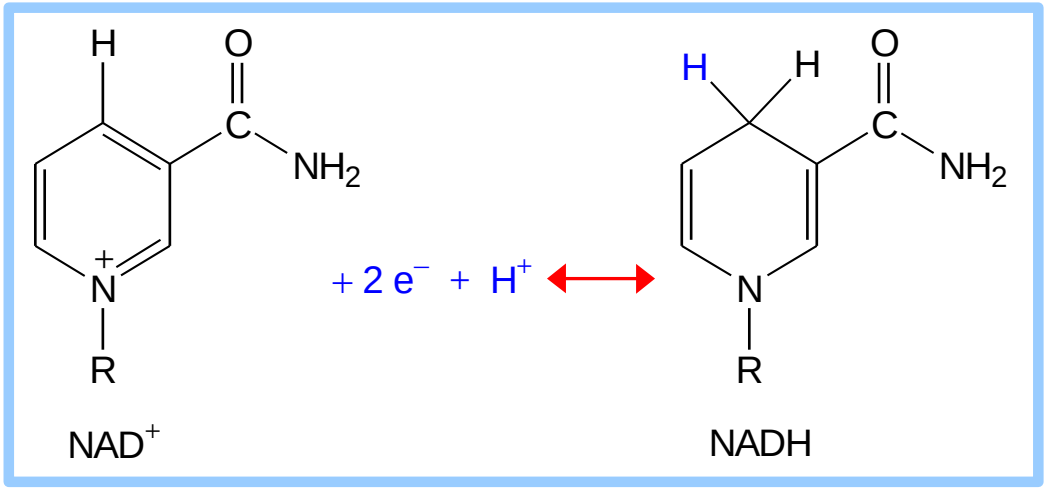
Complex I: NADH-Coenzyme Q Reductase

This complex transfers a pair of electrons from NADH to coenzyme Q (ubiquinine). Another common name for this enzyme complex is *NADH dehydrogenase*. The complex (with an estimated mass of 850 kD) involves more than 30 polypeptide chains, one molecule of flavin mononucleotide (FMN), and as many as seven Fe-S clusters, together containing a total of 20 to 26 iron atoms. By virtue of its dependence on FMN, NADH-UQ reductase is a *flavoprotein*.

$NAD^+/NADH$



The electron transfer reaction may be summarized as :

$NAD^+ + 2e^- + H^+ \leftrightarrow NADH.$

It may also be written as:

$NAD^+ + 2e^- + 2H^+ \leftrightarrow NADH + H^+$

$NADH + [\ FMN] + H^+ \rightarrow [FMNH_2] + NAD^+$

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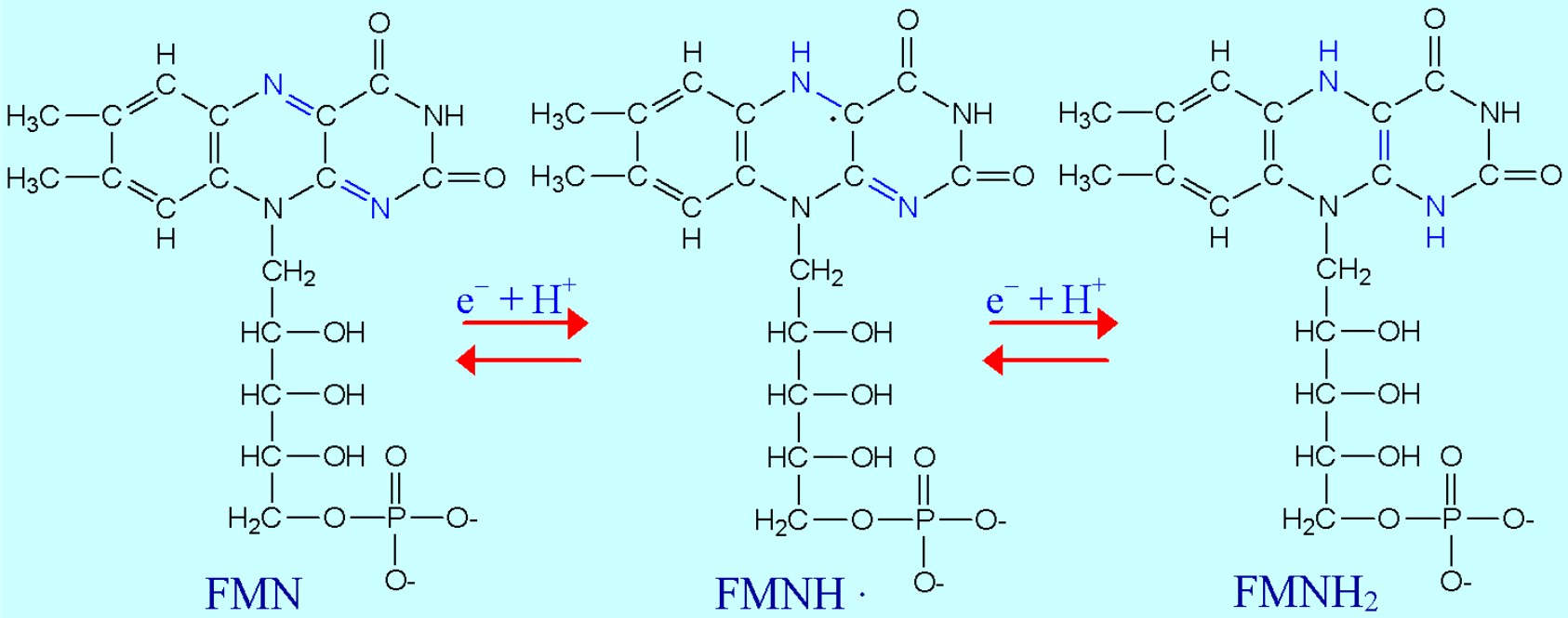

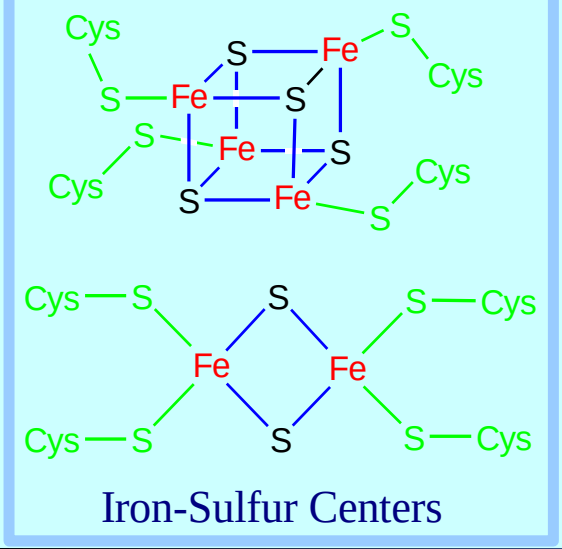

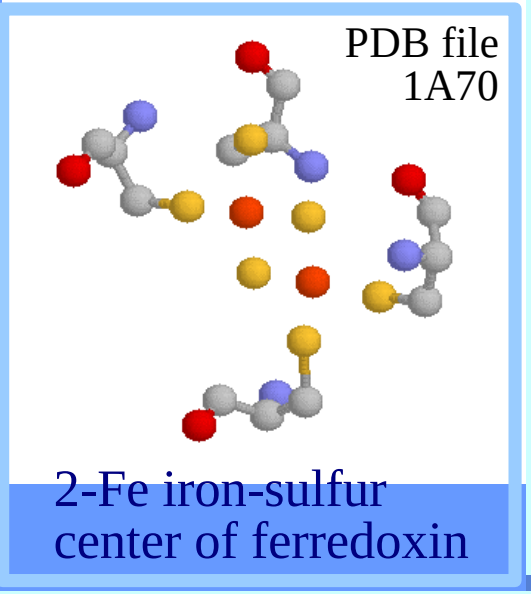

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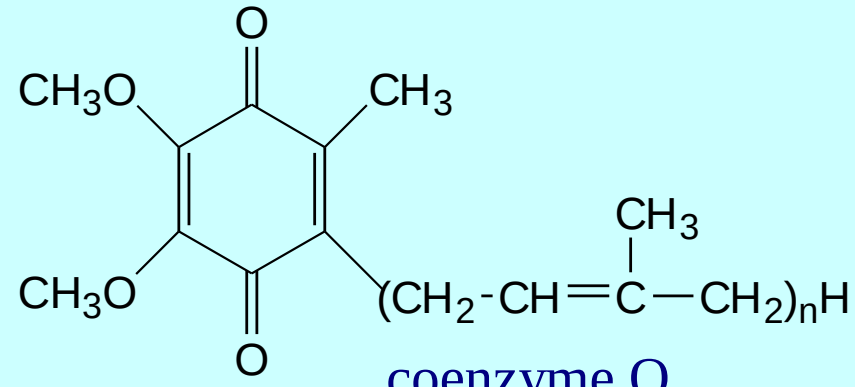
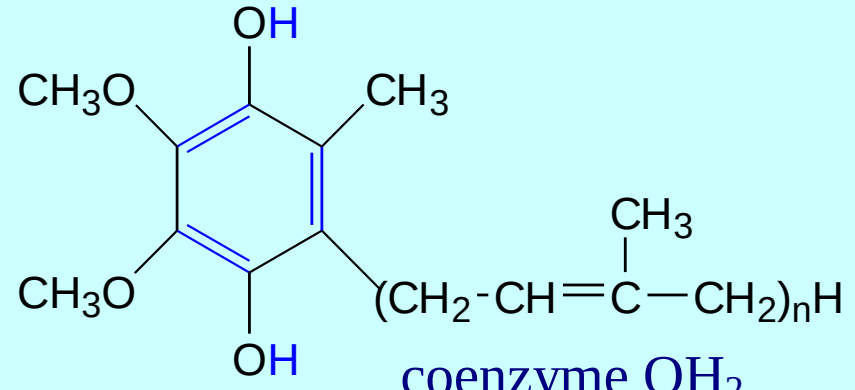
Coenzyme Q is a mobile electron carrier. Its isoprenoid tail makes it highly hydrophobic, and it diffuses freely in the hydrophobic core of the inner mitochondrial membrane. As a result, it shuttles electrons from Complexes I and II to Complex III.



coenzyme Q

$2\,e^- + 2\,H^+$



coenzyme QH_2

$NADH(H^+) + CoQ \rightarrow NAD^+ + CoQH_2$

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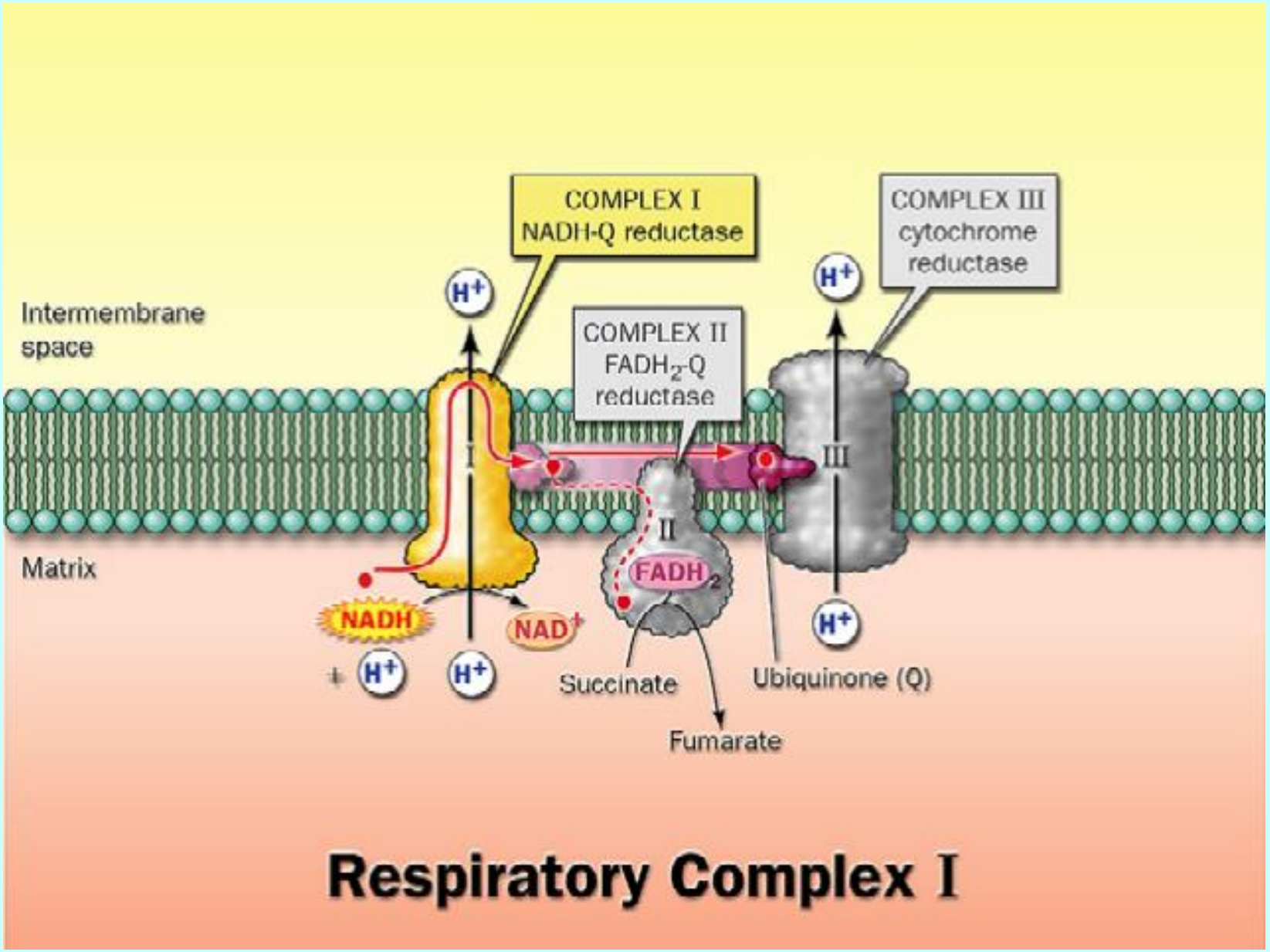

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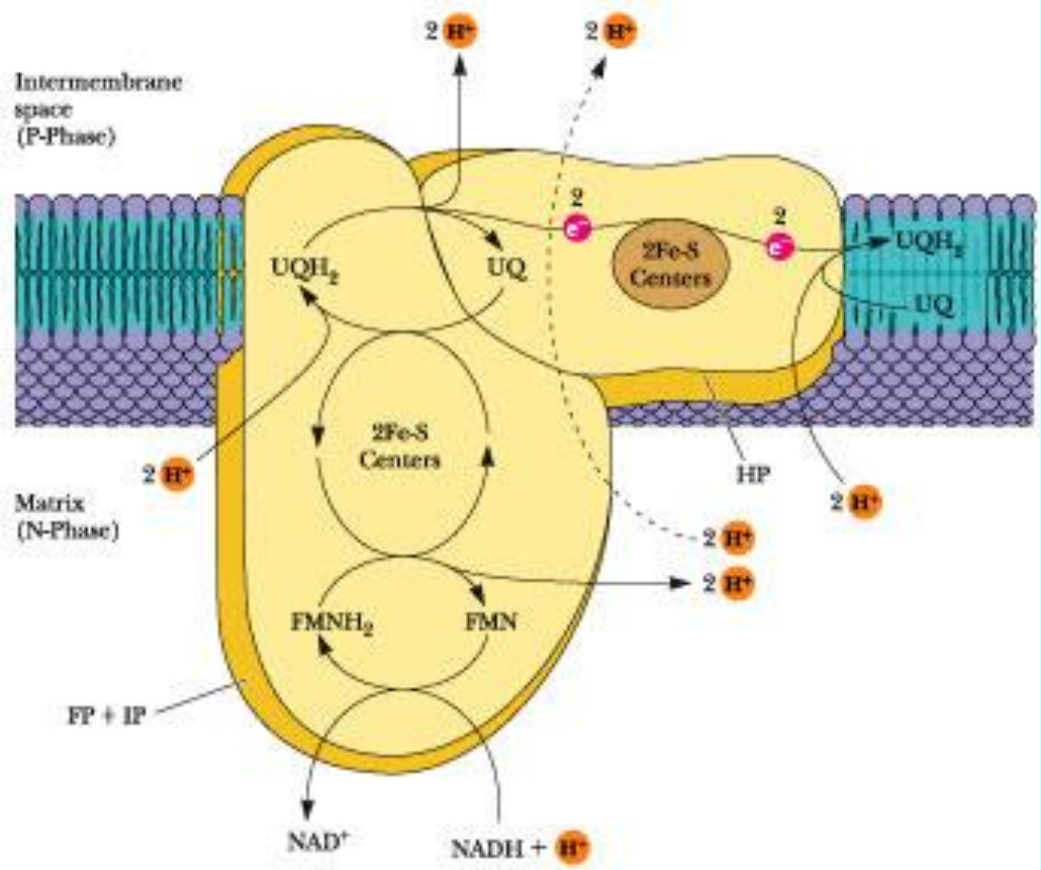
Complex I Transports Protons from the Matrix to the Cytosol

The oxidation of one NADH and the reduction of one UQ by NADH-UQ reductase results in the net transport of protons from the matrix side to the cytosolic side of the inner membrane.



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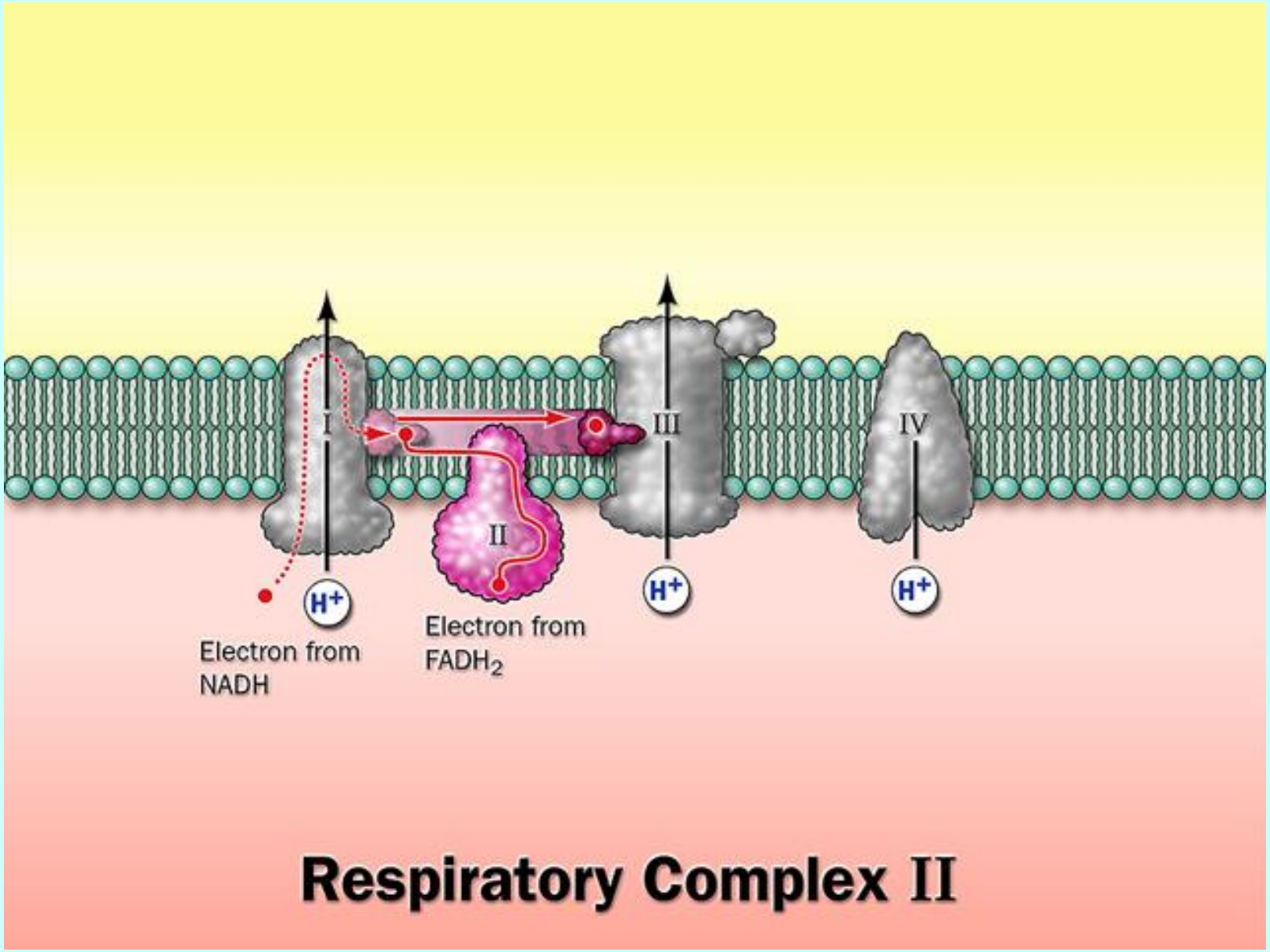
Complex II: Succinate-Coenzyme Q Reductase

- or succinate dehydrogenase. This enzyme has a mass of approximately 100 to 140 kD and is composed of four subunits: two Fe-S proteins of masses 70 kD and 27 kD, and two other peptides of masses 15 kD and 13 kD. Also known as *flavoprotein 2* (FP_2), it contains an FAD covalently bound to a histidine residue, and three Fe-S centers. When succinate is converted to fumarate in the TCA cycle, concomitant reduction of bound FAD to $FADH_2$ occurs in succinate dehydrogenase. This $FADH_2$ transfers its electrons immediately to Fe-S centers, which pass them on to UQ. Proton transport does not occur in this complex.

$$\text{Succinate} \rightarrow \text{fumarate} + 2\ H^+ + 2\ e^-$$

$$UQ + 2\ H^+ + 2\ e^- \rightarrow UQH_2$$



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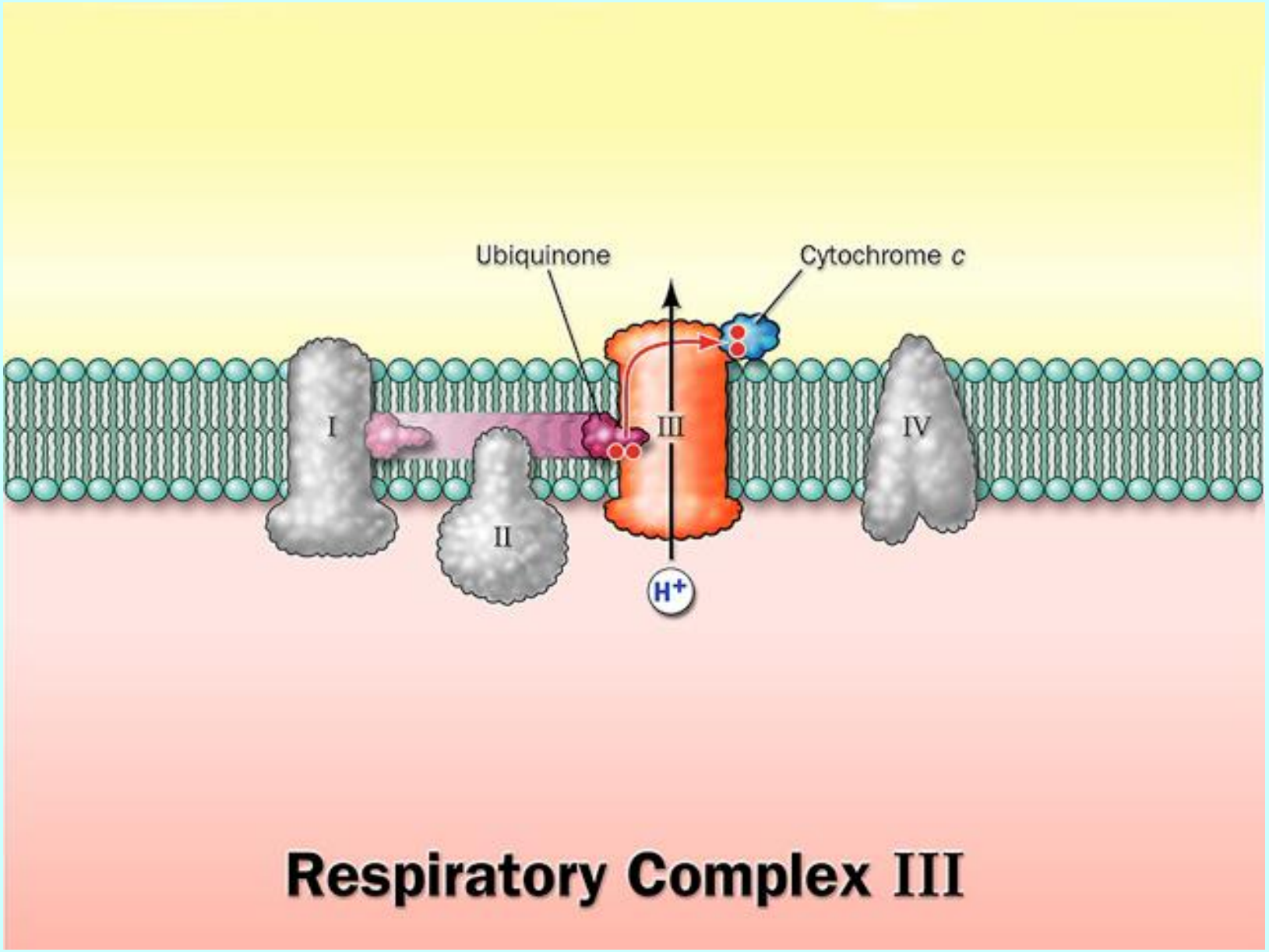
Complex III: Coenzyme Q-Cytochrome *c* Reductase

Reduced coenzyme Q (UQH_2) passes its electrons to cytochrome *c* via a unique redox pathway known as the Q cycle. *UQ-cytochrome c reductase* (UQ-cyt *c* reductase), as this complex is known, involves three different cytochromes and an Fe-S protein. In the cytochromes of these and similar complexes, the iron atom at the center of the porphyrin ring cycles between the reduced Fe^{2+} (ferrous) and oxidized Fe^{3+} (ferric) states.

$$CoQH_2 + \text{cyt.c}(Fe^{3+}) \rightarrow CoQ + \text{cyt.c}(Fe^{2+})$$



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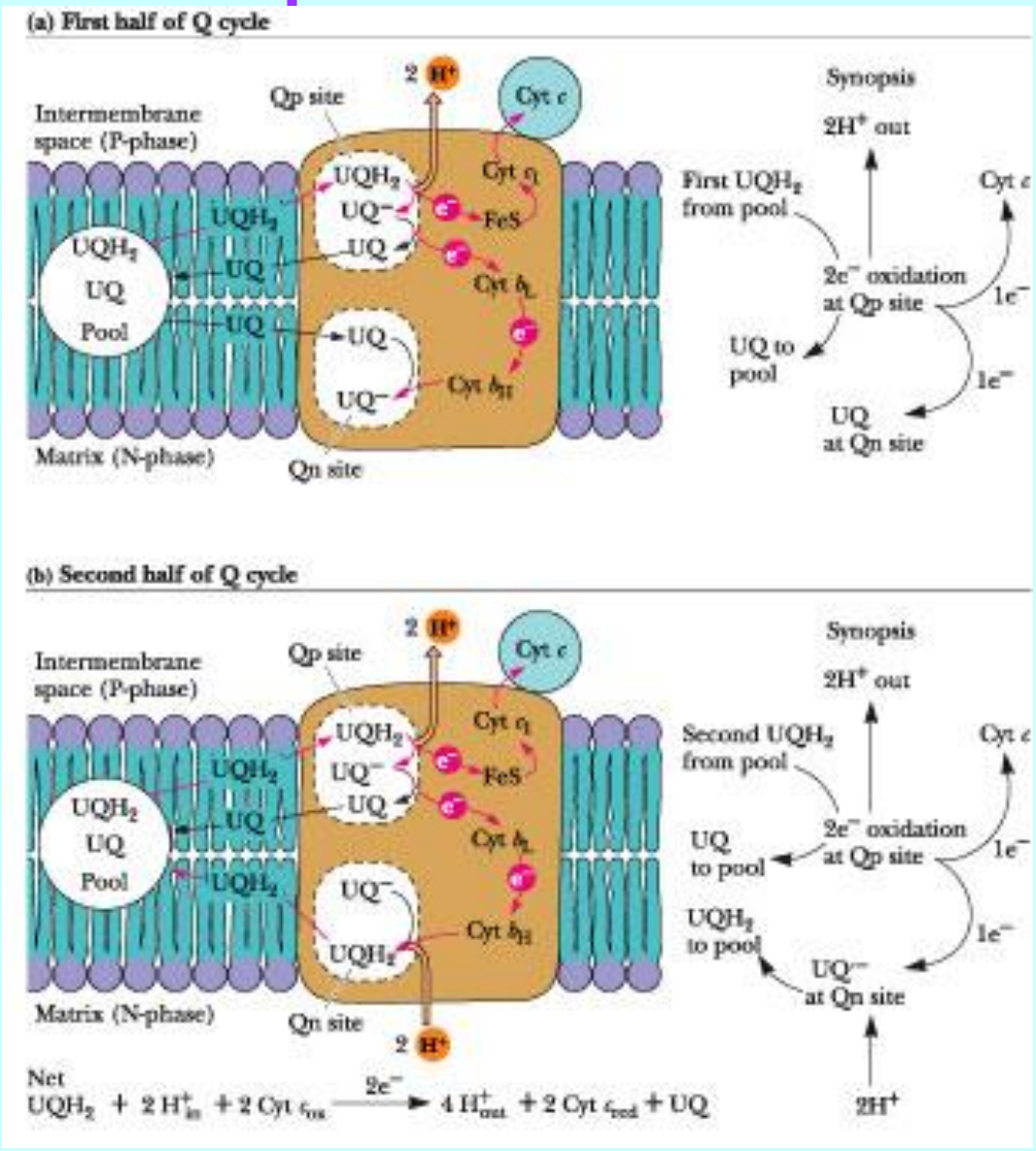
Complex III Drives Proton Transport



The Q cycle in mitochondria.

(a) The electron transfer pathway following oxidation of the first UQH_2 at the Q_p site near the cytosolic face of the membrane.

(b) The pathway following oxidation of a second UQH_2.

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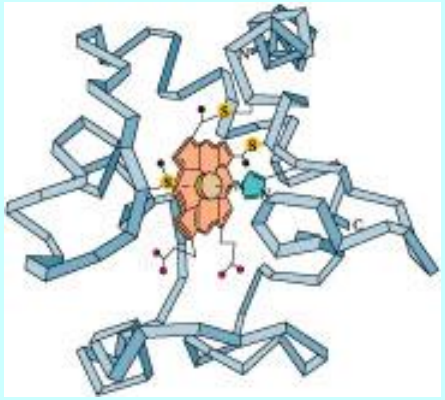
Cytochrome c Is a Mobile Electron Carrier

Electrons traversing Complex III are passed through cytochrome c_1 to cytochrome c. Cytochrome c is the only one of the cytochromes that is water-soluble.



Cytochrome c, like UQ, is a mobile electron carrier. It associates loosely with the inner mitochondrial membrane (in the intermembrane space on the cytosolic side of the inner membrane) to acquire electrons from the Fe-S-cyt c_1 aggregate of Complex III, and then it migrates along the membrane surface in the reduced state, carrying electrons to cytochrome c oxidase, the fourth complex of the electron transport chain.

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Complex IV: Cytochrome c Oxidase

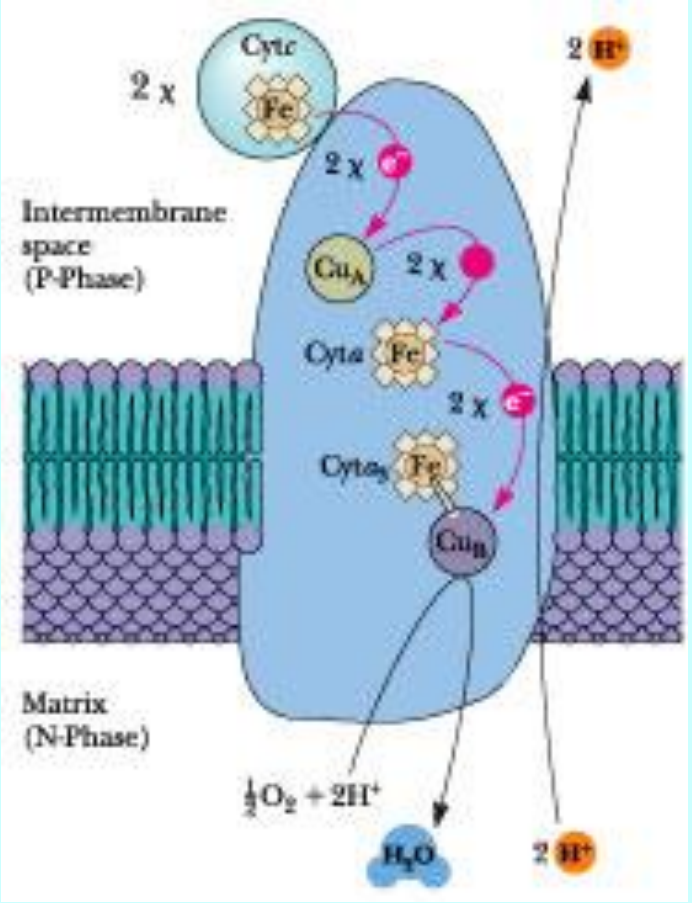
Complex IV is called cytochrome c oxidase because it accepts electrons from cytochrome c and directs them to the four-electron reduction of O_2 to form H_2O.

Thus, O_2 and cytochrome c oxidase are the final destination for the electrons derived from the oxidation of food materials.

Cytochrome *c* oxidase contains two heme centers (cytochromes *a* and a_3) as well as two copper atoms.

$$4 \text{ cyt c } (Fe^{2+}) + 4\ H^+ + O_2 \rightarrow 4 \text{ cyt c } (Fe^{3+}) + 2\ H_2O$$

The electron transfer pathway for cytochrome oxidase. Cytochrome c binds on the cytosolic side, transferring electrons through the copper and heme centers to reduce O_2 on the matrix side of the membrane.



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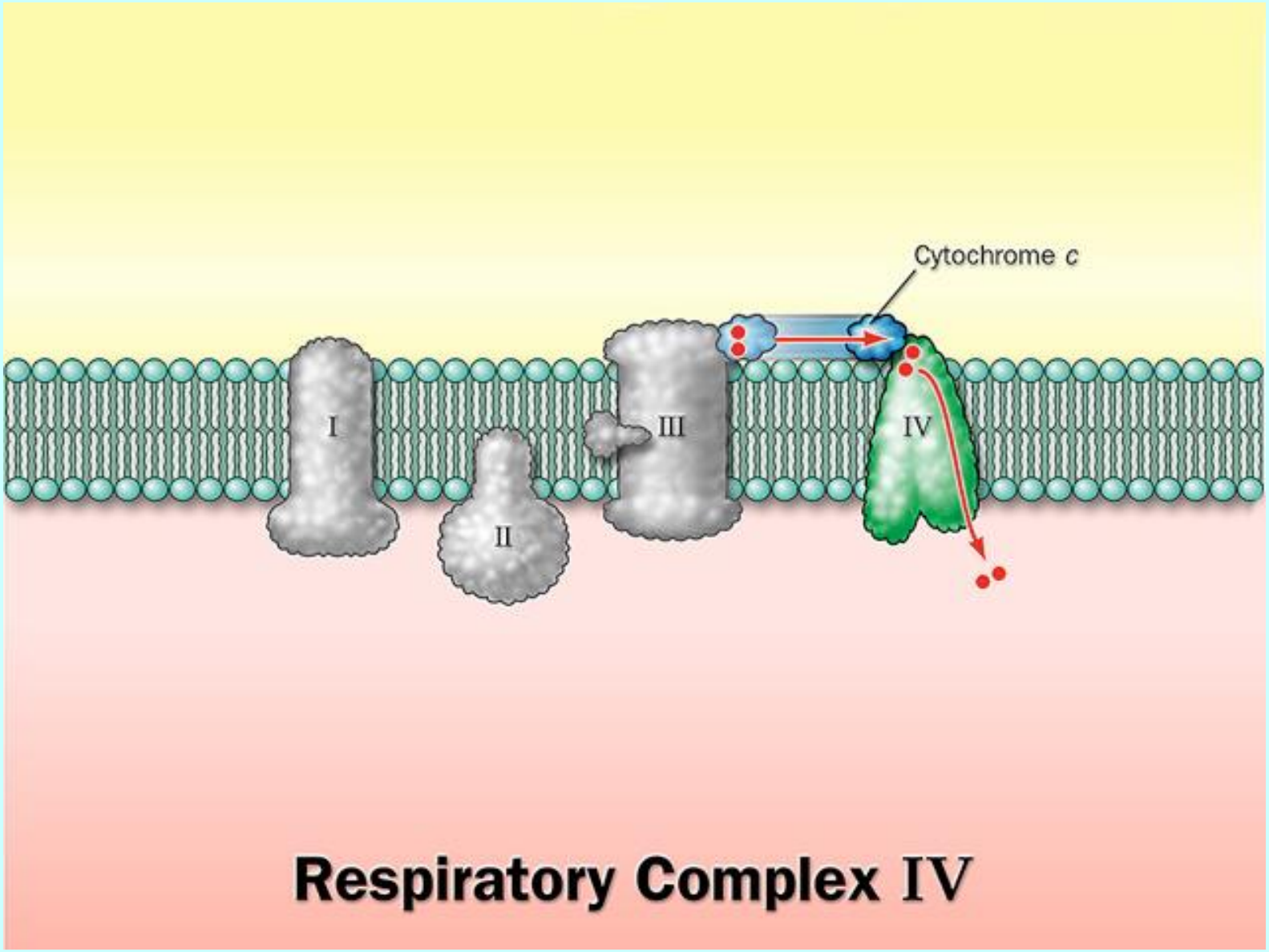

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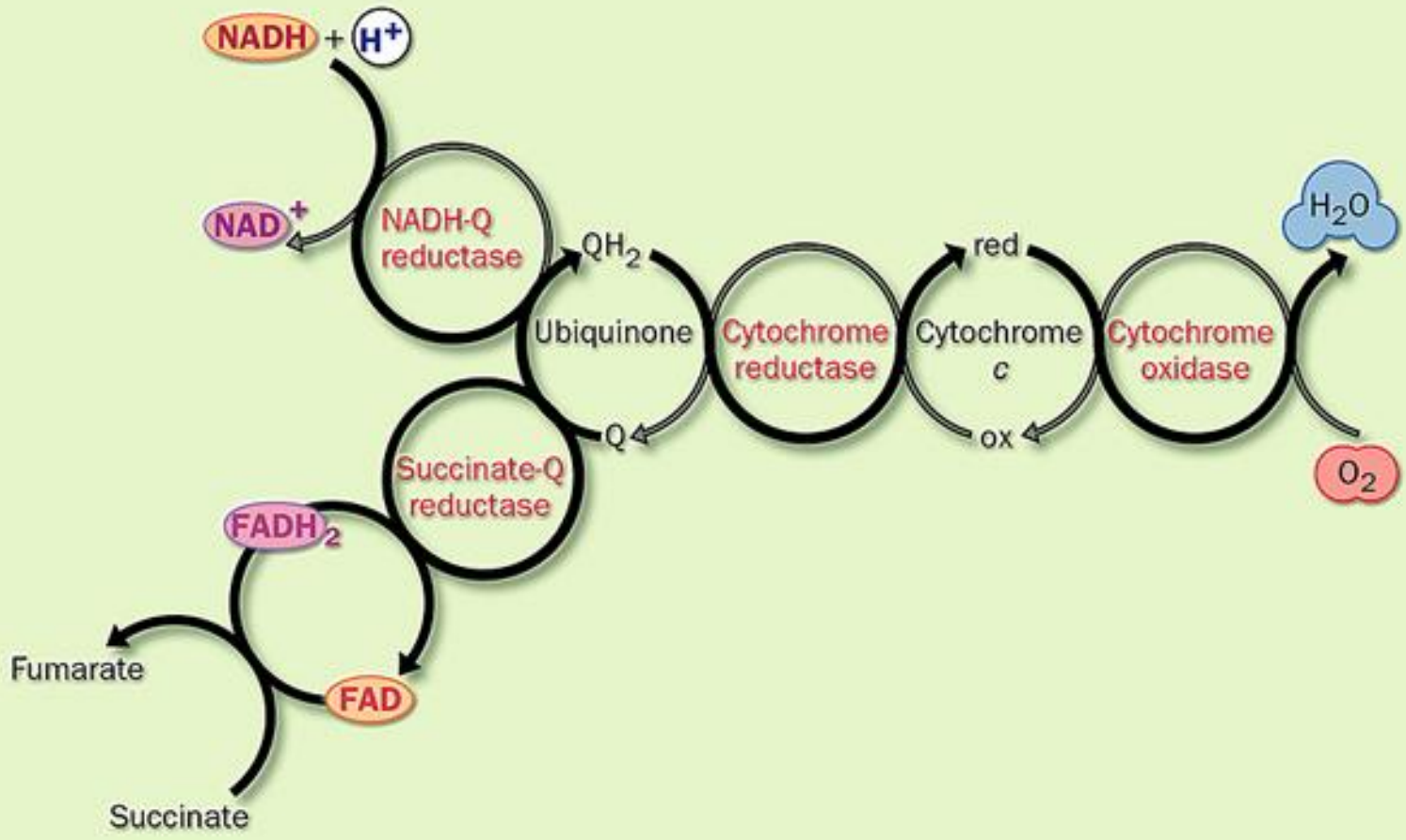
Complex IV Also Transports Protons Across the Inner Mitochondrial Membrane

The reduction of oxygen in Complex IV is accompanied by transport of protons across the inner mitochondrial membrane. Transfer of four electrons through this complex drives the transport of approximately four protons. Four protons are taken up on the matrix side for every two protons transported to the cytoplasm.



Respiratory Chain

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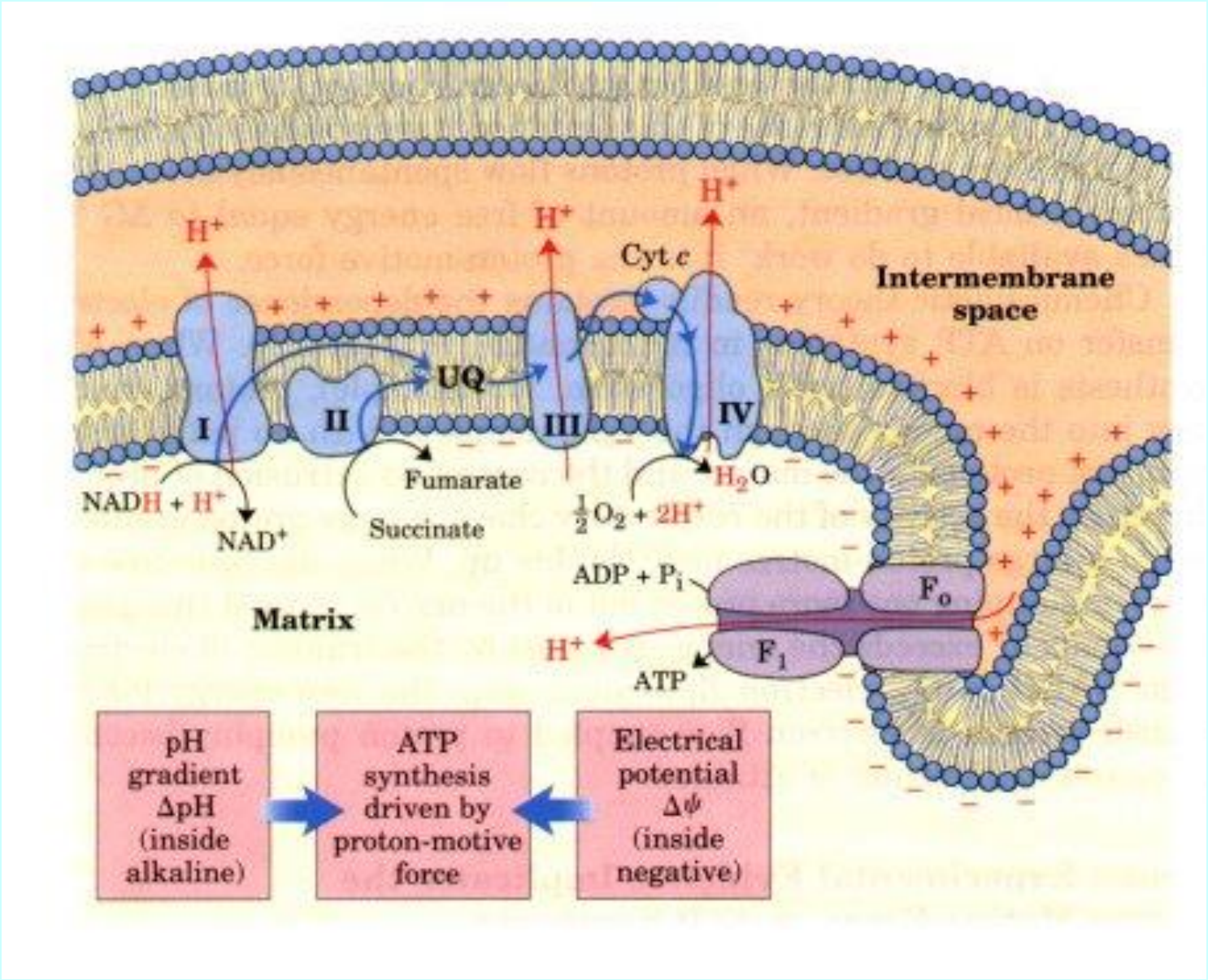
Oxidative phosphorilation,

the process whereby the energy generated by the ETC is conserved by the phosphorilation of ADP to yield ATP.

According to the chemiosmotic coupling theory a mechanism by which the free energy generated during electron transport is utilized to drave ATP synthesis has the following principal features:

1. **As electrons pass through the ETC, protons are transported from the matrix and released into the inner membrane space. As a result, an electrical potential and proton gradient are created across the inner membrane. The electrochemical proton gradient is sometimes referred to as the proton motive force.**
2. **Protons, which are present in the inner membrane space in great excess, can pass through the inner membrane and back into the matrix down their concentration gradient only through special channels. (Recall that the inner membrane itself is impermeable to protons.) As protons pass through a channel, each of which contains an ATP synthase activity, ATP synthesis occurs.**



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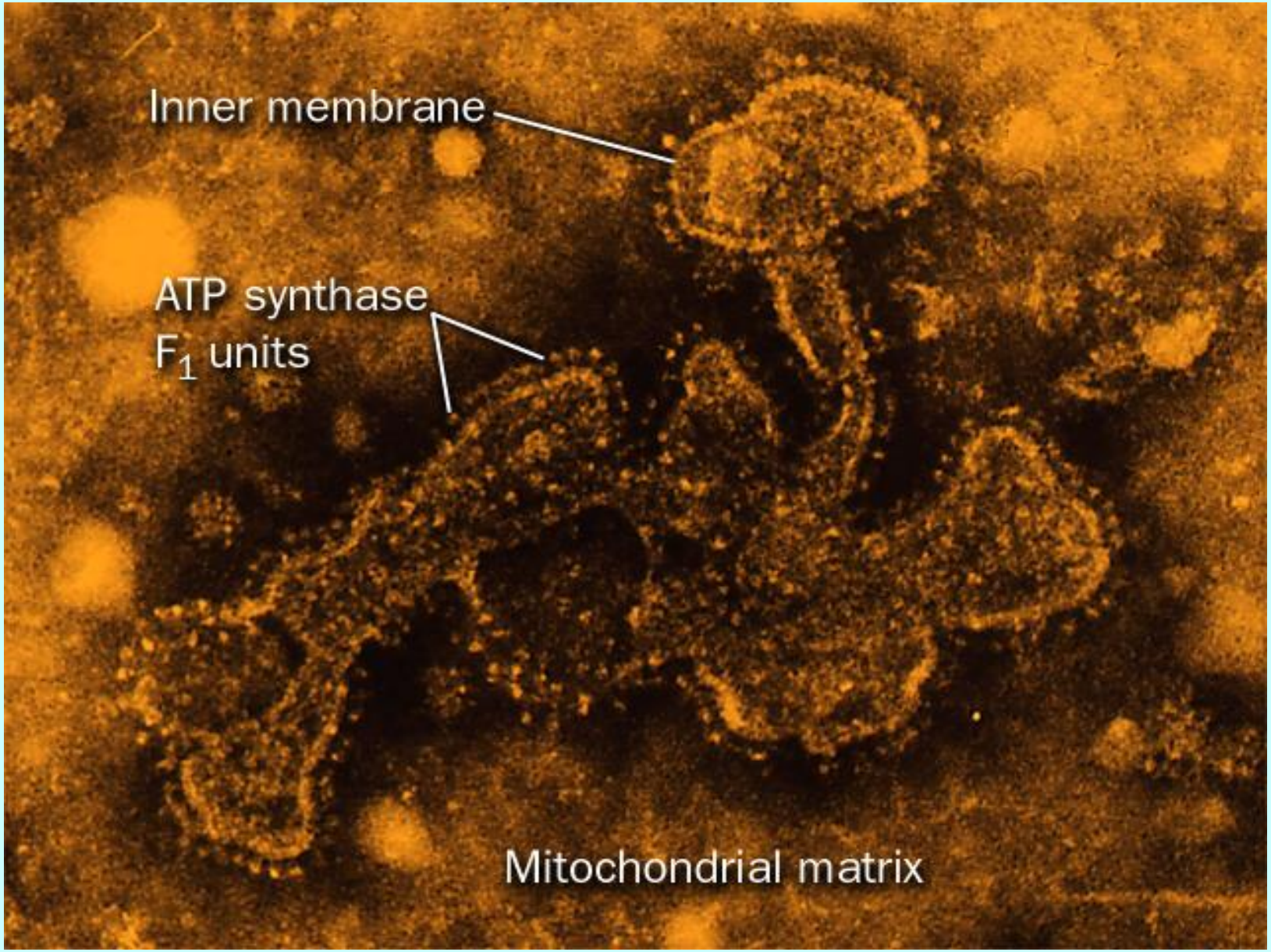
ATP Synthase

The mitochondrial complex that carries out ATP synthesis is called ATP synthase or sometimes F_1F_0-ATPase (for the reverse reaction it catalyzes).

ATP synthase was observed in early electron micrographs of submitochondrial particles (prepared by sonication of inner membrane preparations) as round, 8.5-nm-diameter projections or particles on the inner membrane. In micrographs of native mitochondria, the projections appear on the matrix-facing surface of the inner membrane.



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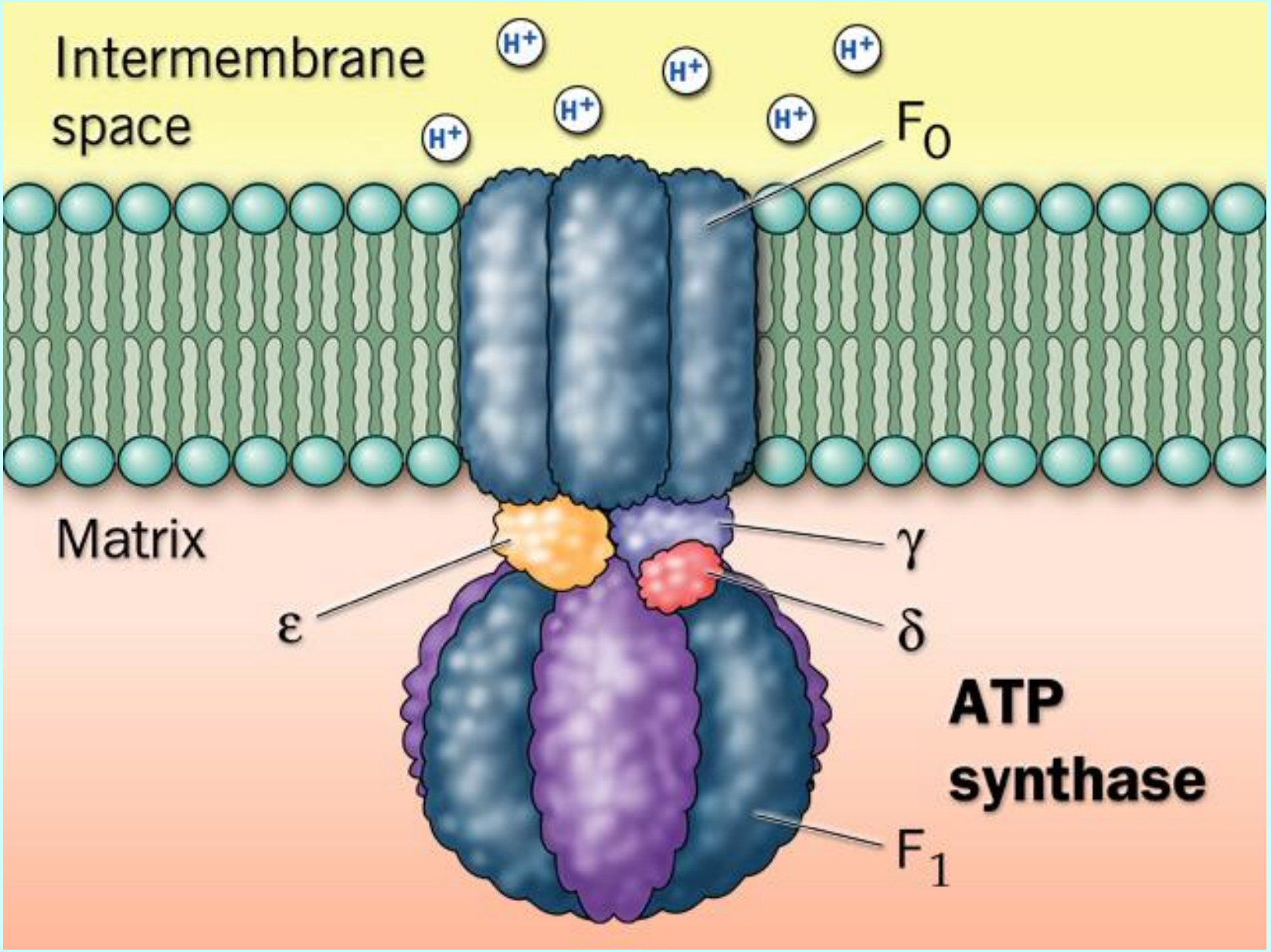

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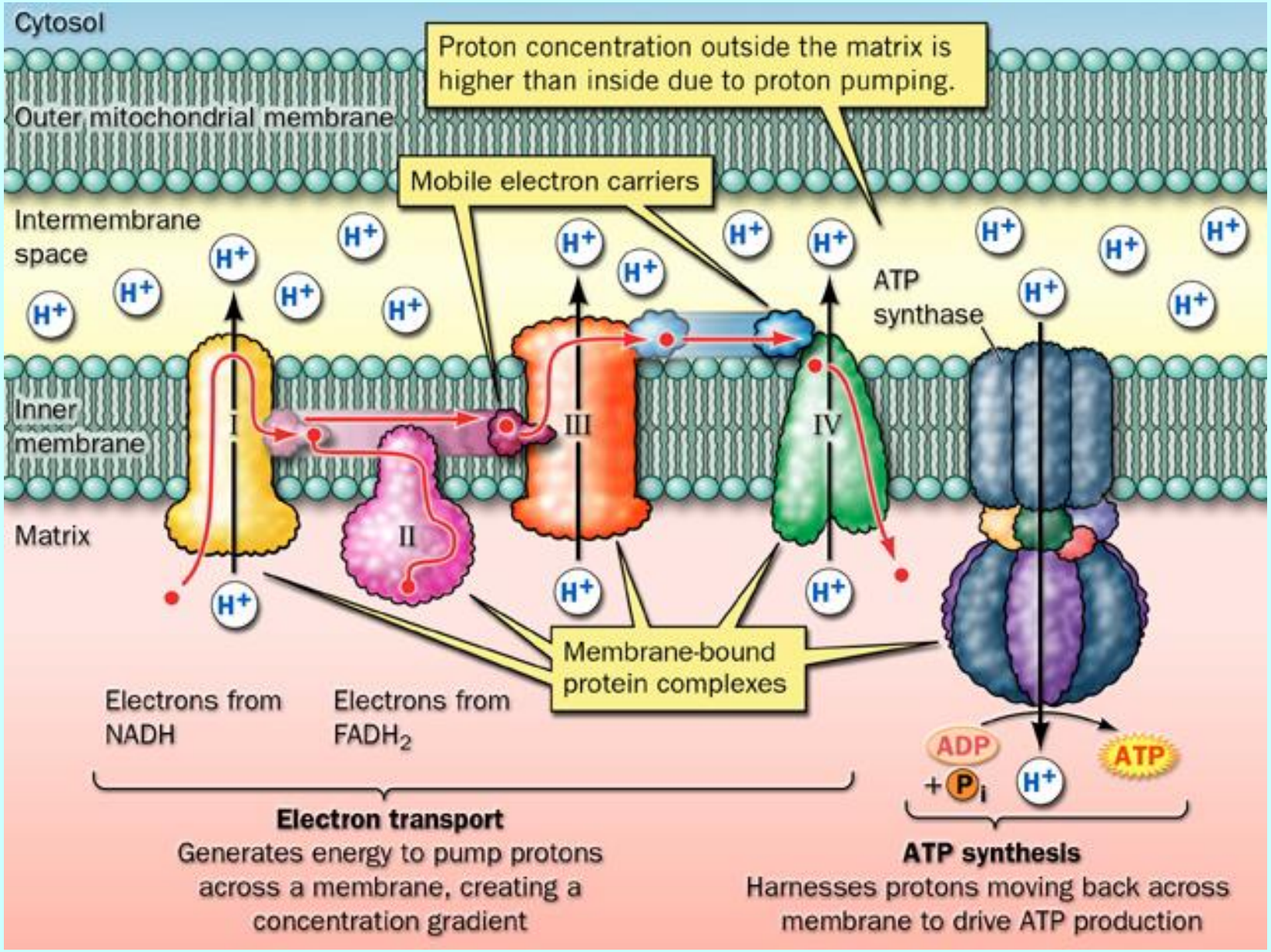
The flow of electrons through Complexes I, III, and IV results in the pumping of protons across the mitochondrial inner membrane, making the matrix alkaline relative to the extramitochondrial space. This proton gradient provides the energy (proton-motive force) for ATP synthesis from ADP and Pi by an inner-membrane protein complex, ATP synthase.



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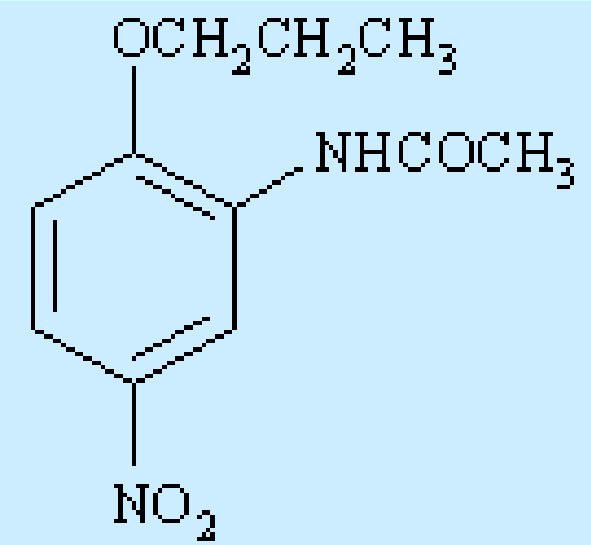
Inhibitors of Dehydrogenases



Isoniaside

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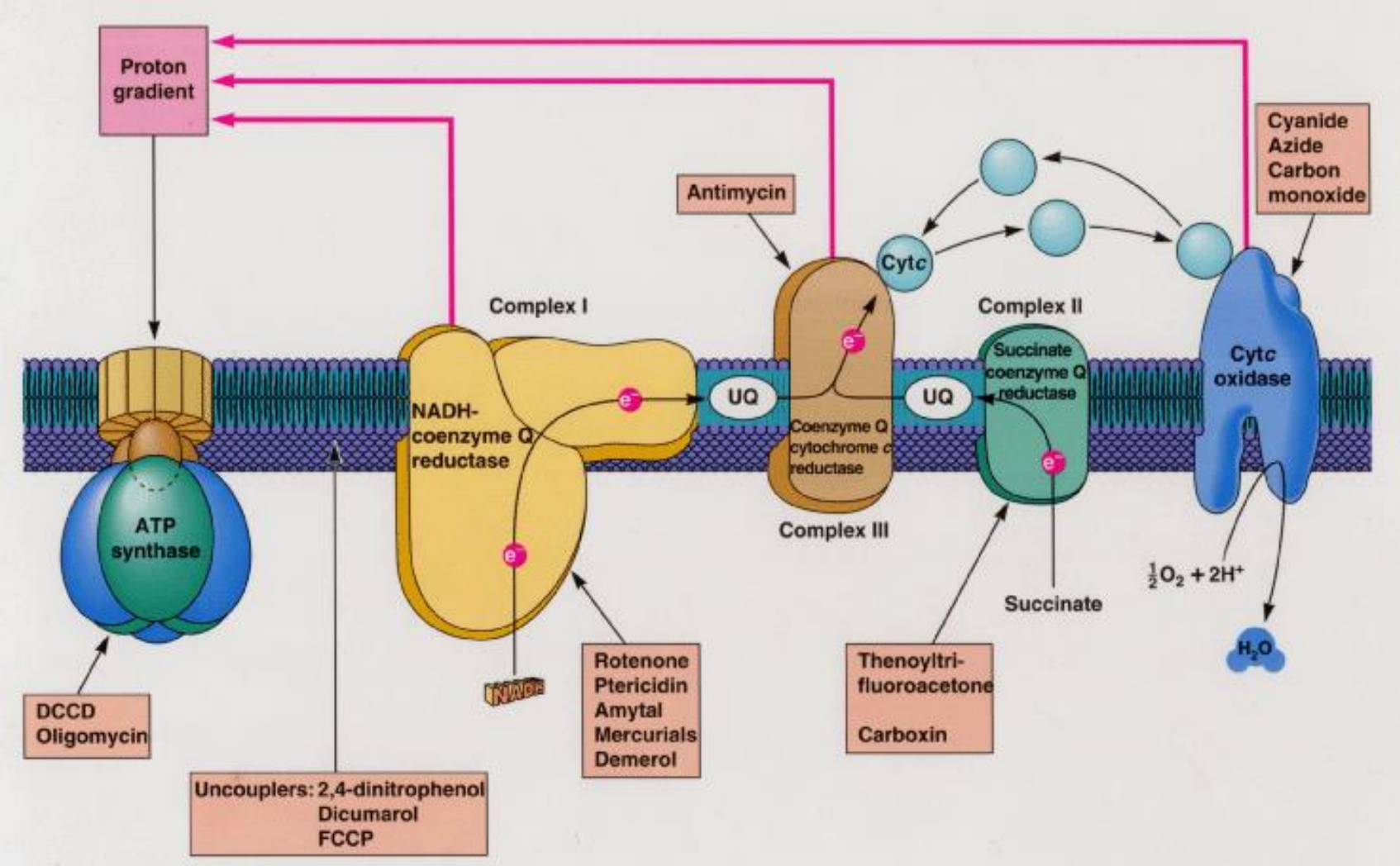
Inhibitors of electron transport and/or oxidative phosphorylation.



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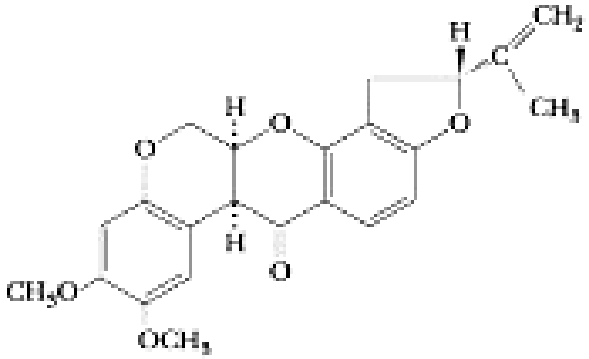
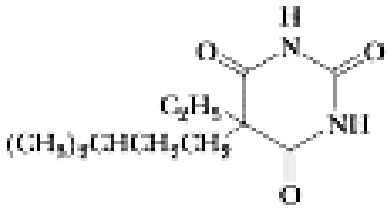
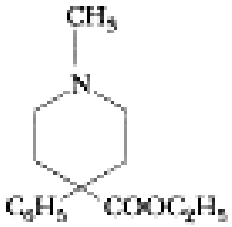


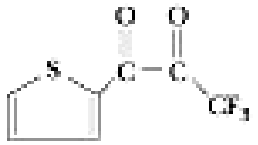
Rotenone



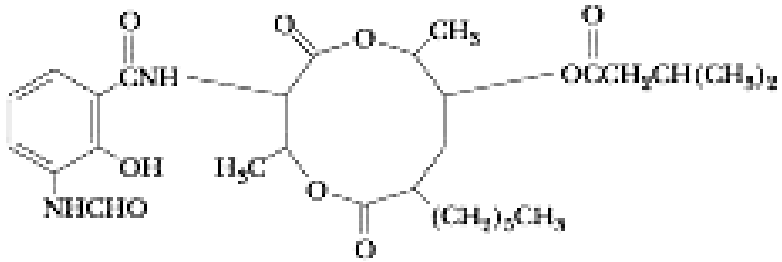
Amytal
(amobarbital)



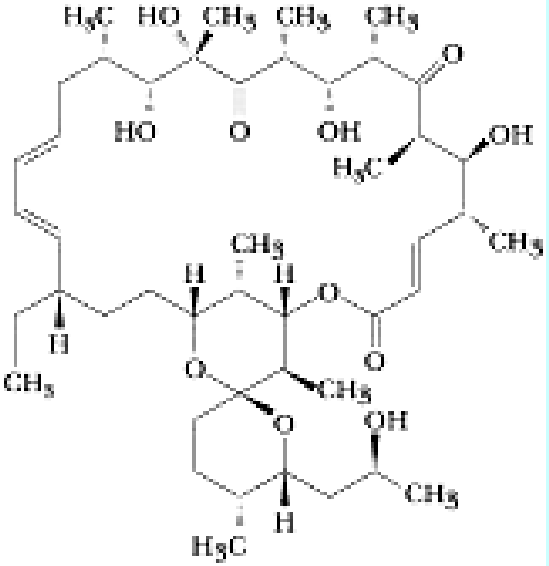
Demerol
(meperdine)



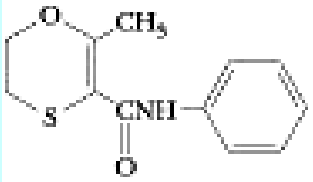
2-Thenoyltrifluoroacetone



Antimycin A_1



Oligomycin A



Carboxin

Dicyclohexylcarbodiimide (DCCD)

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Inhibitors of Complexes I, II, and III Block Electron Transport

Rotenone is a common insecticide that strongly inhibits the NADH-UQ reductase.

Ptericidin, Amytal, and other barbiturates, mercurial agents, and the widely prescribed painkiller Demerol also exert inhibitory actions on this enzyme complex. All these substances appear to inhibit reduction of coenzyme Q and the oxidation of the Fe-S clusters of NADH-UQ reductase.

2-Thenoyltrifluoroacetone and carboxin and its derivatives specifically block Complex II, the succinate-UQ reductase.

Antimycin, an antibiotic produced by Streptomyces griseus, inhibits the UQ-cytochrome c reductase by blocking electron transfer between b_H and coenzyme Q in the Q_n site.

Myxothiazol inhibits the same complex by acting at the Q_p site.

Cyanide, Azide, and Carbon Monoxide Inhibit Complex IV

The cytochrome c oxidase, is specifically inhibited by cyanide (CN^-), azide (N_3^-), and carbon monoxide (CO).

Cyanide and azide bind tightly to the ferric form of cytochrome a_3, whereas carbon monoxide binds only to the ferrous form.

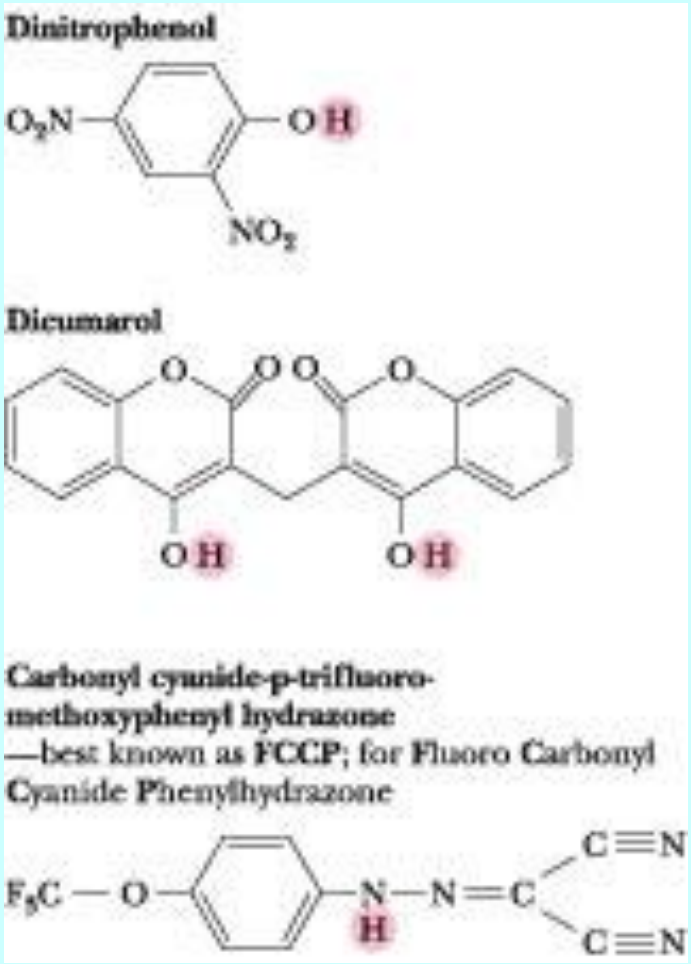
ATP Synthase Inhibitors

Inhibitors of ATP synthase include dicyclohexylcarbodiimide (DCCD) and oligomycin.

DCCD bonds covalently to carboxyl groups in hydrophobic domains of proteins in general, and to a glutamic acid residue of the c subunit of $F_{o\times}$, the proteolipid forming the proton channel of the ATP synthase, in particular. If the c subunit is labeled with DCCD, proton flow through $F_{o\times}$ is blocked and ATP synthase activity is inhibited.

Likewise, oligomycin acts directly on the ATP synthase. By binding to a subunit of $F_{o\times}$, oligomycin also blocks the movement of protons through F_o

Uncouplers Disrupt the Coupling of Electron Transport and ATP Synthase



Uncouplers disrupt the tight coupling between electron transport and the ATP synthase. Uncouplers act by dissipating the proton gradient across the inner mitochondrial membrane created by the electron transport system. Typical examples include :

2, 4-dinitrophenol,
dicumarol,
and carbonyl cyanide-p-trifluoro-methoxyphenyl hydrazone.

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These compounds share two common features: hydrophobic character and a dissociable proton.

As uncouplers, they function by carrying protons across the inner membrane. Their tendency is to acquire protons on the cytosolic surface of the membrane (where the proton concentration is high) and carry them to the matrix side, thereby destroying the proton gradient that couples electron transport and the ATP synthase.

In mitochondria treated with uncouplers, electron transport continues, and protons are driven out through the inner membrane. However, they leak back in so rapidly via the uncouplers that ATP synthesis does not occur. Instead, the energy released in electron transport is dissipated as heat.

Endogenous Uncouplers Enable Organisms To Generate Heat

Certain cold-adapted animals, hibernating animals, and newborn animals generate large amounts of heat by uncoupling oxidative phosphorylation. Adipose tissue in these organisms contains so many mitochondria that it is called brown adipose tissue for the color imparted by the mitochondria.

The inner membrane of brown adipose tissue mitochondria contains an endogenous protein called thermogenin (literally, "heat maker"), or uncoupling protein, that creates a passive proton channel through which protons flow from the cytosol to the matrix.

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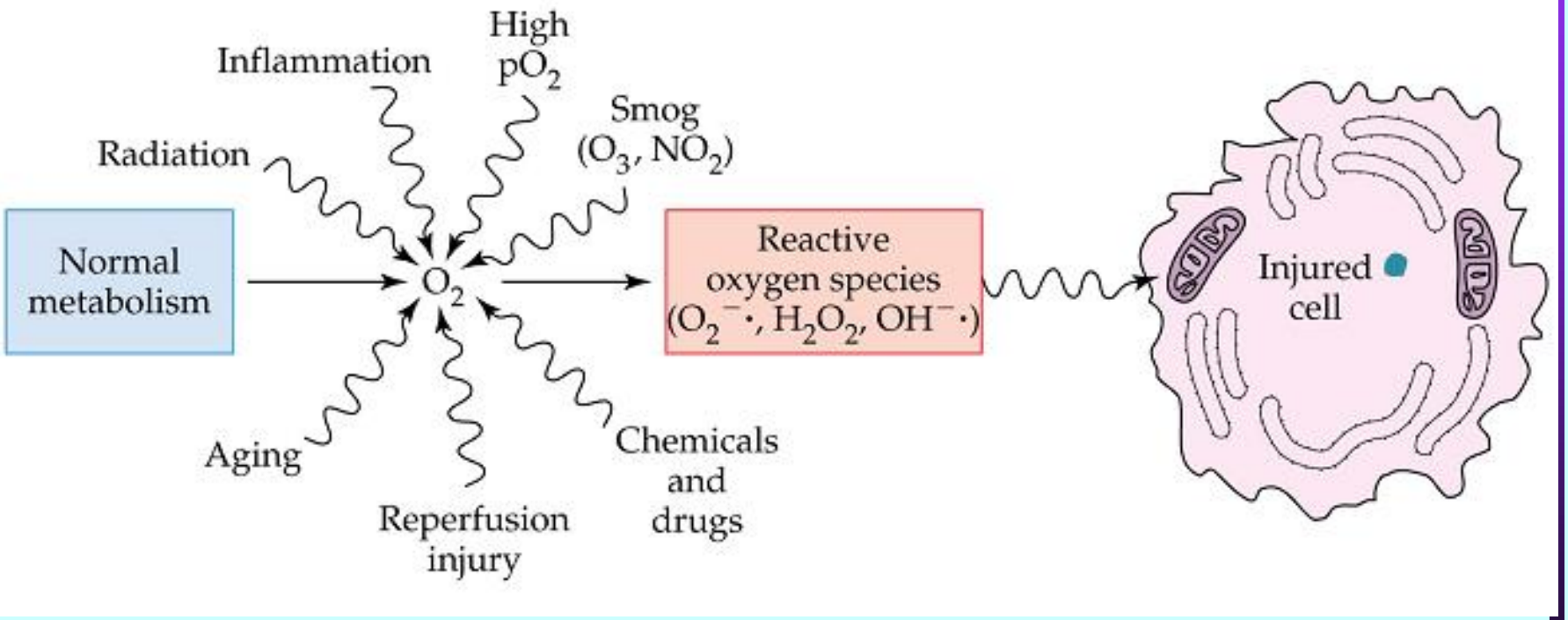
Free-radical Oxidation



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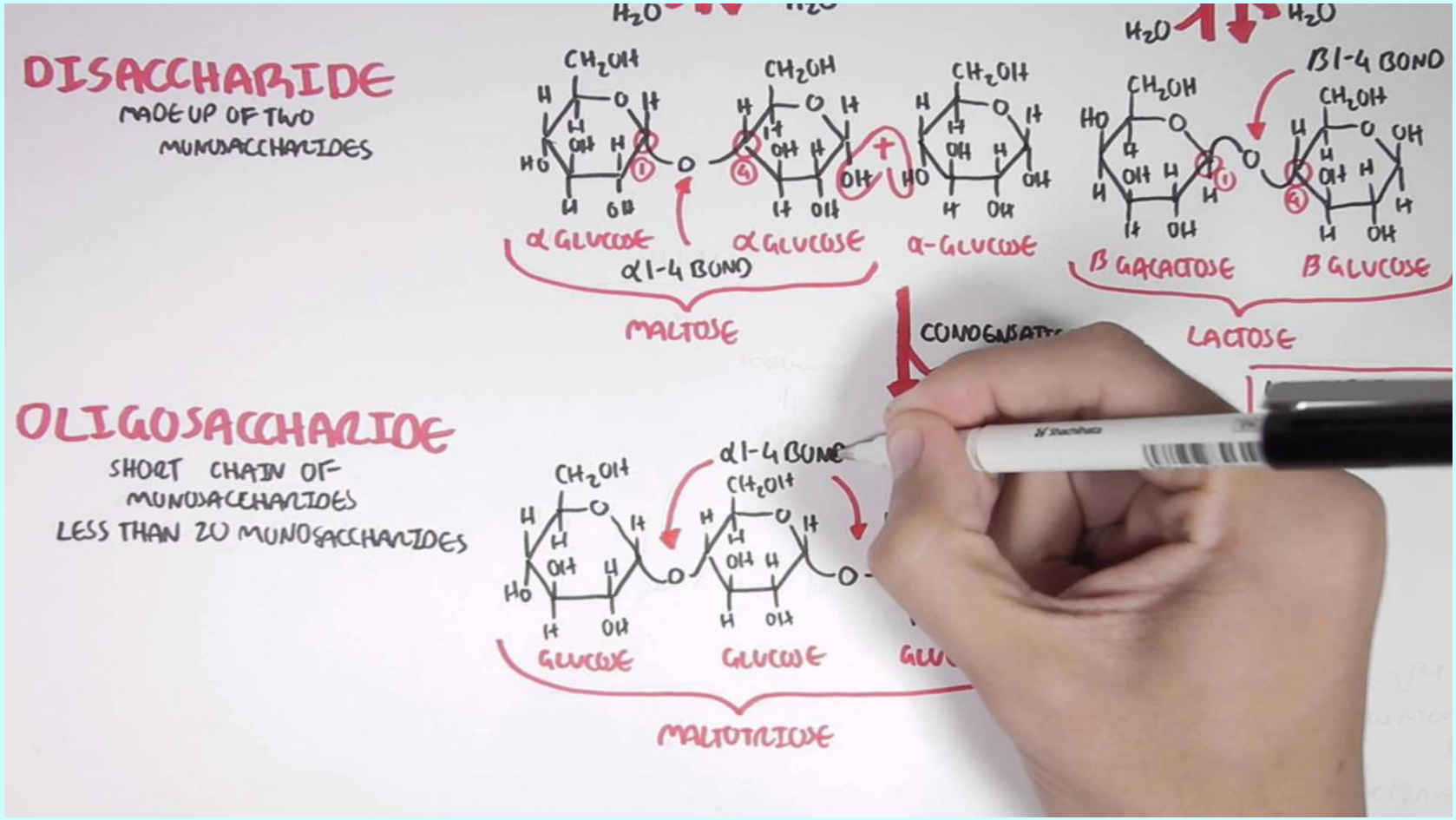
Conclusions

1. Metabolism, the sum total of all the enzyme-catalysed reactions that occur in a living organism is a dynamic, coordinated activity.
2. ATP plays a central role in energy exchange in the body.
3. In aerobic cells catabolism consists of three stages.
4. The citric acid cycle (TCA cycle) is series of biochemical reactions that are responsible for the eventual complete oxidation of organic substrates to form CO2 and H2O.
5. The electron transport chain (ETC) is a series of electron carriers that transfer the electron derived from reduced coenzymes to oxygen.
6. Oxidative phosphorylation is the process in which ATP is formed as a result of the transfer of electrons from NADH or FADH 2 to O 2 by a series of electron carriers.

Do you have any questions?

Thank you for your attention!



https://www.youtube.com/watch?v=JxK5rZxbyQY