Microbial energy metabolism

210BBC210

Mitchell sets sail for the Chemiosmotic New World, despite dire warnings that he will be consumed

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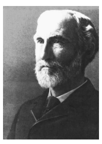
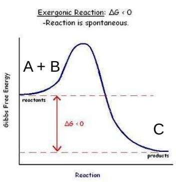
A bit of chemistry
Free energy change

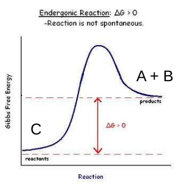


Gibb's Free Energy change is a concept which allows to predict if a reaction is thermodynamically favorable

A + B ↔ C $\Delta G<0$ – spontaneous reaction →, EXErgonic

$\Delta G>0$ – no reaction, ENDErgonic





Free energy change

ΔG^o = change of free energy of reaction at standard state conditions at 1M concentration of reactants. But in reality concentrations may vary!

$A + B \leftrightarrow C$ $\Delta G^o>0$ – no reaction if we mix A, B and C at concentrations of 1M ([A]=[B]=[C]=1M)

$$\Delta G = \Delta G^0 + \ln\frac{[C]}{[A]\times[B]}$$

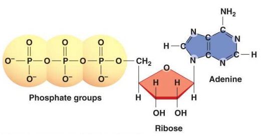
However, if $[A]\times[B] >> [C]$, real $\Delta G<0$ and reaction will go from left to right $\rightarrow$

In particular case of standard conditions $\Delta G=\Delta G^o$ because

$$\Delta G = \Delta G^0 + \ln\frac{1}{1\times1} = \Delta G^0 + 0$$

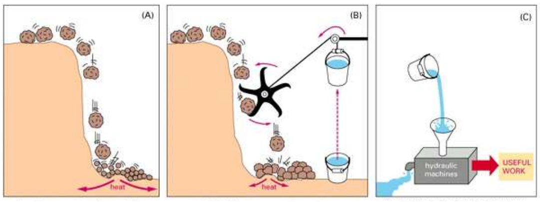
Enzymes accelerate the attainment of equilibrium, but not shift it or reverse reaction. Direction of the reaction is defined by ΔG. Some of the biological reactions have $\Delta G^o>0$, but due to the concentration component (in logarithm) $\Delta G<0$.

Adenosine triphosphate (ATP)



ATP is regarded as a universal source of energy occurring in all cell types. In animals it is produced during the degradation of foodstuff.

$ATP \rightarrow ADP + P_i$ + *energy*

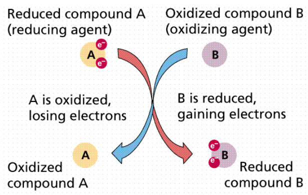


Burning (oxidation) of glucose to CO_2 and H_2O produces heat only

Cells can store energy during glucose oxidation can in form of ATP

ATP can be used to drive any cellular processes

Redox reactions
(reduction-oxidation reactions)



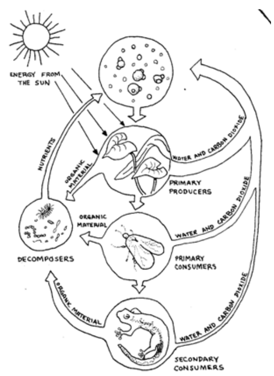
$A_{red} + B_{ox} \rightarrow A_{ox} + B_{red}$

$A_{red} \rightarrow A_{ox} + 2e^-$
$B_{ox} + 2e^- \rightarrow B_{red}$

Midpoint redox potential (E^o) is a tendency of A_{red} to donate electrons

Electrons transferred from A_{red} to B_{ox} if $E^o_{A_{ox}/A_{red}} < E^o_{B_{ox}/B_{red}}$

Photosynthesis and Respiration
(energy conversion)



Reduction of oxygen

$CO_2 + H_2O \overset{+h\nu}{\leftrightarrow} \{CH_2O\} + O_2$

Photosynthetic organisms

Capture of solar energy to use it for reduction of carbon compounds

$\{CH_2O\} + O_2 \leftrightarrow CO_2 + H_2O$ + energy

Animals or microorganisms

Oxidation of food to obtain energy

Animals →

$O_2 + 4e^- + 4H^+ \leftrightarrow 2H_2O$

← Plants

Oxidative phosphorylation

History

W. A. Engelhardt, 1936-39 - measured inorganic and organic phosphate content. Definition of oxidative phosphorylation

Warburg vs ***Thunberg*** and ***Keilin*** - respiratory enzyme vs dehydrogenase

Albert Lehninger – 1948 – mitochondria are the site of energy metabolism

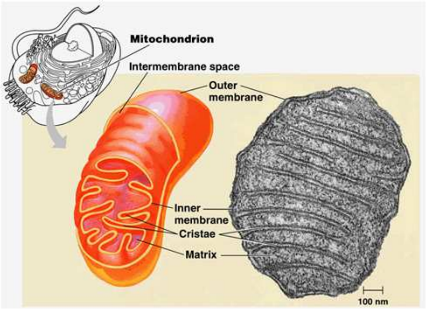
David Green – 50s, isolation and reconstitution of electron transport chain

Piter Mitchell – energy transduction in membranes Nobel Prize 1978

Hartmut Michel – structure of photosynthetic reaction centre Nobel Prize 1988

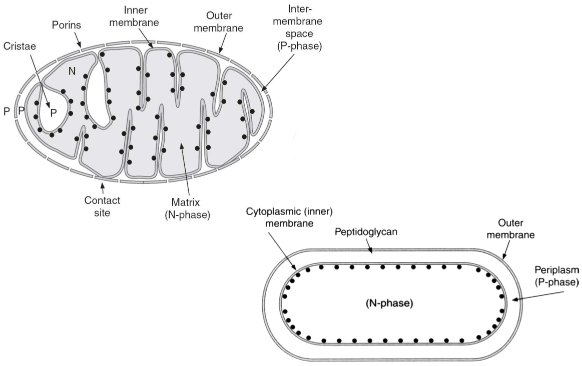
John Walker - structure of ATPase Nobel Prize 1997

Mitochondria – respiring organelle



Also contain its own DNA and its own transcription/translational system – they were prokaryotes long time ago

Membranes of mitochondria and bacteria

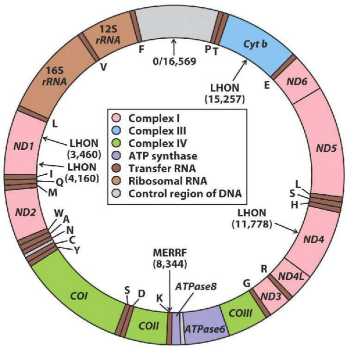


What are mitochondria?

- An intracellular organelle.
- There are 100 to 1000s of mitochondria/cell.
- All mitochondria come from the mother.
- Mitochondria have their own DNA.
- Major functions of mitochondria:
  - Makes energy in the form of ATP.

Endosymbiotic theory

Mitochondrial DNA



Double stranded, circular

- No introns, 80 - 93% coding gene
- No repeats
- Lack histone and DNA repair mechanism ⇒ damage, mutations (free radicals)
- 37 gene: 22 tRNA, 2 rRNA & 13 protein

NUCLEOID
A dynamic complex that consists of several copies of mitochondrial DNA and key maintenance proteins within the organelle.

POLYCISTRONIC
A form of gene organization that results in transcription of an mRNA that codes for multiple gene products, each of which is independently translated from the mRNA.

Locations

- Glycolysis
  - Cytoplasm
- Krebs' TCA
  - Mitochondrial matrix
- Oxidative phosphorylation
  - Inner mitochondrial membrane

Bacteria

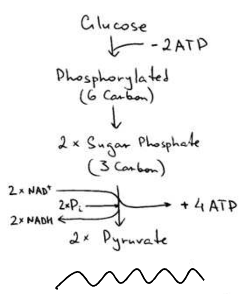
Cytoplasm

Plasma membrane

⇒ **Compartmentalisation**

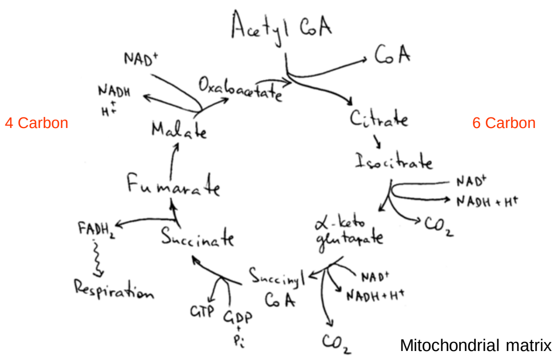
Glycolysis

Cytoplasm

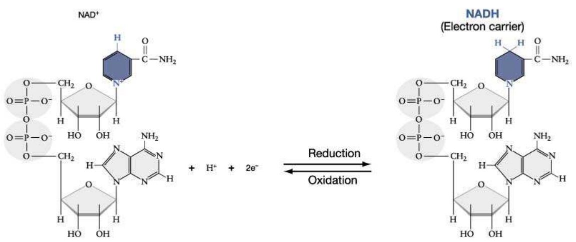


Mitochondrial matrix

Krebs cycle (TCA cycle)



Electron transferring coenzyme



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

After glycolysis and TCA cycle

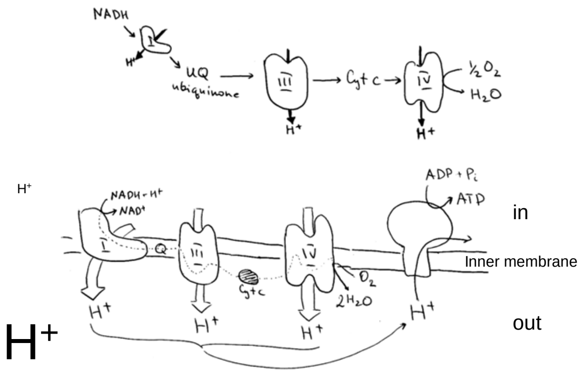
Not much ATP formed
Lots of reduced coenzymes
Per glucose molecule:
- 10 NADH
- 2 $FADH_2$ (!!!)

At the same time:

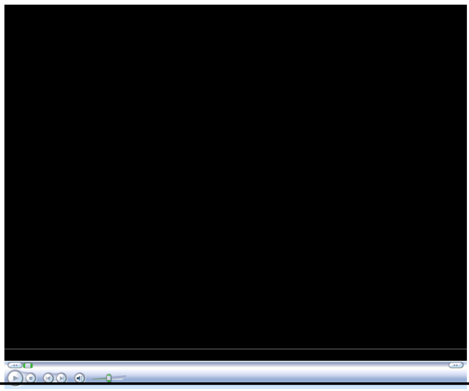
Reoxidation of NADH releases energy
Requires oxygen as oxidant
This energy can be used for ATP synthesis

Respiratory chain couples processes of oxidation and ATP synthesis

Electron transport chain and ATP synthase



Electron transport chain and ATP synthase

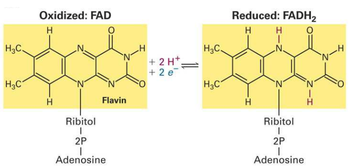


Redox centres

Flavin
Iron- sulphur centres (FeS-centres)
Ubiquinone
Cytochromes

Flavin

Complex I
Complex II = succinate dehydrogenase from Krebs cycle



$FAD + 2e^- + 2H^+ \leftrightarrow FADH_2$

Usually serves as intermediate of electron transfer between $2e^-$ donor and 1e- acceptor

No free flavins in a cell !!!

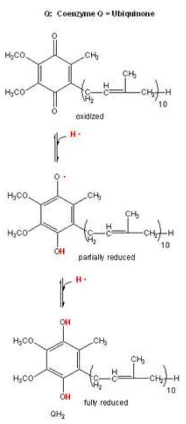
FeS clusters

Complexes I, II, III

Always transfer one electron at the time
Electron is delocalised

Mixed clusters - Ni or Mo in microorganisms
Pyrite = fool's gold. Self assembly (Fe, -SH, S^{2-})
EPR – shows unpaired electrons

Ubiquinone



2 electrons + $2H^+$

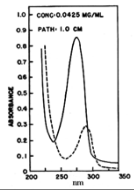
Membrane mobile redox carrier linking Complexes I and II with Complex III

Proton-translocating Q-cycle in complex III

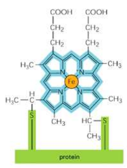
Different *n* for different species (*n*=6-10)

Menaquinone and rhodoquinone in some bacteria and plastoquinone in chloroplasts

Ubiquinone has been discovered in studies on Vitamin A

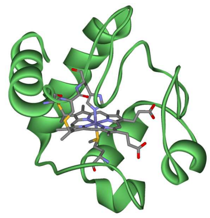


Cytochromes



Cyt *c* (Fe^{3+}) + e^- ↔ Cyt *c* (Fe^{2+})

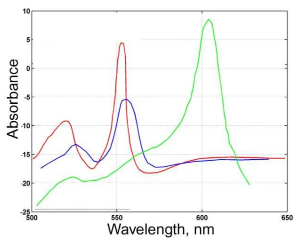
Cytochrome *c*



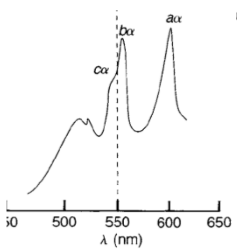
Protein part and haem part containing Fe ion
Cytochromes *a*, *b*, *c* ... + number
As separate single proteins (e.g. cytochrome *c*) or as subunits of enzymatic complexes (Complex II, III, IV)

Respiratory chain cytochromes

Reduced-oxidised spectra
a b c



Reduced-oxidised spectra of mitochondrial membranes

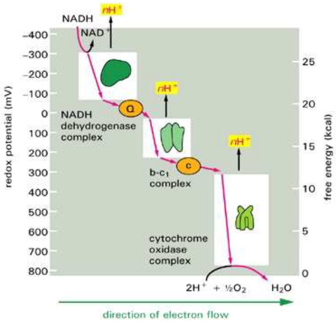


Easy to observe reduction/oxidation as change in optical spectra

Otto Warburg Nobel Prize 1931
Nature and mode of action of the respiratory enzymes

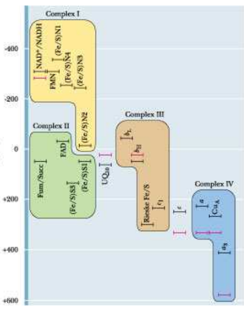
Hugo Theorell Nobel prize 1955
Redox enzymes and biological oxidation

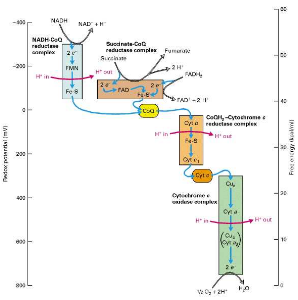
Electron transport chain



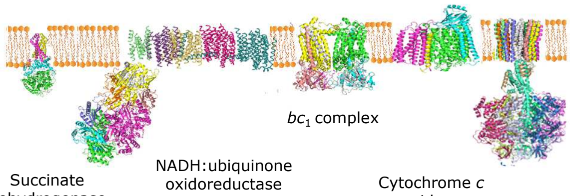
Values of redox potential of respiratory chain components fall downstream from NADH to oxygen.

Electron transport chain





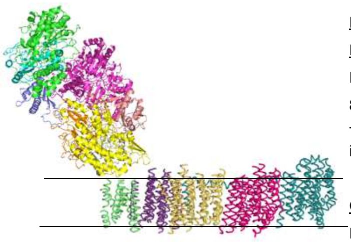
Structure of respiratory chain



Complex I (NADH:ubiquinone oxidoreductase)

$NADH + H^+ + 4H^+_{in} + UQ \leftrightarrow$

$\leftrightarrow NAD^+ + UQH_2 + 4H^+_{out}$



Thermus thermophilus structure (2013)

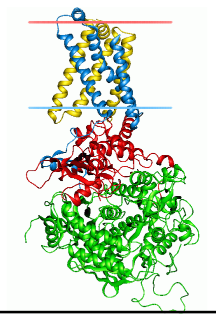
- Eukaryotic enzyme: 40-44 subunits
- Bacterial enzyme: 14 subunits
- Flavin = FMN
- 8 FeS clusters
- Tightly-bound semiquinones as intermediates of electron transfer

Classical inhibitors:

Rotenone, piericidine, MPP^+

Complex II
Succinate dehydrogenase of TCA cycle

$Succinate + UQ \leftrightarrow Fumarate + UQH_2$



- Eukaryotic enzyme: 4 subunits
- Bacterial enzyme: 4 subunits
- Flavin = FAD
- Cytochrome *b*
- Three FeS clusters

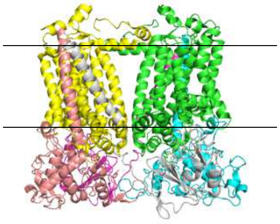
Classical inhibitors:

Malonate, Oxaloacetate

Complex III
bc_1 complex

UQH_2 + 2Cyt *c* (Fe^{2+})+ $2H^+_{in}$ ↔

↔ UQ + 2Cyt *c* (Fe^{3+})+$4H^+_{out}$



Eukaryotic enzyme: 11 subunits

Bacterial enzyme: 3 (+1) subunits

Cytochromes c_1, b_L and b_H

Rieske protein (2Fe2S cluster)

Tightly-bound semiquinones as intermediates of electron transfer

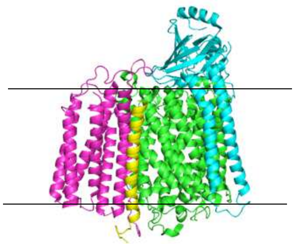
Classical inhibitors:

Antimycin A, myxothiazol

Complex IV
Cytochrome *c* oxidase

4Cyt *c* (Fe^{2+})+ $4H^+_{in}$ + $4H^+_{in}$ + O_2↔

↔ 4Cyt *c* (Fe^{3+})+ $2H_2O$ + $4H^+_{out}$



Eukaryotic enzyme: 13 subunits

Bacterial enzyme: 2-3 subunits

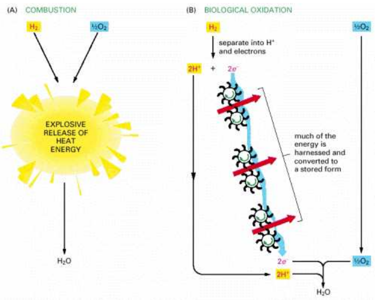
Cytochrome *a*, a_3,

Two copper Cu_A Cu_B centers

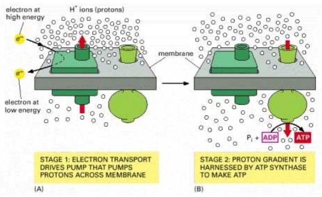
Classical inhibitors:

Cyanide, carbon monoxide, nitric oxide

Oxidative phosphorylation



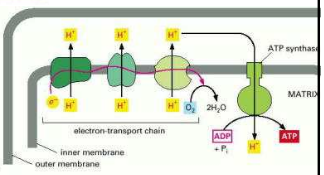
Chemiosmotic theory



Peter Mitchell, Nobel Prize 1978

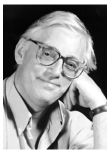
Electron transfer along electron transport chain is coupled with proton translocation at complexes I, II and IV.

The difference in concentration of protons can drive special molecular motor – ATP synthase.



ATP synthase

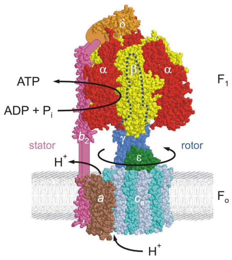
Nobel prize 1997 John Walker



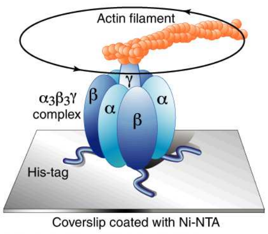
<u>Bacterial enzyme</u>: 8 subunits

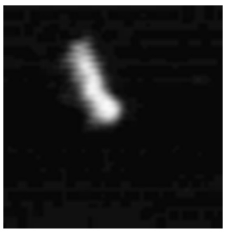
Proton flow through F_o part is coupled with ATP synthesis in the F_1 part

~10H⁺ per 3 molecules of ATP



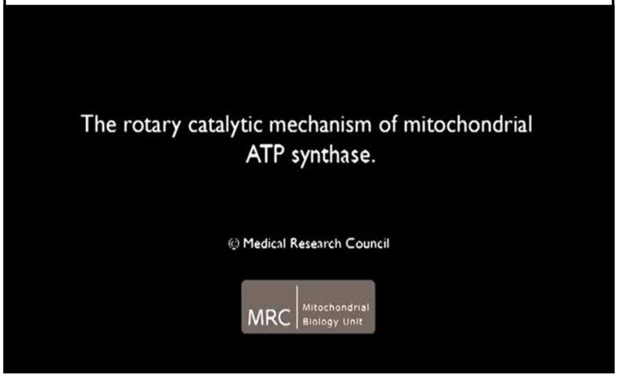
ATP synthase





Yoshida Lab http://www.res.titech.ac.jp/~seibutu/
Kinosita Lab http://www.k2.phys.waseda.ac.jp/Movies.html

ATP-synthase



ATP synthase

PNAS

Structure of the yeast F_1F_o-ATP synthase dimer and its role in shaping the mitochondrial cristae

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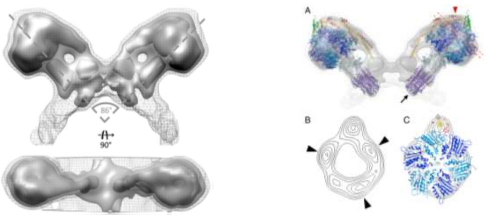
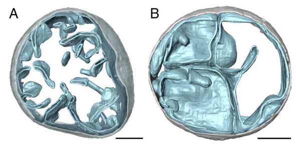
Edited by Richard Henderson, MRC Laboratory of Molecular Biology, Cambridge, United Kingdom, and approved June 29, 2012 (received for review March 16, 2012)

We used electron cryotomography of mitochondrial membranes from wild-type and mutant *Saccharomyces cerevisiae* to investigate the structure and organization of ATP synthase dimers in situ.

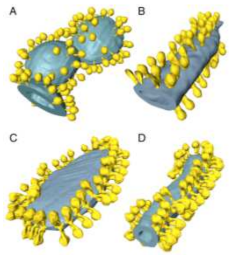
predicted transmembrane helix featuring a GXXXG motif. Subunit *g* has a small N-terminal matrix domain that can be cross-linked to subunit 4 (16), and subunit *e* has a short C-terminal



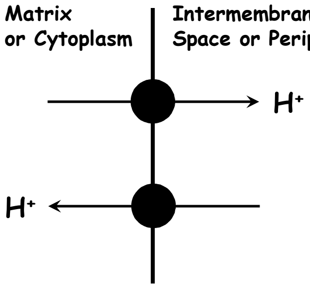


A-WT =ATPase as dimers
B-mutant = without dimers

Formation of ATPase dimers
determines formation of cristae



ATP synthesis in membrane



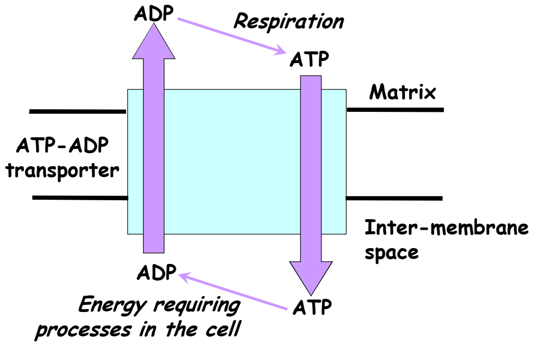
Electron transport chain:
Generates Δp

ATP synthase:
Consumes Δp

ATP synthesis

ATP synthesis in mitochondrial matrix
Needs to be transported out of mitochondria
Requires ATP-ADP transporter
Integral membrane protein
ATP and ADP transport coupled

ATP transport
(in mitochondria!)



Mitochondrial respiration

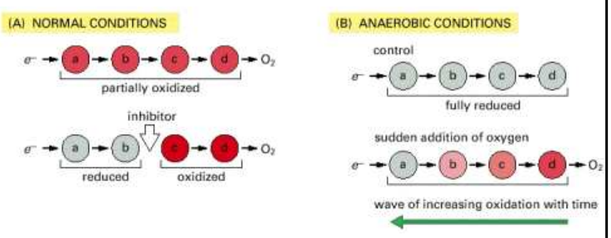
History: Isolated mitochondria + substrates + oxygen

Some compounds block oxygen consumption – <u>respiration</u> <u>inhibitors</u>

Some compounds stop ATP synthesis but not respiration, they break the link between respiration and ATP synthesis – <u>uncouplers</u>

Classical experiments with mitochondria were repeated using bacterial systems: *Paracoccus denitrificance* or *E.coli*

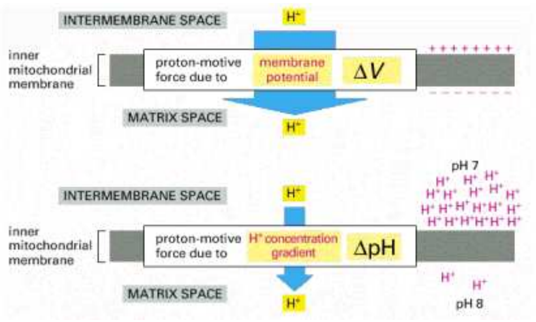
How to study electron transport chain?



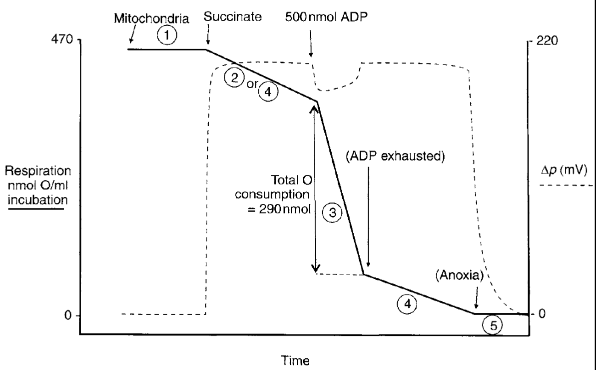
Oxidative phosphorylation inhibitors

- I – Rotenone, piericidine
  - Ubiquinone-like structure
- II – Oxaloacetate, malate
  - Succinate-like structure
- III - Antimycin A, myxothiazol
  - Similar to quinone-binding sites of C-III. Fungicide and insecticide
- IV - Cyanide (CN^-), azide (N_3^-), carbon monoxide (CO), nitric oxide (NO)
  - Similar structures to O_2

Protonmotive force



Mitochondrial (or microbial) respiration



Oxidative phosphorylation

Respiratory control ratio

$H^+/2e^-$ stoichiometry of respiratory chain complexes

H^+/ATP stoichiometry of ATP synthase

ADP/O ratio – how much ADP can be converted to ATP per molecule of oxygen

Reversibility of reactions = reverse electron transfer

Reactive oxygen species generation

Aerobic respiration

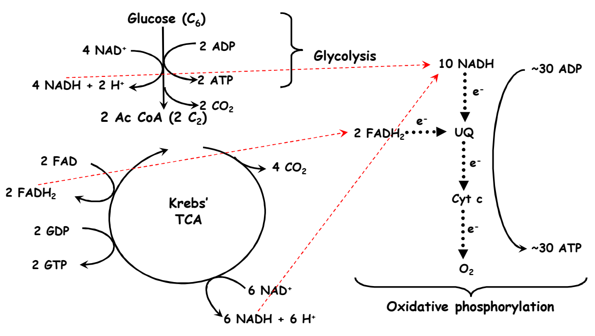
$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$$

Carbon dioxide:
Released in Pyruvate → AcCoA and Krebs' TCA

Oxygen:
Required at the end of oxidative phosphorylation

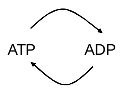
Glucose:
Chemical energy from food

Aerobic respiration



Aerobic respiration

(in mammals!)



Inner mitochondrial membrane ~1400m^2

We consume ~380 *l* of oxygen per day

ATP turnover ~60 kg/day

3×10^{23} H^+ per second through ATP synthase

90% ATP is synthesised during oxidative phosphorylation

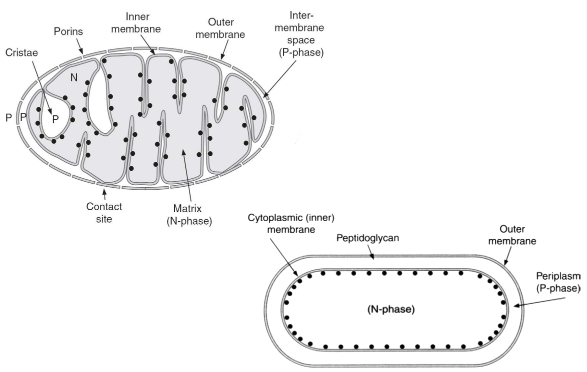
Bacterial energy metabolism

Live in various environment

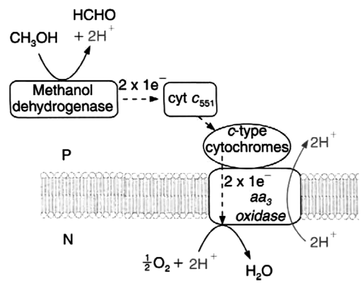
Able metabolise different substrates

Can adopt to the changing environment

Membranes of mitochondria and bacteria



What to do if food is scarce?



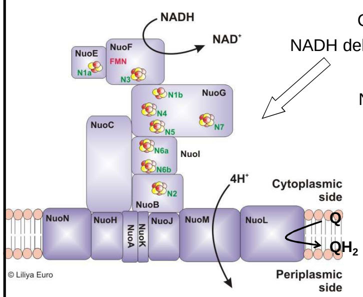
Some bacteria can grow on low carbon substrates like methanol as its sole source of energy. In *P. denitrificans* methanol is oxidised in periplasm and electrons are transferred directly to cytochrome oxidase

Bacterial energy metabolism

In many bacteria efficiency of respiration (ATP:O ratio) is lower than in mitochondria

- More simple machinery of H^+/e^- transport
- Bypassing
- Shortening or branching of the chain

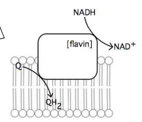
Simplification



Proton translocation

Complex I =
NADH dehydrogenase Type 1
(eukaryotes)

NADH dehydrogenase Type 2
(E.coli, Rhodobacter capsulatus, etc)

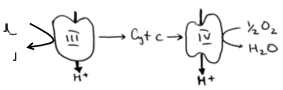


No proton translocation
(not even a membrane protein)

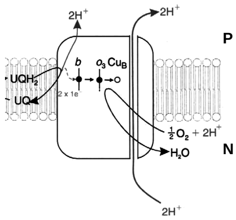
$$NADH + H^+ + Q \leftrightarrow NAD^+ + QH_2$$

Bypassing

bc_1 (III) and cytochrome *c* oxidase (IV) together (*in mitochondria*)



bo_3 oxidase (quinol oxidase) (*E.coli, Burkholderia phymatum*)

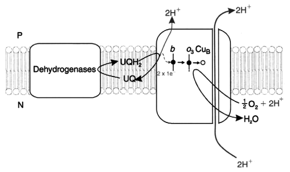


$$2QH_2 + O_2 + 4H^+_{in} \leftrightarrow 2Q + 2H_2O + 4H^+_{out}$$

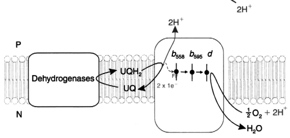
Direct oxidation of quinol by oxygen, bypassing *bc_1* complex and cyt *c* + translocation of protons (but with lower efficiency)

Bypassing and simplification

bo_3 oxidase (quinol oxidase)
(*E.coli, Burkholderia phymatum*)



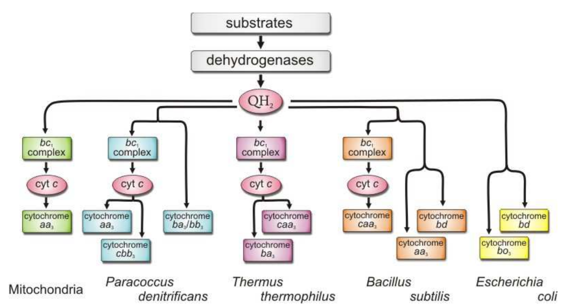
bd oxidase (quinol oxidase)
(no H^+ translocation)
(*E.coli, Klebsiella pneumoniae, Mycobacterium tuberculosis*)



$$2QH_2 + O_2 \leftrightarrow 2Q + 2H_2O$$

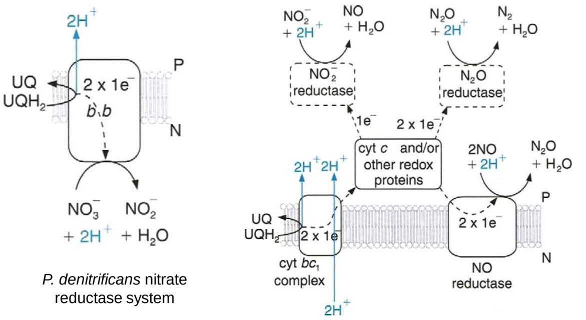
Direct oxidation of quinol by oxygen, bypassing *bc_1* complex and cyt *c* + but no (!!!) translocation of protons

Scheme of Respiratory Chains of mitochondria and bacteria



What to do if the oxygen is absent?

What would be the terminal electron acceptor or where electrons should end up?



$NO_3^- \rightarrow NO_2^- \rightarrow NO \rightarrow N_2O \rightarrow N_2$

What to do if the oxygen is absent?

What would be the terminal electron acceptor or where electrons should end up?

NADH E_o= -320mV

↓

NADH Dehydrogenase Type 1 ⇨ up to 4H+/2e- translocated

↓

Menaquinone E_o= -74mV

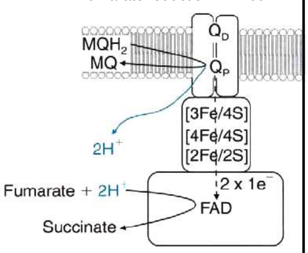
↓

Fumarate reductase Cyt *b*, FeS, FAD

↓

Fumarate E_o= +33mV

Fumarate reduction in *E.coli*



Why use menaquinone instead of ubiquinone?

Fumarate reductase from E.coli

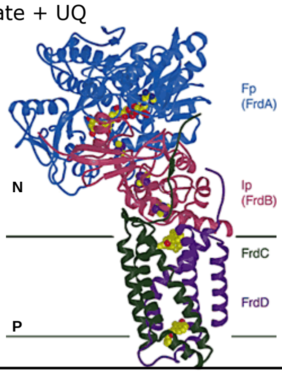
Fumarate + UQH_2 ↔ Succinate + UQ

Very similar to mitochondrial succinate dehydrogenase

4 subunits

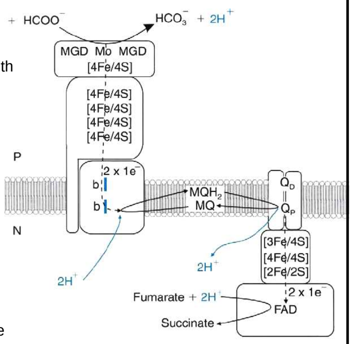
Flavin – FAD

3 FeS clusters



How to generate proton gradient without actual proton translocation?

Oxidation of formiate coupled with fumarate reduction in *E.coli*

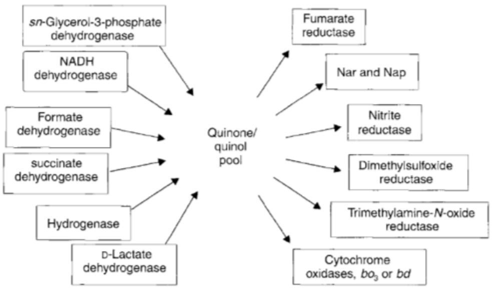


Net reaction:

release $2H^+$ at P-side

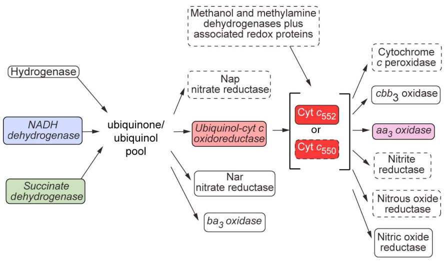
consumption of $2H^+$ at N-side

E. coli respiratory chain



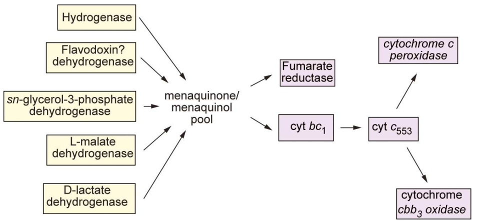
The components present depend on the growth conditions. Menaquinone replaces ubiquinone under anaerobic conditions. Many of the enzymes (e.g. nitrite reductase) have their active sites at the periplasm.

P. denitrificans respiratory chain



The components in italics are constitutive. The other components are induced at appropriate growth conditions and are unlikely to be all present at once. Continuous boxes indicate integral membrane components; dashed lines represent periplasmic components. NADH dehydrogenase, succinate dehydrogenase, ubiquinol cytochrome *c* oxidoreductase and aa_3 oxidase correspond to mitochondrial complexes I-IV.

Helicobacter pylori respiratory chain

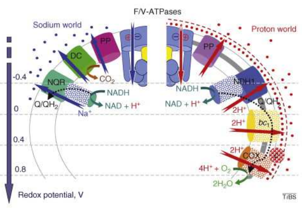


Helicobacter pylori grows at very low oxygen concentrations and has attracted attention as a cause of gastric ulcers and gastric cancer. It is an example of an organism for which more knowledge of its electron transport system has been gained from the sequencing of its genome than from biochemical analyses.

What to do if it is very alkaline outside

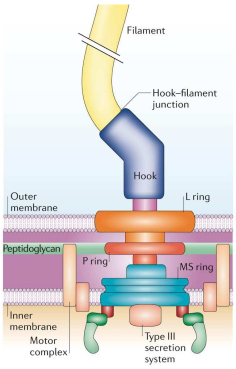
Ions other than H^+ can be used. In certain bacteria gradient of Na^+ is created by special enzymes and can be used by special Na^+ translocating ATP synthase for ATP synthesis.

Sodium bioenergetics: *Halophilic bacteria, Vibrio cholerae, Yersinia pestis*

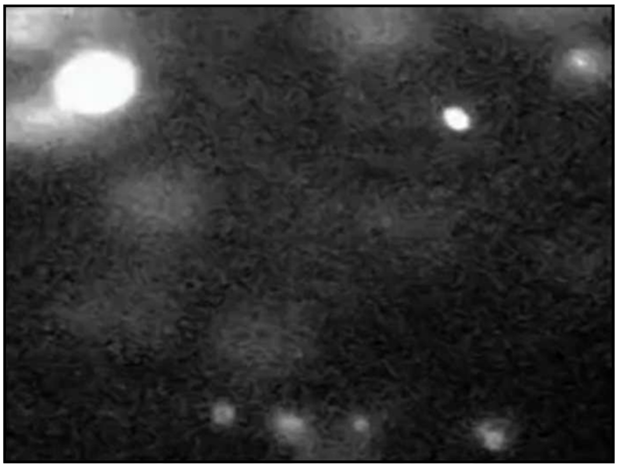


NQR, Na+-translocating NADH:Q oxidoreductase
PP, membrane pyrophosphatase
DC, membrane Na+-transporting decarboxylase

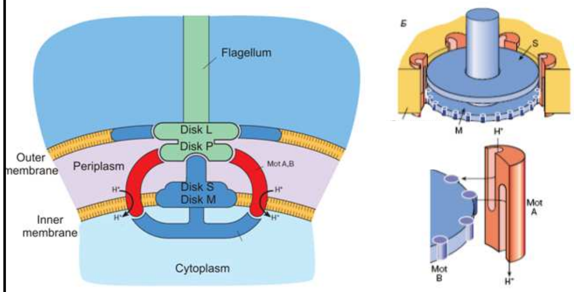
Flagellum = whip

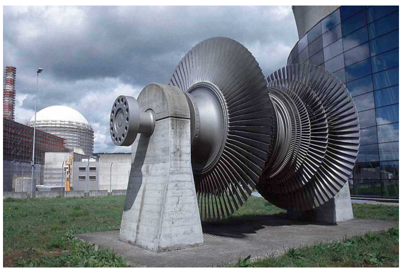


Energy of proton gradient can be converted in to mechanical movement (*E.coli, Helicobacter pylori, Salmonella typhimurium, Halobacterium*)
~10^3 rpm = 300 Hz = 300 revolutions per second



How does it work?

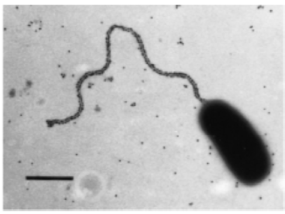




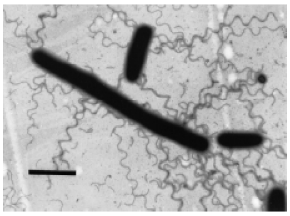
Using two fuels

Vibrio parahaemolyticus possesses two types of flagella. The swimmer cell moves fast in a liquid environments, with a single polar flagellum powered by the Na^+ motive force,. The swarmer cell, propelled by many lateral flagella powered by H^+ gradient and can move slowly through highly viscous environments. 15 000 rev per second on Na^{++}

Sodium motive force

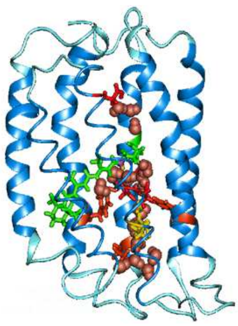


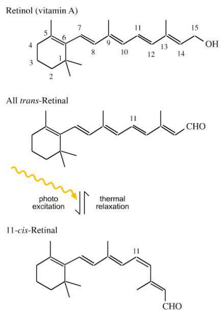
Proton motive force



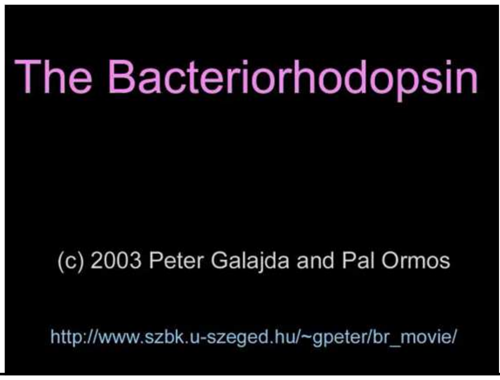
How to use light ?

Bacteriorhodopsin is a protein from halobacteria. It uses light energy it to move protons across the membrane.

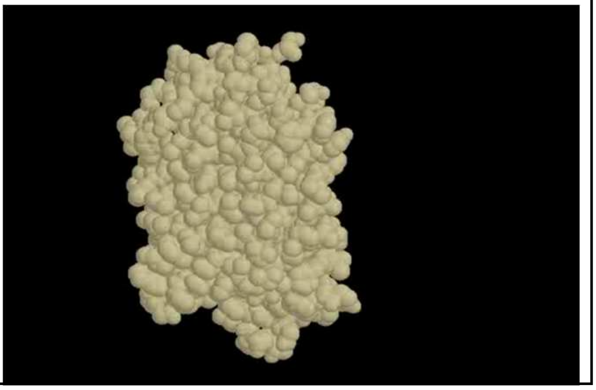




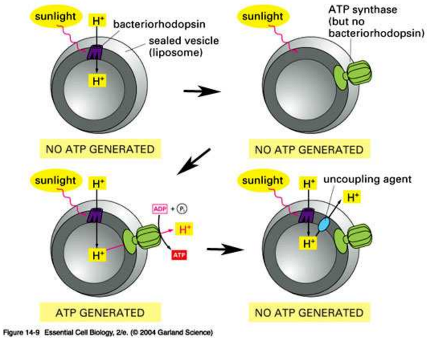
Bacteriorhodopsin



Bacteriorhodopsin



Proof of chemiosmosis



Photosynthesis in bacteria and light phase in chloroplasts

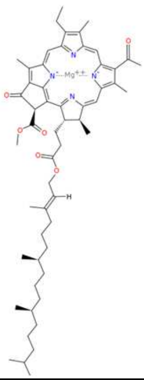
Photosynthesis in bacteria

No mitochondria, no chloroplasts ⇒ everything is located in the same membrane!

Hartmut Michel Nobel prize 1988
Structure of photosynthetic reaction centre

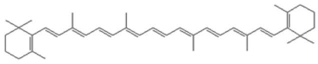
Bacteriochlorophyll and carotenoids

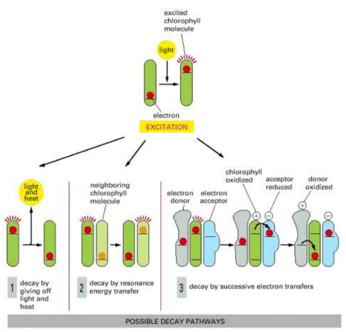
(in light harvesting complexes)



$$P^* \xrightarrow{-e^-} P^+ \xrightarrow{+e^-} P$$

Carotenoids

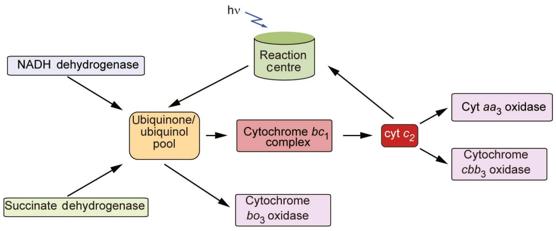




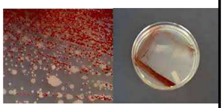
The light energy absorbed by an isolated pigment molecule is completely released as light and heat by process 1. In photosynthesis, by contrast, pigment undergo process 2 in the antenna complex and process 3 in the reaction center.

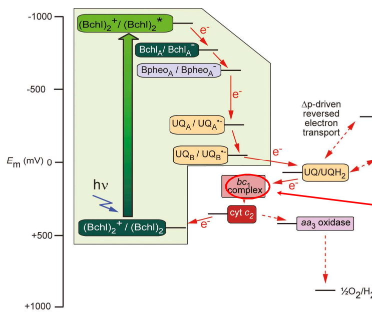
Light driven cyclic electron transfer

(Rh. Sphaeroides)



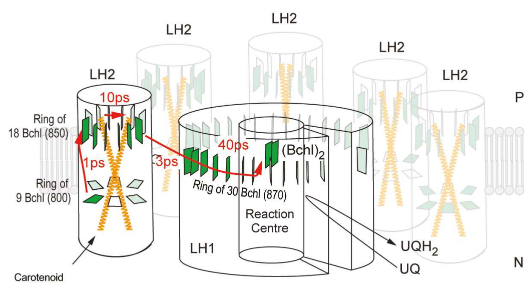
Electron transfer in *Rh. Sphaeroides*





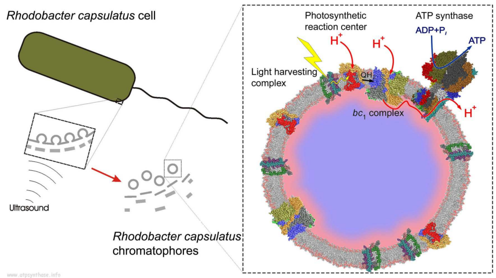
Related to PS II

Organisation of light harvesting complexes

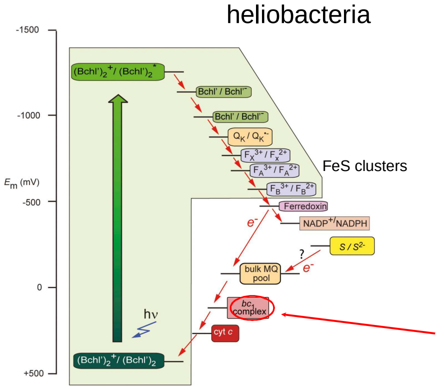


LH2=antennae absorb light at other λ than Bchl and also provides high rate of electron delivery to RC

Light driven electron transfer takes place in chromatophores



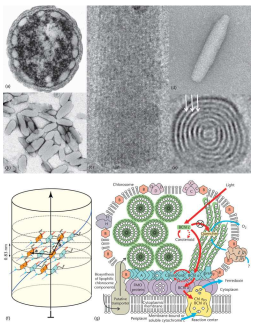
Electron transfer in green sulphur bacteria and heliobacteria



H^+-translocation by complex III

Related to PS I

Electron transfer in green sulphur bacteria and heliobacteria



Greenplants and algae
Oxygen and carbohydrate formation

$\mathbf{CO_2 + H_2O \overset{+h\nu}{\leftrightarrow} \{CH_2O\} + O_2}$

Photosynthetic organisms

Capture of solar energy to use it for reduction of carbon compounds

$\mathbf{\{CH_2O\} + O_2 \leftrightarrow CO_2 + H_2O + energy}$

Animals

Oxidation of food to obtain energy

Animals →

$O_2 + 4e^- + 4H^+ \leftrightarrow 2H_2O$

← Plants

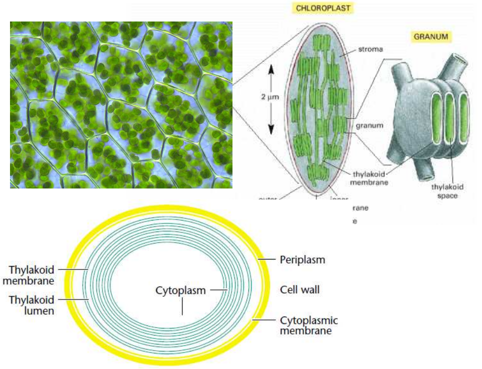
Photosynthesis

- Light reactions:
  - Need light to occur
  - Capture of light energy
  - Generation of pmf and reducing power (NADPH)
- **Dark reactions:**
  - Occur in light and dark
  - **Carbohydrate synthesis**

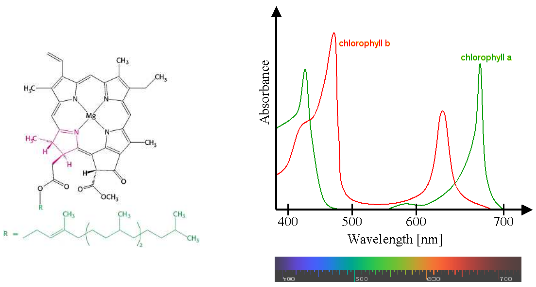
Photosynthesis

- $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$
- Occurs in specialised organelles – chloroplasts
- **Light captured by chlorophyll**
  - Porphyrin
  - Contains Mg^{2+}
  - **Green**

Photosynthesis takes place in chloroplasts or cyanobacteria



Chlorophyll

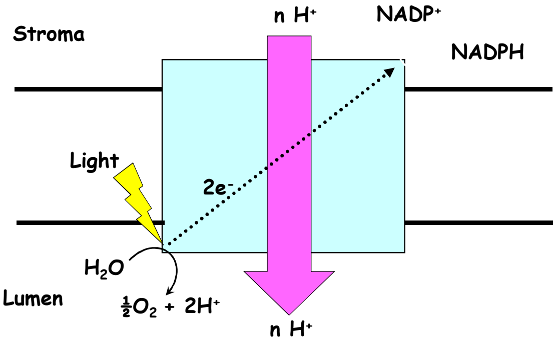


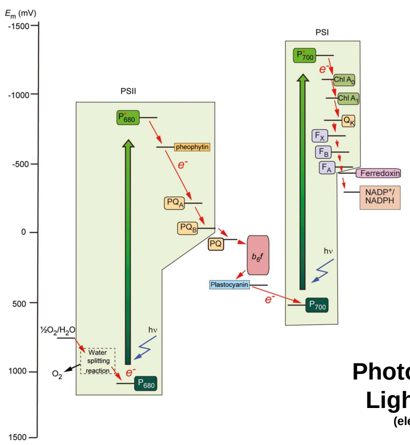
Like haeme, chlorophyll *a* is a cyclic tetrapyrrole. One of the pyrrole rings (shown in red) is reduced. A phytol chain (green) is connected by an ester linkage. Magnesium ion binds at the center of the structure.

Photosynthesis: Light reactions

- Two light absorbing stages:
  - Photosystem II
  - Photosystem I
- Electron transport chains – several complexes of proteins
- **Soluble carriers:**
  - Plastoquinone (Q), lipid soluble
  - **Plastocyanin, water soluble**

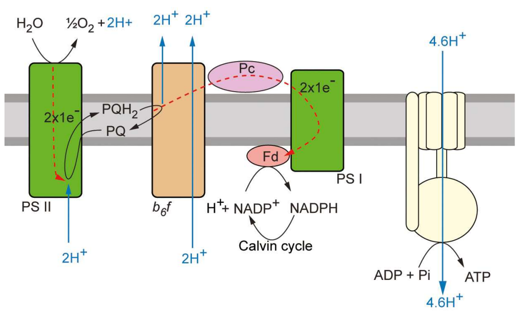
Photosynthesis: Light reactions





Photosynthesis: Light reactions
(electron transfer)

Photosynthesis: Light reactions
(proton translocation)

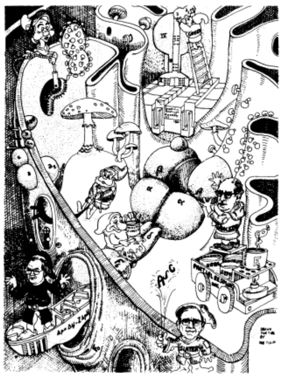


Photosynthesis: Light reactions

- **Products:**
  - Oxygen - released, essential for most life on earth
  - Proton motive force - used for ATP synthesis
  - **NADPH – used in biosynthesis, the Calvin cycle**

Photosynthesis: Light reactions

- Two light absorbing stages:
  - Photosystem II
  - Photosystem I
- Electron transport chains – several complexes of proteins
- **Soluble carriers:**
  - Quinone (Q), lipid soluble
  - **Plastocyanin, water soluble**



Some of the senior figures in the history of oxidative phosphorylation in action. Racker assembles the cold-labile F_1-ATP synthase (negatively stained with phosphotungstate), while Mitchell juggles protons and charges, Slater attempts to grasp the elusive squiggle (the non-existent chemical intermediate that was anticipated before the advent of the chemiosmotic theory), and Boyer induces a conformational strain which has proved to be more important in the ATP synthase itself rather than in coupling electron transport to ATP synthesis

Mitochondria related websites:

Mitochondria Research
http://www.mitochondrial.net/

Complex I home page
http://www.scripps.edu/mem/ci/

Joel Weiner Complex II related webpage
http://www.biochem.ualberta.ca/weinerlab/FrdABCD.htm

The *bc*1 complex home page
http://www.life.illinois.edu/crofts/bc-complex_site/

The Cytochrome Oxidase home page
http://www-bioc.rice.edu/~graham/CcO.html

Boris Feniouk ATP synthase home page
http://www.atpsynthase.info/

Antony Crofts bioenergetics course
http://www.life.illinois.edu/crofts/bioph354/

Bioenergetics course Leeds University
http://www.bmb.leeds.ac.uk/illingworth/oxphos/