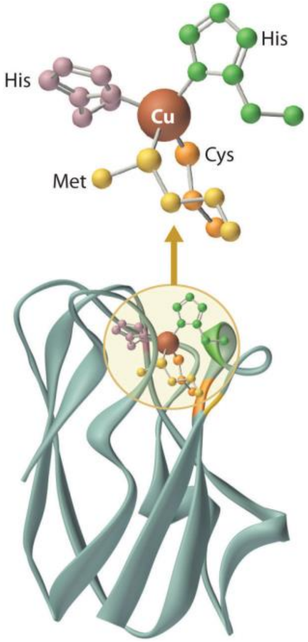
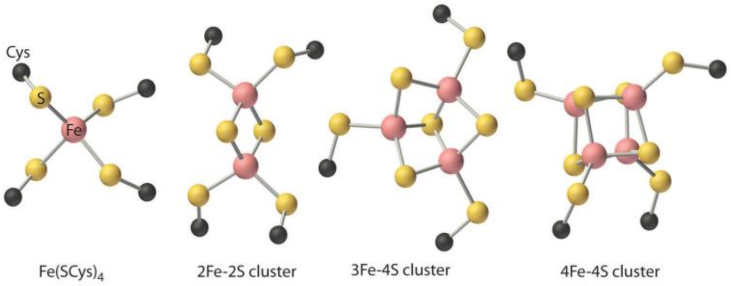
Química de Coordinación

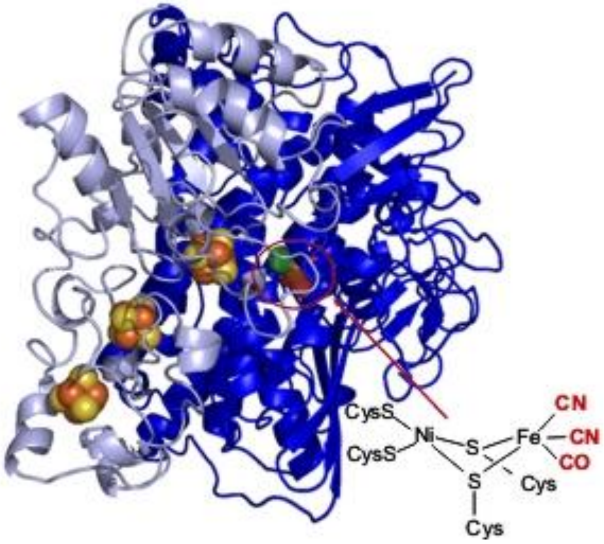
UNAM Mayo 26, 2022

peter.kroneck@uni-konstanz.de
https://www.researchgate.net/profile/Peter-Kroneck

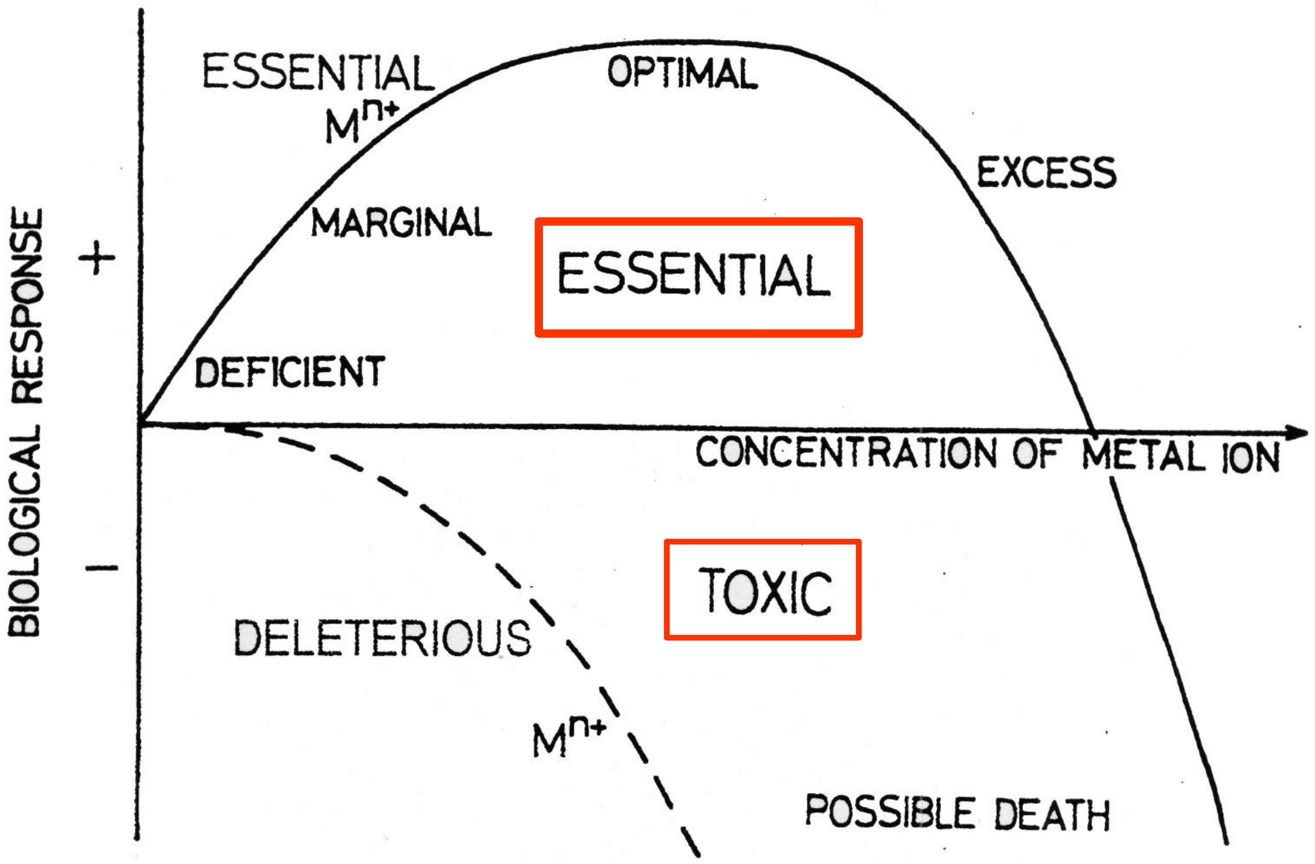
Iones metálicos en sistemas vivos
Metaloenzimas y Metaloproteínas







Bertrand Diagram
Dose-Function Relationship (Cr?)



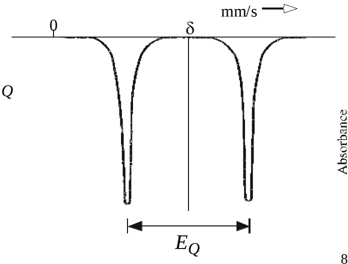
Biological response dependence on the concentration of an essential nutrient (solid curve) and of a deleterious substance (dashed curve)

Spectroscopy is important

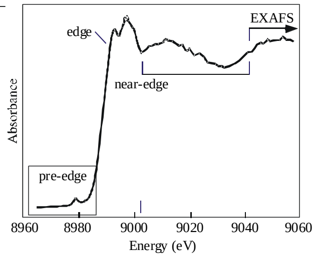
Practical Approaches to Biological Inorganic Chemistry, 1st Edition,
R.R. Crichton, R. Louro, Elsevier, 2013

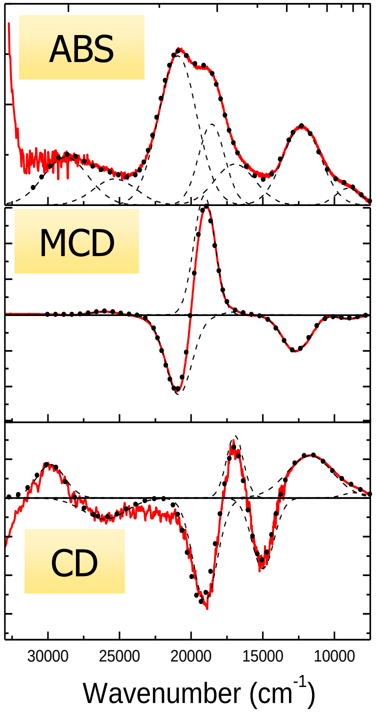
	Gamma	X-ray		UV/vis	Infrared	Microwave	Radio
eV	14000	8000	2000	4 - 1	0.1-0.01	10^{-4} -10^{-5}	10^{-6} -10^{-7}

Möss-
bauer

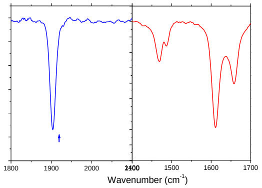


XAS
EXAFS

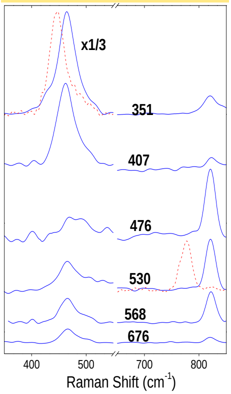




IR

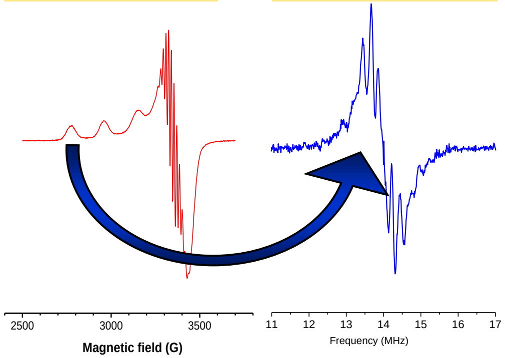


Raman



EPR

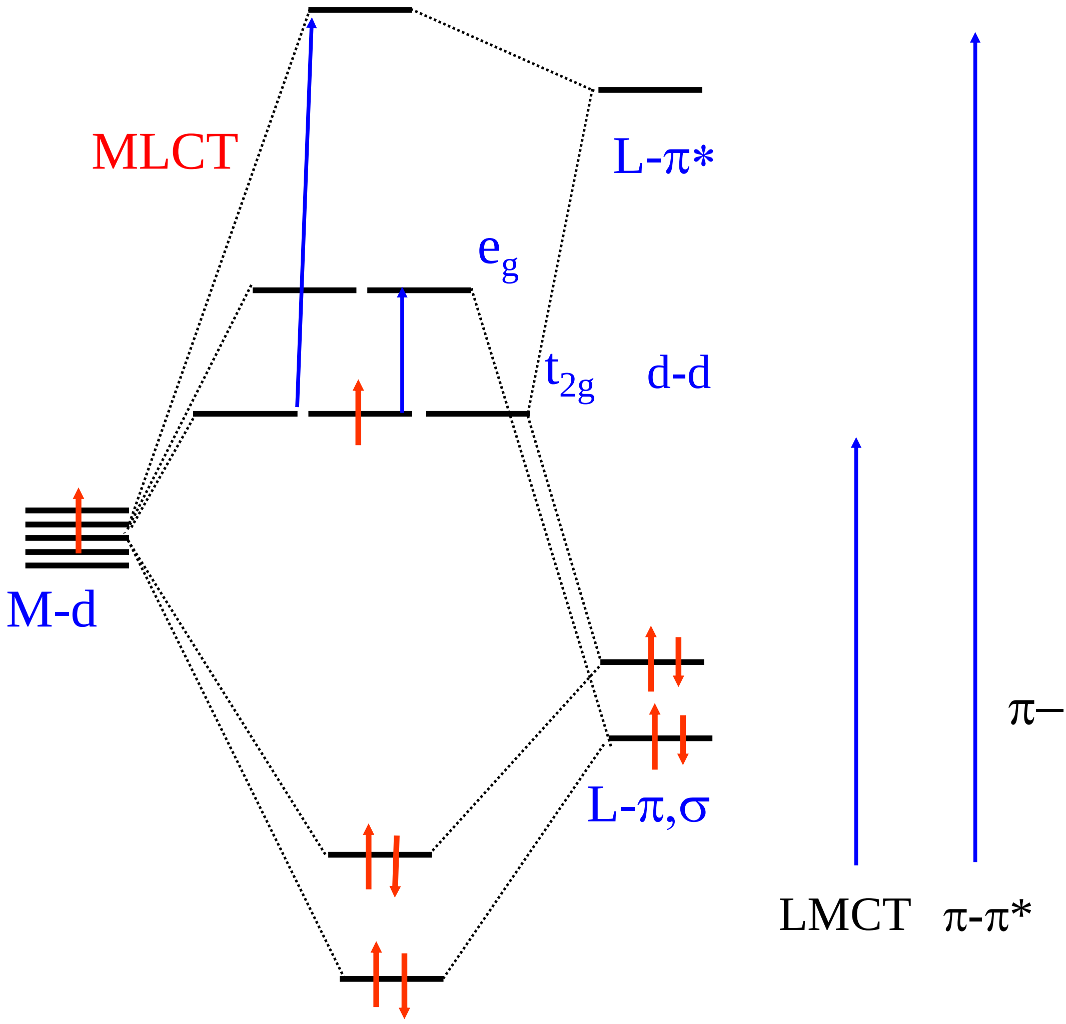
ENDOR



NMR

Optical Properties

Spin and Laporte allowed electronic transitions



Typical Intensities

d-d : $\varepsilon \sim$ 0-500 M^{-1} cm^{-1}

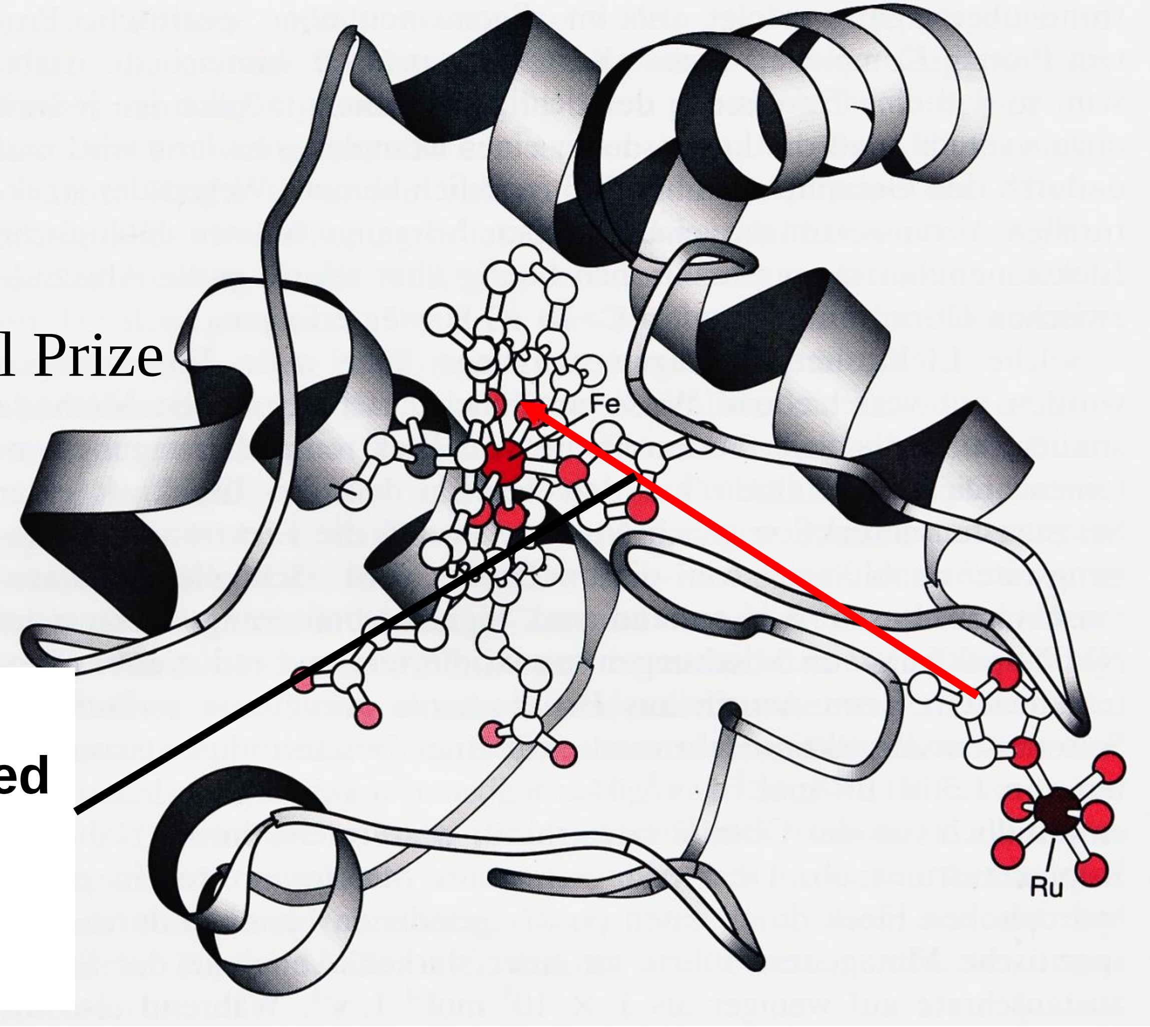
LMCT: $\varepsilon \sim$ 500-15,000 M^{-1} cm^{-1}

MLCT: $\varepsilon \sim$ 500-15,000 M^{-1} cm^{-1}

π−π* : $\varepsilon \sim$ 1000-100,000 M^{-1} cm^{-1}

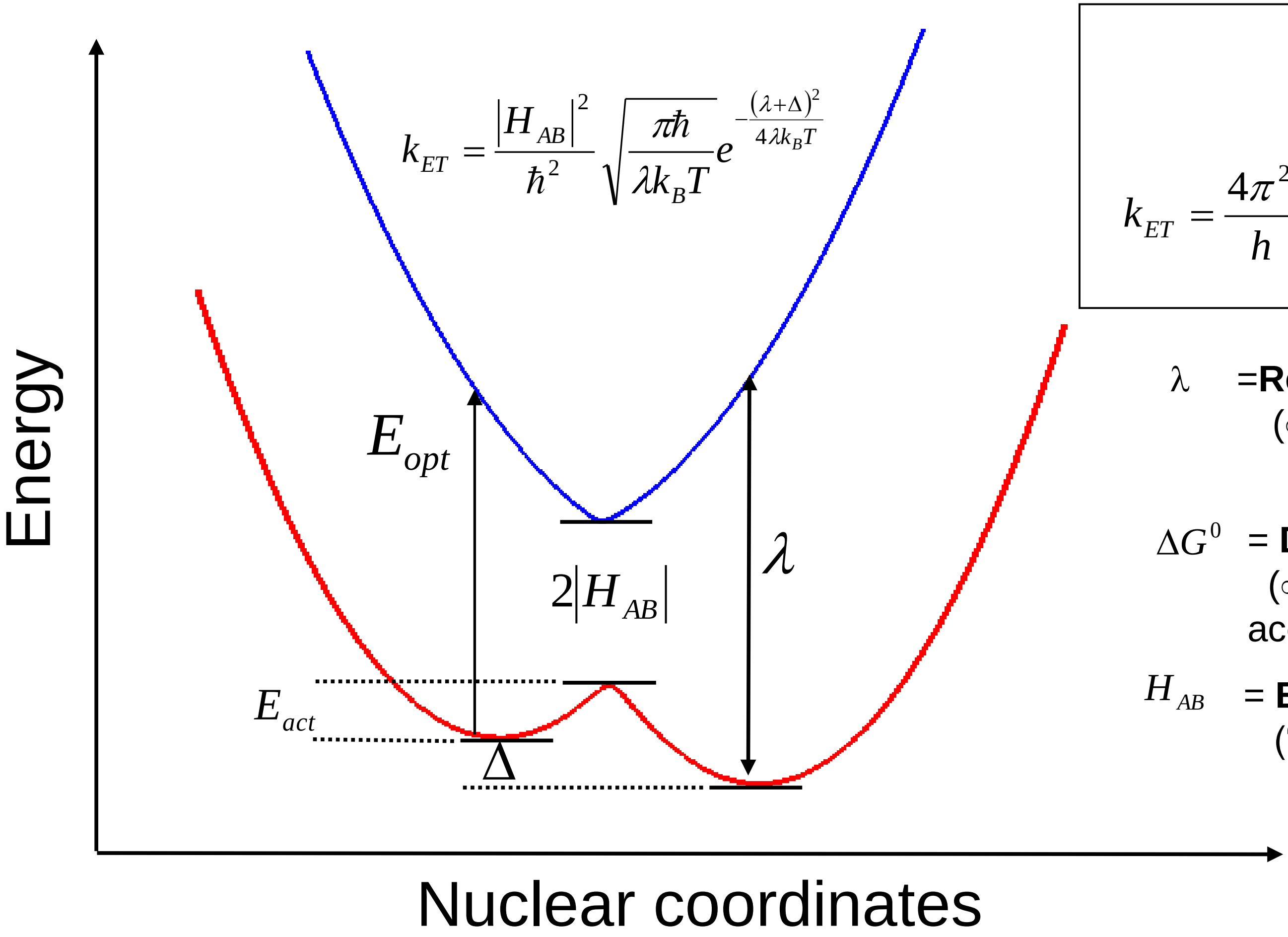
Problem: Electron Transfer through protein matrix

RA Marcus Nobel Prize
Chemistry 1992



Ru-Complex covalently attached to Fe protein cytochrome *c*

Electron transfer: Marcus Theory



$$k_{ET} = \frac{|H_{AB}|^2}{\hbar^2}\sqrt{\frac{\pi\hbar}{\lambda k_B T}}\,e^{-\frac{(\lambda+\Delta)^2}{4\lambda k_B T}}$$

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

$$k_{ET} = \frac{4\pi^2}{h}\underbrace{(4\pi\lambda kT)^{-1/2}\,e^{-\left(\frac{(\Delta G^0-\lambda)^2}{4\lambda kT}\right)}}_{\text{"Franck–Condon Factor"}}\quad\underbrace{H_{AB}^2}_{\text{"Electronic Factor"}}$$

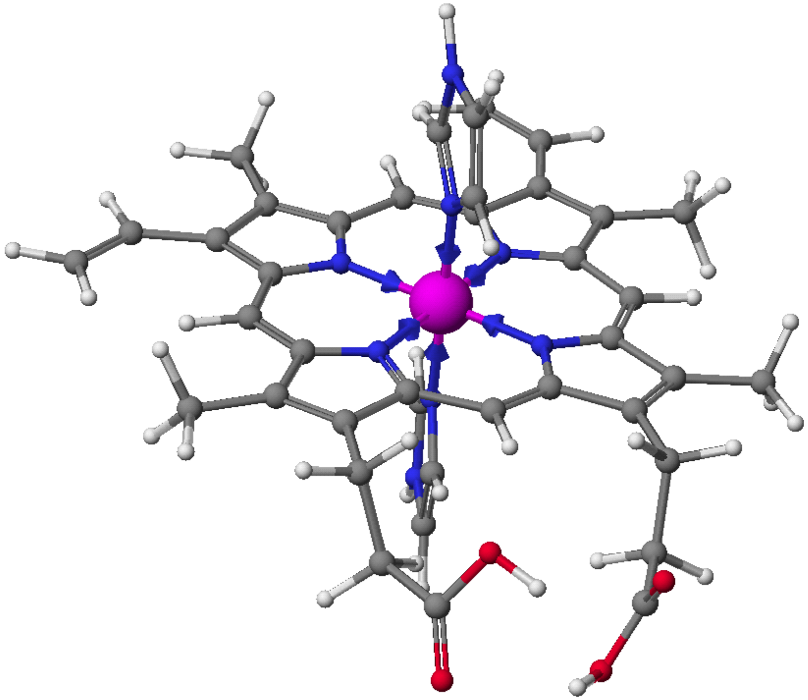
λ =**Reorganization energy**
($\propto$ structural change upon ET)

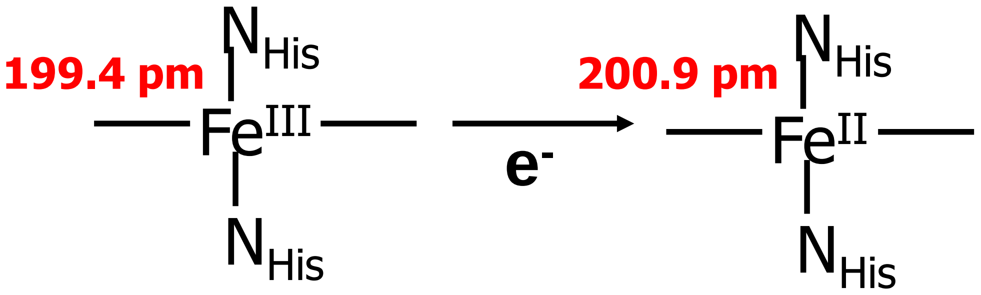
ΔG^0 = **Driving force**
($\propto$ difference of potentials donor vs acceptor)

H_{AB} = **Electronic Coupling**
("overlap of orbitals")

Low (zero) Reorganization Energy

Low-Spin Heme center





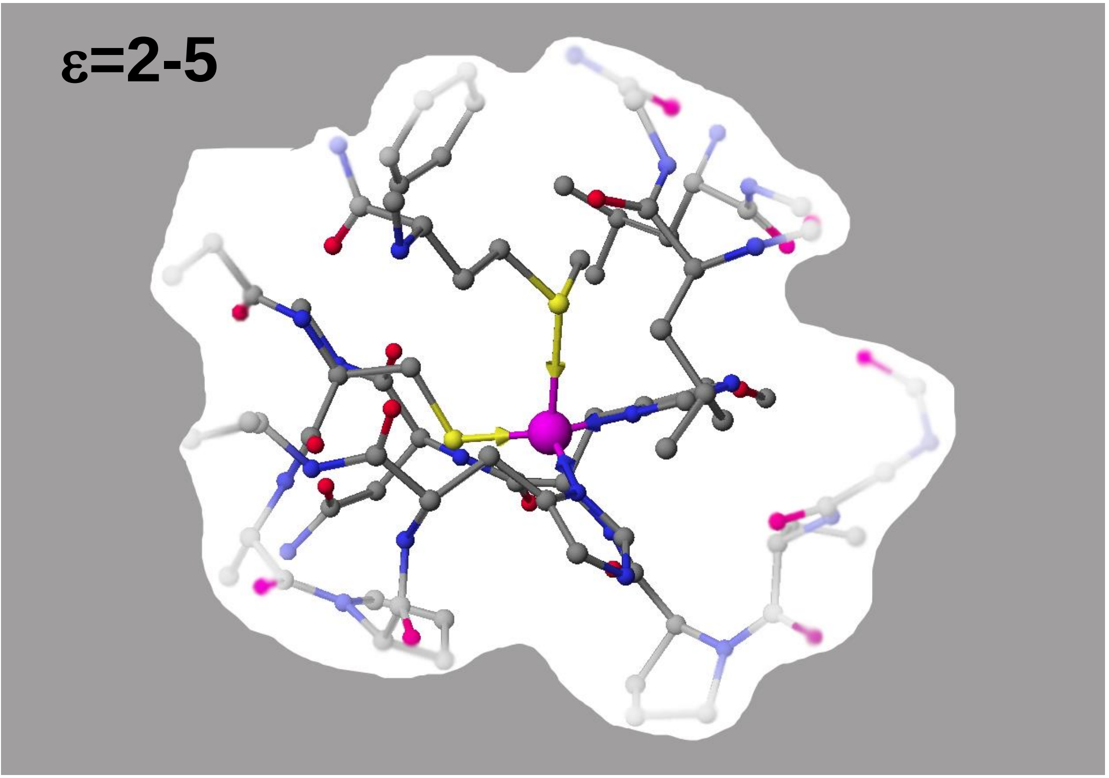
Reorganization Energy

in Cytochromes ≤ 4-5 kcal/mol

Sigfridsson, E.; Olsson, M.H.M.; Ryde, U. (**2001**) *J. Phys. Chem. B*, 105, 5546

Bio-ET/Catalysis
Influence of the protein environment

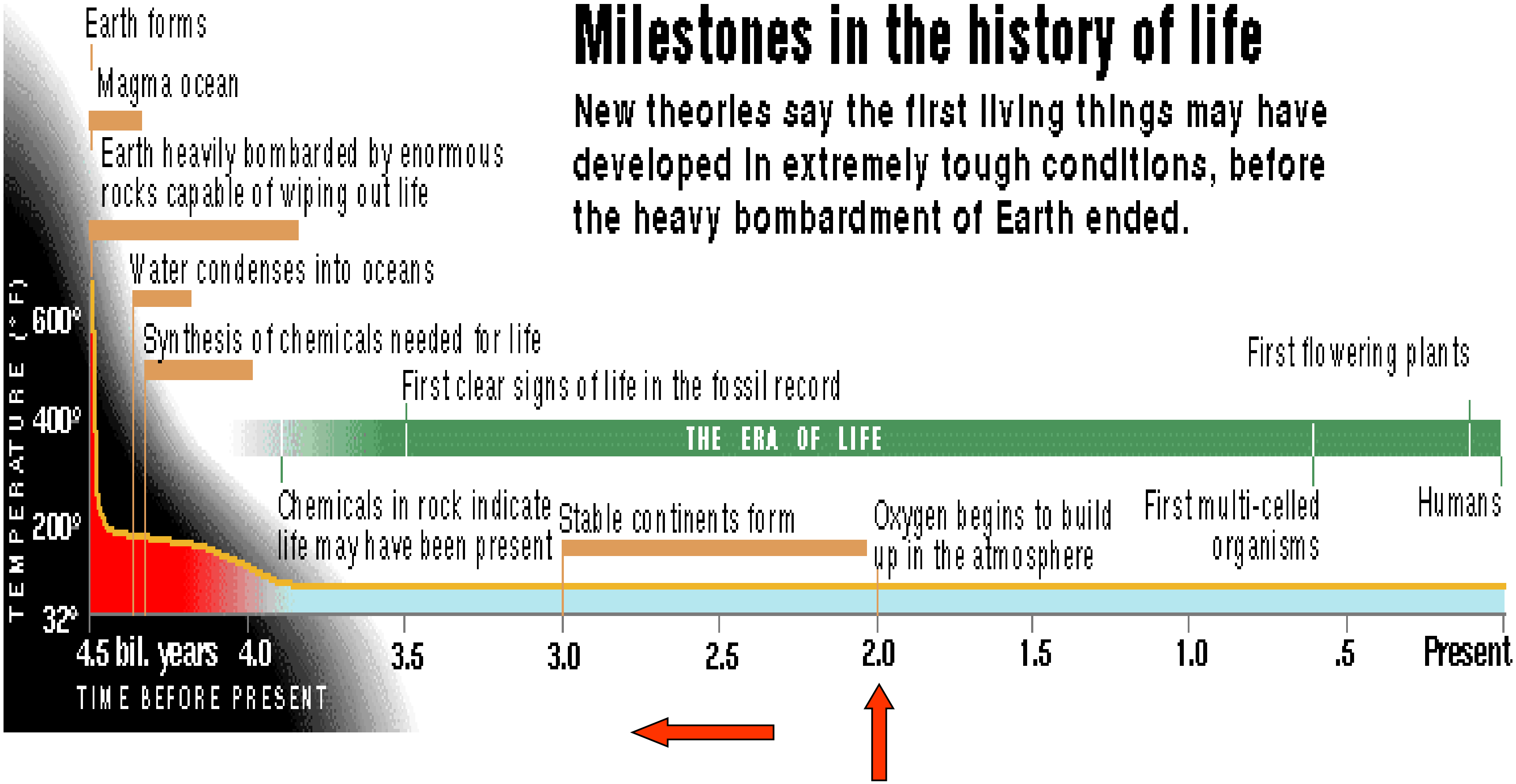
- Stabilization of unfavorable metal-ligand combinations
- Low polarity
  - ➢ Hydrophobic chemistry
- Preformed sites
  - ➢ ‚Entatic State‘
- Substrate specific channels and bindungs sites
- Fine-tuned acid/base chemistry
- Local production of intermediates – transition states



Holm, R.H.; Kennepohl, P.; Solomon, E.I. (1996) *Chem. Rev.*, 96, 2239

Forms of Life – From *Anaerobic* to *Aerobic*

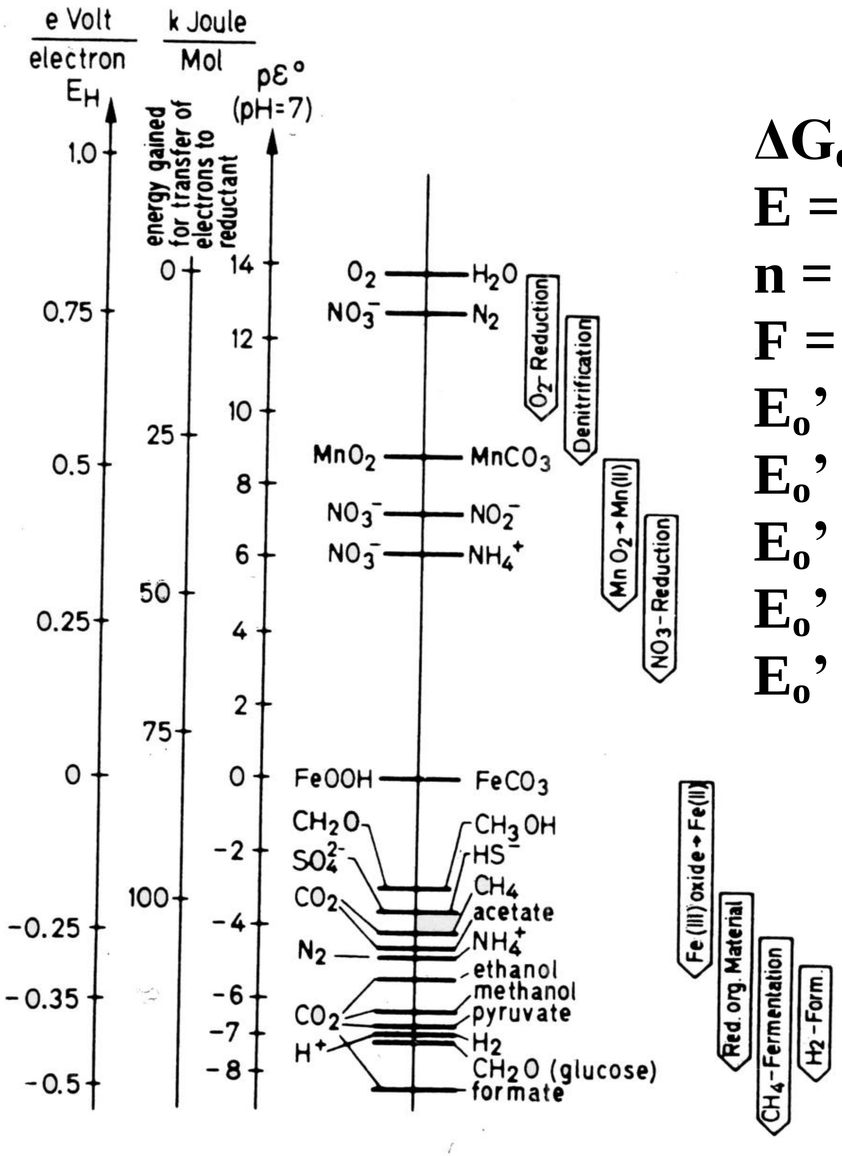
anoxic conditions (-O_2) *vs* oxic conditions (+O_2)



Metals, Microbes, Minerals: The Biogeochemistry of Life, P. Kroneck, M.E. Sosa Torres, Metal Ions in Life Sciences, Vol. 21, 2021

REDOX: Energy Conservation

Thauer et al., Bacteriol. Rev., 41, 100-180 (1977)



$\Delta G_o' = - n \cdot F \cdot \Delta E_o'$

$E = E_o + 2.3\, RT/nF \log_{10} ([OX]/[RED])$

n = number of electrons transferred

F = Faraday constant, R = Gas constant)

E_o' $H^+/1/2H_2$ = - 420 mV (H_2 1.0 atm)

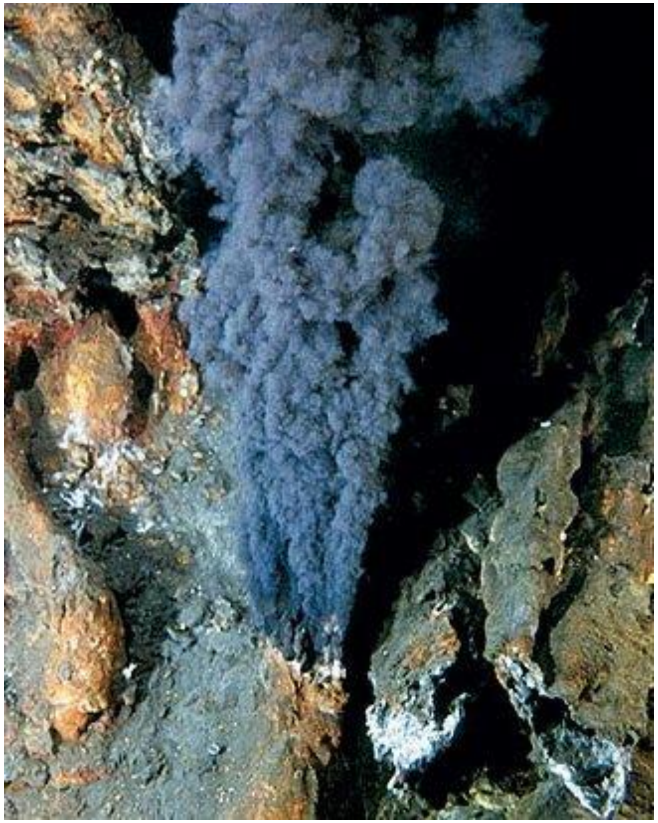
E_o' $NAD^+/NADH$ = - 320 mV

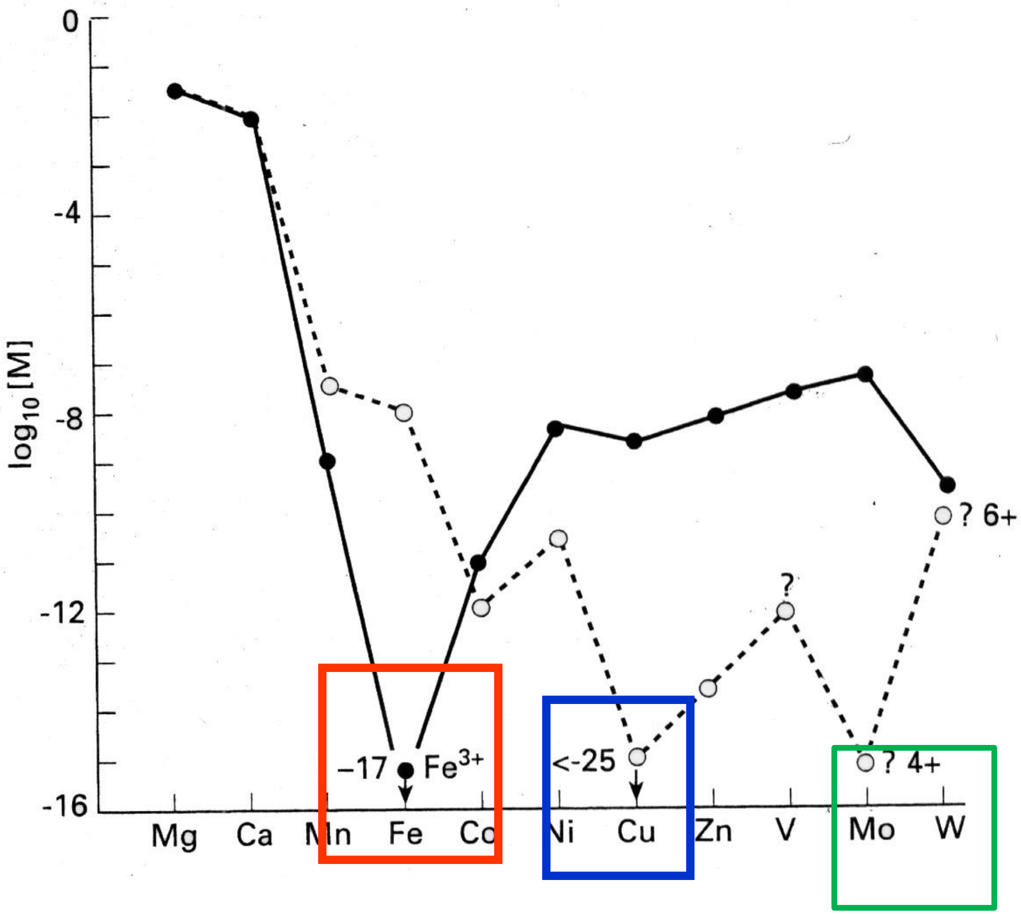
E_o' Cit. *c* ox/red + 220 mV

E_o' S^o/H_2S = - 240 mV

E_o' O_2(1.0 atm)/$2H_2O$ (55 M) = + 820 mV

Bioavailability of Essential Metals Fe, Cu, Mo, W
Solubility
(free elements, in aerated - *vs* sulfidic sea --)

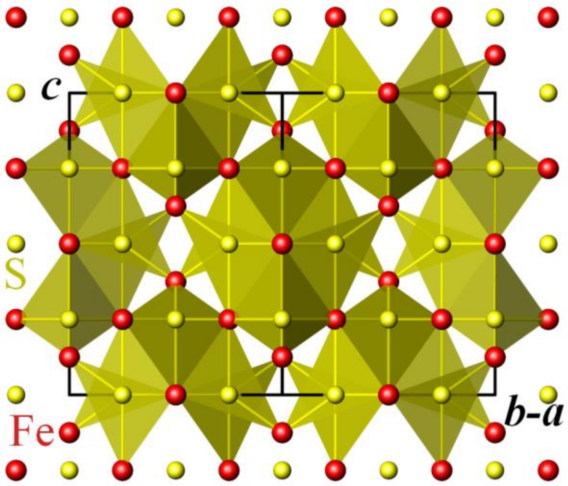


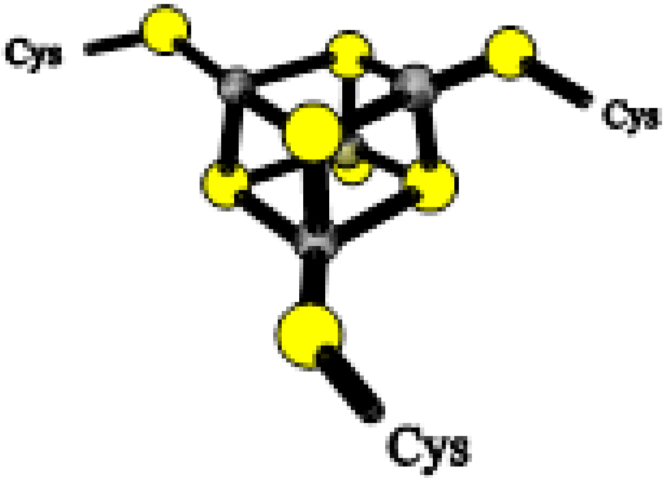


Early Life Catalysts

Candidate for a catalyst: the mineral Greigite, $[Fe_3S_4]$ (Fe(II)Fe(III)$_2$ mineral)

Note: its molecular structure is very similar to that of the [4Fe-4S] unit found in FeS proteins.

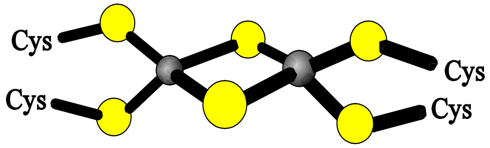




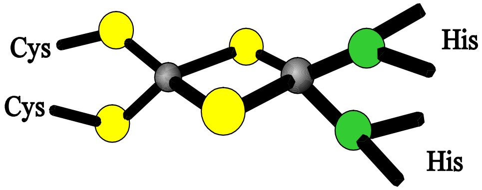
Basic [2Fe-2S] Centers

[2Fe-2S]-Cluster

2 Types:



Plant type [2Fe-2S] (Ferredoxin)



Rieske type [2Fe-2S]

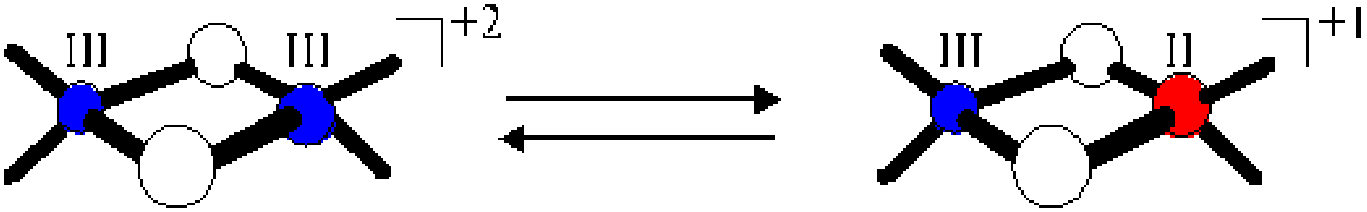
2 tetrahedrally coordinated Fe-Atoms, bridged via 2 acid-labile, inorganic sulfur (S^{2-})

Xtal structures known

Redox potentials: -420 to 0 mV (Plant type), +150 to +350 mV (Rieske)

[2Fe-2S] FeS center

Redox states of [2Fe-2S]-Cluster



ox state

mixed-valent state

high-spin Fe
S = 0 ; diamagnetic

delocalized

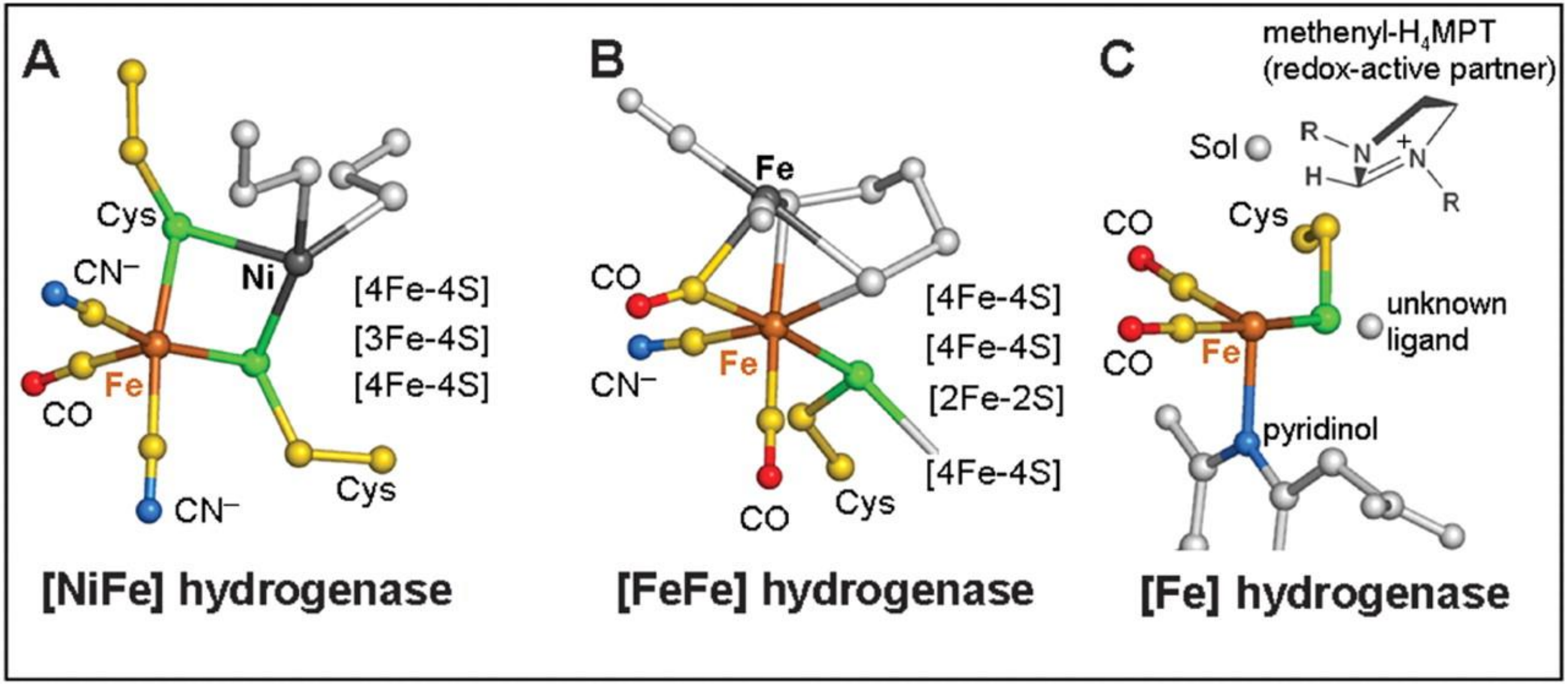
high-spin Fe
S = 1/2 ; paramagnetic; unpaired e^- delocalized over both Fe centers

→ discrete, Fe(II) and Fe(III) centers

- **antiferromagnetic coupling between both Fe centers**
- **$[Fe_2S_2]^+$ with S = 9/2 (2x Fe(2.5)); and $[Fe_2S_2]^0$ (2x Fe(II))**

Dihydrogen = most simple Fuel

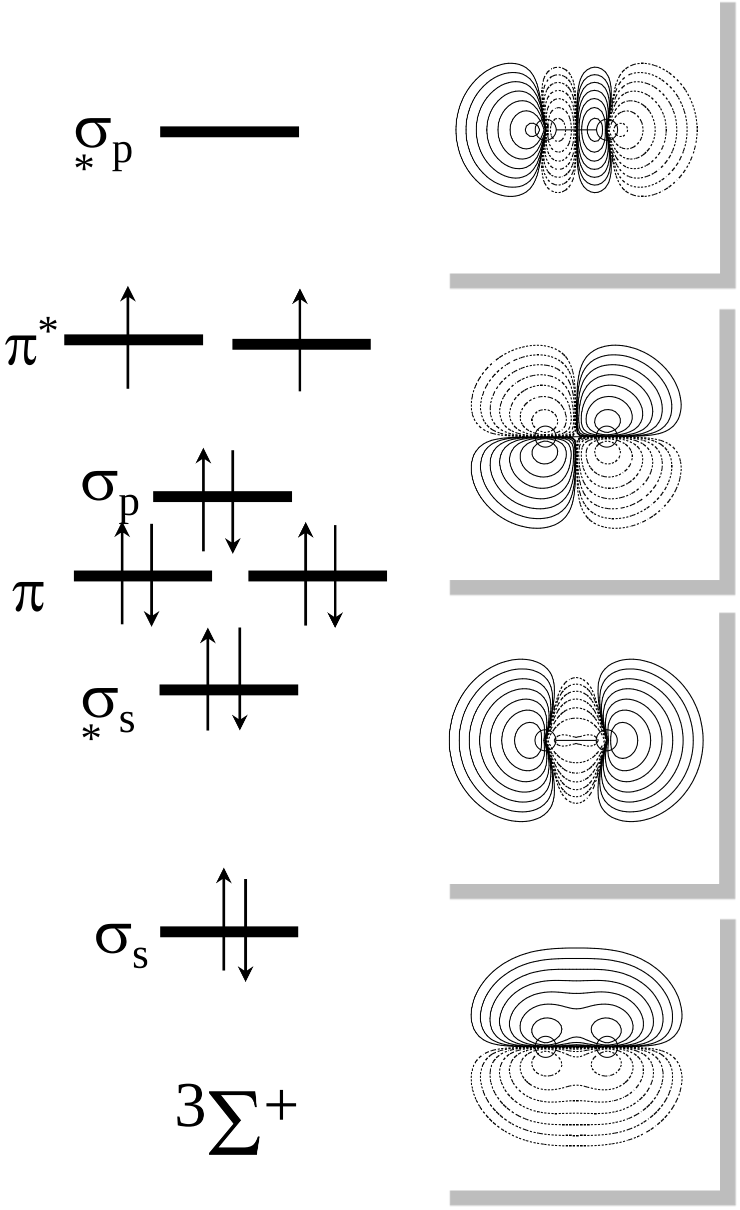
$$H_2 \rightleftarrows 2H^+ + 2e^- \; (H^- + H^+; \; \cancel{H\cdot + H\cdot})$$

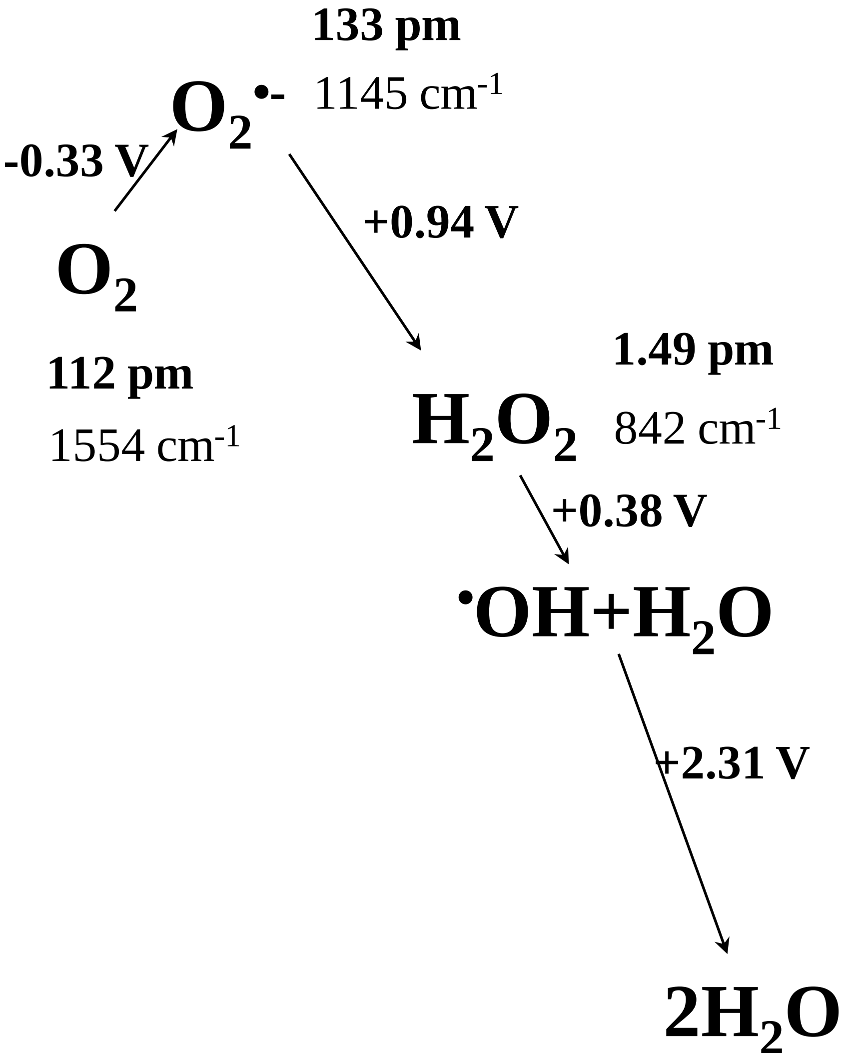


[NiFe] hydrogenase **[FeFe] hydrogenase** **[Fe] hydrogenase**

S. Shima et al. (2008), Science, *321*, 572 - 575

O_2 Activation





O_2

112 pm

1554 cm^{-1}

-0.33 V

$O_2^{\bullet -}$

133 pm

1145 cm^{-1}

+0.94 V

H_2O_2

1.49 pm

842 cm^{-1}

+0.38 V

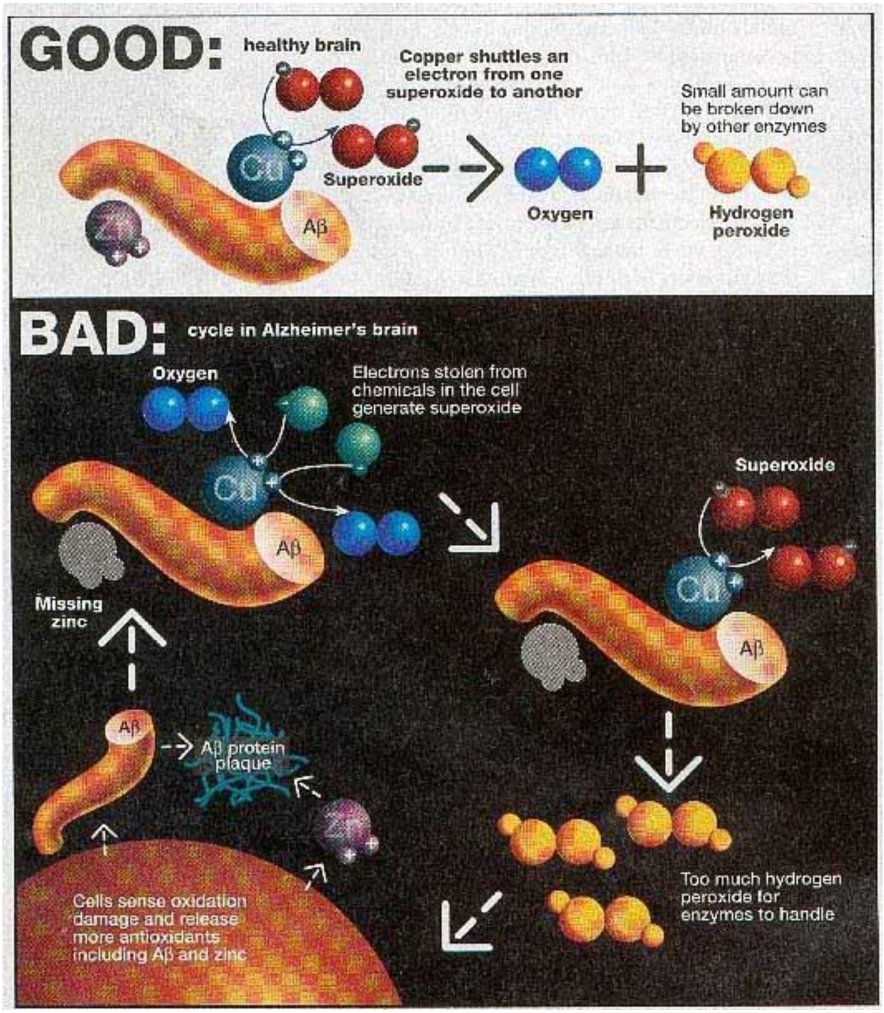
$^{\bullet}OH + H_2O$

+2.31 V

$2H_2O$

E_0 *vs*. NHE at pH 7.25

Alzheimer Disease – Aß Protein Plaque



Initial Steps ?? Depending on status of brain: increased formation of $O_2^{\cdot -}$ and H_2O_2 (Reactive Oxygen Species = ROS)

Cu and Fe proteins
Activation and Transformation of O_2

Otto H. Warburg
Nature Reviews (2011)
11, 325

Otto Heinrich Warburg (1883–1970), was a German physiologist, medical doctor and Nobel laureate. He earned double doctorates in chemistry and medicine, and won the Nobel Prize in 1931, for his research into cellular respiration, showing that cancer thrives in anaerobic (without oxygen) or acidic conditions. He was one of the twentieth century's leading biochemists. He was nominated an unprecedented three times for the Nobel prize for three separate achievements.

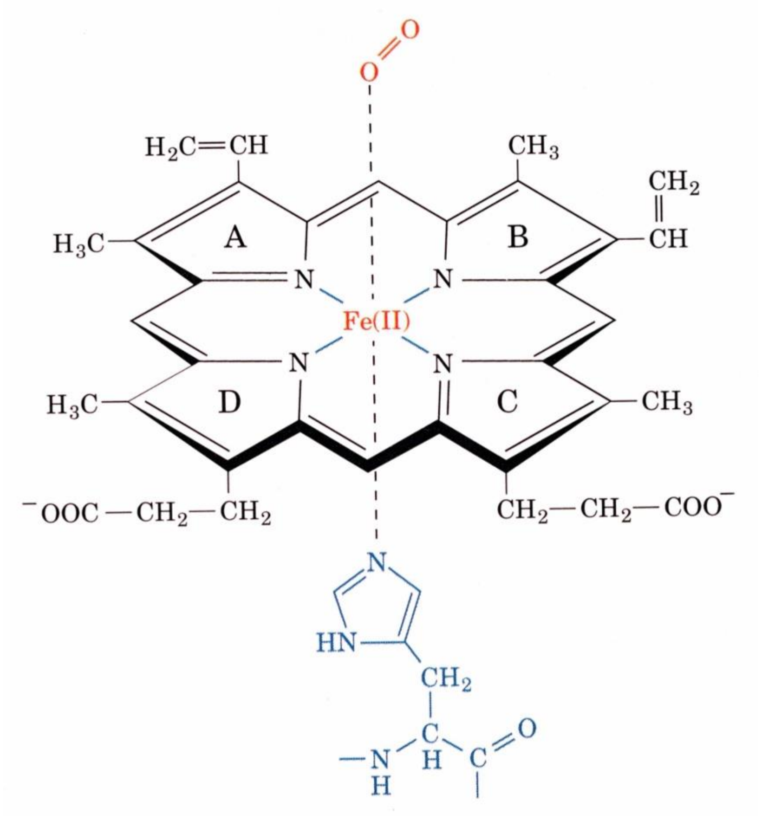
"Cancer, above all other diseases, has countless secondary causes. But, even for cancer, there is only one prime cause. Summarized in a few words, the prime cause of cancer is the replacement of the respiration of oxygen in normal body cells by a fermentation of sugar."

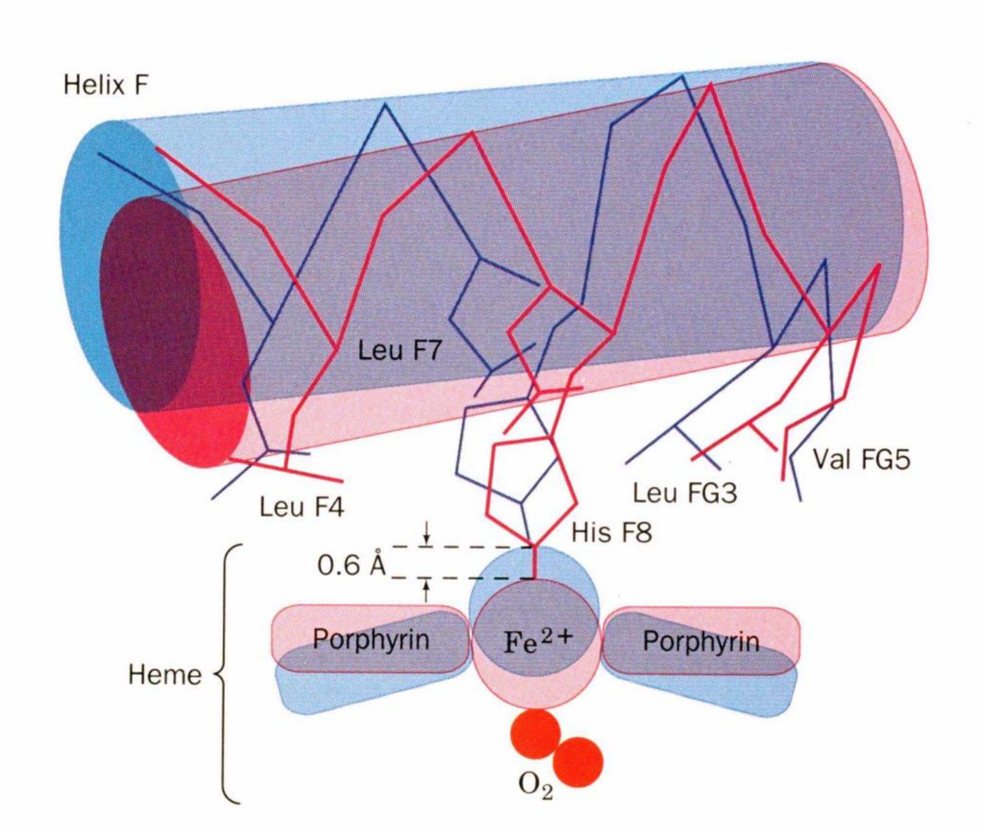
O. Warburg (1956), "On the origin of cancer cells", Science 123, 309–14

Activation of O_2 – Reaction Types

- **Reversible binding of O_2 – Myoglobin, Hemoglobin (Fe), Hemocyanin (Cu-Cu)**
- **$O_2^{\cdot -}$ dismutation – Superoxide Dismutase (Mn, Fe, Ni, Cu, Zn)**
  $O_2^{\cdot -} + O_2^{\cdot -} + 2H^+ \rightarrow O_2 + H_2O_2$
- **H_2O_2 decomposition – Catalase (Mn, heme-Fe)**
  $2\ H_2O_2 \rightarrow 2\ H_2O + O_2$
- **Oxygenases (focus on Monooxgenase Cytochrome P450)**
  $R\text{-}H + O_2 + NADPH + H^+ \rightarrow R\text{-}OH + H_2O + NADP^+$
- **Oxidases (2-electron reduction to H_2O_2; Fe, Cu)**
  $O_2 + 2e^- + 2H^+ \rightarrow H_2O_2$ (focus on Cu enzyme Galactose Oxidase)
- **Oxidases (4-electron reduction to H_2O; heme-Fe, Cu)**
  $O_2 + 4e^- + 4H^+ \rightarrow 2\ H_2O$ (focus on Cu enzyme Ascorbic Acid Oxidase and Fe,Cu enzyme Cytochrome *c* Oxidase)

Reversible O_2 Binding
Myoglobin and Hemoglobin





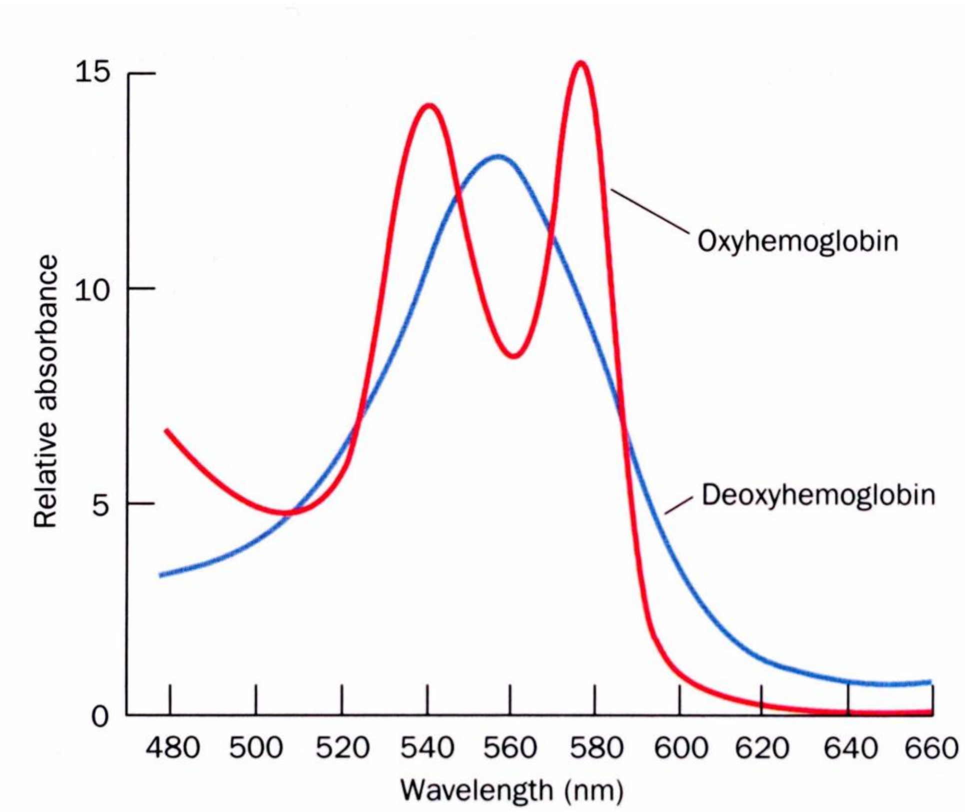
The Fe must be in the Fe(II) (ferrous oxidation) state

Binding of O_2 rearranges the electronic distribution and alters the d orbital energy.

This causes a difference in the absorption spectra.

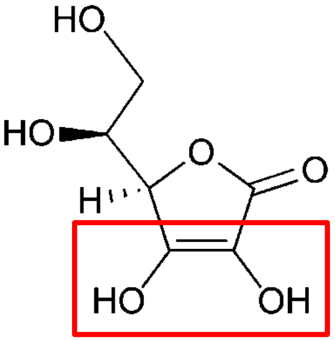
Bluish for deoxy Hb, Redish for Oxy Hb

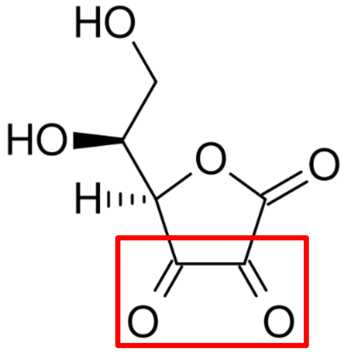
Measuring the absorption at 578 nm allows an easy method to determine the percent of O_2 bound to hemoglobin.



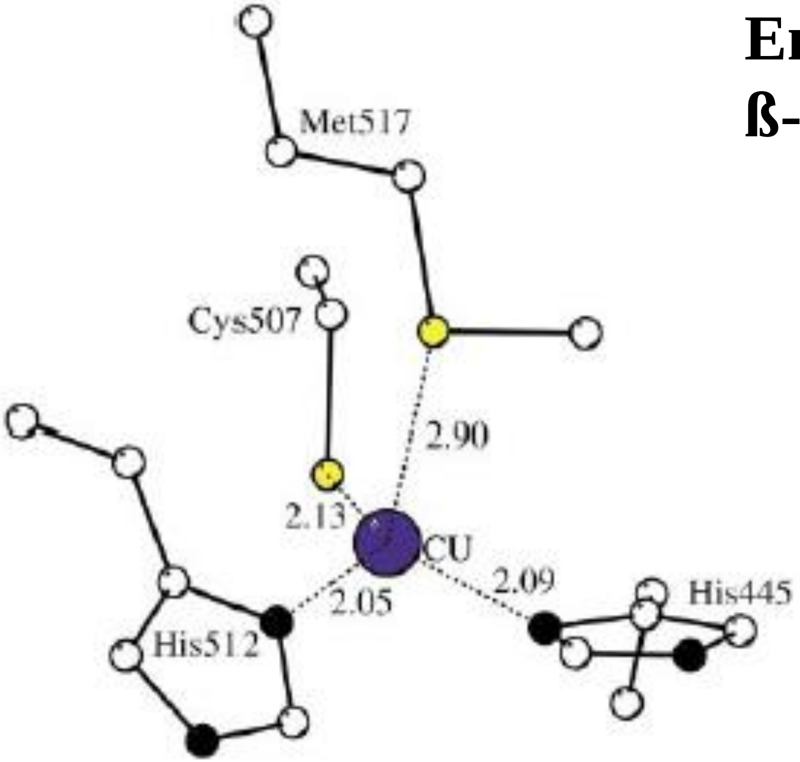
Plant Ascorbic acid (Vitamin c) oxidase

Multi-Copper oxidase (8Cu/homodimer) PDB code 1AOZ

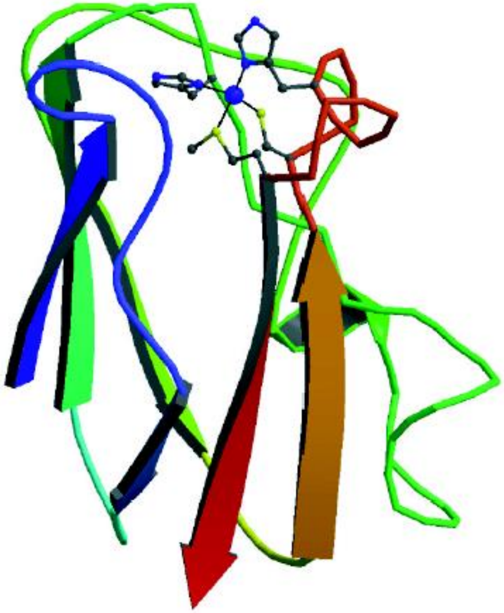




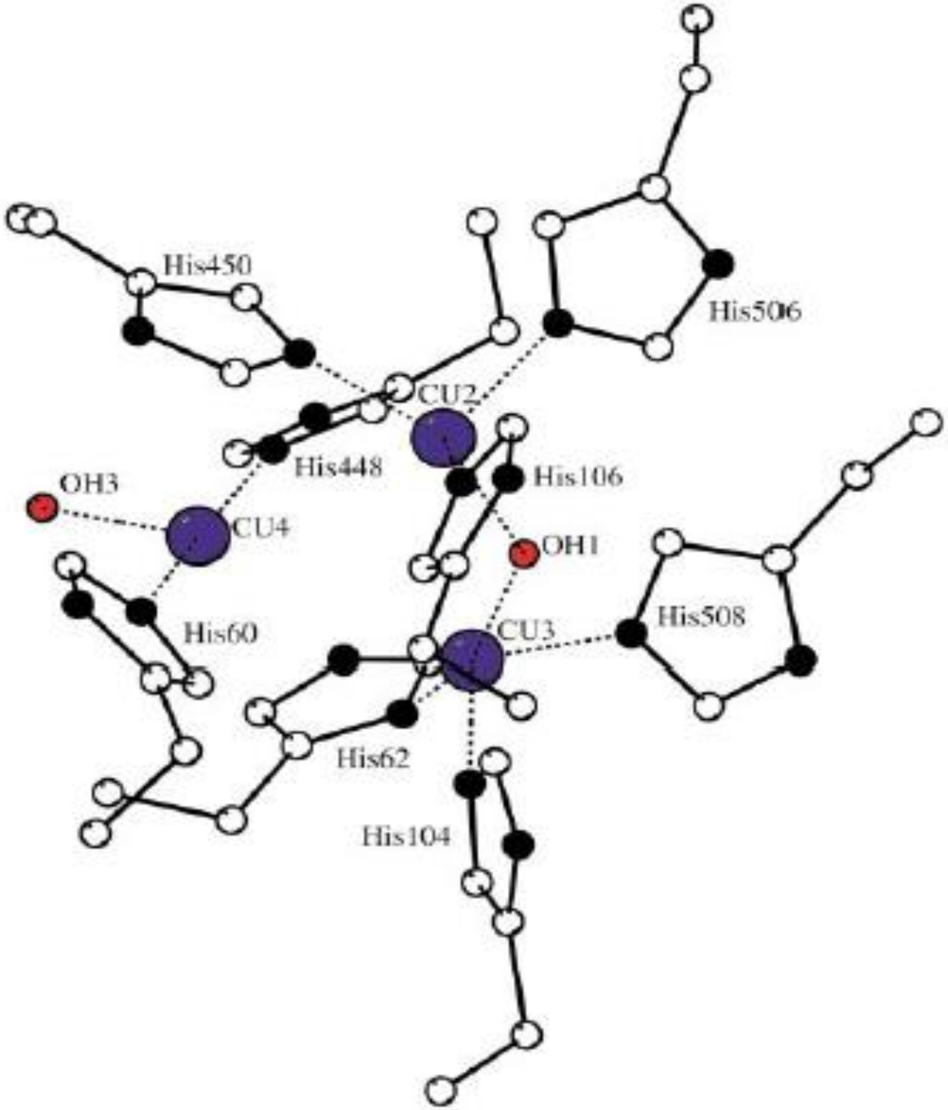
Type 1 Cu ET center (like in Plastocyanin)



Entrance point for electrons
ß-barrel structural module



Trinuclear Cu center - O_2 to H_2O reduction site



Cytochrome *c* oxidase

S. Yoshikawa, K. Muramoto, K. Shinzawa-Itoh Annu. Rev. Biophys. (2011) 40, 205–23
Tomoya Hino, et al. SCIENCE (2010) 330, 1666-1670

$O_2 + 4H^+ + 4H_i^+ + 4e^- \rightarrow H_2O + H_2O + 4H_o^+$ (+ 818 mV)

$N_2O + 2H^+ 2e^- \rightarrow N_2 + H_2O$ (+1355 mV)
$2NO + 2H^+ + 2e^- \rightarrow N_2O + H_2O$ (+1175 mV)

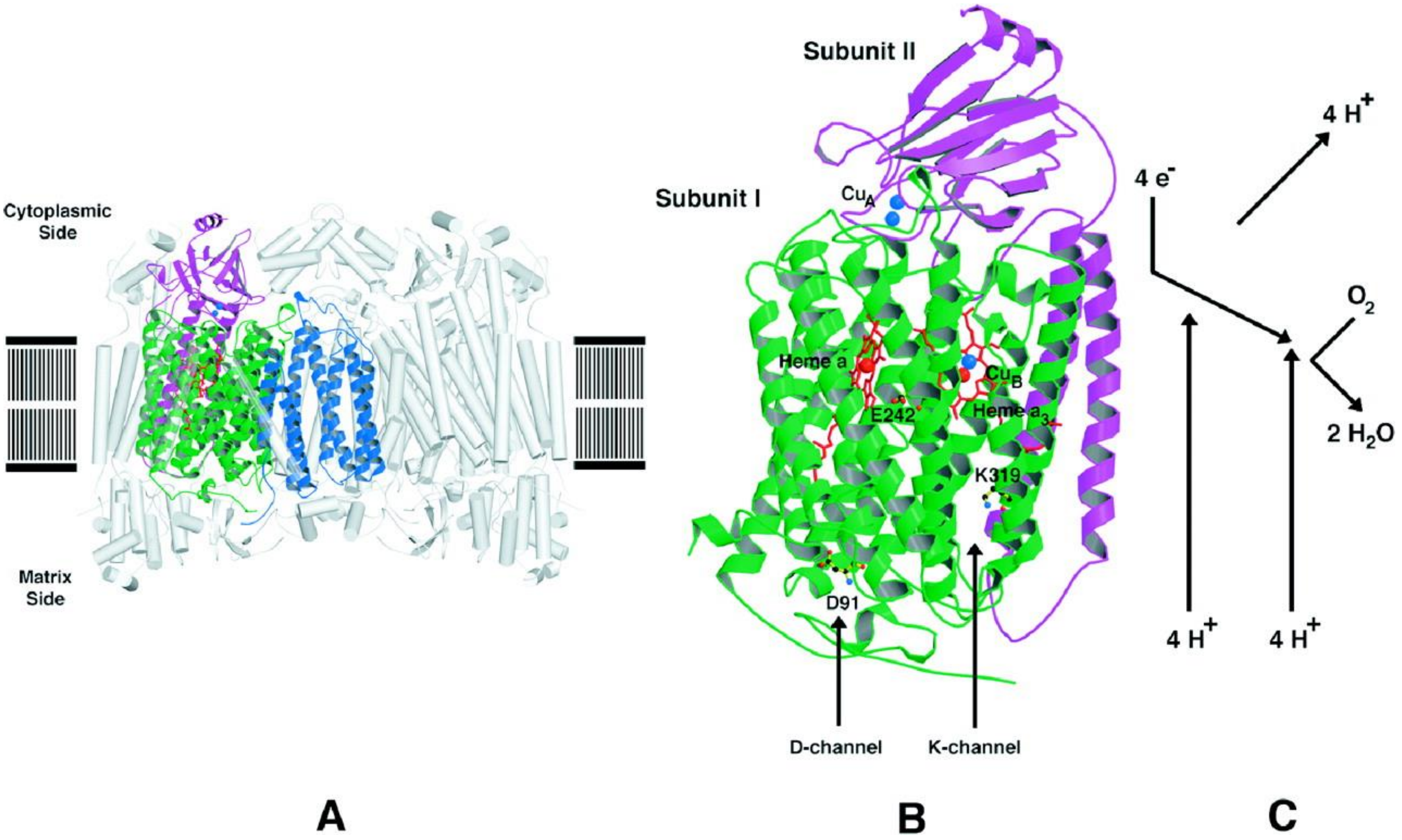
metals (CuA, Fe-heme, Mg, Zn)

e^- transfer (redox; tyrosyl radical ?), H^+transfer (pump)

metal centers: CuA → ET; Fe-CuB → O_2 reduction

Cytochrome *c* oxidase

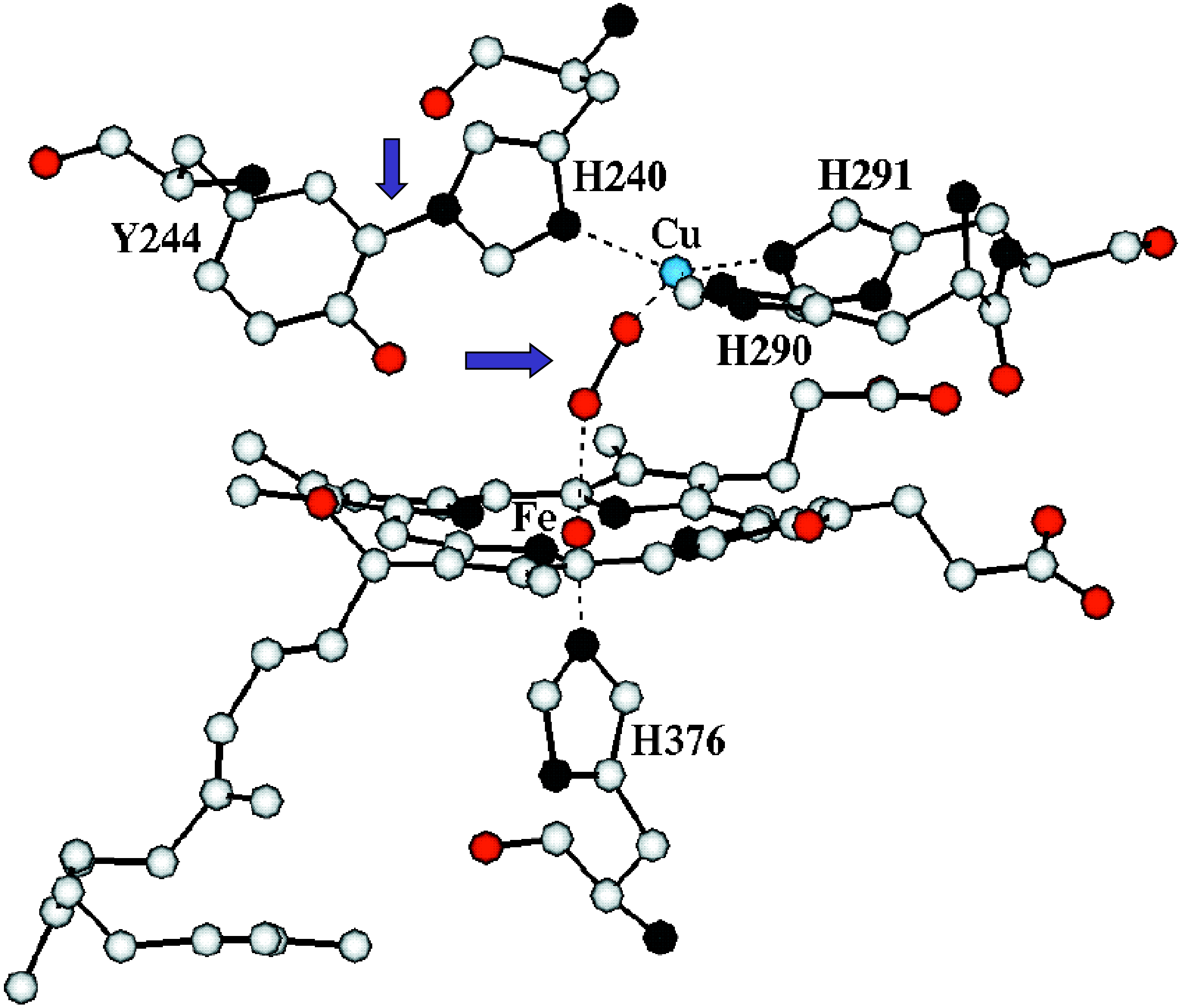
$$O_2 + 4H^+ + \mathit{4H_i^+} + 4e^- \rightarrow H_2O + H_2O + \mathit{4H_o^+}$$



M Saraste Science (1999) 283,1488-1493

Site of O_2 Reduction

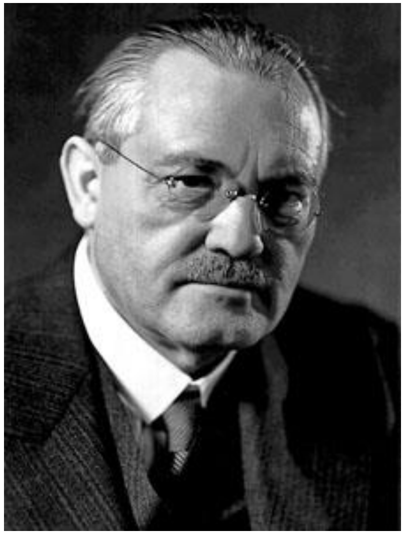
(Fe(III)-Cu(II) State – covalent link Tyr-His)



Heterogenous Catalysis

How to cleave kinetically stable compounds

Fritz Haber
1868 - 1934
Nobel Prize 1918



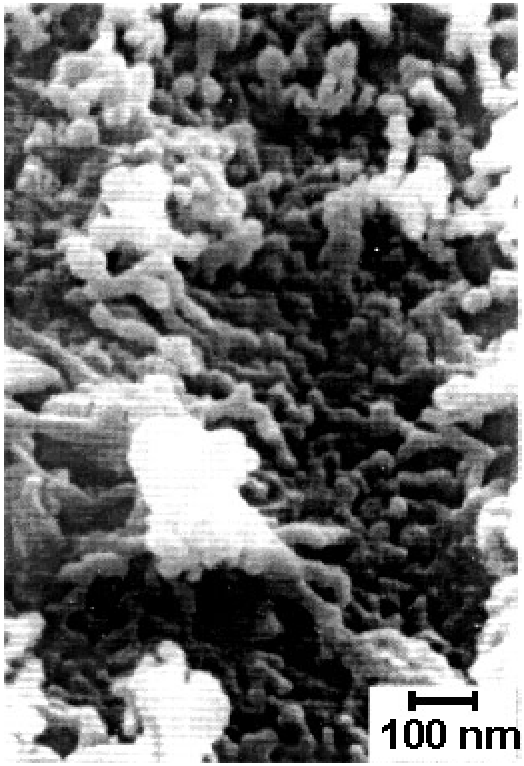
Carl Bosch
1874 - 1940
Nobel Prize 1931

Gerhard Ertl, Fritz-Haber Institute Berlin
(Nobel Laureate/Chemistry/2007)

$$N_2 + 3\ H_2 \rightarrow 2\ NH_3$$

Catalytic synthesis of ammonia

(Haber- Bosch process)



Technical conditions: T ≈ 400°C, p ≈ 300 bar
promoted iron catalyst

BASF S6-10 catalyst (at. %)

	Fe	K	Al	Ca	O
Bulk composition	40.5	0.35	2.0	1.7	53.2
Surface –					
unreduced	8.6	36.2	10.7	4.7	40.0
reduced	11.0	27.0	17.0	4.0	41.0
cat. active spot	30.1	29.0	6.7	1.0	33.2

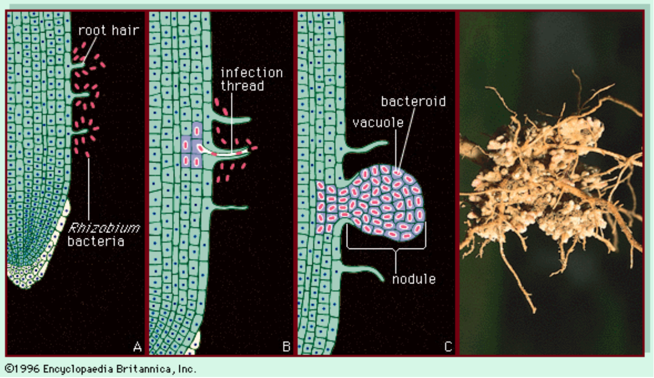
G. Ertl, D. Prigge, R. Schlögl & D. Weiss, J.Catal. 79 (1983), 359

Biological N_2 Fixation

Microorganisms can do the job under „normal conditions“ (T, P)

- **free living soil bacteria, e.g. *Azotobacter vinelandii***
- **Cyanobacteria with specialized cells, e.g. *Anabaena sp.*, *Nostoc sp.*)**
- ***Rhizobia* which live in special plant organelles (root noudles)**

The process, however, is costly. Plants have to deliver up to 25% of their photosynthetically produced ATP to N_2 fixing bacteria in the root nodules.



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Note: N_2 Fixation is done by anaerobes.

N_2 Fixation

http://en.wikipedia.org/wiki/Nitrogenase

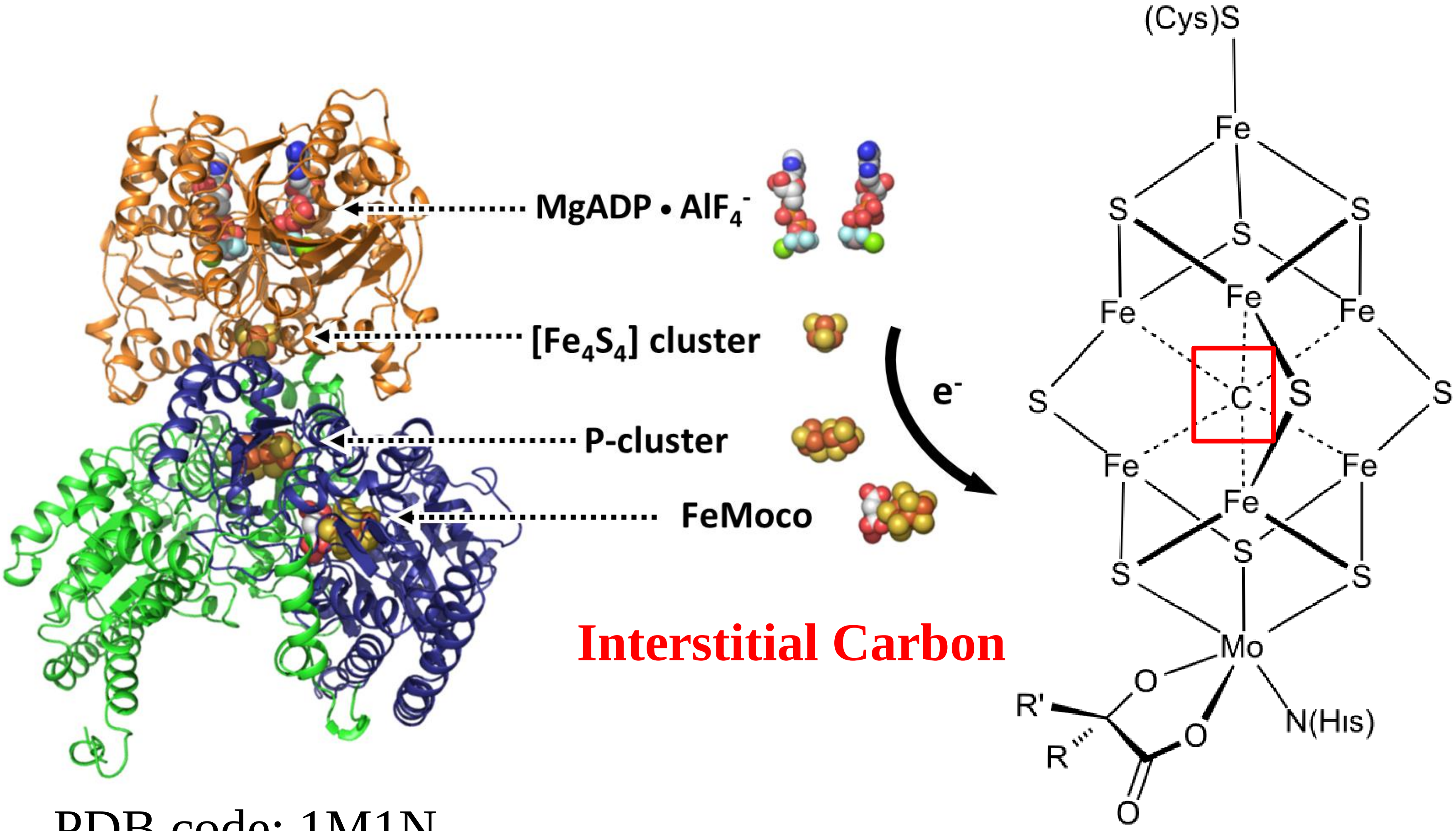
$$\mathrm{N_2 + 8H^+ + 16\ Mg^{2+}ATP + 8e^-}$$

$$\Big\downarrow$$

$$\mathrm{2NH_3 + H_2 + 16\ Mg^{2+}ADP + 16\ P_i}$$

Basic Structural Elements of Nitrogenase

Hu, Ribbe, Acc. Chem. Res. (2010), 43, 475-484; Ramaswamy, Science (2011), 334, 914-915

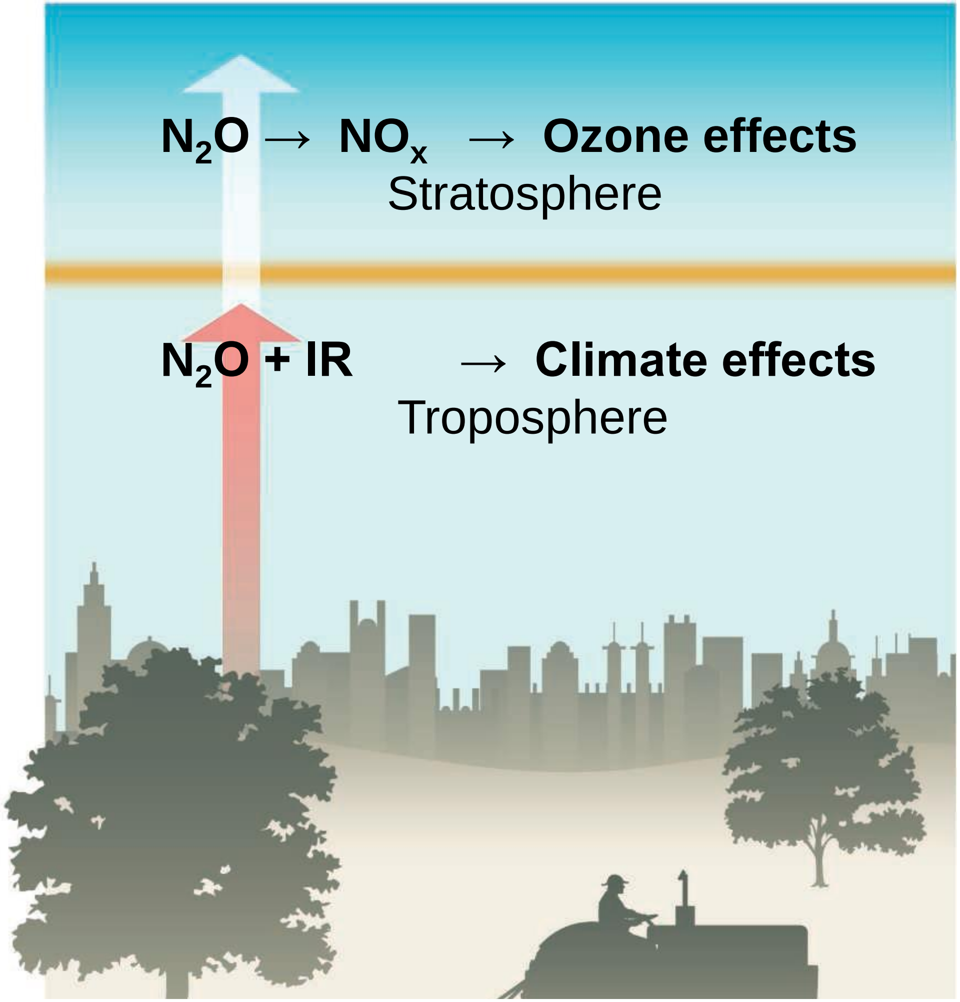


Interstitial Carbon

PDB code: 1M1N

N_2O – Potent Greenhouse Gas

Wuebbles, Science (2009), <u>326</u>, 56-57

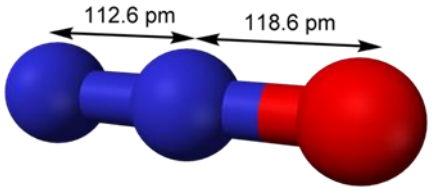


$N_2O \rightarrow NO_x \rightarrow$ Ozone effects

Stratosphere

N_2O + IR → Climate effects

Troposphere



Steady increase in the atmosphere

3rd only to CO_2 and CH_4

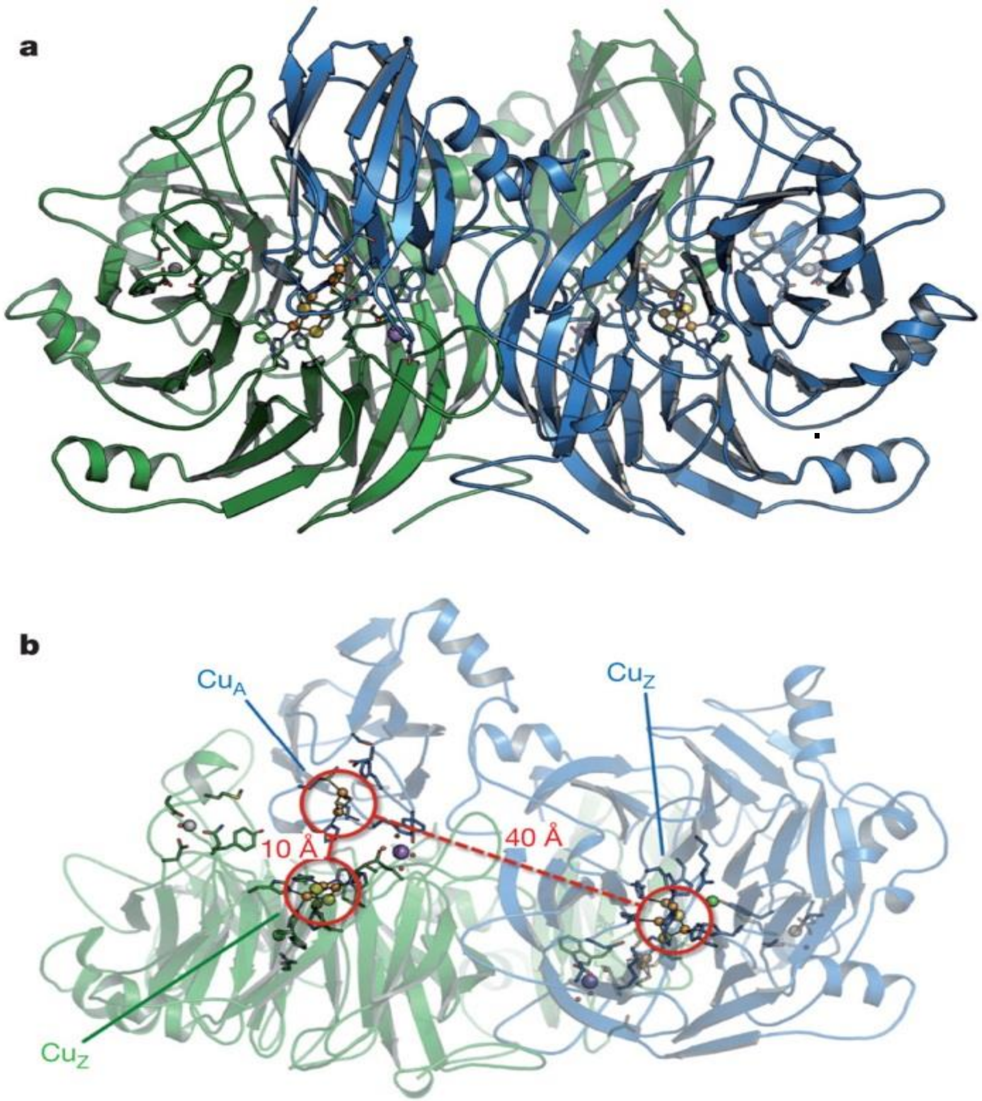
N_2O is isoelectronic to CO_2

green-house effect of N_2O/CO_2 ~ 200

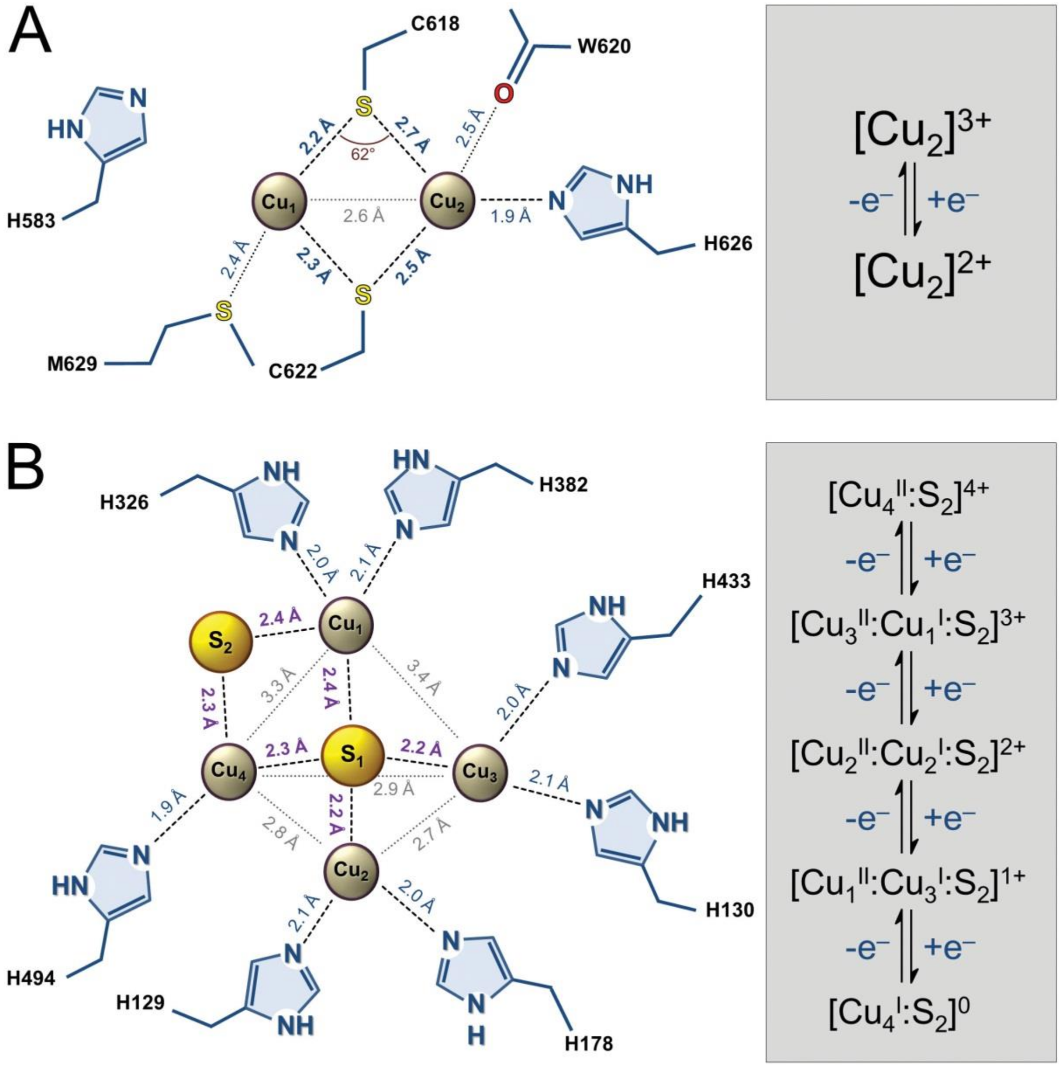
http://epa.gov/climatechange/emissions
/usinventoryreport.html

Nitrous Oxide Reductase is a head-to-tail homodimer, with 6 Cu/monomer

A. Pomowski, W.G. Zumft, P.M.H. Kroneck, O. Einsle (2011) Nature 477, 234-237

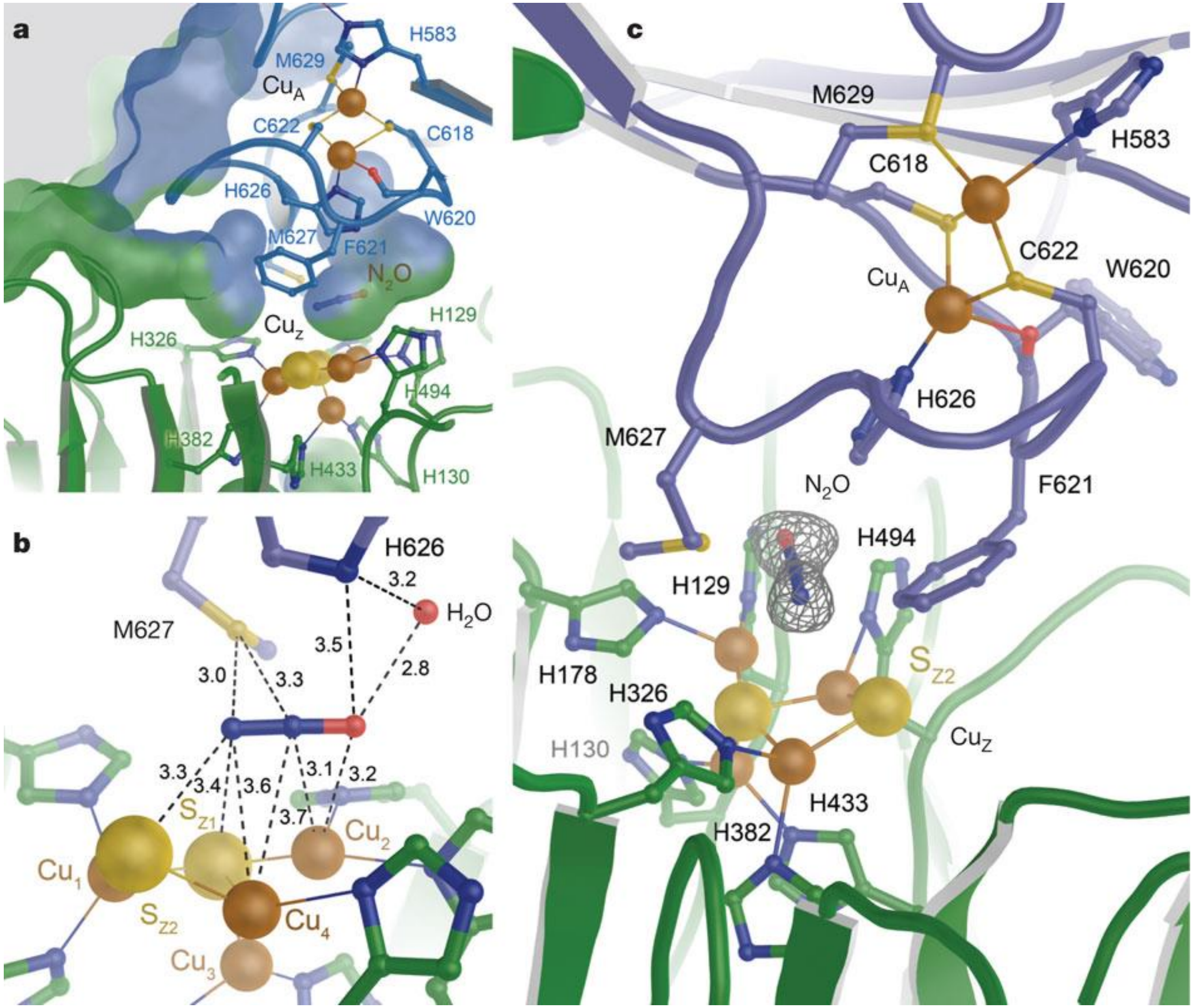


Two novel Copper-Sulfur sites
(A) the dinuclear CuA, (B) the tetranuclear CuZ

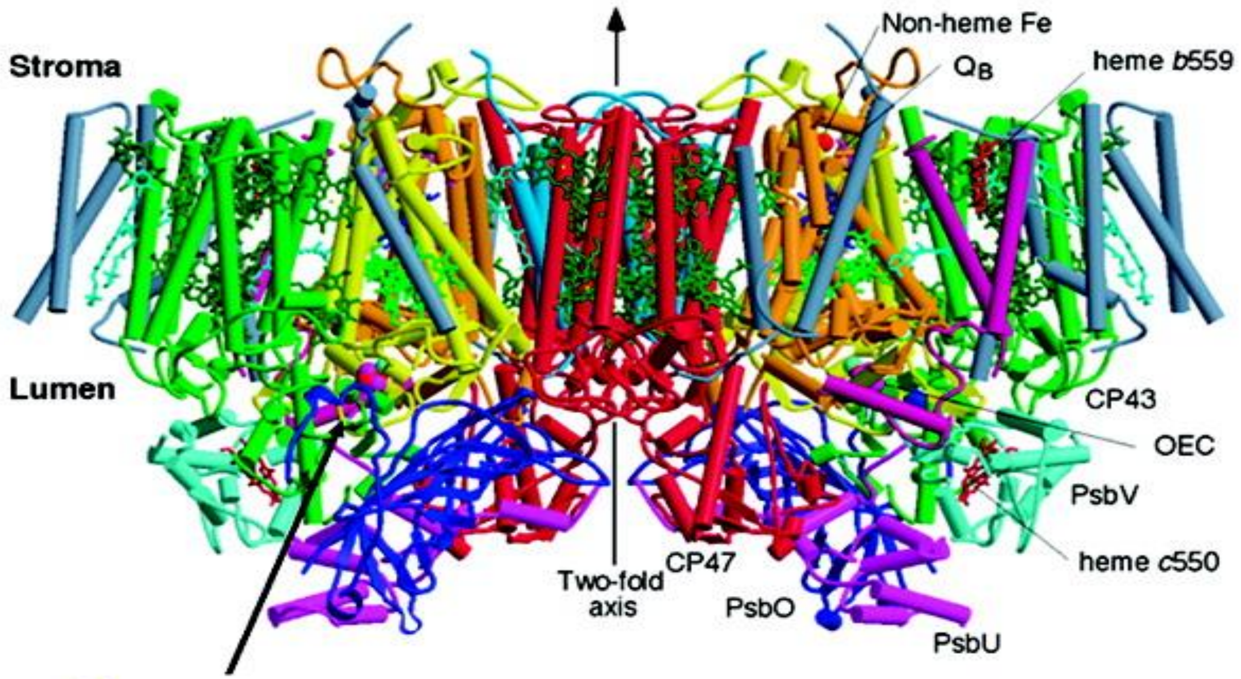


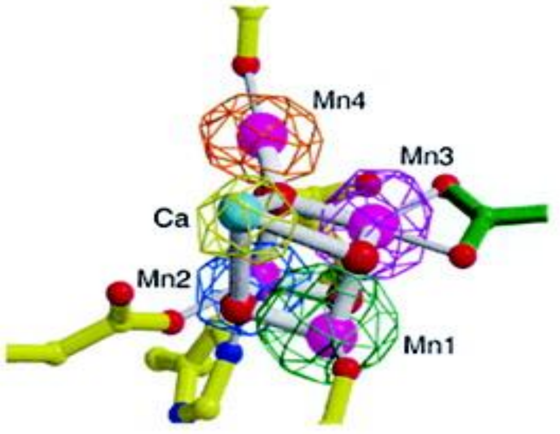
Catalysis: CuA and CuZ operate *in concert*

Xtal under N_2O pressure



The O_2 Evolving Complex – Splitting of H_2O at a $CaMn_4$ catalytic center





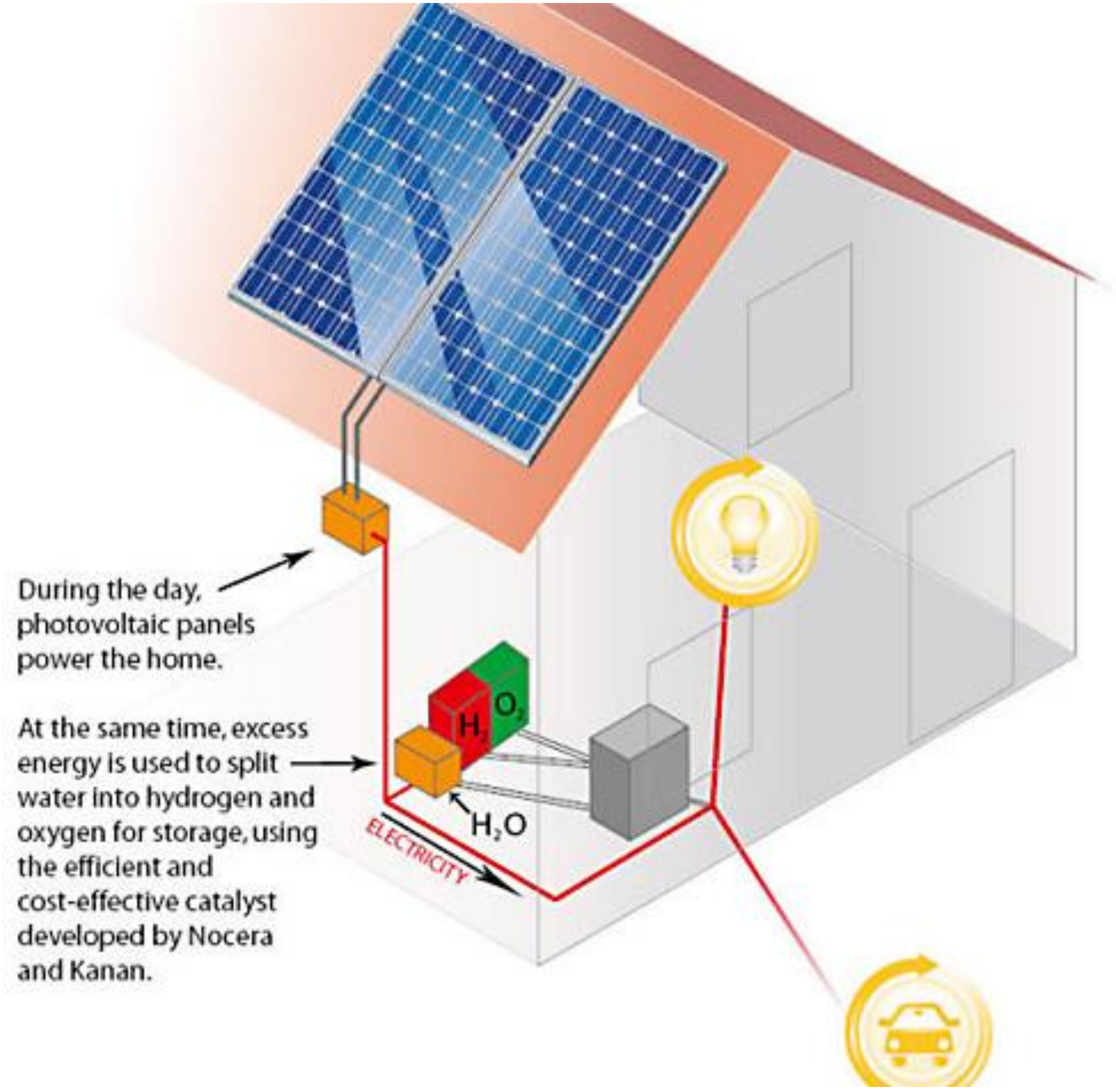
Photosystem II

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

Published in: James Barber; *Inorg. Chem.* **2008,** 47, 1700-1710.
DOI: 10.1021/ic701835r

The Future ? Photosynthesis – *Sun Catalytix*

Dan Nocera, MIT
Acc. Chem. Res. 2012,
45, 767-776



During the day, photovoltaic panels power the home.

At the same time, excess energy is used to split water into hydrogen and oxygen for storage, using the efficient and cost-effective catalyst developed by Nocera and Kanan.

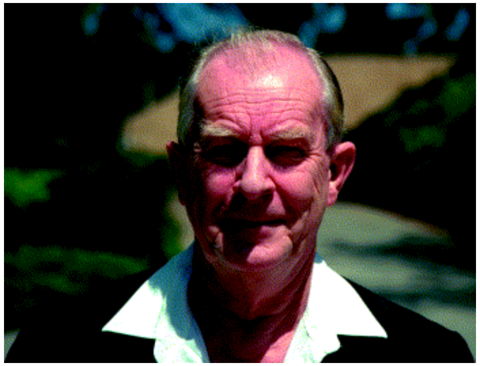
The Future ? Photosynthesis and Modern Housing

Photosynthetic Microalgae

© picture-alliance/dpa

Conclusion

The structural and functional properties of metal ions in biological systems can be understood by combining the principles of coordination chemistry with the knowledge of the unique environment created by biomolecules



Bo G. Malmström, Göteborg, 1927-2000