489--Lectures 3 and 4

Fundamentals of Inorganic Chemistry

(with special relevance to biological systems)

Some slides courtesy of Prof. Xuan Zhao (U. Memphis) and Prof. Yi Lu (U. Illinois)

Fundamentals of Inorganic Chemistry

(with special relevance to biological systems)

Themodynamic Properties

- Preferred oxidation states/coordination # and ligand donor sets
- Hard-Soft Acid-Base Concept
- Chelate Effect
- pKa Effect
- Redox Potentials

Kinetic Aspects

- Ligand Exchange or Substitution Reactions
- Reactivity at Ligand
- Electron Transfer

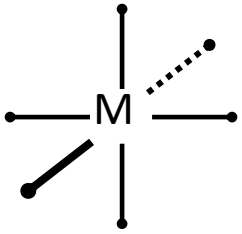
Lippard, S. J.; Berg, J. M. *Principles of Bioinorganic Chemistry*; University Science Books: Mill Valley, CA, 1994.

Oxidation States Available to Essential Bulk and Trace Metals

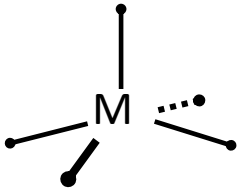
Metal	*Available Oxidation States*						
Na	1						
K	1						
Mg		2					
Ca		2					
V		2	(3)	(4)	(5)		
Cr		2	(3)	(4)	(5)	(6)	
Mn		2	3	4	(5)	(6)	(7)
Fe	1	2	3	4	(5)		
Co	1	2	3				
Ni	1	2	3				
Cu	1	2					
Zn		2					
Mo		2					

The parentheses indicate oxidation levels not normally found in biological molecules.

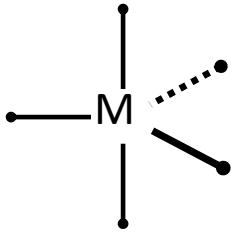
Common Coordination Geometries



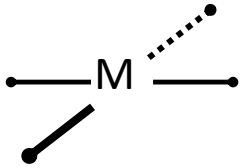
octahedral (Oh)



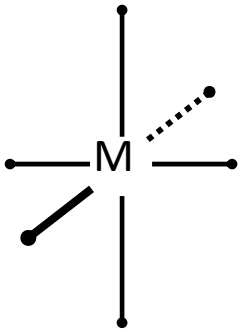
square pyramid (sp)



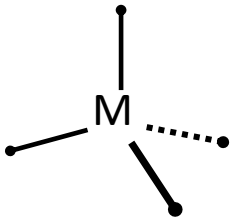
trigonal bipyramidal (tbp)



square planar (sp)



tetragonal (tet)



tetrahedral (Td)

Preferred Coordination Numbers and Geometries for Selected Metal Ions

Cation	*C.N.*	*Geometry*	*Biological Ligands*
Na^{+}	6	Octahedral	O, ether, hydroxyl, carboxylate
K^{+}	6-8	Flexible	O, ether, hydroxyl, carboxylate
Mg^{2+}	6	Octahedral	O, hydroxyl, phosphate
Ca^{2+}	6-8	Flexible	O, carboxylate, carbonyl, (phosphate)
Mn^{2+} (d^{5})	6	Octahedral	O, carboxylate, phosphate N, imidizole
Mn^{3+} (d^{4})	6	Tetragonal	O, carboxylate, phosphate, hydoxide
Fe^{2+} (d^{6})	4	Tetrahedral	S, thiolate
	6	Octahedral	O, carboxylate, alkoxide, oxide, phenolate N, imidazole, porphyrin
Fe^{3+} (d^{5})	4	Tetrahedral	S, thiolate
	6	Octahedral	O, carboxylate, alkoxide, oxide, phenolate N, imidazole, porphyrin
Co^{2+} (d^{7})	4	Tetrahedral	S, thiolate N, imidazole
	6	Octahedral	O, carboxylate N, imidazole
Ni^{2+} (d^{8})	4	Square planar	S, thiolate N, imidazole, polypyrrole (F-430)
	6	Octahedral	uncommon
Cu^{1+} (d^{10})	4	Tetrahedral	S, thiolate, thioether N, imidazole
Cu^{2+} (d^{9})	4	Tetrahedral	S, thiolate, thioether N, imidazole
Cu^{2+} (d^{9})	4	Square planar	O, carboxylate N, imidazole
	6	Tetragonal	O, carboxylate N, imidazole
Zn^{2+} (d^{10})	4	Tetrahedral	O, carboxylate, carbonyl S, thiolate N, imidazole
	5	Square pyramidal	O, carboxylate, carbonyl N, imidazole

The Entatic State

- Coordination geometries that are distorted due to the demands of the protein (torsion angles about C and N in the peptide polymer chain)
- Related to catalytic efficiency of enzyme in that the metal is in a geometry closer to that of the transition state
- *Entasis*: Greek for “stretched” or “under tension”

Reduction Potentials

- $\Delta G = -nFE^0$ E^0 is positive for a spontaneous reaction

In water, iron salts:

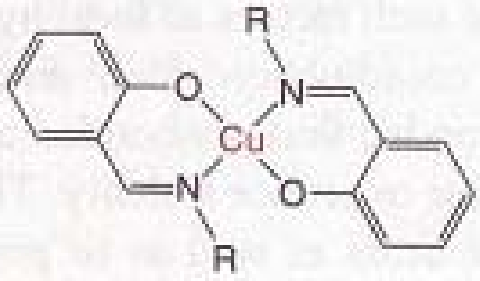
$Fe^{3+} + e^- = Fe^{2+}$ +771 mV

In Rubredoxin

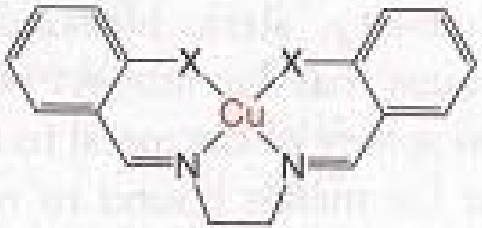
$Fe^{3+} + e^- = Fe^{2+}$ -58 mV

Table 2.4
Effect of ligands on Cu(I)/Cu(II) reduction potential in DMF solution

Compound name	$E_{1/2}$, V[a]
Cu(O-sal)$_2$en	−1.21
Cu(Me-sal)$_2$	−0.90
Cu(Et-sal)$_2$	−0.86
Cu(S-sal)$_2$en	−0.83
Cu(*i*-Pr-sal)$_2$	−0.74
Cu(*t*-Bu-sal)$_2$	−0.66



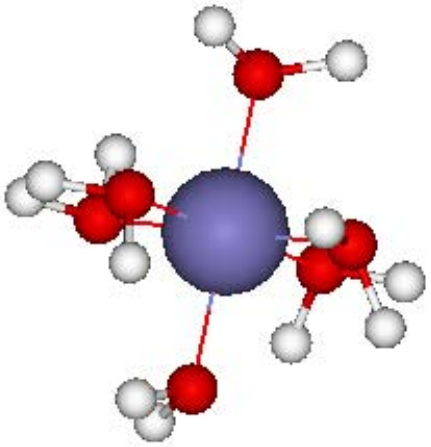
Cu(*R*-sal)$_2$



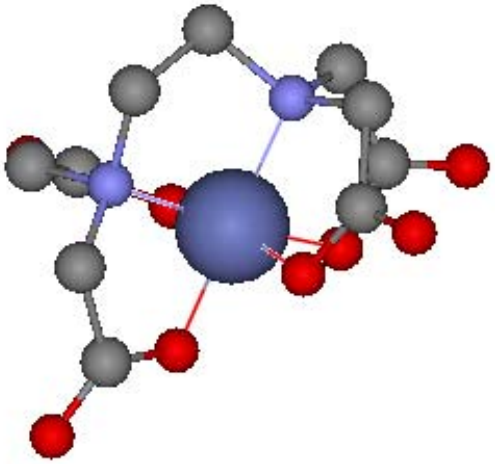
Cu(*X*-sal)$_2$en
X = *O* or *S*

[a]Potential at which the complex is half-oxidized and half-reduced.

Chelate Effect



$[Fe(H_2O)_6]^{2+}$



$[FeEDTA]^{2-}$

● Chelate effect

compare stability constants (298 K):

	log β, K
$[Ni(OH_2)_6]^{2+} + 2NH_3 \rightleftharpoons [Ni(NH_3)_2(OH_2)_4]^{2+} + 2H_2O$	5.04
$[Ni(OH_2)_6]^{2+} + en \rightleftharpoons [Ni(en)(OH_2)_4]^{2+} + 2H_2O$	7.45
$[Ni(NH_3)_2(OH_2)_4]^{2+} + 2NH_3 \rightleftharpoons [Ni(NH_3)_4(OH_2)_2]^{2+} + 2H_2O$	0.78
$[Ni(NH_3)_2(OH_2)_4]^{2+} + en \rightleftharpoons [Ni(en)_2(OH_2)_4]^{2+} + 2NH_3$	2.41
$[Ni(NH_3)_6]^{2+} + 3\ en \rightleftharpoons [Ni(en)_3]^{2+} + 6NH_3$	9.67

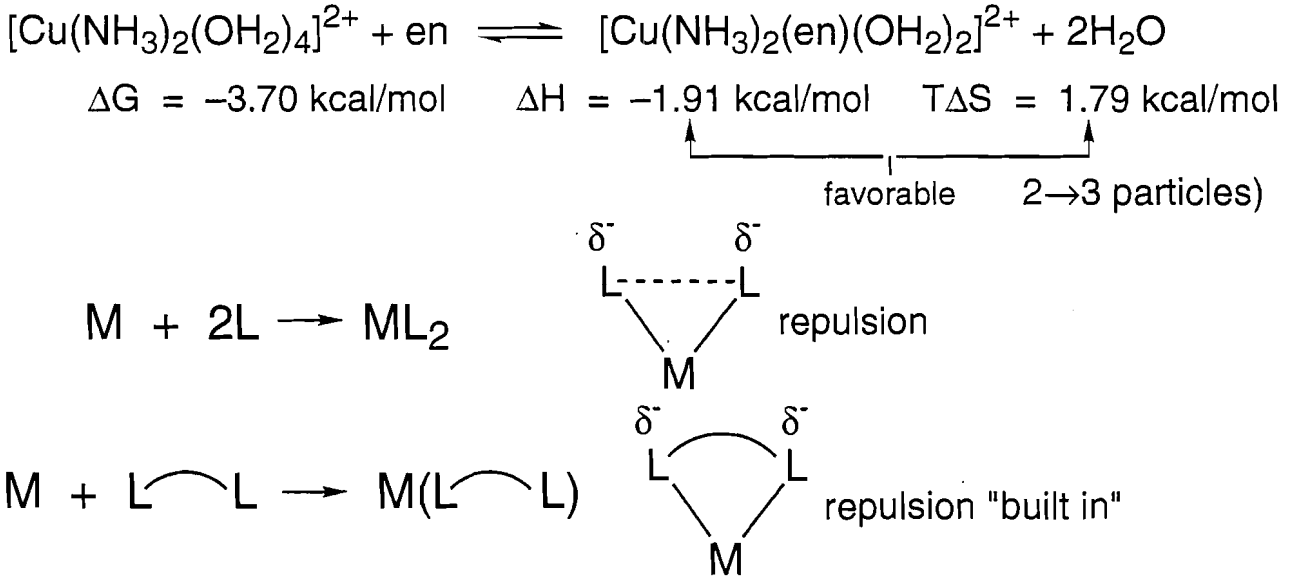
$\Delta H = -2.89$ kcal/mol small favorable contribution

$\Delta H_{SE} = -2.75$ kcal/mol

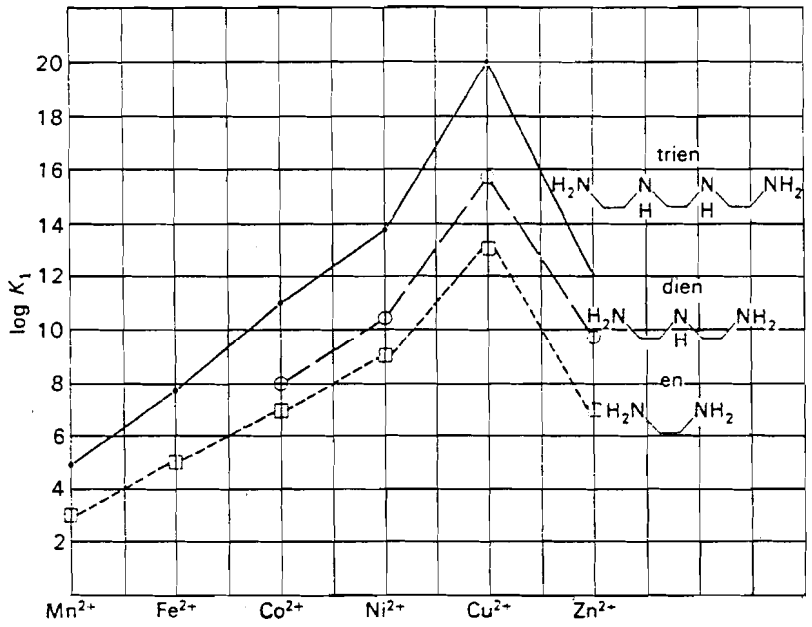
$T\Delta S = 13.2$ kcal/mol

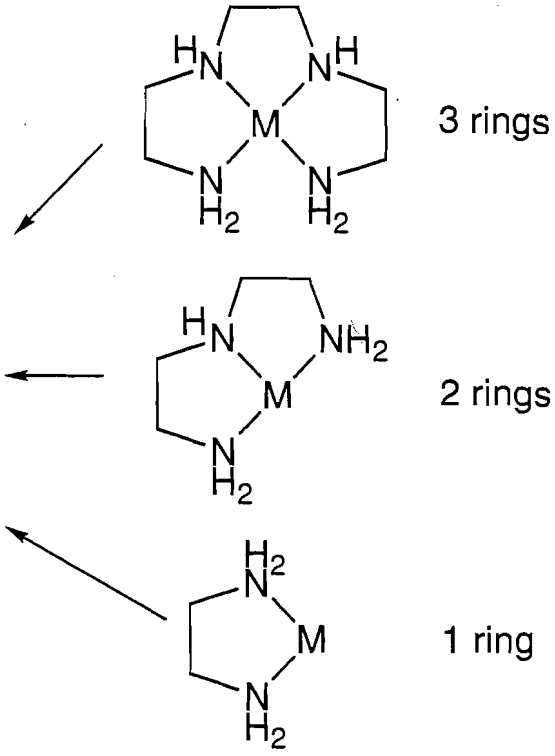
entropy increase (4→7 particles) dominates reaction

(even though NH_3 more strongly solvated than en)

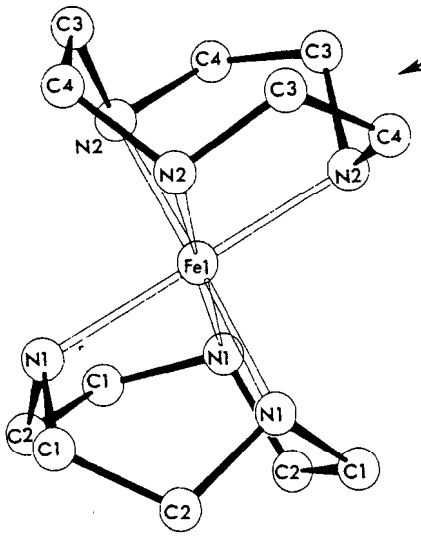

[Cu(NH3)2(OH2)4]2+ + en ⇌ [Cu(NH3)2(en)(OH2)2]2+ + 2H2O
ΔG = −3.70 kcal/mol
ΔH = −1.91 kcal/mol
TΔS = 1.79 kcal/mol
favorable
2→3 particles)
M + 2L → ML2
δ- δ-
L L
M
repulsion
M + L L → M(L L)
δ- δ-
L L
M
repulsion "built in"
M
L
L
ring
closure
M
L
L
Once the first M–L bond is formed, there is a high probability the second bond will form because of the proximity of the other L atom. Corresponding probability is much lower with two unidentate ligands.

● number of chelate rings





Stability increases because enthalpy becomes increasingly negative (increased number of M–N bonds) and entropy increases (more water molecues released).



$[Fe(tacn)_2]^{2+}$

1,4,7-triazacyclononane (tacn)
3 rings/ligand

tacn forms relatively stable complexes with $M^{2+,3+}$

$$[M(OH_2)_6]^{2+} + tacn \rightleftharpoons [M(tacn)(OH_2)_3]^{2+} + 3H_2O$$

	$\log K_1$
Ni(II)	16.24
Cu(II)	17.5
Zn(II)	11.6

favorable ΔH, ΔS;
difficult to break M–N bonds because of semi-rigid ligand structure

Ligand Substitution Reactions

Associative (2nd Order) — Low Coordination #

Dissociative — Coordination # > 6

Ligand Exchange Rates

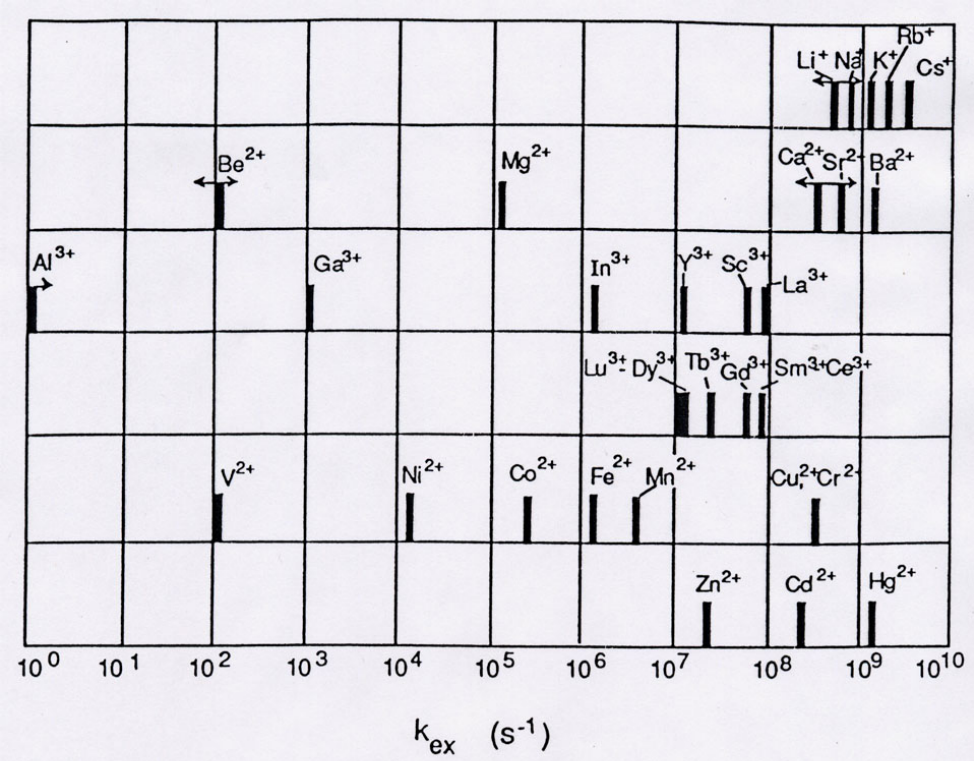


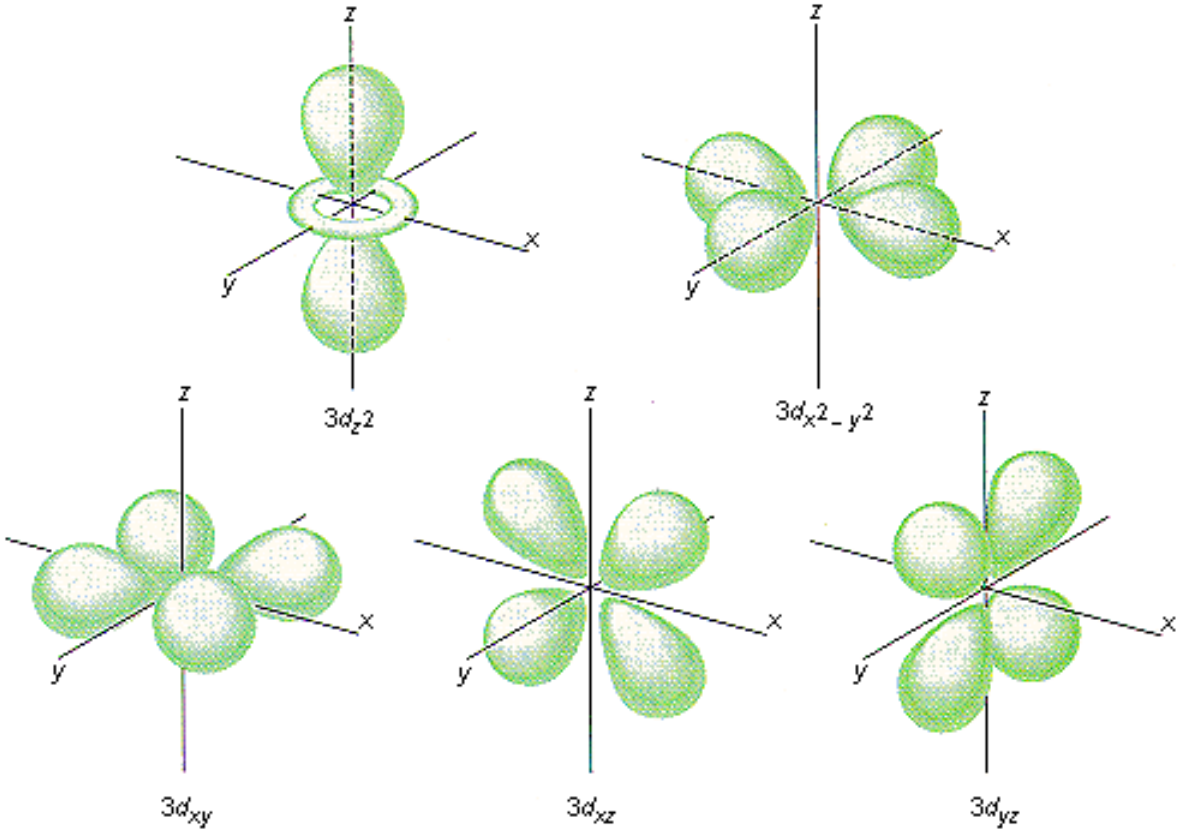
Figure 1.9 Solvent exchange rates for inner-sphere water molecules in M^{n+} (aq). [Adapted from H. Diebler et al., *Pure Appl. Chem.*, *20*, 93–115 (1969).]

Inert: $t_{1/2}$ > 1 min.
Labile: $t_{1/2}$ < 1 min.

$$M(H_2O)_x^{n+} + H_2O^* \leftrightarrow M(H_2O)_{x-1}(H_2O^*)^{n+} + H_2O$$

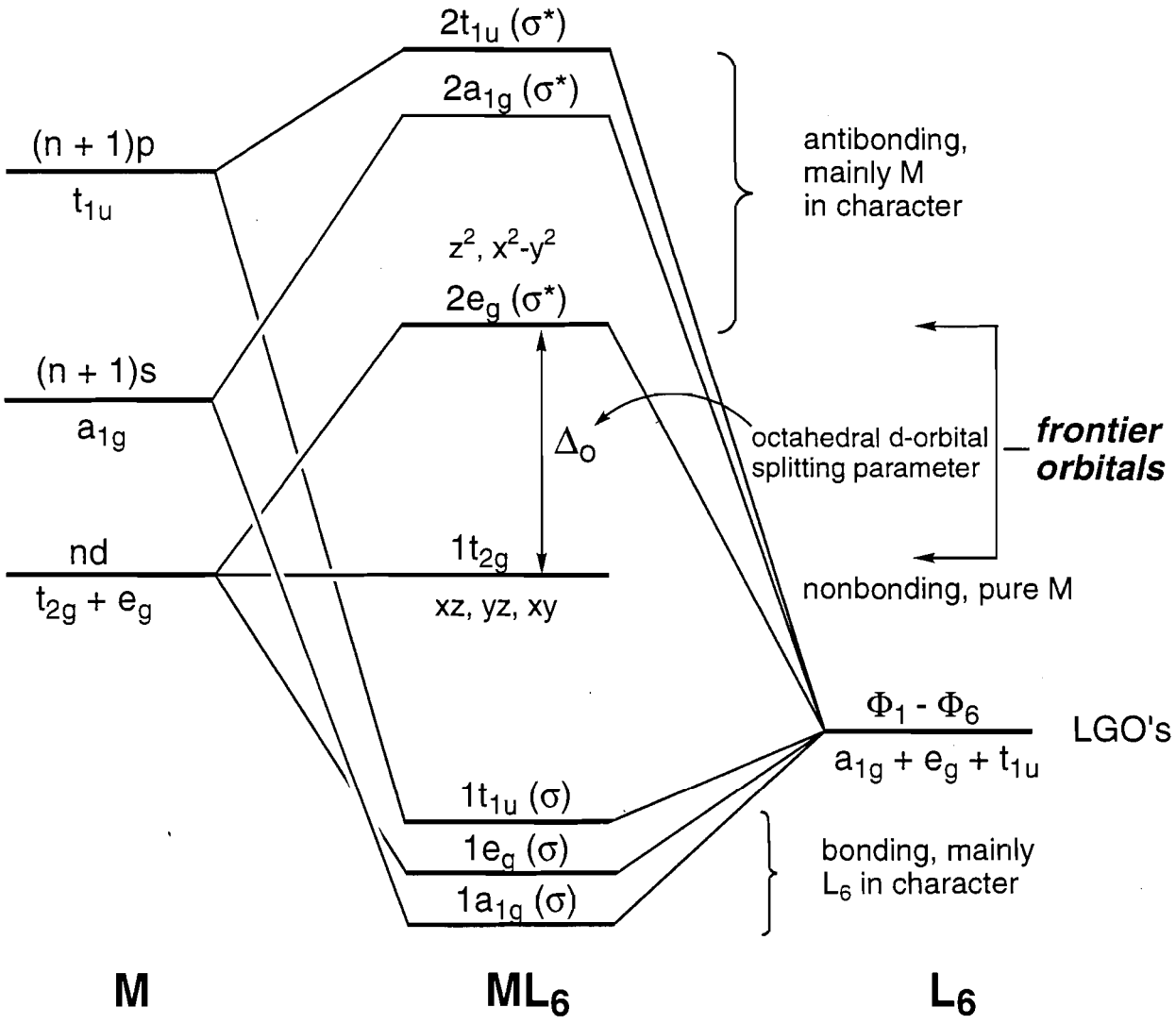
Lower charge: faster; Higher charge: slower
Larger size: faster; smaller size: slower
For transition metal ions: ligand field stabilization energy (LFSE)

The d-orbitals



MO Approach to Bonding in Transition Metal Coordination Complexes

Octahedral Geometry—Sigma bonding ligand like NH_3 or H_2O



Other approaches to bonding in TM Coordination Complexes

1. Valence Bond Theory

    1. Metal has empty hybrid orbitals into which lone pair from Ligand goes to create coordinate covalent bond
        octahedral: d^2sp^3 or sp^3d^2
        tetrahedral: sp^3
        square planar: dsp^2

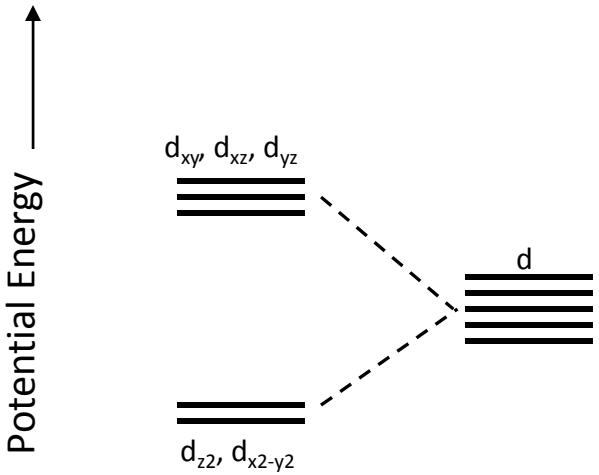
2. Crystal Field Theory

    1. Electrostatic interactions of L and M generate splitting of d-orbitals.

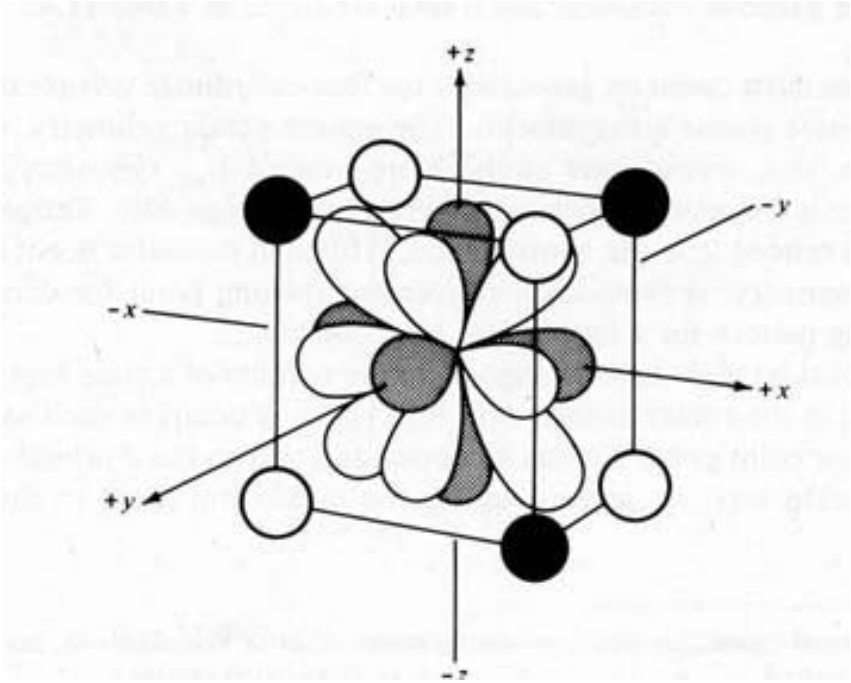
    2. d-orbital splitting pattern depends on geometry

    3. d-orbital splitting energy depends on ligand field strength

Splitting of d-orbitals in different fields

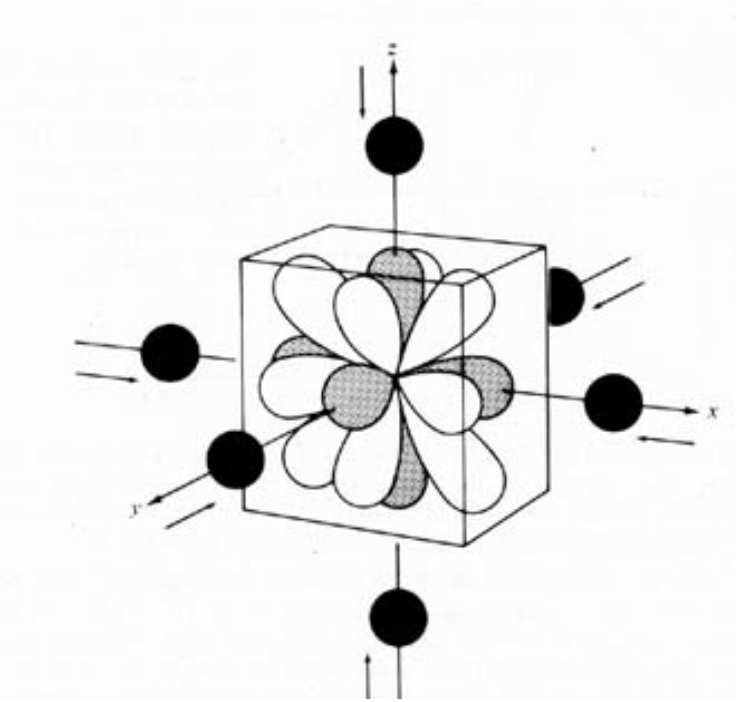


tetrahedral free ion

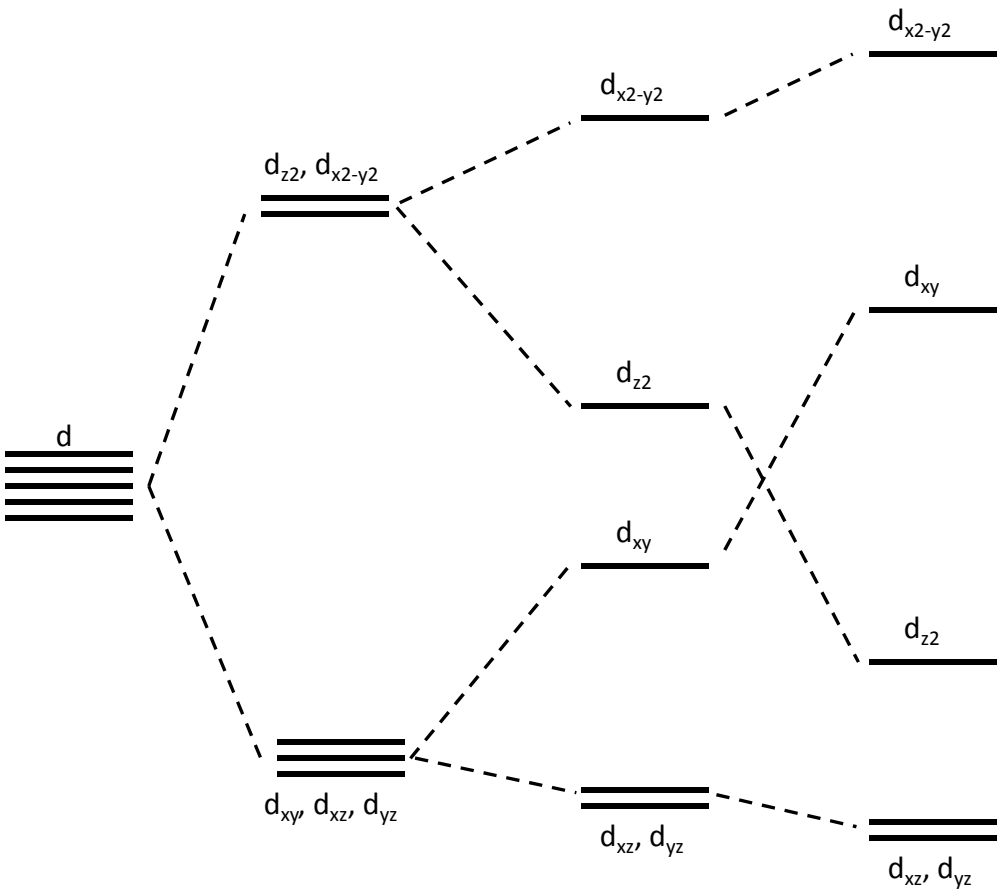


Td

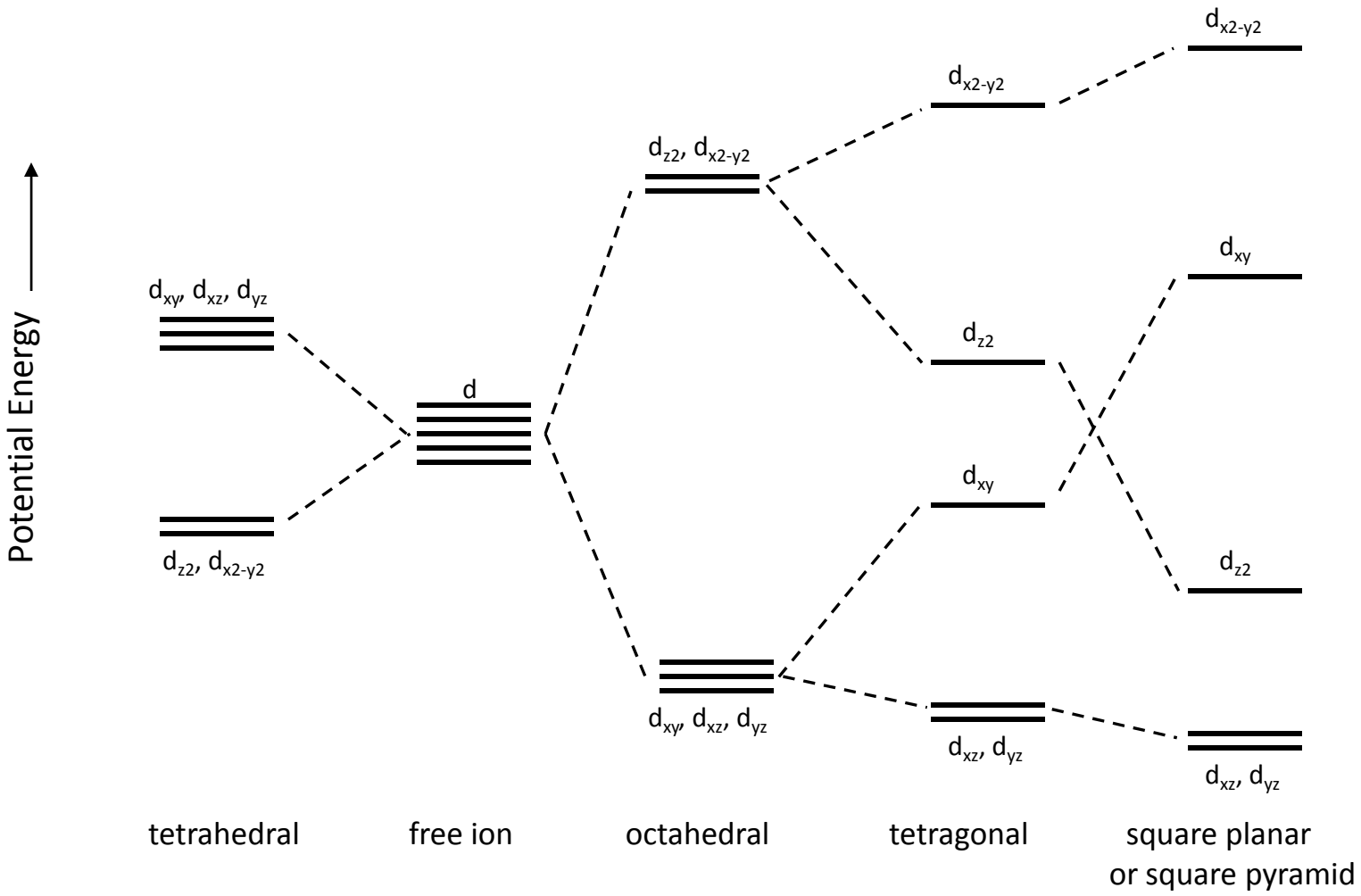
Splitting of d-orbitals in different fields



Oh

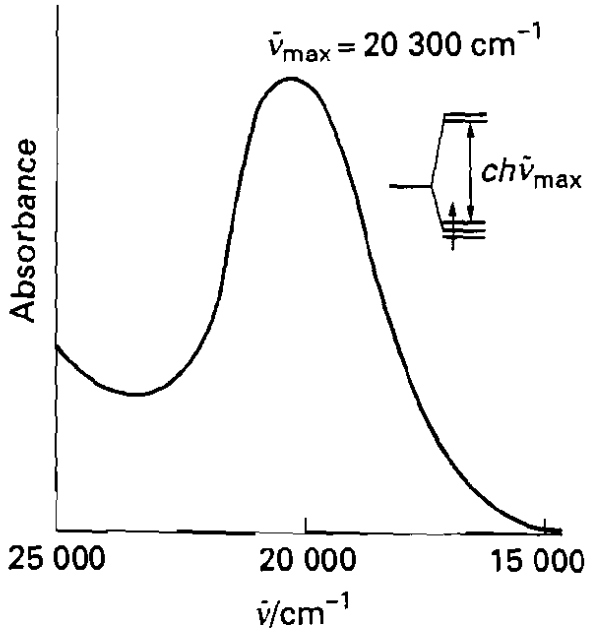


Splitting of d-orbitals in different fields

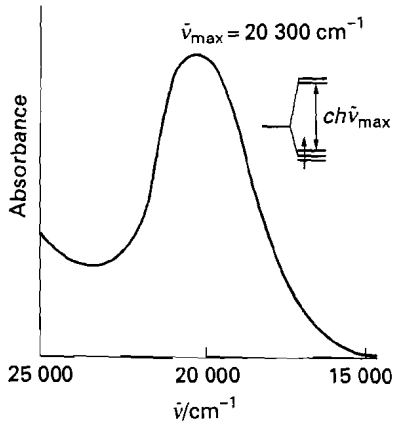


$E = h\upsilon = hc/\lambda$

$E \propto 1/\lambda$ = wavenumber (cm^{-1})



7.10 The optical absorption spectrum of $[Ti(OH_2)_6]^{3+}$.



7.10 The optical absorption spectrum of $[Ti(OH_2)_6]^{3+}$.

Table 7.3 Ligand-field splitting parameters Δ_O of ML_6 complexes*

	Ions	Ligands				
		Cl^-	H_2O	NH_3	en	CN^-
d^3	Cr^{3+}	13.7	17.4	21.5	21.9	26.6
d^5	Mn^{2+}	7.5	8.5		10.1	30
	Fe^{3+}	11.0	14.3			(35)
d^6	Fe^{2+}		10.4			(32.8)
	Co^{3+}		(20.7)	(22.9)	(23.2)	(34.8)
	Rh^{3+}	(20.4)	(27.0)	(34.0)	(34.6)	(45.5)
d^8	Ni^{2+}	7.5	8.5	10.8	11.5	

*Values are in multiples of 1000 cm^{-1}; entries in parentheses are for low-spin complexes.
Source: H.B. Gray, *Electrons and chemical bonding*. Benjamin, Menlo Park (1965).

Electron Transfer

Inner Sphere		direct bridge between metals
Outer Sphere	(precursor complex)	long range (> 30 ang)

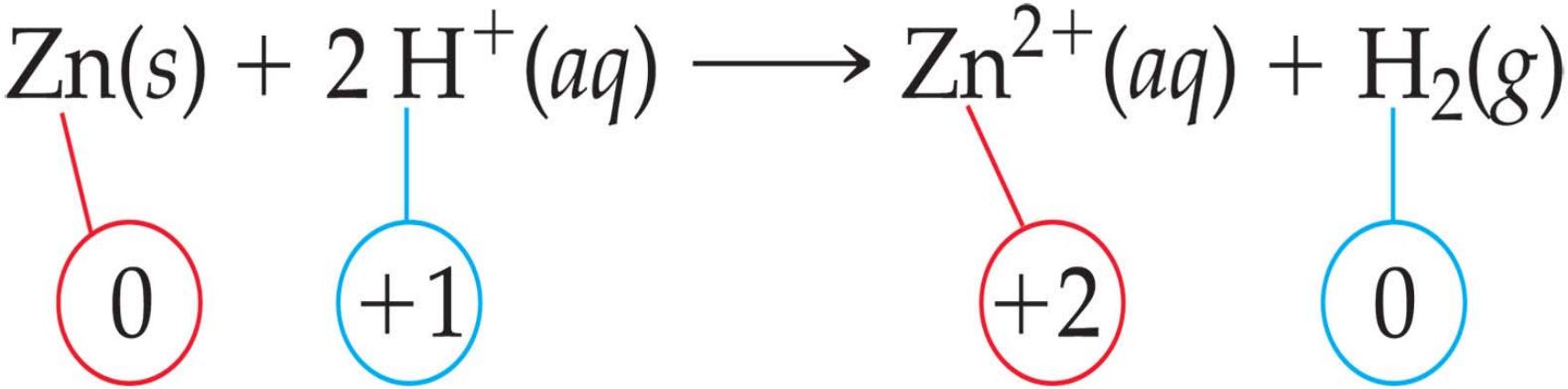
Electrochemistry

In electrochemical reactions, electrons are transferred from one species to another.

$\Delta G^0 = - n F E^0_{cell}$ E^0 is positive for a spontaneous reaction

$\Delta G^0 = - RT \ln K_{eq}$

Oxidation and Reduction



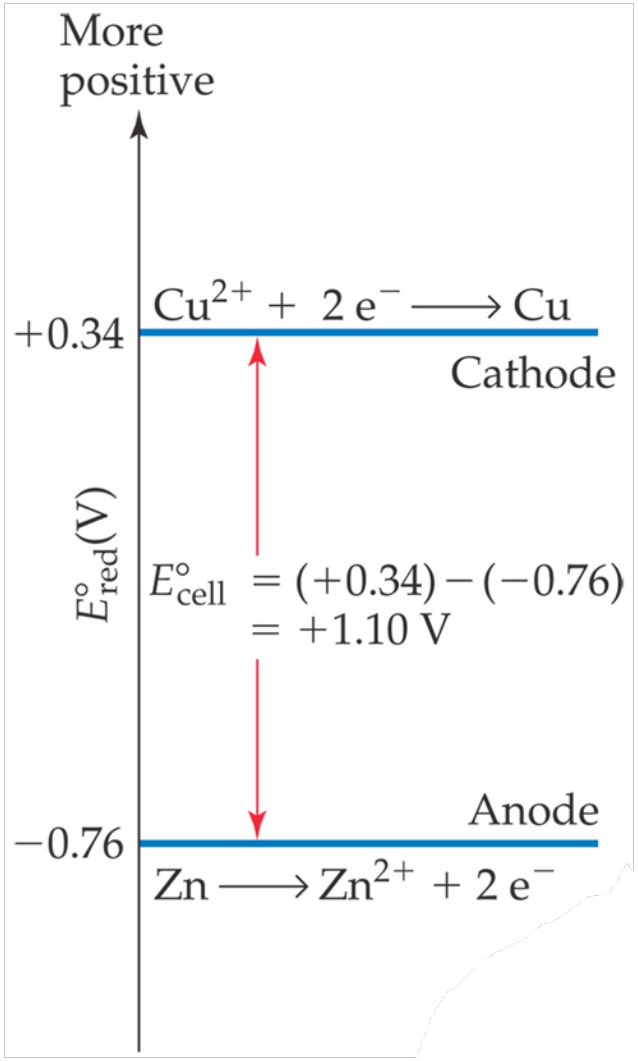
- What is reduced is the oxidizing agent.
  - H^+ oxidizes Zn by taking electrons from it.
- What is oxidized is the reducing agent.
  - Zn reduces H^+ by giving it electrons.

Potential (V)	Reduction Half-Reaction
+2.87	$F_2(g) + 2\,e^- \longrightarrow 2\,F^-(aq)$
+1.51	$MnO_4^-(aq) + 8\,H^+(aq) + 5\,e^- \longrightarrow Mn^{2+}(aq) + 4\,H_2O(l)$
+1.36	$Cl_2(g) + 2\,e^- \longrightarrow 2\,Cl^-(aq)$
+1.33	$Cr_2O_7^{2-}(aq) + 14\,H^+(aq) + 6\,e^- \longrightarrow 2\,Cr^{3+}(aq) + 7\,H_2O(l)$
+1.23	$O_2(g) + 4\,H^+(aq) + 4\,e^- \longrightarrow 2\,H_2O(l)$
+1.06	$Br_2(l) + 2\,e^- \longrightarrow 2\,Br^-(aq)$
+0.96	$NO_3^-(aq) + 4\,H^+(aq) + 3\,e^- \longrightarrow NO(g) + 2\,H_2O(l)$
+0.80	$Ag^+(aq) + e^- \longrightarrow Ag(s)$
+0.77	$Fe^{3+}(aq) + e^- \longrightarrow Fe^{2+}(aq)$
+0.68	$O_2(g) + 2\,H^+(aq) + 2\,e^- \longrightarrow H_2O_2(aq)$
+0.59	$MnO_4^-(aq) + 2\,H_2O(l) + 3\,e^- \longrightarrow MnO_2(s) + 4\,OH^-(aq)$
+0.54	$I_2(s) + 2\,e^- \longrightarrow 2\,I^-(aq)$
+0.40	$O_2(g) + 2\,H_2O(l) + 4\,e^- \longrightarrow 4\,OH^-(aq)$
+0.34	$Cu^{2+}(aq) + 2\,e^- \longrightarrow Cu(s)$
0 [defined]	$2\,H^+(aq) + 2\,e^- \longrightarrow H_2(g)$
−0.28	$Ni^{2+}(aq) + 2\,e^- \longrightarrow Ni(s)$
−0.44	$Fe^{2+}(aq) + 2\,e^- \longrightarrow Fe(s)$
−0.76	$Zn^{2+}(aq) + 2\,e^- \longrightarrow Zn(s)$
−0.83	$2\,H_2O(l) + 2\,e^- \longrightarrow H_2(g) + 2\,OH^-(aq)$
−1.66	$Al^{3+}(aq) + 3\,e^- \longrightarrow Al(s)$
−2.71	$Na^+(aq) + e^- \longrightarrow Na(s)$
−3.05	$Li^+(aq) + e^- \longrightarrow Li(s)$

Reduction potentials for many reactions have been measured and tabulated.

Oxidizing and Reducing Agents

The greater the difference between the two, the greater the voltage of the cell.



Note: We have focused on what ligands do to metals. However metals can also modify the properties of Ligands. Water bound to iron is much more acidic than free water. Deprotonation leads to metal bound hydroxides which in the case of carbonic anhydrase facilitates conversion of carbon dioxide to bicarbonate.