

Transition Metal Chemistry and Coordination Compounds

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The Transition Metals

A periodic table of elements. The transition metals are highlighted in blue. The blue-highlighted elements are: Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, Ge, As, Se, Br, Cd, In, Sn, Sb, Te, I, Pb, Bi, Po, and At. The table includes element symbols, atomic numbers, and group/period information.

1	1A	2	2A	18	8A													
1 H	2 Be	3 Li	4 Be	5 B	6 C													
11 Na	12 Mg	3 3B	4 4B	5 5B	6 6B	7 7B	8	9	10	11 1B	12 2B	13 3A	14 4A	15 5A	16 6A	17 7A	2 He	10 Ne
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr	
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe	
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn	
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110	111	112	(113)	114	(115)	116	(117)	118	

TABLE 22.1

Electron Configurations and Other Properties of the First-Row Transition Metals

	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
Electron configuration									
M	4s ² 3d ¹	4s ² 3d ²	4s ² 3d ³	4s ¹ 3d ⁵	4s ² 3d ⁵	4s ² 3d ⁶	4s ² 3d ⁷	4s ² 3d ⁸	4s ¹ 3d ¹⁰
M ²⁺	—	3d ²	3d ³	3d ⁴	3d ⁵	3d ⁶	3d ⁷	3d ⁸	3d ⁹
M ³⁺	[Ar]	3d ¹	3d ²	3d ³	3d ⁴	3d ⁵	3d ⁶	3d ⁷	3d ⁸
Electronegativity	1.3	1.5	1.6	1.6	1.5	1.8	1.9	1.9	1.9
Ionization energy (kJ/mol)									
First	631	658	650	652	717	759	760	736	745
Second	1235	1309	1413	1591	1509	1561	1645	1751	1958
Third	2389	2650	2828	2986	3250	2956	3231	3393	3578
Radius (pm)									
M	162	147	134	130	135	126	125	124	128
M ²⁺	—	90	88	85	80	77	75	69	72
M ³⁺	81	77	74	64	66	60	64	—	—
Standard reduction potential (V)*									
	-2.08	-1.63	-1.2	-0.74	-1.18	-0.44	-0.28	-0.25	0.34

*The half-reaction is $M^{2+}(aq) + 2e^- \longrightarrow M(s)$ (except for Sc and Cr, where the ions are Sc^{3+} and Cr^{3+} , respectively).

TABLE 22.2**Physical Properties of Elements K to Zn**

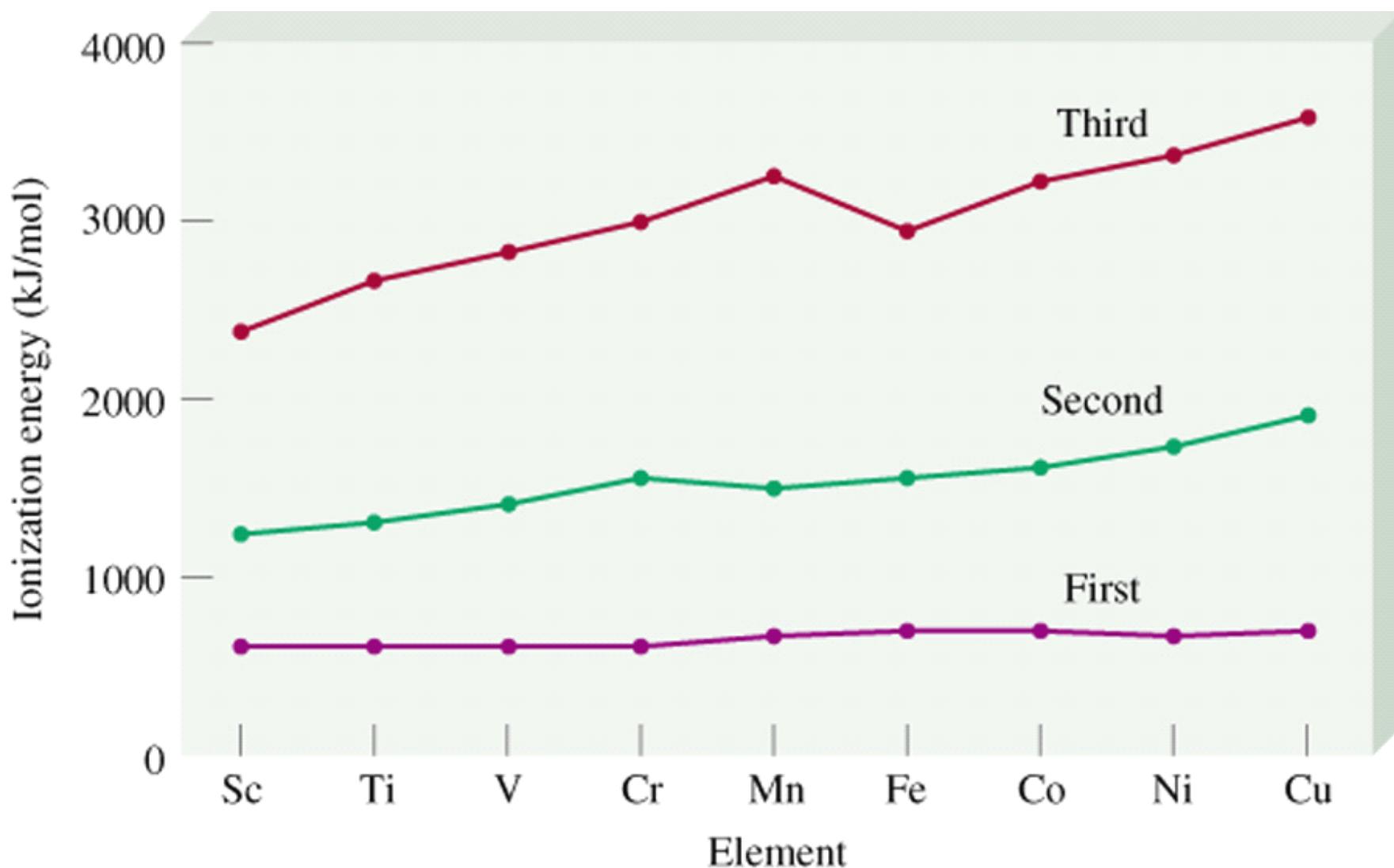
	1A	2A	Transition Metals								2B	
	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
Atomic radius (pm)	235	197	162	147	134	130	135	126	125	124	128	138
Melting point (°C)	63.7	838	1539	1668	1900	1875	1245	1536	1495	1453	1083	419.5
Boiling point (°C)	760	1440	2730	3260	3450	2665	2150	3000	2900	2730	2595	906
Density (g/cm ³)	0.86	1.54	3.0	4.51	6.1	7.19	7.43	7.86	8.9	8.9	8.96	7.14

Oxidation States of the 1st Row Transition Metals

(most stable oxidation numbers are shown in red)

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu
				+7				
			+6	+6	+6			
		+5	+5	+5	+5			
	+4	+4	+4	+4	+4	+4		
+3	+3	+3	+3	+3	+3	+3	+3	+3
	+2	+2	+2	+2	+2	+2	+2	+2
								+1

Ionization Energies for the 1st Row Transition Metals





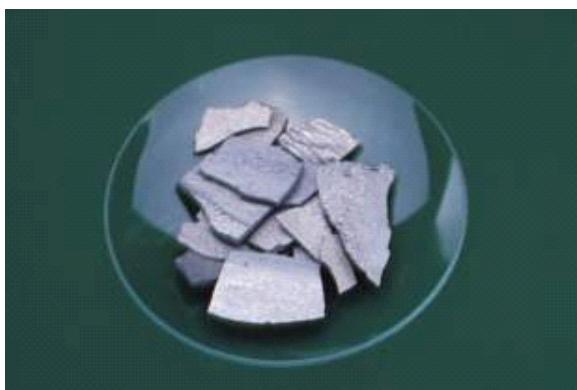
Scandium



Titanium



Vanadium



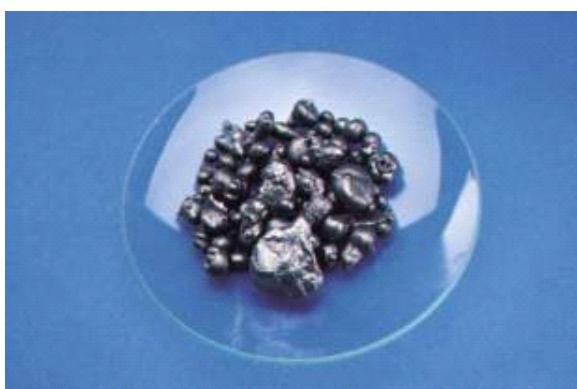
Chromium



Manganese



Iron



Cobalt



Nickel



Copper

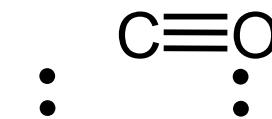
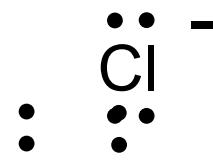
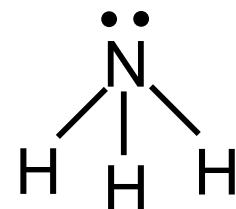
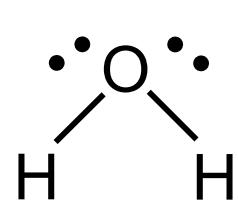
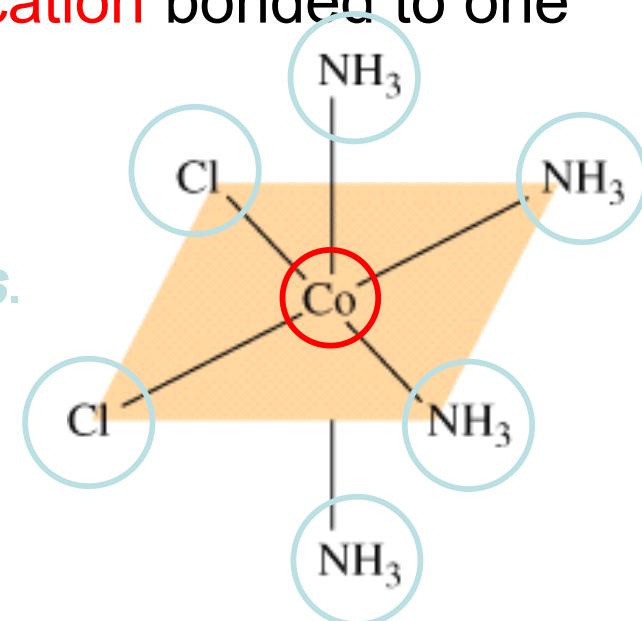
Coordination Compounds

A ***coordination compound*** typically consists of a complex ion and a counter ion.

A ***complex ion*** contains a central **metal cation** bonded to one or more molecules or ions.

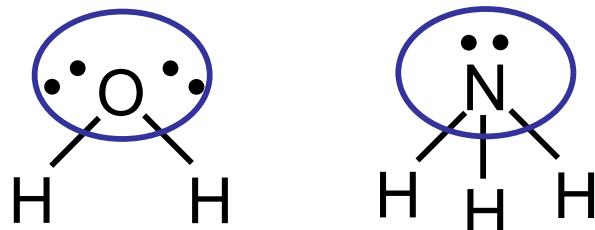
The molecules or ions that surround the metal in a complex ion are called ***ligands***.

A ligand has **at least one** unshared pair of valence electrons



Coordination Compounds

The atom in a ligand that is bound directly to the metal atom is the **donor atom**.



The number of donor atoms surrounding the central metal atom in a complex ion is the **coordination number**.

Ligands with:

one donor atom

monodentate

H_2O , NH_3 , Cl^-

two donor atoms

bidentate

ethylenediamine

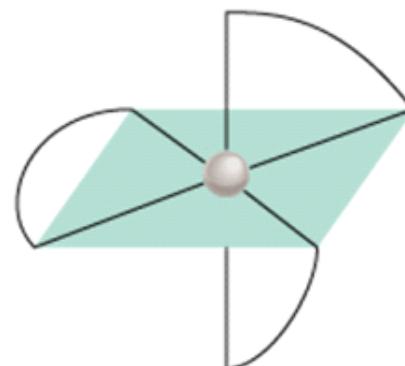
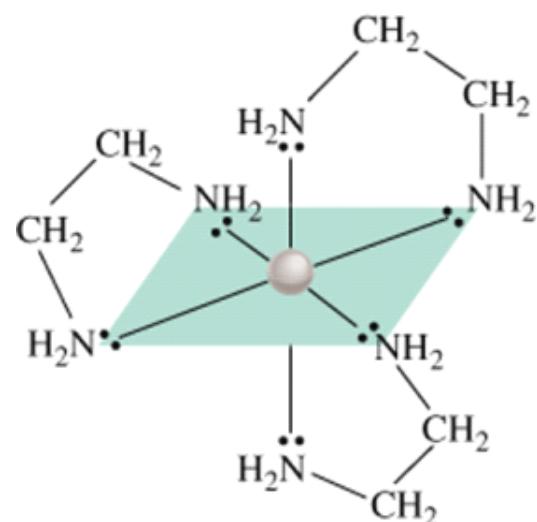
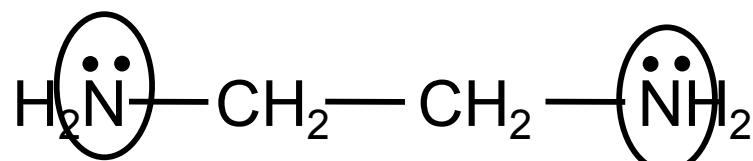
three or more donor atoms

polydentate

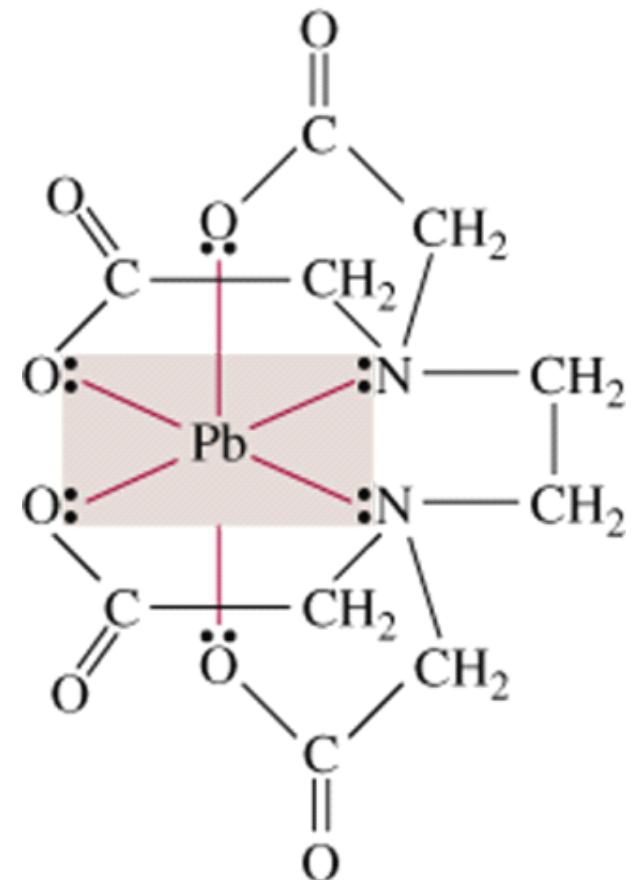
EDTA

Coordination Compounds

bidentate ligand



polydentate ligand
(EDTA)



Bidentate and polydentate ligands are called ***chelating agents***

TABLE 22.3

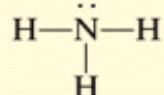
Some Common Ligands

Name

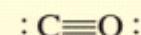
Structure

Monodentate ligands

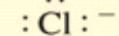
Ammonia



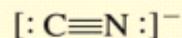
Carbon monoxide



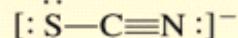
Chloride ion



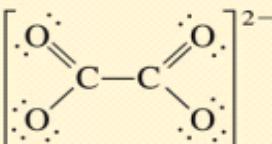
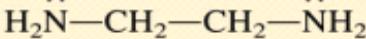
Cyanide ion



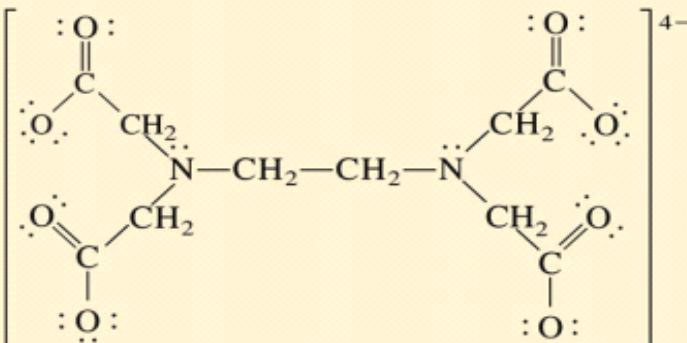
Thiocyanate ion

*Bidentate ligands*

Ethylenediamine



Oxalate ion

Polydentate ligandEthylenediaminetetraacetate
ion (EDTA)



What are the oxidation numbers of the metals in
 $\text{K}[\text{Au}(\text{OH})_4]$ and $[\text{Cr}(\text{NH}_3)_6](\text{NO}_3)_3$?

OH^- has charge of -1

K^+ has charge of +1

$$? \text{Au} + 1 + 4 \times (-1) = 0$$

$$\text{Au} = +3$$

NO_3^- has charge of -1

NH_3 has no charge

$$? \text{Cr} + 6 \times (0) + 3 \times (-1) = 0$$

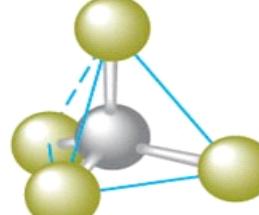
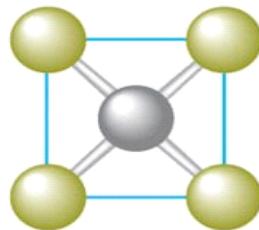
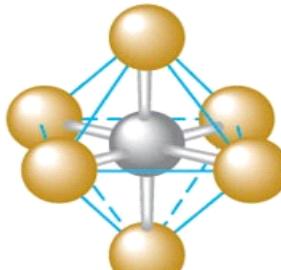
$$\text{Cr} = +3$$

Typical Coordination Numbers for Some Common Metal Ions

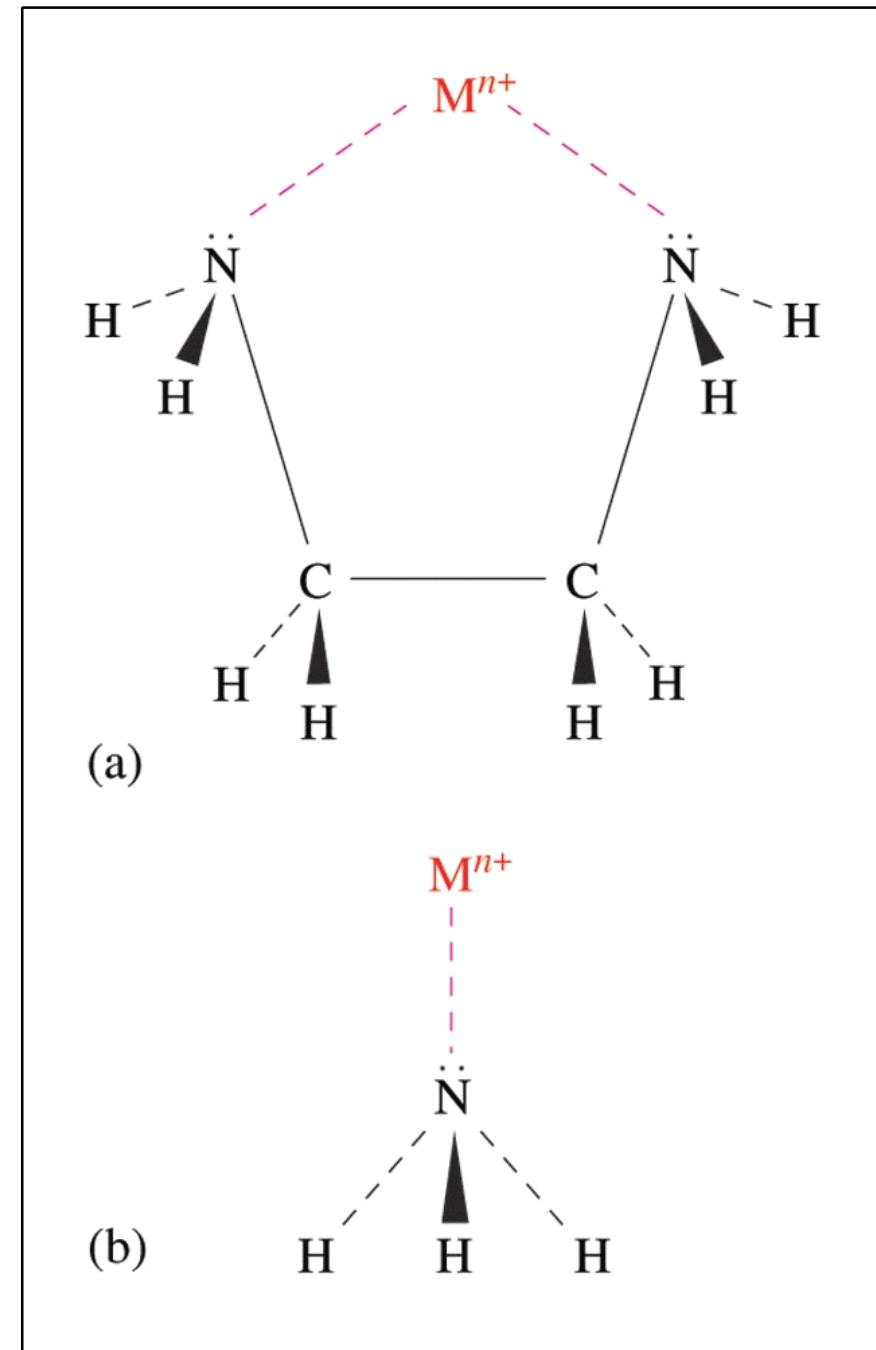
TABLE 21.12 Typical Coordination Numbers for Some Common Metal Ions

M^+	Coordination Numbers	M^{2+}	Coordination Numbers	M^{3+}	Coordination Numbers
Cu^+	2, 4	Mn^{2+}	4, 6	Sc^{3+}	6
Ag^+	2	Fe^{2+}	6	Cr^{3+}	6
Au^+	2, 4	Co^{2+}	4, 6	Co^{3+}	6
		Ni^{2+}	4, 6		
		Cu^{2+}	4, 6	Au^{3+}	4
		Zn^{2+}	4, 6		

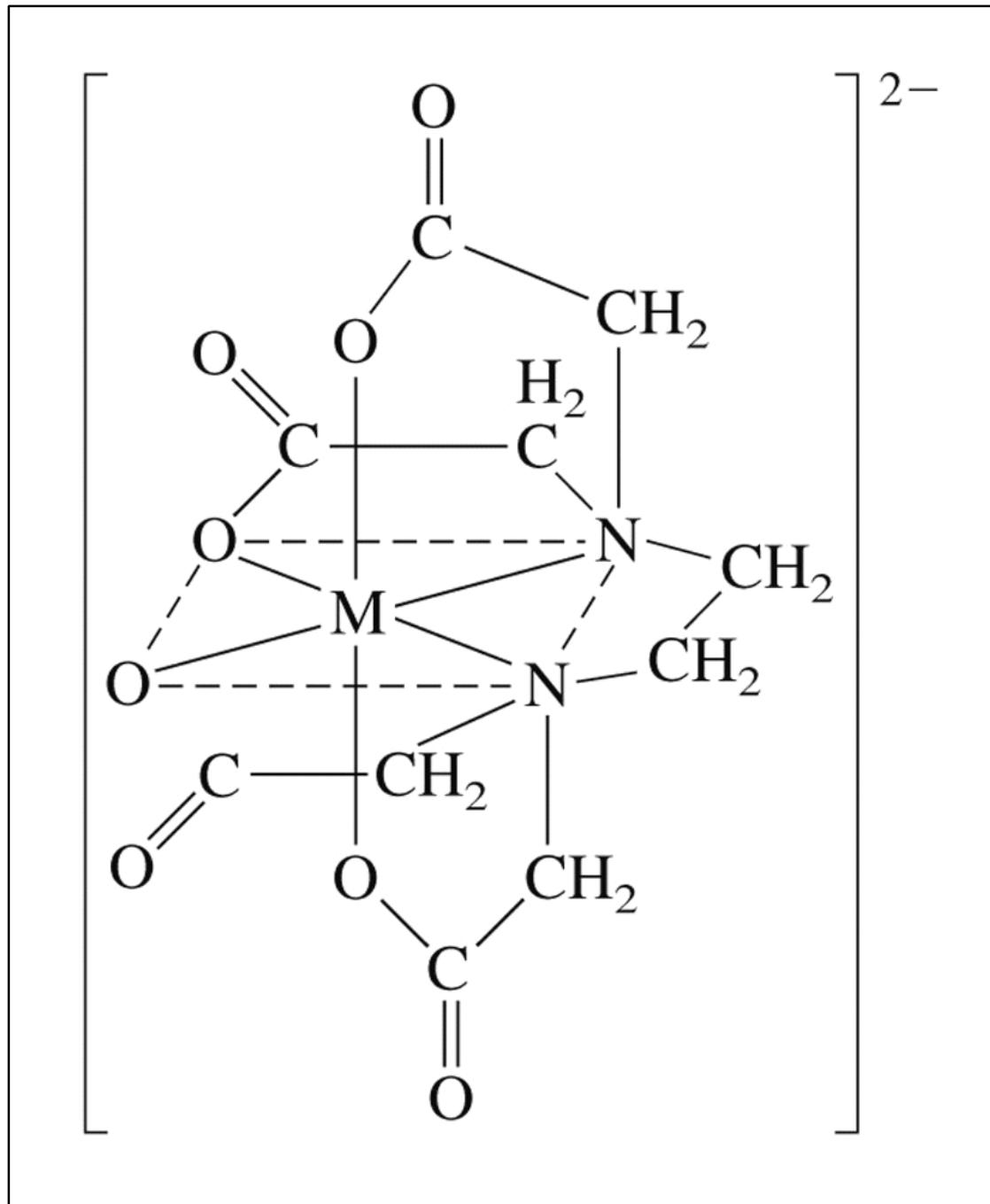
The Ligand Arrangements for Coordination Numbers 2, 4, and 6

Coordination number	Geometry
2	 Linear
4	 Tetrahedral
6	 Square planar
	 Octahedral

a-b Bidentate
and
Monodentate
Ligand



The Coordination of EDTA with a 2^+ Metal Ion



Some Common Ligands

TABLE 21.13 Some Common Ligands

Type	Examples			
Unidentate/monodentate	H_2O NH_3	CN^- NO_2^- (nitrite)	SCN^- (thiocyanate) OH^-	X^- (halides)
Bidentate		Oxalate $\begin{array}{c} \text{O} & \text{O} \\ \parallel & \parallel \\ (-) \text{---} \text{C} & \text{---} \text{C} & \text{---} (-) \\ & \text{O} \text{---} \text{M} & \text{O} \text{---} \text{M} \\ & \text{---} \text{C} & \text{---} \text{C} \\ & \text{O} & \text{O} \end{array}$	Ethylenediamine $\begin{array}{c} \text{H}_2\text{C} & \text{---} & \text{CH}_2 \\ & & \\ \text{H}_2\text{N} & \text{---} \text{M} & \text{---} \text{NH}_2 \end{array}$	
Polydentate		Diethylenetriamine $\begin{array}{c} \text{H}_2\text{N} & \text{---} (\text{CH}_2)_2 & \text{---} \text{NH} & \text{---} (\text{CH}_2)_2 & \text{---} \text{NH}_2 \\ \swarrow & & \uparrow & & \nearrow \\ \text{Three coordinating atoms} \end{array}$	Ethylenediaminetetraacetate $\begin{array}{c} \text{O} & & & \text{O} \\ \parallel & & & \parallel \\ (-) \text{---} \text{O} & \text{---} \text{C} & \text{---} \text{H}_2\text{C} & \text{---} \text{C} & \text{---} \text{O} : (-) \\ & & \swarrow & \uparrow & \swarrow \\ & & \text{N} & \text{---} (\text{CH}_2)_2 & \text{---} \text{N} & \text{---} \text{C} & \text{---} \text{O} : (-) \\ & & \uparrow & & \uparrow & & \uparrow \\ (-) \text{---} \text{O} & \text{---} \text{C} & \text{---} \text{H}_2\text{C} & & \text{CH}_2 & \text{---} \text{C} & \text{---} \text{O} : (-) \\ & & \parallel & & \swarrow & \parallel & \swarrow \\ & & \text{O} & & \text{O} & & \text{O} \end{array}$	Six coordinating atoms

Naming Coordination Compounds

- The cation is named before the anion.
- Within a complex ion, the ligands are named first **in alphabetical order** and the metal atom is named last.
- The names of anionic ligands end with the letter *o*. Neutral ligands are usually called by the name of the molecule. The exceptions are H_2O (aquo), CO (carbonyl), and NH_3 (ammine).
- When several ligands of a particular kind are present, the Greek prefixes *di-*, *tri-*, *tetra-*, *penta-*, and *hexa-* are used to indicate the number. If the ligand contains a Greek prefix, use the prefixes *bis*, *tris*, and *tetrakis* to indicate the number.
- The oxidation number of the metal is written in Roman numerals following the name of the metal.
- If the complex is an anion, its name ends in *-ate*.

TABLE 22.4**Names of Common Ligands in Coordination Compounds**

Ligand	Name of Ligand in Coordination Compound
Bromide, Br^-	Bromo
Chloride, Cl^-	Chloro
Cyanide, CN^-	Cyano
Hydroxide, OH^-	Hydroxo
Oxide, O^{2-}	Oxo
Carbonate, CO_3^{2-}	Carbonato
Nitrite, NO_2^-	Nitro
Oxalate, $\text{C}_2\text{O}_4^{2-}$	Oxalato
Ammonia, NH_3	Ammine
Carbon monoxide, CO	Carbonyl
Water, H_2O	Aquo
Ethylenediamine	Ethylenediamine
Ethylenediaminetetraacetate	Ethylenediaminetetraacetato

TABLE 22.5**Names of Anions
Containing Metal Atoms**

Metal	Name of Metal in Anionic Complex
Aluminum	Aluminate
Chromium	Chromate
Cobalt	Cobaltate
Copper	Cuprate
Gold	Aurate
Iron	Ferrate
Lead	Plumbate
Manganese	Manganate
Molybdenum	Molybdate
Nickel	Nickelate
Silver	Argentate
Tin	Stannate
Tungsten	Tungstate
Zinc	Zincate

What is the systematic name of $[\text{Co}(\text{NH}_3)_5\text{Cl}]\text{Cl}_2$?

Pentaamminechlorocobalt(III) chloride

Cation**Anion**

What is the systematic name of $[\text{K}_3\text{Fe}(\text{CN})_6]$?

Potassium hexacyanoferrate(III)

Cation**Anion**

TABLE 22.5**Names of Anions
Containing Metal Atoms**

Metal	Name of Metal in Anionic Complex
Aluminum	Aluminate
Chromium	Chromate
Cobalt	Cobaltate
Copper	Cuprate
Gold	Aurate
Iron	Ferrate
Lead	Plumbate
Manganese	Manganate
Molybdenum	Molybdate
Nickel	Nickelate
Silver	Argentate
Tin	Stannate
Tungsten	Tungstate
Zinc	Zincate

What is the systematic name of $[\text{Fe}(\text{en})_2(\text{NO}_2)_2]_2\text{SO}_4$?

Bis(ethylenediamine)dinitroiron(III) Sulfate

Cation**Anion**

TABLE 22.5**Names of Anions
Containing Metal Atoms**

Metal	Name of Metal in Anionic Complex
Aluminum	Aluminate
Chromium	Chromate
Cobalt	Cobaltate
Copper	Cuprate
Gold	Aurate
Iron	Ferrate
Lead	Plumbate
Manganese	Manganate
Molybdenum	Molybdate
Nickel	Nickelate
Silver	Argentate
Tin	Stannate
Tungsten	Tungstate
Zinc	Zincate

What is the systematic name of $[\text{Cr}(\text{H}_2\text{O})_4\text{Cl}_2]\text{Cl}$?

tetraaquodichlorochromium(III) chloride

Write the formula of tris(ethylenediamine)cobalt(II) sulfate

