

# Transition Metals and d-Block Metal Chemistry

## Transition Metals (d block elements)

Periodic table showing elements grouped by Period (1-7) and Group (1-18). The Transition Metals (d-block) are highlighted in pink, spanning Groups 3 to 10. Elements K and Ca are highlighted in red, indicating their  $4s^1$  and  $4s^2$  configurations respectively.

Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	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
5	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
6	55 Cs	56 Ba		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
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

What are d-block metals?

The elements in groups 3–12 are defined as the so-called d-block metals.



## Transition Metals (d block elements)

Group →	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Period ↓	1 1 H																	2 He
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5	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
6	55 Cs	56 Ba		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
7	87 Fr	88 Ra		104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Uut	114 Uuq	115 Uup	116 Uuh	117 Uus	118 Uuo

Transition Metals (d-block)

K  
 $4s^1$

Ca  
 $4s^2$

Across period

Sc $4s^2 3d^1$	Ti $4s^2 3d^2$	V $4s^2 3d^3$	Cr $4s^1 3d^5$	Mn $4s^2 3d^5$	Fe $4s^2 3d^6$	Co $4s^2 3d^7$	Ni $4s^2 3d^8$	Cu $4s^1 3d^{10}$	Zn $4s^2 3d^{10}$
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Cr -  $4s^1 3d^5$   
• half filled more stable

Cu -  $4s^1 3d^{10}$   
• fully filled more stable

## Transition Metals (d block elements)

Group → ↓ Period	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
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K  
 $4s^1$

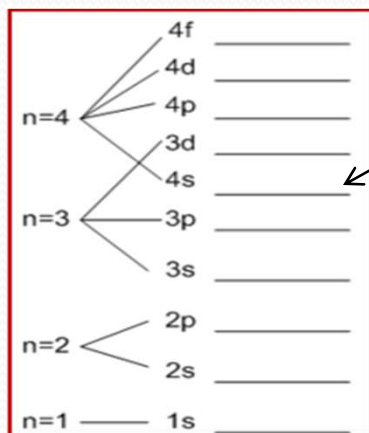
Ca  
 $4s^2$

Across period

Sc $4s^2 3d^1$	Ti $4s^2 3d^2$	V $4s^2 3d^3$	Cr $4s^1 3d^5$	Mn $4s^2 3d^5$	Fe $4s^2 3d^6$	Co $4s^2 3d^7$	Ni $4s^2 3d^8$	Cu $4s^1 3d^{10}$	Zn $4s^2 3d^{10}$
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Cr -  $4s^1 3d^5$   
• half filled more stable

Cu -  $4s^1 3d^{10}$   
• fully filled more stable



Transition metal have partially filled 3d orbitals

- 3d and 4s electrons can be lost easily
- electrons filled from 4s level first then 3d level



## Transition Metals (d block elements)

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

### Transition Metals (d-block)

Across period

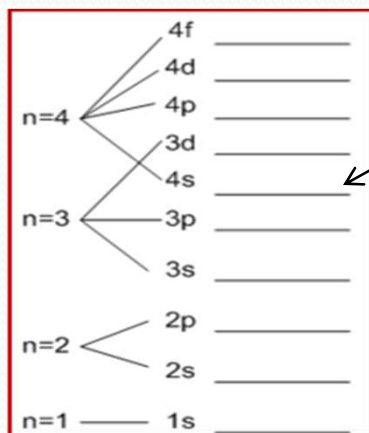
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$

Cr -  $4s^1 3d^5$   
• half filled more stable

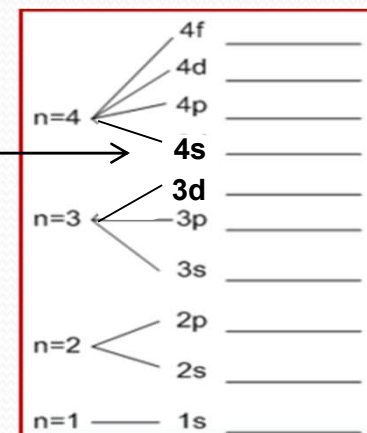
Cu -  $4s^1 3d^{10}$   
• fully filled more stable

### Transition metal have partially filled 3d orbitals

- 3d and 4s electrons can be lost easily
- electrons filled from 4s level first then 3d level
- electrons lost from 4s level first then 3d level



Filling electrons- 4s level lower, filled first



Losing electrons- 4s higher, lose first

## Transition Metals (d block elements)

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Period ↓	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
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### Transition Metals (d-block)

Across period

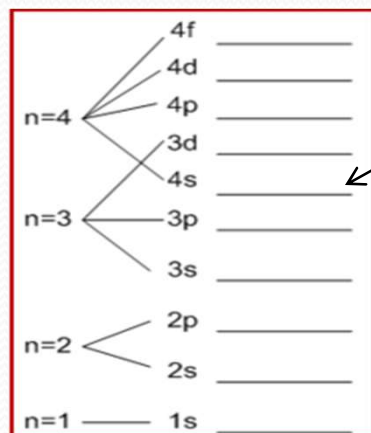
Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$

Cr -  $4s^1 3d^5$   
• half filled more stable

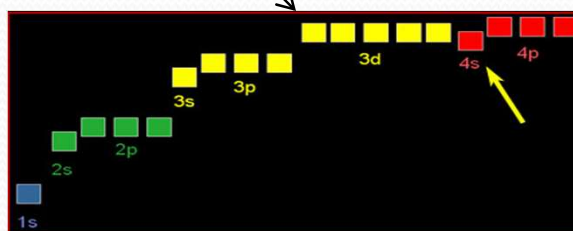
Cu -  $4s^1 3d^{10}$   
• fully filled more stable

### Transition metal have partially filled 3d orbitals

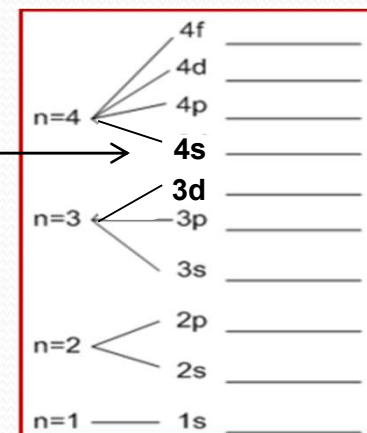
- 3d and 4s electrons can be lost easily
- electrons filled from 4s level first then 3d level
- electrons lost from 4s level first then 3d level
- 3d and 4s energy level close together (similar in energy)



Filling electrons- 4s level lower, filled first



Losing electrons- 4s higher, lose first





*Transition Metals (d block elements)*

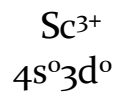
<b>Sc</b> 4s <sup>2</sup> 3d <sup>1</sup>	<b>Ti</b> 4s <sup>2</sup> 3d <sup>2</sup>	<b>V</b> 4s <sup>2</sup> 3d <sup>3</sup>	<b>Cr</b> 4s <sup>1</sup> 3d <sup>5</sup>	<b>Mn</b> 4s <sup>2</sup> 3d <sup>5</sup>	<b>Fe</b> 4s <sup>2</sup> 3d <sup>6</sup>	<b>Co</b> 4s <sup>2</sup> 3d <sup>7</sup>	<b>Ni</b> 4s <sup>2</sup> 3d <sup>8</sup>	<b>Cu</b> 4s <sup>1</sup> 3d <sup>10</sup>	<b>Zn</b> 4s <sup>2</sup> 3d <sup>10</sup>
↓	↓	↓	↓	↓	↓	↓	↓	↓	
<b>Ti<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>2</sup>	<b>V<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>3</sup>	<b>Cr<sup>3+</sup></b> 4s <sup>0</sup> 3d <sup>3</sup>	<b>Mn<sup>4+</sup></b> 4s <sup>0</sup> 3d <sup>3</sup>	<b>Fe<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>6</sup>	<b>Co<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>7</sup>	<b>Ni<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>8</sup>	<b>Cu<sup>2+</sup></b> 4s <sup>0</sup> 3d <sup>9</sup>		

## Incomplete filled d orbitals

Transition metal : d block elements with half/partially filled d orbitals/sublevels in one or more of its oxidation states → therefore, the group 12 metals zinc (Zn), cadmium (Cd) and mercury (Hg) are not typically classified as transition metals

## Transition Metals (d block elements)

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$



*Sc not transition elements.*

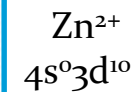
•  $Sc \rightarrow Sc^{3+}$  - (empty d orbital)  
 $4s^2 3d^1 \quad 4s^0 3d^0$

Lose  
Electrons

Ions  
formation

$Ti^{2+}$	$V^{2+}$	$Cr^{3+}$	$Mn^{4+}$	$Fe^{2+}$	$Co^{2+}$	$Ni^{2+}$	$Cu^{2+}$
$4s^0 3d^2$	$4s^0 3d^3$	$4s^0 3d^3$	$4s^0 3d^3$	$4s^0 3d^6$	$4s^0 3d^7$	$4s^0 3d^8$	$4s^0 3d^9$

Incomplete filled d orbitals



*Zn not transition elements.*

•  $Zn \rightarrow Zn^{2+}$  - (fully filled d orbital)  
 $4s^2 3d^{10} \quad 4s^0 3d^{10}$



## Transition Metals (d block elements)

### Transition Metals

- d block elements with half/partially filled d orbitals/sublevels in one or more of its oxidation states*

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$

$\times$ $\downarrow$ $Sc^{3+}$ $4s^0 3d^0$	$\downarrow$ $Ti^{2+}$ $4s^0 3d^2$	$\downarrow$ $V^{2+}$ $4s^0 3d^3$	$\downarrow$ $Cr^{3+}$ $4s^0 3d^3$	$\downarrow$ $Mn^{4+}$ $4s^0 3d^3$	$\downarrow$ $Fe^{2+}$ $4s^0 3d^6$	$\downarrow$ $Co^{2+}$ $4s^0 3d^7$	$\downarrow$ $Ni^{2+}$ $4s^0 3d^8$	$\downarrow$ $Cu^{2+}$ $4s^0 3d^9$	$\times$ $\downarrow$ $Zn^{2+}$ $4s^0 3d^{10}$
	Incomplete filled d orbitals								

*Sc not transition elements.*

•  $Sc \rightarrow Sc^{3+}$  - (empty d orbital)  
 $4s^2 3d^1 \rightarrow 4s^0 3d^0$

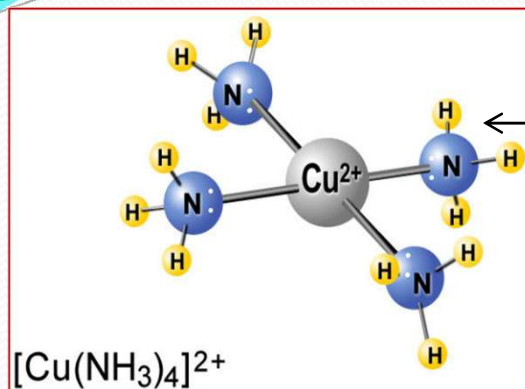
*Zn not transition elements.*

•  $Zn \rightarrow Zn^{2+}$  - (fully filled d orbital)  
 $4s^2 3d^{10} \rightarrow 4s^0 3d^{10}$

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↓ Period																		
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# Transition Metals (d block elements)

## Formation complex ions

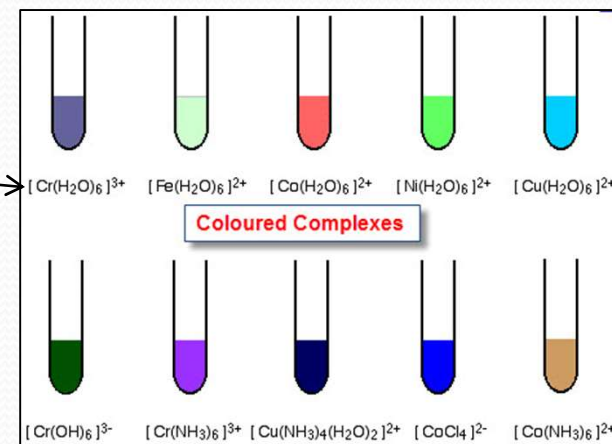


<http://www.dlt.ncssm.edu/tiger/chem8.htm>

## Properties of Transition metals

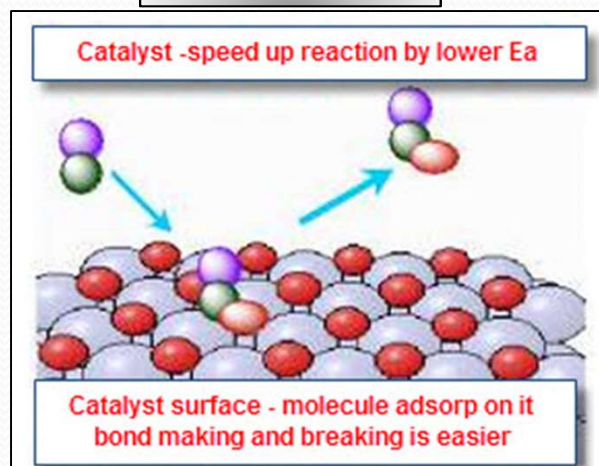
- Formation of complex ions
- Formation coloured complexes
- Variable oxidation states
- Catalytic activity

## Formation coloured complexes



<http://www.chemguide.co.uk/inorganic/transition/features.html>

## Catalytic activity



Sci-Media/Images/Catalytic-converter-catalyst

## Variable Oxidation states

Variable oxidation state							
			<u>+7</u>				
		<u>+6</u>	<u>+6</u>	<u>+6</u>			
	<u>+5</u>	<u>+5</u>	<u>+5</u>	<u>+5</u>	<u>+5</u>		
<u>+4</u>	<u>+4</u>	<u>+4</u>	<u>+4</u>	<u>+4</u>	<u>+4</u>	<u>+4</u>	
<u>+3</u>	<u>+3</u>	<u>+3</u>	<u>+3</u>	<u>+3</u>	<u>+3</u>	<u>+3</u>	<u>+3</u>
<u>+2</u>	<u>+2</u>	<u>+2</u>	<u>+2</u>	<u>+2</u>	<u>+2</u>	<u>+2</u>	<u>+2</u>
							<u>+1</u>
Ti	V	Cr	Mn	Fe	Co	Ni	Cu
[Ar]	[Ar]	[Ar]	[Ar]	[Ar]	[Ar]	[Ar]	[Ar]
3d <sup>2</sup> 4s <sup>2</sup>	3d <sup>3</sup> 4s <sup>2</sup>	3d <sup>5</sup> 4s <sup>1</sup>	3d <sup>5</sup> 4s <sup>2</sup>	3d <sup>6</sup> 4s <sup>2</sup>	3d <sup>7</sup> 4s <sup>2</sup>	3d <sup>8</sup> 4s <sup>2</sup>	3d <sup>10</sup> 4s <sup>1</sup>

<http://elementalolympics.wordpress.com/2011/02/28/variable-oxidation-states-and-catalysts/>



## Transition Metals (d block elements) – Variable Oxidation States

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$

Oxidation state +2 more common on right (Co → Zn)

• Harder to lose electron as Nuclear charge of Co - Zn is getting higher (NC ↑)

Oxidation state +3 more common on left (Sc → Fe)

• Easier to lose electron as Nuclear charge of Sc - Fe is lower (NC ↓)

Oxidation state for Mn is highest +7

Higher oxidation state exist when elements bond to oxygen – oxides/oxyanions

+7				(MnO <sub>4</sub> ) <sup>-</sup>							oxides oxyanion
+6			Cr <sub>2</sub> O <sub>7</sub>	(MnO <sub>4</sub> ) <sup>2-</sup>							
+5		V <sub>2</sub> O <sub>5</sub>									
+4		TiCl <sub>4</sub>	(VO <sub>2</sub> ) <sup>2+</sup>	MnCl <sub>4</sub>							chlorides
+3	ScCl <sub>3</sub>	TiCl <sub>3</sub>	VCl <sub>3</sub>	CrCl <sub>3</sub>	MnCl <sub>3</sub>	FeCl <sub>3</sub>					
+2				CrCl <sub>2</sub>	MnCl <sub>2</sub>	FeCl <sub>2</sub>	CoCl <sub>2</sub>	NiCl <sub>2</sub>	CuCl <sub>2</sub>	ZnCl <sub>2</sub>	
					+7						
				+6	+6						
		+5			+4						
	+4				+3	+3					
	+3	+3		+3	+3	+3					
				+2	+2	+2	+2	+2	+2	+2	

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^2 3d^1$	$4s^2 3d^2$	$4s^2 3d^3$	$4s^1 3d^5$	$4s^2 3d^5$	$4s^2 3d^6$	$4s^2 3d^7$	$4s^2 3d^8$	$4s^1 3d^{10}$	$4s^2 3d^{10}$

## Transition Metals (d block elements) – Variable Oxidation States

Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
$4s^23d^1$	$4s^23d^2$	$4s^23d^3$	$4s^13d^5$	$4s^23d^5$	$4s^23d^6$	$4s^23d^7$	$4s^23d^8$	$4s^13d^{10}$	$4s^23d^{10}$

Oxidation state +2 more common on right (Co → Zn)

• Harder to lose electron as Nuclear charge of Co - Zn is getting higher (NC ↑)

Oxidation state +3 more common on left (Sc → Fe)

• Easier to lose electron as Nuclear charge of Sc - Fe is lower (NC ↓)

Oxidation state for Mn is highest +7

Higher oxidation state exist when elements bond to oxygen – oxides/oxyanions

+7				(MnO <sub>4</sub> ) <sup>-</sup>							oxides oxyanion
+6			Cr <sub>2</sub> O <sub>7</sub>	(MnO <sub>4</sub> ) <sup>2-</sup>							
+5		V <sub>2</sub> O <sub>5</sub>									
+4		TiCl <sub>4</sub>	(VO <sub>2</sub> ) <sup>2+</sup>	MnCl <sub>4</sub>							chlorides
+3	ScCl <sub>3</sub>	TiCl <sub>3</sub>	VCl <sub>3</sub>	CrCl <sub>3</sub>	MnCl <sub>3</sub>	FeCl <sub>3</sub>					
+2				CrCl <sub>2</sub>	MnCl <sub>2</sub>	FeCl <sub>2</sub>	CoCl <sub>2</sub>	NiCl <sub>2</sub>	CuCl <sub>2</sub>	ZnCl <sub>2</sub>	
				+7							
			+6	+6							
		+5		+4							
	+4			+3							
	+3	+3		+3	+3						
				+2	+2	+2	+2	+2	+2	+2	

Oxidation number increases

+3 oxidation state more common

+2 oxidation state more common



# Transition Metal Complexes

## Ligands

- Neutral molecules or ions that have lone pair of electrons that can be used to form bond to metal
- Lewis base = electron pair donor

## Metal

- Lewis Acid = electron pair acceptor
- Can accept more than one Ligand (Lewis base)

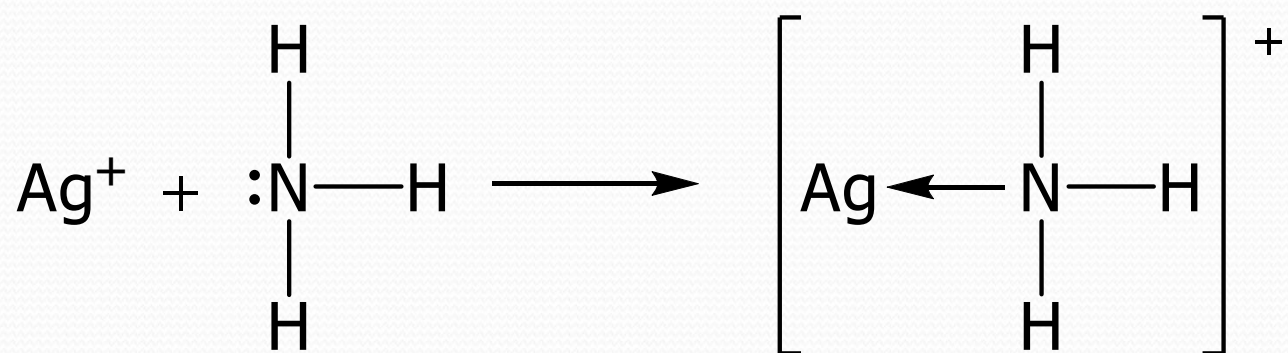
## M—L bond

- Coordinate *covalent* bond
- Lewis acid base adduct formation

# Transition Metal Complexes

## Coordinate Covalent Bond

- Both electrons in shared pair come from same atom



## Coordination Complexes

- Central metal atom surrounded by set of ligands
  - Complex ion:  $[\text{Co}(\text{NH}_3)_6]^{3+}$  ,  $[\text{PtCl}_4]^{2-}$



## Transition Metals (d block elements) – Formation Complex Ions



### Transition Metal ion

- High charged density metal ion, partially filled 3d orbital
- Attract ligand (neutral, anion with lone pair electron)
- Form coordinate covalent bond – lone pair from ligands

### Ligands

- Neutral/anion species that donate lone pair/non bonding electron pair to metal ion (complexing agents)
- Lewis base, lone pair donor – dative bond with metal ion
- Coordination number – number of ligands around central ion



## Transition Metals (d block elements) – Formation Complex Ions

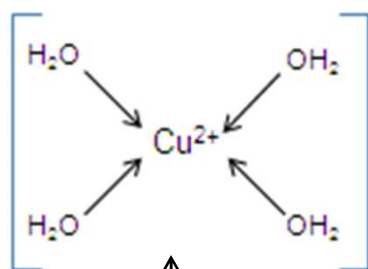


### Transition Metal ion

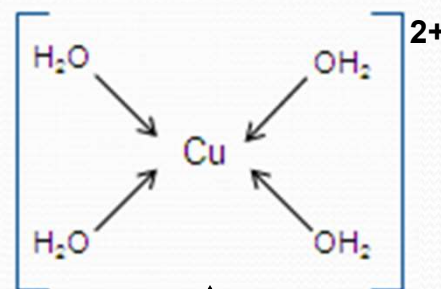
- High charged density metal ion, partially filled 3d orbital
- Attract ligand (neutral, anion with lone pair electron)
- Form coordinate covalent bond – lone pair from ligands

### Ligands

- Neutral/anion species that donate lone pair/non bonding electron pair to metal ion (complexing agents)
- Lewis base, lone pair donor – dative bond with metal ion
- Coordination number – number of ligands around central ion



water



+



+



Complex ion –  $[\text{Cu}(\text{H}_2\text{O})_4]\text{Cl}_2$  also written as  $\text{CuCl}_2$

Complex ion

- 4 water ligands attached
- 4 dative bonds
- Coordination number = 4

Anion

Counter ion

**Coordination complexes:** chemical structures that consist of a metal ion and the surrounding molecules or anions called the ligands.

**Coordination compounds:** are neutral compounds that contain a coordination complex.

**Coordination number:** maximum number of ligands can be accommodated by the metal ion, and is a property of the metal and its associated ligand.



## Transition Metals (d block elements) – Formation Complex Ions

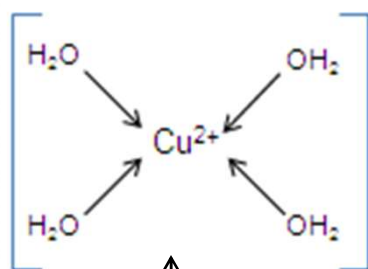


### Transition Metal ion

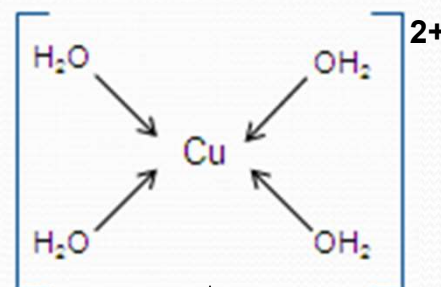
- High charged density metal ion, partially filled 3d orbital
- Attract ligand (neutral, anion with lone pair electron)
- Form coordinate covalent bond – lone pair from ligands

### Ligands

- Neutral/anion species that donate lone pair/non bonding electron pair to metal ion (complexing agents)
- Lewis base, lone pair donor – dative bond with metal ion
- Coordination number – number of ligands around central ion



water



+



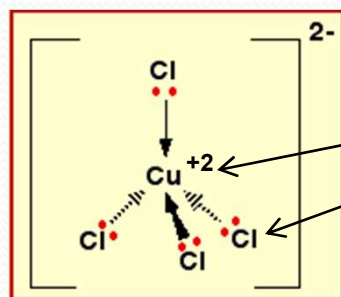
+



Complex ion – [Cu(H<sub>2</sub>O)<sub>4</sub>]Cl<sub>2</sub> also written as CuCl<sub>2</sub>  
Oxidation number +2

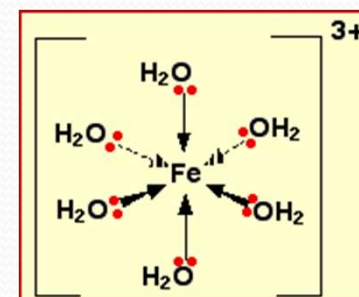
Complex ion  
• 4 water ligands attached  
• 4 dative bonds  
• Coordination number = 4

Anion  
Counter ion



### Drawing complex ion

- Overall charged on complex ion
- Metal ion in the center (+ve charged)
- Ligands attached
- Dative bonds from ligands



# Common Ligands

## 1. Monodentate $M \leftarrow :L$

- 1 donor atom
- 1 lone pair
- 1 bond to metal

### Anions

$F^-$ ,  $Cl^-$ ,  $Br^-$ ,  $I^-$ ,  $O^{2-}$ ,  $S^{2-}$ ,  $NO_2^-$ ,  $C^-$ ,  $OH^-$ ,  
 $SCN^-$ ,  $S_2O_3^{2-}$

### Molecules

$H_2O$ ,  $NH_3$ ,  $CO$



# Common Ligands

## 2. Chelate or Polydentate Ligands

- Have two or more atoms on one molecule with lone pairs
  - Each of which can simultaneously form 2  $e^-$  bonds to  $M^{n+}$
  - Usually 5 or 6-membered rings with  $M$ 
    - Sometimes form 4-membered rings
  - Must be nonlinear molecules

