

# Chapter 2

## Atoms, Molecules & Ions

### I) Atomic Theory of Matter

#### Dalton's Atomic Theory (1808)

- 1) All matter is composed of indivisible **Atoms**
- 2) An **Element** is composed of only one kind of atom which have the same properties
- 3) A **Compound** is composed of atoms of 2 or more elements chemically combined in fixed proportions
- 4) A **Chemical Reaction** involves the rearrangement of atoms

**TODAY** we know some of the postulates are no longer true.

- i.e.
- 1) Atoms are divisible, made up of subatomic particles
  - 2) Elements are made up of more than one kind of atom

Postulates 3 and 4 are still true today

- 3) Compounds follow the Law of Constant composition or law of Definite Proportion (Joseph Louis Proust, 1754-1826)
- 4) Chemical Reaction is explained by the Law of Mass Conservation (Antoine Lavoisier 1743-1794)

### II) Structure of the Atom

\* observations that led to the nuclear atom model & was discovered over a period of time around the turn of the century

#### A) Discovery of the Electron

with the invention of the vacuum pump

- 1) **Sir William Crookes** (English physicist) 1875  
Using an evacuated tube containing metal electrodes connected to external electrical source, he saw a ray emit a flash of light when it hit a phosphorous coated end of a tube. He called the ray a **Cathode Ray** because it moved from the negative electrode (cathode) to the positive electrode (anode). This cathode ray is deflected by both magnetic and electrical fields

2) **Joseph J. Thomson** (British physicist) 1897

Research involving discharging electricity through gases lead to the discovery of the electron

- used a magnetic and electrical fields
- measured mass/charge ratio of cathode particles
- compared to mass/electron (m/e) ratio for lightest charged particle in solution.

concluded:

- particle weighed  $< 1/1837$  as much a H atom
- particle has a negative charge

3) **Robert Millikan** (U.S. physicist) 1909

Measured charge of electron ( $e^-$ ) by observing movement of tiny droplets of oil between electrically charged plates.

overview of the experiment

- x-rays knocked  $e^-$  from air gas molecules
- oil droplet fell through hole of positively charged plate
- $e^-$  stuck to drop of oil giving it a negative charge
- with electric field off: measured rate of fall of oil droplet
- with electric field on and varying the strength of the field: measured rate of fall of oil droplet
- calculated total charge on oil droplet

results of experiment:

- charged always whole-number multiple of minimum charge
- electron charge is  $1.602 \times 10^{-19}$  Coulombs
- electron mass  $9.209 \times 10^{-31}$  kg

## B) Discovery of the Atomic Nucleus

1) **Ernest Rutherford** (British physicist) 1911

After the discovery of radioactivity, Rutherford devised experiments to answer the following question. How does the positively charged  $\alpha$ -particle interact with a solid object?

His experiments involved:

- the use of zinc sulfide coated screens, these screens flashed when struck by an  $\alpha$ -particle
- measuring the deflection of the  $\alpha$ -particles aimed at a thin gold foil
- using the mass, the charge, and the velocity of  $\alpha$ -particle, frequency of large angle deflections and the property of an  $e^-$

results:

- an atom is mostly space occupied by e-
- within this space is a tiny region called a nucleus
- the nucleus contains positively charged particles and the mass of the atom
- the positively charged particles are called **protons**

2) **James Chadwick** (U.S. scientist) 1932

Discovered the neutron which has no charge (neutral) and a mass of  $1.6749 \times 10^{-27}$  kg.

His experiment involved bombarding a thin sheet of beryllium with an  $\alpha$ -particle. The result of this bombardment was a high energy ray emitted by the metal of electrically neutral particles with a mass slightly larger than a proton.

## Summary: Structure of the Atom

Atom: positively charged central nucleus  
surrounded by 1 or more electrons

Nucleus: Incredibly dense  
99.97% of atom's mass  
occupies only 1 ten-trillion of the atoms volume  
consists of protons and neutrons

Atom is electrically neutral so number  $p^+$  in nucleus = number of  $e^-$  surrounding the nucleus

## Summary Table

subatomic particles	location	charge (C)	charge (e)	mass (amu)	mass (kg)
electron ( $e^-$ )	surrounding the nucleus	$-1.602 \times 10^{-19}$	-1	1/1837	$9.10939 \times 10^{-31}$
proton ( $p^+$ )	inside the nucleus	$+1.602 \times 10^{-19}$	+1	~1	$1.67262 \times 10^{-27}$
neutron ( $n^0$ )	inside the nucleus	0	0	~ 1	$1.67493 \times 10^{-27}$

### III. Isotopes and Atomic Masses

#### A) Isotopes

all atoms can be identified by the number of protons and neutrons they contain

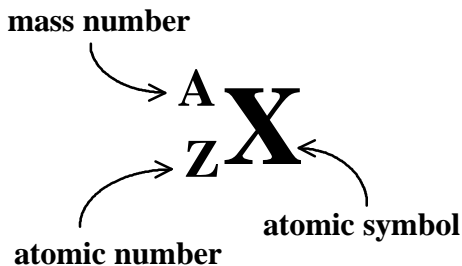
**Atomic number (Z):** number of protons in the nucleus of an atom  
all atoms of a particular element have the same atomic number

**Mass number (A):** the number of protons and neutrons in the nucleus of an atom.  
mass number =  $p^+ + n^0$   
mass number for carbon with  $6 p^+ + 6 n^0 = 12$   
mass number for uranium with  $92 p^+ + 146 n^0 = 238$   
 $e^-$  mass is not included in the mass number since its mass is small compared to the mass of the  $p^+$  or  $n^0$ .

**Isotopes:** Atoms that have the same atomic number but different mass numbers

#### Nuclide Symbol

is used to represent an elemental isotope



e.g. Hydrogen consists of three isotopes:  ${}_1^1\text{H}$ ,  ${}_1^2\text{H}$ ,  ${}_1^3\text{H}$

From the nuclide symbol the number of protons, neutrons and electrons can be determined.

Recall: mass number =  $p^+ + n^0$   
atomic number =  $p^+$   
atoms are electrically neutral:  $e^- = p^+$

## B) Atomic Masses (Atomic Weights)

### 1) Mass Spectrometry

used to obtain accurate masses of atoms

- high energy  $e^-$  collides with atom, resulting in +1 charge on the atom
- sample is vaporized
- bombarded by high energy  $e^-$ 's, making a +1 charged atom
- attracted to negatively charged plate
- pass through evacuated tube and exposed to magnetic field
- path bends and particles fan out according to mass
- strike detecting device, showing relative position to carbon-12 and natural abundance

The mass of an atom is measured most easily relative to the mass of a chosen atomic standard. (using a mass spectrophotometer)

### 2) Calculating atomic masses for elements

Atomic standard: Carbon-12 mass scale,

Carbon-12 is assigned to be 12 atomic mass units (amu)

atomic mass unit (amu):  $1/12$  mass of carbon-12

**Atomic Mass (weight):** an average of the masses of its naturally occurring isotopes weighted according to their fractional abundances.

$[(\text{isotopic mass})(\text{frac. abund.})] + [(\text{isotopic mass})(\text{frac. abund.})] + \dots = \text{atomic weight}$

Example:

Gallium has two naturally occurring isotopes

isotope	isotopic masses	fractional abundance
$^{69}_{31}\text{Ga}$	68.9256 amu	0.6011
$^{71}_{31}\text{Ga}$	70.9247 amu	0.3989

Calculate the atomic weight of gallium

$$\begin{aligned} & ^{69}_{31}\text{Ga} \quad (68.9256\text{amu})(0.6011) = 41.43 \text{ amu} \\ & ^{71}_{31}\text{Ga} \quad (70.9247\text{amu})(0.3989) = \underline{28.29 \text{ amu}} \\ & \text{total atomic weight} \quad = 69.72 \text{ amu} \end{aligned}$$

## IV) The Periodic Table

Periodic table of elements was discovered independently by  
Dmitri Mendeleev (Russian) in 1869  
J. Lothor Meyer (German) in 1870

Arrangement of Elements

- rows increase in Atomic number
- columns contain elements with similar chemical properties

**Refer to a Periodic Table** (inside the front or back cover of your book.)

Description of the periodic table

**Period:** elements in horizontal row (1-7)

**Group:** elements in vertical column (1-18) follow A, B system

A Groups - main group elements (IA - VIIIA)

B Groups - transition elements (IB - VIIB)

Bottom two rows - inner transition metals; lanthanides and actinides

Special group names:

group label	special name	common characteristic
1A	alkali metals	soft metal react with water
2A	alkaline earth metals	highly reactive
7A	halogens	colored, highly reactive nonmetals
8A	noble gases	relatively unreactive nonmetals

**Element Classification: Metals, Nonmetals, or Metalloid**

**Metals:** shiny solids at room temperature (except Hg)  
good conductor of electricity and heat  
malleable (hammered into sheets)  
ductile (drawn into wires)

**Nonmetals:** gases or dull brittle solid at room temperature (except Br)  
poor conductor of electricity and heat (insulators)

**Metalloids:** properties between metals and nonmetals (semimetals)  
good semiconductors

## V) Ions and Molecules

### A) Ions

formed when  $e^-$  are removed or added to a neutral atom (or molecule)

#### 1) Two Types

- a) **Cation:** Positively charged ion  
usually metal  
loses  $e^-$
- b) **Anion:** Negatively charged ion  
usually nonmetal  
gains  $e^-$

*How many  $e^-$  are lost or gained by the elements?*

Elements will lose or gain enough  $e^-$  to obtain a noble gas number of  $e^-$

example:

Na has 11  $e^-$  ; it loses 1  $e^-$  to obtain 10  $e^-$  like Ne

Cl has 17  $e^-$  ; it gains 1  $e^-$  to obtain 18  $e^-$  like Ar

#### 2) Formula and Names for Ions

Chemical Formula for ions: Chemical symbol followed by a superscript of the charge

Main Group Elements

##### a) Metals: lose $e^-$

Ca has 20  $e^-$  ; loses 2  $e^-$  ; now has 18  $e^-$  like Ar

Chemical Formula:  $Ca^{2+}$

Ion Name: name of element followed by ion  
calcium ion

##### b) Nonmetals: gain $e^-$

N has 7  $e^-$  ; gains 3  $e^-$  ; now has 10  $e^-$  like Ne

Chemical Formula:  $N^{3-}$

Ion Name: name of element with -ide ending followed by ion  
nitride ion

c) Exceptions

- Carbon does not form ions
- Sn and Pb can form more than one ion  
 $\text{Sn}^{2+}$ ,  $\text{Sn}^{4+}$  &  $\text{Pb}^{2+}$ ,  $\text{Pb}^{4+}$

Transition Metals

- can form more than 1 cation
- name includes roman numeral to reflect charge on the ion

element:	Fe	iron
ions:	$\text{Fe}^{2+}$	iron(II) ion
	$\text{Fe}^{3+}$	iron (III) ion

- no good way to predict charge on transition metal ions  
(just know some of the more common transition elements, )
- +2 ion is most common

Ion	Ion name
$\text{Cr}^{3+}$	chromium(III)
$\text{Mn}^{2+}$	manganese(II)
$\text{Fe}^{2+}$	iron(II) or ferrous
$\text{Fe}^{3+}$	iron(III) or ferric
$\text{Co}^{2+}$	cobalt(II)
$\text{Ni}^{2+}$	nickel(II)
$\text{Cu}^{2+}$	copper(II)
$\text{Zn}^{2+}$	zinc
$\text{Ag}^+$	silver
$\text{Cd}^{2+}$	cadmium
$\text{Hg}^{2+}$	mercury(II)

Polyatomic Ions

- cluster of nonmetals with an overall net charge
- some polyatomic ions are listed in bold in the following table

## Valences of Some Common Ions

Cations (positive charge)		Anions (negative charge)	
+1		-1	
H <sup>+</sup> hydrogen	H <sub>3</sub> O <sup>+</sup> hydronium	H <sup>-</sup> hydride	MnO <sub>4</sub> <sup>-</sup> permanganate
Li <sup>+</sup> lithium	Hg <sup>+</sup> mercury(I)	F <sup>-</sup> fluoride	ClO <sup>-</sup> hypochlorite
Na <sup>+</sup> sodium		Cl <sup>-</sup> chloride	ClO <sub>2</sub> <sup>-</sup> chlorite
K <sup>+</sup> potassium		Br <sup>-</sup> bromide	ClO <sub>3</sub> <sup>-</sup> chlorate
Ag <sup>+</sup> silver		I <sup>-</sup> iodide	ClO <sub>4</sub> <sup>-</sup> perchlorate
Cu <sup>+</sup> copper(I)		OH <sup>-</sup> hydroxide	HCO <sub>3</sub> <sup>-</sup> hydrogen carbonate
NH <sub>4</sub> <sup>+</sup> ammonium		NO <sub>2</sub> <sup>-</sup> nitrite	C <sub>2</sub> H <sub>3</sub> O <sub>2</sub> <sup>-</sup> acetate
		NO <sub>3</sub> <sup>-</sup> nitrate	HSO <sub>3</sub> <sup>-</sup> hydrogen sulfite
		CN <sup>-</sup> cyanide	HSO <sub>4</sub> <sup>-</sup> hydrogen sulfate
			H <sub>2</sub> PO <sub>4</sub> <sup>-</sup> dihydrogen phosphate
+2		-2	
Mg <sup>2+</sup> magnesium	Cr <sup>2+</sup> chromium(II)	O <sup>2-</sup> oxide	C <sub>2</sub> O <sub>4</sub> <sup>2-</sup> oxalate
Ca <sup>2+</sup> calcium	Co <sup>2+</sup> cobalt(II)	S <sup>2-</sup> sulfide	S <sub>2</sub> O <sub>3</sub> <sup>2-</sup> thiosulfate
Sr <sup>2+</sup> strontium	Mn <sup>2+</sup> manganese(II)	CO <sub>3</sub> <sup>2-</sup> carbonate	HPO <sub>4</sub> <sup>2-</sup> monohydrogen phosphate
Ba <sup>2+</sup> barium	Cd <sup>2+</sup> cadmium	SO <sub>3</sub> <sup>2-</sup> sulfite	
Zn <sup>2+</sup> zinc	Sn <sup>2+</sup> tin(II)	SO <sub>4</sub> <sup>2-</sup> sulfate	O <sub>2</sub> <sup>2-</sup> peroxide
Cu <sup>2+</sup> copper(II)	Pb <sup>2+</sup> lead(II)	CrO <sub>4</sub> <sup>2-</sup> chromate	
Fe <sup>2+</sup> iron(II)	Ni <sup>2+</sup> nickel(II)	Cr <sub>2</sub> O <sub>7</sub> <sup>2-</sup> dichromate	
Hg <sup>2+</sup> mercury(II)			
+3		-3	
Al <sup>3+</sup> aluminum	Cr <sup>3+</sup> chromium(III)	N <sup>3-</sup> nitride	PO <sub>4</sub> <sup>3-</sup> phosphate
Fe <sup>3+</sup> iron(III)	Co <sup>3+</sup> cobalt(III)	P <sup>3-</sup> phosphide	
+4			
Sn <sup>4+</sup> tin(IV)			
Pb <sup>4+</sup> lead(IV)			

## B) Ionic Compounds

- compound composed of ions
- a cation (metal) and an anion (nonmetal)
- involves the transfer of  $e^-$
- compound is electrically neutral  
(the number of positive charges = number of negative charges)

### Formula Unit

a group of atoms or ions explicitly symbolized in the formula  
smallest possible integer number of different ions (elements)

#### 1) Writing Ionic Formula from Ions

An ionic compound is electrically neutral, therefore the total positive charge from the cations is canceled by the total negative charge from the anions. In short, the sum of the positive charges and negative charges in an ionic compound will be zero.

One way to determine the ionic formula is to take the number on the ion charge and make it the subscript on the other atom (or polyatomic ion).

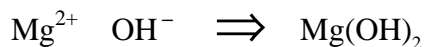
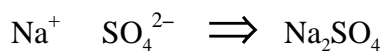
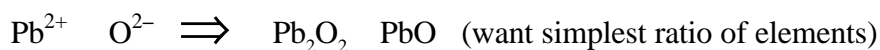
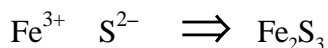
For example what is the formula of potassium oxide?

The ions involved in this compound are  $K^+$  and  $O^{2-}$

The subscript on oxygen will be the number on the charge of potassium, which is 1

The subscript on potassium in the compound will be the number on the charge of oxygen which is 2.

The chemical formula of potassium oxide is  $K_2O$



#### 2) Naming Ionic Compounds

a) **binary compounds**: consisting of 2 elements

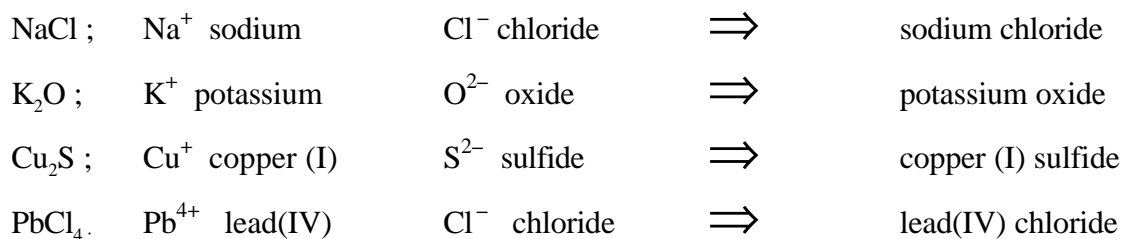
ionic compound name consists of two words

first word is the name of the cation

second word is the name of the anion with an -ide ending

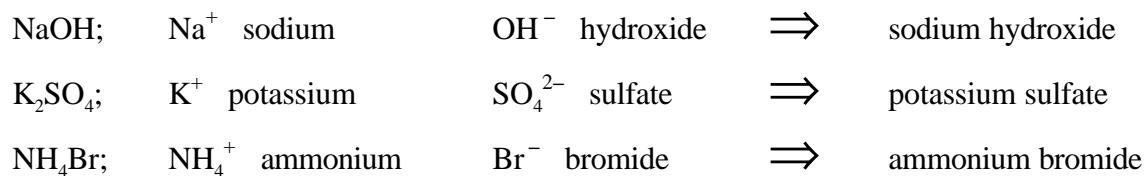
note: the name of the polyatomic ion is used in either the first or second word, it depends if the polyatomic ion in the compound is a cation or an anion.

## Examples



- b) **ternary compounds**: consisting of 3 different elements  
metal with polyatomic ion or polyatomic ion with a nonmetal

examples:



## C) Covalent Compounds (Molecules)

- consist of at least 2 nonmetals
- involves the sharing of e<sup>-</sup> between nonmetal atoms (covalent bond)
- nonmetals are held together by a covalent bond
- no net electrical charge

### 1) **diatomic molecules**

- consisting of atoms of the same element
- seven naturally occurring elements

Element	Name
H <sub>2</sub>	hydrogen
O <sub>2</sub>	oxygen
N <sub>2</sub>	nitrogen
F <sub>2</sub>	fluorine
Cl <sub>2</sub>	chlorine
Br <sub>2</sub>	bromine
I <sub>2</sub>	iodine

(polyatomic molecules: sulfur, S<sub>8</sub>; phosphorus, P<sub>4</sub>)

2) **binary molecules**

- consisting of 2 different elements

Naming: since no ions are involved, must use prefixes to show the number of each element in the molecule. Prefixes are found in the following table.

Name has two words

first word is the name of the first nonmetal shown with appropriate prefix

note: prefix mono- is usually omitted in the first word

second word is the name of the second nonmetal with -ide ending and appropriate prefix

Prefixes showing the number of atoms of each element in the molecule.

# atoms	prefix	atoms	prefix
1	mono-	6	hexa-
2	di-	7	hepta-
3	tri-	8	octa-
4	tetra-	9	nona-
5	penta-	10	deca-

examples:

CO<sub>2</sub> carbon dioxide

PCl<sub>5</sub> phosphorus pentachloride

N<sub>2</sub>O<sub>4</sub> dinitrogen tetroxide

## VI) Chemical Reactions

### A) Writing chemical reactions

In general: reactants  $\xrightarrow{\text{"yields"}}$  products

For example:  $2 \text{H}_2\text{O} \longrightarrow 2 \text{H}_2 + \text{O}_2$

1) coefficients give the number of each compound which reacts or forms in a chem. reaction

More complete:  $2 \text{H}_2\text{O} (\text{l}) \xrightarrow{\text{electricity}} 2 \text{H}_2 (\text{g}) + \text{O}_2 (\text{g})$

2) phase labels (**g**) - gas; (**l**) - liquid; (**s**) - solid;  
(**aq**) - aqueous solution, dissolved in water

3) over the reaction arrow

a) condition of a reaction: electricity; heat ( $\Delta$ )

b) catalyst - substance not consumed in a reaction but speeds up the reaction

### B) Balancing Chemical Reactions

Recall: Law Mass Conservation

same number of atoms should appear on both sides of the reaction.

#### Method for balancing a chemical rxn.

1) Tally up atoms on reactant side and product side

number of atom = coefficient  $\times$  subscript

example:  $2 \text{H}_2\text{O}$  two water molecules consist of 4 H atoms and 2 O atoms

2) Choose an element to begin balancing

3) Change only the coefficients in front of the compounds (do not change the subscripts)

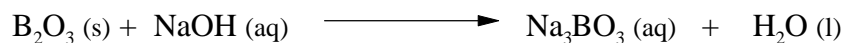
4) Final Check, recount all atoms on both sides of chem. rxn.

Notes:

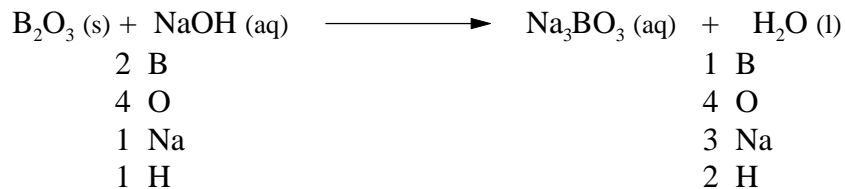
a) first balance elements which show up only in one compound on each sides of the reaction.

b) subscripts located outside the parenthesis multiplies each subscript inside.

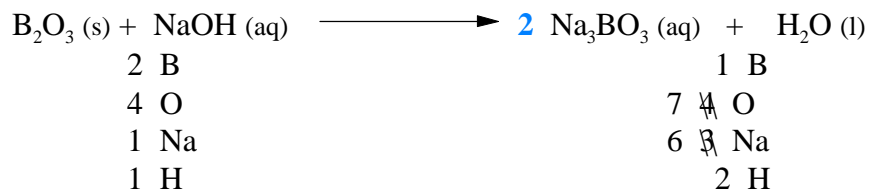
For example:



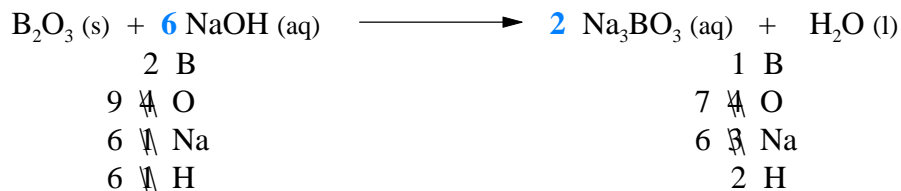
1) tally up the atoms



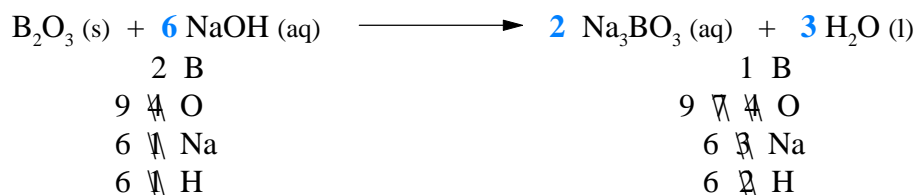
2) pick an atom to start balancing B (boron) and retally the atoms



3) balancing Na (sodium) and retally



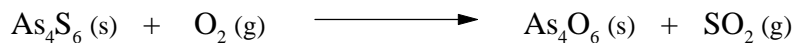
4) balancing H (hydrogen) and retally



5) the reaction is balanced



For practice:



## VII) Naming other various compounds

### A) Naming Acids

Acids: contain 1 or more H atoms as cations

- 1) Binary compounds with anions whose name ends with -ide  
acids name include a prefix hydro- and an ending -ic acid

ionic cpd	ionic cpd name	acid name
HCl	hydrogen chloride	<u>hydrochloric acid</u>
HI	hydrogen iodide	<u>hydroiodic acid</u>

- 2) Oxoacid consist of compounds with hydrogen, oxygen and a central atom derived from oxoanions  
prefixes and ending depend on number of oxygen atoms

number of oxygen	oxoanion		oxoacid	
1 add'l oxygen	per-	-ate	per-	-ic acid
base		-ate		-ic acid
1 less oxygen		-ite		-ous acid
2 less oxygen	hypo-	-ite	hypo-	-ous acid

Example of oxoanions and oxoacids

oxoanions		oxoacids	
$\text{ClO}_4^-$	perchlorate ion	$\text{HClO}_4$	perchloric acid
$\text{ClO}_3^-$	chlorate ion	$\text{HClO}_3$	chloric acid
$\text{ClO}_2^-$	chlorite ion	$\text{HClO}_2$	chlorous acid
$\text{ClO}^-$	hypochlorite ion	$\text{HClO}$	hypochlorous acid

## B) Hydrates

hydrated ionic compound

- a specific number of H<sub>2</sub>O molecules are associated with the formula unit
- shown by a dot between formula unit and water

examples

MgSO<sub>4</sub> • 7H<sub>2</sub>O                      Magnesium sulfate heptahydrate

CaSO<sub>4</sub> • 2H<sub>2</sub>O                      calcium sulfate dihydrate

CuSO<sub>4</sub> • 5H<sub>2</sub>O                      copper(II) sulfate pentahydrate

**Anhydrous compound** are hydrate compounds with the water removed

ANSWERS TO THE BALANCING CHEMICAL REACTION PRACTICE:

