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Chapter 2

Atoms, Molecules and Ions

Ahmad Aqel Ifseisi
Assistant Professor of Analytical Chemistry
College of Science, Department of Chemistry
King Saud University
P.O. Box 2455 Riyadh 11451 Saudi Arabia
Building: 05, Office: 1A7 & AA53
Tel. 014674198, Fax: 014675992
Web site: http://fac.ksu.edu.sa/aifseisi
E-mail: ahmad3qel@yahoo.com
aifseisi@ksu.edu.sa

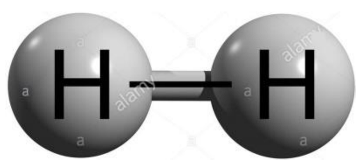
2.5
Molecules and Ions

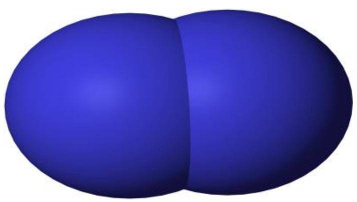
Molecules

A **molecule** is an aggregate of at least two atoms in a definite arrangement held together by chemical forces (also called chemical bonds).

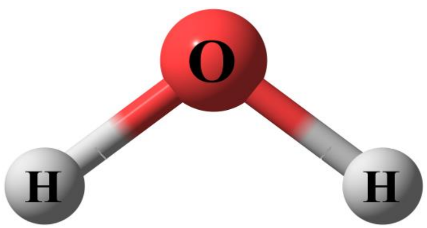
A molecule may contain atoms of the same element or atoms of two or more elements joined in a fixed ratio, in accordance with the law of definite proportions. Thus, a molecule is not necessarily a compound, which, by definition, is made up of two or more elements. Like atoms, molecules are electrically neutral.

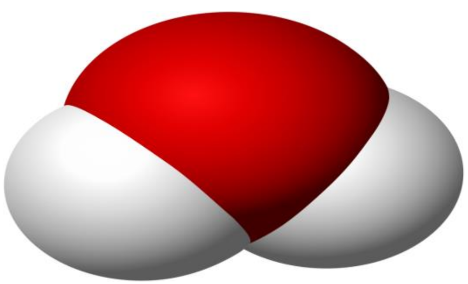
e.g., **Hydrogen gas (H_2)**; is a pure element, but it consists of molecules made up of two H atoms each.

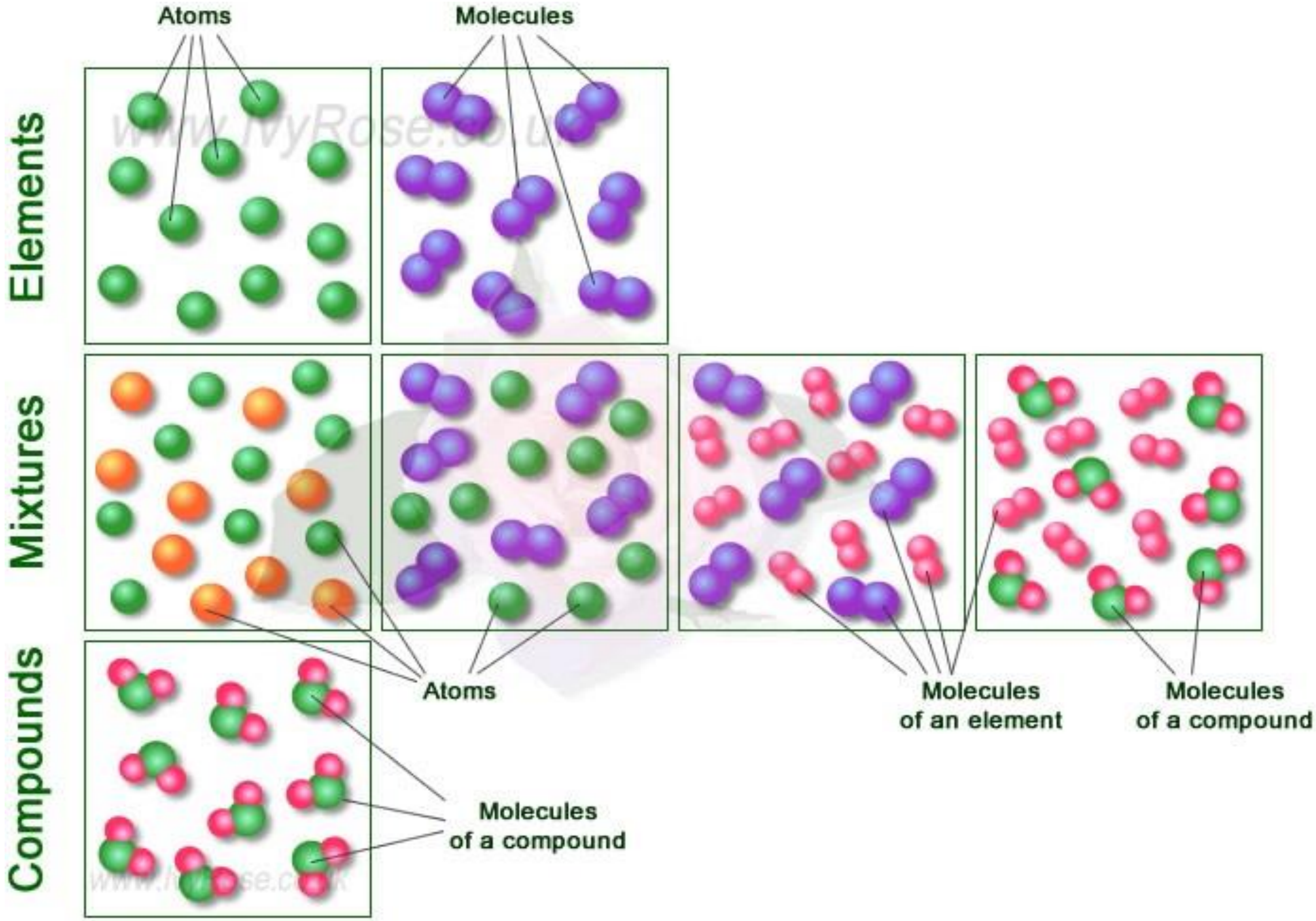




e.g., **Water (H_2O)**; is a molecular compound that contains hydrogen and oxygen in a ratio of two H atoms and one O atom.



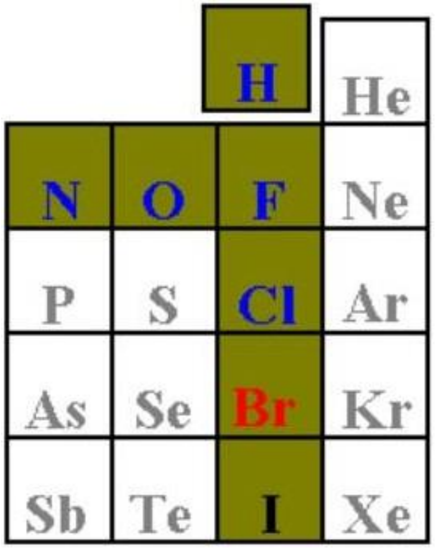




Atoms: represented by single spheres.
Elements: represented by the spheres of the same kind; same size and color.
Molecules: represented by two or more spheres jointed together.
Molecules of elements: represented by two or more spheres of the same kind jointed together.
Molecules of compounds: represented by two or more spheres of the different kind jointed together.

Diatomic molecules

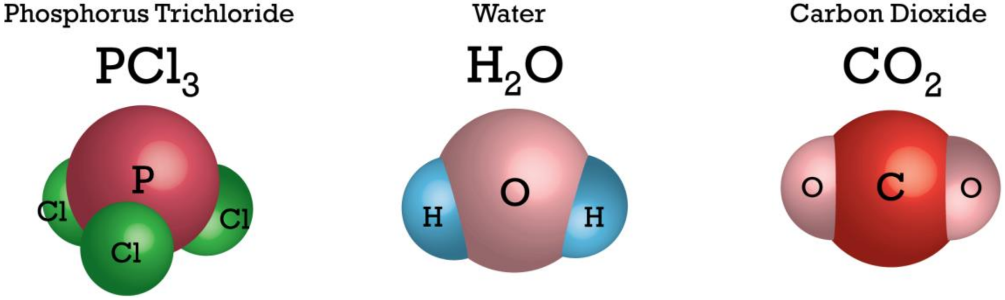
The hydrogen molecule (H_2), is called a **diatomic molecule** because it contains only two atoms. Other elements that normally exist as diatomic molecules are nitrogen (N_2) and oxygen (O_2), as well as the Group 7A elements; fluorine (F_2), chlorine (Cl_2), bromine (Br_2), and iodine (I_2). A diatomic molecule can contain atoms of different elements. e.g., hydrogen chloride (HCl) and carbon monoxide (CO).



The seven diatomic molecules

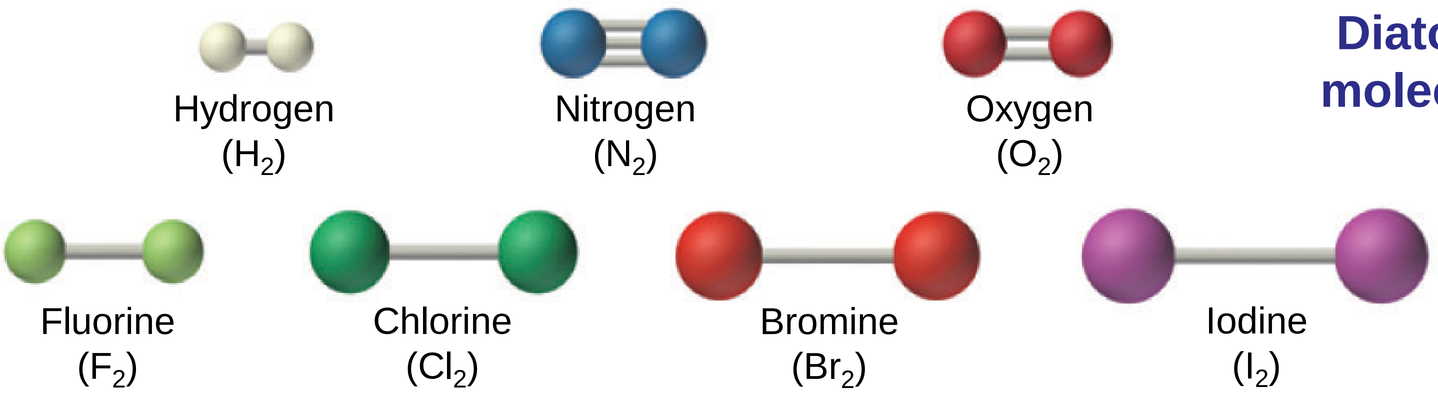
Polyatomic molecules

The vast majority of molecules contain more than two atoms. They can be atoms of the same element, as in ozone (O_3), which is made up of three atoms of oxygen, or they can be combinations of two or more different elements. Molecules containing more than two atoms are called **polyatomic molecules.** Like ozone, water (H_2O) and ammonia (NH_3) are polyatomic molecules.

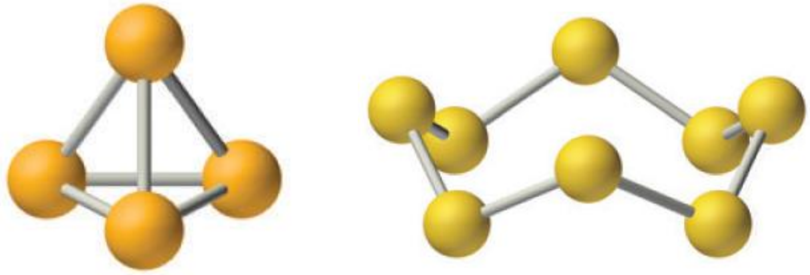


Homonuclear molecules

Molecules composed of only one type of element. Homonuclear molecules may consist of various numbers of atoms. Homonuclear diatomic molecules include H_2, O_2, N_2 and all of the halogens (F_2, Cl_2, Br_2 and I_2). Ozone (O_3) is a triatomic homonuclear molecule. Homonuclear tetratomic molecules include arsenic (As_4) and phosphorus (P_4).



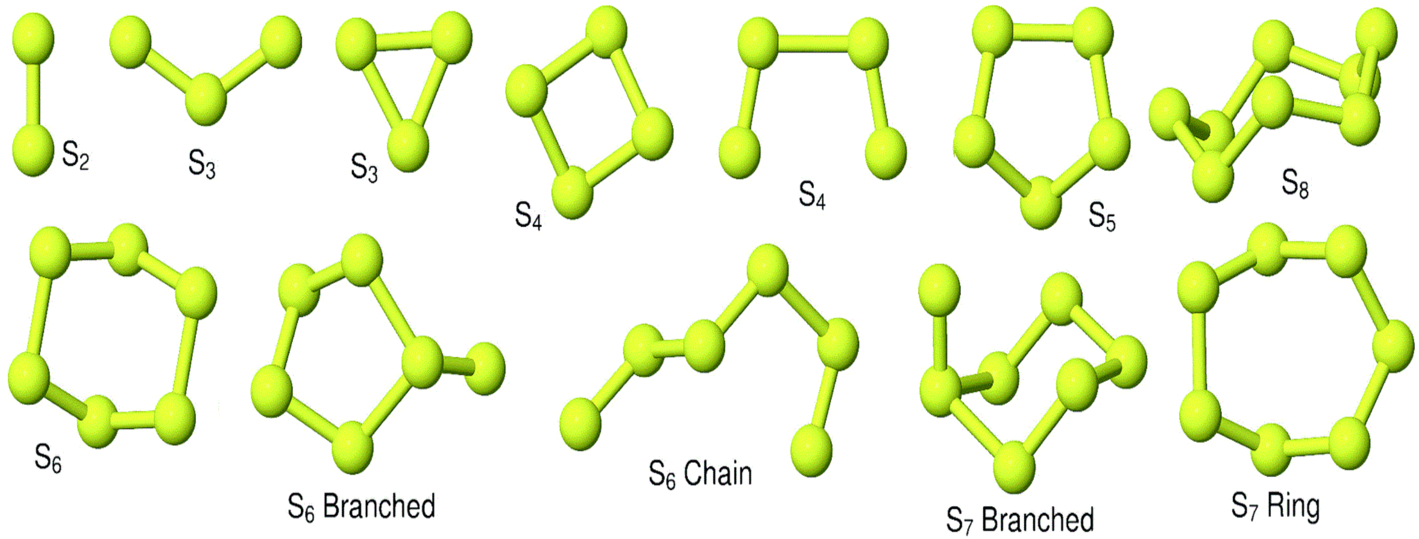
Diatomic molecules

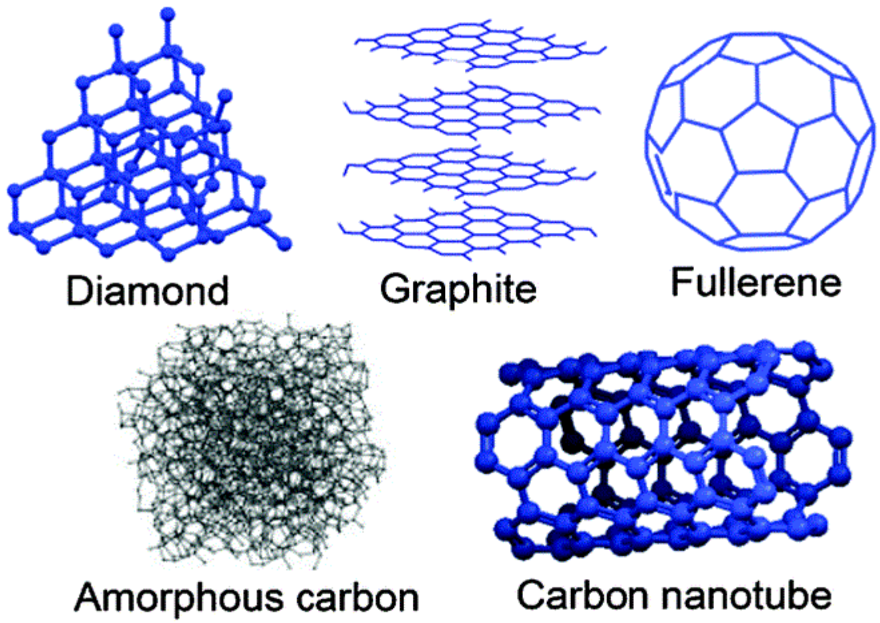


Polyatomic molecules

Allotropes are different chemical forms of the same element (not containing any other element). In that sense, allotropes are all homonuclear.

e.g., Sulfur forms several allotropes containing different numbers of sulfur atoms.





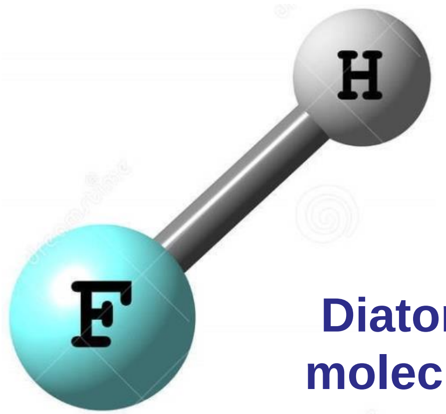
e.g., The element carbon is known to have a number of homonuclear allotrope molecules.

Heteronuclear molecules

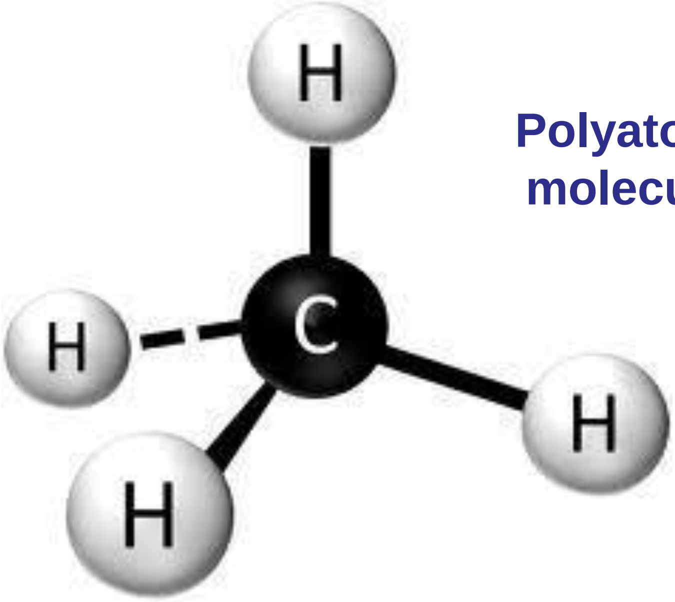
Molecules composed of more than one type of element.

e.g., HCl, HF and CO are diatomic heteronuclear molecules.

e.g., CO_2, CH_4 and NH_3 are polyatomic heteronuclear molecules.



Diatomic molecules



Polyatomic molecules

Ions

An **ion** is an atom or a group of atoms that has a net positive or negative charge.

The number of positively charged protons in the nucleus of an atom remains the same during ordinary chemical changes (chemical reactions), but negatively charged electrons may be lost or gained.

The loss of one or more electrons from a neutral atom results in a **cation,** an ion with a net positive charge. e.g., a sodium atom (Na) can readily lose an electron to become a sodium cation, Na^+:

Na Atom	Na^+ Ion
11 protons	11 protons
11 electrons	10 electrons

On the other hand, an **anion** is an ion whose net charge is negative due to an increase in the number of electrons. A chlorine atom (Cl), for instance, can gain an electron to become the chloride ion, Cl^-:

Cl Atom	Cl^- Ion
17 protons	17 protons
17 electrons	18 electrons

Sodium chloride (NaCl), ordinary table salt, is called an **ionic compound** because it is formed from cations and anions.

An atom can lose or gain more than one electron. Examples of ions formed by the loss or gain of more than one electron are Na^+, Cl^-, Mg^{2+}, Fe^{3+}, S^{2-} and N^{3-}. These ions are called **Monatomic ions** because they contain only one atom.

With very few exceptions, **metals** tend to form **cations** and **nonmetals** form **anions**.

In addition, two or more atoms can combine to form an ion that has a net positive or net negative charge. **Polyatomic ions** such as OH^- (hydroxide ion), CN^- (cyanide ion), and NH_4^+ (ammonium ion) are ions containing more than one atom.

Common Polyatomic Ions		
Ammonium NH_4^+	Nitrate NO_3^-	Thiocyanate SCN^-
Acetate CH_3COO^- or $C_2H_3O_2^-$	Nitrite NO_2^-	Thiosulfate $S_2O_3^{2-}$
Bromate BrO_3^-	Hydroxide OH^-	Hypochlorite ClO^-
Carbonate CO_3^{2-}	Perchlorate ClO_4^-	Sulfate SO_4^{2-}
Chlorate ClO_3^-	Periodate IO_4^-	Sulfite SO_3^{2-}
Chlorite ClO_2^-	Permanganate MnO_4^-	Iodate IO_3^-
Chromate CrO_4^{2-}	Peroxide O_2^{2-}	Silicate SiO_4^{4-}
Cyanide CN^-	Phosphate PO_4^{3-}	Oxalate $C_2O_4^{2-}$
Dichromate $Cr_2O_7^{2-}$	Phosphite PO_3^{3-}	Hydrogen carbonate HCO_3^-

2.6
Chemical Formulas

Molecular Formulas

A **molecular formula** shows the exact number of atoms of each element in the smallest unit of a substance. The molecular formula tells us the actual number of atoms in a molecule.

e.g., $\mathbf{H_2}$ is the molecular formula for hydrogen, $\mathbf{O_2}$ is oxygen, $\mathbf{O_3}$ is ozone, and $\mathbf{H_2O}$ is water. The subscript numeral indicates the number of atoms of an element present. There is no subscript for **O** in $\mathbf{H_2O}$ because there is only one atom of oxygen in a molecule of water, and so the number "one" is omitted from the formula.

The **structural formula** shows how atoms are bonded to one another in a molecule.

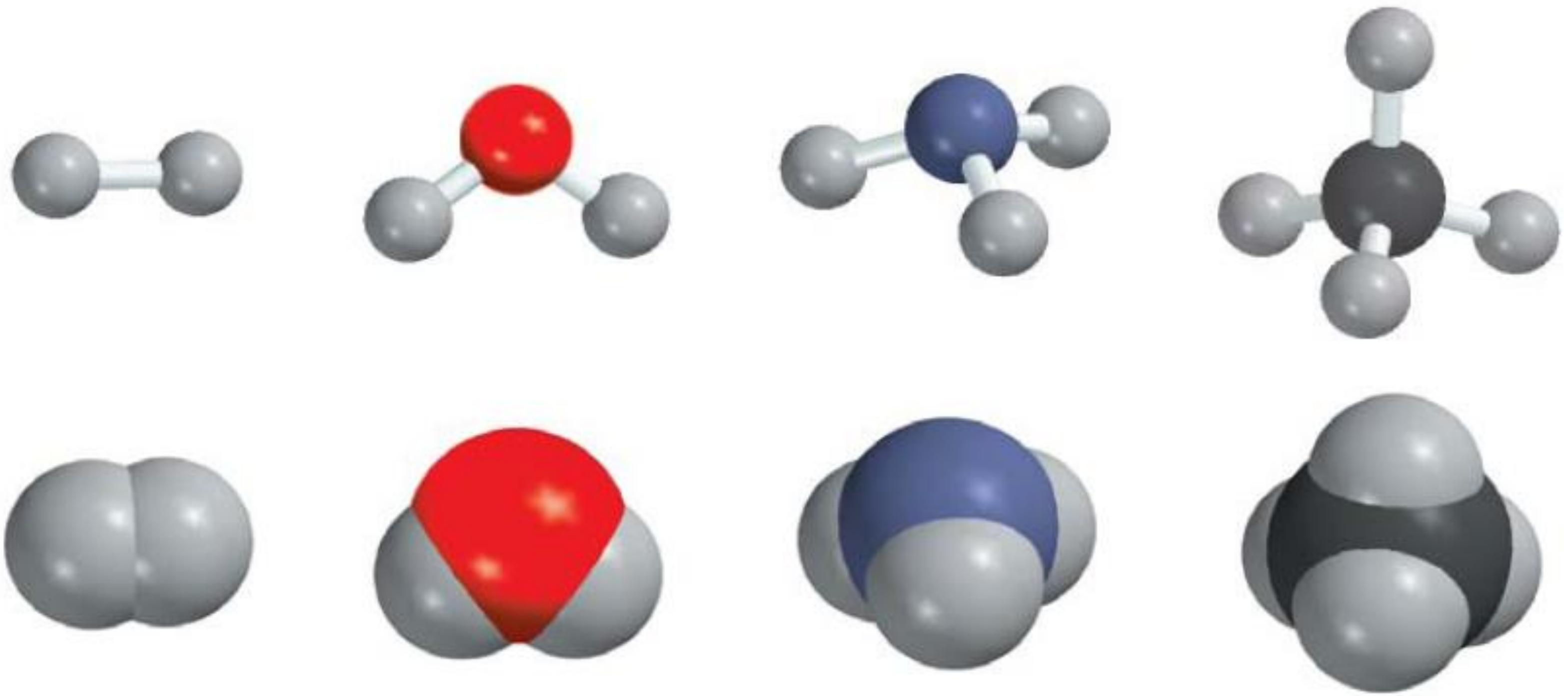
e.g., it is known that each of the two **H** atoms is bonded to an **O** atom in the water molecule. Therefore, the structural formula of water is **H—O—H**. A line connecting the two atomic symbols represents a chemical bond.

Molecular Models

	Hydrogen	Water	Ammonia	Methane
Molecular formula	H_2	H_2O	NH_3	CH_4
Structural formula	H—H	H—O—H	H—N—H (with H below N)	H—C—H (with H above and below C)

Ball-and-stick model

Space-filling model



Molecular and structural formulas and molecular models of four common molecules

Empirical Formulas

Empirical formulas are the simplest chemical formulas; they are written by reducing the subscripts in the molecular formulas to the smallest possible whole numbers.

Molecular formulas are the true formulas of molecules. If we know the molecular formula, we also know the empirical formula, but the reverse is not true.

e.g.,

Molecular formula	Empirical formula
H_2O_2	HO
N_2H_4	NH_2
C_6H_{14}	C_3H_7
H_2O	H_2O
CH_4	CH_4

e.g., Glucose ($C_6H_{12}O_6$), ribose ($C_5H_{10}O_5$), acetic acid ($C_2H_4O_2$), and formaldehyde (CH_2O) all have different molecular formulas but the same empirical formula: CH_2O.

EXAMPLE

Write the empirical formulas for the following molecules:

(a) acetylene (C_2H_2), which is used in welding torches,
Solution: CH

(b) glucose ($C_6H_{12}O_6$), a substance known as blood sugar, and
Solution: CH_2O

(c) nitrous oxide (N_2O), a gas that is used as an anesthetic gas ("laughing gas") and as an aerosol propellant for whipped creams.
Solution: N_2O (the empirical formula for nitrous oxide is the same as its molecular formula).

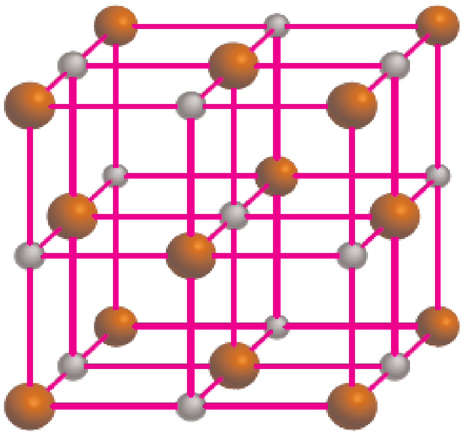
Practice Exercise

Write the empirical formula for caffeine ($C_8H_{10}N_4O_2$), a stimulant found in tea and coffee.

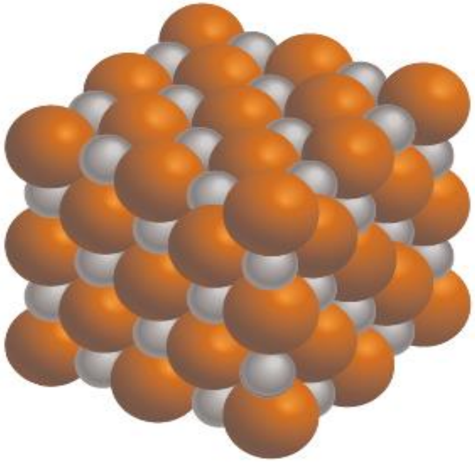
Formula of Ionic Compounds

Ionic compounds are chemical compounds composed of ions held together by electrostatic forces termed ionic bonding. The compound is neutral overall, but consists of positively charged ions called **cations** and negatively charged ions called **anions**.

e.g., a solid sample of sodium chloride (NaCl) consists of equal numbers of Na^+ and Cl^- ions arranged in a three-dimensional network. In such a compound there is a 1:1 ratio of cations to anions so that the compound is electrically neutral.



Structure of solid NaCl



In reality, the cations are in contact with the anions

Crystals of NaCl

The smaller spheres represent Na^+ ions and the larger spheres, Cl^- ions.

The arrangement of cations and anions is such that the compounds are all electrically neutral. For ionic compounds to be electrically neutral, the sum of the charges on the cation and anion in each formula unit must be zero.

Potassium Bromide

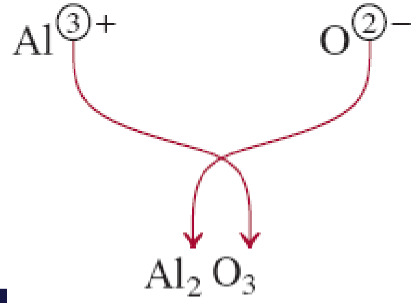
Potassium cation K^+ and bromine anion Br^- combine to form the ionic compound potassium bromide. The sum of the charges is +1 + (-1) = 0, so no subscripts are necessary. The formula is KBr.

Zinc Iodide

Zinc cation Zn^{2+} and iodine anion I^- combine to form zinc iodide. The sum of the charges of one Zn^{2+} ion and one I^- ion is +2 + (-1) = +1. To make the charges add up to zero we multiply the -1 charge of the anion by 2 and add the subscript “2” to the symbol for iodine. Therefore the formula for zinc iodide is ZnI_2.

Aluminum Oxide

The cation is Al^{3+} and the oxygen anion is O^{2-}. The following diagram helps to determine the subscripts for the compound:



The sum of the charges is 2(+3) + 3(-2) = 0.
Thus, the formula for aluminum oxide is Al_2O_3.

EXAMPLE

Calcium Bromide

$1 \times +2 = +2$ $\quad$ $2 \times -1 = -2$

$CaBr_2$

Ca^{2+} $\quad$ Br^-

$+2 + (-2) = 0$

Sodium Carbonate

$2 \times +1 = +2$ $\quad$ $1 \times -2 = -2$

Na_2CO_3

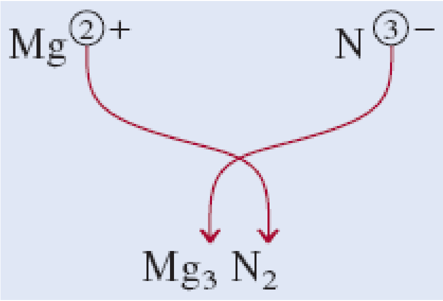
Na^+ $\quad$ CO_3^{2-}

$+2 + (-2) = 0$

EXAMPLE

Write the formula of magnesium nitride, containing the Mg^{2+} and N^{3-} ions.

$$3 \times (+2) + 2 \times (-3) = 0$$



Practice Exercise

Write the formulas of the following ionic compounds:

(a) Chromium sulfate (containing the Cr^{3+} and SO_4^{2-} ions),
Solution: $Cr_2(SO_4)_3$

(b) Titanium oxide (containing the Ti^{4+} and O^{2-} ions).
Solution: Ti_2O_4

2.7
Naming Compounds
(ionic, molecular, acids, bases & hydrates)

Ionic Compounds

Ionic compounds are made up of cations (+ve ions) and anions (-ve ions).

All cations of interest to us are derived from metal atoms (with the important exception of the ammonium ion, NH_4^+).

Metal cations take their names from the elements.

e.g.,

Element	Name	Cation	Name of Cation
Na	sodium	Na^+	sodium ion (or sodium cation)
K	potassium	K^+	potassium ion (or potassium cation)
Mg	magnesium	Mg^{2+}	magnesium ion (or magnesium cation)
Al	aluminum	Al^{3+}	aluminum ion (or aluminum cation)

The anion is named by taking the first part of the element name and adding “-ide.”

Group 4A	Group 5A	Group 6A	Group 7A
C carbide (C^{4-})	N nitride (N^{3-})	O oxide (O^{2-})	F fluoride (F^{-})
Si silicide (Si^{4-})	P phosphide (P^{3-})	S sulfide (S^{2-})	Cl chloride (Cl^{-})
		Se selenide (Se^{2-})	Br bromide (Br^{-})
		Te telluride (Te^{2-})	I iodide (I^{-})

Many ionic compounds are **binary compounds,** or compounds formed from just two elements. For binary compounds, the first element named is the metal cation, followed by the nonmetallic anion.

	Name
NaCl	sodium chloride
KBr	potassium bromide
ZnI_2	zinc iodide
Al_2O_3	aluminum oxide

Na, K, Zn and Al are **metals**

Cl, Br, I and O are **nonmetals**

The "-ide" ending is also used for certain anion groups containing different elements, such as hydroxide (OH^-) and cyanide (CN^-).

e.g.,

LiOH: lithium hydroxide

KCN: potassium cyanide

These and a number of other such ionic substances are called **ternary compounds,** meaning compounds consisting of three elements.

Certain metals, especially the **transition metals**, can form more than one type of cation.

e.g., iron can form two cations: Fe^{2+} and Fe^{3+}. An older nomenclature system that is still in limited use assigns the ending "-ous" to the cation with fewer positive charges and the ending "-ic" to the cation with more positive charges:

Fe^{2+}: ferrous ion

Fe^{3+}: ferric ion

$FeCl_2$ (left) & $FeCl_3$ (right)

The names of the compounds that these iron ions form with chlorine would thus be

$FeCl_2$: ferrous chloride

$FeCl_3$: ferric chloride

Modern nomenclature system called **Stock system**. In this system, the **Roman numeral** I indicates one positive charge, II means two positive charges, and so on.

e.g., manganese (Mn) atoms can assume several different positive charges:

Mn^{2+}: MnO manganese(II) oxide
Mn^{3+}: Mn_2O_3 manganese(III) oxide
Mn^{4+}: MnO_2 manganese(IV) oxide

Thus the names of the previous iron compounds would be:

$FeCl_2$: ferrous chloride becomes iron(II) chloride
$FeCl_3$: ferric chloride becomes iron(III) chloride

TABLE 2.3 in the textbook

Names and formulas of some common inorganic cations and anions

EXAMPLE

Name the following compounds:

(a) $Cu(NO_3)_2$, copper(II) nitrate.

(b) KH_2PO_4, potassium dihydrogen phosphate.

(c) NH_4ClO_3, ammonium chlorate.

Practice Exercise

Name the following compounds:

(a) PbO, Lead(II) oxide

(b) Li_2SO_3, Lithium sulfite

Molecular Compounds

Unlike ionic compounds, molecular compounds contain discrete molecular units. They are usually composed of nonmetallic elements.

Many molecular compounds are binary compounds.

Naming binary molecular compounds is similar to naming binary ionic compounds. We place the name of the first element in the formula first, and the second element is named by adding -ide to the root of the element name.

e.g.,

	Name
HCl	hydrogen chloride
HBr	hydrogen bromide
SiC	silicon carbide

It is quite common for one pair of elements to form several different compounds. In these cases, confusion in naming the compounds is avoided by the use of Greek prefixes to denote the number of atoms of each element present

e.g.,

CO	carbon monoxide
CO_2	carbon dioxide
SO_2	sulfur dioxide
SO_3	sulfur trioxide
NO_2	nitrogen dioxide
N_2O_4	dinitrogen tetroxide

Greek Prefixes

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

Notes in naming compounds with prefixes:

- The prefix “mono-” may be omitted for the first element.
e.g., PCl_3 is named phosphorus trichloride, not monophosphorus trichloride.

- For oxides, the ending “a” in the prefix is sometimes omitted.
e.g., N_2O_4 may be called dinitrogen tetroxide rather than dinitrogen tetraoxide.

Exceptions to the use of Greek prefixes are molecular compounds containing hydrogen. Traditionally, many of these compounds are called either by their common, nonsystematic names or by names that do not specifically indicate the number of H atoms present:

B_2H_6	diborane	CH_4	methane
SiH_4	silane	NH_3	ammonia
PH_3	phosphine	H_2O	water
H_2S	hydrogen sulfide		

EXAMPLE

Name the following molecular compounds:

(a) $SiCl_4$: silicon tetrachloride

(b) P_4O_{10}: tetraphosphorus decoxide

EXAMPLE

Write chemical formulas for the following molecular compounds:

(a) carbon disulfide: CS_2

(b) disilicon hexabromide: Si_2Br_6

Steps for naming ionic & binary molecular compounds.

Compound

- **Ionic**
  - Cation: metal or NH_4^+
  - Anion: monatomic or polyatomic
  - **Cation has only one charge**
    - Alkali metal cations
    - Alkaline earth metal cations
    - Ag^+, Al^{3+}, Cd^{2+}, Zn^{2+}
    - **Naming**
      - Name metal first
      - If monatomic anion, add "–ide" to the root of the element name
      - If polyatomic anion, use name of anion (see Table 2.3)
  - **Cation has more than one charge**
    - Other metal cations
    - **Naming**
      - Name metal first
      - Specify charge of metal cation with Roman numeral in parentheses
      - If monatomic anion, add "–ide" to the root of the element name
      - If polyatomic anion, use name of anion (see Table 2.3)
- **Molecular**
  - Binary compounds of nonmetals
  - **Naming**
    - Use prefixes for both elements present (Prefix "mono–" usually omitted for the first element)
    - Add "–ide" to the root of the second element

Note: the prefix "mono-" is usually omit when there is only one H in the anion.

Acids

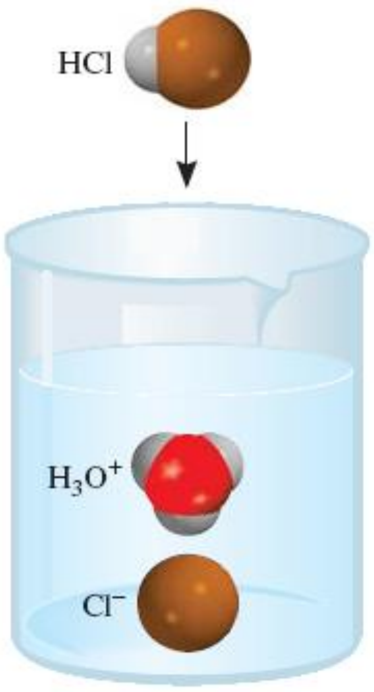
An acid can be described as a substance that yields hydrogen ions (H^+) when dissolved in water (H^+ is equivalent to one proton).

Formulas for acids contain one or more hydrogen atoms as well as an anionic group.

Anions whose names end in "-ide" form acids with a "hydro-" prefix and an "-ic" ending. In some cases two different names seem to be assigned to the same chemical formula.

HCl: hydrogen chloride, or
HCl: hydrochloric acid

The name assigned to the compound depends on its physical state. In the gaseous or pure liquid state, HCl is a molecular compound called hydrogen chloride. When it is dissolved in water (become solution), the molecules break up into H^+ and Cl^- ions; in this state, the substance is called hydrochloric acid.



Oxoacids are acids that contain hydrogen, oxygen and another element (the central element). The formulas of oxoacids are usually written with the H first, followed by the central element and then O.

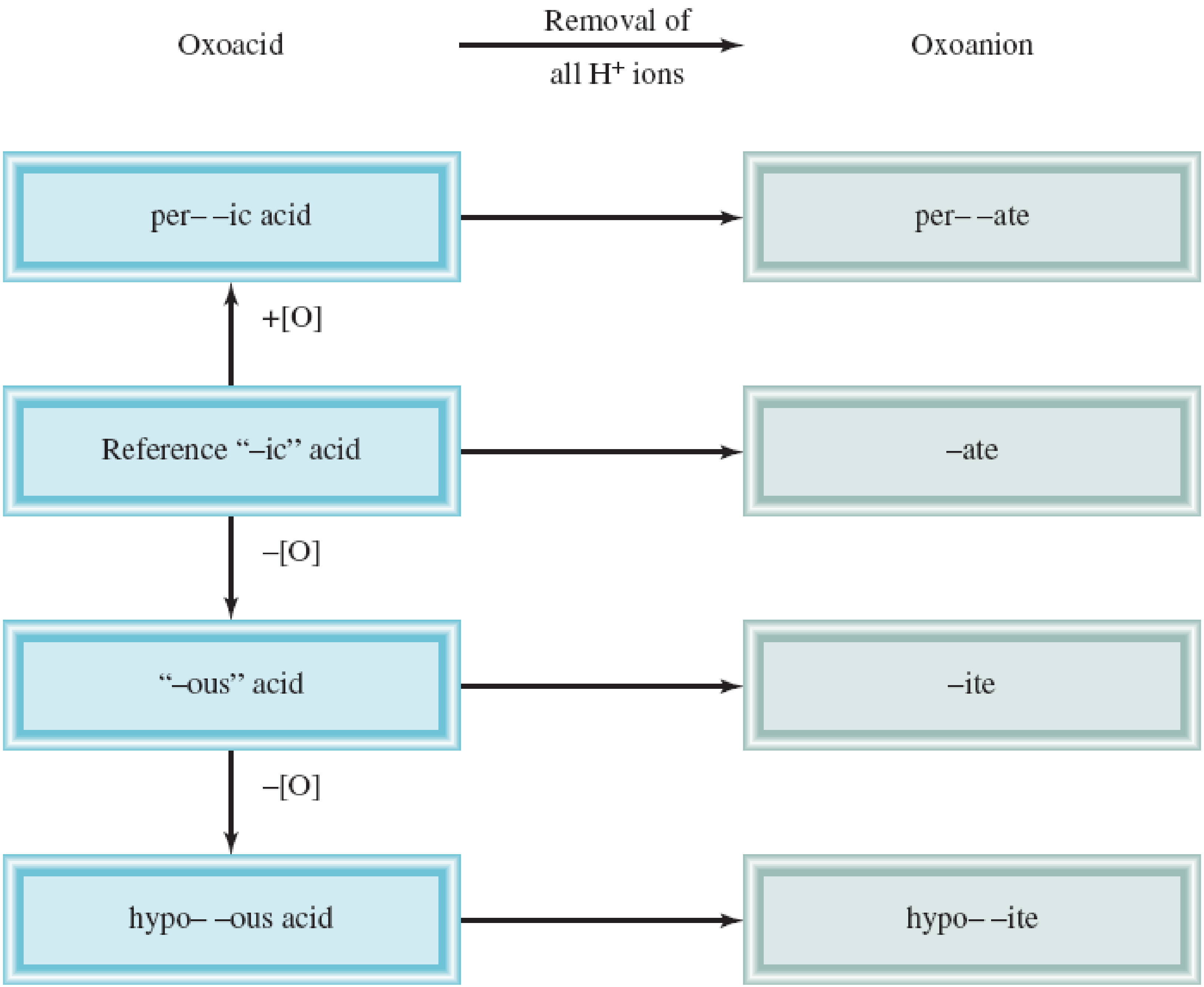
Oxoanions are the anions of oxoacids (oxoacid – H).

We use the following five common acids as references in naming oxoacids:

H_2CO_3	carbonic acid
$HClO_3$	chloric acid
HNO_3	nitric acid
H_3PO_4	phosphoric acid
H_2SO_4	sulfuric acid

Some simple acids

Anion	Corresponding Acid
F^- (fluoride)	HF (hydrofluoric acid)
Cl^- (chloride)	HCl (hydrochloric acid)
Br^- (bromide)	HBr (hydrobromic acid)
I^- (iodide)	HI (hydroiodic acid)
CN^- (cyanide)	HCN (hydrocyanic acid)
S^{2-} (sulfide)	H_2S (hydrosulfuric acid)



Naming oxoacids & oxoanions

Examples (oxoacids)	
$HClO_3$ (chloric acid) + O	$HClO_4$ (perchloric acid)
HNO_3 (nitric acid) – O	HNO_2 (nitrous acid)
$HBrO_3$ (bromic acid) – 2 O	HBrO (hypobromous acid)

Examples (oxoanions)	
H_2CO_3 (carbonic acid) – all H	CO_3^{2-} (carbonate)
$HClO_2$ (chlorous acid) – all H's	ClO_2^- (chlorite)

Examples

H_3PO_4: phosphoric acid
$H_2PO_4^-$: dihydrogen phosphate
HPO_4^{2-}: hydrogen phosphate
PO_4^{3-}: phosphate

e.g.,

Oxoacids	Oxoanions
$HClO_4$ (perchloric acid)	ClO_4^- (perchlorate)
$HClO_3$ (chloric acid)	ClO_3^- (chlorate)
$HClO_2$ (chlorous acid)	ClO_2^- (chlorite)
HClO (hypochlorous acid)	ClO^- (hypochlorite)

EXAMPLE

Name the following oxoacid and oxoanion:

(a) H_3PO_3

start with the reference acid, phosphoric acid (H_3PO_4)

H_3PO_3 has one fewer O atom, it is called phosphorous acid.

(b) IO_4^-

start with the reference acid, iodic acid (HIO_3)

HIO_4 has one more O atom called periodic acid

Remove H to obtain IO_4^- which called periodate.

Bases

A base can be described as a substance that yields hydroxide ions (OH^-) when dissolved in water.

Examples

$NaOH$: sodium hydroxide

KOH: potassium hydroxide

$Ba(OH)_2$: barium hydroxide

NH_3: ammonia

Hydrates

Hydrates: compounds that have a specific number of water molecules attached to them.

The water molecules can be driven off by heating to produce the **anhydrous**; means that the compound no longer has water molecules associated with it.

$CuSO_4 \cdot 5H_2O$ (left) is blue, $CuSO_4$ (right) is white

e.g.,

$CuSO_4 \cdot 5H_2O$	copper(II) sulfate pentahydrate
$BaCl_2 \cdot 2H_2O$	barium chloride dihydrate
$LiCl \cdot H_2O$	lithium chloride monohydrate
$MgSO_4 \cdot 7H_2O$	magnesium sulfate heptahydrate
$Sr(NO_3)_2 \cdot 4H_2O$	strontium nitrate tetrahydrate

Familiar Inorganic Compounds

Common and systematic names of some compounds

Formula	Common Name	Systematic Name
H_2O	Water	Dihydrogen monoxide
NH_3	Ammonia	Trihydrogen nitride
CO_2	Dry ice	Solid carbon dioxide
$NaCl$	Table salt	Sodium chloride
N_2O	Laughing gas	Dinitrogen monoxide
$CaCO_3$	Marble, chalk, limestone	Calcium carbonate
CaO	Quicklime	Calcium oxide
$Ca(OH)_2$	Slaked lime	Calcium hydroxide
$NaHCO_3$	Baking soda	Sodium hydrogen carbonate
$Na_2CO_3 \cdot 10H_2O$	Washing soda	Sodium carbonate decahydrate
$MgSO_4 \cdot 7H_2O$	Epsom salt	Magnesium sulfate heptahydrate
$Mg(OH)_2$	Milk of magnesia	Magnesium hydroxide
$CaSO_4 \cdot 2H_2O$	Gypsum	Calcium sulfate dihydrate


Thank You!