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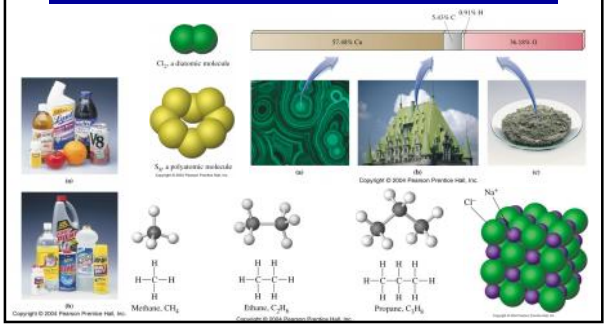
Chapter Two

Atoms, Molecules, and Ions



Laws of Conservation of Mass (質量不滅定律)

The total mass remains constant during a chemical reaction.

Example: Decomposition of mercuric oxide (HgO)

$2HgO_{(s)} = 2Hg_{(l)} + O_{2(g)}$

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Example 2.1 A Conceptual Example

Jan Baptista van Helmont (1579–1644) first measured the mass of a young willow tree and, separately, the mass of a bucket of soil and then planted the tree in the bucket. After five years, he found that the tree had gained 75 kg in mass even though the soil had lost only 0.057 kg. He had added only water to the bucket, and so he concluded that all the mass gained by the tree had come from the water. Explain and criticize his conclusion.

Law of Definite Proportions (定比定律)

Low of constant composition (定組成定律)

All samples of a compound have the same composition; that is, all samples have the same proportions, by mass, of the elements present

Water(H_2O) always contains:

~89% oxygen(O)

~11% hydrogen(H)

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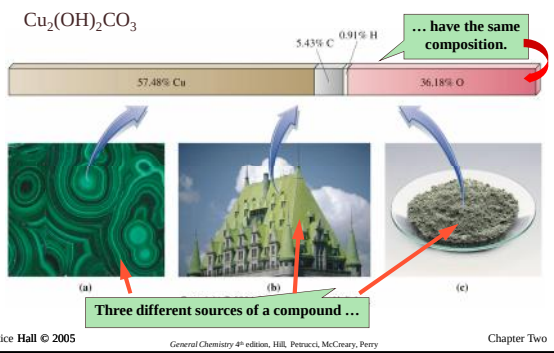
The Law of Definite Proportions



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Example 2.2

The mass ratio of oxygen to magnesium in the compound magnesium oxide is 0.6583:1. What mass of magnesium oxide will form when 2.000 g of magnesium is completely converted to magnesium oxide by burning in pure oxygen gas?

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2.2 John Dalton and the Atomic Theory of Matter

Law of Multiple Proportions
倍比定律

When two or more different compounds of the same two elements are compared, the masses of one element that combine with the a fixed mass of the second element are in the ratio of small whole numbers.

Multiple proportions illustrated

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Law of Multiple Proportions (cont'd)

	Carbon monoxide (CO)	Carbon dioxide (CO_2)
The elements	3.0 g carbon (C) + 4.0 g oxygen (O)	3.0 g carbon (C) + 8.0 g oxygen (O)
The compound	7.0 g carbon monoxide (CO)	11.0 g carbon dioxide (CO_2)
Oxygen-to-carbon mass ratio	4.0 g oxygen / 3.0 g carbon	8.0 g oxygen / 3.0 g carbon

Comparing two mass ratios:

Mass ratio for CO_2 → $\frac{8.0\text{ g oxygen}}{3.0\text{ g carbon}}$

Mass ratio for CO → $\frac{4.0\text{ g oxygen}}{3.0\text{ g carbon}}$

$= \frac{8.0\text{ g oxygen}}{4.0\text{ g oxygen}} = 2:1$

Ratio of oxygen-to-carbon in CO_2 is exactly *twice* the ratio in CO.

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Law of Multiple Proportions (cont'd)

- *Four different* oxides of nitrogen can be formed by combining 28 g of nitrogen with:
- 16 g oxygen, forming Compound I
- 48 g oxygen, forming Compound II
- 64 g oxygen, forming Compound III
- 80 g oxygen, forming Compound IV

What is the ratio 16:48:64:80 expressed as small whole numbers?

- Compounds I–IV are N_2O, N_2O_3, N_2O_4, N_2O_5

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Dalton's Atomic Theory

Proposed in 1803 to explain the law of conservation of mass, law of definite proportions, and law of multiple proportions.

- Matter is composed of *atoms*: tiny, indivisible particles.
- All atoms of a given element are the same.
- Atoms of one element differ from atoms of other elements.
- Compounds are formed when atoms of different elements unite in fixed proportions.
- A *chemical reaction* involves rearrangement of atoms. No atoms are created, destroyed, or broken apart.

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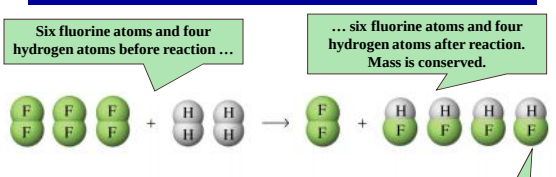
Dalton's Atomic Theory: Conservation of Mass and Definite Proportions

Six fluorine atoms and four hydrogen atoms before reaction …

… six fluorine atoms and four hydrogen atoms after reaction. Mass is conserved.



HF always has one H atom and one F atom; always has the same proportions (1:19) by mass.

2.3 The Divisible Atom

Subatomic Particles

- Protons(質子) and neutrons(中子) are located at the center of an atom (at the **nucleus(原子核)**).
- Electrons (電子) are dispersed around the nucleus.

Table 2.1 Subatomic Particles

Particle	Symbol	Approximate Relative Mass	Relative Charge	Location in Atom
Proton	p^+	1	1+	Inside nucleus
Neutron	n	1	0	Inside nucleus
Electron	e^-	0.000545	1−	Outside nucleus

Isotopes(同位素)

- Atoms that have the same number of protons but different numbers of neutrons are called **isotopes**.
- The **atomic number(原子序)** (*Z*) is the number of protons in the nucleus of a given atom of a given element.
- The **mass number(質量數)** (*A*) is an integral number that is the sum of the numbers of protons and neutrons in an atom.
- The number of neutrons = $A - Z$.

Other Examples of Isotopes

Carbon-14 ***Z* = 6** **so 8 neutrons**

Chlorine-35 ***Z* = 17** **so 18 neutrons**

Uranium-234 ***Z* = 92** **so 142 neutrons**

The number of neutrons = $A - Z$

Isotopes (cont'd)

Atoms can be represented using the element's symbol and the mass number (*A*) and atomic number (*Z*):

$${}^{A}_{Z}\mathrm{E} \qquad {}^{35}_{17}\mathrm{Cl} \qquad {}^{37}_{17}\mathrm{Cl}$$

- How many protons are in chlorine-35?
- How many protons are in chlorine-37?
- How many neutrons are in chlorine-37?

Example 2.3

How many protons, neutrons, and electrons are present in a ^{81}Br atom?

2.4 Atomic Masses
原子量

Atomic Mass

- Atoms are very tiny, so a tiny unit is needed to express the mass of an atom or molecule.
- One **atomic mass unit** (u or a.m.u.) = 1/12 the mass of a C-12 atom.
- $1\ u = 1.66054 \times 10^{-24}\ g$
- The **atomic mass** of an element is the *weighted average* of the masses of the naturally occurring isotopes of that element

Isotope	Percent Abundance	Fractional Abundance
Carbon-12	98.892%	0.98892
Carbon-13	1.108%	0.01108

Example 2.4

Use the data cited above to determine the weighted average atomic mass of carbon.

Example 2.5 An Estimation Example

Indium has *two* naturally occurring isotopes and a weighted average atomic mass of 114.82 u. One of the isotopes has a mass of 112.9043 u. Which is likely to be the second isotope: ^{111}In, ^{112}In, ^{114}In, or ^{115}In?

2.5 The Periodic Table: Elements Organized

Mendeleev's Periodic Table

- Mendeleev arranged the known elements in order of increasing atomic weight from left to right and from top to bottom in groups.
- Elements that closely resembled one another were arranged in the same ***vertical*** group.
- ***Gaps*** were left where undiscovered elements should appear.
- From the locations of the gaps, he was able to predict properties of some of the undiscovered elements.

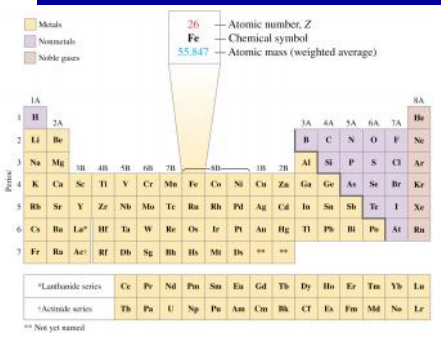
Germanium: Prediction vs. Observation

Table 2.2 Properties of Germanium: Predicted and Observed

Property	Predicted: Eka-silicon[a] (1871)	Observed: Germanium (1886)
Atomic weight	72	72.6
Density, g/cm^3	5.5	5.47
Color	Dirty gray	Grayish white
Density of oxide, g/cm^3	EsO_2: 4.7	GeO_2: 4.703
Boiling point of chloride	$EsCl_4$: below 100 °C	$GeCl_4$: 86 °C
Density of chloride, g/cm^3	$EsCl_4$: 1.9	$GeCl_4$: 1.887

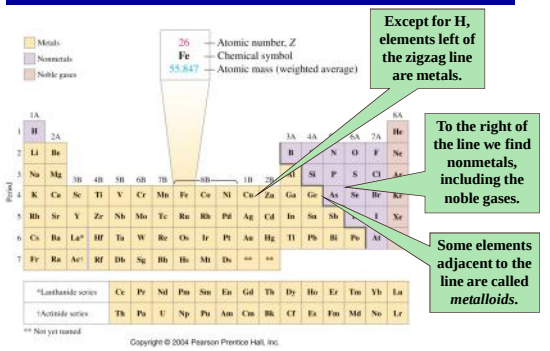
[a] The term "eka" is derived from Sanskrit and means "first." Literally, eka-silicon means "first comes silicon" (and then comes the unknown element).

Modern Periodic Table



Elements are divided into two main classes

The Modern Periodic Table

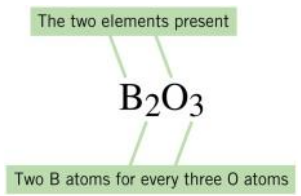


2.6 Molecules and Molecular Compounds

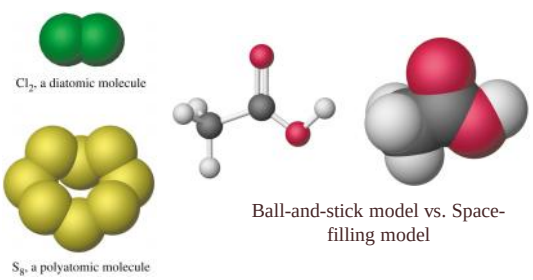
Introduction to Compounds

A **molecule** is a group of two or more atoms held together by *covalent bonds*.

A **chemical formula(**化學式**)** is a symbolic representation of the composition of a compound in terms of its constituent elements.



Molecular Compounds



Ball-and-stick model vs. Space-filling model

Molecules and Formulas

- A ***molecule*** is a group of two or more atoms held together by *covalent bonds*(共價鍵).
- A ***molecular formula***(分子式) gives the number of each kind of atom in a molecule.
- An ***empirical formula***(實驗式) simply gives the (whole number) *ratio* of atoms of elements in a compound.

Compound	*Molecular formula*	*Empirical formula*
Hydrogen peroxide	H_2O_2	**HO**
Octane	C_8H_{18}	**????**

Empirical and Molecular Formulas

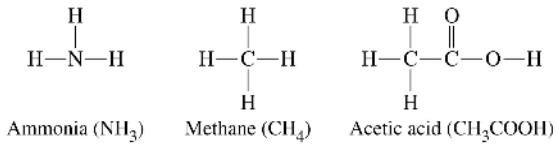
Empirical formula: the ***simplest whole number ratio*** of elements in a compound

Example:
Molecular formula of glucose – $C_6H_{12}O_6$

The elemental ratio C:H:O is 1:2:1, so the empirical formula is CH_2O

Structural Formulas

Shows how atoms are attached to one another.

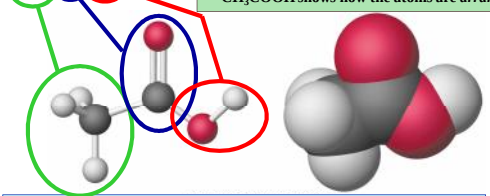


Structural Formulas and Models

- Structural formulas and models show how atoms are attached to one another.

The condensed structural formula for acetic acid is CH_3COOH

$C_2H_4O_2$: two C atoms, four H atoms, two O atoms. CH_3COOH shows how the atoms are *arranged*.



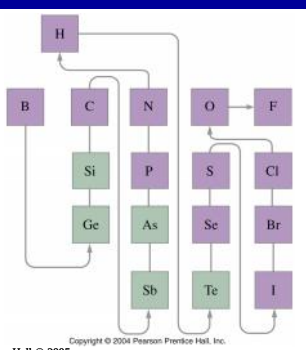
Ball-and-stick model **Space-filling model**

Binary Molecular Compounds

Compounds that are typically comprised of two nonmetallic elements:
e.g., **CO**, **NO**, **HF**

Molecular formulas are usually written with the more "metallic" first – "metallic" means farther left in the period and lower in the group

Which element is named first?



Begin with boron and follow the line to determine the order of naming.

Rule of thumb: the element that is farthest *down* and to the *left* on the periodic table is usually written first.

In a compound consisting of arsenic (As) and sulfur (S), which element is named first?

Naming Binary Molecular Compounds

- The name consists of two words.
- First word: name of the element that appears first in the formula.
- Second word: *stem* of the name of the second element, ending with *-ide*.
- Names are further modified by adding prefixes to denote the numbers of atoms of each element in the molecule.

Names of Binary Compounds

Consider the compounds **CO** and **CO_2**

The compound name consists of two words, one for each element in the compound

Name the element that appears first in the formula: **CARBON**

The second element has an altered name: retain the stem of the element name and replace the ending by *-ide*

→ **OXIDE**

However, both compounds cannot be carbon oxide

Names of Binary Compounds

Consider the compounds **CO** and **CO_2**

The names are further modified by adding ***prefixes*** to denote the numbers of atoms

Number of Atoms	Prefix	Examples[a]
1	mono	NO nitrogen monoxide
2	di	NO_2 nitrogen dioxide
3	tri	N_2O_3 dinitrogen trioxide
4	tetra	N_2O_4 dinitrogen tetroxide
5	penta	N_2O_5 dinitrogen pentoxide
6	hexa	SF_6 sulfur hexafluoride
7	hepta	IF_7 iodine heptafluoride
8	octa	P_4O_8 tetraphosphorus octoxide
9	nona	P_4S_9 tetraphosphorus nonasulfide
10	deca	As_4O_{10} tetraarsenic decoxide

Example 2.6

Write the molecular formula and name of a compound for which each molecule contains six oxygen atoms and four phosphorus atoms.

P_4O_6:Tetraphosphorus hexoxide.

Example 2.7

Write **(a)** the molecular formula of phosphorus pentachloride and **(b)** the name of S_2F_{10}.

(a) PCl_5

(b) Disulfur decafluoride.

2.7 Ions and Ionic Compounds

Ions and Ionic Compounds

Atoms that gain or lose electrons are called **ions**

There is *no change* in the number of *protons* or *neutrons* in the nucleus of the atom.

Positive ions: **CATIONS**

Negative ions: **ANIONS**

Atoms that lose electrons form cations

$Na \rightarrow \mathbf{Na^+} + e^-$

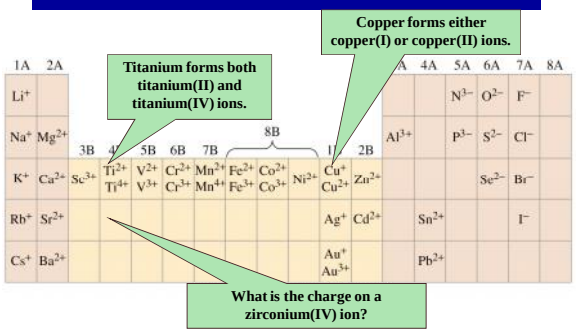
Atoms that gain electrons form anions

$Cl + e^- \rightarrow \mathbf{Cl^-}$

Monatomic Ions

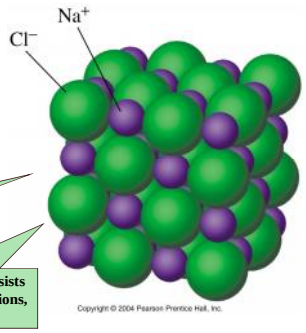
- Group IA metals form ions of 1+ charge.
- Group IIA metals form ions of 2+ charge.
- Aluminum, a group IIIA metal, forms ions with a 3+ charge.
- *Nonmetal* ions of groups V, VI, and VII usually have charges of 3–, 2–, and 1–, respectively.
- Group B metal ions (transition metal ions) often have more than one possible charge. A Roman numeral is used to indicate the actual charge.
- A few transition elements have only one common ion (Ag, Zn, Cd), and a Roman numeral is not often used.

Symbols and Periodic Table Locations of Some Monatomic Ions



Ions and Ionic Compounds (cont'd)

In an **ionic compound**, oppositely charged ions are attracted to each other such that the compound has no net charge.



There are no distinct *molecules* of sodium chloride.

Sodium chloride simply consists of sodium ions and chloride ions, regularly arranged.

Names and Formulas for Ionic Compounds

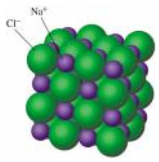
Ionic compounds form when oppositely charged ions are attracted to each other

NaCl

Resulting compound is electrically neutral

Na⁺ **Cl⁻**

(+1) + **(–1)** = **0**



Ionic compound names use the **cation** name followed by the **anion** name

Sodium chloride

Example 2.8

Determine the formula for **(a)** calcium chloride and **(b)** magnesium oxide.

(a) $CaCl_2$

(b) MgO

Example 2.9

What are the names of **(a)** MgS and **(b)** $CrCl_3$?

(a) Magnesium sulfide

(b) Chromium(III) chloride

Polyatomic Ions

- A **polyatomic ion** is a charged group of covalently bonded atoms.
- There are many more polyatomic anions than there are polyatomic cations.
- You should (eventually!) commit to memory much of Table 2.4
- *hypo-* and *per-* are sometimes seen as prefixes in oxygen-containing polyatomic ions (oxoanions).
- *-ite* and *-ate* are commonly found as suffixes in oxygen-containing polyatomic ions.

Polyatomic Ions

Name	Formula	Typical Compound
Cation		
Ammonium ion	NH_4^+	NH_4Cl
Anions		
Acetate ion	$C_2H_3O_2^-$	$NaC_2H_3O_2$
Carbonate ion	CO_3^{2-}	Li_2CO_3
Hydrogen carbonate ion (or bicarbonate ion)[b]	HCO_3^-	$NaHCO_3$
Hypochlorite ion	ClO^-	$Ca(ClO)_2$
Chlorite ion	ClO_2^-	$NaClO_2$
Chlorate ion	ClO_3^-	$NaClO_3$
Perchlorate ion	ClO_4^-	$KClO_4$
Chromate ion	CrO_4^{2-}	K_2CrO_4
Dichromate ion	$Cr_2O_7^{2-}$	$(NH_4)_2Cr_2O_7$
Cyanate ion	OCN^-	$KOCN$
[illegible]	[illegible]	[illegible]
Cyanide ion	CN^-	KCN
Hydroxide ion	OH^-	$NaOH$
Nitrite ion	NO_2^-	$NaNO_2$
Nitrate ion	NO_3^-	$NaNO_3$
Oxalate ion	$C_2O_4^{2-}$	CaC_2O_4
Permanganate ion	MnO_4^-	$KMnO_4$
Phosphate ion	PO_4^{3-}	Na_3PO_4
Hydrogen phosphate ion	HPO_4^{2-}	Na_2HPO_4
Dihydrogen phosphate ion	$H_2PO_4^-$	NaH_2PO_4
Sulfite ion	SO_3^{2-}	Na_2SO_3
Hydrogen sulfite ion (or bisulfite ion)[b]	HSO_3^-	$NaHSO_3$
Sulfate ion	SO_4^{2-}	Na_2SO_4
Hydrogen sulfate ion (or bisulfate ion)[b]	HSO_4^-	$NaHSO_4$
Thiosulfate ion[c]	$S_2O_3^{2-}$	$Na_2S_2O_3$

Polyatomic ions are charged groups of covalently bonded atoms

Example 2.10

Write the formula for (**a**) sodium sulfite and (**b**) ammonium sulfate.

(a) Na_2SO_3

(b) $(NH_4)_2SO_4$

Example 2.11

What is the name of **(a)** NaCN and **(b)** $Mg(ClO_4)_2$?

(a) Sodium cyanide.

(b) Magnesium perchlorate.

Hydrates

- A **hydrate** is an ionic compound in which the formula unit includes a fixed number of water molecules associated with cations and anions.
- To name a hydrate, the compound name is followed by "___hydrate" where the blank is a prefix to indicate the number of water molecules.
- The number of water molecules associated with each formula unit is written as an appendage to the formula unit name separated by a dot.
- Examples: $BaCl_2 \cdot 2\ H_2O$; $CuSO_4 \cdot 5\ H_2O$

Hydrates

A **hydrate** is an ionic compound in which the formula unit includes a fixed number of water molecules associated with cations and anions

Examples:

$BaCl_2 \cdot 2\ H_2O$

$CuSO_4 \cdot 5\ H_2O$

EOS

2.8 Acids, Bases, and Salts

Acids …

- Taste sour, if diluted with enough water to be tasted safely.
- May produce a pricking or stinging sensation on the skin.
- Turn the color of litmus or indicator paper from blue to red.
- React with many metals to produce ionic compounds and hydrogen gas.
- Also react with bases, thus losing their acidic properties.

Bases …

- Taste bitter, if diluted with enough water to be tasted safely.
- Feel slippery or soapy on the skin.
- Turn the color of litmus or indicator paper from red to blue.
- React with acids, thus losing their basic properties.

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Acids and Bases: The Arrhenius Concept

- There are several definitions which may be used to describe acids and bases.
- An **Arrhenius acid** is a compound that ionizes in water to form a solution of H^+ ions and anions.
- An **Arrhenius base** is a compound that ionizes in water to form solutions of OH^- and cations.
- **Neutralization** is the process of an acid reacting with a base to form water and a salt.
- A **salt** is the combination of the cation from a base and the anion from an acid.

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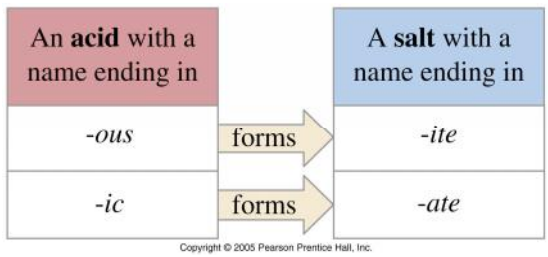

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Table 2.5 Formulas and Names of Some Common Acids and Their Salts

		Sodium Salt	
Formula of Acid	**Name of Acid**	**Formula**	**Name**
HCl	*Hydro*chloric acid	NaCl	Sodium chlor*ide*
HClO	*Hypo*chlor*ous* acid	NaClO	Sodium *hypo*chlor*ite*
$HClO_2$	Chlor*ous* acid	$NaClO_2$	Sodium chlor*ite*
$HClO_3$	Chlor*ic* acid	$NaClO_3$	Sodium chlor*ate*
$HClO_4$	*Per*chlor*ic* acid	$NaClO_4$	Sodium *per*chlor*ate*
H_2S	*Hydro*sulfur*ic* acid	Na_2S	Sodium sul*fide*
H_2SO_3[a]	Sulfur*ous* acid	Na_2SO_3	Sodium sul*fite*
H_2SO_4[a]	Sulfur*ic* acid	Na_2SO_4	Sodium sul*fate*
HNO_2	Nitr*ous* acid	$NaNO_2$	Sodium nitr*ite*
HNO_3	Nitr*ic* acid	$NaNO_3$	Sodium nitr*ate*
H_3PO_4[a]	Phosphor*ic* acid	Na_3PO_4	Sodium phosph*ate*
H_2CO_3[a]	Carbon*ic* acid	Na_2CO_3	Sodium carbon*ate*

[a] Table 2.4 lists anions found in some salts of these acids in which not all of the available H atoms are replaced. If one or more H atoms remains unreplaced, formulas and names must be written accordingly; for example, $NaHSO_4$ is sodium hydrogen sulfate and NaH_2PO_4 is sodium dihydrogen phosphate.

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Acid Nomenclature

- Notice that the acid name is related to the anion name.
  - *Hydro*chlor*ic* acid (HCl), chlor*ide* ion (Cl^-)
  - *Hydro*sulfur*ic* acid (H_2S), sulf*ide* ion (S^{-2})
  - Phosphor*ic* acid (H_3PO_4), phosph*ate* ion (PO_4^{-3})
  - Nitr*ic* acid (HNO_3), nitr*ate* ion (NO_3^-)
  - Nitr*ous* acid (HNO_2), nitr*ite* ion (NO_2^-)