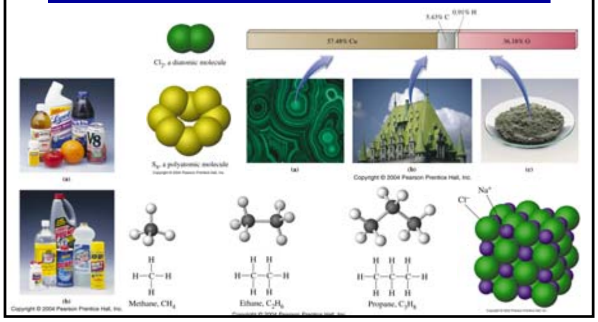
1

Chapter Two

Atoms, Molecules, and Ions



2

Laws of Chemical Combination

- **Law of Conservation of Mass**
  - The total mass remains constant during a chemical reaction.
- **Law of Definite Proportions**
  - All samples of a compound have the same composition, or …
  - All samples have the same proportions, by mass, of the elements present.

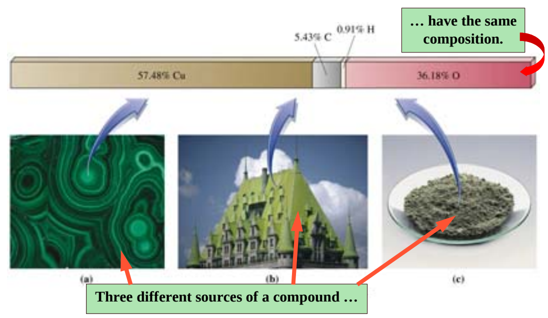
3

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.

4

The Law of Definite Proportions



5

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?

6

Law of Multiple Proportions

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

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	$\frac{4.0 \text{ g oxygen}}{3.0 \text{ g carbon}}$	$\frac{8.0 \text{ g oxygen}}{3.0 \text{ g carbon}}$

Comparing two mass ratios:

Mass ratio for CO_2 / Mass ratio for CO:

$$\frac{\frac{8.0 \text{ g oxygen}}{3.0 \text{ g carbon}}}{\frac{4.0 \text{ g oxygen}}{3.0 \text{ g carbon}}} = \frac{8.0 \text{ g oxygen}}{4.0 \text{ g oxygen}} = 2{:}1$$

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

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

Dalton's Atomic Theory

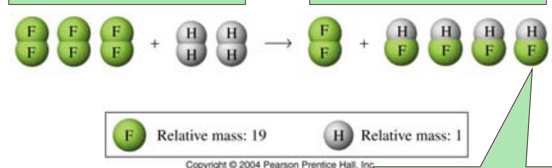
Proposed in 1803 to explain the law of conservation of mass, law of definite proportions, and law of multiple proportions.

- 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.

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.

Subatomic Particles

- Protons and neutrons are located at the center of an atom (at the **nucleus**).
- Electrons 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

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

13

Isotopes (cont'd)

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

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

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

14

Example 2.3

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

15

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** (amu, or u) = 1/12 the mass of a C-12 atom.
- 1 amu = 1.66054×10^{-24} g
- The mass of an atom is not *exactly* the sum of the masses of the protons + neutrons + electrons (we will see why in Chapter 19).

16

Atomic Mass (cont'd)

- Question: do all isotopes of an element have the same mass? Why or why not?
- The atomic mass given on the *periodic table* is the *weighted average* of the masses of the naturally occurring isotopes of that element.

17

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?

18

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.

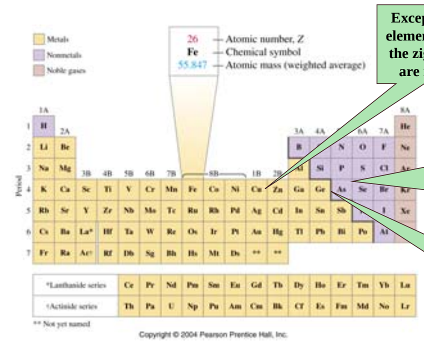
Germanium: Prediction vs. Observation

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).

The Modern Periodic Table



Except for H, elements left of the zigzag line are metals.

To the right of the line we find nonmetals, including the noble gases.

Some elements adjacent to the line are called *metalloids*.

Molecules and Formulas

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

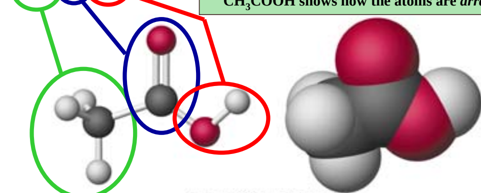
Compound	*Molecular formula*	*Empirical formula*
Hydrogen peroxide	H_2O_2	**HO**
Octane	C_8H_{18}	**????**

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**

Nomenclature

… is the method for naming compounds and writing formulas for compounds.

- We ***could*** have a specific name for each compound—but we would have to memorize each one!
  - Can you imagine having to memorize the names of half a million different inorganic compounds? Twenty million organic compounds??
- Instead we have a *systematic* method—conventions and rules—for naming compounds and writing formulas.

Nomenclature of Binary Molecular Compounds

- ***Binary*** compounds contain ___ elements.
- ***Molecular*** compounds exist as ________.

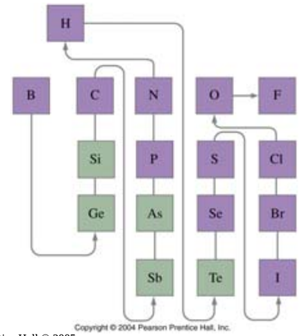
25

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.

26

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?

27

Table 2.3 Numeric Prefixes in Names of Binary Molecular Compounds

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

[a] When the prefix ends in "a" or "o" and the element name begins with "a" or "o," the final vowel of the prefix is usually dropped for ease of pronunciation. For example, nitrogen *monoxide* and not nitrogen *monooxide*.

28

Example 2.6

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

Example 2.7

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

29

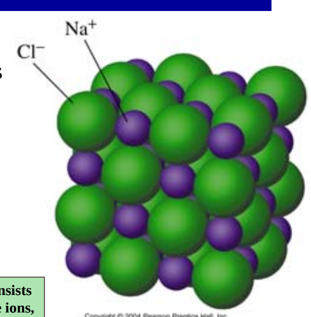
Ions and Ionic Compounds

- An atom that either gains or loses electron(s) is an **ion**.
- There is *no change* in the number of *protons* or *neutrons* in the nucleus of the atom.
- **Cation** – has a *positive* charge from *loss* of electron(s).
- **Anion** – has a *negative* charge from *gain* of electron(s).

30

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.



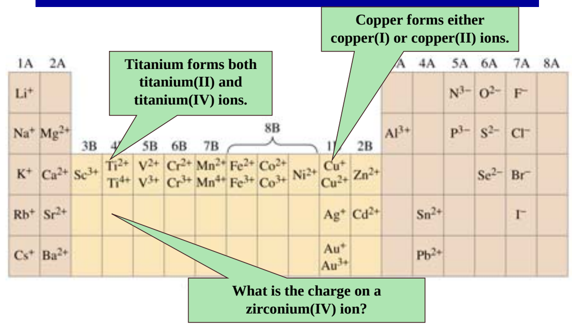
There are no distinct *molecules* of sodium chloride.

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

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



Formulas and Names of Binary Ionic Compounds

- Binary ionic compounds are made up of monatomic cations and anions.
- These combinations must be electrically neutral.
- The **formula unit** is the simplest collection of cations and anions that represents an electrically neutral unit.
- *Formula unit* is to *ion* as ________ is to *atom.*
- To *write a formula*, combine the proper number of each ion to form a neutral unit.
- To *name* a binary ionic compound, name the cation, then the anion.
- Monatomic anion names end in *-ide*.

Example 2.8

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

Example 2.9

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

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.

Table 2.4 Some Common Polyatomic Ions

Name	Formula	Typical Compound
Cation		
Ammonium ion	NH_4^+	NH_4Cl
Anions		
Acetate ion	[a]$C_2H_3O_2^-$	$NaC_2H_3O_2$
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^-	$KOCN$
Thiocyanate ion[c]	SCN^-	$KSCN$
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]	$S_2O_3^{2-}$	$Na_2S_2O_3$

[a] The acetate ion is also represented as CH_3COO^-. [b] The prefix "bi-" means that the ion contains a replaceable H atom. This should not be confused with the prefix "di-," which means two (usually used to represent a doubling of a simpler unit). [c] The prefix "thio-" means that a sulfur atom has replaced an oxygen atom.

37

Example 2.10
Write the formula for (**a**) sodium sulfite and (**b**) ammonium sulfate.

Example 2.11
What is the name of **(a)** NaCN and **(b)** $Mg(ClO_4)_2$?

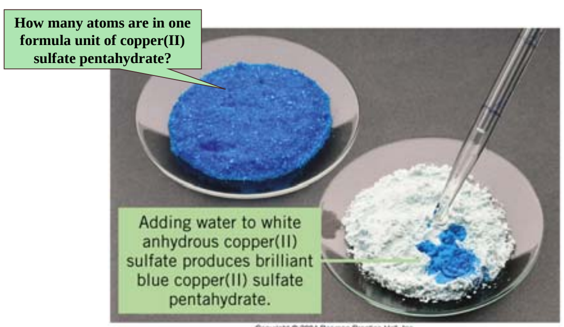
38

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: $BaCl_2 \cdot 2\,H_2O$; $CuSO_4 \cdot 5\,H_2O$

39

Hydrates (cont'd)



40

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.

41

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.

42

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.

43

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

Formula of Acid	Name of Acid	Sodium Salt Formula	Sodium Salt Name
HCl	*Hydro*chlor*ic* 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 sulf*ide*
H_2SO_3[a]	Sulfur*ous* acid	Na_2SO_3	Sodium sulf*ite*
H_2SO_4[a]	Sulfur*ic* acid	Na_2SO_4	Sodium sulf*ate*
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.

44

Acid Nomenclature

- Notice that the acid name is related to the anion name.
  - *Hydro*chlor*ic* acid, chlor*ide* ion
  - *Hydro*sulfur*ic* acid, sulf*ide* ion
  - Phosphor*ic* acid, phosph*ate* ion
  - Nitr*ic* acid, nitr*ate* ion
  - Nitr*ous* acid, nitr*ite* ion

45

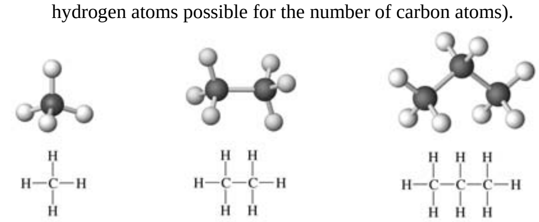
Organic Compounds

- **Organic chemistry** is the study of carbon and its compounds.
- Carbon compounds can have an almost unlimited diversity, because carbon atoms can bond to one another, and to other atoms, to form chains and rings.
- Carbon compounds containing one or more of the elements H, O, N, or S are especially common.
- Many organic compounds have common names as well as systematic names.

46

Alkanes

- **Hydrocarbons** are molecules that contain only hydrogen and carbon atoms.
- **Alkanes** are saturated (have the maximum number of hydrogen atoms possible for the number of carbon atoms).

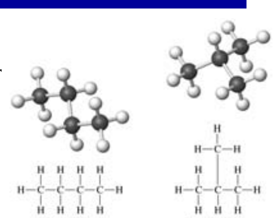


Methane, CH_4 Ethane, C_2H_6 Propane, C_3H_8

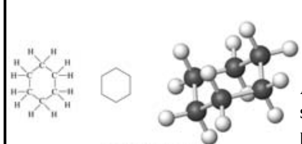
47

Alkanes

Isomers are compounds with the same molecular formula but different structural formulas.



Butane, C_4H_{10} Isobutane, C_4H_{10}



Alkane molecules with ring structures are named with the prefix *cyclo-* and are called **cycloalkanes**.

48

Table 2.6 Word Stems Indicating the Number of Carbon Atoms in Simple Organic Molecules

Stem	Number of C Atoms
meth-	1
eth-	2
prop-	3
but-	4
pent-	5
hex-	6
hept-	7
oct-	8
non-	9
dec-	10

Propane, used in gas grills, is an alkane with _three_ carbon atoms

Butyric acid, which gives rancid butter its "fragrance," contains _four_ carbon atoms.

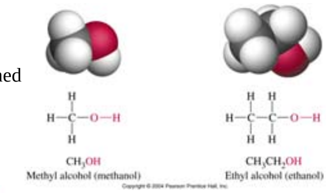
Octane, a component of gasoline, is a(n) ______ which contains _____ carbon atoms.

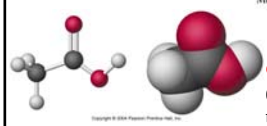
Types of Organic Compounds

- Many organic compounds contain a functional group.
- A ***functional group*** is an atom or group of atoms attached to the hydrocarbon chain, which confers particular physical and/or chemical properties upon the compound.
- Compounds with the same functional group often undergo similar reactions.
- A list of common functional groups is found in Table D.1.

Types of Organic Compounds (cont'd)

For **alcohols**, the functional group is a hydroxyl group attached to the carbon chain.





Carboxylic acids have a carboxyl group (–COOH) attached to the carbon chain; they are acidic (of course! Why else would they be called carboxylic *acids*??).

Cumulative Example

Show that the following experiment is consistent with the law of conservation of mass (within the limits of experimental error): A 10.00-g sample of calcium carbonate was dissolved in 100.0 mL of hydrochloric acid solution (d = 1.148 g/mL). The products were 120.40 g of solution (a mixture of hydrochloric acid and calcium chloride) and 2.22 L of carbon dioxide gas (d = 0.0019769 g/mL).