Learning Objectives

- to understand the differences between covalent and ionic bonding.

The atoms in all substances that contain multiple atoms are held together by electrostatic interactions—interactions between electrically charged particles such as protons and electrons. Electrostatic attraction between oppositely charged species (positive and negative) results in a force that causes them to move toward each other, like the attraction between opposite poles of two magnets. In contrast, electrostatic repulsion between two species with the same charge (either both positive or both negative) results in a force that causes them to repel each other, as do the same poles of two magnets. Atoms form chemical compounds when the attractive electrostatic interactions between them are stronger than the repulsive interactions. Collectively, the attractive interactions between atoms are called chemical bonds.

Chemical bonds are generally divided into two fundamentally different types: ionic and covalent. In reality, however, the bonds in most substances are neither purely ionic nor purely covalent, but lie on a spectrum between these extremes. Although purely ionic and purely covalent bonds represent extreme cases that are seldom encountered in any but very simple substances, a brief discussion of these two extremes helps explain why substances with different kinds of chemical bonds have very different properties. Ionic compounds consist of positively and negatively charged ions held together by strong electrostatic forces, whereas covalent compounds generally consist of molecules, which are groups of atoms in which one or more pairs of electrons are shared between bonded atoms. In a covalent bond, atoms are held together by the electrostatic attraction between the positively charged nuclei of the bonded atoms and the negatively charged electrons they share. This discussion of structures and formulas begins by describing covalent compounds. The energetic factors involved in bond formation are described in more quantitative detail in later.

Ionic compounds consist of ions of opposite charges held together by strong electrostatic forces, whereas pairs of electrons are shared between bonded atoms in covalent compounds.

Covalent Molecules and Compounds

Just as an atom is the simplest unit that has the fundamental chemical properties of an element, a molecule is the simplest unit that has the fundamental chemical properties of a covalent compound. Some pure elements exist as covalent molecules. Hydrogen, nitrogen, oxygen, and the halogens occur naturally as the diatomic ("two atoms") molecules H$_2$, N$_2$, O$_2$, F$_2$, Cl$_2$, Br$_2$, and I$_2$ (part (a) in Figure \(\PageIndex{1}\)). Similarly, a few pure elements exist as polyatomic ("many atoms") molecules, such as elemental phosphorus and sulfur, which occur as P$_4$ and S$_8$ (part (b) in Figure \(\PageIndex{1}\)).

Each covalent compound is represented by a molecular formula, which gives the atomic symbol for each component element, in a prescribed order, accompanied by a subscript indicating the number of atoms of that element in the molecule. The subscript is written only if the number of atoms is greater than 1. For example, water, with two hydrogen atoms and one oxygen atom per molecule, is written as \(\text{H}_2\text{O}\). Similarly, carbon dioxide, which contains one carbon atom and two oxygen atoms in each molecule, is written as \(\text{CO}_2\).
Figure \(\PageIndex{1}\): Elements That Exist as Covalent Molecules. (a) Several elements naturally exist as diatomic molecules, in which two atoms (E) are joined by one or more covalent bonds to form a molecule with the general formula E2. (b) A few elements naturally exist as polyatomic molecules, which contain more than two atoms. For example, phosphorus exists as P4 tetrahedra—regular polyhedra with four triangular sides—with a phosphorus atom at each vertex. Elemental sulfur consists of a puckered ring of eight sulfur atoms connected by single bonds. Selenium is not shown due to the complexity of its structure.

Covalent compounds that predominantly contain carbon and hydrogen are called organic compounds. The convention for representing the formulas of organic compounds is to write carbon first, followed by hydrogen and then any other elements in alphabetical order (e.g., CH4O is methyl alcohol, a fuel). Compounds that consist primarily of elements other than carbon and hydrogen are called inorganic compounds; they include both covalent and ionic compounds. In inorganic compounds, the component elements are listed beginning with the one farthest to the left in the periodic table, as in CO2 or SF6. Those in the same group are listed beginning with the lower element and working up, as in ClF. By convention, however, when an inorganic compound contains both hydrogen and an element from groups 13–15, hydrogen is usually listed last in the formula. Examples are ammonia (NH3) and silane (SiH4). Compounds such as water, whose compositions were established long before this convention was adopted, are always written with hydrogen first: Water is always written as H2O, not OH2. The conventions for inorganic acids, such as hydrochloric acid (HCl) and sulfuric acid (H2SO4), are described in Section 2.5.

For organic compounds: write C first, then H, and then the other elements in alphabetical order. For molecular inorganic compounds: start with the element at far left in the periodic table; list elements in same group beginning with the lower element and working up.

Example \(\PageIndex{1}\)

Write the molecular formula of each compound.

a. The phosphorus-sulfur compound that is responsible for the ignition of so-called strike anywhere matches has 4 phosphorus atoms and 3 sulfur atoms per molecule.

b. Ethyl alcohol, the alcohol of alcoholic beverages, has 1 oxygen atom, 2 carbon atoms, and 6 hydrogen atoms per molecule.

c. Freon-11, once widely used in automobile air conditioners and implicated in damage to the ozone layer, has 1 carbon atom, 3 chlorine atoms, and 1 fluorine atom per molecule.

**Given:** identity of elements present and number of atoms of each

**Asked for:** molecular formula

**Strategy:**
A. Identify the symbol for each element in the molecule. Then identify the substance as either an organic compound or an inorganic compound.

B. If the substance is an organic compound, arrange the elements in order beginning with carbon and hydrogen and then list the other elements alphabetically. If it is an inorganic compound, list the elements beginning with the one farthest left in the periodic table. List elements in the same group starting with the lower element and working up.

C. From the information given, add a subscript for each kind of atom to write the molecular formula.

Solution

a

A. The molecule has 4 phosphorus atoms and 3 sulfur atoms. Because the compound does not contain mostly carbon and hydrogen, it is inorganic.

B. Phosphorus is in group 15, and sulfur is in group 16. Because phosphorus is to the left of sulfur, it is written first.

C. Writing the number of each kind of atom as a right-hand subscript gives \( \text{P}_4\text{S}_3 \) as the molecular formula.

b.

A. Ethyl alcohol contains predominantly carbon and hydrogen, so it is an organic compound.

B. The formula for an organic compound is written with the number of carbon atoms first, the number of hydrogen atoms next, and the other atoms in alphabetical order: \( \text{CHO} \).

C. Adding subscripts gives the molecular formula \( \text{C}_2\text{H}_6\text{O} \).

c

A. Freon-11 contains carbon, chlorine, and fluorine. It can be viewed as either an inorganic compound or an organic compound (in which fluorine has replaced hydrogen). The formula for Freon-11 can therefore be written using either of the two conventions.

B. According to the convention for inorganic compounds, carbon is written first because it is farther left in the periodic table. Fluorine and chlorine are in the same group, so they are listed beginning with the lower element and working up: \( \text{CCl}_3\text{F} \). Adding subscripts gives the molecular formula \( \text{CCl}_3\text{F} \).

C. We obtain the same formula for Freon-11 using the convention for organic compounds. The number of carbon atoms is written first, followed by the number of hydrogen atoms (zero) and then the other elements in alphabetical order, also giving \( \text{CCl}_3\text{F} \).

Exercise \( \PageIndex{1} \)

Write the molecular formula for each compound.

a. Nitrous oxide, also called “laughing gas,” has 2 nitrogen atoms and 1 oxygen atom per molecule. Nitrous oxide is used as a mild anesthetic for minor surgery and as the propellant in cans of whipped cream.

b. Sucrose, also known as cane sugar, has 12 carbon atoms, 11 oxygen atoms, and 22 hydrogen atoms.

c. Sulfur hexafluoride, a gas used to pressurize “unpressurized” tennis balls and as a coolant in nuclear reactors, has 6 fluorine atoms and 1 sulfur atom per molecule.

Answer a

\( \text{N}_2\text{O} \)
Representations of Molecular Structures

Molecular formulas give only the elemental composition of molecules. In contrast, structural formulas show which atoms are bonded to one another and, in some cases, the approximate arrangement of the atoms in space. Knowing the structural formula of a compound enables chemists to create a three-dimensional model, which provides information about how that compound will behave physically and chemically.

Figure \(\PageIndex{2}\): Molecules That Contain Single, Double, and Triple Bonds. Hydrogen (H\(_2\)) has a single bond between atoms. Oxygen (O\(_2\)) has a double bond between atoms, indicated by two lines (=). Nitrogen (N\(_2\)) has a triple bond between atoms, indicated by three lines (≡). Each bond represents an electron pair.

The structural formula for H\(_2\) can be drawn as H–H and that for I\(_2\) as I–I, where the line indicates a single pair of shared electrons, a single bond. Two pairs of electrons are shared in a double bond, which is indicated by two lines—for example, O\(_2\) is O=O. Three electron pairs are shared in a triple bond, which is indicated by three lines—for example, N\(_2\) is N≡N (see Figure \(\PageIndex{2}\)). Carbon is unique in the extent to which it forms single, double, and triple bonds to itself and other elements. The number of bonds formed by an atom in its covalent compounds is not arbitrary. Hydrogen, oxygen, nitrogen, and carbon have very strong tendencies to form substances in which they have one, two, three, and four bonds to other atoms, respectively (Table \(\PageIndex{1}\)).

<table>
<thead>
<tr>
<th>Atom</th>
<th>Number of Bonds</th>
</tr>
</thead>
<tbody>
<tr>
<td>H (group 1)</td>
<td>1</td>
</tr>
<tr>
<td>Atom</td>
<td>Number of Bonds</td>
</tr>
<tr>
<td>----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>O (group 16)</td>
<td>2</td>
</tr>
<tr>
<td>N (group 15)</td>
<td>3</td>
</tr>
<tr>
<td>C (group 14)</td>
<td>4</td>
</tr>
</tbody>
</table>

The structural formula for water can be drawn as follows:

Because the latter approximates the experimentally determined shape of the water molecule, it is more informative. Similarly, ammonia (NH$_3$) and methane (CH$_4$) are often written as planar molecules:

As shown in Figure 3, however, the actual three-dimensional structure of NH$_3$ looks like a pyramid with a triangular base of three hydrogen atoms. The structure of CH$_4$, with four hydrogen atoms arranged around a central carbon atom as shown in Figure 3, is tetrahedral: the hydrogen atoms are positioned at every other vertex of a cube. Many compounds—carbon compounds, in particular—have four bonded atoms arranged around a central atom to form a tetrahedron.

Figure 3: The Three-Dimensional Structures of Water, Ammonia, and Methane. (a) Water is a V-shaped molecule, in which all three atoms lie in a plane. (b) In contrast, ammonia has a pyramidal structure, in which the three hydrogen atoms form the base of the pyramid and the nitrogen atom is at the vertex. (c) The four hydrogen atoms of methane form a tetrahedron; the carbon atom lies in the center.
Methane \((\text{CH}_4)\) has a three-dimensional, tetrahedral structure.

Figures \((\text{PageIndex}(1))\), \((\text{PageIndex}(2))\), and \((\text{PageIndex}(3))\) illustrate different ways to represent the structures of molecules. It should be clear that there is no single “best” way to draw the structure of a molecule; the method used depends on which aspect of the structure should be emphasized and how much time and effort is required. Figure \((\text{PageIndex}(4))\) shows some of the different ways to portray the structure of a slightly more complex molecule: methanol. These representations differ greatly in their information content. For example, the molecular formula for methanol (Figure \((\text{PageIndex}(4a))\)) gives only the number of each kind of atom; writing methanol as \(\text{CH}_4\text{O}\) tells nothing about its structure. In contrast, the structural formula (Figure \((\text{PageIndex}(4b))\)) indicates how the atoms are connected, but it makes methanol look as if it is planar (which it is not). Both the ball-and-stick model (part (c) in Figure \((\text{PageIndex}(4))\)) and the perspective drawing (Figure \((\text{PageIndex}(4d))\)) show the three-dimensional structure of the molecule. The latter (also called a wedge-and-dash representation) is the easiest way to sketch the structure of a molecule in three dimensions. It shows which atoms are above and below the plane of the paper by using wedges and dashes, respectively; the central atom is always assumed to be in the plane of the paper. The space-filling model (part (e) in Figure \((\text{PageIndex}(4))\)) illustrates the approximate relative sizes of the atoms in the molecule, but it does not show the bonds between the atoms. In addition, in a space-filling model, atoms at the “front” of the molecule may obscure atoms at the “back.”

Although a structural formula, a ball-and-stick model, a perspective drawing, and a space-filling model provide a significant amount of information about the structure of a molecule, each requires time and effort. Consequently, chemists often use a condensed structural formula (part (f) in Figure \((\text{PageIndex}(4))\)), which omits the lines representing bonds between atoms and simply lists the atoms bonded to a given atom next to it. Multiple groups attached to the same atom are shown in parentheses, followed by a subscript that indicates the number of such groups.
For example, the condensed structural formula for methanol is CH$_3$OH, which indicates that the molecule contains a CH$_3$ unit that looks like a fragment of methane (CH$_4$). Methanol can therefore be viewed either as a methane molecule in which one hydrogen atom has been replaced by an –OH group or as a water molecule in which one hydrogen atom has been replaced by a –CH$_3$ fragment. Because of their ease of use and information content, we use condensed structural formulas for molecules throughout this text. Ball-and-stick models are used when needed to illustrate the three-dimensional structure of molecules, and space-filling models are used only when it is necessary to visualize the relative sizes of atoms or molecules to understand an important point.

Example  \(\PageIndex{2}\): Molecular Formulas

Write the molecular formula for each compound. The condensed structural formula is given.

\begin{enumerate}
\item Sulfur monochloride (also called disulfur dichloride) is a vile-smelling, corrosive yellow liquid used in the production of synthetic rubber. Its condensed structural formula is ClSSCl.
\item Ethylene glycol is the major ingredient in antifreeze. Its condensed structural formula is HOCH$_2$CH$_2$OH.
\item Trimethylamine is one of the substances responsible for the smell of spoiled fish. Its condensed structural formula is (CH$_3$)$_3$N.
\end{enumerate}

**Given:** condensed structural formula

**Asked for:** molecular formula

**Strategy:**

A. Identify every element in the condensed structural formula and then determine whether the compound is organic or inorganic.

B. As appropriate, use either organic or inorganic convention to list the elements. Then add appropriate subscripts to indicate the number of atoms of each element present in the molecular formula.

**Solution:**

The molecular formula lists the elements in the molecule and the number of atoms of each.

\begin{enumerate}
\item Each molecule of sulfur monochloride has two sulfur atoms and two chlorine atoms. Because it does not contain mostly carbon and hydrogen, it is an inorganic compound. B Sulfur lies to the left of chlorine in the periodic table, so it is written first in the formula. Adding subscripts gives the molecular formula S$_2$Cl$_2$.
\item Counting the atoms in ethylene glycol, we get six hydrogen atoms, two carbon atoms, and two oxygen atoms per molecule. The compound consists mostly of carbon and hydrogen atoms, so it is organic. B As with all organic compounds, C and H are written first in the molecular formula. Adding appropriate subscripts gives the molecular formula C$_2$H$_6$O$_2$.
\item The condensed structural formula shows that trimethylamine contains three CH$_3$ units, so we have one nitrogen atom, three carbon atoms, and nine hydrogen atoms per molecule. Because trimethylamine contains mostly carbon and hydrogen, it is an organic compound. B According to the convention for organic compounds, C and H are written first, giving the molecular formula C$_3$H$_9$N.
\end{enumerate}
Exercise 2: Molecular Formulas

Write the molecular formula for each molecule.

a. Chloroform, which was one of the first anesthetics and was used in many cough syrups until recently, contains one carbon atom, one hydrogen atom, and three chlorine atoms. Its condensed structural formula is CHCl₃.

b. Hydrazine is used as a propellant in the attitude jets of the space shuttle. Its condensed structural formula is H₂NNH₂.

c. Putrescine is a pungent-smelling compound first isolated from extracts of rotting meat. Its condensed structural formula is H₂NCH₂CH₂CH₂CH₂NH₂. This is often written as H₂N(CH₂)₄NH₂ to indicate that there are four CH₂ fragments linked together.

Answer a

CHCl₃
Answer b

N₂H₄

Answer c

C₄H₁₂N₂

Summary

There are two fundamentally different kinds of chemical bonds (covalent and ionic) that cause substances to have very different properties. The atoms in chemical compounds are held together by attractive electrostatic interactions known as chemical bonds. The molecular formula of a covalent compound gives the types and numbers of atoms present. Compounds that contain predominantly carbon and hydrogen are called organic compounds, whereas compounds that consist primarily of elements other than carbon and hydrogen are inorganic compounds. Diatomic molecules contain two atoms, and polyatomic molecules contain more than two. A structural formula indicates the composition and approximate structure and shape of a molecule. Covalent molecular compounds, in contrast, consist of discrete molecules held together by weak intermolecular forces and can be gases, liquids, or solids at room temperature and pressure.