3.1: Bonding in compounds

Chemical bonds

What is a compound?

Compounds are a pure form of matter formed by atoms of more than one element combined in a constant whole number ratio.

The bonds connect the atoms in the compounds. Sharing or transferring some valance electrons from one atom to the other makes the bonds. Noble gases have a full valence shell of eight valence electrons, except helium which has a full valence shell of two valence electrons. The noble gases are the least reactive, i.e., the most inert group of elements.

Octet rule

The octet rule states that atoms of all elements other than noble gases tend to share, lose, or gain valence electrons to acquire the electron configuration of the nearest noble gas having eight valence electrons.

Covalent bonds

A bond formed by sharing electrons is a covalent bond.

When a nonmetal atom combines with another nonmetal atom, they usually make a covalent bond. A covalent bond is a pair of shared electrons, called a **bonding pair** of electrons, where each bonded atom contributes one electron. For example, chlorine has seven valence electrons and needs one more to complete its octet. Hydrogen has one valence electron and requires one more to acquire the electron configuration of helium, i.e., **duet** instead of the octet. Hydrogen and chlorine combine by sharing one electron to make the compound HCl. Similarly, oxygen, nitrogen, and carbon make 2, 3, and 4 covalent bonds with hydrogen to complete their octet and make compounds H_2O, NH_3, and CH_4, respectively, as illustrated in Fig. 3.1.1.

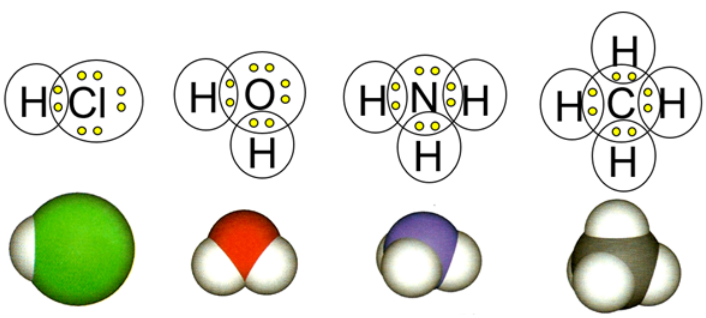

Figure 3.1.1: Examples of covalent bonds where Cl, O, N, and C acquire octet by sharing 1, 2, 3, and 4 electrons, respectively. Hydrogen shares one electron and acquires a duet, i.e., the electron configuration of helium. 2nd row is the space-filling model of the molecule where the white sphere is hydrogen, and the colored is the other atom. Source: "File:Kovalentne veze.png" by Drago Karlo CC BY-SA 4.0

Two atoms can share one, two, or three electrons to make a single, a double, or a triple covalent bond. For example, H_2 has a single bond (H-H), O_2 has a double bond (O=O), and N_2 has a triple bond ($N\equiv N$), where each line between the atoms represent one covalent bond. Fig. 3.1.2 illustrates the formation of three covalent bonds in N_2. A valence electron pair that is not involved in bonding is called a **nonbonding pair**. One nonbonding pair and three bonding pairs complete the octet of each nitrogen atom in the N_2 molecule, as shown in Fig. 3.1.2.

Note

The bonding pair of electrons counts towards the total valence electrons of each bonded atom., i.e., in H-H each hydrogen atom has two valence electrons, and in **:**$N\equiv N$**:** each nitrogen has eight valence electrons; two in the nonbonding pair and six in three bonding pairs.

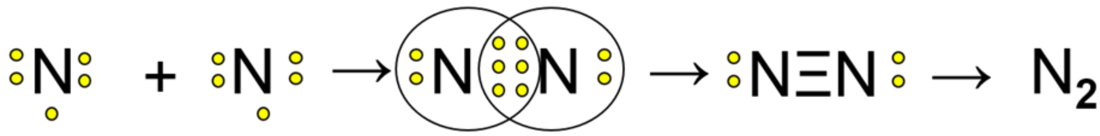

Figure 3.1.2: Illustration of three covalent bond formations between two nitrogen atoms. Source: File:Kovakentna veza dušika.png" by Drago Karlo is licensed under CC BY-SA 4.0

The formula of a covalent compound

A compound is represented by a chemical formula that combines the symbols of its constituent elements. More electropositive elements are usually written first, e.g., HF, NO, CO. Some exceptions to this rule, e.g., NH_3 and CH_4, have more electronegative elements written first. The majority of the covalent compounds exist as discrete molecules. A subscript to the right of the element's symbol represents the number of atoms of the component of the molecule. For example, H_2O has two hydrogen atoms and one oxygen atom in a water molecule. Note that subscript 1 is not written, i.e., the symbol of an element alone represents one atom.

A few covalently bonded compounds are giant molecules where the atoms are held together by a 3D network of bonds. The formula of these compounds shows the simplest whole-number ratio of elements in the compound. For example, Fig. 3.1.3 shows SiO_2 present in high-purity sand and quartz, a giant molecule.

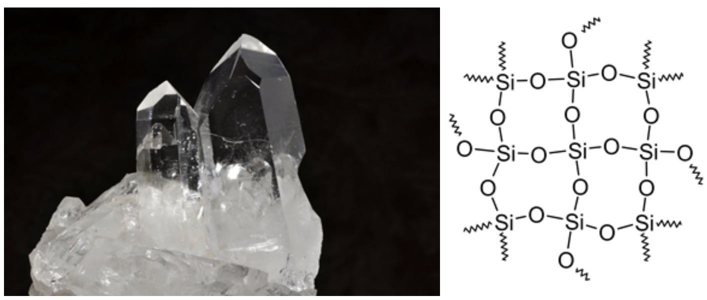

Figure 3.1.3: Quartz crystal composed of SiO_2, and an illustration of covalent bonds in a giant molecule of SiO_2. Source: Parent Géry, Public domain, via Wikimedia Commons, and Roland Mattern / Public domain

Ionic bond

A bond formed by the transfer of electrons from one atom to the other atoms is an ionic bond.

A compound that has ionic bonds is an ionic compound. Usually, metal atoms lose electrons and become cations, and nonmetal atoms gain electrons to become anions. The electrostatic attraction between the opposite charges holds the ions together in the ionic compound. For example, sodium (Na) loses one electron, and fluorine (F) gains one electron to make a compound sodium fluoride (NaF), as illustrated in Fig. 3.1.4.

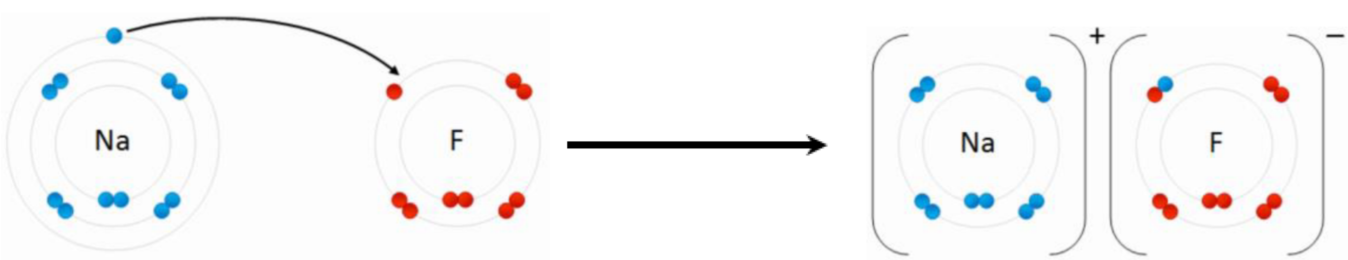

Figure 3.1.4: An example of ionic bond formation between Na and F. Source: modified from: Wdcf / CC BY-SA.

Ionic compounds

Table salt, i.e., NaCl is an example of an ionic compound. The Na completes its octet by losing one electron and becoming Na^+ cation. Losing electrons reduces the electron-electron repulsion, but the electron-nucleus attraction remains the same. Consequently, the electron cloud around the nucleus shrinks. Similarly, the chlorine atom has seven valence electrons. After gaining one electron, it becomes Cl^- anion with its octet complete. Gaining electrons increases the electron-electron repulsion, but the electron-nucleus attraction remains the same. Consequently, the electron cloud around the nucleus expands. Fig. 3.1.5 illustrates the formation of an ionic bond and the accompanying changes in the total number of electrons and sizes relative to the parent neutral atoms in the case of NaCl formation.

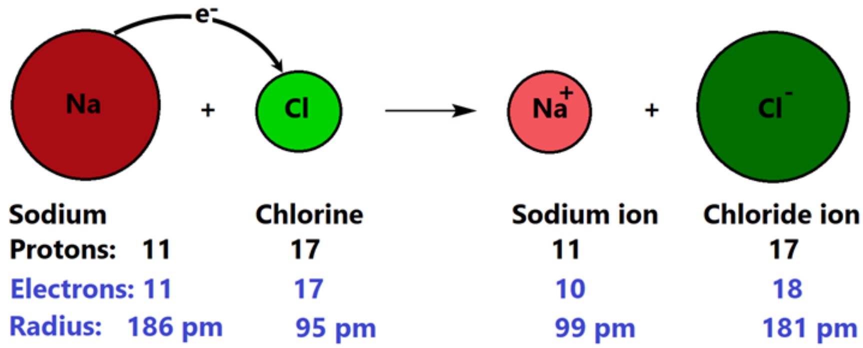

Figure 3.1.5: Illustration of an ionic compound formation by electron transfer from sodium (Na) to chlorine (Cl) making Na^+ cation with one less electron and Cl^- anion with one more electron than their parent neutral atoms. The Na^+ cation is smaller than Na, and the Cl^- anion is large than Cl atom.

The ionic bond is not localized or unidirectional. The electrostatic force is all around the ions. Therefore, the cations surround the anions, and the anion surrounds the cations in a regular array in a 3D crystal lattice. Fig 3.1.6 illustrates the structure of NaCl.

Note

1. The formula of the ionic compounds represents the simplest whole-number ratio of the atoms of the constituent elements.
2. A cation is always smaller in size than its parent neutral atom.
3. An anion is always larger than its parent neutral atom.

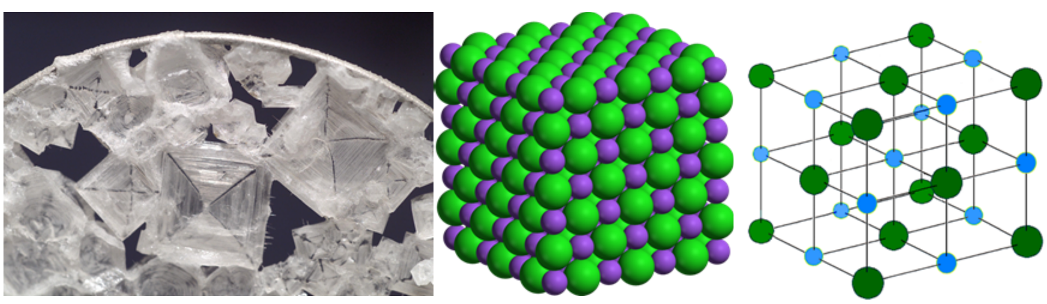

Figure 3.1.6: Sodium Chloride from left: actual crystals in a water bubble within a 50 mm metal loop, model, and crystal lattice. Na^+ is purple or blue, and Cl^- is green in the models. Source: Photograph by the NASA Expedition 6 crew, Public domain, via Wikimedia Commons, Benjah-bmm27 (talk · contribs) / Public domain, and File: H Padleckas / Public domain

Criteria to distinguish between ionic and covalent bond

Usually, a metal and a nonmetal bond is ionic, and the bond between two nonmetals is covalent. Better criteria are based on the difference in electronegativities of the bonded atoms. Electronegativity is the ability of an atom to attract a pair of bonded electrons to itself. If the electronegativity difference is significant, the bonding electrons completely transfer to the more electronegative atom, and the bond is ionic. There is no single value of electronegativity difference to separate ionic and covalent bonds, but usually, the electronegativity difference of more than 1.8 results in an ionic bond. Otherwise, a covalent bond, but the bonding electrons are more towards the more electronegative atom, making it a polar covalent bond. An electronegativity difference less than 0.5 is considered a noncovalent bond, but a true noncovalent bond forms when the bonded atoms are the same element.

Properties of compounds

The properties of the compounds are usually altogether different from the properties of their constituent elements. For example, hydrogen (H_2) is a gas that burns in oxygen, oxygen (O_2) is a gas that assists combustion, but water (H_2O) is a liquid that extinguishes fire. Similarly, sodium (Na) is a soft metal that melts at 97.79 ^oC, chlorine (Cl_2) is yellowish color gas, but sodium chloride (NaCl) is a transparent crystal that melts at 801 ^oC.

The intermolecular interactions in covalent molecules are weak to moderate relative to the strength of covalent bonds or ionic bonds. Therefore, the covalent molecules are usually gases like O_2, NH_3, CH_4, liquids like H_2O, or soft and low melting solids like waxes, glucose ($C_6H_{12}O_6$, mp 146^oC).

Ions in the ionic compounds are held together by strong ionic bonds in a 3D array of crystal lattices. Therefore, ionic compounds are usually hard solids with high melting points. For example, NaCl melts at 801 ^oC. Covalent compounds that exist as a 3D network of covalent bonds, i.e., as giant molecules, are usually hard materials having a higher melting point than ionic compounds. For example, SiO_2 present in sand and quartz is a hard solid that melts at 1,710 ^oC. Diamond –the hardest known substance, is a giant molecule of carbon atoms held together in a 3D network of covalent bonds that melts around 4,027 ^oC.
