4. Bonding

4.1 Types of Bonding

The physical and chemical properties of a substance are largely determined by the nature of the bonding between atoms of the substance. Different types of bonding are possible.

Ionic

When a metal reacts with a non-metal, the product is generally an ionic material. Non-metal atoms take electrons from metal atoms to form anions. Metal atoms lose electrons and become cations. An ionic material is an alternating lattice of cations and anions held together by the strong electrostatic attraction between oppositely charged ions. The bonding in such a material is called *ionic*. For example, NaCl(s) is an ionic material consisting of Na^+ and Cl^- ions. Ionic materials are typically hard, brittle solids with high melting points.

Covalent

Non-metal atoms form *covalent bonds*, wherein they share valence electrons with a neighboring non-metal atom. A covalent bond can be polar (as it is in case of H-Cl), wherein the bonding electrons are closer to the more electronegative atom. A covalent bond can also be completely non-polar (as it is in the case Cl-Cl, or any other homonuclear diatomic). An ionic bond is, in a sense, the extreme of a polarized covalent bond. Covalent bonding frequently extends only over a limited number of atoms. This defines a *molecule*. The associated material is called *molecular*. In the case of a solid or liquid molecular material, the molecules are held together by *intermolecular forces*. These forces are weaker, and such materials generally have lower melting and boiling points than other types of materials (e.g. metals, covalent networks). Most materials consisting of small molecules are gases or liquids. CO_2(g), H_2O(l) and sucrose,$C_{12}H_{24}O_{12}$(s), are examples of molecular materials.

Covalent bonding can extend over an array of vast numbers of atoms. In such a case, the “molecule” is a vast network of atoms connected by covalent bonds. These materials are called *network covalent solids*. They are generally very hard, and have high melting points. For example, diamond is a 3-dimensional network of carbon atoms.

Metallic

In metallic solids, metal atoms share their valence electrons over an array of vast numbers of atoms. This type of bonding is called *metallic*, and is responsible for the unique properties of metals familiar in everyday life. For example, metals are typically solid, often with high melting points. They are also shiny, and mostly silver-colored. They conduct electricity and are somewhat malleable.

Example 4.1: What type of bonding is present in the following substances? (states are shown for each substance at 25°C).

(a) KF(s)	(b) Cu(s)	(c) $LiNO_3$(s)	(d) SF_6(g)	(e) SiO_2(s)
(f) Na(s)	(g) $CaBr_2$(s)	(h) C_2H_6(g)	(i) $MgCO_3$(s)	(j) Br_2(l)

(a) Ionic bonding. KF(s), potassium fluoride, is a compound formed from a metal (potassium) and a non-metal (fluorine). It is ionic, consisting of K^+ and F^- ions. The formula, KF, tells us that there is a one to one ratio of K^+ to F^- ions to balance the charge.

(b) Metallic bonding. Cu(s) is a metal. The chemical formula simply says that the material consists only of copper atoms.

(c) Ionic and covalent bonding. $LiNO_3(s)$ is an ionic compound composed of Li^+ and NO_3^- (nitrate) ions. The nitrate ion is a *polyatomic ion*. It consists of covalently bonded N and O atoms, with a net charge of −1.
(d) Covalent bonding. $SF_6(g)$ is a gas consisting of distinct SF_6 molecules. Each SF_6 molecule is an S atom covalently bonded to six F atoms; both elements are non-metals.
(e) Covalent bonding. Quartz, $SiO_2(s)$, is a network covalent solid. The chemical formula for a network covalent solid tells us the relative amounts of the different types of atoms – here, Si and O. Because it is a continuous network it can be represented as $(SiO_2)_n$.
(f) Metallic bonding. Na(s) is a metal.
(g) Ionic bonding. $CaBr_2(s)$ is an ionic compound composed of Ca^{2+} and Br^- ions. Because the calcium has a +2 charge, whereas bromide is only −1, there are two bromide ions for every calcium ion.
(h) Covalent bonding. Ethane, $C_2H_6(g)$, is a gas of C_2H_6 molecules. The chemical formula for molecular compounds tells us the actual number of each type of atom in one molecule – it is not just the relative amounts of atoms. Here, there are two C atoms and 6 H atoms in every ethane molecule.
(i) Ionic and covalent bonding. $MgCO_3(s)$ is an ionic compound composed of Mg^{2+} and CO_3^{2-} (carbonate) ions. The carbonate ion is a *polyatomic ion*. It consists of covalently bonded C and O atoms, with a net charge of −2.
(j) Covalent bonding. $Br_2(l)$ is a liquid consisting distinct of Br_2 molecules. Covalent bonding holds each Br_2 molecule together.

4.2 Solutions

The different types of materials described above have distinguishing properties when those materials are dissolved in a solvent (often, but not necessarily, water). For example, ionic materials (salts) dissolve in water to form electrolyte solutions – though some salts have extremely small solubility. An electrolyte solution conducts electricity. This is because the ions of the ionic material move around freely in the water solution. They can carry electricity. In contrast, an ionic solid does not conduct electricity as the ions are fixed in lattice positions and cannot move to carry current.

Salts dissolve in water because the ions can be solvated by water molecules (or, ‘hydrated’). Solvation is an example of intermolecular forces – forces of attraction that exist between molecules or between molecules and ions. In this case, we have ions and water molecules. Solvation is strong here because water molecules are polar and are able to align themselves to interact favorably with either a positive or negative ion. This is an example of an ion-dipole force.

e.g.

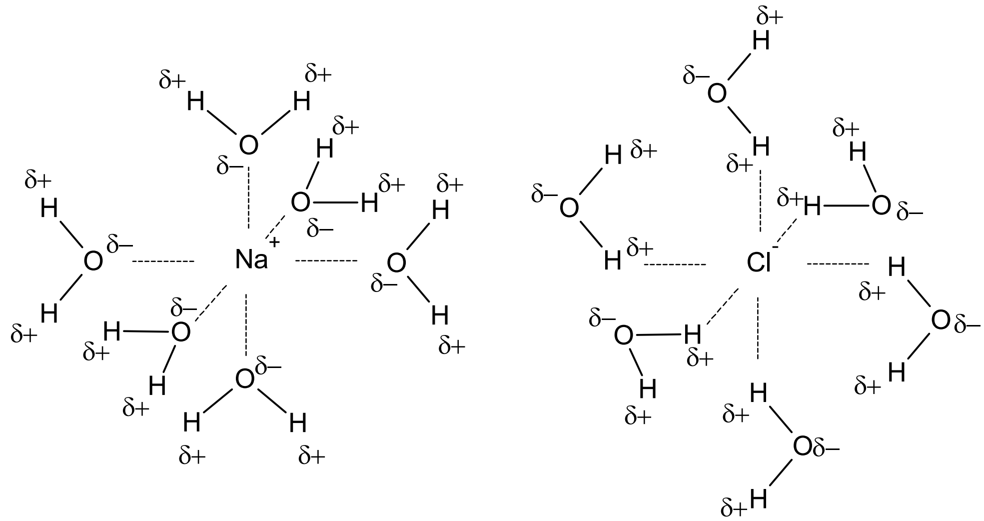


Figure 4.1 Solvation of sodium and chloride ions in aqueous solution. The δ+ and δ– are the partial charges on H and O atoms associated with the polarity of the OH bond.

Water is polar because it is an asymmetric molecule with polar covalent bonds. The H-O bonds are polar because oxygen is more electronegative than hydrogen. Thus, the bonding electrons are shifted toward the O atom. The O atom is slightly negatively charged (δ–), while the H atoms are slightly positively charged (δ+), where δ indicates a partial charge Each water molecule has a permanent, or 'net', dipole.

In water, the two H-O bond dipole moments do not cancel. This is because two lone pairs of electrons on the O atom push the H-O bonds to one side of the molecule.

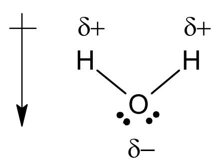


Figure 4.2 Lewis structure and molecular shape of water, showing the partial charges, and the net dipole moment vector (on the left).

Molecular compounds can also dissolve in water. This is again because of intermolecular forces. Compounds with the highest solubilities are those consisting of molecules with net dipole moments – i.e., polar molecules like water. When molecular compounds dissolve in water, in the absence of reaction with water (e.g. acids and bases excluded), the result is a *non-electrolyte solution*. Such solutions do not conduct electricity. When the molecular compound is an acid or a base, it reacts when dissolved in water (see Section 3) producing H_3O^+ or OH^- ions, respectively. These ions move freely in solution, and will carry a current. The solutions of an acid or a base are *electrolyte* solutions.

Dissolution of compounds in other molecular solvents is also important. Many organic solvents (e.g. CCl_4) are non-polar. These solvents best dissolve other non-polar materials. This is because a polar molecule has stronger intermolecular forces when it is surrounded by other polar molecules. The polar compound will not readily dissolve in a non-polar solvent, as it would be solvated by weaker intermolecular forces than are already present in the compound. In summary, "*like dissolves like*".

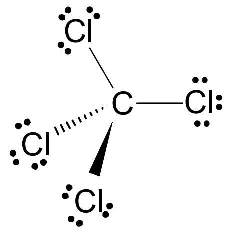
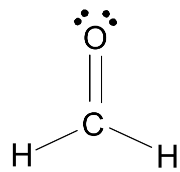
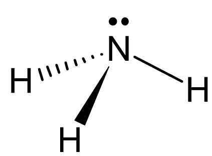


Figure 4.3. Lewis structure of CCl_4: The molecule has polar bonds. However, it is a symmetric molecule (it has a tetrahedral shape). The "wedge" bond indicates a bond coming forward out of the plane of the page, and the "dashed" bond indicates a bond going back behind the plane of the page. In such a way we try to show a 3-dimensional shape in a 2-dimensional drawing. Because of the symmetry all of the bond dipoles cancel out, and it has no permanent dipole (it is a non-polar molecule).

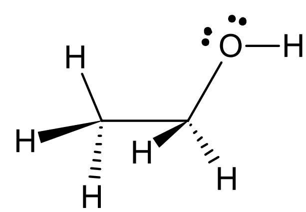
Example 4.2: Consider the following Lewis structures:



Lewis structure and shape of formaldehyde, CH_2O



Lewis structure and shape of ammonia NH_3



Lewis structure of ethanol, C_2H_5OH, showing shape around the O atom – and the C atoms (these atoms appear only as vertices from which four bonds emerge)

Which of the following are electrolyte solutions?

(a) potassium chlorate solution: $KClO_3$(aq)
(b) formaldehyde solution (pH = 7): CH_2O(aq)
(c) acetic acid solution (pH = 3): CH_3COOH(aq)
(d) sodium bromide: NaBr(aq)
(e) ammonia solution (pH = 10): NH_3(aq)
(f) ethanol solution (pH = 7): C_2H_5OH(aq)

(a) Electrolyte solution. $KClO_3$(aq) consists of K^+ and ClO_3^- ions in aqueous solution. These ions move freely and therefore can conduct electricity.
(b) Non-electrolyte solution. Formaldehyde solution contains CH_2O molecules solvated by water molecules. Formaldehyde is neither an acid nor a base in water. The information

that pH = 7 tells us that the solution is neutral. The H atoms in CH_2O are bonded to carbon. They are not acidic. Though the O atom has lone electron pairs, it does not accept H^+ from water. Formaldehyde remains neutral in solution. While it moves freely, it cannot conduct electricity.

(c) Electrolyte solution. CH_3COOH is a weak acid, as indicated by the information that pH = 3. It donates an H^+ to H_2O to form H_3O^+. The H_3O^+ and CH_3COO^- ions move freely in solution and can conduct electricity.

$$CH_3COOH(aq) + H_2O(l) \rightleftharpoons CH_3COO^-(aq) + H_3O^+(aq)$$

(d) Electrolyte solution. NaBr(aq) consists of Na^+ and Br^- ions in aqueous solution. The hydrated Na^+ and Br^- ions can conduct electricity.

(e) Electrolyte solution. NH_3 is a weak base. It accepts an H^+ from H_2O to leaving OH^- and NH_4^+ ions.. The OH^- and NH_4^+ ions move freely in solution and can conduct electricity.

$$NH_3 + H_2O \rightleftharpoons NH_4^+ + OH^-$$

Note also that, because the equilibrium is shifted to the left, this will be a *weak* electrolyte solution. It will only weakly conduct electricity.

(f) Non-electrolyte solution. A molecular solution, and ethanol is neither an acid nor a base in water (pH = 7).

Example 4.3: Which of the following pairs of compounds form solutions?

(a) potassium iodide and water
(b) methane, CH_4, and water
(c) methane, CH_4, and carbon tetrachloride, CCl_4
(d) formaldehyde, CH_2O, and water
(e) formaldehyde, CH_2O, and carbon tetrachloride, CCl_4
(f) ethanol, C_2H_5OH, and water

(a) Solution. KI is ionic. It dissolves in water to form solvated K^+ and I^- ions.
(b) No solution. CH_4 is symmetrical and non-polar. It has very little solubility in a polar solvent such as water.
(c) Solution. CCl_4 is symmetrical and non-polar. It dissolves non-polar compounds like methane.
(d) Solution. CH_2O is asymmetrical. It has a dipole moment arising mainly from the polar C-O bond (a double bond in formaldehyde). It dissolves in polar solvents like water.
(e) No solution. Polar formaldehyde does not dissolve in non-polar carbon tetrachloride.
(f) Solution. Ethanol is polar (primarily because of the O-H bond) and dissolves in polar water.

Problems:

4.1 Identify the types of bonding present in the following materials. Label the material as ionic, molecular, network covalent, or metallic.

(a) $Cl_2(g)$
(b) LiOH(s)
(c) $H_2SO_4(l)$
(d) Fe(s)
(e) $CaCO_3(s)$
(f) C(diamond)
(g) brass – an alloy of mostly copper, zinc and (sometimes) Sn.

4.2 Which of the pairs of material form solutions?

(a) ethane, C_2H_6, and butane, C_4H_{10}.
(b) ethanol, C_2H_5OH, and water

(c) carbon dioxide and carbon tetrachloride, CCl_4
(d) lithium bromide, LiBr, and water
(e) sodium nitrate, $NaNO_3$, and carbon tetrachloride, CCl_4

4.3 Electrolytes can be strong or weak. For example, most acids are molecules that dissociate in water. They react with water to form an anion (the conjugate base) and hydronium ion, H_3O^+. The ions formed can conduct electricity. So, the resulting solution is an electrolyte solution. However, most acids are weak which means they only dissociate to a small extent. Consequently, the ion concentration in solution is small, and the electrical conductivity is also small. Weak acids are therefore *weak electrolytes*. Weak bases are similarly *weak electrolytes*. Ionic materials and strong acids and bases are *strong electrolytes*.

Label each of the following materials as a strong or weak electrolyte, or as a non-electrolyte.

(a) nitric acid, HNO_3
(b) lithium hydroxide, LiOH
(c) ethanol, C_2H_5OH
(d) potassium iodide, KI
(e) ammonia, NH_3
(f) hypochlorous acid, HOCl
(g) sodium hypochlorite, NaOCl