Lecture 5: Bonding Models

Atoms or ions in minerals are glued together by electrical bonds that are ionic, covalent, or metallic. The types and intensities of these bonds in a mineral determine its physical and chemical properties, including hardness, cleavage, and conductivity

Ionic Bonds

Ionic Bonding Model

Atoms have a tendency to achieve a completely filled valence shell like the inert gases. Metals like sodium tend to lose electrons to achieve full valence shells, and nonmetals like chlorine tend to gain electrons. The process of gaining or losing electrons crates ions, and electrostatic forces bring the ions together to form compounds. For example, sodium may lose an electron to chlorine to create Na^+ and Cl^-, and the Coulombic attraction between the resulting ions makes NaCl, or table salt. The attraction between the oppositely charged ions constitutes the ionic bond.

$$Na \rightarrow Na^+ + e^-$$
$$Cl + e^- \rightarrow Cl^-$$
$$Cl^- + Na^+ \rightarrow NaCl$$

The strength of an ionic bond depends on the distance between ions (r) and the product of their charges (q). The mathematical expression for ionic bond strength is very similar to the expression for the Coulomb force:

$$\text{Bond strength} \propto (q_1 q_2)/r$$

Properties of Ionic Materials

Ionically bonded materials usually have moderate hardness and fairly high melting points. They are generally soluble and are poor conductors of electricity because their constituent ions are fairly stable and neither lose nor gain electrons easily. They are usually highly symmetric and nondirectional (isotropic), because their cations tend to evenly surround themselves with as many anions as space permits.

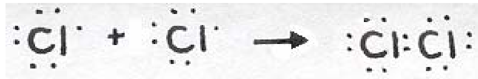
Electronegativity and Predicting Bond Types

The ability of an atom to lose or gain electrons is called electronegativity. Electronegativity is expressed as a dimensionless number between 0 and 4.1, with low numbers indicating a tendency to lose electrons and high numbers indicating a tendency to gain electrons. Electronegativity helps one predict the bonding type between two elements. For example, when an element with low electronegativity bonds with an element with high electronegativity, the bond is typically ionic. When two elements with high electronegativities bond together, the bond is typically covalent.

Covalent Bonds

Covalent Bonding Model

Whereas atoms exchange electrons to achieve a full valence shell in ionic bonds, they share electrons in covalent bonds because neither atom has a strong tendency to give them up completely. For example, when an atom of chlorine bonds with another atom of chlorine, the result is an overlap of the atoms' electron clouds that simultaneously fills the valence shells of both atoms. Covalent bonds are expressed symbolically with Lewis notation, in which valence electrons appear as dots surrounding an atom. For chlorine gas, this looks like:



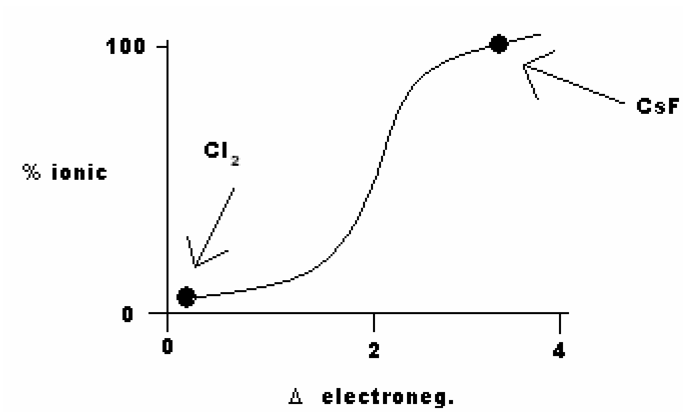
The number of covalent bonds an atom can form depends on the number of electrons needed to form a complete valence shell. For example, carbon and silicon can both form up to four covalent bonds.

Properties of Covalent Materials

Covalent bonds are the strongest of the chemical bonds. Covalently bonded materials generally have very high melting points and are generally insoluble. They typically do not conduct electricity as solids or in solution. Because covalent bonds are highly directional, covalently bonded materials tend to have less symmetry than ionically bonded materials.

Continuum between Covalent and Ionic Bonds

Covalent and ionic bonds are end-member models. Transition states exist between them, and few if any chemical bonds are perfectly ionic or covalent. The percent ionic character of a bond is a function of the difference between the electronegativities of the elements in the bond, as shown in the following diagram.



Metallic Bonds

Metallic Bonding Model

Minerals like native gold and silver have properties that cannot be explained in terms of ionic or covalent bonds. For example, the malleability and electrical conductivity of either metal cannot be readily explained by the localized sharing or complete transfer of electrons. Instead, the bonding electrons in native metals like gold and silver are modeled as highly delocalized and free to move from one atom to the next. The electrons compose a mobile electron glue that keeps the positively charged metal ions from flying apart.

Properties of Metals

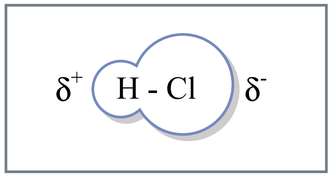
Metals are generally ductile and malleable. They are conductive and not very hard. They are highly symmetric because metallic bonds are nondirectional.

Intramolecular vs. Intermolecular Bonds

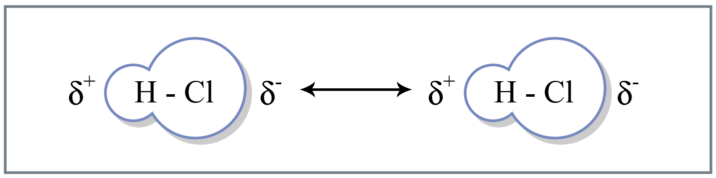
Metallic, covalent, and ionic bonds are all examples of intramolecular bonds, or bonds between the atoms or ions in molecules. Intermolecular bonds are bonds between molecules themselves. These bonds include dipole-dipole bonds, van der Waals bonds, and Hydrogen bonds.

Dipole-dipole Bonds

When the bond between atoms is neither perfectly ionic nor perfectly covalent, shared electrons are located closer to the more electronegative atom. This asymmetric distribution of electrons makes the bond polar and the molecule has a dipole moment. In HCl, for example, the more electronegative chlorine atom has a partial negative charge (δ^-) and the hydrogen atom has a partial positive (δ^+) charge.

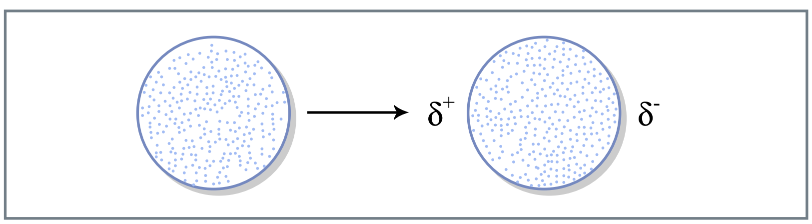


The partially charged ends of such a molecule are attracted to the partially charged ends of other polar molecules. These types bonds are called dipole-dipole bonds.

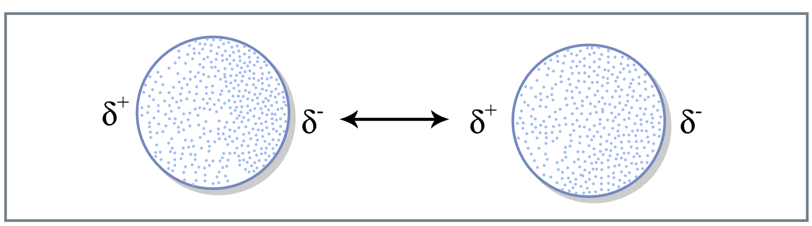


van der Waals Bonds

Gases such as O_2, N_2, and the inert gases all have crystalline forms at very low temperatures even though their molecules are not polar. This results from van der Waals bonds. Van der Waals bonds are electrostatic bonds between atoms or molecules that result from instantaneous asymmetric charge distributions in the atoms and molecules.



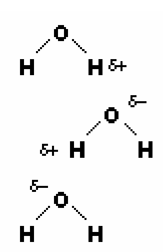
The asymmetric charge distributions create a temporary dipole moment and the atoms or molecules are temporarily attracted by electrostatic forces.



Van der Waals bonds are the bonds between layers of carbon atoms in graphite.

Hydrogen Bonds

A hydrogen bond is a special type of dipole-dipole bond between a positive hydrogen ion and a negative ion like O^{2-}. Because the hydrogen ion is an unshielded proton, it can get very close to negative ions or the negative ends of polar molecules and create strong intermolecular bonds. These bonds are considerably stronger than van der Waals bonds. The best known example of hydrogen bonds is the attraction between hydrogen and oxygen among molecules of water.



<u>Class Handout about Bonding Types</u>

12.108

Bonding and Physical Properties

Bond Type	**Bond Characteristics**	**Associated Physical Properties**
Ionic	Atoms are charged particles. Electrostatic forces hold structure together. Atoms have large differences in electronegativity.	High symmetry. Often isometric. Brittle, not ductile - ions resist position. Break easily. Good cleavage - parts along planes ++++ or ------. Poor electrical conductivity. Bond strength - hardness depends on ionic charge. MgO, H = 6, NaCl, H = 2.5.
Covalent	Atoms satisfy charge balance by sharing electrons with adjacent atoms in hybrid or molecular orbitals. Atoms have little or no difference in electronegativity. Chemical bonds are highly directional.	Exhibit a broad range of physical properties. Physical properties can be highly directional. Depends on symmetry of bonding. Properties can be mixed. Metallic luster & brittleness (FeS_2). High melting point, but soft (graphite). Strength of bonds related to orbital overlap. Strong = large overlap = short bond.
Metallic	Materials with a small number of outer shell electrons. Low first ionization potentials. Generally cations in ionic state. A mobile electron glue keeps the positively-charged ions from flying apart. Bonds are non-directional.	High symmetry. Conduction electrons are an important property. High electrical and thermal conductivity. Soft, low melting points, ductile and metallic luster.
Molecular	Bonding results from asymmetric charge distribution in the atom. Van der Waals forces. Electric dipole moment as a result of higher e^- density on one side of nucleus.	Weak bonding force in all minerals. Low-T crystal forms of gases. Ice, Native Sulfur, Realgar (AsS) and Orpiment (As_2S_3) are natural examples.