14 CHEMISTRY IN THE 21ST CENTURY

Since the beginning of its modernization at the end of the 18th century, chemistry has been continuously and rapidly developing. Since the basis of this development is through the atomic/molecular theory, we can call these 200 years the era of molecular chemistry.

As the beginning of the 21st century approached, chemistry had much success in greatly enlarging its scope. The role of weak interactions was recognized, and the new prospect of supramolecular chemistry opened up.

On the other hand, chemistry has a major responsibility to sustain the environment of the earth, and we must find ways for humans and nature to coexist indefinitely, that is, in modern terminology, to achieve sustainable societies. There is much that chemistry and all chemists should do.

14.1 A novel view of matter

(a) Detection of weak interaction

From the birth of modern chemistry at the end of the 18th century to the end of the 20th century, chemistry has been based on molecules which are composed of atoms and covalent and ionic bonds to connect these. The structure, properties and functions have been explained in terms of molecules. It has been taken for granted that if one can understand each molecule, one can understand the properties and functions of all substances. Chemistry based on such an assumption may be called the **molecular chemistry**.

There were, however, some chemists who suspected such a view might be too shortsighted. Indeed as early as the 1920s, it was already recognized that there were some materials whose structure or properties and functions could not be explicable in terms of molecules. Around that time, the concept of hydrogen bonding was successfully introduced to account for the partial association of water and acetic acid. Hydrogen bonding is beyond the scope of the valence theory formulated by Kekulé. Although hydrogen bonding is in its strength only 1/10 of the normal covalent bond, it helps molecules bind weakly to each other. In this sense, hydrogen bonding may be called a kind of chemical bond.

Another concept, **intermolecular force** or **van der Waals force** was introduced to account for the fact that such nonpolar molecules as H_2 crystallize at extremely low temperatures. The driving force of ionic bonds, *i.e.*, the Couloumb interaction is proportional to the reciprocal of the square of distance. The van der Waals force is proportional to the reciprocal to the sixth power of the distance, and hence a different power.

(b) Clathrate compounds

When an aliphatic hydrocarbon such as octane C_8H_{18} was added to a solution of urea H_2NCONH_2, beautiful crystalline rods were deposited. The crystals were composed of urea and octane, but the ratio was not an integer. Furthermore, by gentle heating, the crystals decomposed into urea and octane. These facts indicated that the two components were not bound by normal covalent or ionic bonds.

The structure of the crystals (called urea adducts at that time) was elucidated by X-ray crystallographic analysis. According to it, urea molecules form a chain by hydrogen bonding, and this chain forms a spiral, leaving an empty column in the middle. Octane molecules are trapped in the empty column, and remains in this cavity by weak interaction.

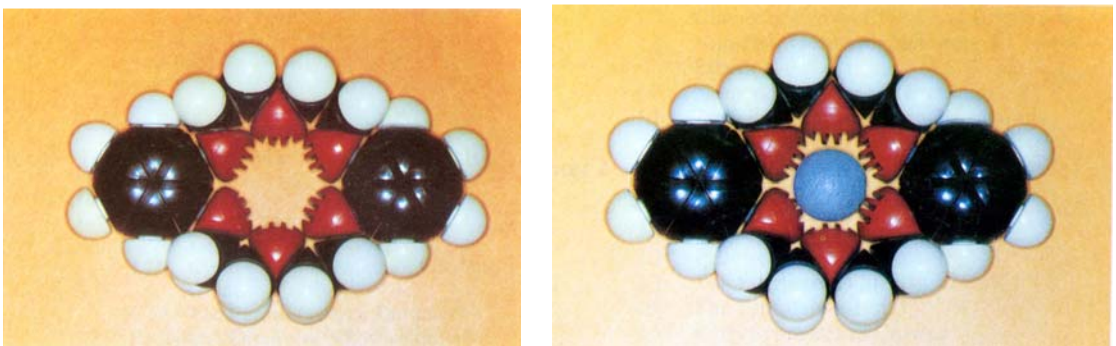
In such compounds, the weak interaction which is beyond the scope of conventional chemical bonds exists. These compounds are now called **inclusion compounds** or **clathrate compounds**. Compounds whose role is similar to that of urea are now called **hosts**, and those whose role is similar to that of octane are called **guests**. A novel branch of chemistry, **host-guest chemistry** has come into being.

Before the urea adducts were discovered, the inclusion compounds with hydroquinone (this compound is used as the reductant in photography) as the host had attracted attention. According to the structure as revealed by X ray crystallographic analysis, three hydroquinone host molecules trap one guest molecule—methanol. The molecular formula of this clathrate compound is $CH_3OH{\cdot}3C_6H_4(OH)_2$. Hydroquinone can also trap guests such as argon.

(c) The discovery of crown ethers

Clathrate compounds such as those of urea or hydroquinone are indeed a kind of surprise to chemists. It must be admitted, however, that in crystals hosts and guests are necessarily close together. In such cases, weak interaction may take place though such an interaction is beyond the scope of conventional chemical bonds. However, the situation should be different in solutions.

Around 1967, the American chemist Charles J. Pedersen (1904-1989) obtained a cyclic ether as a by-product of one of the reactions he was investigating. He paid attention to the strange properties of this ether. This compound was scarcely soluble in methanol, but became easily soluble if he added a sodium salt to the mixture. Furthermore, the benzene solution of this ether could dissolve potassium dichromate $K_2Cr_2O_7$ and exhibited beautiful purple color. He was bold enough to explain these phenomena, saying that sodium ions or potassium ions seem to fall into the cavity at the center of the molecule (Fig. 14. 1).



(a) (b)

Fig. 14.1 Dibenzo-18-crown-6.

(a) free dibenzo-18-crown-6. (b) dibenzo-18-crown-6 captures K^+ ion.

From "*Crown Ethers & Cryptands*" by G. Gokel, Royal Society of Chemistry, 1991

Later it was proved that Pedersen's idea was correct, and indeed, cations were trapped in the cavity of the molecule. He proposed to name the compound a **crown ether** since the shape of the molecule was indeed like a crown, and this proposal was accepted by the chemical world. In 1987, together with the American chemist Donald James Cram (1919-2001) and the French chemist Jean-Marie Lehn (1939-), Pedersen was honored with the Nobel Prize in chemistry.

(d) Chemistry of molecular assemblies

The interaction between crown ethers and alkali metal cations is the weak interaction different from conventional chemical bonds. It turned out that interactions of this type, which exists not only in crystals but also in solutions, are more general than expected. A natural product valinomycin, discovered at the same time, could also capture and transport ions, and furthermore, bring alkali metal cations into living organisms through membranes. Compounds with such a function are called **ionophores**. The similarity in structure between valinomycin, a natural product, and crown ethers, artificial products, is evident though these two compounds are different in origin (Fig. 14. 2).

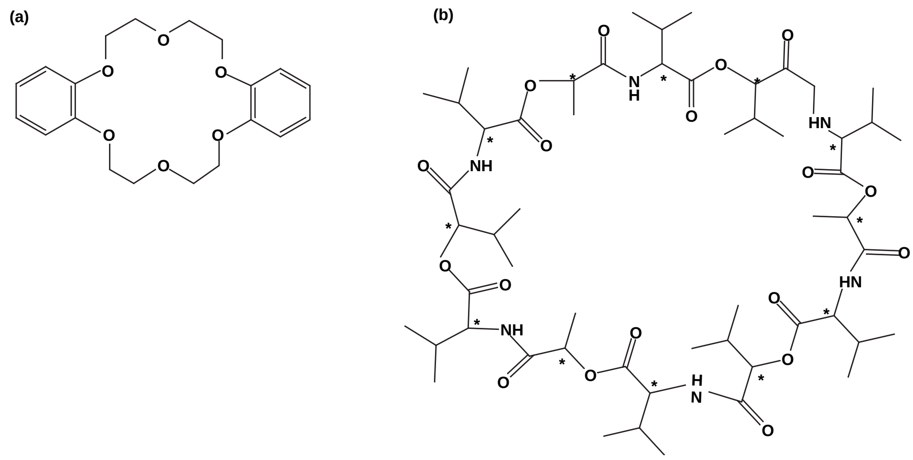


Fig. 14.2 Ionophores which can capture and transport ions.
(a) a synthetic compound: dibenzo-18-crown-6.
(b) a natural compound: valinomycin (antibiotics)

Parallel with the discovery of ionophores, an action has emerged to amalgamate organic chemistry and life science, and inorganic chemistry and life science, in the latter half of the 20th century. A useful clue to understand the mechanism of life is to study the processes (reactions) in which a variety of natural products assemble to form complexes or membranes following some rules. The other clue is the weak interaction between natural products, *i.e.*, formation of cells, catalytic reactions in which enzymes or coenzyme-substrate complexes are involved, and the interaction between hormones or drugs and receptors.

To trace these clues, organic and inorganic chemistry must play a role. A novel branch of science whose purpose is to unify organic chemistry and life science is called **bioorganic chemistry**.

The characteristic feature of substances which control life, *e.g.*, enzymes, is functional groups as discussed in conventional organic chemistry. There are, however, many cases where their functions are more complicated. In several cases these substances have transition elements in their active centers, which has prompted amalgamation of inorganic chemistry and life science, and a new field of science, **bioinorganic chemistry** developed.

Both bioorganic chemistry and bioinorganic chemistry cover not only conventional molecules but also all kinds of assemblies formed by weak interactions among all kind of chemical species (molecules and ions, *etc*). It may be said that bioorganic chemistry and bioinorganic chemistry specifically deal with these assemblies.

(e) Supramolecular chemistry

Now that the role of assemblies is so important, it might be better to give them an appropriate name. Lehn proposed the name "**supramolecule**" and this proposal was widely accepted by the chemical world. Hence chemistry which studies supramolecules will be called **supramolecular chemistry**.

One might anticipate that supramolecules have less order as compared with conventional molecules since the force that binds the constituent particles in the supramolecules is weak interaction rather than strong chemical bonds. This is, however, a misunderstanding. The weak interaction in supramolecules is highly selective, and it is similar to that between enzymes and their substrates which can be comparable with the relation between keys and keyholes. Such intermolecular interaction may have a very high order.

In the 21st century it is expected that molecular chemistry and supramolecular chemistry will develop in parallel. Supramolecular chemistry will deepen not only our understanding of living organisms but also our research in the field of molecular chemistry. It must be admitted that all molecules necessarily interact with molecules around them. An isolated molecule can exist only in cosmic space.

14.2 Balance with nature

(a) The "large scale" effect of substances

Though it is difficult to foretell the direction and extent of the development of chemistry in the 21st century, it is certain that chemistry in the 21st century must keep a good balance with nature. Furthermore, it should aim to restore the environment that has been destroyed to some extent. Chemistry and chemical industry before the middle of the 20th century were allowed to develop without any restriction or responsibility. The damage caused by such a development was widespread.

It was not until the middle of the 20th century that we realized what we had lost due to the rapid and extensive development of chemical industry. As a matter of fact, the number of people who recognized that problem were few. Moreover, the response of the government and the scholarly world was not necessarily immediate. However, with time people have realized that there is a problem.

At the initial stage of the environmental movement, direct effects such as the environmental destruction near factories were pointed out. It took some time before the products of chemical industry themselves were criticized.

The first indication to the effect that environmental destruction by certain products of chemical industry was not merely pollution in industrial zones or urban areas, but a much wider destruction of nature, was raised by the American ecologist Rachel Carson (1907-1964). She published in 1962 "Silent Spring" (Fig. 14. 3) which became a best seller in many countries in the world. The book clearly described the effect of excessive use of agricultural chemicals, particularly, chlorine-containing chemicals.

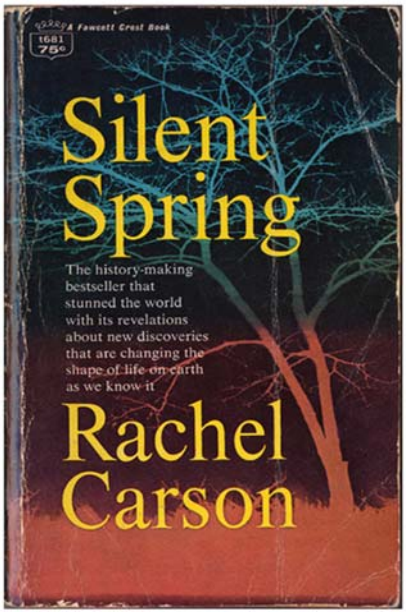


Fig. 14.3 "Silent Spring"
A warning book to the world

Later the aftereffect of defoliants used during the Vietnam War by American troops became a serious social issue. More serious now are such problems as the destruction of the ozone layer by chlorofluorocarbons (freons) and the greenhouse effect (global warming) caused by carbon dioxide. The problem of global warming is closely related to the energy problem. How much energy shall we use and may we use is a very severe problem challenging us.

There is one common point in the problems discussed above. The main cause of problems is the fact that a tremendous amount of substances have been diffused in the environment. The small amounts of agricultural chemicals, freons or defoliants prepared in the laboratories of chemists will not be any serious problem even if diffused. The damage could be localized. However, if these substances are produced on a huge scale and diffused all over the world, serious problems arise. We may call these the “large scale effect” caused by diffusion of chemicals.

In order to predict the “large scale effect” of substances, knowledge obtained by studying the molecular chemistry of a small amount of them is not enough. Before producing and diffusing a substantial amount of a substance, those who use it as well as chemists who make it should know and consider what would happen when such a large amount of that substance is released.

(b) Environmental chemistry

Efforts to protect the earth from further deterioration of its environment gave birth to a new field of chemistry, **environmental chemistry**.

What chemistry can do to ameliorate environmental damage depends on the situation. In the issue of destruction of the ozone layer, chemistry played the decisive role from the beginning. It was chemists who detected the existence of the problem and who proposed the method to solve it. As early as 1974, the American chemist Sherwood Roland (1927-) predicted the possible destruction of the ozone layer. It’s truth was proved in 1985, and the issue was transferred from chemistry to politics. After many discussions and negotiations, final agreement was attained on worldwide scale, and it was decided to prohibit use of freons.

Fig 14.4 F. Sherwood Rowland (1927-)
Nobel Prize in Chemistry (1995)

In 1995, the Nobel Prize in chemistry was given to three chemists including Rowland who made a great contribution to environmental chemistry. It is significant that chemists in this new field of chemistry were given the Nobel Prize. This in turn indicates the world recognized the important role of environmental chemistry.

The role of chemistry for the energy issue is also great. It would be of prime importance to reduce the consumption of fossil fuels in order to conserve the environment and natural resources. Chemistry can contribute to solving the energy issue by manufacturing efficient solar cells or by developing C1 chemistry which aims to convert one-carbon compounds such as carbon dioxide to fuels, *etc*.

In conclusion, the role of chemistry is to strict to achieve the “sustainable society”.
Sustainable society is a beautiful slogan. However, to achieve it is by no means simple. We

believe chemistry can greatly contribute to realize the sustainable society.