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9. Supramolecular Chemistry

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9.1 Introduction:

The study of molecular assemblages occurring in complex environments from a chemical, physical, and biological perspective is known as supramolecular chemistry.

It is a captivating and interdisciplinary field that delves into the interactions between molecules and the assembly of molecular structures beyond traditional covalent bonds, Known colloquially as "chemistry beyond the molecule,". Important Instances of such interactions include hydrogen bonding, metal coordination interactions, ionic bonding, aromatic stacking, halogen bonding and dipolar interactions.

The term supramolecular chemistry was introduced by Lehn in 1978, but the host-guest chemistry of metal ions and macrocyclic hosts in synthetic and biological systems somewhat precedes this definition.

The field has been recognized with two Nobel Prizes: the first in 1987 went to Charles Pedersen, Donald J. Cram, and Jean-Marie Lehn for their work on crown ethers, carcerands, and cryptands; the second one was awarded to Jean-Pierre Sauvage, Sir J. Fraser Stoddart, and Bernard L. Feringa in 2016 for their development of molecular machines.

"Supramolecules" and "molecular assemblies" are the two partially covered topics in supramolecular chemistry, the chemists have primarily drawn inspiration from natural molecules, including proteins, oligonucleotides, lipids, and their multimolecular complexes. Many supramolecular scientists aspire to design and synthesize unique multimolecular supramolecular architecture with comparable functionality and complexity.

The strategy of this chemistry involves a host which is made from molecular precursors by ordinary chemical synthesis, and it subsequently passes through a thermodynamically regulated binding equilibrium with its intended guest. The guest sits within the host's intrinsic binding cavity, a feature that is installed during the host's synthesis, and non-covalent interactions hold the host-guest complex, or "supermolecule," together. The host and guest have a measured mutual binding energy.

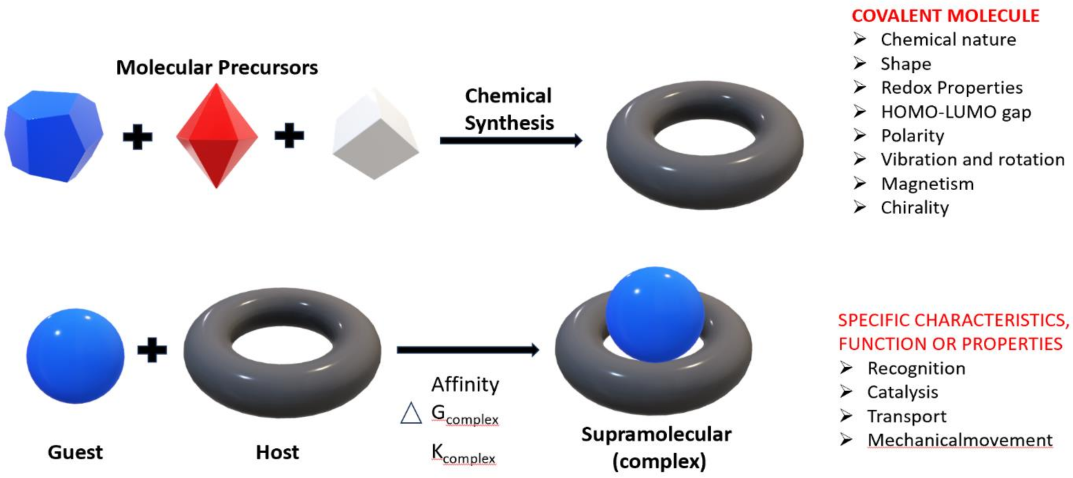


Figure 9.1: Contrast of supramolecular chemistry and the scope of molecules and illustration of how the multicomponent composition of the supermolecule may lead to the manifestation of various functional properties.

9.2 Key Concepts:

A. Molecular Recognition: One of the fundamental aspects of supramolecular chemistry is molecular recognition, where specific molecules interact selectively with one another. This phenomenon is crucial in biological systems, such as enzyme-substrate interactions and DNA base pairing.

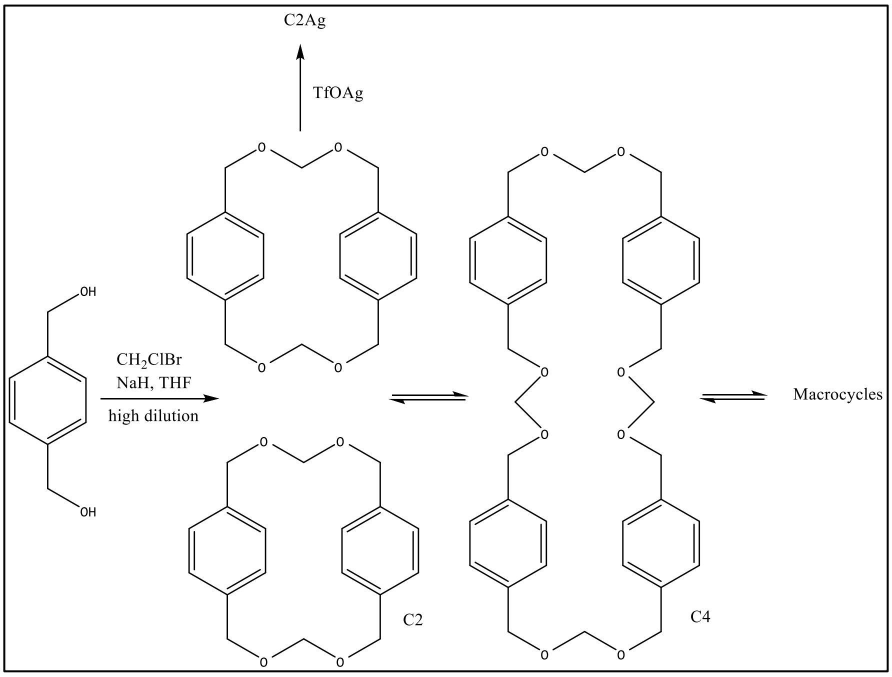
B. Host-Guest Chemistry: Supramolecular chemistry explores host-guest systems, where a host molecule encapsulates a guest molecule within its cavity through non-covalent interactions.

Cucurbiturils, cyclodextrins, and crown ethers are examples of host molecules frequently used in this context.

C. Self-Assembly: Self-assembly involves the spontaneous organization of molecules into well-defined structures without external guidance. This concept is employed in the design of molecular machines, sensors, and functional materials.

D. Supramolecular Catalysis: Catalysis at the supramolecular level has gained attention for its potential applications in organic synthesis. Catalysts based on non-covalent interactions can exhibit enhanced selectivity and efficiency.

E. Dynamic Covalent Chemistry: The field of dynamic covalent chemistry is centered on the synthesis of big complex compounds from simple ones.



Scheme 1

G. **Techniques for Molecular Imprinting:** By employing an appropriate molecular species as a template, a technique known as molecular imprinting can be used to create a host from tiny molecules. A template molecule and functional monomers that assemble around the template and then crosslink to one another are used to create materials that are molecularly imprinted.

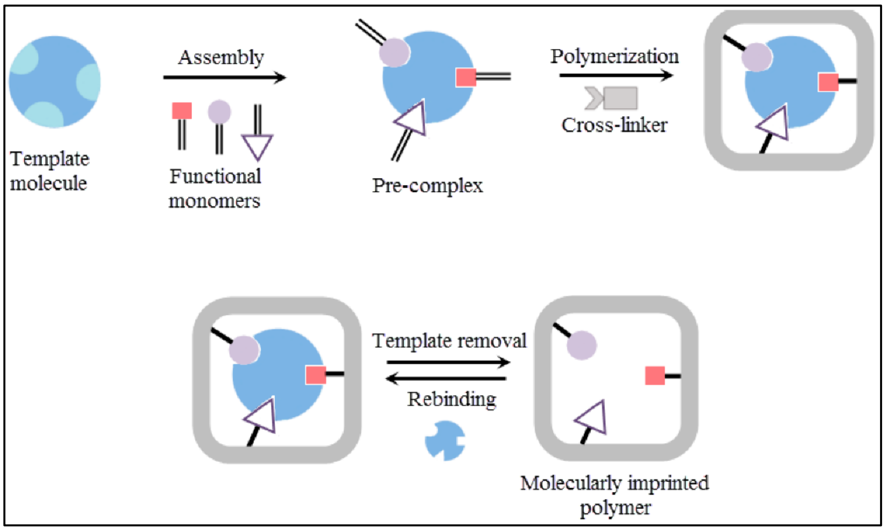


Figure 9.2: Techniques for Molecular Imprinting

9.3 Need for the Study:

The study of supramolecular chemistry is crucial for several reasons, as it not only deepens our understanding of molecular interactions but also opens up avenues for technological advancements and applications across diverse fields.

Here are some key reasons highlighting the need for the study of supramolecular chemistry:

A. **Complex Systems Understanding:** Supramolecular chemistry allows scientists to comprehend and manipulate complex systems at the molecular level. Understanding the non-covalent interactions that govern these systems is essential for deciphering biological processes, chemical reactions, and the behavior of materials.
B. **Molecular Recognition in Biology:** Biological processes often rely on specific molecular recognition events, such as enzyme-substrate interactions and DNA base pairing. Studying supramolecular chemistry provides insights into these crucial biological mechanisms, with potential applications in drug design, diagnostics, and therapeutic interventions.
C. **Design of Functional Materials:** Supramolecular chemistry plays a pivotal role in the design and construction of functional materials with tailored properties. This includes the development of advanced sensors, catalysts, liquid crystals, and other materials that find applications in fields like electronics, photonics, and energy storage.
D. **Drug Delivery and Therapeutics:** The ability to engineer supramolecular structures facilitates the design of drug delivery systems with enhanced specificity and controlled release. This is particularly significant in improving the efficacy and safety of pharmaceuticals.
E. **Nanotechnology Advancements:** Supramolecular chemistry is instrumental in the field of nanotechnology. The construction of nanostructures with specific functionalities, such as nanocarriers for drug delivery or nanoscale sensors, relies on the principles of supramolecular interactions.
F. **Catalysis and Green Chemistry:** Supramolecular catalysts offer unique advantages in catalysing chemical reactions with improved selectivity and efficiency. This can contribute to the development of greener and more sustainable chemical processes.
G. **Molecular Machines and Nanorobotics:** The study of supramolecular chemistry has paved the way for the development of molecular machines and nanorobotics. These nanoscale devices have potential applications in fields ranging from medicine to information technology.
H. **Biosensors and Diagnostics:** Supramolecular chemistry is fundamental to the design of biosensors, enabling the detection of specific biomolecules with high sensitivity and selectivity. This has significant implications for medical diagnostics and environmental monitoring.

I. **Understanding Self-Assembly:** The phenomenon of self-assembly, a key aspect of supramolecular chemistry, is critical for understanding how molecules spontaneously organize into well-defined structures. This knowledge is applied in creating nanomaterials and nanodevices.

J. **Innovation and Technological Advancement:** Ongoing research in supramolecular chemistry drives innovation, leading to the development of new materials, technologies, and methodologies. This field continually expands the possibilities for technological advancement in various scientific domains.

9.4 Applications:

9.4.1 Materials Science and Technology:

Supramolecular analytical chemistry is one of the latest fields of study that combines analytical and supramolecular chemistry. It is primarily concerned with the development and usage of sensors.

Ex: A fluorophore system attached with a crown ether was prepared which was capable of photo inducing electron transfer (PET).

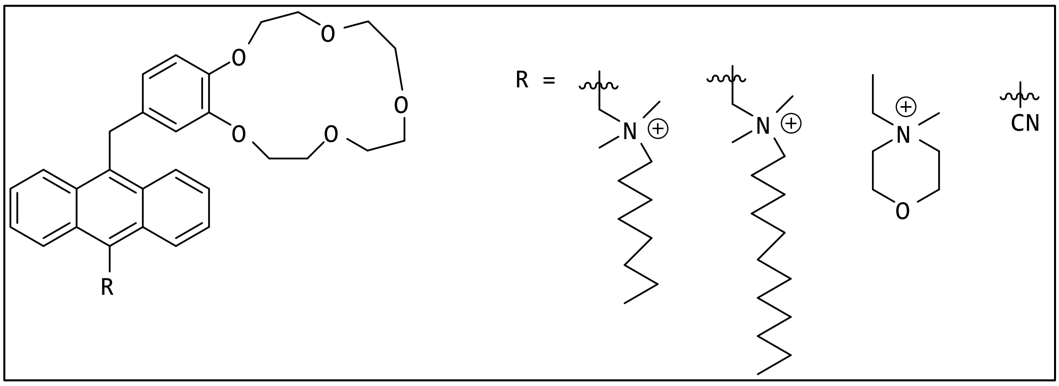


Figure 9.3: Structures of various fluorescent sodium sensors.

9.4.2 Supramolecular Chemistry in Catalyst Recycling:

Chemistry research has long been focused on catalyst recycling because it makes a process more sustainable and profitable.

One potential new technique for facilitating the recycling of homogeneous catalysts is supramolecular chemistry.

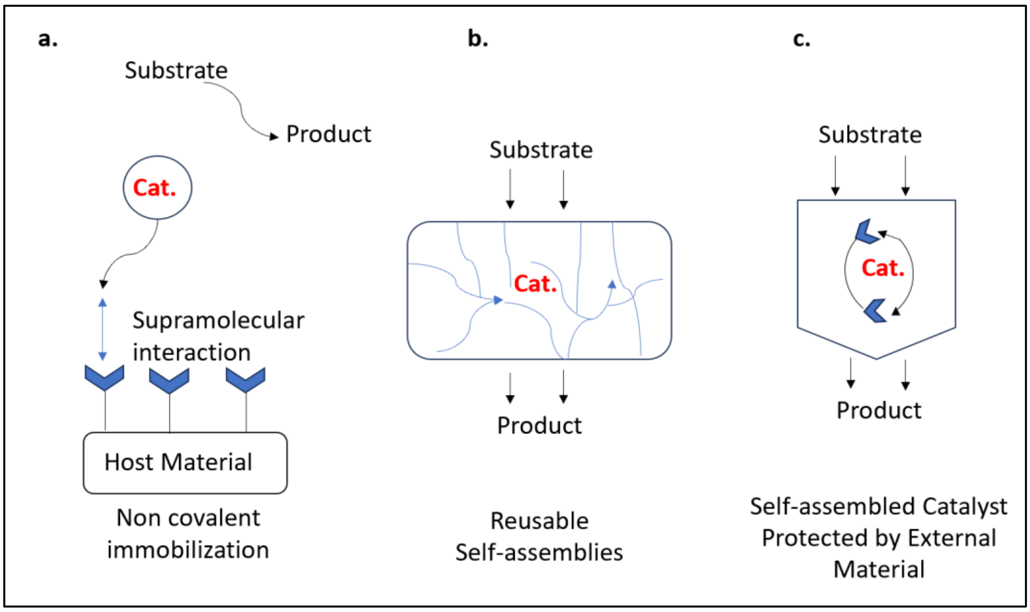


Figure 9.4: Supramolecular Chemistry in Catalyst Recycling

9.4.3 Pharmaceutical Dosage and Formulations:

Another application for this class of supramolecular hosts is made possible by their simple production and derivatization as well as the natural biocompatibility of some cyclodextrins: when delivering drugs. Ex: Curcumin shows restricted clinical efficacy in anticancer activity due to its low water solubility which results in poor bioavailability.

As β-cyclodextrin polymer (β-CDP) have inherent hydrophilic polymer chains and hydrophobic cavities, they are made to form inclusion complex with curcumin which shows remarkable anticancer effect with reduced side effects.

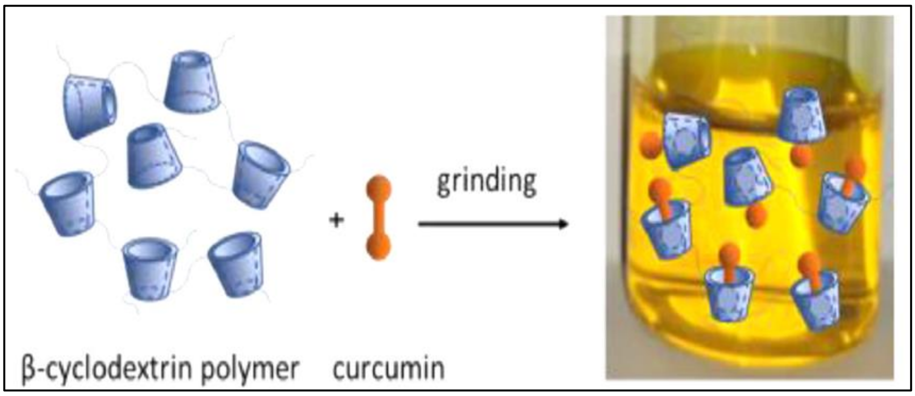


Figure 9.5: Pharmaceutical Dosage and Formulations

9.4.4 Self-Assembled System:

Ex: Upon exposure to the enzyme present in cancer cells, a prodrug needs to break into its parent drug. However, self-assembly offers an alternative approach. A cytotoxic drug needs to be able to be contained in a self-assembling structure, like a vesicle. In the event that a particular part of the vesicle walls is designed to function as a substrate for the relevant enzyme, the enzyme will specifically break the vesicle and release the drug in the area of the cancer cells. The beauty of this approach is that any cytotoxic drug (or mixture of drugs) can be used, and it does not have to first be converted into a prodrug.

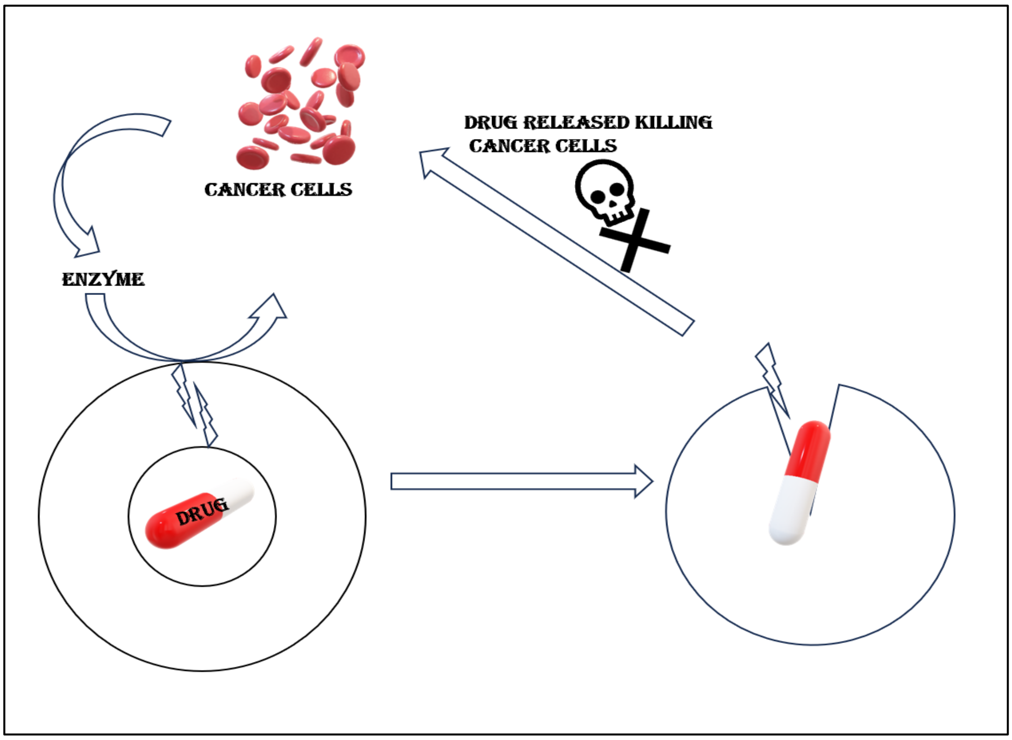


Figure 9.6: Self-Assembled System

9.5 Challenges and Future Prospects:

Key areas of chemistry that contributed to the development of this field have been synthetic chemistry, along with substantial progresses in the characterization of complex chemical systems, not only in solution, but also at interfaces. Electrochemistry is surely among the most powerful tools for characterizing a supramolecular system; moreover, it can also be used to cause changes on it. Despite the significant advancements in supramolecular chemistry, challenges persist, such as achieving precise control over self-assembly processes and enhancing the stability of supramolecular structures.

Future research may focus on harnessing supramolecular interactions for quantum computing, exploring novel functional materials, and advancing the understanding of dynamic systems.

9.6 Conclusion:

Supramolecular chemistry has evolved into a dynamic and versatile field with far-reaching implications across various scientific domains. From the intricate world of molecular recognition to the development of cutting-edge materials and therapeutics, the principles of supramolecular chemistry continue to inspire researchers to unlock new frontiers in science and technology. As advancements in this field continue, the potential for creating novel solutions to complex challenges in medicine, materials science, and beyond is boundless.