7

Historical Perspective on the Discovery of Covalent Organic Frameworks

7.1 Introduction

Reticular chemistry is the study of linking discrete chemical entities through strong bonds into extended frameworks and large discrete molecular structures. In Chapters 1–6, we covered the principles of reticular chemistry for metal-organic frameworks (MOFs) where polynuclear metal clusters are joined by organic linkers. The formation of crystalline extended solids can also be realized by linking only organic building units through covalent bonds between light elements (e.g. H, B, C, N, O, and Si) into covalent organic frameworks (COFs) [1]. The synthetic challenges encountered in the synthesis of COFs are different from those pertaining to MOFs. The great challenge in synthesizing MOFs is controlling the metrics of the building units to open up their structures in a rational way to make crystalline and porous extended solids. This was achieved for the first time by joining polynuclear metal clusters with organic linkers affording architecturally stable and permanently porous materials. As such the challenge in synthesizing MOFs was to make them as crystalline materials and establish their porosity [2]. In organic chemistry, no crystalline extended 2D and 3D structures were known and as such the challenge in realizing COFs was first and foremost to obtain them in crystalline form. To understand the significance of the synthetic realization of COFs and the potential of this class of materials, we provide a historical perspective on how this field has emerged and what were the discoveries of synthetic organic chemistry that influenced its development.

In 1916, Gilbert N. Lewis published his seminal paper introducing the concept of the covalent bond to describe the nature of bonding within molecules [3]. In this work, titled "the atom and the molecule," he addressed the fundamental question of how atoms can be linked to form molecules and how these molecules can be described in the context of structure and reactivity. Since then, drawing from this concept, organic chemists have mastered the craft of synthesizing increasingly elaborate molecules leading to the art and science of total synthesis. Despite the fact that the toolset of organic chemists has been steadily extended over the last century, this methodology was never applied to the synthesis of organic 2D and 3D extended structures, a point highlighted by Roald Hoffmann in 1993: "*Organic chemists are masterful at exercising control in zero dimensions. One subculture of organic chemists has learned to exercise*

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control in one dimension. These are polymer chemists, the chain builders … but in two or three dimensions, it's a synthetic wasteland" [4]. This begs the question as to why this chemistry remained undeveloped for such a long time. One of the reasons for the lack of crystalline organic extended structures is that they would be linked by inert covalent bonds. Thus, reticulating organic building units into crystalline extended structures requires that the process is performed under thermodynamic control to allow for microscopic reversibility. This challenge was addressed with the development of COFs, a class of extended 2D and 3D crystalline extended organic solids [5]. In the context of Lewis' original work, COFs have become the natural extension of the molecule into 2D and 3D [6]. Akin to how molecules pin down atoms in specific arrangements, COFs are geometric arrangements of molecules linked into periodic structures through covalent bonds. The development of COF chemistry has been strongly correlated to the progress made in synthetic organic chemistry. In the following sections, we will highlight important milestones in synthetic organic chemistry, starting with Lewis' conceptual introduction of the covalent bond, and illustrate the impact these developments have had on the field of COFs.

7.2 Lewis' Concepts and the Covalent Bond

Today, the covalent bond represents an integral part of our understanding of chemical bonding. It is defined by IUPAC as "a region of relatively high electron density between nuclei which arises at least partly from sharing of electrons and gives rise to an attractive force and characteristic inter-nuclear distance" [7]. The term "covalent" expresses the notion that electrons are shared between atoms. The origin of this concept can be traced back to 1902 when Gilbert N. Lewis, in an attempt to explain the concept of valence to his students, conveyed his first ideas on chemical bonding on paper. He visualized the outer shell of atoms as a cube with electrons at each vertex. This "cubic atom" explained the concept that chemical bonds are formed by mutual sharing of electrons to give each atom a complete set of eight valence electrons (an "octet"). This was in stark contrast to the widely accepted theory of bonding between atoms at the time. Helmholtz's electron theory of valence assumed that an electron either does or does not completely pass from one atom to another [8]. While this theory had proved useful for the description of polar molecules and ionic compounds, it did not accurately represent the empirical observations for nonpolar molecules.

The cubic atom model based on covalent bonds between atoms explained the behavior observed in the bonding of molecular compounds that could not be accurately described by previous theories. One such example is the behavior of the diatomic halogen molecules as exemplified for the case of iodine in Figure 7.1. I_2 does not form charged ion pairs in solution indicating that the description of a full electron transfer from one iodine atom to the other to form a hypothetical I^+ I^- ion pair is inaccurate. According to Lewis' theory, iodine could now be described by the edge sharing of two cubic iodine atoms resulting in a shared electron pair between them and thus the formation of one

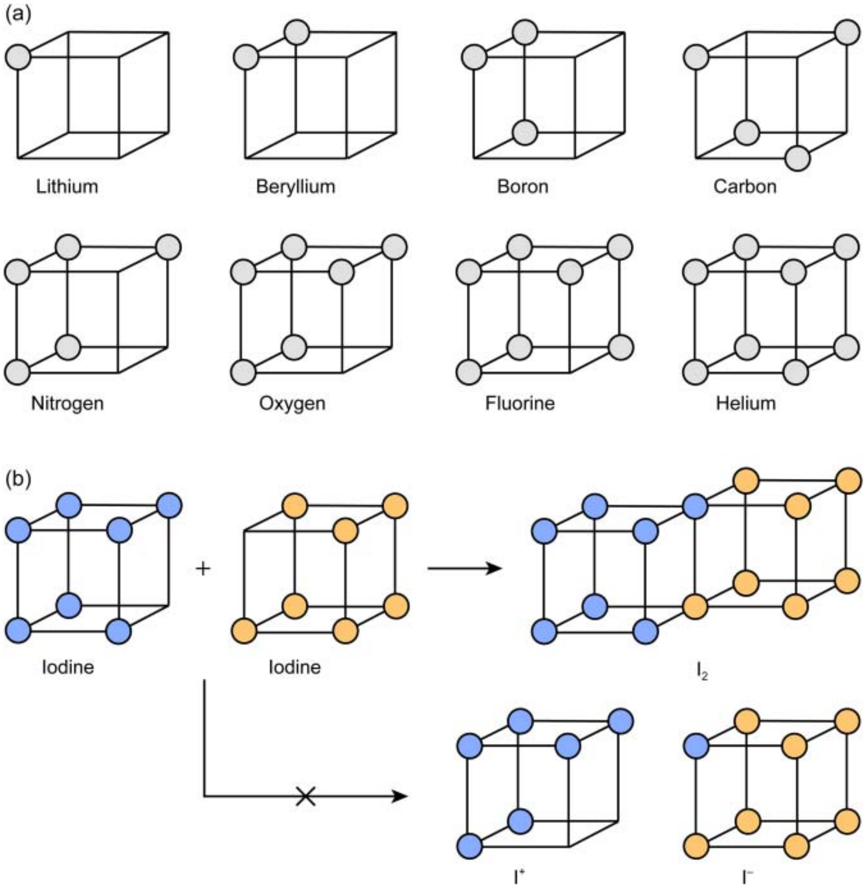

Figure 7.1 Illustration of the concept of Lewis' cubic atom. (a) Valence electrons of lithium, beryllium, boron, carbon, nitrogen, oxygen, fluorine, and helium; highlighting the increase in the number of valence electrons from a single electron in lithium to a closed "shell" of electrons for helium. (b) Atoms can achieve full valence by sharing of electrons as exemplified for the case of iodine. Lewis' theory assumes the sharing of electrons between two iodine atoms to form dimers, which are covalent in character. Here, both iodine atoms achieve full valence. In contrast, Helmholtz' theory is based on the transfer of electrons from one atom to another, where a positively and a negatively charged iodine ion would be formed, only one of which achieves the desired full valence. Color code: (a) valence electrons, gray; (b) valence electrons, light blue and orange.

charge-neutral as opposed to two charged species. This was in good agreement with experimental observations.

Lewis' theory of chemical bonding continued to evolve and, in 1916, he published his seminal article "the atom and the molecule," defining the covalent bond as a pair of electrons shared by two atoms [3]. In this article he explained chemical bonding based on his previously developed model of the cubical atom but moved on to lay out the concept of "Lewis dot structures." This model explained in a comprehensive manner some important empirical observations such as the clear

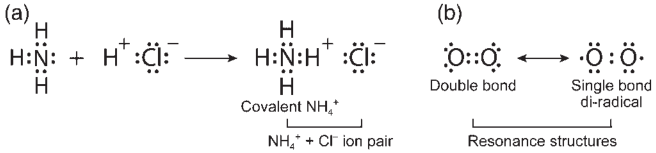

Figure 7.2 Structures of molecules as depicted in Lewis dot structure models. (a) Reaction of NH_3 with H^+Cl^- and the formation of $NH_4^+Cl^-$. A covalent bond is formed between NH_3 and H^+, whereas the resulting NH_4^+ forms an ion pair with the Cl^-. (b) Resonance structures of O_2. The di-radical form is in good agreement with the observed reactivity of oxygen at low temperatures.

distinction between the sharing of an electron pair between ammonia and a proton to form the ammonium cation as opposed to its bonding to chloride ions as a loose ion pair (Figure 7.2a). The case of ammonium ions had long troubled the chemical community as different enantiomers of alkyl-substituted analogs had been isolated indicating a four connected nitrogen atom in spite of the proposed trivalence of nitrogen. Evidently, this observation could not have been rationalized without the concept of the covalent bond and the implied sharing of electrons between atoms. Another problem that previous theories of valence had failed to explain was the structure of oxygen. It was well known at the time that at low temperatures reactions with oxygen often resulted in the formation of peroxo species; however, this contradicted prevailing bonding theories that generally assumed that oxygen as a divalent element forms a double bond in the oxygen molecule. In the Lewis dot structure it becomes apparent that there are two possible isomers for oxygen, one di-radical and one with a double bond, but only the di-radical explained the reactivity of oxygen sufficiently (Figure 7.2b). The implications of the concept of the covalent bond provided the necessary theoretical foundation for the evolving field of organic chemistry, which has since progressed from being purely empirical to a rational and systematic field of science.

7.3 Development of Synthetic Organic Chemistry

In the following decades the discovery of covalent macromolecular structures (1D polymers) by Hermann Staudinger instigated the field of organic performance materials [9]. While the term polymer was coined as early as 1833, the concept of polymers as covalently bonded macromolecular structures proposed by Staudinger in 1920 was a direct consequence of Lewis' work on the theory of the covalent bond. Previously it was assumed that the interactions between the constituents of polymers could be described by mere agglomeration rather than actual chemical bonding. Staudinger realized that macromolecular compounds include many important natural products/compounds such as proteins, enzymes, and nucleic acids as well as a large number of fully synthetic plastics and artificial fibers [9]. The importance of his discovery was recognized by awarding him the Nobel Prize in chemistry in 1953.

Another major milestone was the total synthesis of complex organic natural products. In the years following the conceptual elaboration of the covalent bond, synthesis routes for natural products of increasing complexity were established (Figure 7.3). The first reported synthesis of a naturally occurring molecule, urea, from ammonium cyanate was reported by Friedrich Wöhler in 1828 [10]. At the time it was still believed that organic matter is alive because of a special vital force, a theory commonly referred to as vitalism, and that organic molecules can thus not be synthesized artificially. Wöhler refuted this belief but, nonetheless, this first discovery was a product of serendipity and not the outcome of a devised synthetic strategy. With the elaboration of the covalent bond and the subsequent development of synthetic methodologies organic molecules could now be targeted in a rational manner. In the following decades increasingly complex natural products were synthesized. Initially, small molecules such as tropinone and camphor were reported [11]. The lessons learned from their syntheses were subsequently employed to target more elaborate molecules as exemplified by the landmark report of Robert. B. Woodward's synthesis of strychnine [12]. The most famous examples of how far the synthetic control over organic matter has progressed during the course of the twentieth century are the total synthesis of Vitamin B_{12}, achieved in a joint effort of the groups of Albert Eschenmoser and R. B. Woodward in 1972 [13], and that of Paclitaxel (taxol) by Kyriacos C. Nicolaou and coworkers in 1994 [14]. The latter molecule highlights the impact this development has had. Taxol is used in the chemotherapy of various types of cancer and as such illustrates the importance of the development of synthetic organic chemistry on the pharmaceutical industry.

The synthesis of organic molecules with increasingly complex structures as depicted in Figure 7.3 is a powerful illustration of how synthetic organic chemistry had matured throughout the twentieth century from a science based on empirical observations toward the multistep retrosynthesis of highly complex natural products [16]. The ability to control matter on the atomic level is what sets organic synthesis apart from other fields of chemistry. It allows for *de novo* synthesis of macromolecules and their precise functionalization with high regio- and stereoselectivity.

7.4 Supramolecular Chemistry

With the aforementioned improvements in synthetic methodologies being established, in the 1960s the focus of research shifted from the making of elaborate molecules toward their assembly into more sophisticated architectures. While synthetic chemists were able to target specific molecules, the question of how to deliberately align those molecules with respect to each other in solid materials remained unanswered. The development of macromolecular chemistry has shown that linking of molecular building units resulted in 1D polymers with well-defined sequences. The question then turned to how to expand the synthetic control of organic chemistry from discrete molecules and 1D polymers into 2D and 3D. An early attempt on addressing this problem was the development of supramolecular chemistry, which is concerned with non-covalent interactions between molecules and the resulting phenomena such as molecular recognition, self-assembly, and template synthesis [17].

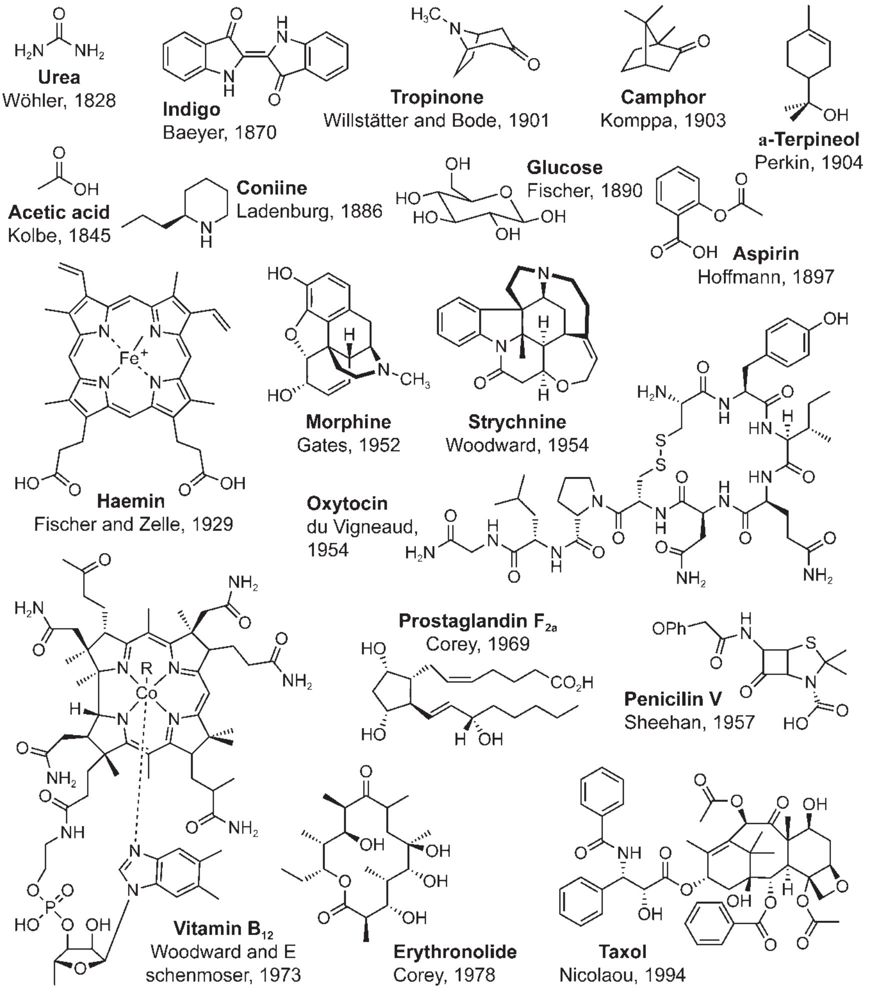

Figure 7.3 Progression of synthetic molecules starting from urea, the first reported synthesis of an organic molecule in 1828, toward increasingly elaborate molecules [10, 15]. The degree to which this field has matured can best be illustrated by the syntheses of the natural product Vitamin B_{12}, which was first synthesized in 1972. The progress in synthetic methodologies had a profound impact on the pharmaceutical industry as illustrated by the designed synthesis of the complex chemotherapy drug taxol in 1994 [13, 14].

Such non-covalent interactions were first observed in the selective molecular recognition of different metal ions by macrocyclic organic molecules. In 1967, Charles J. Pedersen attempted to prepare a complexing agent for divalent cations and accidentally discovered a simple method for the synthesis of crown ethers. In an attempt to link two catecholate moieties through one hydroxyl group on each molecule by a Williamson ether synthesis, he observed the formation

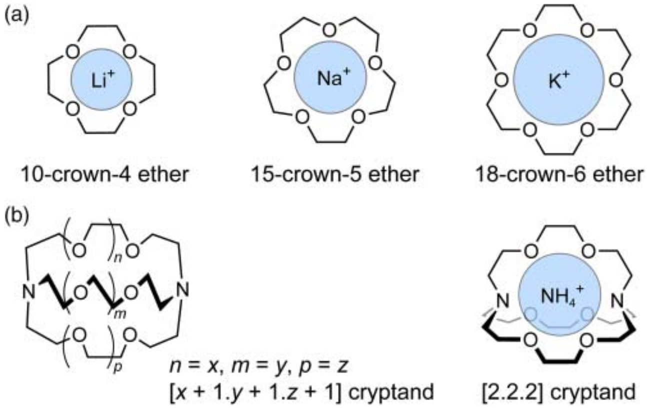

Figure 7.4 (a) Schematics of the 12-crown-4 complex of Li^+, the 15-crown-5 complex of Na^+, and the 18-crown-6 complex of K^+ illustrating the effect of the ring size on the selectivity for different alkali metal cations. (b) Illustration of the structure and nomenclature of a cryptand and the complex of a {2.2.2} cryptand with $NH_4{}^+$.

of a cyclic dibenzo-16-crown-4 polyether as a by-product, which complexed the potassium ion from the reaction mixture. Pedersen realized that this high affinity was due to non-covalent interactions between the oxygen atoms of the crown ether and the positively charged potassium ion. Accordingly, he studied the effect of the ring size on the selectivity for alkaline ions of different sizes [18]. Soon after, Jean-Marie Lehn showed that the selectivity of binding can be increased by an order of magnitude by transitioning from planar macrocyclic crown ethers to organic cages, the so-called cryptands (Figure 7.4) [19].

These examples highlight the importance of exercising control over the metrics and dimensionality of a given system for the rational optimization of host–guest interactions. The study of selective non-covalent interactions inspired researchers to go beyond molecular recognition and guide the organization of molecular building units into large supramolecular architectures through complementary non-covalent interactions in a process termed self-organization [20]. An illustrative example for compounds emanating from this development is the formation of the so-called circular helicate reported by Lehn and coworkers, which forms spontaneously from five linear tris-bipyridine TBPy struts (5,5′-bis(2-(5′-methyl-[2,2′-bipyridin]-5-yl)ethyl)-2,2′-bipyridine) guided by coordination of the bipyridine units to 5 equiv of $FeCl_2$ upon heating in ethylene glycol at 170 °C (Figure 7.5). The center of the resulting pentameric circular helicate has the ideal size to host one of the chloride counter anions. It was shown later that by replacing the $FeCl_2$ starting material with $Fe(SO_4)$, the slightly bigger sulfate ions direct the product away from the pentameric and toward a hexameric circular helicate where the center of the assembly is occupied by a sulfate, rather than a chloride ion (Figure 7.5) [21]. This shows that the assembly process through non-covalent interactions is microscopically reversible and can be carried out

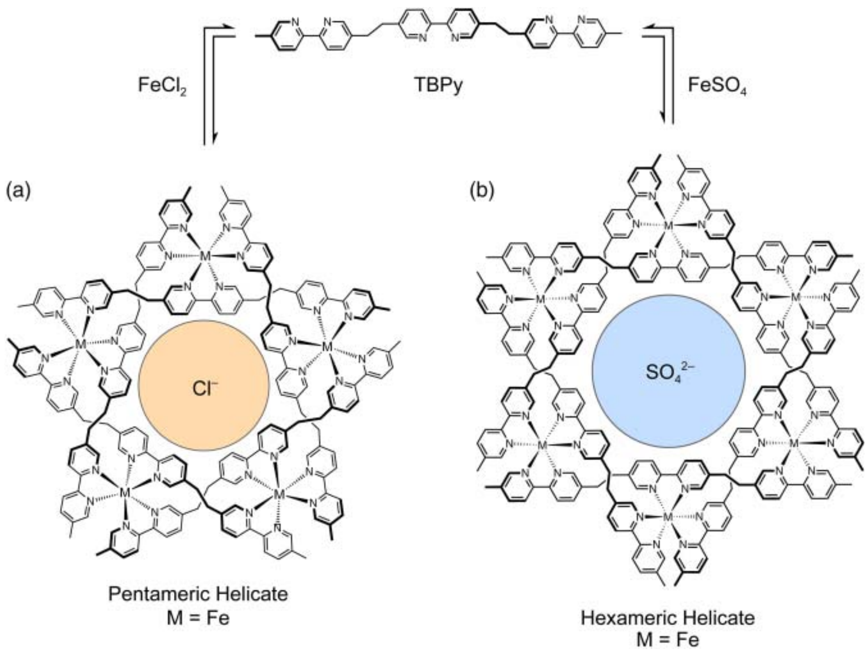

Figure 7.5 Synthesis of pentameric and hexameric circular helicates assisted by metal templation. Reacting linear TBPy with $FeCl_2$ yields the ninefold negatively charged pentameric circular helicate. The central pocket in the assembly is of the right size to accommodate a chloride ion, which templates the formation of the structure. In contrast, reaction of the linker with $Fe(SO_4)$ results in the formation of the 12-fold negatively charged hexameric circular helicate. Here, the sulfate ion resides in the central pocket. The only difference in the reaction conditions between the two systems is the counter anion, which controls the formation of one structure over the other. This fact highlights the dynamic nature of the assembly process.

under thermodynamic control. This is very powerful as it allows to generate the resulting products with 100% yield and without the need for purification.

The idea of supramolecular chemistry, the chemistry beyond the molecule, has initiated the field of crystal engineering where crystal structures of molecular assemblies are designed using complementary non-covalent interactions between the individual components. Here again researchers made use of the fact that dynamic error correction in such assemblies allows for their crystallization in one step. As such, self-organization, for the first time, enabled organic chemists to align molecular building units into solids with predetermined structures [22]. The early examples of how non-covalent interactions between organic molecules and metal ions can lead to the formation of coordination networks has been covered in Chapter 1 in the context of the historical development of MOFs and we refer the reader to this section for a more detailed description. Supramolecular assemblies are difficult to be modified without losing their structural integrity, which can be attributed to the following: functionalization of the building units alters the interactions between the constituents, which in turn often leads to different assemblies and, therefore, performing chemistry on or within assemblies held together by weak interactions is difficult and often results in structural rearrangement. Nonetheless, supramolecular chemistry in general and crystal engineering in particular have had a profound impact on the expansion of organic chemistry beyond the molecule and toward crystalline extended organic solids [22a].

7.5 Dynamic Covalent Chemistry

When comparing supramolecular assemblies to the way in which nature employs self-organization to create complex architectures such as those of proteins or DNA, it becomes apparent that biological macromolecules comprise a primary structure of atoms held together by strong covalent bonds. Only the secondary and tertiary structure that govern the spatial arrangement of the individual building units are due to non-covalent interactions. Inspired by the well-defined covalent backbone prevalent in nature, the formation of covalent macromolecular architectures in synthetic systems and thus strategies for the alignment of molecules not by weak interactions, but by covalent bonds became the focus of attention. At this point it is instructive to take a step back and think about why the formation of large synthetic architectures from molecular building units had thus far exclusively been realized in systems held together by non-covalent bonds but not in entirely covalent materials. Supramolecular assemblies are formed under mild reaction conditions and (largely) thermodynamic control due to the inherent microscopic reversibility of their underlying weak interactions. In contrast, the formation of covalent bonds is in general less reversible because of their inertness. Such kinetically controlled reactions do not exclusively yield the desired product but also side-products. This is not an issue in the realm of molecular chemistry where reaction products can be purified but it inevitably poses a problem for extended crystalline solids where purification is impossible and the formation of pure, crystalline products has to proceed in a single step. It is therefore desirable to carry out covalent organic reactions under conditions allowing for microscopic reversibility and thus for error correction. The reversibility of several organic transformations had been reported but the notion of strategically carrying out organic chemistry under thermodynamic control was not conceptualized until 1999 [23]. The development of what was termed “dynamic covalent chemistry” was in large carried by the field of mechanically interlocking molecules [24]. The simplest example of such species are catenanes (from Latin “catena” for “chain”) where two or more molecular rings are interlocking, thus being held together by mechanical rather than chemical bonding. The first synthetic realization of a molecular catenane was reported in 1983 by Jean-Pierre Sauvage and coworkers. In the synthesis, a CBP (Cu(I)bis-4,4′-(1,10-phenanthroline-2,9-diyl)diphenol) complex is used as a template, which assumes a tetrahedral geometry with the two embracing phenanthroline ligands serving as points of registry for the following ring-closing step. By reacting this template with 2 equiv of DIT (1,14-di-iodo-3,6,9,12-tetraoxy-tetradecane) in a Williamson ether synthesis and subsequent demetalation of the resulting structure it is converted into two discrete interlocking macrocycles (Figure 7.6a) [25]. The template helps to bring the constituents together thus improving the overall yield of the reaction;

however, the formation of the catenane is still only achieved with 72% yield. This is not a big drawback when only two of these rings are entangled but becomes detrimental when more rings are involved. It is therefore not surprising that the field readily absorbed the development of dynamic covalent chemistry as the microscopic reversibility of these reactions allows for significantly higher yields in the final ring-closing step. The library of accessible dynamic covalent reactions has been steadily expanded and in particular reversible Schiff-base chemistry was employed in the synthesis of catenanes, such as the molecular Borromean rings by Sir James F. Stoddart in 2004 (Figure 7.6b). Here, six DFP (2,6-pyridinedicarboxaldehyde) and six bipyridine based diamine moieties (DAB, (([2,2′-bipyridine]-5,5′-diylbis(oxy))bis(4,1-phenylene))dimethanamine) are reacted with 6 equiv of $ZnCl_2$ to form an 18 component molecular architecture of a Borromean ring topology (Figure 7.6b). In this structure, each of the six Zn^{2+} ions is coordinated by one of the six *exo*-bidentate bipyridyl groups formed *in situ* and one of the six *endo*-diiminopyridyl ligands. Upon demetalation, the three molecular macrocycles, while not interlocking with each other, are mechanically entangled in such a way that if only one of the rings is removed the other two can part company. The realization of this structure is possible only due to the microscopic reversibility of the non-covalent coordination of the ligands to the labile Zn^{2+} ions, and more importantly the formation of the

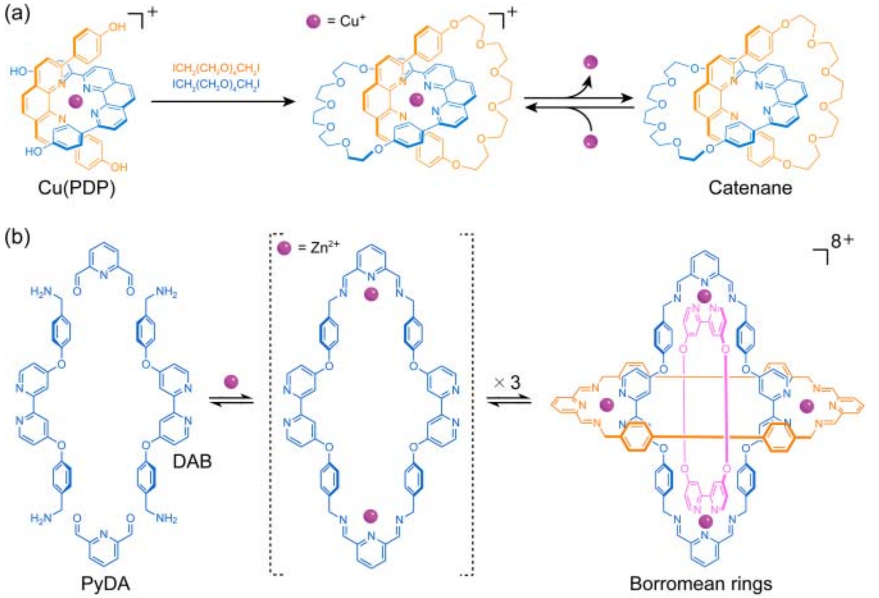

Figure 7.6 Synthetic approach toward (a) a molecular catenane and (b) molecular Borromean rings. (a) Reaction of the CBP complex, serving as a point of registry, with DIT, followed by demetalation of the structure with potassium cyanide results in the formation of a molecular catenane. (b) Reversible imine bond formation between DFP and DAB in the presence of trifluoro acetic acid as a catalyst ensures the formation of the macrocycles with 100% yield where the Zn^{2+} ions serve as templates to bring the individual rings together in the exact manner necessary for the Borromean ring topology.

covalent imine bonds between the organic building units under thermodynamic control in the presence of trifluoro acetic acid as a catalyst.

The strategy of forming molecular catenanes under thermodynamic control has since been applied to the synthesis of a large variety of interlocking molecules. For this purpose, many different dynamic covalent reactions such as imine bond formation, disulfide bond formation, and alkene metathesis have been employed [26, 27]. The development of the field of mechanically interlocking molecules has played a pivotal role in the progression of organic chemistry and both Stoddart and Sauvage were awarded the Nobel Prize in chemistry in 2016.

7.6 Covalent Organic Frameworks

The synthesis of crystalline extended 2D and 3D organic solids, where molecular building units are stitched together through covalent bonds remained an undeveloped area of research throughout the twentieth century as it was widely believed that the product of such reticulation would inevitably be amorphous. The core values at the heart of organic chemistry, the fact that compounds can be made in a controlled fashion, with atomic precision and in pure phase, can, in the case of extended 2D and 3D solids, only be guaranteed if they possess crystallinity [28]. Prior to the development of dynamic covalent chemistry, it was widely accepted that the microscopic reversibility required for the crystallization of organic molecules into covalently linked extended framework structures is difficult, if not impossible, to achieve and this challenge was commonly referred to as the "crystallization problem" [29].

In 2005, Omar M. Yaghi and coworkers reported the first crystalline extended organic frameworks [5a]. The synthesis of the two reported frameworks, termed COF-1 ($[\mathrm{BDBA}]_{boroxine}$, where BDBA = 1,4-phenylenediboronic acid) and COF-5 ($[(\mathrm{HHTP})_2(\mathrm{BDBA})_3]_{boronate\ ester}$, where HHTP = 2,3,6,7,10,11-hexahydroxyterphenylene), was achieved by making use of the reversibility of boroxine and boronate ester formation, respectively. The challenge in the crystallization of COFs formed by such condensation reactions is twofold: the reaction needs to be slowed down and water has to remain in the reaction mixture to allow for full reversibility of the bond formation and thus for error correction. COF-1 is formed from the self-condensation of BDBA at 120 °C. To slow down the reaction, it is carried out in a 1 : 1 v/v solvent mixture of dioxane/mesitylene in which the starting material is not fully soluble. To ensure the reversibility of framework formation, the reaction is carried out in a sealed Pyrex tube preventing the evaporation of water liberated in the condensation. X-ray powder diffraction of the material unambiguously confirmed that COF-1 crystallizes in a layered honeycomb (**hcb**) topology. The layers of COF-1 have openings of 15.1 Å and stack in a staggered conformation along the crystallographic *c*-axis with an interlayer distance of 3.3 Å (Figure 7.7a). This arrangement leads to the formation of zig–zag channels of 7 Å in diameter propagating along the crystallographic *c*-axis thus rendering COF-1 porous. COF-5 is made by the cross-condensation of BDBA with HHTP resulting in a boronate ester

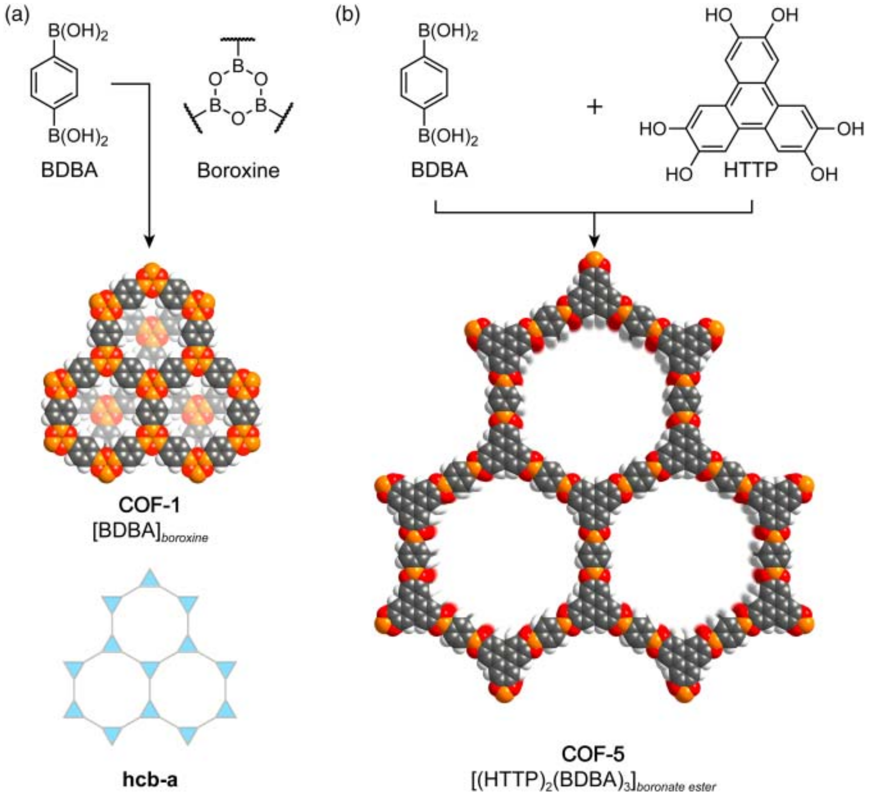

Figure 7.7 Synthetic scheme for the formation of the first examples of covalent organic frameworks, COF-1 and COF-5. (a) Self-condensation of BDBA results in boroxine linkages to yield COF-1 (**hcb** topology). (b) Reticulation of BDBA with HHTP leads to COF-5 through the formation of boronate ester linkages between the constituents. Color code: H, white; B, orange; C, gray; O, red.

linked framework. The condensation reaction requires analogous conditions to those described for COF-1. The resulting framework is also of **hcb** topology; however, here the 2D layers are stacked in an eclipsed fashion resulting in large mesoporous channels of 27 Å in width along the *c*-direction (Figure 7.7b).

The covalent nature of COF-1 and COF-5 endows these materials with excellent thermal stability up to 600 °C. Heating under dynamic vacuum results in the removal of residual solvent molecules from the pores and the activated materials of COF-1 and COF-5 sustain permanent porosity with BET surface areas of 711 and 1590 m^2 g^{-1}, respectively (Figure 7.8).

This first realization of crystalline extended structures composed solely of light atoms and prepared by rational synthesis highlights the added value of reticulating organic building units through covalent bonds as opposed to weak, non-covalent interactions. The strong, directional bonds endow COFs with high thermal and architectural stability and thereby allow for the removal of solvent molecules from their pores. In stark contrast to supramolecular assemblies,

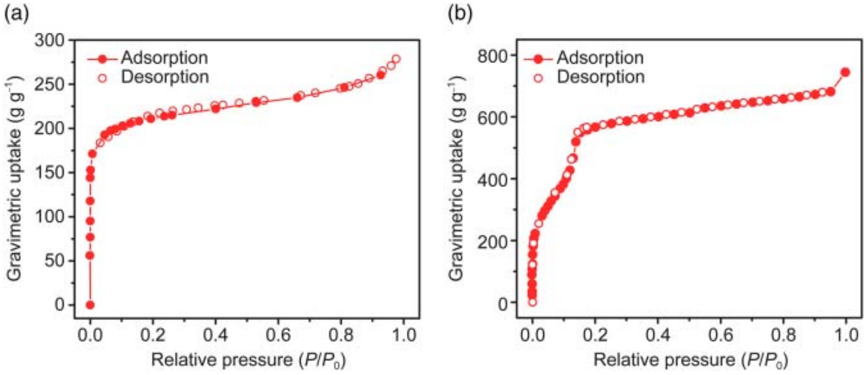

Figure 7.8 N_2 adsorption isotherms of COF-1 and COF-5 at 77 K. (a) COF-1 is microporous and features a Type I isotherm with an uptake of 278 cm^3 g^{-1} and a surface area of 711 m^2 g^{-1}. (b) COF-5 is mesoporous, which is manifested in a Type IV isotherm with an uptake of 744 cm^3 g^{-1} and a surface area of 1590 m^2 g^{-1}. The fact that the desorption branches perfectly trace the adsorption branches in the isotherms corroborates the architectural stability of COF-1 and COF-5 and gives further evidence for their permanent porosity. The adsorption and desorption branches are illustrated as filled and empty circles, respectively.

COFs exhibit permanent porosity which opens up the field of organic chemistry to applications in areas such as gas storage, gas separation, and catalysis to name a few [30].

After the synthesis of extended 2D COFs, the next obvious progression was to expand this chemistry into 3D [5b]. Toward this end the cross-condensation of HHTP with tetrahedral tetratopic TBPM (tetra(4-dihydroxyborylphenyl)methane) gave the crystalline 3D framework COF-108 ($[(\mathrm{TBPM})_3(\mathrm{HHTP})_4]_{boronate\ ester}$), cross-condensation of HHTP with TBPS (tetra(4-dihydroxyborylphenyl)silane) yielded COF-105 ($[(\mathrm{TBPS})_3(\mathrm{HHTP})_4]_{boronate\ ester}$), and self-condensation of TBPM or TBPS was found to afford COF-102 ($[\mathrm{TBPM}]_{boroxine}$) and COF-103 ($[\mathrm{TBPS}]_{boroxine}$), respectively. The synthesis conditions for these COFs follow the basic considerations laid out for their 2D counterparts, the main difference being that the reactions are carried out at a lower temperature of 85 °C as opposed to 120 °C. The reticulation of tetrahedral and trigonal building units leads to 3,4-c nets, and there are two possible topologies for this scenario. COF-102, COF-103, and COF-105 crystallize in a **ctn** topology, whereas COF-108 crystallizes in a **bor** net. Here, we will focus on COF-105 and COF-108. COF-105 has large pores that measure 18.3 Å in diameter. COF-108 has two differently sized pores of 15.2 and 29.2 Å, the latter marking the first mesopore in a 3D COF (Figure 7.9). The large 3D pores in combination with the fact that these materials are entirely constructed from light elements (C, Si, B, O, H) endows these two frameworks with exceptionally low densities of 0.18 and 0.17 g cm^{-3} for COF-105 and COF-108, respectively. These values are markedly lower than those of highly porous MOFs such as MOF-5 (0.59 g cm^{-3}) or MOF-177 (0.42 g cm^{-3}) and COF-105 and COF-108 constituted the lowest density crystals known at the time.

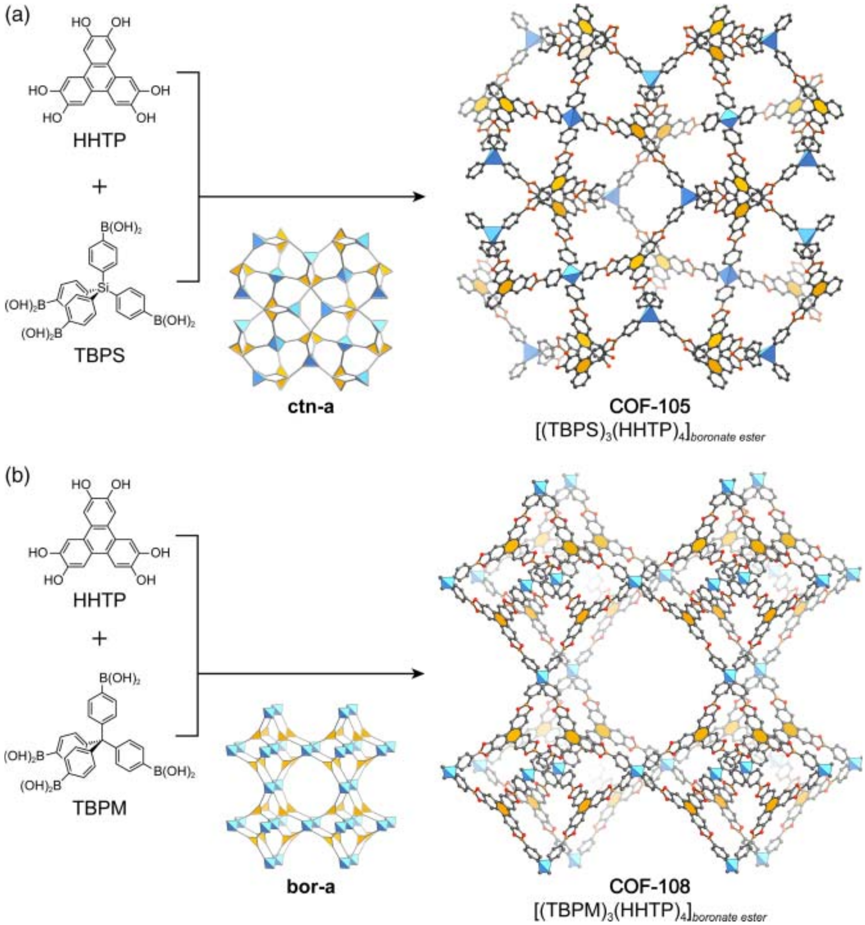

Figure 7.9 Synthetic schemes for COF-108 and COF-105. (a) Reticulation of TBPM with HHTP through boronate ester bonds affords COF-108 (**bor**). (b) Reticulation of TBPS with HHTP affords COF-105 (**ctn**). All hydrogen atoms are omitted for clarity. Tetrahedral carbon and silicon, blue; core of the tritopic linker, orange polygons. Color Code: B, orange; C, gray; O, red.

7.7 Summary

In this chapter we covered the historical development of COFs starting from the conceptual elaboration of the covalent bond by G. N. Lewis. The concept of covalent bonding in organic molecules laid the conceptual foundation that transformed organic chemistry from an observation driven to a systematic and rational field of research. The twentieth century has seen a rapid expansion of the synthetic toolbox of organic chemists as evidenced by the retrosynthesis of complex natural products such as Taxol and Vitamin B_{12}. The large majority of organic transformations employed in such syntheses are kinetically controlled and microscopically irreversible, which hinders their application in the formation of crystalline extended 2D and 3D frameworks. With the advent of supramolecular chemistry, concerned with molecular recognition and self-assembly through microscopically reversible weak intermolecular interactions, an interest in the formation of large macromolecular organic assemblies emerged. The development of dynamic covalent chemistry served as precedent that assembly processes using strong covalent bonds are feasible. The synthetic realization of COF-1 and COF-5, linked by boroxine and boronate ester linkages, respectively, was the first example of reticulation of organic building units into crystalline porous 2D COFs. Subsequently, the generality of this approach toward the synthesis of organic extended structures was demonstrated by the designed synthesis of 3D COFs: COF-102, COF-103, COF-105, and COF-108. In Chapter 8 we will discuss the different linkage chemistries that have since been developed according to the fundamental principles derived in this chapter.

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