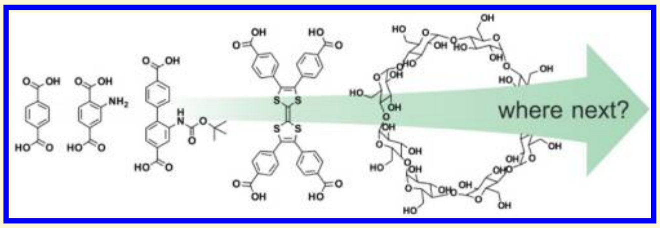
cm CHEMISTRY OF MATERIALS

Metal–Organic Frameworks: Rise of the Ligands[†]

Teng-Hao Chen, Ilya Popov, Watchareeya Kaveevivitchai, and Ognjen Š. Miljanić*

Department of Chemistry, University of Houston, 112 Fleming Building, Houston, Texas 77204-5003, United States

ABSTRACT: Metal–organic frameworks (MOFs) are modular porous materials synthesized from metal cluster nodes and organic linkers that connect these nodes. This rapidly expanding class of structures presents viable platforms for applications in gas sorption and separation, catalysis, sensing, fuel processing, and environmental remediation and as porous conductive materials. These applications are increasingly relying on sophisticated ligands that have functional characteristics either as independent entities (that is, outside of MOFs) or that gain new functions once reticulated into the porous material. Thus, the traditionally inorganic area of MOF research begins to profit more and more from a comprehensive approach which combines insights from organic, inorganic, and materials chemistry. This Perspective highlights some of the second-generation MOFs prepared and studied using this holistic approach.



Chemistry of porous materials has been revolutionized during the past two decades by the development of hybrid organic/inorganic porous materials known as metal–organic frameworks (MOFs).[1] These modularly synthesized and crystallographically ordered structures are composed of metal cluster nodes and rigid organic linkers which connect those nodes. Because of their high and permanent porosities, easily modified surface characteristics, and thermal stability, MOFs are promising materials for uses in gas storage and separation, fuel reprocessing, environmental remediation, sensing, and catalysis. This promise is evidenced by the explosion of recent interest in MOFs: in 2000, 685 papers on the topic were published, and this number almost doubled to 1299 by 2013.[2]

Recent years have brought a revolution within this revolution, with the realization that organic ligands need not be only inert structural elements but could yield tremendous benefits if their functional and reactive nature were to be exploited. This represented quite a significant cultural departure: MOFs were traditionally developed within the domain of solid state inorganic chemistry, meaning that little initial attention was devoted to the ligands, the "O" of the MOFs. The archetypal MOF-5, for example, used simple and chemically completely inert terephthalic acid as its supporting ligand.[3] The past decade has witnessed the synthesis of more and more MOFs with elaborately functionalized organic ligand groups.[4] This Perspective highlights some of these examples; we make no claim to comprehensiveness, and apologize in advance to the authors whose work we omitted.

Properties of small functional molecules are easy to study in solution, but organic chemists typically struggle to translate these characteristics onto the more practically relevant solid-state devices. Solid state brings with it the challenges of unpredictable structures of molecular crystals, aggregation, and self-quenching in the case of optically active materials. MOFs offer distinct advantages in that respect. First, as they are covalently connected structures, positions of individual ligands within the extended structures are predictable to a very high degree. Second, MOFs are not close-packed structures: thus, small molecules can be site-isolated, increasing the probability that they will behave as designed in solution—with the relatively manageable caveat that appropriate ligating groups have to be appended onto the functional organic molecule. In fact, this site isolation can contribute to single molecule reactivity (analogous to that observed using matrix isolation methodology), which can occasionally be difficult to observe even in dilute solution because of interference of solvents or other species. This was illustrated in Long's study of Cr-coordinated benzenes in a MOF-5 derivative, wherein the complexes of Cr with H_2 and N_2 were greatly stabilized relative to solution conditions.[5]

Contributions of organic ligands to the functionality of a MOF can come from their chemical reactivity, their capability to engage in specific (or nonspecific) noncovalent interactions, or simply their physical properties.

Chemical reactivity of organic ligands within MOFs has been extensively explored under the heading of postsynthetic modification (PSM).[6] In this class of protocols, a MOF ligand bears two sets of functional groups: one whose purpose is to bind to a metal and create a MOF, and another which will engage in secondary reactivity once MOF is already formed. For example, Cohen et al. used the exposed amino groups of a carboxylate-based MOF to create highly hydrophobic MOFs through acylation with long-chain acyl chlorides.[7] In a formal reverse of this reaction, Telfer used thermolysis of −NHBoc (Boc = *tert*-butyloxycarbonyl) groups within a low-porosity MOF **1** (Scheme 1) to remove the Boc functionality, thus liberating empty space within the framework **2**.[8] This "spatial

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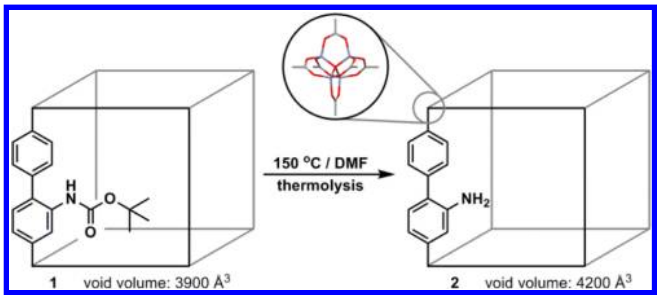
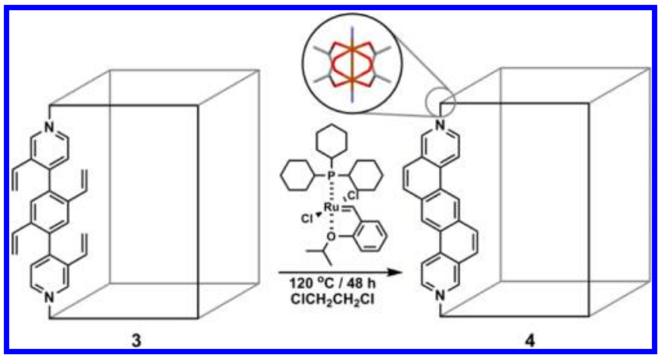
Scheme 1. Postsynthetic Thermolysis Can Be Used To Increase the Free Space within the Pores of a Zn_4O-Based MOF



protecting group" approach can in principle be used to synthesize noninterpenetrated versions of frameworks for which the direct synthesis yields only interpenetrated nets. In both strategies, digestion of the synthesized MOF allowed nuclear magnetic resonance (NMR) spectroscopic analysis of the created material that in turn confirmed the chemical change that occurred on the ligand.

Postsynthetic modification allows the introduction of new function onto ligands, as well as liberation of strongly ligating groups (such as catechols) which would have interfered with MOF synthesis.[9] The MOF environment also opens new avenues of reactivity for the ligand itself. For example, subjecting the bipyridine ligand found within MOF **3**[10] (Scheme 2) to alkene metathesis catalysts in solution resulted in a sluggish and incomplete ring-closing reaction; once this ligand was immobilized and site-isolated within Zn-based MOF **3**, the same transformation proceeded in high yield, giving framework **4**, which contained a polycyclic aromatic hydrocarbon (PAH) moiety.[11]

Scheme 2. Aromatizing Ring Metathesis of a Tetravinyl Substituted Ligand Occurs Readily within MOF 3—and Very Sluggishly Outside of It



Covalent reactions are not the only class of postsynthetic modification available to MOFs. Stoddart et al. and Zaworotko et al. created MOFs containing active domains based on crown ether[12] and calixarene[13] moieties, which can bind electron-poor aromatics and potassium ions, respectively. Using noncovalent recognition, both Stoddart et al.[14] and Loeb et al.[15] incorporated mechanically interlocked molecules (catenanes and rotaxanes) within MOFs. Tailored noncovalent interactions can also contribute to the enhancement of selectivity in gas sorption—which remains among the most actively pursued applications of MOFs. For example, using electrochemically active tetracyanoquinodimethane (TCNQ) ligand as a linker in a Zn-based MOF, Kitagawa et al. have shown enhanced adsorption of O_2 and NO relative to other small gas molecules (C_2H_2, Ar, CO_2, N_2, CO).[16] This rare selectivity was a combined consequence of charge-transfer interactions between TCNQ and these two gaseous guests and the gated opening and closing of the pores of the framework. Zhou and coworkers used precisely designed organic ligands to achieve an optimal steric match between the size of pores and the size of a CO_2 molecule, producing a material with high selectivity for this guest.[17]

Unsurprisingly, one of the major impetuses for the development of organic and organometallic chemistry in MOFs is the potential use of these materials as catalysts. The benefits of MOFs as catalysts are obvious: as insoluble crystalline materials, they are similar to heterogeneous catalysts in their easy recovery and high potential throughput. At the same time, their atomically defined structures and isolation of catalytic sites are clearly reminiscent of homogeneous catalysts, which have been the subject of an immense and sustained research effort in the chemistry community. This broad area of MOF applications has been a subject of a recent perspective[18] and reviews,[19] and we refer the reader to those.

High-energy (i.e., explosive) MOFs have been prepared recently by coordinating nitrogen-rich 4,4′-azo-1,2,4-triazole (atrz, Figure 1) ligand to Cu and Ag.[20] Compared to the free compound, the prepared 3D MOFs exhibit lower sensitivities to shock and friction. At the same time, the Cu-based MOF's detonation energy is calculated to be higher (3.62 kcal g^{-1}) than that of octanitrocubane (1.8 kcal g^{-1})!

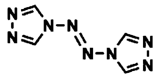

4,4′-azo-1,2,4-triazole (atrz)

Figure 1. Chemical structure of a nitrogen-rich atrz ligand.

Physical properties of ligands can also play a critical role in the applications of MOFs. For example, highly hydrophobic ligands can be used to repel water, while simultaneously maintaining the ability to bind nonpolar guests. This feature was explored by Nguyen and Cohen in MOFs substituted with hydrophobic groups,[7] as well as Omary's[21] and our group[22] in the synthesis and applications of extensively fluorinated MOFs in the binding of hydrocarbons. Other hydrophobic MOFs based on metal pyrazolates were shown to capture volatile organic compounds.[23]

It is well-known that optical properties of organic molecules change as one moves from dilute solution to the solid state. A typical result of such aggregation is fluorescence quenching, but aggregation-induced emission (AIE) has been recently gaining attention.[24] MOFs can also serve as platforms for coordinative immobilization of ligand, changing its emission properties. Dincă's group has recently demonstrated that tetraphenylethylene (TPE) core—which is nonfluorescent in solution—turns its emission ON once incorporated into Zn- and Cd-based MOFs.[25] This effect was observed despite the fact that rotation of ligands was not completely suppressed (Figure 2).

A very exciting and still quite underexplored area of development is the creation of semiconductive and conductive MOFs. As high surface area materials, conductive MOFs could advance the fields of fuel cell, supercapacitor, and battery research, electrochemical sensing, and electrocatalysis.[26] Dincă and co-workers have recently introduced two classes of MOFs

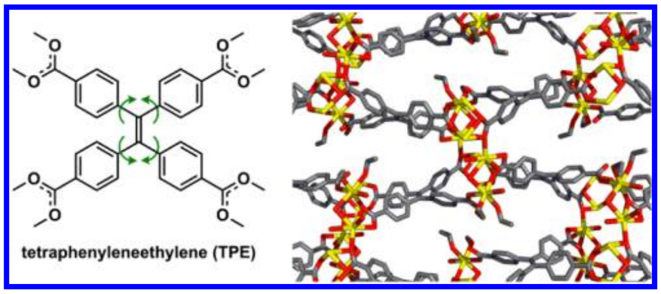


Figure 2. Coordination of TPE-based ligand shown on the left to Cd clusters within a MOF (right) immobilizes it, causing fluorescence enhancement.

with intriguing conductivity profiles. The first one[27] was inspired by the high conductivity of tetrathiafulvalene (TTF)/TCNQ complex; this Zn-based MOF utilizes tetrathiafulvalene–tetrabenzoic acid (H_4TTFTB, shown in Figure 3, left) as the ligand. In this framework, benzoate groups coordinate to Zn, constructing a helical array of [$\pi\cdots\pi$] stacked tetrathiafulvalene (TTF) units. Even without any particular treatment, some of the TTF units are partially oxidized, and this doping contributes to high charge mobility of 0.2 $cm^2\ V^{-1}\ s^{-1}$—higher than that of many polythiophene polymers. Very recently, the same group disclosed a Ni-MOF based on 2,3,6,7,10,11-hexaaminotriphenylene (HATP, shown in Figure 3, right) as the ligand.[28] This crystalline material is composed of infinite 2D hexagonal sheets that form the 3D network through a slipped parallel arrangement of the planes. This material was characterized by remarkably high conductivity for MOFs: 200 S m^{-1} when measured in pellet form, and 4000 S m^{-1} in the thin film.

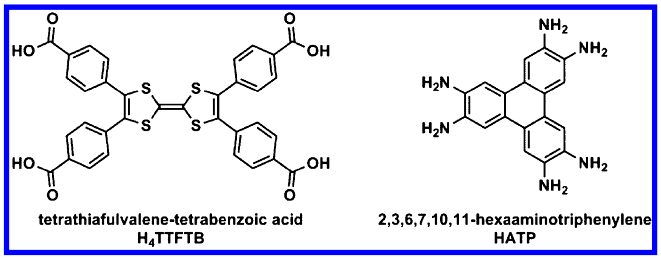


Figure 3. Examples of ligands used by Dincă et al. to construct MOFs with high charge mobilities.

In a very recent study,[29] Allendorf's group has shown that the infusion of electrochemically active TCNQ molecules into the well-known (but nonconductive) HKUST-1[30] framework led to ~10^6-fold increase in conductivity, to approximately 7 S m^{-1}. The conductivity of TCNQ-infiltrated frameworks could be tuned by varying the TCNQ loading. On a molecular level, TCNQ guests replaced the weakly coordinated solvent molecules found in the axial positions of the Cu(II)-paddlewheel clusters of which HKUST-1 is composed, establishing a charge conjugation pathway.

MOFs offer an unprecedented fusion of organic, inorganic, and materials chemistry in a single class of compounds/materials. Brought into the limelight by their numerous possible uses, these materials highlight the benefits of diverse training of graduate students and postdocs. In fact, three of the authors of this manuscript have started their careers as small-molecule chemists and have transitioned into the field of MOFs. This transition was facilitated by the use of characterization techniques such as X-ray crystallography, infrared spectroscopy, or elemental analysis, which are familiar and indispensable for both small molecule and MOF chemists. Importantly and reassuringly, MOFs still offer very direct correlation between the properties of their building blocks in the "small molecule world" and the characteristics of the bulk reticulated material.

What outstanding challenges are still left for these ligand-focused MOFs? It would be intriguing to see an organic reaction be involved in the synthesis of MOFs. At present, all MOFs are prepared by controlled coordination of the prepared ligand to the metal; in principle, it should be possible to polymerize a preformed metal-cluster through a purely organic reaction (e.g., dimerization of terminal alkynes or thiols), offering a complementary synthetic method. In a reverse direction, having fragile organic ligands that can collapse upon mild chemical stimuli would allow the preparation of easily degradable MOFs, beckoning applications in delivery of molecular cargos. Incorporation of functional molecular switches into MOFs could yield materials with well-defined and very different states that could be used to bind and subsequently release a guest or turn optical properties ON and OFF.[31] In the long term, incorporation of structurally more ambitious ligands—e.g., short polymers, DNA oligomers, or peptides—into MOFs could yield mesoporous structures with elaborately functionalized pores that could be used in unique inclusion applications, including binding of biological targets. While mesoporous MOF typically poses challenges in terms of structural sensitivity toward collapse and lowered crystallinity, the prospect of handling these structures has received a fillip by Stoddart and Yaghi's reticulation of ligand **5** (Figure 4), which contained 11 benzene rings in a linear sequence.[32] The resultant MOFs had pore apertures measuring 98 Å in diameter!

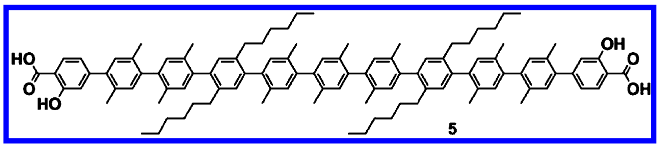


Figure 4. Compound **5** is the longest ligand ever to be incorporated into a MOF.

Finally, the range of emergent phenomena that could be explored within MOFs would be further enhanced if their structures were not always homogeneous and ordered across the entire crystal. Yaghi's work on the chemically heterogeneous multivariate MOFs (MTV-MOFs)—which are created by coordination of metals to a number of similar but nonidentical ligands within the same crystal—shows promising first results in being able to characterize MOFs with limited long-range order.[33] This move toward increased complexity would sacrifice some of the facility of characterization that is associated with crystallographically ordered structures but would undoubtedly open up entirely new avenues for fundamental and practical exploration of next-generation MOFs.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: miljanic@uh.edu.

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

Biography

Ognjen Š. Miljanić was born in Belgrade, then Yugoslavia, in 1978. He holds a Diploma (2000) from the University of Belgrade and a Ph.D. (2005) from the University of California at Berkeley, the latter earned in the group of Prof. Peter Vollhardt while working on carbon-rich molecules. Following a 2005−2008 postdoctoral stay at UCLA with Sir Fraser Stoddart, Ognjen joined the University of Houston (UH) as an Assistant Professor. His research interests include dynamic combinatorial libraries, metal−organic frameworks, and organic fluorophores. He is the recipient of the 2012 NSF CAREER award, UH awards for Excellence in both Teaching (2012) and Research (2014), and a 2013 Cottrell Scholar of the Research Corporation for Science Advancement.

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