

Conceptual Advances from Werner Complexes to Metal–Organic Frameworks

Christian S. Diercks,^{1b} Markus J. Kalmutzki, Nicolas J. Diercks, and Omar M. Yaghi*^{1b}

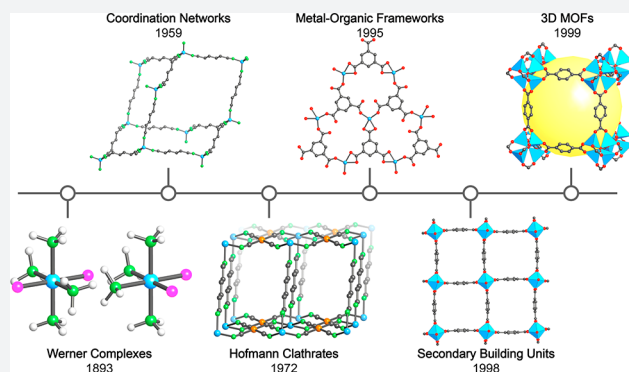
Department of Chemistry, University of California, Berkeley, California 94720, United States

Materials Sciences Division, Lawrence Berkeley National Laboratory, Berkeley, California 94720, United States

Kavli Energy NanoSciences Institute, Berkeley, California 94720, United States

Berkeley Global Science Institute, Berkeley, California 94720, United States

ABSTRACT: Alfred Werner's work on the geometric aspects of how ligands bind to metal ions at the end of the 19th century has given rise, in the molecular realm, to organometallic, bioinorganic, and cluster chemistries. By stitching together organic and inorganic units into crystalline porous metal–organic frameworks (MOFs), the connectivity, spatial arrangement, and geometry of those molecular complexes can now be fixed in space and become directly addressable. The fact that MOFs are porous provides additional space within which molecules can further be transformed and their chemistry controlled. An aspect not available in molecular chemistry but a direct consequence of Werner's analysis of coordination complexes is the ability to have multivariable functionality in MOFs to bring about a continuum of chemical environments, within the repeating order of the framework, from which a substrate can sample and be transformed in ways not possible in molecular complex chemistry.



INTRODUCTION

In 1893 Alfred Werner published his seminal work on the spatial arrangement of ligands around metal centers in coordination complexes.¹ Prior to this work coordination complexes had mostly been described by their composition, and proposed models of their structure arrangement in space were inaccurate.^{2,3} The understanding and description of chemical bonding is at the core of the discipline of chemistry and is fundamental not only in the context of chemical reactivity but also with respect to the design of new materials. Following Alfred Werner's discovery there was a rapid development of coordination chemistry aided by the growing understanding of coordinative bonding in the realm of both molecular complexes and extended structures. The progression in these areas is highlighted in Figure 1. Milestones in the chronological development of metal–complex chemistry and the manifestation of the coordination bond in new directions of synthesis are discussed and their impact on the discovery of metal–organic frameworks (MOFs) elaborated. We show that, by fixing Werner-type complexes into specific spatial arrangements in MOFs, steric and electronic properties can be accessed that otherwise would not be possible without the effects of spatial confinement as in the corresponding discrete complexes.

While Werner's original contribution was concerned with entirely inorganic coordination compounds, it was evident that the same principles apply to the coordination of organic ligands to metal ions. As such, coordination chemistry served

as a platform for studying metal complexes that entail both inorganic and organic entities. It was found early on that direct bonding of metal ions to carbon in organic ligands leads to organometallic complexes. Here, the structure elucidation of ferrocene marked the beginning of the emerging fields of organometallic chemistry and transition metal catalysis employed in organic transformations (Figure 1, 1952).^{4,5} A major contributor to progress in this area was discoveries in bioinorganic chemistry, where the structures of the active sites in enzymes—metal ions and clusters—were determined and synthetically modeled (Figure 1, 1972).⁶ The rapid development of transition metal catalysis that followed was largely carried by the elaboration of a detailed mechanistic understanding of the interactions between organic substrates and the metal centers. Such detailed understanding was still lacking for the interactions of organic molecules with traditional inorganic heterogeneous catalysts such as metals or metal oxides. The tools to study the mechanism of catalysis on the surface of solids were limited, and consequently major efforts were devoted to targeting discrete fragments of their structures. A first progression toward this goal was the extension of coordination bonds from neutral donor ligands to charged ligands such as organic carboxylates that often favor the formation of polynuclear clusters (Figure 1, 1926).⁷ Later, polyoxometalate anions were made and studied as discrete

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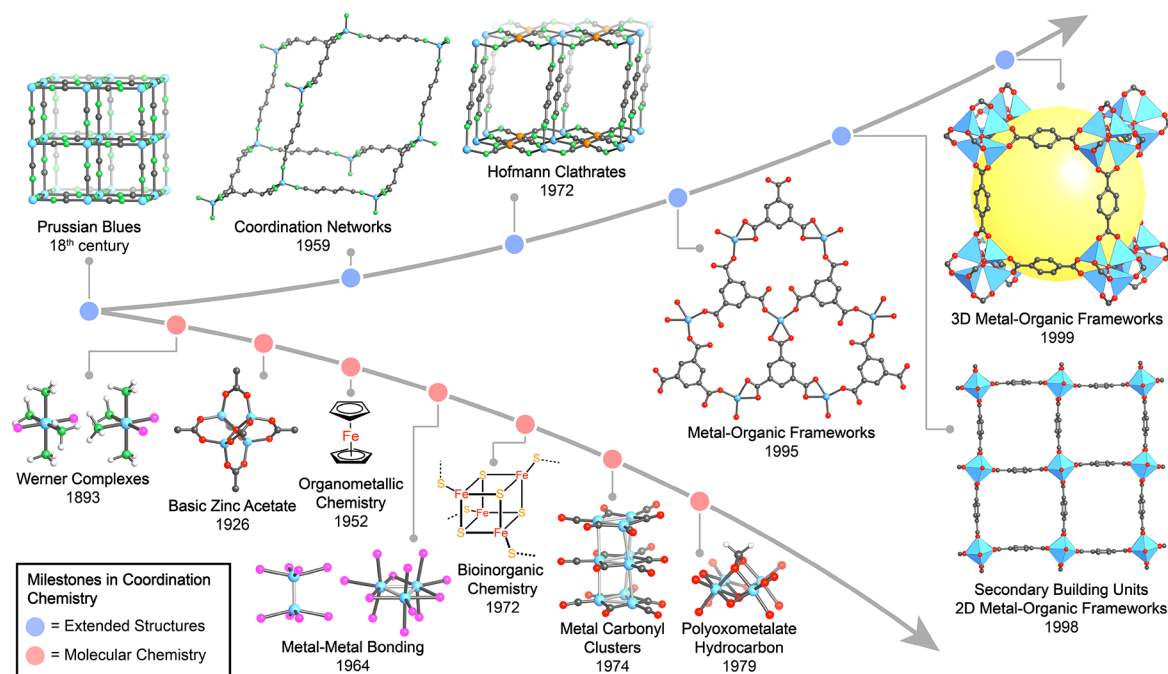


Figure 1. Chronology of advances in coordination chemistry of discrete complexes and extended structures. Important milestones starting from the report of the first extended coordination compound “Prussian Blue” and the elaboration of the coordination geometry in transition metal complexes by Werner to the development of metal–organic frameworks (MOFs). Color code: Metal, blue; second metal, orange; C, gray; N, green; O, red; S, yellow; halide, pink.

analogues of extended metal oxides, commonly employed as catalysts in the petrochemical industry (Figure 1, 1979).⁸ Similarly, metal–metal bound coordination compounds were synthesized and examined as discrete fragments of metals (Figure 1, 1964 and 1974).⁹ While the isolation of discrete coordination complexes initially helped in understanding the reactivity observed for conventional solids, the elucidation of the geometric arrangement of atoms inherent to this chemistry simultaneously motivated the development of novel kinds of extended structures as we describe next.

With respect to extended metal–organic structures it should be noted that coordination networks such as “Prussian Blue” had been known since the early 18th century, but their structures remained elusive (Figure 1, 18th century).¹⁰ In this respect the discovery of Hofmann clathrates provides another early example.¹¹ It was found later that the structure of the original Hofmann clathrate is composed entirely of inorganic constituents: Square planar and octahedral Ni^{2+} ions linked by cyanide into a 2D square grid. Notably, the axial positions of the octahedral metal ions are occupied by ammonia ligands thus pushing the layers apart and creating voids that are accessible for the inclusion of organic guests. With a better understanding of the geometric aspects of the bonding in coordination chemistry, extended networks could now be targeted rationally. It was found later that the capping ammonia ligands can be replaced by organic diamines thereby connecting the layers into a 3D coordination network (Figure 1, 1972). By employing linkers of different length, the size of the cavity could be modulated, and the clathrates’ selectivity be tailored to take up variously sized guest molecules.^{12,13} This control over the metrics of extended structures served as an inspiration for the design of materials that are composed of metal ions linked entirely by organic linkers. Perhaps the synthesis of these coordination networks was further motivated by the fact that crystals of some Werner-type complexes (β -

$[\text{M}(\text{PIC})_4(\text{SCN})_2]$ ($\text{M} = \text{Ni}^{2+}, \text{Co}^{2+}$; PIC = 4-picoline, SCN = thiocyanate) were found to take up gases (nitrogen, oxygen, noble gases, and hydrocarbons) into tiny crevices within their crystal structure. However, upon cycling the uptake and release of those gases, the molecular crystals become nonporous as the open space within the solid is progressively filled due to more efficient packing eventually leading to a nonporous arrangement.¹⁴ By connecting coordination complexes through organic linkers, the extended structures of the first coordination networks (also referred to as coordination polymers) were rendered “open” but were still found to be too frail to sustain permanent porosity upon removal of the guests residing within these cavities (Figure 1, 1959).¹⁵ This limitation can be attributed to two distinct factors: Weak bonding interactions between the linker and the metal centers and the flexibility of the coordination sphere around a single metal node. The use of organic nitrile or pyridine-based neutral *N*-donor linkers in the first generation of coordination networks yielded structures held together by relatively weak coordination bonds. Moreover, the lack of rigidity in the coordination geometry of the single metal nodes proved detrimental to the networks’ architectural stability in the absence of guest molecules.

To address these shortcomings in making permanently porous structures, charged chelating linkers such as carboxylates were employed in linking metal complexes for three reasons: In contrast to the neutral donor-type linkers used in coordination networks, charged linkers offer (i) much stronger bonding to metal ions, (ii) the prospect of neutral frameworks, and (iii) higher architectural stability due to the often observed formation of polynuclear clusters. Such clusters are also referred to as secondary building units (SBUs) in MOF chemistry and serve as anchors, ensuring the stiffness of the local geometry and thus the architectural robustness of the resulting framework. The implementation of this idea started with the report of $\text{Co}(\text{BTC})(\text{Py})_2$ (BTC = 1,3,5-benzene-

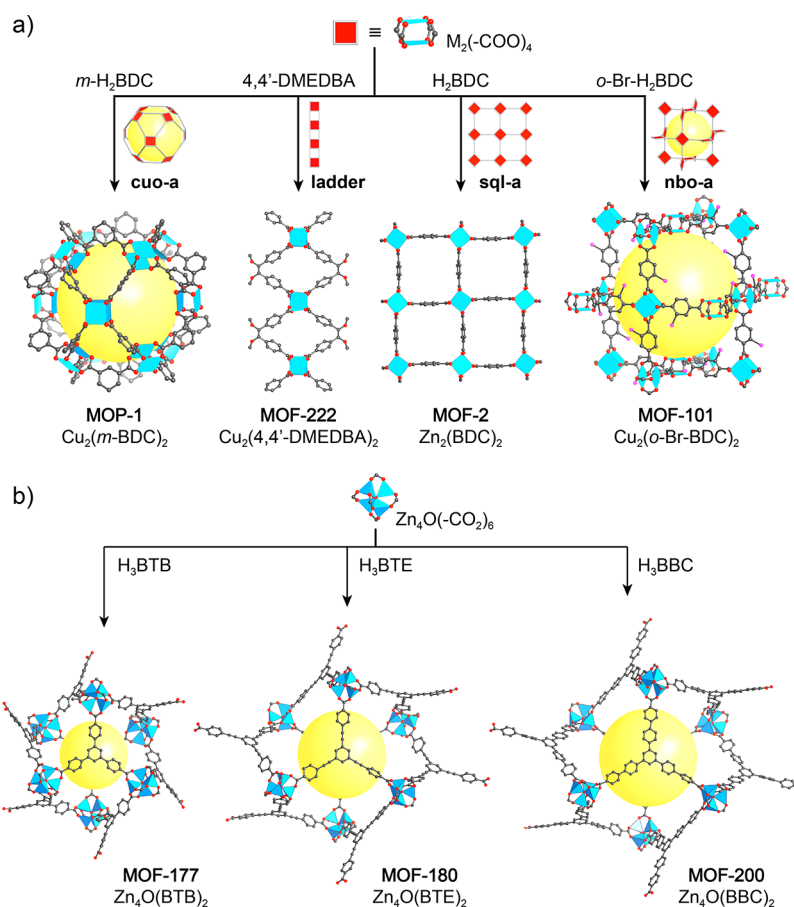


Figure 2. Reticular synthesis of MOFs. (a) Combination of highly symmetric 4-c paddle wheel SBUs with organic linkers featuring different angular constraints allows for targeting of different structure types. Discrete 0D **tcz** topology MOP-1, 1D MOF-222 with a ladder topology, 2D layered MOF-2 of **sql** topology, and the 3D **nbo** framework MOF-101. (b) Construction of MOFs with a given inorganic SBU and organic linkers of different metrics but the same geometry generates isorecticular MOFs where the structure metrics can be adjusted while the topology of the framework is preserved. The isorecticular expansion of MOF-177 (**qom** topology) yields MOF-180 and MOF-200, which are expanded by 1.8- and 2.7-fold, respectively. Color code: M (Zn, Cu), blue; C, gray; O, red. All hydrogen atoms and terminal water ligands are omitted for clarity.

tricarboxylate, Py = pyridine; Figure 1, 1995).¹⁶ The structure of $Co(BTC)(Py)_2$ consists of six-coordinated Co^{3+} ions that are linked through the charged carboxylates of deprotonated trimesic acid (H_3BTC) in the x - y plane and capped by two pyridine ligands. This compound can withstand the removal of the capping pyridine ligands and returns into its pristine structure after treatment with pyridine. The next step in the progression was to apply this chemistry to polynuclear clusters instead of the single metal ions of $Co(BTC)(Py)_2$. The first such structure, MOF-2 [$Zn_2(BDC)_2(H_2O)_2$; BDC = 1,4-benzenedicarboxylate], is composed of dinuclear $Zn_2(-COO)_4$ paddle wheel SBUs that are connected into a 2D square grid through BDC linkers (Figure 1, 1998).¹⁷ The polynuclear SBUs provide the framework with architectural stability. This is supported by the gas adsorption isotherms measured for MOF-2 which represent the first report of permanent porosity in extended metal-organic solids. Shortly after the discovery of 2D MOFs, the first 3D extended framework, MOF-5 [$Zn_4O(BDC)_3$], constructed from octahedral $Zn_4O(-COO)_6$ SBUs and BDC linkers, was reported (Figure 1, 1999).¹⁸ The surface area of MOF-5 constituted the highest reported value for any structure known at the time. Inspired by these reports, the following years saw a rapid development of the chemistry of MOFs, which have come to entail the largest class of synthetic crystalline materials known

today.^{19,20} Fundamentally, reticular synthesis of MOFs is based on the understanding of the structure of coordination compounds established by A. Werner. The geometric and metric information encoded in the discrete molecular building units and the directional bonding between them serve as tools for the designed construction of frameworks with desired structure type and pore metrics.

■ RETICULAR SYNTHESIS OF METAL-ORGANIC FRAMEWORKS

The structural diversity of MOFs originates from the large number of accessible coordination geometries of their inorganic SBUs. By judicious choice of organic linkers of well-defined shape and connectivity these SBUs can be linked into extended frameworks of a desired structure type (topology) in a designed fashion. Most frequently, shape-persistent organic molecules with rigid cores and carboxylate binding groups are employed as linkers to realize architecturally stable frameworks.^{19,20} For a given SBU, the connectivity and overall geometry of the organic linkers influence the structure type resulting from their reticulation. This is exemplified by the formation of 0D, 1D, 2D, or 3D structures from the combination of square 4-connected (4-c) paddle wheel SBUs [$M_2(-COO)_4(L)_2$; M = Cu^{2+} , Zn^{2+} ; L = Lewis bases such as water] with different ditopic organic linkers.

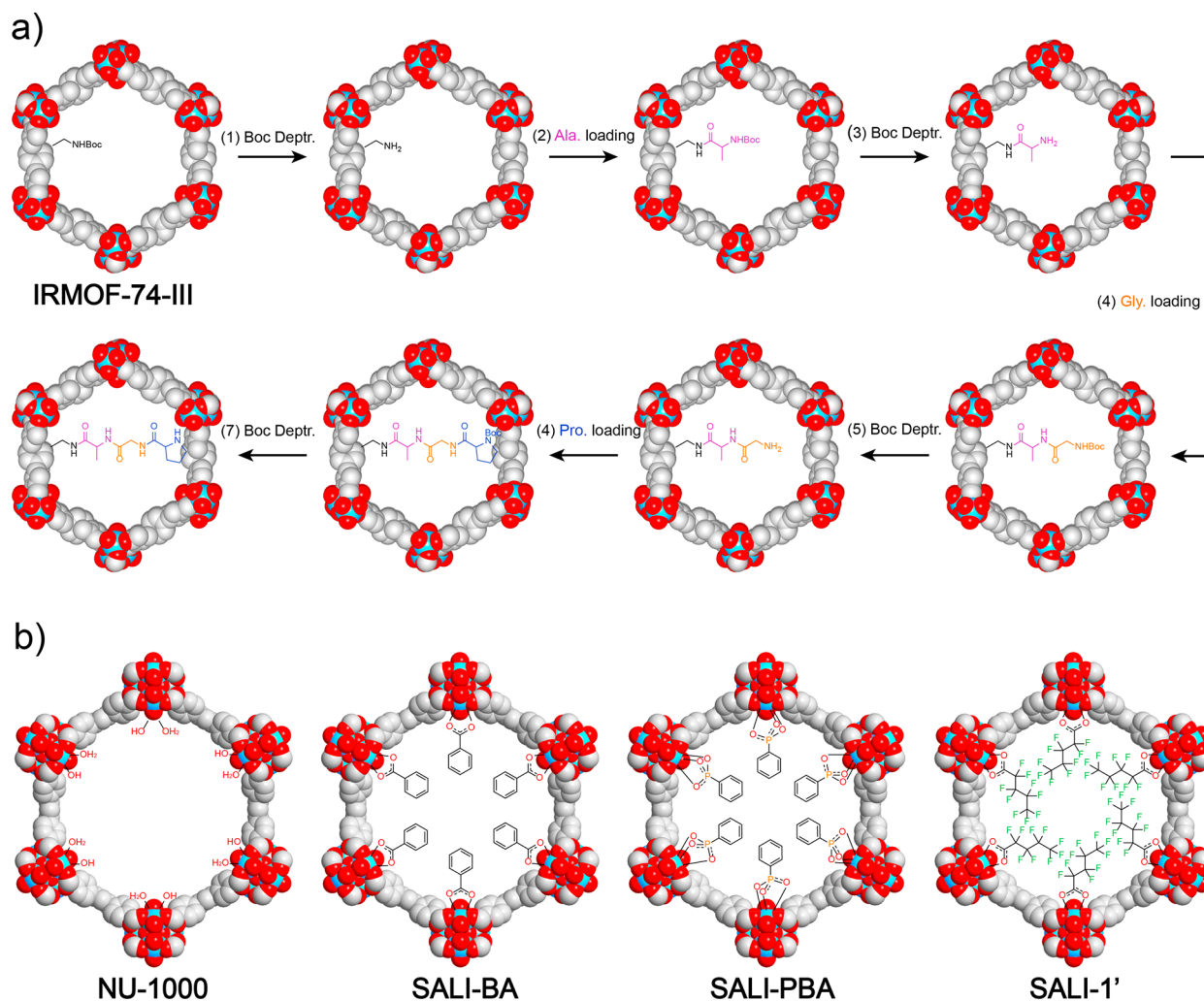


Figure 3. Postsynthesis modification of MOFs by covalent organic and coordination chemistry. (a) The organic linker of MOFs can be modified by covalent transformations, as exemplified by the 7-step incorporation of a tripeptide into the pores of IRMOF-74-III. (b) Functionalization of NU-1000 by solvent-assisted linker exchange. Hydroxyl and water ligands bound to the SBU can be replaced by organic carboxylates or phosphates to yield a series of isostructural MOFs. Color code: M (Mg, Zr), blue; C, gray; O, red. Introduced functional groups are shown as Lewis drawings and, in part a, directly bound to the organic linker and, in part b, to the metal ion. All hydrogen atoms are omitted, and the structures are shown as space filling for clarity.

Here, angular constraints imparted by the linker direct the product formation toward a specific topology (Figure 2a). The combination of copper paddle wheel SBUs with *m*-BDC (*m*-H₂BDC = isophthalic acid) linkers with an angle $\theta = 120^\circ$ between the coplanar carboxylate binding groups yields MOP-1 [Cu₂(*m*-BDC)₂], a discrete 0D metal–organic polyhedron (MOP) of *tcz* topology. In contrast, reticulation of the same SBU with 4,4′-H₂DMEDBA [(*Z*)-4,4′-(1,2-dimethoxyethene-1,2-diyl)dibenzoic acid] having an angle $\theta = 70^\circ$ yields MOF-222 [Cu₂(4,4′-DMEDBA)₂(H₂O)₂] with a 1D ladder topology. Using linear H₂BDC with $\theta = 180^\circ$ between the coplanar binding groups gives the layered MOF-2 of *sql* topology while imparting an angle $\theta = 90^\circ$ between the two carboxylate binding groups of a linear linker results in a 3D extended framework as exemplified by MOF-101 [Cu₂(*o*-Br-BDC)₂; *o*-Br-H₂BDC = 2-bromoterephthalic acid] with an underlying *nbo* net. In this example, a sterically demanding bromo-substituent is appended to the linker to fix the two carboxylate moieties in the required perpendicular orientation.

Organic linkers are crucial not only for targeting a specific structure type but also for expanding or contracting a given

MOF structure with full retention of its topology. Reticulation of expanded or contracted linkers with the same inorganic SBU yields isorecticular frameworks—structures of the same topology but with different metrics. An example for isorecticular expansion is illustrated in Figure 2b. MOF-177 [Zn₄O(BTB)₂; BTB = 4,4′,4″-benzene-1,3,5-triyl-tribenzoate], a framework of *qom* topology, is constructed from 6-c Zn₄O(–COO)₆ SBUs and tritopic, propeller shaped BTB linkers (Figure 2b). Isorecticular expansion of the framework is achieved by replacing BTB with BTE [4,4′,4″-(benzene-1,3,5-triyl-tris(ethyne-2,1-diyl)tribenzoate] or BBC [4,4′,4″-(benzene-1,3,5-triyl-tris(benzene-4,1-diyl)tribenzoate] to yield isostructural frameworks termed MOF-180 [Zn₄O(BTE)₂] and MOF-200 [Zn₄O(BBC)₂], respectively. The expansion of the linker results in an overall expansion of the unit cell volume of MOF-180 and MOF-200 by a factor of 1.8 and 2.7 compared to MOF-177. It is important to note that in the context of isorecticular expansion it is necessary to retain the angular constraints of the parent linker as deviations can result in frameworks of different topology. For instance, the structure of MOF-150 [Zn₄O(TCA)₂; TCA = 4,4′,4″-tricarboxylic acid-

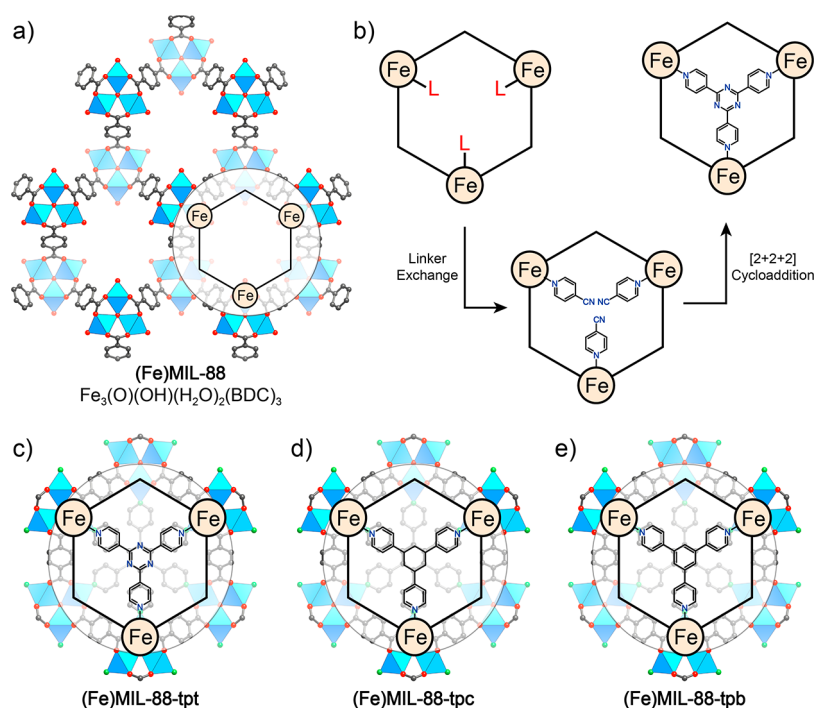


Figure 4. Novel modes of reactivity in MOFs by spatial alignment of functional groups. (a) Structure of (Fe)MIL-88. (b) Schematic representation of the reaction scheme within the pores of (Fe)MIL-88. (c–e) Structures of (Fe)MIL-88-tp, (Fe)MIL-88-tpc, and (Fe)MIL-88-tpb, formed by [2 + 2 + 2] trimerization of nitriles, alkenes, and alkynes, respectively. Color code: Zn, blue; C, gray; O, red. All hydrogen atoms are omitted for clarity.

triphenylamine] is also built from 6-c $\text{Zn}_4\text{O}(\text{COO})_6$ SBUs and trigonal tritopic linkers but has a **pyr** topology rather than the **qom** net of MOF-177, MOF-180, and MOF-200. This is due to the fact that the terminal benzoate groups in TCA can rotate freely and independently around the nitrogen core while in BTB this rotation is restricted by the steric repulsion between the aromatic protons of adjacent phenyl rings of the aryl core.

COVALENT AND COORDINATIVE FUNCTIONALIZATION OF THE PORES

The success of coordination chemistry over the last century is rooted in the notion that both structure and reactivity of molecular transition metal complexes can be altered by tailoring their ligands. In MOFs this concept can, for the first time, be translated into the solid state. Both the organic backbone and the SBU can be modified by covalent and coordinative functionalization.^{21–23} The isorecticular principle has been introduced above in the context of expansion and contraction of structure metrics. Similarly, isostructural frameworks with additional functional groups appended to the organic linker or the inorganic SBU can be obtained with retention of the frameworks' underlying topology. This strategy is not always amenable *in situ* (during framework formation) as certain functionalities interfere with the reticulation process, and thus modification of structures is often performed postsynthetically (Figure 3).^{21–24} Organic ligands of molecular coordination complexes can be prepared in multistep syntheses with a precise control over the resulting species. This is due to organic molecules being constructed from strong, directional, covalent bonds that allow for rational retrosynthesis.²⁵ MOFs serve as a platform for the translation of this concept from molecular solution-based chemistry to

crystalline extended solids. An example for a multistep covalent functionalization of the organic backbone of MOFs was illustrated in functionalized IRMOF-74-III [$\text{Mg}_2(\text{L}(\text{CH}_3)_{(1-x)}(\text{L}-\text{CH}_2\text{NHBoc})_x$); L = 3,3''-dihydroxy-(1,1':4',1''-terphenyl)-4,4''-dicarboxylic acid], where seven consecutive postsynthetic modifications were carried out to covalently incorporate peptides into the pores of the framework, resembling the active sites of enzymes (Figure 3a). It was found that such peptide sequences installed in the pores of IRMOF-74-III can carry out highly specific reactions that were previously only observed in the native enzyme.²⁶ Postsynthetic modification of MOFs is not restricted to covalent alteration of the backbone but can also be affected by coordination of ligands to coordinatively unsaturated metal centers of the SBU or by replacing charged capping ligands. One example is the postsynthetic modification of the SBUs in NU-1000 [$\text{Zr}_6(\mu_3\text{-OH/O})_8(\text{H}_2\text{O/OH})_8(\text{TBAPy})_2$]; TBAPy = 1,3,6,8-tetrakis(4-benzoate)-pyrene], a **csq** topology MOF with 1D mesoporous channels of 3 nm in diameter. Exposing the framework to a concentrated solution of charged ligands such as carboxylates or aromatic phosphates—a process termed solvent-assisted ligand exchange (SALI)—results in partial exchange of the terminal $-\text{OH}$ and $-\text{OH}_2$ groups of the Zr_6O_8 -core SBUs. This method provides a path to a wide range of functionalized NU-100 analogues and is also applicable to other structures (Figure 3b).^{27–29} Finally, predesigned coordination sites can be introduced in the linker to coordinate metal ions to the organic backbone of the structure, and a number of different motifs have been reported in the literature ranging from *N*-type and *O*-type donor ligands to organometallic complexes.²²

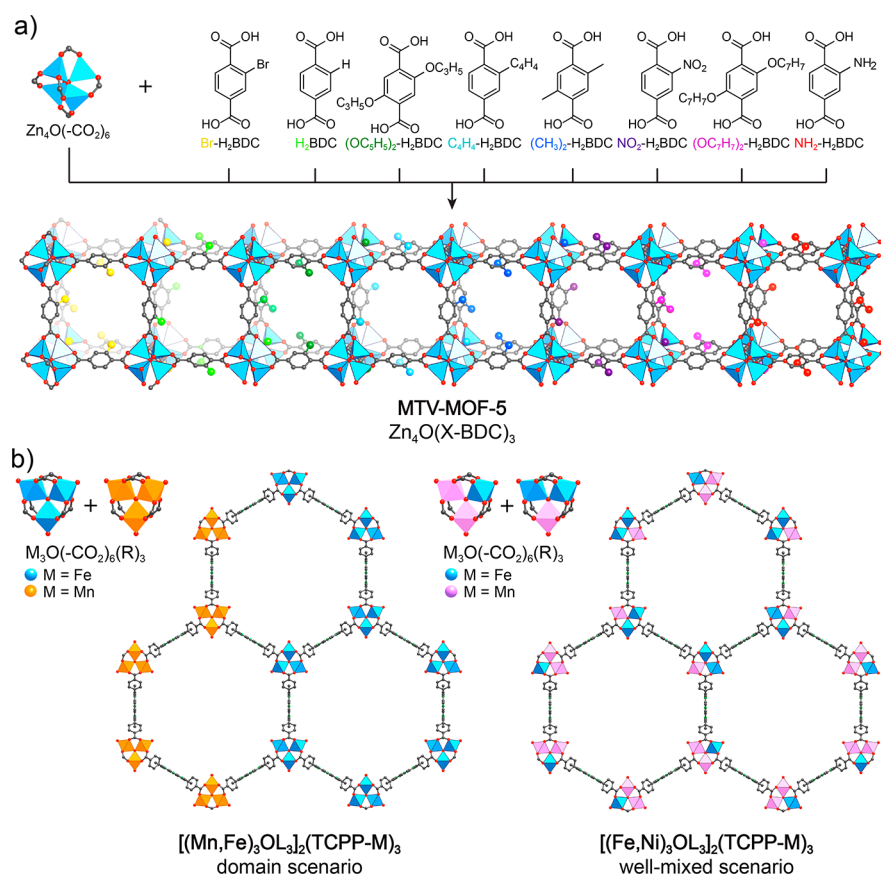


Figure 5. Introduction of heterogeneity into MOFs. (a) Heterogeneity can be introduced by constructing a framework with multiple linkers of the same topology and metrics but bearing various appended functionalities. MTV-MOF-5 is composed of basic zinc carboxylate SBUs and multiple differently functionalized BDC derivatives. In its crystal structure, these derivatives are interchangeable, and their precise location cannot be determined by means of crystallography. (b) Heterogeneity following the multi-SBU approach is found for SBUs that can be constructed from multiple different metals. This is observed in $[(M_A, M_B)_3OL_3](TCPP-M)_3$ where two scenarios are distinguished; well-mixed $[M_3OL_3](-COO)_6$ SBUs are observed in $[(Fe,Ni)_3OL_3](TCPP-M)_3$ whereas a domain-arrangement is found for $[(Mn,Fe)_3OL_3](TCPP-M)_3$. Color code: M, blue/orange/pink; C, gray; N, green; O, red. All hydrogen atoms are omitted for clarity.

PRECISE SPATIAL ARRANGEMENT OF LIGANDS IN MOFS

The fact that the MOF backbone is compositionally and metrically defined, as well as ordered throughout the crystal, allows for spatial alignment of functional groups within specific distances. This holds promise for affecting highly specific chemical transformation in the interior of these structures reminiscent of enzymatic transformations in nature. Coordination chemistry as a discipline has contributed tremendously to mimicking natural catalytic processes. In general, these efforts aimed at mimicking the active sites of enzymes; however, in molecular species the spatial confinement responsible for the preorganization of substrates within the enzyme pocket is absent. This latter aspect is difficult to control in small molecular species but easy to achieve within the confined environment of the pores of MOFs. The potential of such preorganization was illustrated for (Fe)MIL-88 $[(Fe_3(O)(OH)(H_2O)_2)(BDC)_3]$ (Figure 4a).³⁰ When viewed along the hexagonal channels that propagate along the crystallographic *c*-axis, (Fe)MIL-88 features a trigonal arrangement of the Fe^{3+} ions of the 6-c $M_3O(OL)_3(-COO)_6$ SBUs that define a regular triangle (Figure 4b). The axial ligands on these Fe^{3+} ions point toward the center of the channels of the structure. It was reported that terminal ligands bound to those metal centers ($OL = OH^-$, H_2O) in as-synthesized (Fe)MIL-

88 can be postsynthetically exchanged with pyridine linkers, and that upon complete ligand exchange three such pyridine moieties point directly toward each other. This alignment is ideally suited to fix three molecules in the ideal configuration to facilitate trinuclear reactions such as $[2 + 2 + 2]$ cycloadditions.³¹ The power of this approach was illustrated by the successful incorporation and trimerization of three different kinds of linker: 4-cyanopyridine, 4-ethynylpyridine, and 4-vinylpyridine. Heating of the ligand exchanged MOF initiates the $[2 + 2 + 2]$ cycloaddition reactions of the incorporated molecules in the pores which leads to the formation of triazine, benzene, and cyclohexane moieties, respectively (Figure 4c–e). Without the MOF, all three reactions require a specific transition metal catalyst to affect conversion. The fact that no such catalyst is needed within the confines of (Fe)MIL-88 highlights the potential of precise spatial alignment of molecules to facilitate reactions that are otherwise difficult to achieve.

APPORTIONING ORGANIC FUNCTIONALITY AND METAL IONS

The metrically defined backbone and the potential for its precision functionalization have endowed MOFs with function that goes beyond what can be achieved in discrete molecular species. An important aspect in this regard is that

heterogeneity can be introduced onto the ordered backbone of MOFs to achieve “heterogeneity within order”, a feature commonly observed in biological systems but rare in synthetic materials.³² This natural progression of MOF chemistry allows for the introduction of sequences of functionality onto an ordered array that can code for specific function. Heterogeneity in MOFs can be achieved by mixing linkers of the same geometry and metrics but bearing different functional groups and reticulating these into a single framework. One such example is MTV-MOF-5 [Zn₄O(X-BDC)₃, MTV = multivariate], where up to eight derivatives of BDC (X-BDC; X = H, NH₂, Br, NO₂, (CH₃)₂, C₄H₄, (OC₂H₅)₂, and (OC₂H₇)₂) with different functional groups appended to the aromatic core of the BDC linker are combined within one single MOF structure (Figure 5a).³³ The challenge in this context is to mitigate phase separation and obtain all different linkers in one framework of pure phase. Since the employed linkers are of the same connectivity, geometry, and metrics they become effectively interchangeable within the framework, a strict prerequisite for the formation of MTV MOFs. Consequently, in the crystal structure, the different linkers cannot be distinguished (crystallographic disorder); however, the overall crystallinity of the parent MOF-5 backbone is fully retained. Based on NMR data the functionalities of the organic linkers are found to be arranged in one of four scenarios (well-mixed, random, small clusters, and large clusters) depending on the type of functionalities and their ratios.³⁴ Heterogeneity in MOFs can also be introduced by reticulating one organic linker with multiple inorganic SBUs. An example for heterogeneity in frameworks imparted by the SBU is [(M_A,M_B)₃OL₃]₂(TCPP-M_C)₃; M = Fe, Mn, Ni and TCPP = 5,10,15,20-tetra(4-carboxyphenyl)porphine] (Figure 5b).³⁵ This MOF is constructed from [M₃OL₃](−COO)₆ SBUs that can contain multiple different metals. When multiple metal salts are employed in the synthesis of this MOF two different scenarios are observed depending on the chemical nature of the metal ion. In the case where the metal ions that constitute the SBU are of similar ionic radius and electronegativity, the well-mixed scenario (i.e., mixed-metal SBUs) is observed [e.g., [(Fe, Ni)₃OL₃]₂(TCPP-M_C)₃]. In contrast, when the metals differ substantially in their ionic radii and electronegativity, they do not form mixed-metal SBUs leading to the scenario where SBUs built from one kind of metal are arranged in domains [e.g., [(Fe,Mn)₃OL₃]₂(TCPP-M_C)₃ with two different SBUs [Fe₃OL₃](−COO)₆ and [Mn₃OL₃](−COO)₆].

CLOSING REMARKS

Werner complexes have inspired the coordination chemistry of metal ions with organic ligands in the molecular realm giving rise to bioinorganic, organometallic, and cluster chemistry. This has brought a new level of control over the geometric and electronic properties of molecules. By linking metal complexes into MOFs those properties are translated into infinitely extended crystalline solids to encompass space within which molecules can be further controlled and transformed by taking advantage of the effects of spatial confinement. As a result of stitching complexes into stable extended architectures, it has become possible to access metal-based entities (open-metal sites, polynuclear clusters containing multiple different metals, metals in unusual coordination environments) that cannot be realized without a stabilizing framework.^{36–38} The ability to introduce heterogeneity onto the ordered backbone of MOFs makes it possible to create structures featuring a continuum of

chemical functionality as opposed to a limited number of defined states. Consequently, substrates that enter the geometrically defined pores of such MTV-MOFs can sample a vast number of chemical environments as opposed to discrete energy levels of conventional porous solids.³⁹ This concept of heterogeneity within order brings about properties that cannot be attained in both molecular coordination complexes and other classes of extended structures.

AUTHOR INFORMATION

Corresponding Author

*E-mail: yaghi@berkeley.edu.

ORCID

Christian S. Diercks: 0000-0002-7813-0302

Omar M. Yaghi: 0000-0002-5611-3325

Notes

The authors declare no competing financial interest.

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REFERENCES

- Werner, A. Beitrag zur konstitution anorganischer verbindungen. *Z. Anorg. Allg. Chem.* **1893**, *3*, 267–330.
- Blomstrand, C. W. Chemie der jetztzeit. In *C. Winter; Heidelberg*, 1869.
- Jørgensen, S. M. Zur konstitution der kobalt-, chrom-und rhodiumbasen. *Z. Anorg. Allg. Chem.* **1894**, *5*, 147–196.
- Pfab, W.; Fischer, E. Zur kristallstruktur der di-cyclopentadienylverbindungen des zweiwertigen eisens, kobalts und nickels. *Z. Anorg. Allg. Chem.* **1953**, *274*, 316–322.
- Wilkinson, G.; Rosenblum, M.; Whiting, M.; Woodward, R. The structure of iron bis-cyclopentadienyl. *J. Am. Chem. Soc.* **1952**, *74*, 2125–2126.
- Herskovitz, T.; Averill, B. A.; Holm, R. H.; Ibers, J. A.; Philipps, W. D.; Weiher, J. F. Structure and properties of a synthetic analogue of bacterial iron-sulfur proteins. *Proc. Natl. Acad. Sci. U. S. A.* **1972**, *69*, 2437–2441.
- Wyart, J. Structure of basic acetate of zinc determined by x-ray analysis. *Bull. Soc. Fr. Mineral* **1926**, *49*, 148.
- Day, V.; Fredrich, M.; Klemperer, W.; Liu, R. Polyoxomolybdate-hydrocarbon interactions. Synthesis and structure of the CH₂Mo₄O₁₅H₃-anion and related methylenedioxymolybdates. *J. Am. Chem. Soc.* **1979**, *101*, 491–492.
- Calabrese, J. C.; Dahl, L. F.; Chini, P.; Longoni, G.; Martinengo, S. Synthesis and structural characterization of platinum carbonyl cluster dianions, [Pt₃(CO)₃(μ₂-CO)₃]_n²⁻ (n = 2, 3, 4, 5). A new series of inorganic oligomers. *J. Am. Chem. Soc.* **1974**, *96*, 2614–2616.
- Stahl, G. E. Experimenta, observationes, animadversiones. In *Chymicae et Physicae*; Berlin, 1731; pp 281–283.
- Hofmann, K.; Küspert, F. Verbindungen von kohlenwasserstoffen mit metallsalzen. *Z. Anorg. Allg. Chem.* **1897**, *15*, 204–207.
- Iwamoto, T.; Miyoshi, T.; Miyamoto, T.; Sasaki, Y.; Fujiwara, S. The metal ammine cyanide aromatics clathrates. I. The preparation and stoichiometry of the diamminemetal(II) tetracyano-niccolate(II) dibenzene and dianiline. *Bull. Chem. Soc. Jpn.* **1967**, *40*, 1174–1178.
- Nishikiori, S.-I.; Iwamoto, T. Crystal structure of Hofmann-dma-type benzene clathrate bis(dimethylamine)cadmium(II)

tetracyanonickelate(II)-benzene (2/1). *Chem. Lett.* **1984**, *13*, 319–322.

(14) Allison, S. A.; Barrer, R. M. Sorption in the β -phases of transition metal(II) tetra-(4-methylpyridine) thiocyanates and related compounds. *J. Chem. Soc. A* **1969**, *0*, 1717–1723.

(15) Kinoshita, Y.; Matsubara, I.; Saito, Y. The crystal structure of bis(succinonitrilo)copper(I) nitrate. *Bull. Chem. Soc. Jpn.* **1959**, *32*, 741–747.

(16) Yaghi, O. M.; Li, G.; Li, H. Selective binding and removal of guests in a microporous metal–organic framework. *Nature* **1995**, *378*, 703.

(17) Li, H.; Eddaoudi, M.; Groy, T. L.; Yaghi, O. M. Establishing microporosity in open metal–organic frameworks: gas sorption isotherms for Zn(BDC) (BDC = 1,4-benzenedicarboxylate). *J. Am. Chem. Soc.* **1998**, *120*, 8571–8572.

(18) Li, H.; Eddaoudi, M.; O’Keeffe, M.; Yaghi, O. M. Design and synthesis of an exceptionally stable and highly porous metal-organic framework. *Nature* **1999**, *402*, 276.

(19) Yaghi, O. M.; O’Keeffe, M.; Ockwig, N. W.; Chae, H. K.; Eddaoudi, M.; Kim, J. Reticular synthesis and the design of new materials. *Nature* **2003**, *423*, 705.

(20) Furukawa, H.; Cordova, K. E.; O’Keeffe, M.; Yaghi, O. M. The chemistry and applications of metal-organic frameworks. *Science* **2013**, *341*, 1230444.

(21) Wang, Z.; Cohen, S. M. Postsynthetic modification of metal–organic frameworks. *Chem. Soc. Rev.* **2009**, *38*, 1315–1329.

(22) Evans, J. D.; Sumbly, C. J.; Doonan, C. J. Post-synthetic metalation of metal–organic frameworks. *Chem. Soc. Rev.* **2014**, *43*, 5933–5951.

(23) Deria, P.; Mondloch, J. F.; Karagiardi, O.; Bury, W.; Hupp, J. T.; Farha, O. K. Beyond post-synthesis modification: evolution of metal-organic frameworks *via* building block replacement. *Chem. Soc. Rev.* **2014**, *43*, 5896.

(24) Eddaoudi, M.; Kim, J.; Rosi, N.; Vodak, D.; Wachter, J.; O’Keeffe, M.; Yaghi, O. M. Systematic design of pore size and functionality in isoreticular MOFs and their application in methane storage. *Science* **2002**, *295*, 469–472.

(25) Corey, E. J.; Cheng, X.-M. *The logic of chemical synthesis*; Wiley Interscience: New York, 1995.

(26) Fracaroli, A. M.; Siman, P.; Nagib, D. A.; Suzuki, M.; Furukawa, H.; Toste, F. D.; Yaghi, O. M. Seven post-synthetic covalent reactions in tandem leading to enzyme-like complexity within metal–organic framework crystals. *J. Am. Chem. Soc.* **2016**, *138*, 8352–8355.

(27) Deria, P.; Bury, W.; Hupp, J. T.; Farha, O. K. Versatile functionalization of the NU-1000 platform by solvent-assisted ligand incorporation. *Chem. Commun.* **2014**, *50*, 1965–1968.

(28) Deria, P.; Mondloch, J. E.; Tyljanakis, E.; Ghosh, P.; Bury, W.; Snurr, R. Q.; Hupp, J. T.; Farha, O. K. Perfluoroalkane functionalization of NU-1000 *via* solvent-assisted ligand incorporation: synthesis and CO₂ adsorption studies. *J. Am. Chem. Soc.* **2013**, *135*, 16801–16804.

(29) Deria, P.; Bury, W.; Hod, I.; Kung, C.-W.; Karagiardi, O.; Hupp, J. T.; Farha, O. K. MOF functionalization *via* solvent-assisted ligand incorporation: phosphonates vs carboxylates. *Inorg. Chem.* **2015**, *54*, 2185–2192.

(30) Surblé, S.; Serre, C.; Mellot-Draznieks, C.; Millange, F.; Férey, G. A new isoreticular class of metal-organic-frameworks with the MIL-88 topology. *Chem. Commun.* **2006**, No. 3, 284–286.

(31) Wei, Y.-S.; Zhang, M.; Liao, P.-Q.; Lin, R.-B.; Li, T.-Y.; Shao, G.; Zhang, J.-P.; Chen, X.-M. Coordination templated [2 + 2+2] cyclotrimerization in a porous coordination framework. *Nat. Commun.* **2015**, *6*, 8348.

(32) Furukawa, H.; Müller, U.; Yaghi, O. M. Heterogeneity within order” in metal–organic frameworks. *Angew. Chem., Int. Ed.* **2015**, *54*, 3417–3430.

(33) Deng, H.; Doonan, C. J.; Furukawa, H.; Ferreira, R. B.; Towne, J.; Knobler, C. B.; Wang, B.; Yaghi, O. M. Multiple functional groups of varying ratios in metal-organic frameworks. *Science* **2010**, *327*, 846–850.

(34) Kong, X.; Deng, H.; Yan, F.; Kim, J.; Swisher, J. A.; Smit, B.; Yaghi, O. M.; Reimer, J. A. Mapping of functional groups in metal-organic frameworks. *Science* **2013**, *341*, 882–885.

(35) Liu, Q.; Cong, H.; Deng, H. Deciphering the spatial arrangement of metals and correlation to reactivity in multivariate metal–organic frameworks. *J. Am. Chem. Soc.* **2016**, *138*, 13822–13825.

(36) Wang, L. J.; Deng, H.; Furukawa, H.; Gándara, F.; Cordova, K. E.; Yaghi, O. M. Synthesis and characterization of metal-organic framework-74 containing 2, 4, 6, 8, and 10 different metals. *Inorg. Chem.* **2014**, *53*, 5881–5883.

(37) Brozek, C. K.; Dincă, M. Ti³⁺-, V^{2+/3+}-, Cr^{2+/3+}-, Mn²⁺-, and Fe²⁺-substituted MOF-5 and redox reactivity in Cr- and Fe-MOF-5. *J. Am. Chem. Soc.* **2013**, *135*, 12886–12891.

(38) Chen, B.; Eddaoudi, M.; Reineke, T. M.; Kampf, J. W.; O’Keeffe, M.; Yaghi, O. M. Cu₂(ATC)•6H₂O: design of open metal sites in porous metal–organic crystals (ATC: 1, 3, 5, 7-adamantane tetracarboxylate). *J. Am. Chem. Soc.* **2000**, *122*, 11559–11560.

(39) Dong, Z.; Sun, Y.; Chu, J.; Zhang, X.; Deng, H. Multivariate metal–organic frameworks for dialing-in the binding and programming the release of drug molecules. *J. Am. Chem. Soc.* **2017**, *139*, 14209–14216.