# MOFs: from Molecules/Metal Ions to Crystals to Superstructures

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**Abstract:** Metal-Organic Frameworks (MOFs) are among the most attractive porous materials known today, exhibiting very high surface areas, tuneable pore sizes and shapes, adjustable surface functionality, and flexible structures. Advances in the formation of MOF crystals, and in their subsequent assembly into more complex and/or composite superstructures, should expand the scope of these materials in many applications (*e.g.* drug delivery, chemical sensors, selective reactors and removal devices, etc.) and facilitate their integration onto surfaces and into devices. This Concept article aims to showcase recently developed synthetic strategies to control the one-, two- and three-dimensional (1D, 2D and 3D) organisation of MOF crystals.

## Introduction

As atoms are used to make molecules, and molecules, to make objects (*e.g.* crystals, nanoparticles, vesicles, etc.), the resulting objects in turn can be used to make new structures. The self-assembly of discrete objects ranging in size from nanometres to micrometres—and also to millimetres—leads to *superstructures* (also known as *higher-order structures*).[1] This type of self-assembly is especially attractive for three reasons: firstly, different objects that are separately fabricated by incompatible processes and that have different functionalities can be combined into a single composite superstructure that incorporates the respective properties of each component; secondly, the resulting superst ructures can exhibit collective and/or synergic properties arising from the assembly; and lastly, the self-assembly of objects into 1D, 2D and 3D superstructures is a simple route for shaping and dimensionalising them to facilitate their spatial integration onto or into functional surfaces and devices and enables the use of these composite materials in otherwise inaccessible applications. These characteristics, which transcend the possibilities of molecular self-assembly, make the self-assembly of objects across extended and multiple length scales—basically how Nature constructs extremely complex and multifunctional systems—a very powerful strategy to access unique systems and classes of structurally and functionally diverse materials.

## MOF Superstructures

We would like to suggest here that making superstructures from the self-assembly of objects—a strategy highly developed for inorganic nanoparticles—can also be applied to Metal-Organic Frameworks (MOFs). MOFs are a fledgling class of crystalline materials comprising one or more metal components and one or more organic components arranged in highly organised porous structures. They have garnered great attention for their potential in areas such as gas storage and catalysis. We believe that the self-assembly of MOF crystals is particularly useful in making advanced MOF-based architectures whose characteristics (*e.g.* size, shape, functionality, *etc.*) would be too complex to obtain via traditional chemical synthesis. These novel materials are MOF superstructures: higher-dimensionality structures resulting from the 1D, 2D and 3D organisation of MOF crystals. This definition includes those structures made not only of self-assembled MOF crystals, but also of MOF crystals self-assembled with other materials to make MOF composite superstructures.

In this review, we will discuss recently developed strategies for the self-assembly of MOFs, either alone or together with other components, into superstructures. This work includes methods to control the 1D, 2D and 3D organisation of MOF crystals. Using illustrative examples, we classify the processes leading to MOF superstructures and identify four main approaches: *spontaneous higher-order assembly*, *self-assembly using hard templates*, *self-assembly using soft templates* and *self-templated synthesis*.

## Spontaneous Higher-Order Assembly

Figures 1 and 2 show the self-assembly of MOF crystals in solution without the use of templates. Under these conditions, the self-assembly is governed by the balance of attractive forces (*e.g.* electrostatic interactions between opposite charges, hydrogen-bonding, van der Waals interactions, *etc.*) and repulsive forces (*e.g.* electrostatic interactions between similar charges, steric forces, *etc.*) among the MOF crystals as well as between these crystals and the solvent. Through spontaneous organisation of MOF crystals without the use of templates, researchers have created a few promising 1D, 2D and 3D extended superstructures and mesocrystals.

**Extended superstructures**: The formation of extended networks from objects dispersed in a liquid is facilitated by inter-object interactions such as electrostatic, steric or van der Waals forces, and dipole-dipole interactions.[1c] The fact that these interactions

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can strongly influence the organisation of MOF crystals, even in solution, was confirmed by Granick and Yanai.[2] They observed that upon addition of sodium nitrate to a solution of colloidal ZIF-8[3] crystals in ethylene glycol, the van der Waals interactions between the flat facets of the crystals were sufficiently strong to drive the self-assembly of the crystals into objects of various shape (*e.g.* linear, triangular and U-shaped trimmers and linear, rhombic, and square tetramers). In this section, we also refer the reader to an excellent recent review article by Granick *et al.* that addresses the synthesis, stability and assembly of colloidal MOF crystals.[4]

One common method for developing long-range (and also 3D) periodicity involves the evaporation-induced self-assembly of highly monodispersed objects of well-defined shape.[5] For instance, Granick and Yanai obtained tightly packed hexagonal arrangements of the aforementioned colloidal ZIF-8 crystals by drying a suspension of these crystals in *N,N'*-dimethylformamide at 60 ℃. In another example, Wu *et al.* created microrod-like and fishbone-like superstructures, and 2D superlattices, of Prussian Blue by drying an aqueous dispersion of pre-formed cubic Prussian Blue[6] nanocrystals (size: 120 nm) under vacuum (see Figures 1a-c)[7] Significantly, the morphology of the products was highly dependent on the evaporation rate: at higher rates, the rod-like superstructures were favoured, whereas at lower rates, the fishbone-like and 2D superlattices were favoured. The solvent-induced assembly of MOFs is not necessarily restricted to the nanoscale, as exemplified by the creation of large-area, 2D superlattices from the self-assembly of highly monodisperse, cubic microscale (size: 0.9 to 1.5 μm) crystals of M-soc-MOF [$(M_3O(abtc)_{1.5}(H_2O)_3)(H_2O)_3(NO_3)$;[8] M = In(III) and Ga(III); abtc = 3,3',5,5'-azobenzenetetracarboxylate; soc = square octahedron] on surfaces (see Figure 1d).[9]

Interestingly, Granick *et al.* recently reported that external forces are also important factors to consider for promoting the assembly of MOF crystals.[10] They showed that colloidal ZIF-8 crystals could be aligned "facet-to-facet" into well-defined chains under an external electric field. Once alternating voltages at suitable frequencies were applied to a colloidal solution of ZIF-8 crystals in ethylene glycol, dipoles were induced to bring the crystals close together. This proximity enabled the facet-to-facet adhesion by van der Waals interactions.

In special cases, the formation of amorphous coordination polymers can also induce the spontaneous self-assembly of MOFs into superstructures.[11] For example, simply mixing zinc acetate and 2,5-dihydroxy-1,4-benzenedicarboxylic acid in *N,N'*-dimethylformamide leads to the formation of non-ordered, hierarchical superstructures that comprises an amorphous matrix in which Zn-MOF-74[12] nanocrystals are embedded (see Figure 1e).[11b] These superstructures show a bimodal pore size distribution: as a result of being formed by microporous Zn-MOF-74 crystals and a mesoporous amorphous matrix, they exhibit both meso- and microporosity.

**Mesocrystals**: The formation of MOF superstructures can be closely related to crystallisation. In the classic crystallisation theory, the process starts from the formation of a stable nucleus, followed by a simple enlargement of the nuclei by unit-cell replication, through growth of the building blocks (atoms, ions, molecules and small clusters) on the nuclei surfaces. The final product is a single crystal, whose morphology is determined by its intrinsic structure.[1] However, there is a growing number of examples of non-classical crystallisation processes that involve the oriented attachment and partial fusion of nanoparticles/crystals, which results in the formation of *mesocrystals* (see Figure 2a). *Mesocrystal* is an abbreviation of *mesoscopically-structured crystal*: an ordered superstructure of sub-microscale crystals (size: 1 to 1000 nm). To explain the formation of mesocrystals, one must consider a non-classical (*i.e.* nanoparticle-based) crystallisation, rather than a classical (*i.e.* atom, ion, molecule or cluster-based) mechanism. Examples of non-classical processes include the oriented-attachment mechanism proposed by Banfield *et al.*[13], and that of grain-growth after grain-rotation and coalescence (in polycrystalline materials). Cölfen and Antonietti recently described a mechanism, which they called the *non-classical crystallisation mechanism*[14], that comprises three pathways: oriented attachment of nanoparticles, crystallisation of amorphous or liquid precursors, and mesoscale assembly of primary nanoparticles. They attributed this mechanism in the formation of certain biomineral, organic and inorganic superstructures by mesoscale self-assembly of monodispersed nanoparticles.[14]

Recent studies have begun to show that MOFs can crystallise via the oriented attachment and fusion of MOF nanocrystals to create mesocrystals or superstructures. For example, Xie *et al.*, assembled Prussian Blue nanoparticles, under hydrothermal conditions and in the presence of glucose, into microscale cubic or frame-like superstructures (see Figure 2b).[15] Time-dependent experiments (40 minutes, 1.5 hours and 2.5 hours) confirmed the initial formation of cube-shaped nanoparticles (size: *ca.* 10 to 20 nm) at short times, and formation of mosaic superstructures with small deviations in orientation at longer times. Interestingly, when Jiang *et al.* performed similar work with Prussian Blue in which they introduced HCl into the reaction, they obtained microscale octahedrons.[16]

## Self-Assembly Using Hard Templates

The use of physical templates (*e.g.* polymeric and silica particles, alumina membranes, *etc.*) as scaffolds is a general, well-known strategy for making superstructures.[1] For MOFs, hard template-directed strategies should exploit templates with active sites on their surfaces that can facilitate the nucleation and growth of MOF crystals. One way to do this is by functionalising the surface of the templates before using them. Interesting functional groups include carboxylic, hydroxyl, sulphonate and phosphonic/phosphate groups, and N-based molecules; basically, those that are currently used to make MOFs. Another way is to use templates comprising metal ions such as metal oxides. In both of these strategies, the idea is to increase the chemical affinity between the MOF precursor (functional group or metal ion) and the surface template at the solid/liquid interface. This enables coordination (and consequently, MOF crystal growth) to be selectively done on the template surface. In fact, this approach has been extensively applied to grow MOFs on large areas[17] (*e.g.* to create MOF membranes for gas separation) as well as to selectively position MOFs onto functionalised surfaces (*e.g.* containing –COOH, –OH and –NH$_2$).[18]

Based on the aforementioned results, hard-template synthesis offers major potential for the preparation of MOF superstructure composites or freestanding MOF superstructures, whereby the removal of the template triggers the formation of the desired superstructure (*e.g.* hollow spheres).

**MOF composite superstructures**: The recent use of particles, membranes and ordered structures containing these active sites as hard templates suggests that this approach might become very important for synthesising MOF superstructure composites of diverse composition and shape:

*1. Organic polymer microparticles.* Oh *et al.* used carboxylate–terminated polystyrene spheres (diameter: *ca.* 900 nm) as templates to prepare polystyrene@ZIF-8 core–shell composites. They prepared a thin, nanoscale layer of ZIF-8 nanocrystals around the polystyrene spheres by simply exposing the spheres to a methanolic solution of ZIF-8 precursors twice for 10 minutes at 70 ºC.[19]

*2. Mesoporous SiO₂ microparticles.* MOF/SiO₂ composites can incorporate the microporosity of MOFs and the mesoporosity of SiO₂ microparticles. For instance, Coronas *et al.* prepared a uniform ZIF-8 layer (thickness: 700 nm) around mesoporous SiO₂ spheres (diameter: 3 μm).[20] They started by preparing a ZIF-8 seed layer on the surface of silica spheres. Owing to the attractive interactions between the terminal hydroxyl groups of the silica and the Zn(II) ions, this step simply required stirring the SiO₂ spheres in an aqueous solution of zinc nitrate and 2–methylimidazole for 5 minutes. The seeded microspheres were then mixed twice in a solution of the same ZIF-8 precursors. Exploiting a similar functionalisation, Zhang *et al.* employed SiO₂ microparticles as templates: they immobilised Cu(II) ions onto the microparticles surface, in order to promote the surface synthesis of HKUST-1.[21] [22]

*3. Inorganic nanoparticles.* Given that inorganic nanoparticles (*e.g.* gold, silver and iron oxide) can be easily functionalised with surfactants and molecules containing active functional groups, they can served as excellent templates for MOF crystallisation.[23] For example, Qiu *et al.* used iron oxide nanoparticles as a template to synthesise HKUST-1 and Fe-MIL-100[24] crystals (Fig. 5a and b). They synthesised core–shell $Fe_3O_4$@HKUST-1/MIL-100 composite superstructures using a stepwise methodology, in which alternatively dispersed mercaptoacetic acid–functionalised iron oxide nanoparticles in ethanol solutions of the corresponding metal salt and organic ligand precursors.[25] More recently, Kim, Ahn and Moon *et al.* reported a microfluidic-based technology that enables the solvothermal and hydrothermal synthesis of MOFs and MOF-composite superstructures in microdroplets.[26] $Fe_3O_4$@ZIF-8 composites were generated by a two-step, continuous process. Firstly, the iron oxide precursor solution and the oil phase were injected and reacted in a microreactor at 80 ºC for 2 minutes. Then, the resulting iron oxide particles were transported downstream to a second microreactor, to merge and react with a mixture of ZIF-8 precursor (zinc nitrate and 2-methylimidazolate in methanol, and polystyrenesulphonate) at 50 ºC. The initial functionalisation of the iron oxide particles with polystyrenesulphonate induced the selective growth of ZIF-8 nanocrystals on the particle surfaces, affording core-shell $Fe_3O_4$@ZIF-8 composite superstructures (dimensions: 700 ± 50 nm).

*4. Alumina oxide membranes and nanoparticles.* Metal oxides can act as the metal source for MOF crystallisation. For instance, alumina oxide is an excellent source of Al(III) ions. Kitagawa *et al.* have described a fascinating methodology in which they used a 2D alumina template that acts first as an Al(III) source, and then as a structural directing agent (see Figure 3a), in a process that mimics the pseudomorphic mineral replacement observed in geology.[27] The alumina template was first immersed in an aqueous solution of 1,4-naphthalene dicarboxylic acid (H₂ndc), and then heated by

microwave irradiation. It initially reacted with the naphthalene dicarboxylic acid ligand to form the 3D MOF [Al(OH)(ndc)],[28] which comprises infinite 1D chains of Al(OH)₂O₄ functionalised with the naphthalene dicarboxylate ligand. Careful design of the template enabled the formation of a 2D superstructure, which combines the mesoporosity of the parent aluminium oxide with the intrinsic microporosity of the 3D porous MOF (see Figure 3b). The authors then applied the same concept using a 3D alumina template, thereby obtaining a 3D composite superstructure. Interestingly, they investigated the capacity of their 2D and 3D superstructure composites for water/ethanol separation, and found that the 3D superstructure were faster. More recently, the same authors extended this concept to create Au nanorod@alumina@[Al(OH)(ndc)] superstructures (see Figure 4), in which they were able to photothermally control the release of adsorbed species (*e.g.* anthracene).[29]

*5. 3D ordered macroporous inverse-opal structures.* Ordered macroporous MOF superstructures prepared from opaline templates can incorporate the excellent optical properties of these templates--namely, the bright colours generated by diffraction of light. Li *et al.* first used a 3D-ordered, macroporous polystyrene inverse-opal as a template to synthesise a 3D-ordered, macroporous and photonic HKUST-1 superstructure.[30] They synthesised this superstructure by infiltration of a carboxylic-functionalised polystyrene template with a DMSO solution of the HKUST-1 precursors (copper nitrate and trimesic acid). The solvent was then evaporated off at 90 ºC, and the template was subsequently removed with tetrahydrofuran, resulting in the formation of a bright-red colour HKUST-1 superstructure. Importantly, the authors then investigated the optical response of this superstructure upon guest adsorption, and found that exposure of the superstructure to organic solvents (*e.g.* ethanol, toluene, cyclohexane, etc.) for 30 led to a clear shift in the UV/Vis spectrum. They also used this methodology to produce 3D-ordered, macroporous ZIF-8 superstructures, which after exposure to methanol underwent a large blue shift (≈ 75 nm, as detected by the naked eye), thereby confirming that these superstructures offer high potential for use as label-free sensors.

**Freestanding MOF superstructures:** As stated above, the formation of freestanding MOF superstructures using hard templates requires removal of the template. Therefore, any MOFs that are to be used in this methodology must be stable to the removal step. A pioneering work that proved the feasibility of this concept—although the product was not a MOF superstructure—was reported by Martin *et al.*, who utilised alumina membranes as sacrificial templates for synthesising metal-organic Zr(IV)-phosphonate nanotubes.[31] In their methodology, a film of a coordination polymer is initially deposited on the template via layer-by-layer deposition. Subsequent removal of the template by thermal or chemical techniques (*e.g.* using phosphoric acid) leaves behind a tubular structure whose size and shape mimic that of the template. Using the same approach, Oh *et al.* reported the first freestanding MOF superstructures synthesised using sacrificial templates. They dissolved the polystyrene core of the aforementioned polystyrene@ZIF-8 composites[19] by immersing the spherical composites in *N,N'*-dimethylformamide, to obtain hollow spherical superstructures comprising tightly-packed ZIF-8 nanocrystals. They were able to control the thickness of the sphere wall by regulating the number of growth cycles (*i.e.* the number of times that the template was alternately exposed to either of the two MOF precursor solutions). Interestingly, a minimum thickness of

*ca.* 50 to 100 nm, corresponding to 2 to 3 growth cycles, was determined to be critical for the stability of the superstructures produced. Using the same strategy, Qiu *et al.* synthesised hollow HKUST-1 and Fe-MIL-100[32] superstructures.[33] In this case, polystyrene particles were coated with sulphonate groups, and then alternately exposed to either of the two MOF precursor solutions. The authors confirmed that the thickness of the MOF layer around the particles increased with the number of growth cycles and that a critical thickness (*e.g. ca.* 40 to 45 nm for a minimum of 50 cycles for Fe-MIL-100; see Figures 5a and b) was required for stability of the final superstructures.

Peng *et al.* recently published an uncommon but very promising approach to prepare freestanding 2D MOF superstructures.[34] They demonstrated the use of copper hydroxide nanostrand thin films to grow HKUST-1 crystals on the film surfaces until the films are completely consumed, thereby leading to the formation of free-standing HKUST-1 membranes (see Figures 5 c and d). Here, the templates act as an excellent source of Cu(II) ions as well as a structural directing agent. The authors immersed the copper hydroxide thin films in a solution of trimesic acid, water and ethanol at room temperature for 2 hours. In related work, Li *et al.* produced freestanding HKUST-1 and ZIF-8 membranes by using electrospun fibrous mats as templates, which they then simply removed with organic solvents such as ethanol and tetrahydrofuran.[35]

## Self-Assembly Using Soft Templates

Figure 6 illustrates the self-assembly of MOF crystals using soft templates to prepare MOF-based superstructures. MOF synthesis and subsequent self-assembly can be done at the liquid/liquid interface or at the liquid/air interface.

**Liquid/liquid interface**: This approach, commonly known as *interfacial synthesis*, is based on first mixing and structuring two non-miscible solvents containing the MOF precursors, and then localising the MOF reaction/crystallisation at the liquid/liquid interface between the two solvents. To date, crystallisation processes at liquid/liquid interfaces has been extensively involved in the preparation of inorganic or polymeric hollow capsules, and have been found to strongly depend on the stabilisation of these interfaces.

A common way to achieve stable liquid/liquid interfaces is through the use of emulsions. The interface between the two liquids can be used to localise the coordination, nucleation and growth of MOFs. This approach usually comprises three steps: dissolving each precursor in the solvent to be dispersed; preparing water-in-oil (w/o) or reverse (o/w) emulsions with a surfactant; and finally, reacting the MOF precursors in order to spontaneously induce the coordination and thereby limit the MOF growth to the liquid/liquid interface. The reaction can be driven for example by mechanical collision of droplets, or by application of an external stimulus such as temperature, light or microwave radiation. The precise localisation of the coordination at liquid/liquid interfaces was recently reported by Wang *et al.*, who used an organometallic surfactant terminated with cyanoferrate groups to stabilise an o/w emulsion and localise the coordination of Fe(III) ions present in the water phase at the boundary of each oil droplet.[36] Following this principle, Eddaoudi *et al.* prepared very homogeneous Fe-soc-MOF hollow superstructures made of a monolayer shell of assembled microscale cubic crystals (see Figure 6d).[37] They

prepared an emulsion containing the MOF precursors (iron nitrate and 3,3',5,5'-azobenzenetetracarboxylic acid) by stirring a mixture of the precursors and water, dimethylsulphoxide, acetonitrile, *tert*-butylamine and the surfactant tween-85 at room temperature for 1 hour. The resulting emulsion was heated to 120 ºC for 2 hours with continuous stirring. After heating, highly monodisperse Fe-soc-MOF cubes were formed at the liquid/liquid interface of the droplets, where they self-assembled into spherical hollow superstructures having a wall comprising tightly packed MOF crystals. Interestingly, the authors showed that the size of the droplets in the emulsion (and therefore, the diameter of the resulting superstructures) could be controlled by modulating the quantity of surfactant: by using more surfactant, they obtained smaller droplets and consequently, smaller superstructures. For example, at 0.01-0.03 mL tween-85, the superstructures had a diameter of *ca.* 10 to 20 µm and comprised 1,400 to 2,800 crystals, whereas at 0.05 mL tween-85, the superstructures had a diameter of *ca.* 3 to 5 µm and comprised only 30 to 200 crystals.

Related work has been done with Pickering emulsions, which are emulsions stabilised by solid particles that adsorb at the liquid/liquid interface, owing to their partial wetting by both phases. Examples of particles used to create these emulsions include those of silica, bacteria, proteins, gold, clay, metal oxides, carbon black, and latex colloids,[38] and more recently, MOFs.[39] Bradshaw *et al.* exploited the ability of MOF nanocrystals to stabilise Pickering emulsions in order to synthesise hollow, microscale polystyrene capsules containing nanocrystals of two MOFs (ZIF-8 and MIL-101[40]) in the walls.[41] The authors first stabilised o/w Pickering emulsions with pre-synthesised nanocrystals of both MOFs, and then performed controlled polymerisation of the styrene and divinylbenzene contained in the oil phase. In terms of potential applications, the combination of microporous MOF nanocrystals with a hierarchically structured polymer membrane appeared to be effective for the retention of encapsulated dye molecules.

Other researchers have designed more-sophisticated methods for structuring and stabilising liquid droplets of a MOF solution in one solvent added to a MOF solution in a second, immiscible solvent. For example, De Vos *et al.*[42] have devised a microfluidics-based procedure for the fabrication of hollow, spherical, macroscale MOF superstructures (diameter: *ca.* 500 µm) comprising HKUST-1 nanocrystals (see Figure 6e). The HKUST-1 precursors (copper acetate in water, and trimesic acid in octanol) were dissolved separately, and then each solution was delivered by syringe pump to a T–junction, where water droplets were generated by breaking the aqueous reagent solution off into the co-flowing organic ligand solution. The HKUST-1 nanocrystals were then assembled at the interface of the two solutions, leading to the formation of hollow HKUST-1 superstructures with defect–free walls (thickness: *ca.* 2 µm). In terms of potential applications, the authors demonstrated the capacity of these superstructures to encapsulate large dyes such as Rose Bengal, confirming the absence of any leak except for when the superstructures were mechanically broken. In contrast, encapsulated small molecules were able to diffuse through the MOF pores, proving the selective permeation of the superstructures. Owing to these properties, the authors proposed the use of the HKUST-1 superstructures as new delivery systems, chemical sensors, or selective reactors containing molecular catalysts.

**Liquid/air interface**: Most of the aforementioned methods for the synthesis of MOF superstructures at liquid/liquid interfaces demand the generation and stabilisation of droplets (*e.g.* through emulsions) containing at least one of the corresponding MOF precursors for the duration of the reaction. Furthermore, despite the advantages of these methods, they can be extremely challenging and are currently quite limited. This is due to several factors. Firstly, the emulsions that offer the required reaction conditions are difficult to prepare (*e.g.* the use of specific solvents, high temperatures and certain bases). Secondly, there are often solubility problems between the MOF precursors and the constituent (polar or non-polar) solvents of the emulsions. Lastly, the presence of surfactants can be detrimental to MOF synthesis. These drawbacks could limit the scope of these methods.

One solution to the problems encountered in liquid/liquid MOF synthesis is to perform self-assembly at liquid/air interfaces generated in an aerosol, as one can use the same mixtures as those used in solvothermal synthesis.[43][44]In fact, our group has synthesised a wide range of hollow MOF superstructures by exploiting the special conditions that dictate precipitation and reaction during the drying of an aerosol droplet (see Figure 6f).[43] This spray-drying method does not require any additional immiscible solvents, surfactants, emulsifiers or agitation (*e.g.* stirring or sonication). It enables atomisation of MOF-precursor solutions into aerosol droplets that are used as individual reactors for MOF synthesis. In the proposed mechanism, the droplets suspended in a hot-air stream start to evaporate, and then the reactants diffuse to the droplet shell, where their concentration increases until reaching a critical level, at which point the MOF crystallises. During crystallisation, the mobility of the MOF nanocrystals is reduced and therefore, they become closely packed within the droplet shell. Interestingly, the resulting hollow MOF superstructures have a single thin layer of uniformly packed MOF nanocrystals, which hold together the structure.

The versatility of this approach was proven by synthesising hollow MOF superstructures that comprised nanocrystals of HKUST-1, Cu-bdc,[45] NOTT-100,[46] MIL-88A,[47] MIL-88B,[47] MOF-14,[48] MOF-74 [M = Zn(II), Ni(II) and Mg(II)],[12] UiO-66,[49] ZIF-8, a Cu(II) Prussian blue analogue,[6] MOF-5[50] or IRMOF-3.[51] In all cases, the superstructures retained the excellent sorption properties of the parent MOF. Moreover, it was proved that this method enables partial control of the size of HKUST-1 nanocrystals that form the superstructure walls, through tuning of spray-drying parameters (*e.g.* concentration and flow rate). Furthermore, it simultaneously enables synthesis and assembly of different types of nanoMOFs, paving the way to hollow MOF superstructures of greater structural complexity. In terms of potential applications, one advantage of the spray-drying approach is that it enables the combined precipitation/crystallisation of different species within a single droplet, which could be exploited to create advanced encapsulation systems in which an active molecule is entrapped within the MOF shell. As a proof of concept, our group entrapped sodium chloride crystals inside the HKUST-1 shell. We then hypothesised that the rate of crystallisation inside the nebulised droplet is related to the relative mobility of the crystals and therefore, to their relative position in the final composite. Thus, sodium chloride crystals would crystallise before having their mobility reduced, whereas HKUST-1 reactants diffuse to the droplet shell, where they then crystallise. We then demonstrated that the hollow HKUST-1 shells could be used to encapsulate functional materials that would confer the final composite with added functionality, such as magnetism (encapsulation of iron oxide nanoparticles) or luminescence (encapsulation of sodium fluorescein). Finally, we confirmed the efficacy of the resulting magnetic MOF composite superstructures for selective magnetic removal of pollutants (*e.g.* dibenzothiophene).

## Self-Templated Synthesis

Among most common literature approaches to prepare hollow inorganic superstructures is based on self-templating methods. These methods include Ostwald ripening, the Kirkendall effect, galvanic replacement and surface-protected etching processes. The possibility to extend these methods to create hollow MOF superstructures was explored by Wang *et al.*[52], who reported a one-step Ostwald ripening process for the formation of hollow superstructures comprising crystals of a ferrocenyl MOF (see Figure 7a). They synthesised the superstructures by solvothermal reaction of iron chloride with 1,1'-ferrocenedicarboxylic acid in *N,N'*-dimethylformamide at different reaction times. Interestingly, longer reaction times led to larger cavities; at 24 hours of reaction, well-defined hollow superstructures were formed (see Figures 7b-e). This observation suggested that the hollow superstructures form by an Ostwald ripening processes, in which the mass diffuses from the interior of solid aggregates (where crystallites are smaller and less compact) to the exterior (where the crystallites are larger and more compact).

## Summary and Outlook

Recent advances in the self-assembly of MOFs into superstructures should ultimately yield a nearly infinite variety of composite superstructures in 1D, 2D and 3D diverse geometries and boasting cumulative and synergic properties. Control over the 1D, 2D and 3D ordering of these superstructures should enable their ready integration into devices and onto surfaces. However, the synthetic accessibility of MOF superstructures remains in its early stage.

We have surveyed the very recently developed approaches to construct the first-ever MOF superstructures, all of which entail control over MOF crystallisation and/or the subsequent spatial layout of the resulting crystals. We have categorised these methods as *spontaneous higher-order assembly*, *self-assembly using hard templates*, *self-assembly using soft templates* or *self-templated synthesis*.

We strongly believe that the coming years will witness further methodological progress in terms of controlling the composition, size, shape, MOF-crystal packing and interfaces (between MOF crystals and other materials) in MOF superstructures. Given the potential collective and synergistic properties that can arise through assembly of MOF crystals (whether alone or with other materials), we are confident that the forthcoming synthetic advances will ultimately enable the use of MOF superstructures in myriad applications including for example sensors (*e.g.* photonic MOF superstructures);[30] catalysts,[53] systems for magnetic pollutant removal[43] or for triggered delivery (*e.g.* inorganic nanoparticle@MOF composite superstructures);[29] separation agents (*e.g.* membrane-like MOF superstructures);[27] sorbents (SiO$_2$@MOF superstructures);[20] selective reactors and encapsulation systems (*e.g.* capsule-like MOF superstructures).[42]

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## Figure Legends

Figure 1. Schematic of the spontaneous organisation of MOF crystals into microrod-like or fishbone-like superstructures, 2D superlattices, or non-ordered hierarchical superstructures. a-c) Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) images of the self-assembly of Prussian Blue nanocrystals into microrod-like a) and fishbone-like b) superstructures, and 2D superlattices c). Reproduced with permission of reference [7]. d) SEM image of M(III)-soc-MOF microcrystals self-assembled on surfaces in 2D superlattices. Reproduced with permission of reference [9]. e) SEM image of a non-ordered, hierarchical superstructure self-assembled from MOF-74 nanocrystals. Reproduced with permission of reference [11b].

Figure 2. a) Schematic of the formation of mesocrystals built up from the oriented attachment and fusion of nanocrystals. b) SEM image of cubic mesocrystals prepared by the oriented attachment of Prussian Blue nanocrystals. Reproduced with permission of reference [15].

Figure 3. a) Schematic of the preparation of MOF superstructures using a metal oxide membrane that serves as both metal source and structural directing agent. b) SEM images showing the time course of the coordination replication of an alumina oxide template to a 2D superstructure based on [Al(OH)(ndc)] (ndc = 1,4-naphtalene dicarboxylate) crystals. The scale bars correspond to 1µm. Reproduced with permission of reference [27].

Figure 4. a) Illustration of the protocol developed to synthesise Au nanorod@alumina@[Al(OH)(ndc)] superstructures. b and c) TEM images showing the Au nanorods used as templates b), and the resulting superstructures c). Reproduced with permission of reference [29].

Figure 5. Examples of freestanding MOF superstructures. a-b) SEM images of hollow, spherical Fe-MIL-100 superstructures synthesised after 10 a) and 50 b) growth cycles. Reproduced with permission of reference [33]. c-d) SEM images showing the formation of a 2D HKUST-1 superstructure on a copper hydroxide nanostrand thin film after 30 minutes of reaction c), and the resulting freestanding HKUST-1 superstructure after 2 hours of reaction d). Reproduced with permission of reference [34].

Figure 6. (a-c) Schematics showing the relative position of the MOF precursors in the two phases (liquid or air) in the soft-template strategies used to create MOF superstructures. d) Schematic showing the self-assembly of MOF crystals (formed in the aqueous phase) at the oil/water interface (top). Representative SEM images of spherical superstructures comprising self-assembled Fe-soc-MOF (soc = square octahedron) crystals (bottom). Reproduced with permission of reference [37]. e) Schematic showing the formation of microdroplets of one liquid in another liquid, achieved through microfluidics (top). Representative SEM images of hollow, spherical macroscale HKUST-1 superstructures synthesised using the microfluidics method. Reprinted with permission of reference [42]. f) Schematic showing the spray-drying technique for the growth of hollow, spherical superstructures, and the proposed mechanism of formation (top). SEM image of hollow, spherical, macroscale HKUST-1 superstructures fabricated with the spray-drying technique (bottom). Reproduced with permission of reference [43].

Figure 7. a) Schematic illustration of the Ostwald ripening mechanism. b-e) TEM images showing the stepwise formation of hollow, spherical, iron-based ferrocenyl MOF superstructures at different times: 0 b), 2 c), 6 d) and 10 e) hours. Reproduced with permission of reference [52].

## Keywords