Metal-Organic Frameworks and Metal-Organic Cages – A Perspective

Ben S. Pilgrim* and Neil R. Champness*[a]

The fields of metal-organic cages (MOCs) and metal-organic frameworks (MOFs) are both highly topical and continue to develop at a rapid pace. Despite clear synergies between the two fields, overlap is rarely observed. This article discusses the peculiarities and similarities of MOCs and MOFs in terms of synthetic strategies and approaches to system characterisation. The stability of both classes of material is compared, particularly in relation to their applications in guest storage and catalysis. Lastly, suggestions are made for opportunities for each field to learn and develop in partnership with the other.

1. Introduction

The coordination of organic ligands to metal ions has long been a cornerstone of synthetic chemistry, used to construct materials over a wide range of length scales. In recent years, there has been huge growth in many aspects of metal-ligand assembly and entire communities now focus their research into understanding the structure and function of such systems.

The term Metal-Organic Framework, or MOF, has come to define compounds where metal ions, or clusters, are bridged by coordinating organic linkers to form extended structures in up to three dimensions. MOFs are coordination polymers, but are differentiated from other classes of coordination polymers by their void spaces – in addition to repeating organic and inorganic units, they comprise of regularly-sized cavities surrounded by the organic and inorganic 'framework' of the structure.

By contrast discrete (or finite) molecular coordination complexes with an internal void can be referred to as Metal-Organic Cages (MOCs), Metal-Organic Polyhedra (MOPs), or simply cages. These will be referred to as MOCs in this article, although this acronym is not in as widespread use as MOF. A MOC has the same constituent pieces as a MOF, but with the pieces designed so that they assemble into distinct individual complexes, which are typically monodisperse in size, structure, and molecular weight. Like MOFs, MOCs are of interest because of their clearly defined interior cavities.

The successful assembly of both MOFs and MOCs depends on the well-defined coordination preferences of metal ions or clusters. The organic ligands vary by different topicity (number of different sites at which they coordinate), denticity (number of donor interactions they make with an individual metal centre or cluster) and the relative orientation of their coordinating groups. By carefully selecting the appropriate metal, organic ligand, (and in some cases counter ions), assembly towards an extended MOF or discrete MOC can be guided.

Many of the reasons why scientists are interested in MOFs are the same as why they are interested in MOCs. Indeed, in the early days, pioneering work in both fields was often undertaken by the same groups.[1] However, today very few groups are active in both MOF and MOC research, and in the view of the authors, the two communities do not communicate with each other as effectively as they could. This review seeks to highlight the main similarities and differences between MOFs and MOCs in a range of areas.[2] To summarize the entire MOF field or the entire MOC field in one review would be impossible, let alone both, and so this review will necessarily only provide a brief overview, which focuses on recent developments and examples of particular interest to the authors. Nevertheless, we hope that it will inspire more scientists to bridge the gap between the two communities.

2. Structural diversity

The synthesis of MOFs has received extensive attention since the inception of the field. Indeed, the initial studies that developed coordination polymers and MOFs focussed almost exclusively on developing synthetic approaches to multi-dimensional framework arrangements.[3] Significant success has been made in this regard using the basic concepts of the building-block[3b] and reticular chemistry[4] approaches which exploit the geometries of metal cations and clusters in combination with ligand design to control framework connectivity. Using this strategy, many highly complex frameworks have been developed,[5] and the diversity of MOFs is extraordinary, with increasing levels of functionality being incorporated into the resulting materials.[6] The building-block approach and development of reticular chemistry has led to in excess of over 70,000 reported MOF crystal structures by 2016,[7] a number which is now significantly larger and supplemented by materials for which crystal structures have not been reported.

Perhaps the major difference between MOFs and MOCs is that in the formation of MOFs, the components (both metal cations and ligands) are specifically chosen to ensure polymer growth. Metal cations are typically not capped, leaving coordination sites free for ligand coordination, and ligands are chosen to facilitate framework propagation (Figure 1a).[8] Such ligands can be termed 'exodentate', i.e. they have donor atoms oriented outwards to promote bridging between centres. Metals from across the periodic table have been investigated for the formation of MOFs,[6] but first row d-block cations, such as Zn(II) and Cu(II), have received particular focus due to their labile nature[13] which facilitates growth of crystals suitable for single crystal X-ray diffraction (SCXRD) studies. However, the nature of the building-block approach means that no metal is impossible to use in MOF formation and amongst naturally occurring metals it is difficult to find a metal that has not been investigated. Amongst linkers, certain classes of ligands are more commonly studied, e.g. di- and tri-carboxylates,[3b,14] bipyridyls[15] and imidazolates,[16] but this does not preclude

[a] *Dr. B. S. Pilgrim, Prof. N. R. Champness*
School of Chemistry
University of Nottingham
University Park, Nottingham, NG7 2RD (United Kingdom)
E-mail: ben.pilgrim@nottingham.ac.uk
neil.champness@nottingham.ac.uk

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

Chemistry Europe
European Chemical
Societies Publishing

other ligand types which are more commonly encountered in solution phase coordination chemistry, e.g. phosphorus[17] or sulfur-based[18] ligands. Other ligands such as *N*-heterocyclic carbenes are rarely used for MOF propagation, i.e. binding to the metal nodes of the framework, but can be incorporated into MOFs, either decorating or appended to the overall framework.[19] Due to the wide variation in ligand types within MOFs it is readily possible to prepare neutral, cationic and anionic MOFs depending on the specific goal of the research. Neutrally charged MOFs are seen as an attractive target; the absence of charge-balancing anions often viewed as beneficial to maximise porosity. The length of organic linker can be varied in both MOFs and MOCs (Figure 1b). This is often achieved by incorporation of additional benzene rings, due to both their structural rigidity, and the relative ease of ligand synthesis (often courtesy of metal-catalysed cross couplings). With longer linkers, peripheral solubilising groups become crucial to maintain ligand solubility (Figure 2).[20]

The field of MOCs has experienced huge growth in the past 20 years. As MOCs are finite structures unlike MOFs, careful design of the constituent pieces is required to bias formation of discrete molecular entities over extended frameworks. MOCs are designed to benefit from both allosteric and chelate cooperativity.[22] Synthesis must be undertaken in the appropriate concentration regime – polymeric aggregates form if concentrations are too high and assembly does not occur if concentrations are too low.

Several synthetic approaches to MOCs have been developed. The symmetry interaction approach exploits chelating ligands to satisfy all coordination sites on a metal, whilst ensuring that the ligands extend outwards from a metal within the same hemisphere to form a closed structure (Figure 1c). In this approach, it is crucial to ensure both the coordinate vector of the ligand and the chelate plane of the metal are matched to achieve the desired structure.[9,23] Alternatively, the directional bonding approach combines organic ligands with donor atoms in well-defined orientations with metal atoms with fixed angle coordination sites (Figure 1d).[10,24] Whereas these two strategies lead to primarily edge-capped polyhedral MOCs, a third strategy employs ligands as two-dimensional panels to cap faces of polyhedral MOCs (Figure 1e and Figure 1f).[12,25] In both the directional bonding and face panelling approaches, not all metal coordination sites may be required for ligands, and so it is common to add other ligands to block remaining coordination sites to ensure the structure is discrete. (Figure 1e).[11] Huge structural diversity has been achieved using these approaches and others, which include using weaker reversible coordination.[26]

A vast library of structures have been assembled, with the Platonic solids (tetrahedra, cubes, octahedra, dodecahedra[27] and icosahedra[12]), the Archimedean solids (e.g. cuboctahedra[28] and rhombicuboctahedra[29]), and prisms,[30] particular favourites. However, with all these strategies, constructing large MOCs is difficult.[31] Simpler edge-capped structures rapidly become too open to display 'cage'-like properties and ligands for face-capped structures quickly become synthetically challenging to make. This can be somewhat combatted by targeting polyhedra with greater vertex numbers. Some of the largest finite MOCs include an $M_{24}L_{48}$ rhombicuboctahedron,[29] an $M_{30}L_{60}$ icosidodecahedron[32] and $M_{30}L_{60}$ and $M_{48}L_{96}$ assemblies based on tetravalent Goldberg polyhedra.[21] These MOCs hold impressive cavities and approach the size of the largest MOF cavities that have been constructed (Figure 2).[20]

More recent efforts have focussed on designing more structurally-intricate assemblies, mixed ligand and mixed metal[33] assemblies, structures of lower symmetry, and non-racemic chiral architectures.[34] Like MOFs, MOCs can be

Ben S. Pilgrim is a Research Fellow in the Green Chemicals Beacon of Excellence at the University of Nottingham, UK. He studied for his MChem at St John's College, Oxford University, UK from 2005–2009. Ben completed his doctoral studies with Timothy Donohoe in 2013 and then moved to the University of Cambridge, UK on a Herchel Smith Research Fellowship working with Jonathan Nitschke on metal-organic cages. In 2016, Ben was awarded a Royal Commission for the Exhibition of 1851 Research Fellowship to investigate 'Stimuli-responsive molecular containers', and in 2019 moved to Nottingham to start his own lab in supramolecular organic chemistry.

Neil R. Champness is the Professor of Chemical Nanoscience at the University of Nottingham, UK. After completing his PhD at the University of Southampton, UK, with Bill Levason he moved to Nottingham in 1995, reaching his current position in 2004. His research spans chemical nanoscience and all aspects of molecular organization, including surface supramolecular assembly, the synthesis of mechanically interlocked molecules and supramolecular chemistry in the solid-state using crystal engineering aproaches. He has worked on MOFs and related materials for over 25 years.

Ben has received advice and support from Neil since originally meeting at a dinner held by the Royal Commission for the Exhibition of 1851. This contribution arose from their ongoing discussions since Ben moved to the University of Nottingham in 2019. The synergies between their research groups who study metal-organic cages (Ben), and metal-organic frameworks (Neil), led to the original formulation of the ideas described in this perspective.
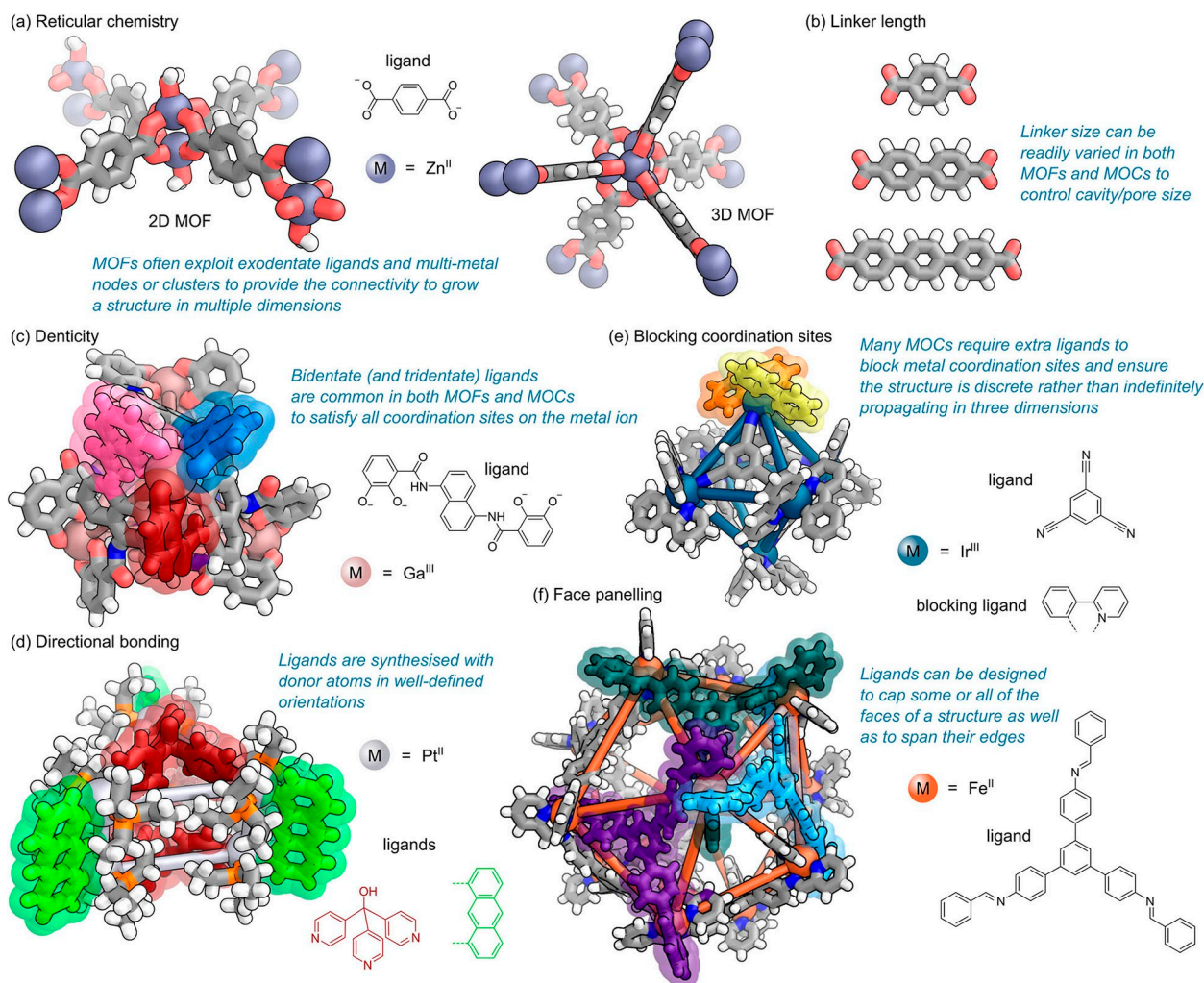
ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

**Chemistry
Europe**
European Chemical
Societies Publishing

Figure 1. Construction strategies: (a) The reticular chemistry of MOFs often employs both exodentate ligands and multi-metal nodes or clusters to grow a framework in multiple dimensions;[8] (b) Linker length can be readily varied in both MOFs and MOCs to control the size of the cavity or pore; (c) Three bidentate chatecholate ligands meeting at a vertex to satisfy the octahedral coordination sphere of Ga(III) in a MOC;[9] (d) The directional bonding approach of using well-defined ligand geometries to control the shape of MOCs;[10] (e) Two bidentate ligands block vacant coordination sites on each vertex of an M_6L_4 octahedral MOC keeping the structure discrete;[11] (f) Face panelling of an $M_{12}L_{12}$ icosahedral MOC, where three faces meeting at each vertex are panelled.[12]

constructed from a wide variety of ligands and metals across the Periodic Table. In particular, Fe(II), Pd(II), Pt(II), Zn(II),[35] Co(II)[36] and Ga(III)[9] have seen widespread use. In terms of the organic ligands, pyridine is unrivalled in ubiquity. It is frequently combined as part of bidentate and tridentate coordination motifs, including bipyridyls,[37] pyridyl imines,[38] pyridyl triazoles[36] and pyridyl pyrazoles.[39] Notable mentions should also be given to phosphines and thioethers (particularly in weak/reversible coordination).[26] Due to the metal ions, most MOCs are cationic, although where the ligand is anionic (eg. chatecholate[9]), then anionic MOCs can also be constructed; neutral MOCs are less frequently reported. Although both MOF and MOC compounds must have cationic and anionic parts of equal overall charge, the finite nature of MOCs means that the counterions can often be considered separate entities in solution and not part of the MOC itself, although the extent to which they are dissociated is obviously highly solvent-dependent.

3. Ease of synthesis

The degree to which a specific MOF, or family of MOFs has been studied depends to a large degree on the commercial availability of the ligand, and to a lesser extent, the metal cation. Indeed perhaps the most widely studied MOFs are those built from commercially available terephthalic acid, e.g. MOF-5[40] and MIL-53.[41] The latter family of MOFs have been reported for a range of different metal cations, mixed metal cations, and for functionalized analogues of the linking terephthalate ligands but, importantly, all having the same framework structure.[41] The synthesis of such MOFs is typically straightforward with hydrothermal or solvothermal syntheses being the methods of choice. The precise method of synthesis is highly dependent on the targeted application, and importantly, the method of characterization that is intended. As the major method of characterization of MOFs is X-ray diffraction, and particularly SCXRD, synthetic methods are conventionally focused on
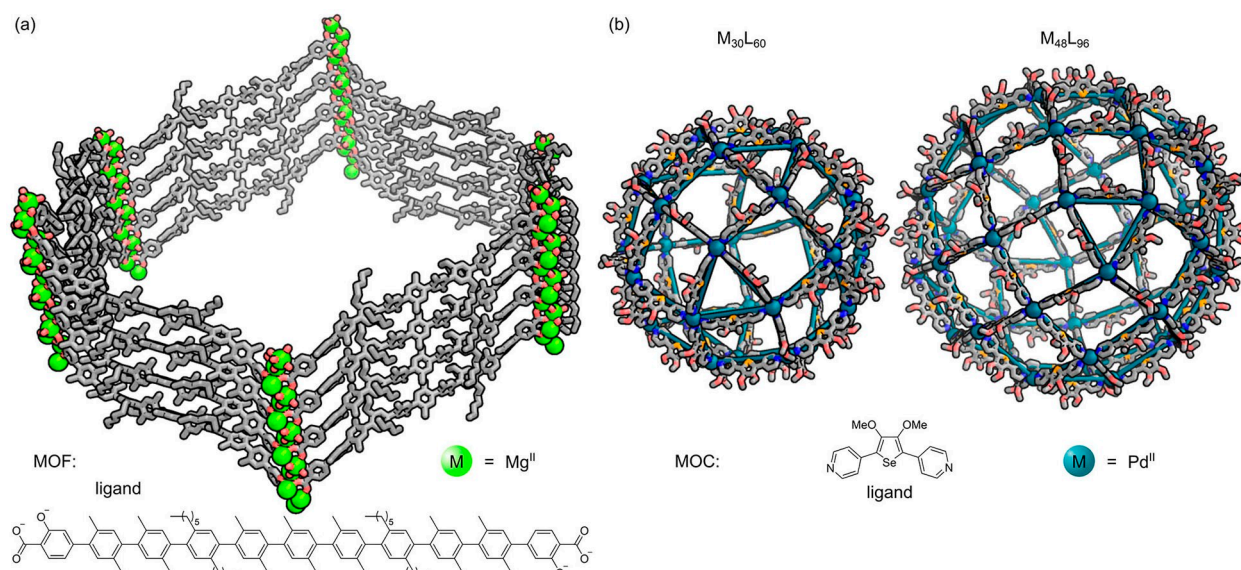
ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

**Chemistry
Europe**
European Chemical
Societies Publishing

Figure 2. A size comparison: (a) A section of the crystal structure of a MOF with a 98 Å pore;[20] (b) The crystal structures of $M_{30}L_{60}$ and $M_{48}L_{96}$ tetravalent Goldberg polyhedral MOCs.[21] Structures are shown to the same scale. Hydrogen atoms have been omitted for clarity.

preparing highly crystalline material. For large scale production, the degree of crystallinity of a sample, and particularly crystallite size, may be less important and therefore it is possible to move away from solvothermal methods. Thus, alternative approaches have become increasingly studied, partly in attempts to prepare MOFs on a large scale. Such studies include mechanochemical,[42] microwave,[43] and even continuous flow synthesis.[44]

If MOFs with specific or complex properties are the targets of a given study, then ligand synthesis can become increasingly laborious. However, a number of approaches to preparing specific, complex materials are known, not least of which is post-synthetic modification[45] of the framework which can allow the introduction of sensitive chemical groups – groups which may not withstand the initial MOF synthesis such as metal complexes[46] – to the framework structure.

Although there are some examples of MOCs that can be constructed entirely from the self-assembly of commercially available components,[38] the majority require ligand synthesis before self-assembly can be attempted. The high reliance on heteroaryl units in the ligands, and the fact that bidentate and tridentate coordination typically require peripheral substituents to be installed on these heteroaryl rings, can make synthesis challenging. Suzuki and other sp^2–sp^2 carbon-carbon bond couplings are clear frontrunners amongst ligand synthesis strategies.

Whereas several MOFs are ubiquitous, fewer MOCs have become highly dominant to the same extent, with most research groups choosing to focus on systems (e.g. certain coordinating groups or design strategies) they have developed in house. Most MOC self-assemblies, at first glance, are straightforward solution-based combinatorial procedures, where the components are mixed and typically heated. The cooperative nature of assembly means, with well-designed pieces, often essentially quantitative assembly of components can be achieved into a single type of structure. However, very slight modifications in many factors (e.g. ligand structure, metal ion, solvent, counterion, temperature, concentration etc.) can completely shut down the assembly process. This perhaps explains why research groups tend to focus on MOCs they have developed themselves, so that they fully understand such nuanced behavior, however this approach does limit the wider applications of such MOCs. As with MOFs, post-synthetic or post-assembly modification is rapidly becoming an important strategy to diversify MOCs after construction, by introducing new reactive functionality, locking-down structures, or inducing structural transformations (see Section 6).[47]

4. Characterisation

In order to determine the structure of a given MOF, the major technique employed is SCXRD. As MOFs are inherently solid-state materials, determining their structure is highly reliant on diffraction techniques, leading to a requirement for crystalline materials. It is also possible to employ powder X-ray diffraction[48] and neutron diffraction[49] studies for similar objectives, although the latter is typically used for specific targets, notably for the identification and characterisation of guest molecules.[50] Other techniques have been used to characterise MOFs, for example solid-state NMR,[51] or specific properties of MOFs, such as spectroscopic studies,[52] magnetism,[53] or conductivity measurements,[18] but probably the most important technique that is commonly used to characterise MOFs is adsorption measurements. The IUPAC definition of a MOF requires 'potential' porosity[54] and therefore the ability of MOFs to adsorb guest molecules, particularly gases, has received extensive study.[55]

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

**Chemistry
Europe**
European Chemical
Societies Publishing

One of the major challenges in MOF research, and in contrast to MOCs, is that it is seldom feasible to purify a product post-synthesis. In limited cases it is possible to manually separate particles of different morphology,[56] but this is rarely an effective method to produce significant quantities of a material. Diffraction is commonly used to prove phase purity of a MOF, but this can present challenges for materials that contain weakly diffracting, minor components or amorphous phases. However, the study of amorphous systems and samples that contain defects has become of increasing interest as these systems have been shown to exhibit unusual properties.[57]

A benefit of MOCs over MOFs is that the toolkit of small molecule characterisation techniques can generally be applied as many MOCs are solution processable. ^{1}H NMR is often the first technique of choice as modern spectrometers can produce high resolution spectra on samples at typical concentrations (e.g. 0.5 mM) of MOC solutions.[58] ^{1}H NMR immediately reveals information on the nature of assembly (discrete assemblies vs diverse combinatorial libraries) and elucidates the symmetry (or lack of) in any structures. Through bond coupling experiments are useful as always, but through space techniques based on the nuclear Overhauser effect (NOEs) really come into their own. Diffusion ordered spectroscopy (DOSY) is particularly powerful for differentiating MOCs based on size.[59] Many MOC counterions and guests incorporate elements that can be usefully studied (e.g. ^{19}F or ^{31}P) and ^{13}C NMR can be useful if concentrations permit. Many MOCs are constructed from aryl/heteroaryl ligands, placing the interior cavity in the ring current shielding zone. Hence, bound guest signals are detected at lower shifts than expected (interestingly the effect is reversed for antiaromatic panels[60]). Binding titrations allow elucidation of association constants and can be performed whether the guest is in slow exchange or fast exchange on the NMR timescale[61] and uptake titrations can determine kinetic parameters of binding.

Metal-ligand charge transfer transitions and the highly conjugated nature of MOC ligands make many MOCs coloured and so UV/Vis spectroscopy is very useful. UV/Vis absorption profiles are highly sensitive to small structural changes (such as occur on guest binding) and hence this is another helpful technique for binding studies.[62] Isothermal titration calorimetry (ITC) is also helpful in this regard.[63]

Unlike MOFs, the finite nature of MOCs means that they can be analysed via mass spectrometry (MS). Under soft electrospray ionisation (ESI) conditions, entire MOCs can be ionised without fragmentation. The multiply-charged MOCs fly with varying numbers of counterions, giving distinct patterns which can aid analysis.[64] With MOCs of low symmetry, or in systems of mixed MOCs, MS can often provide information when there would be too many overlapping signals for ^{1}H NMR spectroscopy to give clear information. MS experiments are usually regarded as qualitative and not quantitative. However, if the response factors under ESI conditions of complexes can be determined, it can enable quantitative determination of species; for example, how guest binding drives a redistribution of host structures within mixed ligand systems.[65] In recent years, ion mobility MS has become more routine for MOC analysis. It is not uncommon for certain metal/ligand combinations to form several different MOCs with the same mass to charge (m/z) ratio, e.g. $[Fe_2L_3]^{4+}$, $[Fe_4L_6]^{8+}$, $[Fe_8L_{12}]^{16+}$.[66] Ion mobility experiments make use of collisions with an inert carrier gas to reveal information on size and shape of assemblies; with MOCs with greater collision cross-sections undergoing more collisions and therefore having longer flight times/lower mobility.[67] This allows ion mobility MS to distinguish between isomeric species of the same m/z that often appear similar/the same in other analysis techniques. An interesting class of stimuli-responsive MOCs containing four dithienylethene photoswitchable units undergo reversible interconversion between closed (Figure 3a) and open (Figure 3b) forms via a light-promoted 6π electrocyclization.[68] The two isomeric open and closed MOCs could be differentiated by ion mobility MS. Not only do the open and closed forms have different guest binding properties, but the presence of chiral guests can also influence the enantioselectivity of the ring closing reaction.

SCXRD remains the gold standard for MOC characterisation, with such analysis a prerequisite for complex structure determination. SCXRD can reveal key non-covalent interactions such as hydrogen bonding, cation-π, anion-π, π–π and C—H-π interactions which can indicate why a particular structure has formed and inspire rational design of new structures.[69] However, growing sufficiently crystalline material and solving structures from diffraction data are both highly demanding, although the latter has been made easier with modern approaches.[70]
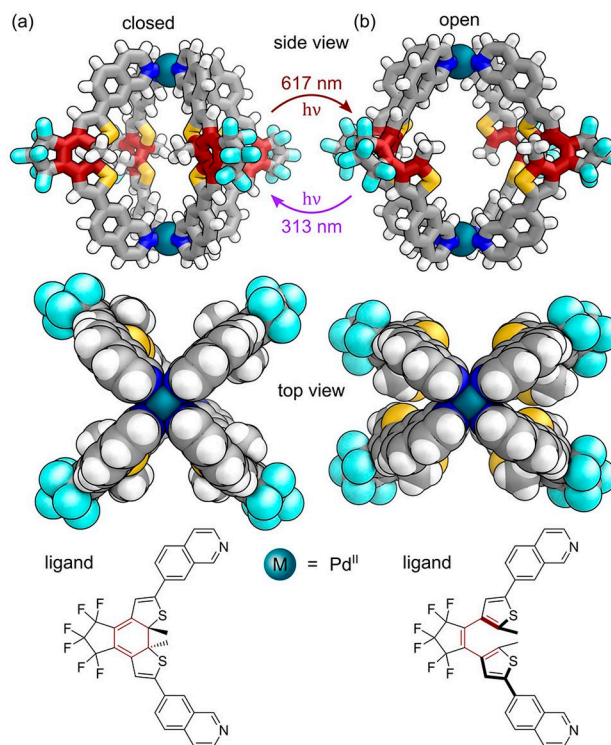

Figure 3. Differentiating between isomeric MOCs: (a) Closed M_2L_4 MOC, and (b) Open M_2L_4 MOC are isomeric structures that can be interconverted by UV/visible light. Although isomers, they can be differentiated by ion mobility mass spectrometry due to different three dimensional shapes.

One clear advantage of MOCs is that it is possible to purify MOCs from non-supramolecular impurities. Although MOCs are typically not stable to polarity-based separations (e.g. silica gel chromatography), MOCs with many metal/ligand combinations can be purified by size exclusion chromatography.[66,71] Different solubility properties of the MOC and its constituent pieces mean precipitation[72] and biphasic extraction techniques also find use. The latter is often the best way of separating mixtures of MOCs from each other. Hence, it is often possible to obtain MOCs in high percentage purities.

In addition to gaining experimental data on MOFs and MOCs, numerous computational studies have been performed on these systems. As MOFs/MOCs contain both metal ions and organic ligands, they are often more challenging to model computationally than purely organic or purely inorganic compounds. More straightforward, albeit often very useful calculations can determine parameters such as pore limiting diameters, cavity diameters, and cavity volumes.[73] Quantifying binding strength is a harder computational problem, and can be more hit and miss in terms of the required accuracy a calculation must provide. Hence computational studies may be better suited for initial high-throughput screens[74] preceding experimental work. Prediction of relative energy of different structural types or indeed possible structures that can form or have a certain property (such as catalytic activity[75]) is the area where computational techniques perhaps have the most to offer. Research groups are now regularly publishing open source code[76] for both MOFs[77] and MOCs.[78] Hundreds of thousands of hypothetical MOF structures have been predicted for example,[79] and thus it is helpful that computational methods can also offer easy identification, classification and searching of large numbers of structures.[80] The application of computational techniques to MOFs/MOCs is constantly evolving and is an area that undoubtedly will see great strides forward made in the 2020s.

5. Stability

MOFs are widely regarded as stable solid-state materials and this is not, in general, an unreasonable view. However, although such materials appear to be robust, there are of course limitations to this stability. For example, one of the most widely studied MOFs, HKUST-1,[14] is known to be stable with respect to the presence of ethanol but not stable to water,[81] in the latter case adsorption of water leads to loss of crystallinity. This instability in the presence of water of one of the most widely studied classes of MOFs, those based on copper(II) paddlewheel complexes, can be addressed by the introduction of sacrificial subunits, or 'crumple zones', that retain the stability of the majority of the MOF following exposure to water.[82] Indeed, studies have demonstrated that some MOFs undergo reversible dissolution and regrowth in some solvents leading to a constantly changing MOF particle surface.[83] Attempts have been made to stabilise MOFs by surface coating and there are undoubtedly opportunities to further develop this aspect of the field.[84]

Considerable effort has been made to address the question of MOF stability and some MOFs have been developed which demonstrate excellent stability under a variety of conditions.[85] A notable family of MOFs that exhibit excellent stability are those based on Zr-carboxylates. Indeed, UiO-66, the parent MOF built from Zr(IV) cations and terephthalate linkers[86] and related ligands has been shown to exhibit stability across a large pH range[87] notably under acidic conditions but also, in certain cases, in basic environments.

Unlike MOFs, MOCs are predominantly self-assembled and studied in solution. Although many MOCs survive transfer to and from the solid state without degradation, most are not regarded as solid-state materials. When working with MOCs in the solid state it is important to consider whether they exhibit the same binding properties (and even have the same structure) as in solution. Recently an $M_{14}L_{24}$ rhombic dodecahedral MOC was shown to encapsulate the important greenhouse gas CO_2 both in solution and in the solid state,[88] and other MOCs are known to encapsulate CO_2[89] and H_2[90] in the solid state. It is crucial to consider not only the internal cavities of MOCs in the solid state, but also the external cavities formed due to solid-state packing, as this may be where binding occurs.[91] Indeed, tailoring interactions between MOCs to direct assembly to higher length scales in the solid state more generally is an active area of research.[92] The stabilisation of carboxylate-based MOCs with a view to realising materials-based applications has recently been reviewed.[93]

In solution phase, acetonitrile and water are the two most popular solvents – solubility and stability in the latter vital for realizing many applications. MOCs can be divided into two categories: (i) those able to form in water,[38] and (ii) those that are kinetically but not thermodynamically stable in water (i.e. can persist in water but unable to form in water).[94] MOCs can also be stable in much less polar solvents (e.g. hydrocarbons), although are challenging to synthesize under such conditions. When dealing with MOCs in solution, careful consideration should be given to factors such as high temperature, extreme pHs, and low/high concentrations, as all can cause decomposition. However, there is much variability depending on the system and there are notable examples of MOCs tolerating extreme conditions.[95] Although MOFs may be more suitable for solid-state materials, MOCs show great promise as soft matter/materials. The high symmetry of MOCs allows them to serve as junctions for cross-linking to form gels. The resulting gel materials have high branch functionality and both hydrogels[96] and organogels[97] have been constructed. Recently, a MOC has been developed that is an ionic liquid in its pure state.[98] This permanently porous liquid was able to bind a number of environmentally-polluting CFCs.

6. Structural transformations

MOFs are known to undergo reversible structural transformations and post synthetic modifications of MOFs is a vast area of research in its own right.[45] In addition to chemical modification of MOFs through the formation of covalent bonds, it is also

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

Chemistry Europe
European Chemical
Societies Publishing

possible to post-metallate MOFs and this allows the introduction of reactive metal complexes,[46] an approach which facilitates the study of catalytic processes (see Section 8).

Even if one does not consider post-synthesis modification processes, MOFs exhibit fascinating flexibility.[99] Perhaps the most famous example of flexible behaviour is the breathing of MIL-47[100] and MIL-53,[101] both of which can convert from large pore to small pore forms (Figure 4). This change in structure, which is accompanied by variation in bond angles at vertices of the MOF, can be triggered by exposure to guest molecules and temperature changes. Perhaps the most interesting aspects of MOF behaviour relate to their ability to host guest molecules, in many cases modifying their behaviour and this aspect of the field is discussed in more detail later (see Section 7).

The dynamic nature of MOCs in solution provides both challenges and opportunities for structural transformations post synthesis. Structural transformations of MOCs can be induced by many factors, as recently reviewed.[102] Structures can adapt as a result of changes in solvent,[103] concentration,[104] temperature,[105] light,[106] and guest binding.[68] The post-assembly modification of MOCs via new covalent bond formation is a particularly active area.[47] Reactions using mild reagents/proceeding under mild conditions such as the azide-alkyne Huisgen cycloaddition[107] and the inverse electron demand Diels-Alder reaction[66,71a,108] have been particularly useful, as have light-promoted electrocyclic reactions (Figure 3).[68] It is also possible for systems of MOCs to reconfigure to form mixed ligand structures, either due to entropic favourability or to stronger guest binding (Figure 5d).[109] Current challenges in the field in particular involve engineering

Figure 4. Reversible structural transformations: The MIL-53 MOF has a flexible framework which can undergo a reversible expansion or contraction (or breathing) in response to various stimuli.[101a] Hydrogen atoms have been omitted for clarity.

systems that can undergo multiple structural transformations in response to multiple different classes of stimuli.[35,66]

7. Range of guest binding ability

Probably the most widely investigated property of MOFs is their ability to act as hosts for guest species. Indeed, the variety of guests that can be trapped by MOFs is extraordinary and arises from the large variation of pore sizes that can be created within these frameworks. Much attention has focussed on small molecule gases, notably H_2, CH_4 and CO_2,[55,110] but other gases such as SO_2 or Xe have also been investigated (Figure 5f).[111] Due to the large porosity of MOFs, including materials with the highest known internal surface areas, remarkable capacity for gas storage has been reported including some of the best materials known.[112] However, to think of MOFs as gas storage agents alone would be unfair, and the range of compounds that have been trapped in MOFs includes much larger molecules, such as fullerenes[113] and even proteins.[20,114] MOFs with extremely large pores, with apertures of up to 98 Å in diameter, have been reported (Figure 2).[20] Proteins and enzymes can be trapped within such materials, indeed, the encapsulation of microperoxidase-11 within the pores of a MOF lead to enhanced catalytic performance of the enzyme.[114] As MOFs are solid-state materials it is also possible to grow MOFs around large guests including proteins,[115] nanoparticles[116] and nanorods.[117]

One of the most interesting new directions of MOF host-guest chemistry is their use as crystalline sponges.[118] As MOFs are typically crystalline in nature it is possible to use the order of the framework to arrange guest molecules into crystalline arrangements. This approach allows the determination of the crystal structure of the guest molecule within the framework. This strategy has enabled the determination of the structure of molecules where there are such small quantities of the material that growing crystals of the target is just not feasible (Figure 5e).[119] The crystalline sponge method has been used to determine the structure of natural products and even to determine the absolute configuration of chiral species.[120] However, there are difficulties with applying the strategy, notably in terms of achieving high loadings and a high degree of order of the guest to allow unequivocal determination of the target structure.[118a]

Whilst metal-organic assemblies can be of huge interest from purely a structural point of view, the guest binding ability of such structures drives the sustained interest in the area. Unlike MOFs, guest binding within MOCs predominantly occurs in solution and the choice of solvent has a huge influence on binding. Acetonitrile and water are perhaps the two most studied solvents – the hydrophobic effect obviously being much more significant in the latter. An area of great promise is in biphasic or triphasic systems of immiscible solvents including hydrocarbon solvents and ionic liquids.[121] MOCs can be designed to preferentially partition into one phase and have unique host-guest chemistry in that phase. Even more excitingly, movement of MOCs between phases in response to
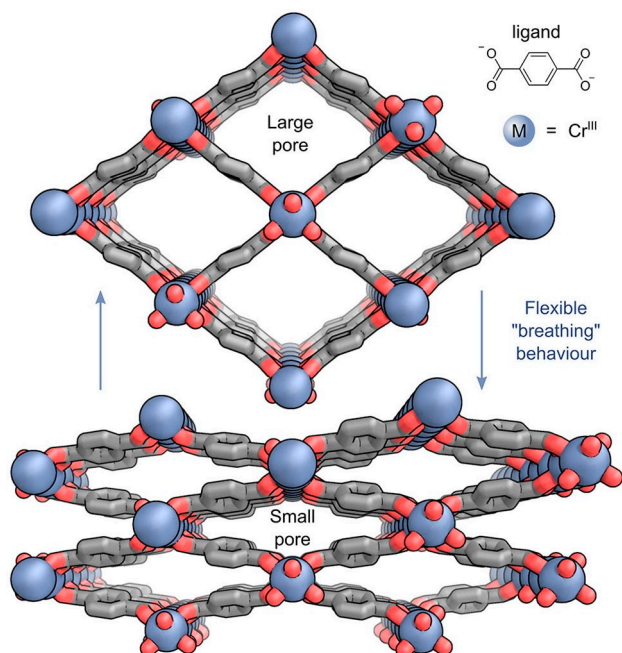
ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

Chemistry Europe
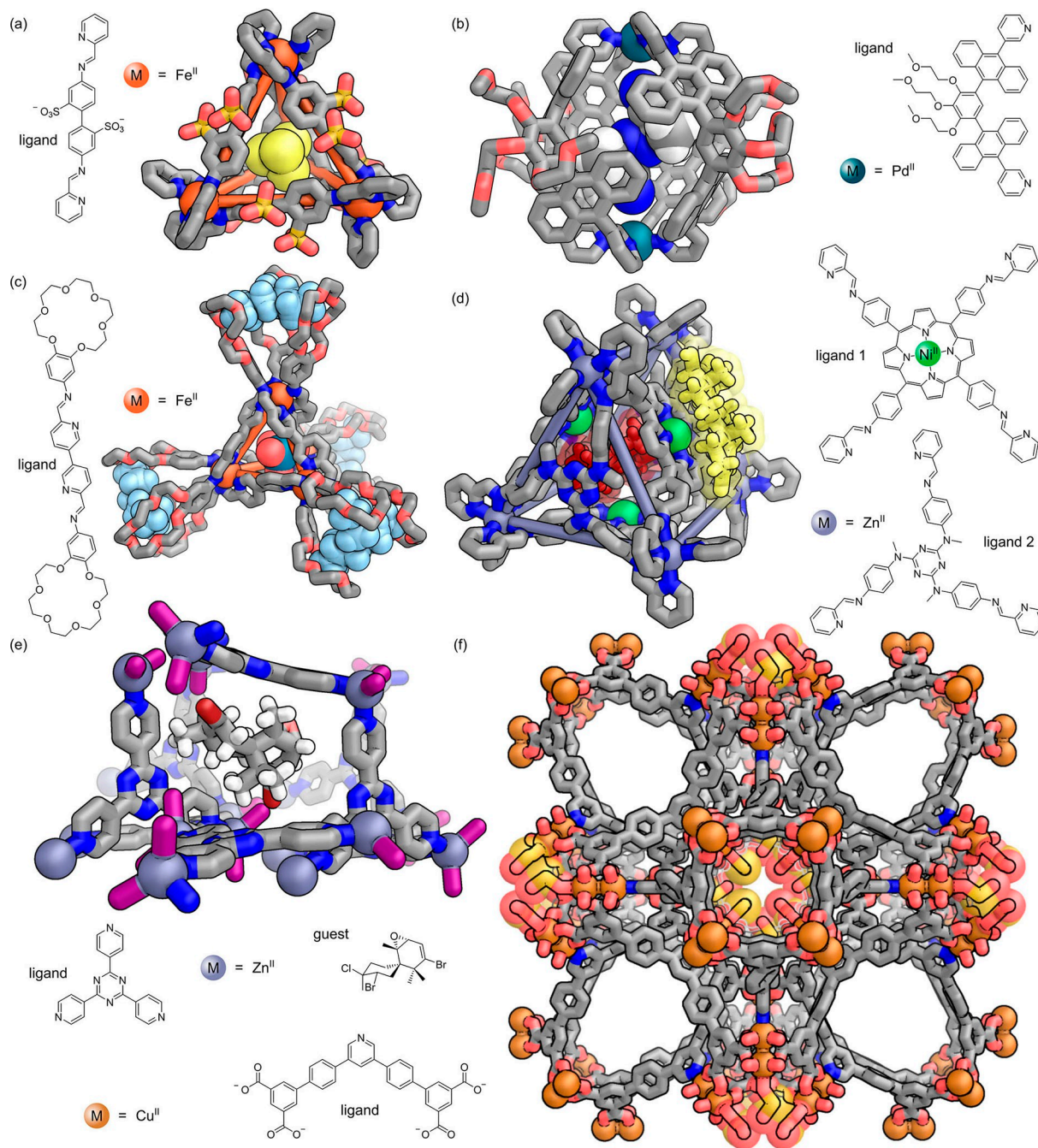European Chemical
Societies Publishing

Figure 5. Guest binding: (a) Normally pyrophoric P_4 is rendered stable inside a tetrahedral M_4L_6 MOC;[38] (b) The rate of decomposition of the radical initiator AIBN is reduced inside an M_2L_4 MOC;[127] (c) External binding of four protonated TREN molecules to the crown ether caps of an MOC allows allosteric regulation of the rate of exchange of the perrhenate guest;[132] (d) Testosterone is bound in distinct interior and exterior binding sites of an $M_6L_3L'_2$ MOC;[109a] (e) MOFs can act as crystalline sponges and uptake small organic molecules enabling the structural determination of natural products by SCXRD;[120] (f) MOFs show great promise for gas uptake applications, such as the desulfurization of waste gas streams by the removal of SO_2.[111b] Hydrogen atoms on the MOCs and MOFs have been omitted for clarity.

chemical stimuli[71a] or heat,[122] allows selective transport of their cargoes, and can be engineered to achieve useful outcomes such as anion extraction from water into a less polar solvent.[123] MOCs can also embed in membranes, where transient guest-binding ability allows them to gate the passage of guests such as the alkali metal cations[124] and the chloride anion[125] across boundaries.

Whilst the majority of guests encapsulated are relatively benign, MOCs have been employed to bind a number of highly reactive species,[126] including the normally pyrophoric P_4 (Figure 5a),[38] AIBN (Figure 5b),[127] and coordinatively-unsaturated transition metal complexes.[128] Although anion binding within MOCs has been studied extensively,[129] this is one area where more work is needed to develop MOCs capable of binding

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

**Chemistry
Europe**
European Chemical
Societies Publishing

highly reactive anions (which tend to interfere with metal-ligand coordination due to strong nucleophilicity), and this influences the types of chemical reactions which MOCs can promote.

More recently, efforts have focused on designing MOCs that can bind multiple guests at once.[130] Here, the clear distinction with MOFs can be seen due to the well-defined relationship between interior and exterior binding sites. Guests can bind in both and this can be readily determined by SCXRD (Figure 5d).[109a] Binding of guests on the exterior faces of MOCs has been shown to both allosterically regulate the binding strength of guests on the interior[131] and the rate of guest exchange within the internal cavity (Figure 5c).[132] An $M_{12}L_{24}$ MOC constructed from extended ligands was able to encapsulate the 8.6 kDa, 3–4 nm-sized globular protein ubiquitin.[133] The cavities of other pseudospherical MOCs have also served as a micro-environment for the construction of extremely monodisperse polymethyl methacrylate particles and silica nanoparticles.[134] However, despite these impressive results, MOFs are still more commonly used to trap larger guests. This is probably a result of the synthetic strategies used for making MOFs which have targeted larger pores since the earliest stages of the field. Thus, MOFs currently maintain an advantage over MOCs for the encapsulation of larger guests.

8. Catalysing chemical reactions

The use of MOFs for catalysis has received attention since the early days of the field. Recent reviews[135] have revealed the ability of MOFs, or complexes hosted by a MOF, to enhance catalytic processes. There are many interesting examples of MOFs which enable catalytic processes and so we focus on two examples here which bridge the conceptual gap between heterogeneous and homogeneous systems. Although MOFs are inherently heterogeneous, their design and porous nature allows both the incorporation of metal complexes more traditionally associated with homogeneous catalysis and diffusion of reagents to and from the active site. Using the anionic MOF $[Et_4N]_3[In_3(BTC)_4]$ (where $H_3BTC =$ benzenetricarboxylic acid), it is possible to entrap the molecular cationic Lewis acidic catalyst $[CpFe(CO)_2L]^+$ (where L represents a weakly bound solvent molecule such as acetone), via cation exchange.[136] Once incorporated within the MOF, the well-defined molecular species catalyses a Diels-Alder reaction and was found to be more readily recycled, in comparison to a homogeneous analogue, over a period of days. A similar approach has been used by the same researchers to incorporate Crabtree's catalyst,[137] $[Ir(cod)(PCy_3)(py)]^+$, within an anionic, sulfonated version of MIL-53(Cr). In this instance, the encapsulated catalyst outperforms its homogenous analogue for the hydrogenation of olefinic alcohols both in terms of overall conversion and in terms of selectivity. The enhanced performance is attributed to the well-defined hydrophilic environment within the MOF pores which also leads to improved stability of the entrapped cationic catalyst.

Another advantage of using MOFs to enclose catalysts is that in specific cases it is possible to study the steps in a reaction sequence by SCXRD.[135a] Recent examples have demonstrated that MOFs can be prepared containing additional binding sites on the struts of the MOF, allowing complexation of additional metal complexes.[138]

In some instances, it is possible to perform reactions at the tethered metal complex, with reagents diffusing through pores to the reactive site, and then to characterise the product by SCXRD, if sufficient conversion is observed. For example, the framework Mn_3L_2L' (L = bis(4-(4-carboxyphenyl)-1H-3,5-dimethylpyrazolyl)methane), undergoes postsynthetic metalation at a vacant di-pyrazole pocket with $Mn(CO)_5Br$ to afford the framework $[Mn_3L_2L'] \cdot [Mn(CO)_3(H_2O)]Br$, capable of site selective reactions (Figure 6a).[138c]

Reaction of the tethered complex with NaN_3 forms $[Mn_3L_2L'] \cdot [Mn(CO)_3N_3]$ (Figure 6b) which in turn reacts with electron deficient alkynes (e.g. dimethylacetylene dicarboxylate or ethyl propiolate), through an azide-alkyne Huisgen cycloaddition reaction to form coordinated triazole species (Figure 6c). The N-alkylated triazole products could be successfully released from the MOF following reaction with MeBr, regenerating the original framework $[Mn_3L_2L'] \cdot [Mn(CO)_3(H_2O)]Br$. Each of these steps occurs via a single crystal to single crystal (SC-SC) process and can be characterised by SCXRD, allowing direct appreciation of the geometry and conformation of the intermediates and products.
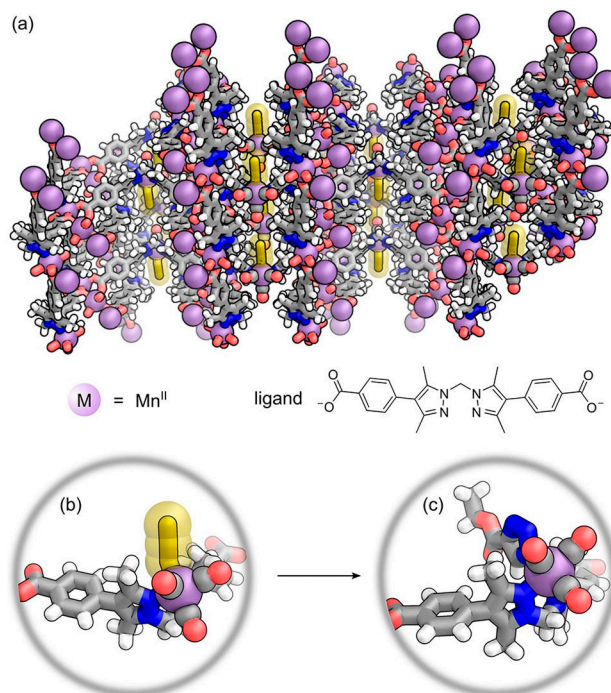

Figure 6. Reaction snapshots with SCXRD of MOFs: (a) Crystal structure of the MOF Mn_3L_2L' after reaction with $Mn(CO)_5Br$ and then NaN_3;[138c] (b) Close up of the Mn catalytic site with bound azide highlighted in gold and three bound CO molecules shown with spacefilling; (c) Close up of a second SCXRD after the Huisgen cycloaddition has occurred, illustrating the coordinated triazole.

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

**Chemistry
Europe**
European Chemical
Societies Publishing

As with MOFs, there has been great interest in employing MOCs for catalysis. Indeed catalysis within MOCs[139] and catalysis within confined systems more generally[140] have both been recently reviewed highlighting the breadth of this field. MOC-based strategies involve bringing reactants into closer proximity (benefitting reactions such as Diels-Alder cycloadditions[25a,141]), the enforcement of guests to adopt more compact conformations (promoting reactions such as the aza-Cope rearrangement[142] and Nazarov cyclization[143]) and increasing the local concentration of the catalyst in the cavity to levels far higher than the overall concentration in solution.[144]

We will focus discussion here on examples where the finite nature of MOCs enables them to exploit reaction-promoting strategies that would not be achievable within MOFs. Unlike MOFs, the finite interior environment of MOCs is always surrounded by the exterior environment of bulk solution. Large guests can bind so that part of the guest is confined within the MOC interior and another part protrudes into bulk solution. MOCs can thus be used as non-covalent protecting groups. For example, flexible linear diterpenoids have to adopt a U-shaped conformation to bind within an M_6L_4 MOC in aqueous solution (Figure 7a).[145] Of the four double bonds in diterpenoids, three are tri-substituted and often similar in reactivity. ^{1}H NMR studies revealed that the two central double bonds experienced greater shielding due to proximity to the MOC's aromatic panels. However, the prenyl group was oriented towards the MOC portal, allowing selective electrophilic addition reactions upon this group with both NBS and *m*CPBA (Figure 7b). Partial guest encapsulation can also promote regioselectivity when the reaction takes place inside the MOC. An encapsulated

rhodium(I) catalyst was able to selectivity hydrogenate the more peripheral alkene over the central alkenes in a polyenol, as the polyenol was not able to penetrate sufficiently far into the cavity for all its double bonds to react.[146] Without the MOC, the similarity in electronic and steric properties led to intractable mixtures of singly and multiply-hydrogenated products.

The high external surface area to volume ratio in MOCs (unlike MOFs) can be further utilized by the realization that the substrate does not have to enter the MOC for catalysis to occur. The hydrolysis of phosphate esters, such as the insecticide dichlorvos, was promoted on the exterior surface of a cubic cobalt(II) M_8L_{12} MOC (Figure 7c).[147] In such cases, MOC assembly provides the necessary cationic but hydrophobic surface to bind both substrate and basic anion required for the reaction. The same MOCs could also catalyze the Kemp elimination of benzisoxazole to 2-cyanophenolate in its cavity, through both interior and exterior binding processes.[39] The cationic MOC bound this reaction substrate in the central cavity but bound anions such as hydroxide around its periphery, resulting in a high local concentration of base which drove the reaction. However, in the presence of high chloride concentrations the reaction became autocatalytic. Initially more chloride bound than hydroxide, inhibiting the reaction, but as the cyanophenolate product (which had the highest binding affinity for the MOC exterior) built up, it preferentially bound to the outside instead and accelerated further reactions inside (Figure 7d and Figure 7e).
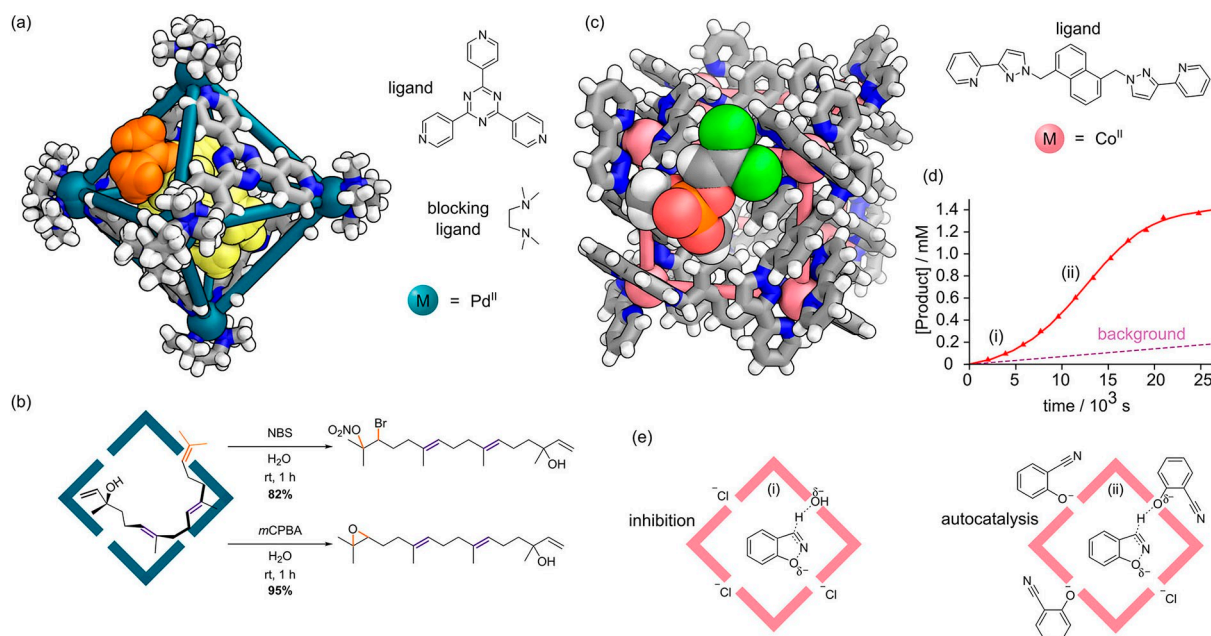

Figure 7. Exploiting the finite nature of MOCs for catalysis: (a) Octahedral M_6L_4 MOC, illustrating the U-shaped conformation of the bound diterpenoid guest observed in the crystal structure (with exposed prenyl group highlighted in orange);[145] (b) Regioselective electrophilic substitution reactions performed on the host-guest complex where central alkenes (highlighted in purple) do not react; (c) Crystal structure of an M_8L_{12} cubic MOC with the insecticide dichlorvos bound on the edge;[147] (d) Rate of Kemp elimination in the M_8L_{12} cubic MOC compared to background rate;[39] (e) Inhibition of Kemp elimination by chloride early in reaction and autocatalysis of Kemp elimination by phenolate later in reaction.

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

Chemistry Europe
European Chemical
Societies Publishing

9. Real world applications

The development of MOFs for real-world applications is constantly evolving with new ideas and directions frequently emerging.[148] Many applications have been proposed and some MOFs are now made on an industrial scale. Interesting applications in gas storage and selective gas separation are beginning to be tested more frequently and it seems only a matter of time before MOFs are being widely used in industrial settings. Fascinating applications have been reported such as the use of MOFs in films to control the ripening of fruit through the controlled release of 1-methylcyclopropene, a competitive inhibitor for the ethylene receptor on some fruits.[149]

There are many exciting possible applications, but one which is receiving increasing attention is the selective capture of water for water harvesting. This is of particular importance in dry climates and environments where water is scarce.[150] Effective water harvesting requires several key characteristics; effective and dynamic water absorption, at low relative humidity, over multiple cycles, over a short period of time. The aluminium-based MOF, MOF-303, [Al(OH)(3,5-pyrazoledicarboxylate)(H$_2$O)] exhibits such properties, with a maximum capacity of 0.48 g of water per gram of MOF.[150a] Indeed this MOF has been tested in the Mojave Desert to collect water using a series of absorption/desorption cycles.

One of the key considerations for the real-world application of MOCs is scale. MOCs can be difficult to prepare and distribute as bulk materials due to problems with aggregation and hence are more promising in fine chemical rather than bulk chemical settings. Many promising biomedical applications of MOCs have been investigated or are currently undergoing study. We will briefly mention some promising areas here, and readers are directed towards more detailed reviews.[151] MOCs have been investigated as anti-cancer agents against at least 15 different types of cancer, with the most common mechanisms of action being apoptosis and membrane damage. Pt, Pd and Ru-based MOCs are most frequently employed. MOCs can act as vectors to deliver drugs such as *cis*-platin directly into cells. They can also be engineered for recognition, being able to recognise sugars, proteins and DNA sequences and provide sensory feedback. Perhaps the most exciting aspect of employing MOCs for biomedical applications over traditional small molecule organics is that multiple functions (anti-cancer activity/drug delivery/recognition and sensing) can easily be performed by a single MOC of appropriate design, with the self-assembly process being used to bring together multiple different components to achieve all the desired functions in a single structure. This has great potential for shaping the future of disease diagnosis and treatment.

10. Summary and outlook

The fields of MOCs and MOFs are both highly successful and continue to develop in many exciting directions. The synergies between the synthetic strategies that are used for both MOCs and MOFs strongly suggest that the two fields have much to learn from one another. However, distinct advantages of each field are apparent, notably solution *vs* solid state behaviour, for MOCs and MOFs respectively, which results in different primary characterisation techniques being used in each field. This distinction between the two fields leads to different potential applications, which in turn directs much of the research endeavour.

Although it is ensured that the two fields will continue to plough their own furrow, there is also significant potential to exploit the distinct advantages of each approach. Studies that seek to combine the two fields are scarce but are becoming increasingly common. The incorporation of MOCs into thin films has been reported, including examples where MOCs are cross-linked to form MOFs.[152] Other studies have demonstrated the incorporation of MOCs into polymer films and gels[153] or the immobilisation of MOCs onto alumina substrates.[154] In the latter study it was demonstrated that the MOCs retained their ability to trap and release guest molecules even when tethered to the material. This demonstrates that it is possible to combine the properties exhibited by MOCs in non-solution environments and raises intriguing questions about building bespoke structures that combine the properties of MOCs and MOFs. A hint of this approach has been demonstrated using suitably functionalised organic cages[155] as ligands for MOF synthesis, allowing the incorporation of pre-arranged porosity and functionality into the framework structure.

This article has sought to illustrate the similarities and differences between MOCs and MOFs and to illuminate some of the opportunities that arise in both fields. In conclusion, we are drawn to the dualism analogy of *yin and yang* from Ancient Chinese philosophy. The MOC and MOF fields, which can seem opposite and possibly even antagonistic of each other at first glance, are far from distinct and are heavily interrelated and complementary to each other. Many intriguing directions of research will emerge from a combined perspective of the underpinning chemistry of both fields.

Conflict of Interest

The authors declare no conflict of interest.

[1] a) M. Fujita, D. Oguro, M. Miyazawa, H. Oka, K. Yamaguchi, K. Ogura, *Nature* **1995**, *378*, 469–471; b) N. Takeda, K. Umemoto, K. Yamaguchi,

ChemPlusChem

Reviews
doi.org/10.1002/cplu.202000408

Chemistry
Europe
European Chemical
Societies Publishing

M. Fujita, *Nature* **1999**, *398*, 794–796; c) K. Biradha, M. Fujita, *Angew. Chem. Int. Ed.* **2002**, *41*, 3392–3395; *Angew. Chem.* **2002**, *114*, 3542–3545.

[2] a) T. R. Cook, Y.-R. Zheng, P. J. Stang, *Chem. Rev.* **2013**, *113*, 734–777; b) S. Pullen, G. H. Clever, *Acc. Chem. Res.* **2018**, *51*, 3052–3064.

[3] a) B. F. Hoskins, R. Robson, *J. Am. Chem. Soc.* **1990**, *112*, 1546–1554; b) O. M. Yaghi, M. O'Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi, J. Kim, *Nature* **2003**, *423*, 705–714.

[4] a) K. E. Cordova, O. M. Yaghi, *Mater. Chem. Front.* **2017**, *1*, 1304–1309; b) Z. Chen, H. Jiang, M. Li, M. O'Keeffe, M. Eddaoudi, *Chem. Rev.* **2020**, ASAP.

[5] V. Guillerm, Ł. J. Weseliński, Y. Belmabkhout, A. J. Cairns, V. D'Elia, Ł. Wojtas, K. Adil, M. Eddaoudi, *Nat. Chem.* **2014**, *6*, 673–680.

[6] S. L. Griffin, N. R. Champness, *Coord. Chem. Rev.* **2020**, *414*, 213295.

[7] P. Z. Moghadam, A. Li, S. B. Wiggin, A. Tao, A. G. P. Maloney, P. A. Wood, S. C. Ward, D. Fairen-Jimenez, *Chem. Mater.* **2017**, *29*, 2618–2625.

[8] a) H. Li, M. Eddaoudi, T. L. Groy, O. M. Yaghi, *J. Am. Chem. Soc.* **1998**, *120*, 8571–8572; b) H. Li, M. Eddaoudi, M. O'Keeffe, O. M. Yaghi, *Nature* **1999**, *402*, 276–279.

[9] D. L. Caulder, R. E. Powers, T. N. Parac, K. N. Raymond, *Angew. Chem. Int. Ed.* **1998**, *37*, 1840–1843; *Angew. Chem.* **1998**, *110*, 1940–1943.

[10] C. J. Kuehl, Y. K. Kryschenko, U. Radhakrishnan, S. R. Seidel, S. D. Huang, P. J. Stang, *Proc. Natl. Acad. Sci. USA* **2002**, *99*, 4932–4936.

[11] O. Chepelin, J. Ujma, X. Wu, A. M. Z. Slawin, M. B. Pitak, S. J. Coles, J. Michel, A. C. Jones, P. E. Barran, P. J. Lusby, *J. Am. Chem. Soc.* **2012**, *134*, 19334–19337.

[12] R. A. Bilbeisi, T. K. Ronson, J. R. Nitschke, *Angew. Chem. Int. Ed.* **2013**, *52*, 9027–9030; *Angew. Chem.* **2013**, *125*, 9197–9200.

[13] D. T. Richens, *Chem. Rev.* **2005**, *105*, 1961–2002.

[14] S. S.-Y. Chui, S. M.-F. Lo, J. P. H. Charmant, A. G. Orpen, I. D. Williams, *Science* **1999**, *283*, 1148–1150.

[15] S. A. Barnett, N. R. Champness, *Coord. Chem. Rev.* **2003**, *246*, 145–168.

[16] A. Phan, C. J. Doonan, F. J. Uribe-Romo, C. B. Knobler, M. O'Keeffe, O. M. Yaghi, *Acc. Chem. Res.* **2010**, *43*, 58–67.

[17] S. G. Dunning, G. Nandra, A. D. Conn, W. Chai, R. E. Sikma, J. S. Lee, P. Kunal, J. E. Reynolds III, J.-S. Chang, A. Steiner, G. Henkelman, S. M. Humphrey, *Angew. Chem. Int. Ed.* **2018**, *57*, 9295–9299; *Angew. Chem.* **2018**, *130*, 9439–9443.

[18] A. Pathak, J.-W. Shen, M. Usman, L.-F. Wei, S. Mendiratta, Y.-S. Chang, B. Sainbileg, C.-M. Ngue, R.-S. Chen, M. Hayashi, T.-T. Luo, F.-R. Chen, K.-H. Chen, T.-W. Tseng, L.-C. Chen, K.-L. Lu, *Nat. Commun.* **2019**, *10*, 1721.

[19] C. I. Ezugwu, N. A. Kabir, M. Yusubov, F. Verpoort, *Coord. Chem. Rev.* **2016**, *307*, 188–210.

[20] H. Deng, S. Grunder, K. E. Cordova, C. Valente, H. Furukawa, M. Hmadeh, F. Gándara, A. C. Whalley, Z. Liu, S. Asahina, H. Kazumori, M. O'Keeffe, O. Terasaki, J. F. Stoddart, O. M. Yaghi, *Science* **2012**, *336*, 1018–1023.

[21] D. Fujita, Y. Ueda, S. Sato, N. Mizuno, T. Kumasaka, M. Fujita, *Nature* **2016**, *540*, 563–566.

[22] L. K. S. von Krbek, C. A. Schalley, P. Thordarson, *Chem. Soc. Rev.* **2017**, *46*, 2622–2637.

[23] D. L. Caulder, C. Brückner, R. E. Powers, S. König, T. N. Parac, J. A. Leary, K. N. Raymond, *J. Am. Chem. Soc.* **2001**, *123*, 8923–8938.

[24] S. R. Seidel, P. J. Stang, *Acc. Chem. Res.* **2002**, *35*, 972–983.

[25] a) M. Yoshizawa, M. Tamura, M. Fujita, *Science* **2006**, *312*, 251–254; b) M. Fujita, M. Tominaga, A. Hori, B. Therrien, *Acc. Chem. Res.* **2005**, *38*, 369–378.

[26] N. C. Gianneschi, M. S. Masar, C. A. Mirkin, *Acc. Chem. Res.* **2005**, *38*, 825–837.

[27] B. Olenyuk, M. D. Levin, J. A. Whiteford, J. E. Shield, P. J. Stang, *J. Am. Chem. Soc.* **1999**, *121*, 10434–10435.

[28] N. K. Al-Rasbi, I. S. Tidmarsh, S. P. Argent, H. Adams, L. P. Harding, M. D. Ward, *J. Am. Chem. Soc.* **2008**, *130*, 11641–11649.

[29] Q.-F. Sun, J. Iwasa, D. Ogawa, Y. Ishido, S. Sato, T. Ozeki, Y. Sei, K. Yamaguchi, M. Fujita, *Science* **2010**, *328*, 1144–1147.

[30] M. Kieffer, B. S. Pilgrim, T. K. Ronson, D. A. Roberts, M. Aleksanyan, J. R. Nitschke, *J. Am. Chem. Soc.* **2016**, *138*, 6813–6821.

[31] B. S. Pilgrim, J. R. Nitschke, *Chem* **2016**, *1*, 19–21.

[32] D. Fujita, Y. Ueda, S. Sato, H. Yokoyama, N. Mizuno, T. Kumasaka, M. Fujita, *Chem* **2016**, *1*, 91–101.

[33] D. Preston, J. J. Sutton, K. C. Gordon, J. D. Crowley, *Angew. Chem. Int. Ed.* **2018**, *57*, 8659–8663; *Angew. Chem.* **2018**, *130*, 8795–8799.

[34] L.-J. Chen, H.-B. Yang, M. Shionoya, *Chem. Soc. Rev.* **2017**, *46*, 2555–2576.

[35] K. Endo, H. Ube, M. Shionoya, *J. Am. Chem. Soc.* **2020**, *142*, 407–416.

[36] M. J. Burke, G. S. Nichol, P. J. Lusby, *J. Am. Chem. Soc.* **2016**, *138*, 9308–9315.

[37] C. R. K. Glasson, G. V. Meehan, M. Davies, C. A. Motti, J. K. Clegg, L. F. Lindoy, *Inorg. Chem.* **2015**, *54*, 6986–6992.

[38] P. Mal, B. Breiner, K. Rissanen, J. R. Nitschke, *Science* **2009**, *324*, 1697–1699.

[39] W. Cullen, A. J. Metherell, A. B. Wragg, C. G. P. Taylor, N. H. Williams, M. D. Ward, *J. Am. Chem. Soc.* **2018**, *140*, 2821–2828.

[40] N. L. Rosi, J. Eckert, M. Eddaoudi, D. T. Vodak, J. Kim, M. O'Keeffe, O. M. Yaghi, *Science* **2003**, *300*, 1127–1129.

[41] F. Millange, R. I. Walton, *Isr. J. Chem.* **2018**, *58*, 1019–1035.

[42] a) M. Klimakow, P. Klobes, A. F. Thünemann, K. Rademann, F. Emmerling, *Chem. Mater.* **2010**, *22*, 5216–5221; b) T. Friščić, *Chem. Soc. Rev.* **2012**, *41*, 3493–3510.

[43] A. Laybourn, J. Katrib, R. S. Ferrari-John, C. G. Morris, S. Yang, O. Udoudo, T. L. Easun, C. Dodds, N. R. Champness, S. W. Kingman, M. Schröder, *J. Mater. Chem. A* **2017**, *5*, 7333–7338.

[44] P. A. Bayliss, I. A. Ibarra, E. Pérez, S. Yang, C. C. Tang, M. Poliakoff, M. Schröder, *Green Chem.* **2014**, *16*, 3796–3802.

[45] Z. Yin, S. Wan, J. Yang, M. Kurmoo, M.-H. Zeng, *Coord. Chem. Rev.* **2019**, *378*, 500–512.

[46] R. J. Young, M. T. Huxley, E. Pardo, N. R. Champness, C. J. Sumby, C. J. Doonan, *Chem. Sci.* **2020**, *11*, 4031–4050.

[47] D. A. Roberts, B. S. Pilgrim, J. R. Nitschke, *Chem. Soc. Rev.* **2018**, *47*, 626–644.

[48] M. Taddei, N. Casati, D. A. Steitz, K. C. Dümbgen, J. A. van Bokhoven, M. Ranocchiari, *CrystEngComm* **2017**, *19*, 3206–3214.

[49] Y. Yan, I. Telepeni, S. Yang, X. Lin, W. Kockelmann, A. Dailly, A. J. Blake, W. Lewis, G. S. Walker, D. R. Allan, S. A. Barnett, N. R. Champness, M. Schröder, *J. Am. Chem. Soc.* **2010**, *132*, 4092–4094.

[50] T. L. Easun, F. Moreau, Y. Yan, S. Yang, M. Schröder, *Chem. Soc. Rev.* **2017**, *46*, 239–274.

[51] B. E. G. Lucier, S. Chen, Y. Huang, *Acc. Chem. Res.* **2018**, *51*, 319–330.

[52] T. J. Reade, T. S. Murphy, J. A. Calladine, R. Horvath, I. P. Clark, G. M. Greetham, M. Towrie, W. Lewis, M. W. George, N. R. Champness, *Philos. Trans. R. Soc. London Ser. A* **2017**, *375*, 20160033.

[53] G. Mínguez Espallargas, E. Coronado, *Chem. Soc. Rev.* **2018**, *47*, 533–557.

[54] S. R. Batten, N. R. Champness, X.-M. Chen, J. Garcia-Martinez, S. Kitagawa, L. Öhrström, M. O'Keeffe, M. P. Suh, J. Reedijk, *Pure Appl. Chem.* **2013**, *85*, 1715–1724.

[55] H. Li, K. Wang, Y. Sun, C. T. Lollar, J. Li, H.-C. Zhou, *Mater. Today* **2018**, *21*, 108–121.

[56] S. A. Barnett, A. J. Blake, N. R. Champness, C. Wilson, *Dalton Trans.* **2005**, 3852–3861.

[57] A. Simonov, A. L. Goodwin, *arXiv* **2019**, arXiv:1912.00366.

[58] A. Pastor, E. Martínez-Viviente, *Coord. Chem. Rev.* **2008**, *252*, 2314–2345.

[59] L. Avram, Y. Cohen, *Chem. Soc. Rev.* **2015**, *44*, 586–602.

[60] M. Yamashina, Y. Tanaka, R. Lavendomme, T. K. Ronson, M. Pittelkow, J. R. Nitschke, *Nature* **2019**, *574*, 511–515.

[61] The following website http://supramolecular.org is an excellent tool for the analysis and simulation of supramolecular binding events.

[62] P. Thordarson, *Chem. Soc. Rev.* **2011**, *40*, 1305–1323.

[63] F. P. Schmidtchen, *Isothermal Titration Calorimetry in Supramolecular Chemistry in Supramol. Chem.* (Eds.: P. A. Gale, J. W. Steed), **2012**.

[64] E. V. Dzyuba, J. Poppenberg, S. Richter, R. W. Troff, C. A. Schalley, *Mass Spectrometry and Gas-Phase Chemistry of Supermolecules: A Primer in Supramol. Chem.* (Eds.: P. A. Gale, J. W. Steed), **2012**.

[65] M. Kieffer, R. A. Bilbeisi, J. D. Thoburn, J. K. Clegg, J. R. Nitschke, *Angew. Chem. Int. Ed.* **2020**, *59*, 11369–11373.

[66] D. A. Roberts, B. S. Pilgrim, G. Sirvinskaite, T. K. Ronson, J. R. Nitschke, *J. Am. Chem. Soc.* **2018**, *140*, 9616–9623.

[67] E. Kalenius, M. Groessl, K. Rissanen, *Nat. Rev. Chem.* **2019**, *3*, 4–14.

[68] R.-J. Li, J. J. Holstein, W. G. Hiller, J. Andréasson, G. H. Clever, *J. Am. Chem. Soc.* **2019**, *141*, 2097–2103.

[69] C. S. Wood, T. K. Ronson, A. M. Belenguer, J. J. Holstein, J. R. Nitschke, *Nat. Chem.* **2015**, *7*, 354–358.

[70] K. Rissanen, *Chem. Soc. Rev.* **2017**, *46*, 2638–2648.

[71] a) B. S. Pilgrim, D. A. Roberts, T. G. Lohr, T. K. Ronson, J. R. Nitschke, *Nat. Chem.* **2017**, *9*, 1276–1281; b) B. P. Burke, W. Grantham, M. J.

Burke, G. S. Nichol, D. Roberts, I. Renard, R. Hargreaves, C. Cawthorne, S. J. Archibald, P. J. Lusby, *J. Am. Chem. Soc.* **2018**, *140*, 16877–16881.

[72] T. K. Ronson, B. S. Pilgrim, J. R. Nitschke, *J. Am. Chem. Soc.* **2016**, *138*, 10417–10420.

[73] E. L. First, C. A. Floudas, *Microporous Mesoporous Mater.* **2013**, *165*, 32–39.

[74] Y. J. Colón, R. Q. Snurr, *Chem. Soc. Rev.* **2014**, *43*, 5735–5749.

[75] A. S. Rosen, J. M. Notestein, R. Q. Snurr, *J. Comput. Chem.* **2019**, *40*, 1305–1318.

[76] L. Turcani, E. Berardo, K. E. Jelfs, *J. Comput. Chem.* **2018**, *39*, 1931–1942.

[77] T. F. Willems, C. H. Rycroft, M. Kazi, J. C. Meza, M. Haranczyk, *Microporous Mesoporous Mater.* **2012**, *149*, 134–141.

[78] T. A. Young, R. Gheorghe, F. Duarte, *J. Chem. Inf. Model.* **2020**, *60*, 3546–3557.

[79] C. E. Wilmer, M. Leaf, C. Y. Lee, O. K. Farha, B. G. Hauser, J. T. Hupp, R. Q. Snurr, *Nat. Chem.* **2012**, *4*, 83–89.

[80] B. J. Bucior, A. S. Rosen, M. Haranczyk, Z. Yao, M. E. Ziebel, O. K. Farha, J. T. Hupp, J. I. Siepmann, A. Aspuru-Guzik, R. Q. Snurr, *Cryst. Growth Des.* **2019**, *19*, 6682–6697.

[81] J. R. Álvarez, E. Sánchez-González, E. Pérez, E. Schneider-Revueltas, A. Martínez, A. Tejeda-Cruz, A. Islas-Jácome, E. González-Zamora, I. A. Ibarra, *Dalton Trans.* **2017**, *46*, 9192–9200.

[82] L. N. McHugh, M. J. McPherson, L. J. McCormick, S. A. Morris, P. S. Wheatley, S. J. Teat, D. McKay, D. M. Dawson, C. E. F. Sansome, S. E. Ashbrook, C. A. Stone, M. W. Smith, R. E. Morris, *Nat. Chem.* **2018**, *10*, 1096–1102.

[83] X. Cui, A. N. Khlobystov, X. Chen, D. H. Marsh, A. J. Blake, W. Lewis, N. R. Champness, C. J. Roberts, M. Schröder, *Chem. Eur. J.* **2009**, *15*, 8861–8873.

[84] R. S. Forgan, *Dalton Trans.* **2019**, *48*, 9037–9042.

[85] M. Ding, X. Cai, H.-L. Jiang, *Chem. Sci.* **2019**, *10*, 10209–10230.

[86] J. Winarta, B. Shan, S. M. McIntyre, L. Ye, C. Wang, J. Liu, B. Mu, *Cryst. Growth Des.* **2020**, *20*, 1347–1362.

[87] M. Kandiah, M. H. Nilsen, S. Usseglio, S. Jakobsen, U. Olsbye, M. Tilset, C. Larabi, E. A. Quadrelli, F. Bonino, K. P. Lillerud, *Chem. Mater.* **2010**, *22*, 6632–6640.

[88] X. Zhang, X. Dong, W. Lu, D. Luo, X.-W. Zhu, X. Li, X.-P. Zhou, D. Li, *J. Am. Chem. Soc.* **2019**, *141*, 11621–11627.

[89] D. Preston, K. F. White, J. E. M. Lewis, R. A. S. Vasdev, B. F. Abrahams, J. D. Crowley, *Chem. Eur. J.* **2017**, *23*, 10559–10567.

[90] C. Pariya, C. R. Sparrow, C.-K. Back, G. Sandí, F. R. Fronczek, A. W. Maverick, *Angew. Chem. Int. Ed.* **2007**, *46*, 6305–6308; *Angew. Chem.* **2007**, *119*, 6421–6424.

[91] M. B. Duriska, S. M. Neville, J. Lu, S. S. Iremonger, J. F. Boas, C. J. Kepert, S. R. Batten, *Angew. Chem. Int. Ed.* **2009**, *48*, 8919–8922; *Angew. Chem.* **2009**, *121*, 9081–9084.

[92] Y. Sun, Y. Yao, H. Wang, W. Fu, C. Chen, M. L. Saha, M. Zhang, S. Datta, Z. Zhou, H. Yu, X. Li, P. J. Stang, *J. Am. Chem. Soc.* **2018**, *140*, 12819–12828.

[93] S. Mollick, S. Fajal, S. Mukherjee, S. K. Ghosh, *Chem. Asian J.* **2019**, *14*, 3096–3108.

[94] E. G. Percástegui, J. Mosquera, T. K. Ronson, A. J. Plajer, M. Kieffer, J. R. Nitschke, *Chem. Sci.* **2019**, *10*, 2006–2018.

[95] Z. Lu, C. B. Knobler, H. Furukawa, B. Wang, G. Liu, O. M. Yaghi, *J. Am. Chem. Soc.* **2009**, *131*, 12532–12533.

[96] J. A. Foster, R. M. Parker, A. M. Belenguer, N. Kishi, S. Sutton, C. Abell, J. R. Nitschke, *J. Am. Chem. Soc.* **2015**, *137*, 9722–9729.

[97] A. V. Zhukhovitskiy, M. Zhong, E. G. Keeler, V. K. Michaelis, J. E. P. Sun, M. J. A. Hore, D. J. Pochan, R. G. Griffin, A. P. Willard, J. A. Johnson, *Nat. Chem.* **2016**, *8*, 33–41.

[98] L. Ma, C. J. E. Haynes, A. B. Grommet, A. Walczak, C. C. Parkins, C. M. Doherty, L. Longley, A. Tron, A. R. Stefankiewicz, T. D. Bennett, J. R. Nitschke, *Nat. Chem.* **2020**, *12*, 270–275.

[99] M. Alhamami, H. Doan, C.-H. Cheng, *Materials* **2014**, *7*, 3198–3250.

[100] K. Barthelet, J. Marrot, D. Riou, G. Férey, *Angew. Chem. Int. Ed.* **2002**, *41*, 281–284; *Angew. Chem.* **2002**, *114*, 291–294.

[101] a) F. Millange, C. Serre, G. Férey, *Chem. Commun.* **2002**, 822–823; b) C. Serre, F. Millange, C. Thouvenot, M. Noguès, G. Marsolier, D. Louër, G. Férey, *J. Am. Chem. Soc.* **2002**, *124*, 13519–13526; c) T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille, G. Férey, *Chem. Eur. J.* **2004**, *10*, 1373–1382.

[102] W. Wang, Y.-X. Wang, H.-B. Yang, *Chem. Soc. Rev.* **2016**, *45*, 2656–2693.

[103] W. M. Bloch, R. Babarao, M. L. Schneider, *Chem. Sci.* **2020**, *11*, 3664–3671.

[104] T.-Z. Xie, K. J. Endres, Z. Guo, J. M. Ludlow, C. N. Moorefield, M. J. Saunders, C. Wesdemiotis, G. R. Newkome, *J. Am. Chem. Soc.* **2016**, *138*, 12344–12347.

[105] S. Chakraborty, W. Hong, K. J. Endres, T.-Z. Xie, L. Wojtas, C. N. Moorefield, C. Wesdemiotis, G. R. Newkome, *J. Am. Chem. Soc.* **2017**, *139*, 3012–3020.

[106] S. Oldknow, D. R. Martir, V. E. Pritchard, M. A. Blitz, W. Colin, G. Fishwick, E. Zysman-Colman, M. J. Hardie, *Chem. Sci.* **2018**, *9*, 8150–8159.

[107] Y.-S. Wang, S. Bai, Y.-Y. Wang, Y.-F. Han, *Chem. Commun.* **2019**, *55*, 13689–13692.

[108] D. A. Roberts, B. S. Pilgrim, J. D. Cooper, T. K. Ronson, S. Zarra, J. R. Nitschke, *J. Am. Chem. Soc.* **2015**, *137*, 10068–10071.

[109] a) F. J. Rizzuto, J. P. Carpenter, J. R. Nitschke, *J. Am. Chem. Soc.* **2019**, *141*, 9087–9095; b) W. M. Bloch, Y. Abe, J. J. Holstein, C. M. Wandtke, B. Dittrich, G. H. Clever, *J. Am. Chem. Soc.* **2016**, *138*, 13750–13755.

[110] a) J.-R. Li, R. J. Kuppler, H.-C. Zhou, *Chem. Soc. Rev.* **2009**, *38*, 1477–1504; b) X. Lin, N. R. Champness, M. Schröder, *Hydrogen, Methane and Carbon Dioxide Adsorption in Metal-Organic Framework Materials in Functional Metal-Organic Frameworks: Gas Storage, Separation and Catalysis* (Ed.: M. Schröder), Springer Berlin Heidelberg, Berlin, Heidelberg, **2010**, pp. 35–76.

[111] a) R.-B. Lin, S. Xiang, H. Xing, W. Zhou, B. Chen, *Coord. Chem. Rev.* **2019**, *378*, 87–103; b) G. L. Smith, J. E. Eyley, X. Han, X. Zhang, J. Li, N. M. Jacques, H. G. W. Godfrey, S. P. Argent, L. J. McCormick McPherson, S. J. Teat, Y. Cheng, M. D. Frogley, G. Cinque, S. J. Day, C. C. Tang, T. L. Easun, S. Rudić, A. J. Ramirez-Cuesta, S. Yang, M. Schröder, *Nat. Mater.* **2019**, *18*, 1358–1365.

[112] Z. Chen, P. Li, R. Anderson, X. Wang, X. Zhang, L. Robison, L. R. Redfern, S. Moribe, T. Islamoglu, D. A. Gómez-Gualdrón, T. Yildirim, J. F. Stoddart, O. K. Farha, *Science* **2020**, *368*, 297–303.

[113] C. García-Simón, M. Garcia-Borràs, L. Gómez, T. Parella, S. Osuna, J. Juanhuix, I. Imaz, D. Maspoch, M. Costas, X. Ribas, *Nat. Commun.* **2014**, *5*, 5557.

[114] V. Lykourinou, Y. Chen, X.-S. Wang, L. Meng, T. Hoang, L.-J. Ming, R. L. Musselman, S. Ma, *J. Am. Chem. Soc.* **2011**, *133*, 10382–10385.

[115] F. Lyu, Y. Zhang, R. N. Zare, J. Ge, Z. Liu, *Nano Lett.* **2014**, *14*, 5761–5765.

[116] C. Rösler, R. A. Fischer, *CrystEngComm* **2015**, *17*, 199–217.

[117] J. W. M. Osterrieth, D. Wright, H. Noh, C.-W. Kung, D. Vulpe, A. Li, J. E. Park, R. P. Van Duyne, P. Z. Moghadam, J. J. Baumberg, O. K. Farha, D. Fairen-Jimenez, *J. Am. Chem. Soc.* **2019**, *141*, 3893–3900.

[118] a) W. M. Bloch, N. R. Champness, C. J. Doonan, *Angew. Chem. Int. Ed.* **2015**, *54*, 12860–12867; *Angew. Chem.* **2015**, *127*, 13052–13059; b) Y. Inokuma, T. Arai, M. Fujita, *Nat. Chem.* **2010**, *2*, 780–783.

[119] Y. Inokuma, S. Yoshioka, J. Ariyoshi, T. Arai, M. Fujita, *Nature Protocols* **2014**, *9*, 246–252.

[120] N. Wada, R. D. Kersten, T. Iwai, S. Lee, F. Sakurai, T. Kikuchi, D. Fujita, M. Fujita, J.-K. Weng, *Angew. Chem. Int. Ed.* **2018**, *57*, 3671–3675; *Angew. Chem.* **2018**, *130*, 3733–3737.

[121] A. B. Grommet, J. R. Nitschke, *J. Am. Chem. Soc.* **2017**, *139*, 2176–2179.

[122] B.-N. T. Nguyen, A. B. Grommet, A. Tron, M. C. A. Georges, J. R. Nitschke, *Adv. Mater.* **2020**, *32*, 1907241.

[123] D. Zhang, T. K. Ronson, J. Mosquera, A. Martinez, J. R. Nitschke, *Angew. Chem. Int. Ed.* **2018**, *57*, 3717–3721; *Angew. Chem.* **2018**, *130*, 3779–3783.

[124] M. Jung, H. Kim, K. Baek, K. Kim, *Angew. Chem. Int. Ed.* **2008**, *47*, 5755–5757; *Angew. Chem.* **2008**, *120*, 5839–5841.

[125] C. J. E. Haynes, J. Zhu, C. Chimerel, S. Hernández-Ainsa, I. A. Riddell, T. K. Ronson, U. F. Keyser, J. R. Nitschke, *Angew. Chem. Int. Ed.* **2017**, *56*, 15388–15392; *Angew. Chem.* **2017**, *129*, 15590–15594.

[126] A. Galan, P. Ballester, *Chem. Soc. Rev.* **2016**, *45*, 1720–1737.

[127] M. Yamashina, Y. Sei, M. Akita, M. Yoshizawa, *Nat. Commun.* **2014**, *5*, 4662.

[128] M. Kawano, Y. Kobayashi, T. Ozeki, M. Fujita, *J. Am. Chem. Soc.* **2006**, *128*, 6558–6559.

[129] R. Custelcean, *Chem. Soc. Rev.* **2014**, *43*, 1813–1824.

[130] F. J. Rizzuto, L. K. S. von Krbek, J. R. Nitschke, *Nat. Rev. Chem.* **2019**, *3*, 204–222.

[131] W. J. Ramsay, J. R. Nitschke, *J. Am. Chem. Soc.* **2014**, *136*, 7038–7043.

[132] L. K. S. von Krbek, D. A. Roberts, B. S. Pilgrim, C. A. Schalley, J. R. Nitschke, *Angew. Chem. Int. Ed.* **2018**, *57*, 14121–14124; *Angew. Chem.* **2018**, *130*, 14317-14320.

[133] D. Fujita, K. Suzuki, S. Sato, M. Yagi-Utsumi, Y. Yamaguchi, N. Mizuno, T. Kumasaka, M. Takata, M. Noda, S. Uchiyama, K. Kato, M. Fujita, *Nat. Commun.* **2012**, *3*, 1093.

[134] K. Harris, D. Fujita, M. Fujita, *Chem. Commun.* **2013**, *49*, 6703–6712.

[135] a) R. J. Young, M. T. Huxley, E. Pardo, N. R. Champness, C. J. Sumby, C. J. Doonan, *Chem. Sci.* **2020**; b) M. Viciano-Chumillas, M. Mon, J. Ferrando-Soria, A. Corma, A. Leyva-Pérez, D. Armentano, E. Pardo, *Acc. Chem. Res.* **2020**, *53*, 520–531; c) W.-G. Cui, G.-Y. Zhang, T.-L. Hu, X.-H. Bu, *Coord. Chem. Rev.* **2019**, *387*, 79–120.

[136] A. Grigoropoulos, G. F. S. Whitehead, N. Perret, A. P. Katsoulidis, F. M. Chadwick, R. P. Davies, A. Haynes, L. Brammer, A. S. Weller, J. Xiao, M. J. Rosseinsky, *Chem. Sci.* **2016**, *7*, 2037–2050.

[137] A. Grigoropoulos, A. I. McKay, A. P. Katsoulidis, R. P. Davies, A. Haynes, L. Brammer, J. Xiao, A. S. Weller, M. J. Rosseinsky, *Angew. Chem. Int. Ed.* **2018**, *57*, 4532–4537; *Angew. Chem.* **2018**, *130*, 4622–4627.

[138] a) A. J. Blake, N. R. Champness, T. L. Easun, D. R. Allan, H. Nowell, M. W. George, J. Jia, X.-Z. Sun, *Nat. Chem.* **2010**, *2*, 688–694; b) W. M. Bloch, A. Burgun, C. J. Coghlan, R. Lee, M. L. Coote, C. J. Doonan, C. J. Sumby, *Nat. Chem.* **2014**, *6*, 906–912; c) M. T. Huxley, A. Burgun, A. Ghodrati, C. J. Coghlan, A. Lemieux, N. R. Champness, D. M. Huang, C. J. Doonan, C. J. Sumby, *J. Am. Chem. Soc.* **2018**, *140*, 6416–6425.

[139] Y. Fang, J. A. Powell, E. Li, Q. Wang, Z. Perry, A. Kirchon, X. Yang, Z. Xiao, C. Zhu, L. Zhang, F. Huang, H.-C. Zhou, *Chem. Soc. Rev.* **2019**, *48*, 4707–4730.

[140] A. B. Grommet, M. Feller, R. Klajn, *Nat. Nanotechnol.* **2020**, *15*, 256–271.

[141] Y. Ueda, H. Ito, D. Fujita, M. Fujita, *J. Am. Chem. Soc.* **2017**, *139*, 6090–6093.

[142] C. J. Brown, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2009**, *131*, 17530–17531.

[143] C. J. Hastings, M. D. Pluth, R. G. Bergman, K. N. Raymond, *J. Am. Chem. Soc.* **2010**, *132*, 6938–6940.

[144] R. Gramage-Doria, J. Hessels, S. H. A. M. Leenders, O. Tröppner, M. Dürr, I. Ivanović-Burmazović, J. N. H. Reek, *Angew. Chem. Int. Ed.* **2014**, *53*, 13380–13384; *Angew. Chem.* **2014**, *126*, 13598–13602.

[145] H. Takezawa, T. Kanda, H. Nanjo, M. Fujita, *J. Am. Chem. Soc.* **2019**, *141*, 5112–5115.

[146] T. A. Bender, R. G. Bergman, K. N. Raymond, F. D. Toste, *J. Am. Chem. Soc.* **2019**, *141*, 11806–11810.

[147] C. G. P. Taylor, A. J. Metherell, S. P. Argent, F. M. Ashour, N. H. Williams, M. D. Ward, *Chem. Eur. J.* **2020**, *26*, 3065–3073.

[148] R. Ricco, C. Pfeiffer, K. Sumida, C. J. Sumby, P. Falcaro, S. Furukawa, N. R. Champness, C. J. Doonan, *CrystEngComm* **2016**, *18*, 6532–6542.

[149] *Nat. Chem.* **2016**, *8*, 987–987.

[150] a) F. Fathieh, M. J. Kalmutzki, E. A. Kapustin, P. J. Waller, J. Yang, O. M. Yaghi, *Sci. Adv.* **2018**, *4*, eaat3198; b) N. Hanikel, M. S. Prévot, F. Fathieh, E. A. Kapustin, H. Lyu, H. Wang, N. J. Diercks, T. G. Glover, O. M. Yaghi, *ACS Cent. Sci.* **2019**, *5*, 1699–1706.

[151] a) H. Sepehrpour, W. Fu, Y. Sun, P. J. Stang, *J. Am. Chem. Soc.* **2019**, *141*, 14005–14020; b) N. Ahmad, H. A. Younus, A. H. Chughtai, F. Verpoort, *Chem. Soc. Rev.* **2015**, *44*, 9–25.

[152] G. Szalóki, S. Krykun, V. Croué, M. Allain, Y. Morille, F. Aubriet, V. Carré, Z. Voitenko, S. Goeb, M. Sallé, *Chem. Eur. J.* **2018**, *24*, 11273–11277.

[153] L. Shao, B. Hua, X. Hu, D. Stalla, S. P. Kelley, J. L. Atwood, *J. Am. Chem. Soc.* **2020**, *142*, 7270–7275.

[154] H. Ryan, C. J. E. Haynes, A. Smith, A. B. Grommet, J. R. Nitschke, *ChemRxiv*. Preprint. https://doi.org/10.26434/chemrxiv.12117483.v1

[155] S. I. Swamy, J. Bacsa, J. T. A. Jones, K. C. Stylianou, A. Steiner, L. K. Ritchie, T. Hasell, J. A. Gould, A. Laybourn, Y. Z. Khimyak, D. J. Adams, M. J. Rosseinsky, A. I. Cooper, *J. Am. Chem. Soc.* **2010**, *132*, 12773–12775.