

From Molecules to Frameworks to Superframework Crystals

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Building chemical structures of complexity and functionality approaching the level of biological systems is an ongoing challenge. A general synthetic strategy is proposed by which progressive levels of complexity are achieved through the building block approach whereby molecularly defined constructs at one level serve as constituent units of the next level, all being linked through strong bonds—"augmented reticular chemistry". Specifically, current knowledge of linking metal complexes and organic molecules into reticular frameworks is applied here to linking the crystals of these frameworks into supercrystals (superframeworks). This strategy allows for the molecular control exercised on the molecular regime to be translated into higher augmentation levels to produce systems capable of dynamics and complex functionality far exceeding current materials.

1. A Strategy for Synthesis of Supercrystals

Chemists have mastered the manipulation of matter on the molecular scale to the point that any molecule that can be conceived can be synthesized given sufficient resources and time.

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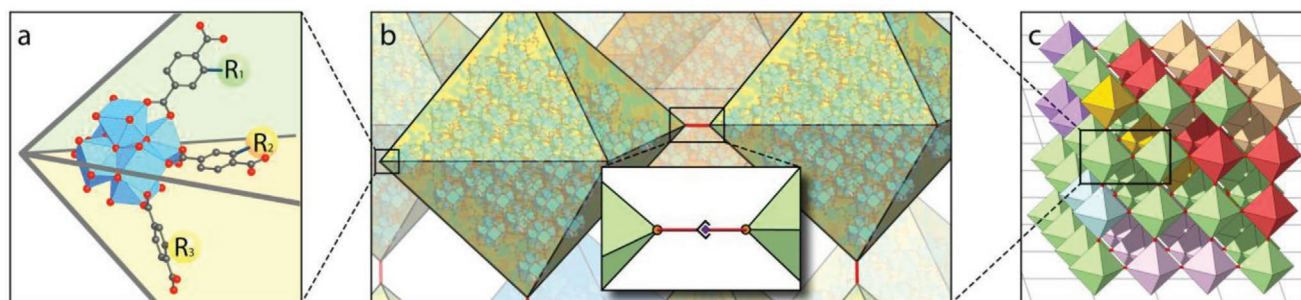
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This has given credence to the notion that the golden era of discovery in chemical synthesis has passed and that, moving forward, the future of innovation in chemistry is limited to the application of its synthetic prowess to neighboring sciences. This thinking bears a striking resemblance to the confidence of physicists at the end of the 19th century who stated that “there are only two small clouds that obscure the sky of physics”. In due time these two small clouds, the physics of objects at extremely small and extremely large sizes, culminated in the development of quantum mechanics and relativity theory, the two pillars of modern physics. Encouraged by this paradigm shift, we

envision that plenty of opportunities exist at the length scales that we are not used to. Chemical synthesis has long focused on the manipulation of atoms, molecules, and solids in the (sub-)nanometer regime; the macroscopic level, the other extreme of the size spectrum, remains a largely undeveloped chemical space. Macroscopic structures built with atomic precision could be one of the answers to the search of new synthetic frontiers, renewing the prospect of chemical synthesis as a pivotal driving force of scientific progress.

Reticular chemistry has enabled chemists to link discrete molecular building blocks into designed structures such as metal–organic frameworks (MOFs) and covalent organic frameworks (COFs).^[1–5] A target topology is first envisioned, and its nodes are matched by molecular units amenable to being linked together by strong bonds, as illustrated in **Scheme 1**. This process, termed augmentation, yields frameworks whose metrics can be precisely tailored by the size of the constituent building units so chosen. While, at its current stage, this chemistry is employed for linking discrete molecular building units, the next logical progression is to extend the principle of augmentation to chemistries governing larger size regimes. We envision that frameworks constructed at one level are to serve as building units for the next level toward achieving more complex architectures of progressively larger size scales. In other words, molecules are linked together to make crystals (**Scheme 1a**) and then these crystals are linked further into supercrystals (**Scheme 1b**). We refer to this process of making chemical structures as “augmented reticular chemistry” and the resulting supercrystals as “superframeworks” (**Scheme 1c**). The advantage of such augmentation strategy is that superframeworks preserve the flexibility and precision with which the original molecular frameworks are made and modified. We seek



Scheme 1. Schematic illustration of augmented reticular chemistry realized by designing progressively increasing size and complexity. a) $\text{Zr}_6\text{O}_4(\text{OH})_4(-\text{CO}_2)_{12}$ cluster is connected by 1,4-benzenedicarboxylate linker bearing variable functionalities (R_1 , R_2 , and R_3 , represented in green, light orange, and yellow spheres) into an extended framework, UiO-66 (UiO = University of Oslo),^[8] which crystallized into an octahedral shaped crystal. b) These crystals are further linked to each other in a vertex-to-vertex manner. c) A superframework is made of framework crystals of various functionalities. Color code for atomic illustration: Zr: blue; C: grey; O: red.

to show that such superframeworks are potentially capable of functions not too dissimilar in concept from those carried out by biological systems.^[6,7]

2. Augmentation with Molecular Precision

A direct consequence of increasing the dimensions of framework building units is the concomitant increase in guest-accessible void space while the fundamental connectivity of the lattice (i.e., structure type) is retained. This concept, referred to as augmentation, was key in the development of reticular chemistry and it is illustrated in **Figure 1** for the closest packing of spheres in the face-centered-cubic lattice (fcc). It is widely known that the fcc arrangement is adopted by many dense inorganic solids where atoms or ions are packed to minimize the amount of empty space (Figure 1). Each atom or ion in an fcc lattice has 12 nearest neighbors leaving no room for additional chemical species (≈ 0.1 nm voids for Cu). In contrast UiO-66 (UiO = University of Oslo), the MOF constructed from 12-connected $\text{Zr}_6\text{O}_4(\text{OH})_4(-\text{CO}_2)_{12}$ clusters linked by linear ditopic terephthalate linkers, is also based on the fcc, yet, in stark contrast, it is now a highly porous structure (≈ 0.6 nm voids, Figure 1).^[8] This is due to the fact that the dimensions of the building units have been increased by an order of magnitude and the vertices of the lattice have been spaced apart by the organic linkers. Based on this kind of augmentation, frameworks of many structure types have been designed and, owing to their accessible internal pores, have found widespread applications. Pores of frameworks serve to encompass space on the nanoscale suitable for the functionalization with organic moieties and for the interaction with incoming guest molecules.^[9]

Herein, we explore the question of whether this augmentation approach can be further applied to control the formation of structures within the macroscopic regime. Recent efforts at least on the molecular scale showed that instead of using the discrete $\text{Zr}_6\text{O}_4(\text{OH})_4(-\text{CO}_2)_{12}$ clusters of UiO-66 one can also link much larger 12-connected building units. In the case of linking intrinsically porous truncated metal–organic octahedra (Figure 1), this increases the porosity of the resulting DUT-49 (DUT = Dresden University of Technology) structure even

further and endows it with a complex hierarchical pore system (largest pore of ≈ 2.6 nm).^[10–12] Nonetheless, a more drastic increase in the size of constituents is needed to approach the goal of controlling the design of matter on the macroscopic length scale. We believe that frameworks need to be constructed from more sizable units, such as crystals, such that structures can encompass superordinate mesopores and accommodate larger guests such as macromolecules, nanoparticles, and aggregates thereof.

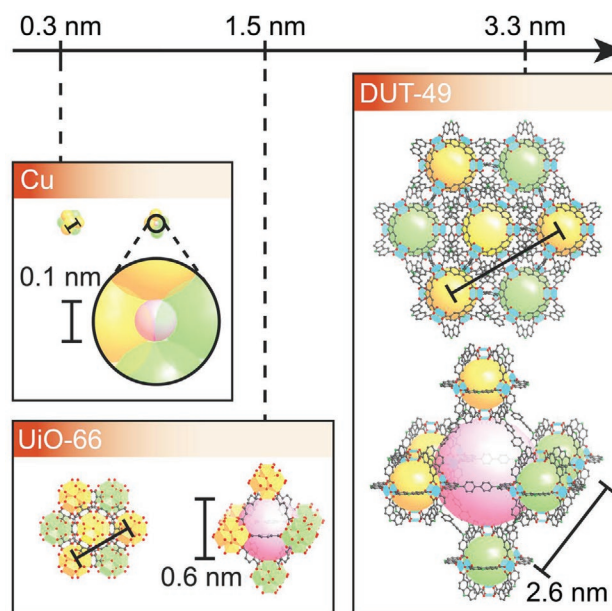


Figure 1. The augmentation strategy applied to face-centered-cubic lattice (fcc). In metallic Cu, atoms pack closely into the fcc lattice. This is viewed along the (111) direction to show the stacking of layers (yellow, light orange, and green). The octahedral pore, as represented by the pink sphere, is enclosed by six atoms from two neighboring layers (light orange and green). Augmentation of this topology yields the structure of UiO-66,^[8] where the atom in Cu is now replaced by a $\text{Zr}_6\text{O}_4(\text{OH})_4(-\text{CO}_2)_{12}$ cluster. Further progression in augmentation is exemplified by the structure of DUT-49 (DUT = Dresden University of Technology),^[10] where a truncated metal–organic octahedron cage serves as the 12-connected node. Color code: O, red; C, grey; N, green; Cu, blue.

The principle of augmentation from molecules to framework crystals, and further to supercrystals, lies in the fact that the most appealing way to link objects is by targeting periodic arrangements. Here, the simple combination of vectors and repeating units is determinant of the way how matter and voids are allocated in space. In contrast to random packing, the periodic construction of framework backbones is both a conceptual and practical way to design highly functional structures with a defined chemical environment at every single position. In this context, a structure as complex as superframeworks can be described entirely by its overall topology, as well as the underlying topologies of the constituent molecular frameworks.

To achieve high precision in constructing large objects, this augmentation strategy relies on the use of atomically defined framework structures as building units in themselves. The definitiveness of structure on the atomic level is indispensable as it prevents the accumulation of defects between objects upon augmentation and thus increases the complexity of the final objects without falling into chaos.

Another feature of frameworks as building units that is vital to the augmentation approach is their ability to be post-synthetically modified.^[13] The reticulation of molecular building units preserves their chemical identities such that the entire framework can be chemically transformed in the same way as discrete molecules. Indeed, the corresponding superframeworks can also be subject to precise modification of their constituents and therefore functionalization of the void space. This potentially imparts a high level of complexity and functionality to these structures, which distinguishes them from assemblies of dense inorganic nanoparticles.^[14] A prerequisite to achieve such functionalization of frameworks is a robust backbone constructed by covalent bonds. Here, strong linkages ensure architectural, mechanical, and chemical stability, and thus prevent structural collapse when subjected to chemical reactions or physical stress.

An outcome of this strategy is the evolution of dynamics with each stage of augmentation. Molecules capable of dynamics in solution lack a rigid backbone which could serve as a platform for their precise alignment in space.^[15,16] Reticular chemistry at the crystal stage enables large amplitude motion with full retention of robustness and definitiveness of structure.^[17–19] The augmentation into superframeworks creates superordinate pores and further extends such dynamics to a larger length scale.

3. Tailored Chemistry of Frameworks

3.1. Backbone Construction

Two general strategies are being practiced in the construction of framework backbones. In topology-guided reticular synthesis, a target structure type is identified as the blueprint, then deconstructed into its underlying geometric units, and finally specified in chemical details.^[1,20] This strategy is useful when targeting known structure types, or unprecedented yet simple, highly symmetrical topologies (topologies of minimal transitivity). In contrast, another emphasis in reticular synthesis is on piecing together judiciously chosen molecular precursors to deliberately explore unknown topological outcomes, instead

of targeting a specific topology at the outset. With the knowledge of how geometrical, chemical, and compositional features of molecular building units direct their linking, this approach is particularly helpful in discovering new structure types and extending the landscape and scope of framework materials.^[21] The product obtained from practicing these two strategies are crystals of framework structures. To use these crystals as building blocks for the next-level augmentation, a control over their size and shape is critical, and significant progress has been made.^[22–25]

3.2. Surface Functionalization

The periodic extension of a framework backbone terminates when it reaches the crystal surface, which is capped by specific functional groups. The functionalization of framework surfaces can be deliberately controlled to modulate the chemophysical behavior of framework crystals required for their augmentation into the next level (Figure 2a). Such functional groups can be installed through conjugation reactions with pendent organic linkers on the crystal surface (Figure 2b). Excess carboxylate groups, for example, exposed on the surface of the MOF are activated and coupled with amine-containing polymers^[26] and proteins.^[27] Alternatively, metal ions on the framework surfaces are amenable to functionalization through ligand substitution reactions (Figure 2c). This can be achieved by using foreign terminal ligands to replace either pendent linkers or the coordinating solvents on linker-depleted framework surfaces, leading to crystals functionalized with molecular monolayers,^[28] synthetic polymers,^[29,30] lipids,^[31] and nucleic acids.^[32] One feature that distinguishes MOFs from inorganic crystals is the presence of organic building units, which provide a unique way to functionalize MOF crystal surfaces (Figure 2d).^[33,34] Reactive moieties on the linker can be varied and post-synthetically modified without compromising the integrity of the framework backbone. Functionalizing reagents larger than the pore aperture, such as nucleic acids, confines their click reaction to the crystal surface without accessing the interior.^[33]

4. Framework Crystals as Building Blocks to Superframeworks

When moving toward superframeworks, the framework crystals themselves now become building units. The linking of these crystals can be done through their pre-programmed surface functional moieties, which facilitates interparticle interactions for building the final superframework structures. The fundamental fact that the framework backbone and the post-synthetically functionalized surface can be independently tuned allows for reticular control to be exerted in a hierarchical manner. Molecules, polymers, and DNA strands (Figure 2e–h) that are attached to framework crystal surfaces can serve to enable the assembly and connection of large objects through interactions of various strength (Figure 2i–l).

Self-assembly of reticular crystals often results in dense packing when the radius of the framework core far exceeds the thickness of its functional corona, driven by the entropy

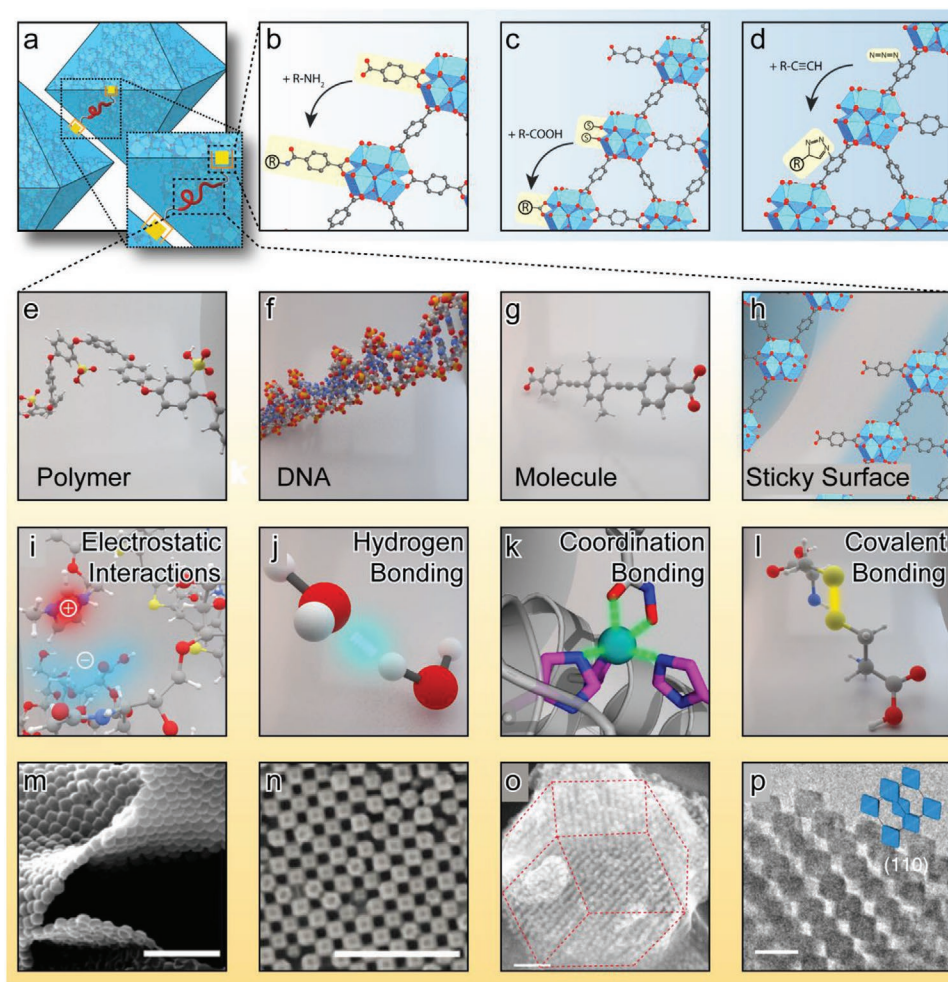


Figure 2. Surface functionalization of frameworks and linking of frameworks into superframeworks. a) Schematic illustration of octahedral UiO-66 crystals (blue) which are connected with each other through functionalities (red) appending from the sites (yellow) on their surface. b–d) Three strategies have been developed to attach functionalities on the surface of framework crystals: b) the exchange of pendent linker, c) replacement of ligand on surface metal sites, and d) covalent modification on surface linker. e–h) The functionalities on crystal surface used for augmentation can be: e) polymers, f) DNA, g) organic linkers, and h) sticky surfaces. i–l) Linkages between crystals can be based on the interactions of increasing strength: i) electrostatics, j) hydrogen, k) coordination, and l) covalent bonds. m–p) Examples of superframeworks constructed by ZIF-8 (ZIF = zeolitic imidazolate framework) crystals (m,n) and UiO-66 crystals (o,p). Scale bars are 1 μm (m), 2 μm (n), 200 nm (o), and 100 nm (p). m) Reproduced with permission.^[38] Copyright 2019, American Chemical Society. n) Reproduced with permission.^[40] Copyright 2019, Wiley-VCH. o,p) Reproduced under the terms of CC-BY Creative Commons Attribution International license (<https://creativecommons.org/licenses/by/4.0>).^[48] Copyright 2020, The Authors, published by Springer Nature.

maximization principle.^[14] This has been observed in the superstructures of soc-MOFs (soc = square–octahedral),^[35] UiO-66,^[36,37] and ZIF-8 (ZIF = zeolitic imidazolate framework) (Figure 2m,n),^[36,38–40] where cubic, octahedral, rhombic dodecahedral, and truncated rhombic dodecahedral crystals are closely packed into their superlattices. The alignment of nanoparticles to form dense arrangements has been extensively studied for semiconductors, metals, and metal oxides.^[14,41,42]

Deviation from closest packing was demonstrated in the assembly of truncated rhombic dodecahedral soc-MOF crystals, which did not pack into the dense rhombohedral lattice but instead into a cubic one.^[35] Such cubic arrangement preserves void space in the size of hundreds of nanometers between crystals, and this is sufficient for the inclusion of large macromolecules. Here, the periodic alignment of crystals introduces a

new interface in the superordinate pore: the external surface of nano-sized crystals now becomes the internal surface of superframeworks. Inherent defects on this interface, such as partially coordinated linkers and undercoordinated metal sites, will bring about new types of covalent and coordinative functionalization, respectively. The non-close-packing configuration results from the free energy contribution of interparticle interactions, commonly dominant in assemblies of small spheres tethered with long hydrocarbon chains.^[14,43–45] Condensing such spheres generates elastic repulsion of ligand chains, leading to internal surface minimization and hence non-close packing configurations.

New assembly chemistry can arise from framework materials, where polymer chains are tethered on spatially separated metal clusters on the surface with a low density, possibly rendering less elastic repulsion and more efficient van der Waals

packing of hydrocarbon chains in an overlapping corona. In addition, an open framework can allow the penetration of polymer chains dangling from the neighboring crystal surface into its interconnected pores, where internal functional groups appended on the reticular backbone recognize polymer moieties and thus facilitate core–shell cross-interactions between crystals.

Stronger than van der Waals packing are Coulombic attractions between oppositely charged crystals resulting in the formation of ionic supercrystals.^[46] Net charges accumulate on MOF crystals when either undercoordinated metal sites or organic linkers are excessively populated on the surface. This can also be achieved by using polyelectrolyte chains to cap crystal surfaces.^[30] In addition, guest ionizable groups residing in the frameworks' pores endow extra charges if their oppositely charged counterions are too bulky to pass through the pore apertures but form counterion clouds surrounding the crystal.

A fundamentally different approach to assembling crystals involves highly specific, orthogonal interactions between nucleic acids attached on their surfaces.^[47] The hybridization of complementary sequences guided by hydrogen bonding and entropic factors drives inter-crystal bond formation. Such weak binding coupled with the polyvalent cooperative interaction allows the system to self-correct defects and achieve ordered arrangements. To take advantage of the programmable interaction of nucleic acids, the assembly behavior of MOF nanocrystals has been studied by attaching phosphate-modified oligonucleotides on UiO-66 nanoparticles.^[33] Specifically, such particles were assembled around Au nanoparticles of varying sizes and stoichiometries that are functionalized with the complementary DNA strands, forming 11 distinct MOF–inorganic core–satellite clusters.^[32]

In another example, UiO-66 and Au nanoparticles in a 1:1 stoichiometric ratio were joined by surface-attached complementary nucleic acids into binary superlattices (Figure 2o).^[48] The hybrid crystals formed in a rhombic dodecahedral shape, which is the Wulff polyhedron for a CsCl-type lattice. Other than spherical MOF nanoparticles, octahedral crystals of UiO-66 with self-complementary DNA sticky ends crystallized into body-centered-cubic (bcc) lattices, a configuration that maximizes DNA bonding interactions between the neighboring anisotropic crystals (Figure 2p).^[48]

Strong chemical bonds have been used for constructing supercrystals. Covalent crosslinking between functional groups dangling from nanoparticle surface allows the formed supercrystal of Au nanoparticle maintain structural integrity in otherwise destructive organic solvents.^[49] Covalently linked iron oxide nanoparticle supercrystals exhibited exceptional isotropic mechanical properties.^[50] Other than linking into close-packed supercrystals, directional linkage between entities as large as proteins has been achieved. The octahedral ferritin was engineered in its C_3 symmetric positions with tripodal Zn coordination sites.^[51] The coordination of Zn to these sites followed by further connection with an organic ditopic linker built a bcc crystal, where each ferritin connects to eight neighbors through the histidine–Zn–hydroxamate coordination bond. Covalent linkages have also been employed in the crystallization of extended protein assemblies. A single-point mutant of the C_4

symmetric protein RhuA exemplifies this strategy, where the proteins are connected to one another by disulfide bonds into a 2D square grid lattice.^[52] Such covalent chemistry has yet to be explored in the construction of superframeworks. However, we envision that a robust superframework requires strong, directional bonding to connect its constituents, when reactive functional groups on their external surface are chemically linked. To avoid the formation of close packing, it is necessary to spatially confine such reactive groups to specific positions on the framework nanocrystals.^[53,54] Such site selective modification allows for the control over the connectivity and geometry of framework crystals for the augmentation into superframeworks of target structure types.

An even stronger connection between crystals can be afforded when a direct contact is established between the crystalline cores, where multiple crystals are fused into a single continuous one. Particularly, desorption of surface ligands resulted in oriented attachment of PbSe nanocrystals through their {100} and {110} facets, producing single-crystalline buckled honeycomb superstructures.^[55] In another example, PbS nanocrystals are merged into 2D single-crystal sheets through oriented attachment of the {110} facets. The facets of MOF crystals that are depleted with surfactants, but rich in either dangling organic linkers or undercoordinated metal ions, can serve as “sticky surfaces” for aligning and merging with other ones bearing complementary surface species.^[56]

We encourage the use of strong linkage in building superframeworks to produce materials, which are robust in a wide range of usage conditions. Reluctance in embracing covalent chemistry often originates from the fear that covalent linking of nanocrystals usually leads to undesired, disordered precipitate. The success of MOFs and COFs (augmentation of molecules into frameworks) has proven that the crystallization problem can be overcome by using reversible covalent bonds to allow for self-correction of defects and avoid the formation of amorphous product.^[57] When covalent bonds are used to connect crystals, the obtained superframework are built with strong linkage across all length scales, from atom to molecule, crystal, and monolith. Such structures are expected to be very strong and resistant against chemical and mechanical damages. On the contrary, the assemblies of crystals by weak interactions cannot take full advantage of reticular chemistry and typically lack the stability required in many applications.

5. Porous Photonic Crystals

Superframeworks provide a structural basis for making porous photonic crystals. Photonic crystals display opalescence visible to the naked eye when the lattice period is comparable to visible wavelength.^[58] The augmentation of frameworks on the supercrystal stage offers a unique opportunity to endow photonic crystals with high porosity, showing great promise in sensing applications. Millimeter-sized MOF supercrystals constructed by ≈ 200 nm ZIF-8 crystals were found to behave as periodic dielectrics and show angle-dependent opalescence.^[36] Such long-range ordered superstructures feature a photonic bandgap that can be tuned by controlling the size of the constituent ZIF-8 crystals. The optical reflection shifted linearly toward

shorter wavelengths at small crystal sizes, spanning from red to blue color. In order to develop photonic sensors, solvent in the micropores of ZIF-8 as well as the intercrystal superordinate pores can be fully evacuated without structural collapse, allowing for the entry of guest molecules. Upon the adsorption of analyte substances, the photonic bandgap varied according to the change of refractive index. The measured bandgap shift can be used to distinguish vapors of different alcohols which the superframeworks are exposed to. Photonic properties of superframeworks can be further modulated by the orientation of the ZIF-8 crystal units.^[40] By adjusting the amount of surfactants used for superframework construction, ZIF-8 crystals formed (111)-, (110)-, and (100)-oriented fcu superlattices, with pronounced change in color.

6. Dynamic Superframeworks

The internal voids within frameworks enable large amplitude motion of their constituents in the solid state. This motion can be either dependent or independent of the backbone.^[59] Specifically, dynamics of the backbone (global dynamics) cause an overall contraction or expansion and thus an increase or decrease in the structure metrics and pore volume of the framework. Such structures cooperatively switch between two

or more distinct states with full retention of long-range order, a phenomenon commonly referred to as 'breathing' for structures whose expansion or contraction is not uniform along all coordinates, or 'swelling' for those expand or contract uniformly (Figure 3a).^[60,61] Breathing MOFs are exemplified by MIL-53 (MIL = Materials Institute Lavoisier) (Figure 3b), which is able to change its cell volume by around 50% in a reversible manner.^[60] The variation of the hinge angle between neighboring linkers enables extensive elongation and shrinkage of the rhombus channel along two orthogonal directions, respectively. The swelling dynamics, on the other hand, are characteristic of another MOF, MIL-88, which exhibits cell volume expansion up to 230%, without changing the shape of the pore (Figure 3c).^[62] Other than global dynamics, in dynamics that are independent of the backbone (local dynamics) the overall structure metrics of the framework remain unaltered, but the pore environment can be modulated through an external stimulus. Such dynamics can be achieved by appending for instance photo-switchable moieties onto the backbone of the framework.^[63]

6.1. Local Dynamics in Superordinate Pores

Large cavity sizes combined with multivariate functionalities endow superframeworks with the ability to manipulate the

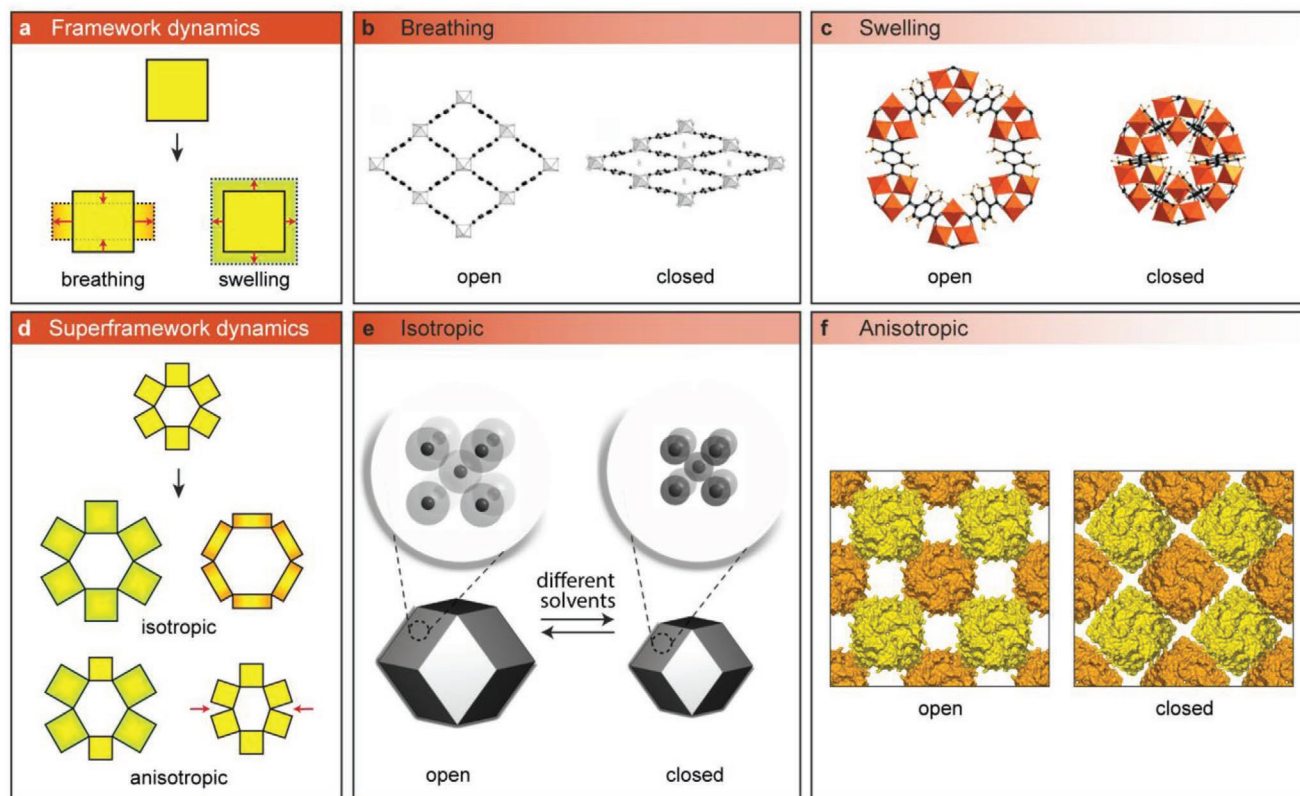


Figure 3. Dynamics in frameworks and superframeworks. a) Illustration of dynamics at the framework level: the breathing and swelling mode. b) The breathing of MIL-53 (MIL = Materials Institute Lavoisier). c) The swelling of MIL-88. d) Illustration of dynamics at the superframework level: swelling of a superframework enabled by swelling or breathing of constituent frameworks; breathing of a superframework enabled by partial swelling of constituent frameworks or by rotation of their linkages. e) Swelling of a supercrystal of gold Au nanoparticles connected by flexible DNA shells. f) Breathing of a protein lattice enabled by its flexible linkage.^[52] b) Reproduced with permission.^[60] Copyright 2004, Wiley-VCH. c) Reproduced with permission.^[62] Copyright 2011, American Chemical Society. e) Reproduced with permission.^[65] Copyright 2019, American Chemical Society.

dynamics of guest objects. The functional groups appended onto a framework backbone can interact with protein moieties to alter their energy landscapes, thus stabilizing one specific conformation over others. The encapsulation of cytochrome *c* in the Tb-mesoMOF exemplifies this concept.^[64] Cytochrome *c* exceeds the size of Tb-mesoMOF's pore aperture and has to undergo a conformational change during its translocation into the framework cavity. In the encapsulated non-native conformation, certain hydrophobic residues, such as Trp59, previously hidden inside the protein now become more distant from the heme center and more exposed to the hydrophobic framework backbone. Superframeworks, encompassing mesoscale cavities can be further exploited to regulate the structure and function of large protein complexes with a high level of kinetic control, analogous to protein chaperones.

6.2. Amplified Global Dynamics

The dynamics of superframework backbones can arise from the inherent flexibility of the constituent frameworks (Figure 3d). When these dynamic frameworks are connected by rigid linkages, their breathing and swelling results in the corresponding size change of enclosed superordinate pores and consequently induce a swelling behavior at the supercrystal stage. In this process, the original pore dynamics of molecular frameworks are manifested in alteration of crystal metrics, and finally amplified into the pore expansion or contraction of superframeworks. A pronounced change in the superlattice parameters was observed in the case of supercrystals of Au nanoparticles, where their DNA shell was covalently crosslinked (Figure 3e).^[65] Upon exposure to organic solvents of different polarity, the DNA shell exhibited flexibility that was transformed to a shrinkage on the superlattice level.

Other than swelling, a breathing mode can be introduced at the supercrystal stage when flexible linkages are employed for connecting crystals (Figure 3d), which allows for the distortion of the superordinate pore in response to stimuli at a larger length scale, such as the inclusion of protein complexes. Breathing can also occur in a single supercrystal constructed from multiple different frameworks, when a stimulus triggers the swelling of only one type of such units, leading to the elongation of the superordinate pore along specific orientations. When frameworks and their linkages are both flexible, the resulting global dynamics in superframeworks can be further controlled such that the swelling or the breathing of the superordinate pores can be independently effected by two orthogonal stimuli. This dynamic behavior can lead to photonic materials responsive to external stimuli, such as light, chemical stress, and pressure or temperature changes. Although transference of dynamics from the crystal level to higher levels has not been demonstrated, frameworks made from proteins (large size regime) have been reported to exhibit breathing dynamics (Figure 3f).^[52] A 2D lattice made by connecting proteins through disulfide bond exhibited coherent lattice motion between fully open and fully closed states, afforded by a remarkable extent of hinging about the flexible disulfide linkages. The compression of the interprotein hinge angle from $>80^\circ$ to 17° was accompanied by an anisotropic shrinkage of the pore from a square shape to an elongated one.

7. Integrated Reaction Systems

The linking of framework building units can integrate multiple reaction pathways into a network, where each molecular framework processes one reaction step, thus serving as a node of the reaction network. Two reaction nodes are topologically connected in the network when the product of one node is the precursor of the other. Reaction nodes can also be associated due to their regulatory roles—the product of one node antagonistically quenches the reaction in another node by competing with its reaction intermediate. Although using superframeworks for systems chemistry remains preliminary, below, we present the design principles for achieving this goal, including those for connecting reaction nodes and separating those that work in parallel to avoid undesired crosstalk.

7.1. Separated Reaction Nodes Operating in Parallel

One advantage of integrating multiple reactive units into a single monolith is to confine otherwise incompatible chemical processes in compartmentalized locations. This effect was demonstrated in an early example of two different star polymers, one encapsulating in its core an acid catalyst and the other a base catalyst.^[66] The site isolation of these catalysts suppressed their mutual deactivation, allowing for a one-pot reaction cascade. In another example, amphiphilic triblock copolymers were functionalized with two metal catalysts in different domains of the micelle, which catalyzed alkyne hydration in the hydrophobic core and the asymmetric transfer hydrogenation of the intermediate ketone in the hydrophilic shell, respectively.^[67] Well-defined metal–organic cages have also been used for this purpose. $M_{12}L_{24}$ -type (M stands for metal and L for linker) molecular capsules encapsulated separately a (2,2,6,6-tetramethylpiperidin-1-yl)oxyl catalytic moiety for an oxidation reaction and a MacMillan's catalyst for Diels–Alder chemistry in a two-step cascade; the latter catalyst can be promptly oxidized by the former without site isolation.^[68] An M_4L_6 tetrahedral cage enabled the combination of enzymatic and transition metal catalysis in tandem reactions, where organometallic catalysts, such as Au(I) and Ru(II) complexes, were segregated from enzymes including esterases, lipases, and alcohol dehydrogenases in solution.^[69] The encapsulation of the organometallic complexes prevented their diffusion into bulk media and consequently deactivation by binding to amino acid residues on the proteins, making it possible to carry out classic organic reactions in the presence of biocatalysts. Given the independence between compartmentalized chemical reactions, we envision that superframeworks have great potential in housing complex chemical networks without undesired crosstalk between unconnected compartments.

7.2. Apportionment of Cooperative Reaction Nodes

When two reaction nodes are topologically connected in the reaction network, their spatial distance and arrangement have to be carefully considered in order to achieve optimal mass transfer and production. Nature has evolved with highly

coordinated metabolons (i.e., multienzyme complexes), where co-operating active sites are brought into close proximity such that an intermediate can be accurately channeled without dilution into the bulk media of the cell.^[70] Such co-localization optimizes the concentration of substrates and intermediates, matches reaction kinetics along the same cascade, and controls metabolic crosstalk between different pathways. Inspired by nature, the development of engineered metabolic pathways has emphasized the increase in the effective concentration of pathway components thus alleviating flux imbalance. Synthetic protein scaffolds were built to spatially recruit metabolic enzymes in a designable manner, which achieved 77-fold improvement in product titer.^[71] Kinetic studies coupled with simulations of scaffolded multienzyme systems provided design rules for promoting substrate channeling.^[72] Specifically, the probability that the product of the first reaction channels to the second active site drops quickly when the interenzyme distance increases in the range from 1 to 10 nm, according to Brownian dynamics. At a given interenzyme distance, direct alignment of the active sites is highly favored. When the distance exceeds 1 nm between active sites, significant channeling occurs only if diffusion of the intermediate is bound through interactions with the surface or scaffold between active sites. Therefore, the spatial arrangement of framework units in a superframework becomes a key element in the design of a sophisticated reaction network; framework units should be apportioned according to their association in the reaction network.

7.3. Nonreactive Framework Units for Substrate Channeling

Reaction nodes of the network can be connected by framework components responsible for mass transport and molecule separation. Millimeter-sized MOF-5 single crystals have been demonstrated to separate mixtures of organic molecules over distances of only a few hundred micrometers, serving as miniature chromatography columns.^[73] The efficiency of separation within crystals derives from an interplay between the diffusive transport and fleeting noncovalent interactions between the migrating molecules and the MOF scaffold. Such transport units in the integrated reaction network can feed reaction centers selectively and channel products into desired compartments.

7.4. An Integrated Reaction Network for CO₂ Transformation

It is expected that superframeworks can function in an analogous way to biological systems by integrating multiple components, each designed for a specific function. This is illustrated by analogy to the photosynthetic reaction center (Figure 4), where CO₂ is captured and transformed into various chemicals and fuels driven by solar energy. A wide variety of photoautotrophic organisms possess a CO₂ concentrating mechanism to compensate for the relatively low affinity of ribulose-1,5-bisphosphate carboxylase-oxygenase (RuBisCO) for CO₂.^[74] Typically, this is achieved through the generation of HCO₃⁻ from atmospheric CO₂ and the conversion of the accumulated

HCO₃⁻ back to CO₂ in the proximity of RuBisCO, both catalyzed by carbonic anhydrase. A similar process can be accomplished in MOFs where open metal sites^[75–77] or alkylamine functionalities^[78,79] are covalently tethered to the organic linker to facilitate CO₂ capture and release with a low cost of energy. The connection of these components to additional catalytic building units allows the photosynthetic reaction to be carried out at a high CO₂ level (reduction, Figure 4). In the Calvin cycle, the subsequent transformation of CO₂ to organic compounds is catalyzed by RuBisCO and many other enzymes, with the consumption of the energy and electrons generated in the light reaction.^[80] The fundamental fact that chemical and structural features of reticular structures can be rationally designed with atomic precision can afford not only the activity and selectivity of CO₂ reduction found in nature, but also desired optoelectronic properties outperforming natural efficiencies (light harvesting, Figure 4).^[81,82] The reduced carbon species can further be catalytically converted into a variety of value-added chemical compounds through oxidative functionalization,^[83–88] which can be sorted and processed in parallel within a single superframework (oxidation, Figure 4). As such, the augmentation at the supercrystal stage allows for the integration of multiple framework components into compartmentalized functional domains in a single highly sophisticated miniature factory system.

8. Outlook

The building-up of MOF supercrystals outlined in this article in essence presents a moonshot for chemists where new and useful macrostructures can be designed with the same celebrated precision of molecular chemistry. Thus, going from molecules to frameworks of molecules and to supercrystals, while maintaining precision of design and molecular definition, represents a fantastic scientific challenge for chemists. It is not an unlikely target as it is a natural extension of molecular chemistry and its values.

Compared with nature, augmented reticular chemistry occupies a distinctive design space that can be accessed by human's creativity. It was pointed out that nature follows the path of least resistance, often using the most common materials to accomplish a task.^[89] While the chemical compositions for living systems are strictly limited to a few chemical elements, building units amenable to reticular synthesis can be derived from a vast number of building units that is constantly being expanded by synthetic chemists. Another factor that contributes to the intrigue of augmented reticular chemistry is the range of functions that can be pursued, for utilizing energy and mass in a desired manner, not necessarily relevant to an organism's survival. Even for those having counterparts in nature, synthetic efforts can target superior efficiency, which is not constrained by the energy requirement of survival. Augmented reticular chemistry provides a platform to explore proactively with clear blueprints and dedicated purposes. When moving to complex systems as we envisioned here, developing strategies like natural selection into laboratory settings becomes critical. High-throughput screening offers a practical methodology to accelerate the discovery of reticular structures.^[90] This can be combined with deep-learning

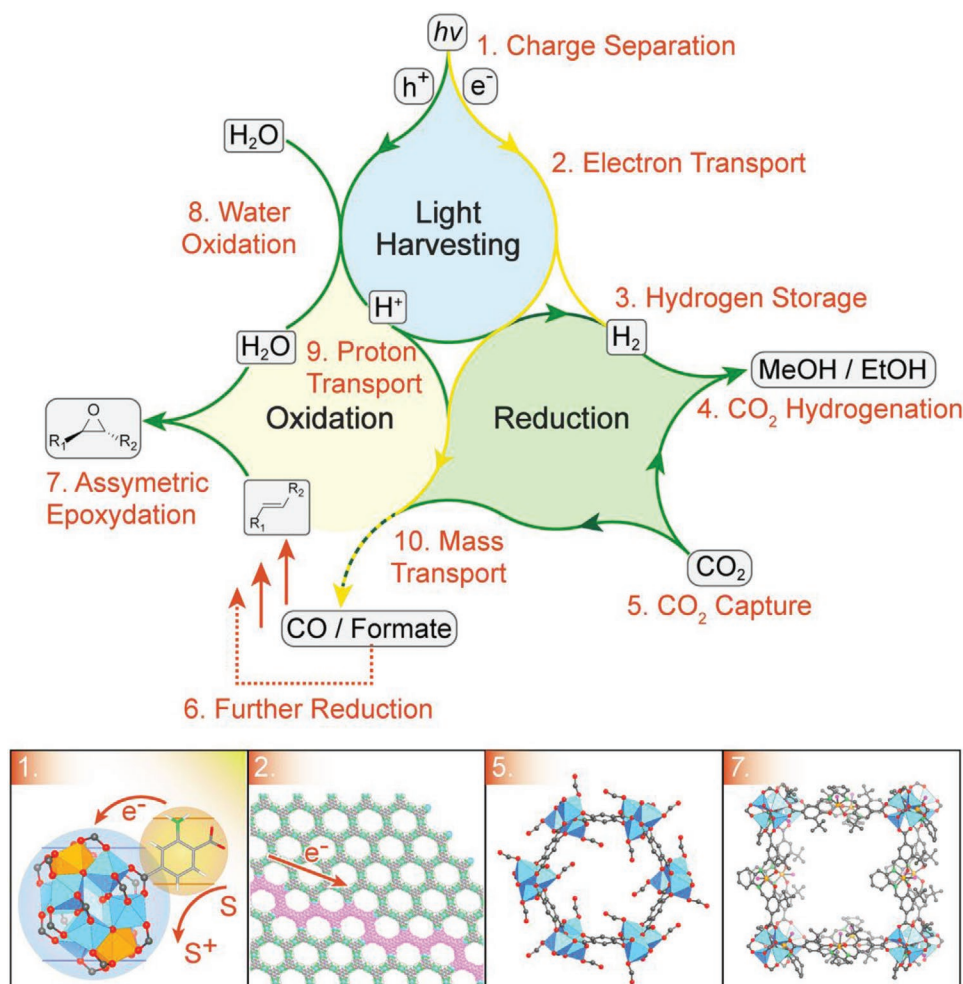


Figure 4. The flow of charge and reactants in an integrated reaction system. Electrons and holes separated from light harvesting are injected into the reaction network. CO_2 captured from atmosphere is reduced into chemicals and fuels through the consumption of these electrons or their intermediate carrier, H_2 , which is derived from water and stored for later use in dark conditions. On the other side, H_2O_2 , the oxidation product of water transforms the chemicals and fuels, the product of reduction cycle, into rich and functional chemicals on demand, by, for instance, asymmetric epoxidation. Each of these reaction sites (molecular framework) is compartmentalized within the whole system (superframework), with reactants, products, protons, and charge carriers channeled in between. Examples of reticular structures capable of carrying out these processes include PCN-415(NH_2) (PCN = porous coordination network)^[93] for charge separation, $\text{Ni}_3(2,3,6,7,10,11\text{-hexaiminotriphenylene})_2$ ^[94] for electron transport, MOF-74^[77] for CO_2 capture, and CMOF-2 (CMOF = chiral MOF)^[83] for asymmetric epoxidation.

algorithms^[91,92] to discern the optimal combination of framework units at each augmentation level.

To truly harness the potential of this vast design space, the consummate researcher has to be a scientist who navigates intellectually and practically in many fields: chemistry (atoms, bonds, molecules, and their reactivity), physics (energy flux and gradients, and their transformations on all scales), biology (programmable complexity, hierarchy, dynamics, and adaptability), computer science (big data and machine-learning algorithms), material science (lithography and additive manufacturing), and engineering (robotics and products). Already, many practitioners of reticular science lie in these different fields but work largely independently. In order to elevate this field, it becomes necessary to synergize expertise from different fields into what we call augmented reticular chemistry.

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Conflict of Interest

The authors declare no conflict of interest.

Keywords

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- [1] O. M. Yaghi, M. O’Keeffe, N. W. Ockwig, H. K. Chae, M. Eddaoudi, J. Kim, *Nature* **2003**, 423, 705.
- [2] C. S. Diercks, O. M. Yaghi, *Science* **2017**, 355, eaal1585.
- [3] O. M. Yaghi, M. J. Kalmutzki, C. S. Diercks, *Introduction to Reticular Chemistry: Metal–Organic Frameworks and Covalent Organic Frameworks*, Wiley-VCH, Weinheim, Germany **2019**.
- [4] R. Freund, S. Canossa, S. M. Cohen, W. Yan, H. Deng, V. Guillermin, M. Eddaoudi, D. G. Madden, D. Fairen-Jimenez, H. Lyu, L. K. Macreadie, Z. Ji, Y. Zhang, B. Wang, F. Haase, C. Woll, O. Zaremba, J. Andreo, S. Wuttke, C. S. Diercks, *Angew. Chem., Int. Ed.*, <https://doi.org/10.1002/anie.202101644>.
- [5] R. Freund, O. Zaremba, G. Arnauts, R. Ameloot, G. Skorupskii, M. Dinca, A. Bavykina, J. Gascon, A. Ejsmont, J. Goscianska, M. Kalmutzki, U. Lachelt, E. Ploetz, C. Diercks, S. Wuttke, *Angew. Chem., Int. Ed.*, <https://doi.org/10.1002/anie.202106259>.
- [6] U. G. K. Wegst, H. Bai, E. Saiz, A. P. Tomsia, R. O. Ritchie, *Nat. Mater.* **2015**, 14, 23.
- [7] M. Eder, S. Amini, P. Fratzl, *Science* **2018**, 362, 543.
- [8] J. H. Cavka, S. Jakobsen, U. Olsbye, N. Guillou, C. Lamberti, S. Bordiga, K. P. Lillerud, *J. Am. Chem. Soc.* **2008**, 130, 13850.
- [9] Z. Ji, H. Z. Wang, S. Canossa, S. Wuttke, O. M. Yaghi, *Adv. Funct. Mater.* **2020**, 30, 2000238.
- [10] U. Stoeck, S. Krause, V. Bon, I. Senkovska, S. Kaskel, *Chem. Commun.* **2012**, 48, 10841.
- [11] J. J. Perry, J. A. Perman, M. J. Zaworotko, *Chem. Soc. Rev.* **2009**, 38, 1400.
- [12] F. Nouar, J. F. Eubank, T. Bousquet, L. Wojtas, M. J. Zaworotko, M. Eddaoudi, *J. Am. Chem. Soc.* **2008**, 130, 1833.
- [13] Z. Wang, S. M. Cohen, *Chem. Soc. Rev.* **2009**, 38, 1315.
- [14] M. A. Boles, M. Engel, D. V. Talapin, *Chem. Rev.* **2016**, 116, 11220.
- [15] W. Danowski, T. van Leeuwen, S. Abdolazadeh, D. Roke, W. R. Browne, S. J. Wezenberg, B. L. Feringa, *Nat. Nanotechnol.* **2019**, 14, 488.
- [16] V. V. Balzani, A. Credi, F. M. Raymo, J. F. Stoddart, *Angew. Chem., Int. Ed.* **2000**, 39, 3348.
- [17] K. Barthelet, J. Marrot, D. Riou, G. Ferey, *Angew. Chem., Int. Ed.* **2002**, 41, 281.
- [18] T. K. Maji, R. Matsuda, S. Kitagawa, *Nat. Mater.* **2007**, 6, 142.
- [19] Y. Z. Liu, Y. H. Ma, Y. B. Zhao, X. X. Sun, F. Gandara, H. Furukawa, Z. Liu, H. Y. Zhu, C. H. Zhu, K. Suenaga, P. Oleynikov, A. S. Alshammari, X. Zhang, O. Terasaki, O. M. Yaghi, *Science* **2016**, 351, 365.
- [20] M. O’Keeffe, O. M. Yaghi, *Chem. Rev.* **2012**, 112, 675.
- [21] J. Yang, Y. B. Zhang, Q. Liu, C. A. Trickett, E. Gutierrez-Puebla, M. A. Monge, H. Cong, A. Aldossary, H. Deng, O. M. Yaghi, *J. Am. Chem. Soc.* **2017**, 139, 6448.
- [22] M. Sindoro, N. Yanai, A. Y. Jee, S. Granick, *Acc. Chem. Res.* **2014**, 47, 459.
- [23] J. Troyano, A. Carne-Sanchez, C. Avci, I. Imaz, D. Maspocho, *Chem. Soc. Rev.* **2019**, 48, 5534.
- [24] T. He, X. Xu, B. Ni, H. Wang, Y. Long, W. Hu, X. Wang, *Nanoscale* **2017**, 9, 19209.
- [25] P. Hirschle, C. Hirschle, K. Boll, M. Doblinger, M. Hohn, J. M. Tuffnell, C. W. Ashling, D. A. Keen, T. D. Bennett, J. O. Radler, E. Wagner, M. Peller, U. Lachelt, S. Wuttke, *Chem. Mater.* **2020**, 32, 2253.
- [26] A. Zimpel, T. Preiss, R. Roder, H. Engelke, M. Ingrischi, M. Peller, J. O. Radler, E. Wagner, T. Bein, U. Lachelt, S. Wuttke, *Chem. Mater.* **2016**, 28, 3318.
- [27] S. Jung, Y. Kim, S. J. Kim, T. H. Kwon, S. Huh, S. Park, *Chem. Commun.* **2011**, 47, 2904.
- [28] M. Kondo, S. Furukawa, K. Hirai, S. Kitagawa, *Angew. Chem., Int. Ed.* **2010**, 49, 5327.
- [29] R. Roder, T. Preiss, P. Hirschle, B. Steinborn, A. Zimpel, M. Hohn, J. O. Radler, T. Bein, E. Wagner, S. Wuttke, U. Lachelt, *J. Am. Chem. Soc.* **2017**, 139, 2359.
- [30] A. Zimpel, N. Al Danaf, B. Steinborn, J. Kuhn, M. Hohn, T. Bauer, P. Hirschle, W. Schrimpf, H. Engelke, E. Wagner, M. Barz, D. C. Lamb, U. Lachelt, S. Wuttke, *ACS Nano* **2019**, 13, 3884.
- [31] W. Zhu, G. L. Xiang, J. Shang, J. M. Guo, B. Motevalli, P. Durfee, J. O. Agola, E. N. Coker, C. J. Brinker, *Adv. Funct. Mater.* **2018**, 28, 1705274.
- [32] S. Wang, C. M. McGuirk, M. B. Ross, S. Wang, P. Chen, H. Xing, Y. Liu, C. A. Mirkin, *J. Am. Chem. Soc.* **2017**, 139, 9827.
- [33] W. Morris, W. E. Briley, E. Auyeung, M. D. Cabezas, C. A. Mirkin, *J. Am. Chem. Soc.* **2014**, 136, 7261.
- [34] K. Xie, Q. Fu, Y. He, J. Kim, S. J. Goh, E. Nam, G. G. Qiao, P. A. Webley, *Chem. Commun.* **2015**, 51, 15566.
- [35] M. Pang, A. J. Cairns, Y. Liu, Y. Belmabkhout, H. C. Zeng, M. Eddaoudi, *J. Am. Chem. Soc.* **2012**, 134, 13176.
- [36] C. Avci, I. Imaz, A. Carne-Sanchez, J. A. Pariente, N. Tasios, J. Perez-Carvajal, M. I. Alonso, A. Blanco, M. Dijkstra, C. Lopez, D. Maspocho, *Nat. Chem.* **2017**, 10, 78.
- [37] G. Lu, C. Cui, W. Zhang, Y. Liu, F. Huo, *Chem. Asian J.* **2013**, 8, 69.
- [38] Y. Katayama, M. Kalaj, K. S. Barcus, S. M. Cohen, *J. Am. Chem. Soc.* **2019**, 141, 20000.
- [39] N. Yanai, S. Granick, *Angew. Chem., Int. Ed.* **2012**, 51, 5638.
- [40] C. Avci, Y. Liu, J. A. Pariente, A. Blanco, C. Lopez, I. Imaz, D. Maspocho, *Small* **2019**, 15, e1902520.
- [41] C. B. Murray, C. R. Kagan, M. G. Bawendi, *Science* **1995**, 270, 1335.
- [42] Y. Lin, A. Boker, J. He, K. Sill, H. Xiang, C. Abetz, X. Li, J. Wang, T. Emrick, S. Long, Q. Wang, A. Balazs, T. P. Russell, *Nature* **2005**, 434, 55.
- [43] E. V. Shevchenko, D. V. Talapin, N. A. Kotov, S. O’Brien, C. B. Murray, *Nature* **2006**, 439, 55.
- [44] A. C. Balazs, T. Emrick, T. P. Russell, *Science* **2006**, 314, 1107.
- [45] Y. Zhao, K. Thorkelsson, A. J. Mastroianni, T. Schilling, J. M. Luther, B. J. Rancatore, K. Matsunaga, H. Jinnai, Y. Wu, D. Poulsen, J. M. Frechet, A. P. Alivisatos, T. Xu, *Nat. Mater.* **2009**, 8, 979.
- [46] A. M. Kalsin, M. Fialkowski, M. Paszewski, S. K. Smoukov, K. J. Bishop, B. A. Grzybowski, *Science* **2006**, 312, 420.
- [47] M. R. Jones, N. C. Seeman, C. A. Mirkin, *Science* **2015**, 347, 1260901.
- [48] S. Wang, S. S. Park, C. T. Buru, H. Lin, P. C. Chen, E. W. Roth, O. K. Farha, C. A. Mirkin, *Nat. Commun.* **2020**, 11, 2495.
- [49] J. Dey, S. J. Lee, J. Kim, S. H. Lim, J. M. Ha, M. J. Lee, S. M. Choi, *Nano Lett.* **2021**, 21, 258.
- [50] A. Dreyer, A. Feld, A. Kornowski, E. D. Yilmaz, H. Noei, A. Meyer, T. Krekeler, C. Jiao, A. Stierle, V. Abetz, H. Weller, G. A. Schneider, *Nat. Mater.* **2016**, 15, 522.
- [51] P. A. Sontz, J. B. Bailey, S. Ahn, F. A. Tezcan, *J. Am. Chem. Soc.* **2015**, 137, 11598.
- [52] Y. Suzuki, G. Cardone, D. Restrepo, P. D. Zavattieri, T. S. Baker, F. A. Tezcan, *Nature* **2016**, 533, 369.
- [53] A. Umemura, S. Diring, S. Furukawa, H. Uehara, T. Tsuruoka, S. Kitagawa, *J. Am. Chem. Soc.* **2011**, 133, 15506.
- [54] Y. Zhao, R. H. Bernitzky, M. J. Kory, G. Hofer, J. Hofkens, A. D. Schluter, *J. Am. Chem. Soc.* **2016**, 138, 8976.
- [55] M. P. Boneschanscher, W. H. Evers, J. J. Geuchies, T. Altantzis, B. Goris, F. T. Rabouw, S. A. van Rossum, H. S. van der Zant,

- L. D. Siebbeles, G. Van Tendeloo, I. Swart, J. Hilhorst, A. V. Petukhov, S. Bals, D. Vanmaekelbergh, *Science* **2014**, 344, 1377.
- [56] C. Schliehe, B. H. Juarez, M. Pelletier, S. Jander, D. Greshnykh, M. Nagel, A. Meyer, S. Foerster, A. Kornowski, C. Klinke, H. Weller, *Science* **2010**, 329, 550.
- [57] J. Jiang, Y. Zhao, O. M. Yaghi, *J. Am. Chem. Soc.* **2016**, 138, 3255.
- [58] J. D. Joannopoulos, P. R. Villeneuve, S. H. Fan, *Nature* **1997**, 386, 143.
- [59] A. Schneemann, V. Bon, I. Schwedler, I. Senkovska, S. Kaskel, R. A. Fischer, *Chem. Soc. Rev.* **2014**, 43, 6062.
- [60] T. Loiseau, C. Serre, C. Huguenard, G. Fink, F. Taulelle, M. Henry, T. Bataille, G. Ferey, *Chem. - Eur. J.* **2004**, 10, 1373.
- [61] C. Mellot-Drazniak, C. Serre, S. Surble, N. Audebrand, G. Ferey, *J. Am. Chem. Soc.* **2005**, 127, 16273.
- [62] P. Horcajada, F. Salles, S. Wuttke, T. Devic, D. Heurtaux, G. Maurin, A. Vimont, M. Daturi, O. David, E. Magnier, N. Stock, Y. Filinchuk, D. Popov, C. Riekel, G. Ferey, C. Serre, *J. Am. Chem. Soc.* **2011**, 133, 17839.
- [63] J. W. Brown, B. L. Henderson, M. D. Kiesz, A. C. Whalley, W. Morris, S. Grunder, H. X. Deng, H. Furukawa, J. I. Zink, J. F. Stoddart, O. M. Yaghi, *Chem. Sci.* **2013**, 4, 2858.
- [64] Y. Chen, V. Lykourinou, C. Vetromile, T. Hoang, L. J. Ming, R. W. Larsen, S. Ma, *J. Am. Chem. Soc.* **2012**, 134, 13188.
- [65] S. Lee, C. Y. Zheng, K. E. Bujold, C. A. Mirkin, *J. Am. Chem. Soc.* **2019**, 141, 11827.
- [66] B. Helms, S. J. Guillaudeau, Y. Xie, M. McMurdo, C. J. Hawker, J. M. J. Frechet, *Angew. Chem., Int. Ed.* **2005**, 44, 6384.
- [67] J. Lu, J. Dimroth, M. Weck, *J. Am. Chem. Soc.* **2015**, 137, 12984.
- [68] Y. Ueda, H. Ito, D. Fujita, M. Fujita, *J. Am. Chem. Soc.* **2017**, 139, 6090.
- [69] Z. J. Wang, K. N. Clary, R. G. Bergman, K. N. Raymond, F. D. Toste, *Nat. Chem.* **2013**, 5, 100.
- [70] K. Jorgensen, A. V. Rasmussen, M. Morant, A. H. Nielsen, N. Bjarnholt, M. Zagrobely, S. Bak, B. L. Moller, *Curr. Opin. Plant Biol.* **2005**, 8, 280.
- [71] J. E. Dueber, G. C. Wu, G. R. Malmirchegini, T. S. Moon, C. J. Petzold, A. V. Ullal, K. L. J. Prather, J. D. Keasling, *Nat. Biotechnol.* **2009**, 27, 753.
- [72] J. L. Lin, L. Palomec, I. Wheeldon, *ACS Catal.* **2014**, 4, 505.
- [73] S. Han, Y. Wei, C. Valente, I. Lagzi, J. J. Gassensmith, A. Coskun, J. F. Stoddart, B. A. Grzybowski, *J. Am. Chem. Soc.* **2010**, 132, 16358.
- [74] A. Kaplan, L. Reinhold, *Annu. Rev. Plant Physiol. Plant Mol. Biol.* **1999**, 50, 539.
- [75] S. R. Caskey, A. G. Wong-Foy, A. J. Matzger, *J. Am. Chem. Soc.* **2008**, 130, 10870.
- [76] D. Britt, H. Furukawa, B. Wang, T. G. Glover, O. M. Yaghi, *Proc. Natl. Acad. Sci. USA* **2009**, 106, 20637.
- [77] P. D. Dietzel, R. E. Johnsen, H. Fjellvag, S. Bordiga, E. Groppo, S. Chavan, R. Blom, *Chem. Commun.* **2008**, 47, 5125.
- [78] A. M. Fracaroli, H. Furukawa, M. Suzuki, M. Dodd, S. Okajima, F. Gandara, J. A. Reimer, O. M. Yaghi, *J. Am. Chem. Soc.* **2014**, 136, 8863.
- [79] T. M. McDonald, J. A. Mason, X. Kong, E. D. Bloch, D. Gygi, A. Dani, V. Crocella, F. Giordanino, S. O. Odoh, W. S. Drisdell, B. Vlasisavljevich, A. L. Dzubak, R. Poloni, S. K. Schnell, N. Planas, K. Lee, T. Pascal, L. F. Wan, D. Prendergast, J. B. Neaton, B. Smit, J. B. Kortright, L. Gagliardi, S. Bordiga, J. A. Reimer, J. R. Long, *Nature* **2015**, 519, 303.
- [80] M. Calvin, A. A. Benson, *Science* **1948**, 107, 476.
- [81] S. Lin, C. S. Diercks, Y. B. Zhang, N. Kornienko, E. M. Nichols, Y. Zhao, A. R. Paris, D. Kim, P. Yang, O. M. Yaghi, C. J. Chang, *Science* **2015**, 349, 1208.
- [82] C. S. Diercks, Y. Liu, K. E. Cordova, O. M. Yaghi, *Nat. Mater.* **2018**, 17, 301.
- [83] F. Song, C. Wang, J. M. Falkowski, L. Ma, W. Lin, *J. Am. Chem. Soc.* **2010**, 132, 15390.
- [84] D. Sun, F. Sun, X. Deng, Z. Li, *Inorg. Chem.* **2015**, 54, 8639.
- [85] J. Baek, B. Rungtaweeworani, X. Pei, M. Park, S. C. Fakra, Y. S. Liu, R. Matheu, S. A. Alshmiri, S. Alshehri, C. A. Trickett, G. A. Somorjai, O. M. Yaghi, *J. Am. Chem. Soc.* **2018**, 140, 18208.
- [86] M. H. Xie, X. L. Yang, Y. He, J. Zhang, B. Chen, C. D. Wu, *Chem. - Eur. J.* **2013**, 19, 14316.
- [87] K. Manna, P. F. Ji, Z. K. Lin, F. X. Greene, A. Urban, N. C. Thacker, W. B. Lin, *Nat. Commun.* **2016**, 7, 12610.
- [88] D. J. Xiao, E. D. Bloch, J. A. Mason, W. L. Queen, M. R. Hudson, N. Planas, J. Borycz, A. L. Dzubak, P. Verma, K. Lee, F. Bonino, V. Crocella, J. Yano, S. Bordiga, D. G. Truhlar, L. Gagliardi, C. M. Brown, J. R. Long, *Nat. Chem.* **2014**, 6, 590.
- [89] L. Eadie, T. K. Ghosh, *J. R. Soc., Interface* **2011**, 8, 761.
- [90] R. Banerjee, A. Phan, B. Wang, C. Knobler, H. Furukawa, M. O'Keeffe, O. M. Yaghi, *Science* **2008**, 319, 939.
- [91] P. Raccuglia, K. C. Elbert, P. D. F. Adler, C. Falk, M. B. Wenny, A. Mollo, M. Zeller, S. A. Friedler, J. Schrier, A. J. Norquist, *Nature* **2016**, 533, 73.
- [92] H. Lyu, Z. Ji, S. Wuttke, O. M. Yaghi, *Chem* **2020**, 6, 2219.
- [93] S. Yuan, J. S. Qin, H. Q. Xu, J. Su, D. Rossi, Y. Chen, L. Zhang, C. Lollar, Q. Wang, H. L. Jiang, D. H. Son, H. Xu, Z. Huang, X. Zou, H. C. Zhou, *ACS Cent. Sci.* **2018**, 4, 105.
- [94] D. Sheberla, L. Sun, M. A. Blood-Forsythe, S. Er, C. R. Wade, C. K. Brozek, A. Aspuru-Guzik, M. Dinca, *J. Am. Chem. Soc.* **2014**, 136, 8859.



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