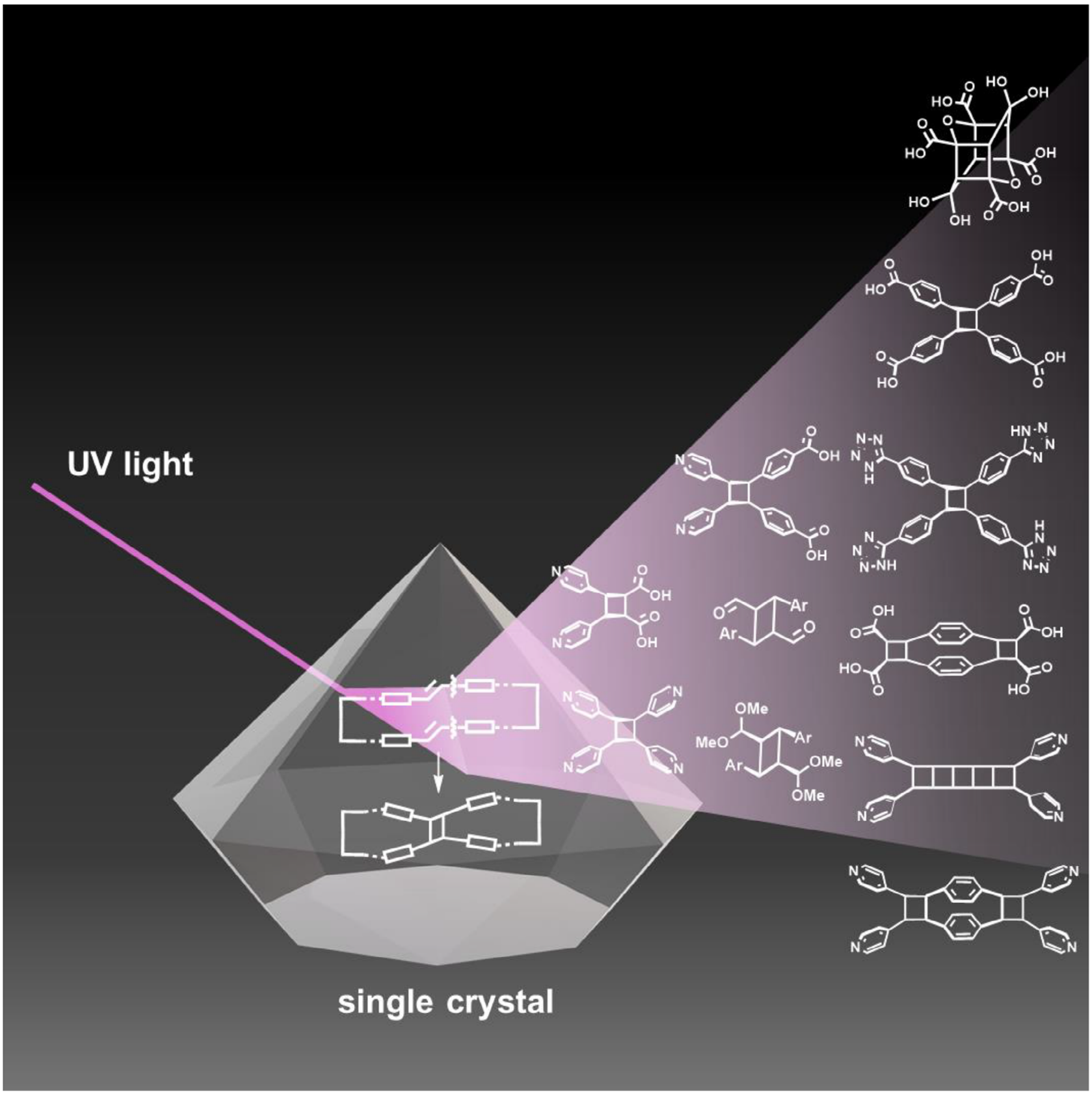
Chemistry—A European Journal
Review
doi.org/10.1002/chem.202500756
Chemistry Europe
European Chemical Societies Publishing
www.chemeurj.org

Supramolecular Matter Through Crystal Engineering: Covalent Bond Formation to Postsynthetic Modification

Changan Li[a] and Leonard R. MacGillivray*[b]



Supramolecular chemistry can transform organic synthesis by revealing that crystalline materials are not static but rather dynamic environments for controlled covalent bond formations and manipulations. This review focuses on how supramolecular chemistry can be developed to direct molecular synthesis in the organic solid state, directing reliable C—C bond formations to enable transformations difficult or impossible in solution. Special attention is given to postsynthetic modifications that serve to broaden the functional scope of solid-state reactivity allowing organic crystals to be developed as molecular flasks and a form of supramolecular matter.

1. Introduction

Once dismissed as static and unreactive, organic crystals have been regarded as "cemetery of chemistry,"[1] where chemical reactions that form molecules were considered not possible owing to the crystalline state being rigid and constrained. However, advancements in X-ray crystallography and the advent of crystal engineering have transformed this view,[2] revealing the organic solid state as a dynamic medium wherein covalent bond-forming reactions can be accomplished with high fidelity.[3–6]

> "What would happen if we could arrange the atoms one by one the way we want them?"
> - Richard P. Feynman 1959 lecture in "There's Plenty of Room at the Bottom"

The field of supramolecular chemistry itself has provided powerful avenues to expand the landscape of molecular synthesis. An origin of how supramolecular chemistry controls organic synthesis is the templated formation of 18-crown-6 by K^+ ions (Scheme 1).[7–8] The metal preorganizes ethylene glycol units to react in the solution phase. A crystal, by contrast, exhibits a kind of static order where it can be difficult to conceive of the medium being used to plan and perform organic synthesis. A crystal is a supramolecule *par excellence* as enunciated by Duntiz who further iterated that the crystalline state itself is a state of "matter" to be manipulated in and of itself.[9]

The degree of molecular order that defines the organic solid state, however, is exploitable for organic synthesis. In addition to being a medium where intermolecular interactions (e.g., hydrogen bonds, halogen bonds, metal coordination) are expressed with near-perfect precision and fidelity,[6,10–14] as well as quantitatively, crystals offer positional control of reactivity such that products difficult or completely unattainable in solution can be created.[4] In that way, crystals can, in principle, serve as "molecular flasks" where functionalized reactants generate products that are ultimately amendable to downstream chemical transformations (*e.g.*, post-modifications) and applications.[15]

It is with these ideas in mind that this review discusses recent work of our group and others (Scheme 2), on strategies and emerging developments to use the organic solid state as a medium akin to a flask to perform organic synthesis. We describe efforts involving molecular recognition and crystal engineering to direct the [2+2] photodimerization in the solid state, with an emphasis on post-modifications of resulting cyclobutanes to allow for the solid state to be as a playground to form covalent bonds. In that way, the solid state can be likened to a form of supramolecular matter to support and manipulate progress in organic synthetic chemistry.

2. Supramolecular Control of Chemical Reactivity in Crystals

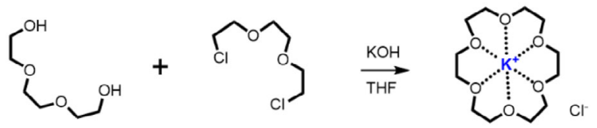
Work of Schmidt in the 1960s and 1970s involving cinnamic acids established geometry criteria for topochemical control of chemical reactivity in solid state.[16] Building on early crystal data and observations of chemical reactivity,[17–19] Schmidt identified molecular orientation (i.e., parallel) and distance (i.e., < 4.2 ÅA) requirements for a [2+2] photodimerization to occur in solids.[16] The ability to achieve the geometric prerequisites, however, beyond cinnamic acids and polymorphs (α and β) remained a major challenge. When molecules assemble and pack to form a crystal, the relative orientations of molecules are exceedingly difficult to predict and control.[20–23] The energy landscape that describes packing of molecules in the solid state is shallow, being driven by the anisotropic shapes and electric features of molecules such that alkenes will usually not conform to the geometry criteria for a reaction.[3,24]

During the past two decades, we have described an approach that uses small organic molecules and metal-organic complexes to enforce a needed directional element to control how molecules are oriented and react in the solid state.[4,25–27] We have shown that noncovalent bonds can be exploited to assemble, control, and dictate positional arrangements of reactants whereby alkenes are enforced to react to form covalent bonds (Scheme 2). We have used hydrogen bonding and halogen bonding,[28–30] as well as metal and boron coordination,[31–36] to direct reactivity to confront challenges of crystal packing. Chalcogen-bonding interactions have also recently been exploited.[37] The approach permits alkenes of different sizes, shapes, and functionalities to be deliberately assembled to react. The method has provided access to complex organic molecules such as ladderanes and [2.2]cyclophanes,[30,38–40] as well as cubane-like cages,[41] that are challenging to generate in solution.

---

[a] *C. Li*
Department of Chemical Engineering, Columbia University in the City of New York, New York, NY 10027, USA

[b] *L. R. MacGillivray*
Département de Chimie, Université de Sherbrooke, Sherbrooke, QC J1K 2R1, Canada
E-mail: leonard.macgillivray@usherbrooke.ca



Scheme 1. Templated synthesis of 18-crown-6 directed by K^+ ion.

In our initial report,[25] we directed a [2+2] photodimerization of 1,2-*trans*-bis(4-pyridyl)ethylene (**bpe**) (i.e., m = 1) in the solid state using 1,3-dihydroxybenzene (resorcinol or **res**) as a template (Scheme 3). Through cocrystallllization, the four-component assembly 2(**res**)·2(**bpe**) sustained by O—H···N hydrogen bonds was generated. The C═C bonds of the alkenes were aligned and stacked parallel, being separated by 3.65 Å. The geometry satisfied the topochemical requirements for a photoreaction.[16] Under UV light, the alkenes reacted to generate *rctt*-tetrakis(4-pyridyl)cyclobutane (**tpcb**) (i.e., n = 1) in 100% yield. The pyridines essentially acted as "handles" to be "grabbed" by the **res** templates for the hydrogen bonding and to allow for the C═C bonds to be preorganized to react.

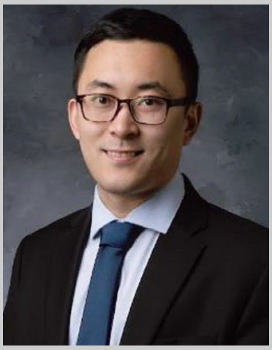
For comparisons, consider the solution and solid-state behaviors of **bpe** as a sole component. As described by Smets and Vansant in the 1980s,[42] UV irradiation of **bpe** in methanol affords a product mixture: *rctt*- (23%) and *rtct*- (6%) photodimers, *trans*- (39%), and *cis*- (21%) isomers, as well as photoreduction and solvent photoaddition products (11%). The alkene itself was also shown to be unreactive, with the molecule forming a layered structure and the C═C bonds being separated on the order of 5.72 Å (CCDC ref: 1 828 730). The use of the **res** template both enabled the reactivity of **bpe** in the solid state and allowed the generation of a single product. The template can be separated from the cyclobutane using basic extraction.

We then applied **res** to build more complex products. Specifically, we hypothesized that the templated reactivity could coexist with added functional groups. We envisaged that the reaction could generate highly strained concatenated cyclobutane rings or ladderanes. The reaction would require the assembly of added C═C groups (i.e., m = 2, 3) in the form of polyenes. In doing so, the self-assembly process would need to be tolerant to an increase in size of the reactants supplied by the added C═C bonds. Ladderane generation was ultimately successful,[30] with the quantitative and gram-scale formation [3]- and [5]-ladderanes (i.e., n = 3, 5) using 5-methoxy-**res** (**5-OMe res**) as the template (Scheme 3). We also used other **res** templates, such as 4-benzyl-**res** (**4-benz res**) to build *ortho*-, *meta*-, and *para*- [2.2]cyclophanes in up to quantitative yield,[38–40] with an unexpected stereoisomer of the [2.2]metacyclophane isomer also forming. The first complete "total syntheses" of a family of [2.2]cyclophanes in the solid state was achieved.[38]

3. Functional Groups and Post-modifications

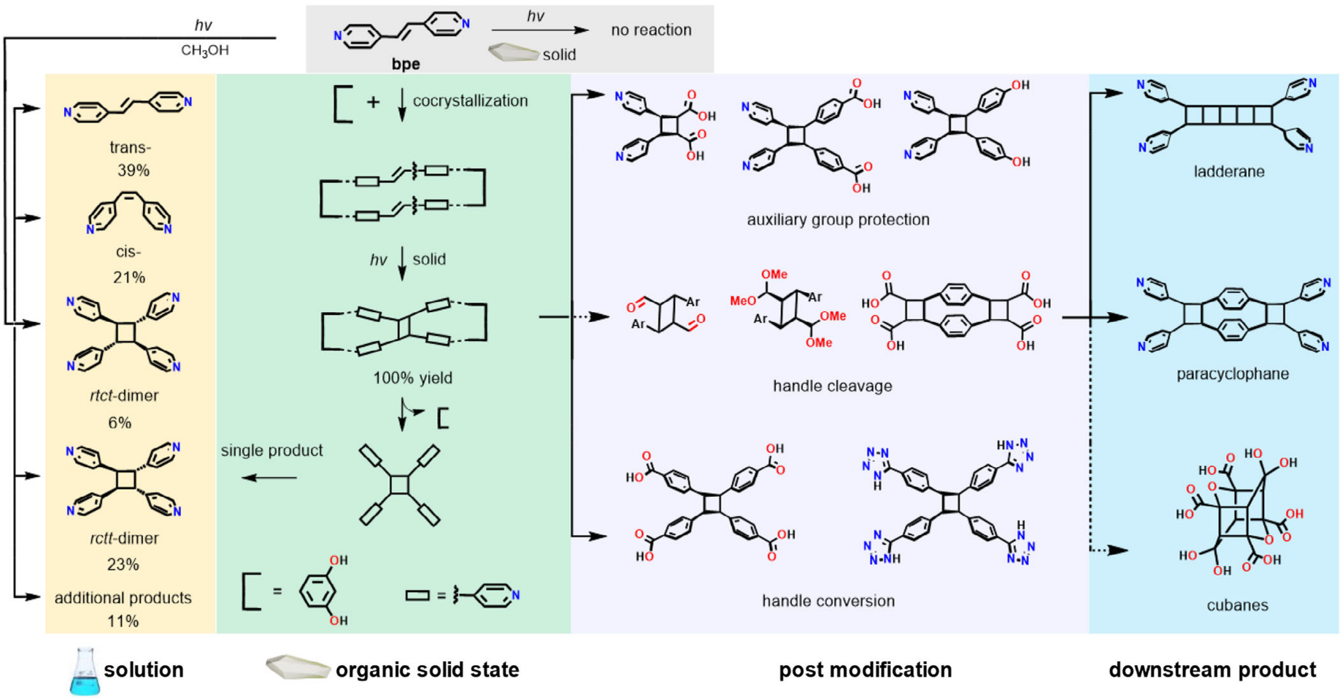
Following initial reports, we turned to integrate more complex functionalities (e.g., heteroatoms) into the products. It was expected, however, that added functionality would likely interfere with the hydrogen bonding between the template and reactants. For success, the template would need to successfully compete with structural and electronic demands of the added groups, and particularly those that act as hydrogen-bond donors and/or acceptors. The problem would need to be circumvented if the crystalline state was to be generally used to form molecules inaccessible in solution or forbiddingly difficult without a solid-state "head start."

Three approaches have, to date, been identified: (i) auxiliary group protection,[43,44] (ii) handle cleavage,[45,46] and (iii) handle conversion[47] (Table 1). The emergence of postsynthetic modifications related to MOFs was an inspiration.[48–52] Post-modification involves transforming a chemical structure following a supramolecular synthesis (e.g., crystallization) to allow for chemical functionality to be integrated into a final product (e.g., MOF). For templated reactions in crystals, this would first require alkenes to be predesigned for optimal interaction with a template to support the assembly of the C═C bonds and C—C bond forming photoreaction. Approaches (i) and (ii) are two-step processes wherein a functional group is modified, or "masked", prior to cocrystallllization and the photoproduct is then modified post reaction to restore original functionality. Approach (iii) is a one-step process wherein the alkene is derivatized with a group that both participates in the noncovalent interaction with the

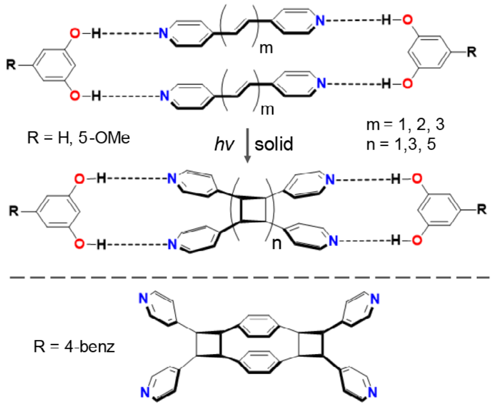


Changan Li obtained his Ph.D. degree in Chemistry at the University of Iowa under the supervision of Prof. Leonard R. MacGillivray in 2022. His Ph.D. dissertation focused on the self-assembly of organic molecules to create photoactive solids for applications in organic synthesis and materials science. Changan is currently a postdoctoral research scientist in the Department of Chemical Engineering at Columbia University, where he focuses on self-assembly of DNA nanomaterials.

Leonard R. MacGillivray is a Professor of Chemistry and a Canada Excellence Research Chair (CERC) in Crystal Engineering for Green Chemistry and Sustainable Materials in the Département de Chimie at the Université de Sherbrooke. Before joining the Université de Sherbrooke in 2023, he was a Professor of Chemistry in the Department of Chemistry at the University of Iowa (2000-2024) where he also served as departmental chairperson from 2019–2023.



Scheme 2. Supramolecular template approach to access complex molecular architectures via the solid state (arrows show general connections of ideas and dotted lines represent uses of similar supramolecular strategies of our group).



Scheme 3. Templated syntheses up to tricyclobutanes directed by **res** templates. Cyclobutanes lined with 4-pyridyl groups.

Table 1. Strategies to access organic functional groups.

Strategy	Post-modified group	Overall steps	Installed group
Auxiliary group protection	Ester	2	Carboxylic acid[43] Phenol[44]
Handle cleavage	Imine	2	Aldehyde[45] Carboxylic acid[46]
Handle conversion	Aryl nitrile	1	Tetrazole[47] Carboxylic acid[47]

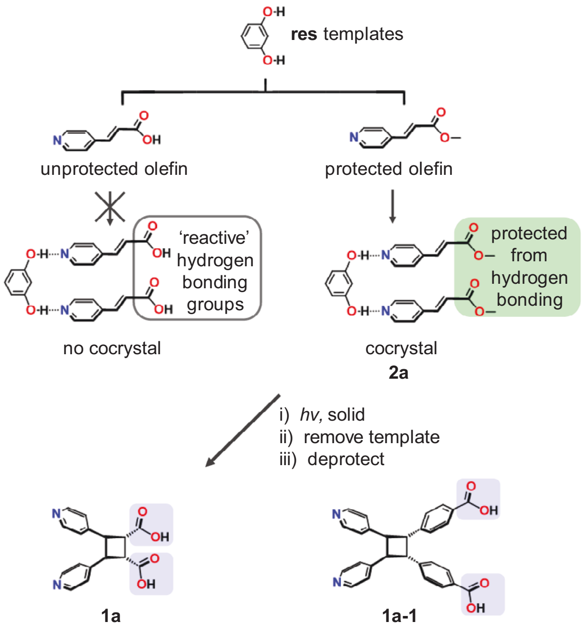
template and is amenable to post-modification, ideally to a variety of groups. Approach (iii) essentially involves "preprogramming" the alkene for molecular recognition and a post reaction chemical conversion.

3.1. Auxiliary Group Protection

Auxiliary group protection has, to date, involved protecting a functional group located distal to the position of the template. Protecting groups in organic synthesis generally allow for temporary derivatization of chemical functionality within a molecule to permit a chemical transformation to occur, effectively preventing participation of the group in an undesired reaction.[53] The strategy being more associated with reactions in solution, allows for chemical transformations to occur selectively and efficiently. The plan was to protect a functional group of an alkene that might, otherwise, disrupt the hydrogen bonding with the template and photoreaction.

Our initial example involved a targeted synthesis of the head-to-head *cis*-diacid **1a**.[43] The cyclobutane possesses both pyridyl and acid groups (Scheme 4). The pyridyl groups were expected to form hydrogen bonds with a **res** template; however, the -CO_2H group was also expected to compete for hydrogen bonding with the -OH groups of **res**. Carboxylic acids are well established to form strong hydrogen bonds with pyridyls and molecules that possess both functional groups (*e.g.*, isonicotinic acid) were known to self-assemble by -$CO_2H\cdots N$(pyridine) hydrogen bonds to generate highly insoluble hydrogen-bonded polymers (Figure 1).[54]

Initial cocrystalllizations of **res** with the corresponding acrylic acid were unsuccessful. The acid preferred to crystallize on its own to generate a hydrogen-bonded polymer. However, when



Scheme 4. Auxiliary group protection — ester to acid.

Figure 1. X-ray structure showing hydrogen-bonded 1D polymer of isonicotinic acid sustained by CO_2H-pyridine hydrogen bond.

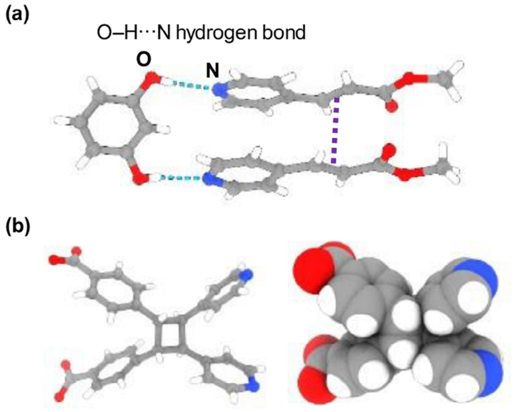
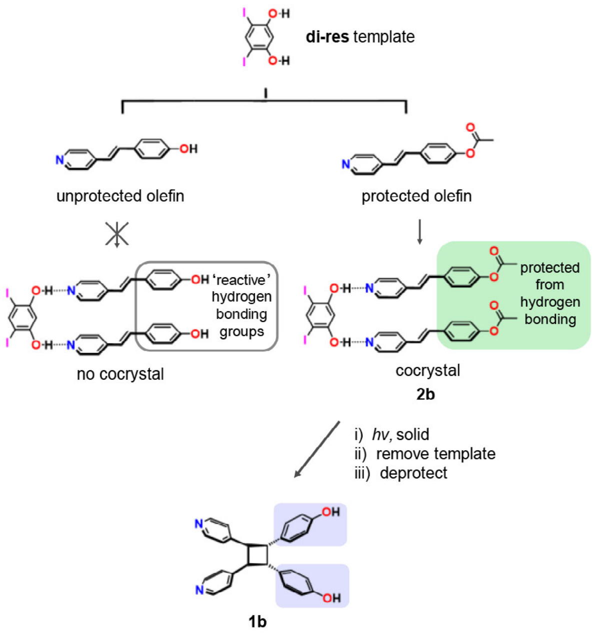


Figure 2. X-ray structures: (a) reactive assembly **2a** with parallel C=C bonds and (b) ball-stick and space-filling views of dicarboxylate of **1a-1**.



Scheme 5. Auxiliary group protection — ester to phenol.

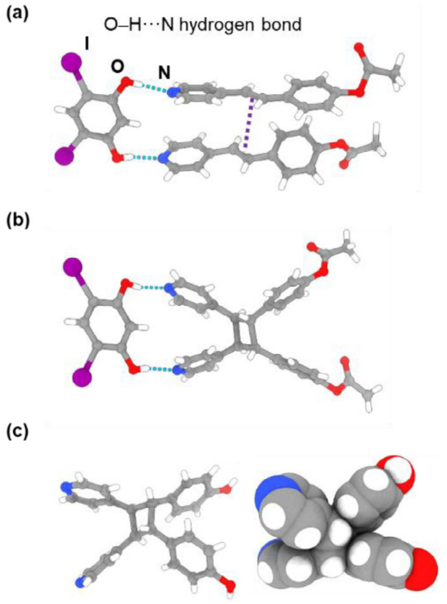
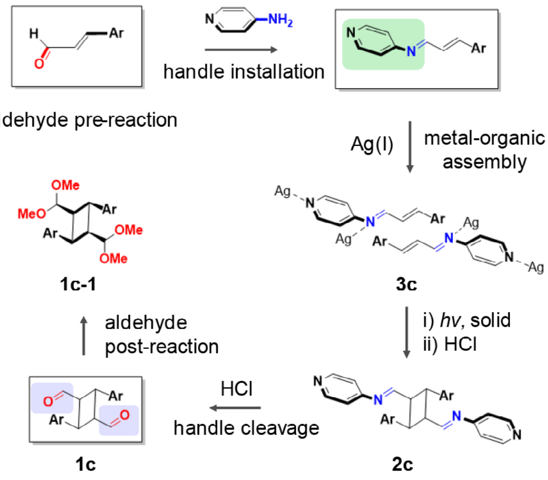


Figure 3. X-ray structures: reactive assembly **2b** (a) before, (b) after photoreaction, and (c) ball-stick and space-filling views of **1b**.

the acid group was temporarily converted precocrystallizations to an ester (Figure 2), cocrystals of **res** with the ester alkene readily formed (Figure 2a). Upon UV-irradiation, the alkene reacted to generate the head-to-head diester in quantitative yield. Following separation from **res**, the diester was post-modified with base to reinstall the -CO_2H groups to give **1a** (Figure 2b). The initial conversion of acid to ester, thus, allowed for the -CO_2H group to essentially be protected from participating in undesired hydrogen bonds with the pyridyl group. The strategy was also applied to generate an elongated ester.

We then later applied auxiliary protection using an ester to a phenolic alkene to synthesize the head-to-head *cis*-bis(phenol) **1b** (Scheme 5).[44] The phenol was converted to an ester precocrystallization (Figure 3). Cocrystallization of a dihalogenated **res** with the ester alkene then afforded a hydrogen-bonded cocrystal **2b** that photoreacted to give the corresponding diester in quantitative yield (Figures 3a,b).

The targeted cyclobutane **1b** was formed by converting the ester back to phenol (Figure 3c). The photoproduct was revealed



Scheme 6. Imine formation and metal-organic assembly generated an aldehyde using the solid state.

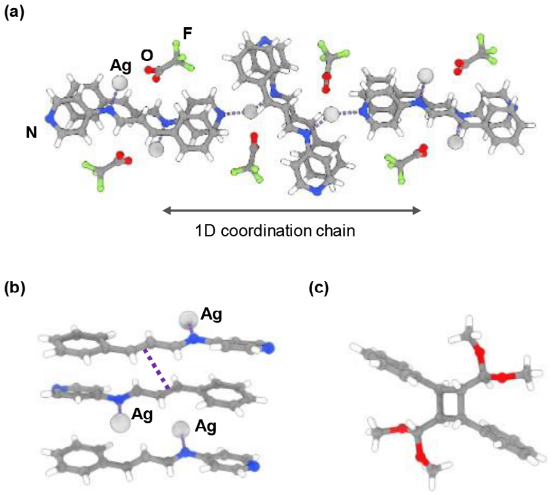
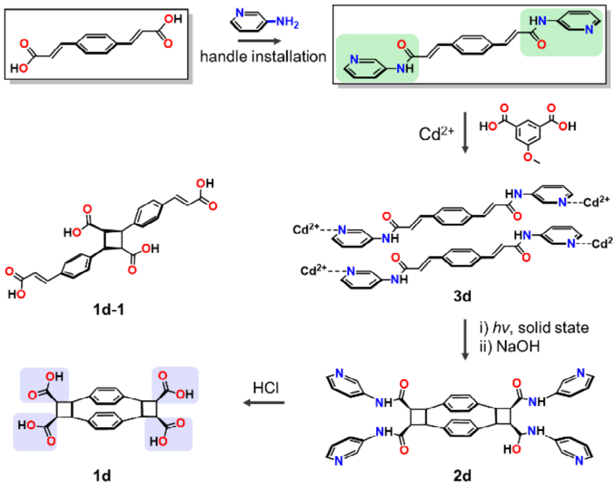


Figure 4. X-ray structures showing: (a) layering of 1D chains of **3c**, (b) stacking of the C═C bonds, and c) **1c-1**.



Scheme 7. Carboxy-cyclobutane isomers were synthesized using amide bonds and solid-state cycloaddition in coordination polymers.

to self-assemble in the solid state to give a 3D hydrogen-bonded network that conforms to a **mok** topology.[55,56] The **mok** net— being akin to the structure of diamond—had only been observed in metal-organic materials.[57–59]

3.2. Handle Cleavage

Pyridyl groups, while reliable hydrogen-bond acceptors, or handles for templates, are limited for postsynthetic modifications. A pyridyl group is electron-deficient, which makes the ring system less reactive, for example, in post-synthetic electrophilic aromatic substitutions.[60–62] The N-atom can also coordinate with reagents (e.g., catalysts) in a reaction and lead to undesired side reactions. To overcome the limitation, we hypothesized that a temporary covalent bond could be used to connect the pyridyl group to an alkene. The pyridyl could then be removed by post reaction to allow for installation of a different functional group.

The imine bond -C═N was identified as a temporarily point of attachment between a pyridyl and C═C bond.[45] Specifically, we described a two-step sequence based on: 1) imine formation followed by 2) metal-coordination to assemble C═C bonds to photoreact (Scheme 6). The approach was realized by reaction of cinnamaldehyde with 4-amino-pyridine (Figure 4). The alkene assembled with Ag(I) ions to form a 1D chain coordination polymer **3c** (Figure 4a). UV-irradiation allowed for quantitative conversion of the alkene to the head-to-tail cyclobutane **2c** (Figure 4b). Removal of the pyridyl ring was then achieved with acid to give α-truxilaldehyde **1c**. The structure of the cyclobutane was authenticated as the tetramethyl acetal **1c-1** (Figure 4c).

Zhu et al. later reported a handle cleavage involving coordination bonds, dienes, and amides to generate cyclobutanes decorated with carboxylic acids (Scheme 7).[46] Reaction with bis(3-pyridyl)amide afforded the Cd(II) coordination polymer **2d** with dienes that photoreacted to give, following removal of the metal ions, a [2.2]paracyclophane decorated with amide groups (Figure 5). Hydrolysis of the cyclophane in a post-modification installed the acid groups of **1d**. The monocyclobutane **1d-1** was also formed.

3.3. Handle Conversion

We expected an approach that involves direct conversion of the handle used in the molecular recognition to a different functional group to be attractive since a functionalization prior to cocrystallization would be circumvented. We, thus, turned to identify a handle that could both: (i) act as a hydrogen-bond acceptor with a **res** and (ii) be easily modified post reaction.[47] A handle with a capacity to be transformed into a variety of functional groups would be especially desired.

Aryl nitriles were identified for handle conversion (Scheme 8). The nitrile group is among the most versatile in organic synthetic chemistry, able to be transformed into a variety of functionalities (*e.g.*, acids, aldehydes, amines, amidines, tetrazoles).[63–65] While

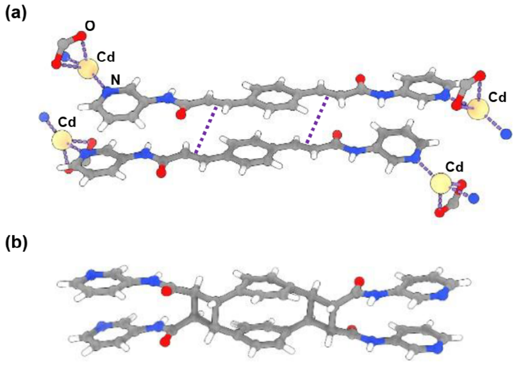
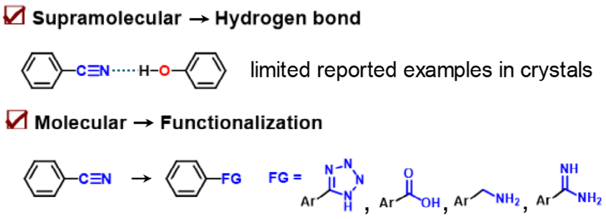
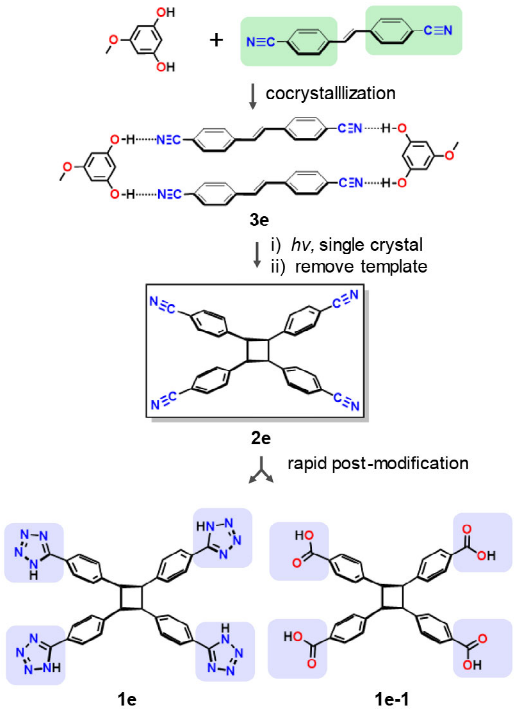


Figure 5. X-ray structures: (a) coordination polymer **3d** and (b) photoproduct **2d**.



Scheme 8. Aryl nitrile for hydrogen bonding and post-modification.



Scheme 9. Integration of aryl nitriles for solid-state construction of covalent bonds and access to diverse chemical species by post-modification.

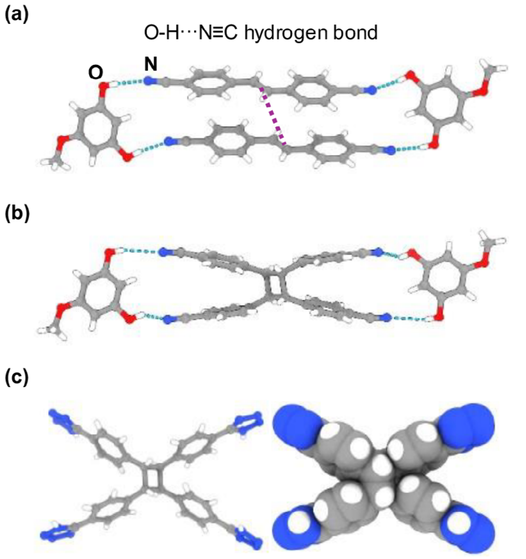
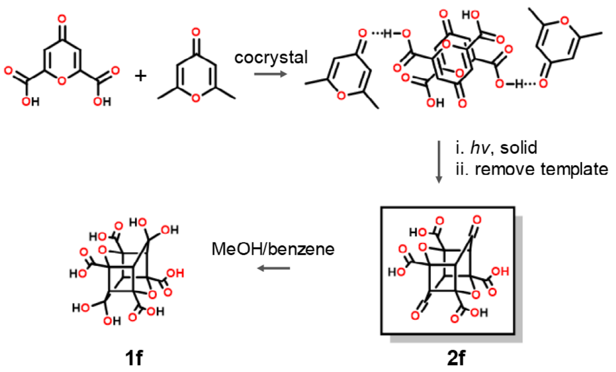


Figure 6. X-ray structures: (a) photoactive assembly **3e**, (b) generated photoproduct **2e**, and (c) stick (left) and space-filling (right) of tetrazole **1e**.



Scheme 10. Constructions of a tetra-acid cage in a binary cocrystal composed of two cyclohexadienes.

nitriles were known to function as a hydrogen-bond acceptors, general behavior in the solid state had also not been addressed.[66–69]

To demonstrate the handle conversion strategy, we aimed to synthesize the cyclobutane **2e** (Scheme 9). Specifically, when *trans*-bis(4-cyano)stilbene was cocrystallized with **MeO-res**, a binary cocrystal formed wherein the C═C bonds were preorganized to react (Figure 6). UV-radiation resulted in a [2+2] photodimerization that generated **2e** as a single product in quantitative yield (Figures 6a,b). Once separated from the template, a post- modification of the cyclobutane by treatment with azide ion afforded the corresponding tetrazole **1e** (Figure 6c). We also demonstrated conversion of **2e** to the corresponding tetracarboxylic acid **1e-1**.

3.4. Cages and Cocrystals

While ditopic templates based on **res** provide reliable control of reactivity in cocrystals, we have also very recently expanded the process of cocrystallization in a different way to generate cubanes (Scheme 10).[41] In particular, we reported a cyclohexadiene diacid in a binary cocrystal of two different cyclohexadienes to react to generate the cubane-like tetraacid **1f** (Figure 7). The cocrystal consisted of chelidonic acid assembling with 2,6-dimethyl-γ-pyrone by O—H···O hydrogen bonds in a layered

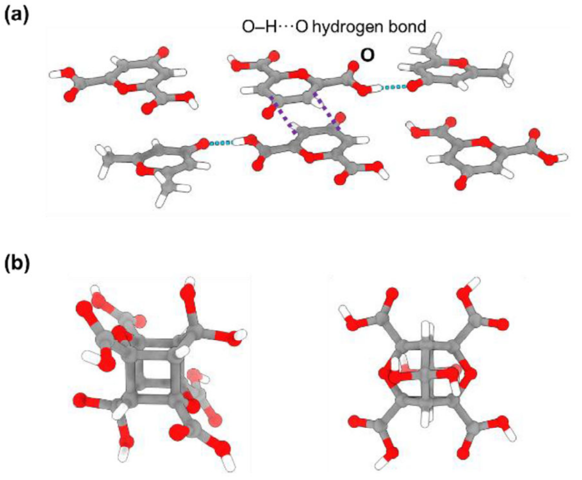


Figure 7. X-ray structure: (a) stacking of the diacid in binary cocrystal, and (b) stick perspectives (left and right) of cage **1f**.

structure (Figure 7a). The structure of the cubane-like photocage was authenticated wherein the keto groups was transformed to gem diols (Figure 7b). The study presented the first structural characterization of cubane-like cages obtained from organic crystals.[70]

4. Summary and Outlook

In this review, we have described advances to employ cocrystals and related reactive metal-organic materials, to perform organic synthesis in the solid state. As the research continues to develop, we expect an increasing number of reactions in solids to be amenable to advance uses of crystalline solids for the synthesis of complex molecules. As reported by extensive work by Sureshan and coworkers, the topochemical azide—alkyne cycloaddition can be broadly employed to form polymers, and promising to generate molecules.[71–73] Cocrystals that support more than one reaction have also now been reported.[74] The precise control of molecular arrangements combined with abilities to introduce functional groups through postsynthetic modifications is expected to further allow the solid state to be used strategically to perform organic synthesis. As additional strategies emerge and are inspired by confluences of organic synthesis and materials chemistry, the solid state can behave in function as a form of supramolecular matter. We expect the inherent stability and scalability of solid-state processes to also offer practical applications, particularly in industrial and technological settings that embody processes of supramolecular synthesis and manufacturing.[75]

Acknowledgments

We gratefully acknowledge financial support from Canada Excellence Research Chairs program, as well as the National Science Foundation of the USA.

Conflict of Interests

The authors declare no conflict of interest.

Data Availability Statement

Data cited in review article are available publicly in references.

Keywords: crystal engineering · post-modification · solid-state chemistry · supramolecular chemistry

[1] J. D. Dunitz, V. Schomaker, K. N. Trueblood, *J. Phys. Chem.* **1988**, *92*, 856.
[2] G. R. Desiraju, *Angew. Chem., Int. Ed.* **2007**, *46*, 8342.
[3] K. Biradha, R. Santra, *Chem. Soc. Rev.* **2013**, *42*, 950.
[4] L. R. MacGillivray, G. S. Papaefstathiou, T. Frišcˇic´, T. D. Hamilton, D.-K. Bucˇar, Q. Chu, D. B. Varshney, I. G. Georgiev, *Acc. Chem. Res.* **2008**, *41*, 280.
[5] D. Braga, F. Grepioni, *Angew. Chem., Int. Ed.* **2004**, *43*, 4002.
[6] K. Tanaka, F. Toda, *Chem. Rev.* **2000**, *100*, 1025.
[7] C. J. Pedersen, *J. Am. Chem. Soc.* **1967**, *89*, 7017.
[8] C. J. Pedersen, *Angew. Chem., Int. Ed.* **1988**, *27*, 1021.
[9] J. D. Dunitz, *Pure Appl. Chem.* **1991**, *63*, 177.
[10] G. K. Kole, J. J. Vittal, *Chem. Soc. Rev.* **2013**, *42*, 1755.
[11] M. H. Mir, L. L. Koh, G. K. Tan, J. J. Vittal, *Angew. Chem., Int. Ed.* **2009**, *2*, 400–403.
[12] G. R. Desiraju, *Chem. Commun.* **1997**, 1475.
[13] G. R. Desiraju, *Angew. Chem., Int. Ed.* **1995**, *34*, 2311–2327.
[14] W. Xiao, C. Hu, M. D. Ward, *J. Am. Chem. Soc.* **2014**, *136*, 14200.
[15] Y. Inokuma, M. Kawano, M. Fujita, *Nat. Chem.* **2011**, *3*, 349.
[16] G. Schmidt, *Pure Appl. Chem.* **1971**, *27*, 647.
[17] M. Cohen, G. Schmidt, *J. Chem. Soc.* **1964**, 1996–2000.
[18] M. Cohen, G. Schmidt, F. Sonntag, *J. Chem. Soc.* **1964**, 2000–2013.
[19] G. Schmidt, *J. Chem. Soc.* **1964**, 2014–2021.
[20] J. W. Steed, *CrystEngComm* **2003**, *5*, 169.
[21] B. Moulton, M. J. Zaworotko, *Chem. Rev.* **2001**, *101*, 1629.
[22] C. B. Aakeröy, *Acta Crystallogr., Sect. B: Struct. Sci.* **1997**, *53*, 569.
[23] A. Gavezzotti, *Acc. Chem. Res.* **1994**, *27*, 309.
[24] V. Ramamurthy, K. Venkatesan, *Chem. Rev.* **1987**, *87*, 433.
[25] L. R. MacGillivray, J. L. Reid, J. A. Ripmeester, *J. Am. Chem. Soc.* **2000**, *122*, 7817.
[26] I. G. Georgiev, L. R. MacGillivray, *Chem. Soc. Rev.* **2007**, *36*, 1239.
[27] G. Campillo-Alvarado, L. R. MacGillivray, *Synlett* **2021**, *32*, 655.
[28] M. A. Sinnwell, L. R. MacGillivray, *Angew. Chem., Int. Ed.* **2016**, *55*, 3477.
[29] L. R. MacGillivray, *J. Org. Chem.* **2008**, *73*, 3311.
[30] X. Gao, T. Friščić, L. R. MacGillivray, *Angew. Chem., Int. Ed.* **2004**, *43*, 232.
[31] G. S. Papaefstathiou, Z. Zhong, L. Geng, L. R. MacGillivray, *J. Am. Chem. Soc.* **2004**, *126*, 9158.
[32] Q. Chu, D. C. Swenson, L. R. MacGillivray, *Angew. Chem., Int. Ed.* **2005**, *44*, 3569.
[33] C. Li, G. Campillo-Alvarado, D. C. Swenson, L. R. MacGillivray, *Inorg. Chem.* **2019**, *58*, 12497.
[34] G. Campillo-Alvarado, K. P. D'mello, D. C. Swenson, S. Santhana Mariappan, H. Höpfl, H. Morales-Rojas, L. R. MacGillivray, *Angew. Chem.* **2019**, *131*, 5467.
[35] S. Bhandary, M. Beliš, L. Bourda, A. M. Kaczmarek, K. Van Hecke, *Angew. Chem., Int. Ed.* **2023**, *62*, e202304722.
[36] S. Bhandary, M. Belis, R. Shukla, L. Bourda, A. M. Kaczmarek, K. Van Hecke, *J. Am. Chem. Soc.* **2024**, *146*, 8659.
[37] J. Alfuth, O. Jeannin, M. Fourmigué, *Angew. Chem., Int. Ed.* **2022**, *61*, e202206249.
[38] T. Frisˇcˇic´, E. Elacqua, S. Dutta, S. M. Oburn, L. R. MacGillivray, *Cryst. Growth Des.* **2020**, *20*, 2584.
[39] T. Friščić, L. R. MacGillivray, *Aust. J. Chem.* **2006**, *59*, 613.
[40] T. Friščič, L. R. MacGillivray, *Chem. Commun.* **2003**, 1306–1307.
[41] C. Li, M. A. Sinnwell, D. C. Swenson, L. R. MacGillivray, *Chem. Commun.* **2021**, *57*, 6725.

[42] J. Vansant, S. Toppet, G. Smets, J.-P. Declercq, G. Germain, M. Van Meerssche, *J. Org. Chem.* **1980**, *45*, 1565.

[43] E. Elacqua, P. Kaushik, R. H. Groeneman, J. C. Sumrak, D. K. Bučar, L. R. MacGillivray, *Angew. Chem., Int. Ed.* **2012**, *51*, 1037.

[44] S. M. Oburn, M. A. Sinnwell, D. P. Ericson, E. W. Reinheimer, D. M. Proserpio, R. H. Groeneman, L. MacGillivray, *IUCrJ* **2019**, *6*, 1032.

[45] S. M. Oburn, D. C. Swenson, S. S. Mariappan, L. R. MacGillivray, *J. Am. Chem. Soc.* **2017**, *139*, 8452.

[46] R.-R. Zhu, T. Wang, L. Zhao, L. He, F. Gao, L. Du, Q.-H. Zhao, *Inorg. Chem. Front.* **2021**, *8*, 1997.

[47] C. Li, D. C. Swenson, L. R. MacGillivray, *Chem. - Eur. J.* **2022**, *28*, e202200978.

[48] M. Kalaj, S. M. Cohen, *ACS Cent. Sci.* **2020**, *6*, 1046.

[49] M. Kandiah, S. Usseglio, S. Svelle, U. Olsbye, K. P. Lillerud, M. Tilset, *J. Mater. Chem.* **2010**, *20*, 9848.

[50] Z. Wang, S. M. Cohen, *Chem. Soc. Rev.* **2009**, *38*, 1315.

[51] A. D. Burrows, C. G. Frost, M. F. Mahon, C. Richardson, *Angew. Chem.* **2008**, *120*, 8610.

[52] K. K. Tanabe, Z. Wang, S. M. Cohen, *J. Am. Chem. Soc.* **2008**, *130*, 8508.

[53] P. G. Wuts, T. W. Greene, *Greene's protective groups in organic synthesis*, John Wiley & Sons, **2006**, p. p.

[54] F. Takusagawa, A. Shimada, *Acta Crystallogr., Sect. B: Struct. Sci.* **1976**, *32*, 1925.

[55] M. O'Keeffe, *Kristallogr. Cryst. Mater.* **1991**, *196*, 21.

[56] C. Bonneau, M. O'Keeffe, *Acta Crystallogr. A.* **2015**, *71*, 82.

[57] Y. Gong, Y.-C. Zhou, T.-F. Liu, J. Lü, D. M. Proserpio, R. Cao, *Chem. Commun.* **2011**, *47*, 5982.

[58] X. Zhang, P. Xing, X. Geng, D. Sun, Z. Xiao, L. Wang, *J. Solid State Chem.* **2015**, *229*, 49.

[59] J. Liang, X.-L. Wang, Y.-Q. Jiao, C. Qin, K.-Z. Shao, Z.-M. Su, Q.-Y. Wu, *Chem. Commun.* **2013**, *49*, 8555.

[60] J. A. Joule, *Heterocyclic Chemistry*, CRC Press, London **2020**, p.

[61] M. Schlosser, F. Mongin, *Chem. Soc. Rev.* **2007**, *36*, 1161.

[62] C. K. Mcgill, A. Rappa in *Advances in the chichibabin reaction*, *44*, Elsevier, **1988**, pp. 1–79.

[63] F. A. Carey, R. J. Sundberg, *Advanced organic chemistry: part A: structure and mechanisms*, Springer Science & Business Media, **2007**, p. p.

[64] A. J. Fatiadi, *Triple-Bonded Functional Groups (1983) Supplement C: Part 2*, New York **1983**, *2*, 1057-1303.

[65] Y. Xia, H. Jiang, W. Wu, *Eur. J. Org. Chem.* **2021**, *2021*, 6658.

[66] D. R. Turner, A. J. Edwards, R. O. Piltz, *CrystEngComm* **2012**, *14*, 6447.

[67] D. Yan, A. Delori, G. O. Lloyd, T. Friščić, G. M. Day, W. Jones, J. Lu, M. Wei, D. G. Evans, X. Duan, *Angew. Chem., Int. Ed.* **2011**, *50*, 12483.

[68] J. Y. Le Questel, M. Berthelot, C. Laurence, *J. Phys. Org. Chem.* **2000**, *13*, 347.

[69] N. Ziao, J. Graton, C. Laurence, J.-Y. L.e Questel, *Acta Crystallogr., Sect. B: Struct. Sci.* **2001**, *57*, 850.

[70] J. F. Eubank, V. C. Kravtsov, M. Eddaoudi, *J. Am. Chem. Soc.* **2007**, *129*, 5820.

[71] H. Balan, K. M. Sureshan, *Nat. Commun.* **2024**, *15*, 6638.

[72] R. Khazeber, G. S. Kana, K. M. Sureshan, *Angew. Chem.* **2024**, *136*, e202316513.

[73] K. Hema, K. M. Sureshan, *Acc. Chem. Res.* **2019**, *52*, 3149.

[74] N. Juneja, G. C. George III, K. M. Hutchins, *Angew. Chem., Int. Ed.* **2025**, *64*, e202415567.

[75] V. Balzani, M. Clemente-Leon, A. Credi, B. Ferrer, M. Venturi, A. H. Flood, J. F. Stoddart, *Proc. Natl. Acad. Sci* **2006**, *103*, 1178.

Manuscript received: February 26, 2025
Revised manuscript received: March 31, 2025
Version of record online: April 21, 2025