Self-Assembly

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Design Rules: A Net and Archimedean Polyhedra Score Big for Self-Assembly

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> *“It would seem almost as though there were a cordon drawn round the upper part of these great peaks beyond which no man may go.”*
> Eric Shipton, Upon That Mountain[1]

Chemists have an insatiable appetite to connect and contort atoms and molecules into assemblages of increasing structural complexity. Wöhler’s synthesis of urea from ammonium cyanate[2] was a starting point of modern organic chemistry while organic chemists today can lay claim to being able to fabricate the most complex molecules formed by nature. The synthesis of a target molecule with utmost atom economy, yield, and in the smallest number of steps according to a well-formulated retrosynthesis are common goals of the modern-day synthetic organic chemist.[3]

In just over the last decade, there has been a movement to perform targeted syntheses of a different type. Rather than covalent bonds, chemists have used noncovalent bonds in the field of supramolecular chemistry[4] to construct complex assemblies of molecules. Many goals of synthetic organic chemistry remain intact (e.g. yield), yet the synthesis is performed in a single step using a process known as self-assembly.[5] In self-assembly, functional groups govern how multiple copies of molecular subunits interact and become arranged in space through relatively weak and reversible noncovalent forces such as π stacking, hydrogen bonding, and coordination bonds. Ward and co-workers have just described a spectacular example of a self-assembly that affords a very large supramolecular cage.[6] The construction of the cage finds design principles not only in the chemistry of nature but also in solid geometry as outlined by Archimedes and Plato.

Molecular assemblies that surround and encapsulate guests provide intriguing opportunities for chemists. By placing a guest molecule within a confined interior, a supramolecular cage can be used for “ship-in-a-bottle” applications such as chemical reactivity, catalysis, and separations, as well as drug delivery.[7] Whereas an organic chemist is often confronted with a challenge to devise a roadmap to a complex target molecule isolated from nature, a supramolecular chemist is confronted with formulating how to form an assembly of molecules for specific, downstream applications (e.g. recognition, catalysis). Clearly, nature practices encapsulation as illustrated by the ability of viruses to contain RNA and DNA within shells of self-assembled proteins. Water molecules self-assemble to encapsulate guests within hydrogen-bonded cages, or clathrate hydrates,[8] while C_{60} fullerene can accommodate guests within the interior.[9] A burning question has centered on how self-assembly can be harnessed rationally to form such stunning spherical cages.

In the report, Ward and co-workers describe a supramolecular cage assembled from 20 molecular ions sustained by 72 hydrogen bonds.[6] The shape of the cage conforms to one of the 13 Archimedean polyhedra, namely, a truncated octahedron while the interior encloses approximately 2200 $Å^3$ that accommodates an impressive array of guests.

To place the work presented into perspective, it is instructive to recount past work in the field. Early studies to synthesize supramolecular cages based on purely organic components, as that of Ward and co-workers, were reported in 1993: In seminal work, Rebek and co-workers described the self-assembly of two molecules through eight hydrogen bonds that form a capsule with a structure that conforms to a molecular tennis ball and possesses an interior cavity of approximately 50 $Å^3$.[10] An important feature was that the subunits—glycolurils—exhibited curvature, which is necessary for a cage with a shape based on only two components. In 1997, MacGillivray and Atwood then reported a cage based on 14 subunits sustained by 60 hydrogen bonds and an interior of approximately 1375 $Å^3$.[11] The subunits—bowl-shaped molecules known as calix[4]resorcinarenes—also exhibited curvature; however, the shape of the cage conformed to a chiral Archimedean polyhedron known as a snub cube, which is based on subunits that are completely flat.

The 13 Archimedean solids, and the related 5 Platonic solids, comprise limited ways to enclose space using subunits that are flat and, thus, do not exhibit curvature. Curvature, instead, arises when the subunits, in the form of polygons, meet along edges. The MacGillivray and Atwood cage demonstrated how space can be enclosed with components that, albeit curved, provided flat sticky surfaces, in the form of squares, for self-assembly. The Archimedean and Platonic solids, thus, represented targets for supramoleular chemists.[12] The cage of 1997 possessed a cavity that was up to four times larger than previous cages.

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In the case of Ward and co-workers, the supramolecular design has largely come full circle. The group of Ward had previously reported the self-assembly of guanidinium (G) mono- and disulfonate (SO) compounds that readily form hydrogen-bonded solids composed of two-dimensional (2D) nets based on tiling of hexagons (Figure 1 a).[13] At least 500 examples of the nets are known. The threefold symmetry and N–H$^+$···$^-$O–S hydrogen bond complementarity of the G ions and SO moieties promoted the 2D nets to form. The robustness of the architecture, while impressive, enticed the group to consider how to push the self-assembly to other frameworks. An alternative to the net might be using subunits that frustrate the formation of the layered structure. Frustration would be achieved by effectively modifying self-assembly demands of one of the components.

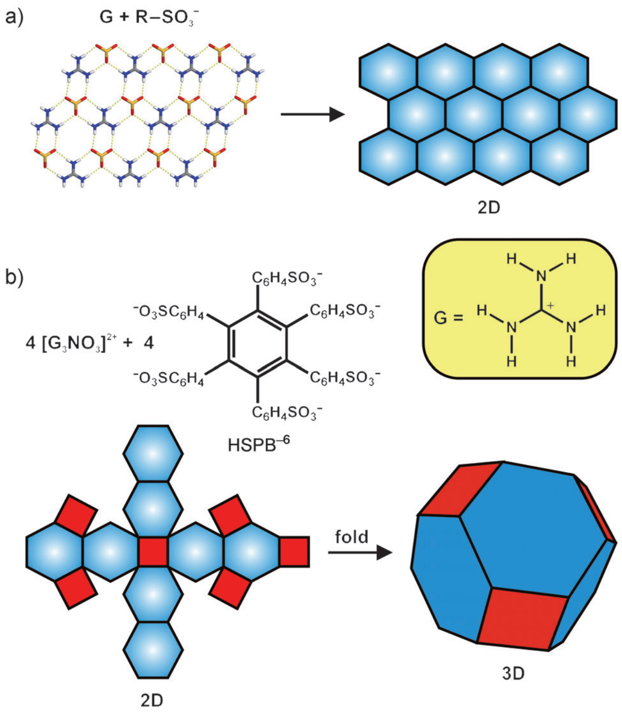

Figure 1. Truncated octahedron (3D) from a quasihexagonal tile (2D). a) Earlier work by Ward et al.;[13] b) recent work by Ward et al.[6]

The rigid hexasulfonate HSPB^{6-} ion was selected to frustrate the 2D framework (Figure 1 b). According to modelling, two end hydrogen bond acceptor S groups of an HSPB^{6-} ion would prefer to interact side-on with two comparably separated G units of a [G$_3$NO$_3$]$^{2+}$ ion. The arrangement would contrast the 2D net, wherein three S units interact with a single G ion to propagate the quasihexagonal structure. The side-on interaction would result in four HSPB^{6-} tiles and four [G$_3$NO$_3$]$^{2+}$ tiles that fold into a complex polyhedron. The shape of the polyhedron would conform to a truncated octahedron, one of the 13 Archimedean solids. Nature, too, exhibits remarkable flexibility in self-assembly as demonstrated by the cylindrical and spherical shapes of viruses[12] as well as by graphite, nanotubes, and C$_{60}$ as flat, cylindrical, and spherical allotropes of carbon, respectively. For Ward and co-workers, the supramolecular Archimedean cage would form using subunits all of which are virtually flat.

A self-assembly to generate the polyhedron was realized by block-shaped crystals with facets reflective of the symmetry of the polyhedron. Single-crystal X-ray experiments revealed the components to form a lattice of four HSPB^{6-} tiles and four [G$_3$NO$_3$]$^{2+}$ tiles in the configuration of the truncated octahedron (Figure 2). A total of 72 hydrogen bonds stitched the components: 24 N–H$^+$···$^-$O–N hydrogen bonds within the [G$_3$NO$_3$]$^{2+}$ tiles and 48 along the all-important edges. The octahedron easily accommodates a sphere with a diameter of 12 Å (diameter of C$_{60}$ is approximately 10 Å), with the total free volume approaching 2200 Å^3. Neighboring cages were connected by sodium ions that defined channels of cross-section 4.6 Å × 4.6 Å. The framework topology is akin to that of the mineral sodalite and zeolite A.[6]

Hydrogen-bonded cages are usually quite fragile. The polyhedron of Ward and co-workers, remarkably, tolerated a

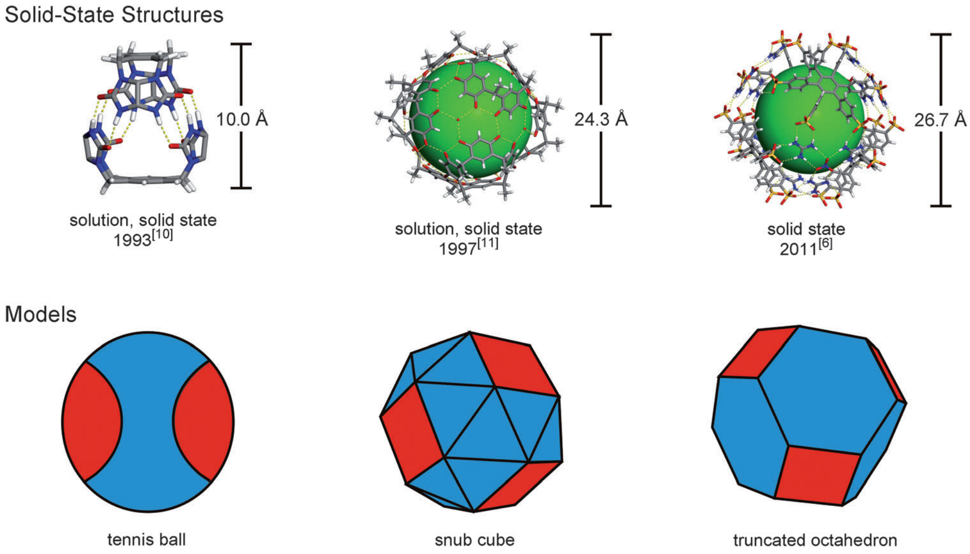

Figure 2. Cage compounds that conform to a tennis ball, snub cube, and truncated octahedron, respectively.

wide range of guests. Hydrogen-bonding guests did not disrupt the framework, while both positive (e.g. $[Al(DMF)_6]^{3+}$) and negative ions (e.g. $CoCl_4^{2-}$) could occupy the polyhedron. The polyhedron was also used as a "flask" to generate novel metal iodide nanoclusters that may lead to semiconductor quantum dots and related electronic materials.

No discussion on supramolecular cages is complete without mentioning the use of coordination chemistry to generate spheroids, coordination capsules, and metal–organic polyhedra.[14] Archimedean and Platonic polyhedra have been generated with curvature supplied by bridging ligands and bonding at metal centers. Fujita and co-workers, for example, have recently described an elegant sphere-in-a-sphere complex.[15] The field of dynamic covalent chemistry has also been employed by Warmuth and co-workers to generate an organic cube and octahedron.[16]

The ascent of target-oriented synthesis since the work of Wöhler[2] has led to levels of synthetic sophistication that rise to demands of nature and exhibit ample room to grow.[3] As demonstrated by Ward and co-workers,[6] supramolecular chemists now carry out target-oriented syntheses that involve balancing subtleties of intermolecular forces that adhere to strict geometry requirements of space as governed by nature. The future of synthesizing targeted self-assembled structures is nascent and can be expected to afford cages, and other complex supramolecular frameworks,[4] that meet and surpass our imaginations.

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