Reticular Chemistry for Highly Porous Metal–Organic Frameworks: the Chemistry and Applications

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CONSPECTUS: Current global crises related to clean energy and the environment entail the development of materials that are capable of addressing these challenges. Metal–organic frameworks (MOFs), a class of functional materials assembled from metal-containing nodes and organic ligands via coordination bonds, have been successfully developed for various applications, including catalysis, toxic chemical removal, and gas storage and separation, due to their highly tailorable nature and precisely engineered pore structures. In particular, the exceptionally high surface areas and porosities of MOFs are two of their most attractive characteristics and place them among the best porous materials for the storage of clean energy gases, such as hydrogen and methane. Reticular chemistry stands out as a prominent approach for the design of MOFs as this strategy allows for the rational top-down design of frameworks guided by topological nets to afford extended framework structures with precise architectural arrangements at the molecular level. Bridging the gap between reticular chemistry design strategies and highly porous MOFs can facilitate the development of next-generation high-performance materials through state-of-art chemical design.

In this Account, we summarize our group's efforts over the past years towards the synthesis and applications of highly porous MOFs inspired by reticular chemistry. First, we describe how we leveraged reticular chemistry to synthesize NU-1500, which is based on the 6-connected edge-transitive **acs** net, from the assembly of triptycene-based ligands and high-valent metal trimers. This delicate design is amenable to isoreticular expansion, and including an additional phenyl group in the rigid triptycene-based ligand of NU-1500 yields NU-1501. Importantly, NU-1501-Al exhibits both a high gravimetric Brunauer–Emmett–Teller (BET) area of 7310 $m^2 g^{-1}$ – the current record after satisfying the four BET consistency criteria – and a volumetric BET area of 2060 $m^2 cm^{-3}$. The high porosity and surface area place NU-1501 among the most promising adsorbents for the storage of methane and hydrogen. Second, we illustrate the rational synthesis of highly porous and stable Zr-MOFs based on edge-transitive nets: 1) the successful isoreticular expansions of NU-1000 (4,8-connected **csq** net) form hierarchical mesoporous MOFs with pore sizes of up to 6.7 nm; 2) the assembly of Zr_6 clusters and tetracarboxylates yields the NU-1100 series (4,12-connected **ftw** net) with BET areas of 4300 – 6500 $m^2 g^{-1}$; 3) the use of hexacarboxylates, in combination with Zr_6 clusters, results in the formation of the NU-1600 series (6,12-connected **alb** net) with BET areas of 2000 – 4500 $m^2 g^{-1}$. Third, we leveraged a reticular exploration strategy to access mesoporous uranium-based MOFs, NU-1300 (3,4-connected **tbo** net, 2100 $m^2 g^{-1}$) and NU-1301 (3-connected **nun** net, 4750 $m^2 g^{-1}$). In particular, we investigated the structurally complex NU-1301, which formed serendipitously from the combination of uranyl clusters and triangular carboxylates to afford a structure with the largest unit cell among all reported MOFs.

Finally, we provide an overview of potential applications of these highly porous MOFs, including water capture, catalysis, methane storage, hydrogen storage, and the separation of organic dyes and biological macromolecules. We hope that this Accounts article may serve as a blueprint and stimulate researchers to develop the next generation of highly porous materials for energy- and environmental-related applications and beyond.

■ KEY REFERENCES

- Chen, Z.; Li, P.; Zhang, X.; Li, P.; Wasson, M. C.; Islamoglu, T.; Stoddart, J. F.; Farha, O. K. Reticular access to highly porous acs-MOFs with rigid trigonal prismatic linkers for water sorption. *J. Am. Chem. Soc.* **2019**, *141*, 2900-2905.[1] Reticular chemistry allows for the rational design and precise synthesis of highly porous MOFs based on the assembly of 6-connected metal trimers and 6-connected trigonal prismatic ligands. These MOFs can be used as efficient water adsorbents.
- Chen, Z.; Li, P.; Anderson, R.; Wang, X.; Zhang, X.; Robison, L.; Redfern, L. R.; Moribe, S.; Islamoglu, T.; Gómez-Gualdrón, D. A.; Yildirim, T.; Stoddart, J. F.; Farha, O. K. Balancing volumetric and gravimetric uptake in highly porous materials for clean energy. *Science* **2020**, *368*, 297-303.[2] Ultraporous NU-1501, which is precisely assembled from metal trimers and trigonal prismatic ligands and exhibits balanced gravimetric and volumetric BET areas, displays outstanding performance for the storage

of methane and hydrogen with balanced gravimetric and volumetric uptakes.

- Chen, Z.; Li, P.; Wang, X.; Otake, K.-i.; Zhang, X.; Robison, L.; Atilgan, A.; Islamoglu, T.; Hall, M. G.; Peterson, G. W.; Stoddart, J. F.; Farha, O. K. Ligand-directed reticular synthesis of catalytically active missing zirconium-based metal–organic frameworks. *J. Am. Chem. Soc.* **2019**, *141*, 12229-12235.[3] The assembly of a series of trigonal prismatic hexacarboxylates and Zr_6 clusters forms isoreticular MOFs based on the edge-transtive 6,12-connected **alb** net. Rapid catalytic hydrolysis of toxic nerve agents occurs atLewis acidic Zr active sites present in the defective MOFs.
- Li, P.; Vermeulen, N. A.; Malliakas, C. D.; Gómez-Gualdrón, D. A.; Howarth, A. J.; Mehdi, B. L.; Dohnalkova, A.; Browning, N. D.; O'Keeffe, M.; Farha, O. K. Bottom-up construction of a superstructure in a porous uranium-organic crystal. *Science* **2017**, *356*, 624– 627.[4] Serendipitous exploration led to the construction of a structurally complex uranium-based MOF, NU-1301, from simple building blocks. The anionic NU-1301 has the lowest framework density and the largest unit cell among all MOFs, and it can selectively encapsulate many cationic guest molecules.

1. INTRODUCTION

Current global challenges related to clean energy and environmental concerns necessitate the development of functional materials. Metal–organic frameworks (MOFs), which are are periodic framework structures assembled from metal-containing clusters or ions and organic linkers via strong coordination bonds, comprise a versatile class of nanoporous functional materials potentially capable of meeting these challenges. For example, MOFs feature highly tailorable and precisely engineered pore structures, which has led to the development of MOFs for numerous targeted applications, including catalysis, chemical sensing, toxic chemical removal, and gas storage and separation.[5-11] Moreover, applications such as water capture, bioinspired catalysis, encapsulation of enzymes, and hydrogen and methane storage leverage the exceptionally high surface areas and porosities of MOFs – perhaps their most attractive properties – and places them among the best porous materials for these uses.[2, 8, 12-17]

For example, hydrogen and methane are promising alternatives to liquid gasoline fuels that are currently used around the world due to both their significantly smaller carbon footprints and their remarkably high energy densities per unit mass.[18-19] Developing materials that enable reversible and high-capacity storage of these gaseous fuels can enable society to shift dependency from fossil fuels to clean, alternative energy sources and realize a carbon-neutral energy system. In this regard, an ideal candidate material would exhibit a balance between high gravimetric and volumetric capacities for hydrogen and methane at ambient temperatures; highly porous MOFs with ultrahigh surface areas are excellent candidate adsorbents that can potentially address practical concerns related to both the weight and the volume of the adsorbed gas storage systems. Additionally, highly porous MOFs with large, tunable pore apertures have shown remarkable performance as catalysts since the diffusion of substrates into the confined nanospace within the pores during catalysis leads to favorable enhancements in reactivity, and these tailorable pore geometries have also been leveraged to separate or encapsulate large biological macromolecules, such as enzymes.[16-17]

In addition to these applications, precise synthetic approaches can facilitate the efficient development of highly porous MOF materials with targeted pore sizes and geometries for use in energy- and environment-related applications. In this regard, reticular chemistry stands out as one of the most prominent approaches as it permits the rational top-down design and precise architectural assembly of MOFs at the molecular level using respective inorganic and organic building units.[20-23] For example, edge-transitive nets, which are networks that contain only one type of edge, commonly exist in extended crystalline network structures; applying a reticular design strategy with a focus on edge-transitive nets has guided the assembly of several classes of important MOFs. Moreover, employing reticular chemistry to explore various combinations of molecular building blocks with different geometries can even lead to the unanticipated discovery of unexpected crystalline structures.[4, 24-25] These reticular chemistry-aided synthetic approaches allowed our group to successfully develop a series of highly porous MOFs through a combination of rational design, directional synthesis, and occasionally, serendipitous discovery.

In this Account, we summarize recent advances our group has made regarding the synthesis and applications of highly porous MOFs that were motivated by reticular chemistry. First, we focus on the rational design and synthesis of highly porous MOFs with the edge-transitive 6-connected **acs** net – NU-1500[1] and NU-1501[2] – based on the assembly of metal trinuclear clusters and trigonal prismatic triptycene-based ligands (**Figure 1**). With a Brunauer–Emmett–Teller (BET) surface area of 7310 $m^2\ g^{-1}$, NU-1501-Al is the current record holder for highest BET surface area after satisfying all four BET consistency criteria. We further illustrate the relationship between intricate structural features required for efficient water sorption and clean energy gas storage. Second, we elaborate on the development of highly porous and stable Zr-MOFs based on the edge-transitive nets **csq** (NU-1000 series),[26] **ftw** (NU-1100 series),[27-28] and **alb** (NU-1600 series).[3] Hierarchical mesoporous Zr-**csq**-MOFs can encapsulate enzymes for diverse catalytic applications,[29-30] and Zr-**alb**-MOFs can effectively catalytically hydrolyze nerve agents and nerve agent simulants at the metal nodes, which contain Lewis acidic Zr active sites.[3] Finally, we discuss the reticular exploration that lead to the synthesis of two ultraporous uranium-based MOFs – NU-1300[31] (**tbo** net) and NU-1301[4] (**nun** net) – their application in the separation of organic dyes and enzymes. Notably, NU-1301 is the least dense MOF reported to date and contains the largest unit cell of any MOF, and we highlight the benefits of this synthetic strategy that afforded access to this record-breaking material.

2. RETICULAR CHEMISTRY AND HIGH POROUS MOFS

Reticular chemistry has played an important role in the development of new crystalline framework materials, and MOFs in particular, over the past two decades. Conceptually, the synthesis of MOFs using reticular chemistry can be divided into three parts: 1) rational design and synthesis based on a targeted net; 2) isoreticular expansions or contractions; 3) reticular exploration involving serendipitous discovery. Edge-transitive nets and minimal edge-transitive nets, which are usually related to parent edge-transitive nets, commonly exist in MOF structures and offer a rational strategy to predict and design a desired framework (i.e., strategies 1 and 2).[23, 32-33] On the other hand, researchers combining metal salts and organic ligands with different geometries using a reticular exploration approach (strategy 3) enabled the serendipitous discovery of many important MOFs that formed unpredicted frameworks.[4, 24-25] These MOFs can consist of a new type of polynuclear cluster, or they are based on nets with either low connectivity or a high transitivity, which means there are a large number of combinations of potential polyhedral or cages that can form. Generally, using these types of nets to predict MOF structures is difficult, so both serendipitous discovery and rational design strategies have been beneficial for the development of the MOF field. In this section, we provide a brief overview of the reticular design process and further isoreticular expansion of a class of MOFs to illustrate the rationality of using edge-transitive nets for MOF synthesis.

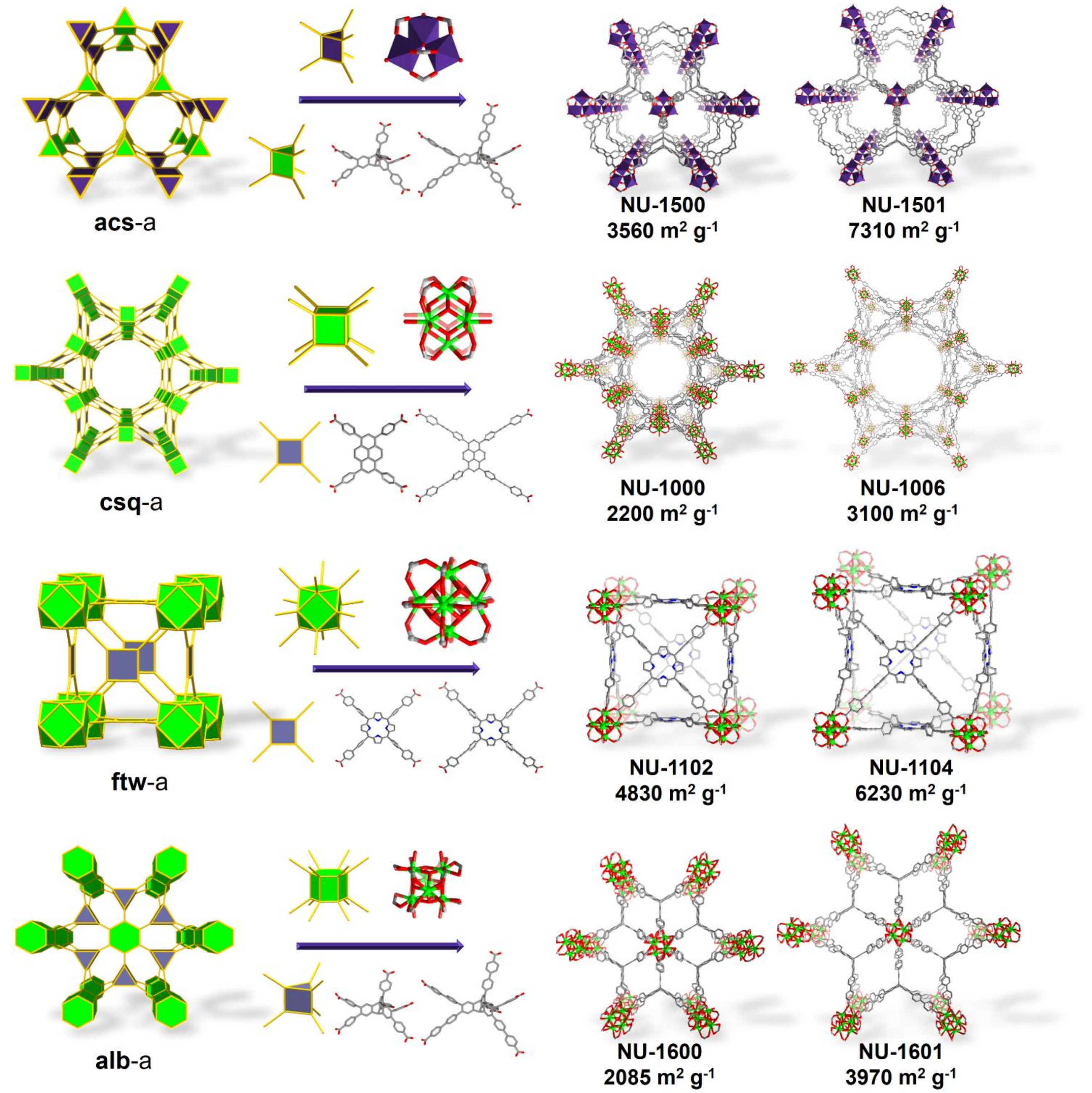
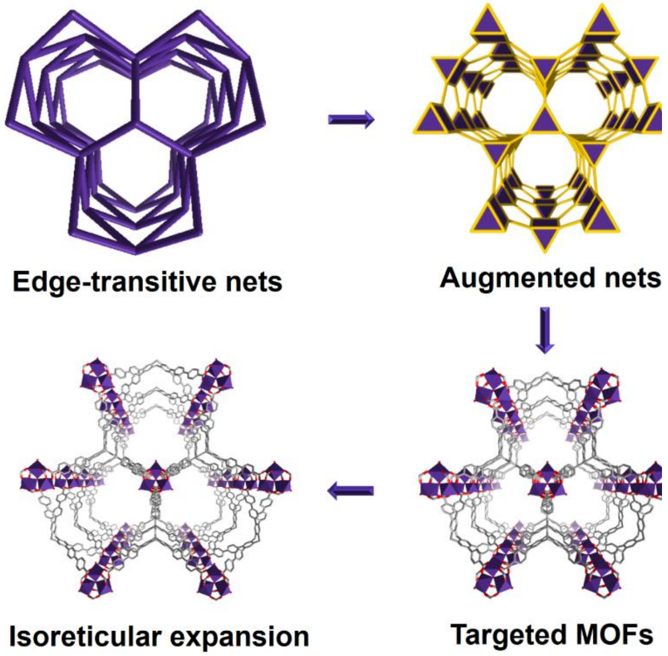


Figure 1. Selected highly porous MOFs with edge-transitive nets developed by our group.

Currently, the Reticular Chemistry Structure Resource (RCSR) database[21] contains 53 basic 3-periodic edge-transitive nets and another five 2-periodic edge-transitive nets, which are amenable to the rational design of MOFs.[34] Here, we use the 6-connected **acs** net as an example to illustrate both the net-guided design and synthesis of MOFs and an



isoreticular chemistry approach (**Figure 2**). The first step for this design strategy involves net augmentation to generate an augmented net, known as "net-a", which contains important geometric details for the potential building units. This process involves the substitution of an n-connected vertex in the original net with a polyhedron or polygon (e.g., a 3-connected vertex is substituted with a triangle). Augmented nets are also helpful for visualization, so they are often used to represent original nets. Next, reasonable inorganic and organic building units, as suggested by an augmented net, can be purposely selected and assembled into a targeted MOF. This process requires a comprehensive understanding of the composition of inorganic building blocks, geometric information of organic ligands, and the coordination interactions between metal ions and linkers. For example, the **acs**-a net features trigonal prismatic building blocks, meaning the inorganic node and organic linkers will both need to exhibit the same coordination geometry. Metal-oxo clusters based on trivalent metals coordinate to 6 carboxylates in this desired geometry, and we designed a hexatopic triptycene-based linker to also form this trigonal prismatic geometry. Finally, applying isoreticular chemistry to expand or contract the original structure offers control over the macroscopic performance of MOFs with the same net. For instance, incorporating an additional phenyl ring in each arm of the linker in NU-1500 affords the isoreticular-expanded analogue NU-1501 that exhibits a significant increase in the BET surface area from 3560 $m^2 g^{-1}$ to 7310 $m^2 g^{-1}$ while still forming the same net.

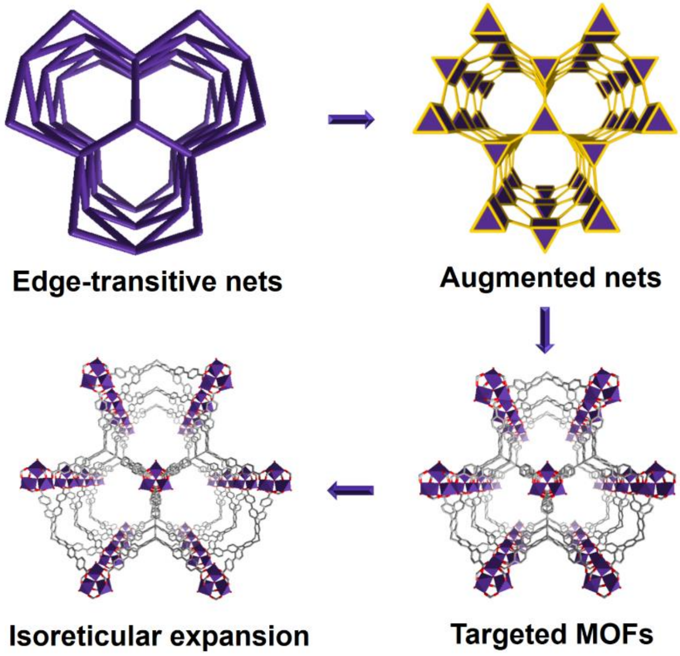


Figure 2. Illustration of the design, synthesis, and isoreticular chemistry of MOFs based on edge-transitive nets.

Isoreticular chemistry is a powerful strategy that enables the construction of highly porous MOFs by delicately expanding pore size and pore volume while maintaining the underlying topology.[2, 8, 12, 35-36] As an example, the isoreticular expansion of **rht**-MOF-1,[37] leads to the construction of a series of highly porous MOFs based on copper paddlewheel building units, including NU-100, NU-109, and NU-110 with BET areas of 6140 m^2 g^{-1}, 7010 m^2 g^{-1}, and 7140 m^2 g^{-1}, respectively (**Figure 3**).[35-36] In many cases, the isoreticular expansion of a MOF may lead to the formation of interpenetrated networks, which occurs when two or more individual frameworks are catenated with each other and result in a significant decrease in porosity. Importantly, the highly connected nature of the 3,24-connected **rht** net prohibits the formation of interpenetrated networks during isoreticular expansions, enabling the construction of highly porous MOFs based on this blueprint net.

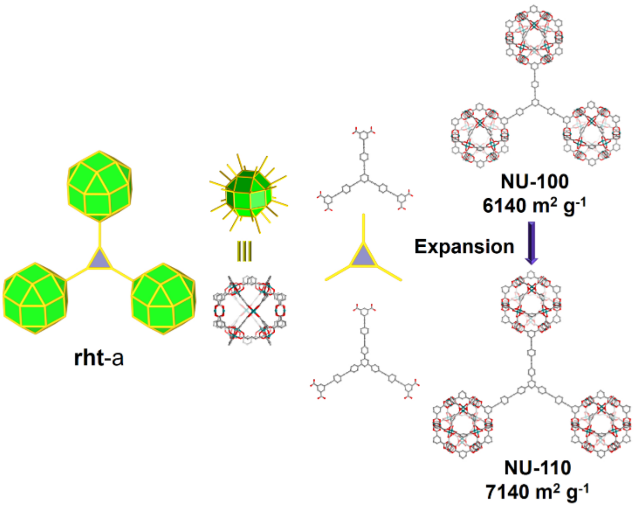


Figure 3. Isoreticular expansion of MOFs based on the **rht** net.

3. HIGHLY POROUS MOFS BASED ON METAL TRINUCLEAR CLUSTERS

Inorganic nodes based on high valent metal ions, such as Al^{3+}, Fe^{3+}, Cr^{3+}, and Sc^{3+}, are promising for constructing highly porous MOFs because these ions form strong metal–oxygen coordination bonds to carboxylate-based linkers, and the inherent stability of the resulting MOFs allows them to remain intact during the activation process and to retain optimal porosity.[38] Additionally, metal trinuclear clusters based on trivalent metal ions are well-established molecular building blocks that are commonly employed in the synthesis of MOFs. For example, MOF-235[39] and MIL-88[40] are representative examples of MOFs assembled from linear, ditopic carboxylate linkers and metal trimers that form trigonal prisms. The combination of these building blocks forms a framework based on the edge-transitive 6-connected **acs** net. These MOFs are often flexible due to the dynamic movement of coordination angles between ligands and metal trimers, and the isoreticular expansion of this net can sometimes result in catenated frameworks.[41] Inspired by reticular chemistry, we envisioned that replacing linear, ditopic linkers with trigonal prismatic ligands of higher connectivity and keeping the same trigonal prismatic metal trimers can, in principle, also form an **acs**-MOF while avoiding the formation of catenated frameworks.

To investigate this strategy, we selected a rigid and trigonal prismatic hexacarboxylic acid, coined as peripherally extended triptycene (H_6PET), as an organic building unit. The assembly of PET^{6-} and metal trimers forms a series of rigid, non-catenated MOFs, NU-1500-M ($[M_3(\mu_3\text{-}O)(H_2O)_2(X)(PET)]$; X = Cl or OH; M = Al, Sc, Fe, or Cr), based on the expected **acs** net (**Figure 4**).[1] NU-1500-M are microporous materials that contain one kind of hexagonal channel with a pore size of ~1.4 nm and BET areas of ~3560 m^2 g^{-1}. Notably, NU-1500-Cr maintains its optimal porosity even when activated directly from water, highlighting the highly robust Cr–O coordination bonds that form throughout this framework. We further evaluated the water sorption performance of NU-1500-Cr and found that it adsorbs ~1.09 g g^{-1} of water at P/P_0 = 0.90. Due to its uniform pore size, continuous pore filling of water results in an S-shaped adsorption isotherm with a step uptake at P/P_0 = ~0.45. The deliverable capacity of water at 298 K for this MOF in the relative humidity range of 40%–60% is among the highest of all porous materials, which is attributed to a combination of high porosity, step uptake, and a small adsorption-desorption hysteresis. Additionally, the high hydrolytic stability of NU-1500-Cr permits consecutive adsorption-desorption cycles without any observed loss in uptake or performance. These properties highlight NU-1500-Cr as a candidate for applications based on water adsorption, such as adsorption cooling systems and water capture directly from air.

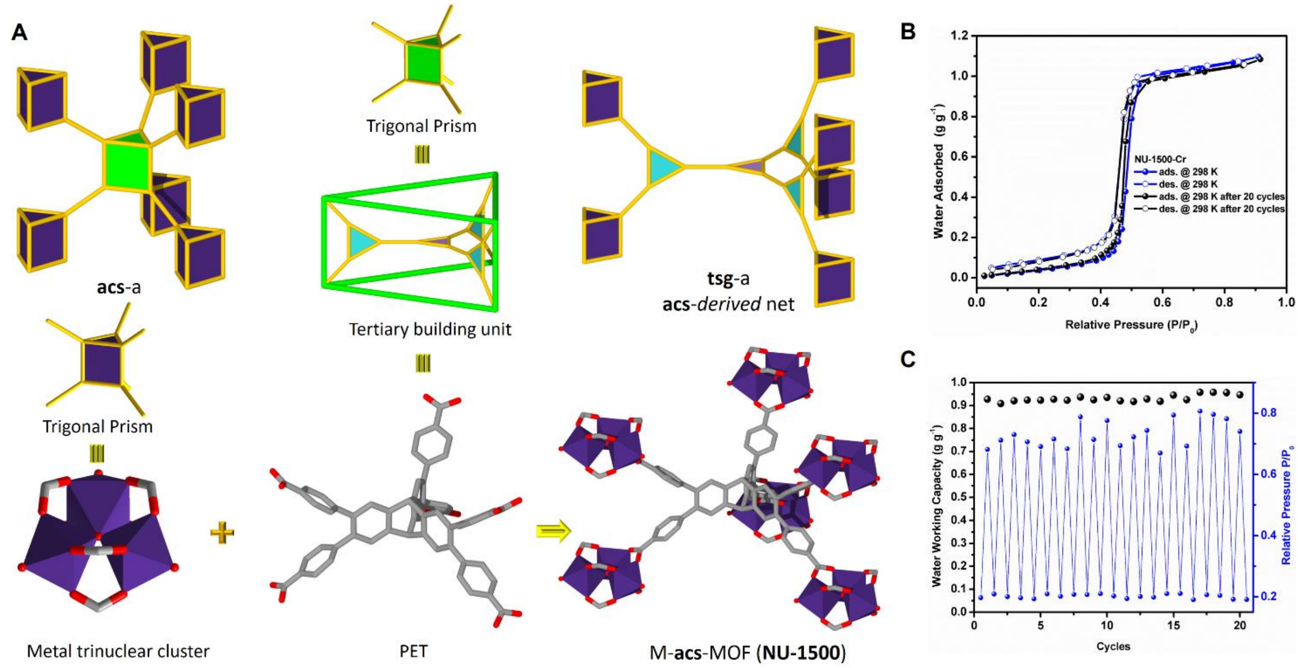


Figure 4. (A) Illustration of the design and synthesis of NU-1500 based on the **acs** net. (B-C) Water sorption isotherms and 20 cycles of adsorption-desorption tests for NU-1500-Cr. Reprinted with permission from ref[1]. Copyright 2019 American Chemical Society.

Intriguingly, NU-1500 shows both a high surface area and porosity considering its relatively small pore aperture of 1.4 nm. For example, NU-1500-Al has a BET area of 3560 $m^2\ g^{-1}$ and an experimental pore volume of 1.46 $cm^3\ g^{-1}$. This unique combination of properties suggests that the isoreticular expansion of the NU-1500 platform can potentially generate ultraporous materials, which are highly desirable for gas storage applications. In particular, the development of adsorbents with high storage capacities for hydrogen and methane can potentially enable society to realize the transformation from traditional energy sources based on fossil fuels to cleaner energy sources, which may eventually lead to a carbon neutral cycle. Based on this reasoning, we conducted molecular simulations using a database of 2800 MOFs, including 50 isoreticular structures to NU-1500, which revealed a comprehensive relationship between MOF structures and both hydrogen and methane storage performance.[2] Moreover, these simulation results indicated that a MOF assembled from metal trimers and extended triptycene-based linkers similar to those found in NU-1500 displays balanced gravimetric and volumetric performance towards hydrogen and methane storage, minimizing the trade-off in performance that has become apparent when maximizing either gravimetric or volumetric capacity on their own.

We applied isoreticuar chemistry to synthesize this targeted MOF, denoted as NU-1501 ([$M_3(\mu_3\text{-}O)(H_2O)_2(OH)(PET\text{-}2)$] (M = Al or Fe)), and combined metal trimers (i.e., Al_3O and Fe_3O) and triptycene-based ligands in which each arm was extended by one phenyl unit relative to the H_6PET linker used in NU-1500 (**Figure 5**).[2] The N_2 adsorption isotherm for NU-1501-Al at 77 K after supercritical CO_2 activation reveals both a high gravimetric BET area of 7310 $m^2\ g^{-1}$ – the current record for all porous materials while satisfying the four BET consistency criteria – and a volumetric BET area of 2060 $m^2\ cm^{-3}$ based on the calculation from the crystallographic density. Moreover, the gravimetric BET area of NU-1501-Al increases to up to 9150 $m^2\ g^{-1}$ if satisfying only the first two consistency criteria of BET theory. These impressive results are corroborated by Ar adsorption isotherms of NU-1501-Al at 87 K, which show similar results. In contrast to traditional ultraporous MOFs with BET areas greater than 6000 $m^2\ g^{-1}$ that typically contain large mesopores of several nanometers in diameter, NU-1501-Al contains relatively narrow mesopores with pore sizes less than 2.5 nm, as well as a relatively small pore volume of ~2.90 $cm^3\ g^{-1}$. These structural features enable NU-1501-Al to maintain its high volumetric surface area while also demonstrating a record high gravimetric BET area. These balanced gravimetric and volumetric surface areas minimize the trade-off in performance observed when maximizing only one value and make NU-1501 a promising candidate for the on-board storage of hydrogen and methane for vehicular applications.

Indeed, high-pressure hydrogen and methane adsorption experiments of NU-1501-Al reveal an outstanding storage performance towards these gases, similar to the data predicted by molecular simulation. Experimentally, NU-1501-Al shows a high gravimetric H_2 deliverable capacity of 14.0 wt% under a combined temperature and pressure swing condition from 77 K/100 bar (adsorption) to 160 K/5 bar (desorption) while maintaining a reasonably high volumetric working capacity of 46.2 g L^{-1}. Owing to its high porosity, NU-1501-Al displays an experimental gravimetric H_2 uptake of ~2.9 wt% at 100 bar and 296 K – among the highest for all MOFs – while maintaining a volumetric uptake of 8.4 g L^{-1}. Methane adsorption studies showed NU-1501-Al displays a 5-80 bar deliverable capacity of ~0.54 g g^{-1} or 214 cm^3 (STP) cm^{-3} at 270 K and ~0.44 g g^{-1} or 174 cm^3 (STP) cm^{-3} at 296 K, respectively. Due to the high porosity and surface area, NU-1501-Al shows an even higher performance at higher operational pressure with a 5-100 bar deliverable capacity of ~0.60 g g^{-1} or 238 cm^3 (STP) cm^{-3} at 270 K and ~0.50 g g^{-1} or 198 cm^3 (STP) cm^{-3} at 296 K. Combined, these impressive hydrogen and methane storage properties place NU-1501 among the most promising adsorbents for the storage and delivery of these clean energy carriers. The successful development of NU-1501 illustrate the importance of reticular chemistry for the efficient synthesis of highly porous MOF materials.

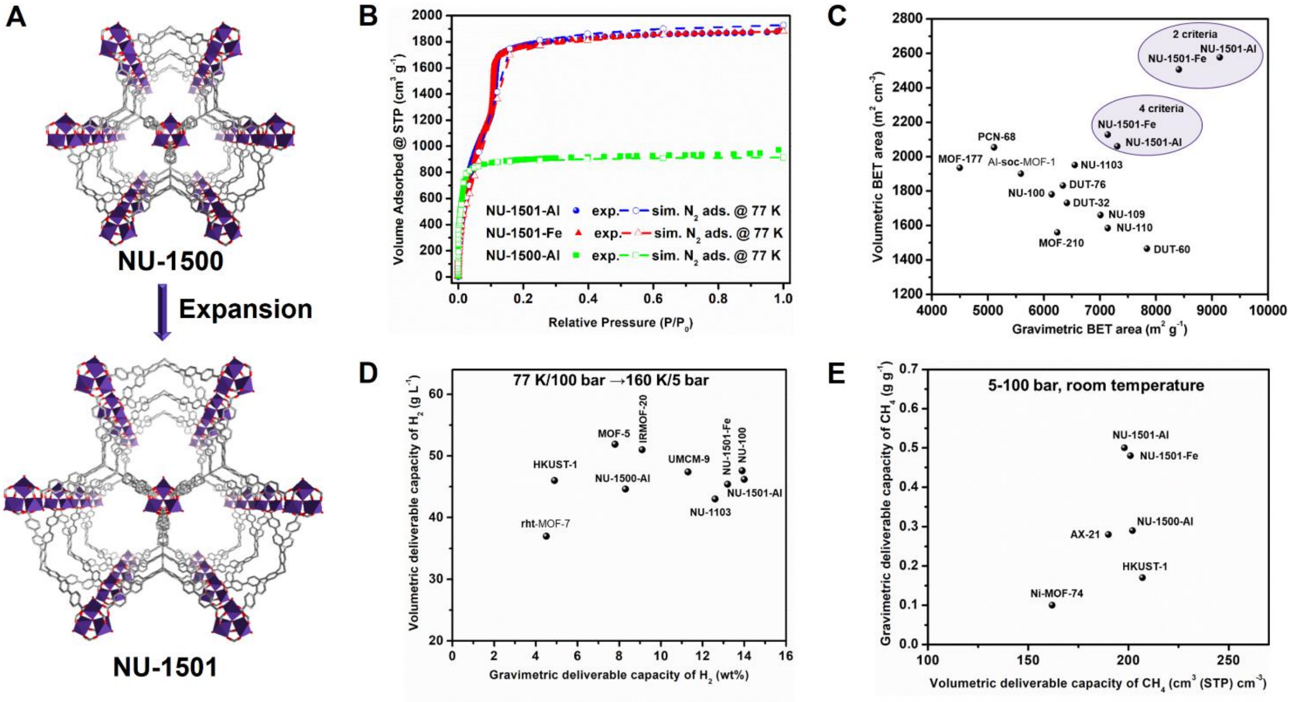


Figure 5. (A) Illustration of isoreticular expansion of NU-1500 to NU-1501. (B-E) N_2 adsorption isotherms, BET areas, hydrogen and methane storage performances of NU-1501 and NU-1500. From ref[2]. Reprinted with permission from AAAS.

4. HIGHLY POROUS MOFS BASED ON ZIRCONIUM-BASED CLUSTERS

In addition to the high valent metal-based trinuclear clusters described in the previous section, hexanuclear zirconium-based clusters (Zr_6) have also shown great promise as versatile building blocks that enable the construction of stable, highly porous MOFs.[42-43] The pioneering discovery of UiO-66,[42] a zirconium-based MOF (Zr-MOF) with the **fcu** net, paved the way for the synthesis of diverse functional Zr-MOFs through reticular chemistry. The versatile connectivity of Zr_6 nodes, which can range from 4- to 12-connected depending on the linker employed, allows for the formation of Zr-MOFs with highly tunable pore sizes and pore geometries. The majority of Zr-MOFs explored to date are based on edge-transitive nets because these platforms are amenable to rational synthesis and are easy to expand or contract via isoreticular chemistry. Our group has been interested in developing Zr-MOFs through a rational design strategy: starting from the original net, a reticular expansion of the parent MOF affords isoreticular Zr-MOFs with significantly higher porosities and surface areas. In this section, we summarize our recent progress towards the synthesis of highly porous Zr-MOFs based on three nets: 4,8-connected **csq**, 4,12-connected **ftw**, 6,12-connected **alb**.

4.1 Zr-MOFs based on the csq net

The assembly of zirconium-based clusters and tetracarboxylates can generate Zr-MOFs based on several edge-transitive nets, including **csq**, **ftw**, **scu**, **shp**, **she**, and **sqc** on account of the versatile connectivity and coordination modes available to the Zr_6 cluster.[43] The controlled synthesis of one phase over other phases can sometimes be very challenging depending on many factors, such as reaction conditions or the geometry of tetracarboxylic ligands. For example, Zr-MOFs with the **csq** net (e.g., the NU-1000[26, 44] series) are favored when the torsion angle between backbone core and side arms of the ligand is close to 60°, while Zr-MOFs with the **ftw** net are preferred when this torsion angle is near 0° due to the desired coordination geometry between carboxylates and Zr nodes in the respective framework.

NU-1000 (**csq**), with a formula of $Zr_6(\mu_3\text{-}O)_4(\mu_3\text{-}OH)_4(OH)_4(H_2O)_4(L)_2$, is assembled from 8-connected Zr_6 nodes and tetracarboxylate pyrene-based linkers. It consists of one type of hexagonal channel (~3.3 nm) and one type of triangular channel (~1.3 nm) along the c-axis, as well as interconnected windows between these two channels. Our group previously showed that this type of hierarchical, interconnected pore system enables the encapsulation of enzymes with a high degree of accessibility due to presence of the triangular channels and interconnected windows that allow for the diffusion of substrates through the pores.[45]

Building from this work, we envisioned that this MOF offers an ideal platform not only for the encapsulation of enzymes, but also for diverse catalytic applications of these encapsulated enzymes using isoreticular analogues with larger pore channels and windows. To accomplish this, our group designed organic ligands with desired geometric conformation (i.e., torsion angles between the pyrene core and side arms of around 60°) by modifying the arms of ligands with extended conjugated systems, fused aromatic groups, or sterically hindered groups.[26] The assembly of these extended tetracarboxylate linkers and Zr salts results in the successful expansion of NU-1000, forming a group of hierarchical mesoporous MOFs (i.e., NU-100x, x = 3, 4, 5, 6, 7) with pore sizes of up to 6.7 nm (**Figure 6**).[26] Our group applied this platform as a cell-free immobilized enzyme system by encapsulating both enzymes and co-enzymes in the MOF for cascade catalytic reactions without using living cells. Importantly, this isoreticular MOF platform allows for the systematic control of the sizes of channels and bridging windows, and MOFs with larger pore sizes display much faster diffusion rates for subtrates and coenzymes than those with smaller pores. Our group recently expanded on this concept and showed that the hierarchical mesoporous NU-1006 can successfully encapsulate the enzyme formate dehydrogenase (FDH) for the bioelectrocatalytic and photocatalytic reduction of CO_2 to formic acid.[29-30] In this context, reticular chemistry plays a vital role in the development of highly porous isoreticular MOFs with precise, hierarchical pore structures for targeted catalytic applications.

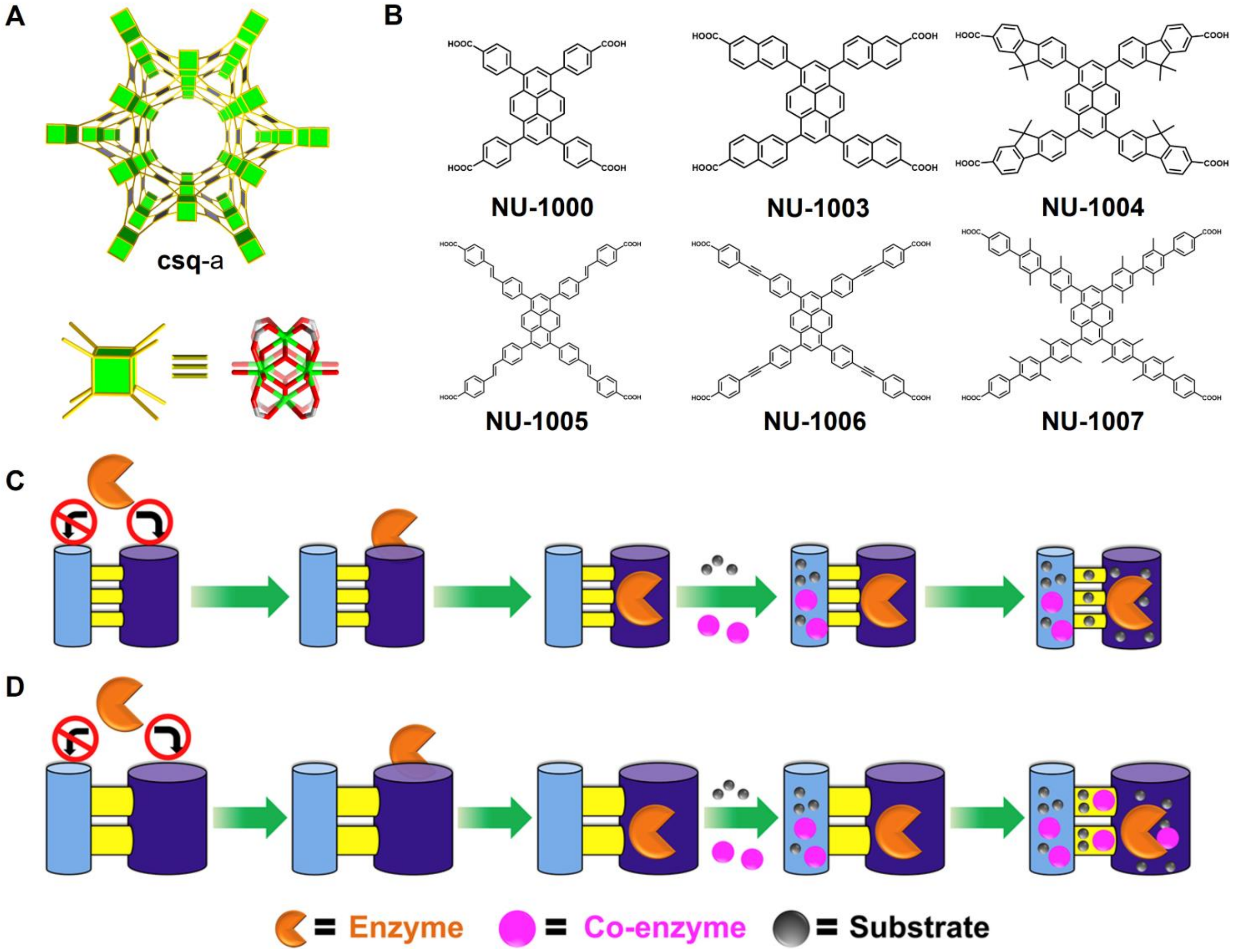


Figure 6. (A) Illustration of csq-a net and related inorganic Zr_6 nodes for NU-1000 series. (B) ligands for NU-100x, x =0, 3, 4, 5, 6, 7. (C-D) Schematic of immobilization of enzymes and coenzymes in NU-1000 series for biocatalytic transformation. Reprinted with permission from ref[26]. Copyright 2018 Elsevier Inc.

4.2 Zr-MOFs based on the ftw net

As mentioned in the previous section, Zr-MOFs with the **ftw** net are favorable when the torsion angle between the backbone core and side arms of a ligand is close to 0°. Building from the pyrene-based linker used in NU-1000, we envisioned that the installation of acetylene groups between the pyrene core and benzoic acid-based arms would afford a linker with the desired planar geometry (**Figure 7**). Indeed, we successfully synthesized the Zr-MOF NU-1100 with 4,12-connected **ftw** net based on the assembly of Zr_6 clusters and this planar tetracarboxylate-based linker.[27-28] We designed a series of tetratopic linkers that contain the same planar geometry between the core and the carboxylate that coordinates to the Zr_6 node to successfully access the isoreticular series of Zr-MOFs (i.e, NU-110x, x = 0, 1, 2, 3, 4; ($Zr_6(\mu_3\text{-}O)_4(\mu_3\text{-}OH)_4(L)_3$). N_2 adsorption experiments at 77 K revealed the highly porous nature of these Zr-MOFs, as exemplified by NU-1103 and NU-1104 that show BET areas of 6550 $m^2\ g^{-1}$ and 6230 $m^2\ g^{-1}$, respectively. Importantly, strong Zr–O coordination bonds throughout the frameworks impart exceptional water stability to these MOFs as demonstrated by nearly identical N_2 adsorption isotherms obtained for NU-1103 before and after water treatment. Water stability is an important consideration since MOFs with poor water stability may lose surface area or crystallinity upon exposure to moisture during processing for practical applications. Moreover, due to their high porosities and surface areas, the highly porous NU-1100 series of MOFs shows good performance towards the storage of hydrogen and methane.[27, 46] In combination with the high water stability, the NU-1100 series may find use in practical applications for the storage and delivery of these gases.

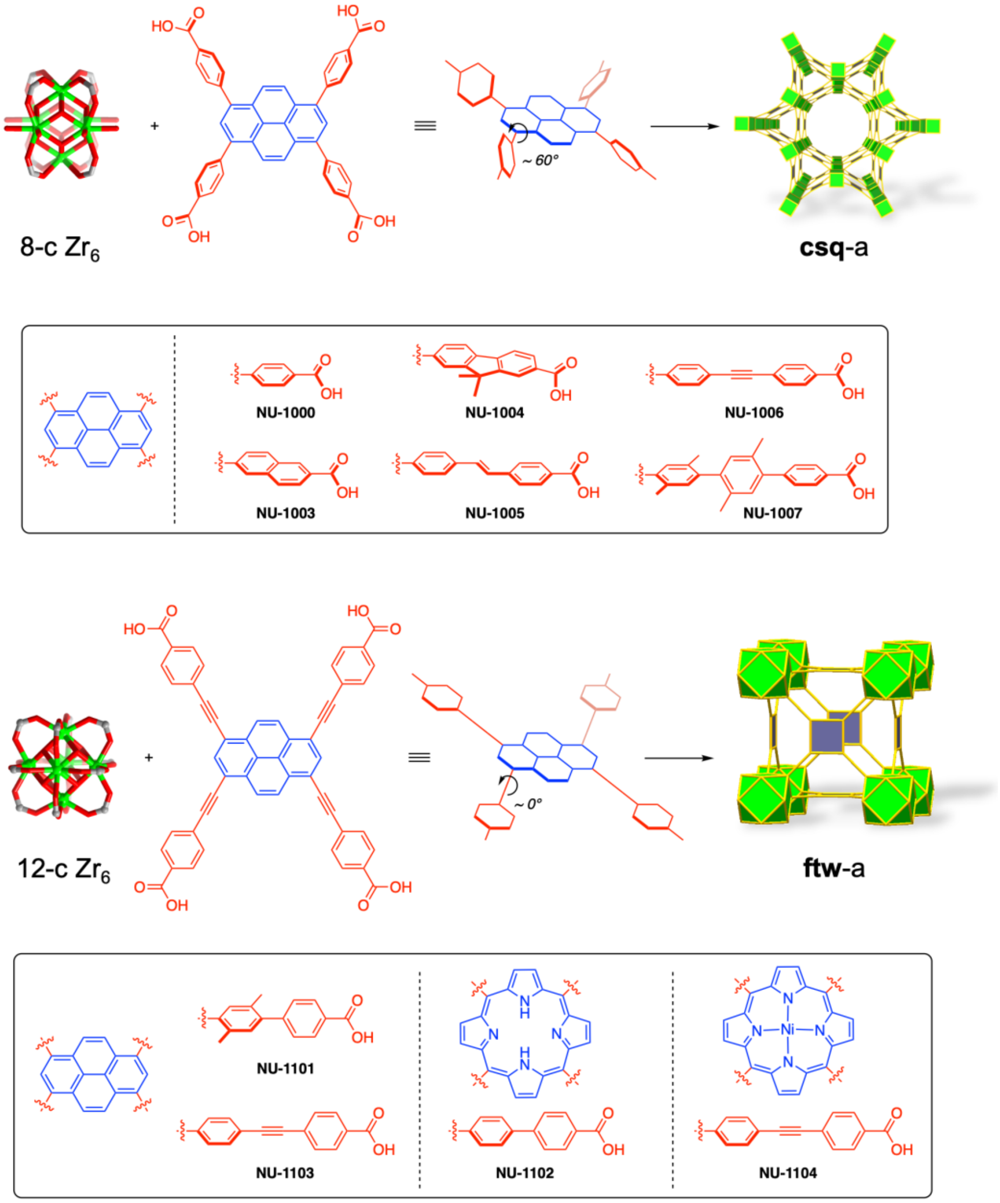


Figure 7. (A) Illustration of relationship of the linker structure and outcome Zr-MOFs with different topologies.

4.3 Zr-MOFs based on the alb net

Highly connected edge-transitive nets, which contain one type of edge, are of prime importance for the synthesis of MOF structures because of their remarkable designability and controllability.[22-23] For example, the (6,12)-connected **alb** net is an important edge-transitive net and the sole possible network that forms via the assembly of trigonal prismatic and hexagonal prismatic building units.[33, 47] Prior to our work, there were no reported Zr-MOFs based on the **alb** net due to synthetic challenges associated with designing building blocks for these MOFs with the proper geometry, so we set out to synthesize a Zr-MOF with this missing edge-transitive net. To begin our investigation, we selected the triptycene-based hexacarboxylate ligand H_6PET, denoted as PET-1, to assemble with zirconium salts to form a Zr-MOF, termed NU-1600, with an ideal formula of $Zr_6(\mu_3\text{-}O)_2(\mu_3\text{-}OH)_6(HCOO)(OH)(H_2O)(PET\text{-}1)_2$ (**Figure 8**). Notably, NU-1600 contains 12-connected Zr_6 clusters that adopt a hexagonal prismatic geometry, which is rarely observed for this node.[3] NU-1600 is microporous and displays a BET area of 2085 $m^2\ g^{-1}$, along with a moderate pore volume of 0.82 $cm^3\ g^{-1}$. The highly connectivity of the **alb** net suggests that the practicable isoreticular expansion of this MOF platform may allow access to even more highly porous MOFs.

Indeed, the assembly of extended triptycene-based ligands (e.g., PET-2 and PET-3) and zirconium salts under similar conditions to those employed for NU-1600 affords two mesoporous Zr-MOFs, NU-1601 and NU-1602, which are isoreticular to NU-1600. N_2 adsorption isotherms at 77 K revealed significantly higher apparent BET areas for NU-1601 and NU-1602 (3970 $m^2 g^{-1}$ and 4500 $m^2 g^{-1}$, respectively) relative to that of NU-1600. Similarly, NU-1601 and NU-1602 also show enhanced pore volumes of 1.75 $cm^3 g^{-1}$ and 2.36 $cm^3 g^{-1}$, respectively.

We hypothesized that the significant BET areas and pore volumes for this series of MOFs would enable rapid diffusion of subtrates to catalytically active, Lewis acidic Zr sites at the nodes. In this regard, we explored the catalytic performance of these isoreticular Zr-MOFs for the Lewis acid-catalyzed hydrolysis of an organophosphorus nerve agent, soman (GD), under basic conditions. For practical nerve agent detoxification systems used in protective suits and masks, the use of a solid-phase base, such as linear polyethyleneimine (PEI), is more feasible than the volatile *N*-ethylmorpholine that is typically used in solution-phase hydrolysis reactions. These hydrolysis experiments revealed that the NU-1600/PEI composite exhibits an initial half-life of ~12 min, which is significantly faster than NU-1600 in the absence of PEI (~20% conversion after 400 min). Combined, this suggests the NU-1600/PEI composite can be deployed for the efficient detoxification of an actual chemical warfare agent. More generally, this design strategy targeted towards the synthesis of the missing edge-transitive net within within Zr-MOFs yielded highly catalyically active frameworks with exceptional surface areas and pore volumes, ultimately highlighting the effectiveness of this reticular synthetic strategy.

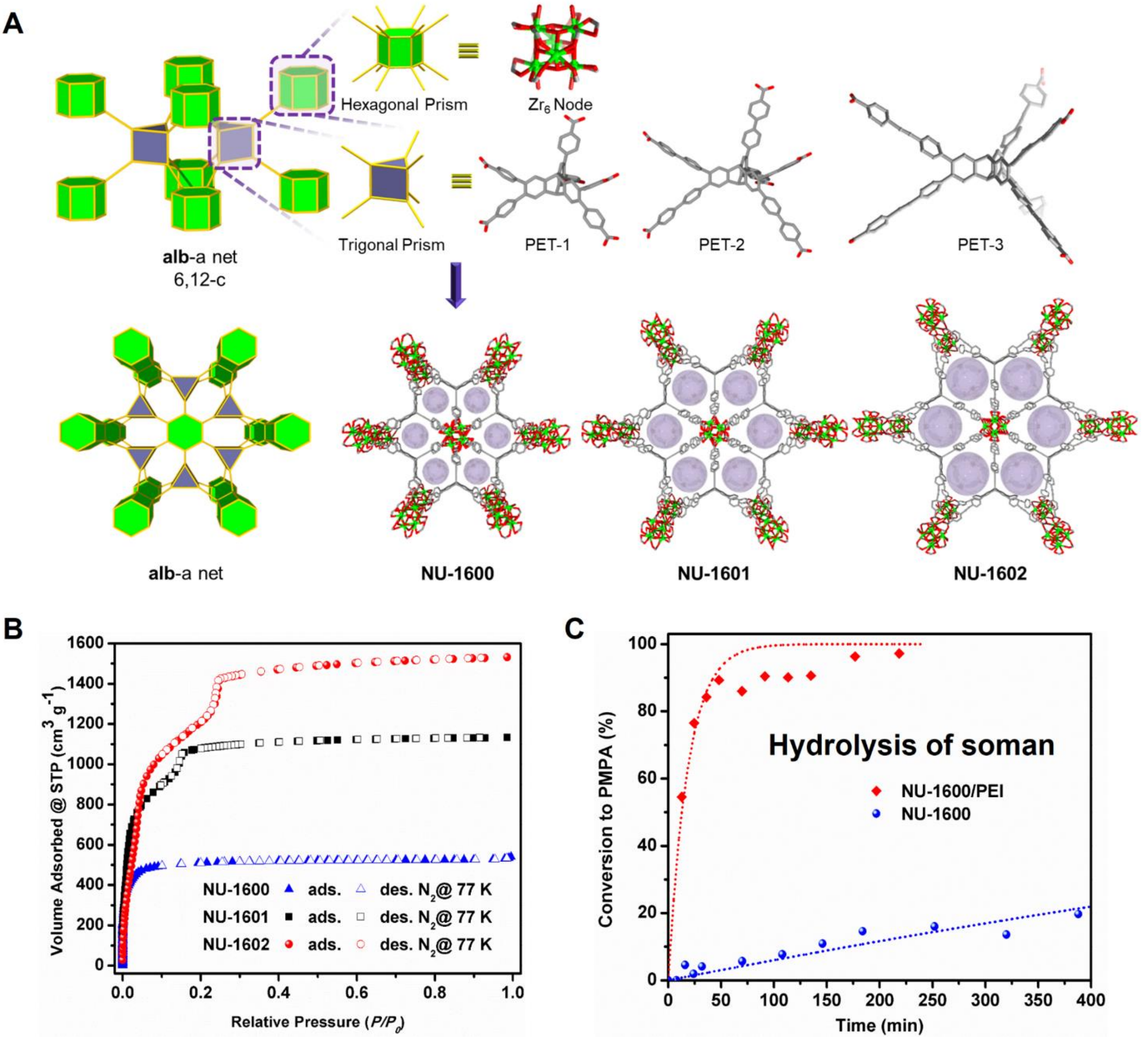


Figure 8. (A) Illustration of the design and synthesis of NU-160x (x=0, 1, 2) based on the **alb** net. (B) N_2 sorption isotherms at 77 K (C) Conversion vs. time data for the hydrolysis of soman. Reprinted with permission from ref[3]. Copyright 2019 American Chemical Society.

5. HIGHLY POROUS MOFS WITH URANIUM-BASED NODES

In addition to synthesizing MOFs from trivalent metal trimer- and zirconium-based nodes, our group has also developed highly porous MOFs using uranium-based nodes. Specifically, these MOFs feature uranyl carboxylate nodes with high-valent U(VI) ions that are formulated as $[UO_2(COO)_3]^-$, meaning these nodes can be deployed as negatively charged building blocks for the construction of anionic MOFs.[48] Geometrically, uranyl carboxylate is a trigonal planar node if the carbon centers of the three coordinated carboxylates are considered points of extension. The combination of these planar inorganic nodes with nonplanar organic ligands has a strong likelihood of generating highly porous, edge-transitive 3-periodic MOFs. To probe this hypothesis, our group explored the assembly of nonplanar tetracarboxylate linkers and trigonal planar uranyl nodes into a uranium-based MOF, NU-1300 (**Figure 9**).[31] Topological analysis revealed NU-1300, $|(C_2H_8N)_4|[(UO_2)_4L_3]$, is based on the 3,4-connected edge-transitive **tbo** net, considering the uranyl nodes and tetracarboxylate as triangular and square building units, respectively. The **tbo** net is often the most observed 3-periodic net when connecting such 3-connected triangular and 4-connected square building units, although there are some other possible competing phases that were not observed following the synthesis of NU-1300 under these conditions.

N_2 adsorption isotherms obtained at 77 K after supercritical CO_2 activation revealed that NU-1300 has an apparent BET area of 2100 $m^2\ g^{-1}$ and an experimental pore volume of 2.8 $cm^3\ g^{-1}$. The large pore size and the window aperture are about 3.9 nm and 2.4 nm, respectively. In addition, this mesoporous MOF remains stable following water treatment due to the strong U–O coordination bonds that form in this framework. Inspired by the highly porous structure that contains anionic building units, our group further explored using NU-1300 for the separation of organic dyes and proteins, and we found that NU-1300 can effectively separate cationic organic dyes from anionic dyes and can selectively separate a characteristic pair of proteins (i.e., cytochrome c and a-lactabumin) based on their surface charges.

Due to it low connectivity, the 3-connected uranyl node presents an excellent platform for the reticular exploration of 3-periodic MOFs that feature organic ligands with different geometries and connectivities. Although the final MOF structure may be difficult to predict *a priori* using this approach, this type of serendipitous reticular exploration is important for promoting and diversifying the field of MOFs[4, 24-25]. In this context, our group explored the assembly of uranyl nodes and a simple, nonplanar tritopic carboxylate linker with carboxylate arms perpendicular to the central benzene core. This assembly results in a highly porous uranium-based MOF, NU-1301, with a high degree of structural complexity.[4] NU-1301, $|(C_2H_8N)|[(UO_2)L]$, crystallizes in a cubic space group of Fd-3m and consists of 816 uranyl nodes and 816 organic ligands in the unit cell (a = 173.262(4) Å). Notably, this unit cell is the largest among nonbiological crystal structures. Additionally, NU-1301 with H^+ counterions has a framework density of 0.124 $g\ cm^{-3}$ – the lowest among all MOFs reported to date. Topological analysis revealed that NU-1301 is based on a new 3-connected net, **nun**. Cuboctahedron-shaped cages, which are assembled from $[UO_2(COO)_3]^-$ nodes and tritopic ligands, were predicted to serve as potential tiles to construct a 3-periodic structure. However, the complex nature of the **nun** net, which is comprised of 17 types of nodes and 18 types of edges, makes it extremely difficult to design such a structure with a high degree of complexity from the original net and highlights the benefits of the reticular exploration approach.

NU-1301 contains several types of cavities with pore sizes of up to 6.2 nm. The argon adsorption isotherm obtained at 87 K revealed that NU-1301 has an apparent BET area of 4750 $m^2\ g^{-1}$ and an experimental pore volume of 3.9 $cm^3\ g^{-1}$, both of which are the highest values among actinide-based MOFs. Similar to NU-1300, a combination of the anionic nodes and large mesopores in NU-1301 make this MOF suitable for the separation of cationic organic dyes and proteins from anionic analogues. In addition, cationic surfactants with hydrophilic or hydrophobic tails can be used to post-synthetically tune the hydrophilicity/lipophilicity of NU-1301, further emphasizing the potential utility of this framework.

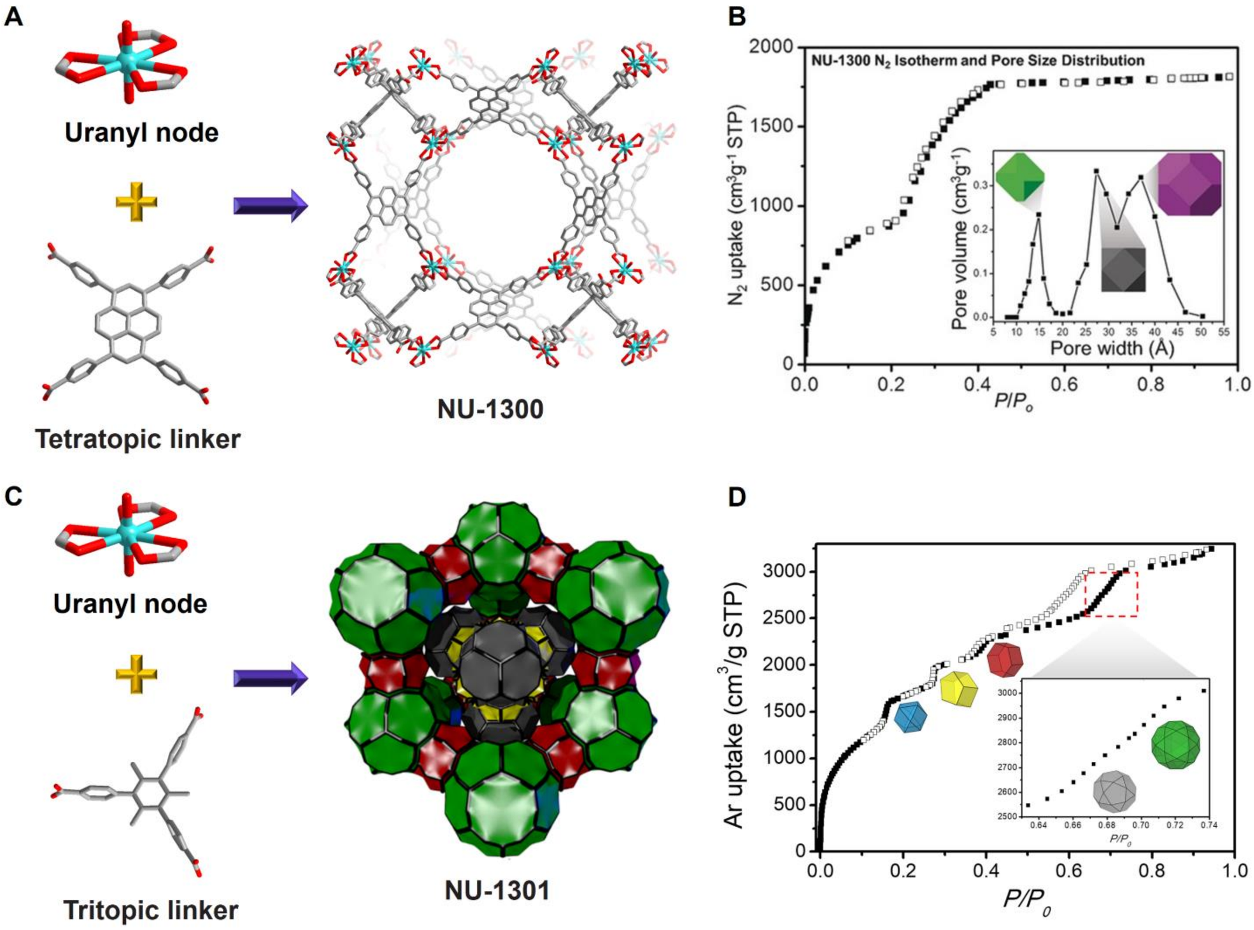


Figure 9. Illustration of the synthesis and gas sorption isotherms of NU-1300 (A-B) and NU-1301 (C-D). **Figure 9B** was reprinted with permission from ref[31]. Copyright 2016 John Wiley and Sons. From ref[4]. **Figure 9C** and **9D** were reprinted with permission from AAAS.

6. CONCLUSIONS AND OUTLOOK

We have highlighted our recent progress leveraging reticular chemistry to synthesize robust and highly porous MOFs, with a particular focus on frameworks that feature carboxylate-based linkers and nodes comprised of trivalent metal trinuclear clusters, hexanuclear zirconium clusters, and uranyl ions. By focusing on edge-transitive nets, this reticular strategy enables both the rational design of MOFs and the reticular exploration of MOFs with new types of topological nets that are difficult to predict *a priori*. Furthermore, the strong metal–oxygen coordination bonds that form between the high-valent metal centers and carboxylate linkers impart exceptional stability to these frameworks and allow these materials to retain their high porosities and accessible pore volumes following activation to remove solvent guest molecules. As a result, we've demonstrated that these newly developed MOF structures can be employed in a variety of applications, including water capture, clean energy gas storage, encapsulation of enzymes, nerve agent hydrolysis, and the selective separation of molecules, depending on the inherent structural features for each specific MOF.

Moving forward, we anticipate several future directions that can potentially promote the development of even more porous framework materials. In order to realize these advances, one key area of interest lies in the development of more precise synthetic strategies empowered by reticular chemistry to generate highly porous MOFs from the assembly of simple building units into targeted complex structures. Rather than relying on sophisticated ligands to access highly porous MOFs, which is prevelant in many design strategies used today, this transformation in methodology would afford similarly complex MOFs with targeted properties using only simple and relatively inexpsensive linkers. In particular, these design schemes will be most effective when used in tandem with emerging, widely applicable, and highly precise molecular simulations; the successful merger of these two strategies will undoubtedly accelerate the discovery of highly porous frameworks with desired properties that can be feasibly synthesized via reticular chemistry. Finally, the design and synthesis of highly porous, multicomponent MOFs that contain related building units arranged in a predetermined order remains a significant goal for this field. In principle, these multicomponent materials could be programmed to exhibit unique synergistic properties beyond what is possible for each of the single component frameworks on their own, opening the door to significant advances for many of the potential applications that employ MOFs. For example, a multicomponent MOF could possibly capture carbon dioxide from air through an adsorption process and then efficiently convert carbon dioxide to a value-added product via a catalytic transformation.

To this end, we hope that this Account can serve as a blueprint to bridge the gap between reticular chemistry design strategies and robust, highly porous MOFs. Ultimately, we anticipate these approaches will facilitate the development of next-generation high-performance materials via state-of-art chemical design.

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Author Contributions

⊥Z. C. and K. O. K. contributed equally to this paper.

Conflict of Interest

O.K.F. has a financial interest in NuMat Technologies, a startup company that is seeking to commercialize MOFs.

Biographies

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ACKNOWLEDGMENT

The authors gratefully acknowledge support from the Defense Threat Reduction Agency (HDTRA1-18-1-0003, HDTRA1-19-1-0010, and HDTRA1-19-1-0007); the U. S. Department of Energy's Office of Energy Efficiency and Renewable Energy(EERE) under award no. DE-EE0008816; the U. S. Department of Energy (DOE) Office of Science, Basic Energy Sciences

Program for Separation (DE-FG02-08ER15967); the Army Research Office, under Award Number W911NF1910340; the Inorganometallic Catalyst Design Center, an EFRC funded by the DOE, Office of Science, Basic Energy Sciences (DE-SC0012702); the U.S. Department of Energy, National Nuclear Security Administration, under Award Number DE-NA0003763; the Air Force Research Laboratory (FA8650-15-2-5518); the Northwestern University Institute for Catalysis in Energy Processes (ICEP), funded by the DOE, Office of Basic Energy Sciences (Award Number DE-FG02-03ER15457). K.O.K. gratefully acknowledges support from the IIN Postdoctoral Fellowship and the Northwestern University International Institute for Nanotechnology. Finally, we would like to thank the present and alumni group members who contributed to works of this Account, and our collaborators, particularly, professors J. Fraser Stoddart, Joseph T. Hupp, Randall Q. Snurr, Taner Yildirim, Diego A. Gómez-Gualdrón, Christos D. Malliakas, Michael O'Keeffe, B. Layla Mehdi, Alice Dohnalkova, Nigel D. Browning.

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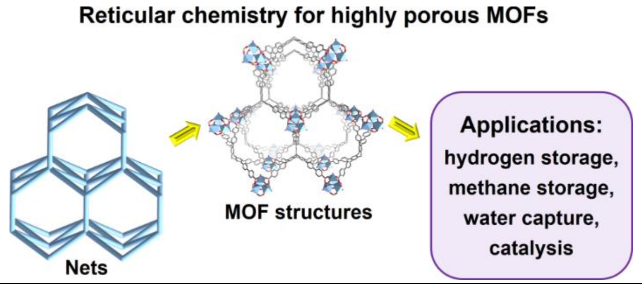
Reticular chemistry for highly porous MOFs
Nets
MOF structures
Applications:
hydrogen storage,
methane storage,
water capture,
catalysis