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COMMUNICATION

Constructing chiral MOFs by functionalizing 4,2':6',4''-terpyridine with long-chain alkoxy domains: rare examples of *neb* nets

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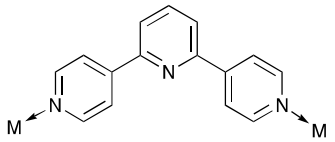
***Abstract*: Reactions of 4'-(4-^{n}alkyloxyphenyl)-4,2':6',4''-terpyridines (alkyl = hexyl or nonyl) with $Co(NCS)_2$ lead to three structurally characterized chiral 3D assemblies which adopt rare *neb* topologies. For the ^{n}hexyl-functionalized ligands, both enantiomorphic lattices of the *neb* nets (crystallizing in the tetragonal space groups $P4_12_12$ and $P4_32_12$, respectively) are presented.**

The coordination chemistry of the divergent ligands 4,2':6',4''- and 3,2':6',3''-terpyridine is dominated by the assembly of extended 1D chain or 2D sheet structures or discrete metallomacrocycles.[1,2,3,4] 4,2':6',4''-Terpyridines (4,2':6',4''-tpy) coordinate only through the outer two pyridine donors, providing the V-shaped tecton shown in Scheme 1. This coordination motif is well-established and entry into higher-dimensionality architectures is typically accomplished by introducing donor groups in the 4'-position. In addition to the widespread use of pyridinyl[5,6,7] and carboxylate[8,9,10,11,12,13] functionalities, sulfonate donors have also been used to access 3D frameworks.[14] 3D-networks utilizing only the two pendant donors of the 4,2':6',4''-tpy domain are relatively rare, although the reaction of 4'-(pyridin-2-yl)-4,2':6',4''-tpy and $Co(NCS)_2$ gives a 3D structure in which the pyridinyl substituent is not coordinated.[15] This is an unusual case where combination of a simple 4,2':6',4''-tpy ligand and $Co(NCS)_2$ leads to a 3D framework; more usually, 2D (4,4) or (6,3) nets result.[16,17,18] A (4,4) net also forms when $CoCl_2{\cdot}6H_2O$ reacts with 4'-(3,4-dimethoxyphenyl)-4,2':6',4''-tpy.[19]

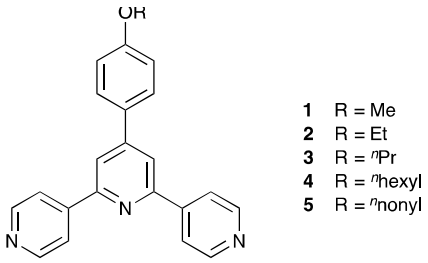
Although coordination polymers and networks containing a wide variety of 4,2':6',4''-tpy or 3,2':6',3''-tpy ligands are known, it remains a challenge to code for 3D frameworks rather than 1D-chains or 2D-nets in the absence of additional coordination domains or of co-ligands. To direct the assembly of 3D architectures predicated upon 4,2':6',4''- and 3,2':6',3''-tpy motifs, we have adopted two strategies. In the first, we have used ditopic ligands[20] containing 'back-to-back' 4,2':6',4''-tpy or 3,2':6',3''-tpy domains.[21,22,23] In the second, we have selected metal-nodes which prefer 6- (or higher) coordination numbers, e.g. reaction between the tpy ligands and $Co(NCS)_2$.[16,17,18] or $Cd(NO_3)_2{\cdot}4H_2O$.[24,25,26]



Scheme 1. Divergent coordination mode of the archetype 4,2':6',4''-tpy ligand.

One way to modify assembly algorithms is with 4'-(4-alkyloxyphenyl)-4,2':6',4''-terpyridines (Scheme 2) in which the steric demands of the 4'-substituent are altered. We have shown that 1D $[Zn_2(OAc)_4(4'\text{-}(4\text{-}ROC_6H_4)\text{-}4,2':6',4''\text{-tpy})]_n$ coordination polymers in which the main packing interactions are π-stacking between arene domains are favoured for small R groups, whereas with longer-chain alkoxy units in which van der Waals interactions are important, discrete complexes $[Zn_2(OAc)_4(4'\text{-}(4\text{-}ROC_6H_4)\text{-}4,2':6',4''\text{-tpy})_2]$ form.[27] In a second example, functionalization of the spacer in ditopic 4,2':6',4''-tpy ligands with ^{n}octyloxy chains directs the formation of 2D→2D parallel interpenetrated nets, whereas single nets result with methoxy-substituents.[21,22] We recently reported the assembly of 2D (4,4) nets in the reactions of $Co(NCS)_2$ with ligands **1**–**3** (Scheme 2).[17] In each net, the Co atom acts as a 4-connecting, planar node; subtle differences in packing resulted in inter-sheet separations increasing from 8.936 Å (R = Me, Scheme 2) to 9.228 Å (R = Et) to 9.305 Å (R = ^{n}Pr). The most significant differences in packing arose from the intrusion of the longer alkoxy chains through the cavities in adjacent sheets.[17] These results prompted us to investigate the effects of futher

increasing the length of the alkyl chains, and we report here the assembly of infrequently observed *neb* nets with 6^6 cage units.[28]



1 R = Me
2 R = Et
3 R = ^{n}Pr
4 R = ^{n}hexyl
5 R = ^{n}nonyl

Scheme 2. The structures of the 4'-(4-alkyloxyphenyl)-4,2':6',4''-terpyridine ligands **1**–**5**.

Ligands **4** and **5** were prepared as previously reported.[27] Single crystals of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ were grown at room temperature by layering an MeOH solution of anhydrous $Co(NCS)_2$ over a $CHCl_3$ solution of **4** (36.9 mg, 0.09 mmol). Two different crystals were selected from the bulk material for single-crystal structure determination. These crystallized in the tetragonal space groups $P4_12_12$ and $P4_32_12$, respectively. Since $P4_12_12$ and $P4_32_12$ constitute an enantiomorphic pair, the structure of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ is inherently chiral. However, since the Flack parameters are 0.21(3) and 0.16(2), respectively, each structure contains 21% or 16% of the second enantiomorph. We discuss the local details of the structure for only one structure (that in space group $P4_32_12$). The bulk sample was characterized by powder diffraction (see Fig. S1†).

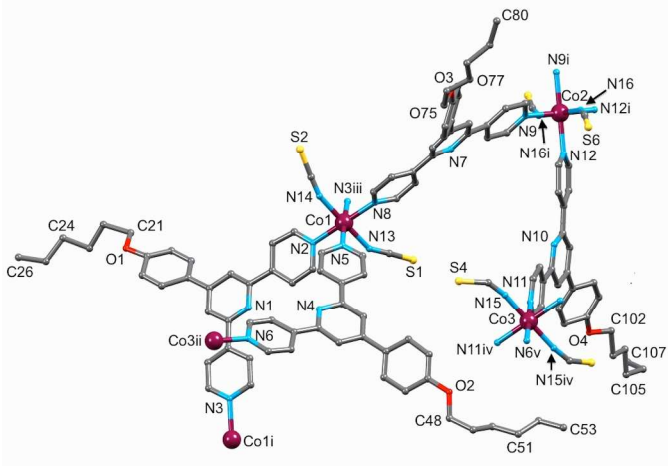


Fig. 1. The asymmetric unit of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ with symmetry-generated atoms (space group $P4_32_12$); H atoms are omitted and only the major sites of the disordered sites (see text) are shown. Symmetry codes: i = y, *x*, 1–*z*; ii = $-^1/_2+y$, $^1/_2-x$, $^1/_4+z$; iii = $^1/_2-y$, $-^1/_2+x$, $-^1/_4+z$; iv = 1–*y*, 1–*x*, $^3/_2-z$; v = $^1/_2-x$, $^1/_2+y$, $^7/_4-z$. Selected bond distances: Co1–N2 = 2.166(5), Co1–N3iii = 2.173(5), Co1–N5 = 2.129(5), Co1–N8 = 2.159(5), Co1–N13 = 2.100(6), Co1–N14 = 2.082(6), Co2–N12 = 2.209(5), Co2–N12i = 2.209(5), Co2–N16 = 2.093(7), Co2–N9 = 2.170(3), Co3–N6 = 2.163(5), Co3–N11 = 2.182(5), Co3–N15 = 2.073(7) Å.

Fig. 1 shows the asymmetric unit of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ with symmetry-generated atoms. Each of the three independent Co atoms is octahedrally sited with a *trans* arrangement of *N*-bonded thiocyanato ligands. The thiocyanates containing S2, S4 and S6 are disordered and each has been modelled over two sites of 60.3/39.7, 62.1/37.9 and 56.4/43.6% occupancies, respectively. Each of the four independent ligands **4** coordinates through the outer two pyridine rings, consistent with previously reported coordination modes.[1,2] The Co–N bond distances (see caption to Fig. 1) and bond angles within the coordination spheres are unexceptional. No significant deviations from planarity are noted for the tpy units; twist angles between pairs of bonded pyridine rings range from 6.5 to 16.3°. Each phenyl ring is, as expected on steric grounds, twisted with respect to the pyridine ring to which it is attached (range of angles = 36.1 to 37.6°).

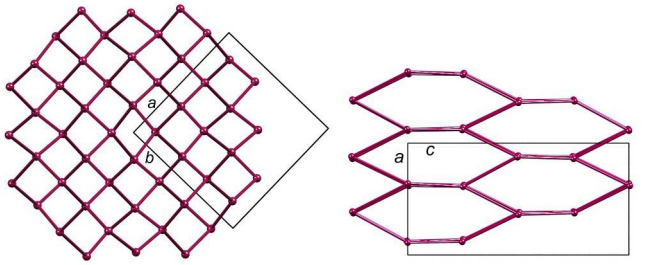
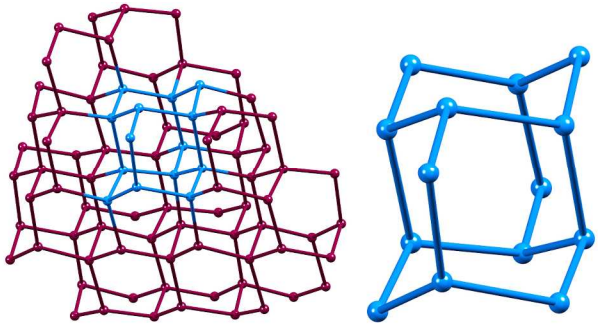


Fig. 2. $[Co_2(NCS)_4(\mathbf{4})_4]_n$ (space group $P4_32_12$): views down the crystallographic *c* and *b* axes, generated using TOPOS and Mercury.



(a) (b)

Fig. 3. (a) TOPOS/Mercury representation of the structure of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ showing Co nodes. (b) The fundamental 6^6 unit of the *neb* topology excised from the framework shown in (a).

The structure shown in Fig. 1 propagates into a 3D framework. The differences in coordination environments about Co1, Co2 and Co3 in $[Co_2(NCS)_4(\mathbf{4})_4]_n$ are structurally insignificant and the framework is uninodal. Fig. 2 shows views down the crystallographic *c* and *b* axes, generated using a combination of TOPOS[29] and Mercury (v. 3.7).[30,31] The 4-fold screw axes that define the chirality (i.e. opposite handednesses in each of space groups $P4_12_12$ and $P4_32_12$, Fig. S2†) of the lattice run along the *c*-axis. Views down either the *a* or *b*-axes (Fig. 2, right) reveal the 6-membered rings present in the 4-connected net. The combination of 4-coordinate nodes and 6-membered rings is reminiscent of diamond. However, whereas a diamond net consists of interconnected 6^4 cage units, Fig. 3 illustrates that the 4-connected framework in $[Co_2(NCS)_4(\mathbf{4})_4]_n$ is constructed from 6^6 cage units.[28] Each Co...Co edge of the 3D framework is spanned by one ligand **4** and the hexyloxy-

chains are in close to extended conformations, directed along the *a*- and *b*-axes (Fig. 4).

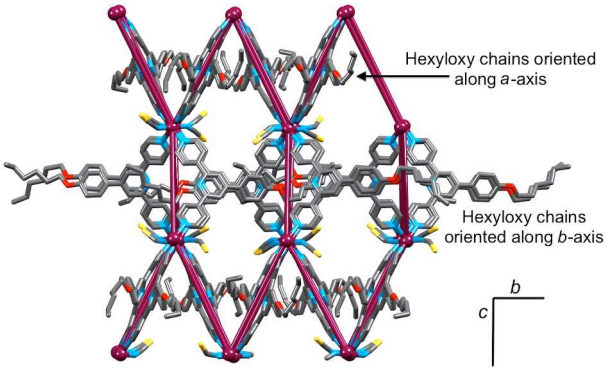


Fig. 4. TOPOS/Mercury representation of $[Co_2(NCS)_4(\mathbf{4})_4]_n$ with superimposed ligand structures (H atoms omitted) viewed down the *a*-axis.

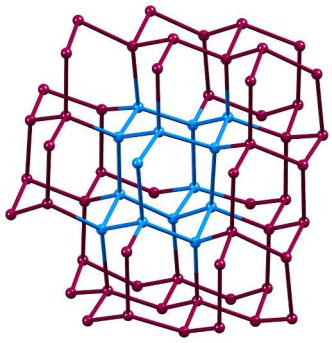


Fig. 5. TOPOS representation of part of the *neb* net in $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$ showing Co nodes; one 6^6 cage that characterizes the *neb* net is shown in blue

The reaction of **5** with $Co(NCS)_2$ led to single crystals of $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$. The compound crystallizes in the tetragonal space group $P4_12_12$, once again signifying a chiral network. The asymmetric unit contains three independent Co atoms and four independent ligands **5**, and structural details within the coordination sphere of each Co atom are analogous to those shown in Fig. 1 for $[Co_2(NCS)_4(\mathbf{4})_4]_n$. As in the latter, the Co–N(NCS) bond distances (range 2.065(5) to 2.107(5) Å) in $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$ are shorter than the C–N(tpy) bond lengths (range 2.153(5) to 2.175(4) Å). All thiocyanate ligands and solvent molecules are ordered. The bulk material for $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$ was characterized by powder diffraction (see Fig. S3†).

Replacing ligand **4** (*n*hexyloxy chains) by **5** (*n*nonyloxy chains) has little effect on the overall structure, although the unit cell expands slightly along the *a* and *b* axes in response to the accommodation of the longer alkyl chains which are oriented along these axes (Fig. 4). In the two enantiomorphs of $[Co_2(NCS)_4(\mathbf{4})_4]_n$, $a = b = 23.7111(4)$ and $c = 46.9783(7)$ Å ($V = 26412.0(9)$ Å^3), and $a = b = 23.68444(16)$ and $c = 46.9716(4)$ Å ($V = 26348.8(4)$ Å^3), respectively, while in $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$, $a = b = 23.88216(9)$ and $c = 46.8514(3)$ Å ($V = 26722.0(3)$ Å^3). This expansion also leads to inclusion of solvate of crystallization. Fig. 5 reveals the assembly of the chiral *neb* net in $[\{Co_2(NCS)_4(\mathbf{5})_4\}\cdot 2CHCl_3\cdot MeOH]_n$, confirming that a change from *n*hexyloxy to *n*nonyloxy functionality has no effect on the overall architecture.

In addition to the scarcity of the *neb* net among coordination polymers and hydrogen-bonded networks,[32] we note that the space groups $P4_12_12$ and $P4_32_12$ are relatively rare. A search of the Cambridge Structural Database[33,34] (CSD which contains ~800,000 entries) using Conquest[35] v. 5.37 (with November 2015 update) revealed 1563 and 1346 hits for $P4_12_12$ and $P4_32_12$, respectively.

To assess the impact of the long alkoxy chains, we have four benchmark structures. In $[Co(NCS)_2(4'\text{-(pyridin-2-yl)-}4,2':6',4''\text{-tpy})]_n$, the pyridin-2-yl substituent is non-coordinating[15] and spatially analogous to the phenyl spacer in ligands **4** and **5**. Although the 3D network was not defined in the original work,[15] inspection of the structure (CSD refcode XUVPAH) reveals interpenetrating *nbo* frameworks (Fig. S4†). Modification with small alkoxy domains leads to 2D (4,4) nets in $[\{Co(NCS)_2(\mathbf{1})_2\}\cdot 4CHCl_3]_n$ and $[\{Co(NCS)_2(\mathbf{2})_2\}\cdot 4CHCl_3]_n$ and $[\{Co_2(NCS)_4(\mathbf{3})_4\}\cdot 2CHCl_3\cdot 1.5MeOH]_n$; these structures all exhibit head-to-tail π-stacking of 4'-(4-alkoxyphenyl) units with the alkyl units protruding into the holes in adjacent sheets. In the current work, we have demonstrated that longer tails switch the structure to an unusual 3D *neb* network in which the extended alkyl chains thread through the lattice. We also note that the chiral MOFs described in this work assemble from achiral nodes and linkers.[36]

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Notes and references

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†Electronic Supplementary Information (ESI) available: Experimental and crystallographic details. Fig. S1 and S3: Powder diffraction data and additional figures of lattices in $[Co_2(NCS)_4(\mathbf{4})_4]_n$; Fig. S4. interpenetrating *nbo* nets in $[Co(NCS)_2(4'\text{-(pyridin-2-yl)-}4,2':6',4''\text{-tpy})]_n$ (refcode XUVPAH). CCDC 1474325-1474327. See DOI: 10.1039/b000000x/

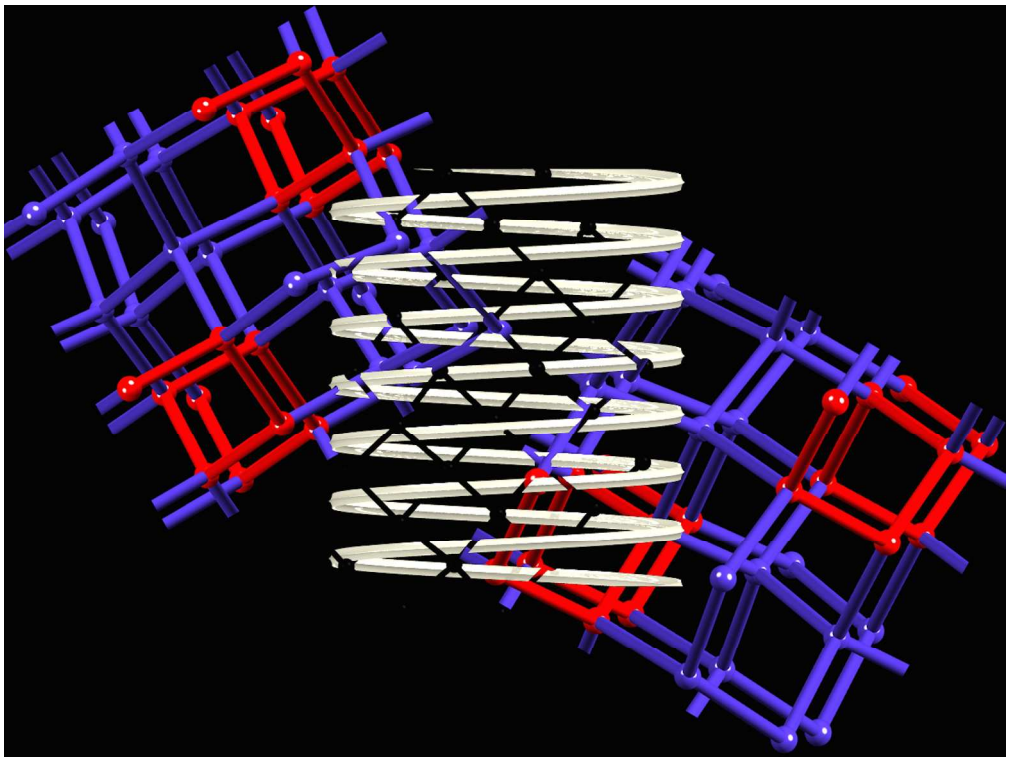
1 C. E. Housecroft, *Dalton Trans*., 2014, **43**, 6594.
2 C. E. Housecroft, *CrystEngComm*, 2015, **17**, 7461.
3 G. Zhang, J. Tan, T. Phoenix, D. R. Manke, J. A. Golen and A. L. Rheingold, *RSC Adv.*, 2016, **6**, 9270 and references therein.
4 L. Li, Y. Z. Zhang, C. Yang, E. Liu, J. A. Golen and G. Zhang, *Polyhedron*, 2016, **105**, 115 and references therein.
5 Y.-Q. Chen, G.-R. Li, Z. Chang, Y.-K. Qu, Y.-H. Zhang and X.-H. Bu, *Chem. Sci*., 2013, **4**, 3678 and references therein.
6 C. Liu, Y.-B. Ding, X.-H. Shi, D. Zhang, M.-H. Hu, Y.-G. Yin and D. Li, *Cryst. Growth Des*., 2009, **9**, 1275.
7 X. Li, X.-L. Chi, Y.-C. Xu, Y. Chen, Q. Yang, X.-S. Zeng, H.-L. Xu and D.-R. Xiao, *Inorg. Chim. Acta*, 2016, **445**, 160.
8 P. Yang, M.-S. Wang, J.-J. Shen, M.-X. Li, Z.-X. Wang, M. Shao and X. He, *Dalton Trans*., 2014, **43**, 1460 and references therein.
9 F. Yuan, J. Xie, H.-M. Hu, C.-M. Yuan, B. Xu, M.-L. Yang, F.-X. Dong, G.-L. Xue, *CrystEngComm*, 2013, **15**, 1460 and references therein.
10 Y. Li, Z. Ju, B. Wu and D. Yuan, *Cryst. Growth Des*., 2013, **13**, 4125 and references therein.
11 Y. Xi, W. Wei, Y. Xu, X. Huang, F. Zhang and C. Hu, *Cryst. Growth Des.*, 2015, **15**, 2695.
12 B. Xu, B. Liu, H.-M. Hu, Y. Cheng, Z. Chang and G. Xue, *Polyhedron*, 2015, **96**, 88.
13 F. Yuan, R. An, H.-M. Hu, S.-S. Shen, X. Wang, M.-L. Yang and G. Xue, *Inorg. Chem. Comm*., 2015, **56**, 1.
14 L. Zhang, J.-D. Zheng, Y.-T. Chen, S.-R. Zheng, J. Fan and W.-G. Zhang, *CrystEngComm*, 2015, **17**, 5538.
15 Z. Yin, S. Zhang, S. Zheng, J. A. Golen, A. L. Rheingold and G. Zhang, *Polyhedron*, 2015, **10**, 139.
16 Y. M. Klein, A. Prescimone, E. C. Constable and C. E. Housecroft, *CrystEngComm*, 2015, **17**, 6483.
17 Y. M. Klein, A. Prescimone, E. C. Constable and C. E. Housecroft, *Polyhedron*, 2016, **103A**, 58.
18 E. C. Constable, C. E. Housecroft, M. Neuburger, S. Vujovic, J. A. Zampese and G. Zhang, *CrystEngComm.*, 2012, **14**, 3554.
19 U.P. Singh, S. Narang, P. Pachfule and R. Banerjee, *CrystEngComm*, 2014,**16**, 5012.
20 J. Yoshida, S.-I. Nishikiori and H. Yuge, *J. Coord. Chem.*, 2013, **66**, 2191.
21 E. C. Constable, C. E. Housecroft, S. Vujovic and J. A. Zampese, *CrystEngComm*m 2014, **16**, 3494.
22 S. Vujovic, E. C. Constable, C. E. Housecroft, C. D. Morris, M. Neuburger and A. Prescimone, *Polyhedron*, 2015, **92**, 77
23 Y. M. Klein, E. C. Constable, C. E. Housecroft and A. Prescimone *CrystEngComm*, 2015, **17**, 2070.
24 E. C. Constable, G. Zhang, C. E. Housecroft, M. Neuburger and J. A. Zampese, *CrystEngComm*, 2009, **11**, 2279.
25 E. C. Constable, G. Zhang, C. E. Housecroft, M. Neuburger and J. A. Zampese, *CrystEngComm*, 2010, **12**, 3733.
26 Y. M. Klein, A. Prescimone, E. C. Constable and C. E. Housecroft, *CrystEngComm*, 2015, **17**, 6483.
27 Y. M. Klein, E. C. Constable, C. E. Housecroft, J. A. Zampese and A. Crochet, *CrystEngComm*, 2014, **16**, 9915.
28 D.-S. Li, Y.-P. Wu, J. Zhao, J. Zhang and J. Y. Lu, *Coord. Chem. Rev.*, 2014, **261**, 1.
29 V. A. Blatov, A. P. Shevchenko, TOPOS Professional v. 4.0, Samara State University, Russia.
30 C. F. Macrae, P. R. Edgington, P. McCabe, E. Pidcock, G. P. Shields, R. Taylor, M. Towler and J. van de Streek, *J. Appl. Cryst*., 2006, **39**, 453.
31 C. F. Macrae, I. J. Bruno, J. A. Chisholm, P. R. Edgington, P. McCabe, E. Pidcock, L. Rodriguez-Monge, R. Taylor, J. van de Streek and P. A. Wood, *J. Appl. Cryst.*, 2008, **41**, 466.
32 See for example: O. Ermer and A. Eling, *J. Chem. Soc. Perkin Trans 2*, 1994, 925.
33 F. H. Allen, Acta Crystallogr., 2002, **B58**, 380.
34 C. R. Groom, I. J. Bruno, M. P. Lightfoot and S. C. Ward, Acta Crystallogr., 2016, **B72**, 171.
35 I. J. Bruno, J. C. Cole, P. R. Edgington, M. Kessler, C. F. Macrae, P. McCabe, J. Pearson and R. Taylor, *Acta Crystallogr*., 2002, **B58**, 389.
36 See for example: N. Chen, M.-X. Li, P. Yang, X. He, M. Shao and S.-R. Zhu, *Cryst. Growth Des.*, 2013, **13**, 2650 and references therein,
37 S. J. Coles and P. A. Gale, *Chem. Sci.*, 2012, **3**, 683.

TOC

Constructing chiral MOFs by functionalizing 4,2':6',4''-terpyridine with long-chain alkoxy domains: rare examples of *neb* nets

Y. Maximilian Klein, Alessandro Prescimone, Mateusz B. Pitak, Simon J.Coles, Edwin C. Constable and Catherine E. Housecroft

Three chiral 3D MOFs with uncommon *neb* topologies assemble from $Co(NCS)_2$ and 4'-(4-^{n}alkyloxyphenyl)-4,2':6',4''-terpyridines (alkyl = hexyl or nonyl).



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