Highly branched and loop-rich gels via formation of metal–organic cages linked by polymers

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Materials and Methods

Materials

All non-deuterated solvents, including anhydrous solvents in Sure/Seal™ containers, and polyethylene glycol (PEG, $M_n = 2\, \text{kDa}$), and 4-(1-pyrenyl)butyric acid were purchased from Sigma-Aldrich®. Pyridine-3-boronic acid pinacol ester and pyridine-4-boronic acid pinacol ester were purchased from Ark Pharm, Inc. Palladium(II) nitrate dihydrate and tetrakis(triphenylphosphine)palladium were purchased from Strem Chemicals, Inc. All deuterated solvents were purchased from Cambridge Isotope Laboratories, Inc. All other reagents and solvents were purchased from VWR® or Sigma-Aldrich®. All purchased reagents and solvents were used as supplied unless otherwise noted. All air-sensitive reactions were executed using standard Schlenk techniques. All filtration in vacuo, unless stated otherwise, was carried out over MAGNA nylon filter disks (Maine Manufacturing, LLC) with 0.45 µm pore size. Spectra/Por® 7 standard regenerated cellulose dialysis tubing (8 kDa molecular weight cut-off (MWCO), 25.5 mm diameter) was purchased from Spectrum® Laboratories.

Chromatography methods

Liquid chromatography–mass spectrometry (LC/MS) were performed on an Agilent 1260 LC system equipped with an Advanced Materials Technology HALO® C18 high performance column. Solvent gradients consisted of mixtures of Milli-Q® water with 0.1% acetic acid.
(AcOH) and HPLC-grade acetonitrile. Mass spectra were obtained using an Agilent 6130 single quadrupole mass spectrometer.

Preparative high performance liquid chromatography (prep-HPLC) was performed on an Agilent Technologies 1260 Infinity system equipped with a ZORBAX 300SB-C18 PrepHT column (ID x Length = 21.2 x 150 mm; particle size = 5 µm). Eluent flow rate was 20 mL/min, and the eluent composition consisted of mixtures of nano-pure water with 0.1% acetic acid (AcOH) and HPLC-grade acetonitrile. The eluent gradient consisted of a linear ramp from 20% to 60% acetonitrile during 0—18 min, followed by a ramp to 100% acetonitrile during 18-20 min. Polymer samples were dissolved at a concentration of 100 mg/mL, and injected in 1.0 or 0.50 mL volumes. The instrument was controlled using the OpenLAB PrepLC software.

Column chromatography was performed on a Biotage® Isolera One with Accelerated Chromatographic Isolation™ flash chromatography system, using Biotage® KP-Sil SNAP cartridges at the recommended flow rates (e.g., 50 mL/min for 100 g SNAP cartridge).

Gel permeation chromatography (GPC) measurements were performed in tetrahydrofuran (THF) using an Agilent 1260 Infinity system with variable-wavelength diode array (254, 450, and 530 nm) and a refractive index detector, guard column (Agilent PLgel; 5µm; 50 x 7.5 mm), and three analytical columns (Agilent PLgel; 5µm; 300 x 7.5 mm; 10^5, 10^4, and 10^3 Å pore sizes). The instrument was calibrated with low-dispersity polystyrene (PS) standards between 1.7 and 3150 kg/mol. All runs were performed at 1.0 mL/min flow rate at 25 °C. The number-average molar mass (M_n), weight-average molar mass (M_w), and dispersity index (Đ = M_w/M_n) of PL1 and PL2 were calculated by applying the conversion from polystyrene samples described by Sado and Mori (values of t = 0.916, s = 1.21, derived for PEG, were used for PL1 and PL2). S1

Solution nuclear magnetic resonance spectroscopy methods

1H nuclear magnetic resonance (^1H NMR) and 13C nuclear magnetic resonance (^13C NMR) spectra were recorded on two Bruker AVANCE-400 NMR spectrometers (NIH Grant # 1S10RR013886-01). Chemical shifts are expressed in parts per million (ppm), and splitting patterns are designated as s (singlet), d (doublet), t (triplet), m (multiplet), and b (broad). Scalar coupling constants J are reported in Hertz (Hz). MestReNova LITE v5.2.5-4119 software (Mestrelab Research S.L.) was used to analyze the NMR spectra. ^1H and ^13C NMR spectra were referenced to solvent peaks as reported in literature. S2

Magic angle spinning nuclear magnetic resonance spectroscopy methods

Variable temperature ^1H magic-angle spinning solid-state nuclear magnetic resonance (VT ^1H MAS NMR) spectra were recorded on a 11.7 T (500 MHz, ^1H) home-built NMR spectrometer (courtesy of Dr. David Ruben, Francis Bitter Magnet Laboratory-MIT). The gel samples immediately after mixing components were loaded via syringe into a 4 mm RevNMR-style zirconia rotor (60 µl fill-volume) which was sealed with a Kel-F cap to reduce the ^1H background signal. The spectra were collected using a spinning frequency (ωr/2π) of 10 kHz with 128 co-added transients and a recycle delay of 3 seconds. Sample temperatures were varied between 20 and 70 °C and spectra were collected every 5 minutes over a period of eight hours. ^1H spectra were referenced to solvent peaks as reported in literature. S2
Mass spectrometry methods

*Vide supra* for LC/MS methods.

High-resolution mass spectrometry (HRMS) was obtained using either (1) a Bruker Daltonics® APEXIV 4.7 Tesla Fourier Transform Ion Cyclotron Resonance Mass Spectrometer (FT-ICR-MS) with a direct analysis in real time (DART) or electrospray ionization (ESI) ion sources (NSF Grant #CHE-0234877) or (2) the Bruker Impact HD q-TOF mass spectrometer coupled to a 1290 uHPLC (see ESI-TOF mass spectrum of Pd2(L2)4 paddlewheels below).

Matrix-assisted laser desorption ionization-time of flight mass spectrometry (MALDI-TOF) was carried out using a Bruker Daltonics® Omnimicro® MALDI-TOF instrument, operated using the FlexControl™ version 1.1 software. The data was analyzed using XMass software. The instrument was operated in a reflectron mode (200 ns pulsed ion extraction; reflector voltage = 19.7 kV; lens voltage = 9 kV; detector gain = 20x) with positive ion detection (ion source voltage = 19.0 kV). The laser was operated at a 60-65% intensity at a sampling rate of 1 shot per 1.0 ns, and ~200-1000 shots were averaged to achieve the desired signal-to-noise ratio. The target had a “Scout 49” geometry. The samples were prepared as follows: first, the matrix solution was prepared by making a saturated solution of α-cyano-4-hydroxycinnamic acid (CHCA) in 1:1 water/acetonitrile with 1% trifluoroacetic acid (TFA). Polymer samples were dissolved at a concentration of 2.5-5 mg/mL in acetonitrile. To 40 µL of the matrix solution was added 4 µL the solution of the polymer sample. 0.5 µL of this solution was spotted in several locations on the MALDI target plate. The reconstituted solution of Calibration Mixture 2 from the Sequazyme™ Peptide Mass Standards Kit (Applied Biosystems, part # P2-314300) was diluted 1:24 (v/v %) with the matrix solution, and 0.5 µL of this solution was spotted over half of the sample spots for each sample on the MALDI target plate. These standards provided for internal mass spectrum calibration. In cases where ionization of the polymer sample was hindered by the presence of the standards, external standard calibration was employed.

Microscopy methods

Cryogenic transmission electron microscopy (cryo-TEM) was performed on holey carbon grids by plunge freezing in liquid ethane using a Gatan Cryo-Plunge3 instrument, a Gatan Liquid Nitrogen Single Tilt Holder, and a JEOL 2100 FEG microscope. The samples were prepared similarly to the standard preparation of polyMOCs (*vide infra*), except at a low concentration ([PL1] = 4.6 mM) to afford soluble hyperbranched network fragments. Thus, PL1 (6.3 mg, 2.3 µmol) in a 2-mL scintillation vial was dissolved in 350 µL DMSO-d6, and to it was added a solution of Pd(NO3)2·2H2O (0.67 mg, 2.5 µmol) in 150 µL DMSO-d6 via micropipette; the reaction mixture was heated at 70 °C for 1 d. 200 µL of the resulting solution was then dialyzed against Milli-Q® water (700 mL, 1 d) in a 8 kDa MWCO dialysis tubing (*vide supra*), affording 760 µL of aqueous solution, which was used directly (undiluted) for microscopy.

Molecular dynamics simulation methods

The simulated model system consisted of fully atomistic ligands and metal ions whose interactions were mediated by an implicit solvent. The effect of the implicit solvent is to (1)
screen electrostatic interactions via a generalized reaction field method [Tironi, I.; Sperb, R.; Smith, P.; van Gunsteren, W. A Generalized Reaction Field Method for Molecular Dynamics Simulations. J. Chem. Phys. 1995, 102, 5451], and (2) to exert random impulsive forces on the atoms via Langevin dynamics [Yun-yu, S.; Lu, W.; Van Gunsteren, W. On the Approximation of Solvent Effects on the Conformation and Dynamics of Cyclosporin A by Stochastic Dynamics Simulation Techniques. Mol. Simul. 1988, 1, 369–383]. Following the simulation work presented by Yoneya and Fujita (Refs. 50 and 51 of the main text) we did not explicitly describe the presence of negative counter-ion species and utilized the cationic dummy atom (CaDA) model [Pang, Y. Novel Zinc Protein Molecular Dynamics Simulations: Steps Toward Antiangiogenesis for Cancer Treatment. J. Mol. Model. 1999, 5, 196–202] to describe Pd$^{2+}$ and the metal-ligand coordination. In the CaDA model metal ligand binding is described empirically through Coulombic interactions between partial charges on the ligand molecules and those on a model Pd$^{2+}$ complex consisting of a neutral Pd core bonded to four dummy atoms, each with a partial charge of $+0.5$ and arranged in a square planar geometry.

Simulations were carried out using GROMACS (version 5.02) [Berendsen, H.J.C., van der Spoel, D. and van Drunen, R., GROMACS: A message-passing parallel molecular dynamics implementation, Comp. Phys. Comm. 91 (1995), 43-56]. For the L1-type ligands the inter- and intra-molecular interactions, along with the Ligand-Pd$^{2+}$ Van der Waals interactions were described using a standard model force field. The details of the force field, along the associated GROMACS topology files, were adapted directly from simulations of Yoneya and Fujita, which can be found in the Methods sections of Ref. 51 of the main text. Therefore, our model of the para-substituted bis-pyridine (L1) monomers differ from that described in reference 51 only in that our model includes both the repulsive and attractive contribution to the short-range Lennard-Jones potential (in reference 51 they use a modified GROMACS package that includes the repulsive-only WCA short range potential). The additional presence of Lennard-Jones attractions in our simulations results in a decrease in overall computational efficiency, but is otherwise expected to have a negligible effect on the results. To model the L2-type ligand (the meta-substituted bis-pyridine) we modify the L1 model by exchanging the position of adjacent nitrogen and carbon atoms while retaining the force field parameters and partial charges of the original para-substituted ligand (see Supplementary Figure S27). Reorganizing atoms in this manner allows us to isolate the influence of the Pd-N bite angle on the metal-ligand complexes.

In the gel-forming system each ligand is bound to a partner ligand via long and flexible polymer chains. An explicit model of such a system dramatically increases the number of atoms being simulated and also introduces a long timescale relaxation process associated with chain entanglement. Here we have utilized an efficient compromise in which the effect of the flexible polymer linker is described implicitly, in the form of a ligand-ligand pair potential. The pair potential is meant to mimic the effect of the polymer linker on the relative positions of connected pairs of ligands. The effect is primarily entropic and is, as we have treated it, directly related to the statistics that govern the end-to-end distance of the isolated polymer.

We modeled the effect of flexible polymer linker through the addition of a pair potential, $w(r)$, acting between the bridging carbon atoms of pairs of ligand molecules (those with partial charge of $-0.162$ in Fig. S27). In particular we took $w(r)$ to be equal to the potential of mean force governing the end-to-end distance of a model polymer linker. This pair potential was generated based on simulations of an idealized version of the PEG linker. Given that the persistence length of PEG, $l = 3.8\text{Å}$, is approximately equal to the monomer size we modeled
configurations of the 2.2kDa linker as a three-dimensional self-avoiding random walk with steps of length \( l \) randomly distributed around a unit sphere. By sampling the statistics of this idealized model polymer we determined the end-to-end PMF and tabulated it for use as a user-input pair potential in GROMACS. Supplementary Figure S28 contains a plot of the potential of mean force used to model the 2.2kDa linker.

The potential used to describe the flexible ligand-ligand polymer linker imparts forces that are much smaller than those involved in ligand-metal coordination. The distribution of cluster sizes is therefore quite insensitive to the details of \( w(r) \). However, because this potential imposes spatial correlations on specific pairs of ligands, the network-forming properties system can be sensitive to the specific details of \( w(r) \). The sensitivity is most pronounced in the statistics of inter-MOC connectivity where the probability for loop formation can be controlled by varying the shape of \( w(r) \). For instance, \( w(r) \) can be chosen to mimic a very short linker (keeping ligand pairs very close) so that loop formation is enhanced or to mimic a long linker (leveraging the entropic driving force that prevents configurations with very small end-to-end distances) so that loop formation is reduced. Our procedure is approximate but gives rise to ligand-ligand correlations that are in reasonable agreement with our physical expectations.

Simulations consisted of 96 metal ions and 192 ligands (or 96 macromers), enough to form four fully assembled M\(_{12}\)L\(_{24}\) type clusters, in a cubic, periodically replicated simulation cell with side length 18.7nm. Initial configurations were generated by randomly distributing ligands and metal ions subject to the constraint that the initial separation between any two species be greater than 1.5nm. For the polyMOC formation, \( \text{PL1} \) and \( \text{PL2} \) were placed randomly but at an initial fixed distance of 2.6 nm for the 2.2kDa PEG chain. Simulations were carried out in the NVT ensemble with a 2 fs time step. For each ligand model (4 in total, i.e., \( \text{L-para} \), \( \text{L-meta} \), and \( \text{PL1} \) and \( \text{PL2} \)) we generated 20 individual trajectories. Each trajectory consisted of an initial 1 ns equilibration run at a temperature of 500K, followed by a 1 \( \mu \)s production run at a temperature of 350 K. The details of the implicit solvent and the thermostat were identical to those described in Ref. 52.

The results presented in Supplementary Figure S26A of the main text indicate that the \( \text{L-para} \) ligands tend to form large and sometimes system-spanning clusters. To explore the effect of concentration on the formation of very large ligand-metal clusters we carried out a set of simulations in which 192 \( \text{L-para} \) ligands and 96 metal ions were placed in a larger periodically replicated cubic cell, one with side length 30 nm. In Supplementary Figure S26B we present the distribution of cluster sizes, \( P(y) \), that emerged from this ‘low concentration’ simulation compared to that of the high concentration simulation (the latter is an excerpt of the data plotted in Supplementary Figure S26A). To facilitate a side-by-side comparison, each curve has been normalized over the same increment, specifically \( 0 \leq y \leq 50 \). At low concentration we observe a significantly reduced probability for observing clusters with \( y > 50 \), and in fact the distribution of cluster sizes for \( y \leq 50 \) are quite similar for the low and high concentration simulations. This indicates that the presence of large clusters is either the result of exceeding a percolation threshold in ligand concentration or a preferential stabilization of such clusters due to self-interaction through the periodic boundaries of the system.

**Crystallography methods**

Low-temperature (100 K) diffraction data (\( \varphi \)- and \( \omega \)-scans) were collected on a Bruker X8 Kappa Duo four-circle diffractometer coupled to a Smart Apex2 CCD detector, with Mo \( K_\alpha \)
radiation ($\lambda = 0.71073$ Å) from an $\mu$S micro-source. The diffractometer was purchased with the help of funding from the National Science Foundation (NSF) under Grant Number CHE-0946721. The structure was solved by direct methods using SHELXS\textsuperscript{54} and refined against $F^2$ on all data by full-matrix least squares with SHELXL-97\textsuperscript{55} following established refinement strategies\textsuperscript{56}.

The final cif file was checked using the IUCr checkCIF routine, and below, we list the Alerts of level A and B as they appear in the output checkCIF file and the justification for each.

**Alert level A**

**SHFSU01_ALERT_2_A** The absolute value of parameter shift to su ratio > 0.20 Absolute value of the parameter shift to su ratio given 6.596 Additional refinement cycles may be required.

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**PLAT080_ALERT_2_A** Maximum Shift/Error ......................... 6.60 Why ?

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**Alert level B**

**PLAT201_ALERT_2_B** Isotropic non-H Atoms in Main Residue(s) ....... 1 Report

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**PLAT430_ALERT_2_B** Short Inter D...A Contact O10N .. O2A .. 2.74 Ang.

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**PLAT601_ALERT_2_B** Structure Contains Solvent Accessible VOIDS of . 192 Ang3

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**PLAT934_ALERT_3_B** Number of (Iobs-Icalc)/SigmaW > 10 Outliers .... 3 check

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded from this structure.

**PLAT975_ALERT_2_B** Check Calcd Residual Density 0.62A From O4S  1.54 eA-3

**Author Response:** Structure refinement is not complete. Data are of low quality and so is the structure. Paddlewheel connectivity is confirmed but not much else can be concluded
from this structure.

Small-angle neutron scattering (SANS) methods

Small-angle neutron scattering (SANS) measurements were performed at the National Institute of Standards and Technology (NIST) Center for Neutron Research (NCNR) (Gaithersburg, MD, USA). The scattered neutron intensity was measured as a function of scattering variable \( q \), where \( q = (4\pi/\lambda) \sin(\theta/2) \) and \( \theta \) is the scattering angle. The beam was monochromated to a wavelength, \( \lambda \), of 6 Å. Three sample-to-detector distances of 1 m, 4 m, and 13 m were used to cover a total \( q \) range of 0.004 to 0.5 Å\(^{-1}\). 400 µL of each sample (gels prepared at 3.54 wt. % of polymer network) was loaded into titanium sample cells with a 1 mm path length. Experiments were performed on the NGB 30 m SANS instrument. Collected data were reduced and analyzed using the SANS macros package provided by the NCNR\(^{S7}\). The resulting data were placed on an absolute scale and corrected for background electronic noise, detector inhomogeneity, and empty cell scattering using standard techniques.

Scattering data for both samples were fit using a sum of two models, the power law model and the core chain model. The power law model is primarily used to show the presence of a larger entangled network, and describes the scattering intensity as \( I(q) = Aq^{-n} \). The core-chain model, due to Hore et al.\(^{S8}\), is a slightly modified version of the reported model.\(^{S9}\) The original Hore core-shell-chain model in ref. 2 was used to describe an inorganic iron oxide core with a shell layer of dense polymer brush, surrounded by grafted polymer chains with excluded volume. Here, the shell layer element is omitted but the model remains intact otherwise. In addition, the core in the present system is not inorganic entirely, but a mixed composition of Pd and bis-pyridine ligand. Most importantly, the model does not assume that the chains are Gaussian, and allows the excluded volume of the chains to vary. For this reason, Debye functions are omitted in favor of a more detailed description of polymer chain scattering.

The scattering intensity is calculated from the sum of the spherical core form factor, core-chain form factor correlations, chain-chain correlations, and the form factor of a polymer chain with excluded volume. The form factor amplitude of the spherical core is given by \( F_A(q) \),

\[
F_A(q) = \left( \frac{\rho_{\text{core}} - \rho_{\text{solvent}}}{\rho_{\text{core}}} \right) \frac{3j_1(qr_{\text{core}})}{qr_{\text{core}}} \]  (0.1)

where \( j_1 \) is a spherical Bessel function of order 1, \( r_{\text{core}} \) is the radius of the paddlewheel or cage, \( V_{\text{core}} \) is the volume of the paddlewheel or cage, \( \rho_{\text{core}} \) is the scattering length density (SLD) of the paddlewheel or cage, and \( \rho_{\text{solvent}} \) is the SLD of the solvent.

Scattering from polymer chains is described by the form factor amplitude and form factor of the polymer chains, \( F_B(q) \) and \( P_B(q) \), respectively. Note that because polymer chains are fractal in nature, the form factor is a separate function from the form factor amplitude. The functions are given by,

\[
F_B(q) = \frac{1}{2vU^{1/2v}} \gamma \left( \frac{1}{2v}, U \right) \]  (0.2)

\[
P_B(q) = \frac{1}{vU^{1/2v}} \gamma \left( \frac{1}{2v}, U \right) - \frac{1}{vU^{1/2v}} \gamma \left( \frac{1}{v}, U \right) \]  (0.3)

where the lower incomplete gamma function reads
The parameter $U = q^2 a^2 N^2 \nu / 6$ contains the scattering variable $q$, the statistical segment length of the polymer chain ($a$), the degree of polymerization of the chain ($N$), and the excluded volume parameter $\nu$.

The total macroscopic scattering cross section for $N_p/V$ density of nanoparticles with $N_g$ grafted polymer chains per particle, including the power law term, is then expressed as

$$\frac{d\Sigma(q)}{d\Omega} = N_p \left[ \frac{F_A(q)^2}{q^2} \left( \frac{\rho_{\text{chain}} - \rho_{\text{solvent}}}{\rho_{\text{chain}}} \right)^2 + \frac{1}{q^2} \left( \frac{\rho_{\text{chain}} - \rho_{\text{solvent}}}{\rho_{\text{chain}}} \right)^2 \right] + B$$

where $E_A = j_0(q r_{\text{core}})$ is a spherical Bessel function, and $B$ is the constant incoherent background.

The radius of gyration for the chains surrounding the paddlewheel or cage is calculated from the parameters of Eq. (1.5) as

$$R_g^2 = \frac{N^2 \nu a^2}{(2\nu+1)(2\nu+2)}$$

The SLDs for the core of each sample were calculated using an average of the PEG and palladium SLD on the basis of the composition of the two components. Using the NCNR SLD calculator, the bis-pyridine SLD was $1.98 \times 10^{-6}$ Å$^2$, the Pd SLD was $4.02 \times 10^{-6}$ Å$^2$, and DMSO-d6 had an SLD of $5.28 \times 10^{-6}$ Å$^2$. The composition of the components, calculated on the basis of the density and mass for paddlewheel and cage gels (gel-2 and gel-1, respectively), was 70% ligand and 30% Pd yielding an initial SLD of $2.59 \times 10^{-6}$ Å$^2$. The initial SLD does not take into account the possible presence of PEG or DMSO within the core, and so is only an initial approximation. The calculated radii, resulting from the core-chain model fits, for the paddlewheel and cage structures were $0.55 \pm 0.054$ nm and $1.70 \pm 0.25$ nm, respectively. The calculated number of ligands, also from the core-chain model fits, for the paddlewheel and cage structures, $N_g$, were approximately 4 and 20, respectively. The excluded volume parameter ($\nu$), calculated from the core-chain model fit, for the paddlewheel gel and cage gel, was $0.574$ and $0.595$, respectively. A value of $\nu$ that is close to $0.6$ is indicative of a swollen polymer chain (i.e., $R_g \sim N^{0.6}$). The radius of gyration ($R_g$) calculated using Eq (1.6) with parameters obtained from the core-chain model fits were $0.49$ nm and $0.45$ nm, respectively, for paddlewheel and cage gel.

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Rheometry methods...
Frequency sweep and strain sweep experiments were performed on an Anton Paar MCR 301 rheometer. The rheometer was outfitted with a Peltier heating system with an environmental enclosure for temperature control. A disposable parallel-plate geometry (radius = 12 mm) was used and coupled with a disposable bottom plate, with the typical gap of 1.00 mm between the two plates. Frequency sweep experiments were performed from 0.1 to 100 rad/s at 1% strain, which was first confirmed to be in the linear viscoelastic regime using strain sweep experiments. Gel samples were prepared either on the plate in-situ or in 1-dram vials (vide infra) and subsequently transferred onto the rheometer. Experiments were performed at 25 °C and the evaporation of solvent (DMSO-d6) was negligible within the typical measurement time (< 1 hour).

Fluorimetry methods

Fluorimetry was carried out using Fluorolog®-3 spectrofluorometer from Jobin Yvon Horiba using the DataMax for Windows™ driving software. The following parameters were used during the fluorimetry: (1) integration time = 0.25 s; (2) increment = 1 nm; (3) excitation wavelength: 340 nm; (4) Detector HV S = 950 V and R = 0 V; bandpass slits: excitation1 = 3.000 nm; emission1 = 5.000 nm. The data was analyzed using OMNIC™ software and plotted in OriginPro 8.5. The samples for fluorimetry were prepared by depositing a fragment of the gel into a cylindrical hole (2 mm diameter x 0.9 mm depth) within a sample holder, sandwiching the sample holder with the gel between two square glass cover slips to stabilize the gel and prevent solvent evaporation, and using the front-face geometry to collect the fluorescence.

Gel swelling methods

Two sets of gels (3 gels per set) were prepared in tared 1-dram vials – one set from macromer PL1 and the other set from macromer PL2 – following the general polyMOC synthesis method (vide infra), except at 0.500 x the scale: i.e., 10.13 mg of macromer was used to prepare gels with [macromer] = 24 mM (Supplementary Figure S31). To each gel was added 3.8 mL DMSO, and the gels were allowed to stand at RT for 5 d, at which time the excess DMSO was removed via syringe, and any residual DMSO was wicked away by gently dabbing the gels in the vials with Kimwipes®. Vial inversion tests confirmed the materials remained in the gel state (see Supplementary Figure S31). The gels in the vials were weighed, and the swelling ratio for each was determined by dividing the mass of the swollen gel by the dry mass of the network (dry mass of the network = mass of macromer + mass of Pd(NO3)2 – 2H2O = 10.13 mg + 1.00 mg = 11.13 mg) (Supplementary Table S3). Averages and standard deviations were computed for the three trials.

Computations of network branch functionality f from G’ via phantom network theory of rubber elasticityS10, S11

A measurement of $G' \sim |G|$ (i.e., $G' \gg G''$) allows us in principle to compute $f$ in our polyMOCs and thereby validate the conclusions derived from the simulations. The phantom network theory was deemed most appropriate for the analysis of our polyMOCs, because it explicitly relates $|G|$ and $f$.S11
\[ |G| = \frac{\rho RT}{M_{\text{chain}}} \left( f - \frac{2}{2} \right), \]

where \( \rho \) is the mass density of the elastically active polymer chains, \( R \) is the universal gas constant \((8.31446 \times 10^6 \text{ cm}^3 \text{ Pa} \cdot \text{K}^{-1} \cdot \text{mol}^{-1})\), \( T \) is the temperature (in this case 298.15 K), \( M_{\text{chain}} \) is the number-average molecular weight \( (M_n) \) of the polymer chain separating the junctions (taken here to be equal to \( M_n \) of the macromers = 2700 g/mol).\(^{S11}\) Crucially, \( \rho \) is not known \textit{a priori} because an unknown fraction of the polymer chains may form primary loop defects (and therefore not contribute to \( \rho \) (dangling chain ends were not observed by NMR and can therefore be ignored).  A key realization is that to a first-order approximation (i.e., accounting only for primary loops) \( \rho \) scales linearly with the true \( f \) of the network – in other words a deviation of \( f \) from \( f_{\text{ideal}} \) by \( x \% \) is expected to yield the same \( x \% \) deviation of \( \rho \) from \( \rho_{\text{ideal}} \). Thus, we have

\[ \rho = \frac{f}{f_{\text{ideal}}} \rho_{\text{ideal}}, \]

and substitution of the expression for \( \rho \) into the expression for \( |G| \) yields

\[ |G| = \frac{\rho_{\text{ideal}} \cdot RT}{f_{\text{ideal}} \cdot M_{\text{chain}}} (f - 2). \]

In the case of polyMOCs derived from \textbf{PL1} or \textbf{PL2}, where no macromer is replaced with free ligand \textbf{L1} or \textbf{L2}, \( f_{\text{ideal}} \) is taken to be 24 or 4, respectively, values expected for \( M_{12L24} \) or \( M_{2L4} \) cages, and consistent with \( \bar{\gamma} \) at 1 \( \mu \text{s} \) computed above for the corresponding networks \((21 \pm 6 \text{ and } 5.3 \pm 0.7, \textit{vide supra})\). When a fraction \( r \) of macromer \textbf{PL1} or \textbf{PL2} is replaced with \textbf{L1} or \textbf{L2}, respectively, new \( f_{\text{ideal}} \) becomes equal to \((1 - r) \cdot (f_{\text{ideal}} \text{ when } r = 0) \) because the free ligands do not contribute to the branch functionality: i.e., \( f_{\text{ideal}} = (1 - r) \cdot 24 \) for \textbf{gel-1}, and \( f_{\text{ideal}} = (1 - r) \cdot 4 \) for \textbf{gel-2}.

\( G' \) and \( G'' \) at \( \omega = 10 \text{ rad/s} \) were measured for all polyMOCs with varying fractions \( r \) of macromer replaced with \textbf{L1} or \textbf{L2} (Supplementary Table S4). Thus, when \( G' \gg G'' \), as is the case for all of our polyMOCs at \( \omega = 10 \text{ rad/s} \), \( G' \) can be used in place of \( |G| \). Note: for the comparison of \( f \) for \textbf{gel-1} and \textbf{gel-2} before and after annealing, \( G' \) at \( \omega = 100 \text{ rad/s} \) was utilized. A sample calculation is provided below for a \textbf{gel-1} gel where \( r = 0.125 \). The volume of the gel is the added volume of DMSO-\(d^6 \) and the polymer network (the latter was estimated to be the same as that of PEG with \( M_n = 2000 \), which was measured to be 0.8273 mL/g).

\[
G'@10 \frac{\text{rad}}{s} = 4762.1 \text{ Pa} = \frac{(\text{mass of polymer})}{(\text{volume of gel})} \cdot 8.31446 \times 10^6 \text{ mL} \cdot \text{Pa} \cdot \text{K}^{-1} \cdot \text{mol}^{-1} \cdot 298.15 \text{ K} \]

\[
= \frac{(1 - 0.125) \cdot 24 \cdot 2700 \frac{\text{g}}{\text{mol}}}{0.01772 \text{ g} \cdot 0.8273 \text{ mL/g} + 0.300 \text{ mL}} \cdot 43720.6 \text{ mL} \cdot \text{Pa} \cdot \text{g}^{-1} \cdot (f - 2) \]
\[
= 2462.1 \text{ Pa} \cdot (f - 2) \]

\[ \therefore f = 2 + \frac{4762.1 \text{ Pa}}{2462.1 \text{ Pa}} = 3.93 \]
Modified Syntheses of Previously Reported Compounds

**(3,5-di(pyridin-4-yl)phenyl)methanol L1.** 

To a 20-mL microwave vial equipped with a magnetic stir-bar were added 3,5-dibromobenzyl alcohol (0.442 g, 1.66 mmol), pyridine-4-boronic acid pinacol ester (0.750 g, 3.66 mmol), potassium carbonate (2.297 g, 16.6 mmol), and tetrakis(triphenylphosphine)palladium (0.192 g, 0.166), and the vessel was crimped shut, evacuated and refilled with nitrogen three times. To the vessel via syringe were added anhydrous N,N-dimethylformamide (DMF, 13.5 mL) and then de-ionized water (0.280 mL, 15.5 mmol) which had first been sparged with argon for 30 min. The vessel was briefly evacuated until bubbling was observed, and then refilled with nitrogen, and briefly sparged with argon (10-15 sec). The vessel was heated in the oil bath for 60 h at 100 °C, with precipitated palladium black observed after 24 h. At the conclusion of the reaction, the vessel was brought to RT, and the contents of the vessel were filtered in vacuo over tightly-packed Celite® 545 on a medium-porosity glass frit, rinsing the flask and Celite with chloroform (3 x 50 mL). The filtrate was subjected to washes with water (5 x 150 mL), followed by drying over Na2SO4, filtration over a medium-porosity frit, and concentration via rotary evaporation. The crude material was subjected to chromatography on silica gel (CH2Cl2/MeOH step gradient: 9.8:2 → 9.5:0.5 → 9:1; L1 eluted during the second step, Rf = 0.087 in CH2Cl2/MeOH = 9.5:0.5). The fractions containing the desired product were combined, concentrated by rotary evaporation, and triturated with CH2Cl2 (3 x 1 mL) quickly to remove traces of a co-eluting, but more readily soluble in CH2Cl2 impurity. The CH2Cl2 rinsings were concentrated by rotary evaporation and triturated with tetrahydrofuran (THF, 4 x 1 mL) quickly. The two portions of triturated solids were combined and dried in vacuo affording L1 (0.2035 g, 46.7 % yield, ≥ 99% pure by LCMS) as a white to faint-yellow powdery solid. 1H NMR (400 MHz, DMSO-d6, 25 °C): δ 8.68 (dd, J = 4.5, 1.6 Hz, 4H), 8.06 (t, J = 1.7 Hz, 1H), 7.87-7.80 (m, 6H), 5.40 (t, J = 5.7 Hz, 1H), 4.68 (d, J = 5.4 Hz, 2H). 13C NMR (100 MHz, DMSO-d6, 25 °C): δ 150.26, 146.75, 144.72, 138.06, 125.58, 123.77, 121.49, 62.57. FT-ICR-DART HRMS: calcd. for C17H14N2O [M+H]+, most abundant m/z = 263.1179; found, 263.1160.

**Polyethylene glycol (PEG)-diacid** (Mn = 2.2 kDa) was synthesized following the general protocol disclosed in patent US 8,067,505 B2 for the synthesis of PEG diacid from PEG diol, except beginning with PEG-diol (Mn ~ 2.0 kDa) and using sodium tert-butoxide instead of potassium tert-butoxide (the former formed a dispersion in 1:1 tert-butanol/toluene and was transferred via syringe with a 16-gauge needle). Product was isolated as a powdery white solid in 89% (7 g scale) or 93% (3.5 g scale) yields. 1H NMR (400 MHz, DMSO-d6, 25 °C): δ 13.35–12.01 (b, 2H), 4.01 (s, 4H), 3.71–3.43 (m, 184H). MALDI-TOF: Mn = 2.27 kDa; calcd. for C98H194O52 [M+Na]+, most abundant m/z = 2227.2; found, 2227.2. Mn (1H NMR) = 2.16 kDa. Mn = 2.2 kDa was employed in the calculations for reactions involving this PEG-diacid.

Self-assembly of the Pd12(L1)24 cage and Pd2(L2)4 paddlewheel

**Pd12(L1)24 cage.** To a 2-mL vial with L1 (13.13 mg, 0.05006 mmol) dissolved in 366.7 µL of DMSO-d6 was added via micropipette a solution of Pd(NO3)2·2H2O (6.67 mg, 0.02503 mmol) in
133.3 µL of DMSO-\(\text{d}_6\). The head-space of the vial was briefly purged with argon, the vial was closed with a screw-cap, and the resultant mixture was immediately vortexed, giving rise to a light-yellow liquid with small gelatinous pieces dispersed in it. The mixture was heated at 70 °C for 8 h, during the course of which, it became a light yellow homogeneous solution. \(^1\)H NMR indicated quantitative conversion of the components to Pd\(_{12}(\text{L1})_{24}\) cage assemblies. \(^1\)H NMR (400 MHz, DMSO-\(\text{d}_6\), 25 °C): \(\delta\) 9.49 (bs, 96H), 8.38 (bm, 120H), 7.95 (bs, 48H), 5.40 (bs, 24H), 4.57 (bs, 48H). \(^1\)C NMR (100 MHz, DMSO-\(\text{d}_6\), 25 °C): \(\delta\) 151.27 (b), 149.46, 145.24, 135.01, 127.18 (b), 124.34 (b), 62.18.

Pd\(_2(\text{L2})_4\) paddlewheel. To a standard NMR tube with \text{L2} (13.13 mg, 0.05006 mmol) dissolved in 366.7 µL of DMSO-\(\text{d}_6\) was added via micropipette a solution of Pd(NO\(_3\))\(_2\)·2H\(_2\)O (6.67 mg, 0.02503 mmol) in 133.3 µL of DMSO-\(\text{d}_6\). The resultant mixture was agitated briefly to afford a light-yellow homogeneous solution; the head-space of the NMR tube was briefly purged with argon, and the NMR tube was sealed. The mixture in the NMR tube was heated at 70 °C for 8 h. \(^1\)H NMR indicated quantitative conversion of the components to Pd\(_2(\text{L2})_4\) paddlewheel assemblies. \(^1\)H NMR (400 MHz, DMSO-\(\text{d}_6\), 25 °C): \(\delta\) 10.22 (s, 8H), 9.45 (d, \(J = 5.6\) Hz, 8H), 9.06 (s, 4H), 8.49 (d, \(J = 7.1\) Hz, 8H), 7.91 (dd, \(J = 7.9, 5.9\) Hz, 8H), 7.79 (s, 8H), 5.13 (b*), 4.55 (s, 8H). \(^1\)C NMR (100 MHz, DMSO-\(\text{d}_6\), 25 °C): \(\delta\) 150.19, 149.23, 145.51, 138.51, 138.38, 134.98, 127.82, 126.02, 124.07, 62.38. FT-ICR-ESI HRMS: calcd. for C\(_{36}\)H\(_{36}\)Br\(_4\)N\(_4\) [M – 3(NO\(_3\))\(^-\)]\(^3+\), most abundant \(m/z = 441.4132\); found, 441.4141. *The resonance corresponding to the ROH proton is extremely broad and overlapping with nearby peaks, preventing accurate integration.

**Synthesis of L2, L3, telechelic PEG macromers PL1 and PL2, and free ligand-substituted polyMOC gels**

\((3,5\text{-di(pyridin-3-yl)phenyl})\text{methanol} \text{L2}.\) To a 100-mL round-bottom flask equipped with a magnetic stir-bar were added 3,5-dibromobenzyl alcohol (0.680 g, 2.56 mmol), pyridine-3-boronic acid pinacol ester (1.154 g, 5.63 mmol), potassium carbonate (3.536 g, 25.6 mmol), and tetrakis(triphenylphosphine)palladium (0.295 g, 0.255), and the vessel was sealed with a septum, evacuated and refilled with nitrogen three times. To the vessel via syringe were added anhydrous \(\text{N,N}\)-dimethylformamide (DMF, 20.7 mL) and then de-ionized water (0.430 mL, 23.9 mmol) which had first been sparged with argon for 30 min. The vessel was briefly evacuated until bubbling was observed, and then refilled with nitrogen, and briefly sparged with argon (10-15 sec). The vessel was heated in the oil bath for 60 h at 100 °C, with precipitated palladium black observed after 24 h. At the conclusion of the reaction, the vessel was brought to RT, and the contents of the vessel were filtered \textit{in vacuo} over tightly-packed Celite® 545 on a medium-porosity glass frit, rinsing the flask and Celite with MeOH (2 mL) and chloroform (3 x 70 mL). The filtrate was subjected to washes with water (4 x 100 mL and 1 x 500 mL), followed by drying over Na\(_2\)SO\(_4\), filtration, and concentration \textit{via} rotary evaporation. The remainder was subjected to chromatography on silica gel (CH\(_2\)Cl\(_2\)/MeOH step gradient: 10:0 \(\rightarrow\) 9.5:0.5 \(\rightarrow\) 9:1; L2 eluted during the second step, \(R_f = 0.10\) in CH\(_2\)Cl\(_2\)/MeOH = 9.5:0.5). The fractions containing the pure desired product were combined, concentrated by rotary evaporation, and dried \textit{in vacuo} affording L2 (0.3284 g, 48.9 % yield, \(\geq 98.5\%\) pure by LCMS) as a white to faint-yellow powdery solid. \(^1\)H NMR (400 MHz, DMSO-\(\text{d}_6\), 25 °C): \(\delta\) 9.01 (dd, \(J = 2.4, 0.8\) Hz, 2H), 8.60 (dd, \(J = 4.8, 1.6\) Hz, 2H), 8.20 (ddd, \(J = 8.0, 2.4, 1.6\) Hz, 2H), 7.93 (t, \(J = 1.7\) Hz, 1H), 7.72
**3,5-di(pyridin-4-yl)benzyl 4-(pyren-1-yl)butanoate L3.** To a 1-dram scintillation vial with a magnetic stir-bar were added L1 (0.0400 g, 0.153 mmol), 4-(1-pyrenyl)butyric acid (0.0440 g, 0.153 mmol), N-(3-dimethylaminopropyl)-N′-ethylcarbodiimide hydrochloride (EDC .HCl) (0.0380 g, 0.198 mmol), and 4-(dimethylamino)pyridine (DMAP) (0.0048g, 0.040 mmol). The vial was brought into the glove box, and to it was added dichloromethane (DCM, 0.5 mL), and the reaction mixture was sealed and allowed to stir for 24 h. The reaction mixture was then removed from the glove box and loaded directly onto silica gel packed inside a 2-mL Pasteur pipette for column chromatography, using ethyl acetate as the eluent (Rf of L3 = 0.10). The fractions containing L3 were combined, concentrated via rotary evaporation, and subjected to column chromatography using ethyl acetate as the eluent. Rotary evaporation of the combined fractions containing the pure product, followed by drying at 60 °C overnight on the Schlenk line afforded L3 (0.0687 g, 84.6 %) as a beige-yellow powdery solid. 

1H NMR (400 MHz, DCM-d2, 25 °C): δ 8.66 (dd, J = 4.6, 1.6 Hz, 4H), 8.29 (d, J = 9.3 Hz, 1H), 8.17 (dd, J = 7.6, 1.1, Hz, 1H), 8.14 (dd, J = 7.7, 1.0 Hz, 1H), 8.10 (d, J = 7.8 Hz, 1H), 8.05 (d, J = 9.3 Hz, 1H), 8.03 (s, 2H), 7.99 (t, J = 7.6 Hz, 1H), 7.88—7.83 (m, 2H), 7.72 (d, J = 1.7 Hz, 2H), 7.60 (bd, J = 6.0 Hz, 4H), 5.25 (s, 2H), 3.41 (t, J = 7.6 Hz, 2H), 2.56 (t, J = 7.3 Hz, 2H), 2.23 (tt, J = 7.6, 7.3 Hz, 2H). 

13C NMR (100 MHz, DCM-d2, 25 °C): δ 173.41 (ester carbon), 150.64, 147.80, 139.92, 138.79, 136.25, 131.79, 131.25, 130.35, 129.12, 127.82, 127.78, 127.69, 127.66, 127.07, 126.31, 125.90, 125.37, 125.33, 125.24, 125.19, 125.15, 123.69, 122.08, 65.95, 34.18, 33.01, 27.19. 

FT-ICR-DART HRMS: calcd. for C37H28N2O2 [M+H] + , most abundant m/z = 533.2224; found, 533.2216.

**PL1.** To a 20-mL microwave vial equipped with a magnetic stir-bar were added finely powdered L1 (0.300 g, 1.14 mmol), PEG-diacid (Mn = 2.2 kDa, 0.7741 g, 0.35 mmol), EDC.HCl (0.4336 g, 2.26 mmol), and DMAP (0.0870 g, 0.712), and the vessel was brought into the glove box. To the vessel was added DCM (3.84 mL), ensuring that the solid was washed down the walls of the vial, and the vial was crimped and set to stir at RT. During the first several minutes, most of the solid dissolved, giving rise to a yellow solution. After 25 h, the vessel was removed from the glove box and concentrated via rotary evaporation. The product was extracted from the oily mixture with toluene (3 x 2 mL), filtering the extracts through Celite® 545 packed in Pasteur pipettes. The combined extracts were concentrated by rotary evaporation, redissolved in 2 mL toluene, and precipitated into cold (~ -10 – -20 °C) diethyl ether (35 mL). The vial containing the solution of crude product was rinsed with an additional 0.5 mL toluene, and this rinsing was also subjected to precipitation. The precipitation was allowed to proceed overnight at -20 °C, and the precipitated product was collected by filtration in vacuo, rinsing with cold diethyl ether (2 x 40 mL, 1 x 100 mL). Quickly, while still cold, the white solid was transferred from the filter disk to a 20-mL scintillation vial and was dried in vacuo overnight. The dry solid (~950 mg) was redissolved in water (9.5 mL, 18.2 MΩcm at RT, from Milli-Q® system), filtered through a nylon syringe filter with 0.45 µm-pore size, and subjected to prep-HPLC purification. The combined pure fractions were diluted with sat. NaHCO3(aq.) until pH was ~7–8. The aqueous phase was divided into two portions and the product was extracted from each one with DCM (5 x
300 mL). The combined extracts were dried over anhydrous Na₂SO₄, concentrated by rotary evaporation, re-dissolved in 1 mL DCM, and precipitated into cold diethyl ether (35 mL). The vial containing the dissolved pure product was rinsed with an additional 0.5 mL DCM, and this rinsing was also subjected to precipitation. The precipitation was allowed to proceed overnight at -20 °C, and the precipitated product was collected by filtration in vacuo, rinsing with cold diethyl ether (2 x 40 mL, 1 x 100 mL). Quickly, while still cold, the white solid was transferred from the filter disk to a 20-mL scintillation vial and was dried in vacuo overnight, affording PL₁ (0.3752 g, 40 % yield) as a soft white solid. ¹H NMR (400 MHz, CD₂Cl₂, 25 °C): δ 8.69 (bdd, J = 4.3, 1.4 Hz, 8H), 7.88 (t, J = 1.7 Hz, 2H), 7.73 (d, J = 1.7 Hz, 4H), 7.59 (dd, J = 4.5, 1.7 Hz, 8H), 5.33 (s, 4H), 4.22 (s, 4H), 3.80—3.37 (m, 204H). ¹³C NMR (100 MHz, CD₂Cl₂, 25 °C): δ 170.55, 150.77, 147.64, 140.04, 138.23, 127.83, 126.09, 122.07, 71.33, 70.90 (b), 70.86, 68.98, 66.19. MALDI-TOF: Mₙ = 2.7 kDa; calcd. for C₁₃₂H₂₁₈N₄O₅₂ [M+H]⁺, most abundant m/z = 2693.5; found, 2693.6. GPC (THF, 25 °C): Mₙ = 2.83 kDa, Mₚ = 2.73 kDa (obtained via conversion from values determined via calibration with polystyrene standards); Đ = 1.03. Mₙ (¹H NMR) = 2.87 kDa. Mₙ = 2.7 kDa was employed in the calculations for reactions involving PL₁.

PL₂. PL₂ was prepared identically to PL₁, except using L₂ instead of L₁. PL₂ was isolated as a soft white solid (0.4208 g, 45 % yield). ¹H NMR (400 MHz, CD₂Cl₂, 25 °C): δ 8.90 (dd, J = 2.3, 0.5 Hz, 4H), 8.62 (dd, J = 4.8, 1.6 Hz, 4H), 7.97 (dd, J = 7.9, 2.4, 1.7 Hz, 4H), 7.79 (t, J = 1.7 Hz, 2H), 7.65 (d, J = 1.7 Hz, 4H), 7.42 (dd, J = 7.9, 4.8, 0.8 Hz, 4H), 5.33 (s, 4H), 4.22 (s, 4H), 3.81—3.36 (m, 194H). ¹³C NMR (100 MHz, CD₂Cl₂, 25 °C): δ 170.56, 149.34, 148.64, 139.64, 139.08, 136.16, 134.83, 127.01, 126.32, 124.03, 71.32, 70.90 (b), 70.85, 68.98, 66.32. MALDI-TOF: Mₙ = 2.7 kDa; calcd. for C₁₃₂H₂₁₈N₄O₅₂ [M+H]⁺, most abundant m/z = 2693.5; found, 2693.8. GPC (THF, 25 °C): Mₙ = 2.81 kDa, Mₚ = 2.74 kDa (obtained via conversion from values determined via calibration with polystyrene standards); Đ = 1.03. Mₙ (¹H NMR) = 2.76 kDa. Mₙ = 2.7 kDa was employed in the calculations for reactions involving PL₂.

PolyMOC gels with macromer replaced with free ligand. General synthesis: The procedure is identical to that used for the synthesis of regular polyMOC gels, except during the preparation of the macromer solution, x% of the macromer was replaced with 2 equivalents of the corresponding free ligand to achieve the same total concentration of dipyridine ligands (e.g., when x% = 25%, instead of 20.25 mg of macromer PL₁, 15.18 mg of PL₁ (0.56 µmol) was combined with 0.98 mg of L₁ (0.38 µmol) in 210.0 µL DMSO-d₆).

Supplementary References
S1. Mori, S. Calibration of size exclusion chromatography columns for determination of polymer molecular weight distribution. Analytical Chemistry 53, 1813-1818 (1981).
S2. Fulmer, G. R. et al. NMR Chemical Shifts of Trace Impurities: Common Laboratory Solvents, Organics, and Gases in Deuterated Solvents Relevant to the Organometallic Chemist. Organometallics 29, 2176-2179 (2010).
S3. Kienberger, F. et al. Static and Dynamical Properties of Single Poly(Ethylene Glycol) Molecules Investigated by Force Spectroscopy. Single Molecules 1, 123-128 (2000).
S4. Sheldrick, G. Phase annealing in SHELX-90: direct methods for larger structures. Acta Crystallogr., Sect. A: Fundam. Crystallogr. 46, 467-473 (1990).
S5. Sheldrick, G. A short history of SHELX. *Acta Crystallogr., Sect. A: Fundam.* Crystallogr. 64, 112-122 (2008).

S6. Müller, P. Practical suggestions for better crystal structures. *Crystallogr. Rev.* 15, 57-83 (2009).

S7. Kline, S. R. *Journal of Applied Crystallography* 2006, 39, 895–900.

S8. Hore, M. J. A.; Ford, J.; Ohno, K.; Composto, R. J.; Hammouda, B. *Macromolecules* 2013, 46, 9341–9348.

S9. Hammouda, B. *Advances in Polymer Science* 1993, 106, 87-133.

S10. Guth, E. & James, H. M. Elastic and Thermoelastic Properties of Rubber like Materials. *Ind. Eng.Chem.* 33, 624-629, (1941).

S11. Rubinstein, M. & Colby, R. *Polymers Physics*. (Oxford, 2003).

S12. Tominaga, M. *et al.* Finite, spherical coordination networks that self-organize from 36 small components. *Angew. Chem., Int. Ed.* 43, 5621-5625 (2004).

S13. Harris, J. M., Kozlowski, A. & Guo, L. Method of preparing carboxylic acid functionalized polymers. US Patent 8,067,505 filed 9 Feb., and issued 29 Nov. 2011.

**Supplementary Figure S1**

\[ ^1H \text{NMR of L1 at 25}^\circ \text{C in DMSO-d6.} \ a,b,c \text{These resonances are due to water (a), methanol (b, ~3%) and residual DMSO-d5 (c).} \]
Supplementary Figure S2

$^{13}$C NMR of L1 at 25 °C in DMSO-$d_6$. α This resonance is due to DMSO-$d_6$. 

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Supplementary Figure S3

FT-ICR-ESI mass spectrum of L1. Peaks marked with slashes correspond to the background signals.
Supplementary Figure S4

$^1$H NMR of L2 at 25 °C in DMSO-$d^6$. $^a,b$ These resonances are due to water (a) and residual DMSO-$d^6$ (b).
Supplementary Figure S5

$^{13}$C NMR of L2 at 25 °C in DMSO-$d_6$. a This resonance is due to DMSO-$d_6$. 
Supplementary Figure S6

FT-ICR-ESI mass spectrum of L2. Peaks marked with slashes correspond to the background signals.
Supplementary Figure S7

$^1$H NMR of L3 at 25 °C in DCM-$d^2$. $^a,b$These resonances are due to H grease ($a$) and residual DCM-$d^2$ ($b$).
Supplementary Figure S8

$^{13}$C NMR of L3 at 25 °C in DCM-$d_2$. $^a$This resonance is due to DCM-$d_2$ ($a$).
Supplementary Figure S9

A portion of the FT-ICR-DART mass spectrum of L3 showing the isotope distribution of the parent ion of L3 [M+H]^+. 
Supplementary Figure S10

$^1$H NMR of Pd$_{12}$(L1)$_{24}$ cage assembly at 25 °C in DMSO-$d^6$. a, b, c These resonances are due to water (a), methanol (b, 2% per L1) and residual DMSO-$d^5$ (c).
Supplementary Figure S11

$^{13}$C NMR of Pd$_{12}$(L1)$_{24}$ cage assembly at 25 °C in DMSO-$d_6$. $^\text{a}$This resonance is due to DMSO-$d_6$. 

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Supplementary Figure S12

$^1$H NMR of Pd$_2$(L$_2$)$_4$ paddlewheel assembly at 25 °C in DMSO-$d_6$. a, b These resonances are due to water (a) and residual DMSO-$d_5$ (b).
Supplementary Figure S13

$^{13}$C NMR of Pd$_2$(L$_2$)$_4$ paddlewheel assembly at 25 °C in DMSO-$d_6$. aThis resonance is due to DMSO-$d_6$. 

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Supplementary Figure S14

High resolution ESI-TOF mass spectrum of the Pd₂(L₂)₄ paddlewheel assembly.
Supplementary Figure S15

$^1$H NMR of PEG-diacid ($M_n$=2.2 kDa) at 25 °C in DMSO-$d_6$. $^a,b$ These resonances are due to water ($a$) and residual DMSO-$d_5$ ($b$). Inset is the zoomed-in region corresponding to the carboxylic acid proton resonance.
Supplementary Figure S16

MALDI-TOF mass spectrum of PEG-diacid (Mₙ = 2.2 kDa).
Supplementary Figure S17

$^1$H NMR of PL1 at 25 °C in CD$_2$Cl$_2$. a This resonance is due to residual CHDCl$_2$ (see inset).
Supplementary Figure S18

$^{13}$C NMR of PL1 at 25 °C in CD$_2$Cl$_2$. *a* This resonance is due to CD$_2$Cl$_2$. 
Supplementary Figure S19

$^1$H NMR of PL2 at 25 °C in CD$_2$Cl$_2$. *a* This resonance is due to residual CHDCl$_2$ (see inset).
Supplementary Figure S20

$^{13}$C NMR of PL2 at 25 °C in CD$_2$Cl$_2$. *a* This resonance is due to CD$_2$Cl$_2$. 
Supplementary Figure S21

MALDI-TOF mass spectrum of PL2.
Supplementary Figure S22

GPC (THF, 25 °C, *vide supra*) analysis of PL1 and PL2.

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Supplementary Figure S23

Cryo-TEM micrograph of the solutions of hyperbranched polymer networks, which consist of cages (and clusters of cages) prepared from PL1 and Pd(NO₃)₂•2H₂O at a sufficiently low concentration ([PL1] = 4.6 mM) to avoid gelation, dialyzed against Milli-Q® water (vide supra). The spherical features with a diameter of ~30-40 nm correspond to these clusters of cages.
Supplementary Figure S24

VT $^1$H MAS NMR spectroscopy (500 MHz, DMSO-$d_6$, $\omega_r/2\pi = 10$ kHz) of the gel-1 ([PL1] = 24 mM) before, during, and after annealing.
Supplementary Figure S25

 VT $^1$H MAS NMR spectroscopy (500 MHz, DMSO-$d_6$, $\omega_{r/2}\pi = 10$ kHz) of gel-2 ([PL2] = 24 mM) before, during, and after annealing.
Supplementary Figure S26

A. Distribution of cluster sizes for systems with L-para and L-meta ligands are plotted with blue or red bars, respectively. The data representing polyMOC networks derived from PL1 and PL2 are plotted with points using the same colors. B. The probability distribution for observing a cluster of size $y$ in a low concentration simulation (system sidelength = 30 nm) is plotted with green boxes. For comparison, the similar distribution for high concentrations (system sidelength = 18.7 nm) is plotted in blue boxes, however scaled so that the normalization is equivalent on the increment of $0 \leq y \leq 50$. 

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Supplementary Figure S27

A rendering of the Pd$^{2+}$ complex, the para-substituted bis-pyridine ligand ($L$-para), and the meta-substituted bis-pyridine ligand ($L$-meta). The atoms are labeled with their respective partial charges, given in units of electronic charge.
**Supplementary Figure S28**

**A.** The ligand-ligand pair potential used for simulating macromers. **B.** The pair potential acts on the central carbon atoms of two specific ligands.
Supplementary Figure S29

Frequency sweeps in oscillatory rheology at 1.0 % strain amplitude for gel-1 ([PL1] = 24 mM) before (A) and after annealing for 4 h at 80 °C (B), and the same frequency sweep measurements for gel-2 ([PL2] = 24 mM) before (C) and after annealing for 4 h at 80 °C (D).
Supplementary Figure S30

Stress vs. strain plots before and after thermal annealing for gel-1 ([PL1] = 24 mM, A) and gel-2 ([PL2] = 24 mM, B). Green arrows indicate points used for the determination of the yield stresses and strains.
Supplementary Figure S31

A. Three samples of gel-1 ([PL1] = 24 mM) in 1-dram vials as prepared after annealing for 4 hours at 80 °C. B. Three samples of gel-2 ([PL2] = 24 mM) in 1-dram vials as prepared after annealing for 4 hours at 80 °C. C. PolyMOC gels shown in panel A after swelling with 3.8 mL DMSO during the course of 5 days and then removing the excess DMSO. D. Gels shown in panel B after swelling with 3.8 mL DMSO during the course of 5 days and then removing the excess DMSO. E. Inversion test on the swollen polyMOCs confirms that they are still gels.
Supplementary Figure S32

A. Gel-1 in DMSO-d\textsuperscript{6} ([PL1] = 24 mM) as prepared (left), after cutting into two pieces with a spatula blade (center left, cut region marked with a red box), and after annealing for 4 h at 80 °C (center right), respectively. These photographs were taken from the bottom of a 1-dram vial, which contained the gel. The unhealed cut is easily visualized by separating the two parts of the gel around the cut (highlighted by the red triangle in the photo on the right). B. Gel-2 in DMSO-d\textsuperscript{6} ([PL2] = 24 mM) as prepared (left), after cutting into two pieces with a spatula blade (center left, cut region marked with a red box), and after annealing for 4 h at 80 °C (center right), respectively. These photographs were taken from the bottom of a 1-dram vial, which contained the gel. The damage was visibly healed in the region highlighted by the green box; the photo on the right depicts the monolith nature of the healed gel. No solvent was added or pressure applied to facilitate healing.
Supplementary Figure S33

Fluorescence spectra of pristine gel-1 gel (5.9 wt. %, blue trace), and the same gels with 12.5% PL1 replaced with L3 before (black) and after (red trace) swelling with DMSO (~66-fold excess) for 2 d; the “after swelling” fluorescence spectrum (red) has been scaled by the ratio of gel mass before and after swelling (264.5 mg/126.7 mg), since approximately identical amounts of gels were used for the fluorescence measurements (vide supra).
Supplementary Figure S34

Frequency sweeps in oscillatory rheology at 1.0 % strain amplitude for four different samples of gel-1 ([PL1] = 24 mM) after annealing for 4 h at 80 °C (left), and the same frequency sweep measurements for four different samples gel-1 with 12.5 % PL1 replaced with L3 after annealing for 4 h at 80 °C (right). The $G'$ for gel-1 gels is 4.7 ± 0.8 kPa, and the $G'$ of the L3-modified gel-1 gels is 4.6 ± 0.7 kPa. Note that a new batch of PL1 was used for these measurements.
**Supplementary Table S1**

Rheometry characterization of the polyMOC gels via frequency sweeps

| Macromer used for gel | $G'(100 \text{ rad/s}), \text{ initial} / \text{ Pa}$ | $G''(100 \text{ rad/s}), \text{ initial} / \text{ Pa}$ | $G'(100 \text{ rad/s}), \text{ annealed} / \text{ Pa}$ | $G''(100 \text{ rad/s}), \text{ annealed} / \text{ Pa}$ |
|-----------------------|---------------------------------|---------------------------------|---------------------------------|---------------------------------|
| PL1                   | 10377                           | 1202.1                          | 4869.4                          | 664.34                          |
| PL1                   | 9677.4                          | 895.03                          | 5531                            | 768.5                           |
| PL1                   | 16011                           | 1332.7                          | 5090.1                          | 842.28                          |
| PL2                   | 3392                            | 440                             | 2160.6                          | 303.51                          |
| PL2                   | 2374.1                          | 450.28                          | 1805.5                          | 317.41                          |
| PL2                   | 3150.3                          | 486.15                          | 1703.6                          | 292.29                          |
## Supplementary Table S2

### Rheometry characterization of the polyMOC gels via strain sweeps

| Macromer used for gel | Yield stress, initial / Pa | Yield strain, initial / % | Yield stress, annealed / Pa | Yield strain, annealed / % |
|-----------------------|-----------------------------|----------------------------|-----------------------------|----------------------------|
| PL1                   | 1480                        | 14.7                       | 298                         | 7.07                       |
| PL1                   | 2670                        | 21.5                       | 351                         | 7.07                       |
| PL1                   |                             |                            | 142                         | 4.81                       |
| PL2                   | 2980                        | 106                        | 1970                        | 106                        |
| PL2                   | 2190                        | 72.2                       | 1860                        | 106                        |
| PL2                   | 2530                        | 72.2                       | 1690                        | 106                        |
**Supplementary Table S3**

Swelling ratio quantification for the polyMOC gels derived from **PL1** and **PL2**

| Macromer used to make the gel | Dry mass (g) | Mass of swollen gel (g) | Swelling ratio |
|-------------------------------|-------------|-------------------------|----------------|
| **PL1**                      | 0.01113     | 0.23241                 | 20.9           |
| **PL1**                      | 0.01113     | 0.27353                 | 24.6           |
| **PL1**                      | 0.01113     | 0.25938                 | 23.3           |
| **PL2**                      | 0.01113     | 1.71175                 | 154            |
| **PL2**                      | 0.01113     | 1.65467                 | 149            |
| **PL2**                      | 0.01113     | 1.85764                 | 167            |
### Supplementary Table S4

The effect of % macromer replaced on $G'$, $G''$ and $f$ of polyMOC gels (averages of 3-4 trials)

| % Macromer replaced | $G'(10 \text{ rad/s})$ of gel-1 / Pa | $G''(10 \text{ rad/s})$ of gel-1 / Pa | $G'(10 \text{ rad/s})$ of gel-2 / Pa | $G''(10 \text{ rad/s})$ of gel-2 / Pa | $f$ of gel-1 | $f$ of gel-2 |
|----------------------|-------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|--------------|--------------|
| 0                    | 5989.8                              | 554.1                               | 1780.1                              | 49.0                                | 4.45         | 2.12         |
| 6.25                 | 5487.0                              | 465.5                               | 4.24                                |                                      |              |              |
| 12.5                 | 5726.2                              | 374.4                               | 561.4                               | 23.1                                | 4.33         | 2.04         |
| 18.75                | 2974.5                              | 245.6                               |                                      |                                      | 3.20         |              |
| 25                   | 2952.8                              | 209.0                               | 111.8                               | 11.4                                | 3.19         | 2.01         |
| 33.333               | 1909.5                              | 151.6                               |                                      |                                      | 2.77         |              |
| 41.67                | 1355.8                              | 92.2                                |                                      |                                      | 2.54         |              |
| 50                   | 740.59                              | 68.4                                |                                      |                                      | 2.29         |              |