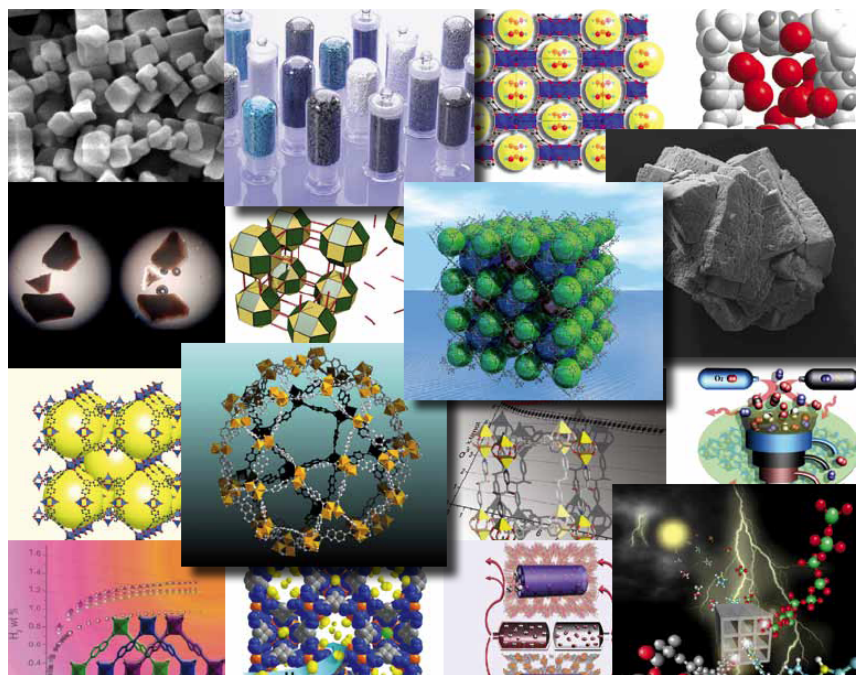


*Metal-Organic Frameworks:
Applications in Heterogeneous Catalysis*



Jack Terrett
MacMillan Group Meeting
June 19th, 2013

Porous Materials

■ Zeolites

- Aluminosilicate minerals (purely inorganic)
- Widely used in heterogeneous catalysis on an industrial scale
- Structurally stable at high temperature
- Applications in gas separation, petrochemical cracking, and water purification
- Accessible and highly organized pores/cavities (pore size typically below 1 nm)



Porous Materials

■ Zeolites

- Aluminosilicate minerals (purely inorganic)
- Widely used in heterogeneous catalysis on an industrial scale
- Structurally stable at high temperature
- Applications in gas separation, petrochemical cracking, and water purification
- Accessible and highly organized pores/cavities (pore size typically below 1 nm)



■ Mesoporous materials

- Silica and alumina based
- Large pore sizes (2–50 nm)
- Amorphous structure with disordered channels

Porous Materials

■ Zeolites

- Aluminosilicate minerals (purely inorganic)
- Widely used in heterogeneous catalysis on an industrial scale
- Structurally stable at high temperature
- Applications in gas separation, petrochemical cracking, and water purification
- Accessible and highly organized pores/cavities (pore size typically below 1 nm)



■ Mesoporous materials

- Silica and alumina based
- Large pore sizes (2–50 nm)
- Amorphous structure with disordered channels

■ Activated carbon

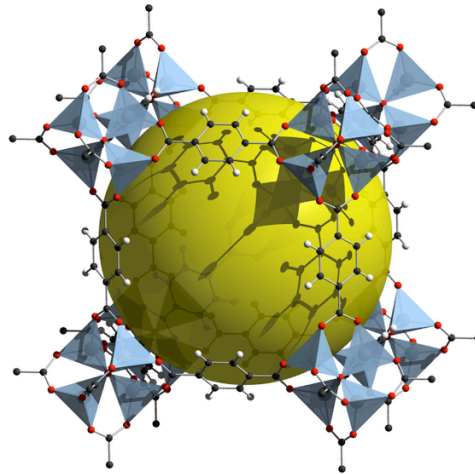
- High surface area and open porosity (variable channel sizes)
- Disordered: hexagonal carbon layers with various cross-linking
- Numerous applications in gas sorption and catalysis



Porous Materials

■ Metal Organic Frameworks (MOFs)

- Metal Organic Materials (MOMs), Porous Coordination Polymers (PCPs)
- Combines inorganic nodes (metal ions or clusters/SBUs) with organic linkers/struts
- Permanent microporosity (pore sizes typically range from 5 Å – 2 nm)
- Synthesized under mild conditions, low thermal stability (compared to zeolites)
- Facile modification of starting components
- Predictable structure and reactivity enable fine-tuning for desired application



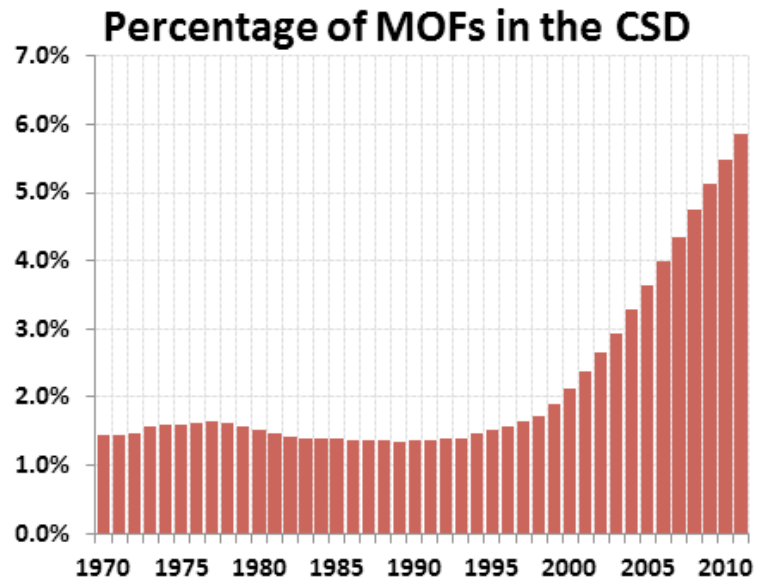
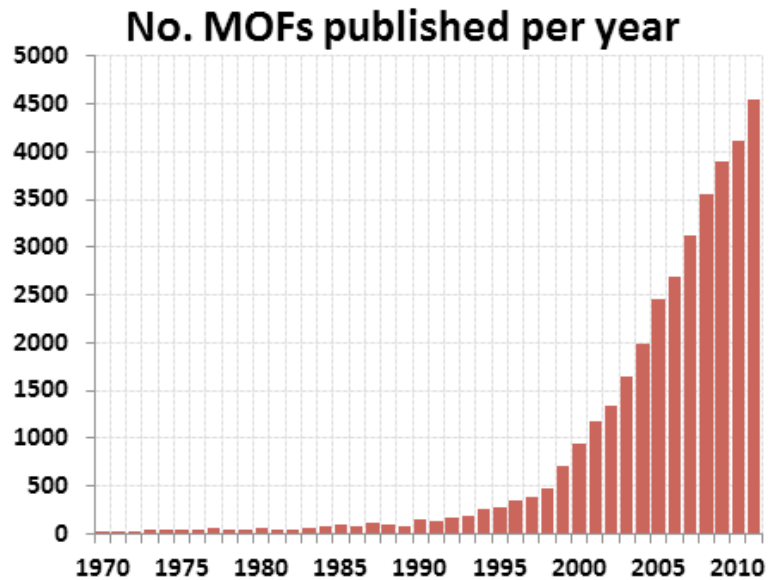
MOF-5

Metal-Organic Frameworks: Design and Application, Edited by L. R. MacGillivay, **2010**, John Wiley & Sons, Inc.

Metal-Organic Frameworks: Applications from Catalysis to Gas Storage, Edited by D. Farrusseng, **2011**, Wiley-VCH.

The Explosive Growth of Metal-Organic Frameworks

- The number of reported MOF structures has increased dramatically over the past 40 years



Cambridge Crystallographic Data Centre (CCDC) Blog, Pete Wood, 9th January 2013

Cambridge Structural Database (1970-2010)

The Explosive Growth of Metal-Organic Frameworks

- The number of reported MOF structures has increased dramatically over the past 40 years
- The field of MOF chemistry has already warranted several thematic journal issues:

Chemical Society Reviews **2009**, Vol. 38, Iss. 5

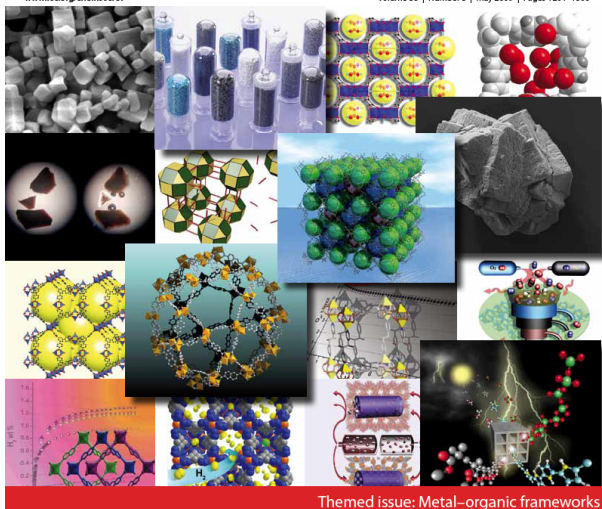
Chemical Reviews **2012**, Vol. 112, Iss. 2

Chem Soc Rev

Chemical Society Reviews

www.rsc.org/chemsorev

Volume 38 | Number 5 | May 2009 | Pages 1201–1508



ISSN 0306-012

RSC Publishing

Guest editors: Jeffrey Long and Omar Yaghi
CRITICAL REVIEW
Omar M. Yaghi et al.
Secondary building units, nets
and bonding in the chemistry of
metal-organic frameworks
TUTORIAL REVIEW
Takashi Uemura, Nobuhiko Yanai
and Susumu Kitagawa
Polymerization reactions in porous
coordination polymers

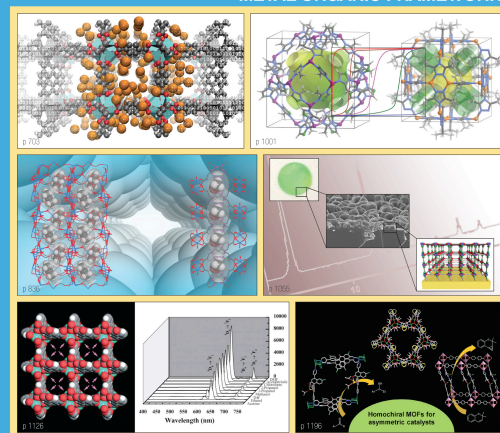


0306-0012(2009)38:5:1-4

CHEMICAL REVIEWS

FEBRUARY 2012 VOLUME 112 NUMBER 2 pubs.acs.org/CR

METAL-ORGANIC FRAMEWORKS



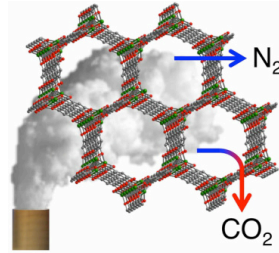
ACS Publications
MOST TRUSTED. MOST CITED. MOST READ.

www.acs.org

Applications of Metal-Organic Frameworks

Metal-Organic Frameworks

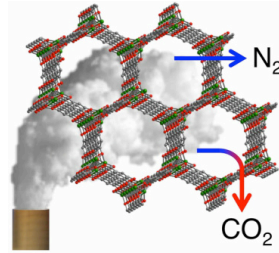
Applications of Metal-Organic Frameworks



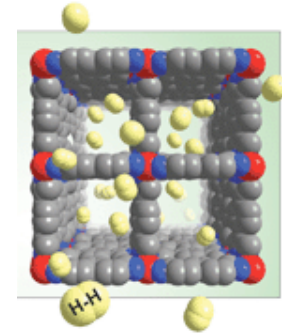
CO₂ Capture

Metal-Organic Frameworks

Applications of Metal-Organic Frameworks



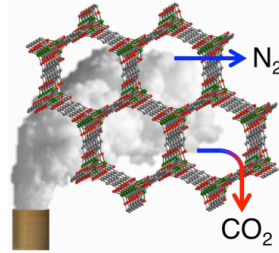
CO₂ Capture



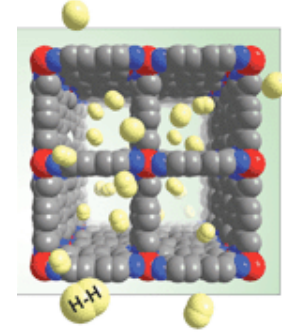
Gas Storage

Metal-Organic Frameworks

Applications of Metal-Organic Frameworks

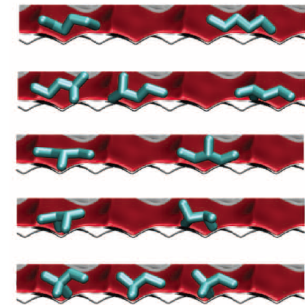


CO₂ Capture



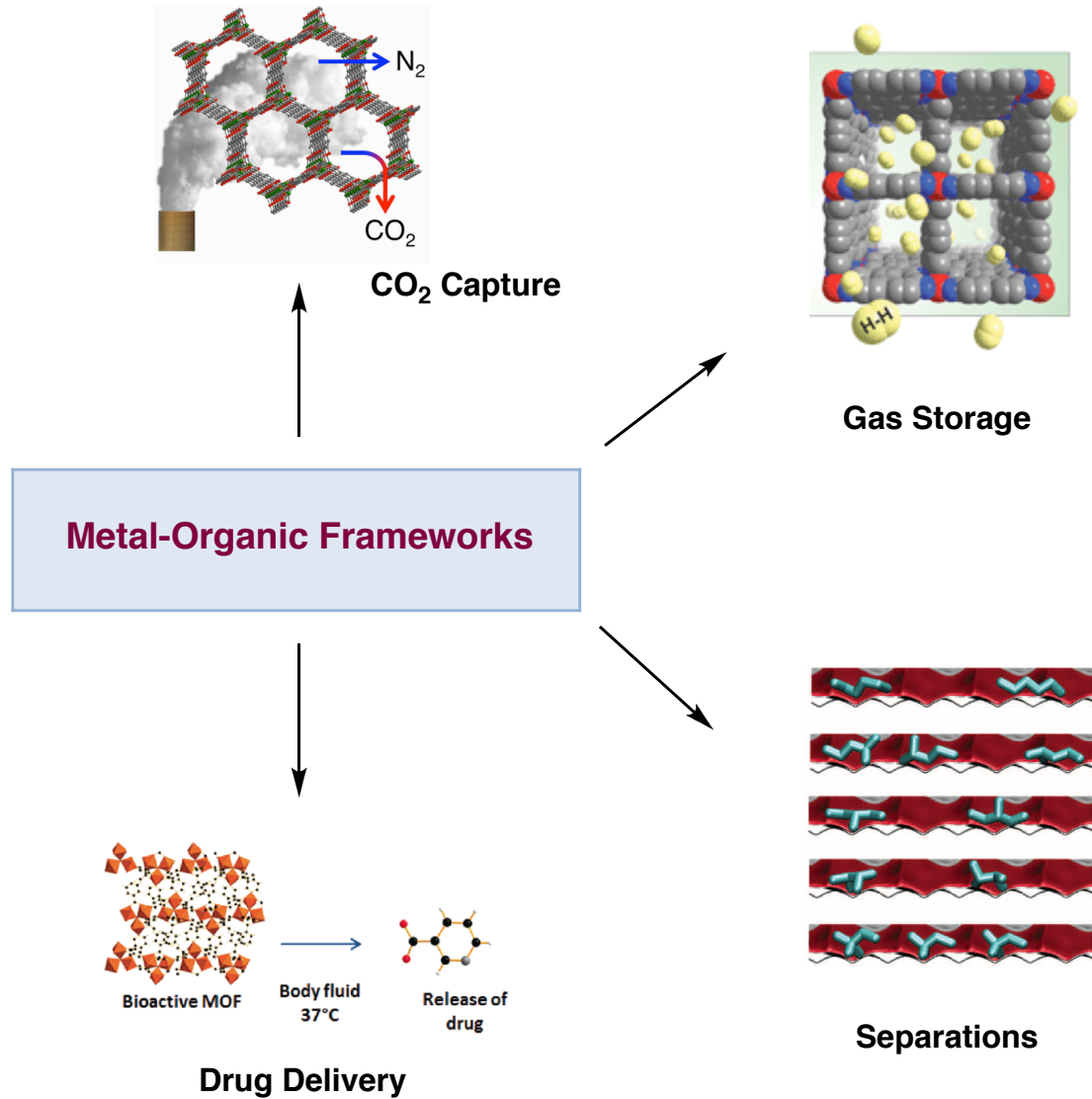
Gas Storage

Metal-Organic Frameworks

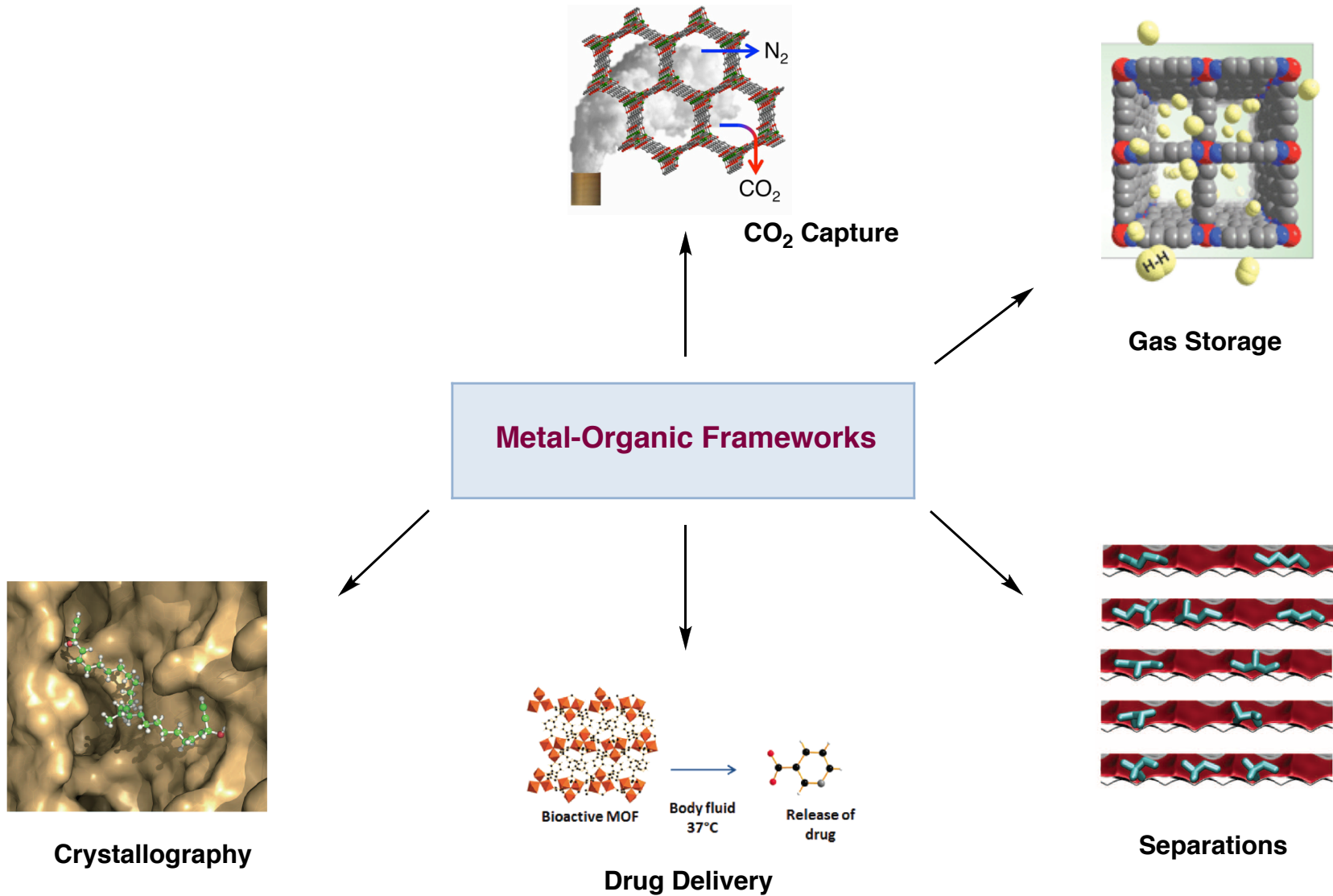


Separations

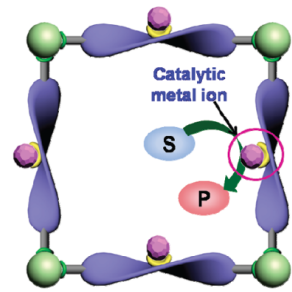
Applications of Metal-Organic Frameworks



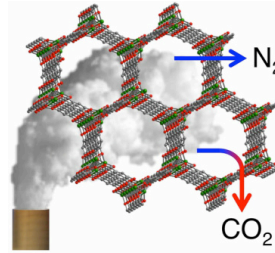
Applications of Metal-Organic Frameworks



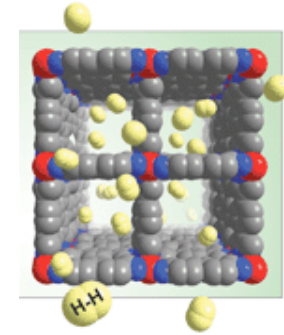
Applications of Metal-Organic Frameworks



Catalysis

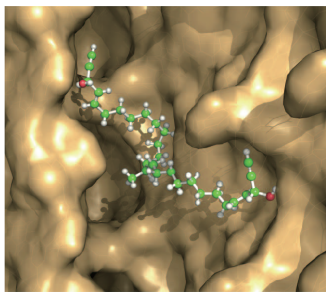


CO₂ Capture

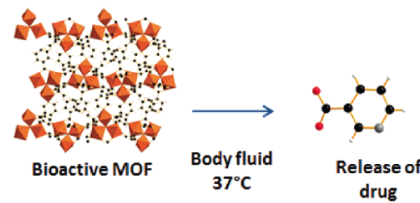


Gas Storage

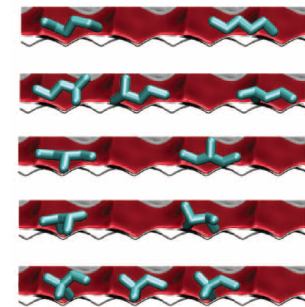
Metal-Organic Frameworks



Crystallography



Drug Delivery

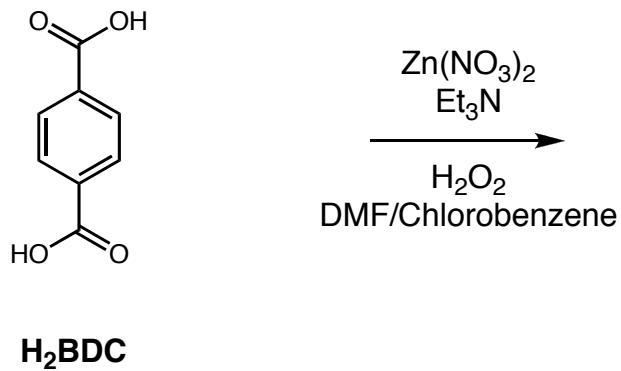


Separations

Important Developments in MOF Scaffold Design

■ Yaghi and coworkers synthesized one of the first porous, crystalline, desolvated MOFs

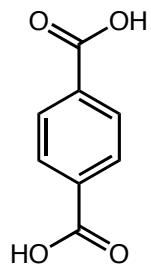
- Incorporation of dicarboxylate linker caused a revolution in porous framework design
- Structure obtained through the coordination with Zn^{2+} ions in DMF
- Zn_4O SBUs serve as nodes to form 3D cubic scaffold **MOF-5**



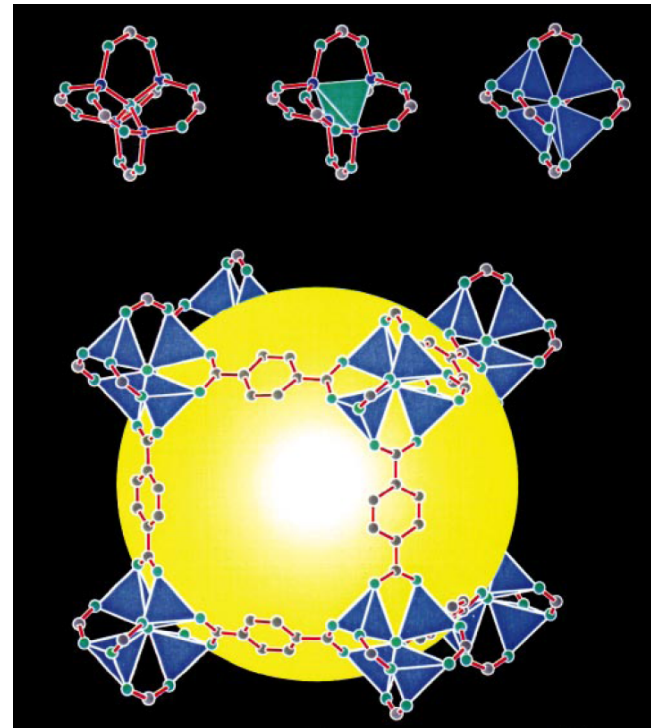
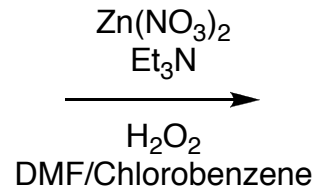
Important Developments in MOF Scaffold Design

■ Yaghi and coworkers synthesized one of the first porous, crystalline, desolvated MOFs

- Incorporation of dicarboxylate linker caused a revolution in porous framework design
- Structure obtained through the coordination with Zn^{2+} ions in DMF
- Zn_4O SBUs serve as nodes to form 3D cubic scaffold **MOF-5**



H₂BDC



Li, H.; Eddaoudi, M.; O'Keefe, M.; Yaghi, O. M. *Nature* **1999**, *402*, 276-279.

Important Developments in MOF Scaffold Design

- Yaghi and coworkers synthesized one of the first porous, crystalline, desolvated MOFs
 - Large and small cavities could accommodate substrates with width of 15.1 Å and 11.0 Å, respectively
 - Channel aperture has width of 8.0 Å
 - Solvent displacement (with CHCl₃) followed by vacuum, evacuates pores without losing stability
 - Lowest recorded density of any crystalline material (**MOF-5** = 0.59 g/cm³)

Important Developments in MOF Scaffold Design

■ Yaghi and coworkers synthesized one of the first porous, crystalline, desolvated MOFs

- Large and small cavities could accommodate substrates with width of 15.1 Å and 11.0 Å, respectively
- Channel aperture has width of 8.0 Å
- Solvent displacement (with CHCl_3) followed by vacuum, evacuates pores without losing stability
- Lowest recorded density of any crystalline material (**MOF-5** = 0.59 g/cm³)

Desolvated stability of **MOF-5** has important applications in gas adsorption

Set the groundwork for a large number of catalytic MOF scaffolds

What are the Advantages to MOF Catalysis?

- MOFs combine the benefits of both heterogeneous and homogeneous catalysis

Heterogeneous Catalysis

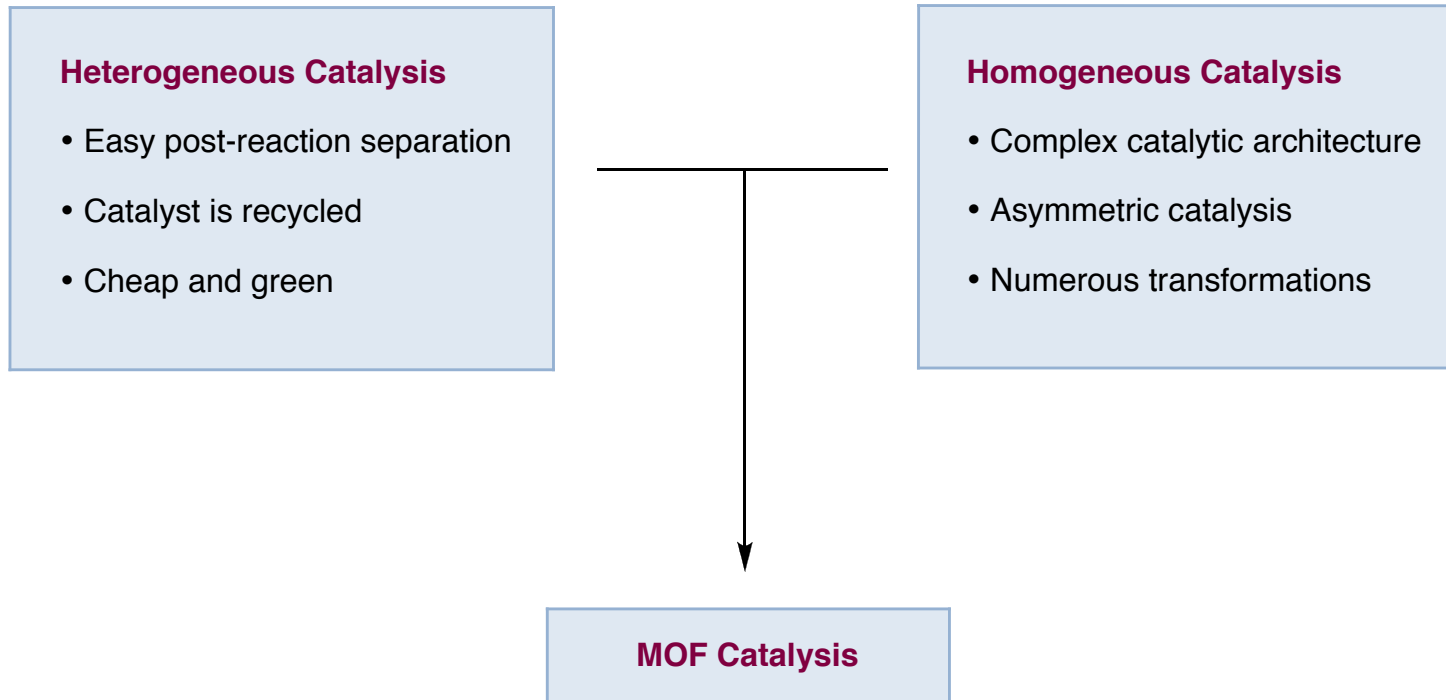
- Easy post-reaction separation
- Catalyst is recycled
- Cheap and green

Homogeneous Catalysis

- Complex catalytic architecture
- Asymmetric catalysis
- Numerous transformations

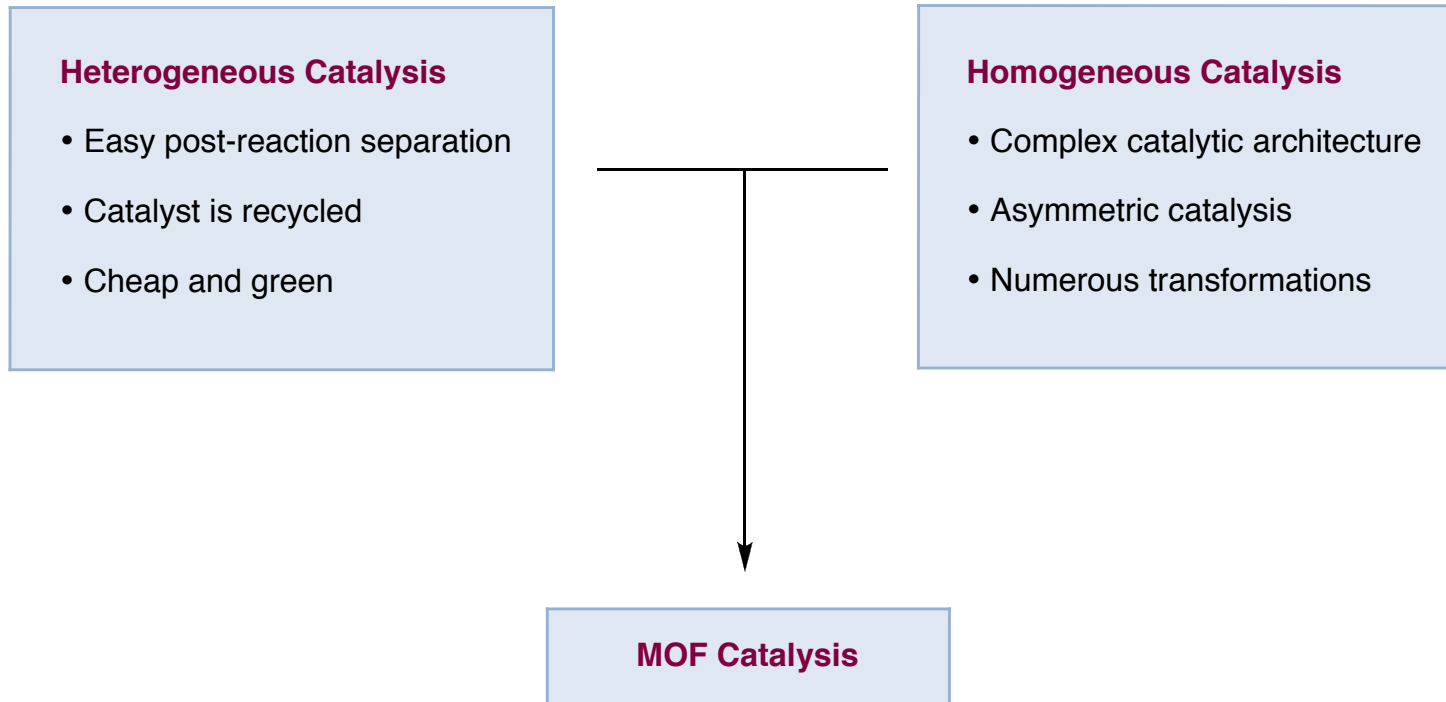
What are the Advantages to MOF Catalysis?

- MOFs combine the benefits of both heterogeneous and homogeneous catalysis



What are the Advantages to MOF Catalysis?

- MOFs combine the benefits of both heterogeneous and homogeneous catalysis

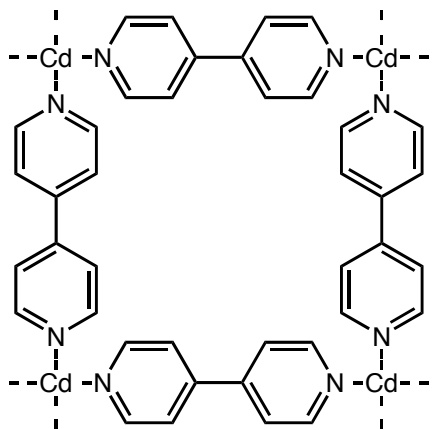


Can further advantages be obtained from combining these two catalytic approaches?

Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

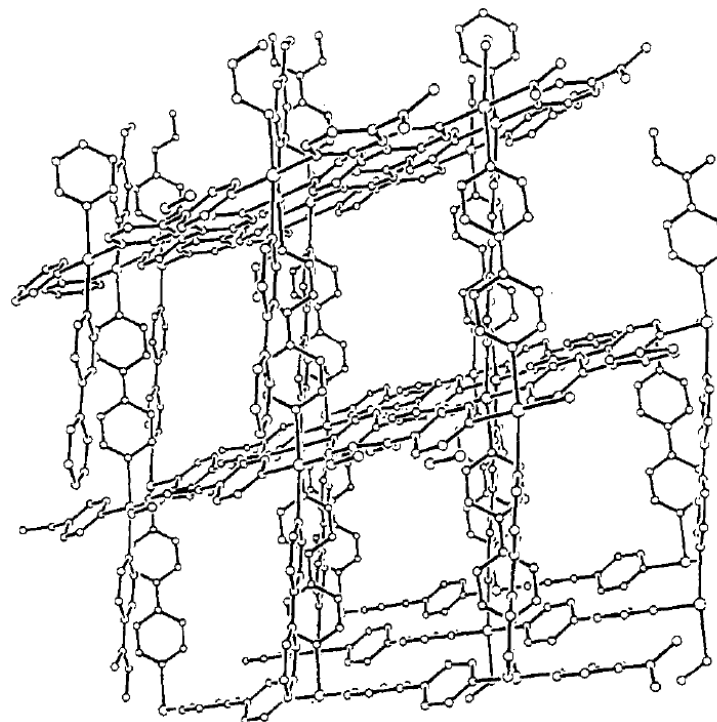
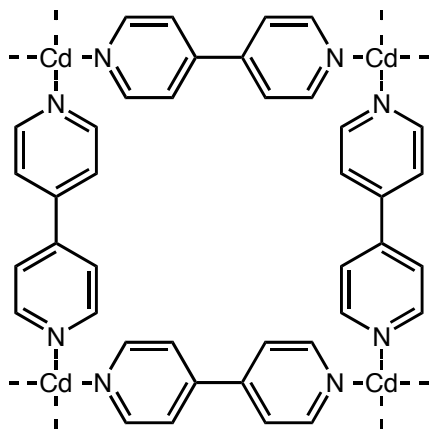
- Combining $\text{Cd}(\text{NO}_3)_2$ and (4,4'-bpy) produced 2D network of $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$
- Each Cd(II) node has distorted octahedral geometry (nitrate ions occupy apical positions)
- Focused on clathration of aromatic guests with high shape specificity



Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

- Combining $\text{Cd}(\text{NO}_3)_2$ and (4,4'-bpy) produced 2D network of $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$
- Each Cd(II) node has distorted octahedral geometry (nitrate ions occupy apical positions)
- Focused on clathration of aromatic guests with high shape specificity

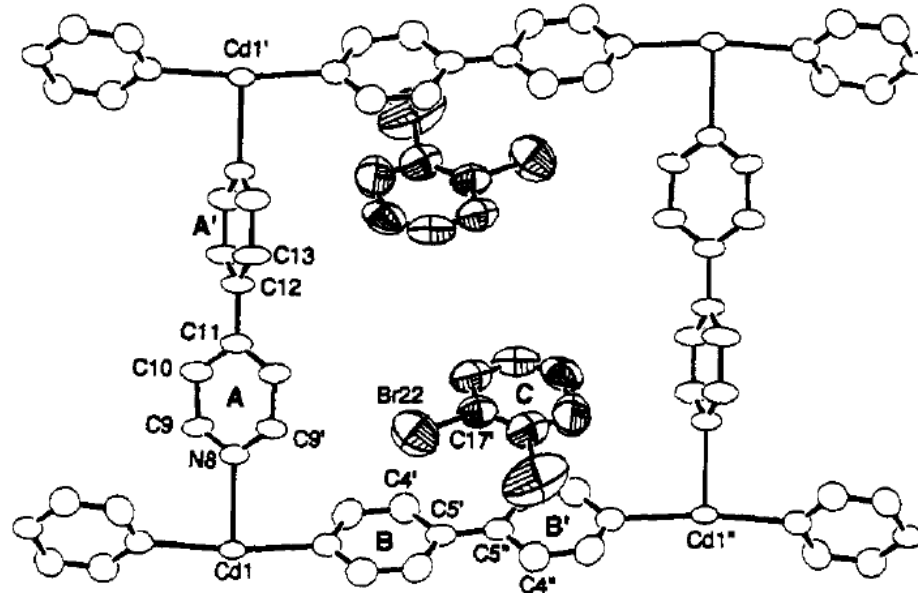


Fujita, M.; Kwon, Y. J.; Washizu, S.; Ogura, K. *J. Am. Chem. Soc.* **1994**, *116*, 1151-1152.

Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

- Combining $\text{Cd}(\text{NO}_3)_2$ and (4,4'-bpy) produced 2D network of $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$
- Each Cd(II) node has distorted octahedral geometry (nitrate ions occupy apical positions)
- Focused on clathration of aromatic guests with high shape specificity
- *o*-dibromobenzene is clathrated efficiently, but *meta* and *para* isomers are not

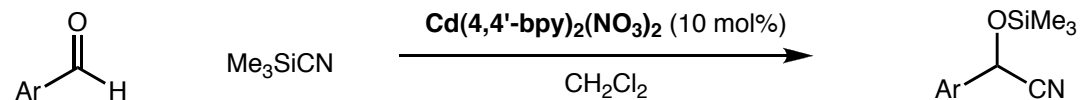


Fujita, M.; Kwon, Y. J.; Washizu, S.; Ogura, K. *J. Am. Chem. Soc.* **1994**, *116*, 1151-1152.

Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

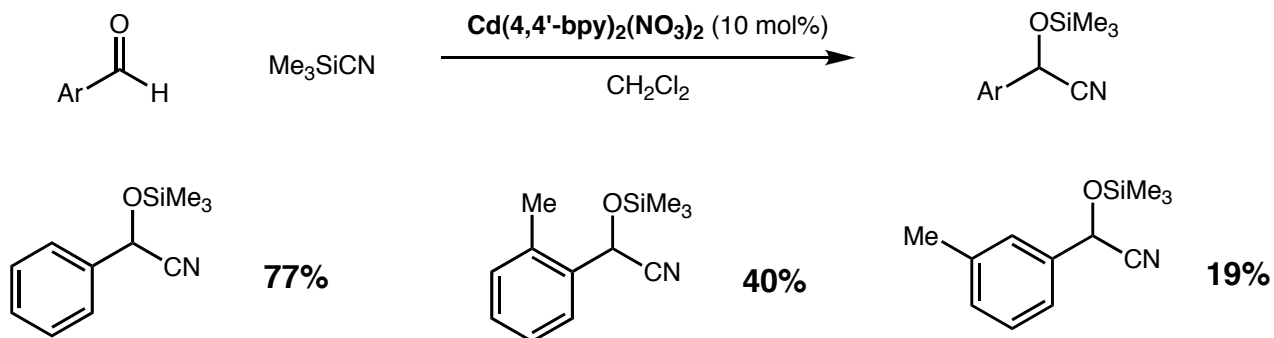
- $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$ catalyzes the cyanosilylation of aldehydes
- $\text{Cd}(\text{NO}_3)_2$ or 4,4'-bpy alone do not catalyze the reaction
- Filtration of MOF shuts down reactivity = catalysis is heterogeneous



Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

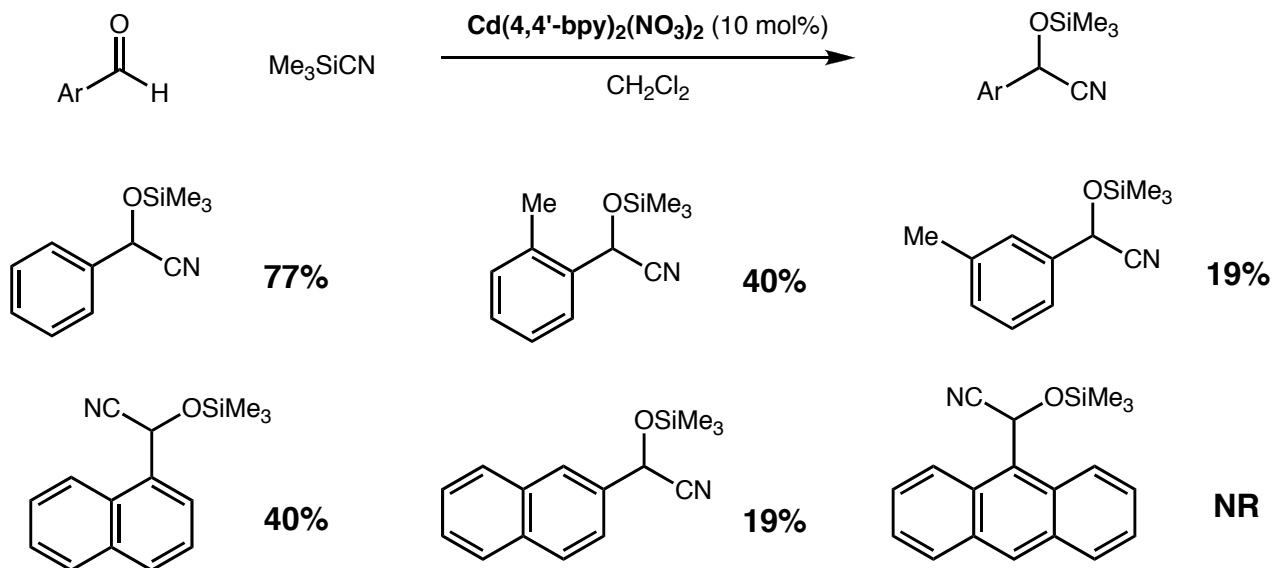
- $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$ catalyzes the cyanosilylation of aldehydes
- $\text{Cd}(\text{NO}_3)_2$ or 4,4'-bpy alone do not catalyze the reaction
- Filtration of MOF shuts down reactivity = catalysis is heterogeneous



Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

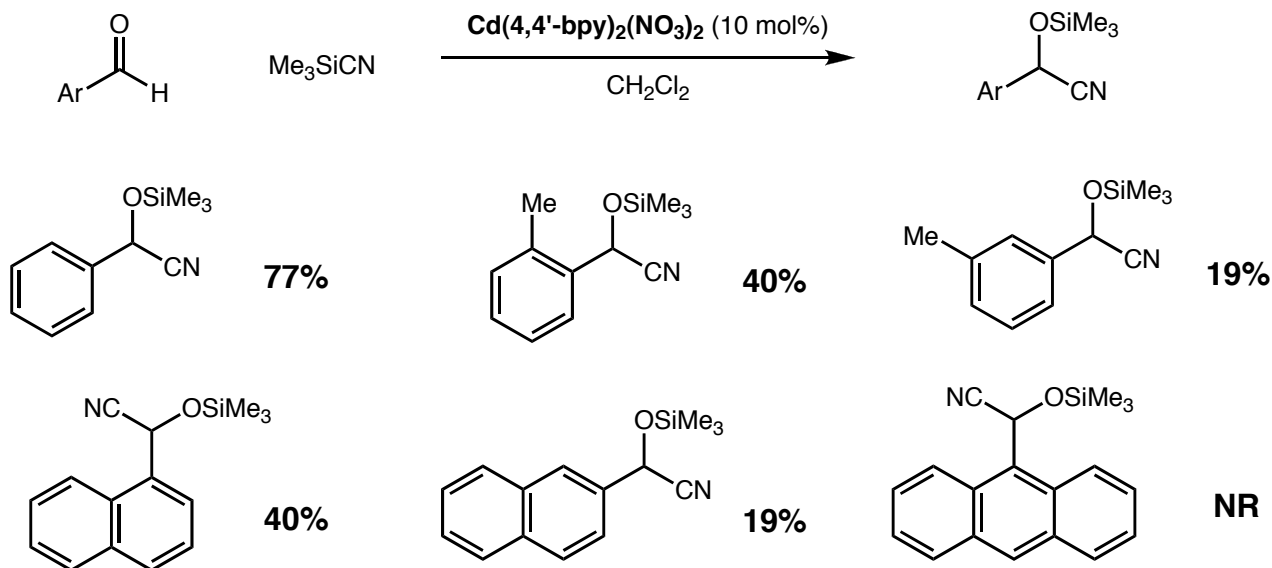
- $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$ catalyzes the cyanosilylation of aldehydes
- $\text{Cd}(\text{NO}_3)_2$ or 4,4'-bpy alone do not catalyze the reaction
- Filtration of MOF shuts down reactivity = catalysis is heterogeneous



Early Reports of Metal-Organic Framework Catalysis

■ First report of MOF catalysis by Fujita and coworkers in 1994

- $\text{Cd}(4,4'\text{-bpy})_2(\text{NO}_3)_2$ catalyzes the cyanosilylation of aldehydes
- $\text{Cd}(\text{NO}_3)_2$ or 4,4'-bpy alone do not catalyze the reaction
- Filtration of MOF shuts down reactivity = catalysis is heterogeneous



Moderate substrate shape specificity attributed to cavity size of MOF scaffold

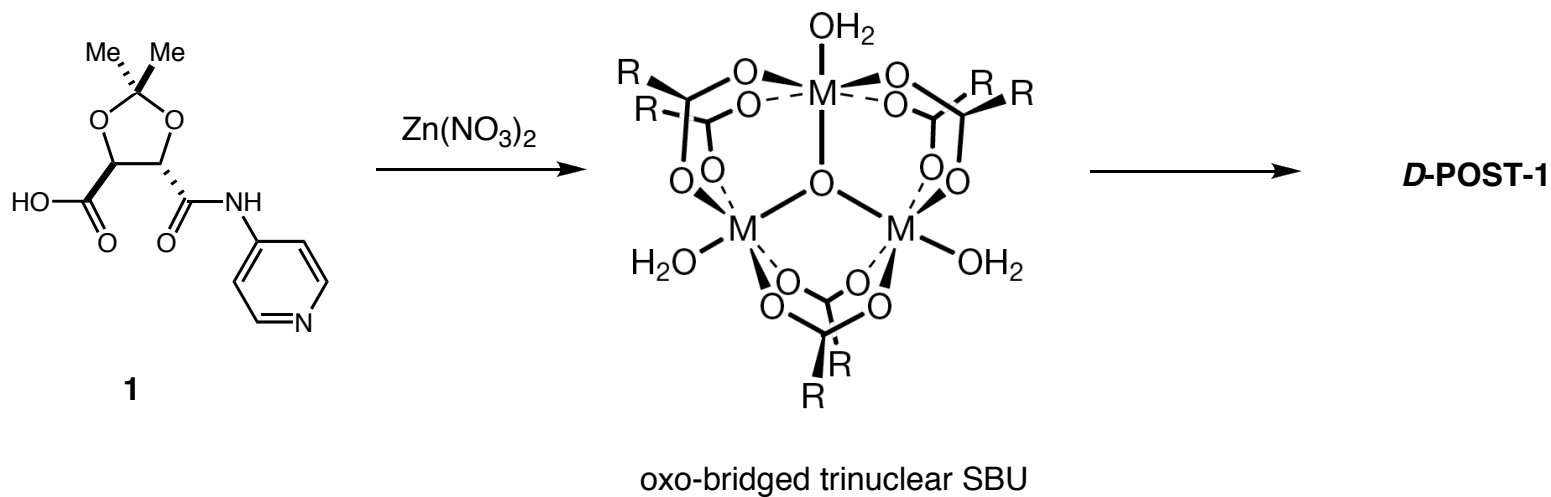
First Report of Metal-Organic Framework Asymmetric Catalysis

- First report of asymmetric MOF catalysis by Kim and coworkers in 2000
 - Utilizes metal-organic clusters as secondary building units (SBUs)
 - Oxo-bridged trinuclear Zn carboxylates assembled from linker **1** and $\text{Zn}(\text{NO}_3)_2$
 - Homochiral framework **POST-1** (Pohang University of Science and Technology)

First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000

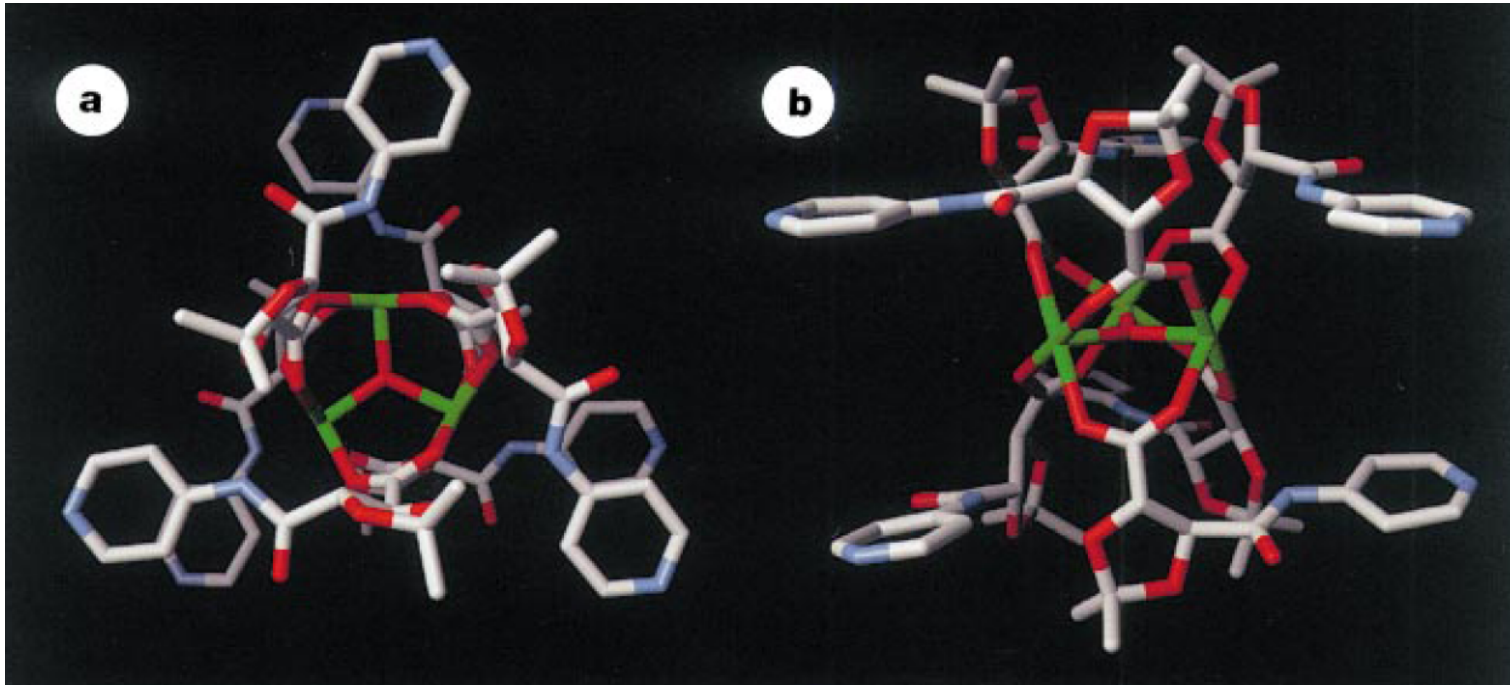
- Utilizes metal-organic clusters as secondary building units (SBUs)
- Oxo-bridged trinuclear Zn carboxylates assembled from linker **1** and $\text{Zn}(\text{NO}_3)_2$
- Homochiral framework **POST-1** (Pohang University of Science and Technology)



First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000

- Utilizes metal-organic clusters as secondary building units (SBUs)
- Oxo-bridged trinuclear Zn carboxylates assembled from linker **1** and $\text{Zn}(\text{NO}_3)_2$
- Homochiral framework **POST-1** (Pohang University of Science and Technology)

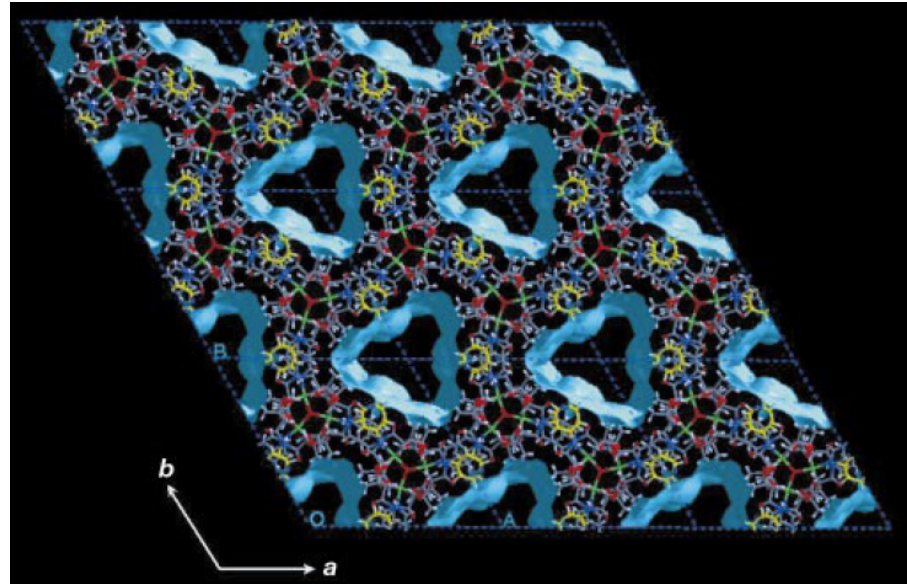
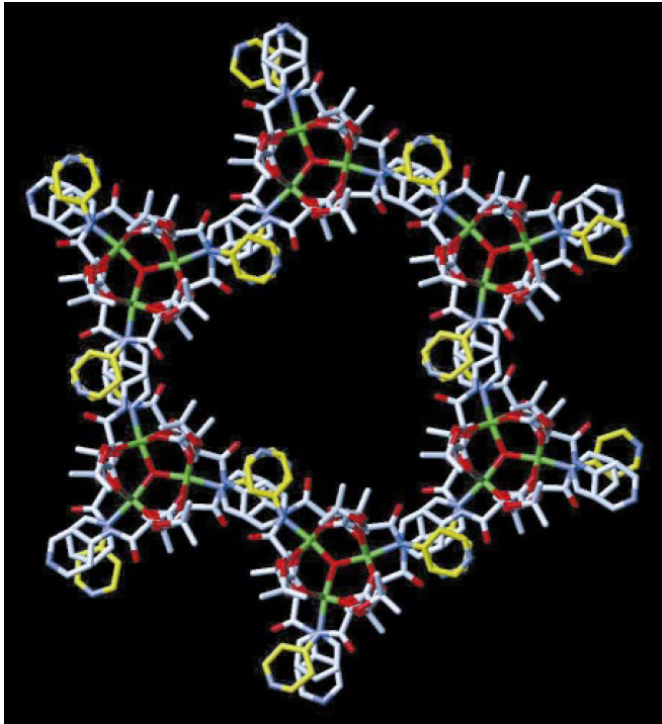


Seo, J. S.; Whang, D.; Lee, H.; Jun, S. I.; Oh, J.; Jeon, Y. J.; Kim, K. *Nature* **2000**, *404*, 982-986.

First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000

- 3 of 6 pyridyl groups replace Zn-bound H_2O and connect SBUs in 2D network
- Remaining 3 pyridyl groups extend into pore with no framework interaction
- 2D layers stack to form large triangular chiral channels ($\sim 13 \text{ \AA}$ side length)



Seo, J. S.; Whang, D.; Lee, H.; Jun, S. I.; Oh, J.; Jeon, Y. J.; Kim, K. *Nature* **2000**, *404*, 982-986.

First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000

- 2 of the 3 channel pyridyl groups are protonated to conserve charge neutrality
- Protons can be exchanged for metal ions (Na⁺, K⁺, Rb⁺) or converted to *N*-alkyl pyridinium ions
- First example of enantioselective inclusion of chiral metal complexes into porous materials:

Ru(bpy)₃²⁺ can be bound with 66% ee in favor of the Δ form

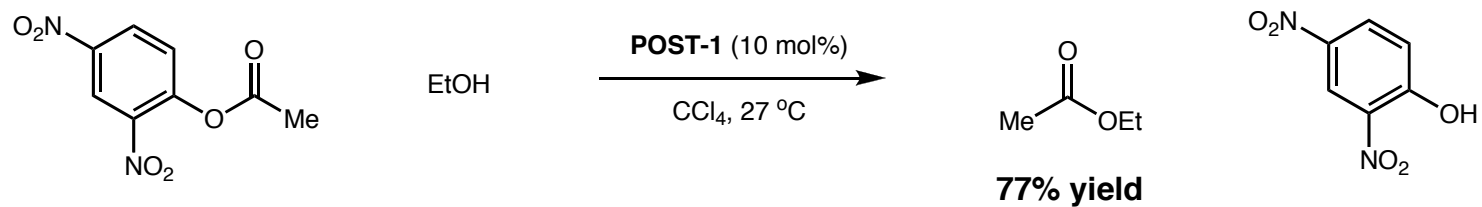
First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000

- 2 of the 3 channel pyridyl groups are protonated to conserve charge neutrality
- Protons can be exchanged for metal ions (Na^+ , K^+ , Rb^+) or converted to *N*-alkyl pyridinium ions
- First example of enantioselective inclusion of chiral metal complexes into porous materials:

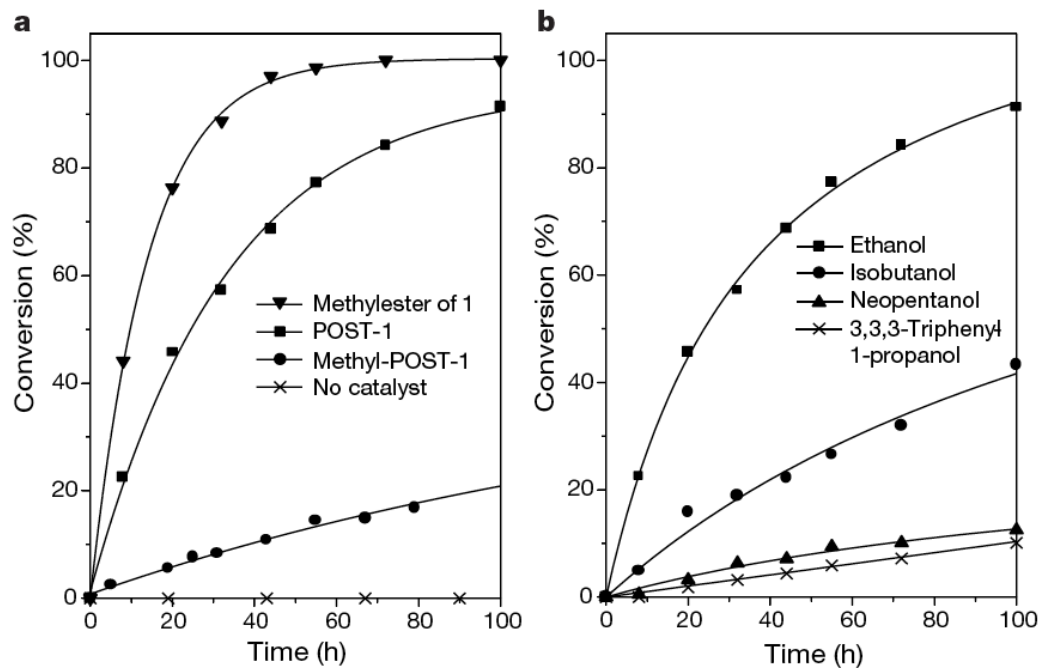
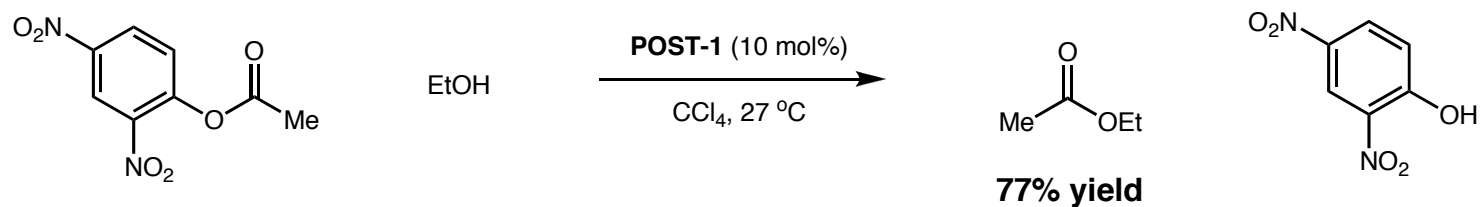
$\text{Ru}(\text{bpy})_3^{2+}$ can be bound with 66% ee in favor of the Δ form

- POST-1 is competent transesterification catalyst



First Report of Metal-Organic Framework Asymmetric Catalysis

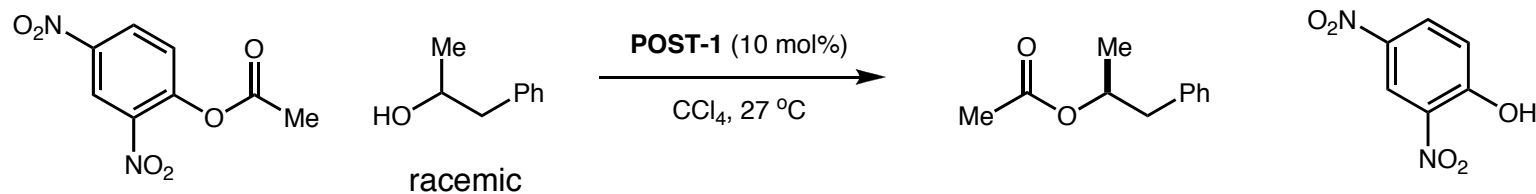
■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000



Seo, J. S.; Whang, D.; Lee, H.; Jun, S. I.; Oh, J.; Jeon, Y. J.; Kim, K. *Nature* **2000**, *404*, 982-986.

First Report of Metal-Organic Framework Asymmetric Catalysis

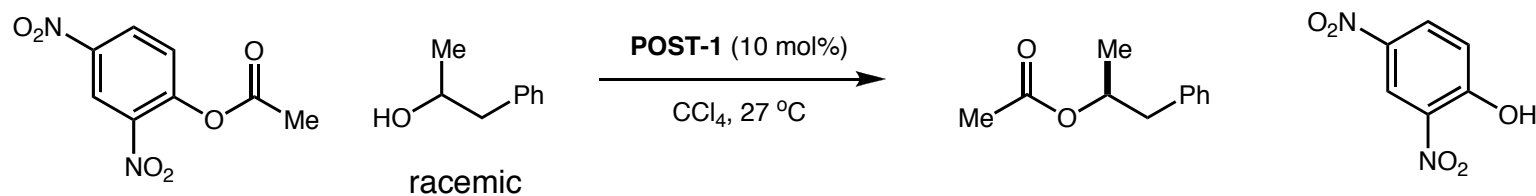
■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000



Catalyst	<i>S</i> (%)	<i>R</i> (%)	ee (%)
<i>L</i> -POST-1 (<i>R,R</i>)	45.9	54.1	8.2
<i>D</i> -POST-1 (<i>S,S</i>)	54.2	45.9	8.3
Pyridine	49.6	50.5	0.9

First Report of Metal-Organic Framework Asymmetric Catalysis

■ First report of asymmetric MOF catalysis by Kim and coworkers in 2000



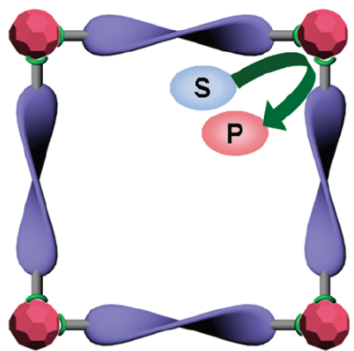
Catalyst	<i>S</i> (%)	<i>R</i> (%)	ee (%)
<i>L</i> -POST-1 (<i>R,R</i>)	45.9	54.1	8.2
<i>D</i> -POST-1 (<i>S,S</i>)	54.2	45.9	8.3
Pyridine	49.6	50.5	0.9

8% enantiomeric excess produced through transesterification catalyzed by homochiral MOF

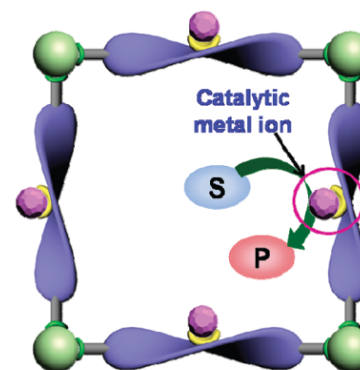
First observation of asymmetric induction mediated by a porous metal-organic framework

Diverse Strategies for Metal-Organic Framework Catalysis

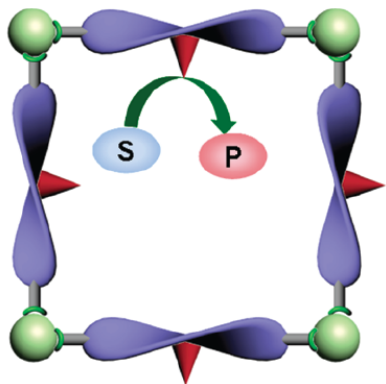
■ Metal node catalysis



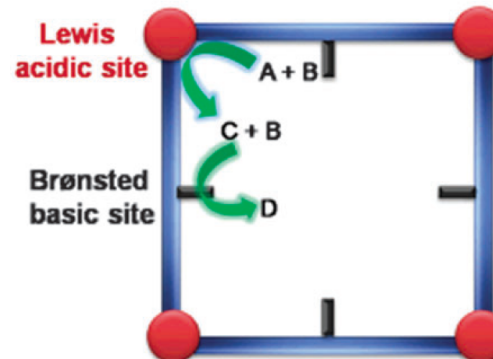
■ Privileged metal catalyst



■ Organocatalytic linkers

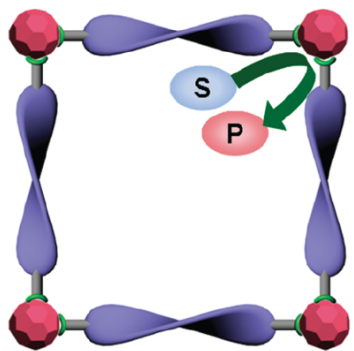


■ Multifunctional catalysis

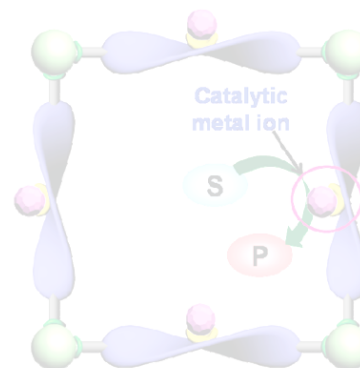


Diverse Strategies for Metal-Organic Framework Catalysis

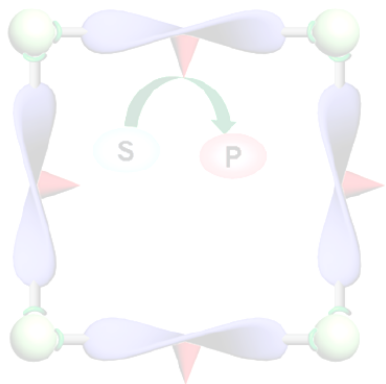
■ Metal node catalysis



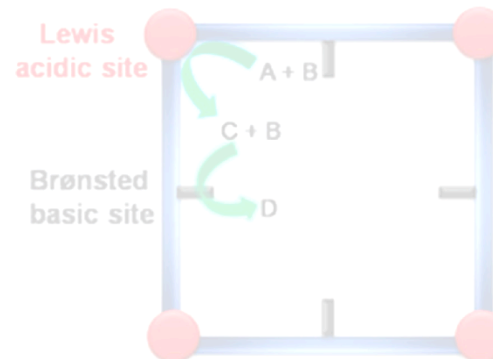
■ Privileged metal catalyst



■ Organocatalytic linkers



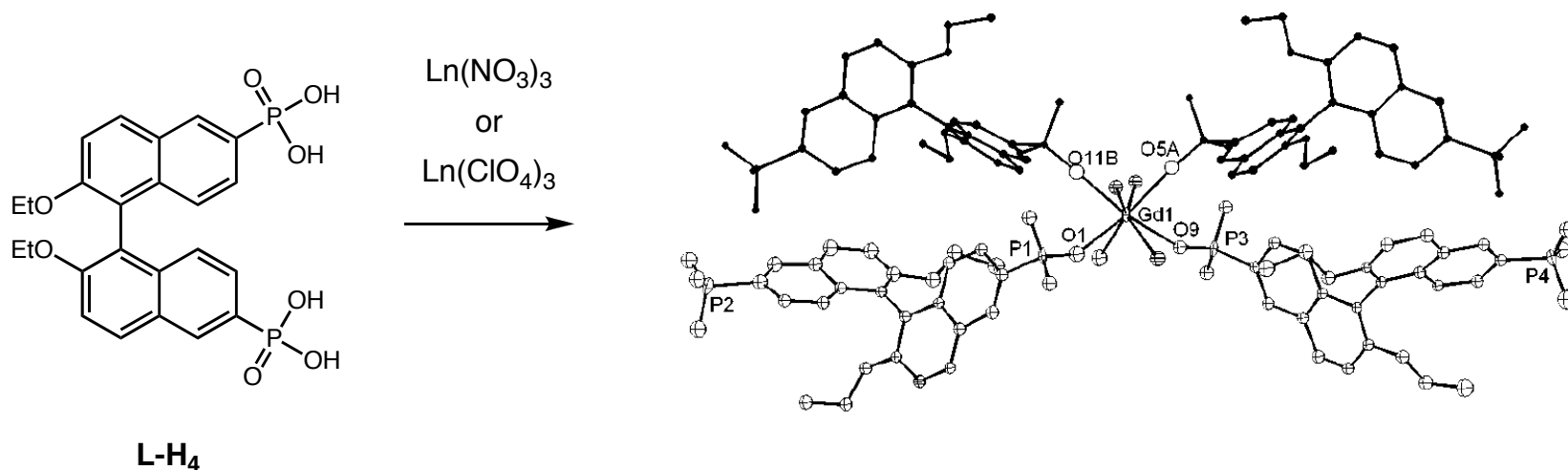
■ Multifunctional catalysis



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

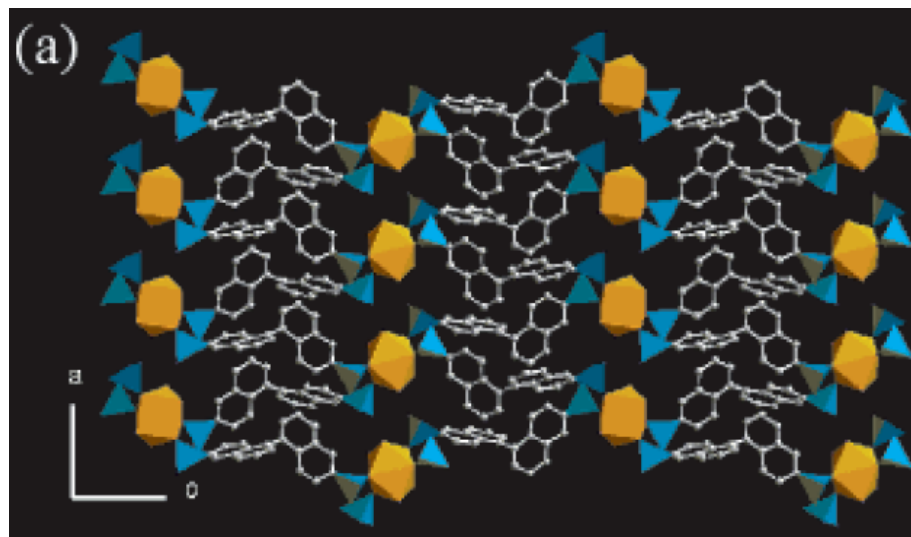
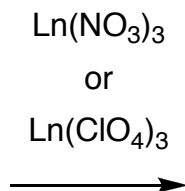
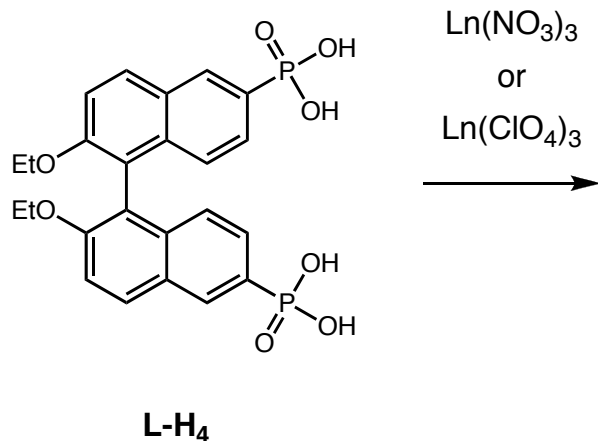
- Porous, lamellar structure contains two phosphonate ligands (**L-H₂** and **L-H₃**)
- Series of MOFs synthesized with various lanthanides (La, Ce, Pr, Nd, Sm, Gd, Tb)
- MOFs comprised of general formula: [Ln(**L-H₂**)(**L-H₃**)(H₂O)₄]•xH₂O



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

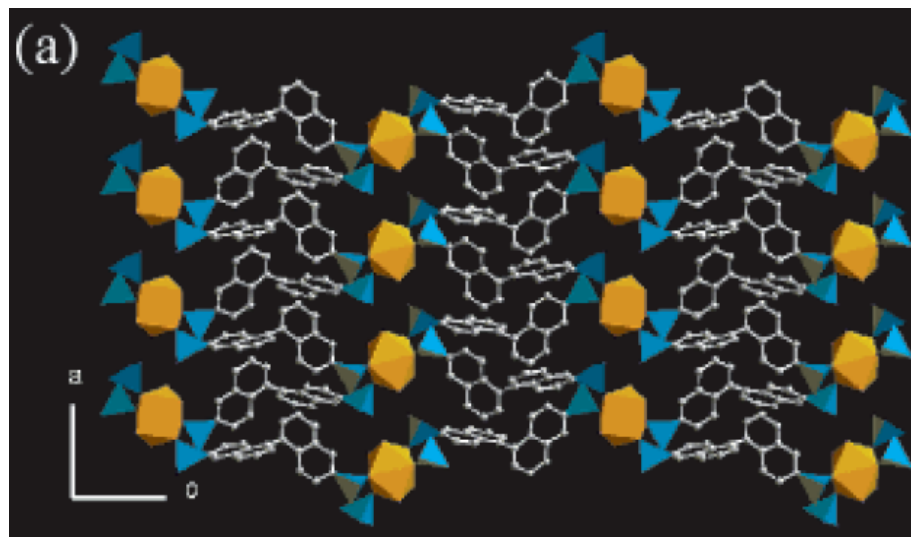
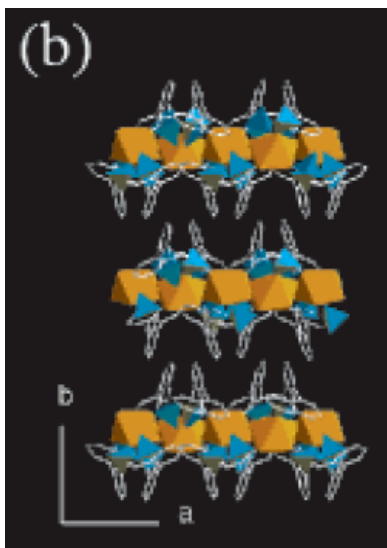
- Porous, lamellar structure contains two phosphonate ligands (**L-H₂** and **L-H₃**)
- Series of MOFs synthesized with various lanthanides (La, Ce, Pr, Nd, Sm, Gd, Tb)
- MOFs comprised of general formula: [Ln(**L-H₂**)(**L-H₃**)(H₂O)₄]•xH₂O



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

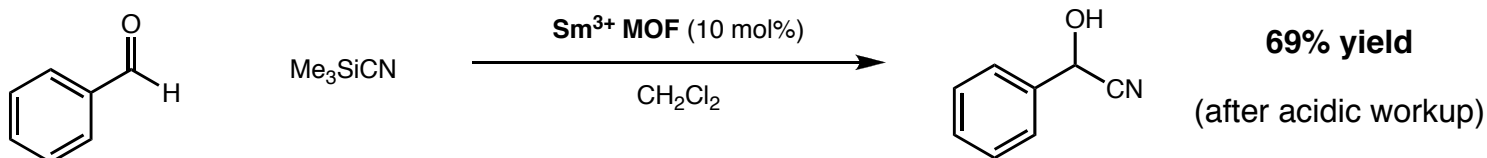
- Porous, lamellar structure contains two phosphonate ligands (**L-H₂** and **L-H₃**)
- Series of MOFs synthesized with various lanthanides (La, Ce, Pr, Nd, Sm, Gd, Tb)
- MOFs comprised of general formula: [Ln(**L-H₂**)(**L-H₃**)(H₂O)₄]•xH₂O



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

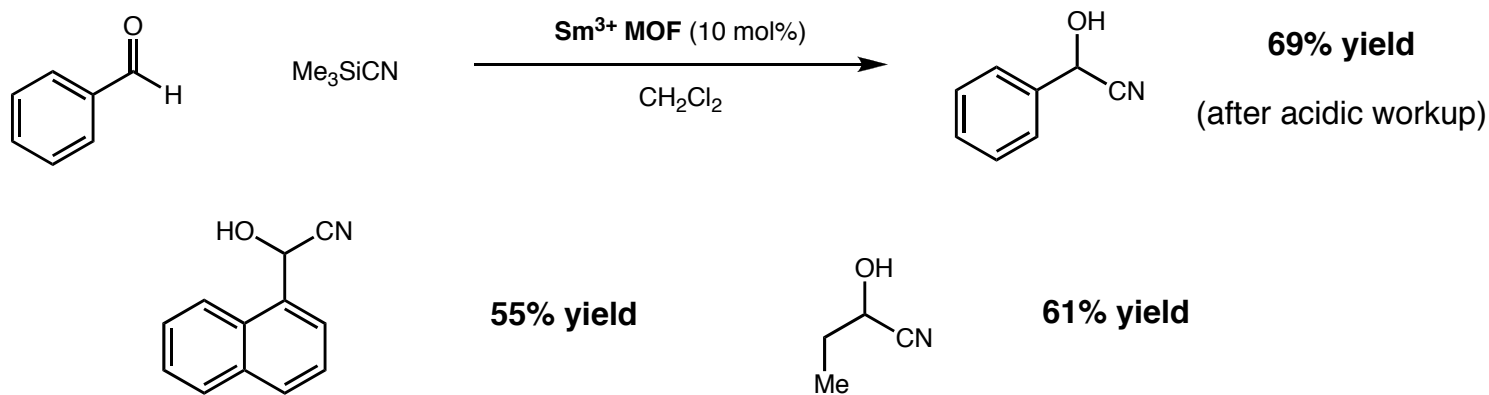
- Asymmetric channels around nodes (~12 Å)
- Possesses both Lewis and Brønsted acid sites
- Catalyzes the cyanosilylation of aldehydes



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

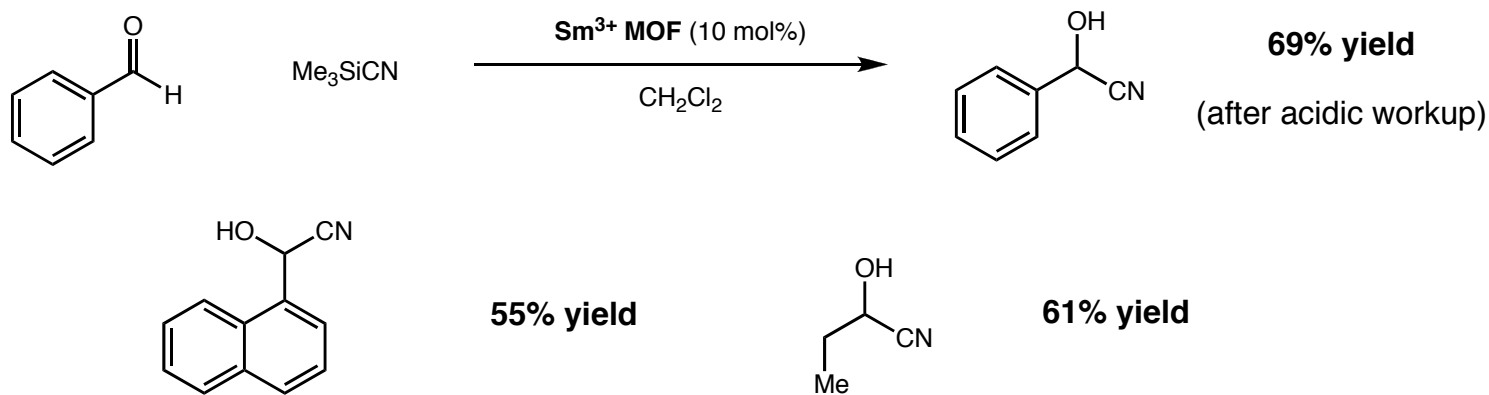
- Asymmetric channels around nodes (~12 Å)
- Possesses both Lewis and Brønsted acid sites
- Catalyzes the cyanosilylation of aldehydes



Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

- Asymmetric channels around nodes (~12 Å)
- Possesses both Lewis and Brønsted acid sites
- Catalyzes the cyanosilylation of aldehydes

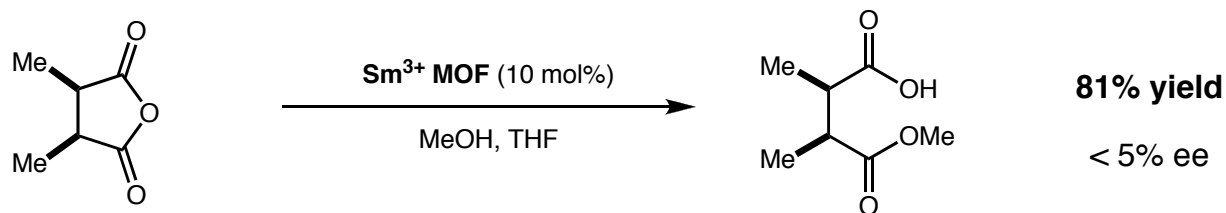


- Indiscrimination between substrates suggests MOF pores swell to accommodate larger aldehydes
- All three products were racemic (< 5% ee)

Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

- Lewis acid promoted ring opening of *meso*-anhydrides catalyzed by Sm³⁺ MOF

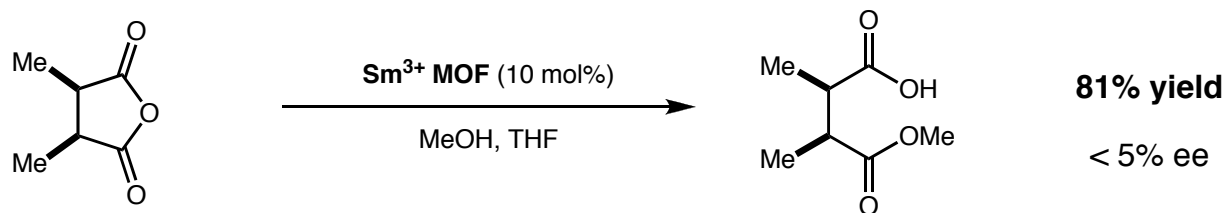


- Both cyanosilylation and ring opening are heterogeneous (reactivity ceases after filtration of MOF)
- Catalyst can be recycled multiple times with no loss in reactivity

Metal Node Catalysis - Lanthanide Phosphonates

■ Homochiral Ln³⁺(bisphosphonates) represent early foray into asymmetric metal node catalysis

- Lewis acid promoted ring opening of *meso*-anhydrides catalyzed by Sm³⁺ MOF



- Both cyanosilylation and ring opening are heterogeneous (reactivity ceases after filtration of MOF)
- Catalyst can be recycled multiple times with no loss in reactivity

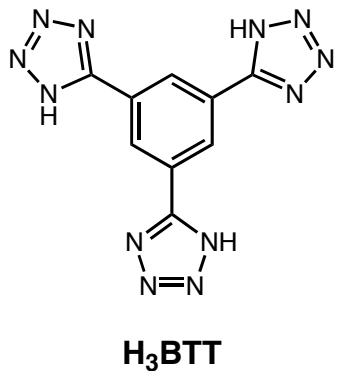
■ *R*-Sm(III)(bisphosphonate) enables enantioselective separations



Metal Node Catalysis - Mn^{2+} Nodes

■ Long and coworkers showed unsaturated Mn^{2+} nodes in MOFs act as Lewis acid catalysts

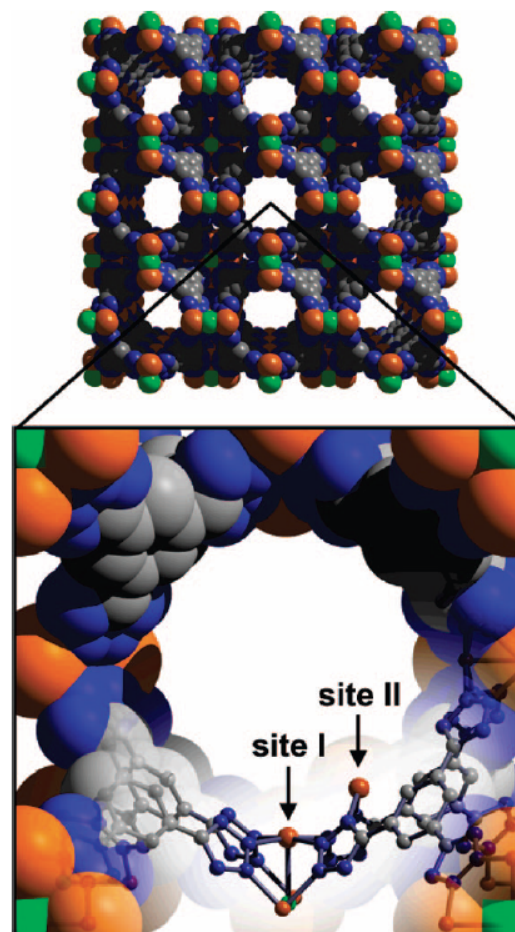
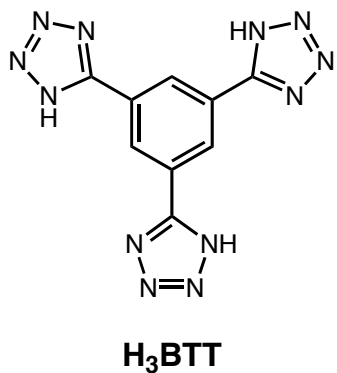
- Efforts to improve H_2 adsorption have resulted in numerous MOFs with coordinatively unsaturated metal nodes
- Application as Lewis acidic sites has proven successful
- $Mn_3[(Mn_4Cl)_3(BTT)_8(MeOH)_{10}]_2$ contains exposed Mn^{2+} nodes within pores and on surface



Metal Node Catalysis - Mn^{2+} Nodes

■ Long and coworkers showed unsaturated Mn^{2+} nodes in MOFs act as Lewis acid catalysts

- Efforts to improve H_2 adsorption have resulted in numerous MOFs with coordinatively unsaturated metal nodes
- Application as Lewis acidic sites has proven successful
- $Mn_3[(Mn_4Cl)_3(BTT)_8(MeOH)_{10}]_2$ contains exposed Mn^{2+} nodes within pores and on surface

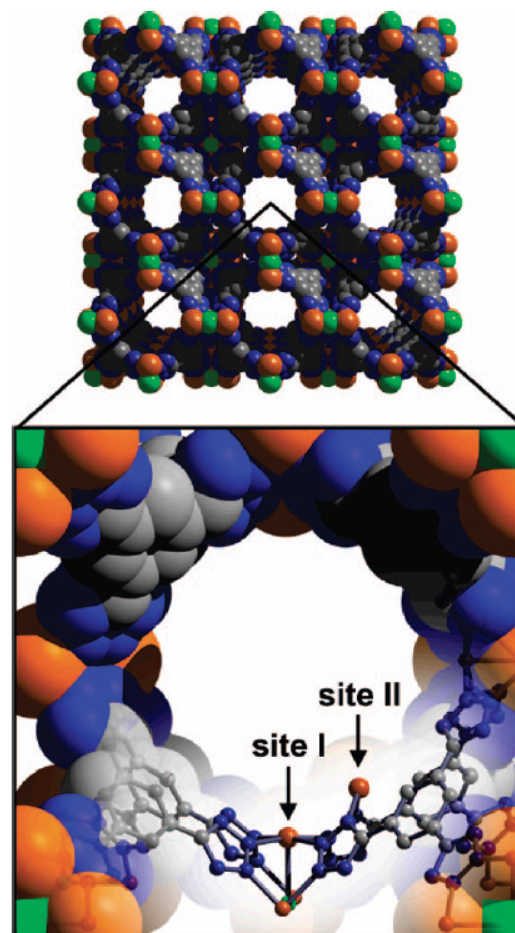


Metal Node Catalysis - Mn^{2+} Nodes

■ Long and coworkers showed unsaturated Mn^{2+} nodes in MOFs act as Lewis acid catalysts

- Efforts to improve H_2 adsorption have resulted in numerous MOFs with coordinatively unsaturated metal nodes
- Application as Lewis acidic sites has proven successful
- $Mn_3[(Mn_4Cl)_3(BTT)_8(MeOH)_{10}]_2$ contains exposed Mn^{2+} nodes within pores and on surface

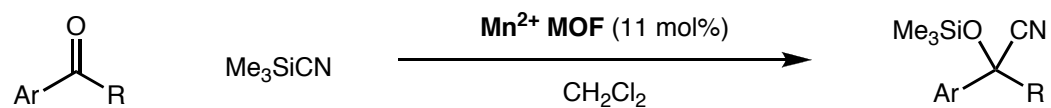
- Site I = five-coordinate Mn^{2+}
- Site II = two-coordinate Mn^{2+}
- Both sites positioned to interact with substrate
- 10 Å-wide channel, accessible pore



Metal Node Catalysis - Mn^{2+} Nodes

■ Mn^{2+} nodes catalyse the cyanosilylation of aromatic ketones and aldehydes

- Convenient route to cyanohydrin products
- Significant improvement in yield relative to pioneering work by Lin in 2001 (Ln bisphosphonates)

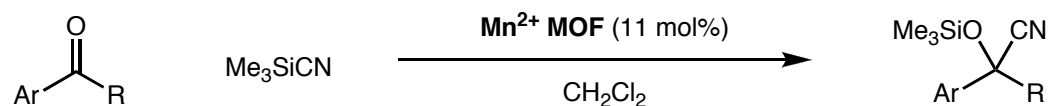


entry	Ar	R	time (h)	yield (%) ^b
1	phenyl	H	9	98
2	1-naphthyl	H	9	90
3	4-phenoxyphenyl	H	9	19
4	biphenyl	H	9	18
5	phenyl	CH_3	24	28
6	biphenyl	CH_3	24	1

Metal Node Catalysis - Mn^{2+} Nodes

■ Mn^{2+} nodes catalyse the cyanosilylation of aromatic ketones and aldehydes

- Convenient route to cyanohydrin products
- Significant improvement in yield relative to pioneering work by Lin in 2001 (Ln bisphosphonates)



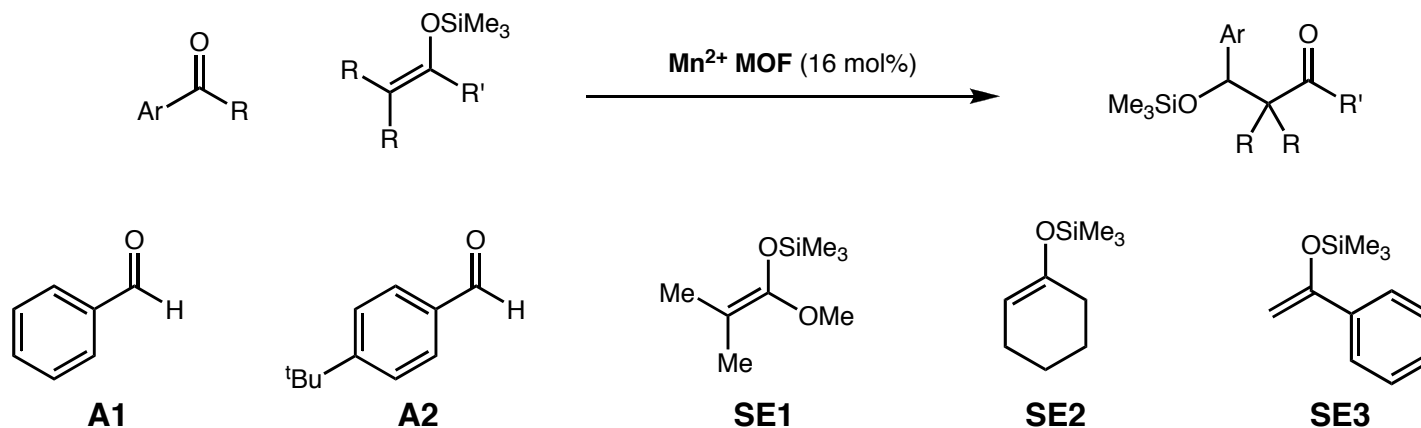
entry	Ar	R	time (h)	yield (%) ^b
1	phenyl	H	9	98
2	1-naphthyl	H	9	90
3	4-phenoxyphenyl	H	9	19
4	biphenyl	H	9	18
5	phenyl	CH_3	24	28
6	biphenyl	CH_3	24	1

- Filtration of catalyst after 4 h shuts down reactivity = catalyst is heterogeneous in nature
- IR C–O stretches of 1698 cm^{-1} and 1686 cm^{-1} show benzaldehyde is coordinated by Mn^{2+}
- Significant substrate size selectivity is observed - **one of the first examples in MOF catalysis**

Metal Node Catalysis - Mn^{2+} Nodes

■ Mn^{2+} nodes also catalyse the Mukaiyama-Aldol reaction

- Despite this transformation typically requiring stonger Lewis Acids, the Mn^{2+} nodes are competent



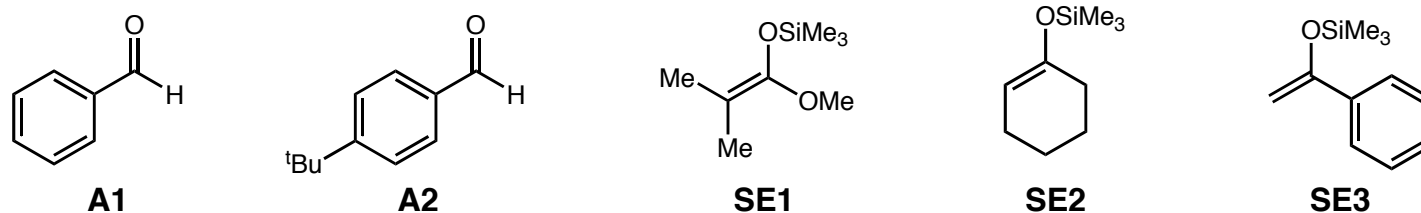
entry	aldehyde	silyl enolate	time (h)	solvent	yield (%) ^b
1	A1	SE1	99	CH ₂ Cl ₂	63
2	A2	SE1	99	CH ₂ Cl ₂	24
3	A1	SE2	99	CH ₂ Cl ₂	<1
4	A1	SE3	99	CH ₂ Cl ₂	<1
5 ^c	A1	SE1	6	DMF	8 ^d
6 ^c	A1	SE1	6	DMF	51

^cRun at -45 °C. ^dNo catalyst added.

Metal Node Catalysis - Mn^{2+} Nodes

■ Mn^{2+} nodes also catalyse the Mukaiyama-Aldol reaction

- Surprisingly DMF improved reactivity despite being a highly coordinating solvent
- In CH_2Cl_2 , only 16% yield after 6 h with A1 and SE1
- DMF may activate silyl enolate through coordination with Si-O bond
- Mn^{2+} nodes and DMF may act synergistically to activate both coupling partners independently



entry	aldehyde	silyl enolate	time (h)	solvent	yield (%) ^b
1	A1	SE1	99	CH_2Cl_2	63
2	A2	SE1	99	CH_2Cl_2	24
3	A1	SE2	99	CH_2Cl_2	<1
4	A1	SE3	99	CH_2Cl_2	<1
5 ^c	A1	SE1	6	DMF	8 ^d
6 ^c	A1	SE1	6	DMF	51

^cRun at -45 °C. ^dNo catalyst added.

Metal Node Catalysis - Mn²⁺ Nodes

■ Mn²⁺ nodes also catalyse the Mukaiyama-Aldol reaction

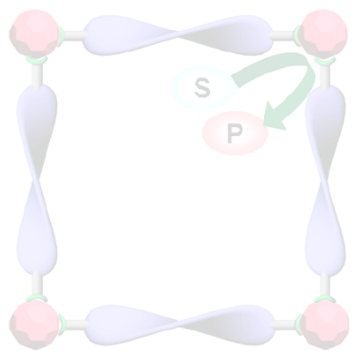
- Surprisingly DMF improved reactivity despite being a highly coordinating solvent
- In CH₂Cl₂, only 16% yield after 6 h with A1 and SE1
- DMF may activate silyl enolate through coordination with Si–O bond
- Mn²⁺ nodes and DMF may act synergistically to activate both coupling partners independently

MOF containing Mn²⁺ functions as effective Lewis acid catalyst

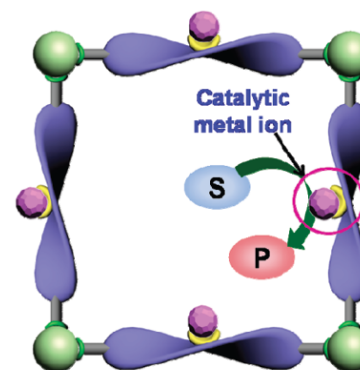
- Both cyanosilylation of carbonyls and Mukaiyama-Aldol reaction achieved
- Pore dimensions control substrate reactivity based on size
- Metal node catalysis is a reliable activation method, maintains MOF structure and porosity

Diverse Strategies for Metal-Organic Framework Catalysis

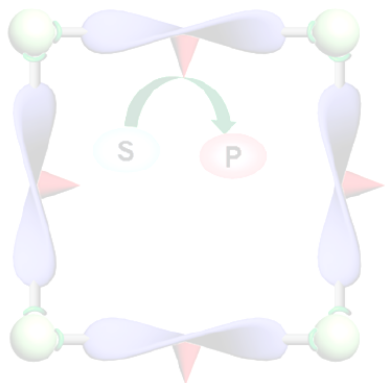
■ Metal node catalysis



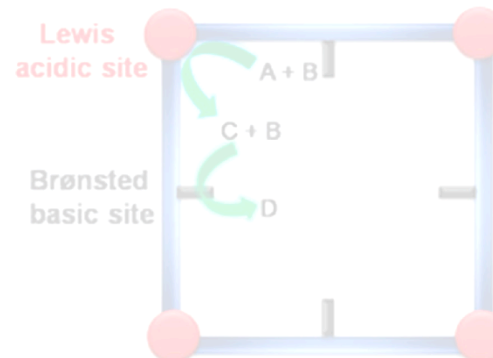
■ Privileged metal catalyst



■ Organocatalytic linkers



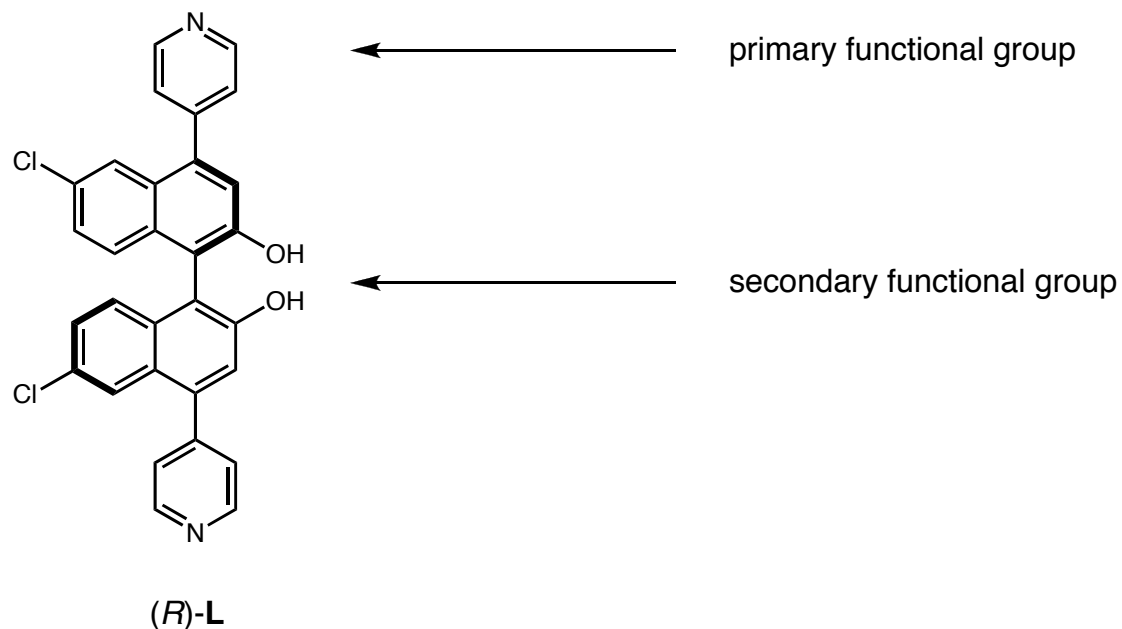
■ Multifunctional catalysis



Privileged Metal Catalysts - BINOLate

■ Lin and coworkers showed incorporation of BINOL ligand to form homochiral MOF

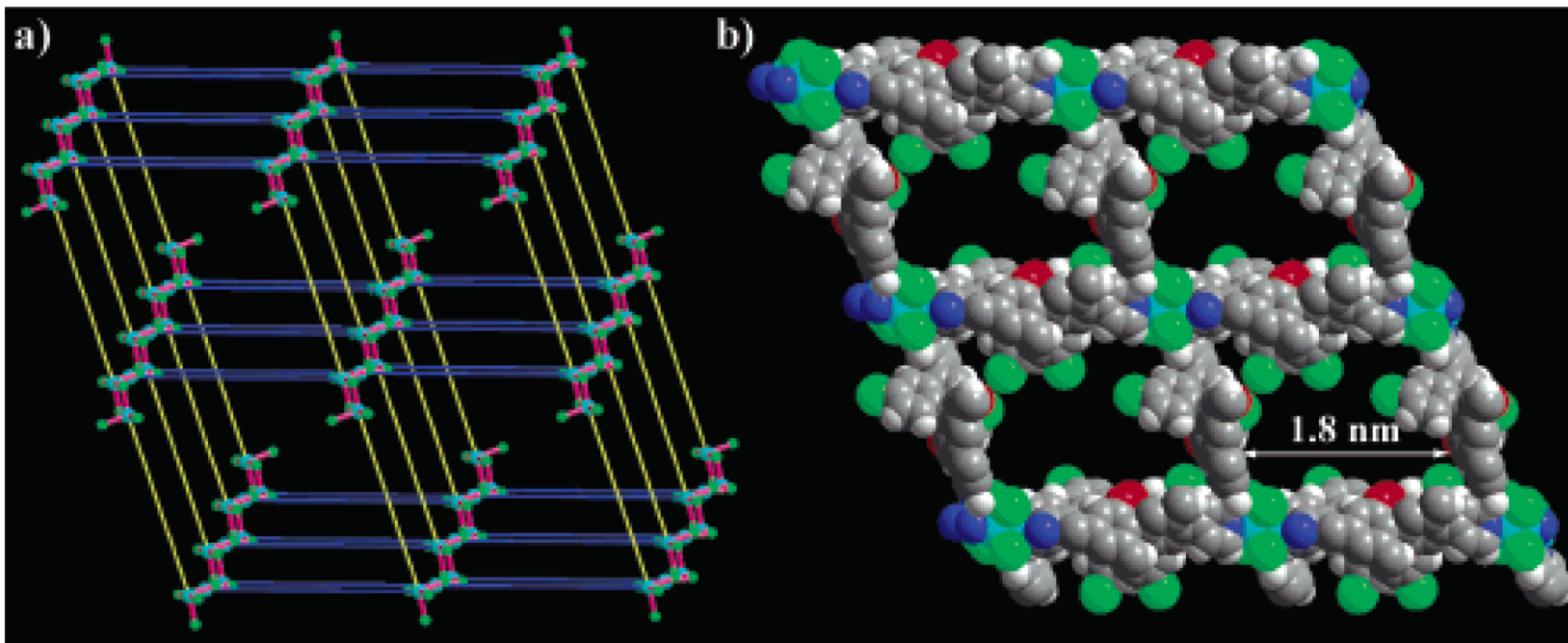
- BINOL linker contains pyridyl primary functional groups
- Chiral secondary groups can act as asymmetric catalytic sites
- In combination with CdCl_2 , (*R*)-**L** forms MOF with $[\text{Cd}(\mu\text{-Cl})_2]_n$ SBUs bridged by **L**



Privileged Metal Catalysts - BINOLate

■ Lin and coworkers showed incorporation of BINOL ligand to form homochiral MOF

- BINOL linker contains pyridyl primary functional groups
- Chiral secondary groups can act as asymmetric catalytic sites
- In combination with CdCl_2 , (*R*)-L forms MOF with $[\text{Cd}(\mu\text{-Cl})_2]_n$ SBUs bridged by L

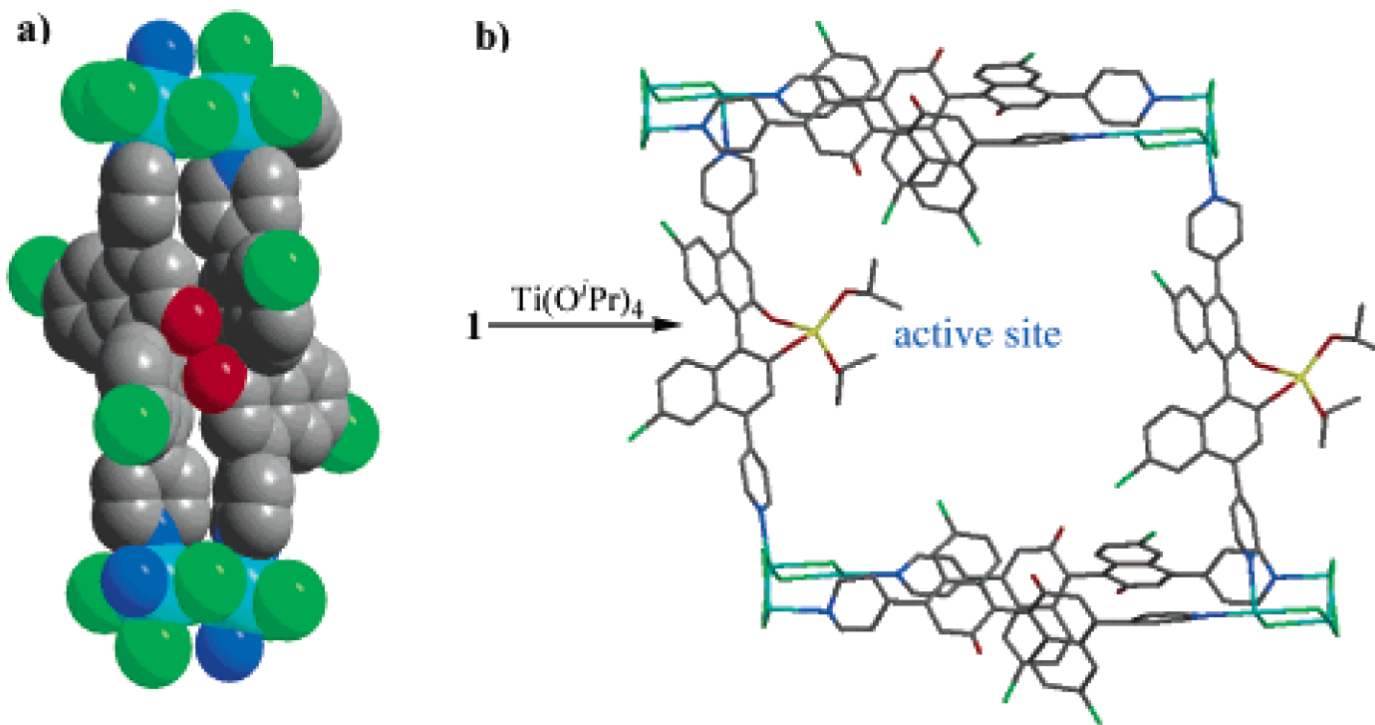


Wu, C. D.; Hu, A.; Zhang, L.; Lin, W. *J. Am. Chem. Soc.* **2005**, *127*, 8940-8941.

Privileged Metal Catalysts - BINOLate

■ BINOLate MOF **1** binds $\text{Ti}(\text{O}^i\text{Pr})_2$ to form active catalyst

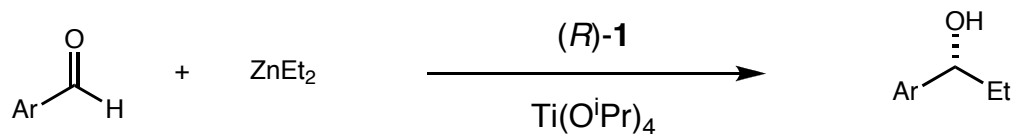
- Strong H-bonding and π - π interactions hold two horizontal **L** linkers together (catalytically inactive) (**a**)
- Axial linker serves as active catalytic site with dihydroxy groups directed into the open channel (**b**)



Privileged Metal Catalysts - BINOLate

■ BINOLate MOF **1**•Ti catalyzes enantioselective ZnEt₂ addition to aromatic aldehydes

- Affords chiral secondary alcohols through Lewis Acidic activation
- Enantioselectivity matches homogeneous variant closely

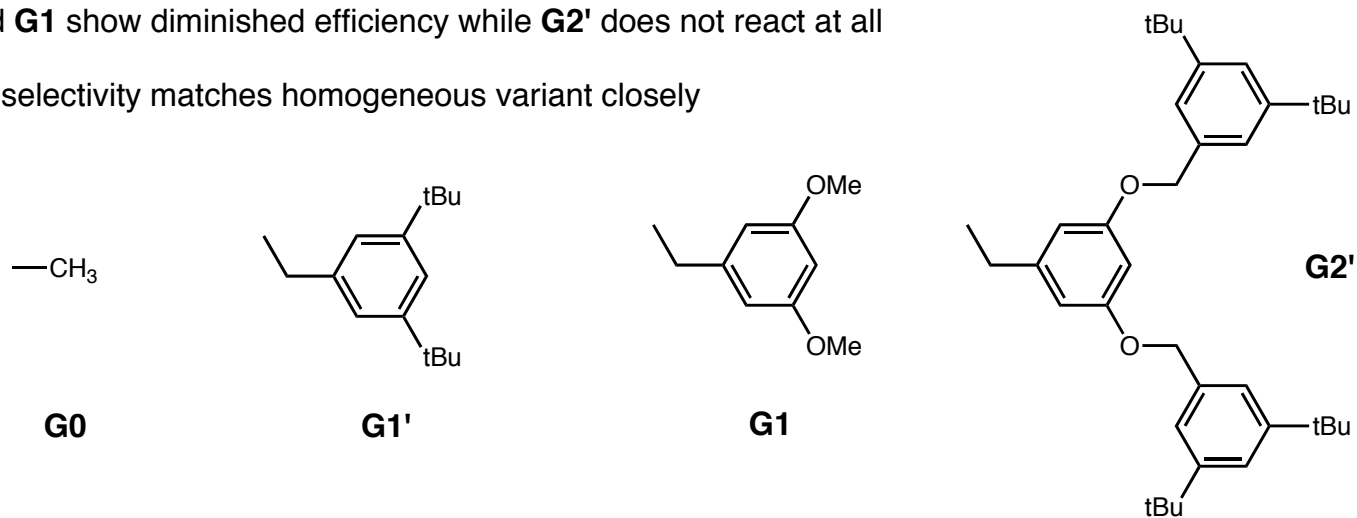


Ar	BINOL/Ti(O ⁱ Pr) ₄		1 •Ti	
	conv %	ee %	conv %	ee %
1-Naph	>99	94	>99	93
Ph	>99	88	>99	83
4-Cl-Ph	>99	86	>99	80
3-Br-Ph	>99	84	>99	80

Privileged Metal Catalysts - BINOLate

■ Size selectivity experiments show catalysis is occurring exclusively within the pores

- **G1'** and **G1** show diminished efficiency while **G2'** does not react at all
- Enantioselectivity matches homogeneous variant closely



Ar	BINOL/Ti(O ⁱ Pr) ₄		1•Ti	
	conv %	ee %	conv %	ee %
4'-G ₀ OPh	>99	80	>99	88
4'-G ₁ 'OPh	>99	75	73	77
4'-G ₁ OPh	>99	78	63	81
4'-G ₂ 'OPh	95 ^b	67 ^b	0	—

Privileged Metal Catalysts - BINOLate

■ Size selectivity experiments show catalysis is occurring exclusively within the pores

- **G1'** and **G1** show diminished efficiency while **G2'** does not react at all
- Enantioselectivity matches homogeneous variant closely

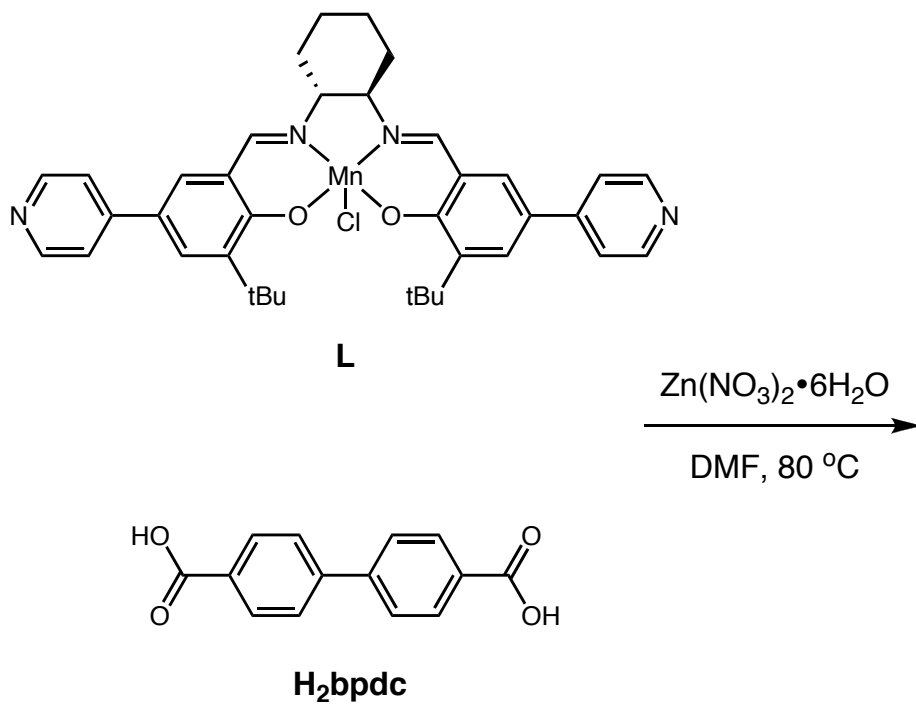
■ **1•Ti** established as a heterogeneous, more reactive BINOL catalyst

- Catalyst loading is lower for MOF than homogeneous ligand (13 mol% compared to 20 mol%)
- Only one third of **L** ligands are involved in catalysis
- Degree of asymmetric induction surpasses that of any previous homochiral MOF

Privileged Metal Catalysts - Salen

■ Hupp and Nguyen have installed Mn(salen) linkers into MOF scaffold

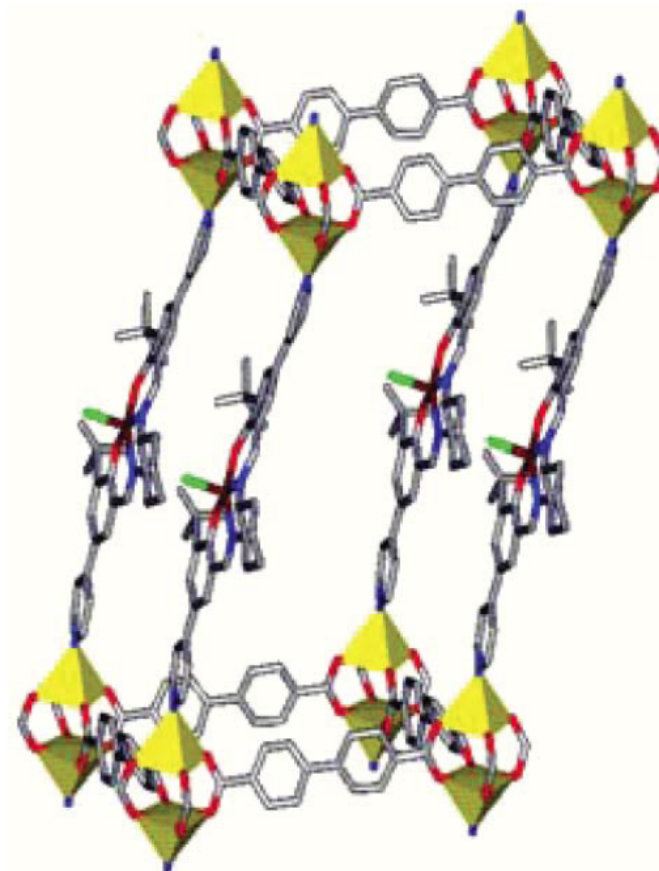
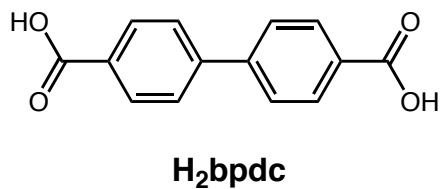
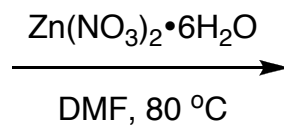
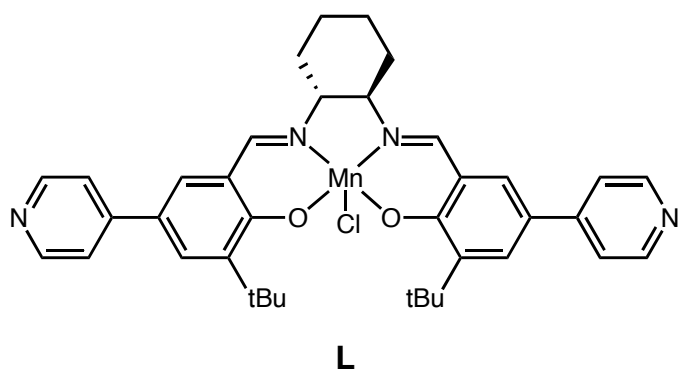
- A multi-ligand approach imparts structural stability (**L** and **H₂bpdc**)



Privileged Metal Catalysts - Salen

■ Hupp and Nguyen have installed Mn(salen) linkers into MOF scaffold

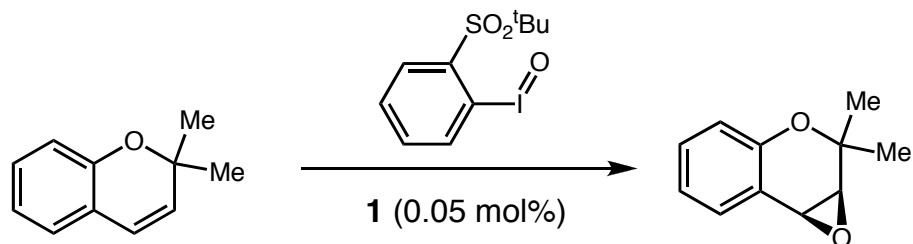
- A multi-ligand approach imparts structural stability (**L** and **H₂bpdc**)



Privileged Metal Catalysts - Salen

■ Mn(salen) MOF (**1**) is highly effective asymmetric catalyst for olefin epoxidation

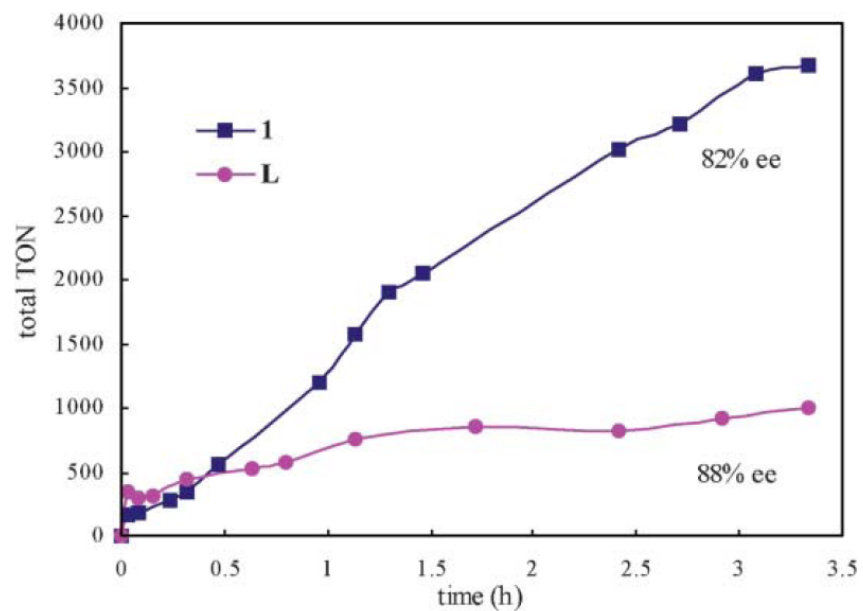
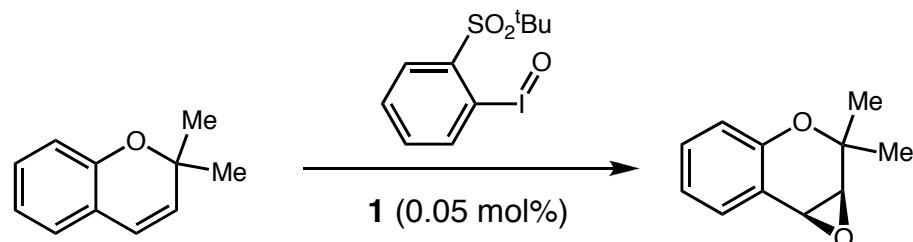
- Examined catalytic activity with 2,2-dimethyl-2H-chromene



Privileged Metal Catalysts - Salen

■ Mn(salen) MOF (**1**) is highly effective asymmetric catalyst for olefin epoxidation

- Examined catalytic activity with 2,2-dimethyl-2H-chromene

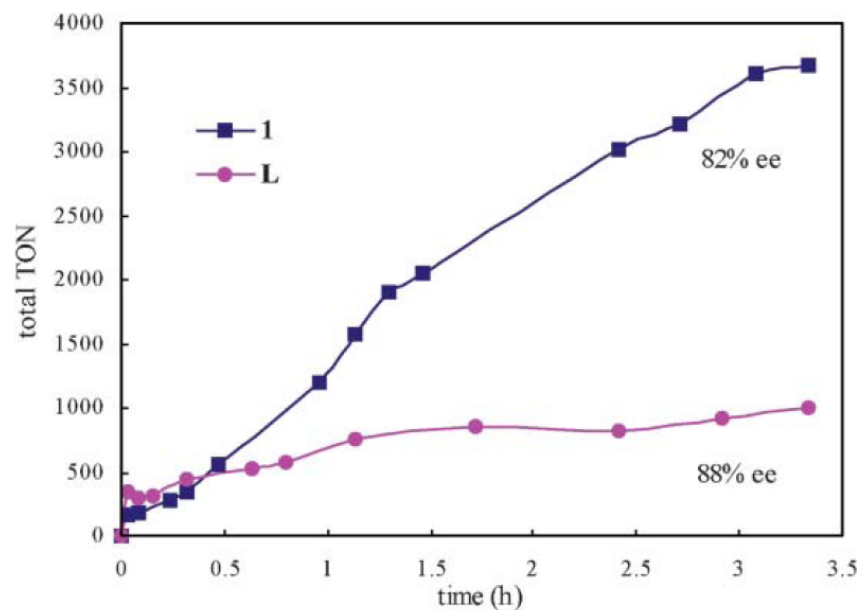


Cho, S. H.; Ma, B.; Nguyen, S. T.; Hupp, J. T.; Albrecht-Schmitt, T. E. *Chem. Commun.* **2006**, 24, 2563-2565.

Privileged Metal Catalysts - Salen

■ Mn(salen) MOF (1) is highly effective asymmetric catalyst for olefin epoxidation

- Immobilization of salen complexes avoids oxidative deactivation
- Minor decrease in % ee possibly due to electronic withdrawing effect of pyridyl-zinc binding



Cho, S. H.; Ma, B.; Nguyen, S. T.; Hupp, J. T.; Albrecht-Schmitt, T. E. *Chem. Commun.* **2006**, 24, 2563-2565.

Privileged Metal Catalysts - Salen

■ Mn(salen) MOF (**1**) is highly effective asymmetric catalyst for olefin epoxidation

- Immobilization of salen complexes avoids oxidative deactivation
- Minor decrease in % ee possibly due to electronic withdrawing effect of pyridyl-zinc binding
- Size selectivity experiments shows catalysis occurs predominantly within pores
- Intentional catalyst oxidation of MOF surface dramatically improves substrate size selectivity
- Recycling **1** shows similar reactivity and identical enantioselectivity

Table 1 Recyclability of **1** in the asymmetric epoxidation of 2,2-dimethyl-2*H*-chromene^a

Entry	Cycle ^b	Yield [%] ^c	TON	ee [%] ^d
1	1st	71	1430	82
2	2nd	71	1420	82
3	3rd	66	1320	82

Privileged Metal Catalysts - Metalloporphyrins

- Metalloporphyrins have recently become a new class of catalytically active linkers in MOFs
 - PIZA-3 showed first catalytic activity, but exclusively on exterior of framework

Suslick, K. S.; Bhyrappa, P.; Chou, J. -H.; Kosal, M. E.; Nakagaki, S.; Smithenry, D. W.; Wilson, S. R. *Acc. Chem. Res.* **2005**, *38*, 263-291.

Shultz, A. M.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *J. Am. Chem. Soc.* **2009**, *131*, 4204-4205.

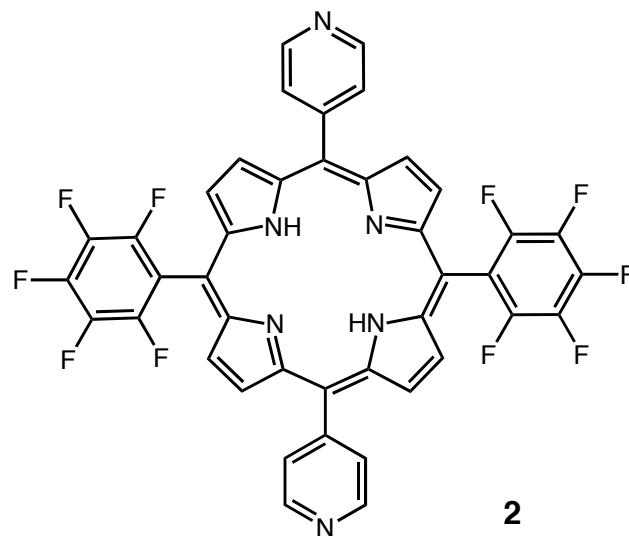
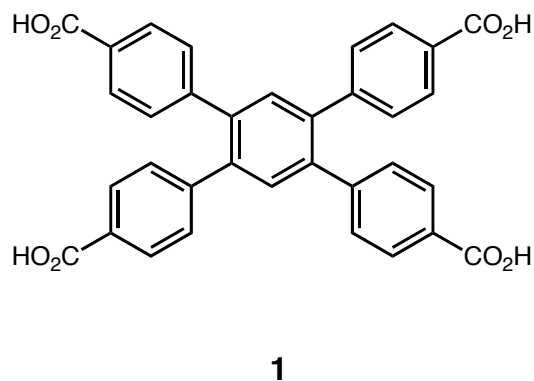
Privileged Metal Catalysts - Metalloporphyrins

■ Metalloporphyrins have recently become a new class of catalytically active linkers in MOFs

- PIZA-3 showed first catalytic activity, but exclusively on exterior of framework

■ Mixed-ligand strategy enables metalloporphyrin incorporation with large pore size

- Tetratopic linker **1** adds rigidity to MOF and results in permanent microporosity
- Free-base porphyrin **2** avoids interpenetration or catalyst deactivation
- **2** gets metallated with Zn during solvothermal synthesis



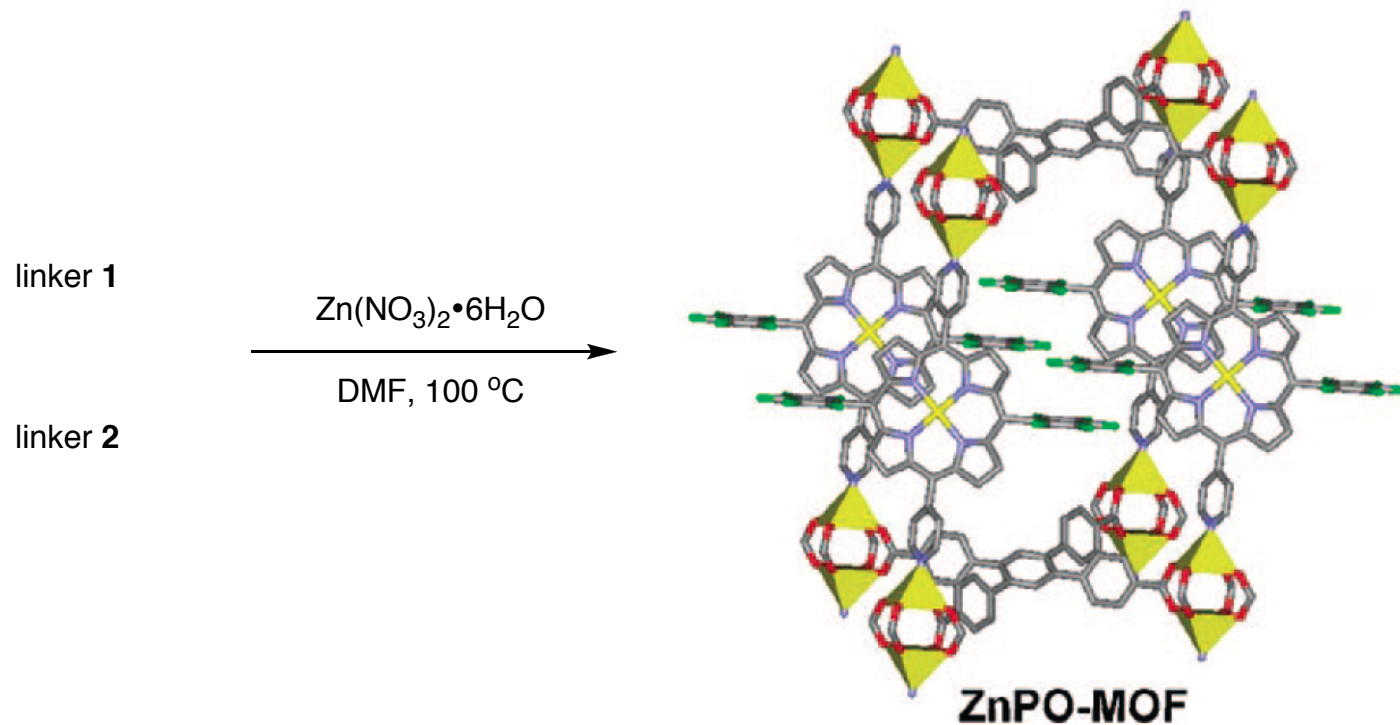
Suslick, K. S.; Bhyrappa, P.; Chou, J. -H.; Kosal, M. E.; Nakagaki, S.; Smithenry, D. W.; Wilson, S. R. *Acc. Chem. Res.* **2005**, *38*, 263-291.

Shultz, A. M.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *J. Am. Chem. Soc.* **2009**, *131*, 4204-4205.

Privileged Metal Catalysts - Metalloporphyrins

■ Mixed-ligand strategy enables metalloporphyrin incorporation with large pore size

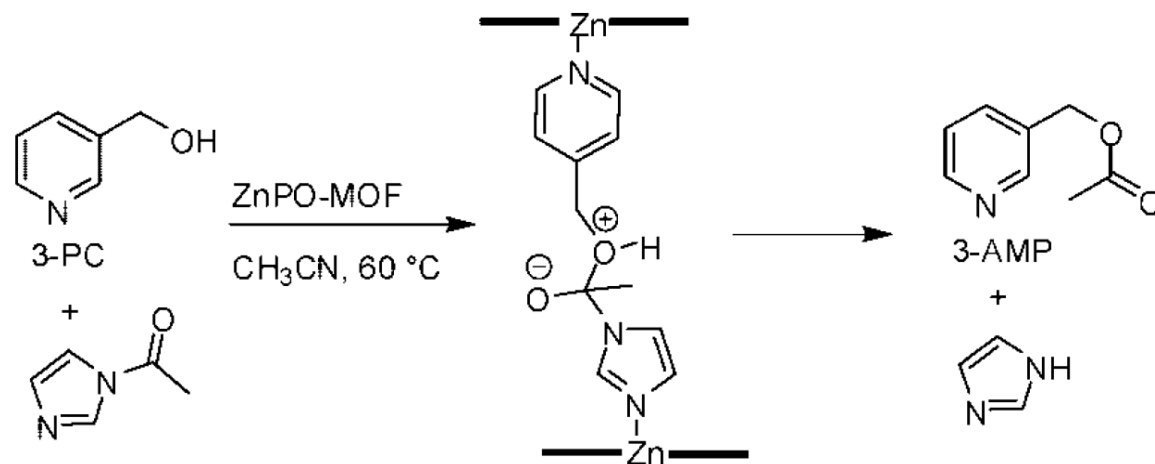
- Tetratopic linker **1** adds rigidity to MOF and results in permanent microporosity
- Free-base porphyrin **2** avoids interpenetration or catalyst deactivation
- **2** gets metallated with Zn during solvothermal synthesis



Shultz, A. M.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *J. Am. Chem. Soc.* **2009**, *131*, 4204-4205.

Privileged Metal Catalysts - Metalloporphyrins

- ZnPO-MOF shows catalytic activity for acyl-transfer reaction



Observed 2420-fold rate enhancement compared to uncatalyzed reaction

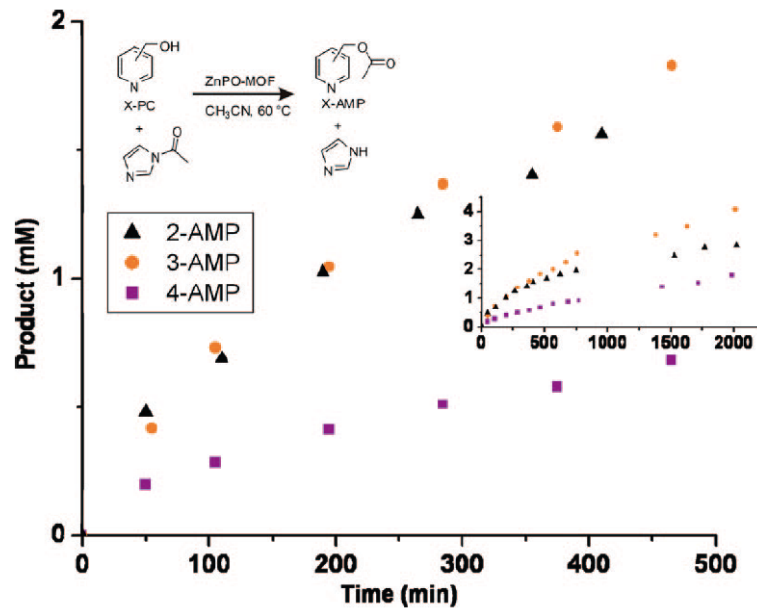
Privileged Metal Catalysts - Metalloporphyrins

- ZnPO-MOF shows catalytic activity for acyl-transfer reaction

- Three possible mechanistic explanations for rate acceleration with ZnPO-MOF:
 - 1) Lewis Acid activation
 - 2) Coordination to Zn concentrates both reactants within pores (no effect to activation energy)
 - 3) Coordination to Zn orients and aligns reactants for favorable acyl transfer

Privileged Metal Catalysts - Metalloporphyrins

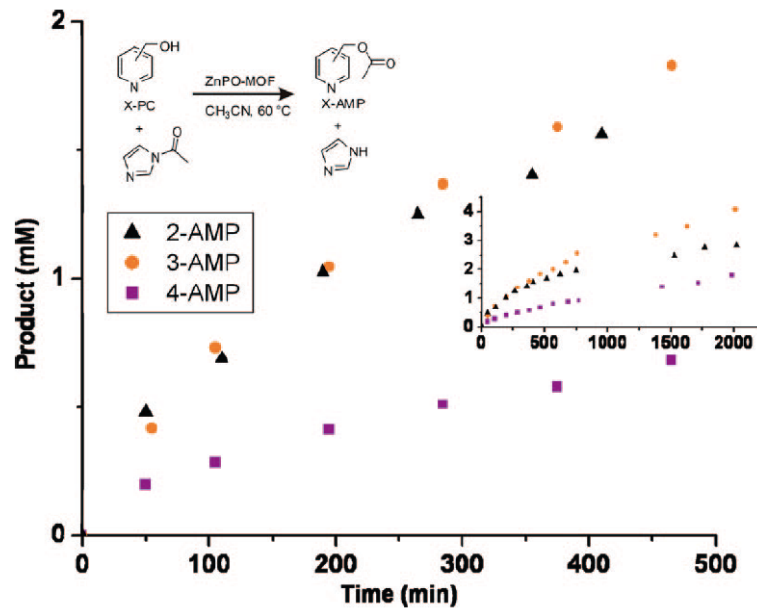
- ZnPO-MOF shows catalytic activity for acyl-transfer reaction
- Three possible mechanistic explanations for rate acceleration with ZnPO-MOF:
 - 1) Lewis Acid activation
 - 2) Coordination to Zn concentrates both reactants within pores (no effect to activation energy)
 - 3) Coordination to Zn orients and aligns reactants for favorable acyl transfer



Shultz, A. M.; Farha, O. K.; Hupp, J. T.; Nguyen, S. T. *J. Am. Chem. Soc.* **2009**, *131*, 4204-4205.

Privileged Metal Catalysts - Metalloporphyrins

- ZnPO-MOF shows catalytic activity for acyl-transfer reaction
- Three possible mechanistic explanations for rate acceleration with ZnPO-MOF:
 - 1) Lewis Acid activation
 - 2) Coordination to Zn concentrates both reactants within pores (no effect to activation energy)
 - 3) Coordination to Zn orients and aligns reactants for favorable acyl transfer



Little sensitivity to reaction rate with differing substrate isomers - 3rd mechanism is unlikely to be significant

Privileged Metal Catalysts - Metalloporphyrins

- ZnPO-MOF shows catalytic activity for acyl-transfer reaction
- Three possible mechanistic explanations for rate acceleration with ZnPO-MOF:

Reaction with homogeneous (tetraphenylporphyrin)Zn = ~22-fold rate enhancement

Both LA activation and preconcentration (more significant) are active

Privileged Metal Catalysts - Metalloporphyrins

■ ZnPO-MOF shows catalytic activity for acyl-transfer reaction

■ Three possible mechanistic explanations for rate acceleration with ZnPO-MOF:

Reaction with homogeneous (tetraphenylporphyrin)Zn = ~22-fold rate enhancement

Both LA activation and preconcentration (more significant) are active

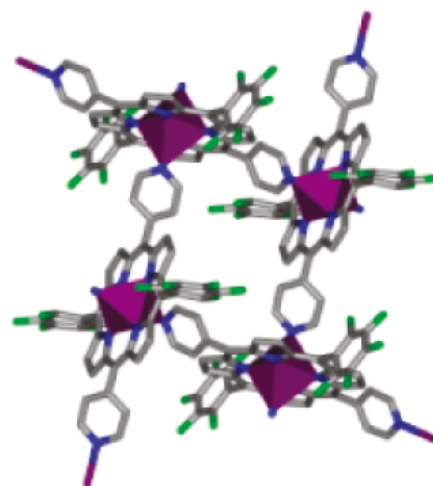
■ Inhibitory effect:

- Imidazole product acts as modest inhibitor of catalytic Zn sites (stronger Lewis base than NAI)

Privileged Metal Catalysts - Metalloporphyrins

■ Expanding metalloporphyrin-containing MOFs to different metals has proved challenging

- Pre-installing metal resulted in it acting as an auxiliary node
- The free base would sequester zinc ions during MOF synthesis

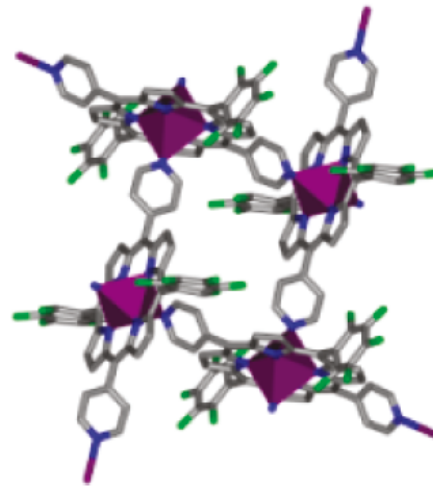


M = MnCl

Privileged Metal Catalysts - Metalloporphyrins

■ Expanding metalloporphyrin-containing MOFs to different metals has proved challenging

- Pre-installing metal resulted in it acting as an auxiliary node
- The free base would sequester zinc ions during MOF synthesis



M = MnCl

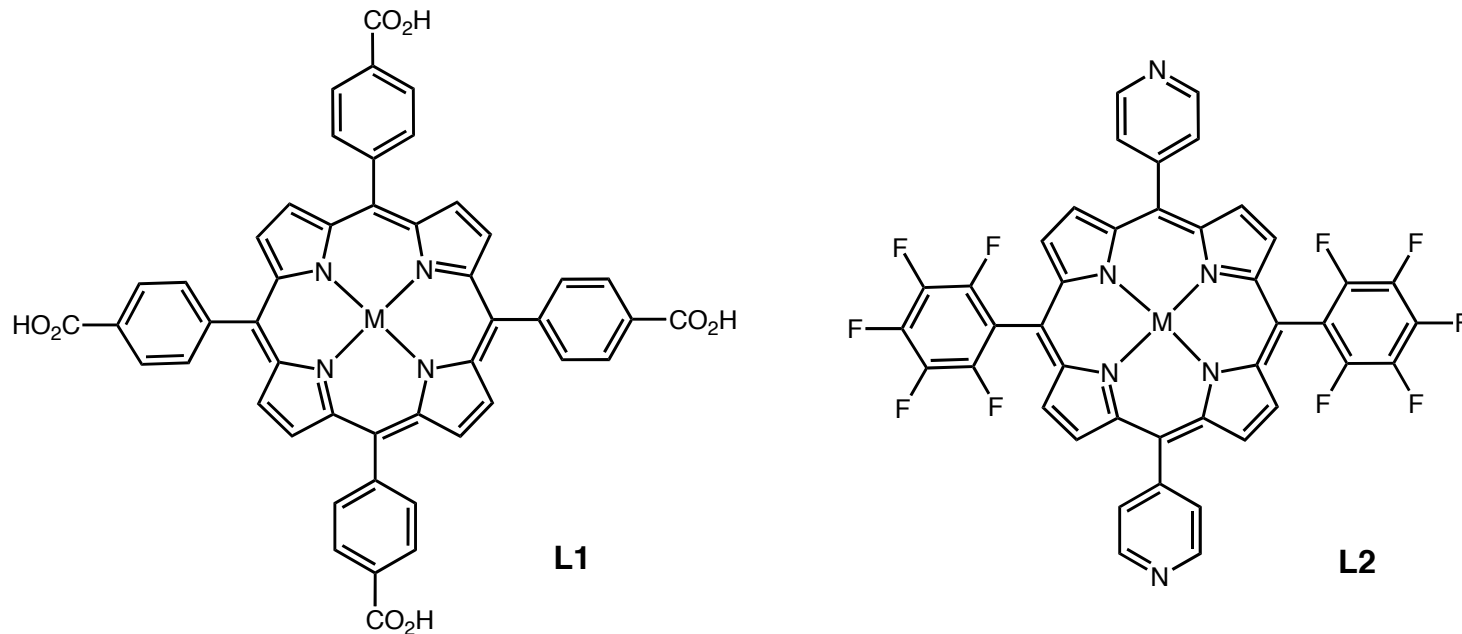
■ New synthetic approach enables incorporation of a variety of metalloporphyrins

- **RPMs** - Robust Porphyrinic Materials possess two unique metal-containing linkers

Privileged Metal Catalysts - Metalloporphyrins

■ RPMs employ two metalloporphyrin linkers **L1** and **L2**

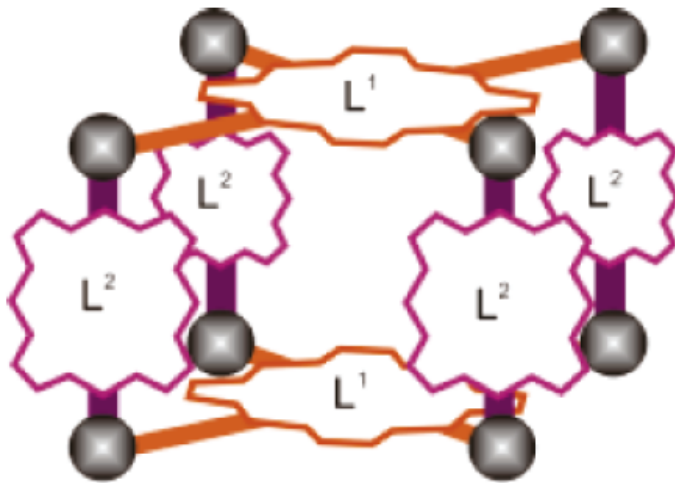
- Steric bulk on **L1** prevents coordination to metalloporphyrin site
- Solubility effects: low concentration of dipyrridyl subunit **L2** favors coordination at paddlewheel nodes
- Order of ligand addition is essential: **L2** added after **L1** and $\text{Zn}(\text{NO}_3)_2$ have begun to assemble



Privileged Metal Catalysts - Metalloporphyrins

■ RPMs can contain numerous metal catalytic sites

- **L1** = Al^{3+} , Pd^{2+} , Fe^{3+} , or free base (Zn^{2+})
- **L2** = Mn^{3+} or free base (Zn^{2+})
- Fe- and Mn-porphyrins axially ligate Cl^- , Al-porphyrin axially ligates HO^-
- MOF structures are identical: **L1** forms 2D sheets with dimeric Zn nodes, pillared by **L2**



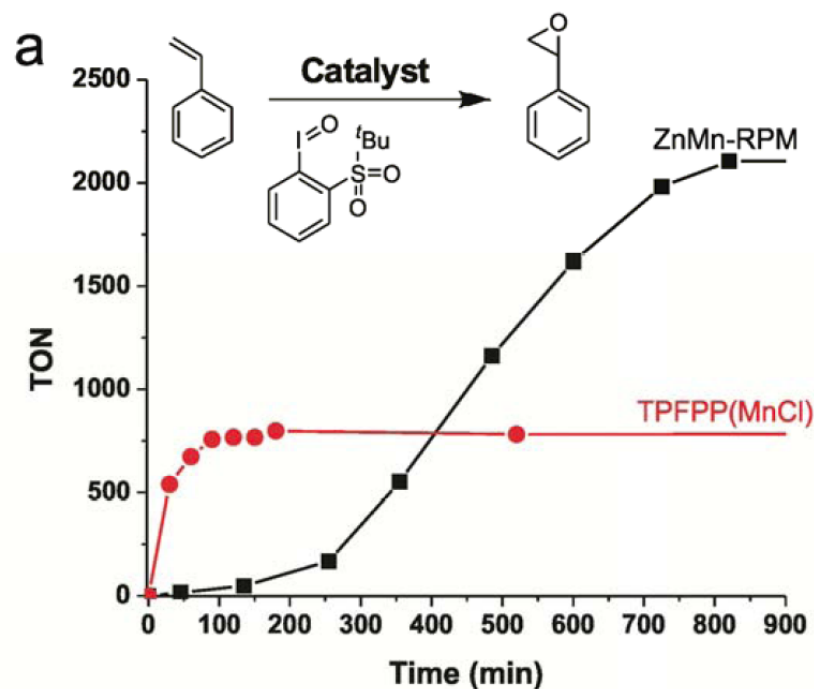
Metal-to-metal **L1** distance = 22 Å

Metal-to-metal **L2** distance = 16.6 Å

Privileged Metal Catalysts - Metalloporphyrins

■ ZnMn-RPM (M1M2-RPM) functions as effective heterogeneous oxidation catalyst

- Epoxidation of styrene and hydroxylation of cyclohexane
- Deactivation of MOF catalytic sites avoided due to difficulty in forming μ -oxo dimer complexes



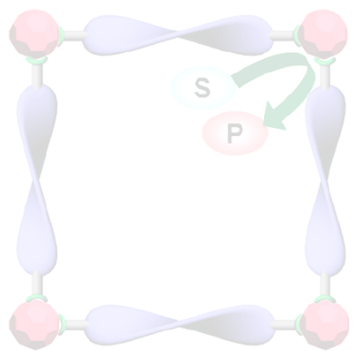
- Homogeneous Mn(porphyrin) showed 780 turnovers, before catalyst deactivation
- ZnMn-RPM showed 2150 turnovers before depletion of oxidant
- Induction period due to slow diffusion in and out of MOF pores

Privileged Metal Catalysts - Metalloporphyrins

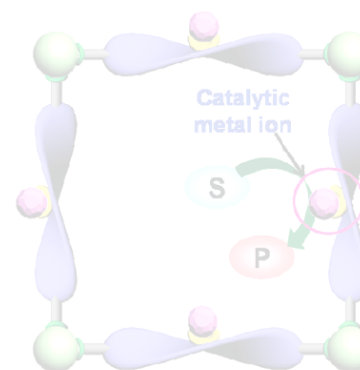
- RPMs = first class of dual metalloporphyrin incorporation into MOF scaffold
- Versatile and modular method for diverse metalloporphyrin MOF synthesis
- Potential for multiple catalytic sites and therefore cooperative/synergistic catalysis

Diverse Strategies for Metal-Organic Framework Catalysis

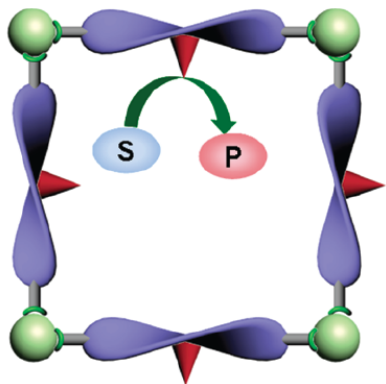
■ Metal node catalysis



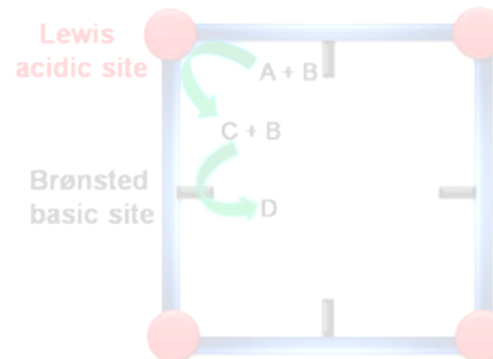
■ Privileged metal catalyst



■ Organocatalytic linkers



■ Multifunctional catalysis



Organocatalytic Linkers

■ Inherent difficulties with installing organocatalytic units in MOFs

- Interfere with synthesis - coordination to metal ions possible
- Catenation/interpenetration may prevent porous structure formation

Organocatalytic Linkers

■ Inherent difficulties with installing organocatalytic units in MOFs

- Interfere with synthesis - coordination to metal ions possible
- Catenation/interpenetration may prevent porous structure formation

■ Protected organocatalytic linkers can avoid these pitfalls (post-synthetic modification)

- Thermolabile Boc protecting group removed upon heating
- Prevents interpenetration and allows facile access to pores
- Reveals active amino functional group

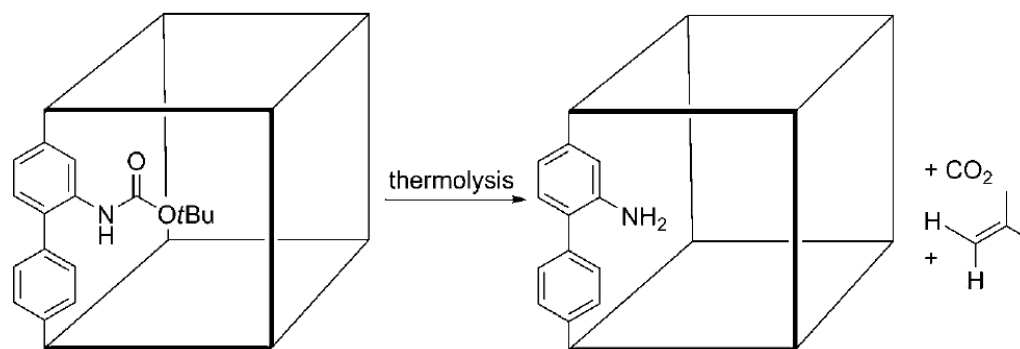
Organocatalytic Linkers

■ Inherent difficulties with installing organocatalytic units in MOFs

- Interfere with synthesis - coordination to metal ions possible
- Catenation/interpenetration may prevent porous structure formation

■ Protected organocatalytic linkers can avoid these pitfalls (post-synthetic modification)

- Thermolabile Boc protecting group removed upon heating
- Prevents interpenetration and allows facile access to pores
- Reveals active amino functional group



Organocatalytic Linkers

■ Protected organocatalytic linkers can avoid these pitfalls (post-synthetic modification)

- Thermolabile Boc protecting group removed upon heating
- Prevents interpenetration and allows facile access to pores
- Reveals active amino functional group

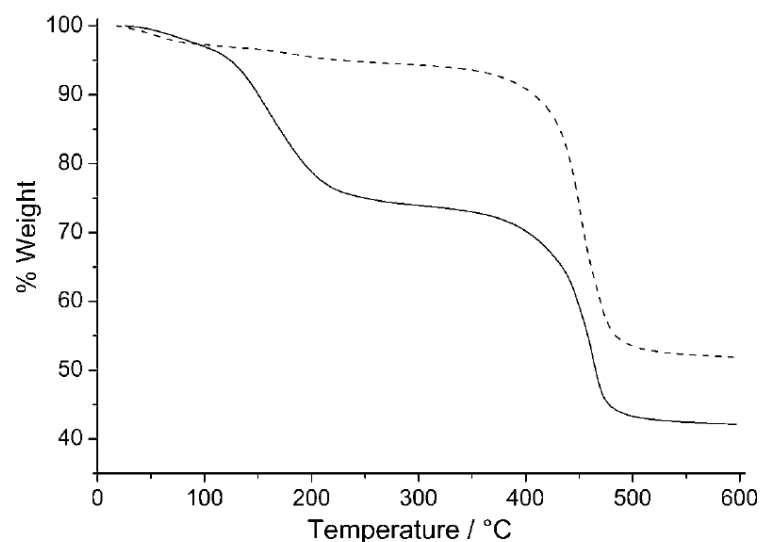
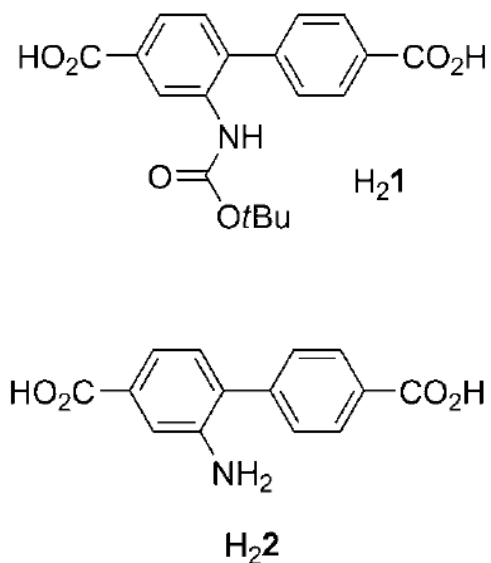


Figure 2. Thermogravimetrograms of [Zn₄O(1)₃] (solid line) and [Zn₄O(2)₃] (dashed line) recorded under a N₂ atmosphere with a heating rate of 5 °C min⁻¹.



Organocatalytic Linkers - Proline

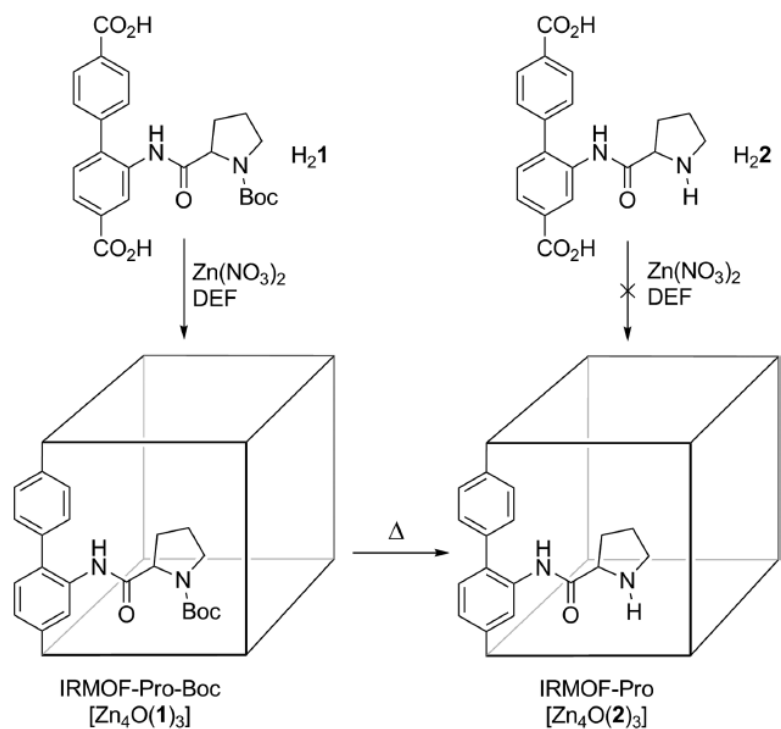
■ Shane Telfer - cubic Zn(II) IRMOF-Pro contains organocatalytic proline motif

- "Isorecticular" cubic framework (IRMOF)
- Unprotected organic linker ineffective in MOF synthesis
- Post-synthetic thermal Boc-deprotection necessary

Organocatalytic Linkers - Proline

■ Shane Telfer - cubic Zn(II) IRMOF-Pro contains organocatalytic proline motif

- "Isorecticular" cubic framework (IRMOF)
- Unprotected organic linker ineffective in MOF synthesis
- Post-synthetic thermal Boc-deprotection necessary



Organocatalytic Linkers - Proline

■ Shane Telfer - cubic Zn(II) IRMOF-Pro contains organocatalytic proline motif

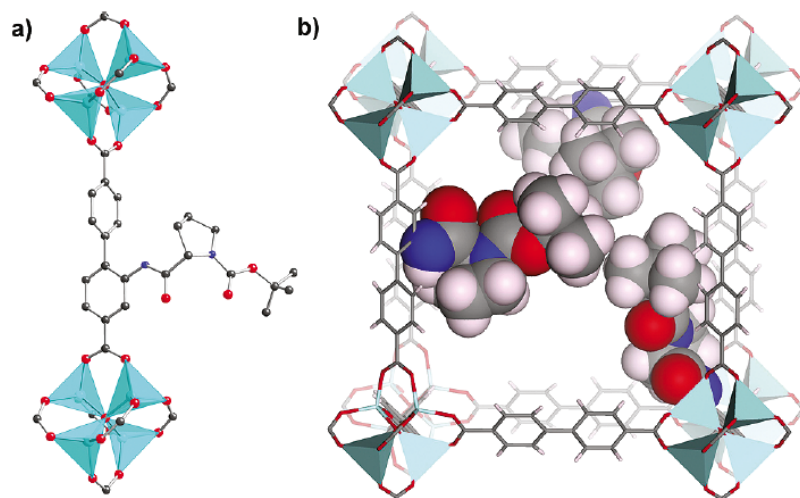


Figure 1. Structure of IRMOF-Pro-Boc as determined by X-ray crystallography. (a) Ligand strut and Zn₄O nodes. Gray = C; red = O; blue = N; turquoise = Zn. Hydrogen atoms have been omitted for clarity. (b) Typical cubic repeating unit. One set of the statistically disordered N-Boc-proline side chains is shown.

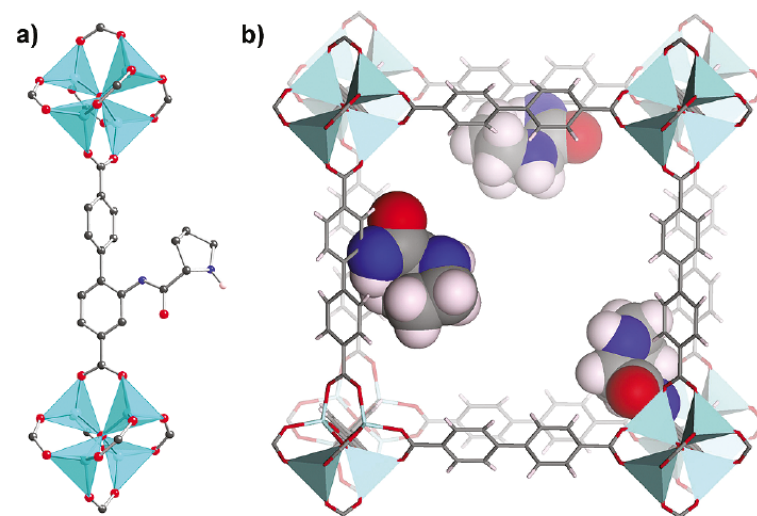


Figure 3. Structure of IRMOF-Pro as determined by X-ray crystallography. (a) Ligand strut and Zn₄O nodes. Gray = C; red = O; blue = N; turquoise = Zn. Most of the hydrogen atoms have been omitted for clarity. (b) Typical cubic repeating unit. One set of the statistically disordered proline side chains is shown.

Organocatalytic Linkers - Proline

■ IRMOF-Pro demonstrates catalytic activity for asymmetric aldol reaction

Scheme 2. Aldol Reactions of Acetone and Cyclopentanone with 4-Nitrobenzaldehyde Catalyzed by IRMOF-Pro



Ketone/catalyst	Time (h)	Cat. mol % ^a	dr (syn : anti) ^b	ee ^b
acetone				
IRMOF-Pro	40	100	–	29% ^c
IRMOF-Pro-Boc	60	≥ 50	–	No reaction
H ₂ 2	96	20	–	52%
cyclopentanone				
IRMOF-Pro	30	100	1 : 3	3% (syn), 14% (anti)
IRMOF-Pro-Boc	30	≥ 50	No reaction	–
H ₂ 2	96	20	2 : 3	86% (syn), 78% (anti)

Organocatalytic Linkers - Proline

■ IRMOF-Pro demonstrates catalytic activity for asymmetric aldol reaction

Scheme 2. Aldol Reactions of Acetone and Cyclopentanone with 4-Nitrobenzaldehyde Catalyzed by IRMOF-Pro



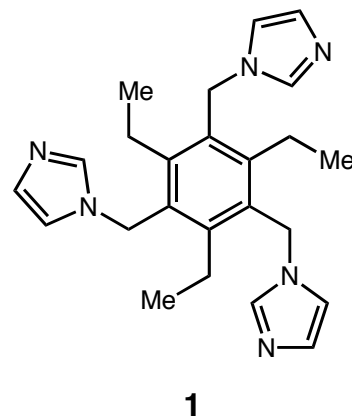
■ Poor enantioselectivity attributed to:

- Minor degree of organic linker racemization in post-synthetic deprotection step
- Low facial selectivity towards enamine intermediate in large framework pore
- Absence of H-bond donors on organocatalytic unit

Organocatalytic Linkers - N-Heterocyclic Carbenes

■ TIF-1 demonstrates first example of NHC sites installed in MOF

- Tripodal imidazolate framework-1 comprised of Co(II) nodes with linker **1**
- Utilizes metal imidazolates as carbene precursors
- Post-synthetic deprotonation should reveal catalytic site



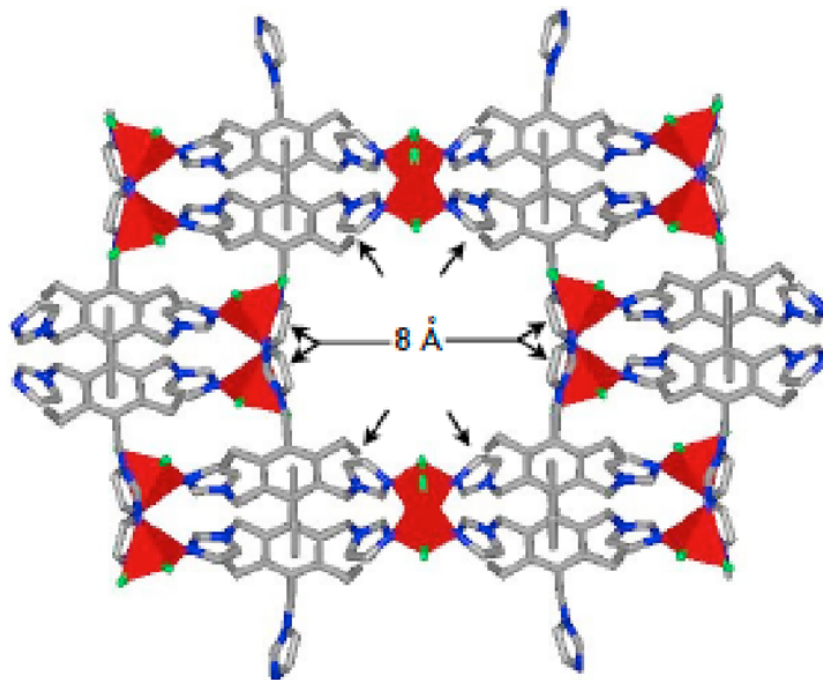
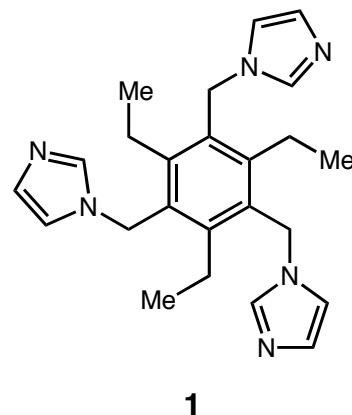
Willans et al. *Dalton Trans.* **2009**, 6480-6482.

Lalonde, M. B.; Farha, O. K.; Scheidt, K. A.; Hupp, J. T. *ACS Catal.* **2012**, 2, 1550-1554.

Organocatalytic Linkers - N-Heterocyclic Carbenes

■ TIF-1 demonstrates first example of NHC sites installed in MOF

- Tripodal imidazolate framework-1 comprised of Co(II) nodes with linker **1**
- Utilizes metal imidazolates as carbene precursors
- Post-synthetic deprotonation should reveal catalytic site



Willans et al. *Dalton Trans.* **2009**, 6480-6482.

Lalonde, M. B.; Farha, O. K.; Scheidt, K. A.; Hupp, J. T. *ACS Catal.* **2012**, 2, 1550-1554.

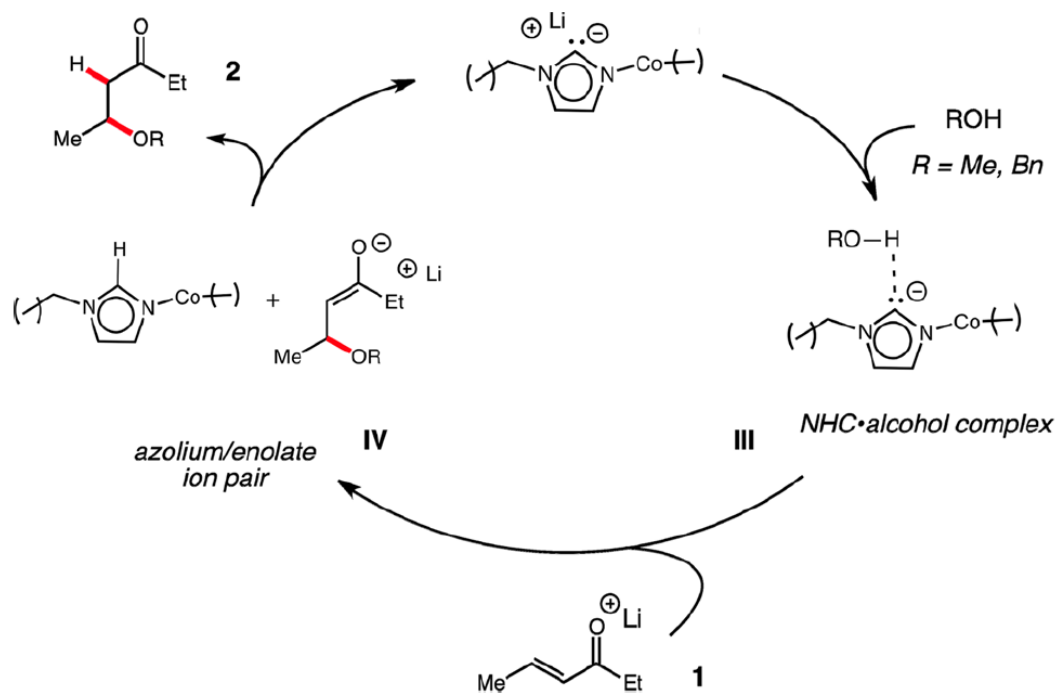
Organocatalytic Linkers - N-Heterocyclic Carbenes

- TIF-1 catalyzes the conjugate addition of alcohols to α,β -unsaturated ketones
 - NHC sites function as Brønsted bases following n-BuLi deprotonation
 - Initially believed to be C4 or C5 deprotonation (*a*NHCs) due to inaccessible C2 position in pore
 - Size selective experiments suggest catalysis occurs on exterior of MOF (not within pores)

Organocatalytic Linkers - N-Heterocyclic Carbenes

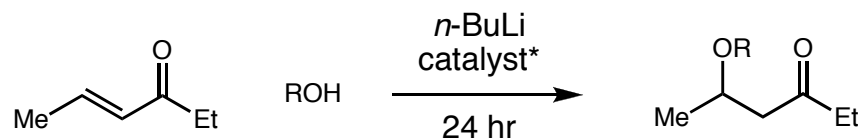
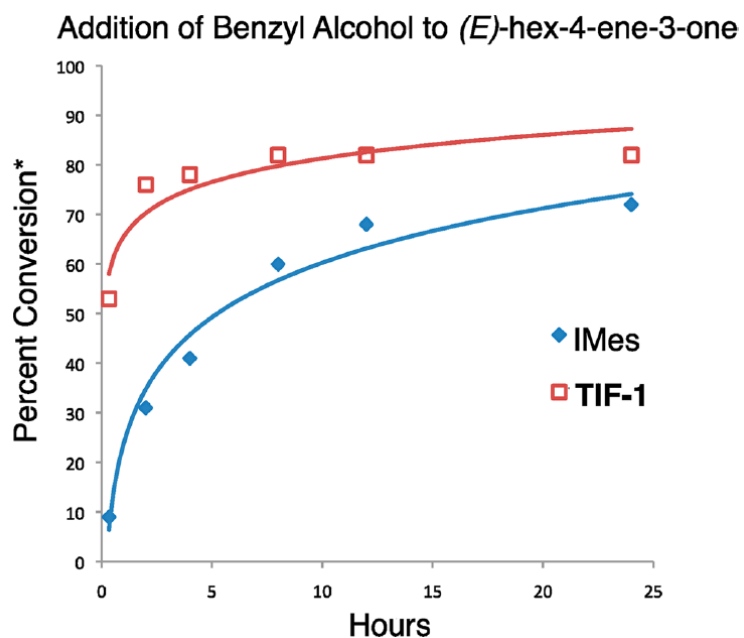
■ TIF-1 catalyzes the conjugate addition of alcohols to α,β -unsaturated ketones

- NHC sites function as Brønsted bases following n-BuLi deprotonation
- Initially believed to be C4 or C5 deprotonation (aNHCs) due to inaccessible C2 position in pore
- Size selective experiments suggest catalysis occurs on exterior of MOF (not within pores)



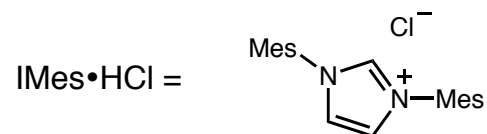
Organocatalytic Linkers - N-Heterocyclic Carbenes

■ TIF-1 catalyzes the conjugate addition of alcohols to α,β -unsaturated ketones



Alcohol	Catalyst	Yield
MeOH	IMes•HCl	77%
MeOH	TIF-1	65%
BnOH	IMes•HCl	72%
BnOH	TIF-1	83%

*0.8 mol% for TIF-1, 5 mol% for IMes•HCl



Organocatalytic Linkers - N-Heterocyclic Carbenes

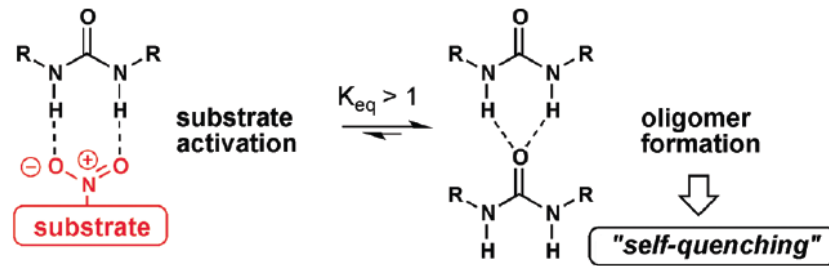
■ TIF-1 - first example of MOF-based NHC catalysis

- Only 1 in 20,000 imidazole groups are involved in catalysis (on surface)
- Several orders of magnitude more reactive than homogeneous analog
- Presence of tightly coordinated Li^+ to carbene may explain heightened reactivity
- Enlarging channels may greatly improve TIF-1 reactivity

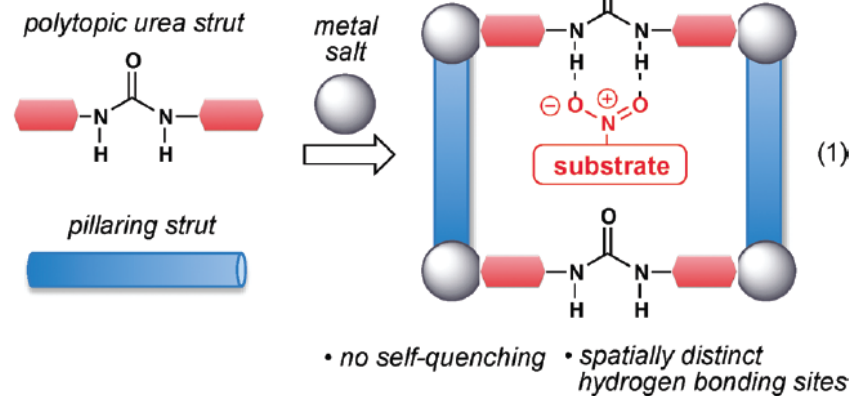
Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 contains hydrogen-bonding urea strut

- Example of installing homogeneous catalyst in heterogeneous structure
- Urea MOF would avoid oligomerization of homogeneous H-bonding catalyst (self-quenching)
- Structurally rigid linker could separate catalytic functionalities in MOF



Urea Metal Organic Framework

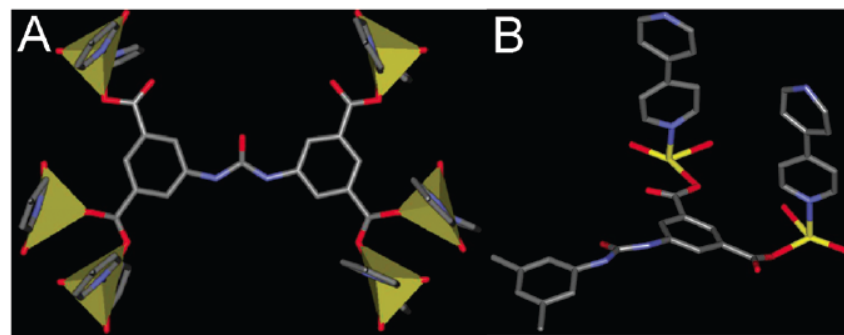
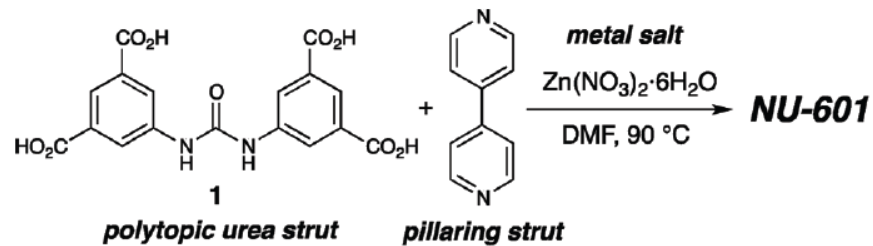


Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 - $\text{Zn}(4,4'\text{-bpy})_2(1\text{-4H})$

- Carboxylic acid groups on urea linker: metal-binding sites and increases N-H acidity
- Urea group more thermally stable than thiourea in MOF synthesis

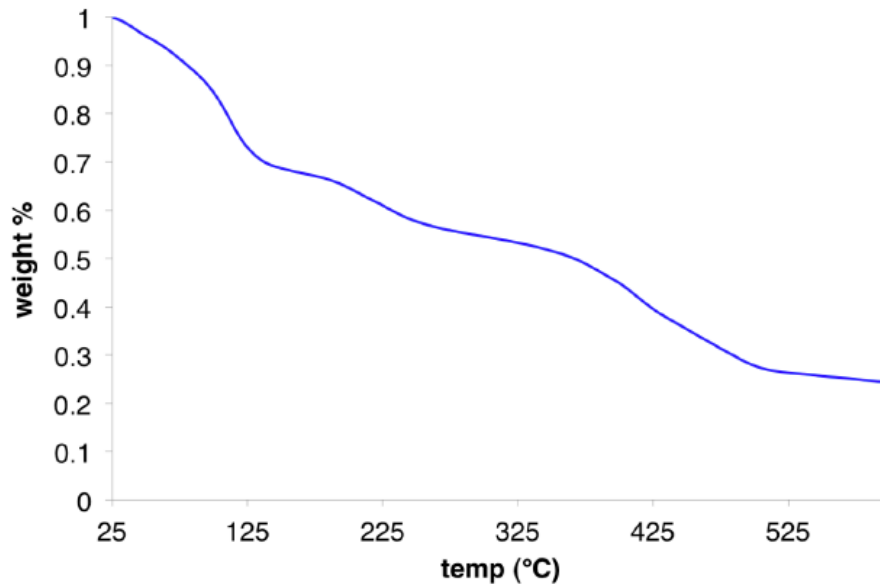
Scheme 1. (top) Synthesis of NU-601; (bottom) Views of (A) 1 and the Zn_2 Nodes and (B) the Repeating Unit of NU-601^a



Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 - catalytic activity requires accessible pores

- Residual DMF remains in pores through H-bonding to urea N-H bonds
- Thermal activation proved problematic (as demonstrated by TGA and PXRD)

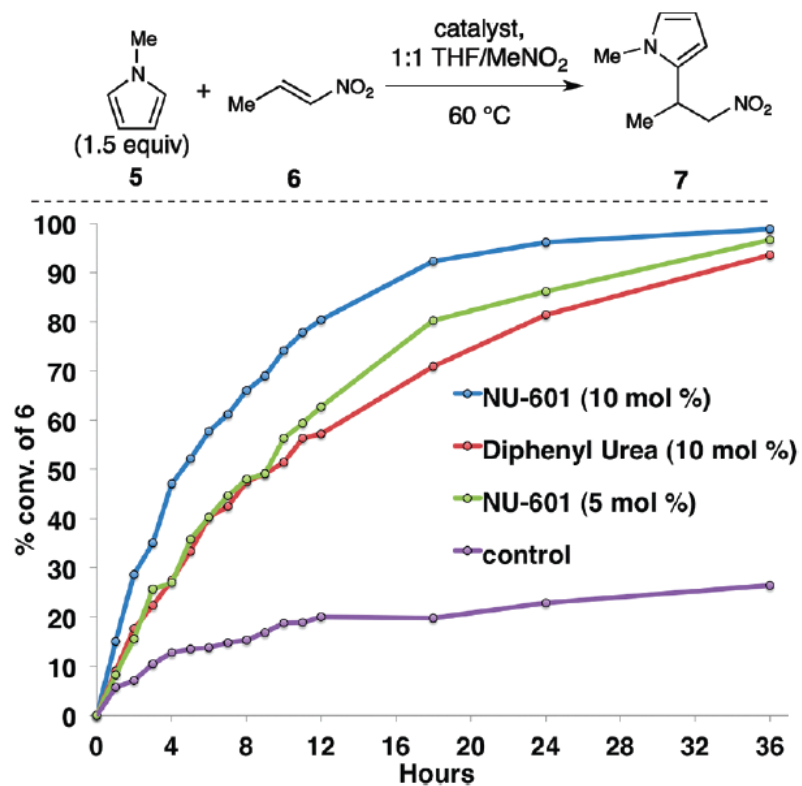


- ~30% weight loss at 125 °C
- At 200 °C, second weight loss occurs
- PXRD revealed loss of crystallinity after heating and DMF still present
- Solvent exchange with MeNO₂ over 4 days successfully removed DMF

Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 catalyzes Friedel-Crafts reaction between *N*-methylpyrrole and (*E*)-1-nitroprop-1-ene

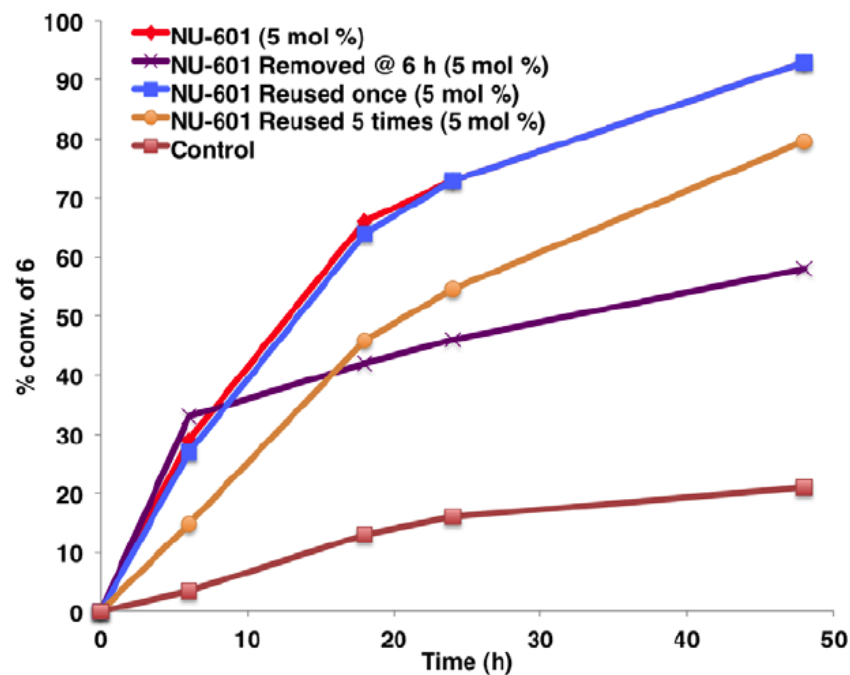
- Polar solvent combination promotes more H-bonding exchange/catalyst turnover (toluene was ineffective)
- After 36 hours, 98% of **6** was consumed



Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 catalyzes Friedel-Crafts reaction between *N*-methylpyrrole and (*E*)-1-nitroprop-1-ene

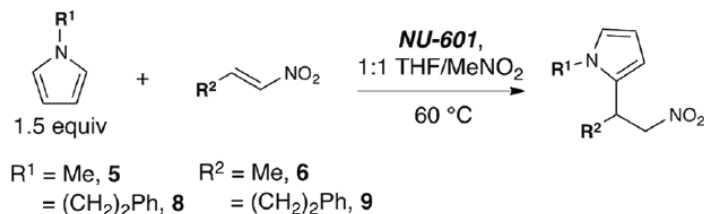
- Control experiments show catalyst is heterogeneous in nature
- Only slight degradation in reactivity after multiple cycles



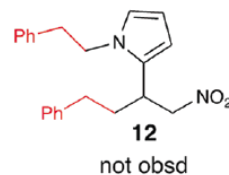
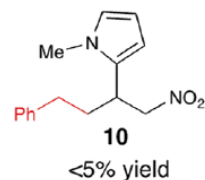
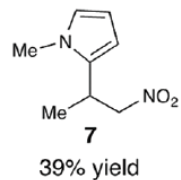
Organocatalytic Linkers - Hydrogen-bonding Ureas

■ NU-601 catalysis is size selective

- Size selectivity experiments demonstrate that *catalysis occurs predominantly within pores of framework*
- Sterically encumbered pyrroles cannot enter the porous network
- In equimolar amounts of **6** and **9**, **5** forms product **7** exclusively (13% yield)

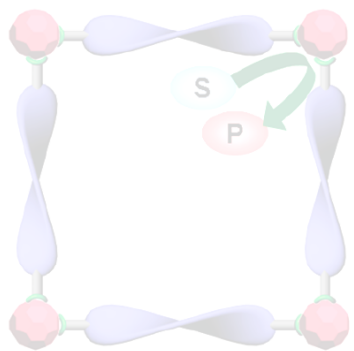


observed @ 48 h ($^1\text{H NMR}$ or GC)

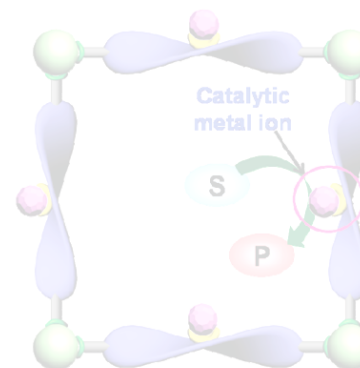


Diverse Strategies for Metal-Organic Framework Catalysis

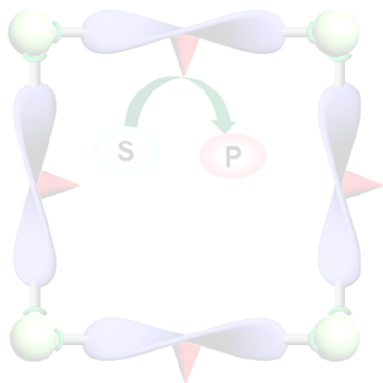
■ Metal node catalysis



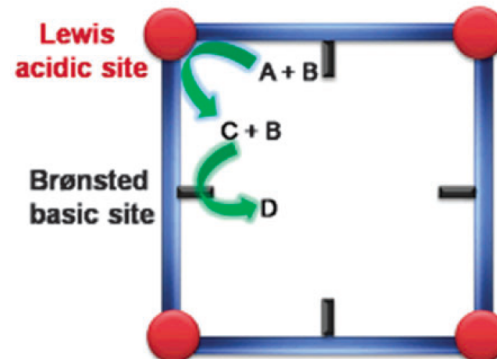
■ Privileged metal catalyst



■ Organocatalytic linkers



■ Multifunctional catalysis

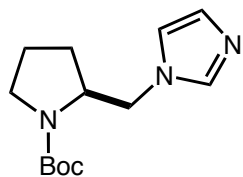


Cooperative Catalysis - Photoredox Organocatalysis

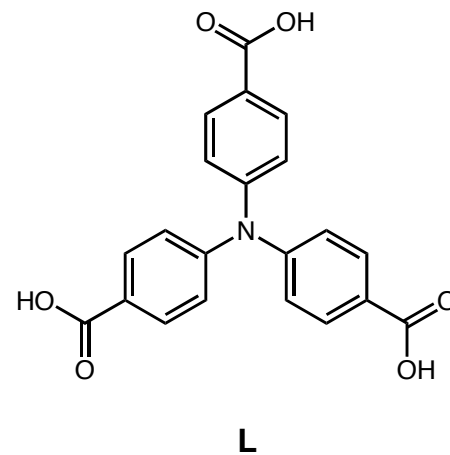
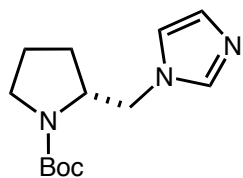
■ Duan and coworkers combined organocatalytic and photoactive units into single MOF scaffold

- Organocatalytic group = *L* or *D*-Boc-2-(imidazole)-1-pyrrolidine (**BCIP**)
- Photoredox catalyst = 4,4',4''-nitrilotribenzoic acid (**L**)

L-BCIP



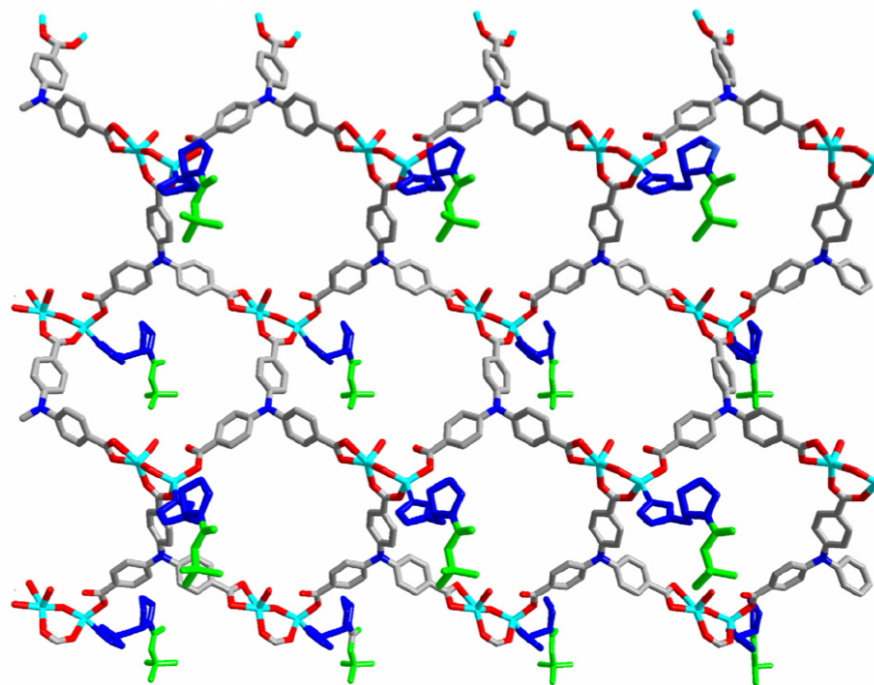
D-BCIP



Cooperative Catalysis - Photoredox Organocatalysis

■ Duan and coworkers combined organocatalytic and photoactive units into single MOF scaffold

- Heating **L-BCIP** and **L** with $\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ yielded **Zn-BCIP1**
- Post-synthetic deprotection gave catalytically active **Zn-PYI1**
- **Zn-PYI1** is 2D sheet of **L** struts and binuclear Zn nodes.
- Imidazole coordinates to Zn nodes and points proline functionality into open cavities



Wu, P.; He, C.; Wang, J.; Peng, X.; Li, X.; An, Y.; Duan, C. *J. Am. Chem. Soc.* **2012**, *134*, 14991-14999.

Cooperative Catalysis - Photoredox Organocatalysis

■ Zn-PY11 competent catalyst in the α -alkylation of aldehydes

- Enamine formed at organocatalytic site from aldehyde substrate
- Triphenylamine motif reduces bromomalonate through SET event
- C-C bond formation occurs within pore in an asymmetric manner



Cooperative Catalysis - Photoredox Organocatalysis

■ Zn-PYI1 competent catalyst in the α -alkylation of aldehydes

- Enamine formed at organocatalytic site from aldehyde substrate
- Triphenylamine motif reduces bromomalonate through SET event
- C-C bond formation occurs within pore in an asymmetric manner



$$E_{1/2}(\text{Zn-PYI1}^+/\text{Zn-PYI1}^*) = -2.12 \text{ V vs. SCE}$$

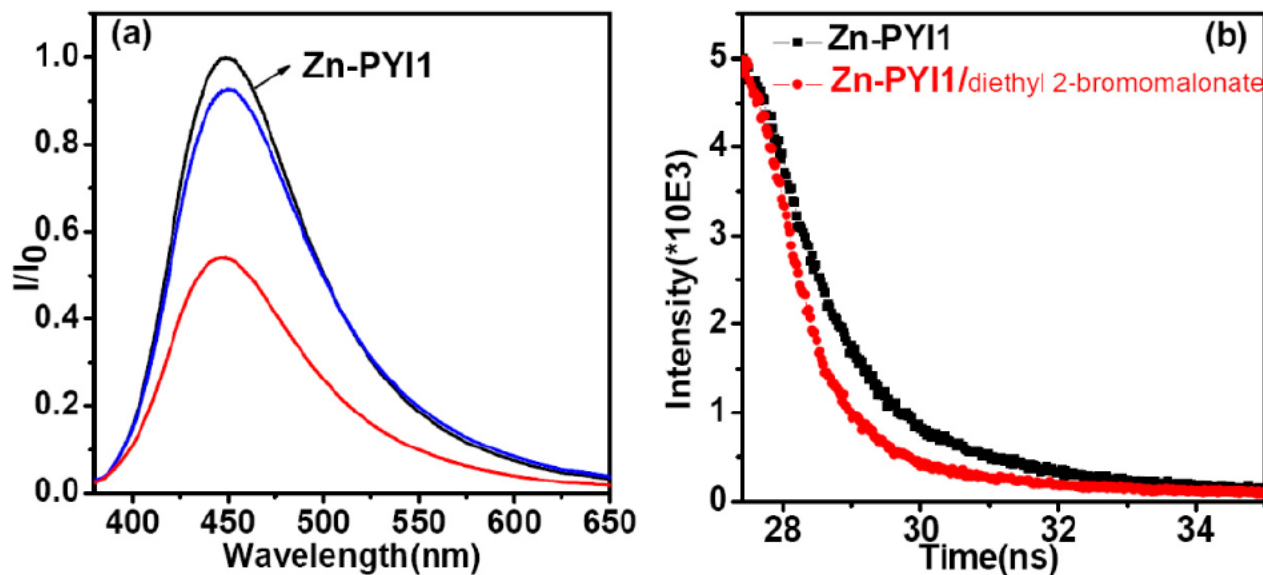
$$E_{1/2}(\text{Zn-PYI1}^+/\text{Zn-PYI1}) = +0.84 \text{ V vs. SCE}$$

$$E_{1/2}^{\text{red}}(\text{diethyl 2-bromomalonate}) = -0.49 \text{ V vs. SCE}$$

Cooperative Catalysis - Photoredox Organocatalysis

■ Zn-PY11 competent catalyst in the α -alkylation of aldehydes

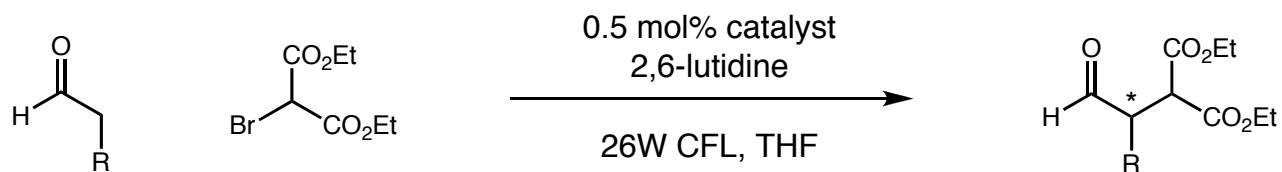
- ^1H NMR confirmed 1 equiv. aldehyde adsorbed per pyrrolidine moiety
- Luminescence intensity decreased upon addition of bromomalonate but not aldehyde
- Supports mechanistic hypothesis that reduction of bromomalonate occurs first

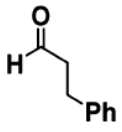
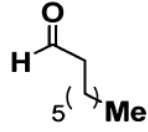
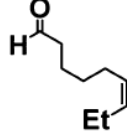


Cooperative Catalysis - Photoredox Organocatalysis

■ Zn-PYI1 competent catalyst in the α -alkylation of aldehydes

- High reaction efficiency and enantioselectivity: % yield (% ee)
- Control experiments show that deprotected Zn-PYI is necessary for any reactivity
- Reaction is heterogeneous in nature and the catalyst can be recycled



Entry	Catalyst			
	Zn-PYI1 ^a	74(+92)	65(+86)	84(+92)
	Zn-PYI2 ^a	73(-81)	61(-78)	85(-89)
	Ho-TCA/L-PYI ^b	86(+20)	90(+21)	93(+20)
	Ho-TCA/D-PYI ^b	85(-21)	90(-20)	95(-20)
	MOF-150/L-PYI ^b	67(+21)	78(+24)	80(+20)
	MOF-150/D-PYI ^b	62(-22)	73(-22)	80(-21)

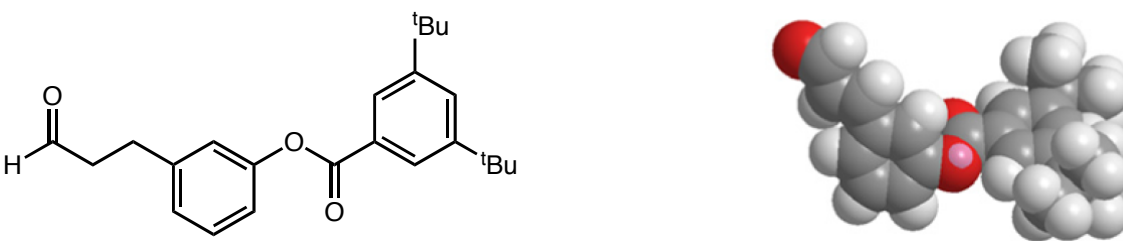
Wu, P.; He, C.; Wang, J.; Peng, X.; Li, X.; An, Y.; Duan, C. *J. Am. Chem. Soc.* **2012**, *134*, 14991-14999.

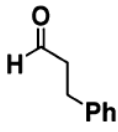
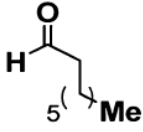
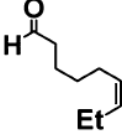
Cooperative Catalysis - Photoredox Organocatalysis

■ Zn-PYI1 compared to other photoactive MOFs: Ho-TCA and MOF-150

- Differences in reaction efficiency attributed to redox potentials
- Superior % ee with **Zn-PYI1** due to restricted environment within pores
- Use of bulky aldehydes unsuccessful, demonstrating catalysis occurs primarily within pores

7% yield



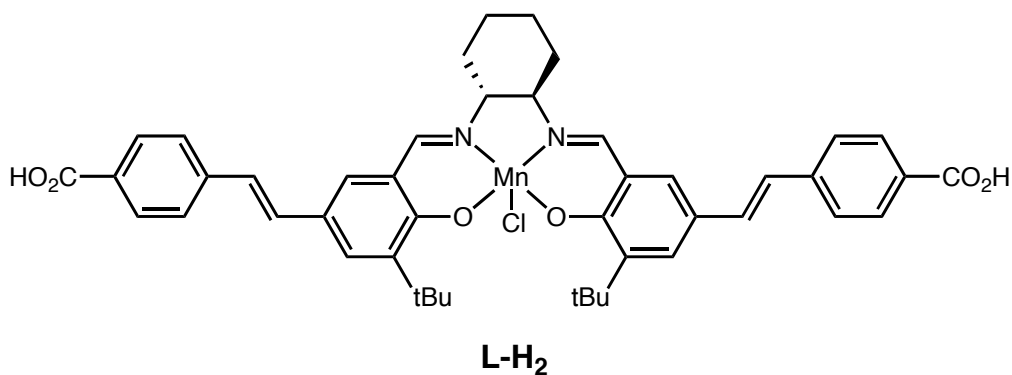
Entry	Catalyst			
Zn-PYI1 ^a		74(+92)	65(+86)	84(+92)
Zn-PYI2 ^a		73(-81)	61(-78)	85(-89)
Ho-TCA/L-PYI ^b		86(+20)	90(+21)	93(+20)
Ho-TCA/D-PYI ^b		85(-21)	90(-20)	95(-20)
MOF-150/L-PYI ^b		67(+21)	78(+24)	80(+20)
MOF-150/D-PYI ^b		62(-22)	73(-22)	80(-21)

Wu, P.; He, C.; Wang, J.; Peng, X.; Li, X.; An, Y.; Duan, C. *J. Am. Chem. Soc.* **2012**, *134*, 14991-14999.

Sequential Asymmetric Catalysis

■ Lin and coworkers combined metal node and Mn(salen) linker catalysis for sequential reactions

- Installation of **L-H₂** linker with Zn(NO₃)₂•6H₂O produces two structurally unique MOFs
- DEF yields **CMOF-1** while DBF yields **CMOF-6'**



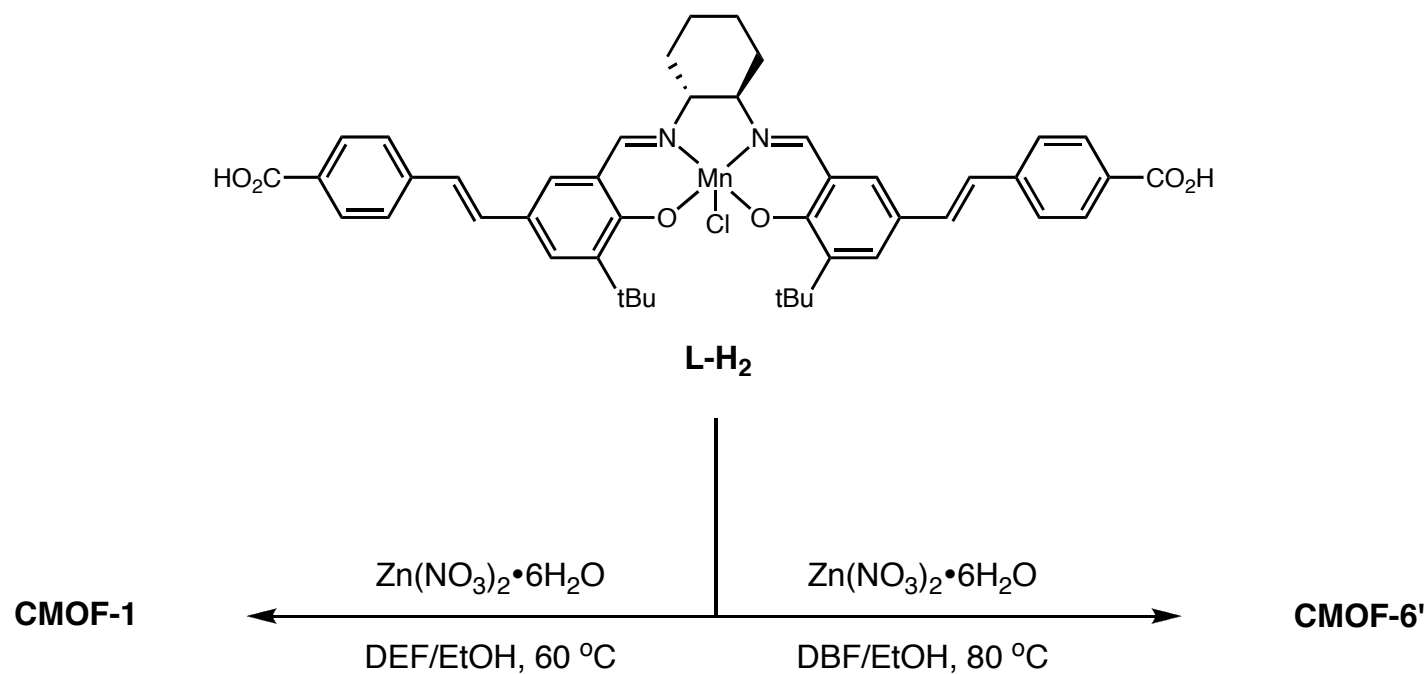
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

Sequential Asymmetric Catalysis

■ Lin and coworkers combined metal node and Mn(salen) linker catalysis for sequential reactions

- Installation of **L-H₂** linker with Zn(NO₃)₂•6H₂O produces two structurally unique MOFs
- DEF yields **CMOF-1** while DBF yields **CMOF-6'**



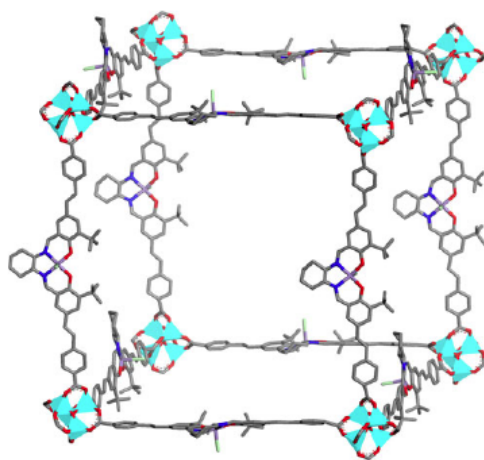
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

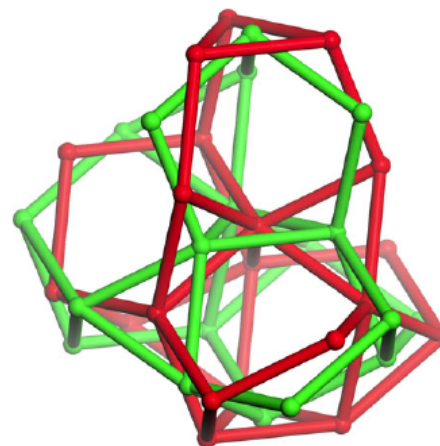
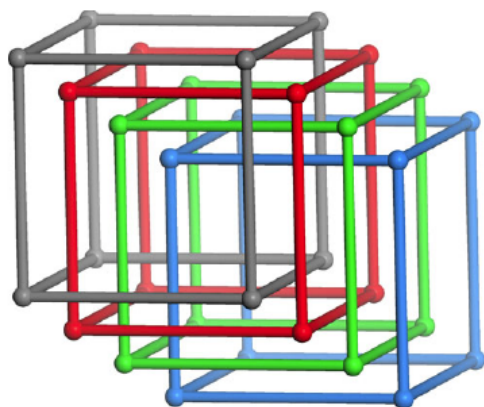
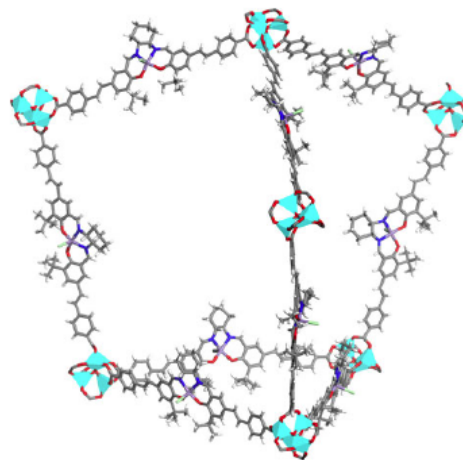
Sequential Asymmetric Catalysis

■ **CMOF-1** is cubic (4-fold interpenetration), **CMOF-6'** is cuboctahedral (2-fold interpenetration)

CMOF-1



CMOF-6'



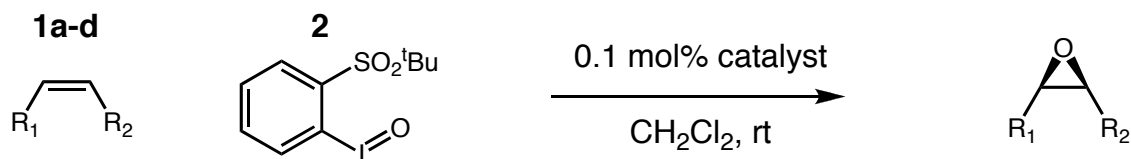
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

Sequential Asymmetric Catalysis

■ CMOF-1 and CMOF-6' catalyze sequential epoxidation-epoxide opening reaction

- Mn(salen) linkers catalyze the asymmetric epoxidation of alkenes
- Zn SBUs catalyze the stereo and regioselective epoxide opening



entry	catalyst	alkene	conv. (%) ^b	ee (%) ^c
1	CMOF-1		>99	23
2	CMOF-6'		96	22
3 ^d	L ₃ -Me ₂		60	64
4	CMOF-1		93	82
5	CMOF-6'		83	82
6 ^d	L ₃ -Me ₂		80	87
7	CMOF-1		84	83
8	CMOF-6'		71	84
9 ^d	L ₃ -Me ₂		90	92
10	CMOF-1		74	74
11	CMOF-6'		64	72
12 ^d	L ₃ -Me ₂		81	88

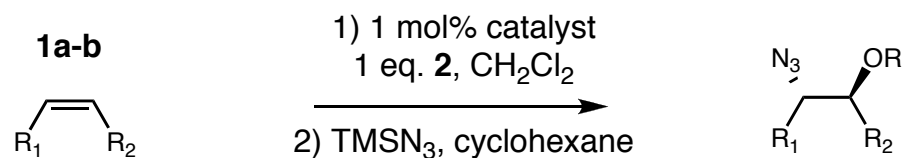
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

Sequential Asymmetric Catalysis

■ CMOF-1 and CMOF-6' catalyze sequential epoxidation-epoxide opening reaction

- Homogeneous Mn(salen) linkers do not effect epoxide opening (< 5% yield)
- Single regioisomer and diastereomer



entry	catalyst	alkene	product	conv. (%) ^a	ee (%) ^b
1	CMOF-1			40	39 (39)
2	CMOF-6'			60	50 (48)
3	CMOF-1			41	86 (84)
4	CMOF-6'			57	81 (82)

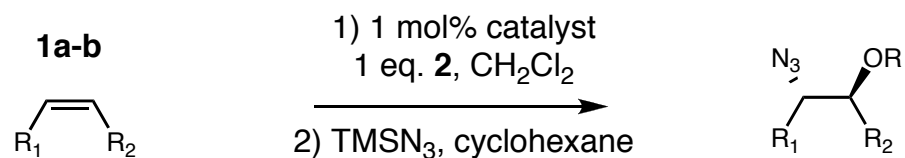
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

Sequential Asymmetric Catalysis

■ CMOF-1 and CMOF-6' catalyze sequential epoxidation-epoxide opening reaction

- Homogeneous Mn(salen) linkers do not effect epoxide opening (< 5% yield)
- Single regioisomer and diastereomer



- Lower yield for CMOF-6' in epoxidation step due to less accessible Mn(salen) sites
- Larger channel sizes in CMOF-6' = higher sequential catalytic activity
- Isolation of multiple active sites in MOF scaffold enable successful tandem catalysis

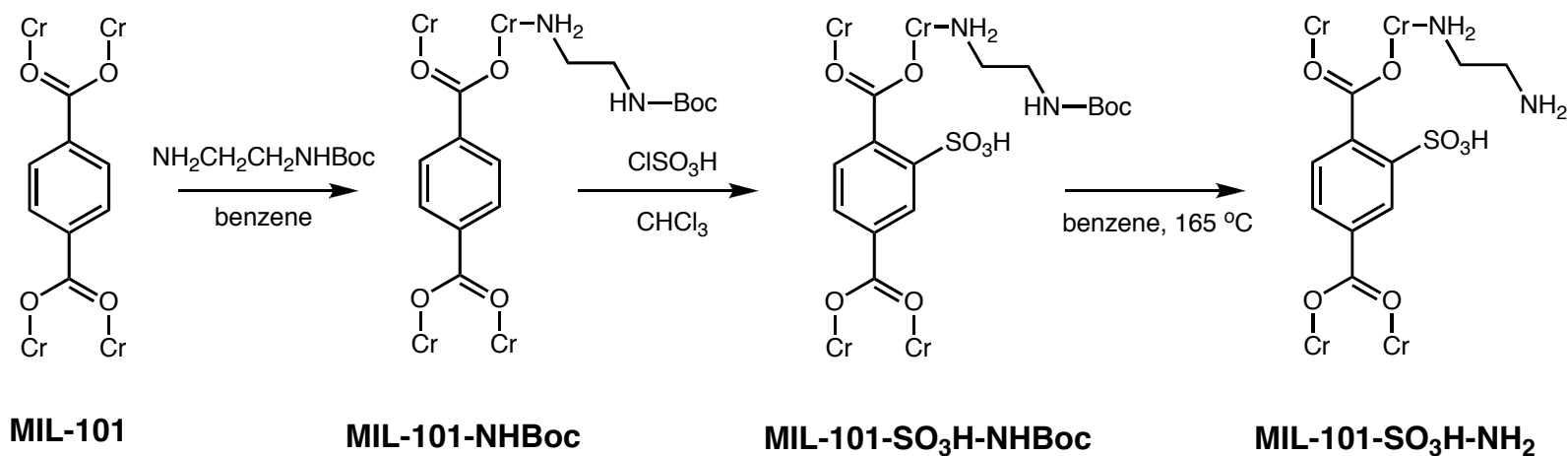
Song, F.; Wang, C.; Lin, W. *Chem. Commun.* **2011**, 47, 8256-8258.

Song, F.; Zhang, T.; Wang, C.; Lin, W. *Proc. R. Soc. A.* **2012**, 468, 2035-2052.

Tandem Catalysis - Organo-bifunctionalization

■ Shi and coworkers used PSM to install multiple catalytic sites on MIL-101

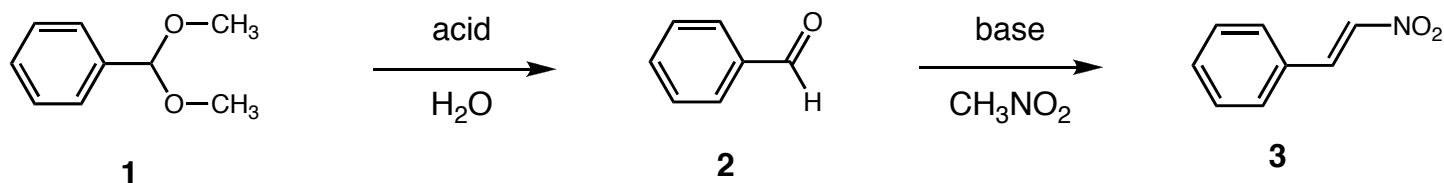
- First example of an organo-bifunctionalized MOF
- Grafting a functional group onto a coordinately unsaturated metal node (step 1)
- Installing second functional group onto organic linker (step 2)
- **MIL-101-SO₃H-NH₂** contains both Lewis acidic and Lewis basic catalytic sites



Tandem Catalysis - Organo-bifunctionalization

■ MIL-101-SO₃H-NH₂ tested in tandem acetal hydrolysis-Henry reaction

- Bifunctionalized MOF functioned far superior to monofunctionalized MOFs
- Homogeneous mixture of free acid and base showed no activity
- **MIL-101** was less efficient despite open Cr³⁺ Lewis acidic site (87% conversion after 24 hr)



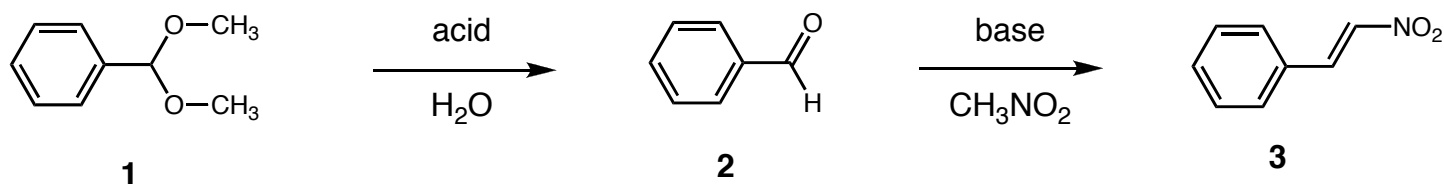
Entry	Catalyst	Conv. of 1 [%]	Yield of 2 [%]	Yield of 3 [%]
1	MIL-101-SO₃H-NH₂	100	3	97
2	MIL-101-SO₃H-NHBOC	100	100	Trace
3	MIL-101-NH₂	Trace	Trace	Trace
4	MIL-101-SO₃H	100	100	0
5	MIL-101-SO₃H-NH₂ + <i>p</i> -toluene sulfonic acid	100	95.5	4.5
6	MIL-101-SO₃H-NH₂ + ethylamine	Trace	Trace	Trace
7	<i>p</i> -Toluene sulfonic acid + ethylamine	Trace	Trace	Trace

Li, B.; Zhang, Y.; Ma, D.; Li, L.; Li, G.; Li, G.; Shi, Z.; Feng, S. *Chem. Commun.* **2012**, 48, 6151-6153.

Tandem Catalysis - Organo-bifunctionalization

■ MIL-101-SO₃H-NH₂ tested in tandem acetal hydrolysis-Henry reaction

- Bifunctionalized MOF functioned far superior to monofunctionalized MOFs
- Homogeneous mixture of free acid and base showed no activity
- **MIL-101** was less efficient despite open Cr³⁺ Lewis acidic site (87% conversion after 24 hr)



- **MIL-101-SO₃H-NH₂** demonstrates new PSM strategy to bifunctionalize MOFs
- Grafting method allows facile diversification
- Important example: multifunctional catalysis in MOFs opens up new areas of reactivity

The Future of MOF Catalysis

■ Numerous advantages to employing MOF-based heterogeneous catalysis

- Customizable scaffold and microporosity enables diverse yet controllable reactivity
- Incorporation of homogeneous analogs allow for asymmetric catalysis
- Easy post-reaction separation and recyclability
- Enhanced catalyst stability and substrate size selectivity

The Future of MOF Catalysis

■ Numerous advantages to employing MOF-based heterogeneous catalysis

- Customizable scaffold and microporosity enables diverse yet controllable reactivity
- Incorporation of homogeneous analogs allow for asymmetric catalysis
- Easy post-reaction separation and recyclability
- Enhanced catalyst stability and substrate size selectivity

■ What's next?

- Multifunctional catalysis that cannot be accessed in a homogeneous manner
- "Enzyme mimics" - defined chiral environments for substrate binding, orientation, and catalysis
- Cascade catalysis - formation of complex products from simple substrates due to multiple catalytic sites
- Bottom line: demonstrating catalysis that is unique to metal-organic frameworks