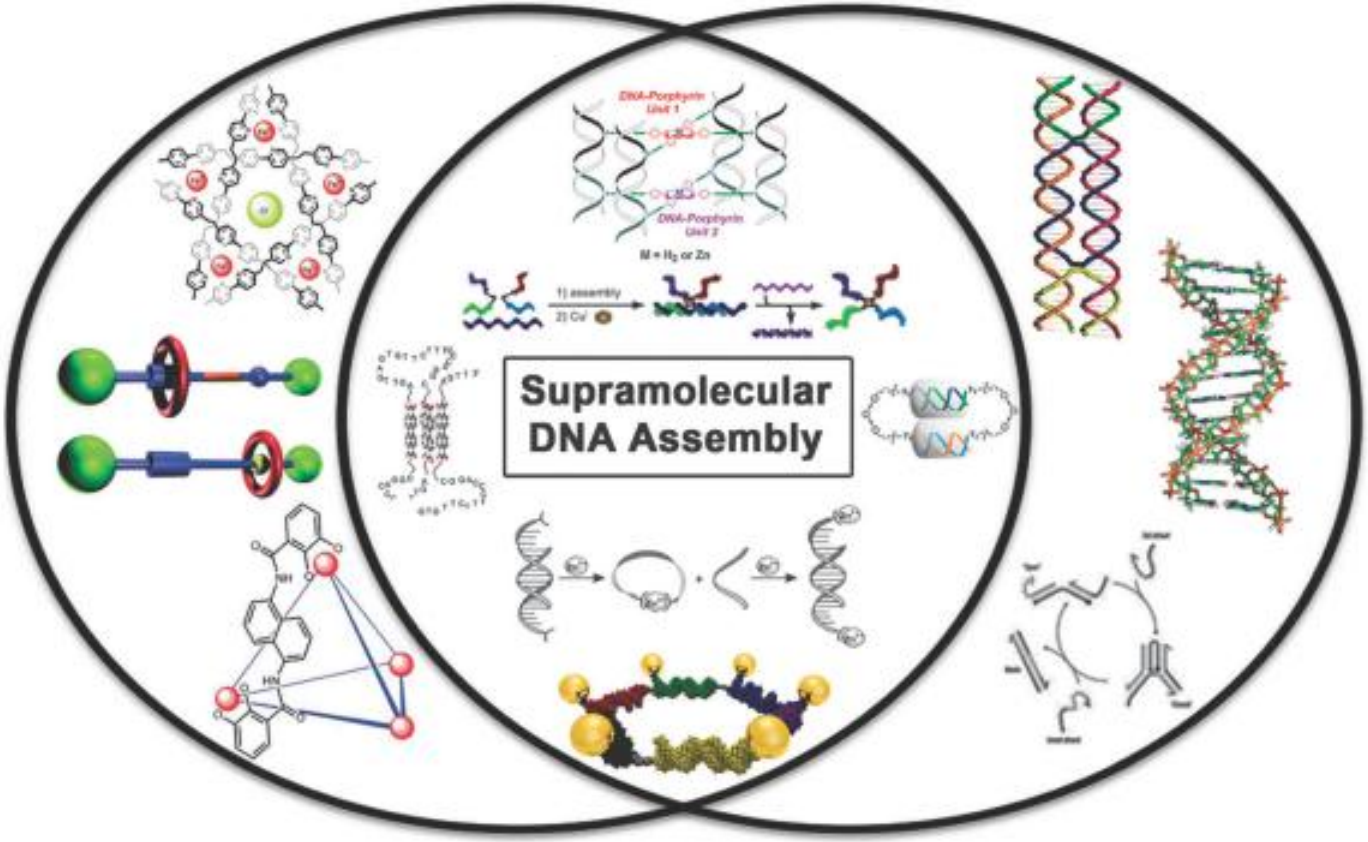
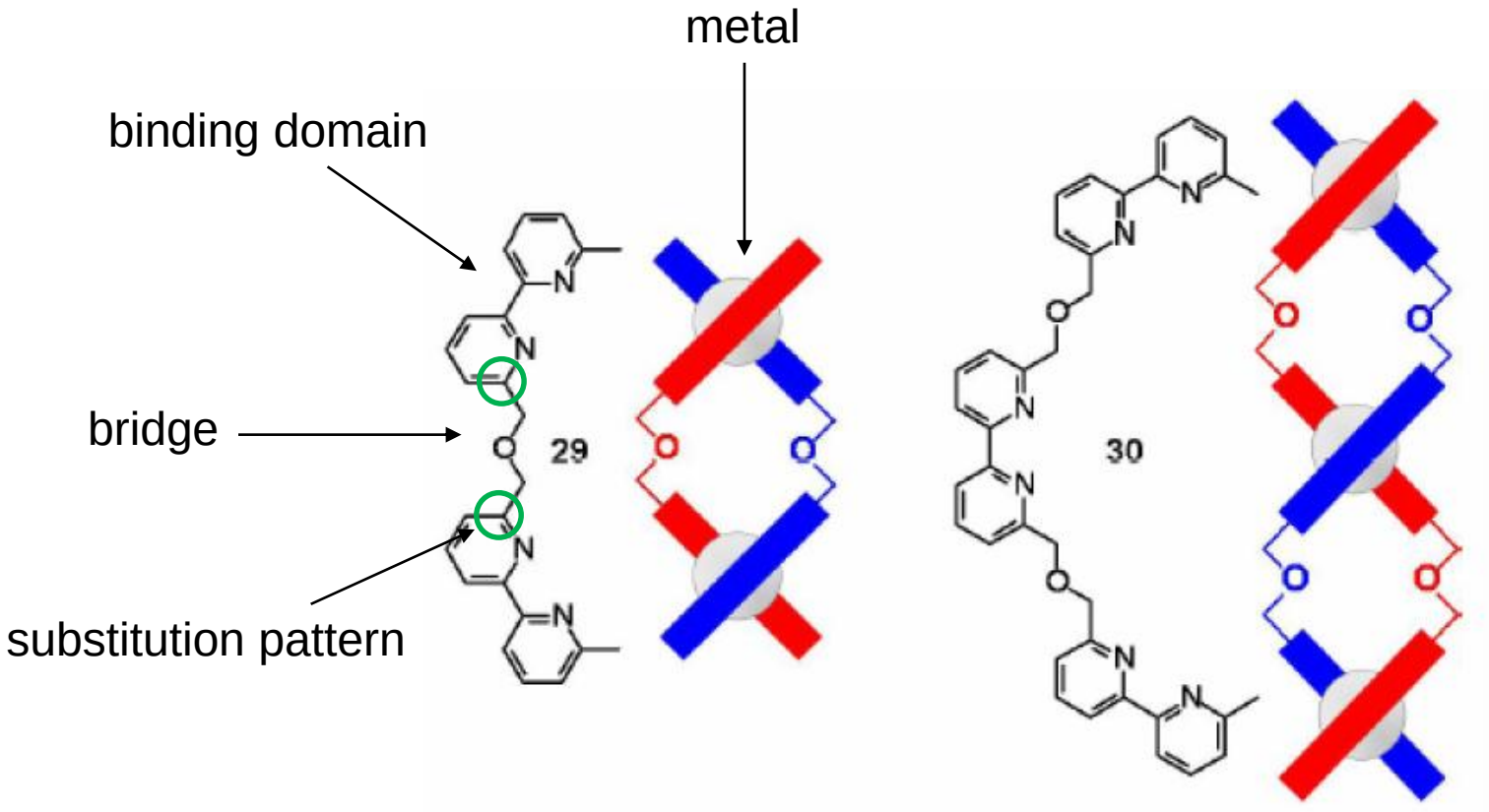
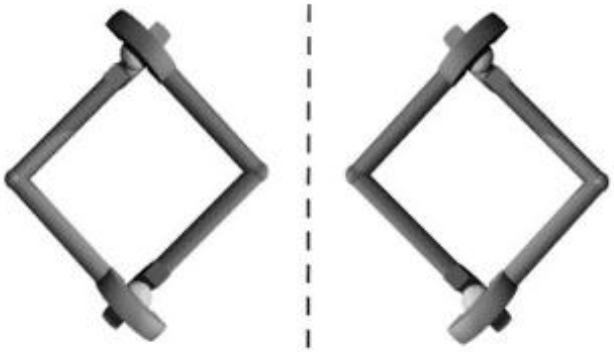
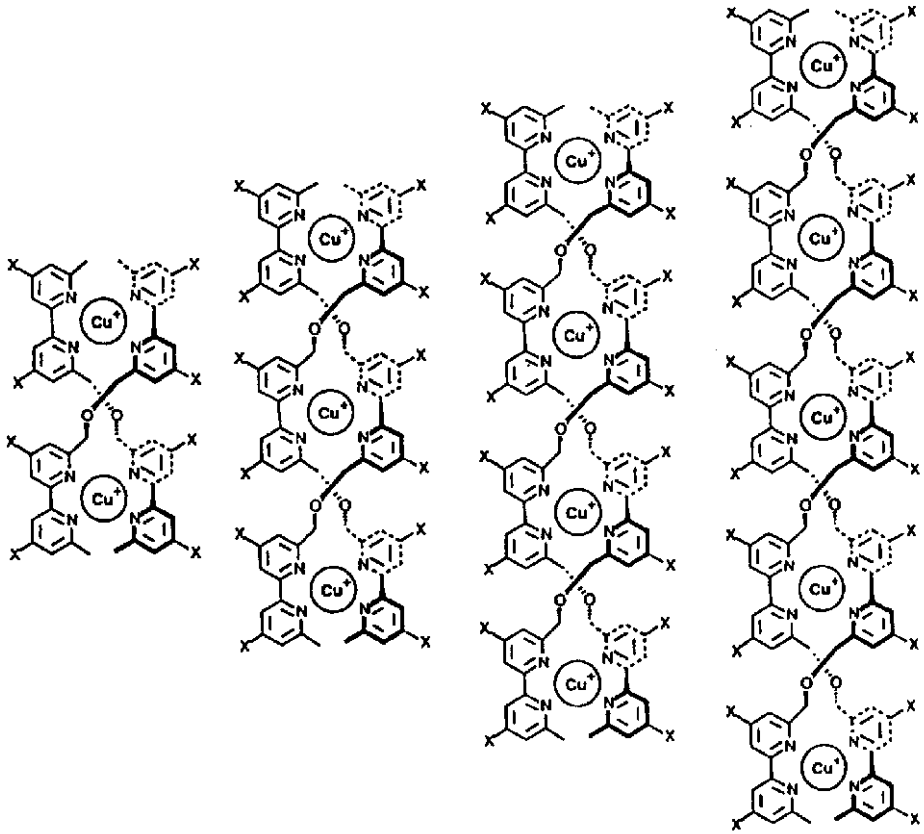

DNA-Porphyrin Unit 1
DNA-Porphyrin Unit 2
M = H2 or Zn
1) assembly
2) Cu2+
Supramolecular DNA Assembly

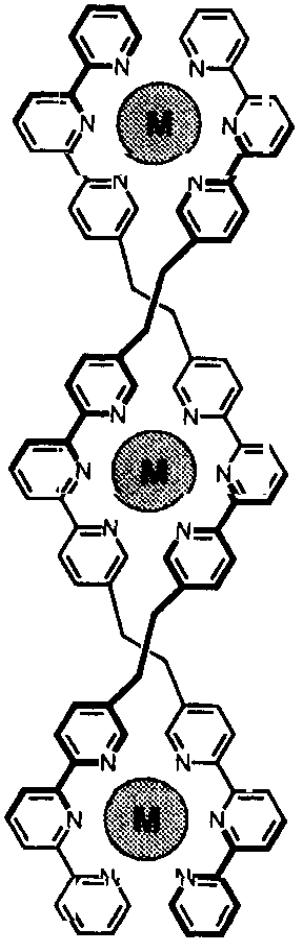
Double stranded helicates



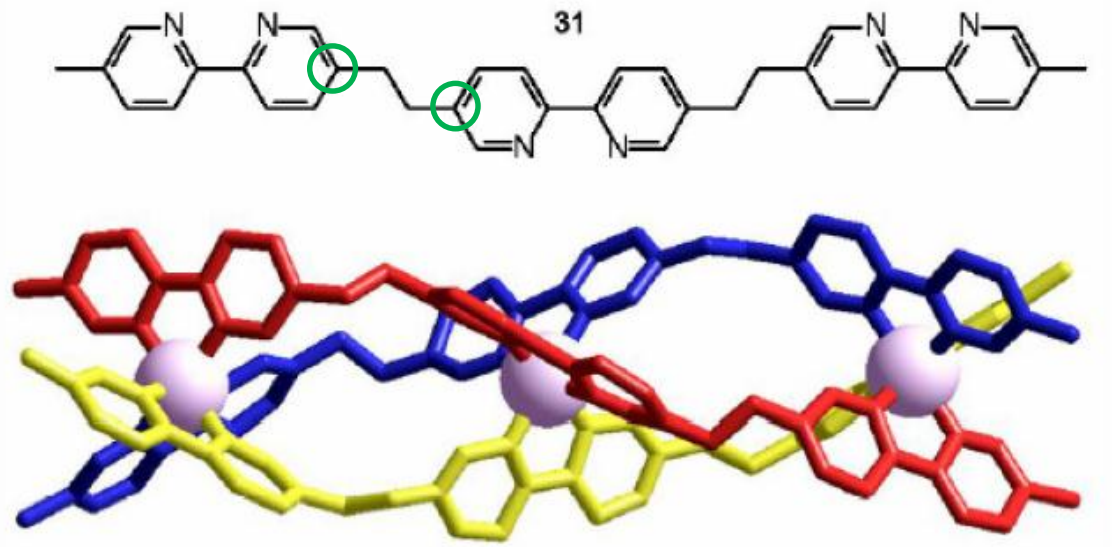


Double helicates



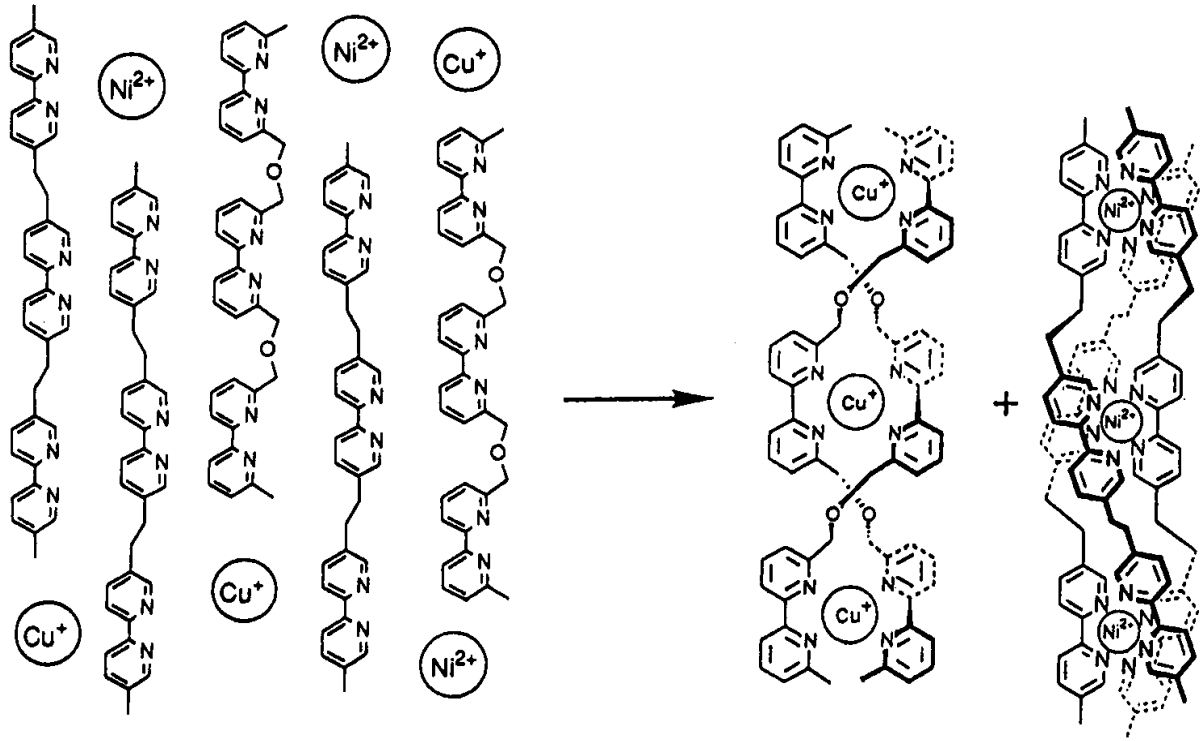

M
M
M

Triple stranded helicates

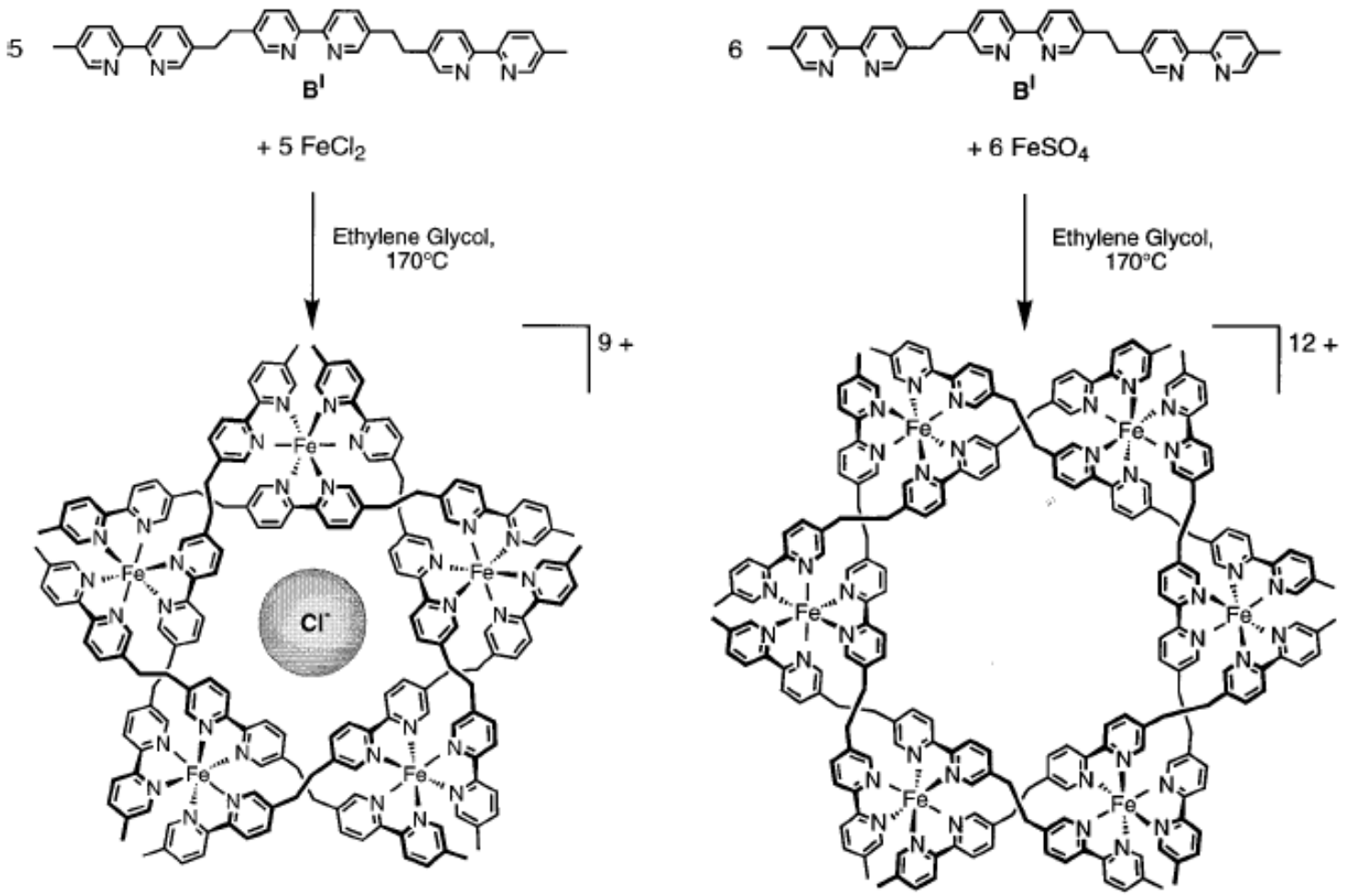


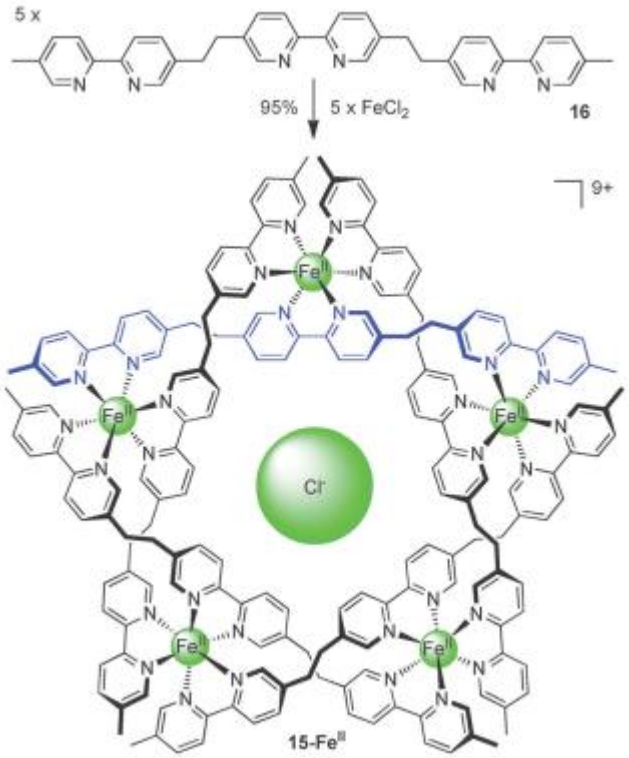
- Ni(II) : octahedral geometry
- one ligand can not wrap around one Ni(II) cation : trimerization
- other metals: Co(II), Fe(II), lanthanides

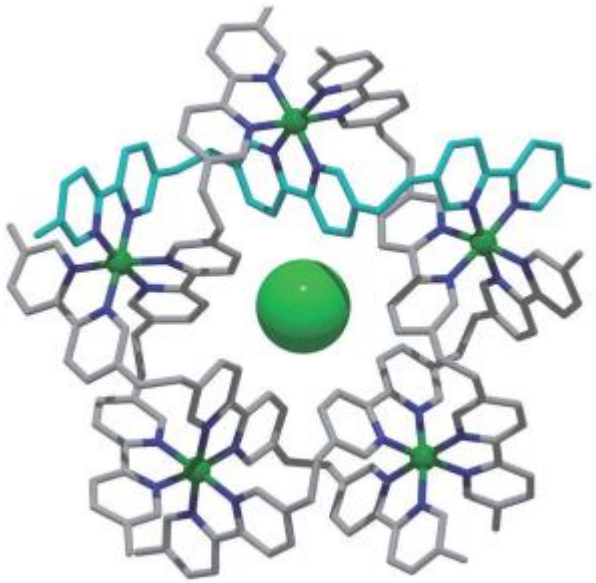
Double and Triple Helicates: an example of Selective-Recognition

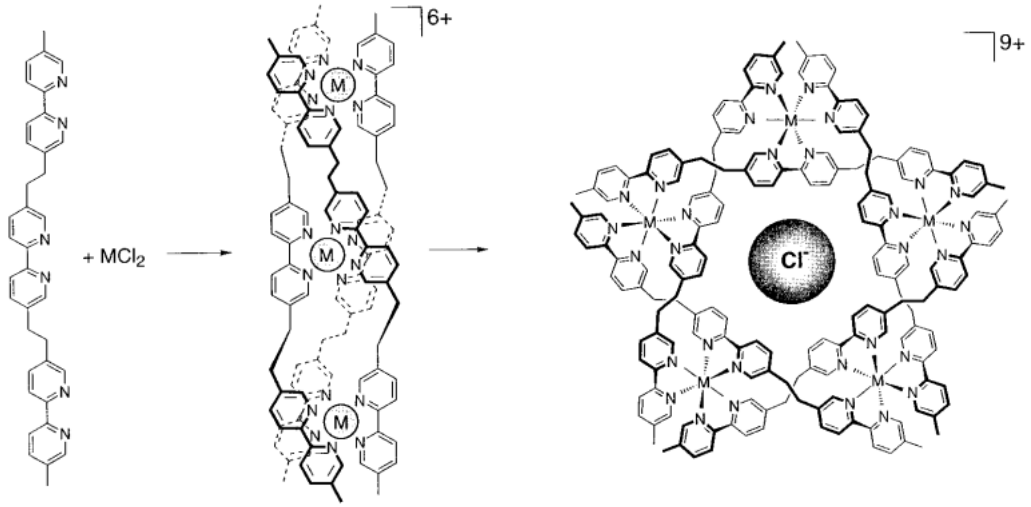


Cyclic Helicates




5 x
95%
5 x FeCl2
16
9+
Fe
Cl
15-Fe

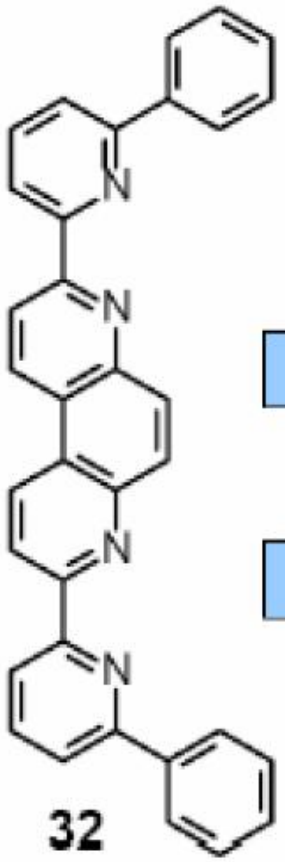




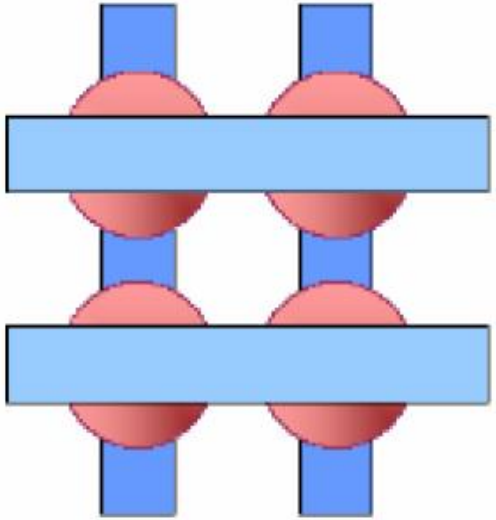
^{1}H-NMR

ESI-MS

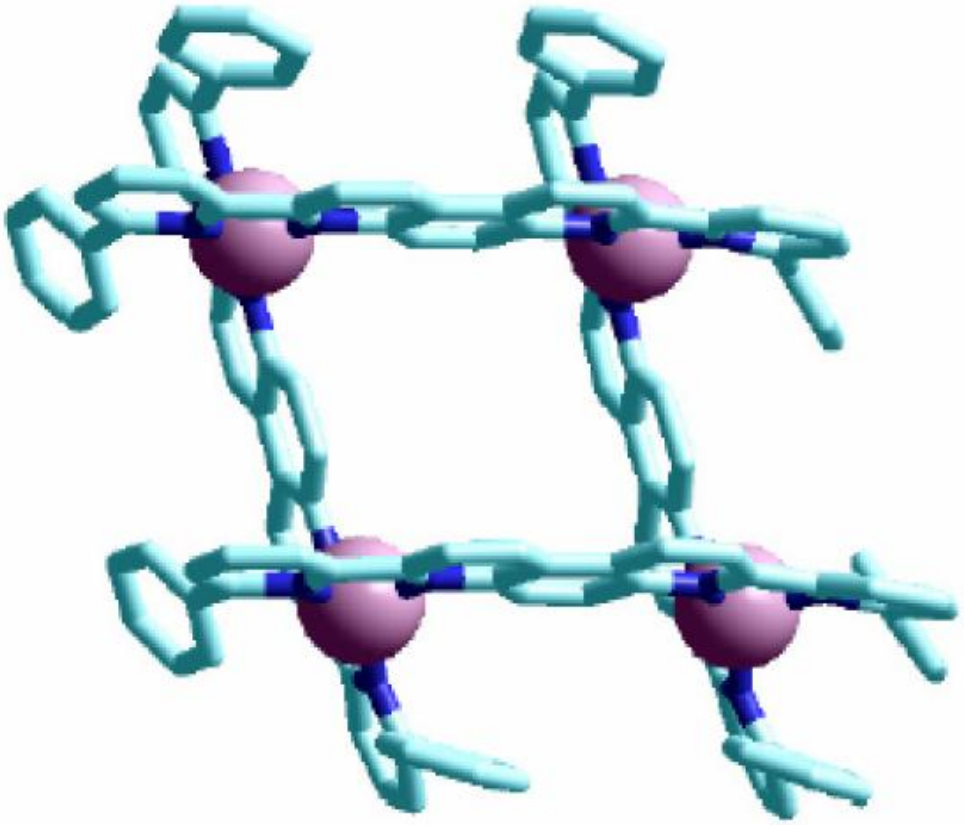
Molecular Grids



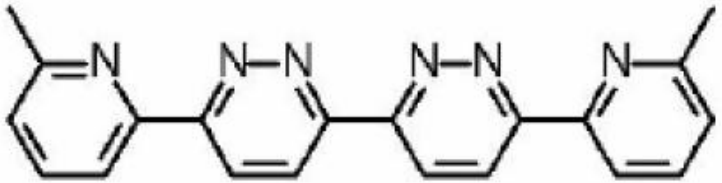
32



2X2 Cu(I) grid

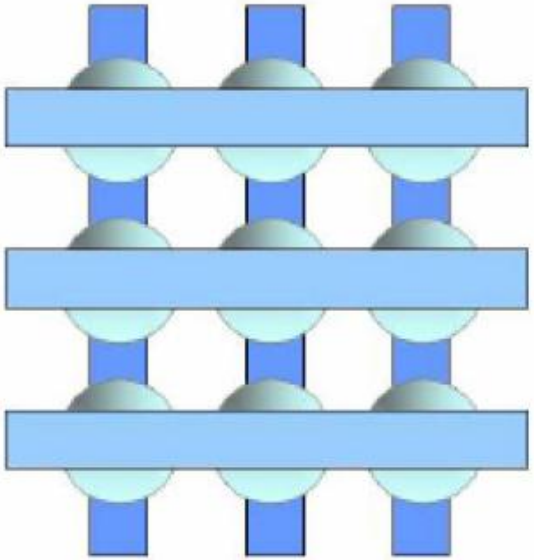


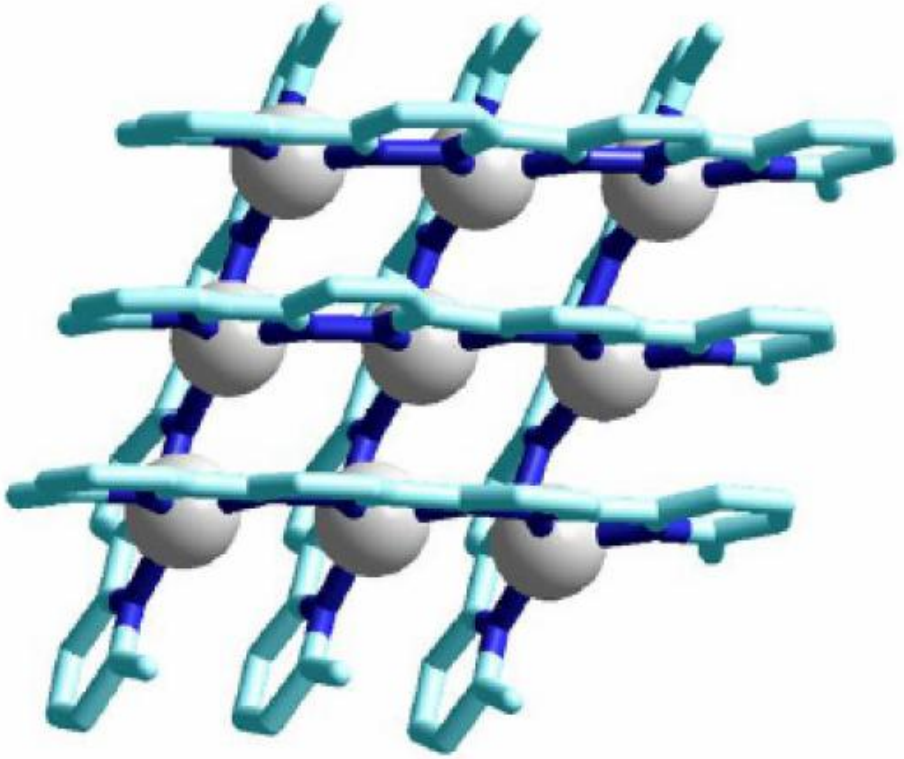
Molecular Grids



33

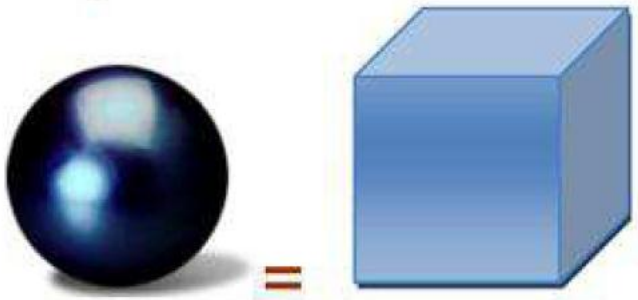
3X3 Ag(I) grid

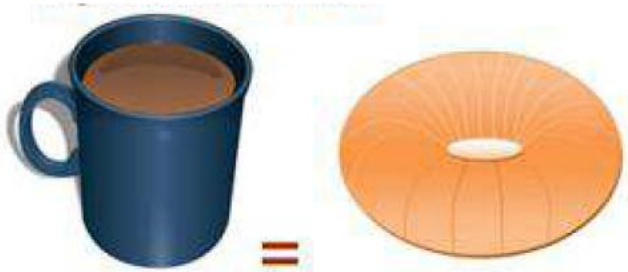




Topology

In topology, angles, distances or shapes have no meaning
But the object cannot be cut





Molecular graph

Representation of the bonds between atoms with no interest in their chemical nature

(a)

→ planar graph

One possible conformation with no crossing in 2D representation

Topological chemistry

- If two molecules are different only for their graphs, they are **topological isomers**

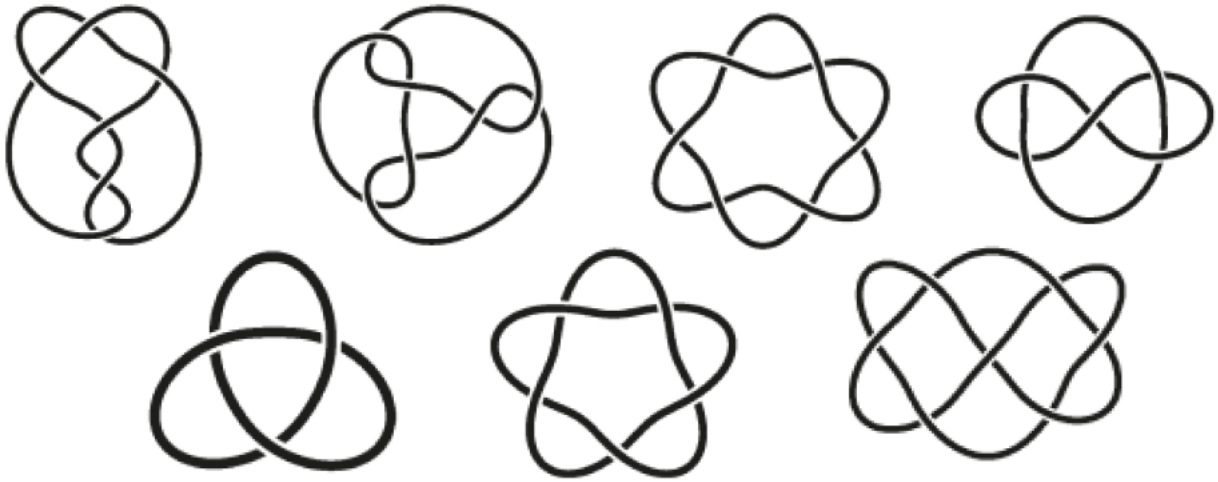
a is an isomer of **b** and **c**.
b and **c** are topological enantiomers.

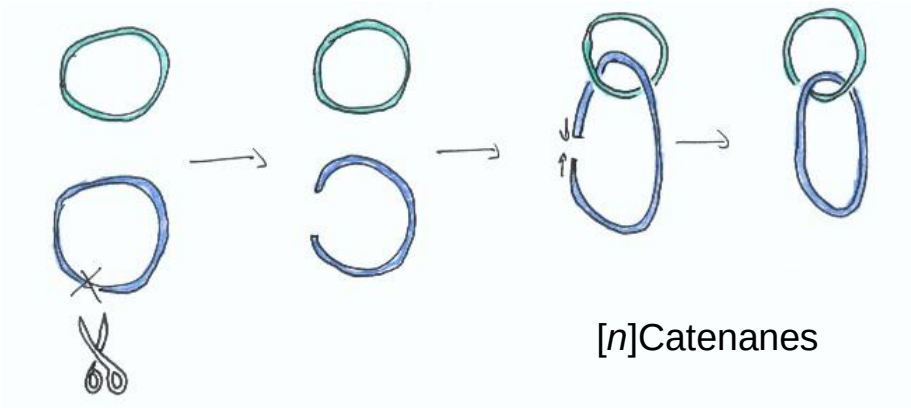
Molecular graph

non-planar graph

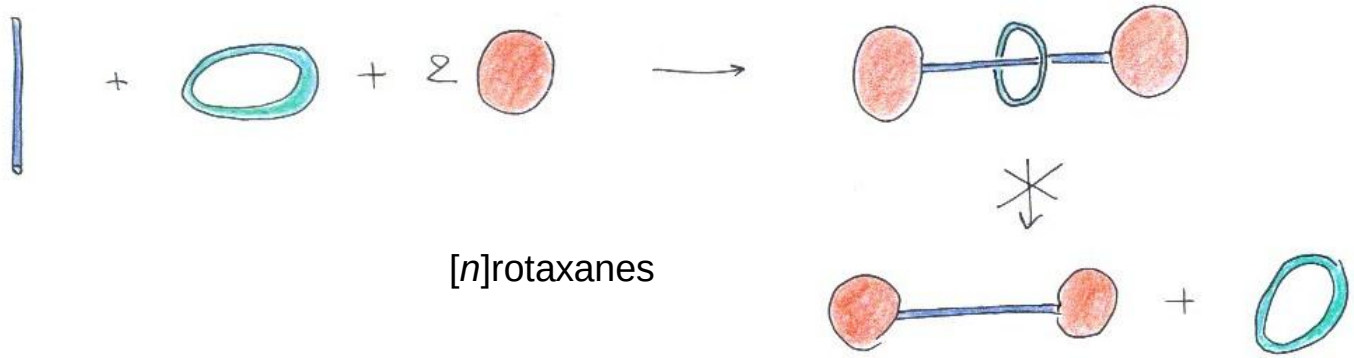
No possible conformation with no crossing in 2D representation

topological chemistry is the chemistry of molecules having a non planar graph

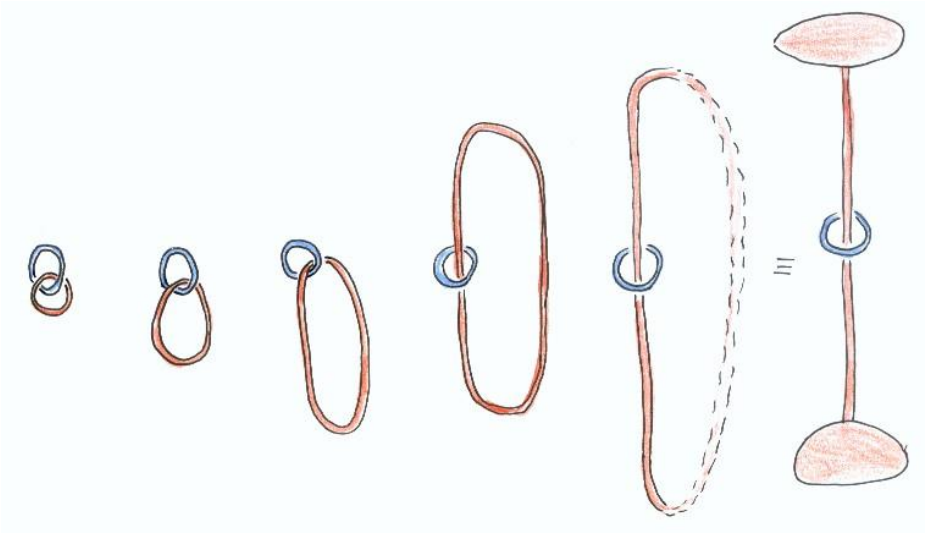




[*n*]Catenanes

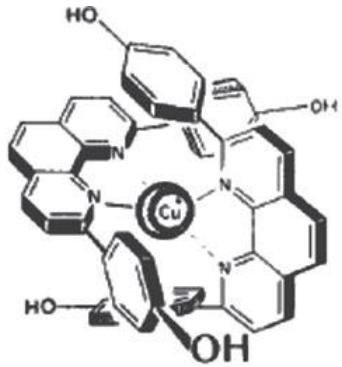


[*n*]rotaxanes

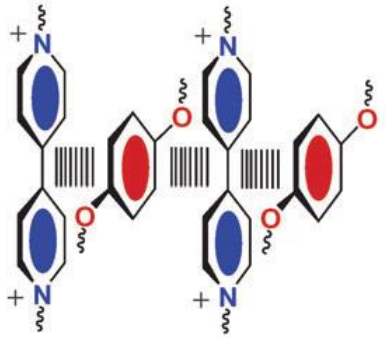


knots

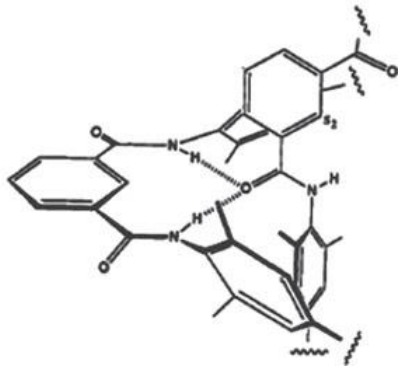
1



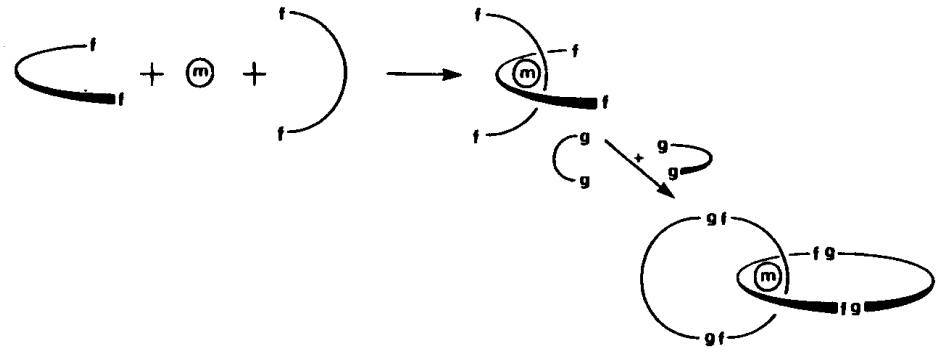
2

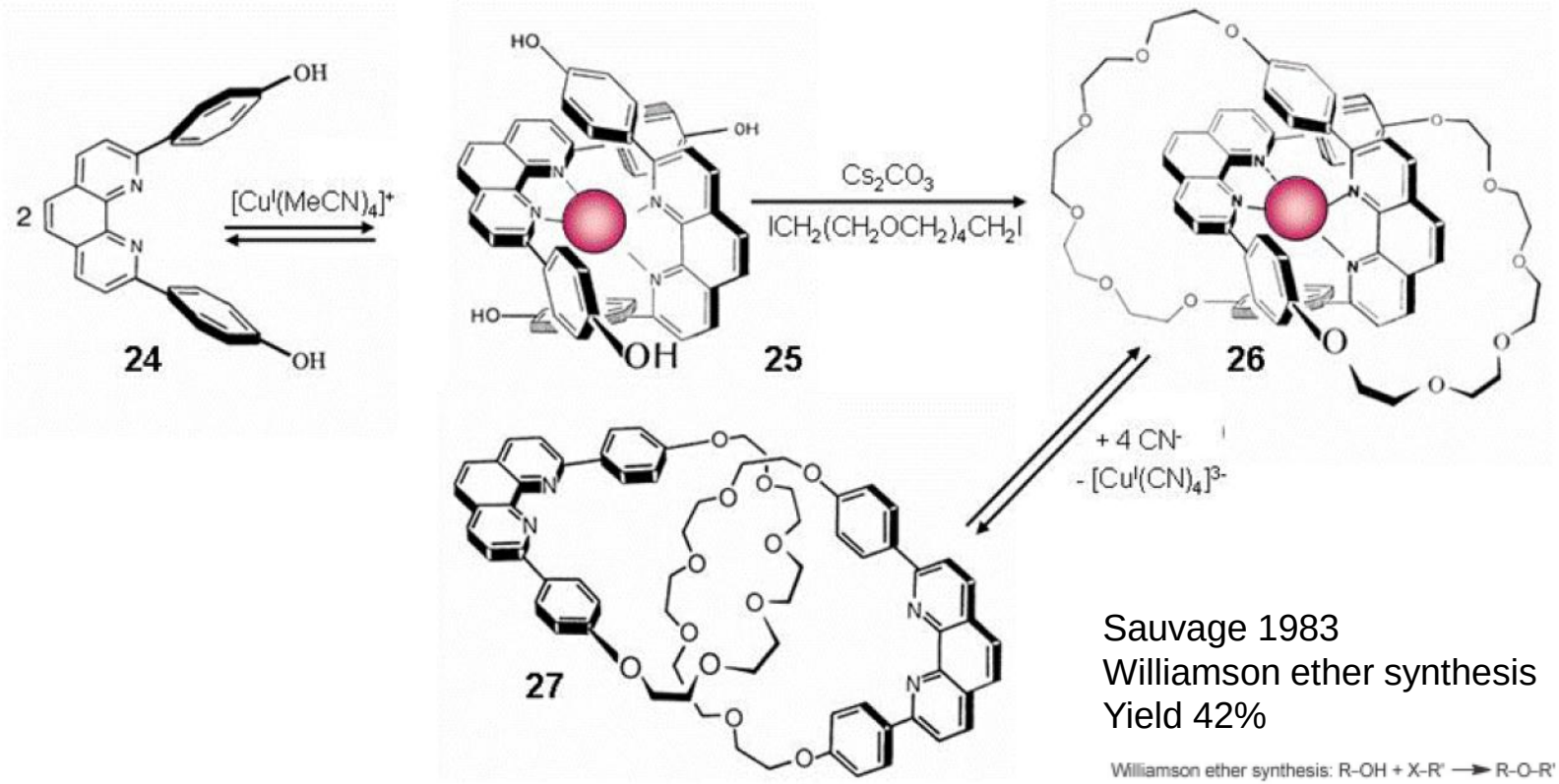


3



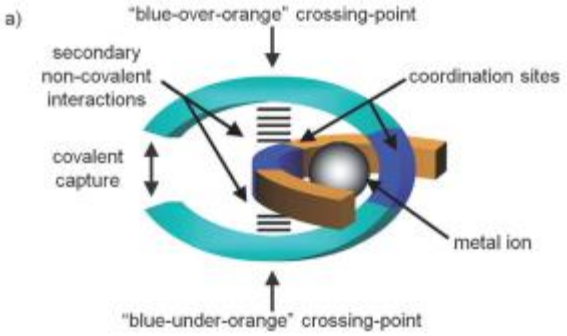
[*n*]Catenani

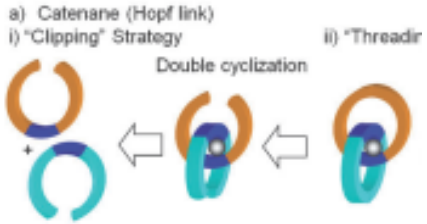


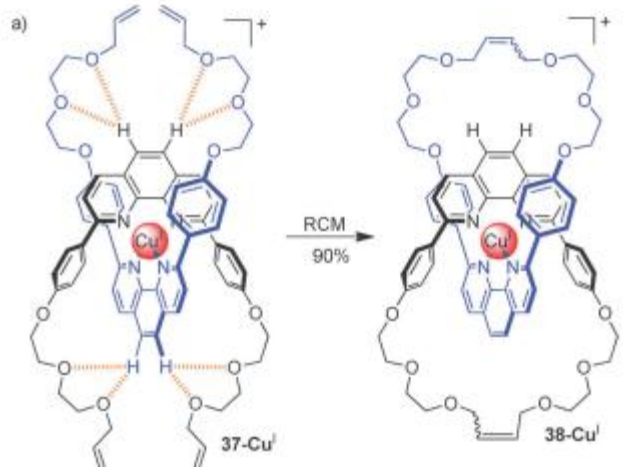


Sauvage 1983
Williamson ether synthesis
Yield 42%

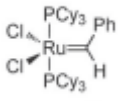
Williamson ether synthesis: R–OH + X–R' ⟶ R–O–R'

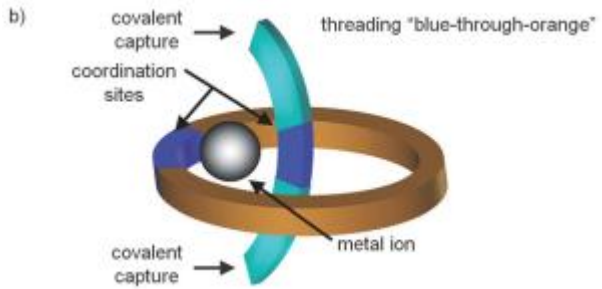




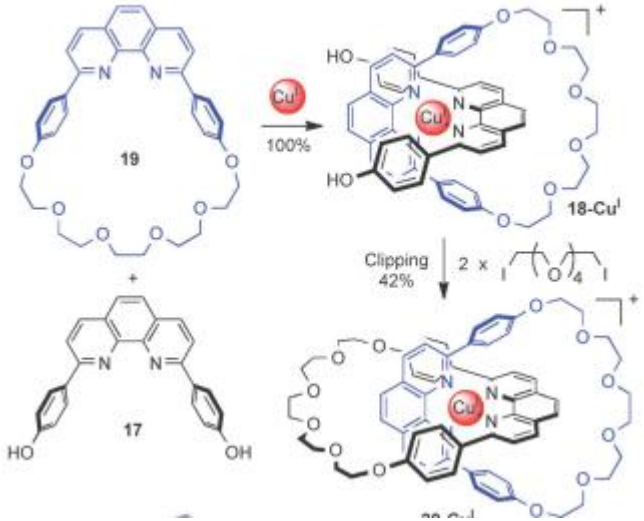


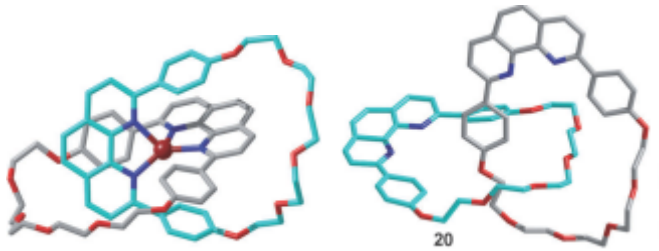
Ring closing metathesis (RCM): 2 x 



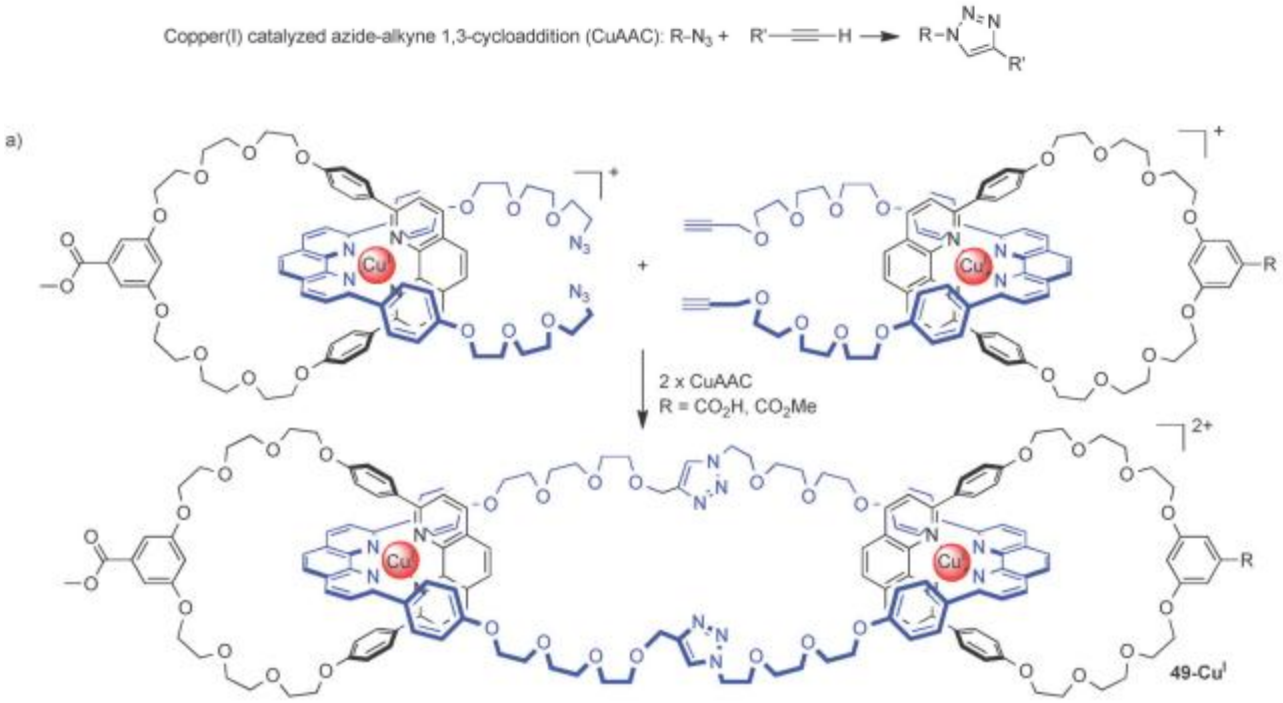

b)
covalent capture
coordination sites
threading "blue-through-orange"
metal ion
covalent capture


ii) "Threading-followed-by-clipping" strategy
Single cyclization


19
17
HO
OH
Cu
100%
HO
HO
18-Cu
Clipping
42%
2 x


20

Reaction	year	A		B		h/c	catalyst
Glaser	1869	RC≡CH	sp	RC≡CH	sp	homo	Cu
Ullmann	1901	Ar-X	sp^2	Ar-X	sp^2	homo	Cu
Sonogashira	1975	RC≡CH	sp	R-X	sp^3 sp^2	cross	Pd and Cu
Negishi	1977	R-Zn-X	sp^3, sp^2, sp	R-X	sp^3 sp^2	cross	Pd or Ni
Stille	1978	R-SnR_3	sp^3, sp^2, sp	R-X	sp^3 sp^2	cross	Pd
Suzuki	1979	R-$B(OR)_2$	sp^2	R-X	sp^3 sp^2	cross	Pd
Hiyama	1988	R-SiR_3	sp^2	R-X	sp^3 sp^2	cross	Pd
Buchwald-Hartwig	1994	R_2N-R SnR_3	sp	R-X	sp^2	cross	Pd


Copper(I) catalyzed azide-alkyne 1,3-cycloaddition (CuAAC): R-N3 +
a)
2 x CuAAC
R = CO2H, CO2Me
49-Cu^I

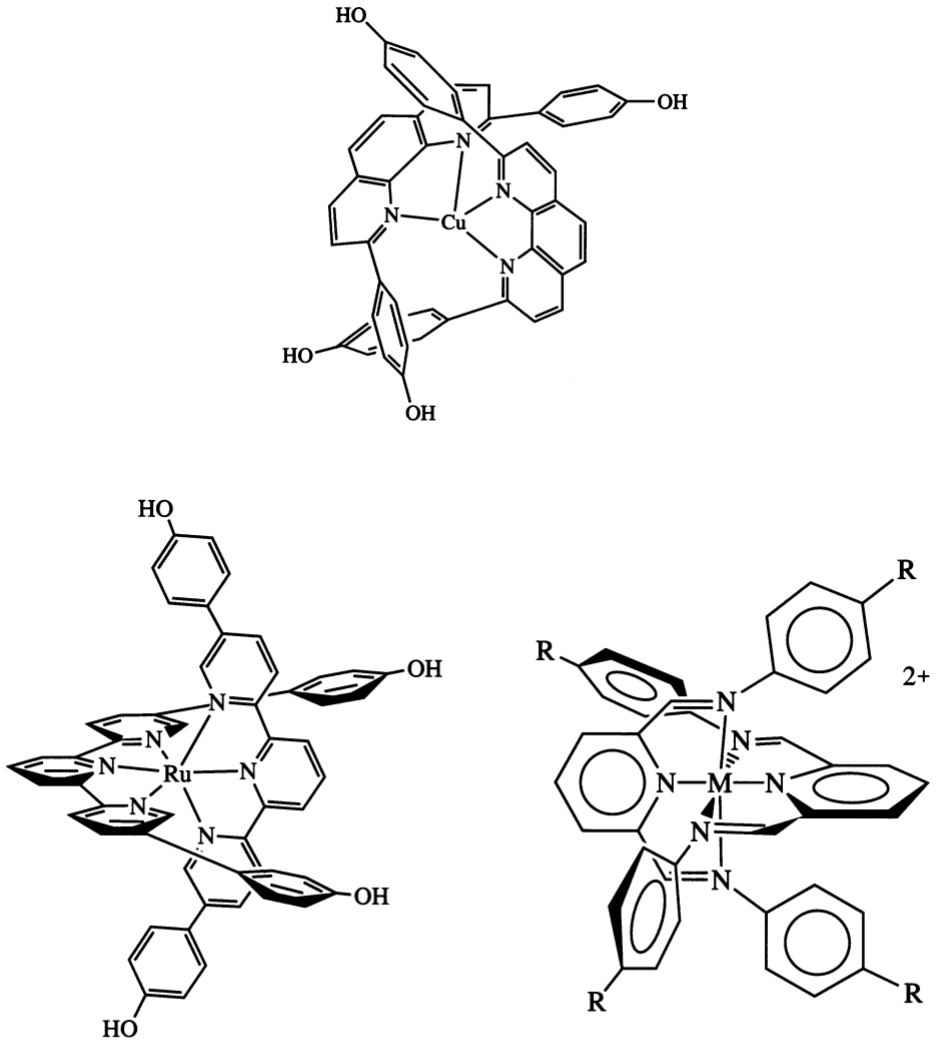
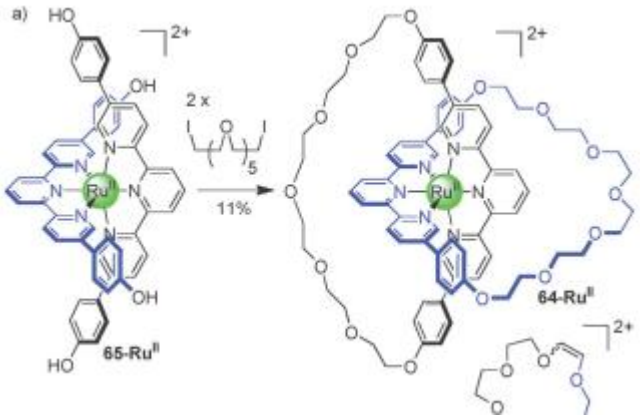
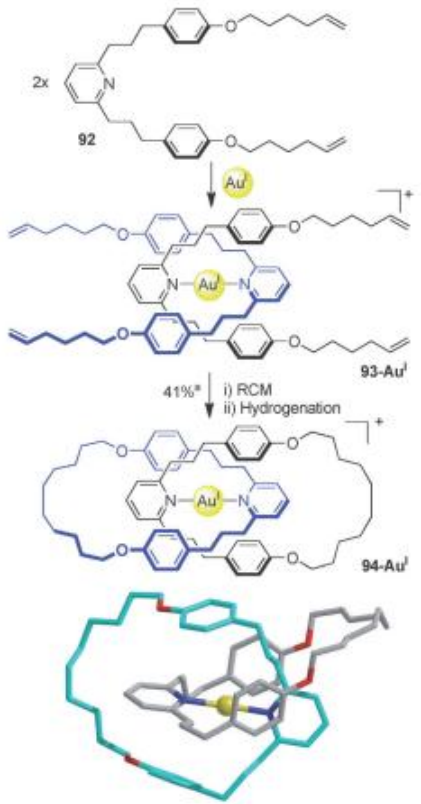
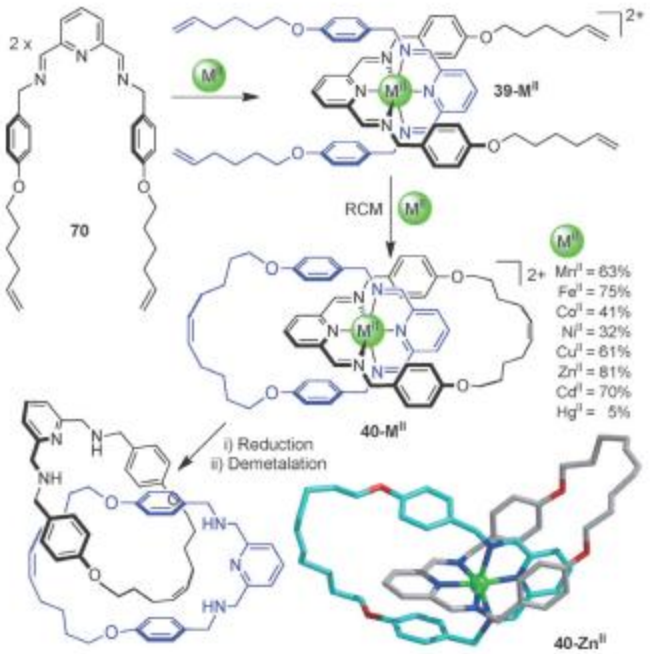


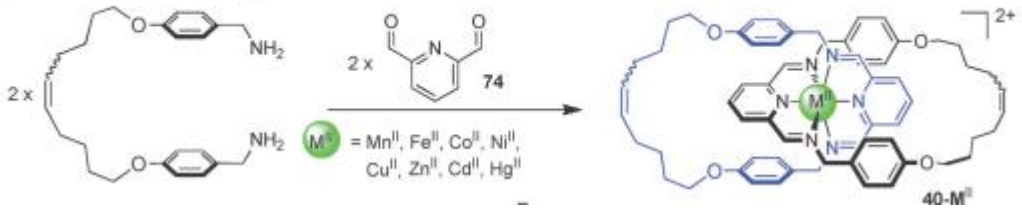
Fig. 13. (a) Sauvage's Ru-terpy octahedral template complex, (b) Vance's Schiff-base octahedral template complex.


a)
HO
OH
2+
2 x
5
11%
OH
HO
65-Ru^{II}
64-Ru^{II}
2+
2+

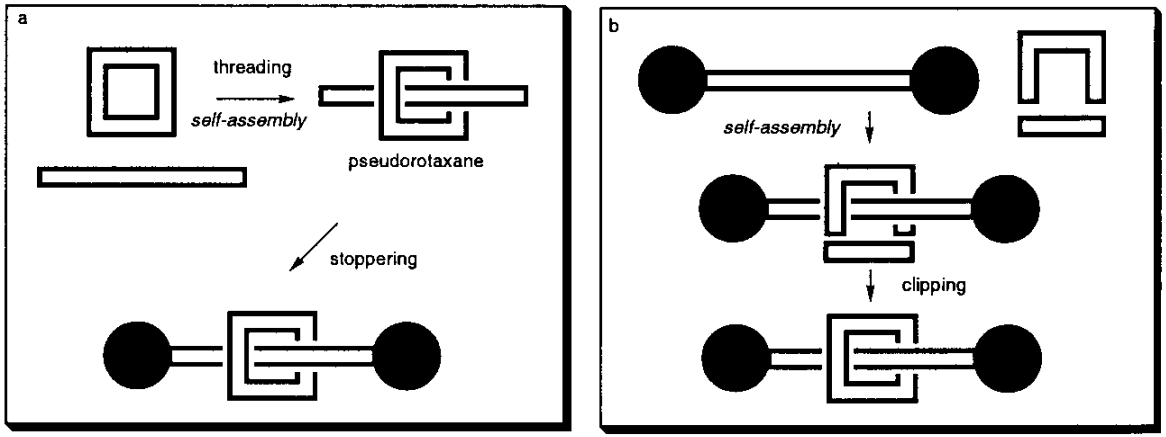

2x
92
Au^{I}
+
93-Au^{I}
41%*
i) RCM
ii) Hydrogenation
+
94-Au^{I}



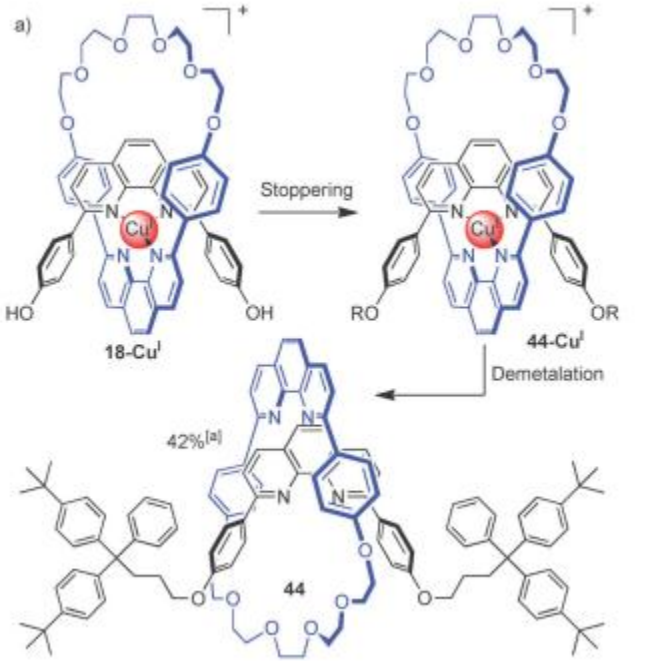
c) Imine bond formation: $R\text{-}NH_2 + R'\text{-}CHO \longrightarrow R\text{-}N{=}CH\text{-}R'$

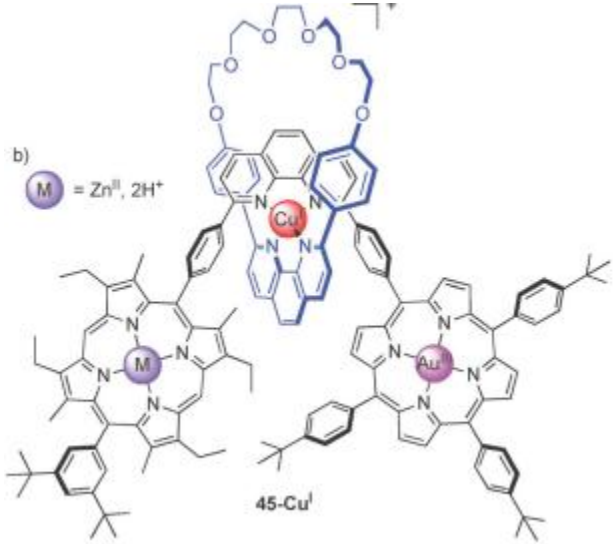


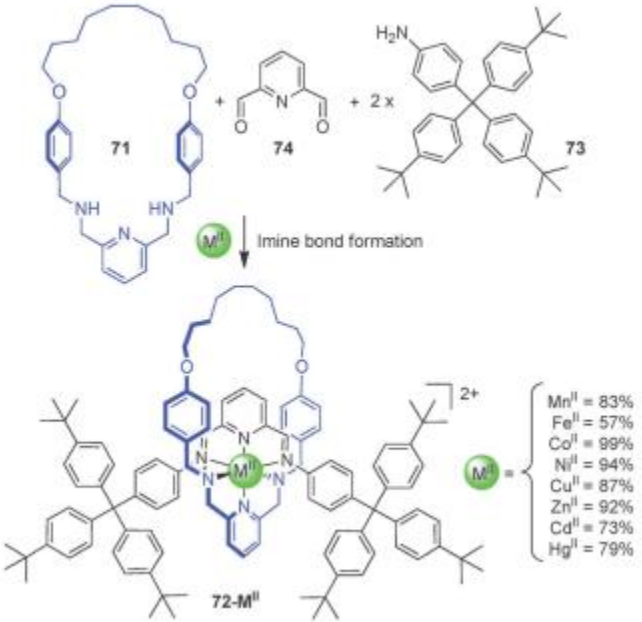
[2]Rotaxani

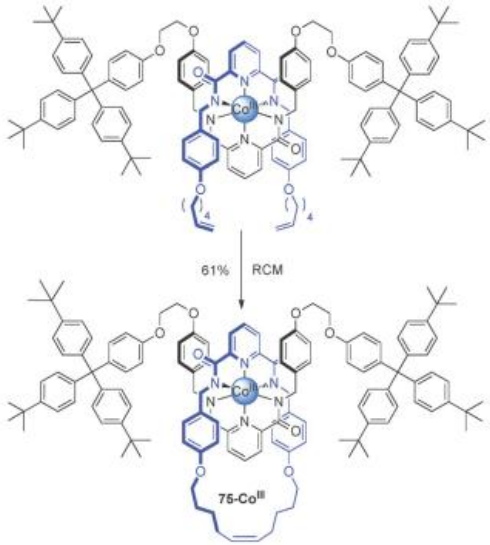


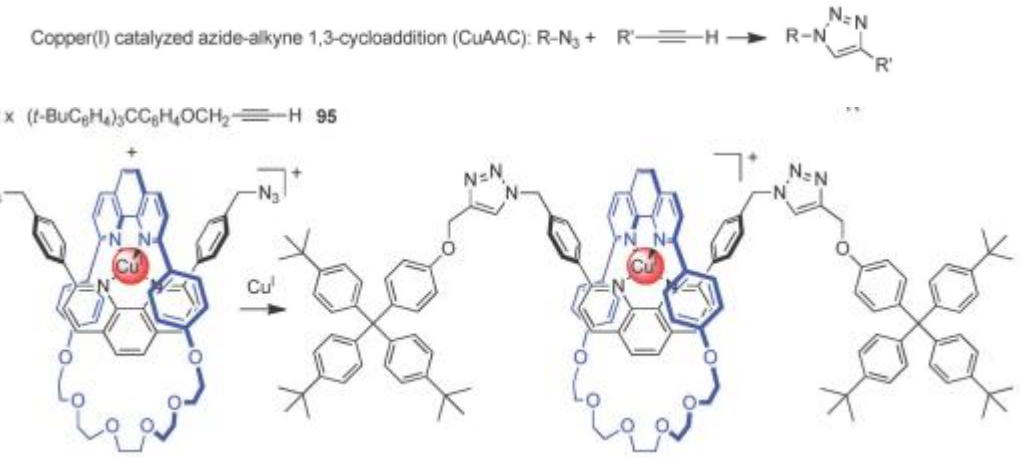
[2] Rotaxane synthesis by a) threading and b) clipping.

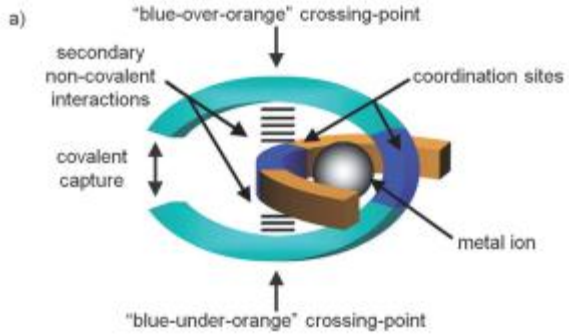

a)
Stoppering
HO
OH
RO
OR
18-Cu^{I}
44-Cu^{I}
Demetalation
42%[a]
44

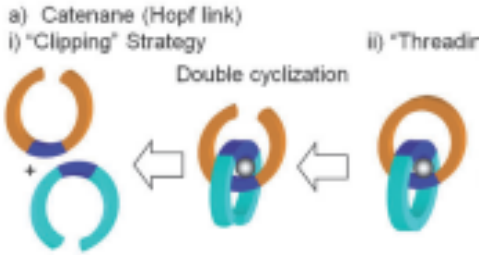

b)
M = Zn^{II}, 2H^{+}
45-Cu^{I}

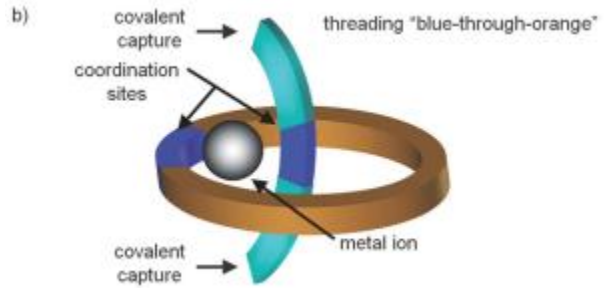

71
74
73
+ 2 x
NH
HN
N
O
H_2N
M^{II}
Imine bond formation
2+
Mn^{II} = 83%
Fe^{II} = 57%
Co^{II} = 99%
Ni^{II} = 94%
Cu^{II} = 87%
Zn^{II} = 92%
Cd^{II} = 73%
Hg^{II} = 79%
72-M^{II}


61%
RCM
Co^{II}
75-Co^{II}

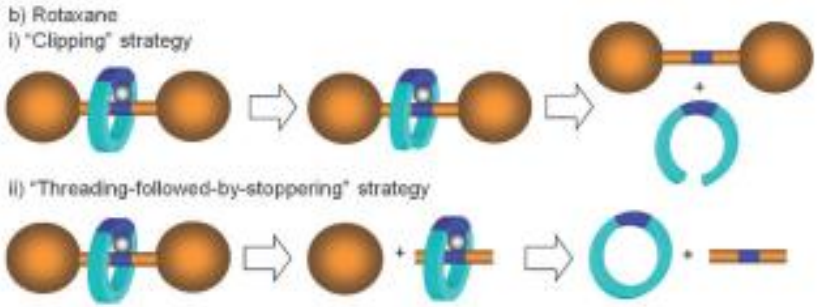

Copper(I) catalyzed azide-alkyne 1,3-cycloaddition (CuAAC): R-N3 + R'—≡—H → R-N(N=N)-C(R')=C
2 x (t-BuC6H4)3CC6H4OCH2—≡—H 95
N3
N3
Cu
Cu
Cu
Cu
Cu(I)
O
N
N=N

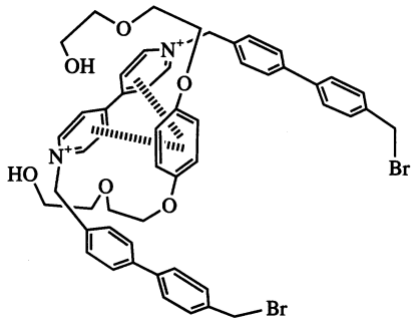

a)
"blue-over-orange" crossing-point
secondary
non-covalent
interactions
coordination sites
covalent
capture
metal ion
"blue-under-orange" crossing-point

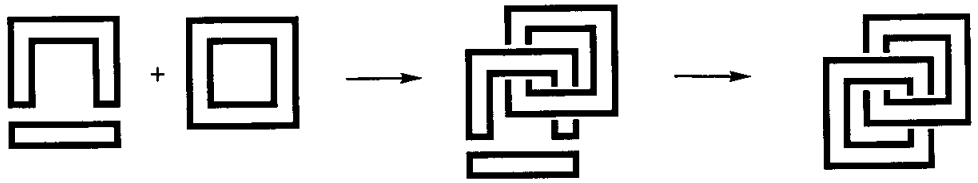

a) Catenane (Hopf link)
i) "Clipping" Strategy
ii) "Threadir
Double cyclization


b)
covalent
capture
threading "blue-through-orange"
coordination
sites
metal ion
covalent
capture

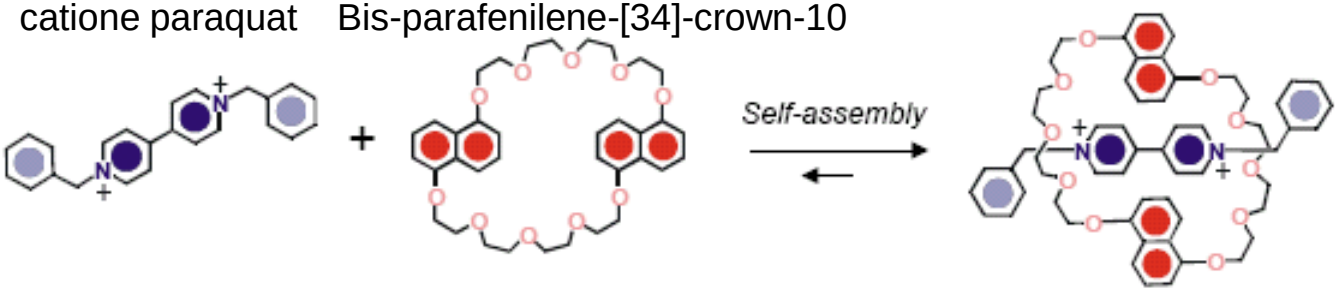

ii) "Threading-followed-by-clipping" strategy
Single cyclization

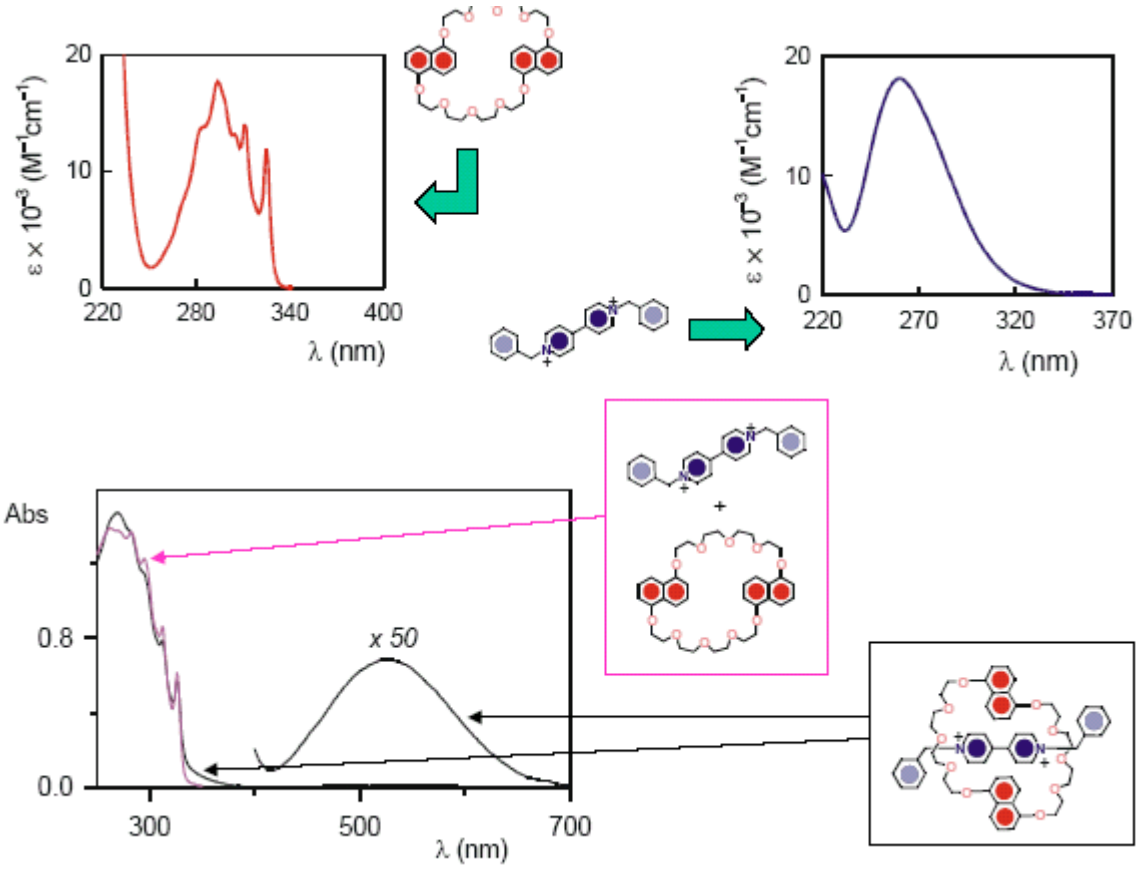

b) Rotaxane
i) "Clipping" strategy
ii) "Threading-followed-by-stoppering" strategy

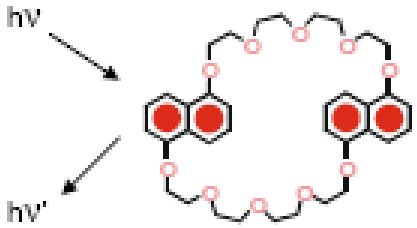

O
OH
N+
O
N+
HO
O
O
Br
Br

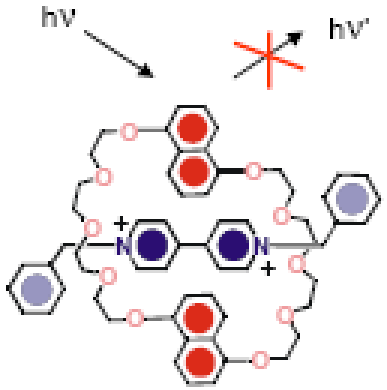


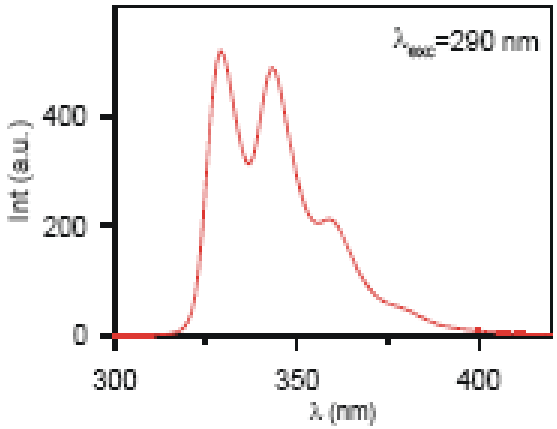
catione paraquat Bis-parafenilene-[34]-crown-10

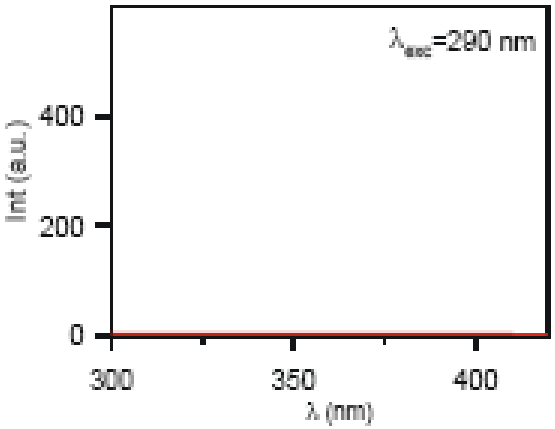


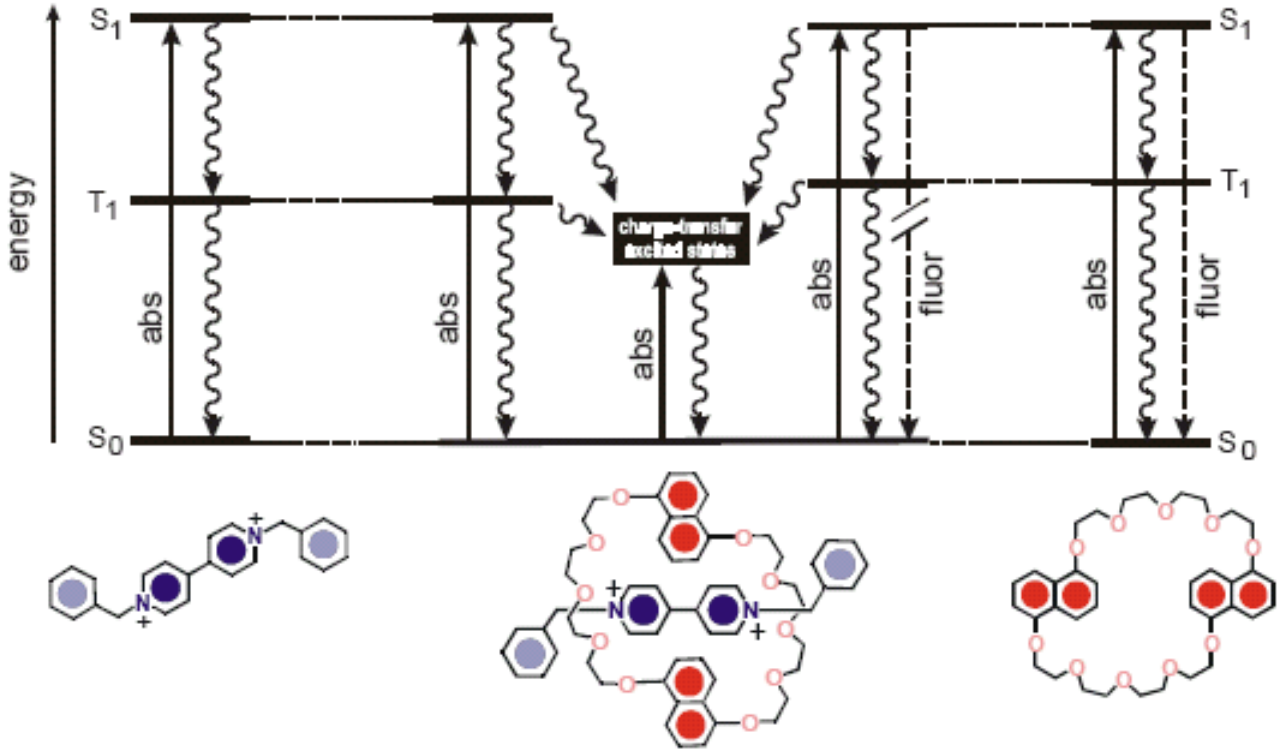

20
10
0
ε × 10⁻³ (M⁻¹cm⁻¹)
220
280
340
400
λ (nm)
20
10
0
ε × 10⁻³ (M⁻¹cm⁻¹)
220
270
320
370
λ (nm)
Abs
0.8
0.0
x 50
300
500
700
λ (nm)

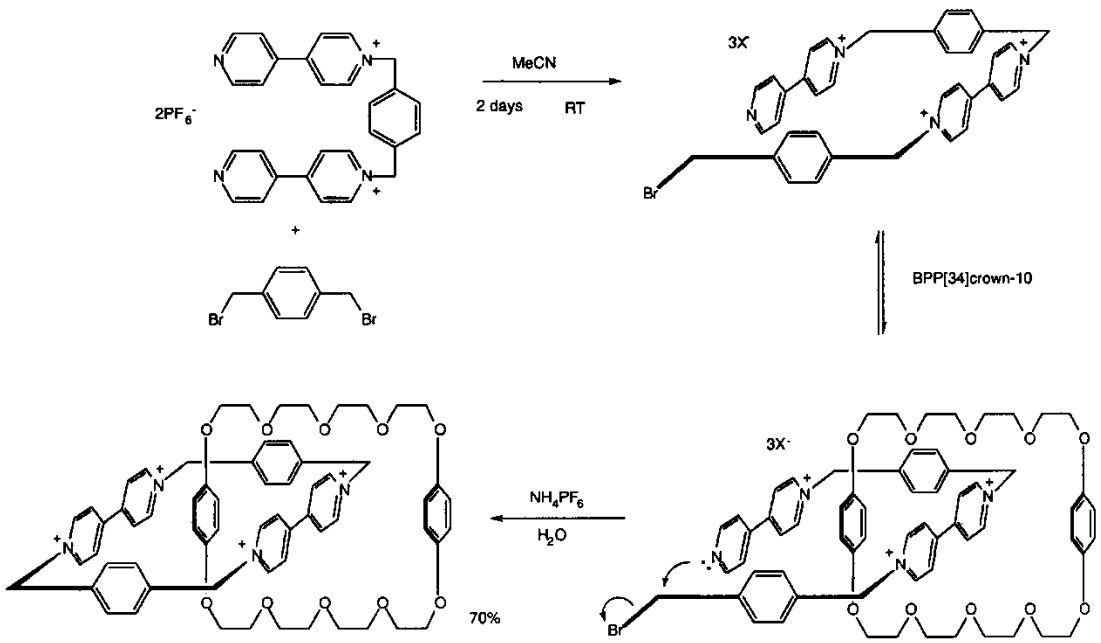

hν
hν'

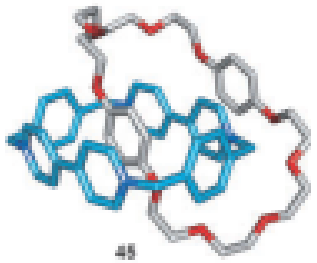

hν
hν'
N
N
+
+


λexc=290 nm
Int (a.u.)
400
200
0
300
350
400
λ (nm)

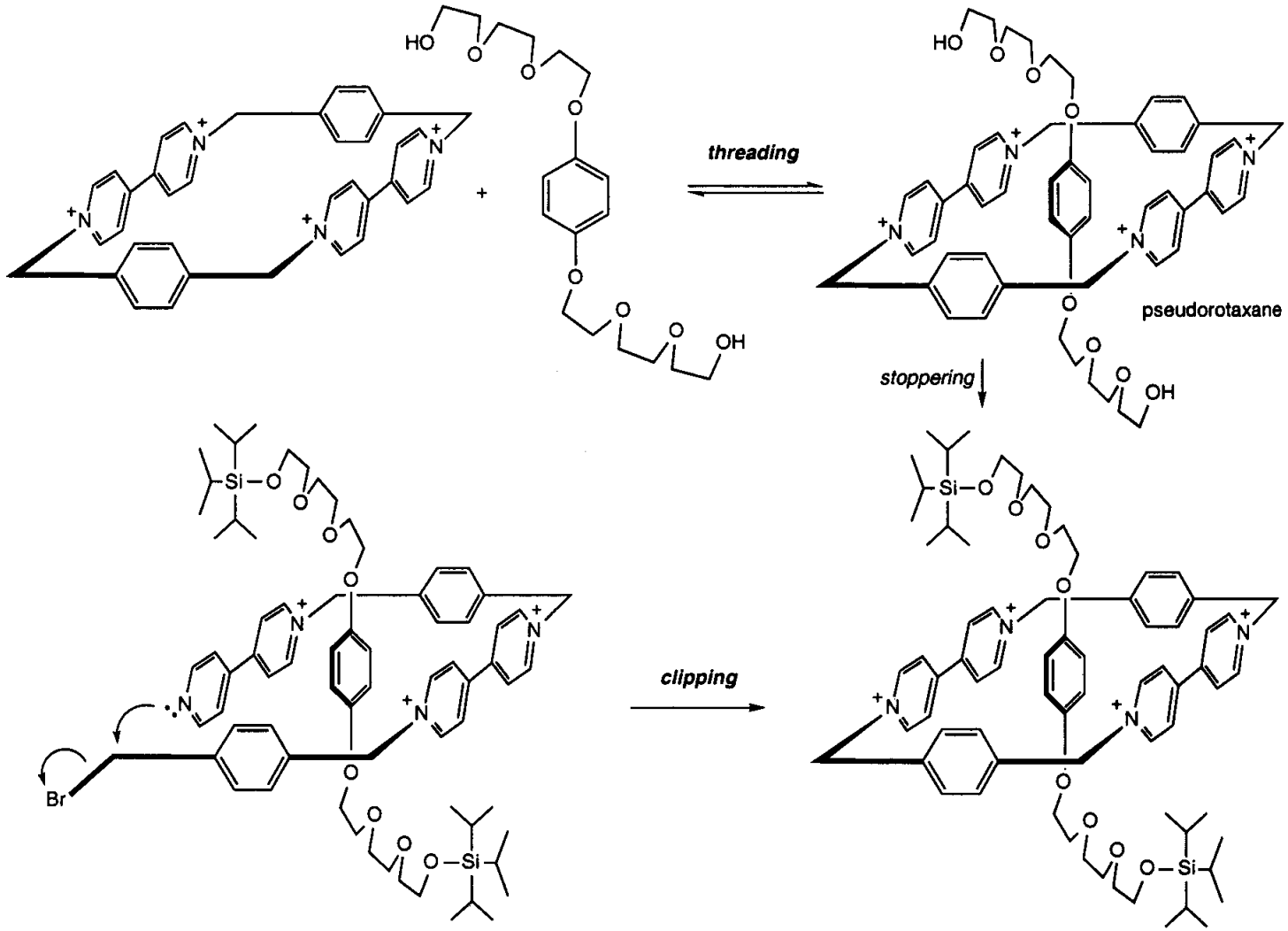

λexc=290 nm
Int (a.u.)
400
200
0
300
350
400
λ (nm)


energy
S1
T1
S0
abs
abs
abs
charge-transfer excited states
abs
fluor
abs
fluor
S1
T1
S0

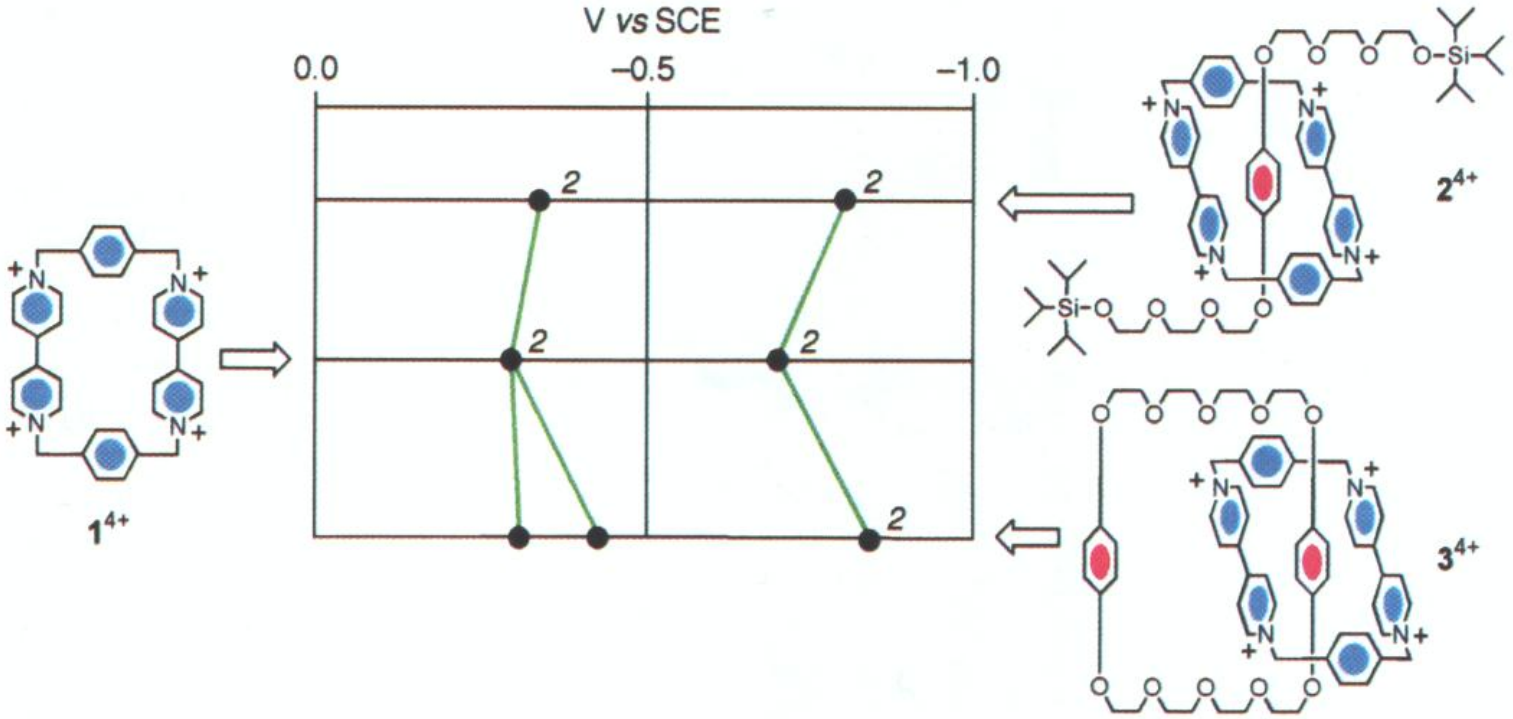


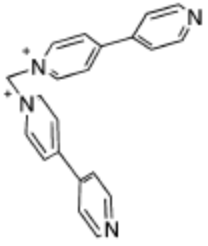


45

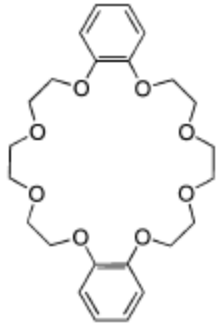


Synthesis of a rotaxane by two different routes: threading and clipping.

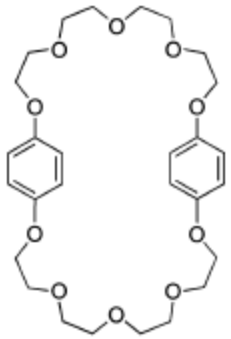

V vs SCE
0.0
–0.5
–1.0
2
2
2
2
2
2
1^{4+}
2^{4+}
3^{4+}
N+
Si
O



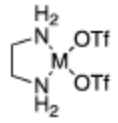
1·2PF_6



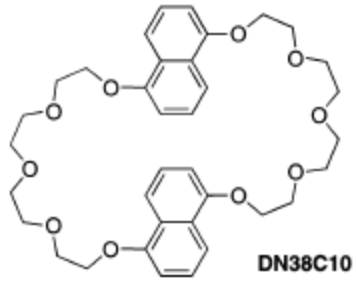
DB24C8



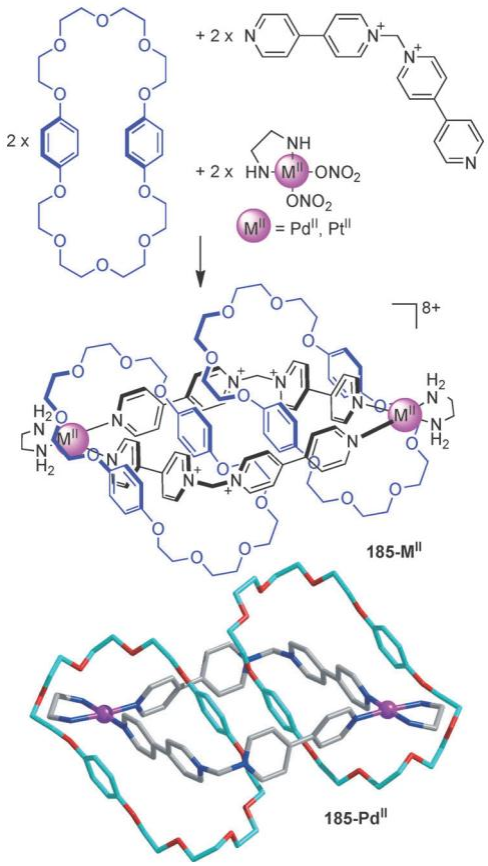
BPP34C10

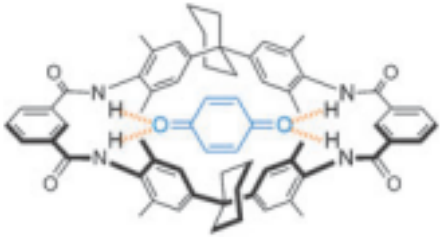


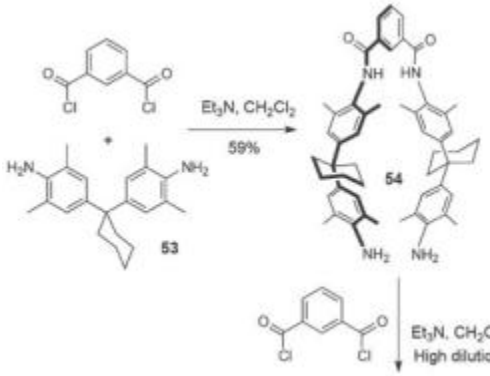
2a M = Pd
2b M = Pt

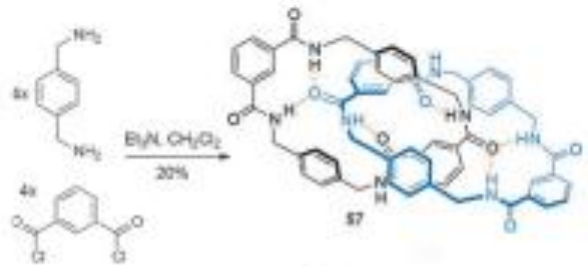


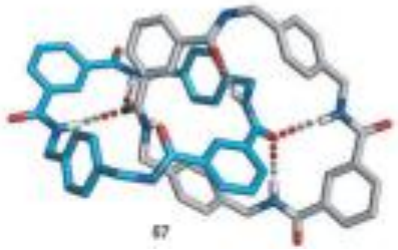
DN38C10

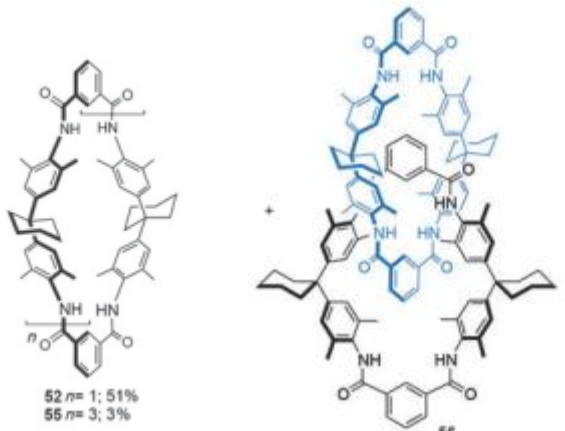

2 x
+ 2 x
+ 2 x
M^{II} = Pd^{II}, Pt^{II}
8+
185-M^{II}
185-Pd^{II}

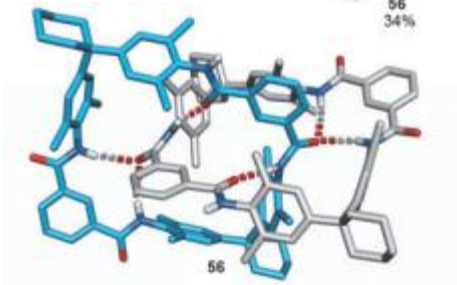



Et3N, CH2Cl2
59%
53
54
Et3N, CH2Cl2
High dilution

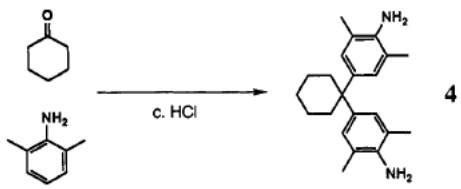

Et3N, CH2Cl2
20%
57


57

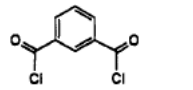

52 n= 1; 51%
55 n= 3; 3%
56
34%


56

Scheme I

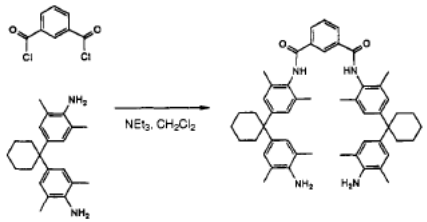


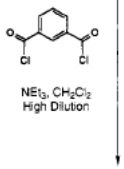
4



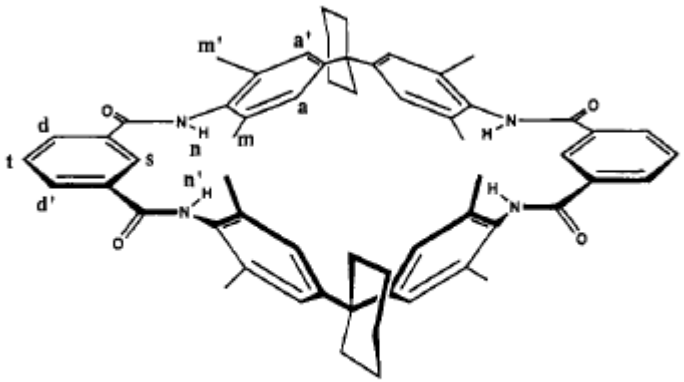
1

Scheme II

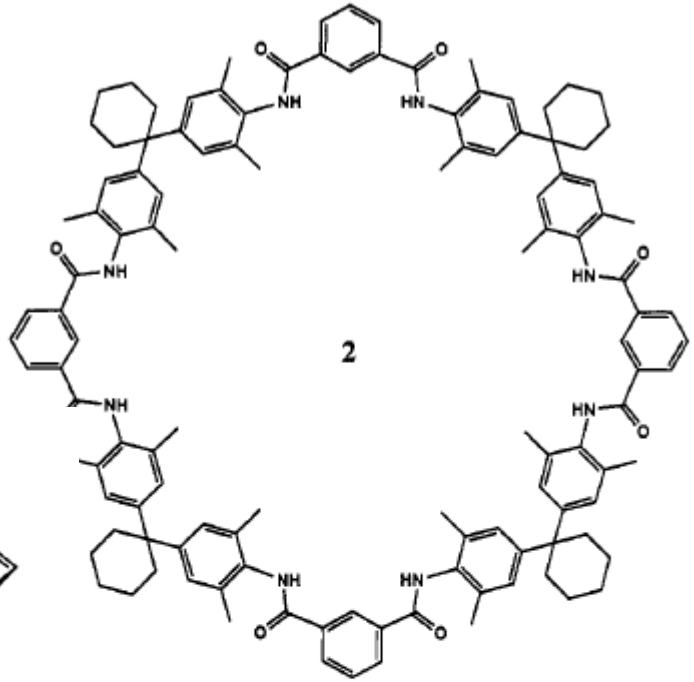




1 + 2 + 3

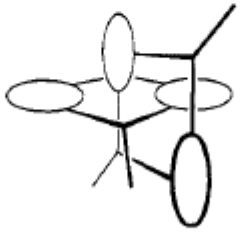


1

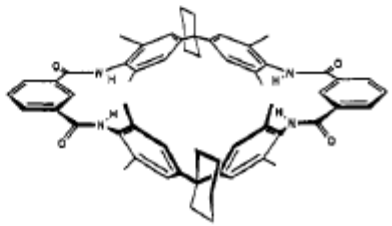


2

3



≡

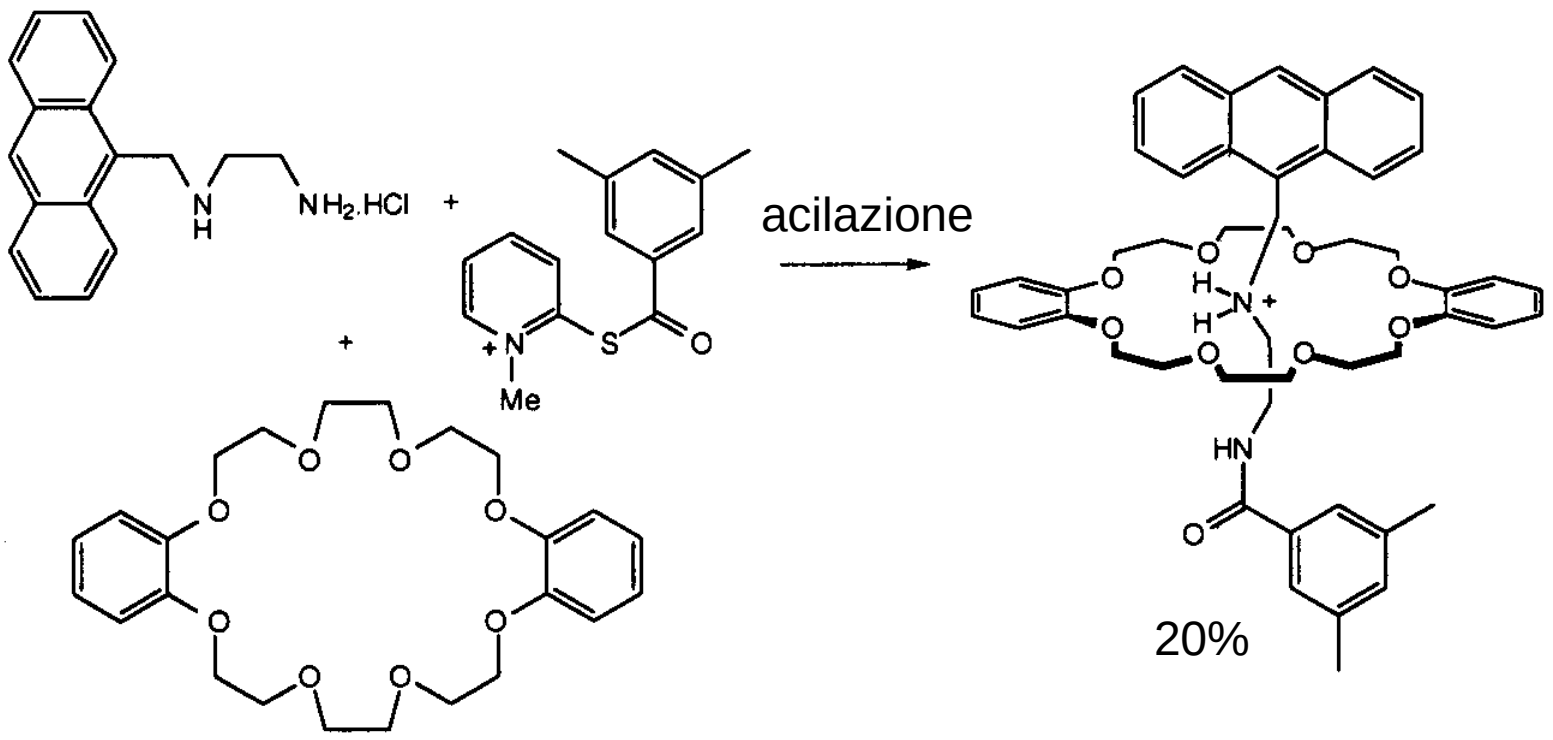


Cyclic Dimer 1, Cyclic Tetramer 2, and Catenane 3 (Scheme II). **5**, 1 g, and 0.4 mL of triethylamine were dissolved in 250 mL of dry dichloromethane and transferred to a dropping funnel. Isophthaloyl dichloride (0.26 g) was similarly dissolved in 250 mL of dry dichloromethane and transferred to an identical dropping funnel. These two solutions were added dropwise to 1200 mL of dry dichloromethane over a period of 4 h with stirring under nitrogen. The reaction mixture was then stirred for a further 12 h. The precipitate was filtered off and the solvent evaporated under reduced pressure. The products were chromatographed on silica with chloroform–ethanol eluant. Fraction A was eluted with chloroform. Fraction B was eluted with chloroform–ethanol (99:1). Fraction C was eluted with chloroform–ethanol (98:2). All three fractions were recrystallized from chloroform–pentane.

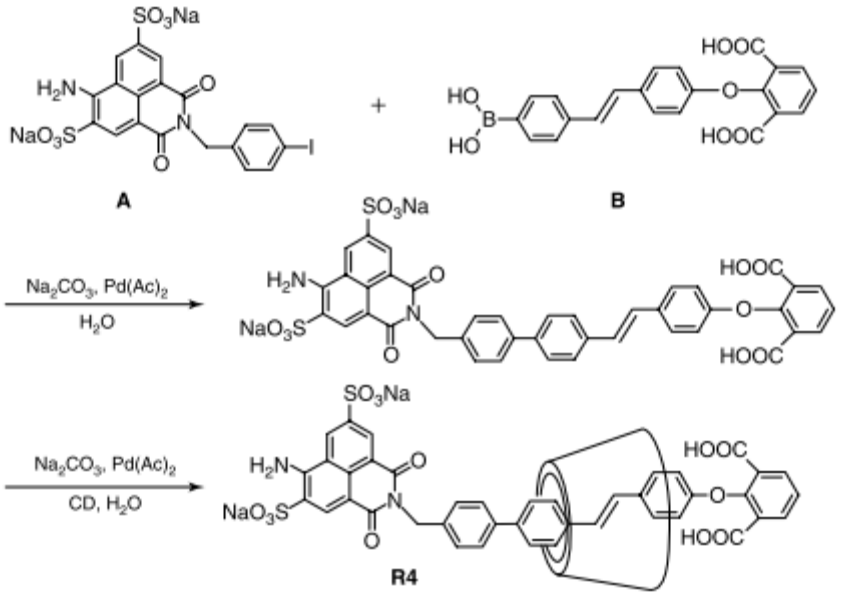
Fraction A was obtained as a white crystalline solid (400 mg, 34%). The NMR data are discussed in the main text. m/z 1806 (MH^+); $C_{120}H_{128}N_8O_8$ requires $M^+ = 1808$.

Fraction B was obtained as a white powder (600 mg, 51%). Spectroscopic data were as for the cyclic dimer **1** from Scheme I.

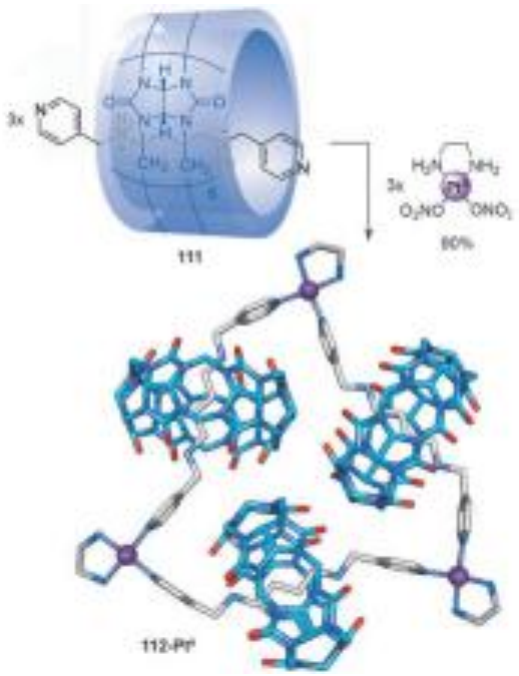
Fraction C was obtained as a white powder (50 mg, 5%). NMR ($CDCl_3/CD_3OD$) δ 8.41 (4 H, s), 7.98 (8 H, d), 7.43 (4 H, t), 6.96 (16 H, s), 2.21 (16 H, br), 2.10 (48 H, s), 1.52 (24 H, br). m/z 1806 (MH^+); $C_{120}H_{128}N_8O_8$ requires $M^+ = 1808$.


NH2.HCl
+
+
N
Me
S
O
acilazione
H
N
HN
20%

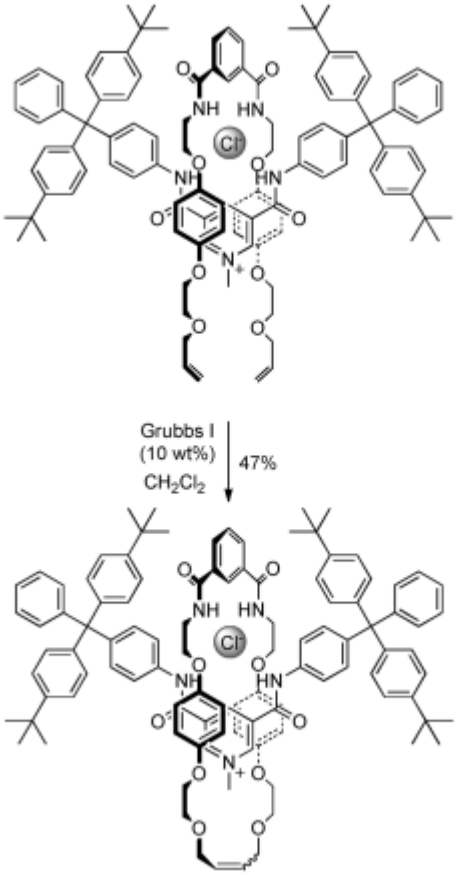
Hydrophobic effect

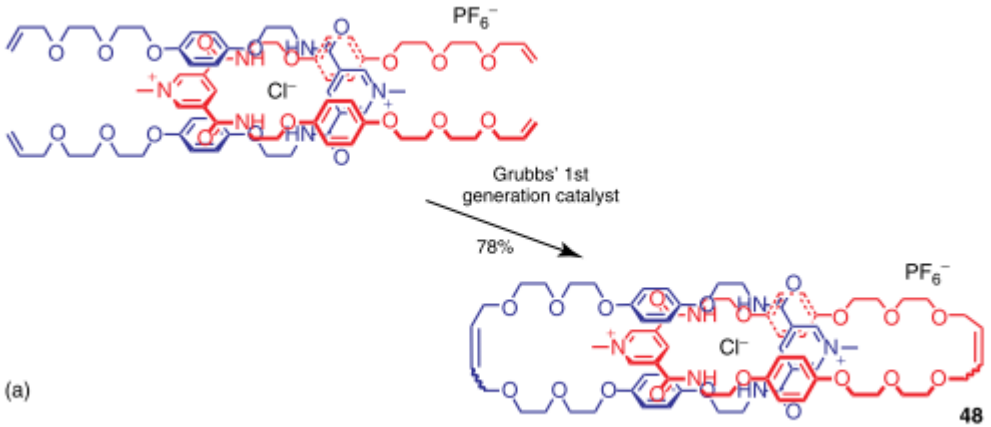


Hydrophobic effect



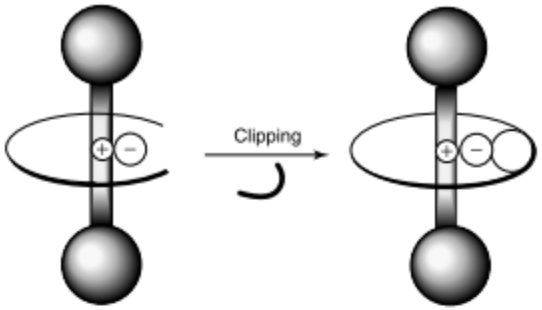
Anion templating

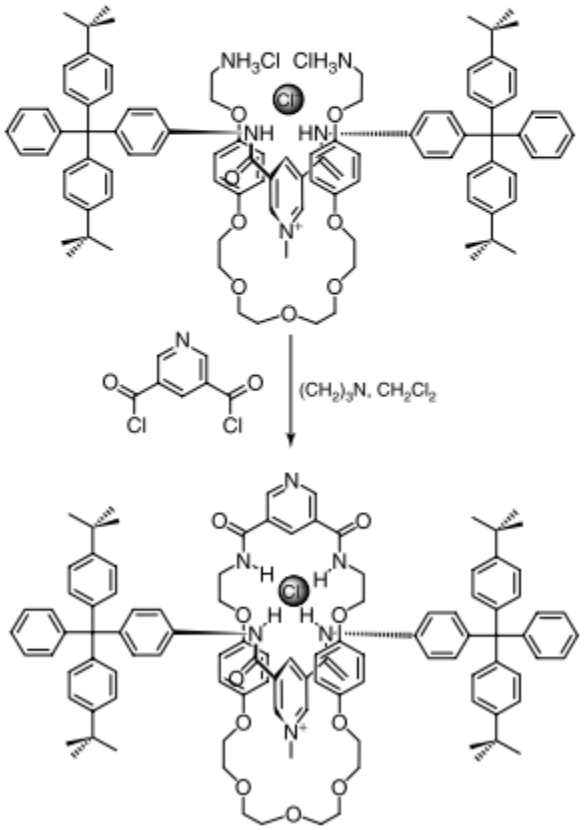




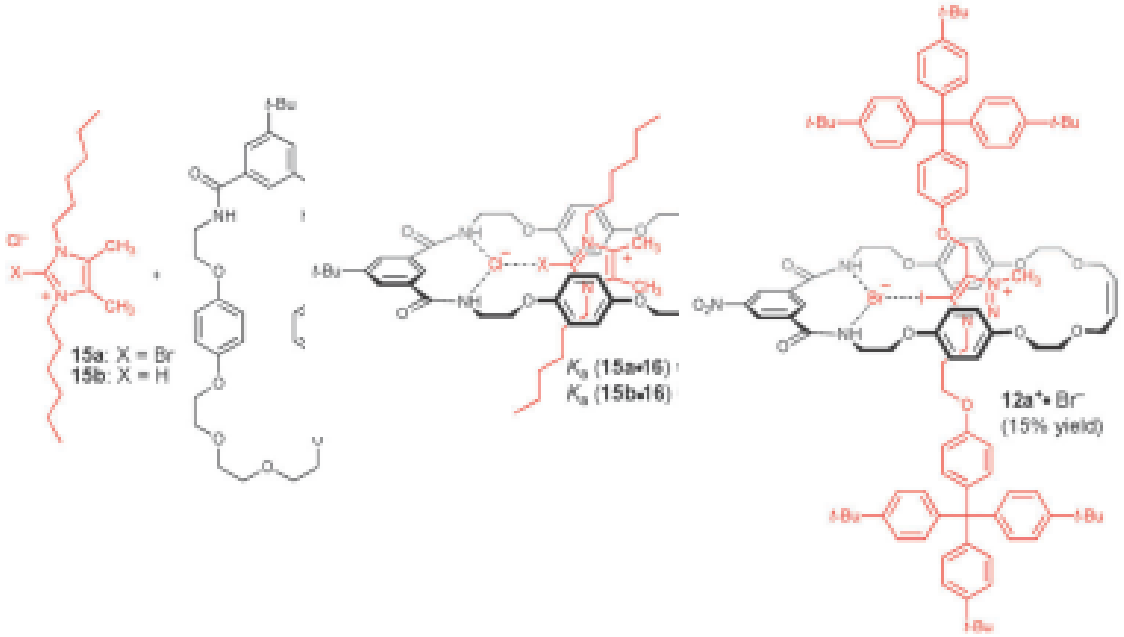
(a)

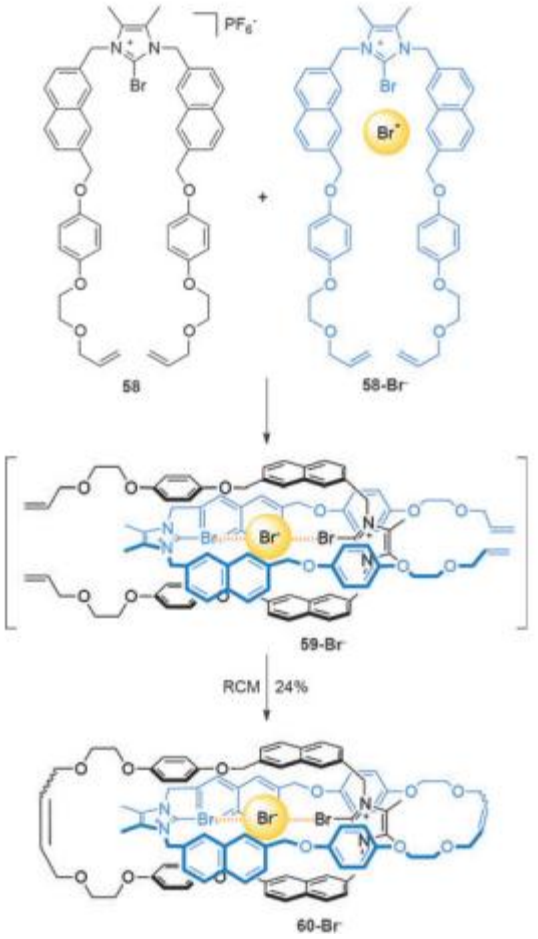
Anion templating

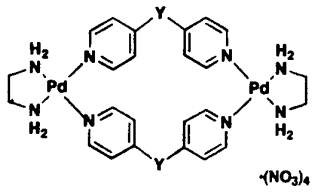


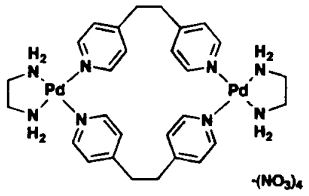


Halogen bond templating



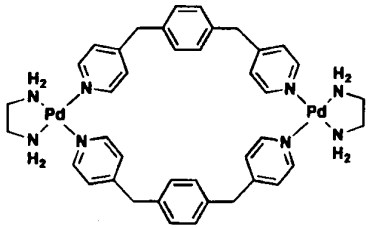


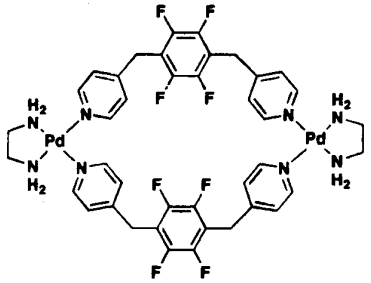

Y
Pd
Pd
$\cdot(NO_3)_4$

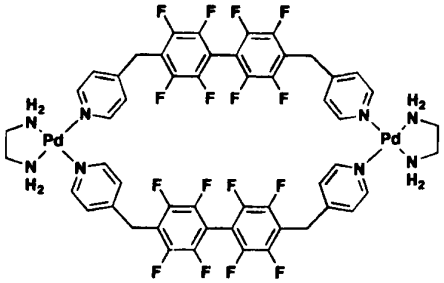

Pd
Pd
$\cdot(NO_3)_4$

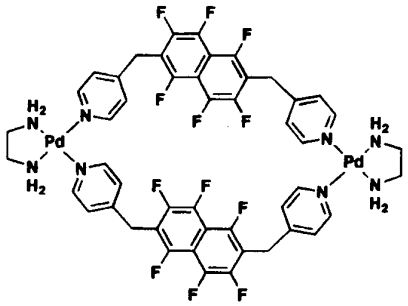
Y = CH_2

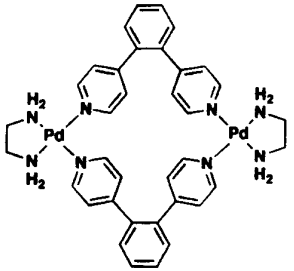
Y = $C(OH)_2$

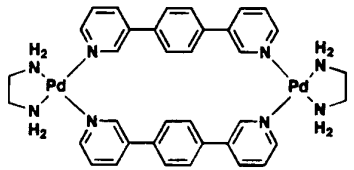

Pd
Pd


F
Pd
Pd

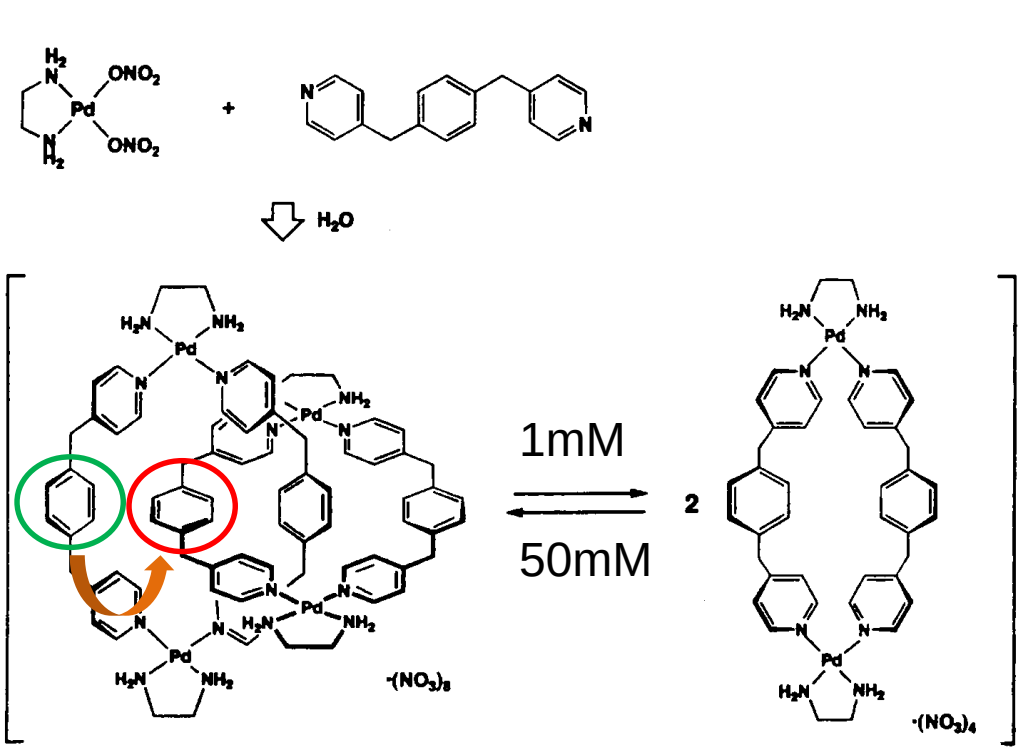

F
Pd
Pd

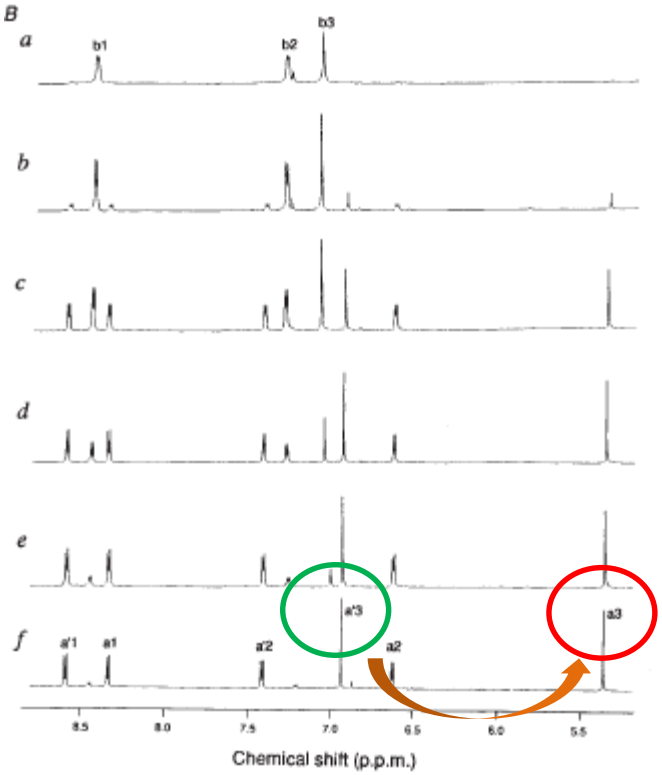

F
Pd
Pd

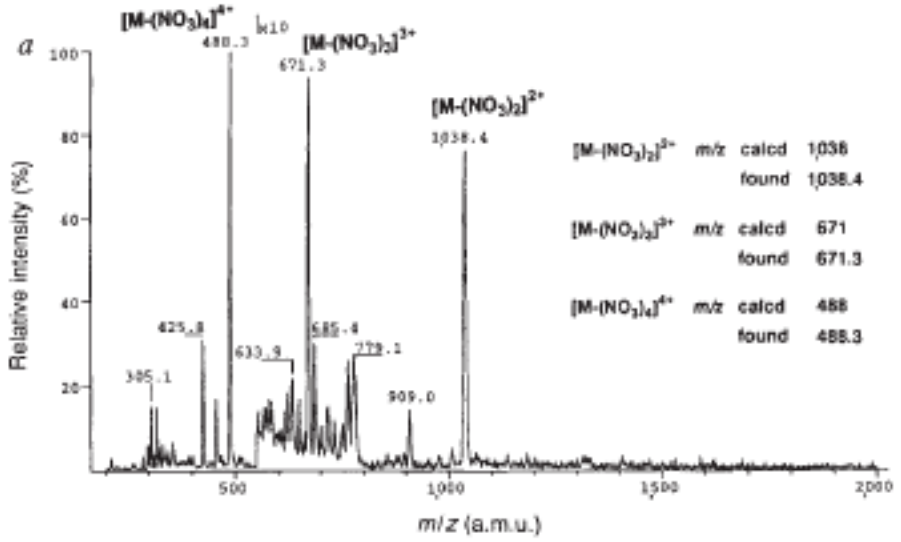

Pd
Pd

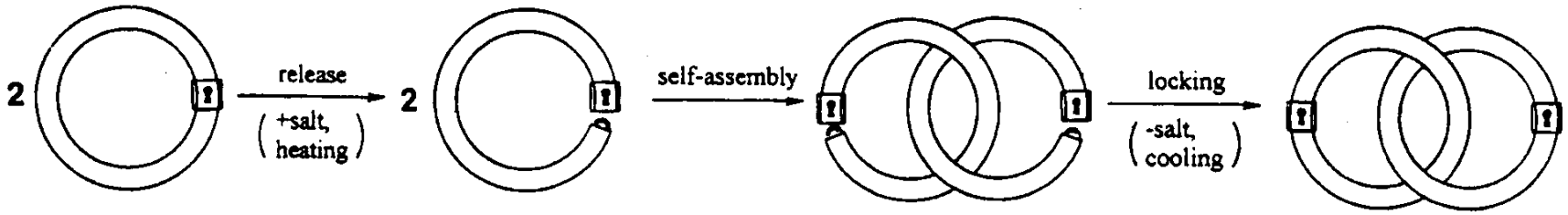

Pd
Pd

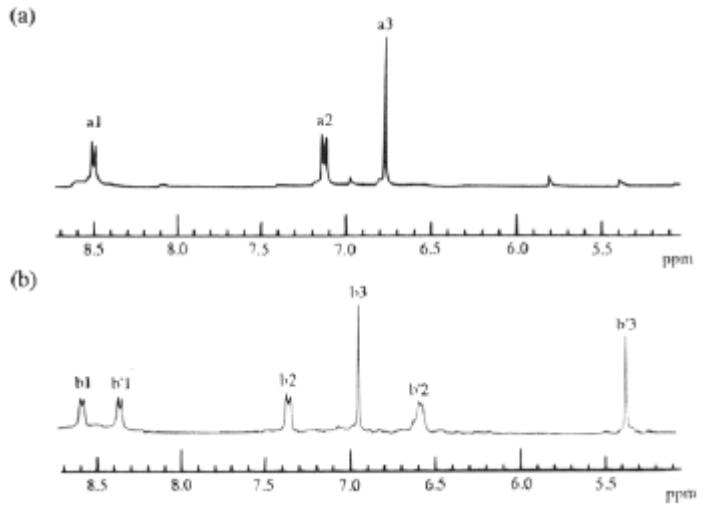
Catenani

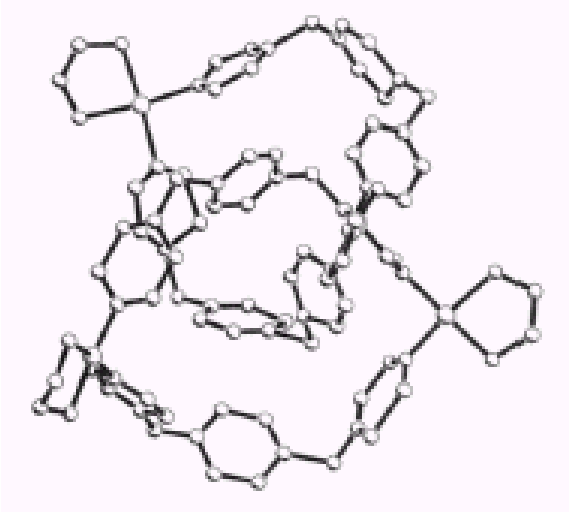

ONO2
ONO2
+
H2O
1mM
50mM
2
·(NO3)8
·(NO3)4


B
a
b1
b2
b3
b
c
d
e
f
a'1
a1
a'2
a'3
a2
a3
8.5
8.0
7.5
7.0
6.5
6.0
5.5
Chemical shift (p.p.m.)

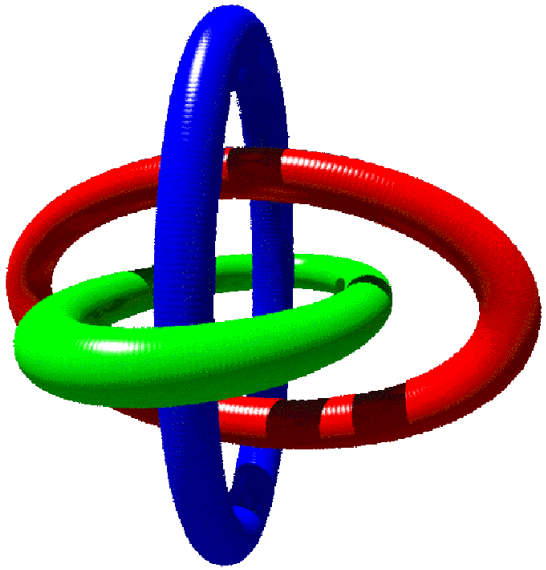

a
[M-(NO3)4]4+
488.3
x10
[M-(NO3)3]3+
671.3
[M-(NO3)2]2+
1038.4
425.8
633.9
585.4
779.1
385.1
909.0
Relative intensity (%)
100
80
60
40
20
500
1000
1500
2000
m/z (a.m.u.)
[M-(NO3)2]2+ m/z calcd 1,038
found 1,038.4
[M-(NO3)3]3+ m/z calcd 671
found 671.3
[M-(NO3)4]4+ m/z calcd 488
found 488.3


2
release
(+salt, heating)
2
self-assembly
locking
(-salt, cooling)


(a)
a1
a2
a3
8.5
8.0
7.5
7.0
6.5
6.0
5.5
ppm
(b)
b1
b'1
b2
b3
b'2
b'3
8.5
8.0
7.5
7.0
6.5
6.0
5.5
ppm

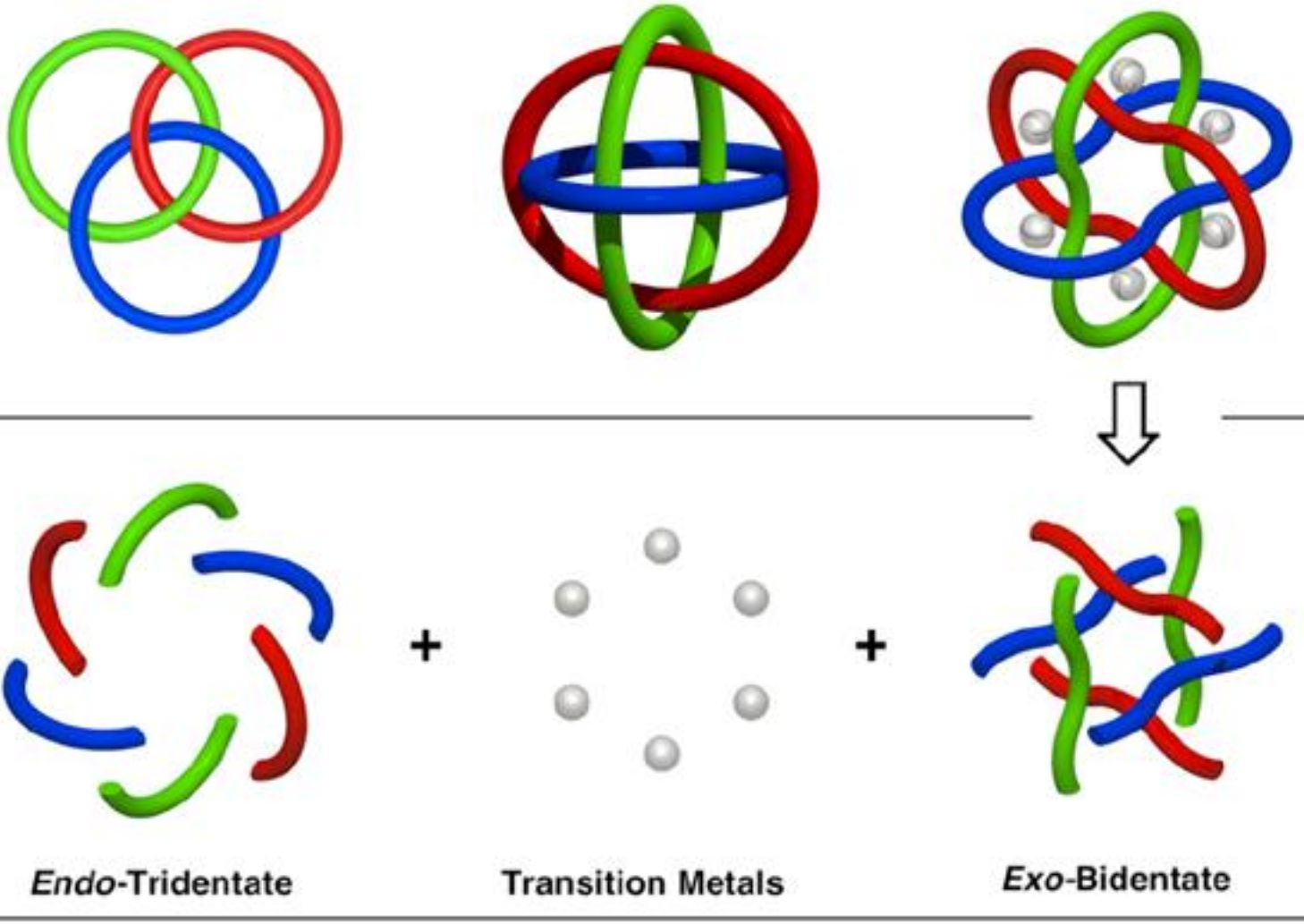


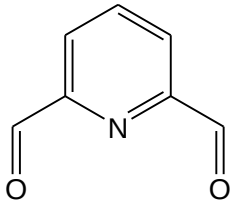
Borromean Rings



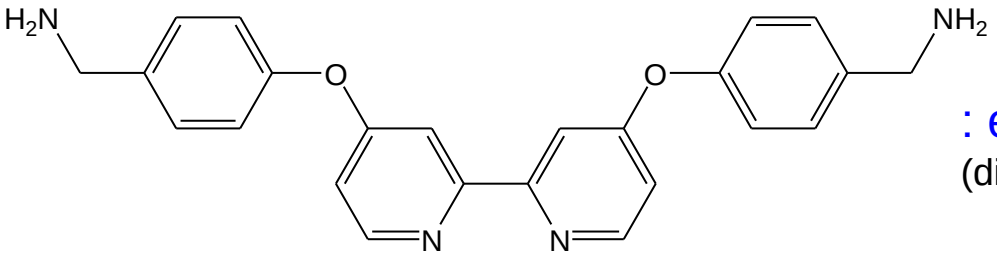
three identical rings. Each ring is inside a second one and outside the third one. No catenation.
4 connections: *endo/eso/endo/eso*

Nodo Borromeo

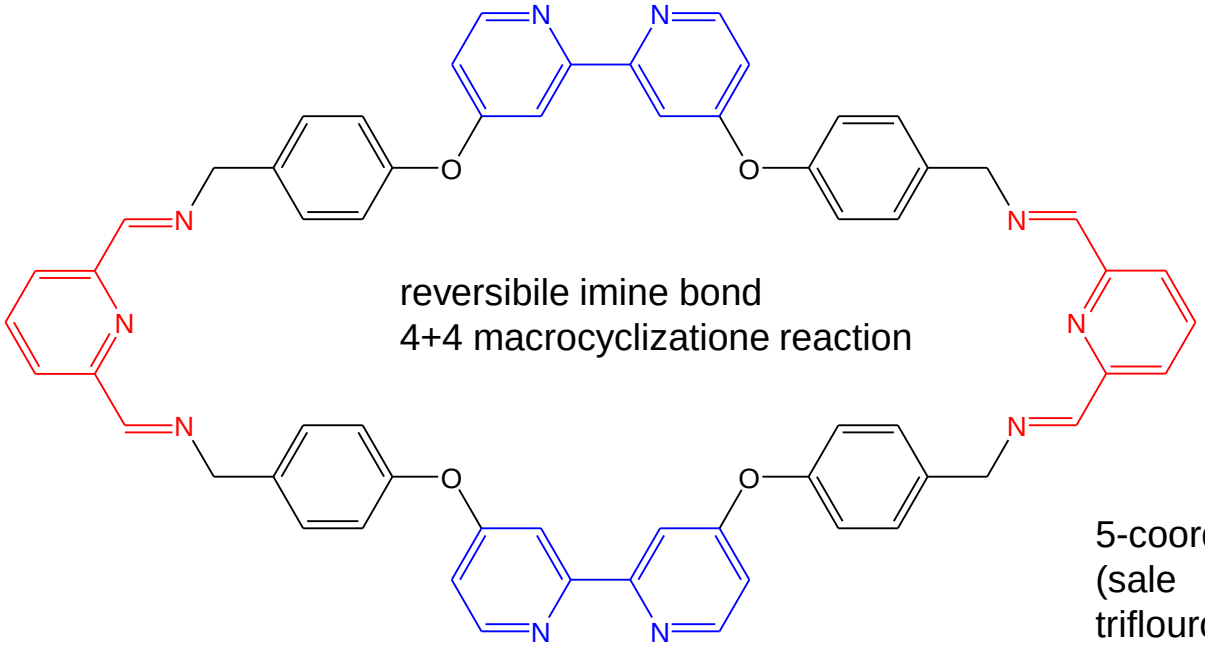




: endo-tridentate (2,6 diformilpyiridine DFP)

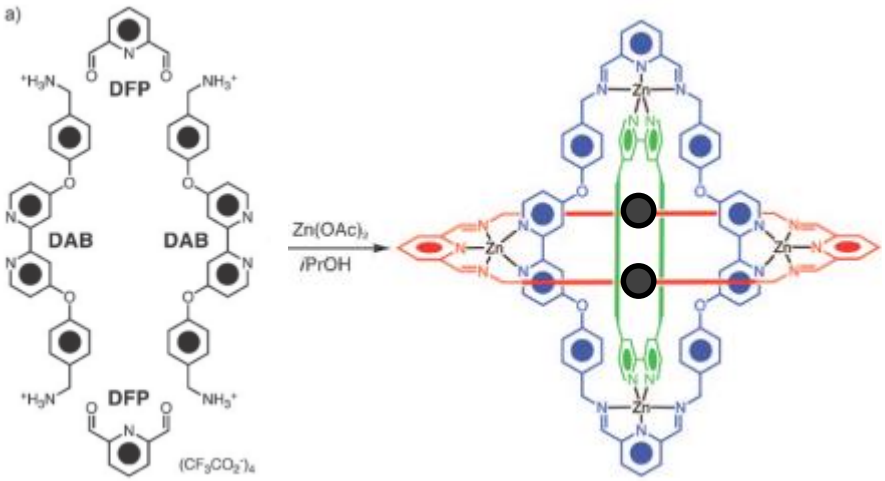


: exo-bidentate
(diamminobipyridiyl ligand DAB)



reversibile imine bond
4+4 macrocyclizatione reaction

5-coordinated Zn(II)
(sale
triflouroacetatato)



After 2 days 90°C, MeOH
NMR, mass spectrometry (ESI)

Carica: 12^{+}
Controioni: $12TFA^{-}$

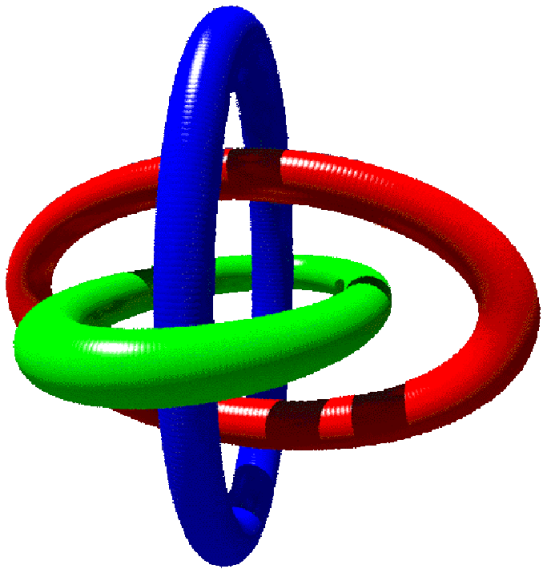
endo-tridentate
2,6 diformilpyiridine (DFP)

exo-bidentate
diamminobipyridiyl ligand (DAB)

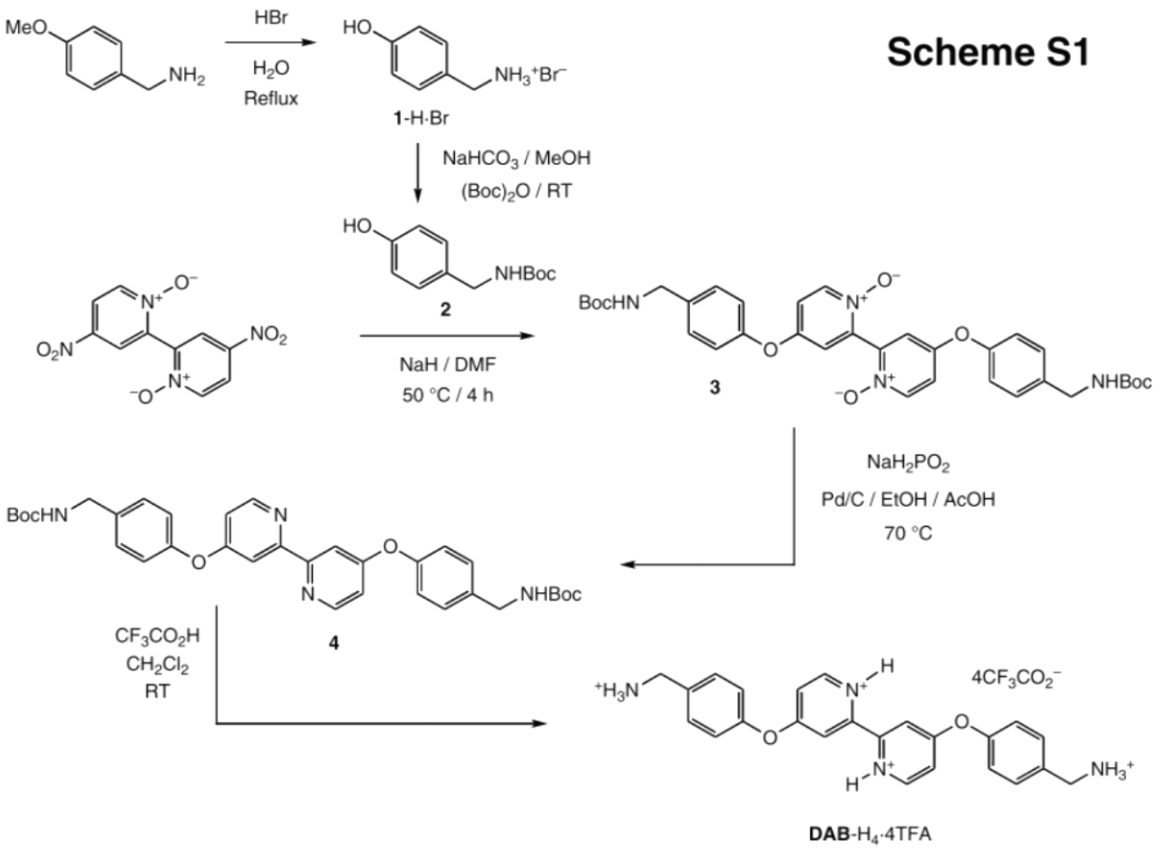
5-coordinated Zn(II)
(sale triflouroacetatato)

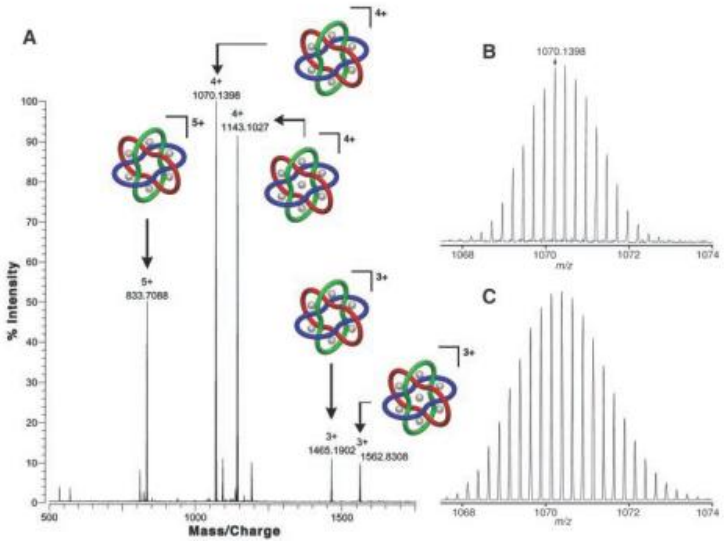
reversibile imine formation

reversible coordination



Scheme S1


MeO
NH2
HBr
H2O
Reflux
HO
NH3+Br−
1-H·Br
NaHCO3 / MeOH
(Boc)2O / RT
HO
NHBoc
2
O2N
NO2
NaH / DMF
50 °C / 4 h
BocHN
NHBoc
3
NaH2PO2
Pd/C / EtOH / AcOH
70 °C
BocHN
NHBoc
4
CF3CO2H
CH2Cl2
RT
+H3N
4CF3CO2−
NH3+
DAB-H4·4TFA



$[M\text{-}3TFA]^{3+}$
$[M\text{-}4TFA]^{4+}$
$[M\text{-}5TFA]^{5+}$

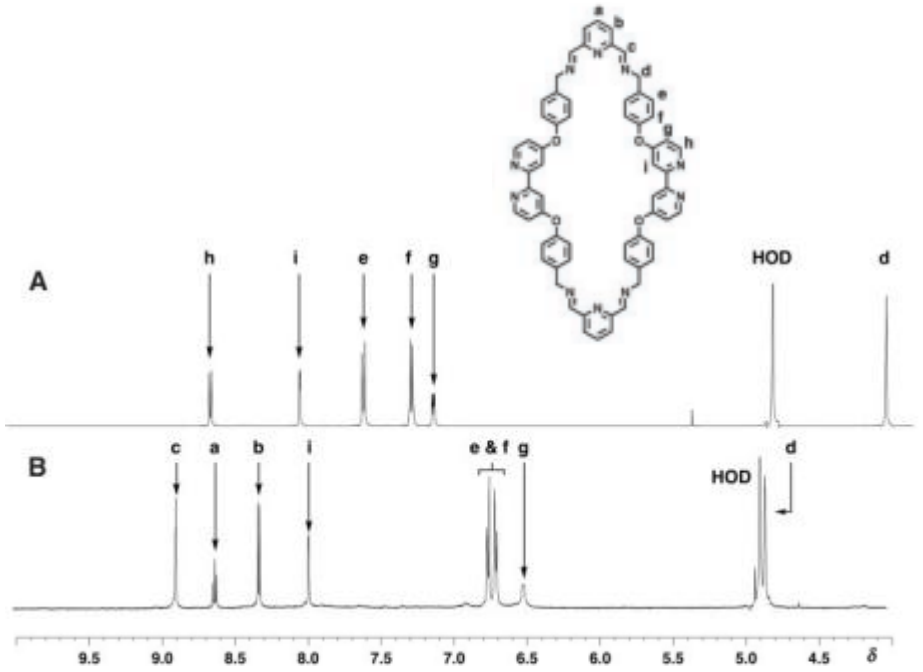
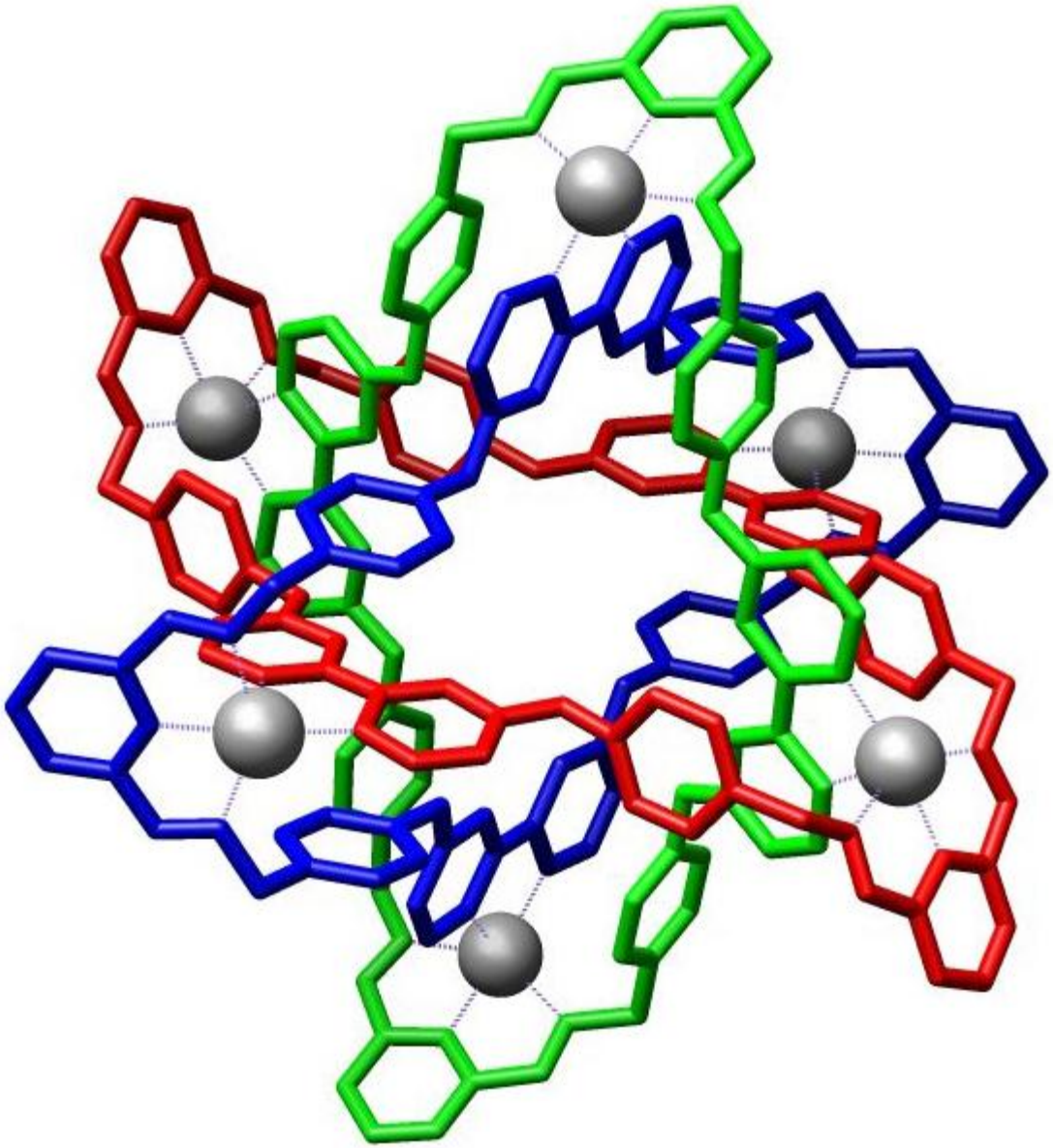
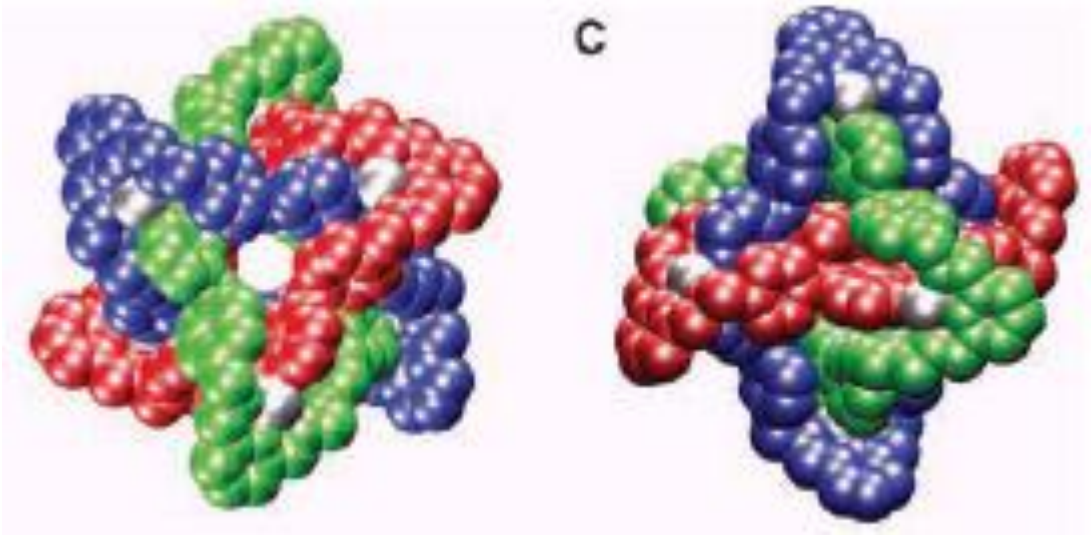
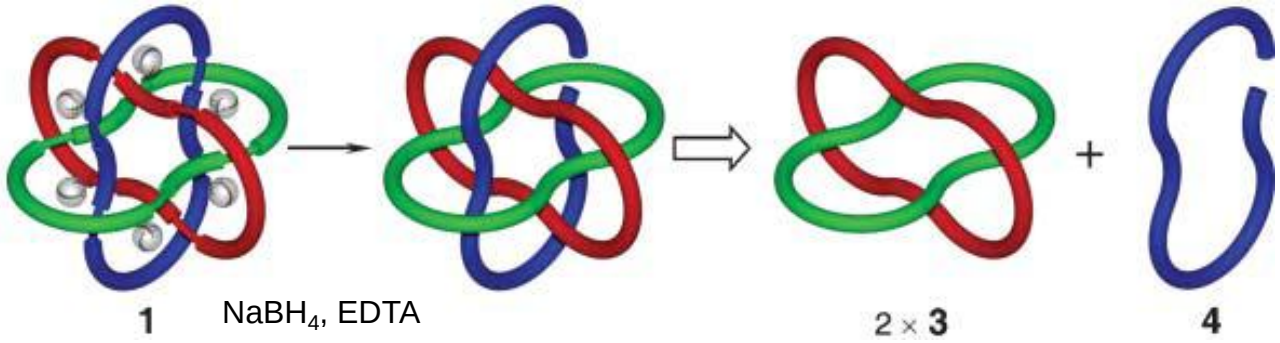


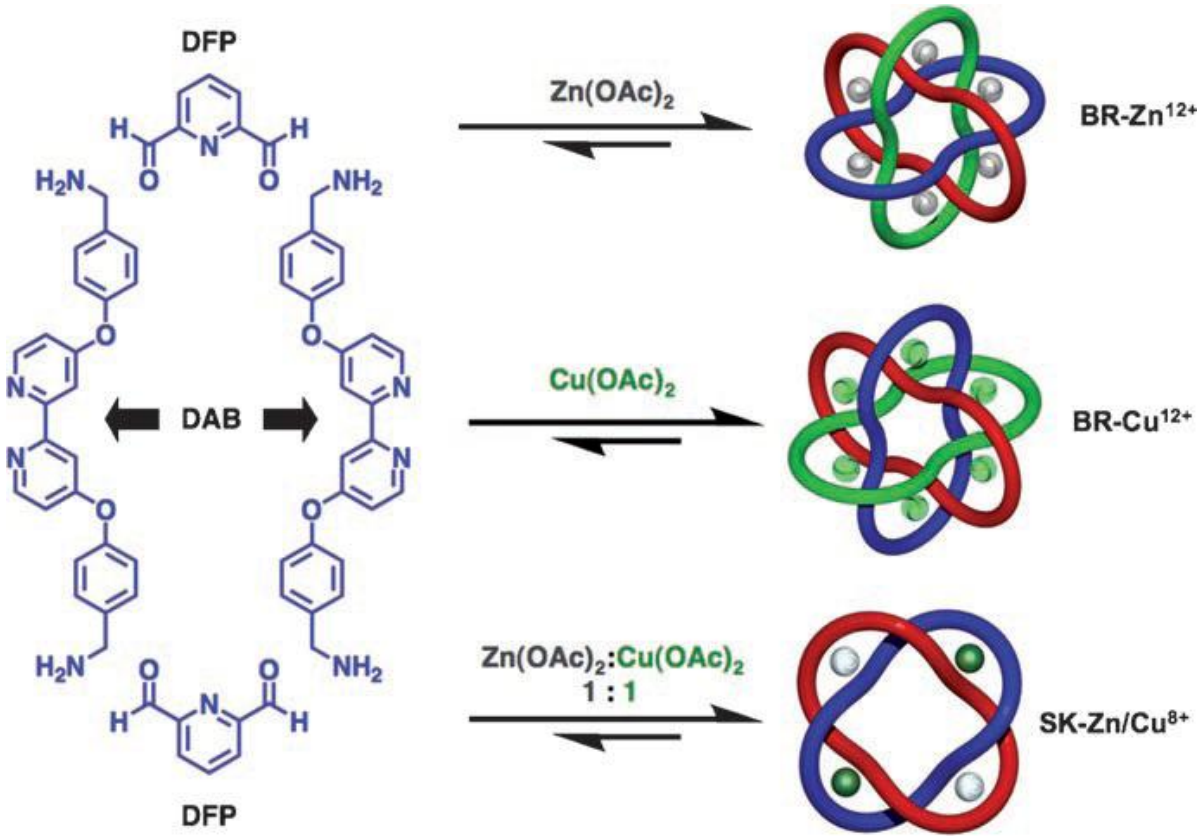
Fig. 2. The ^{1}H NMR spectra (CD_3OD, 298 K) of (**A**) the *exo*-bidentate ligand-containing starting material **DAB**-H_4·4TFA (500 MHz), (**B**) the molecular Borromean rings **BR**·12TFA (600 MHz)



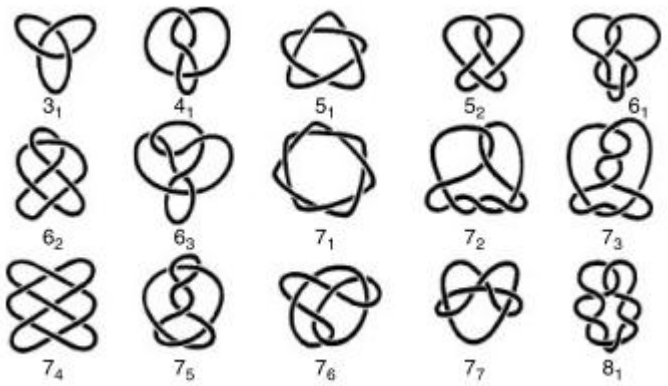


6 Zn(II) bound to one bipy and one dimminopyridine (in the solid state 6th position occupied by triluoroacetate (TFA); S_6 symmetry π-π stacking ech bipy between 2 phenols 3.61-3.66 Å; 12^+


1
NaBH4, EDTA
2 × 3
4


DFP
DAB
DFP
Zn(OAc)2
BR-Zn12+
Cu(OAc)2
BR-Cu12+
Zn(OAc)2:Cu(OAc)2
1 : 1
SK-Zn/Cu8+

Nodi Molecolari e Links



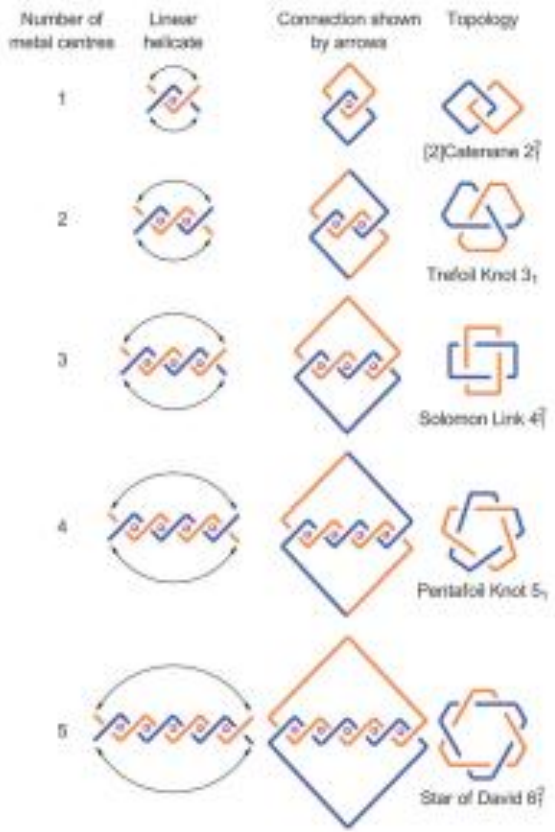


Fig. 3 The linear helicate strategy to interlocked molecules introduced by Sauvage.[48] To date the first three entries of this table have been realised experimentally using this strategy, generating catenanes,[4] trefoil knots[38] and doubly-interlocked [2]catenanes (Solomon links)[47] using one, two and three metal centres, respectively. The synthesis of a pentafoil knot or triply-interlocked [2]catenane (the 'Star of David' topology) from a linear helicate has thus far proved unsuccessful.[48]

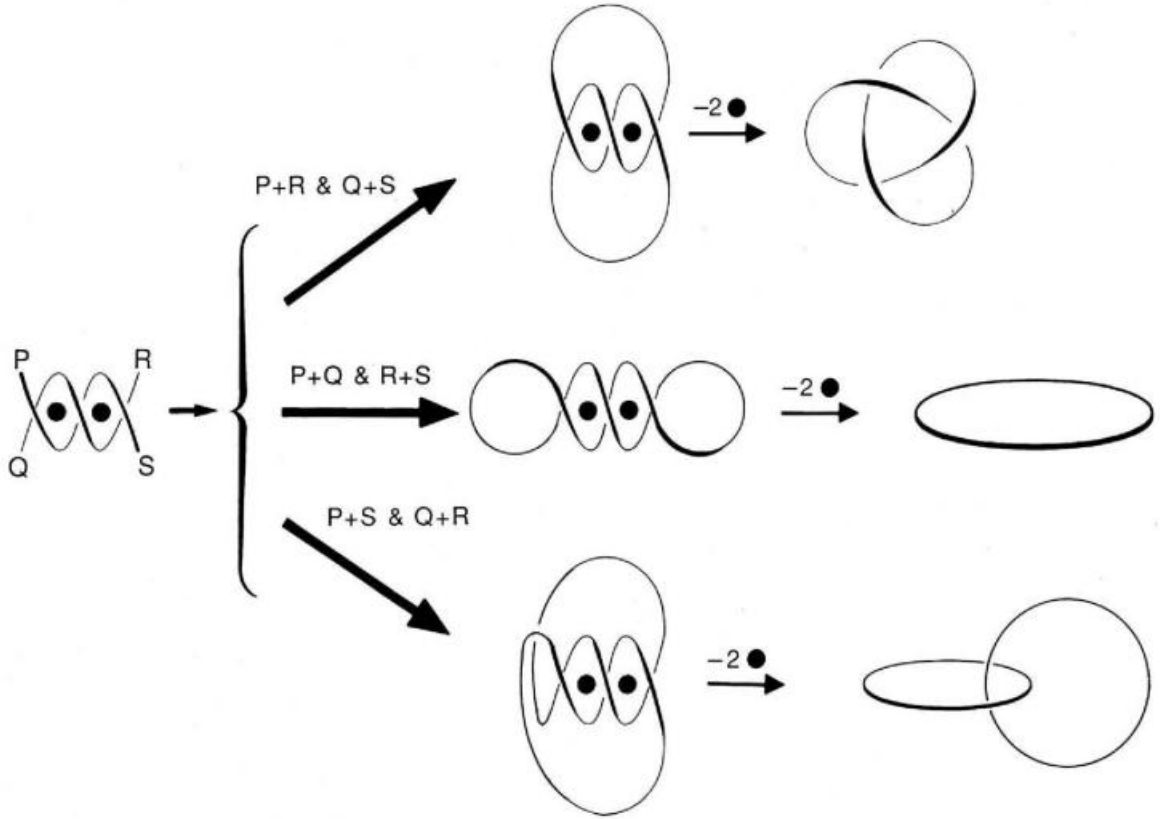


Figure 23. A guide for demonstrating the synthesis of topologically different molecules from the precursor to the trefoil knot.

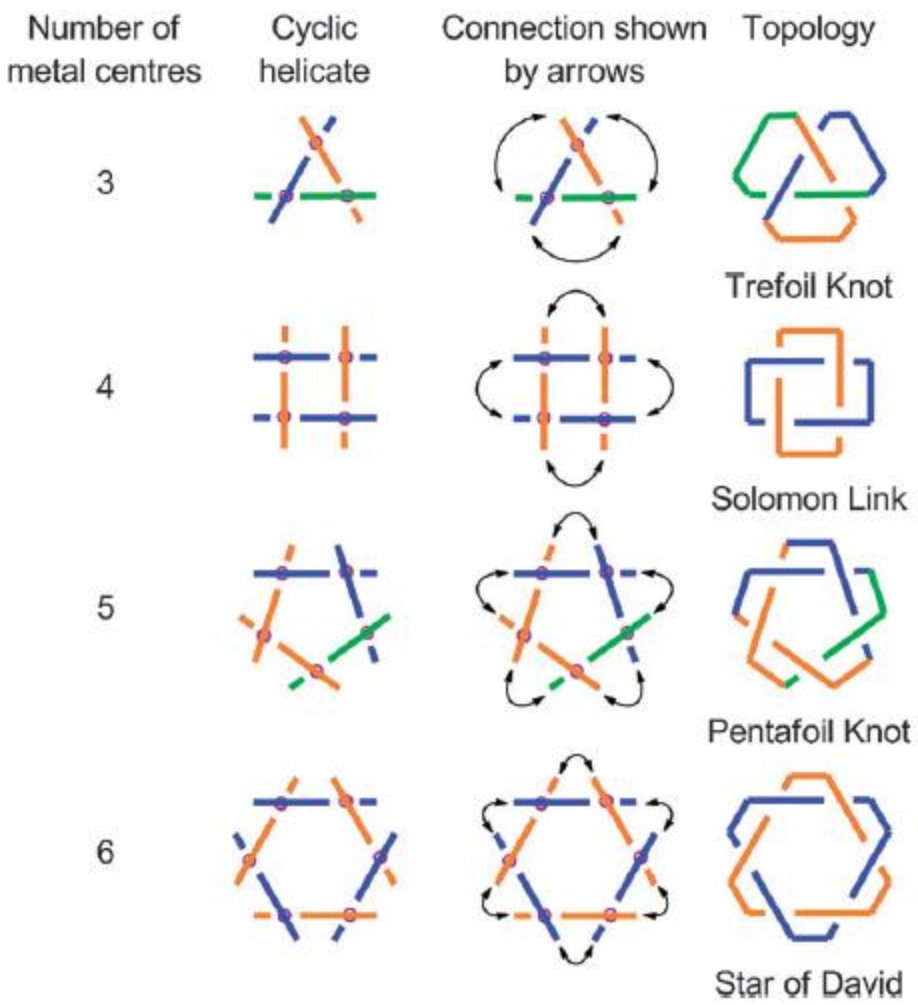
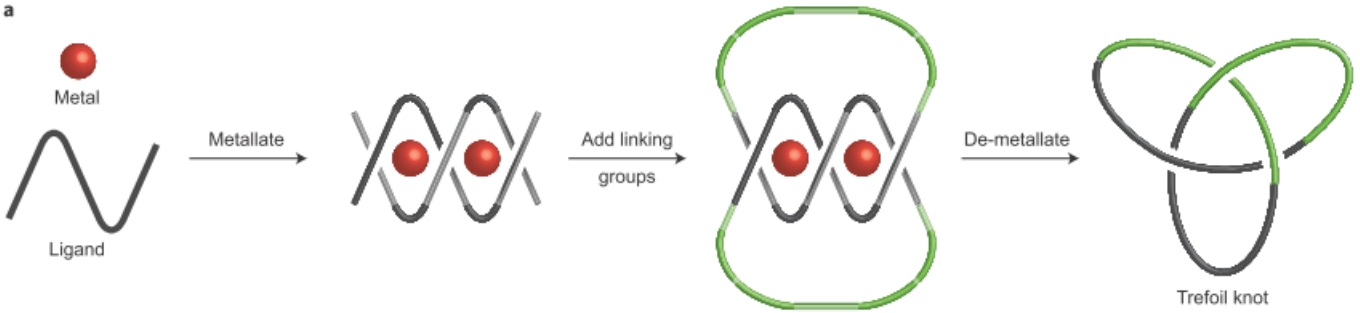
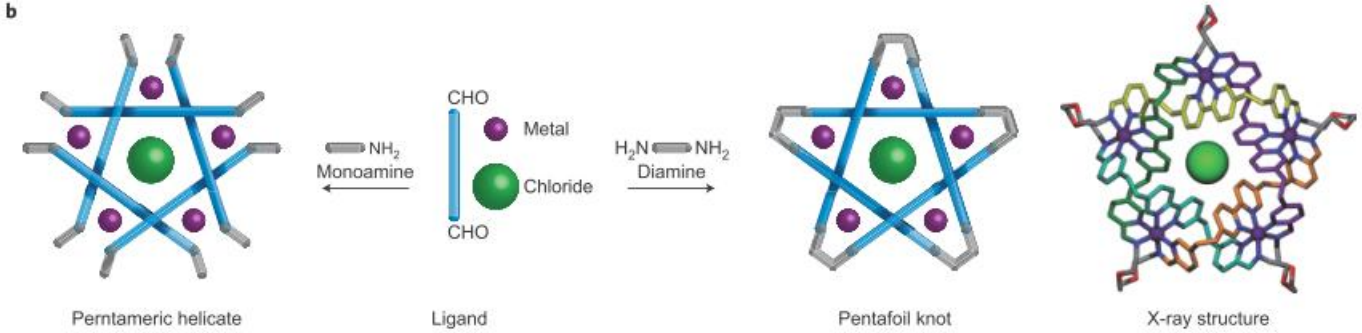


Fig. 5 The potential of circular metal helicates to form molecular knots and links by connecting adjacent end-groups. To date only a pentafoil knot has been prepared through this strategy.[73]


a
Metal
Ligand
Metallate
Add linking
groups
De-metallate
Trefoil knot


b
NH2
Monoamine
CHO
Metal
Chloride
CHO
H2N
NH2
Diamine
Perntameric helicate
Ligand
Pentafoil knot
X-ray structure

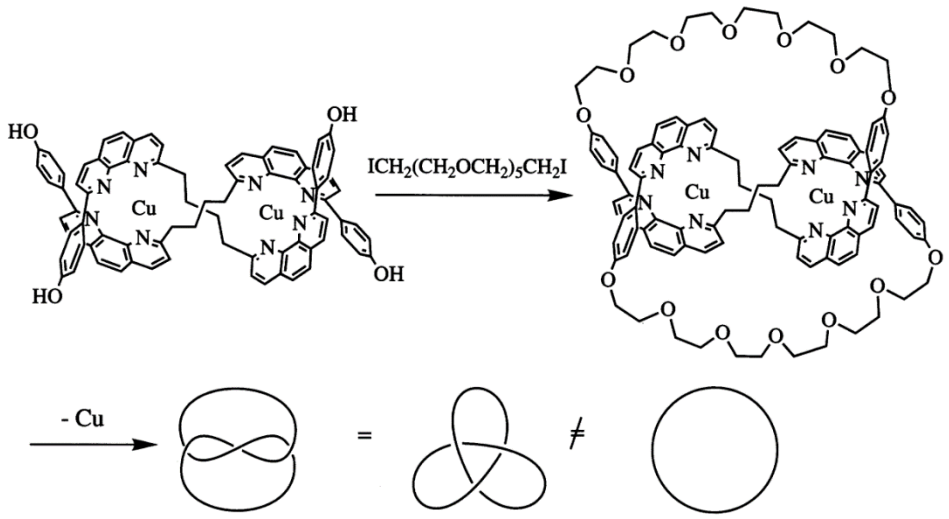
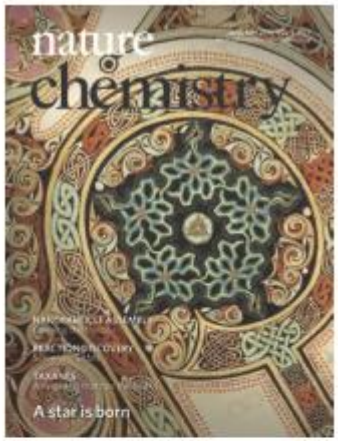


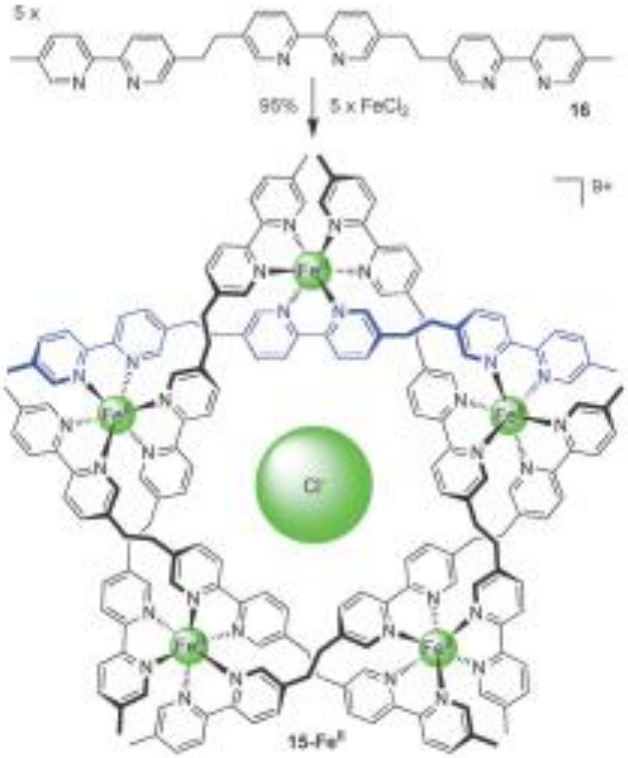
Fig. 8. Synthesis of the first trefoil knot using a two-anchor helical template.

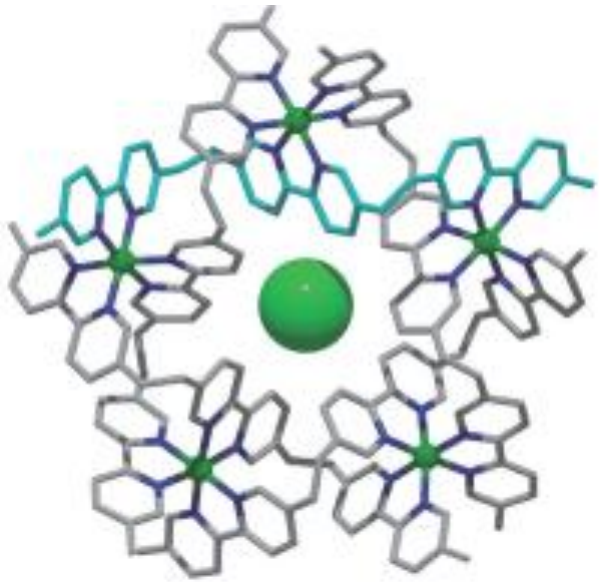


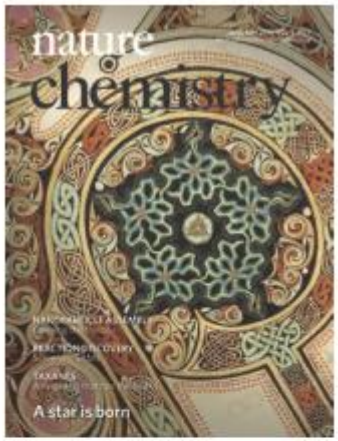
COVER IMAGE

The cover image features the interlaced 'rho' character from Matthew 1:18 in the Lindisfarne Gospels as a backdrop for the X-ray crystal structure of the most complex non-DNA molecular knot synthesized so far. A team led by David Leigh prepared the 160-atom-long pentafoil knot in a one-step reaction from ten organic building blocks and five iron(II) cations. They use a single chloride anion as a template, which, in the solid-state structure, is located at the centre of the pentafoil knot and exhibits ten **CH···Cl**$^-$ hydrogen bonds.

Article p15; News & Views p7







COVER IMAGE

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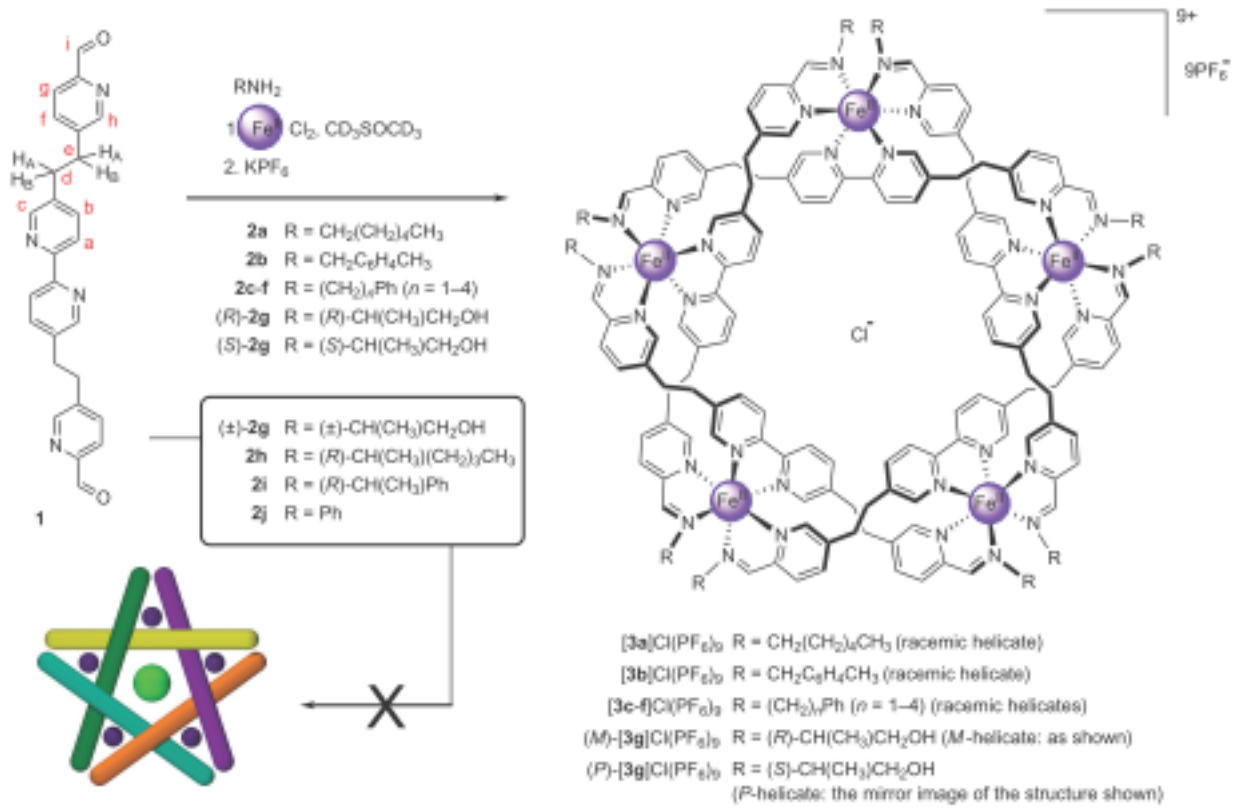
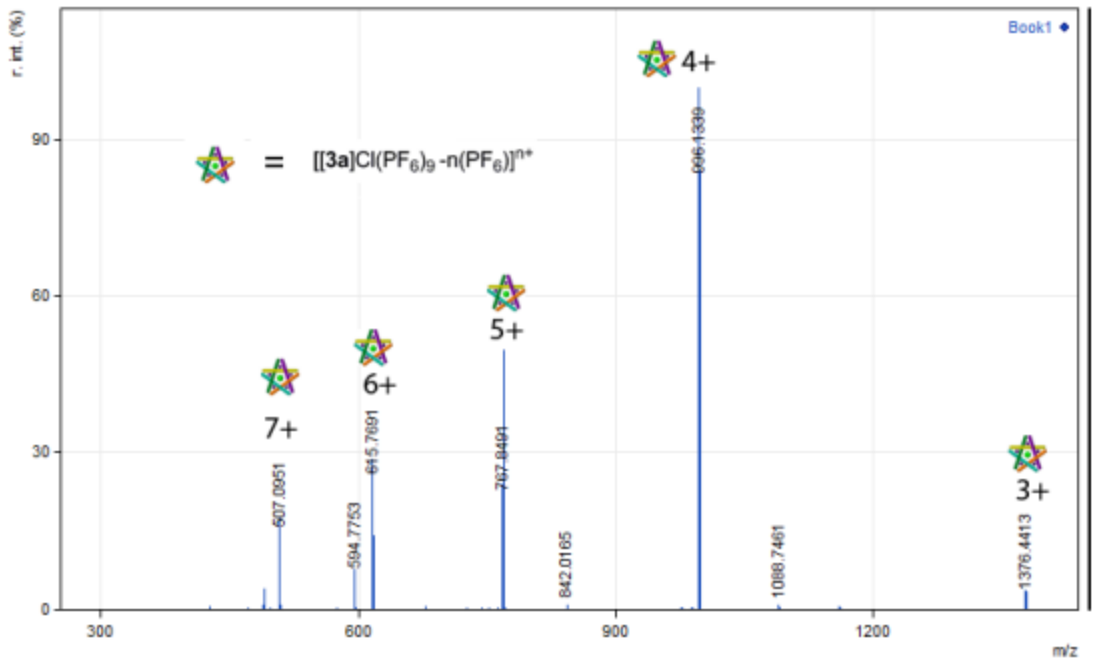
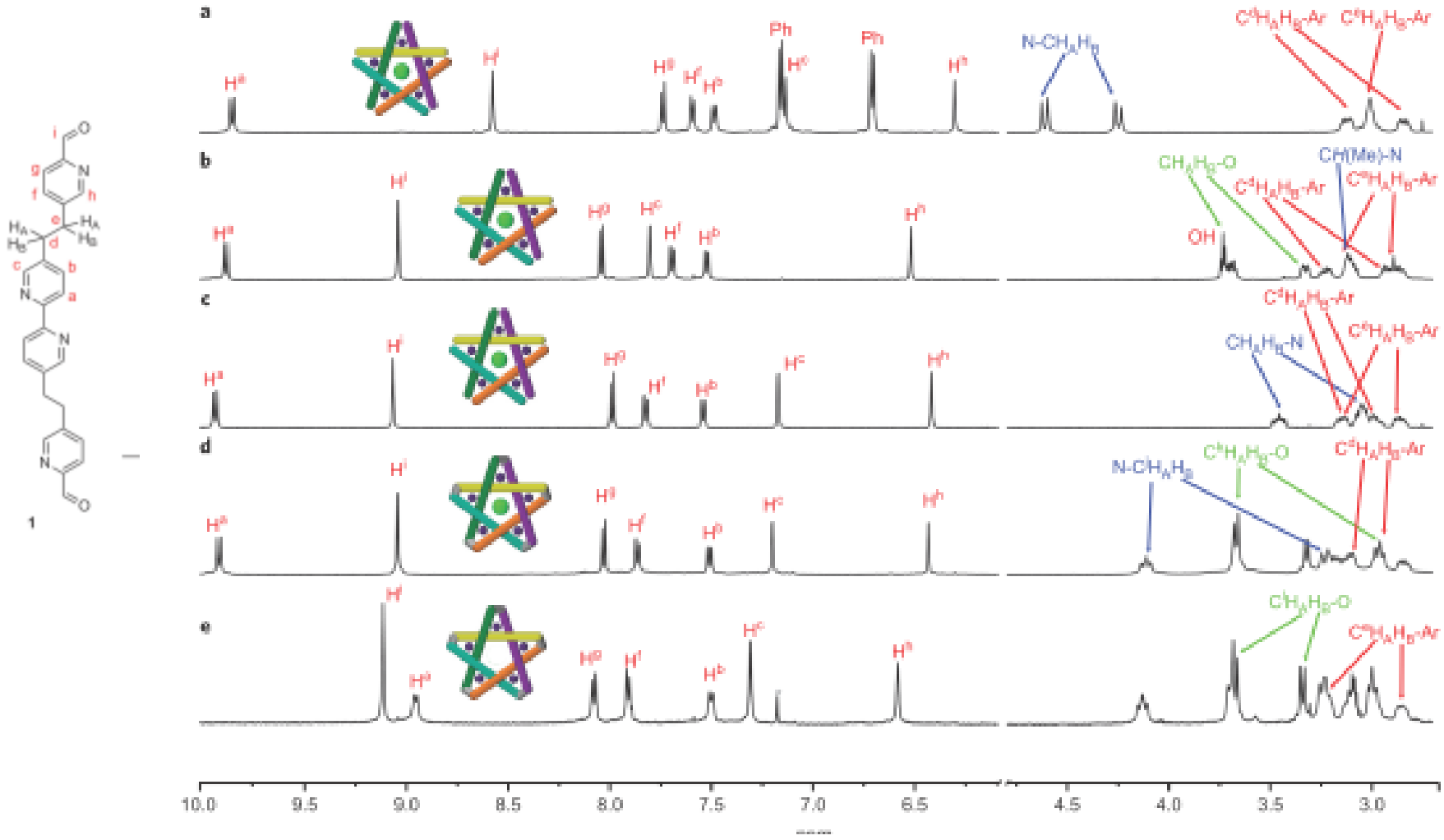
Article p15; News & Views p7




Book1
r. int. (%)
90
60
30
0
300
600
900
1200
m/z
= [[3a]Cl(PF6)9 -n(PF6)]n+
4+
5+
6+
7+
3+
996.1339
767.8491
615.7691
607.0951
594.7753
842.0165
1088.7461
1376.4413


a
b
c
d
e
Ph
Ph
N-CHAHB
CHAHB-Ar
CHAHB-Ar
CHAHB-O
CH(Me)-N
OH
CHAHB-N
10.0
9.5
9.0
8.5
8.0
7.5
7.0
6.5
4.5
4.0
3.5
3.0

1

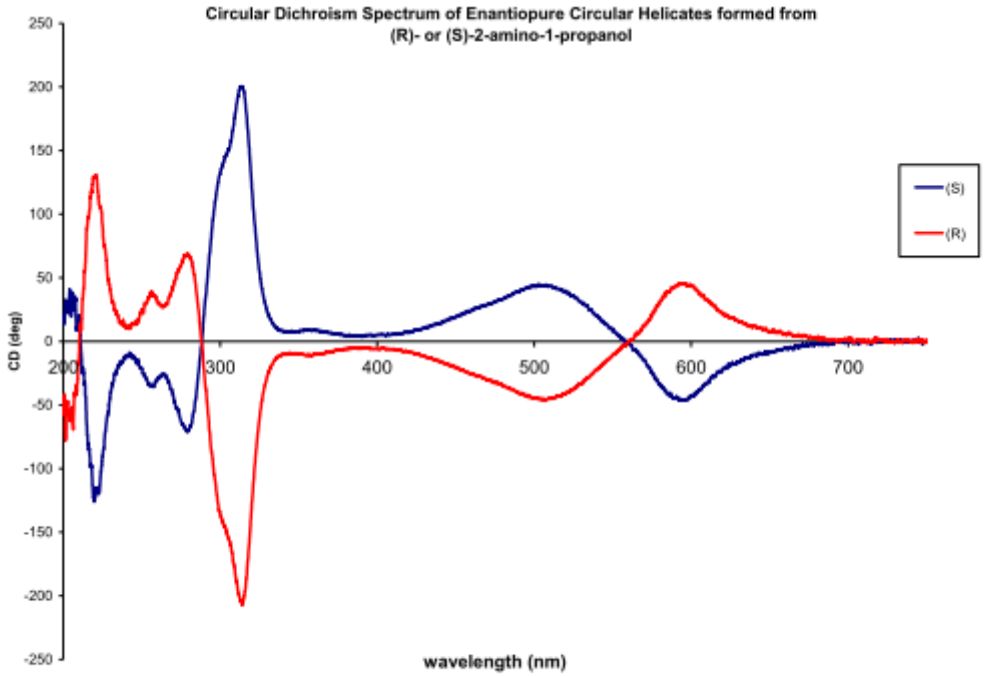
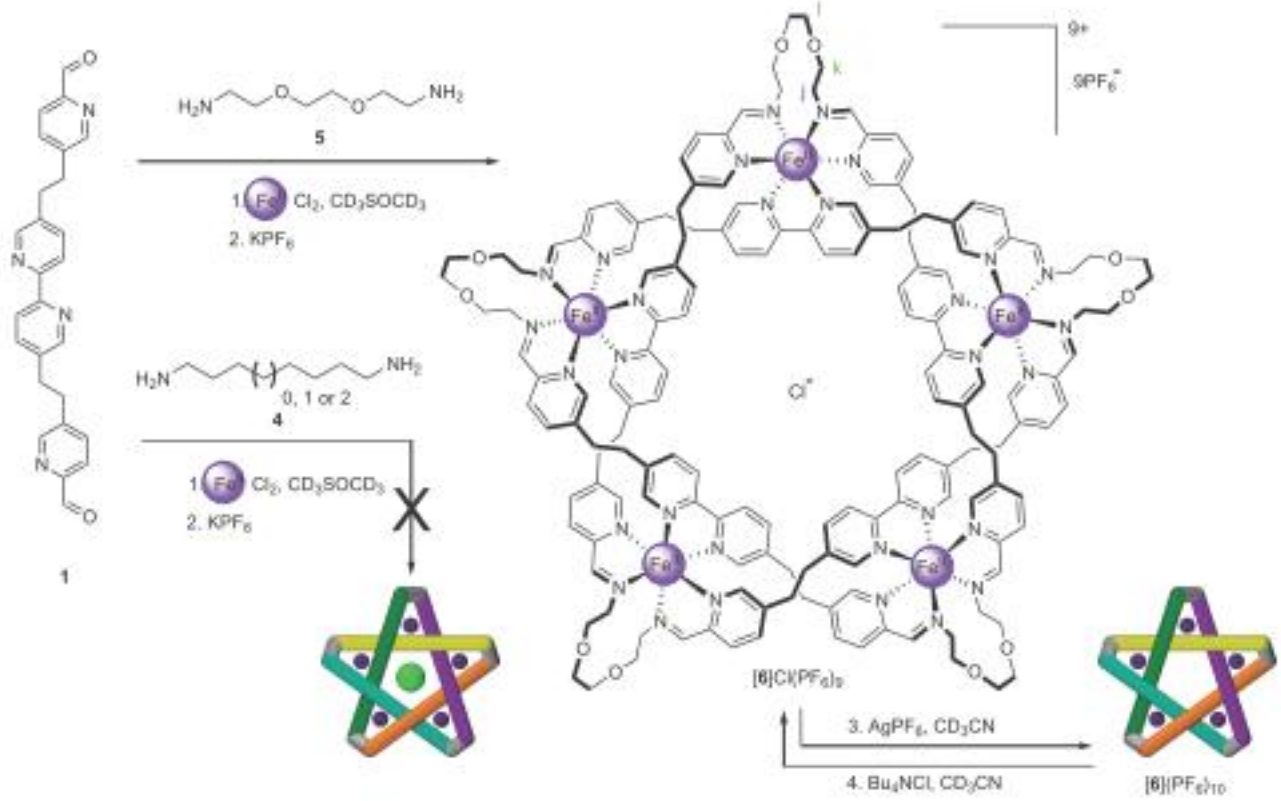


Figure S8 Circular dichroism spectra of (*R*)-[**3g**]Cl$(PF_6)_9$ and (*S*)-[**3g**]Cl$(PF_6)_9$ in MeCN.


1
5
1. Fe2+ Cl2, CD3SOCD3
2. KPF6
4
0, 1 or 2
1. Fe2+ Cl2, CD3SOCD3
2. KPF6
9+
9PF6-
[6]Cl(PF6)9
3. AgPF6, CD3CN
4. Bu4NCl, CD3CN
[6](PF6)10

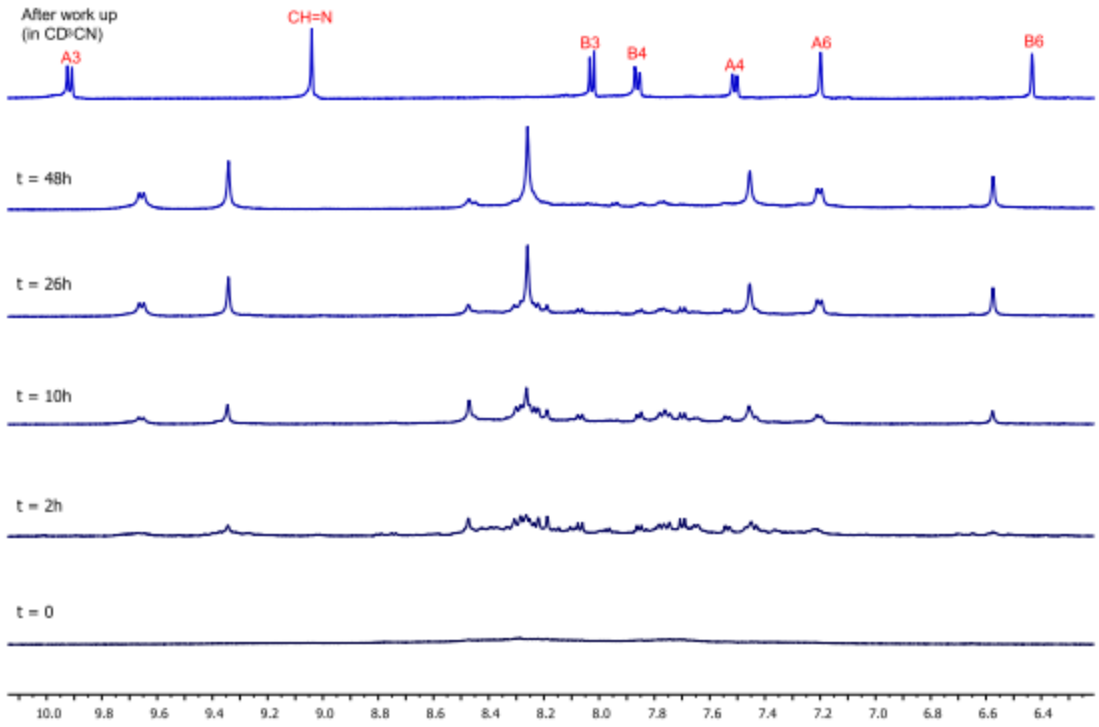
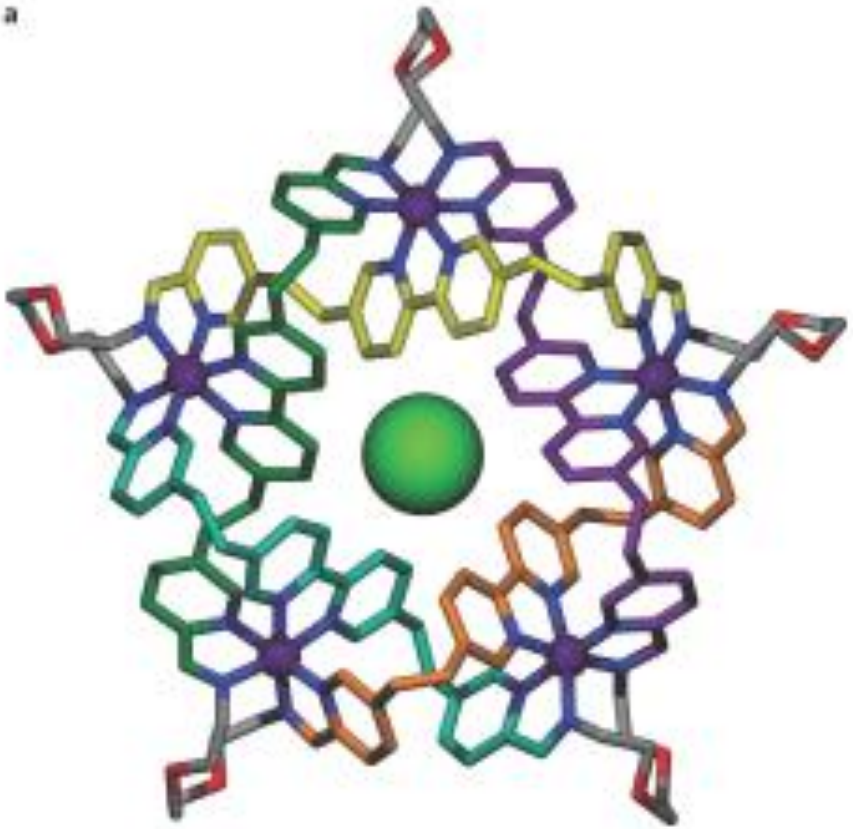
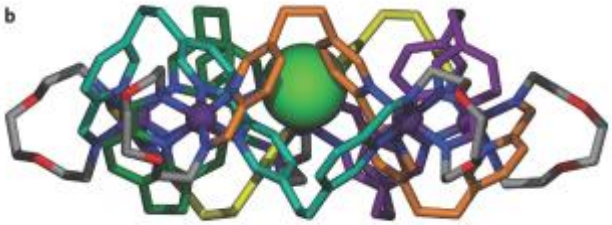


Figure S9 Formation of pentafoil knot $[\mathbf{6}]^{10+}$ monitored by ^{1}H NMR (DMSO-d_6, 500 MHz), aromatic region of spectrum shown. Spectra were collected of the crude reaction mixture after t = 0 (bottom), 2h, 10h, 26h and 48h. The top spectra is of the same sample after work-up (^{1}H NMR in CD_3CN) with ^{1}H NMR assignments indicated.

a



b



Interlocked Molecules

DOI: 10.1002/anie.201007963

Strategies and Tactics for the Metal-Directed Synthesis of Rotaxanes, Knots, Catenanes, and Higher Order Links

Jonathon E. Beves, Barry A. Blight, Christopher J. Campbell, David A. Leigh, and Roy T. McBurney*

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Template synthesis of molecular knots†

Cite this: *Chem. Soc. Rev.*, 2013, **42**, 1700

Jean-François Ayme,[ab] Jonathon E. Beves,[a] Christopher J. Campbell[a] and David A. Leigh*[ab]

Received 28th June 2012

DOI: 10.1039/c2cs35229j

www.rsc.org/csr

This *tutorial review* outlines the different template strategies that chemists have employed to synthesise knotted molecular topologies. Metal ion coordination, hydrogen bonding and aromatic donor–acceptor interactions have all been used to direct the formation of well-defined crossing points for molecular strands. Advances in the methods used to covalently capture the interwoven structures are highlighted, including the active metal template strategy in which metal ions both organise crossing points and catalyse the bond forming reactions that close the loop to form the topologically complex product. Although most non-trivial knots prepared to date from small-molecule building blocks have been trefoil knots, the first pentafoil knot was recently synthesised. Possible future directions and strategies in this rapidly evolving area of chemistry are discussed.

https://www.youtube.com/watch?v=voihgqHlU_4