Corso di Chimica Supramolecolare

(LM in Chimica @units)

AA 2016/2017

Prof. E. Iengo
eiengo@units.it

Supramolecular Chemistry - definitions

- the chemistry beyond the molecules: molecules are already formed

- the chemistry of molecular assemblies and of the intermolecular bond: association of molecules

- the chemistry of the non covalent bond: weak interactions

Bottom-up approach

Nano objects

Smart and functional materials

Supramolecular Chemistry - vocabulary

Host-Guest, Self-assembly, Supramolecular Assembly, Design, Control, Non covalent Interactions, Electrostatic Int., Anion-Π Int., Solvent effects,…

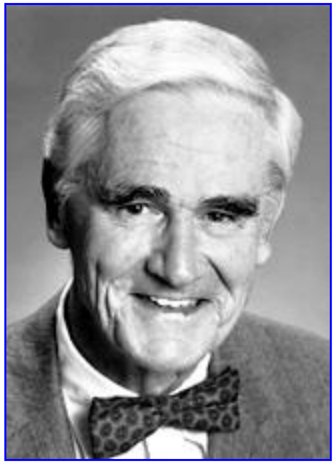
Molecular machines, containers, nanoscale flasks, nanoassemblies, supramolecular architectures, cages, trasporters, molecular magnets, nanoparticles, nanoballs, channels, tubes,…

Macrocycles, Cucubiturils, Helicates, Rotaxanes, Catenanes, Dendrimers..

Functional and complex nanomaterials and devices (smart materials, MOFs, polymers, gels, SAMs..)

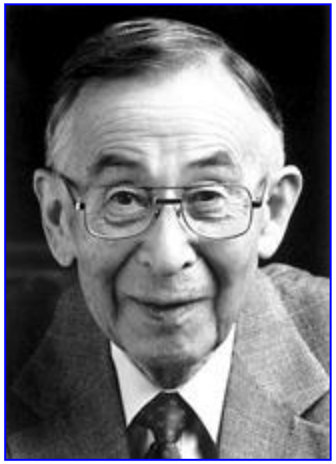
Imaging, Sensing, Recognition, Catalysis, Switching, …

Nobel Prize in Chemistry, 1987



Cram

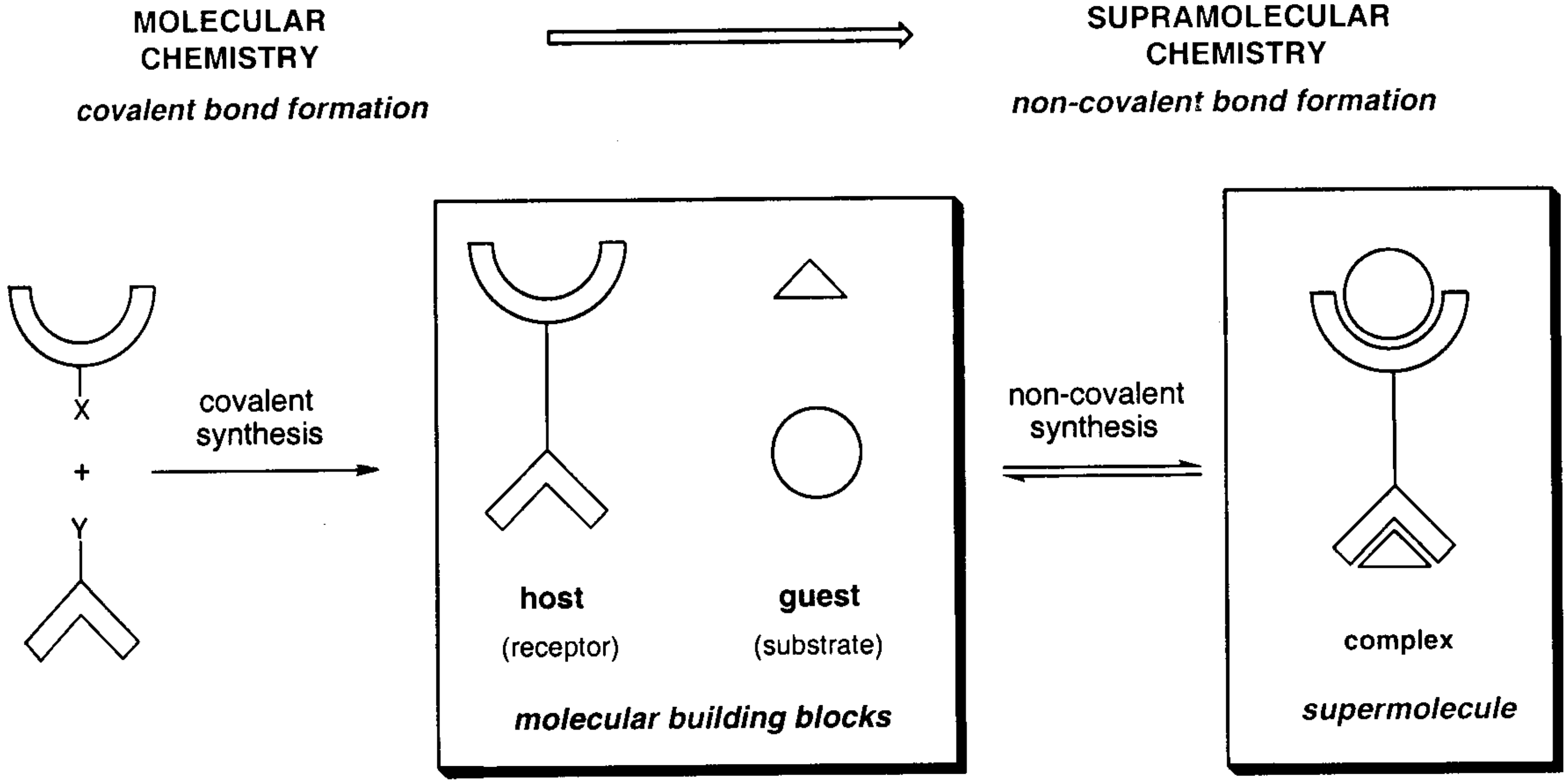
Lehn



Pedersen

«for their development and use of molecules with structure-specific interactions of high selectivity»

http://nobelprize.org/nobel_prizes/chemistry/laureates/1987/



MOLECULAR CHEMISTRY

covalent bond formation

SUPRAMOLECULAR CHEMISTRY

non-covalent bond formation

X

+

Y

covalent synthesis

host

(receptor)

guest

(substrate)

molecular building blocks

non-covalent synthesis

complex

supermolecule

The Nobel Prize in Chemistry, 2016

J-P. Sauvage

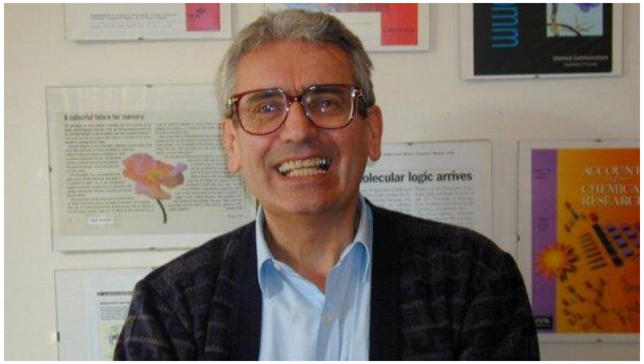
Sir J. F. Stoddart

B. L. Feringa

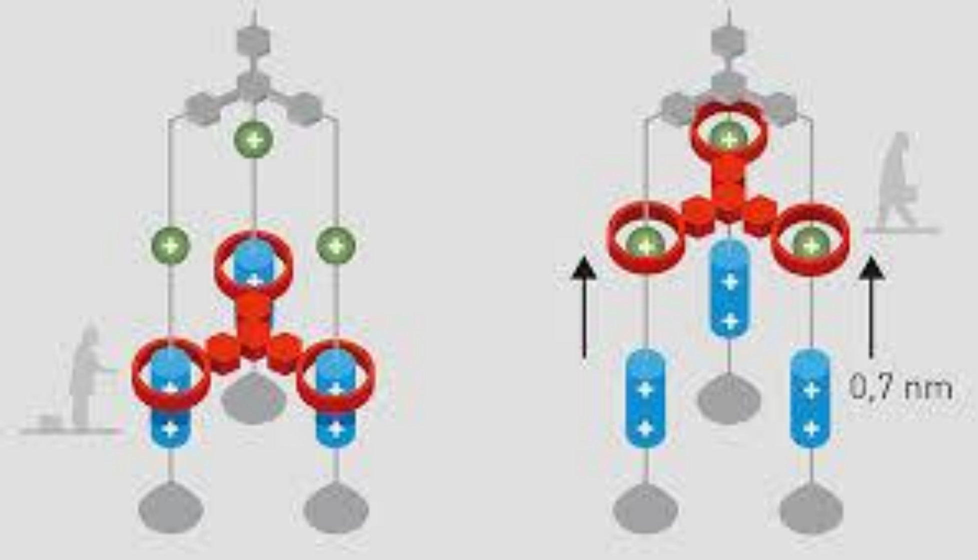
"for the design and synthesis of molecular machines"

https://www.nobelprize.org/nobel_prizes/chemistry/laureates/2016/

Chimica, il Nobel mancato

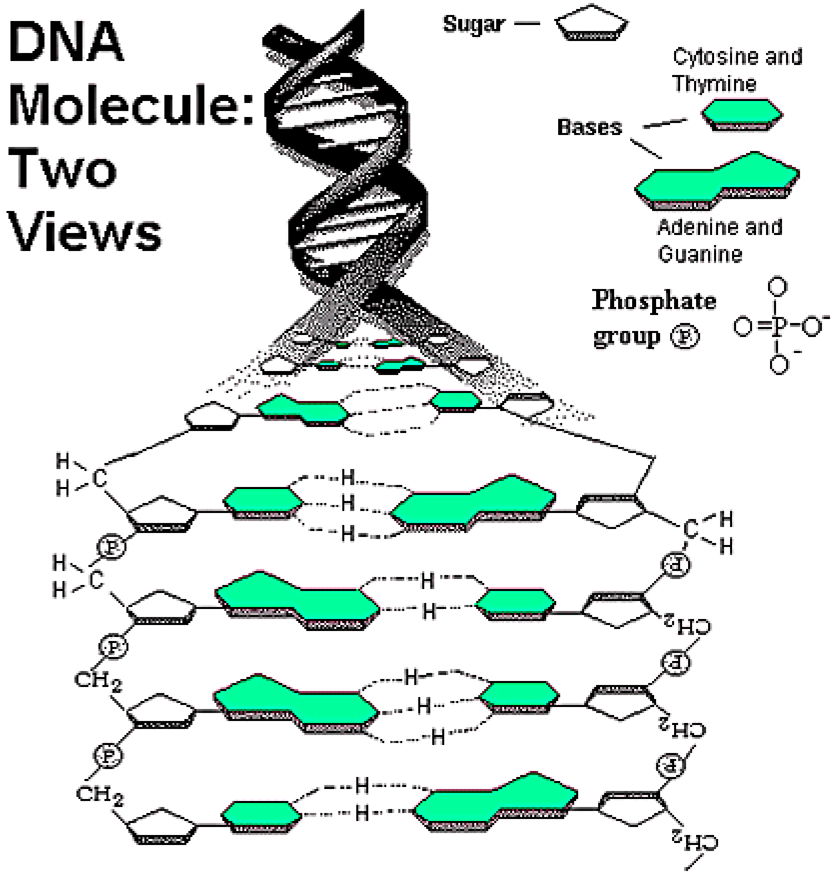


Prof. Vincenzo Balzani, docente emerito dell‘Università di Bologna

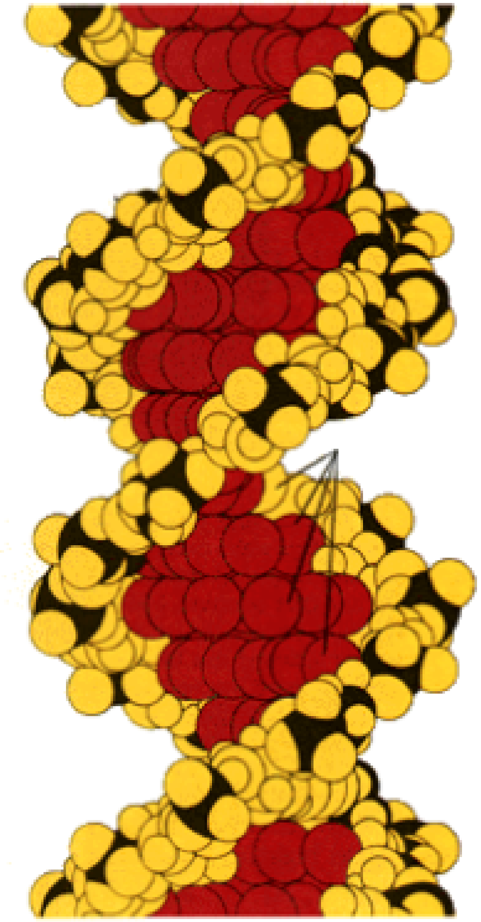

0,7 nm

The original inspiration: Supramolecular systems in Nature

DNA



Information Storage



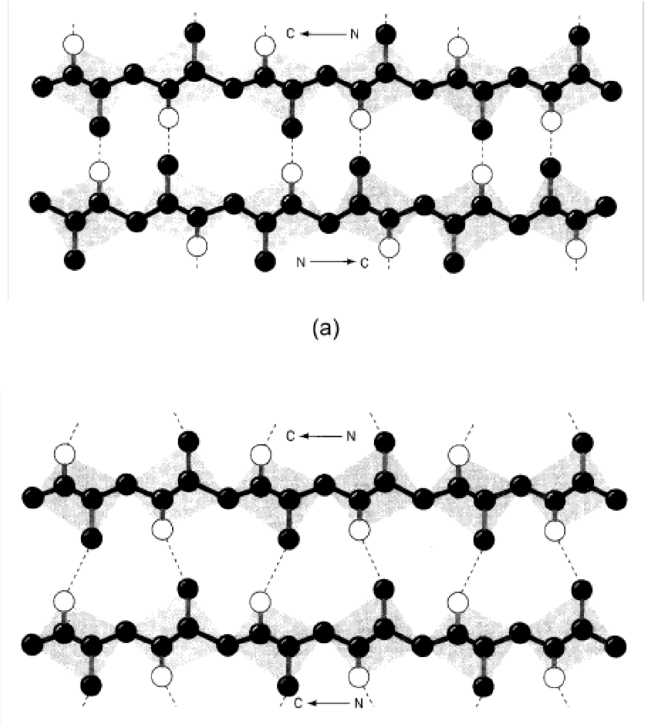
Watson & Crick 1953

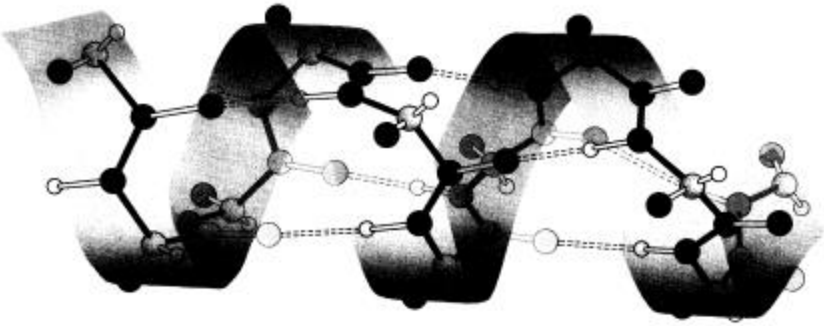
The ultimate supramolecular material?

- Encodes gigabytes of data
- Can Self-Replicate
- Built-in Error Correction
- Is the basis of life

The original inspiration:
Supramolecular systems in Nature

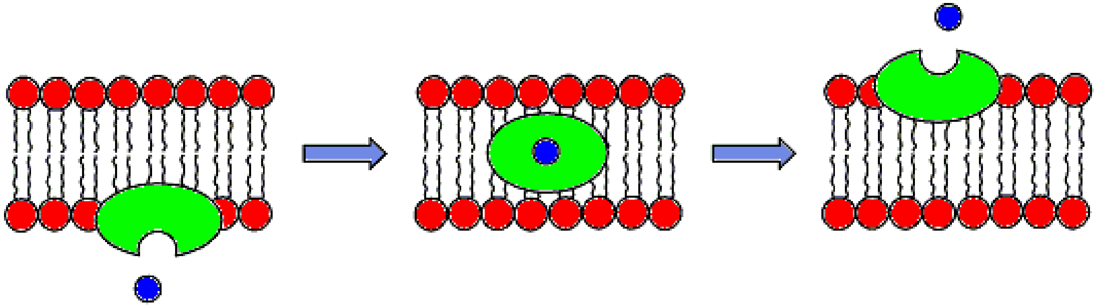
PROTEINS





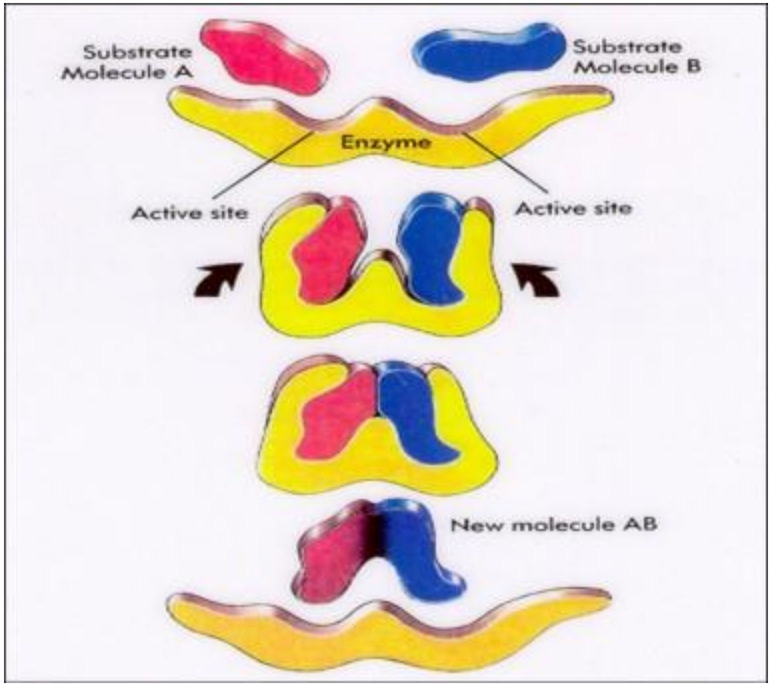
The original inspiration:
Supramolecular systems in Nature

MEMBRANES and TRANSMEMBRANE CARRIERS



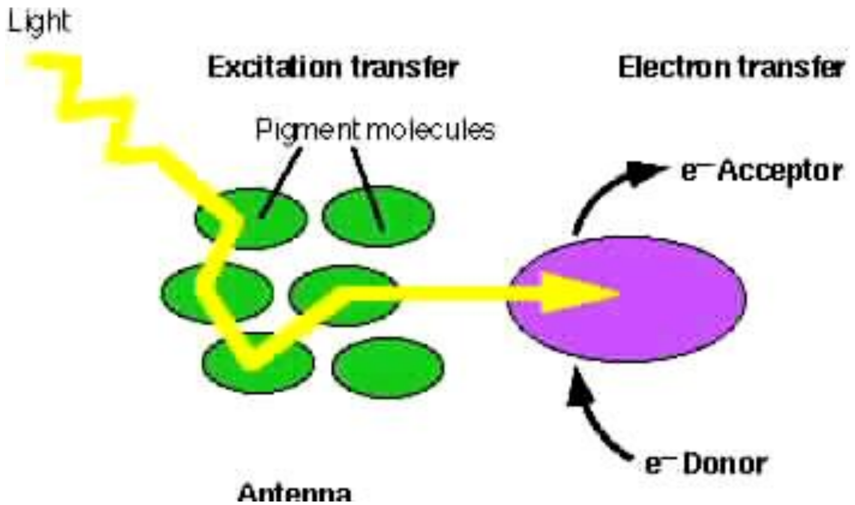
The original inspiration:
Supramolecular systems in Nature

ENZYMES

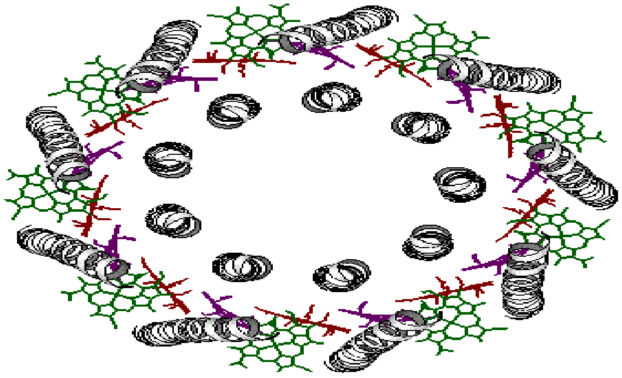


The original inspiration:
Supramolecular systems in Nature

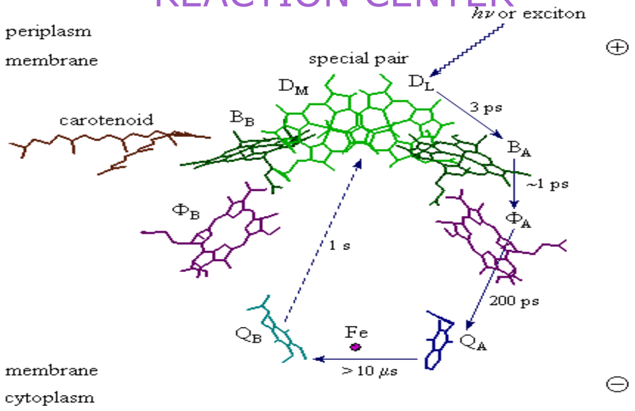
THE PHOTOSYNTHETIC APPARATUS



ANTENNA UNITS

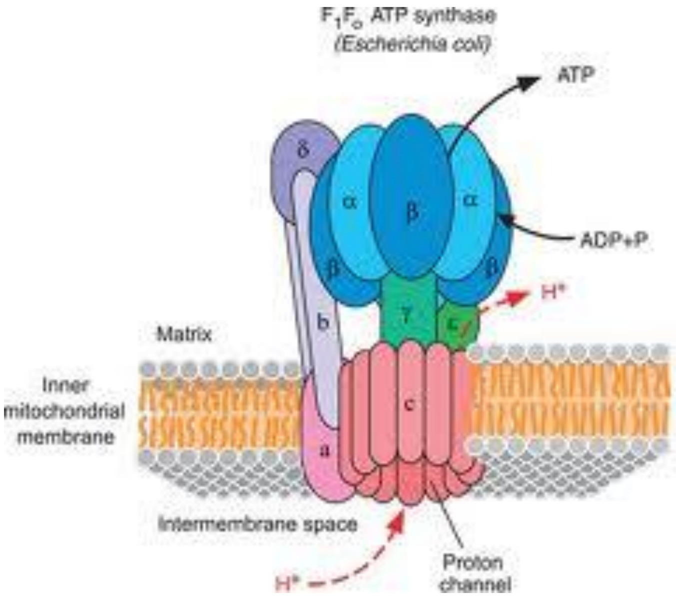


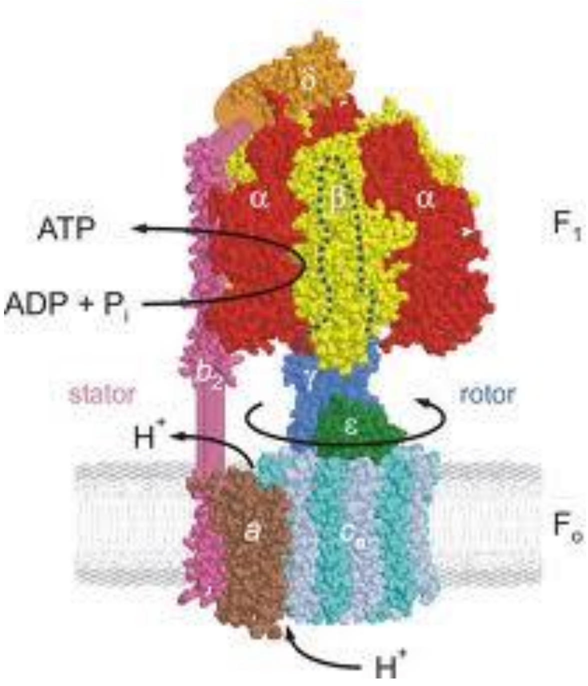
REACTION CENTER

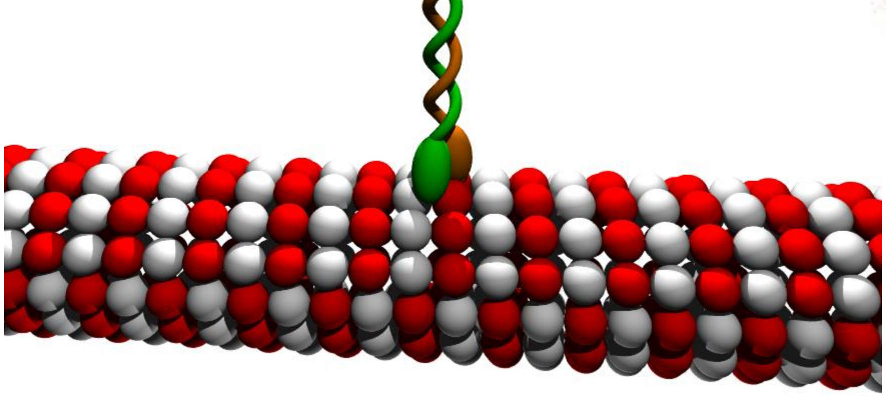


The original inspiration:
Supramolecular systems in Nature

ATP Synthase and KINESIN

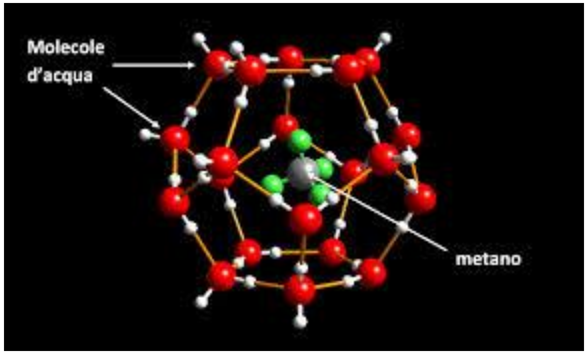




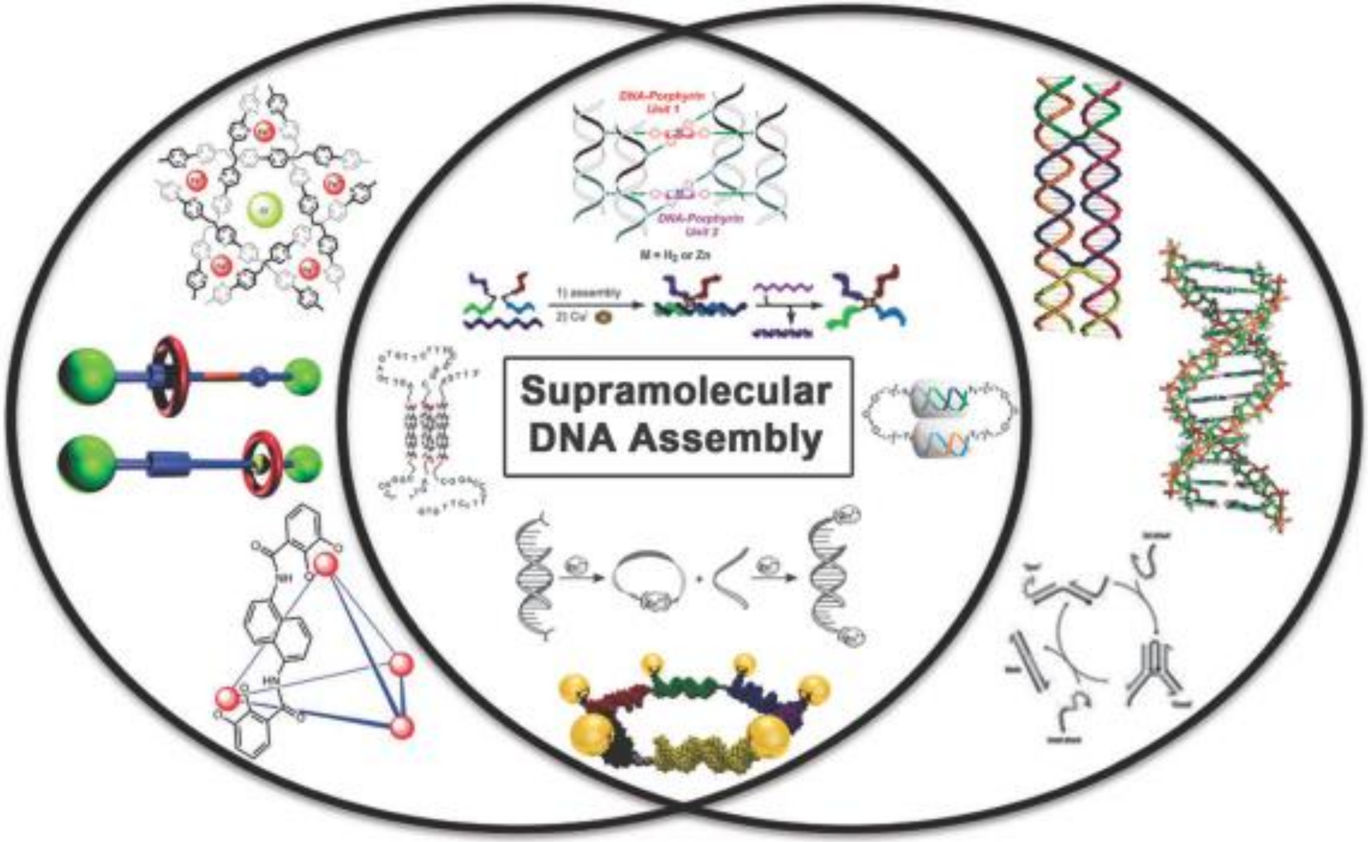


The original inspiration:
Supramolecular systems in Nature

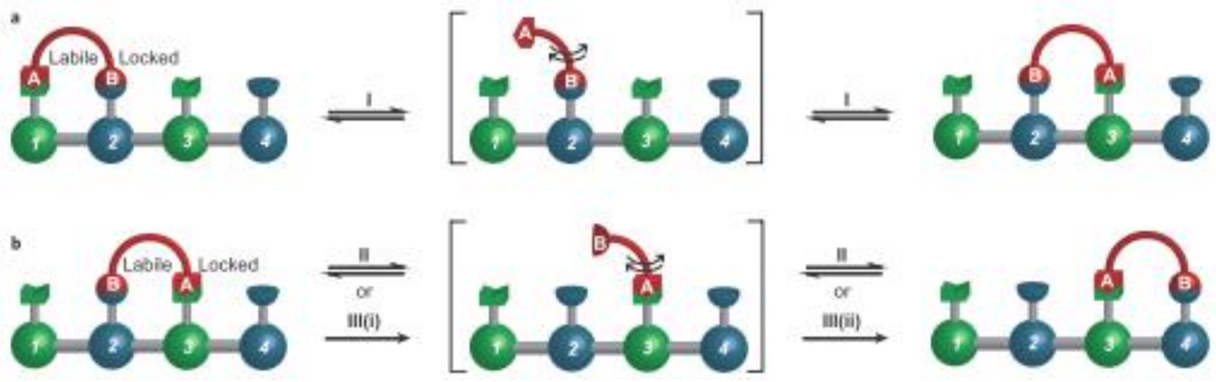
METHANE CLATHRATE (Siberian craters)



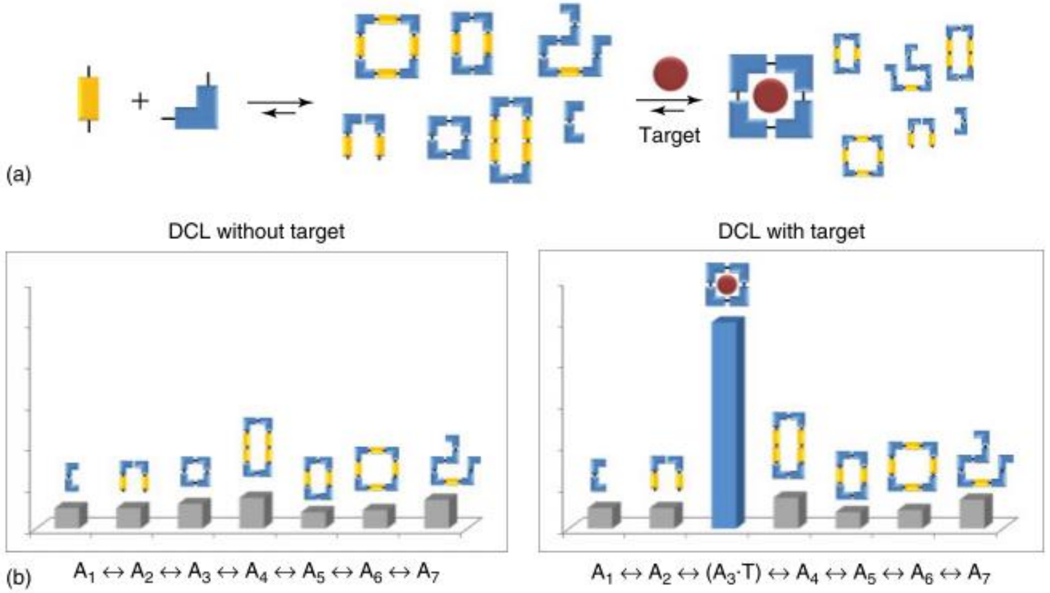
The bridge:
Supramolecular ARTIFICIAL and NATURAL systems



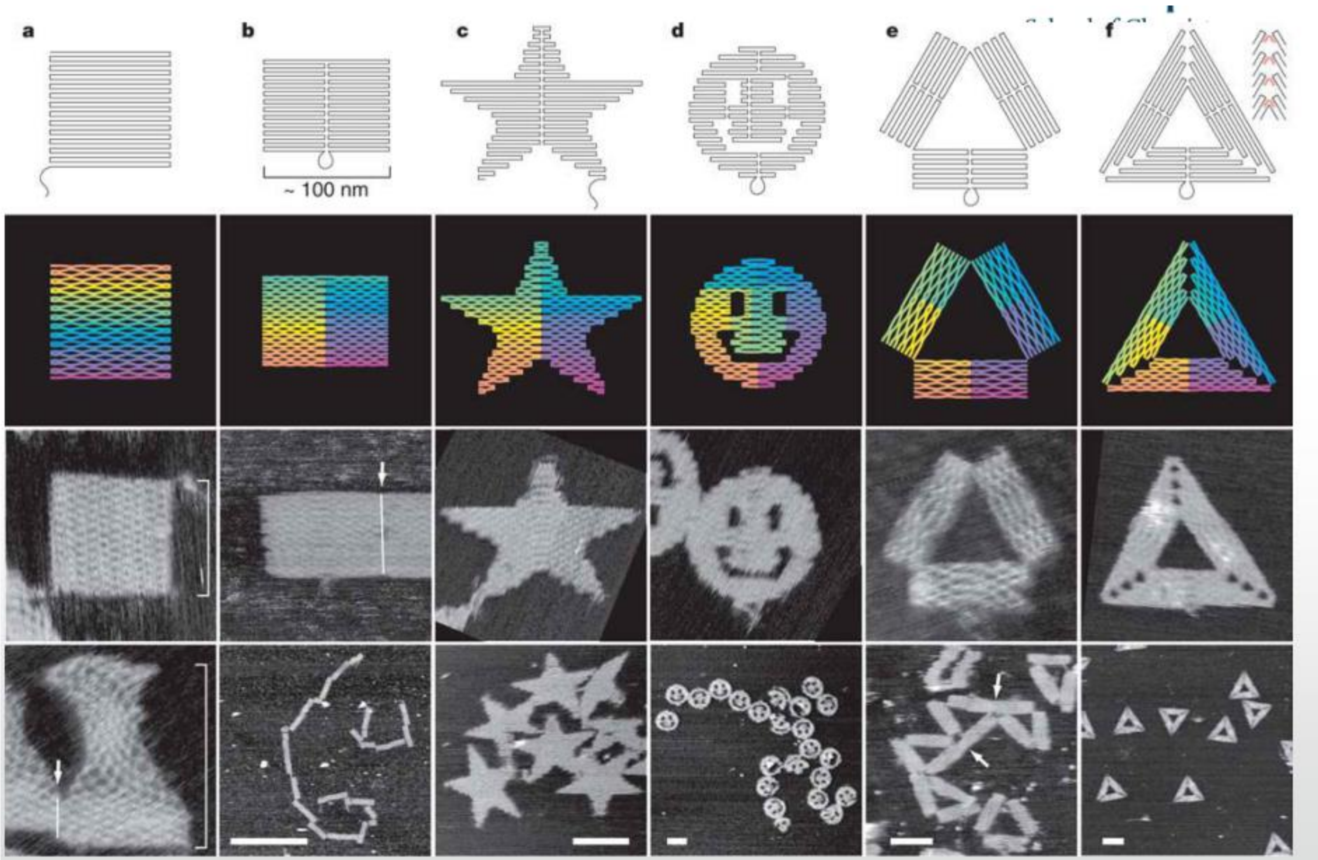
A synthetic molecule that CAN WALK DOWN A TRACK



DYNAMIC COMBINATORIAL LIBRARIES

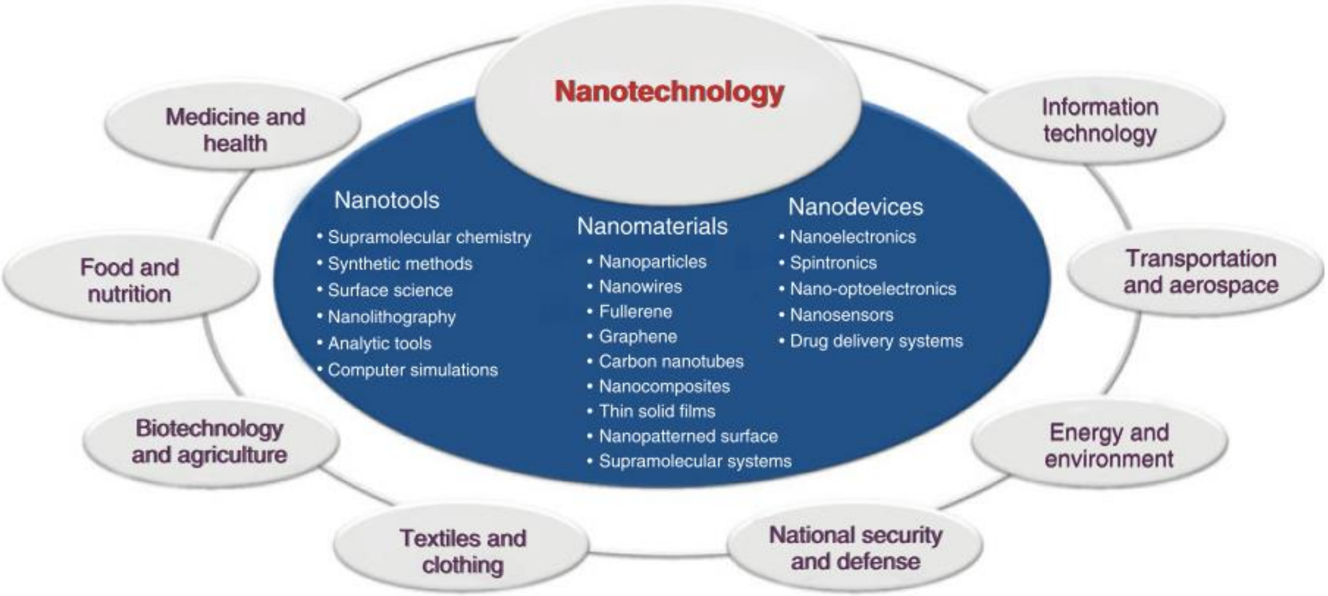


Folding DNA to create
NANOSCALE SHAPES AND PATTERNS



P.W. Rothemund, *Nature* **2006**

From Supramolecular Chemistry to Nanotechnology



Nanotechnology

Nanotools
- Supramolecular chemistry
- Synthetic methods
- Surface science
- Nanolithography
- Analytic tools
- Computer simulations

Nanomaterials
- Nanoparticles
- Nanowires
- Fullerene
- Graphene
- Carbon nanotubes
- Nanocomposites
- Thin solid films
- Nanopatterned surface
- Supramolecular systems

Nanodevices
- Nanoelectronics
- Spintronics
- Nano-optoelectronics
- Nanosensors
- Drug delivery systems

Medicine and health

Information technology

Food and nutrition

Transportation and aerospace

Biotechnology and agriculture

Energy and environment

Textiles and clothing

National security and defense

Bibliography

1. J.-M. Lehn *Supramolecular Chemistry: Concepts and Perspectives*, WCH, Weinheim (Germany), **1995**.

2. J. W. Steed, J. L. Atwood *Supramolecular Chemistry*, J. Wiley & Sons, UK, **2000**.

3. J. W. Steed, D. R. Turner, K. J. Wallace *Core Concepts in Chemistry and Nanochemistry*, Wiley, Chichester, **2007**.

4. H.-J. Schneider, A. Yatsimirsky *Principles and Methods in Supramolecular Chemistry*, J. Wiley & Sons, UK, **2000**.

5. L. F. Lindoy, I. M. Atkinson *Self-Assembly in Supramolecular Chemistry*, in *Monograms in Supramolecular Chemistry*, J. F. Stoddart ed., Royal Society of Chemistry, UK, **2000**.

6. V. Balzani, M. Venturi, A. Credi *Molecular Devices and Machines*, Wiley-VCH, Weinheim (Germany), **2003**.

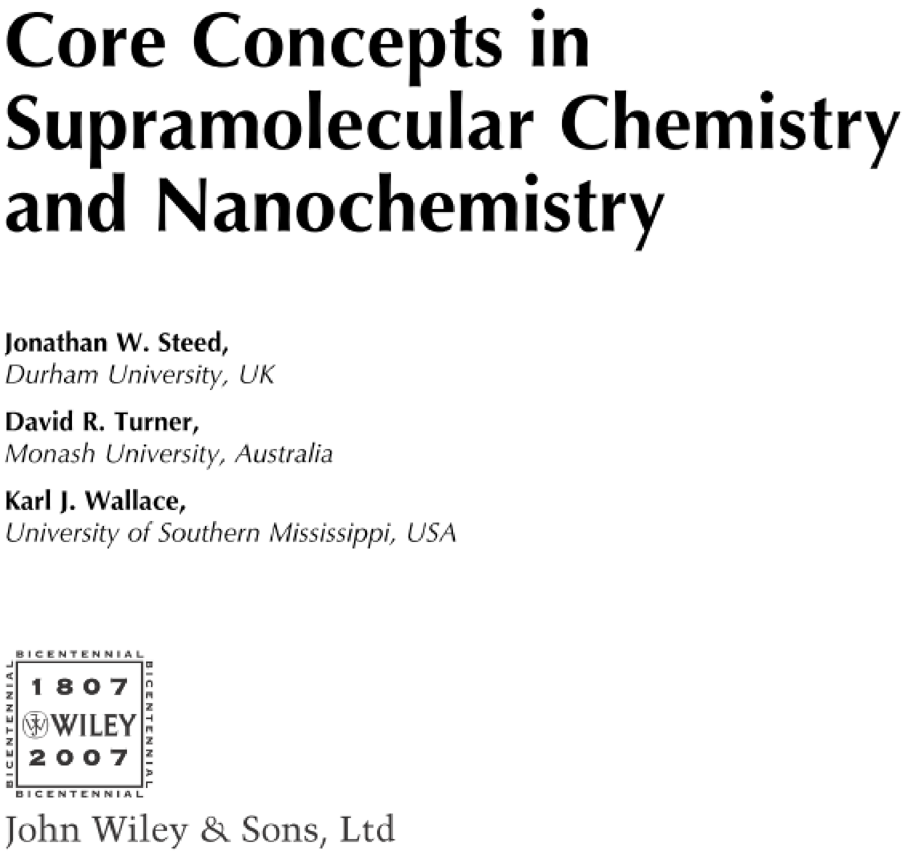
7. P. J. Cragg *A Practical Guide to Supramolecular Chemistry*, J. Wiley & Sons, UK, **2005**.

8. C. A. Schalley (Ed.) *Analytical Methods in Supramolecular Chemistry*, Wiley VHC, Weinheim (Germany), **2007**.

9. P. W. N. M. Van Leeuwen Supramolecular Catalysis, Wiley-VCH, Weinheim (Germany), **2008**.

10. J.-P. Sauvage (Ed.) Perspectives in Supramolecular Chemistry, Wiley-VCH, Weinheim (Germany), **2007**.

Bibliography

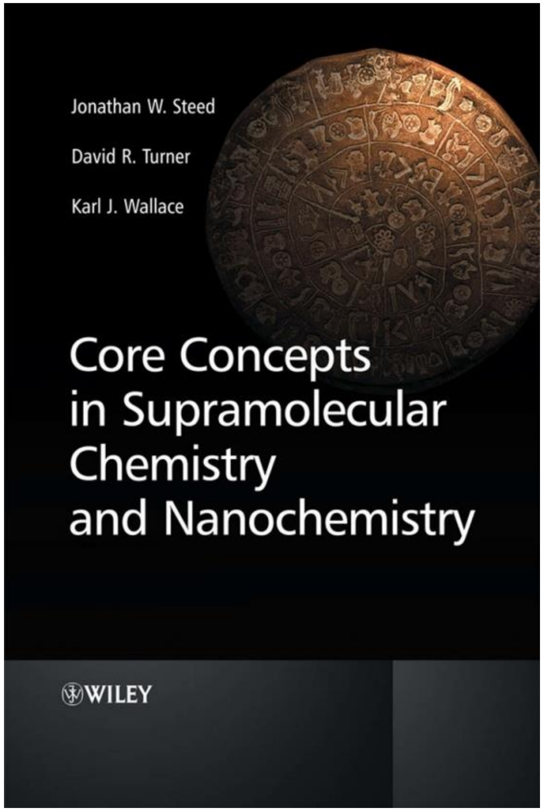


Core Concepts in Supramolecular Chemistry and Nanochemistry

Jonathan W. Steed,
Durham University, UK
David R. Turner,
Monash University, Australia
Karl J. Wallace,
University of Southern Mississippi, USA

BICENTENNIAL
1807
WILEY
2007
BICENTENNIAL

John Wiley & Sons, Ltd



Jonathan W. Steed
David R. Turner
Karl J. Wallace

Core Concepts
in Supramolecular
Chemistry
and Nanochemistry

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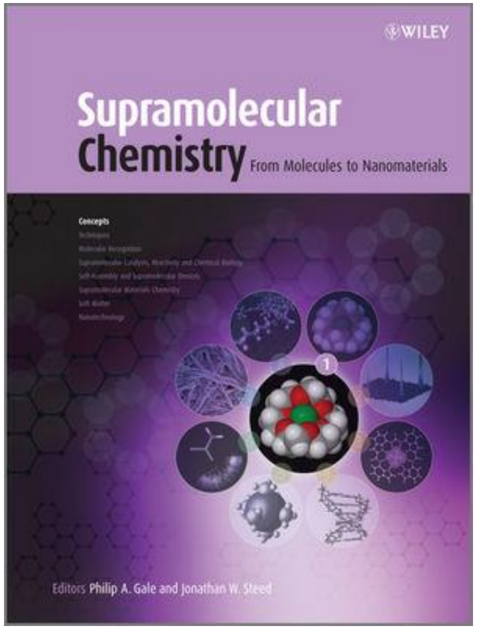
Bibliography



Supramolecular Chemistry: From Molecules to Nanomaterials, 8 Volume Set
Jonathan W. Steed (Editor-in-Chief), Philip A. Gale (Editor-in-Chief), Wiley.

Programma

Interazioni non covalenti

Recettori 1

cationi/anioni/molecole neutre

Metodi Analitici

Recettori 2

Cavitandi/Contenitori molecolari

- Covalenti
-Auto-assemblati (legami H, legami M, legami covalenti dinamici)
-Applicazioni: isolamento di intermedi instabili; reattività nello spazio confinato; catalisi

Fotofisica in breve

<u>(Prof. M.T. Indelli, UniFe)</u>

Programma

Topological Chemistry

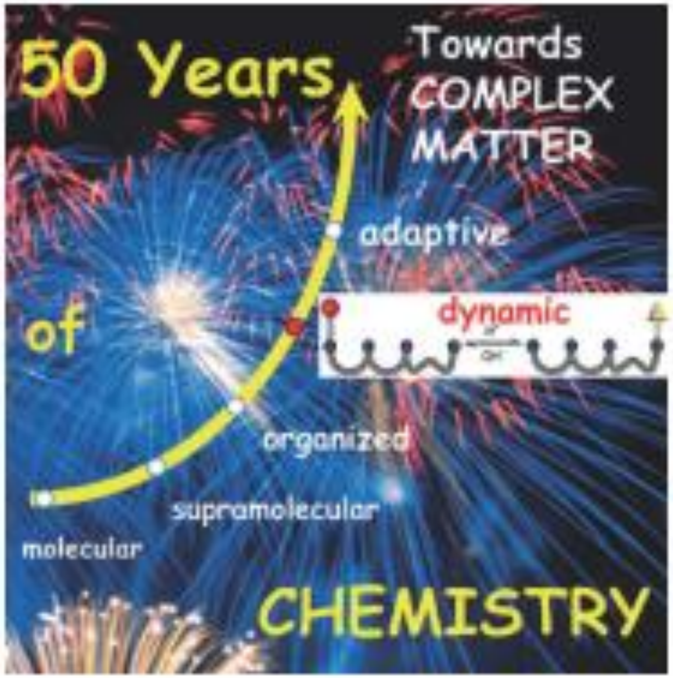
Elicati/Catenani/Rotaxani/Nodi

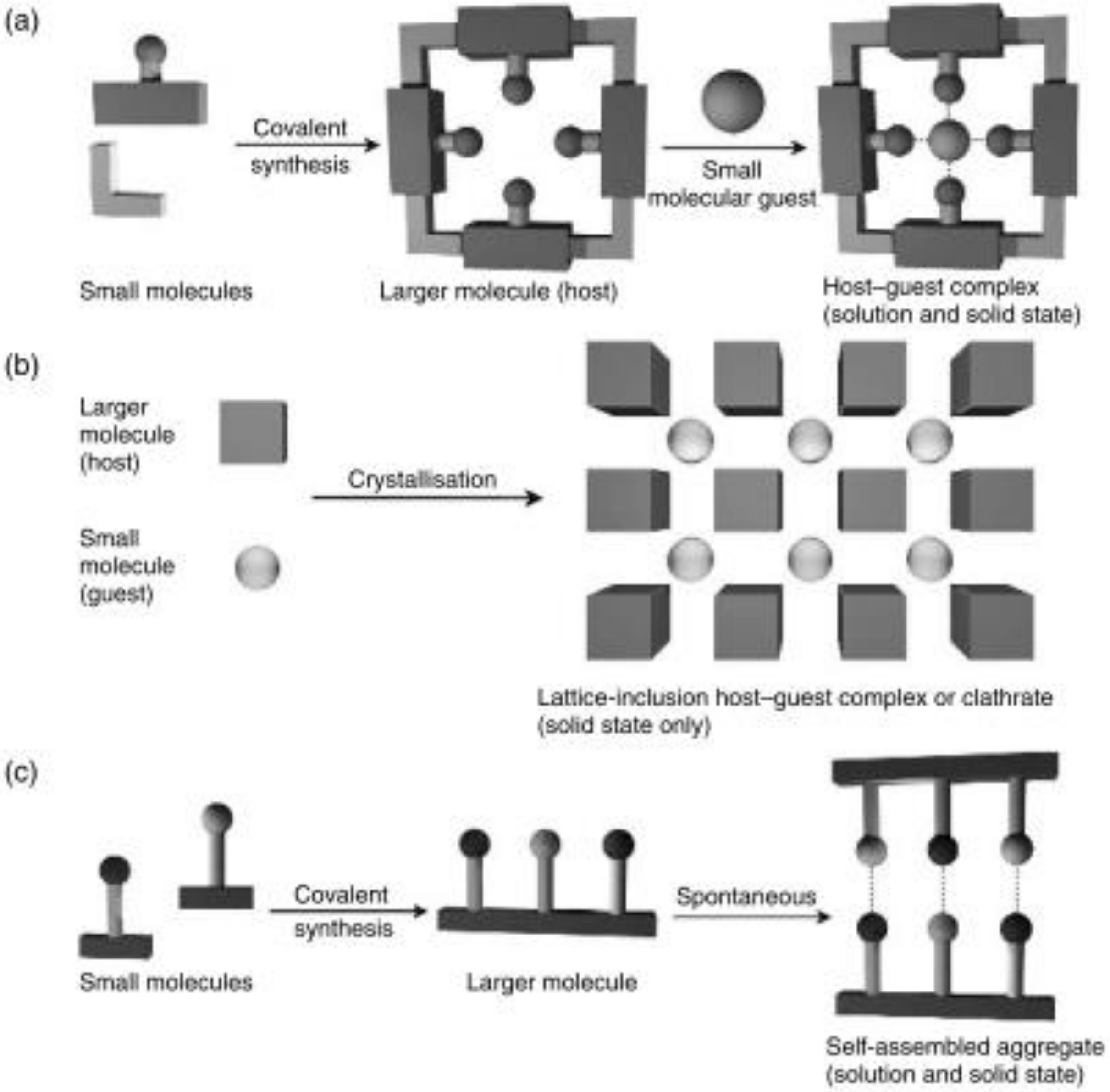
(Pro.f B. Colasson, Università *Paris* Descartes, Francia 4h)

Dispositivi e Macchine molecolari

Determinazione delle Costanti di Associazione
(Prof. P. Tecilla 4h)

Sensori

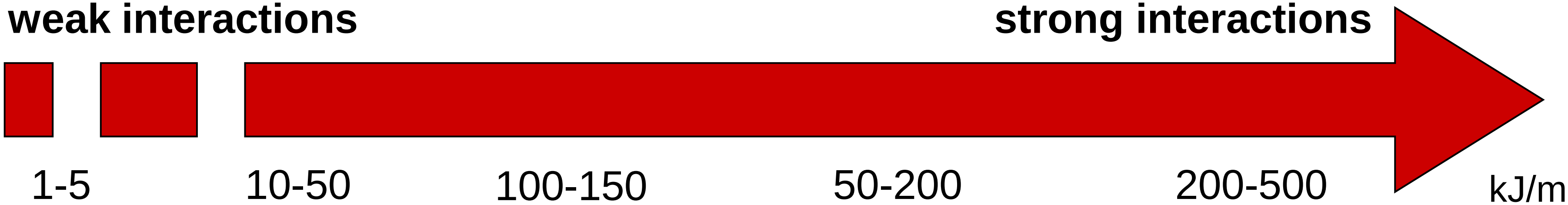

50 Years
Towards
COMPLEX
MATTER
adaptive
dynamic
of
organized
supramolecular
molecular
CHEMISTRY


(a)
Covalent synthesis
Small molecular guest
Small molecules
Larger molecule (host)
Host–guest complex (solution and solid state)
(b)
Larger molecule (host)
Small molecule (guest)
Crystallisation
Lattice-inclusion host–guest complex or clathrate (solid state only)
(c)
Covalent synthesis
Spontaneous
Small molecules
Larger molecule
Self-assembled aggregate (solution and solid state)

Weak (Reversible) Intermolecular Interactions

- Electrostatic
- π-π
- Cation-π/ Anion-π/CH-π
- H Bonding
- Halogen Bonding
- Metal-Ligand Coordination
- Reversible Covalent Bonding
- Chelate Effect
- Macrocyclic Effect
- Hydrophobic Effect

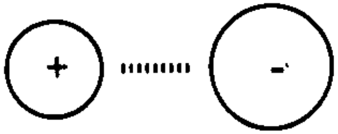
Weak Intermolecular Interactions



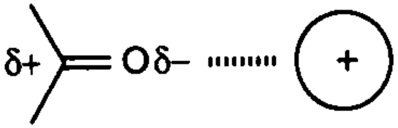
weak interactions **strong interactions**

1-5	10-50	100-150	50-200	200-500	kJ/mol
Van der Waals	H bond π-π	charge-charge	metal-ligand	covalent	

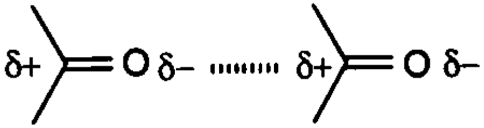
Electrostatic Interactions



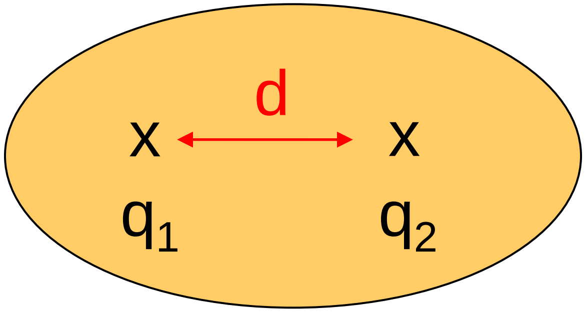
Charge-Charge Interactions 100-350 kJ/mol



Dipole-Charge Interactions 50-200 kJ/mol



Dipole-Dipole Interactions 5-50 kJ/mol



$$\boxed{W = \frac{1}{4\pi\varepsilon_0}\,\frac{q_1 q_2}{\varepsilon\, d}}\ \text{(J)}$$

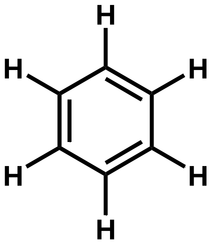
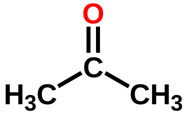
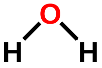
vacuum permittivity

dielectric constant (nature of solvant)

ε(vacuum) = 1

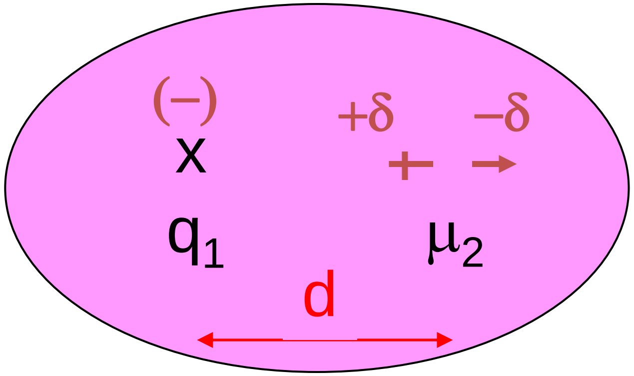
apolar medium ⇔ ε small (~ 2)
polar medium ⇔ ε big (H_2O ~ 80)

dielectric constant of the solvant

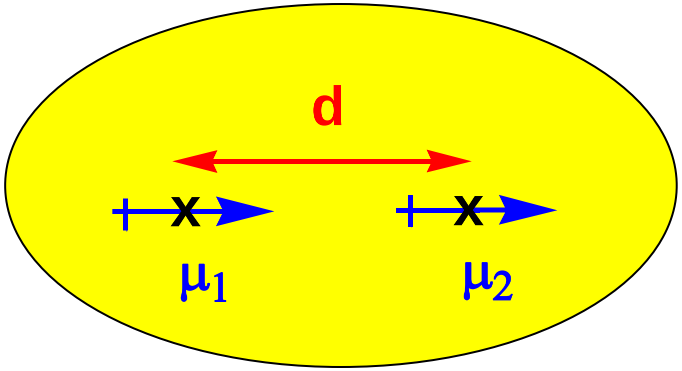
		ε
Benzene		**2,3**
Acetone		**20,7**
Ethanol	CH_3CH_2OH	**24,3**
water		**78,5**

apolar → **polar**

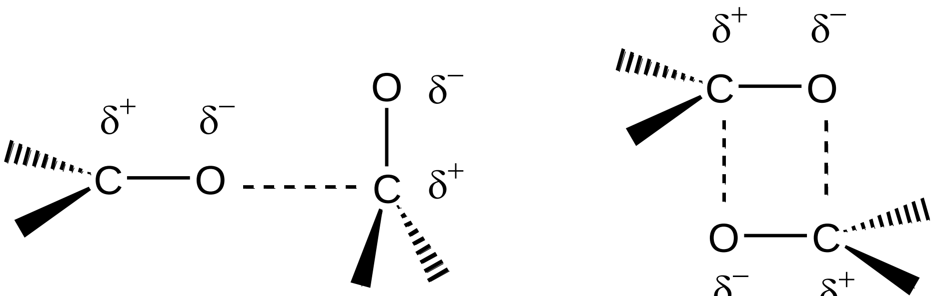
ε = 78.5 d = 0.5 nm => W = 3.75 kJ.mol^{-1}
ε = 2 d = 0.5 nm => W = 140 kJ.mol^{-1}



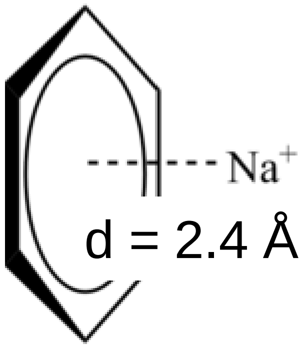
$$\boxed{W = -\,C^{te} \times \frac{|q|\,\mu_2}{\varepsilon\, d^2}}$$



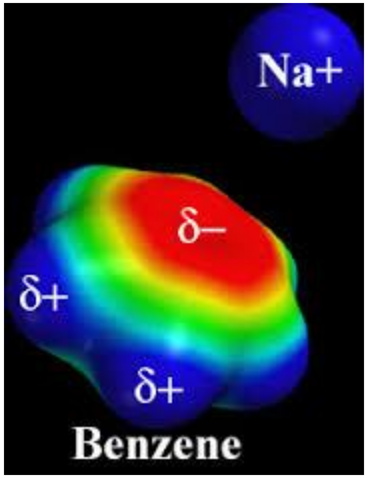
$$\boxed{W = -\,C^{te}\,\frac{\mu_1\,\mu_2}{\varepsilon\, d^3}}$$

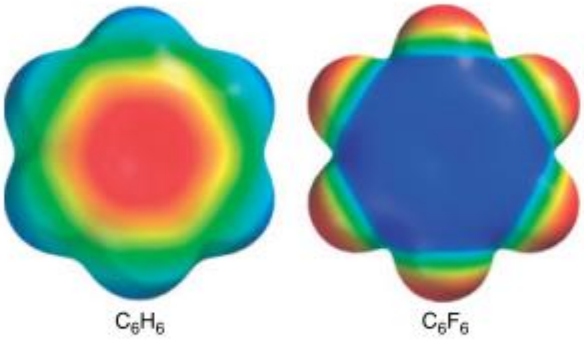


Cation-π Interactions



d = 2.4 Å



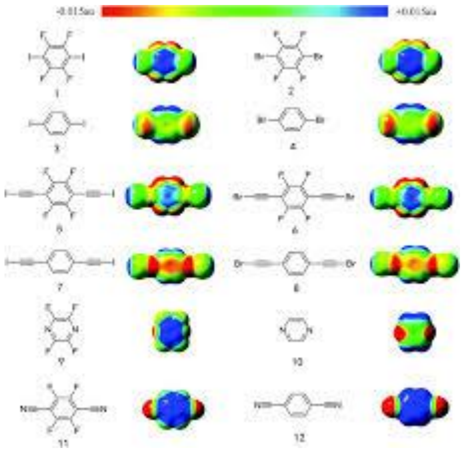


Anion-π Interactions

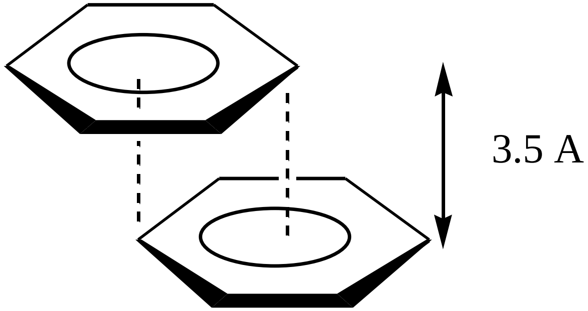
Proposed by three research groups of theoreticians independently in 2002 based on their theoretical calculations, anion −π interactions are defined as attractive interactions between negatively charged species and electron-deficient aromatic rings.

Typical anion−π interaction indicates the attraction of an anion species to the centroid of an aromatic ring.

In comparison to a plethora of theoretical calculations of anion−π interactions, experimental studies on these intriguing noncovalent bond interactions are limited.

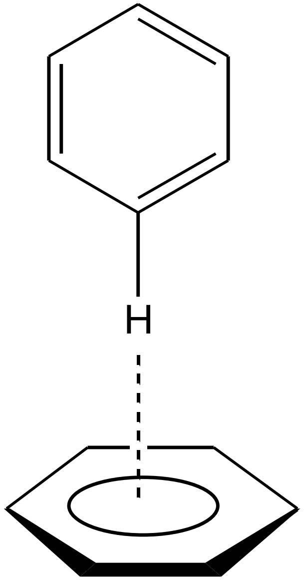


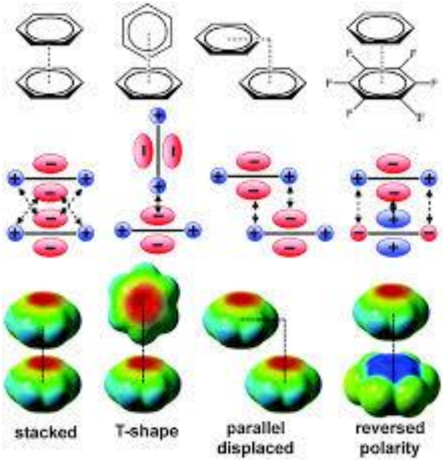
π-π Interactions up to 50 kJ/mol



face to face

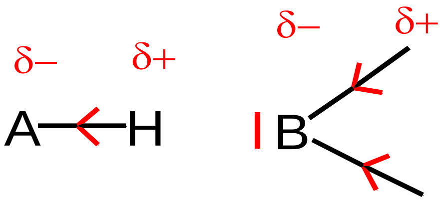
edge to face



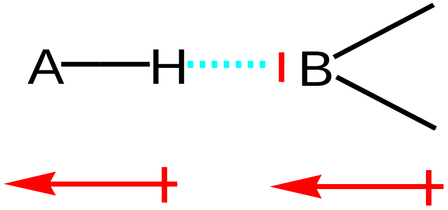


C.A. Hunter and J.K.M. Sanders, ***The Nature of π - π interactions***, *J. Am. Chem. Soc.*, **1990**, *112*, 5525;
E.-I. Kim, S. Paliwal and C.S. Wilcox, ***Measurements of molecular electrostatic field effects in edge-to-face aromatic interactions and CH- π interactions with implications for protein folding and molecular recognition***, *J. Am. Chem. Soc.*, **1998**, *120*, 11192.

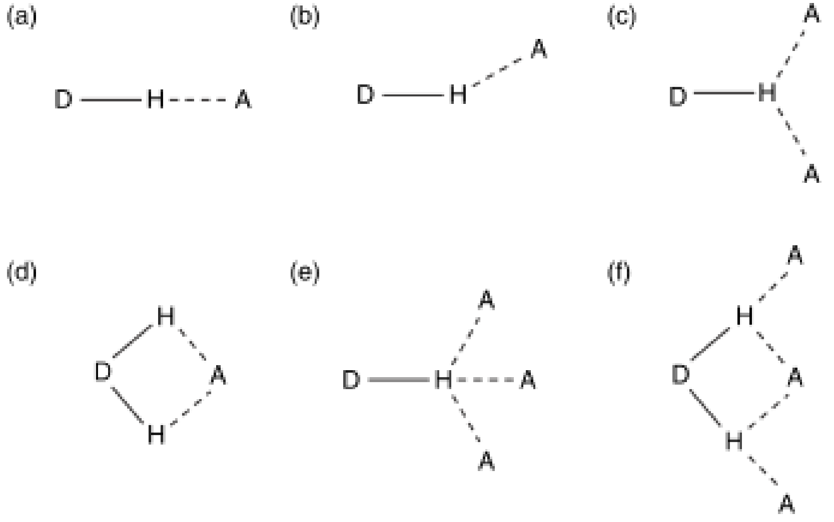
H Bond 4-120 kJ/mol



A, B electronegative or electrondeficient atoms



permanent dipoles



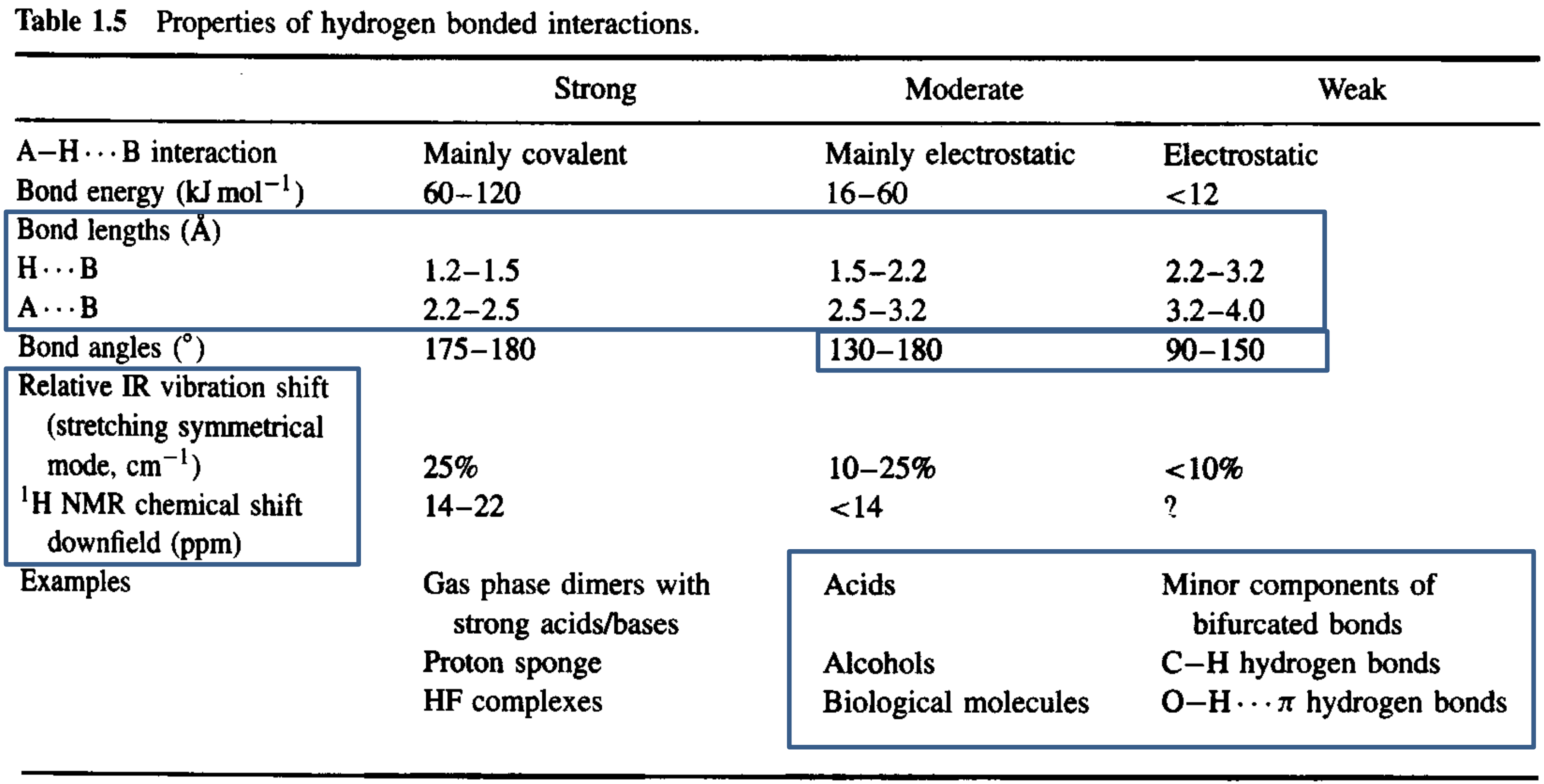


Table 1.5 Properties of hydrogen bonded interactions.

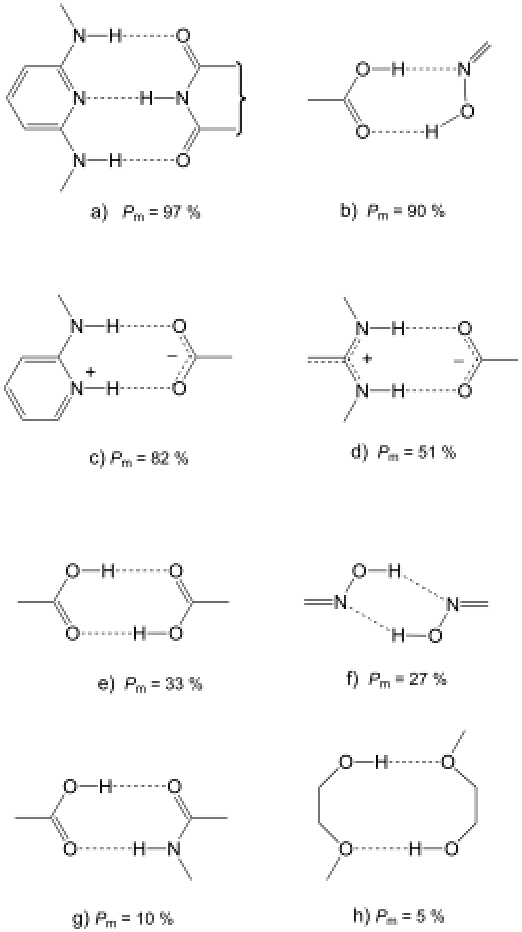
	Strong	Moderate	Weak
A–H···B interaction	Mainly covalent	Mainly electrostatic	Electrostatic
Bond energy (kJ mol^{-1})	60–120	16–60	<12
Bond lengths (Å)			
H···B	1.2–1.5	1.5–2.2	2.2–3.2
A···B	2.2–2.5	2.5–3.2	3.2–4.0
Bond angles (°)	175–180	130–180	90–150
Relative IR vibration shift (stretching symmetrical mode, cm^{-1})	25%	10–25%	<10%
^{1}H NMR chemical shift downfield (ppm)	14–22	<14	?
Examples	Gas phase dimers with strong acids/bases	Acids	Minor components of bifurcated bonds
	Proton sponge	Alcohols	C–H hydrogen bonds
	HF complexes	Biological molecules	O–H···π hydrogen bonds

G.A. Jeffrey**, *An Introduction to Hydrogen Bonding,*** Oxford University Press: Oxford, **1997**.

The Hydrogen Bond in the Solid State

Thomas Steiner*

Angew. Chem. Int. Ed. **2002**, *41*, 48–76



a) $P_m = 97\ \%$

b) $P_m = 90\ \%$

c) $P_m = 82\ \%$

d) $P_m = 51\ \%$

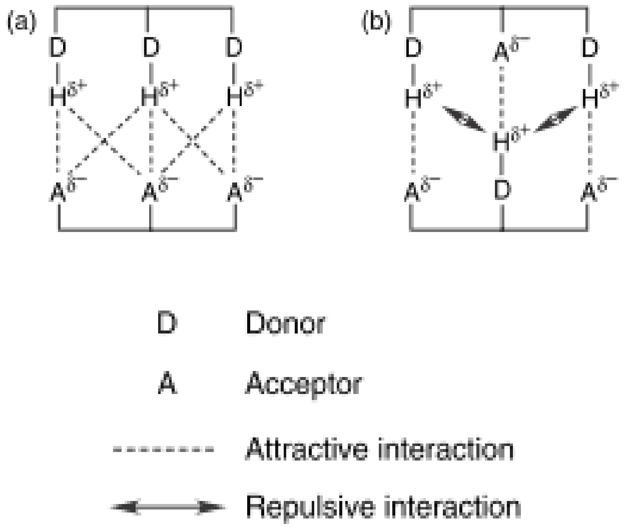
e) $P_m = 33\ \%$

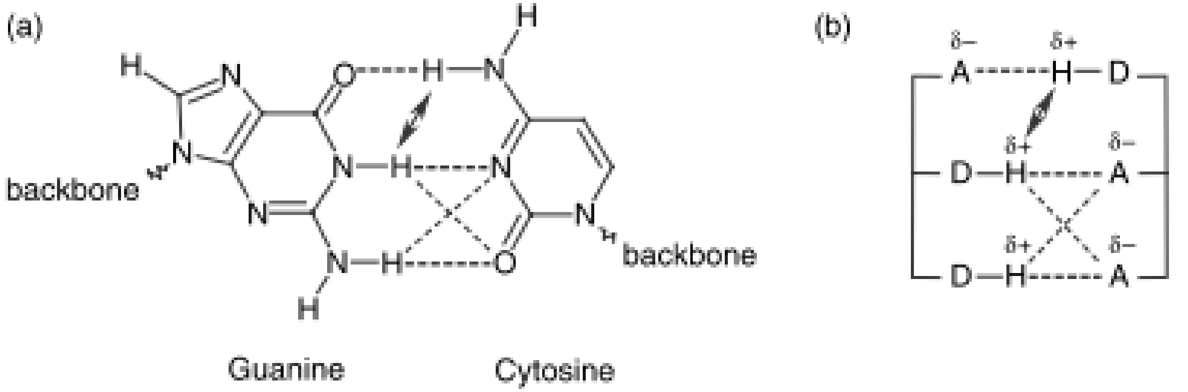
f) $P_m = 27\ \%$

g) $P_m = 10\ \%$

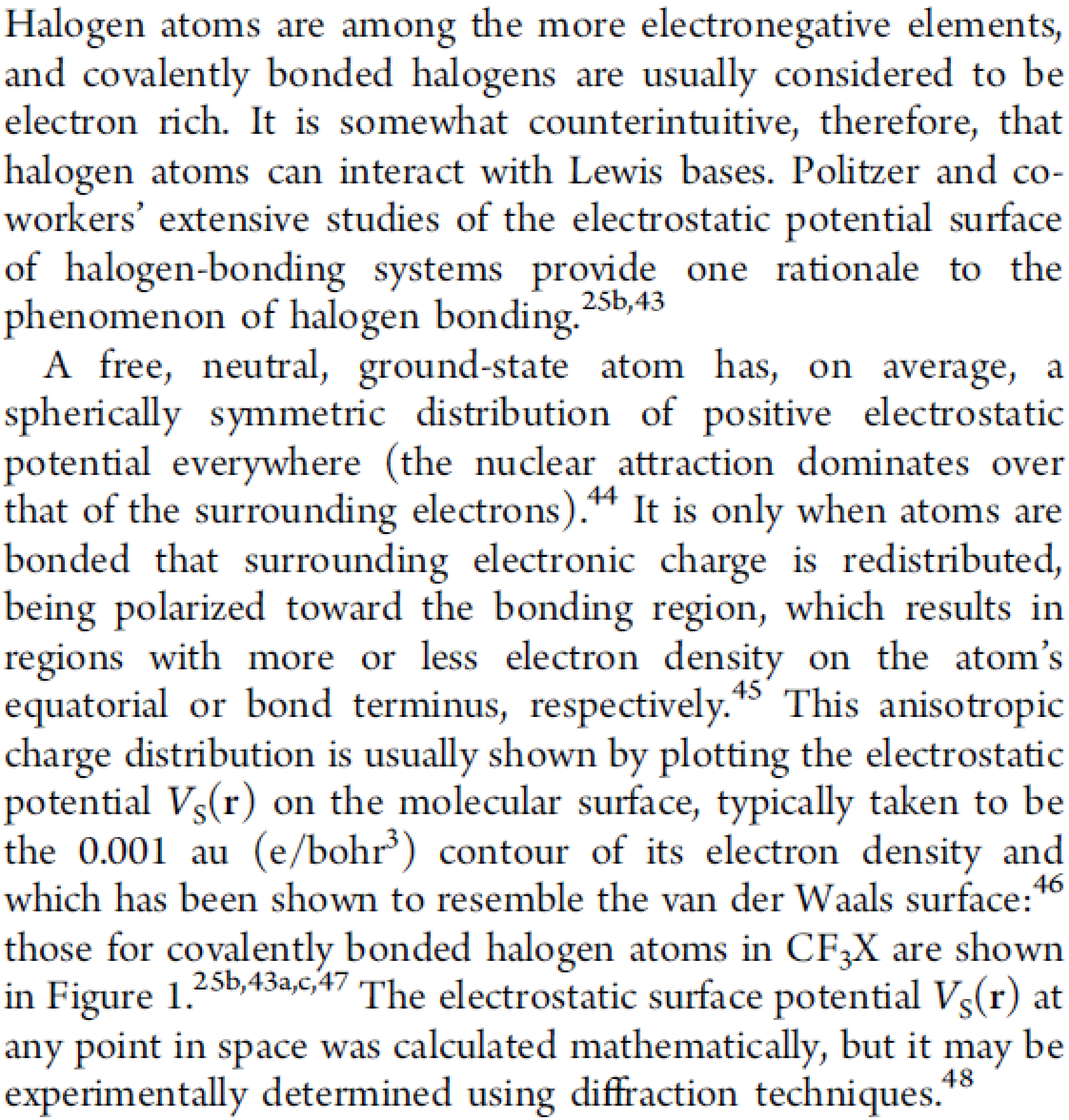
h) $P_m = 5\ \%$

Scheme 17. Eight examples of intermolecular hydrogen bond motifs with their probability of formation (P_m) in crystals.[122] Notice that P_m of the carboxy–oxime heterodimer (b) is much higher than that of the carboxylic acid (e) and oxime homodimers (f).


(a)
D
D
D
Hδ+
Hδ+
Hδ+
Aδ−
Aδ−
Aδ−
(b)
D
Aδ−
D
Hδ+
Hδ+
Hδ+
Aδ−
D
Aδ−
D Donor
A Acceptor
Attractive interaction
Repulsive interaction


(a)
H
N
N
O
H
N
H
backbone
N
H
N
N
N
O
N
N
H
backbone
H
Guanine
Cytosine
(b)
δ−
δ+
A
H
D
δ+
δ−
D
H
A
δ+
δ−
D
H
A

Halogen Bond



Halogen atoms are among the more electronegative elements, and covalently bonded halogens are usually considered to be electron rich. It is somewhat counterintuitive, therefore, that halogen atoms can interact with Lewis bases. Politzer and co-workers' extensive studies of the electrostatic potential surface of halogen-bonding systems provide one rationale to the phenomenon of halogen bonding.[25b,43]

A free, neutral, ground-state atom has, on average, a spherically symmetric distribution of positive electrostatic potential everywhere (the nuclear attraction dominates over that of the surrounding electrons).[44] It is only when atoms are bonded that surrounding electronic charge is redistributed, being polarized toward the bonding region, which results in regions with more or less electron density on the atom's equatorial or bond terminus, respectively.[45] This anisotropic charge distribution is usually shown by plotting the electrostatic potential $V_S(\mathbf{r})$ on the molecular surface, typically taken to be the 0.001 au (e/bohr^3) contour of its electron density and which has been shown to resemble the van der Waals surface:[46] those for covalently bonded halogen atoms in CF_3X are shown in Figure 1.[25b,43a,c,47] The electrostatic surface potential $V_S(\mathbf{r})$ at any point in space was calculated mathematically, but it may be experimentally determined using diffraction techniques.[48]

Halogen Bond

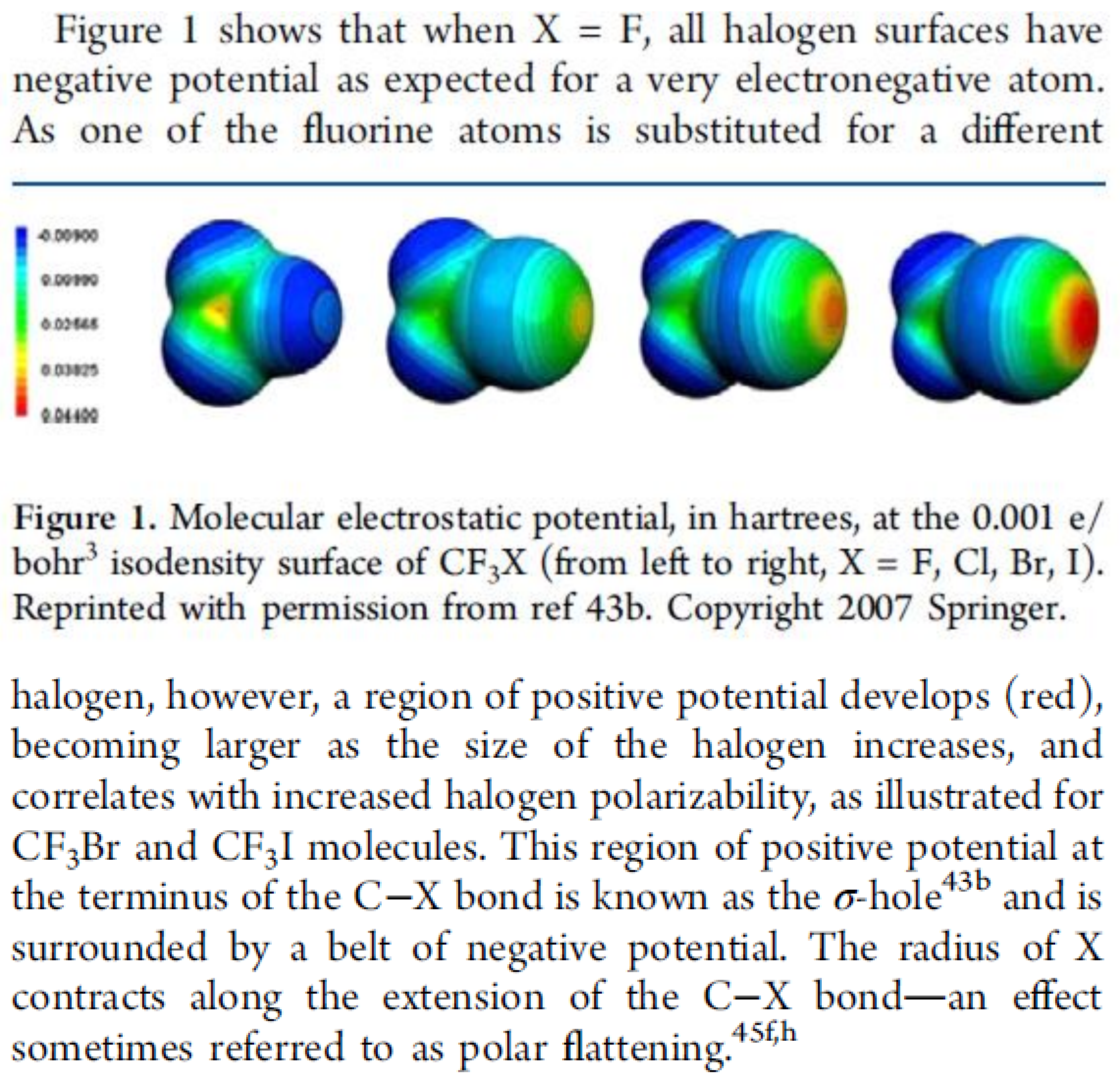
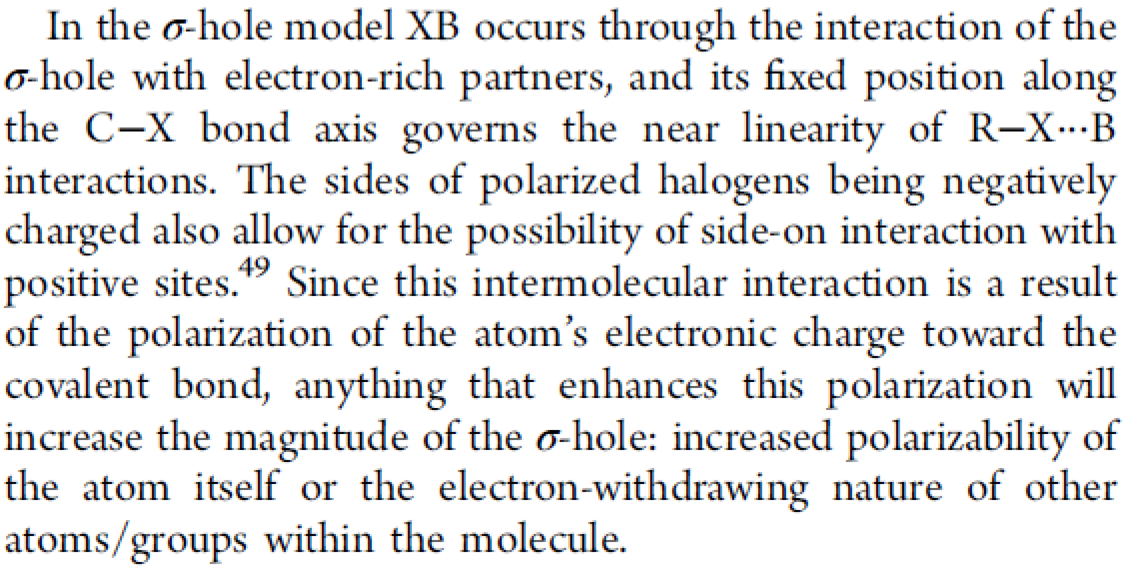


Figure 1 shows that when X = F, all halogen surfaces have negative potential as expected for a very electronegative atom. As one of the fluorine atoms is substituted for a different halogen, however, a region of positive potential develops (red), becoming larger as the size of the halogen increases, and correlates with increased halogen polarizability, as illustrated for CF_3Br and CF_3I molecules. This region of positive potential at the terminus of the C–X bond is known as the σ-hole[43b] and is surrounded by a belt of negative potential. The radius of X contracts along the extension of the C–X bond—an effect sometimes referred to as polar flattening.[45f,h]

Figure 1. Molecular electrostatic potential, in hartrees, at the 0.001 e/bohr^3 isodensity surface of CF_3X (from left to right, X = F, Cl, Br, I). Reprinted with permission from ref 43b. Copyright 2007 Springer.

Halogen Bond



In the σ-hole model XB occurs through the interaction of the σ-hole with electron-rich partners, and its fixed position along the C–X bond axis governs the near linearity of R–X···B interactions. The sides of polarized halogens being negatively charged also allow for the possibility of side-on interaction with positive sites.[49] Since this intermolecular interaction is a result of the polarization of the atom's electronic charge toward the covalent bond, anything that enhances this polarization will increase the magnitude of the σ-hole: increased polarizability of the atom itself or the electron-withdrawing nature of other atoms/groups within the molecule.

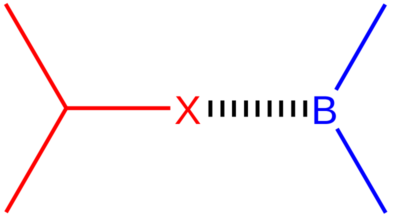
Halogen Bond

In 2009 the International Union of Pure and Applied Chemistry (IUPAC) started a project (project no. 2009-032-1-100) having the aim " to take a comprehensive look at intermolecular interactions involving halogens as electrophilic species and classify them"
http://www.halogenbonding.eu/
http://www.iupac.org/web/ins/2009-032-1-100

An IUPAC recommendation defining these interactions as halogen bonds was issued in 2013 when the project was concluded: This definition states that

" A halogen bond occurs when there is evidence of a net attractive interaction between an electrophilic region associated with a halogen atom in a molecular entity and a nucleophilic region in another, or the same, molecular entity. "

Halogen Bond



B : Lewis base (neutral or anionic)

X : electron-poor halogen atom

- Very directional (180°, but also other geometries)
- As strong as H-bond
- Often encountered in solid state, more rarely in solution

molecule	atom	bond producing a σ-hole
H_3C-F	F	C−F
H_3C-Cl	Cl	C−Cl
H_3C-Br	Br	C−Br
H_3C-I	I	C−I
F_3C-F	F	C−F
F_3C-Cl	Cl	C−Cl
F_3C-Br	Br	C−Br
F_3C-I	I	C−I
NC−F	F	C−F
NC−Cl	Cl	C−Cl
NC−Br	Br	C−Br
NC−I	I	C−I
Dihalogens		
F−F	F	F−F
Cl−Cl	Cl	Cl−Cl
Br−Br	Br	Br−Br
Focus on Bromine		
$Br-C\equiv C-Br$	Br	C−Br
H_3Si-Br	Br	C−Br
F_3Si-Br	Br	Si−Br
H_3Ge-Br	Br	Ge−Br
H_2N-Br	Br	N−Br
F_2N-Br	Br	N−Br
H_2P-Br	Br	P−Br
F_2P-Br	Br	P−Br
HO−Br	Br	O−Br
FO−Br	Br	O−Br
HS−Br	Br	S−Br
FS−Br	Br	S−Br
F−Br	Br	F−Br
Cl−Br	Br	Cl−Br

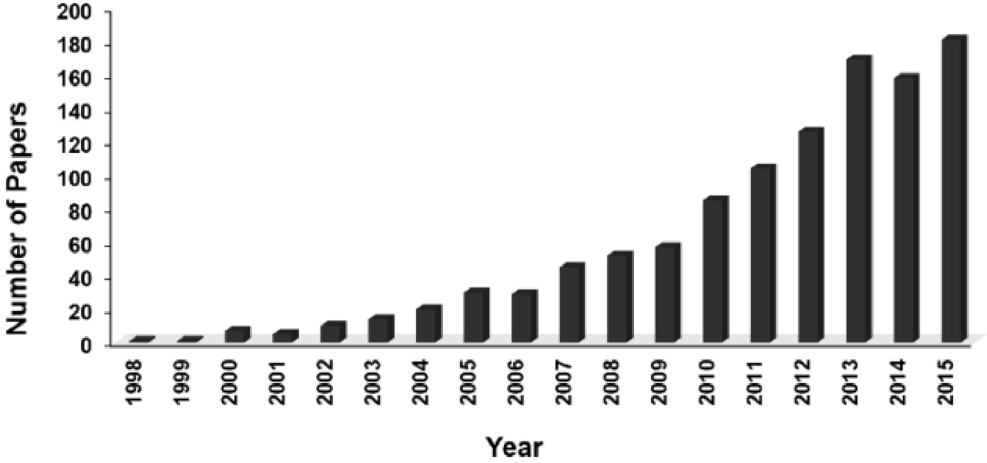


Figure 5. Number of papers per year having "halogen bonding" in the title and/or abstract (source SciFinder, search performed in November 2015).

CHEMICAL REVIEWS

Review

pubs.acs.org/CR

DOI: 10.1021/acs.chemrev.5b00484

The Halogen Bond

Gabriella Cavallo,[†] Pierangelo Metrangolo,[*,†,‡] Roberto Milani,[‡] Tullio Pilati,[†] Arri Priimagi,[§] Giuseppe Resnati,[*,†] and Giancarlo Terraneo[†]

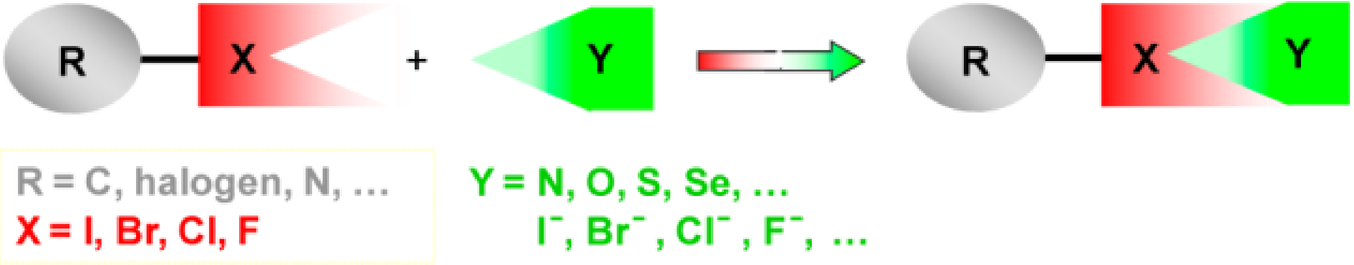


Figure 1. Schematic representation of the halogen bond.

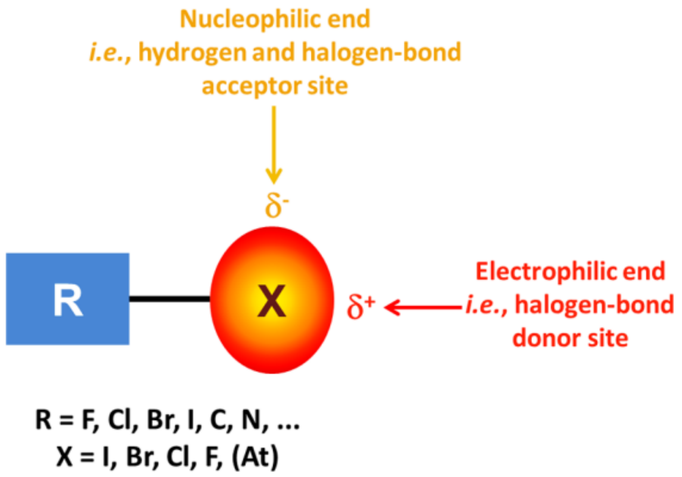
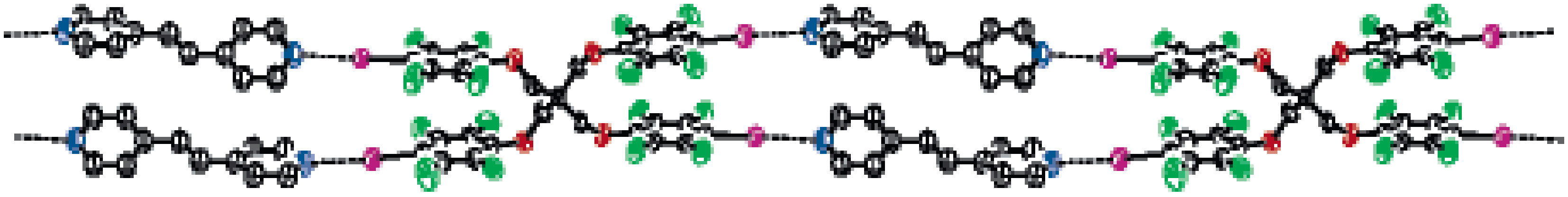
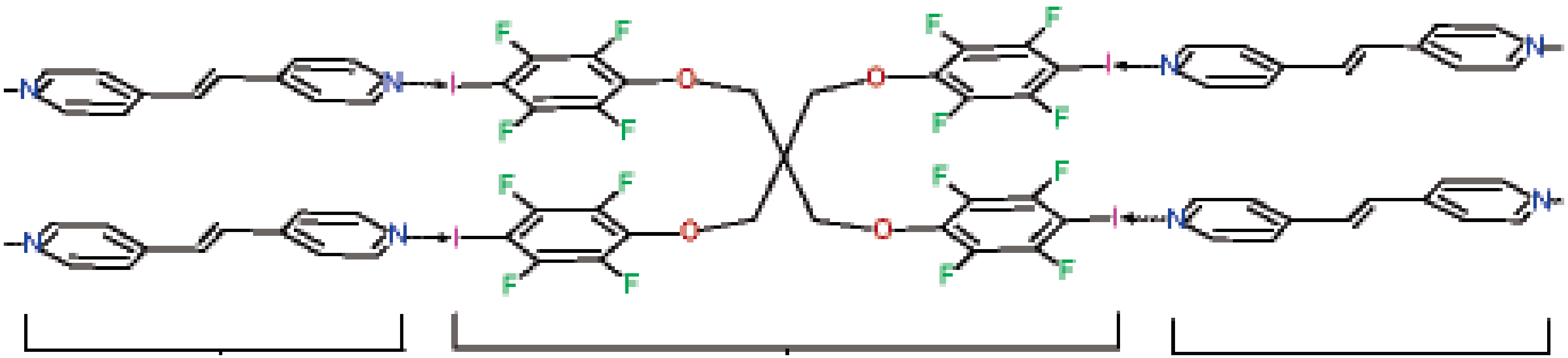


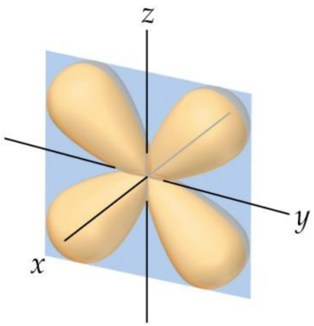
Figure 21. Schematic representation of the anisotropic distribution of the electron density around covalently bound halogen atoms and the pattern of the resulting interactions.



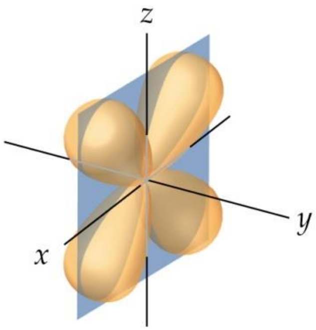
14



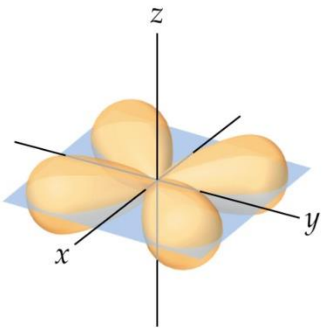
Metal-Ligand Interaction



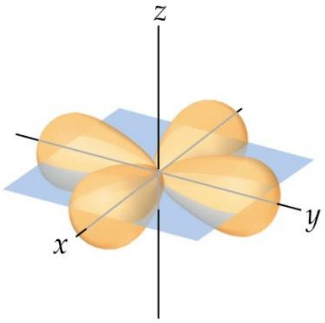
d_{yz}



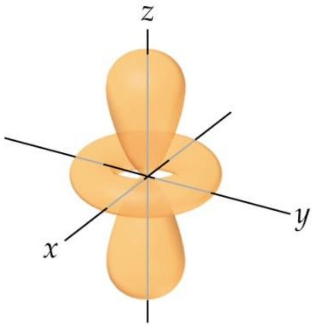
d_{xz}



d_{xy}

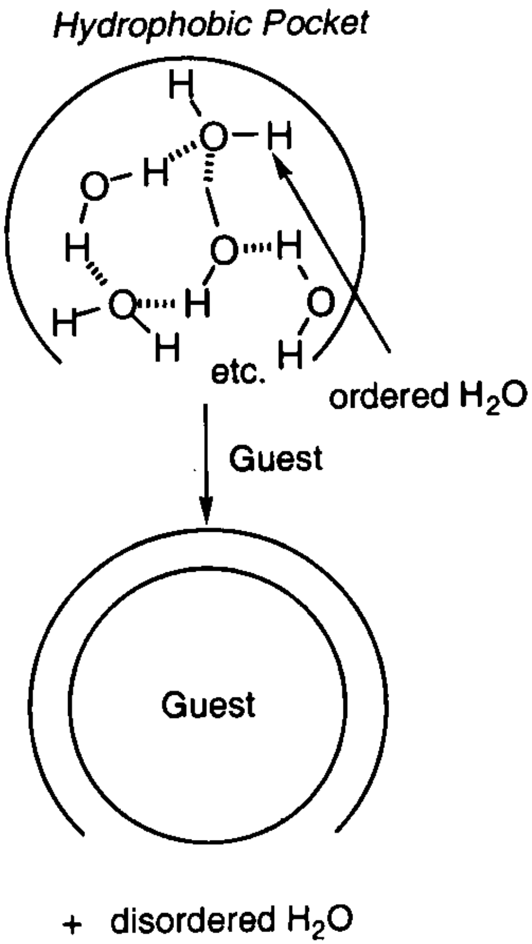


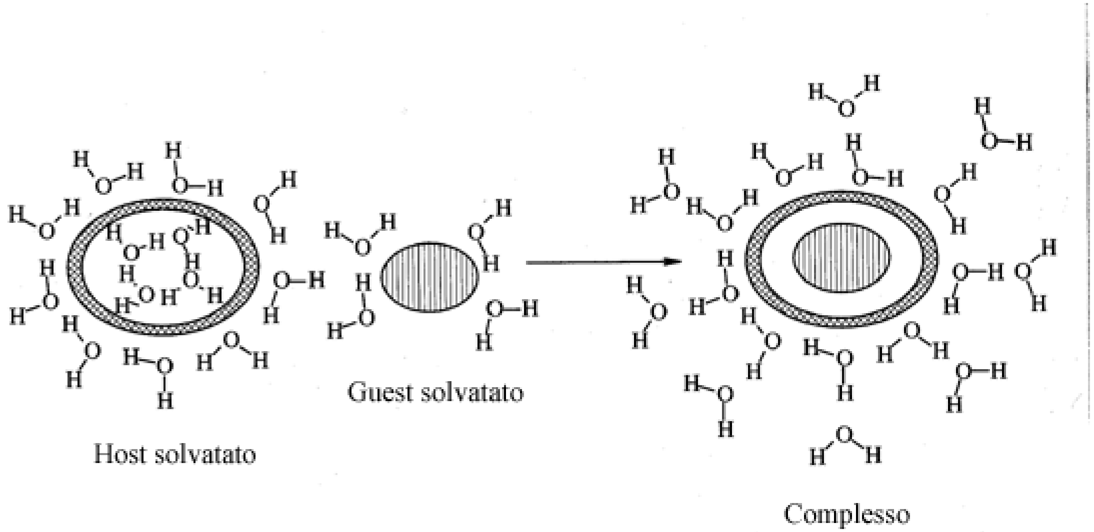
$d_{x^2-y^2}$



d_{z^2}

Hydrophobic Effect





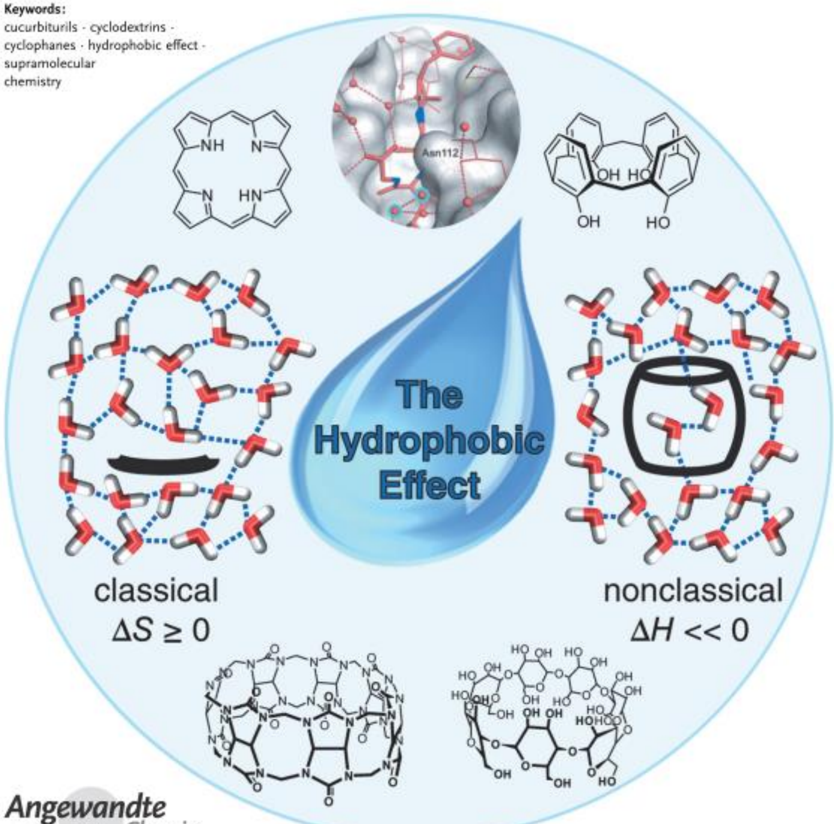
DOI: 10.1002/anie.201310958

Hydrophobic Effect

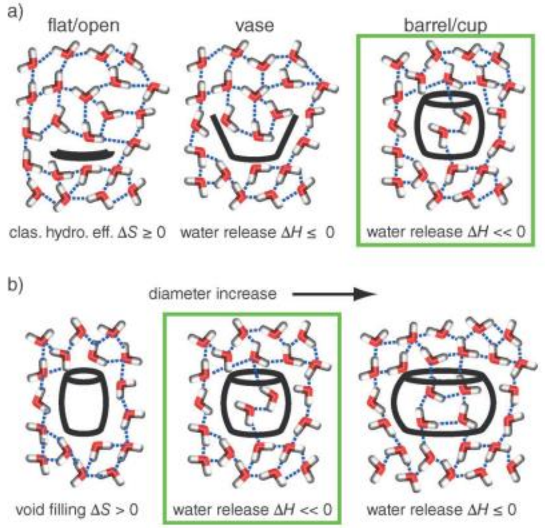
The Hydrophobic Effect Revisited—Studies with Supramolecular Complexes Imply High-Energy Water as a Noncovalent Driving Force

Frank Biedermann, Werner M. Nau,* and Hans-Jörg Schneider**

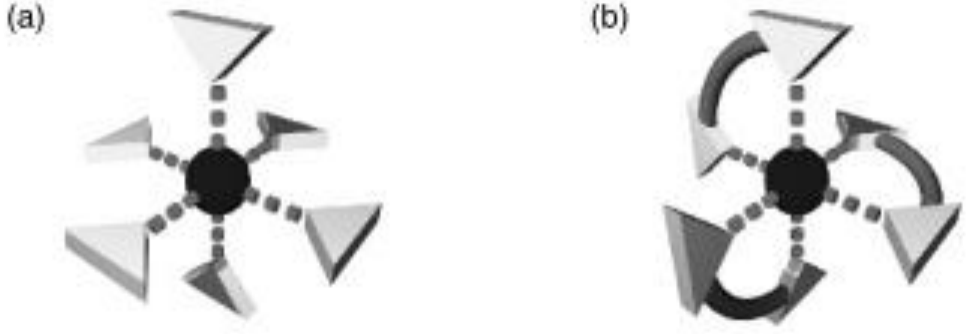
Keywords:
cucurbiturils · cyclodextrins · cyclophanes · hydrophobic effect · supramolecular chemistry



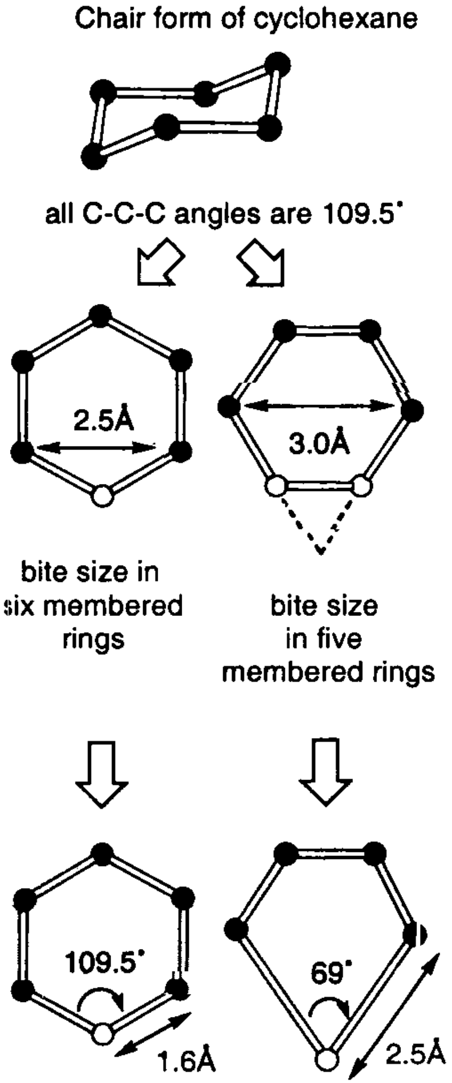
Angewandte International Edition Chemie


a)
flat/open
vase
barrel/cup
clas. hydro. eff. ΔS ≥ 0
water release ΔH ≤ 0
water release ΔH << 0
b)
diameter increase
void filling ΔS > 0
water release ΔH << 0
water release ΔH ≤ 0

Chelate Effect



$$[Ni(NH_3)_6]^{2+} + 3NH_2CH_2CH_2NH_2 \overset{\log K = 8.76}{\rightleftharpoons} [Ni(NH_2CH_2CH_2NH_2)_3]^{2+} + 6NH_3$$



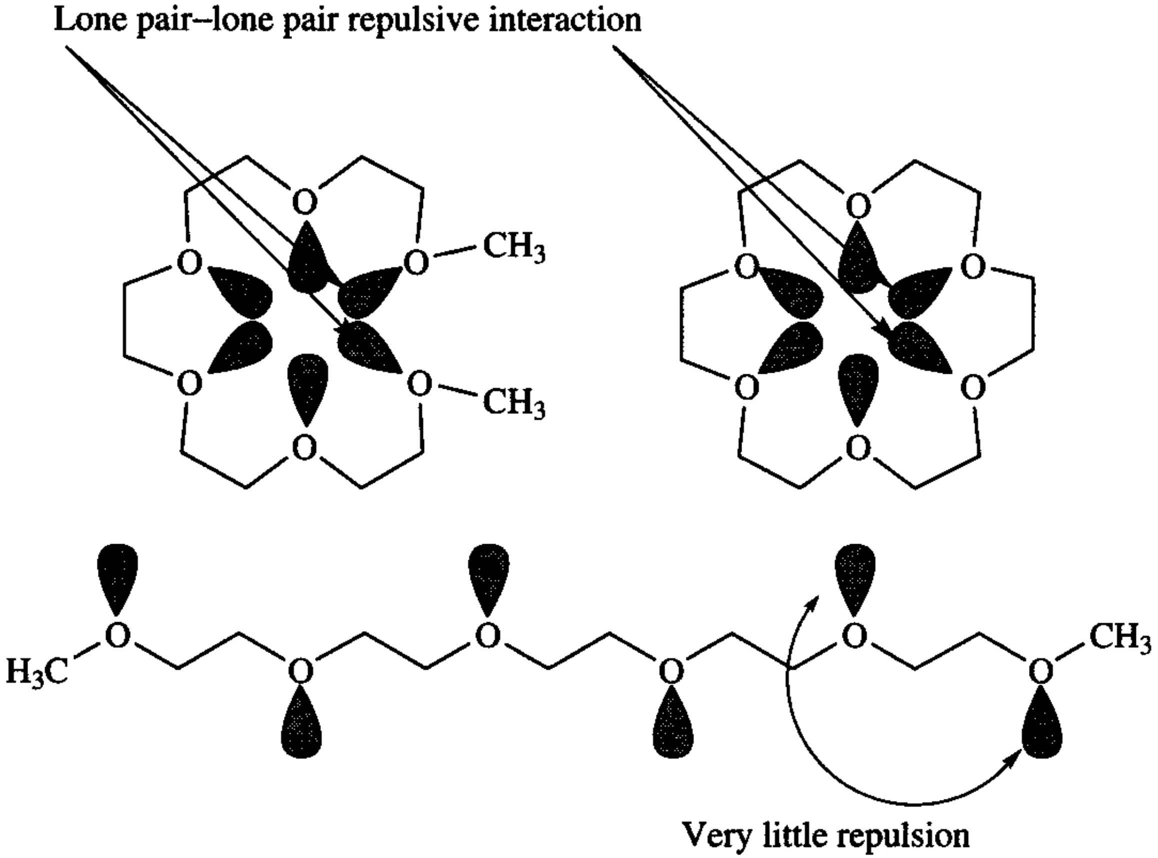
Chair form of cyclohexane

all C-C-C angles are 109.5˚

bite size in six membered rings

bite size in five membered rings

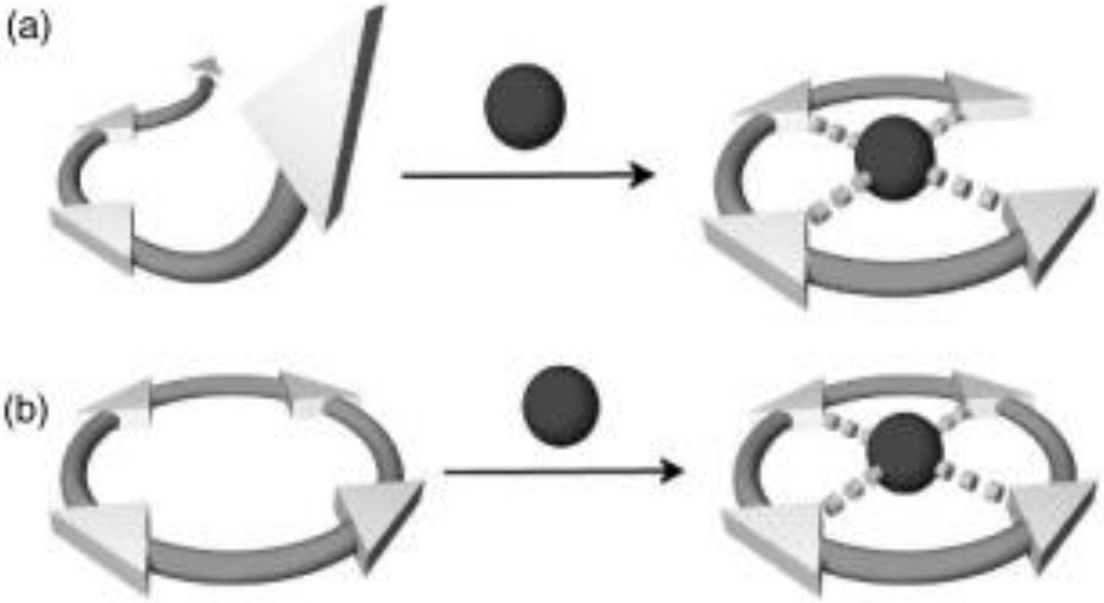
Macrocyclic Effect



Lone pair–lone pair repulsive interaction

Very little repulsion

Macrocyclic Effect



Chelate and Macrocyclic Effects

$$[\mathrm{Ni(H_2O)_6}]^{2+} + 6\mathrm{NH_3} = [\mathrm{Ni(NH_3)_6}]^{2+} + 6\mathrm{H_2O}$$

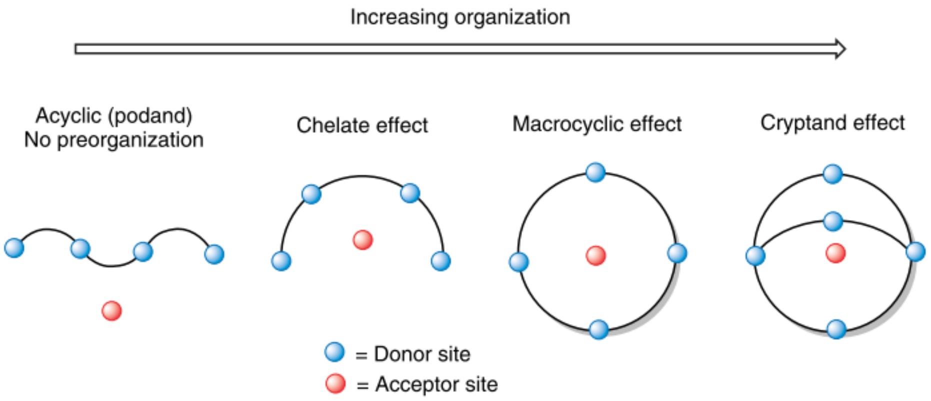
$$\beta \sim 10^{9},\ \Delta G = -51.8\ \mathrm{kJ\ mol^{-1}},$$

$$\Delta H = -100\ \mathrm{kJ\ mol^{-1}},\ \Delta S = -163\ \mathrm{J\ mol^{-1}K^{-1}}$$

$$[\mathrm{Ni(H_2O)_6}]^{2+} + 3\mathrm{en} = [\mathrm{Ni(en)_3}]^{2+} + 6\mathrm{H_2O}$$

$$\beta \sim 10^{18},\ \Delta G = -101.8\ \mathrm{kJ\ mol^{-1}},$$

$$\Delta H = -117\ \mathrm{kJ\ mol^{-1}},\ \Delta S = -42\ \mathrm{J\ mol^{-1}K^{-1}}$$



Recettori

cationi

anioni

molecole neutre

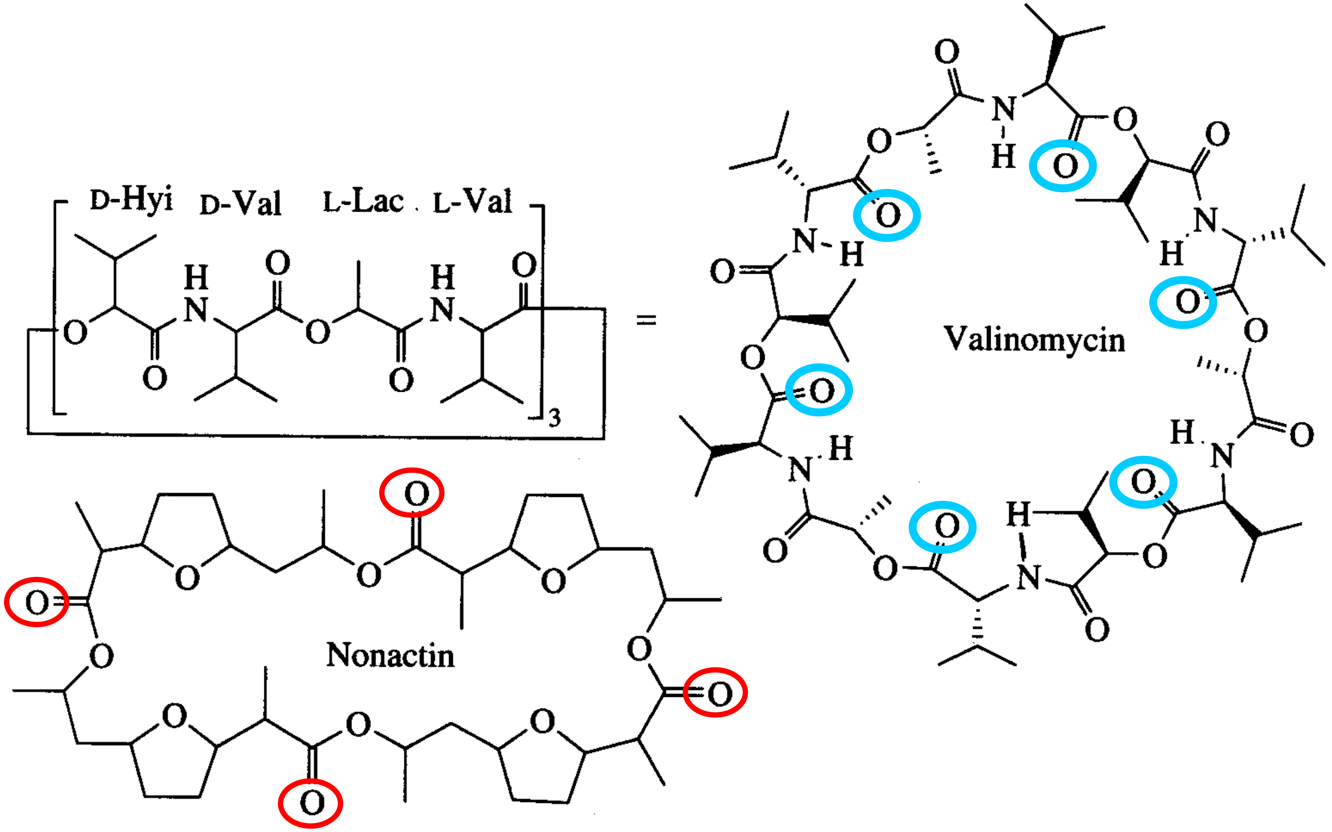
Metodi Analitici

Cavitandi

Contenitori molecolari

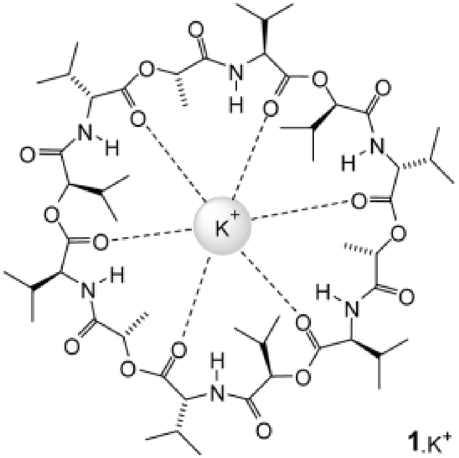
-covalenti
-auto-assemblati (legami idrogeno, legami di coordinazione, legami covalenti dinamici)

Cations and anions are ubiquitous in biological and chemical systems and their efficient and selective recognition is one of the main goals of Supramolecular Chemistry. As a matter of fact, research in this field started with Pressman's 1964 discovery[1] that valinomycin and other natural antibiotics increase the permeability of lipid bilayer membranes through the selective binding of potassium ion, and with Pedersen's finding[2] that macrocyclic polyethers (crowns) are able to complex salts of alkali metal ions and dissolve them in organic media. Since then, the topic of ion recognition by synthetic receptors has developed tremendously and is still quite fertile as testified to by the recent review articles and books concerning cation[3-7] and anion[8,9] complexation and sensing. More recently, a special role in ion

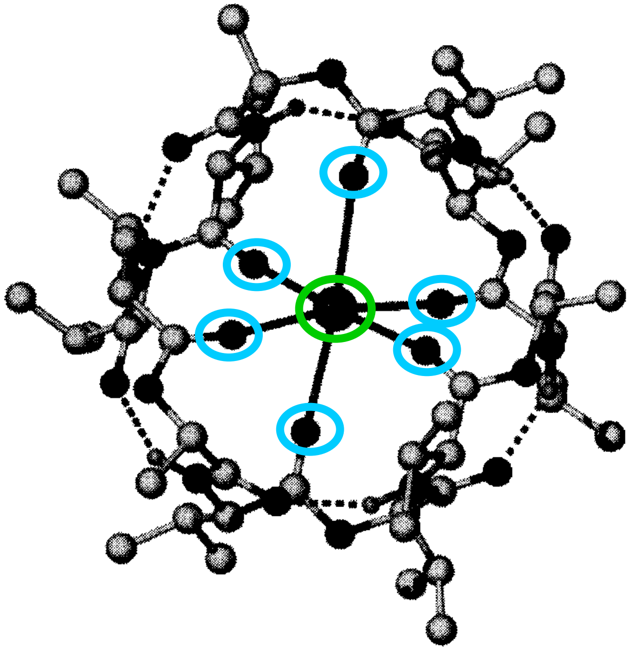


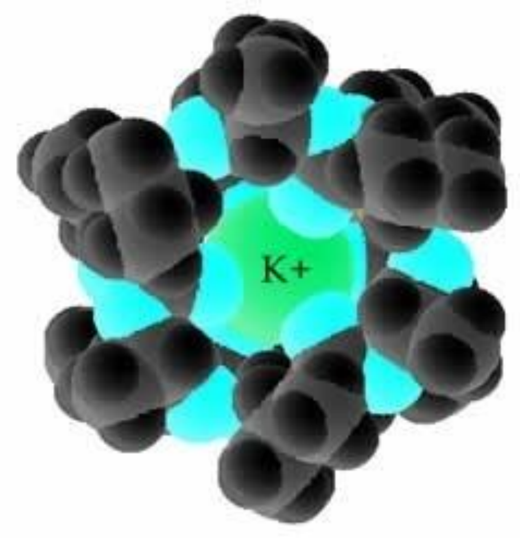
Valinomycin

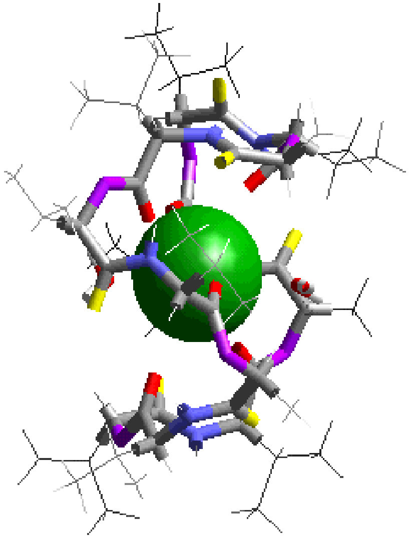
Nonactin



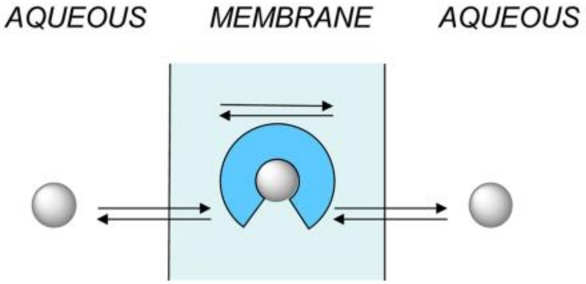
1.K+



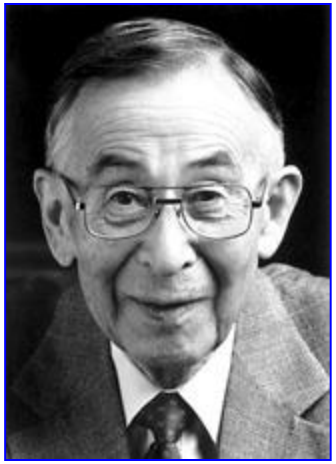


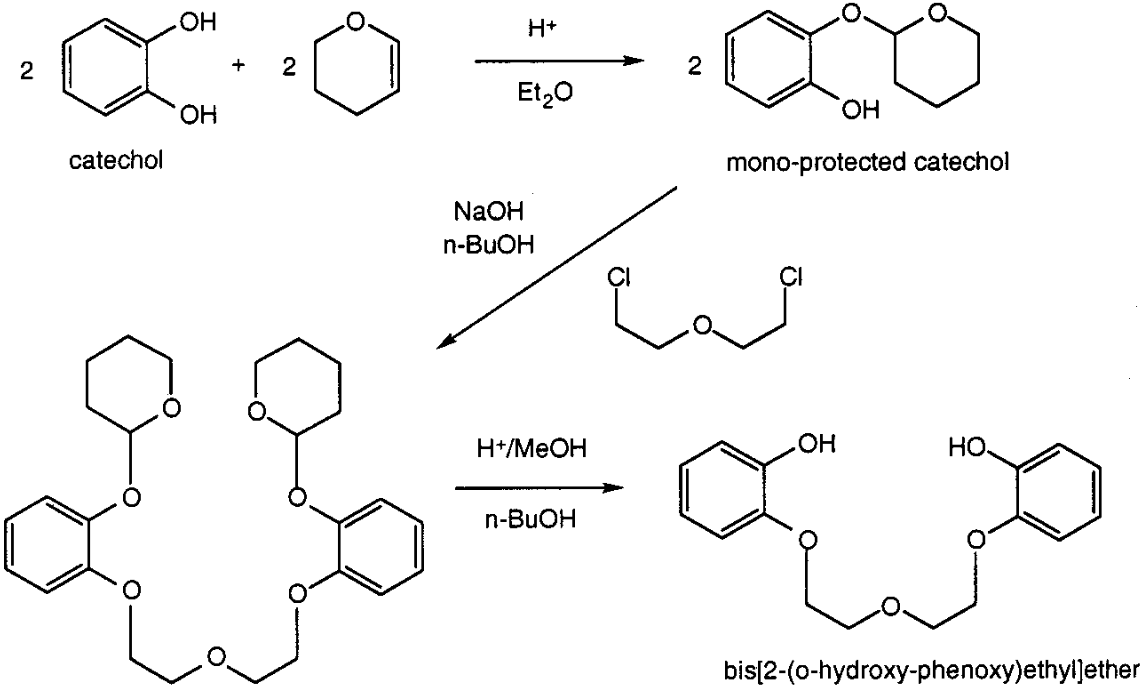


$$K_{K+}/K_{Na+} = 10^5$$

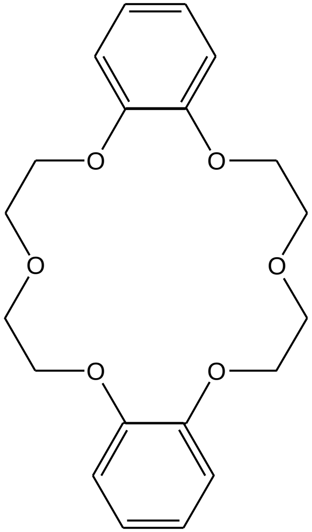


PEDERSEN (Nobel 1987), studio di leganti multi dentati per rame e vanadio (Dupont, anni ‘60)





Intended synthesis of Pedersen’s ligands

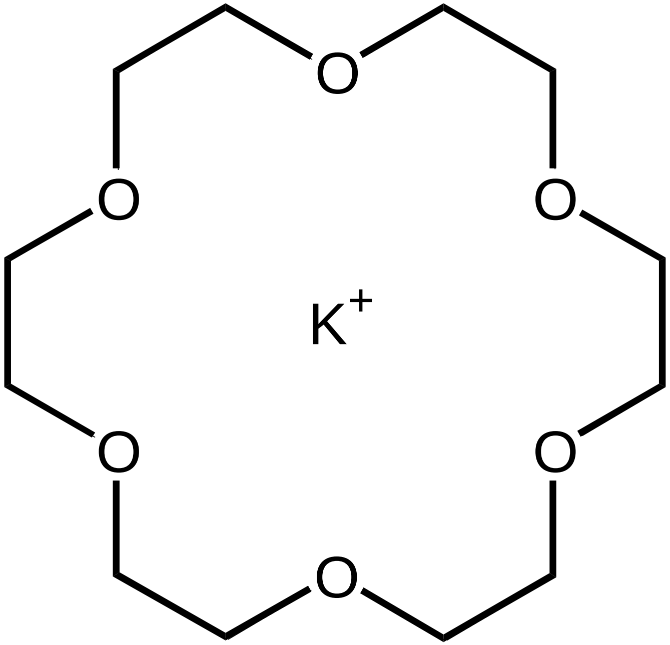


dibenzo[18]crown-6 - sottoprodotto

ETERI CORONA (Crown Ethers)

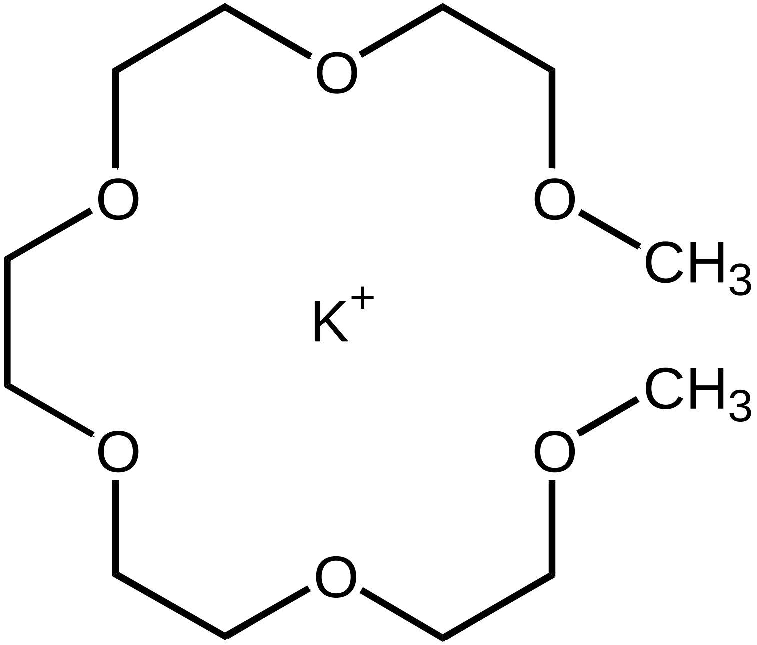
(monocilci = CORANDI)

[18]crown-6

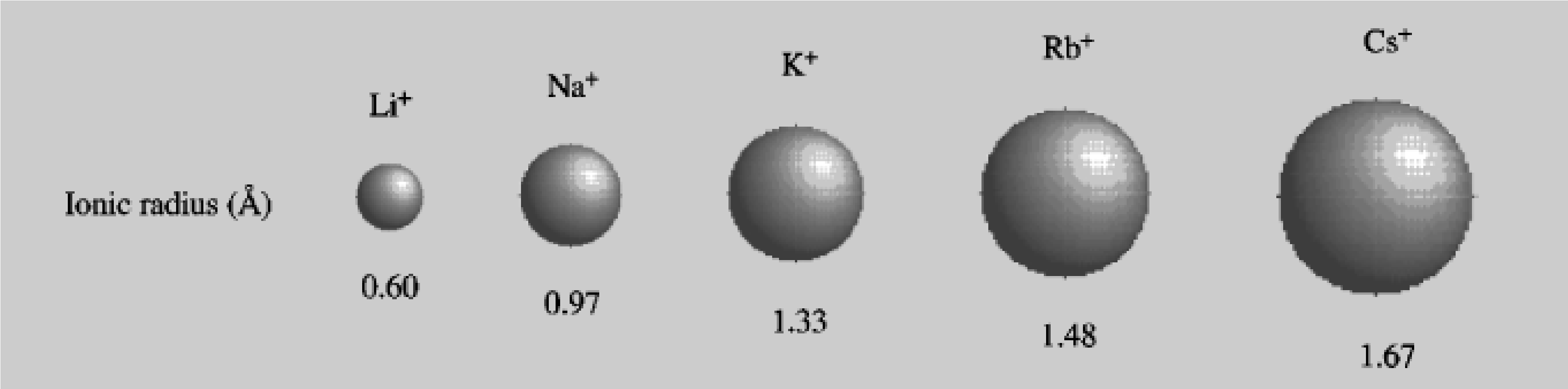


log K = 6.08

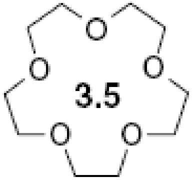
Pentametileneglicol-dietiletere



log K = 2.3

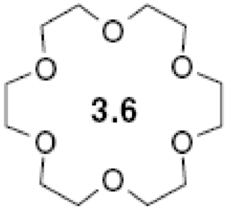


OPTIMAL SPATIAL FIT or SIZE-MATCH



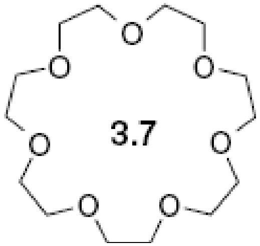
3.5

[15]crown-5
Complementary to Na$^+$



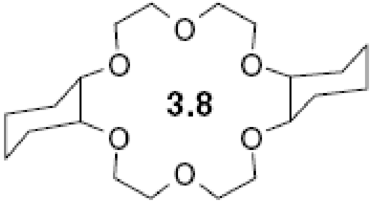
3.6

[18]crown-6
Complementary to K$^+$



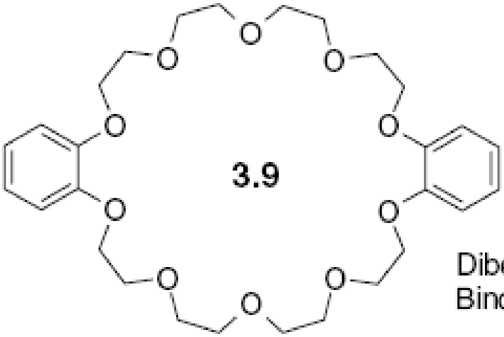
3.7

[21]crown-7
Complementary to Cs$^+$



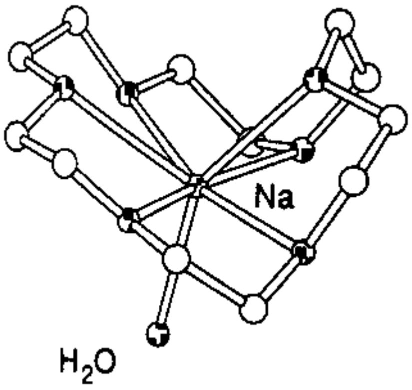
3.8

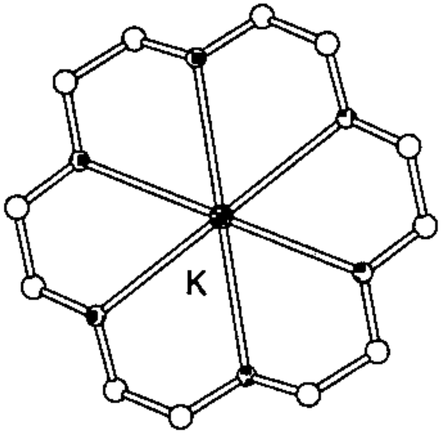
Dicyclohexyl[18]crown-6
More conformationally rigid

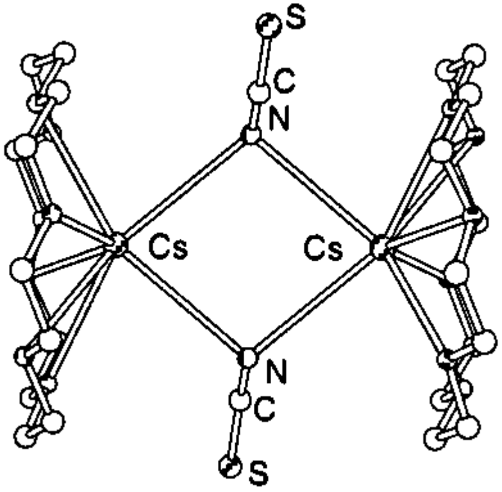


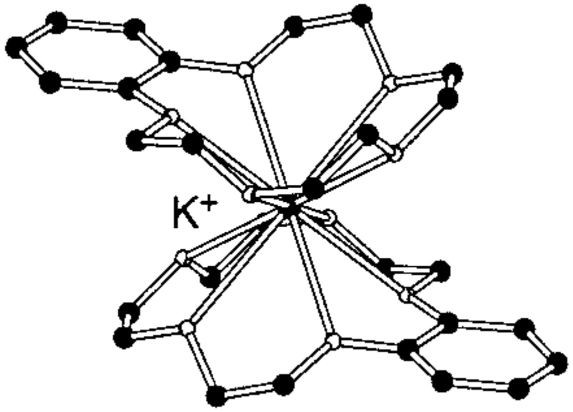
3.9

Dibenzo[30]crown-10
Binds two Na$^+$ ions

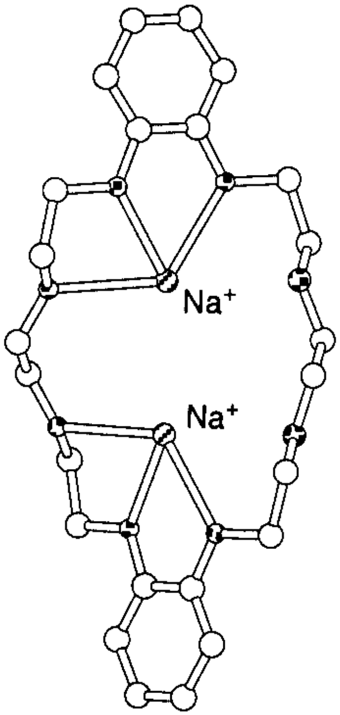








The crystal structure of two benzo-15-crown-5 molecules forming a 'sandwich complex' with a potassium cation



The crystal structure of $2Na^+$–[24]crown-8

Cationi ***hard*** formano complessi in cui le interazioni coulombiane sono dominanti

Cationi ***soft*** formano complessi in cui è dominante il legame covalente.

Ioni metallici di tipo ***a*** sono principalmente:

- ioni dei metalli alcalini e alcalino-terrosi
- ioni metallici leggeri e con elevata carica: Ti^{4+}, Fe^{3+}, Co^{3+}, Al^{3+}

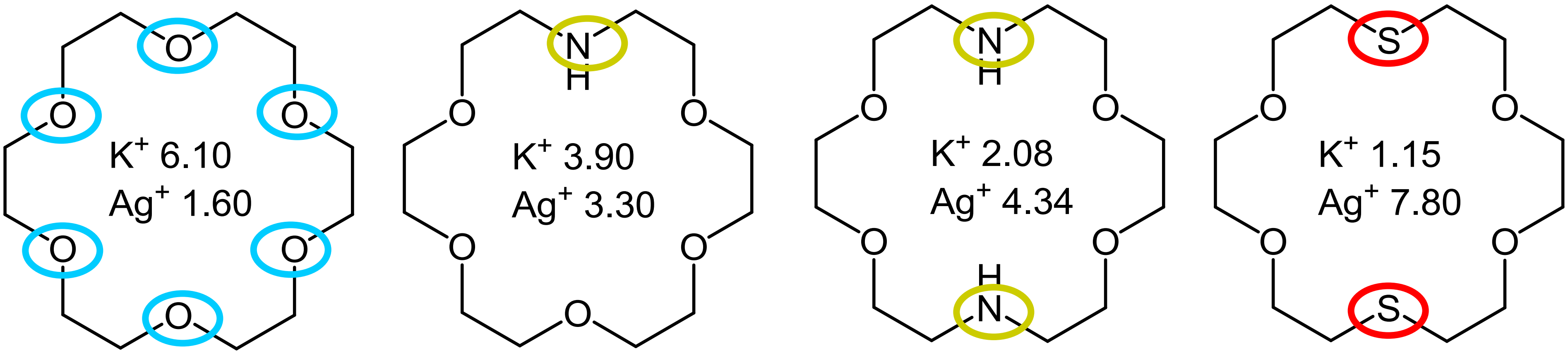
Ioni metallici di tipo ***b*** sono principalmente:

- ioni pesanti di metalli di transizione: Hg_2^{2+}, Hg^{2+}, Pt^{2+}, Pt^{4+}, Ag^{+}, Cu^{+}
- ioni di metalli in bassi stati di ossidazione, ad es. nei metallo carbonili

Alcuni ioni (Fe^{2+}; Co^{2+} ; Ni^{2+}; Cu^{2+} ; Zn^{2+}; Pb^{2+}) formano complessi le cui stabilità non possono essere pronosticate sulla base della classificazione hard/soft: essi formano la classe *border-line*

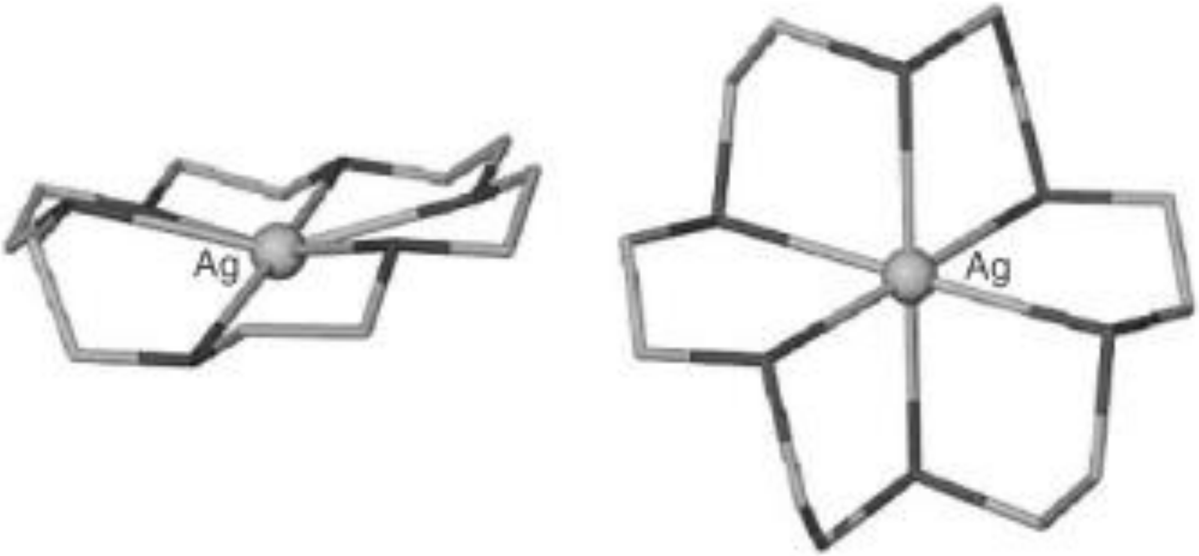
La costante di stabilità dei complessi di questi ioni con un dato legante segue l'ordine, noto come serie di **Irving-Williams**:

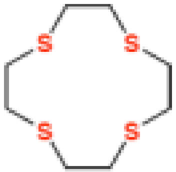
$$Ca^{2+} < Mg^{2+} < Mn^{2+} < Fe^{2+} < Co^{2+} < Ni^{2+} < \mathbf{Cu^{2+}} > Zn^{2+} > Pb^{2+}$$



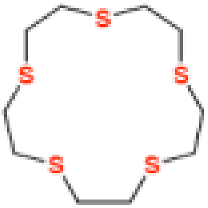
Aza-crown

Tio-crown

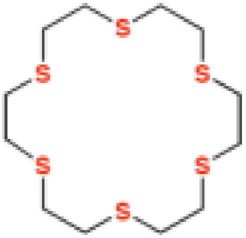




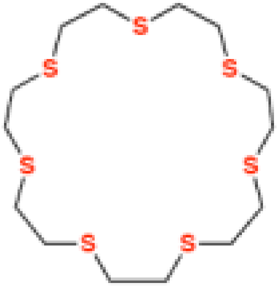
[12]S$_4$



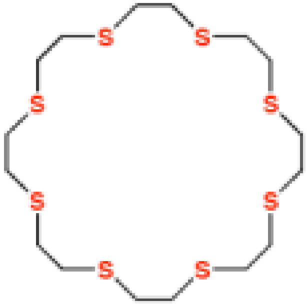
[15]S$_5$



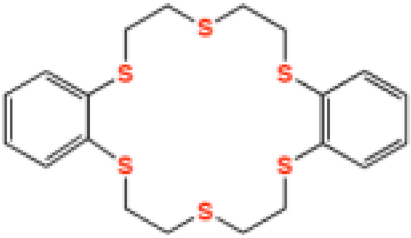
[18]S$_6$



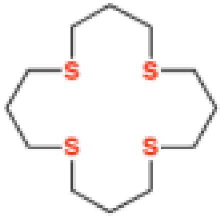
S



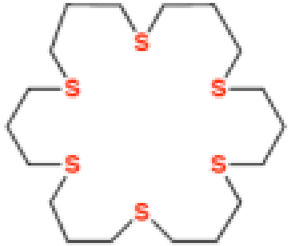
[24]S$_8$



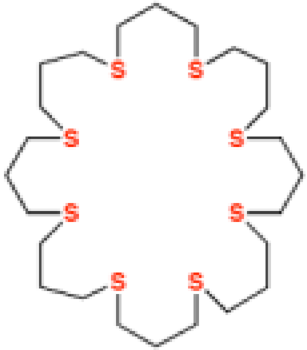
Dibenzo[18]S$_6$



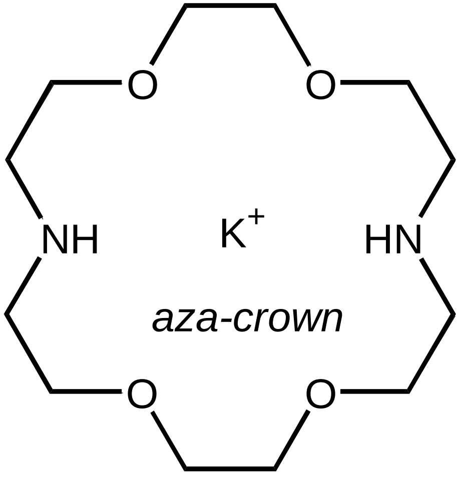
[16]S$_4$



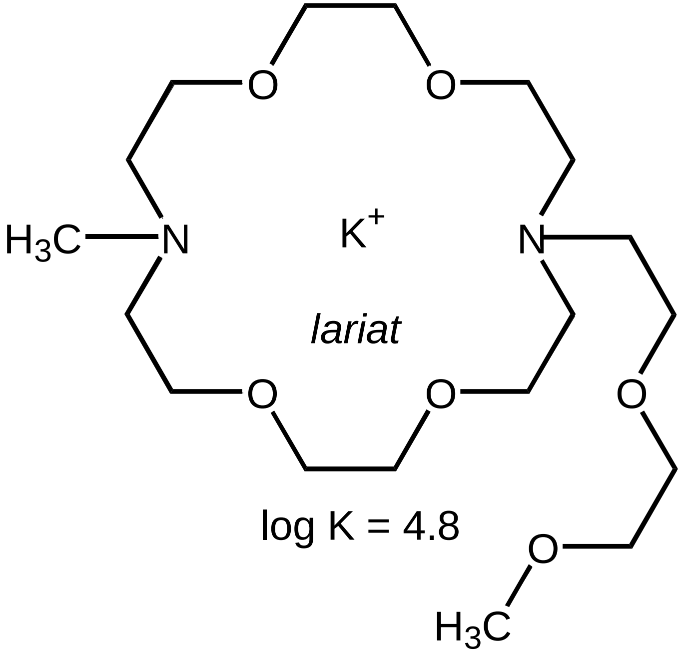
[24]S$_6$



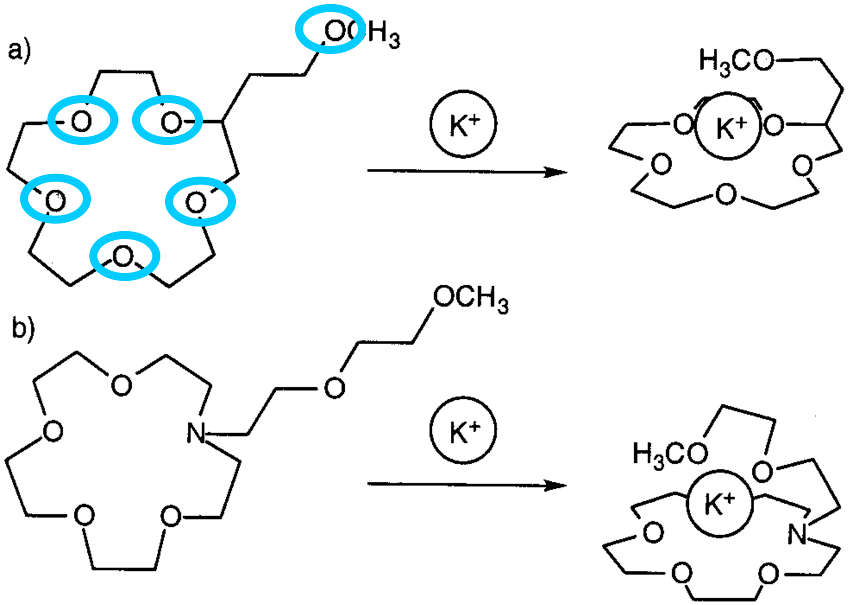
[32]S$_8$



log K = 2.04



log K = 4.8



(a) Carbon and (b) nitrogen pivot lariat crown ethers binding potassium cations.

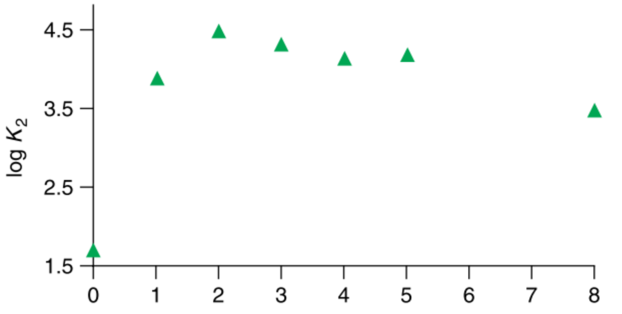
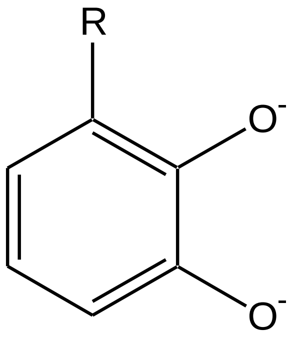


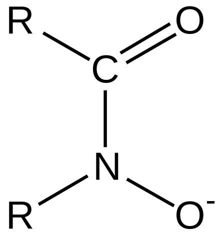
Figure 17 Na^+ complexation by aza-15-crown-5 lariat ethers with n oxygen donor atoms in the side arm ($n = 0–8$).[57]

SIDEROFORI – bioaccesibilità del ferro, Fe(III) altamente insolubile



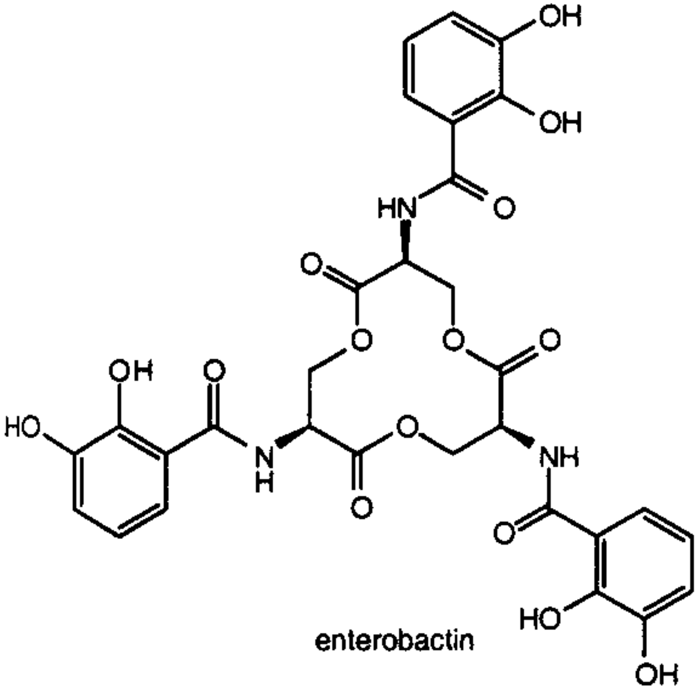
catecolato

Recettori con carica complessiva −6

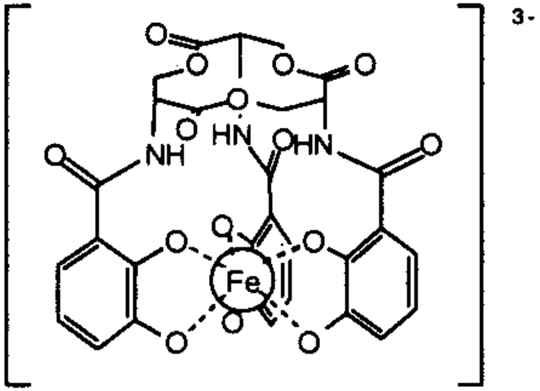


idrossammato

Recettori con carica complessiva −3



enterobactin

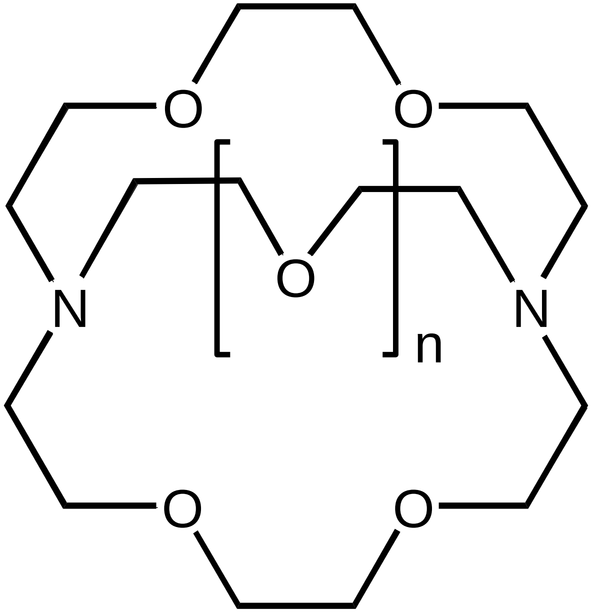


[enterobactin-Fe(III)]$^{3-}$ complex

K(Fe^{III}) = 10^{52}

Enantiomero Δ

LEHN (Nobel 1987), estensione dei sistemi monociclici a sist. biciclici (CRIPTANDI,anni ‘60)

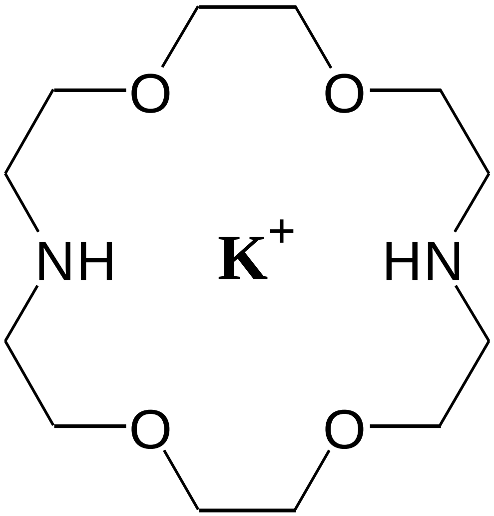


n = 1, criptando [2,2,1]

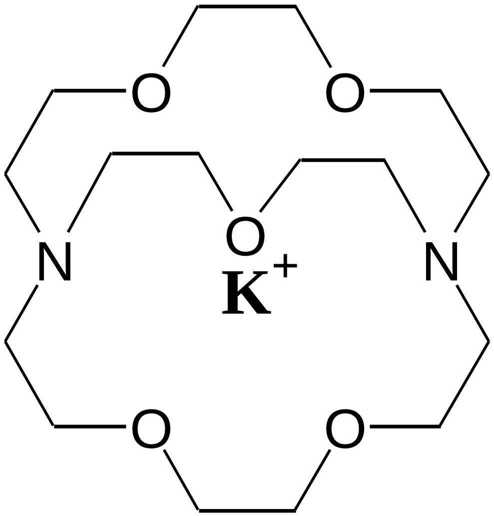
n = 2, criptando [2,2,2]

Na⁺

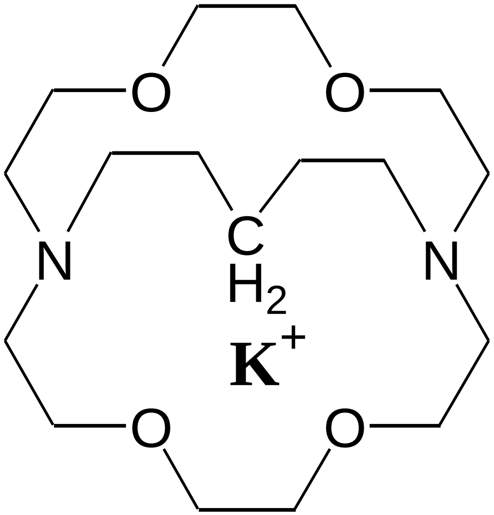
K⁺



logK = 2.0

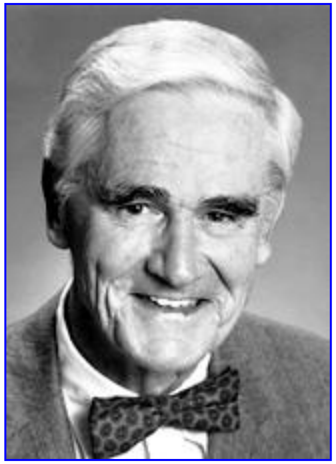


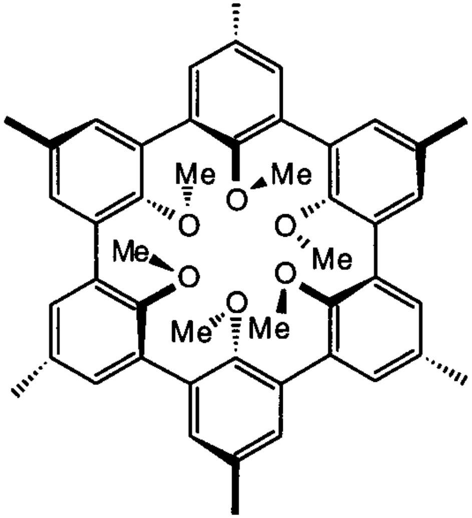
logK = 7.0



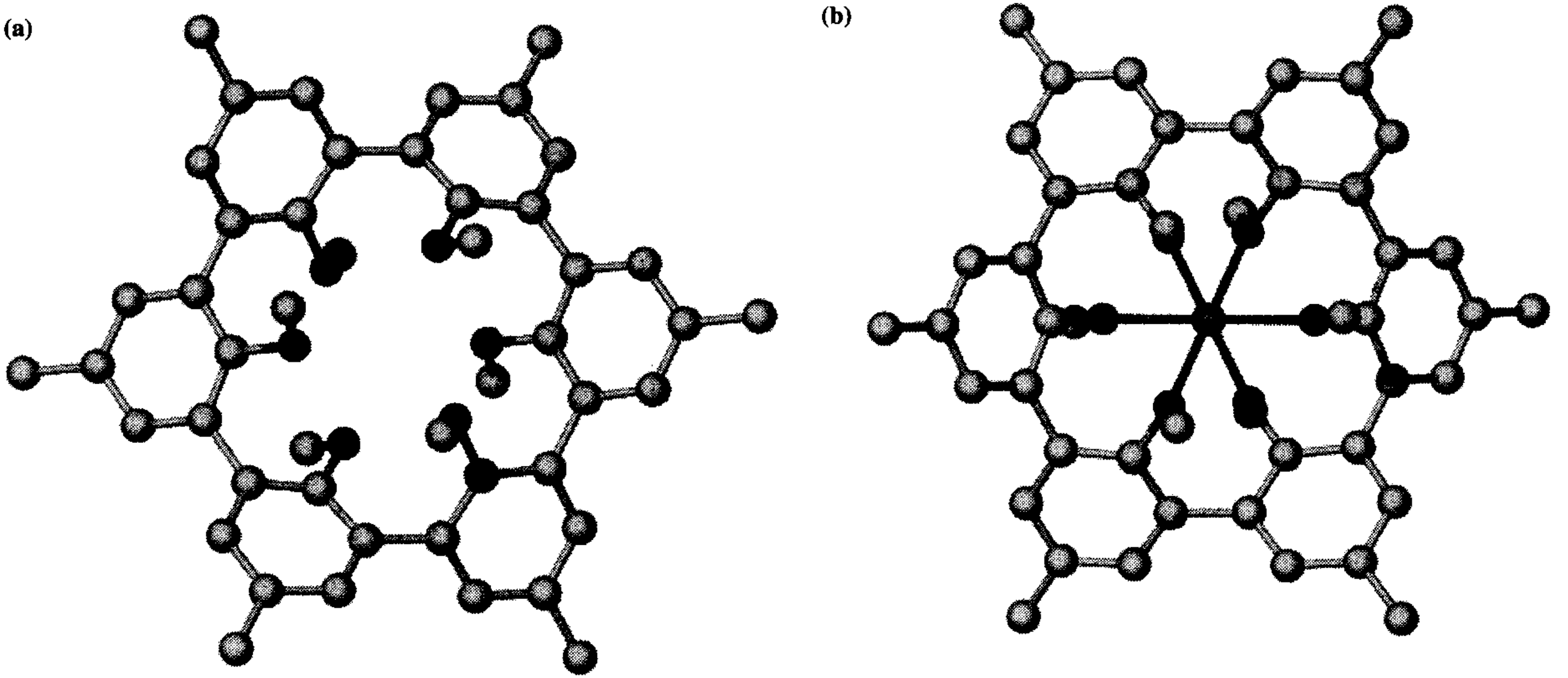
logK = 5.4

CRAM (Nobel 1987) - preorganizzazione

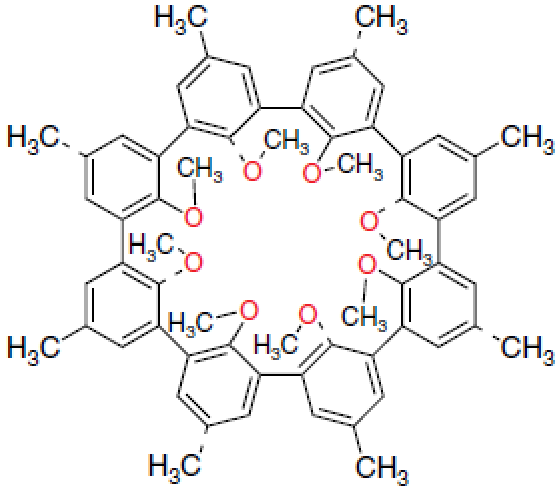




Sferandi
(*p*-metilanisolo)



X-ray crystal structures of **(a)** free spherand (**3.30**) and **(b)** its Li^+ complex (after Trueblood *et al.* 1981).


H3C
CH3
H3C
CH3
O
CH3
O
CH3
CH3
O
O
CH3
H3C
O
O
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H3C
O
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O
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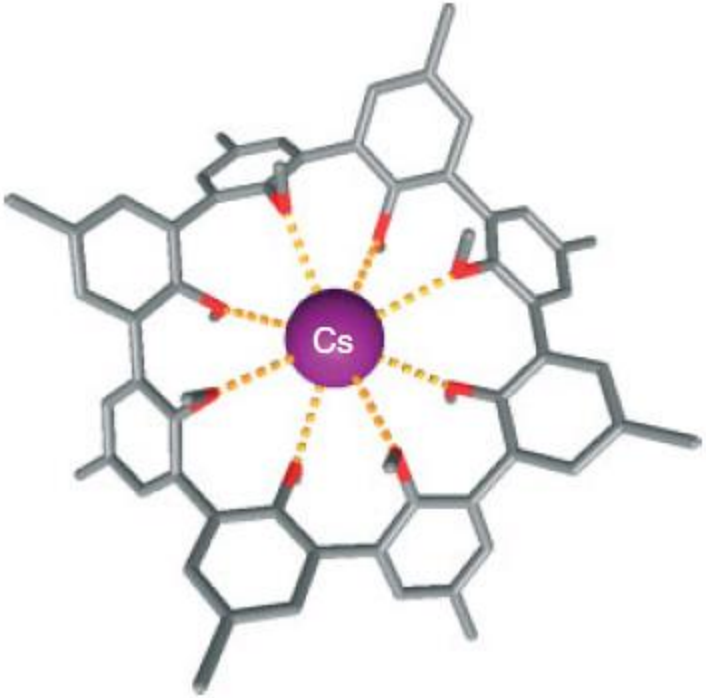
H3C
CH3
H3C
CH3


Cs

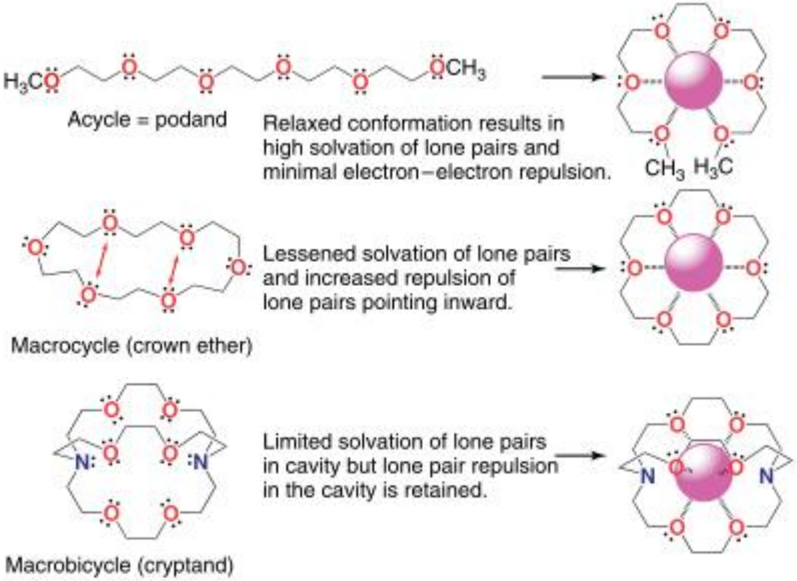
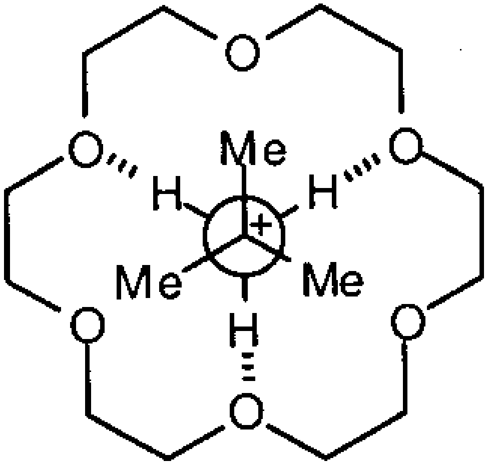


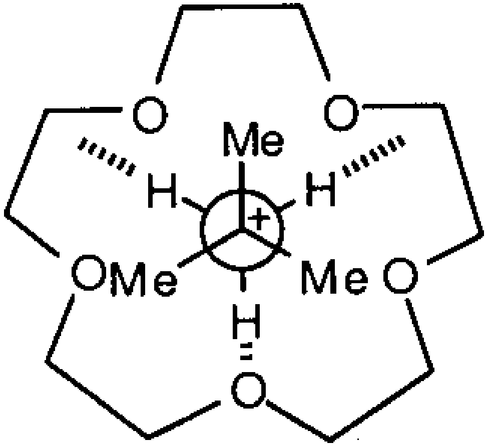
Table 3 Stability constants (log K) in methanol at 25 °C for the binding of alkali metal ions with ionophores that have increasingly complex design and dimension.[33]

Ionophore	Li^+	Na^+	K^+	Rb^+	Cs^+
Pentaglyme	—	1.5	2.2	—	—
Tripod	<2	2.2	2.3	<2	—
Valinomycin	<0.7	0.9	4.7	5.2	4.4
[18]Crown-6	~0	4.4	6.1	5.4	4.7
[2.2.2]Cryptand	2.6	8.0	10.8	9.0	4.4
Spherand[a]	>16.8	14.1	—	—	—

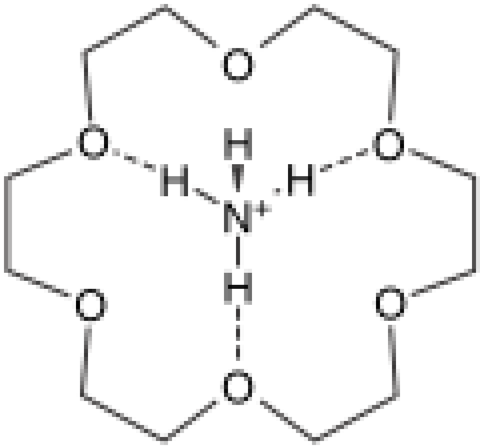
[a] In $CDCl_3$ saturated with H_2O.[35]



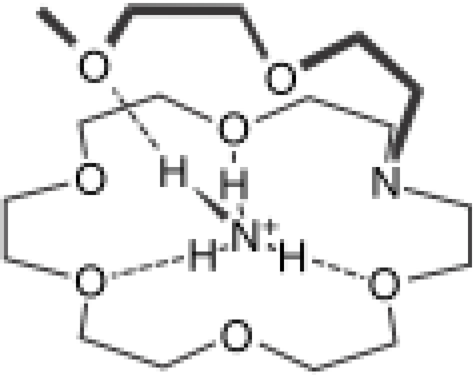
strong complex
ideal arrangement of hydrogen bond
donors and acceptors



weaker complex
mismatch in geometry of hydrogen bond
donors and acceptors



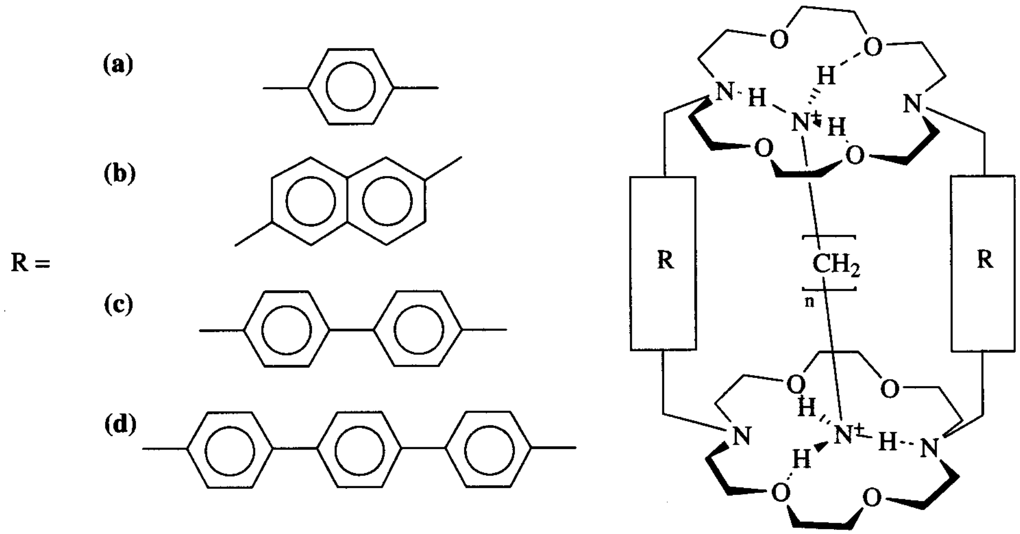
log *K* = 4.35

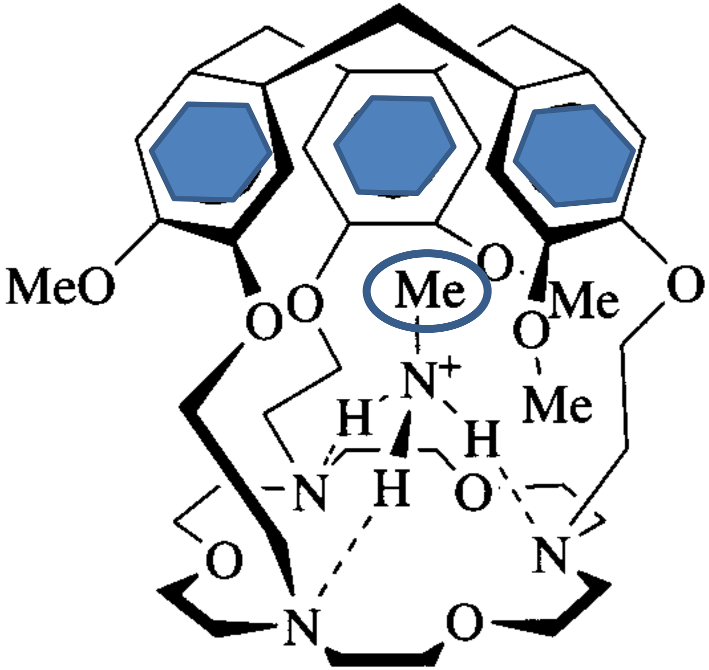


2.23·NH_4^+

log *K* = 4.75

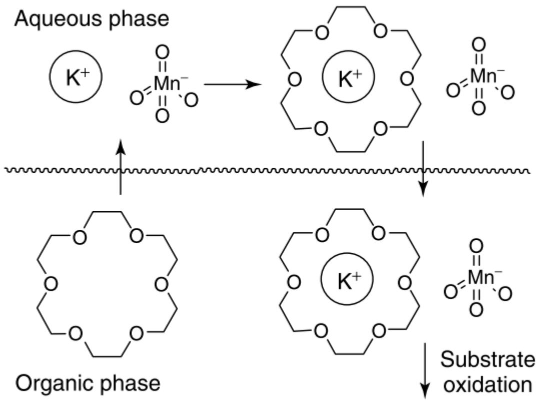
Recettori Politopici

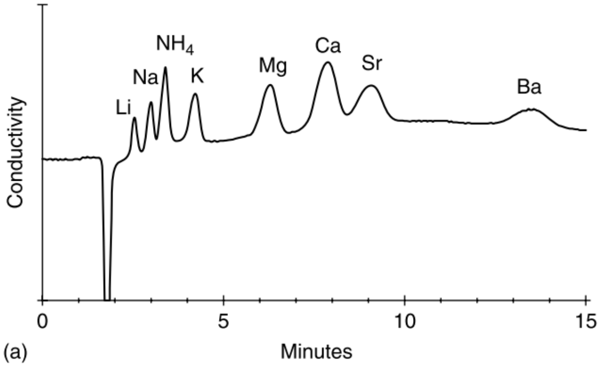


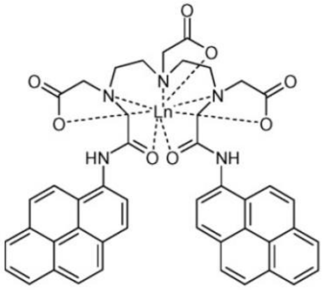


ciclotriveratrilene

corando

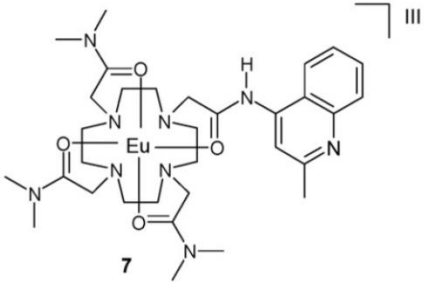






1

Ln = Er(III), Nd(III) and Yb(III)



7

Thermodynamic selectivity : ratio of the binding constant for one guest over another:

$$H + G_1 \rightleftharpoons [HG_1] \qquad K_1$$

$$H + G_2 \rightleftharpoons [HG_2] \qquad K_2$$

$$\text{selectivity} = \frac{K_1}{K_2}$$

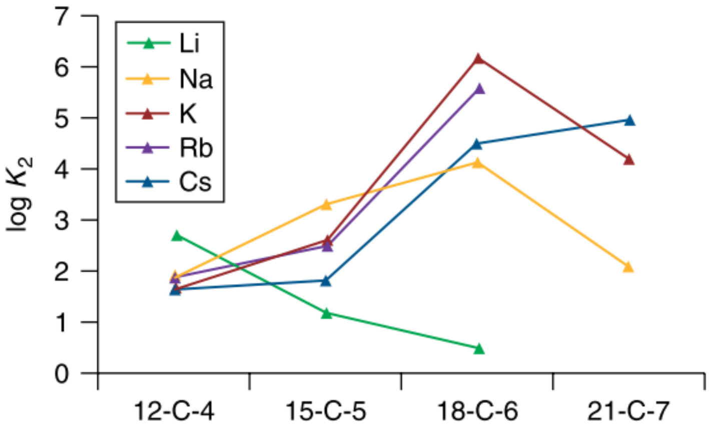
Selectivity is a consequence of preorganization, complementarity…
Needs to be calculated at equilibrium in the same conditions
Temperature! Solvent!

Kinetic selectivity : preference of a host for the fastest transformation of a substrate over another (Michaelis-Menten model)

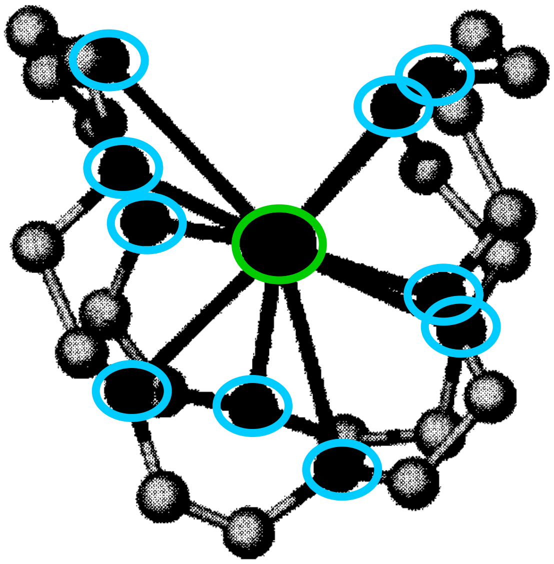
-transport
-catalysis
-sensing and signaling

Selettività

Size-match o optimal-fit (progressivamente più determinante aumentando la rigidità /preorganizzazione dell’Host) – distanza tra i dipoli del macrociclo e la carica ionica



[30]crown-10



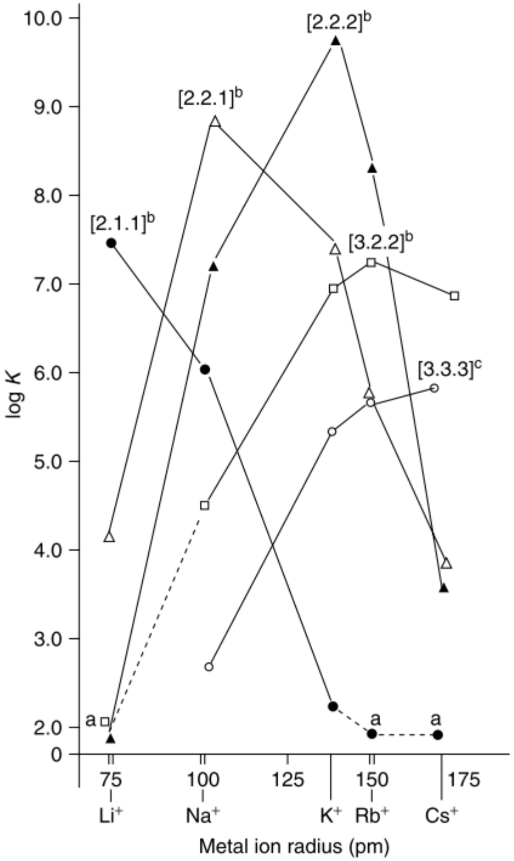


Figure 2 Selectivity of cryptands among alkali metal cations (a, value reported <2.0; b, in 95% CH_3OH; c, in methanol).

Selettività

Natura degli atoni donatori (O vs N VdW radius simile: hard/soft acid-base theory;

Numero e orientazione degli atomi donatori (pesa di più per cationi di M transizione, che per alcalini; alcalinoterrosi e REM).

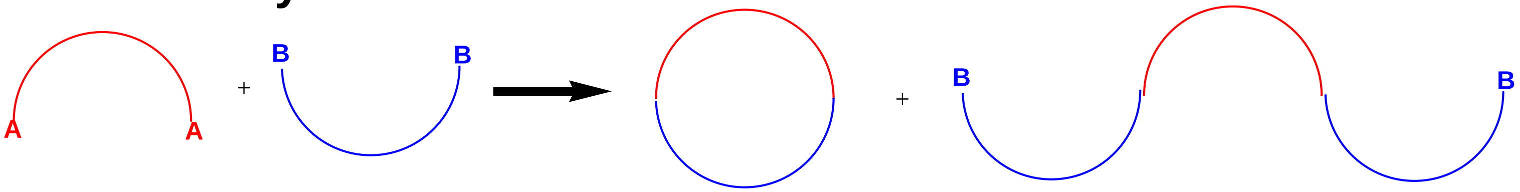
Carica elettrostatica dello ione: a parità di raggio ionico, carica maggiore può corrispondere a maggiore energia di idratazione (*cfr* Ca^{2+} vs Na^{+});

Solvatazione dell'host

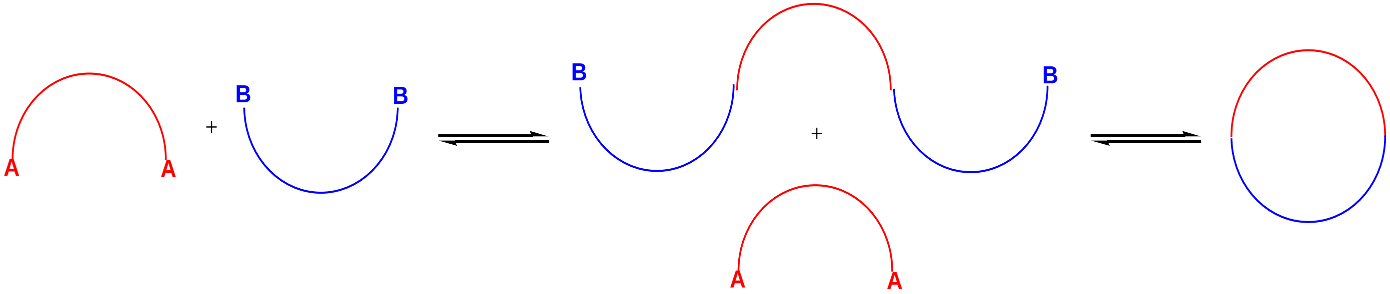
Solvente – competitivo per i dipoli/ costante dielettrica

natura del contro-ione

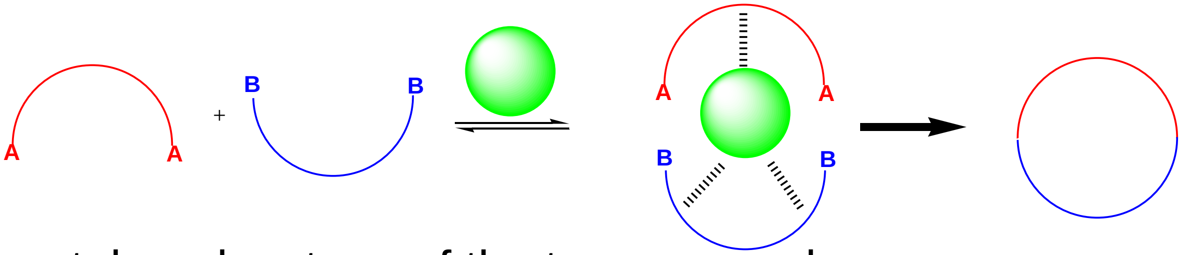
- **covalent synthesis** : under kinetic control



  - classical organic chemistry. Irreversible bond formation
  - highly stable molecules.
  - not adapted to big molecules. low yield
- **non covalent synthesis** : under thermodynamic control

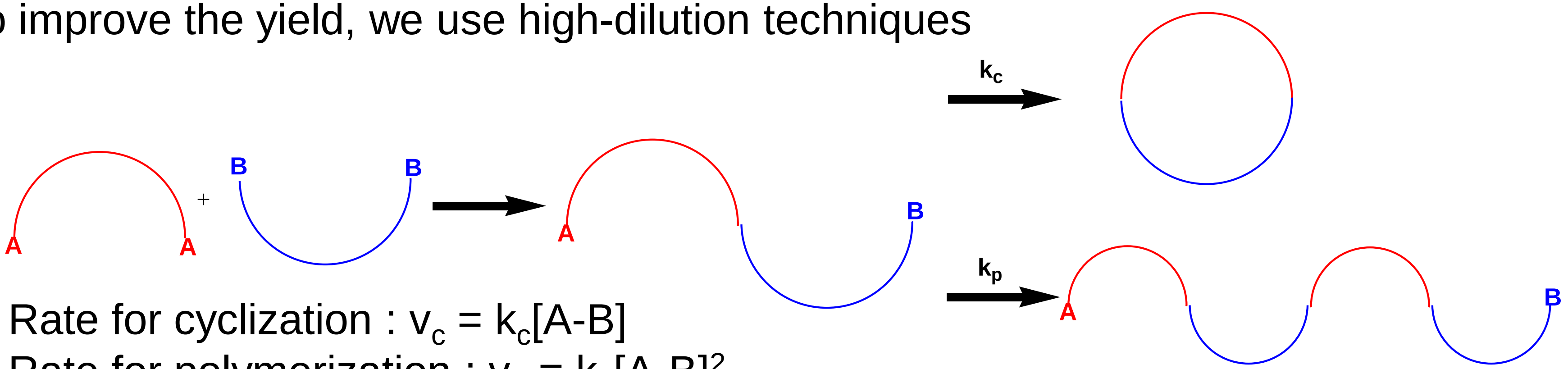


  - thermodynamic directed synthesis. Reversible bond formation
  - lower stability
  - adapted to big molecules. high yield
- a **mix**



  - take advantage of the two approaches

To improve the yield, we use high-dilution techniques



Rate for cyclization : $v_c = k_c[\text{A-B}]$

Rate for polymerization : $v_p = k_p[\text{A-B}]^2$

- the more dilute, the more cyclic product is formed
- the reaction has to be fast

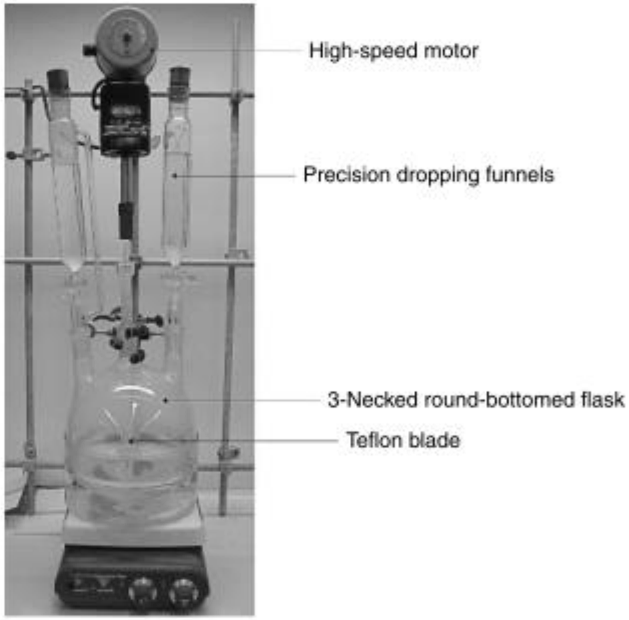
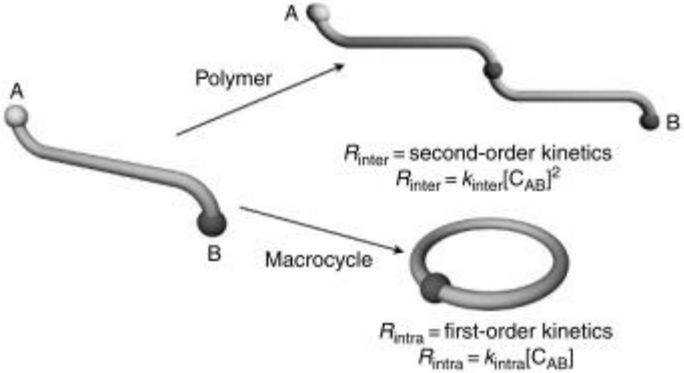
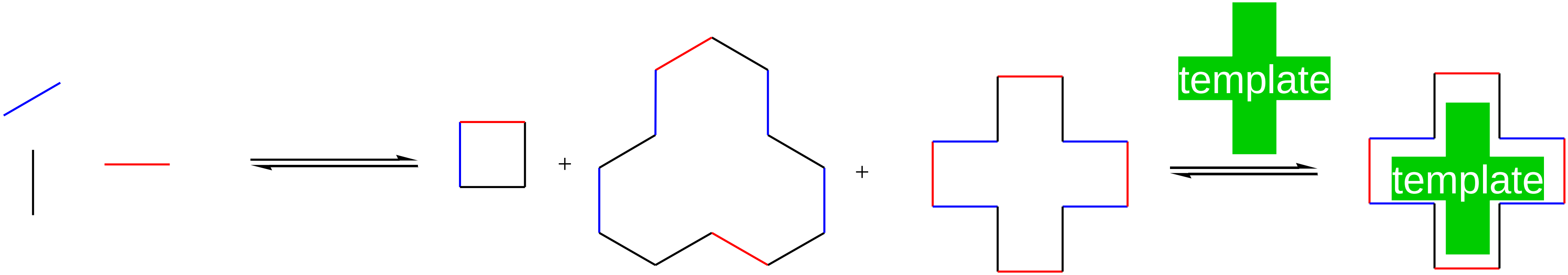
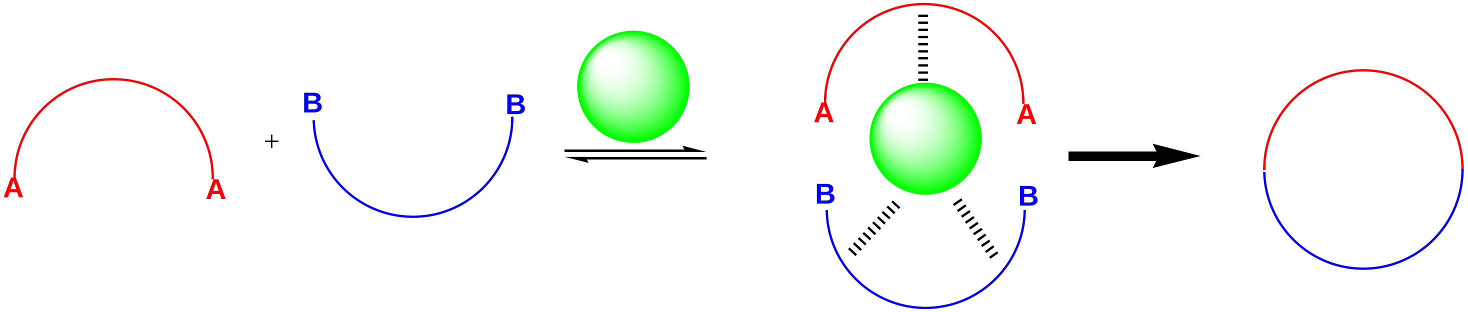


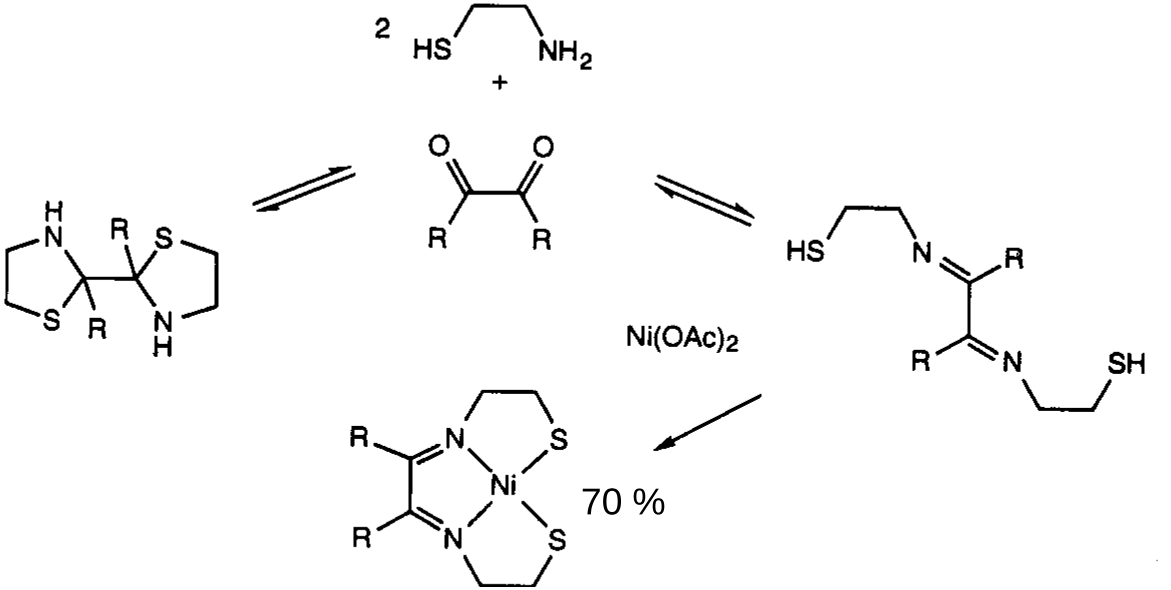
Figure 2.1 Typical apparatus used for high-dilution synthesis.




template
template

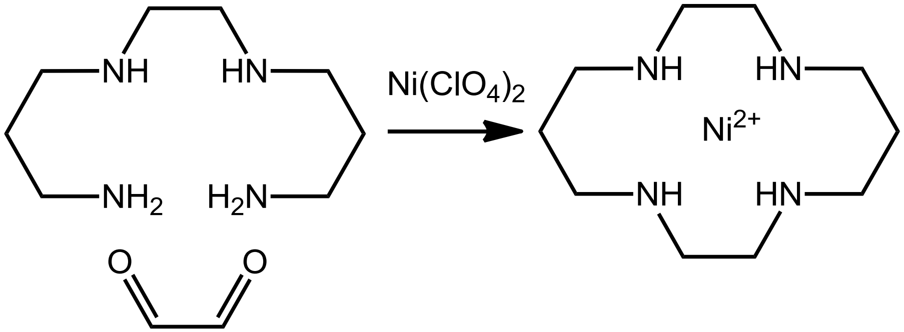

A
A
B
B
A
A
B
B

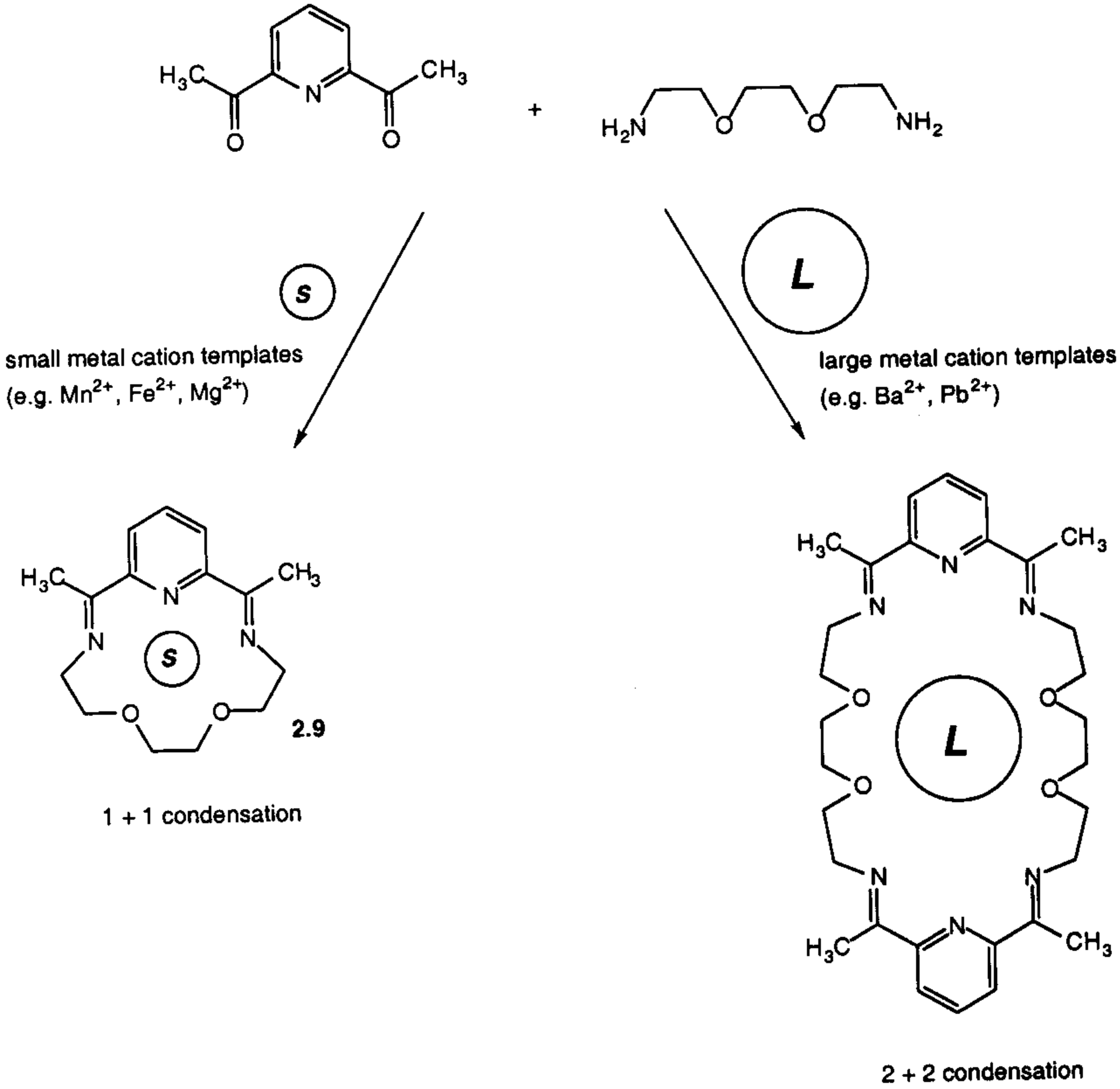
a) thermodynamic template effect

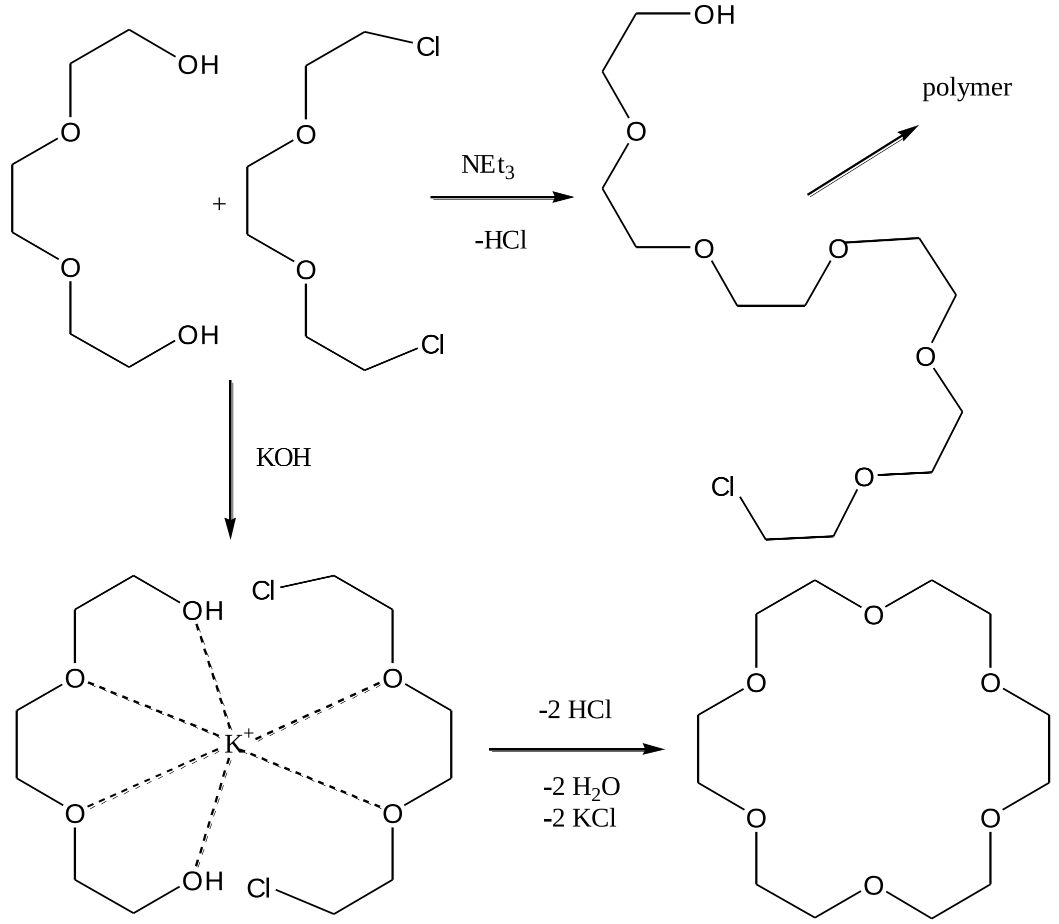


70 %

Effetto templato cinetico CYCLAM (base di Schiff)

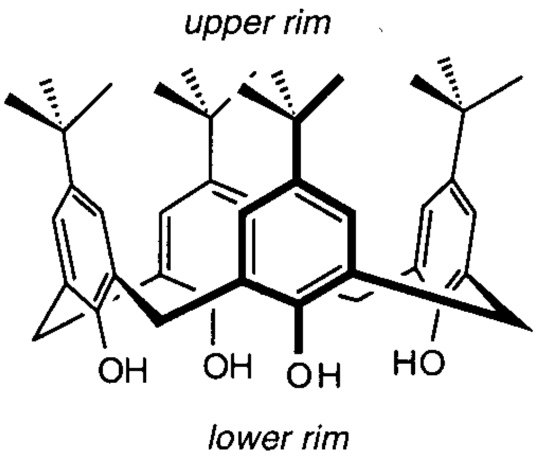



H$_3$C
CH$_3$
N
O
O
+
H$_2$N
O
O
NH$_2$
S
small metal cation templates
(e.g. Mn^{2+}, Fe^{2+}, Mg^{2+})
L
large metal cation templates
(e.g. Ba^{2+}, Pb^{2+})
2.9
1 + 1 condensation
2 + 2 condensation



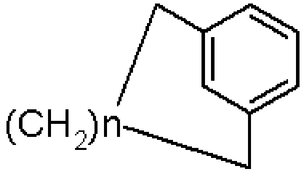
Demetallazione:
gruppi amminici – protonazione
debolm coordinat – estrazione con acqua
complessante più forte
variaz stato ox- inerzia/labilità

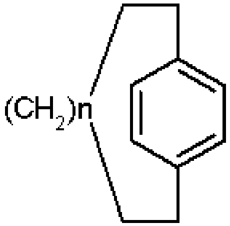
Calix[n]areni

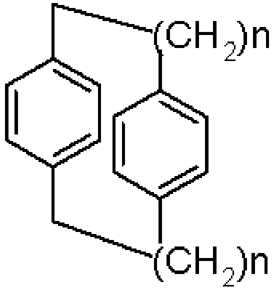


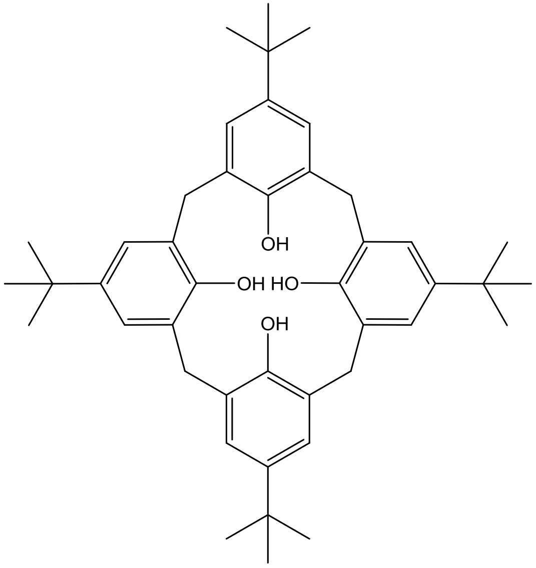
p-tert-Butylcalix[4]arene.

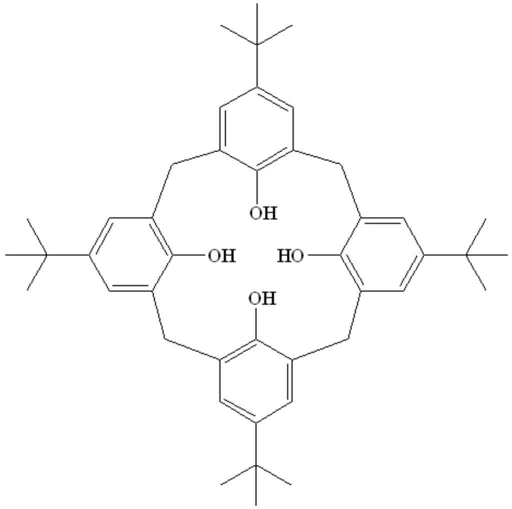
Ciclofani

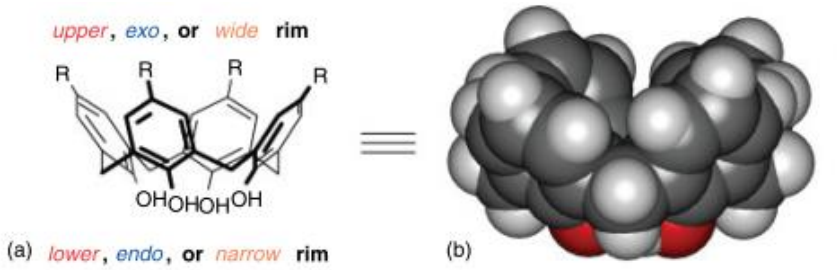


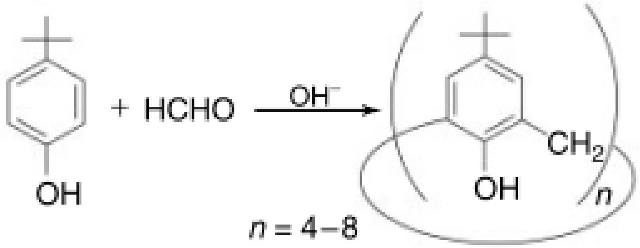


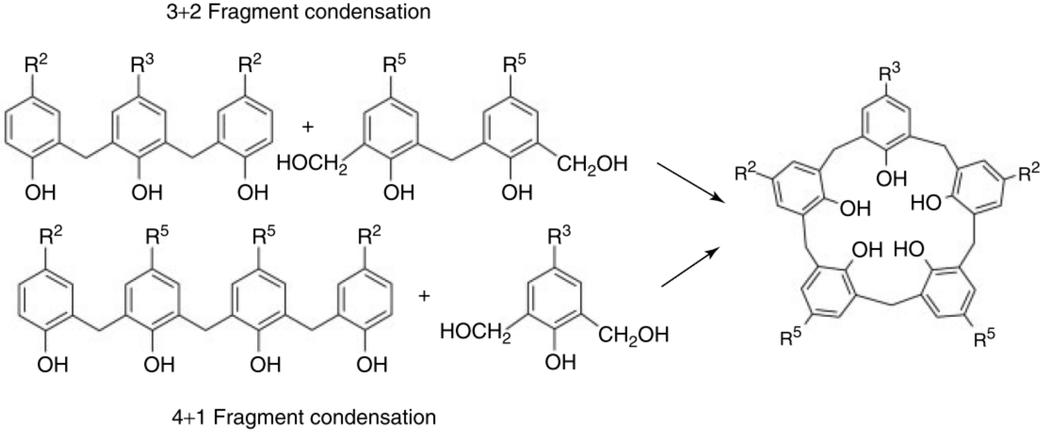


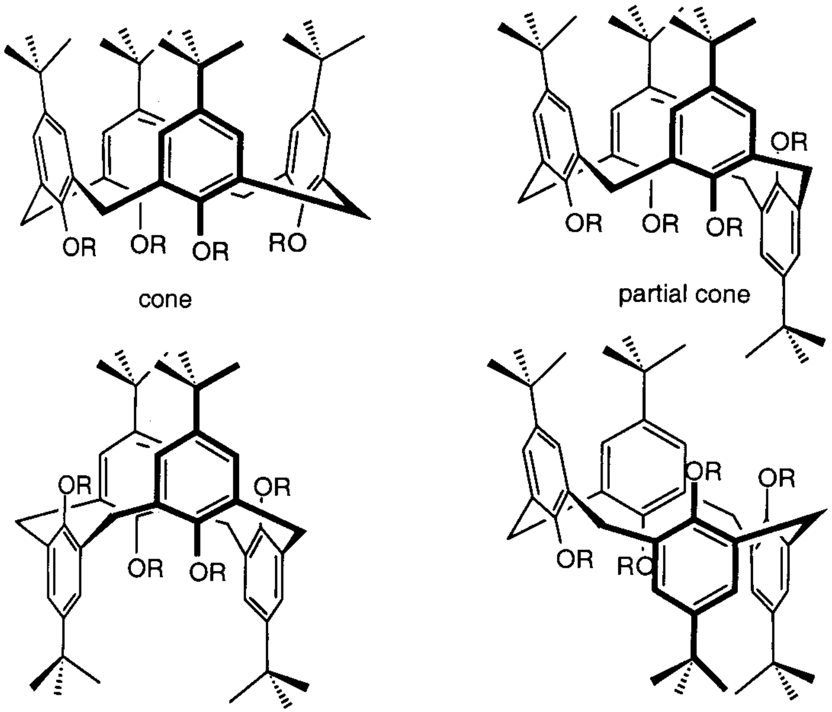



OH
OH
HO
OH


upper, exo, or wide rim
R
R
R
R
OH
OH
OH
OH
≡
(a)
lower, endo, or narrow rim
(b)


+ HCHO
OH⁻
OH
CH2
OH
n
n = 4–8


3+2 Fragment condensation
R2
R3
R2
OH
OH
OH
+
R5
R5
HOCH2
CH2OH
OH
OH
R2
R5
R5
R2
OH
OH
OH
OH
+
R3
HOCH2
CH2OH
OH
4+1 Fragment condensation
R3
R2
R2
OH
OH
HO
OH
HO
R5
R5



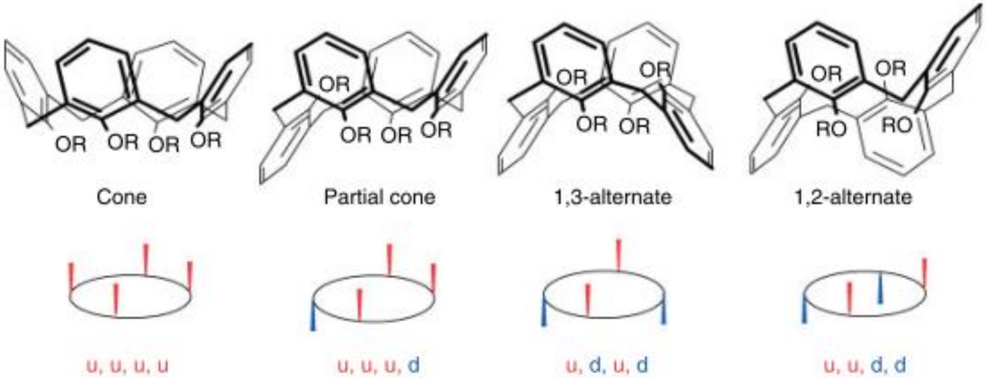
cone

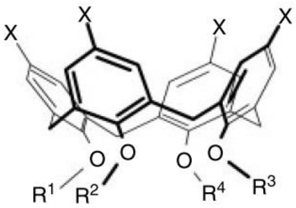
partial cone

1,3-alternate

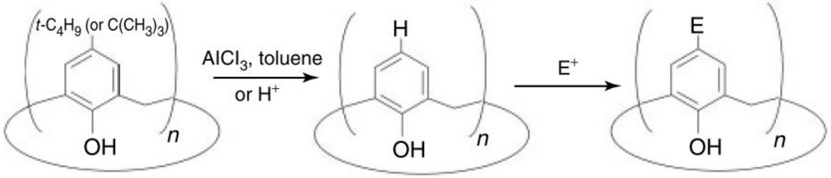
1,2-alternate

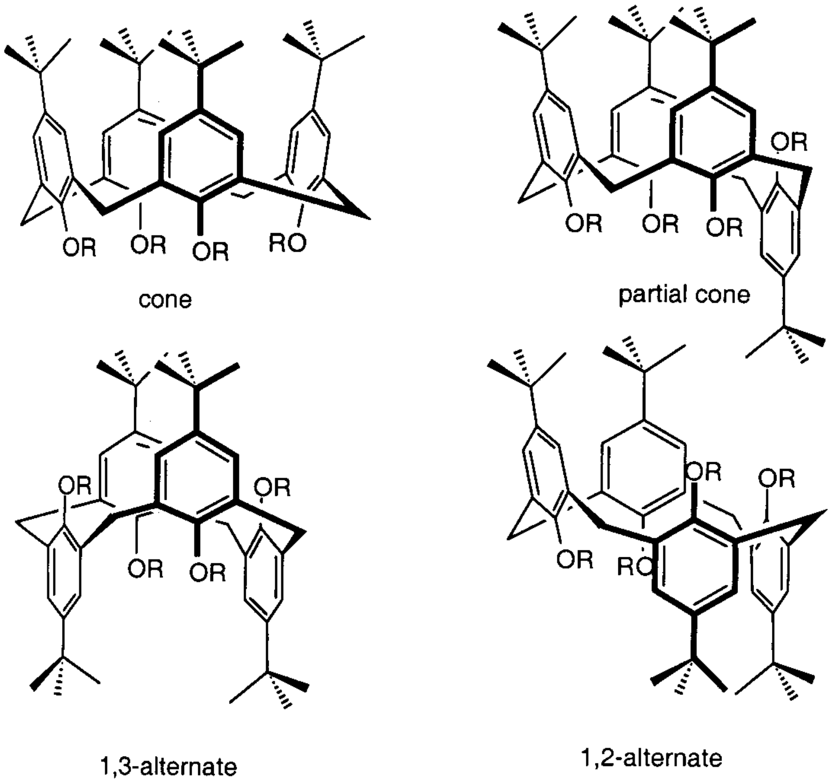
Conformations adopted by calix[4]arenes.



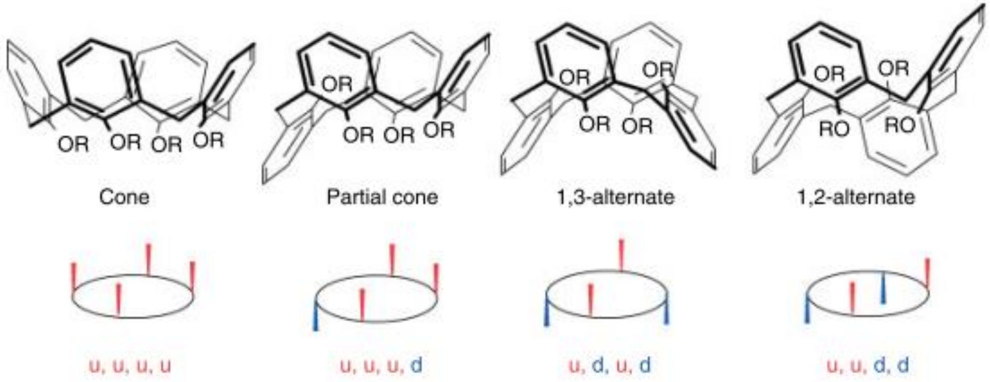


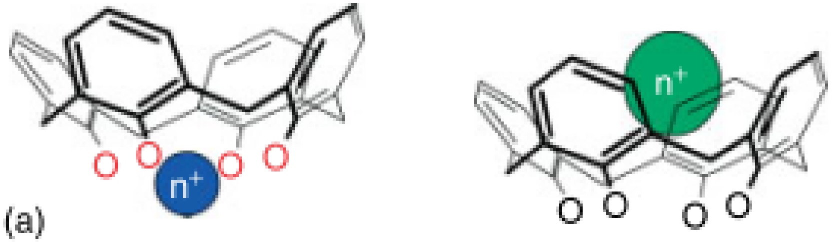
2a: R^1-R^4 = alkyl
2b: R^1, R^2 = alkyl, R^3, R^4 = OH
2c: R^1, R^3 = alkyl, R^2, R^4 = OH
2d: R^1 = alkyl, R^2–R^4 = OH
2e: R^1–R^3 = alkyl, R^4 = OH

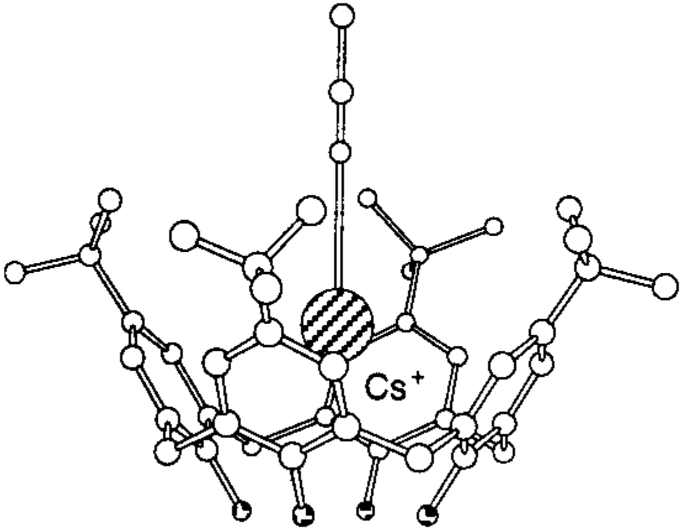


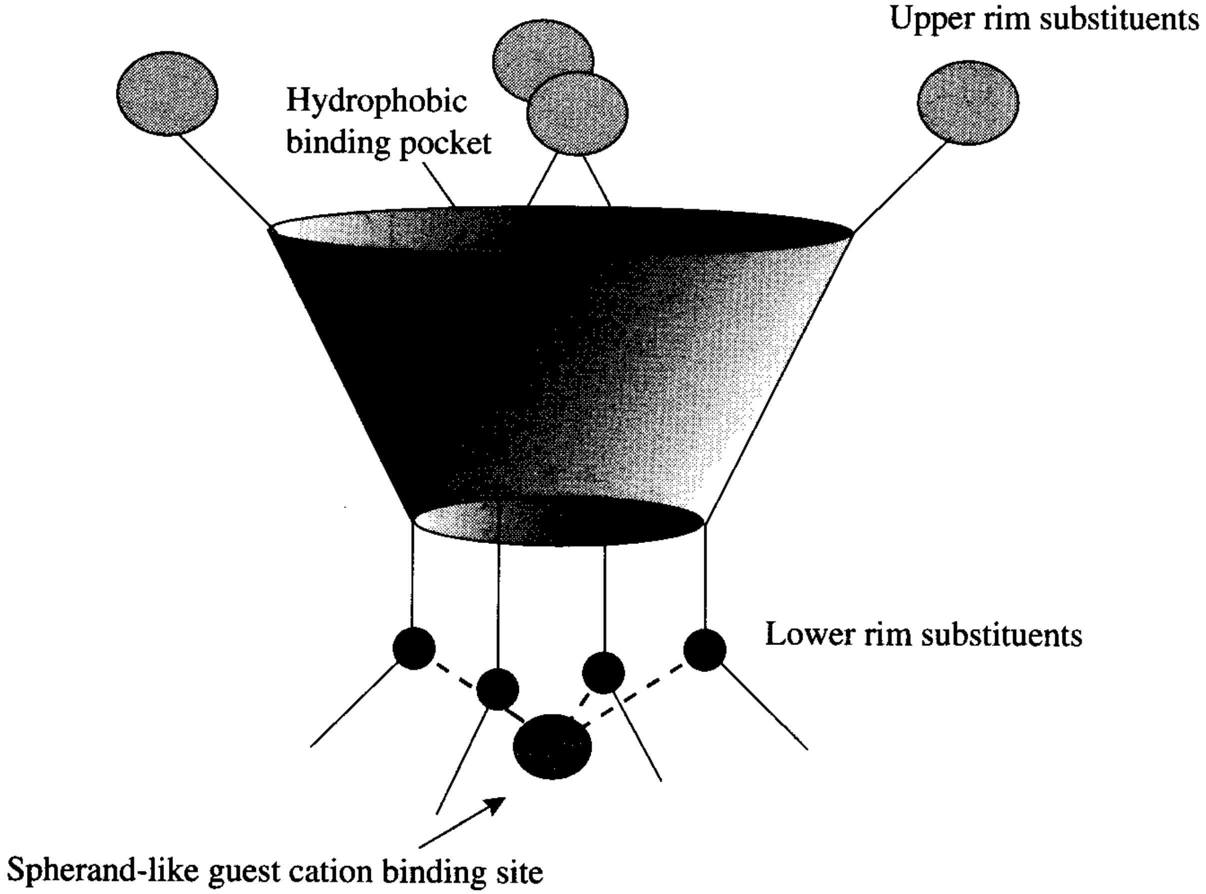


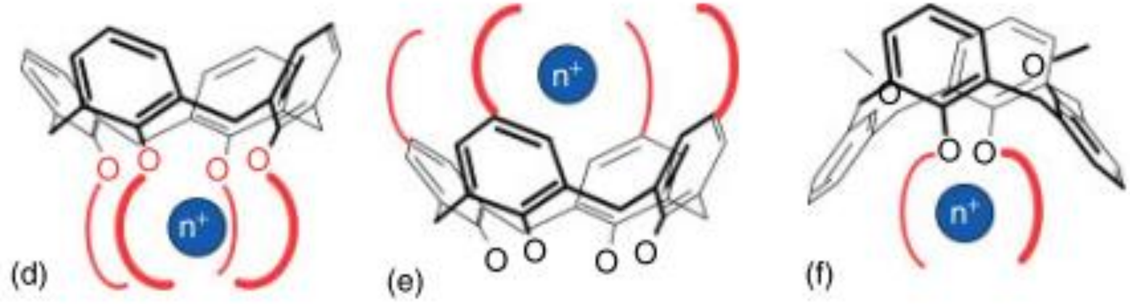
Conformations adopted by calix[4]arenes.

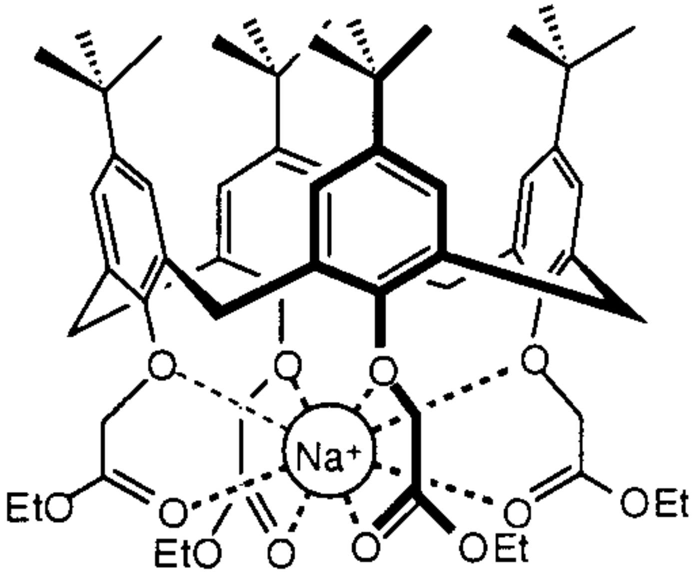


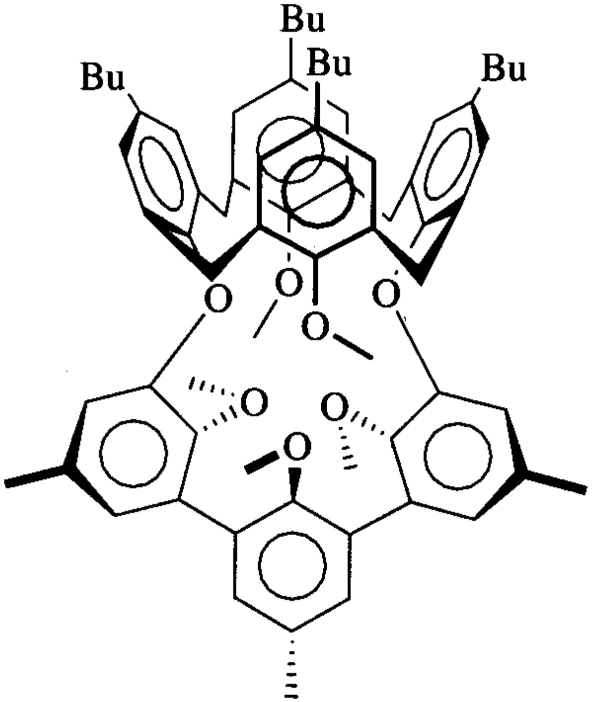

O
O
n+
O
O
(a)
n+
O
O
O
O


Cs+

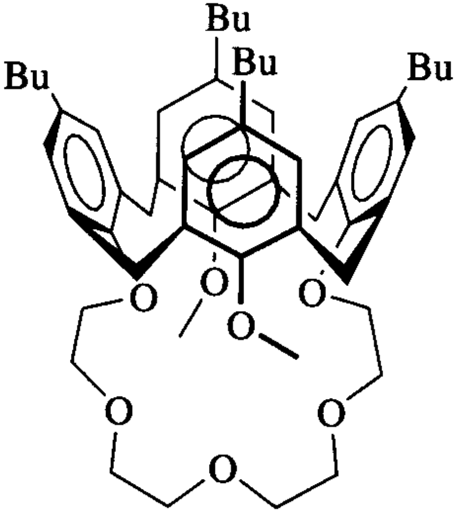

Upper rim substituents
Hydrophobic binding pocket
Lower rim substituents
Spherand-like guest cation binding site


(d)
(e)
(f)
n+
n+
n+
O

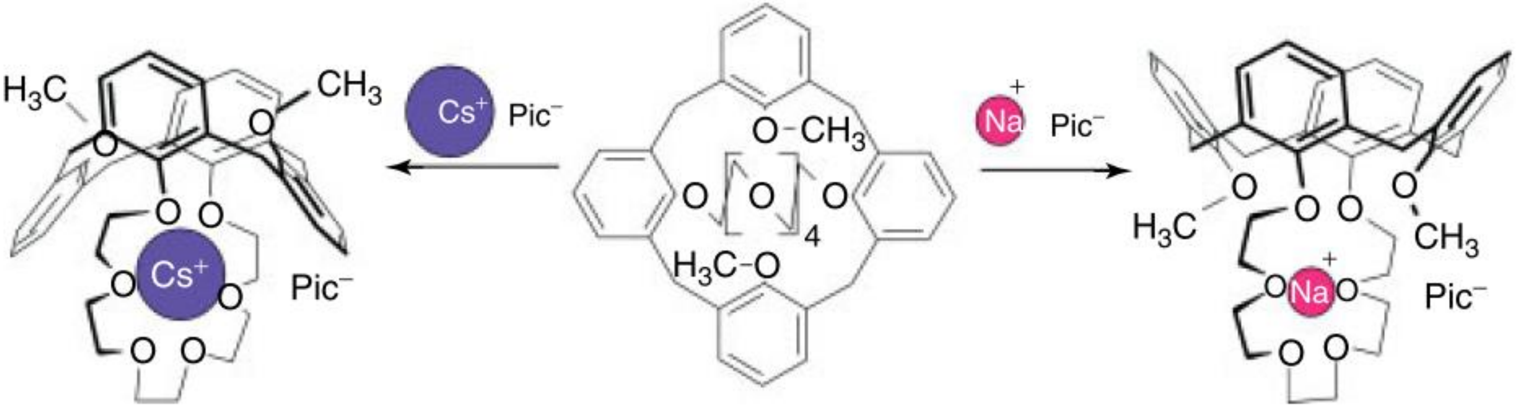

Na+
EtO
EtO
OEt
OEt
O



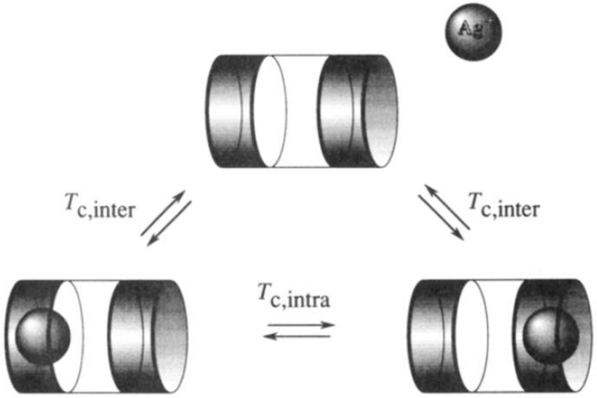
Calix-sferando

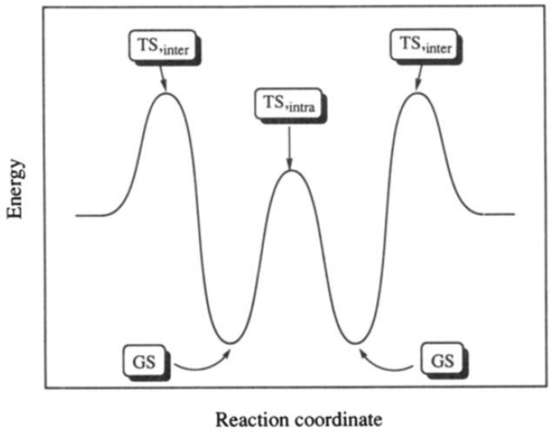


Calix-crown

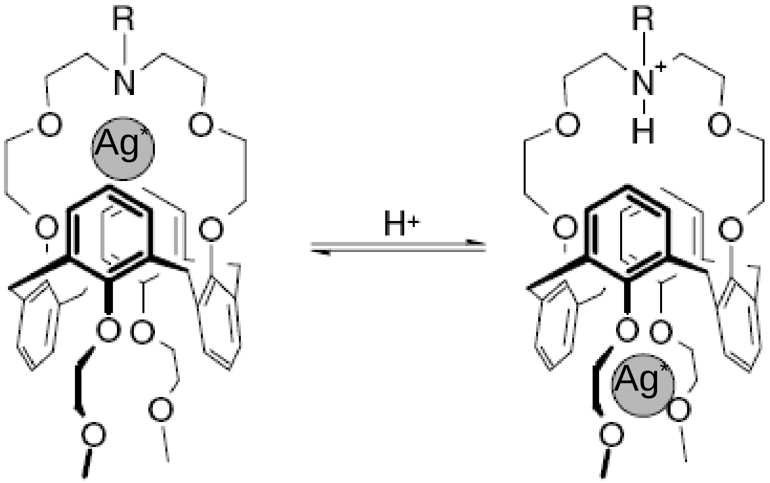

H3C
CH3
Cs+
Pic−
O−CH3
O
O
O
4
H3C−O
Na+
Pic−
H3C
CH3
Cs+
Pic−
Na+
Pic−

Cation tunnelling



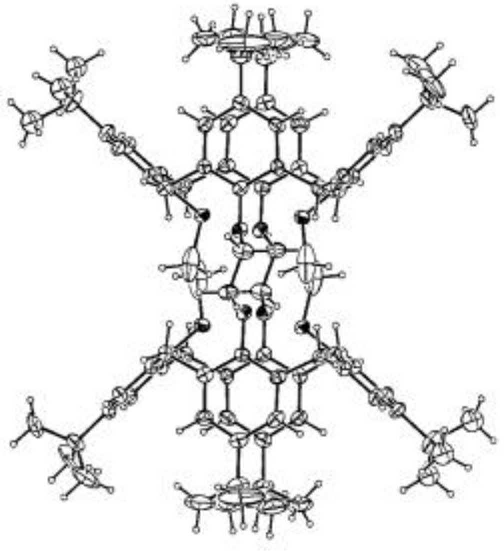


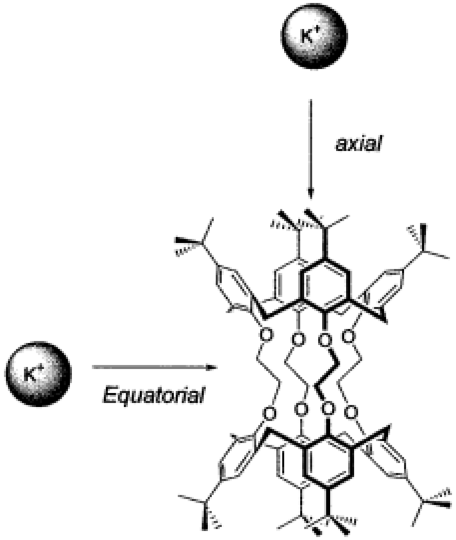
Cation tunnelling: Ag$^+$ syringe

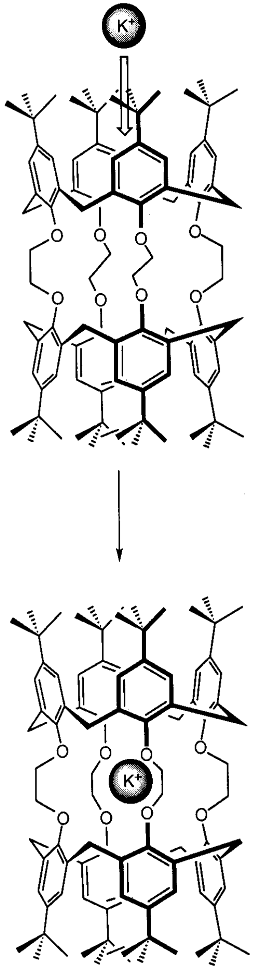


Calix-tubes

J. AM. CHEM. SOC. ■ VOL. 124, NO. 7, 2002 1341

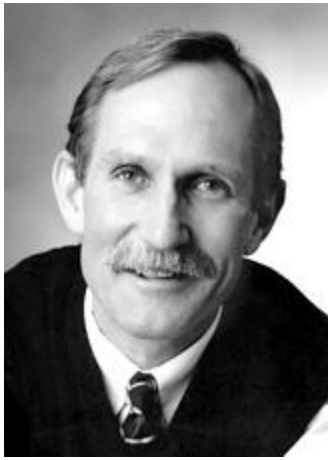






Potassium encapsulation in calix[4]tube

http://www.nobelprize.org/nobel_prizes/chemistry/laureates/2003/



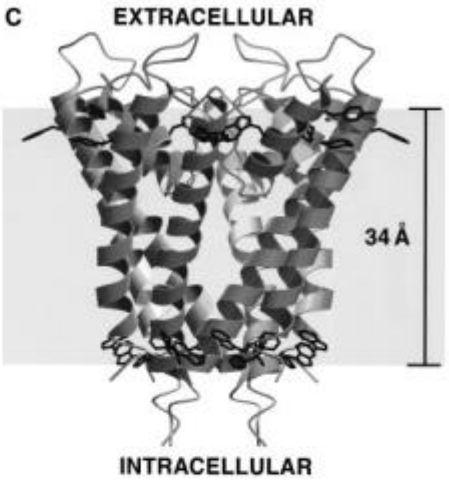
Peter Agre **Roderick MacKinnon**

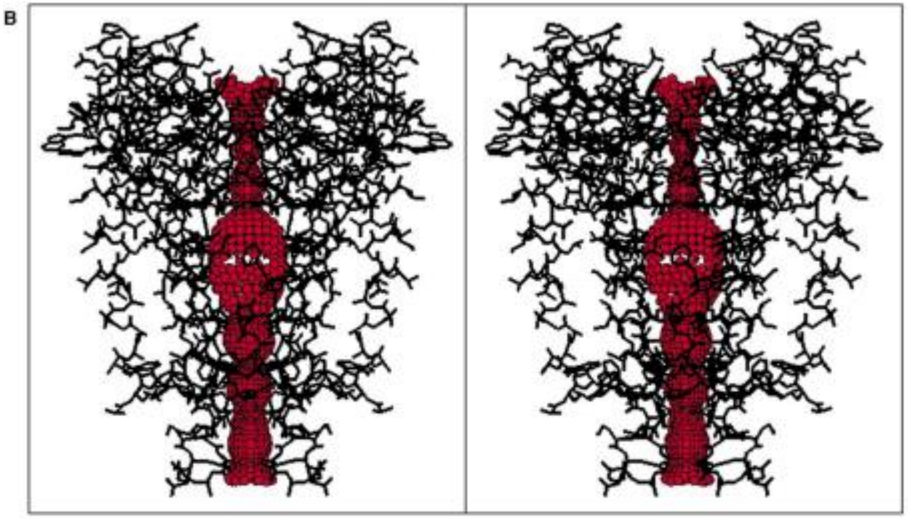
The Nobel Prize in Chemistry 2003 was awarded *"for discoveries concerning channels in cell membranes"* jointly with one half to Peter Agre *"for the discovery of water channels"* and with one half to Roderick MacKinnon *"for structural and mechanistic studies of ion channels“*.

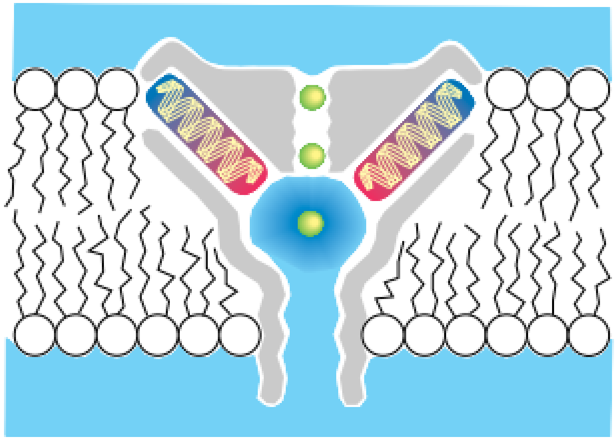
The Structure of the Potassium Channel: Molecular Basis of K^+ Conduction and Selectivity

Declan A. Doyle, João Morais Cabral, Richard A. Pfuetzner,
Anling Kuo, Jacqueline M. Gulbis, Steven L. Cohen,
Brian T. Chait, Roderick MacKinnon*

Science **280**, 69 (1998);
DOI: 10.1126/science.280.5360.69

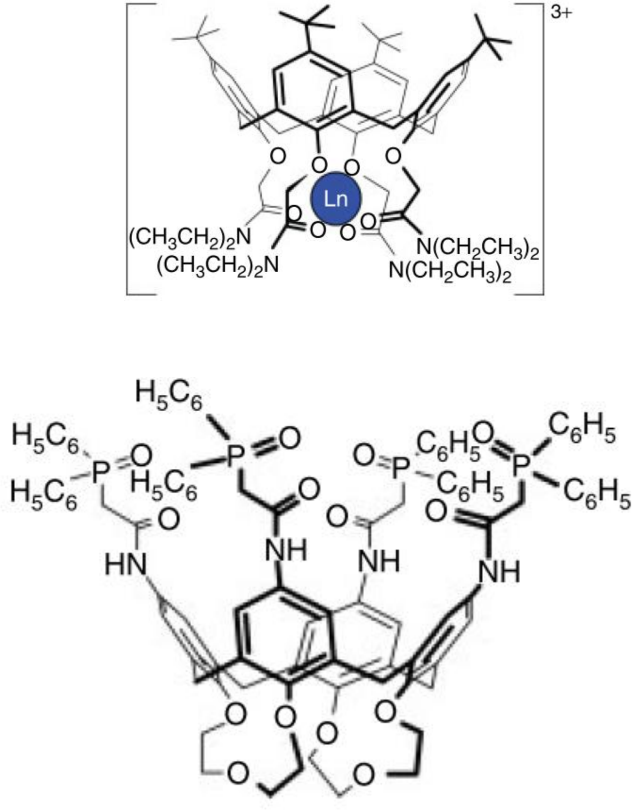

C
EXTRACELLULAR
34 Å
INTRACELLULAR

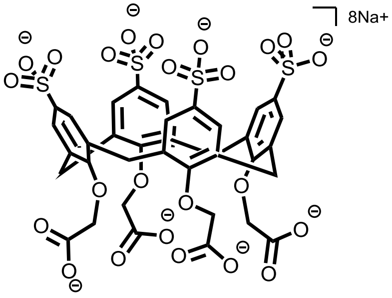

B



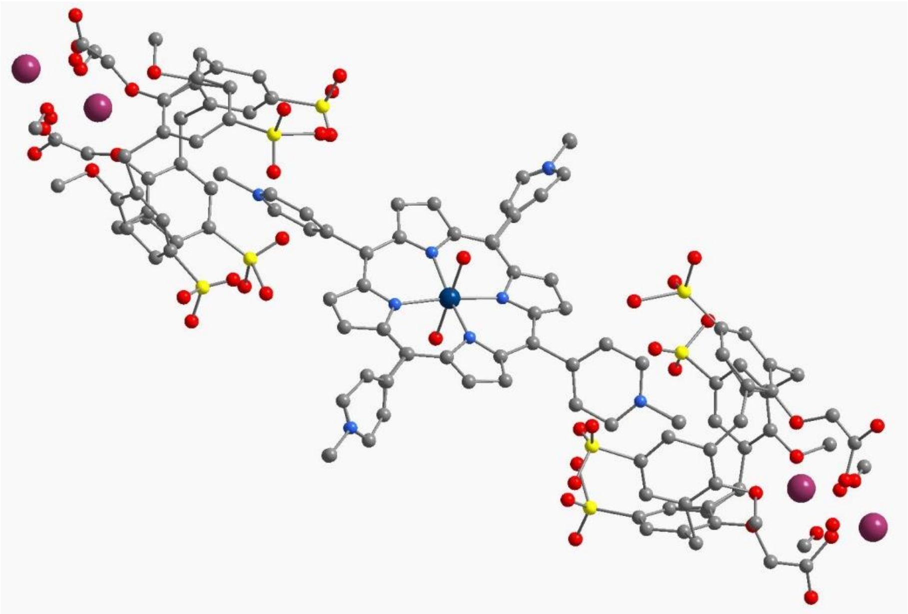
Ln^{3+} recognition

(treatment of radiactive waste/extraction- high distribution coefficiet even from very acidic water solutions)

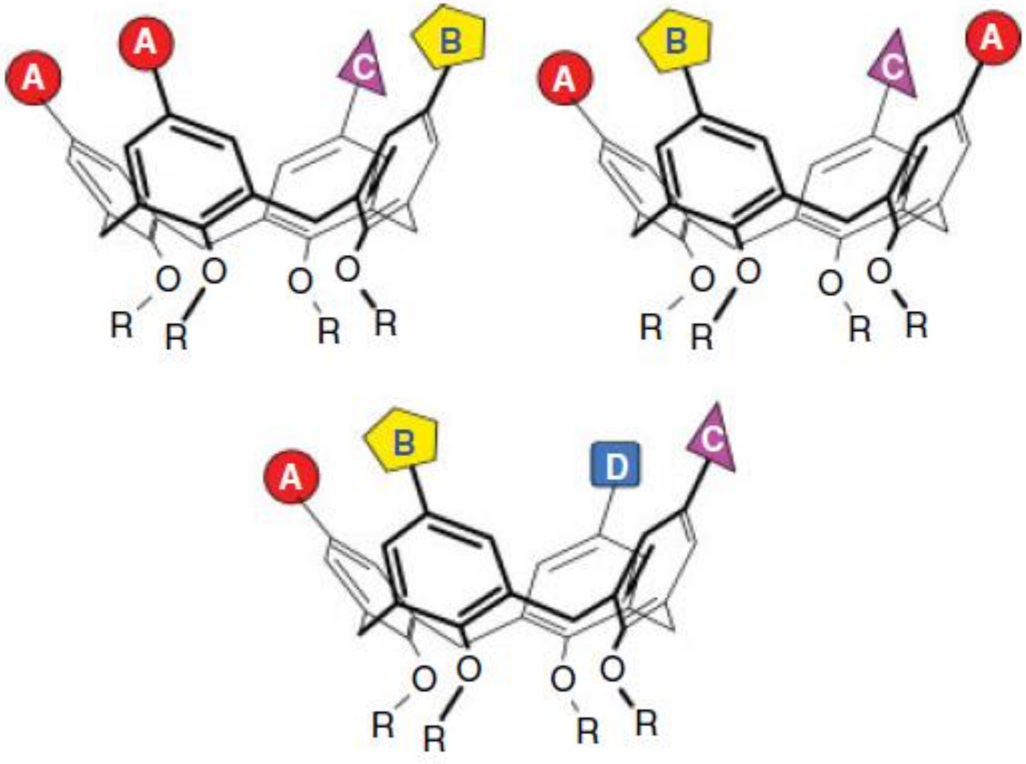




C_4TsTc



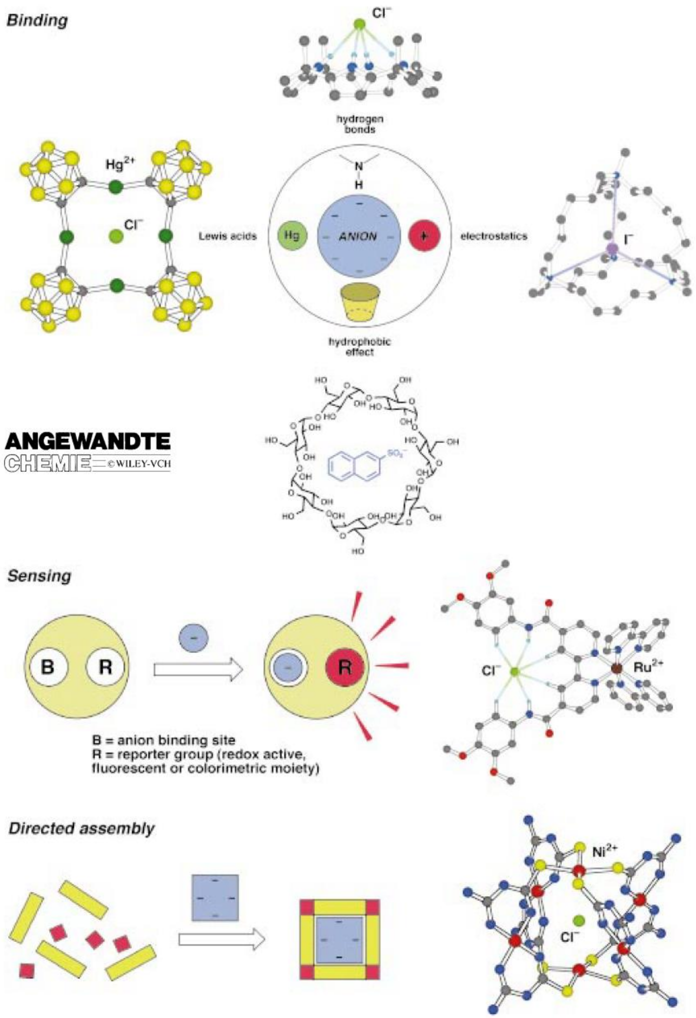
Chirality



Anion Recognition and Sensing: The State of the Art and Future Perspectives

Paul D. Beer* and Philip A. Gale*

Angew. Chem. Int. Ed. 2011, 50, 1845–1848



Supramolecular Chemistry of Anions

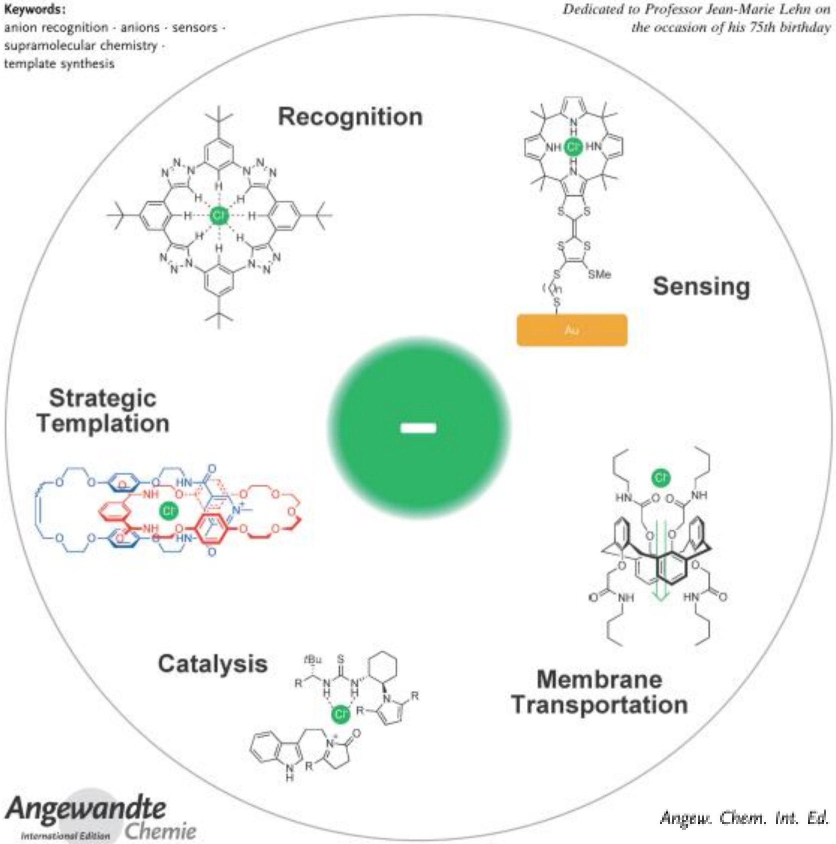
DOI: 10.1002/anie.201309937

Advances in Anion Supramolecular Chemistry: From Recognition to Chemical Applications

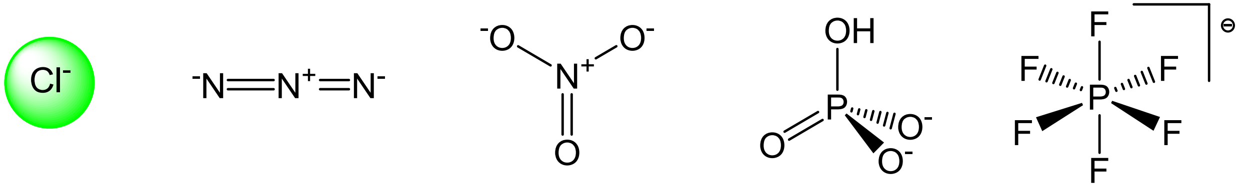
Nicholas H. Evans and Paul D. Beer**

Keywords:
anion recognition · anions · sensors · supramolecular chemistry · template synthesis

Dedicated to Professor Jean-Marie Lehn on the occasion of his 75th birthday



- anions are large and require receptors of bigger size than cations - r($F^–$) ≈ rK^+
- large diversity of shapes and geometries (spherical, linear, trigonal, tetrahedral…)



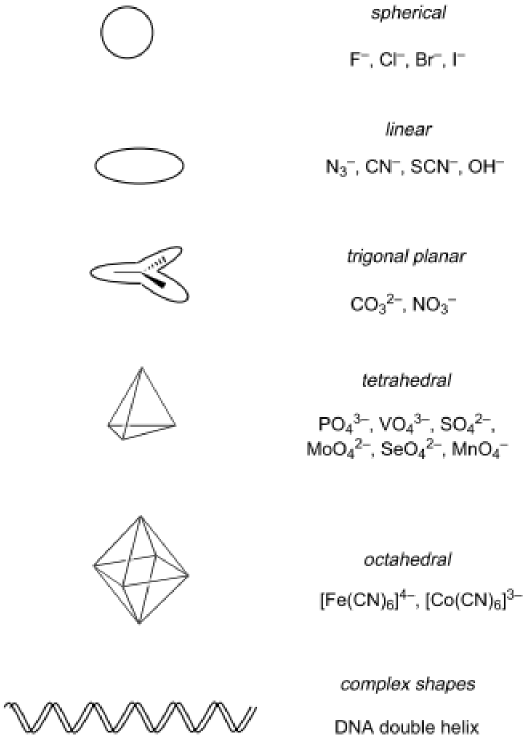
- high free energies of hydration

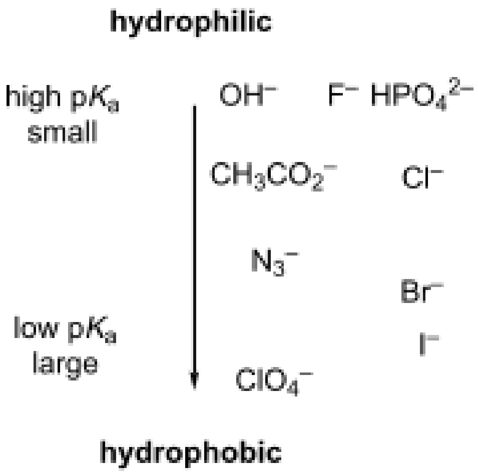
$\Delta_rG°_{hydr}(F^–) = –465$ kJ.mol^{-1} $\Delta_rG°_{hydr}(K^+) = –295$ kJ.mol^{-1}

- anions are sensitive to pH (crucial for recognition on water)
- anions are coordinatively saturated : only weak interactions (H bond, electrostatic, Van der Waals), no strict coordination number
- Lewis bases

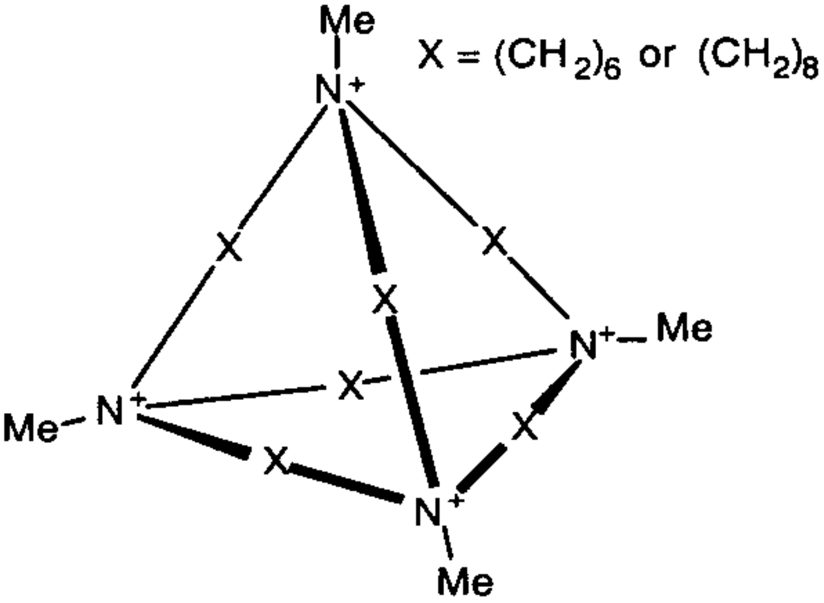
Table 1. A comparison of the radii *r* of isoelectronic cations and anions in octahedral environments.[7]

Cation	*r* [Å]	Anion	*r* [Å]
Na^+	1.16	F^-	1.19
K^+	1.52	Cl^-	1.67
Rb^+	1.66	Br^-	1.82
Cs^+	1.81	I^-	2.06





Host cationici



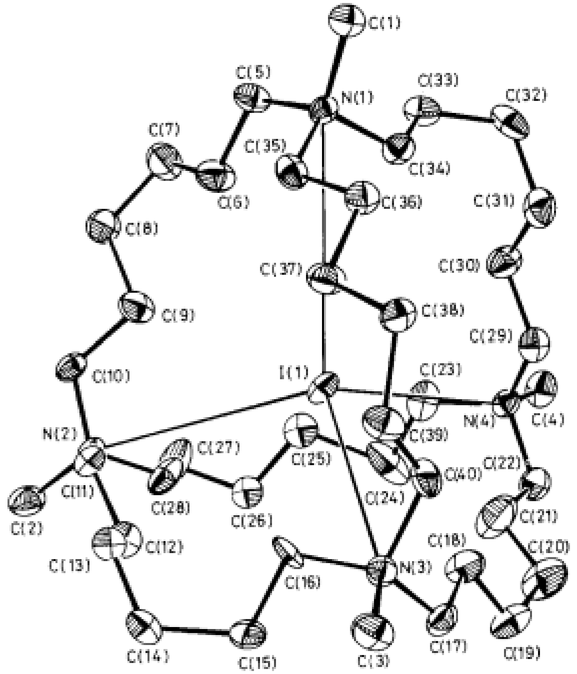
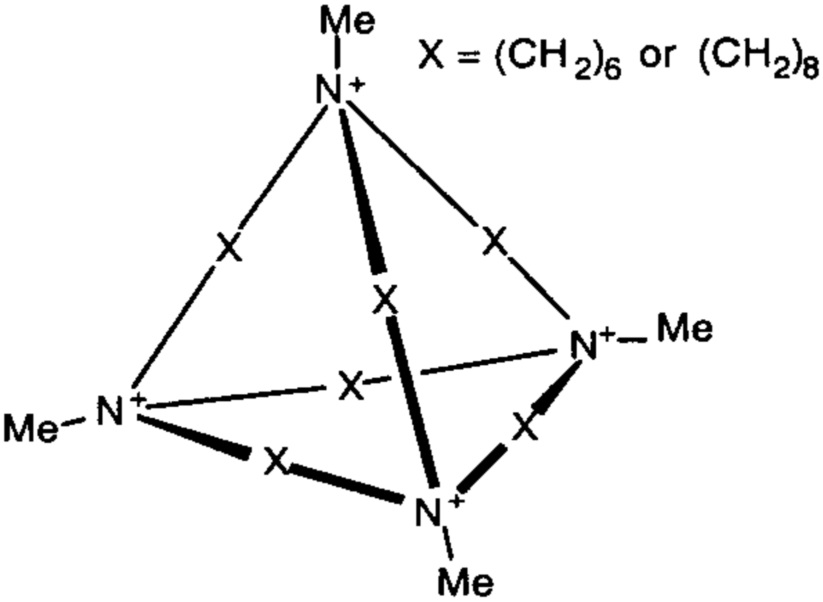


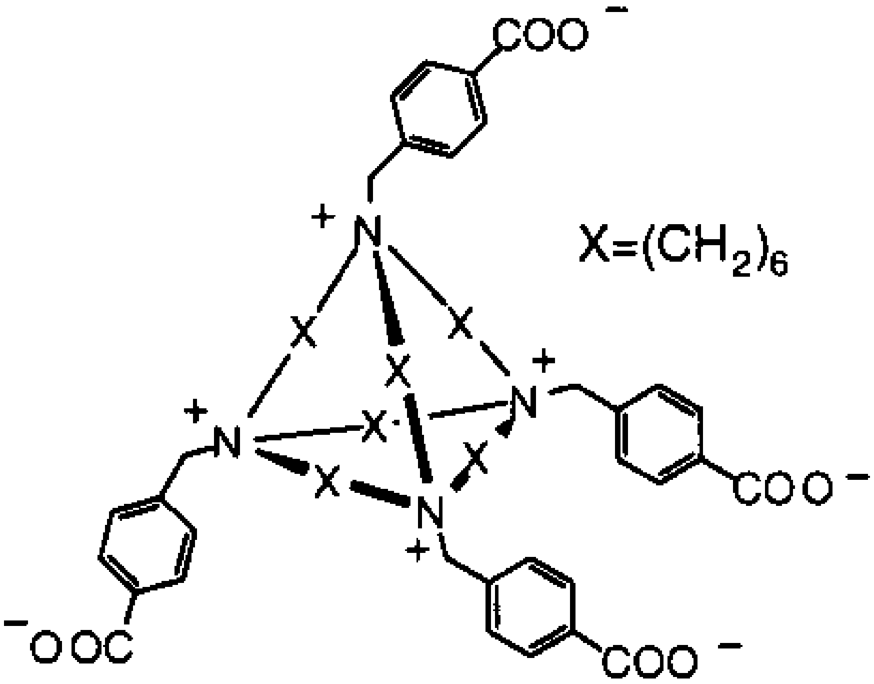
Figure 2. The X-ray crystal structure of the iodide complex of receptor **1**

Schmidtchen

Host cationici



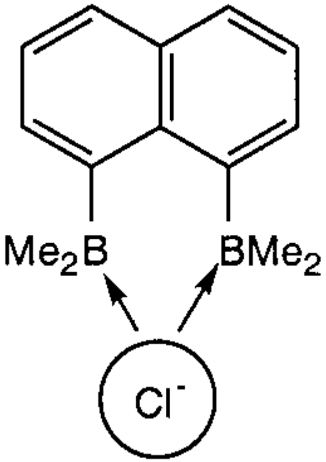
Host zwitter-ionici



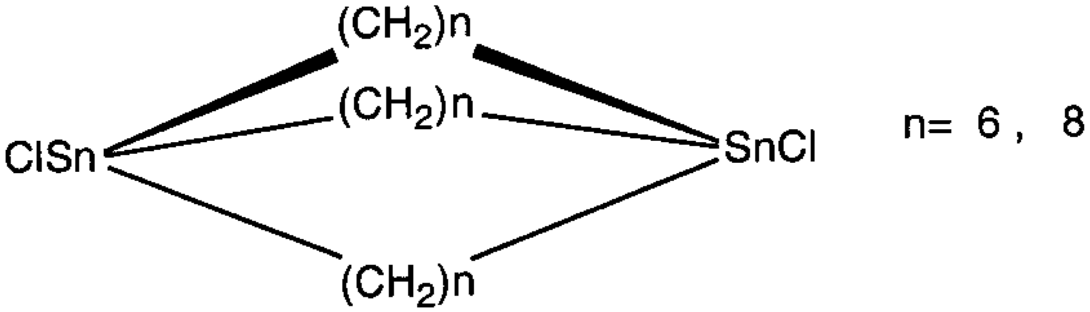
$K(Br^-) = 1020\ (H_2O)$

$K(Br^-) = 2150\ (H_2O)$

Selettività <<
$K(Br^-) = 1020$ $K(I^-) = 500$ $K(Cl^-) = 50$

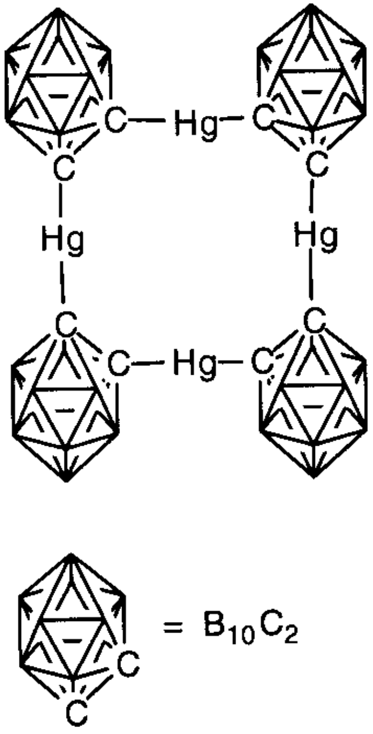


Organo-Boro

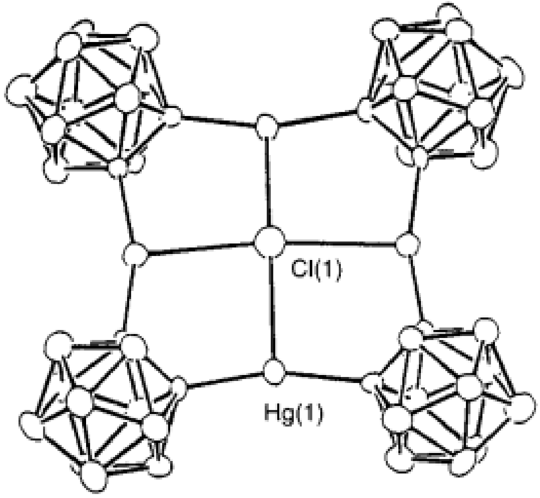


Organotin cryptand encapsulates fluoride anions.

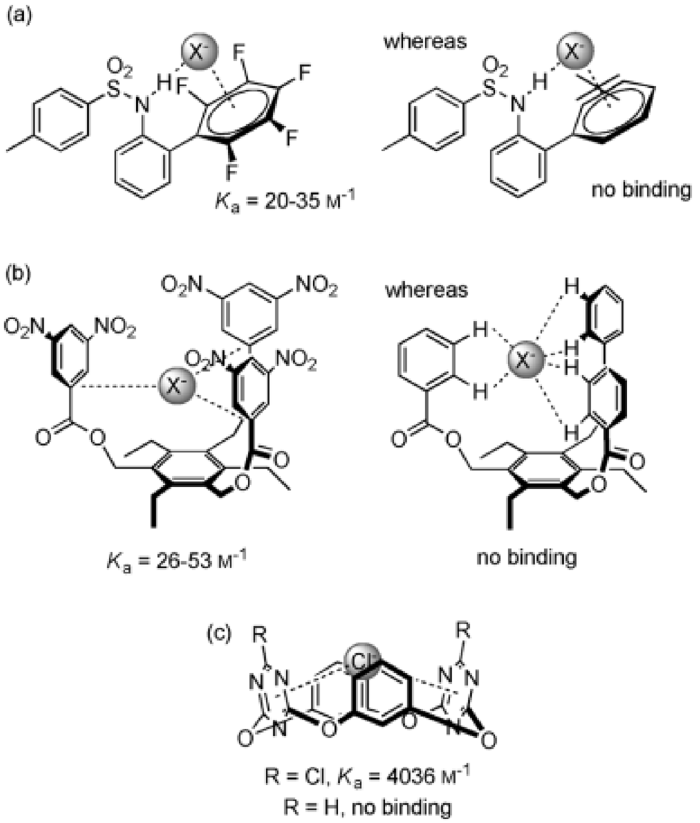
Organo-Sn(IV)



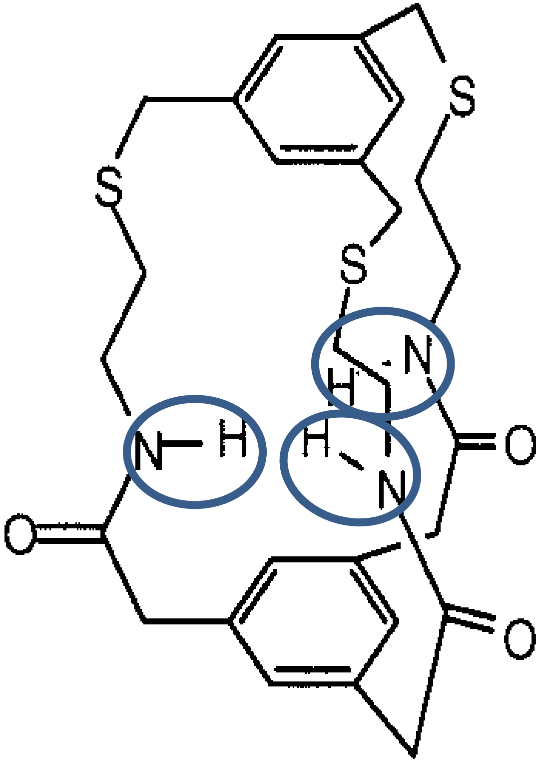
Organo-Hg(II)



Hawthorne

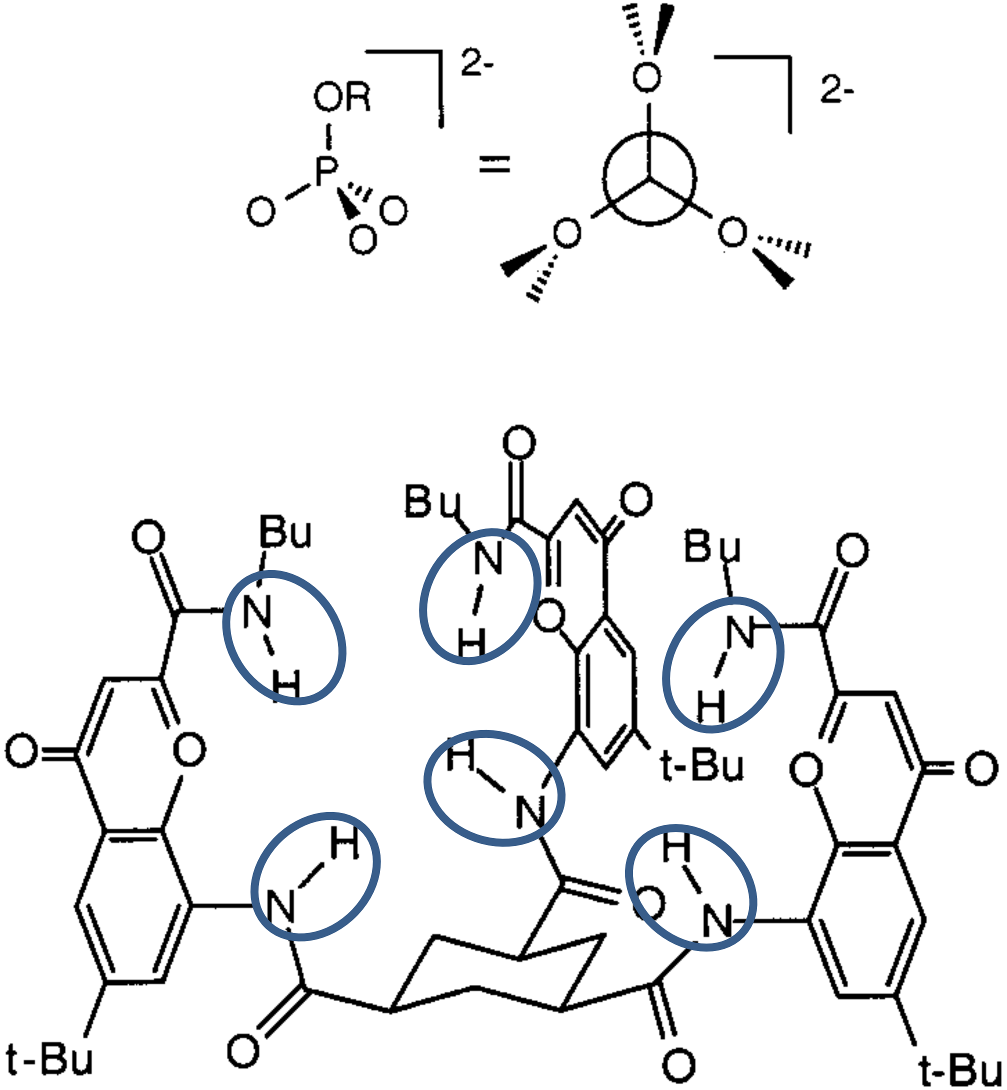

(a)
whereas
X⁻
O_2
S
N
H
F
K_a = 20-35 M^{-1}
no binding
(b)
whereas
O_2N
NO_2
X⁻
H
O
K_a = 26-53 M^{-1}
no binding
(c)
R
N
Cl
O
R = Cl, K_a = 4036 M^{-1}
R = H, no binding

Berryman



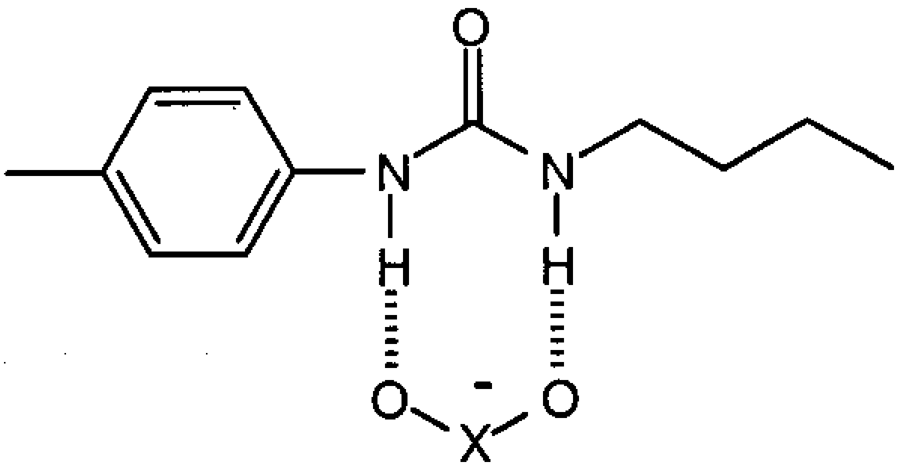
Hydrogen bonding receptor
for fluoride anions.

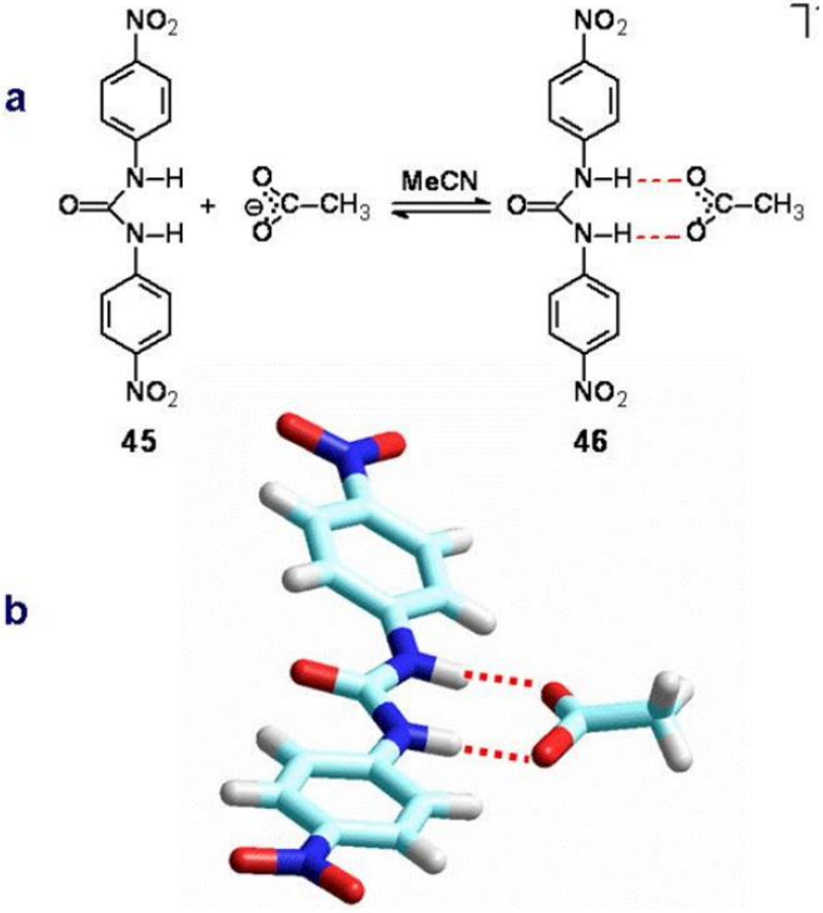
Pascal



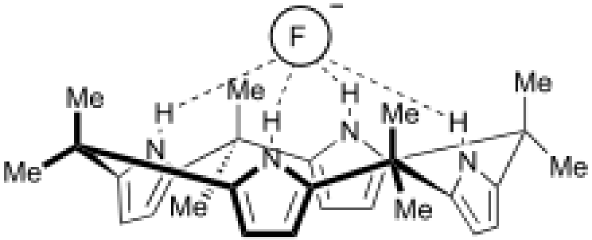
Trigonal receptors can bind phosphate anions strongly in competitive solvents.

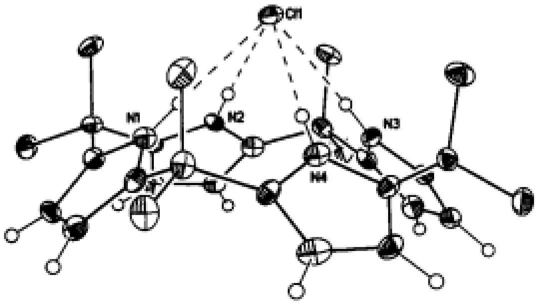
Raposo

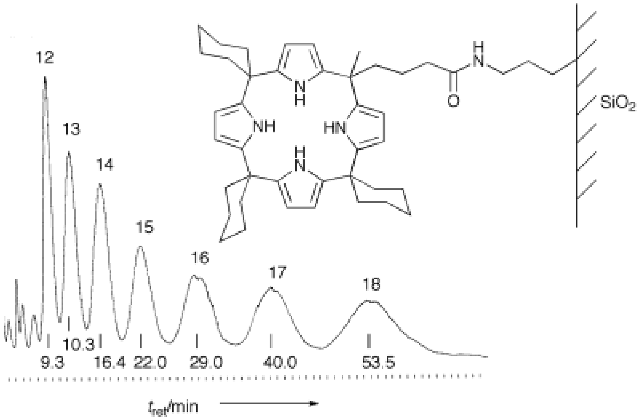

O
N
H
N
H
O
X
O
-

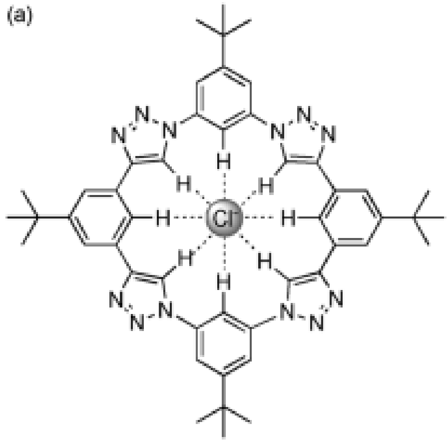

a
NO2
N–H
O
N–H
NO2
+
O
C–CH3
O
MeCN
N–H
O
C–CH3
N–H
NO2
NO2
45
46
b

Fabrizzi



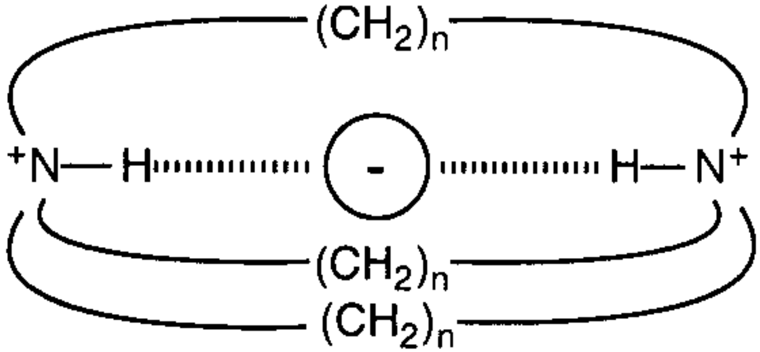




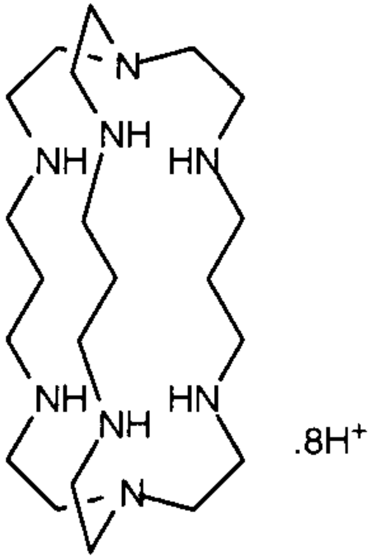


HPLC Separation of oligonuclotides of different lenght

Sessler

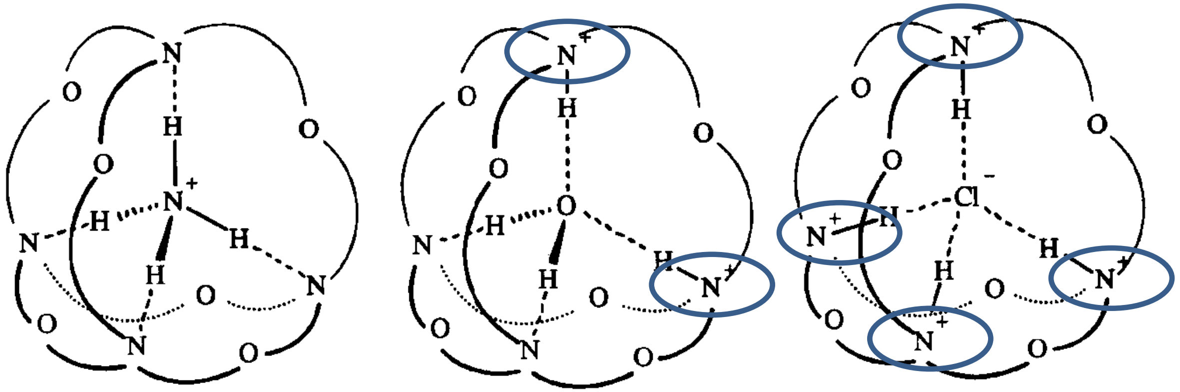


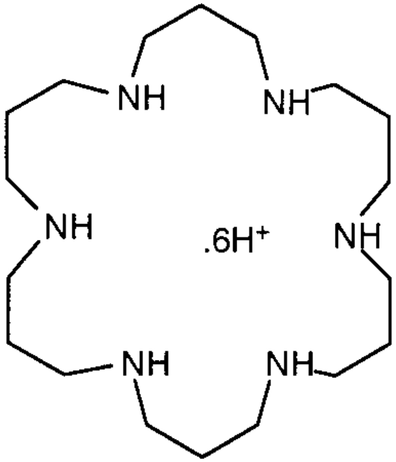
poliazamacrocicli

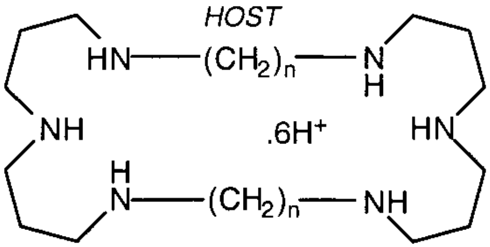


Receptors for anions.

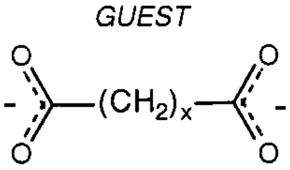
Lehn





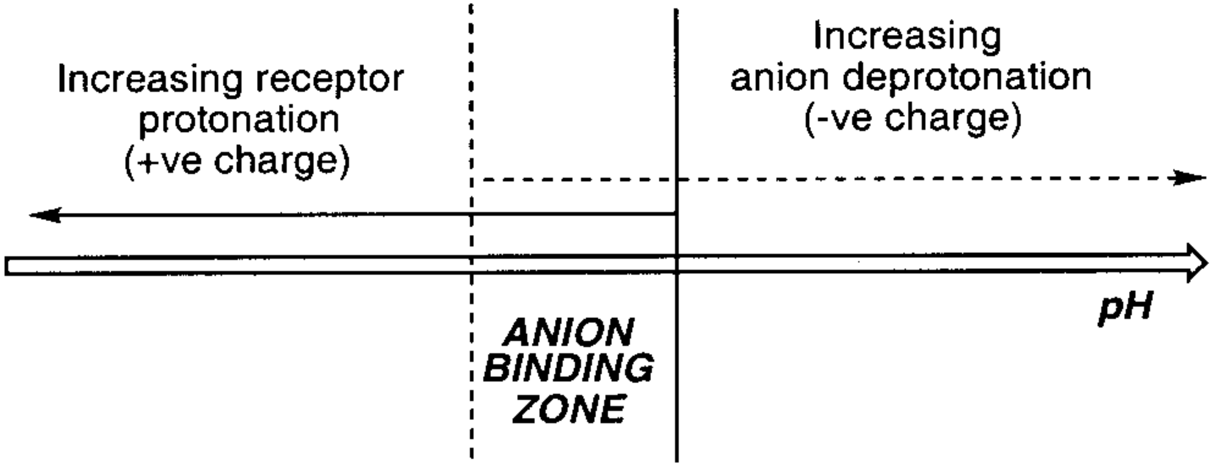


3.18a, n=7
3.18b, n=10

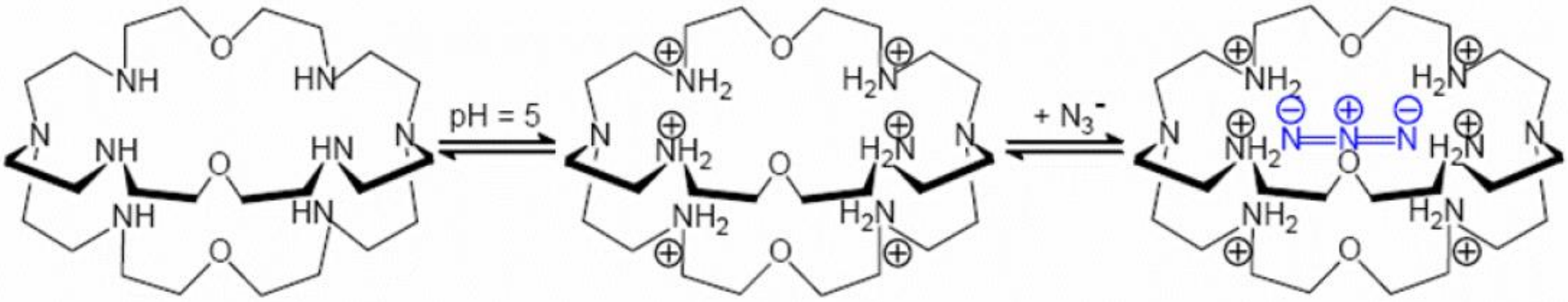


Receptor **3.18** is specific for dicarboxylates of defined chain lengths.

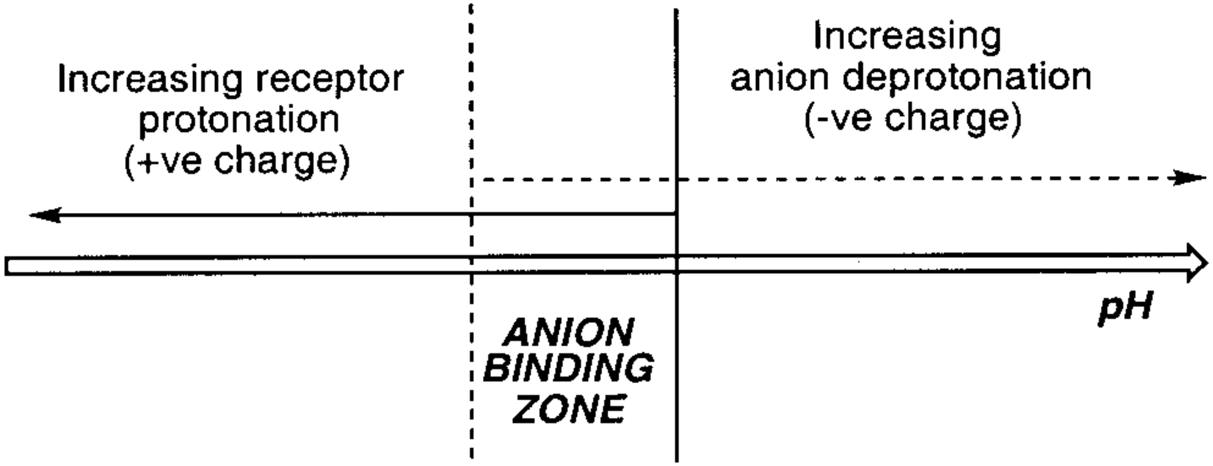
Lehn



Balance between host protonation and guest deprotonation.



51 **52** **53**



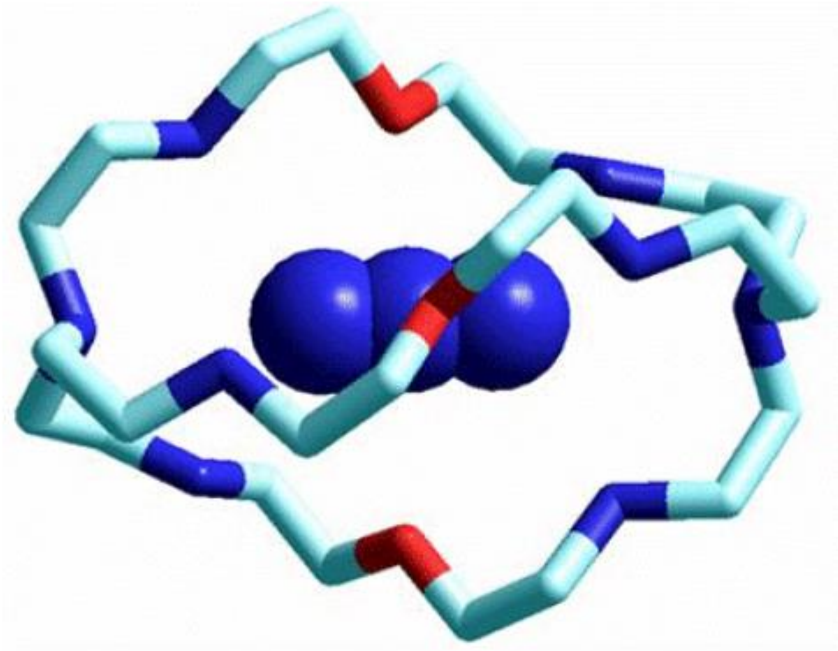
Increasing receptor protonation (+ve charge)

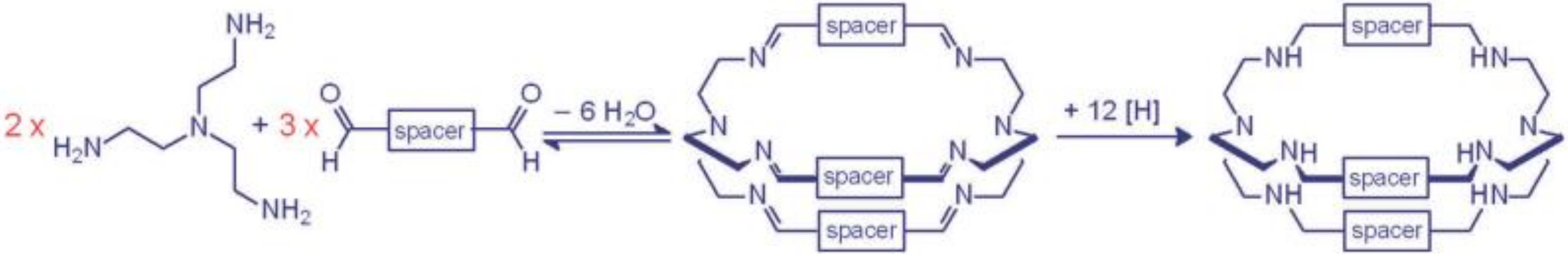
Increasing anion deprotonation (-ve charge)

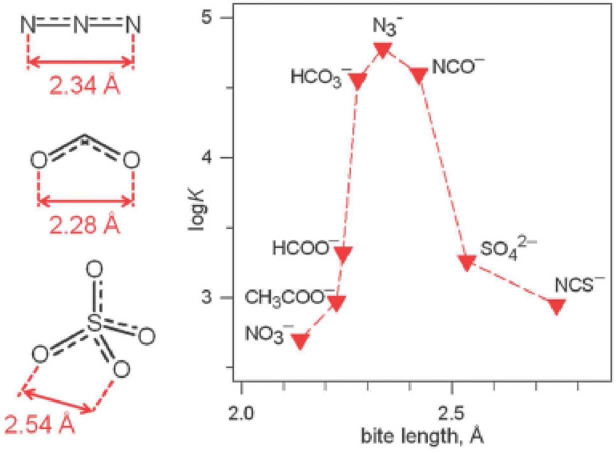
pH

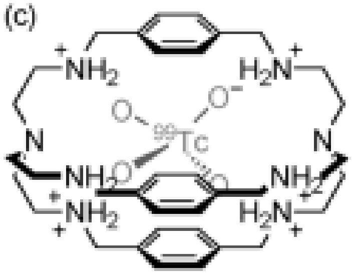
ANION BINDING ZONE

Balance between host protonation and guest deprotonation.

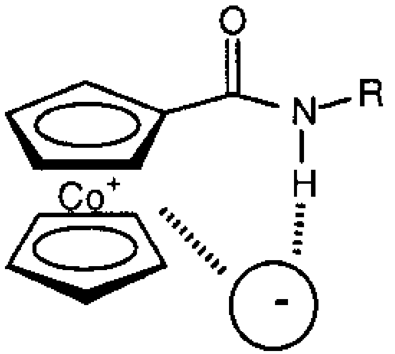



2 x
H2N
NH2
NH2
N
+ 3 x
O
H
spacer
– 6 H2O
+ 12 [H]
N
NH
HN

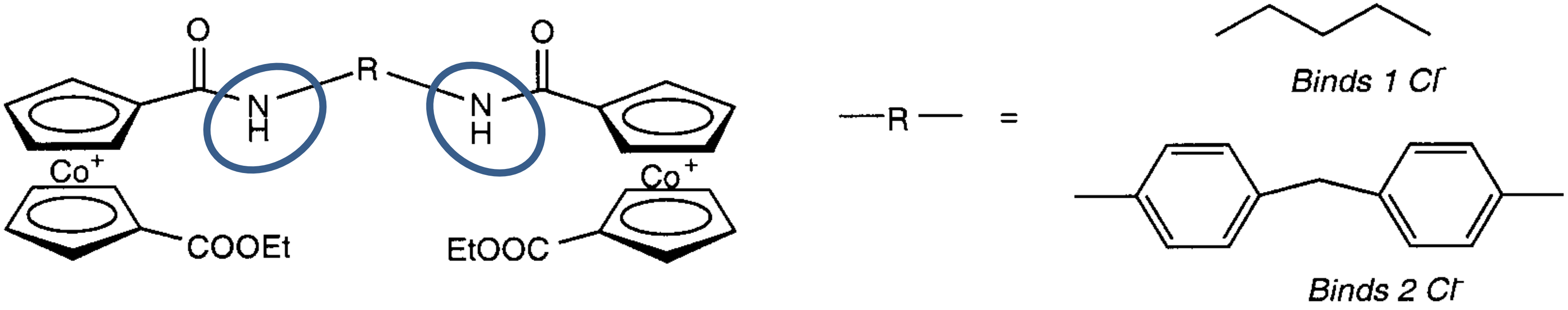

2.34 Å
2.28 Å
2.54 Å
N3-
HCO3-
NCO-
HCOO-
SO4 2-
CH3COO-
NCS-
NO3-
logK
5
4
3
2.0
2.5
bite length, Å


(c)
NH2
H2N
N
99Tc
O
+

Fabrizzi

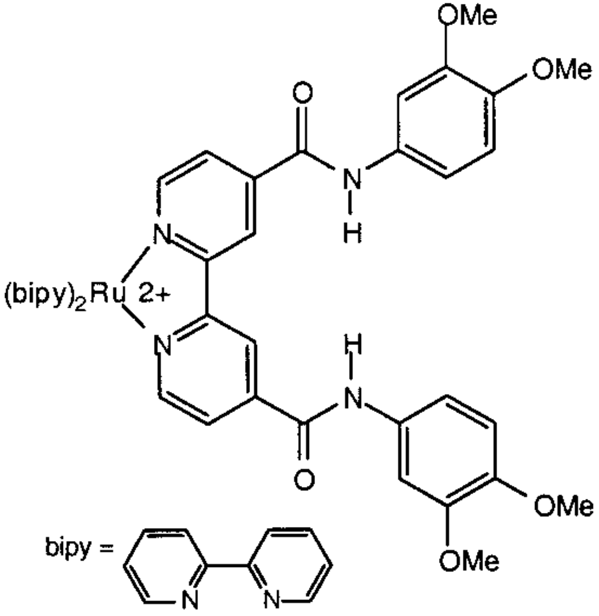


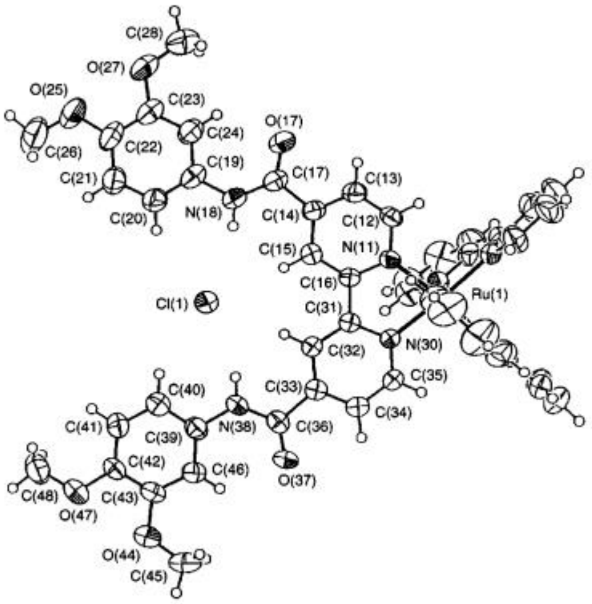
Amide functionalized cobaltocenium binds anions.



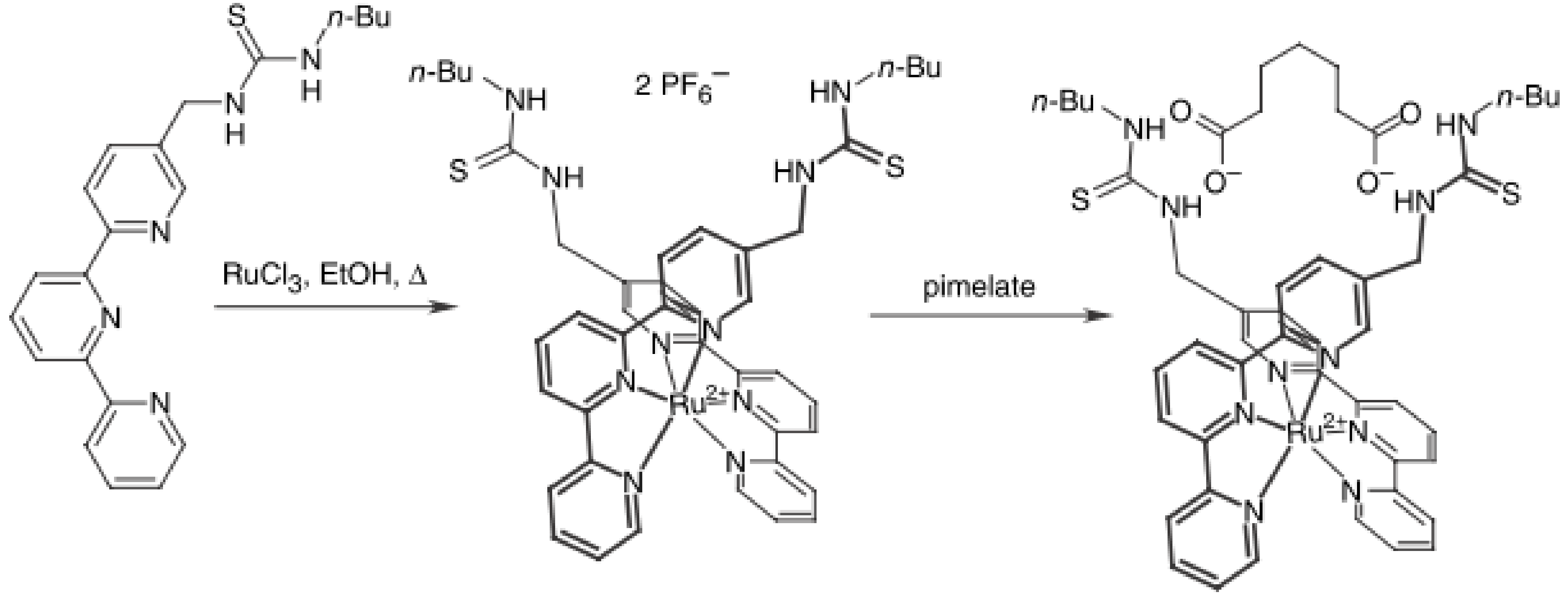
Cobaltocenium based anion receptors have easily tunable binding sites.

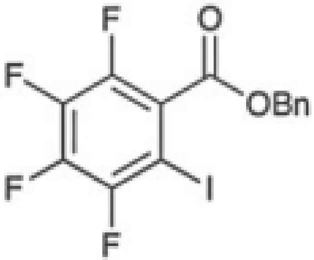
Beer

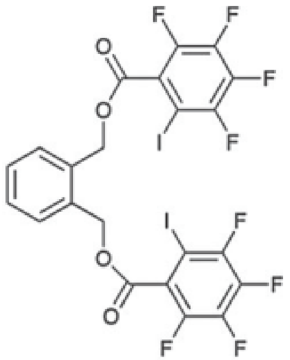

OMe
OMe
O
N
H
N
(bipy)$_2$Ru 2+
N
H
N
O
OMe
OMe
bipy =
N
N

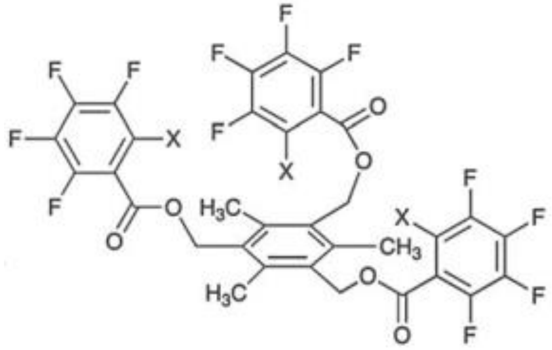

C(28)
O(27)
C(23)
O(25)
C(24)
O(17)
C(22)
C(26)
C(19)
C(17)
C(13)
C(21)
C(14)
C(12)
C(20)
N(18)
C(15)
N(11)
C(16)
Ru(1)
Cl(1)
C(31)
C(32)
N(30)
C(35)
C(40)
C(33)
C(34)
C(41)
N(38)
C(36)
C(39)
C(42)
C(46)
O(37)
C(48)
C(43)
O(47)
O(44)
C(45)

Beer


S
n-Bu
NH
NH
N
RuCl$_3$, EtOH, Δ
2 PF$_6^-$
HN
Ru^{2+}
pimelate
O
O$^-$

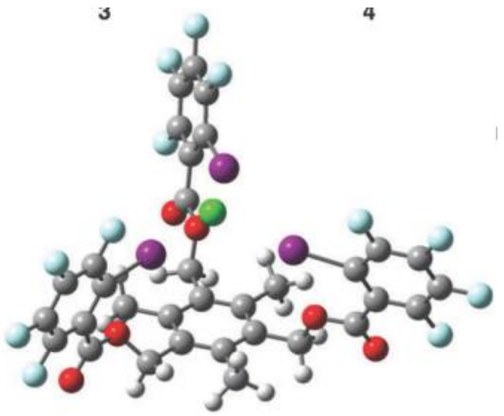




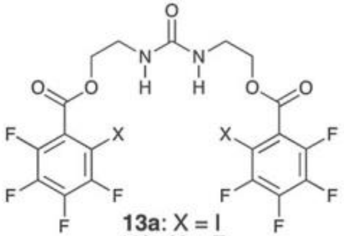


ortho-substituted iodotetrafluroroarenes on to trimethylbenzene scaffold

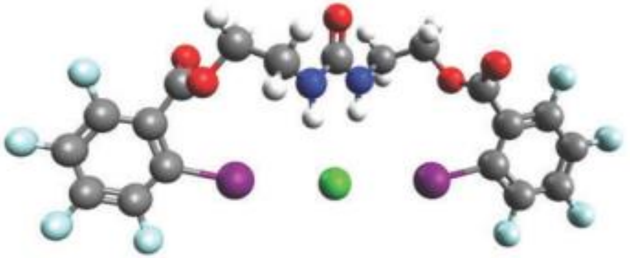
In acetone: $Cl^{-} > Br^{-} > I^{-}$



Taylor



13a: X = I
13b: X = F



(a)

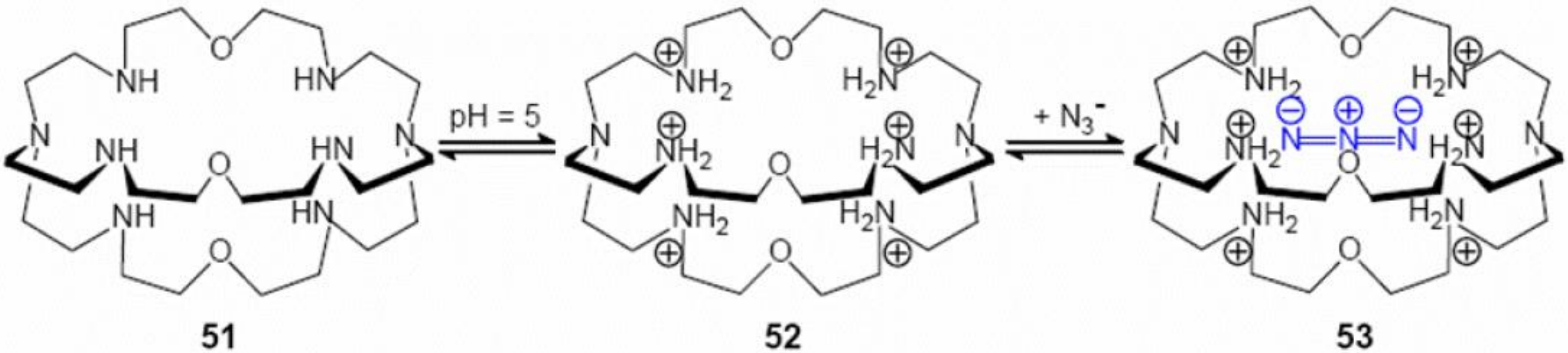
A cascade complex.

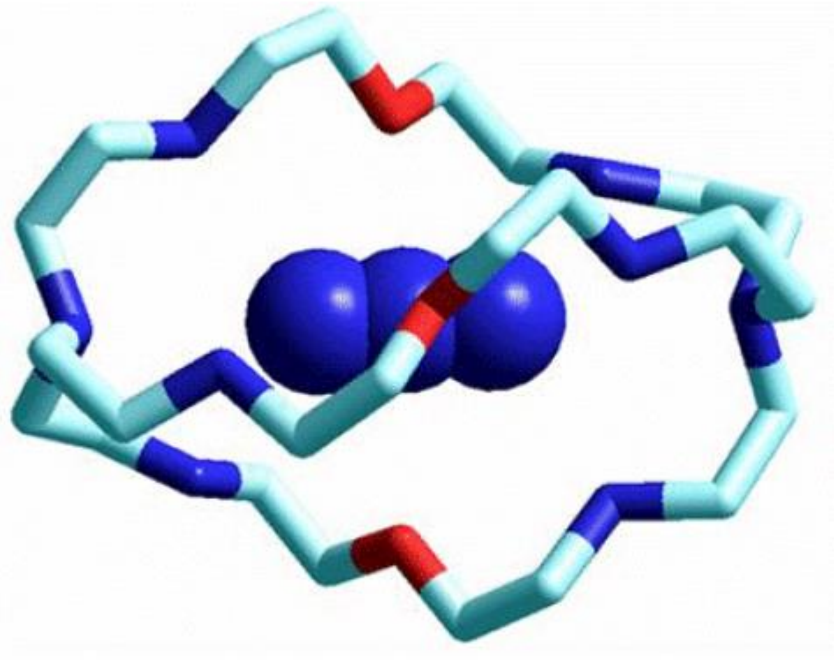
(b)

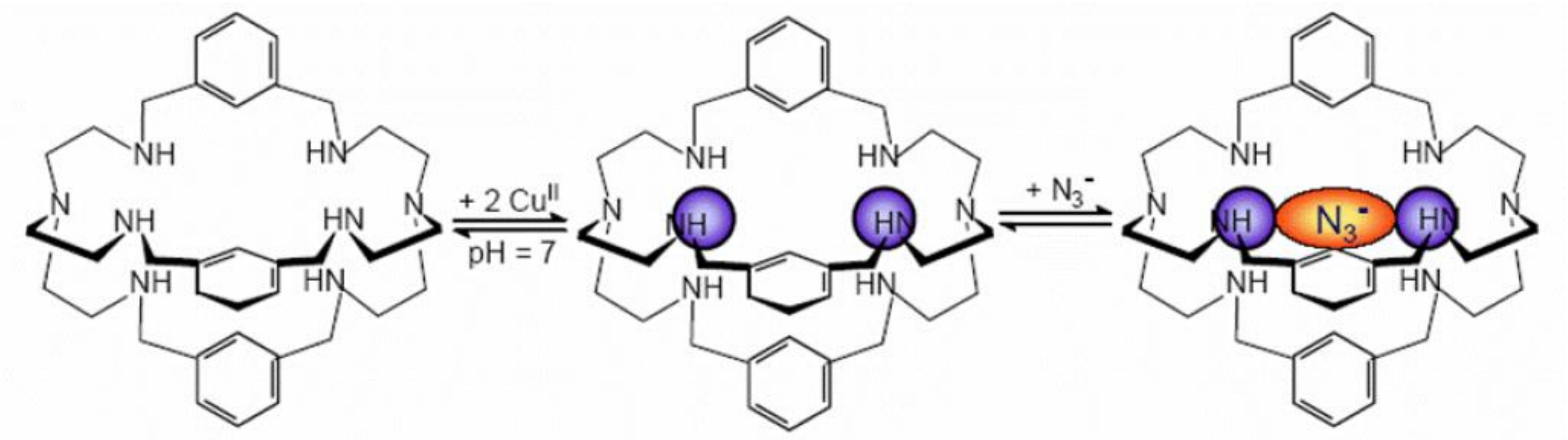
Receptor with individual cation and anion recognition sites.

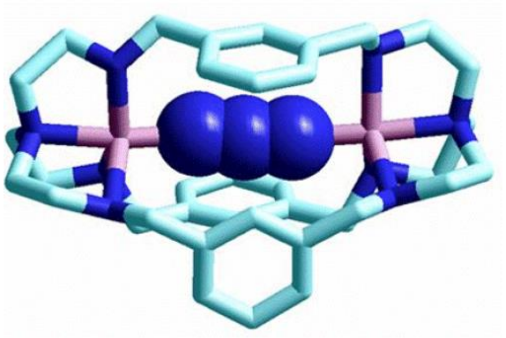
(c)

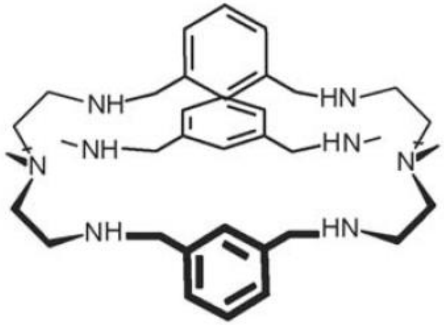
Receptor for zwitterionic guests.


pH = 5
+ N_3^-
51
52
53

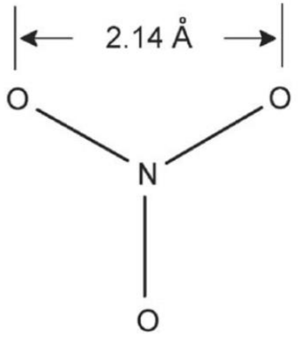


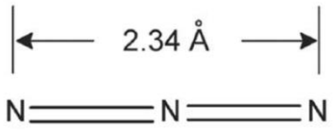

NH
HN
N
NH
HN
N
NH
HN
+ 2 Cu^{II}
pH = 7
+ N_3^-
N_3^-





7





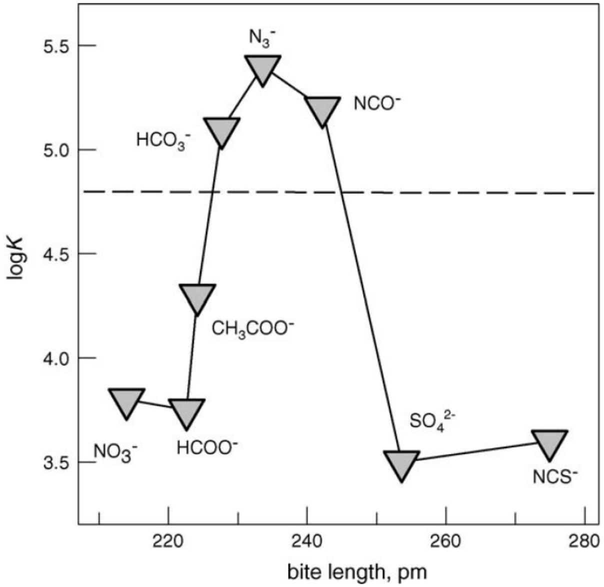
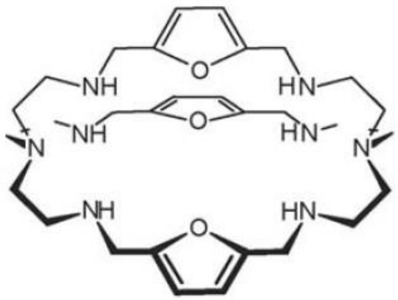


Fig. 8. Peak selectivity in the inclusion of polyatomic anions by the $[Cu_2^{II}(\mathbf{7})]^{4+}$ cryptate. The dimetallic receptor does not recognise the shape of the anion, but its *bite*, i.e. the distance between two consecutive donor atoms.



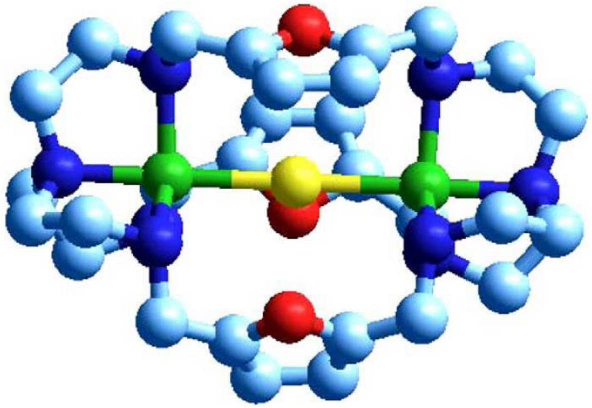


Fig. 3. The structure of the $[Cu_2^{II}(\mathbf{6})(Br)]^{3+}$ supercryptate. The bromide ion bridges the two Cu^{II} centres. Each Cu^{II} ion experiences an axially compressed trigonal bipyramidal geometry, typically observed in tren and bistren complexes.

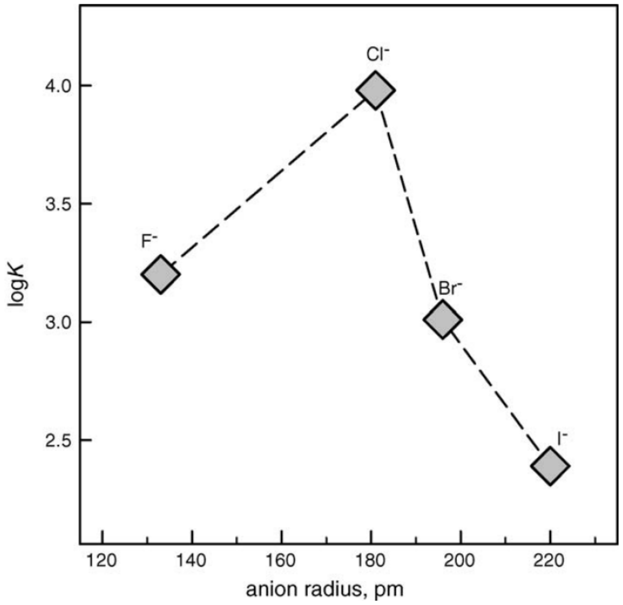
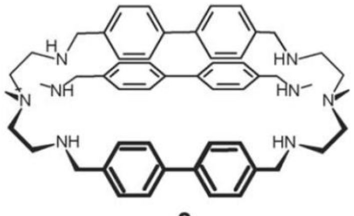
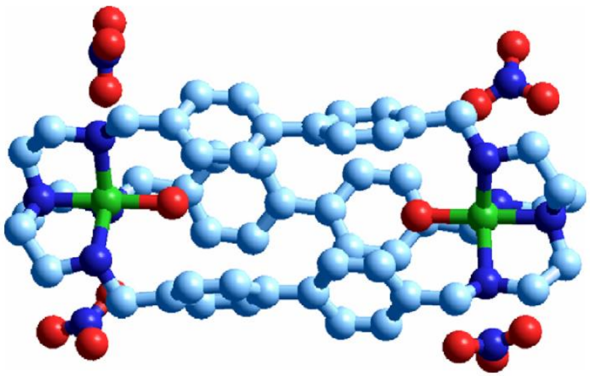


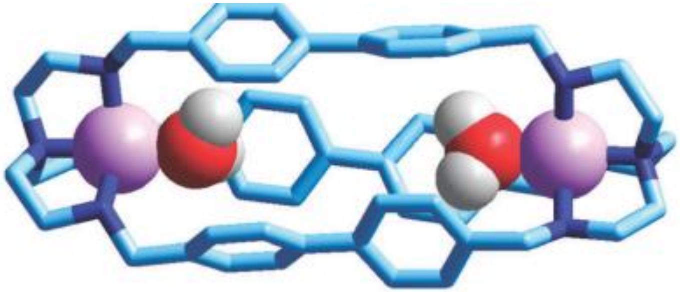
Fig. 6. Selectivity pattern for the inclusion equilibrium: $[Cu_2^{II}(\mathbf{6})]^{4+} + X^- = [Cu_2^{II}(\mathbf{6})(X)]^{3+}$ equilibrium (X^- = halide anion, aqueous solution, buffered at pH 5.2).

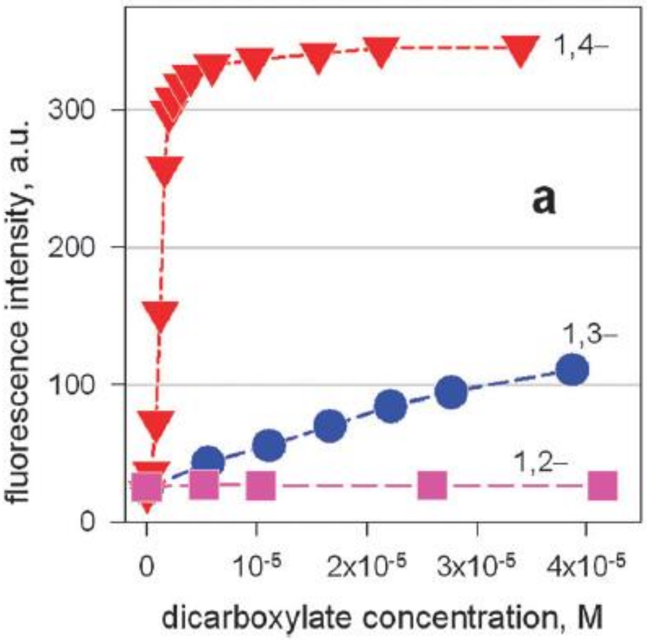
If log *K* values are plotted versus halide ion radius, a defined selectivity pattern in favour of chloride is observed (see Fig. 6). Notice that the anion size effect is rather moderate, ranging within an interval of 1.2 log units. It is possible that it is not determined by steric factors, but simply reflects the coordinating tendencies of halide ions towards transition metals (i.e. their position in the spectrochemical series: $Cl^- > F^- > Br^- > I^-$).



8







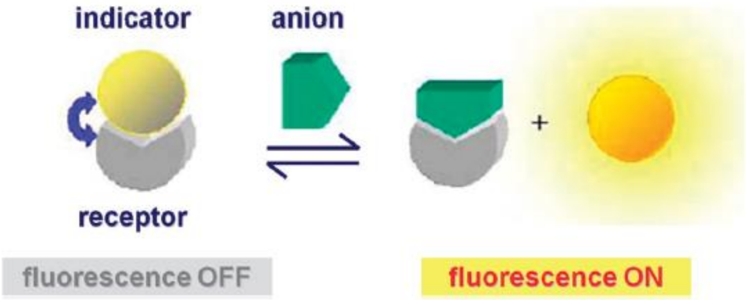


Fig. 22 The fluorescent indicator displacement paradigm. The receptor quenches the emission of the indicator through an intracomplex mechanism. When displaced by the anion, the indicator releases its fluorescence, thus signalling anion recognition.[55]

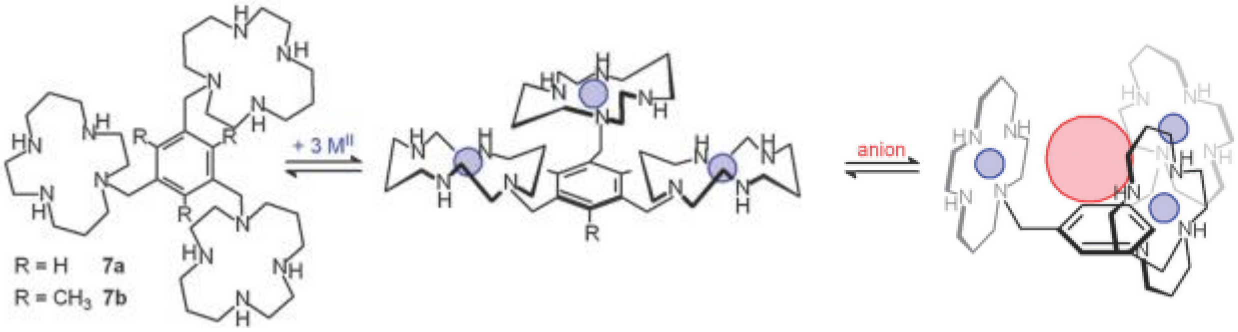
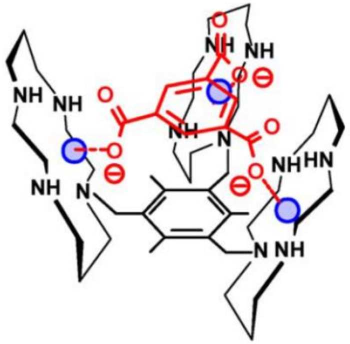
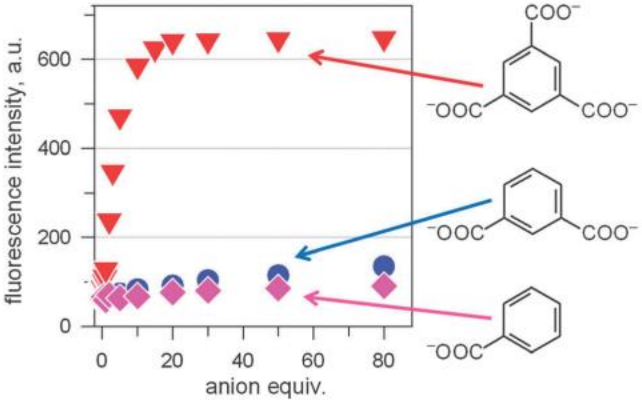
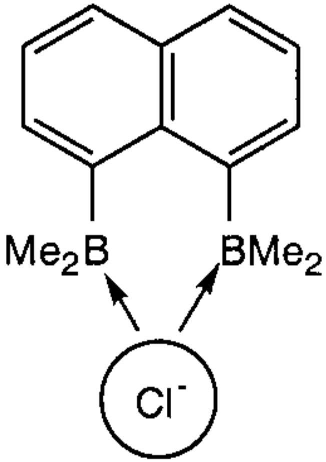
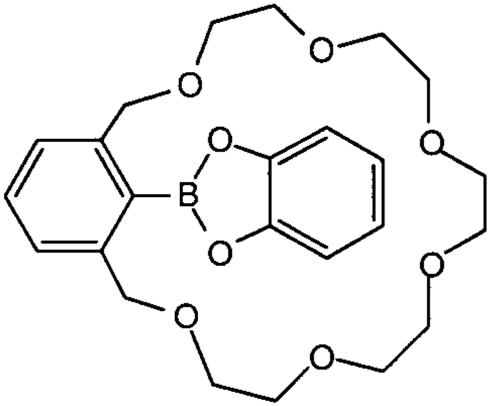


Fig. 25 The crystal structure of the complex salt $[\mathrm{Ni^{II}}_3(\mathbf{7a})](\mathrm{ClO_4})_6\cdot\mathrm{H_2O}$.[58] Non-coordinating $\mathrm{ClO_4^-}$ ions and water molecule have been omitted for clarity, as well as hydrogen atoms. Each low-spin $\mathrm{Ni^{II}}$ centre shows a square coordination geometry.




fluorescence intensity, a.u.
0
200
400
600
0
20
40
60
80
anion equiv.
COO⁻
⁻OOC
COO⁻
⁻OOC
COO⁻
⁻OOC





Ditopic receptor for binding ion pairs.

KF anidro in CH_2Cl_2

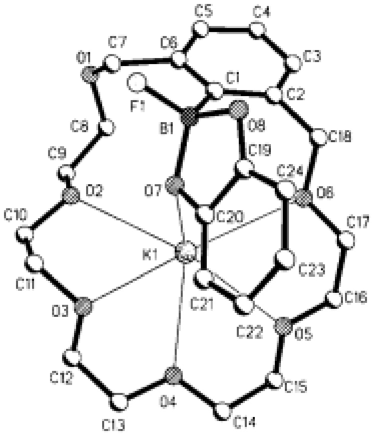
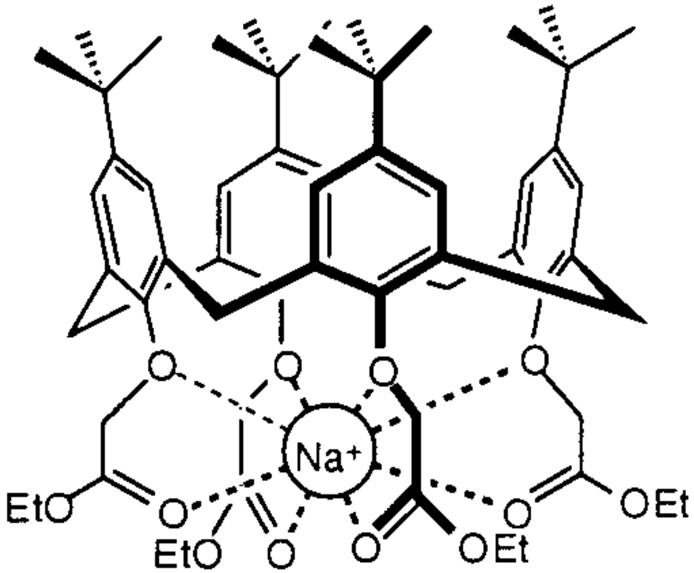
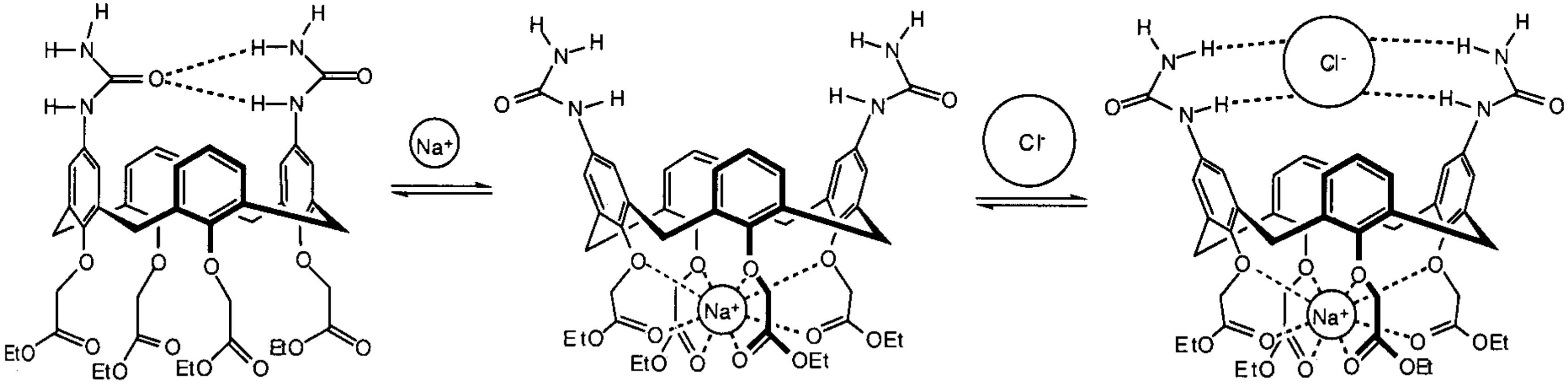
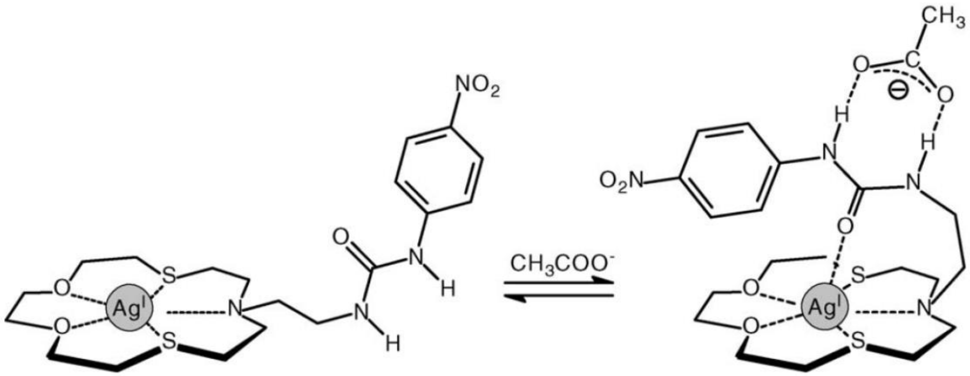


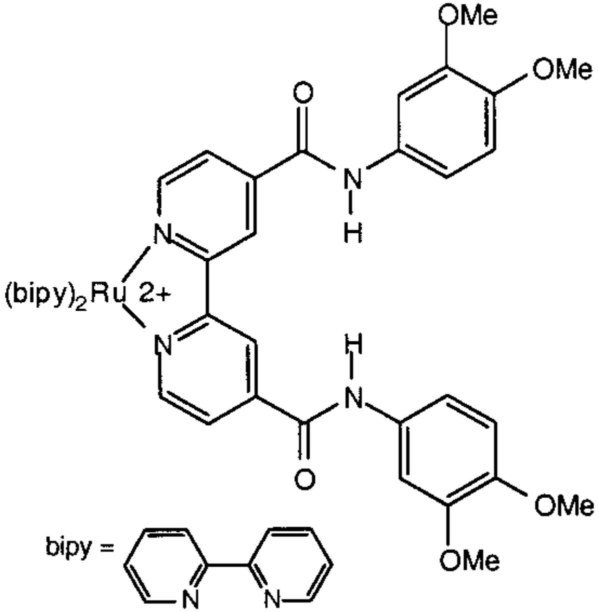
Figure 19. The X-ray crystal structure of the potassium fluoride complex of receptor **136** (hydrogen atoms are omitted). Reproduced with permission from ref. [152]. Copyright© VCH 1991.

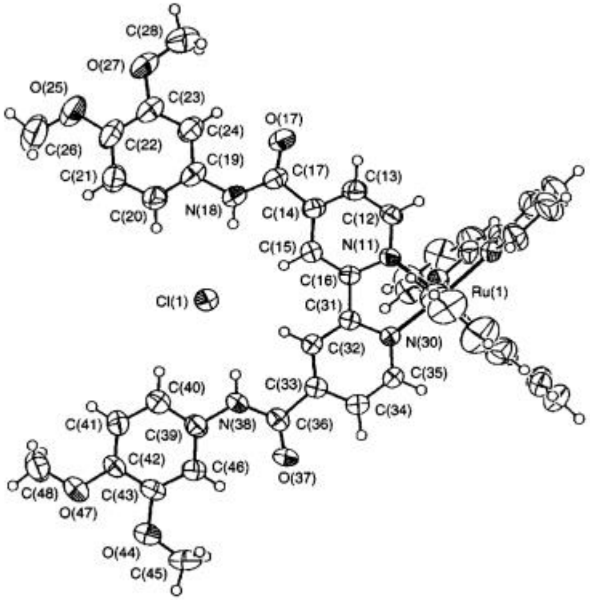

Na+
EtO
EtO
O
O
OEt
OEt

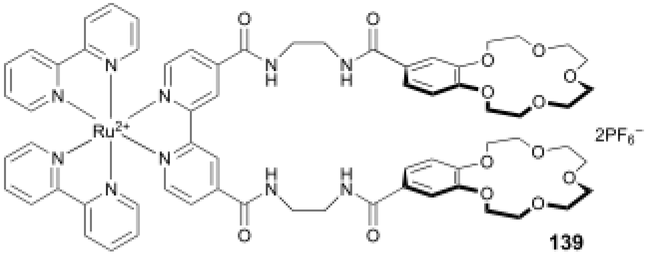

Na+
Cl-
EtO
OEt
H
N
O



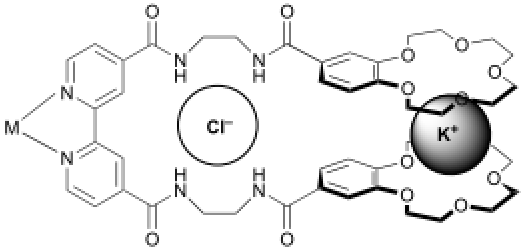
Scheme 4. Enhanced affinity of the urea subunit toward acetate, through coordination of the carbonyl oxygen atom to the proximate $\mathrm{Ag^I}$ centre.

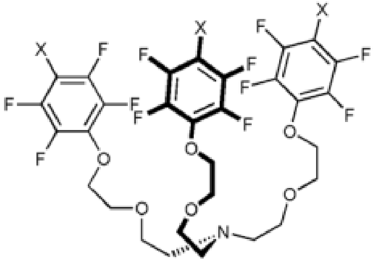

OMe
OMe
O
N
H
(bipy)2Ru 2+
N
N
H
N
O
OMe
OMe
bipy =


C(28)
O(27)
O(25)
C(23)
C(24)
O(17)
C(26)
C(22)
C(19)
C(17)
C(13)
C(21)
C(20)
N(18)
C(14)
C(12)
C(15)
N(11)
C(16)
Ru(1)
Cl(1)
C(31)
C(32)
N(30)
C(35)
C(33)
C(40)
C(34)
C(41)
C(39)
N(38)
C(36)
C(42)
C(46)
C(48)
C(43)
O(37)
O(47)
O(44)
C(45)

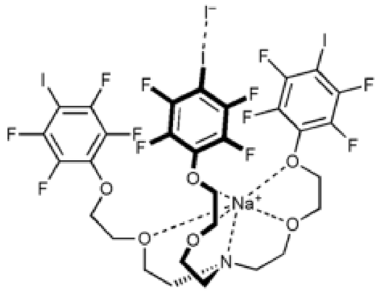

Ru2+
2PF6−

139

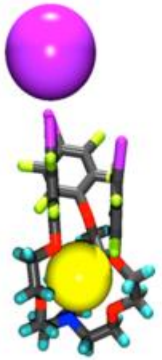

M
Cl−
K+



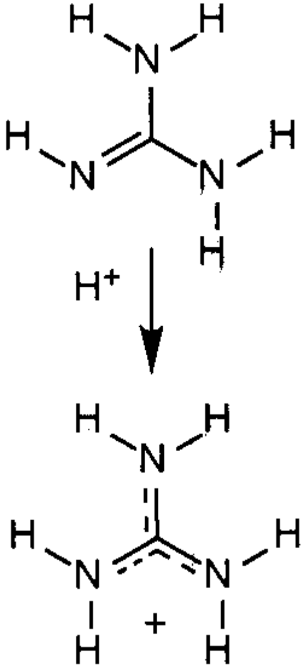
2a: X = I
2b: X = F



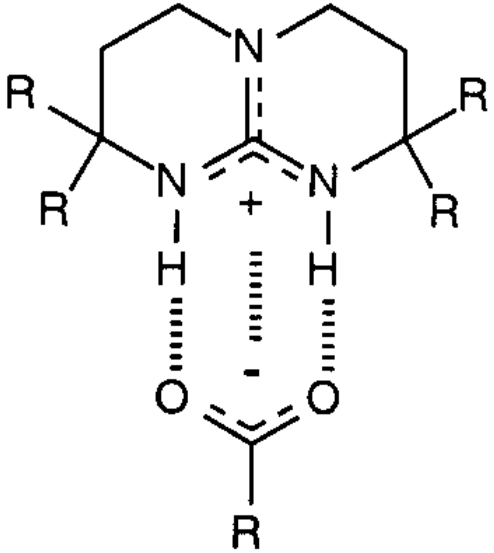
2a---NaI



K_a (**2a**---NaI) = 2.6 x 10^5 M^{-1}
K_a (**2b**---NaI) = 1.3 x 10^4 M^{-1}
$\Delta\Delta G_{XB}$ = 7 kJ/mol

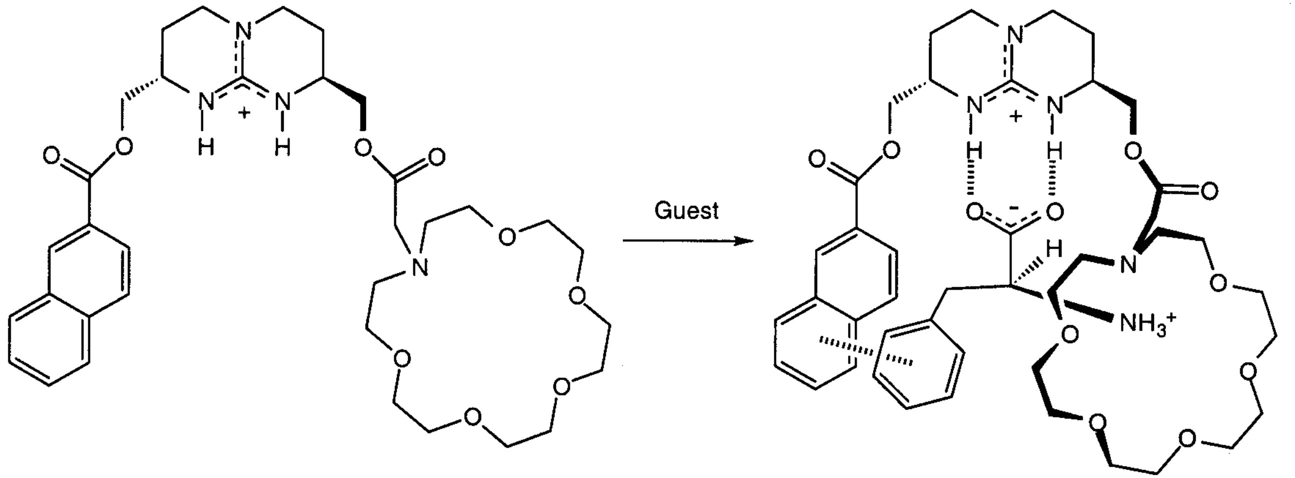


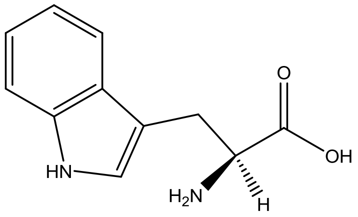
pKa = 13.6



Bicyclic guanidinium is preorganized and complementary for binding bidentate anions.

Estrazione di aa con catene laterali aromatiche (Phe, Trp) in CH_2Cl_2





Three point receptor for the selective recognition and extraction of zwitterionic amino acids.