TEMPLATE-DIRECTED SYNTHESES OF CATENANES

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The art and science of introducing mechanical-interlocking at the molecular level in order to generate catenanes – molecules composed of two or more macrocyclic components – offers the opportunity of constructing a new range of molecular compounds possessing intriguing properties. However, the topological features displayed by catenanes has rendered the syntheses of such molecular compounds an extremely challenging task for synthetic chemists to address. Their early syntheses were based upon either statistical approaches – the threading of a small amount of a macrocycle on to an acyclic precursor as a chance event – or directed approaches, relying upon the temporary introduction of covalent bonds in the multistep synthesis of a so-called precatenane, followed by its conversion ultimately into a catenane. These approaches afforded catenanes in very low yields overall and only after following tedious and laborious synthetic procedures. Fortunately, however, with the advent of supramolecular chemistry, template-directed methods that allow us to self-assemble [*n*]catenanes much more efficiently have become available. Numerous successful template-directed syntheses have now emerged – some by chance and others by design. These methods have been based upon (i) metal coordinating, (ii) hydrogen bonding, (iii) solvophobic, and/or (iv) π–π stacking interactions which have been found to govern self-assembly processes to catenated compounds from appropriate precursors. Their relative simplicity, the high degree of control with which they can be employed, and the remarkable efficiency with which they proceed has already provided the opportunity to synthetic chemists to self-assemble a series of [*n*]catenanes, incorporating from two up to five mechanically-interlocked macrocyclic components.

Key words: Catenanes; Self-assembly; Template-directed synthesis.

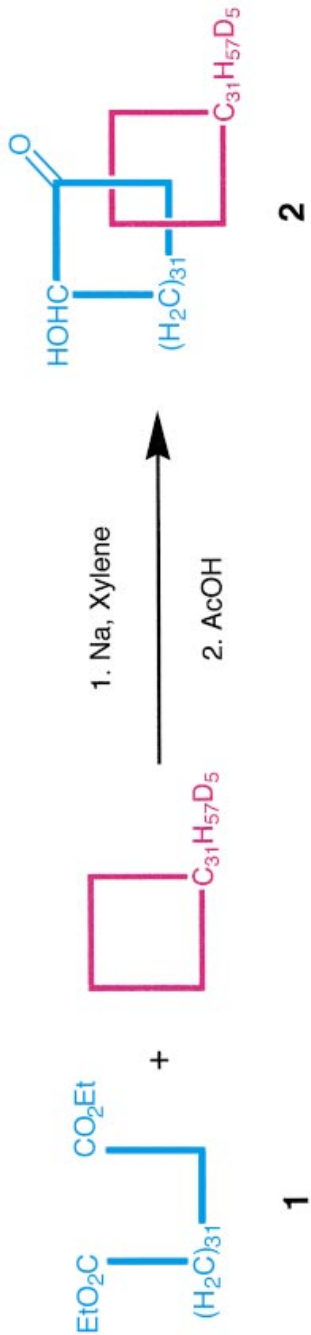
1. MECHANICALLY-INTERLOCKED MOLECULES

Catenanes[1] are molecules composed of two or more mechanically-interlocked macrocyclic components. Schematic representations of 2, 3, and $2n + 5$ mechanically-interlocked rings in the shape of a [2]-, a [3]-, and a [$2n + 5$]catenane, respectively, are illustrated in Fig. 1. The n macrocyclic components of each [n]catenane are not covalently linked to each other: instead "mechanical bonds" are responsible for holding them together. Dismembering of an [n]catenane can be achieved only after "cutting" one or more of the rings – *i.e.*, after cleavage of one or more covalent bonds in the molecule. Thus, rather than an assembly of n molecules, an [n]catenane is a discrete molecular compound possessing well-defined structural and functional properties which differ significantly from those of its individual macrocyclic components. As a result of the potential properties arising from their unusual topologies, catenanes have not only been considered as challenging synthetic targets but they have also been viewed as prototypes for the development of new and novel kinds of molecular structures. Moreover, the discovery[2] of many naturally-occurring catenated species has done much to stimulate the search for appropriate and efficient synthetic procedures to construct catenated compounds in the chemical laboratory. In this review, we illustrate, with the aid of a few selected examples, how the synthesis of catenanes has evolved over the last three decades from the very low-yielding early experimental approaches to the relatively simple and highly-efficient procedures of the present day.

2. STATISTICAL SYNTHESES

The most obvious approach to the generation of a [2]catenane involves threading of a preformed macrocyclic on to an acyclic species to afford an intermediate possessing a "wheel-and-axle" geometry – *i.e.*, a pseudorotaxane. Subsequent macrocyclisation of the acyclic species mechanically-interlocks the preformed and the newly-generated macrocycles, yielding a [2]catenane. However, the crucial threading step is an entropically unfavourable one which means that, in the absence of any noncovalent bonding interactions, the formation of the pseudorotaxane-like intermediate is only "statistically" driven. As a consequence, a very small amount of the precursor macrocycle is threaded on to the precursor acyclic species in the reaction medium with the result that the [2]catenane can only be obtained in a very low yield. Nonetheless, the very first [2]catenane was synthesised (Scheme 1) successfully by Wasserman[3] using a statistical approach. Acyloin condensation of **1** was performed in xylene at 140 °C in the presence of a very large excess of a preformed pentadeuterated cycloalkane to afford the [2]catenane **2** in a yield of less than 1%. Evidence for the formation of the [2]catenane **2** was obtained – after its careful isolation from the reaction mixture – by cleavage of the acyloin ring, releasing the easily identified intact pentadeuterated cycloalkane.

FIG. 1
Schematic representations of a [2], a [3], and a [2*n* + 5]catenane


EtO2C
(H2C)31
CO2Et
1
+
C31H57D5
1. Na, Xylene
2. AcOH
HOHC
(H2C)31
C31H57D5
O
2

SCHEME 1

Bismacrocyclisation, after double twisting of a ladder-shaped molecule, affords a so-called Mobius strip. The observation that catenanes can be formed after the cleavage of the links connecting the two strands of the Mobius strip prompted Wolovsky[4a] and Wasserman *et al.*[4b], independently and simultaneously, to employ such an approach in attempts to generate catenanes. Indeed, mass spectrometric analyses of the products of metal-catalysed metathesis of cyclic olefins revealed the presence of catenanes in small quantities. These catenated structures were believed to be formed as a result of a "Möbius strip mechanism". However, recently Bickelhaupt *et al.*[5] have suggested that the formation of catenanes from the metal-catalysed metathesis of cyclic olefins can result from a straigthforward statistical threading process.

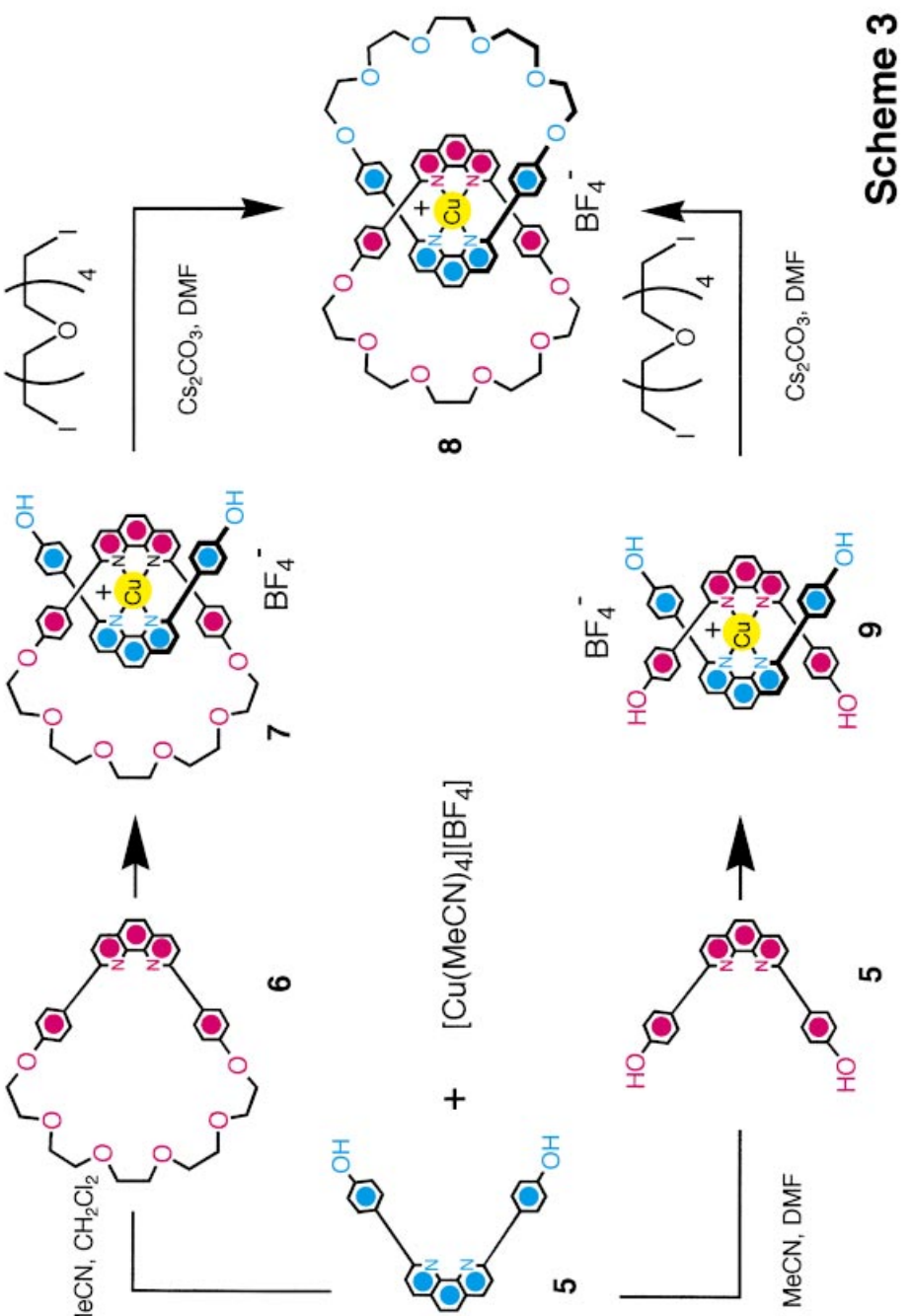
3. DIRECTED SYNTHESES

The directed synthesis of a [2]catenane involves the multistep construction of a "pre-catenane" incorporating two interlocking macrocyclic rings which are connected to each other by one or more covalent bonds. Cleavage of these covalent bonds affords the [2]catenane in which the two macrocyclic components are held together by mechanical rather than covalent bonds. This elegant approach has been used successfully by Schill *et al.*[1b] to generate a number of [2]- and [3]catenanes. One of the first [2]catenanes prepared[6] by a directed synthesis is illustrated in Scheme 2. The pre-catenane **3** was obtained after some eleven steps and the cleavage of the ketal linkage, as well as of the nitrogen to aromatic ring bond, required five additional steps to afford the [2]catenane **4** in a very low yield overall.

4. METAL TEMPLATE-DIRECTED SYNTHESES

The low-yielding statistical syntheses and the tedious and time-consuming directed syntheses signalled the need for new synthetic approaches to catenanes. The breakthrough in the field came with the method developed by Sauvage *et al.*[1e–1g,7] who brought supramolecular chemistry[8] to the rescue. By employing transition metals possessing well-defined coordination geometries and appropriate organic ligands the threading of a macrocycle on to an acyclic species can be directed[9] efficiently by the metal–ligand complex formation. Mixing the acyclic phenanthroline-based ligand **5** with $[Cu(MeCN)][BF_4]$ at room temperature in $MeCN/CH_2Cl_2$ in the presence of the pre-formed phenanthroline-based macrocycle **6** afforded[10] (Scheme 3) quantitatively the complex **7** possessing a pseudorotaxane-like geometry. The macrocyclisation of **7** was performed under high dilution conditions in DMF with pentaethylene glycol bisiodide and Cs_2CO_3 to afford[10] the [2]catenate **8** in a yield of 42%. Alternatively, the complex **9** could be assembled[10b,11] quantitatively from **5** and $[Cu(MeCN)][BF_4]$ at room temperature in MeCN/DMF. Bismacrocyclisation of the acyclic ligands incorporated within **9**, when performed under high dilution conditions in DMF with pentaethylene glycol bis-

SCHEME 2


Scheme 3
MeCN, CH2Cl2
6
7
BF4-
Cs2CO3, DMF
8
BF4-
MeCN, DMF
5
+ [Cu(MeCN)4][BF4]
5
BF4-
9
Cs2CO3, DMF

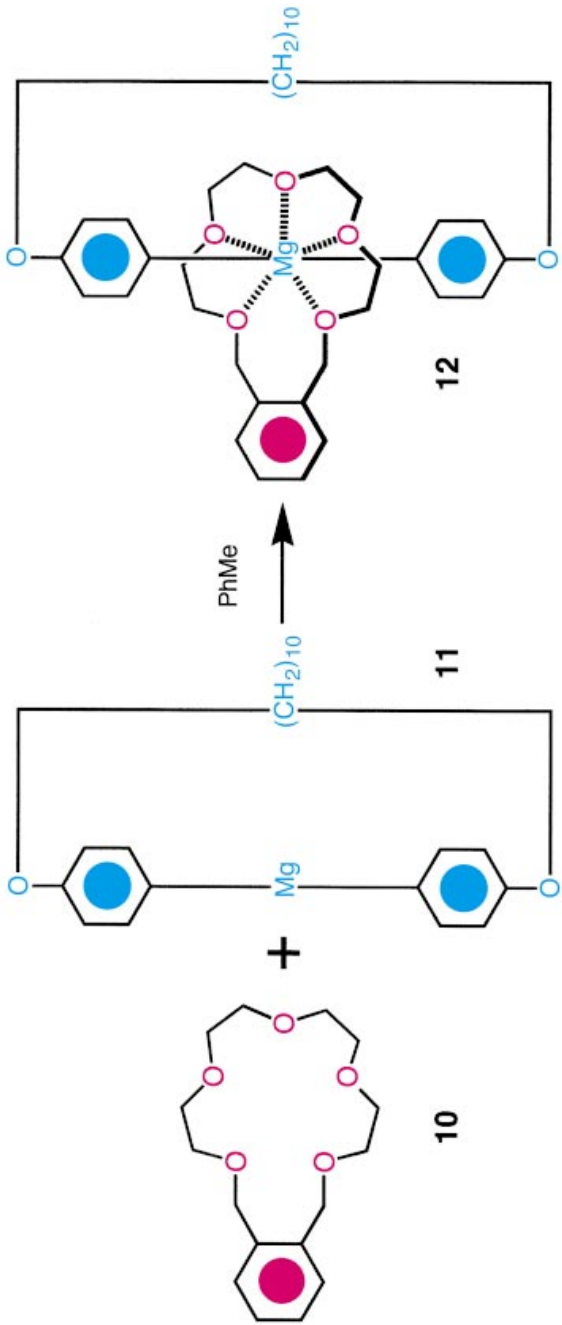
iodide and Cs_2CO_3, gave[10b,11] the [2]catenate **8** in a yield of 27%. Demetallation of the [2]catenate **8** was achieved[10,11] quantitatively by stirring a solution of **8** with KCN in H_2O/MeCN at room temperature. This efficient template-directed methodology was extended subsequently to the synthesis of a large number of singly- and doubly-interlocked [*n*]catenanes[1e–1g,7,12].

The first organometallic catenane was described by Bickelhaupt *et al.*[13] who exploited the ability of crown ethers to bind metal cations. Mixing the crown ether **10** and the organomagnesium macrocycle **11** in PhMe afforded (Scheme 4) the [2]catenane **12**. The formation of this [2]catenane occurs after (i) spontaneous dissociation of one of the aryl–magnesium bonds of **11**, (ii) complexation of the resulting $Ar–Mg^+$ cation by the crown ether **10**, and (iii) recombination of the aryl–magnesium bond to regenerate the organomagnesium macrocycle *now* mechanically-interlocked by the crown ether. A detailed ^1H NMR spectroscopic investigation of the process in octadeuteriotoluene revealed[13], beside the formation of the [2]catenane **12**, the complexation of the macrocycle **11** by the crown ether **10** as a result of an "alongside" association. The equilibrium between the two species – *i.e.*, the [2]catenane **12** and the "alongside complex" – is temperature dependent, with the [2]catenane being the major species present in octadeuteriotoluene at low temperatures.

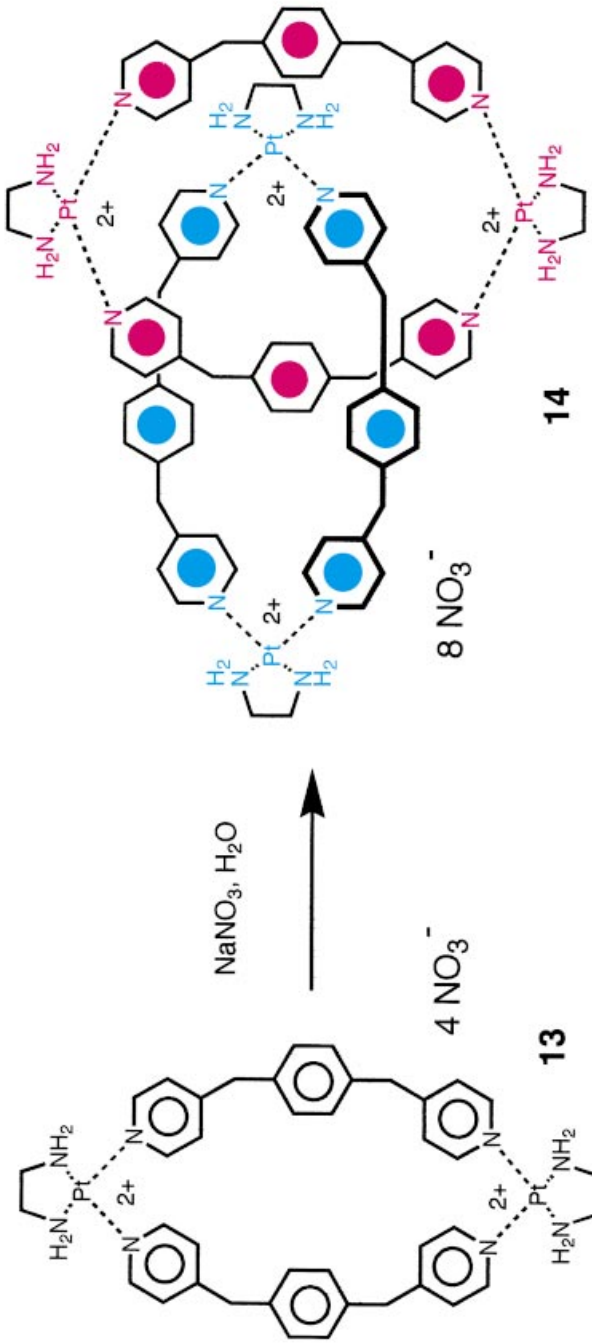
The quantitative self-assembly[14] of [2]catenanes has been achieved quite elegantly by Fujita *et al.*[15], employing pyridine-based ligands and transition metals possessing square planar geometries, such as Pt^{2+} or Pd^{2+}. In the example illustrated in Scheme 5, the [2]catenane **14** self-assembles[15b] quantitatively from the preformed dinuclear macrocycle **13** when it is heated at 100 °C in a highly polar medium, such as a concentrated aqueous solution of $NaNO_3$. Under these forcing conditions, the ligand–platinum bonds are reversible, and so sequential ligand exchange between the two individual dinuclear macrocycles produces[15c] an intermediate Möbius strip compound which, again by ligand exchange, is transformed into the [2]catenane **14**. Presumably, strong edge-to-face intercomponent interactions[16] between aromatic units within the catenane drive the process thermodynamically towards the mechanically-interlocked compound.

5. HYDROGEN BONDING TEMPLATE-DIRECTED SYNTHESES

A large number of catenanes incorporating mechanically-interlocked macrocylic lactams have been synthesised[17] as a result of template-directed syntheses governed by hydrogen bonding interactions[18]. The method was discovered[17a] accidentally by Hunter while synthesising the macrocyclic lactam incorporated in the [2]catenane **18** (Scheme 6) in its free form – a receptor for *p*-benzoquinone. Reaction of isophthaloyl chloride **15** with the diamine **16** in the presence of Et_3N in CH_2Cl_2 afforded[17a] the intermediate diamine **17**. Macrocyclisation of **17** with **15** was performed[17a] under high dilution conditions to yield the desired free macrocyclic lactam in a yield of 51% in addition to the unexpected [2]catenane **18** in a yield of 34%. Very shortly thereafter, the one-step



SCHEME 4



SCHEME 5

R 18 20
H
OMe
15
COCl
COCl
Et3N, CH2Cl2
17
NH2
NH2
R = H
Et3N, CH2Cl2
16
H2N
NH2
R = OMe
Et3N, CH2Cl2
16
H2N
NH2
R 15 19
H
OMe
21
H2N
NH2
Et3N, CH2Cl2
R = H
22

Scheme 6

synthesis of the [2]catenane **20** was reported by Vogtle *et al.*[17e]. In this case, a high dilution reaction of the diamine **16** with the bischloride **19** afforded[17e], in a single step, the [2]catenane **20** in a yield of 8%. In order to understand the mechanism of the "unexpected" catenation, a number of catenanes incorporating different substituents on the bischloride precursor have been self-assembled[17f] following one- and/or the two-step procedures. This systematic investigation prompted[17f] the authors to suggest that catenation occurs after (i) the formation of individual macrocyclic lactams in their free forms, (ii) binding by the macrocyclic lactams of their acyclic precursors with pseudorotaxane-like geometries as a result of a network of hydrogen bonding interactions involving the amide groups, and (iii) macrocyclisation at the termini of the bound acyclic species to afford two mechanically-interlocked identical macrocyclic lactam rings. The self-assembly of the related [2]catenane **22** was discovered accidentally by Leigh *et al.*[17l] in an attempt to synthesise the corresponding macrocyclic lactam in its free form – a receptor which had been designed to bind CO_2. In this case, the high dilution reaction of the commercially-available precursors **15** and **21** afforded[17l] the [2]catenane **22** in a yield of 20% in a single step. Presumably, the catenane self-assembles following the formation of a pseudorotaxane-like intermediate complex in the reaction medium.

6. CATENANES INCORPORATING CYCLODEXTRINS

The first unsuccessful attempt to synthesise a [2]catenane, which was reported by Lüttringhaus *et al.*[19] in 1958, was based on the ability of α-cyclodextrin (α-CD) to bind acyclic organic molecules with pseudorotaxane-like geometries in aqueous solutions. However, the desired macrocyclisation of some acyclic hydroquinone-based dithiols included within the cavity of α-CD did not afford the desired disulfides and hence [2]catenanes on oxidation. Some 35 years later, the same design logic was employed[20] successfully using a Schotten–Baumann reaction in our own research laboratories to self-assemble the first catenanes incorporating cyclodextrins. Reaction of the diamine **23** with terephthaloyl chloride **24** in basic aqueous solution and in the presence of β-cyclodextrin (β-CD) afforded[20] (Scheme 7) four different catenanes. The [2]catenanes **25** and **26** were obtained in yields of 3.0 and 0.8%, respectively. The [3]catenanes – the two topological stereoisomers **27** and **28** differing only in the relative orientation of their cyclodextrin components – were obtained as an approximately equimolar mixture in an overall yield of 1.1% and were separated successfully by reverse phase HPLC and characterised by ^{13}C NMR spectroscopy.

Scheme 7

7. DONOR/ACCEPTOR TEMPLATE-DIRECTED SYNTHESES

7.1. From Pseudorotaxanes to Catenanes

The π-electron rich hydroquinone-based macrocyclic polyether bis-*p*-phenylene-34-crown-10 binds[21] the π-electron deficient bipyridinium-based bis(hexafluorophosphate) salt, Paraquat, to afford the 1 : 1 complex **29** (Fig. 2) possessing a pseudorotaxane-like geometry both in solution and in the solid state. The complex formation is driven by (i) π–π stacking interactions[22] between the complementary aromatic units and (ii) [C–H...O] hydrogen bonds between the hydrogen atoms – [CH_3–N] and [CH–N] – in the α-positions with respect to the nitrogen atoms on the bipyridinium unit. By reversing the roles of the recognition sites, the possibility of generating a bipyridinium-based cyclophane able to bind acyclic hydroquinone-based polyethers was envisaged. Indeed, the tetracationic cyclophane, cyclobis(paraquat-*p*-phenylene), binds[23] a wide range of π-electron rich acyclic polyethers, affording pseudorotaxane-like complexes, such as **30**, in solution as well as in the solid state. The pseudorotaxane-like geometries adopted by the 1 : 1 complexes **29** and **30** laid the basis for the donor/acceptor template-directed syntheses (Scheme 8) of the [2]catenane **34** incorporating the two macrocyclic receptors of the 1 : 1 complexes **29** and **30** mechanically-interlocked[23c,24]. Alkylation of the bis(hexafluorophosphate) salt **32** with the dibromide **33**, performed at ambient temperature and pressure, affords a tricationic intermediate which is bound by the hydroquinone-based macrocyclic polyether **31** with a pseudorotaxane-like geometry. The subsequent macrocyclisation to give the tetracationic cyclophane component is template-directed by the π-electron rich macrocyclic polyether component incorporated within the pseudorotaxane-like intermediate to afford the [2]catenane **34** in a remarkable yield of 70%, following counterion exchange. Similarly, the [2]catenane **36** was self-assembled[25], by employing the 1,5-dioxynaphthalene-based macrocyclic polyether **35** instead of **31**, in a yield of 51% under otherwise identical conditions.

7.2. Self-Assembly of [n]Catenanes

The relative simplicity and remarkable efficiency of the donor/acceptor template-directed syntheses developed in our own research laboratories has led to extending this approach to the self-assembly of [*n*]catenanes incorporating more than two interlocking macrocyclic components. Enlargement of either the π-electron rich and/or the π-electron deficient macrocyclic components of the [2]catenanes **34** and **36** is required in order for it to become possible to construct higher catenanes. Reaction of the bis(hexafluorophosphate) salt **37** – in which the two bipyridinium units are separated by longer bitolyl spacer units – with the dibromide **38** in the presence of either **31** or **35** at room temperature and ambient pressure gave[26] (Scheme 9) the [3]catenanes **39** or **40** in yields of 25 and 30%, respectively, after counterion exchange. As a result of the enlargement

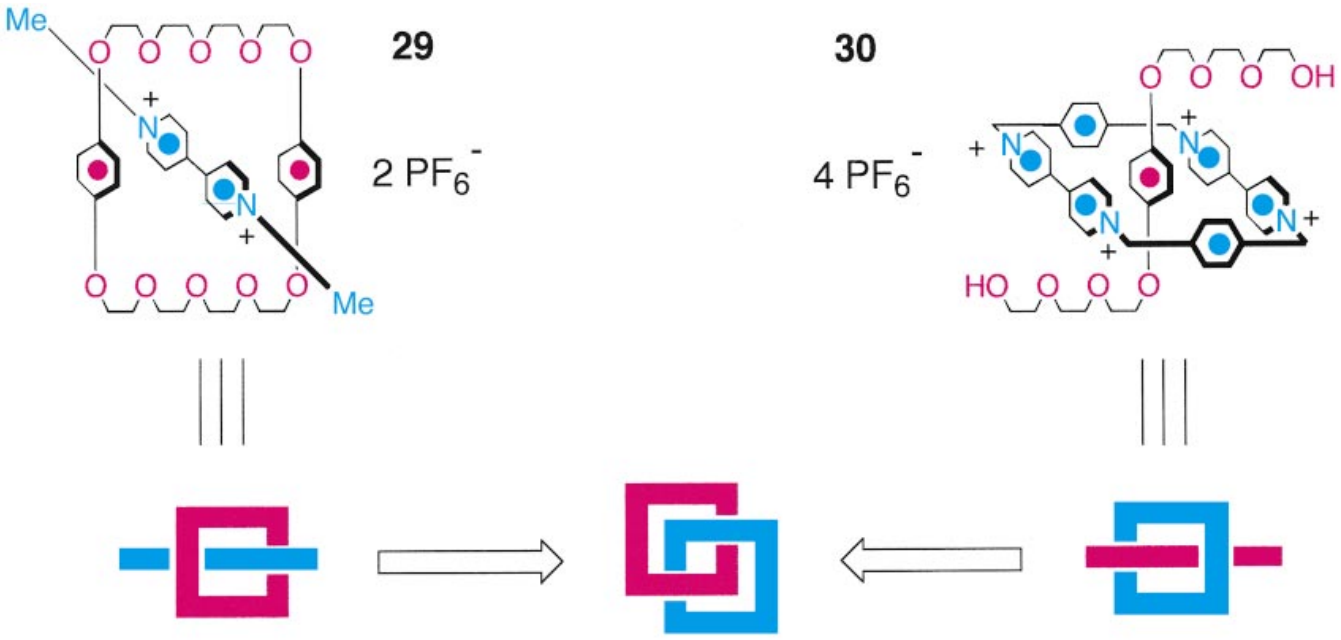
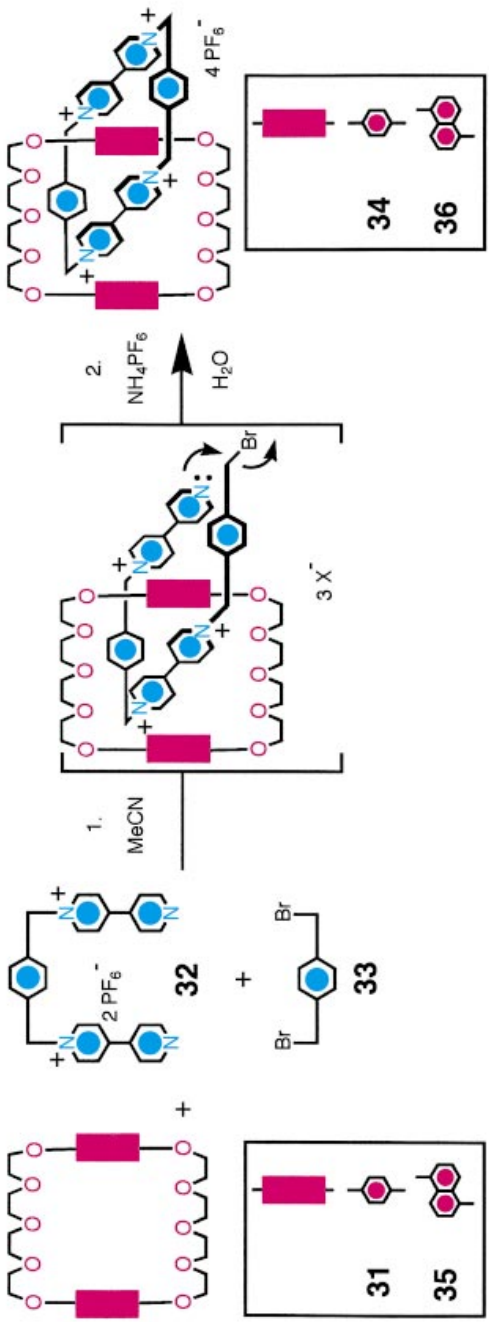
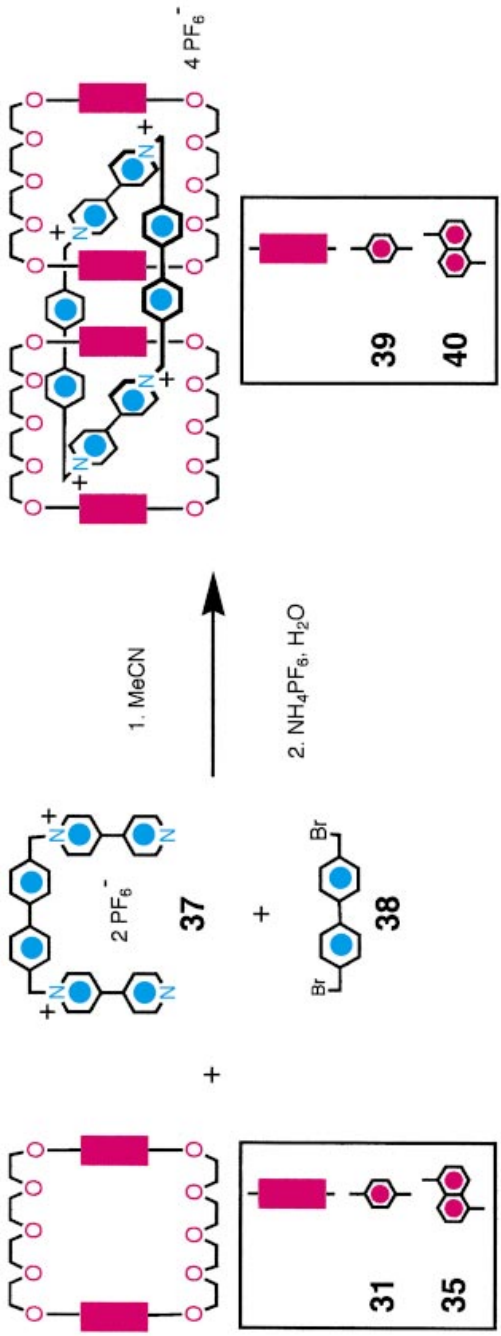


FIG. 2
From donor/acceptor pseudorotaxane-like complexes to catenanes



SCHEME 8



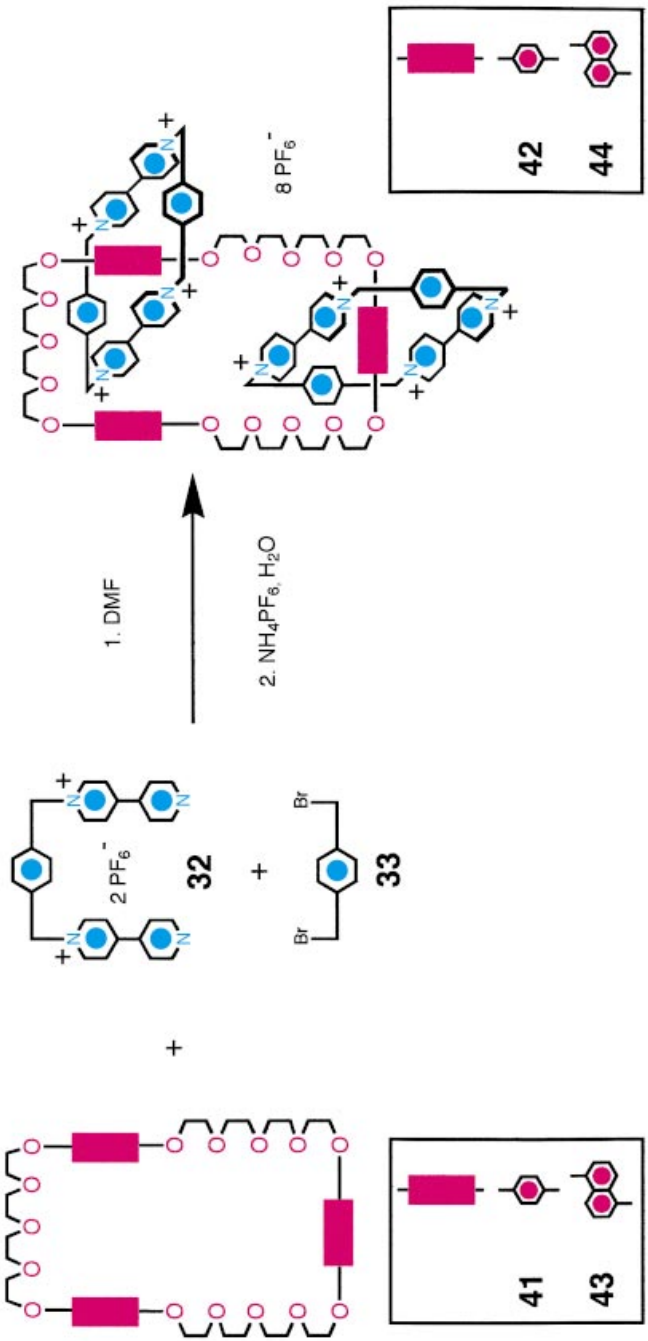
SCHEME 9

of the tetracationic cyclophane component, two π-electron rich aromatic units can be incorporated simultaneously into its cavity, thus providing the opportunity of mechanically-interlocking three macrocyclic ring components. By reversing the design logic – *i.e.*, enlarging the π-electron rich macrocyclic polyether – two bipyridinium units can be inserted simultaneously inside the cavity of the macrocyclic polyether. Reaction of the bis(hexafluorophosphate) **32** with the dibromide **33** in the presence of the hydroquinone-based macrocyclic polyether **41** at room temperature under 10 kbar of pressure afforded[27] (Scheme 10) the [3]catenane **42** in a yield of 15% following counterion exchange. When the reaction was repeated in the presence of the 1,5-dioxynaphthalene-based macrocyclic polyether **43**, ultrahigh pressure reaction conditions were not required and the [3]catenane **44** was isolated[28], after counterion exchange, in a yield of 15%.

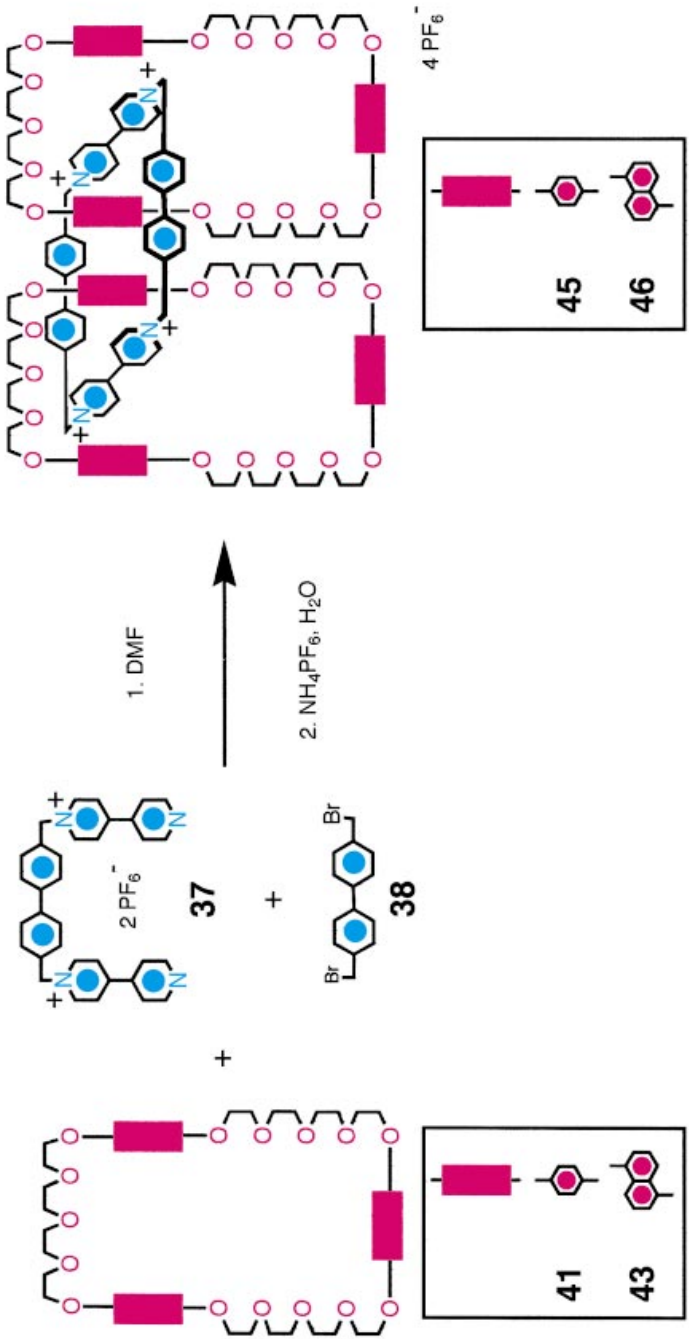
The next step towards higher [*n*]catenane was the mechanical-interlocking of an enlarged π-electron rich macrocyclic polyether component with an enlarged π-electron deficient tetracationic cyclophane component. Reaction at ambient temperature and pressure of the bis(hexafluorophosphate) salt **37** with the dibromide **38** in the presence of either **41** or **43** gave[27,29] (Scheme 11) the [3]catenanes **45** or **46** in yields of 3.5 and 6.0%, respectively. The [3]catenanes **45** and **46** incorporate two π-electron rich aromatic units within the cavities of their enlarged tetracationic cyclophane components, but only one bipyridinium unit within each of their two enlarged π-electron rich macrocyclic polyether components. As a result, one additional bipyridinium unit can subsequently be inserted within each of their two π-electron rich macrocyclic polyether components. Further reaction of the [3]catenane **45**, incorporating hydroquinone-based macrocyclic polyethers, with the bis(hexafluorophosphate) salt **32** and the dibromide **33** under 14 kbar at room temperature gave[27] (Scheme 12) the [4]catenane **47** in a yields of 22% and a very small amount (<1%) of the [5]catenane **48** following counterion exchange. On the contrary, reaction of the [3]catenane **46** incorporating 1,5-dioxynaphthalene-based macrocyclic polyether components with the bis(hexafluorophosphate) salt **32** and the dibromide **33**, performed at ambient temperature and pressure, afforded[29] the [4]catenane **49** and the [5]catenane **50** in the somewhat better yields of 31 and 5%, respectively.

7.3. Characterisation and Properties

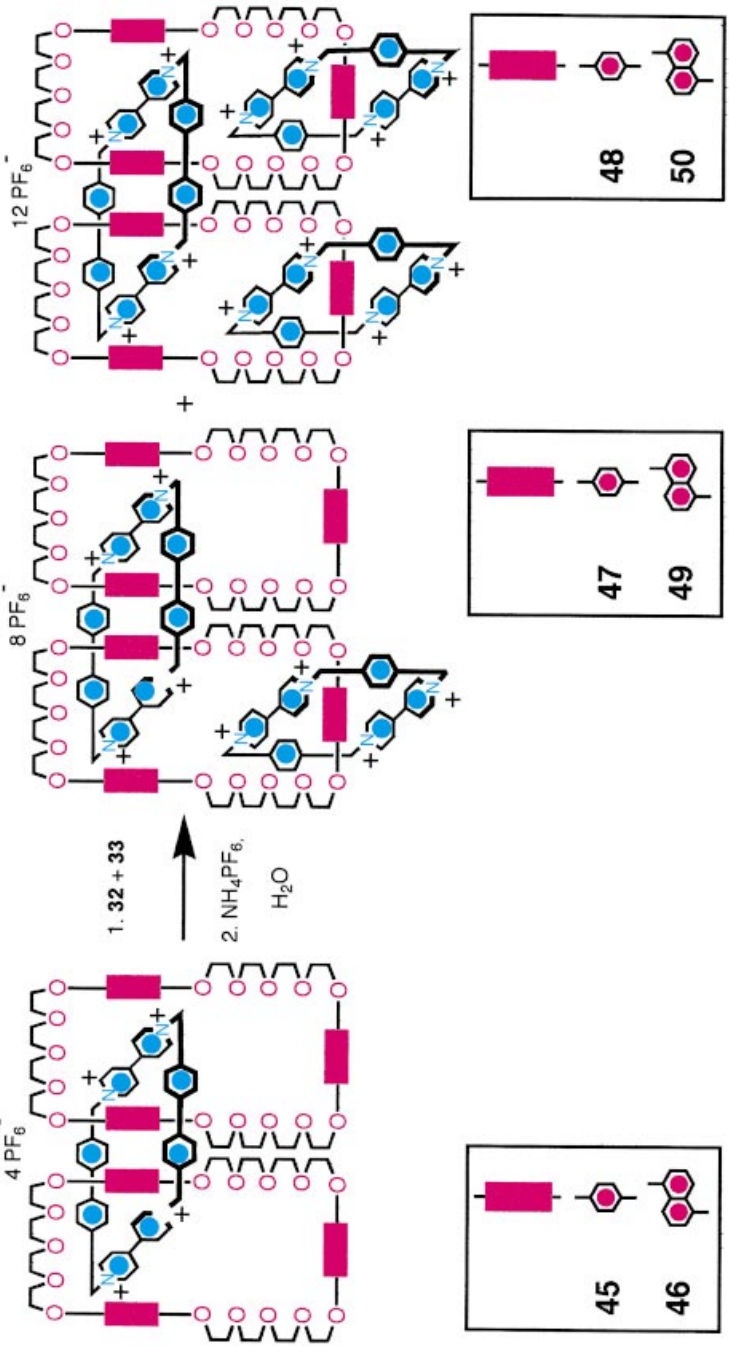
Purification of the [*n*]catenanes incorporating complementary π-electron rich macrocyclic polyether and π-electron deficient tetracationic cyclophane components was performed by column chromatography employing silica gel as the stationary phase. Their characterisation was achieved by single crystal X-ray crystallography, by liquid secondary ion (LSI) and electrospray (ES) mass spectrometries, by ^{1}H and ^{13}C NMR spectroscopies, and by elemental analysis. The fascinating topologies of these mechanically-interlocked structures were unequivocally demonstrated by X-ray crystal-



SCHEME 10



SCHEME 11



SCHEME 12

lographic analyses performed on single crystals of the catenanes grown by the vapour diffusion technique. The X-ray crystal structure (Fig. 3) of the [2]catenane **34** reveals[23c,24] the mechanical bond holding together the two macrocyclic components. A π-donor/π-acceptor/π-donor/π-acceptor stack is formed by the complementary aromatic units which are separated by the interplanar π–π stacking distances of *ca* 3.5 Å. The π-donor/π-acceptor stack propagates along one of the crystallographic directions, as a result of "alongside" π–π stacking interactions involving adjacent [2]catenane molecules in the crystal. In addition, secondary stabilising interactions, particularly (i) [C–H...O] hydrogen bonds between two of the hydrogen atoms in the α-positions with respect to the nitrogen atoms on the bipyridinium unit located "inside" the cavity of the macrocyclic polyether and some of the polyether oxygen atoms, as well as (ii) edge-to-face T-type interactions between two of the hydrogen atoms attached to the hydroquinone ring located "inside" the cavity of the tetracationic cyclophane and the face-on π-clouds of the *p*-xylene spacers, are also observed. The X-ray crystal structure (Fig. 4) of the [3]catenane **39** reveals[26] the three mechanically-interlocked macrocyclic ring components. In addition to the "usual" [C–H...O] hydrogen bonds and edge-to-face T-type interactions, a π-donor/π-acceptor/π-donor/π-donor/π-acceptor/π-donor stack is formed within each [3]catenane molecule, once again with interplanar separations of *ca* 3.5 Å.

In solution, the ring components of the [2]catenane **34** are free to circumrotate (Fig. 5) through each others' cavities. Exchange of the "alongside" and "inside" hydroquinone rings (Process I) is a achieved by circumrotation of the macrocyclic polyether component through the cavity of the tetracationic cyclophane component. Exchange of the "alongside" and "inside" bipyridinium units (Process II) is achieved by circumrotation of the tetracationic cyclophane component through the cavity of the macrocyclic poly-

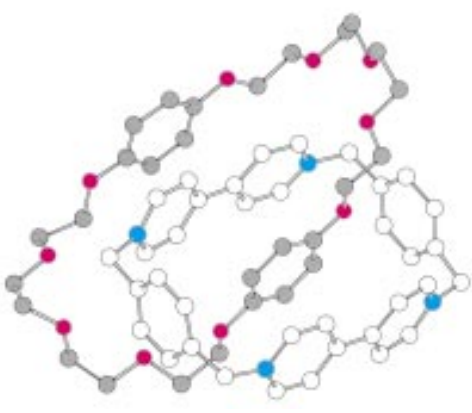


FIG. 3
Ball-and-stick representation of the geometry adopted in the solid state by the [2]catenane **34**

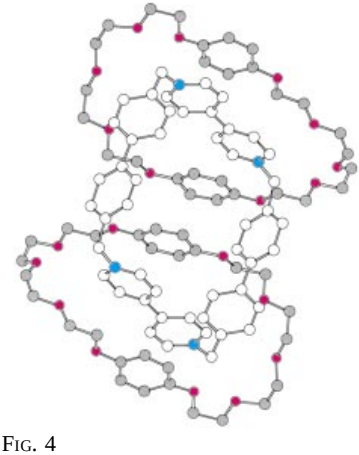


FIG. 4
Ball-and-stick representation of the geometry adopted in the solid state by the [3]catenane **39**

4 PF6-
Process I
Process II
4 PF6-
Process I
Process II
4 PF6-
4 PF6-

ether component. Process I is slow on the ^{1}H NMR timescale at room temperature and the "alongside" hydroquinone ring can be easily distinguished from the "inside" one – the latter gives raise to a singlet centred on *ca* δ 3.4 as a result of the shielding effect exerted upon it by the sandwiching bipyridinium units. On the contrary, Process II is fast on the ^{1}H NMR timescale at this temperature and the "alongside" and "inside" bipyridinium units are indistinguishable. The free energies of activation associated with Process I and II (15.6 and 12.3 kcal mol^{-1} at coalescence temperatures of 354 and 250 K, respectively) were obtained[23c,24] by a variable temperature ^{1}H NMR spectroscopic investigation performed in a selection (CD_3COCD_3, CD_3CN, and CD_3SOCD_3) of solvents over a range (198–373 K) of temperatures.

The redox properties of the [2]catenane **34** were investigated[23c,24] by cyclic voltammetry. In the case of the tetracationic cyclophane **51** (Fig. 6) in its free form, two consecutive bielectronic reduction waves (–283 and –709 mV) are observed. The first wave corresponds to the $[bipyridinium]^{2+}/[bipyridinium]^{+}$ reduction and involves two simultaneous monoelectronic additions to the two identical $[bipyridinium]^{2+}$ units. The second wave corresponds to the $[bipyridinium]^{+}/[bipyridinium]$ reduction and involves, again, two simultaneous monoelectronic additions to the two identical $[bipyridinium]^{+}$ units. In the case of the [2]catenane **34**, the two $[bipyridinium]^{2+}$ units are no longer equivalent – one is located "inside" and the other "alongside" the cavity of the macrocyclic polyether. As a result, two consecutive monoelectronic reduction waves (–310 and –437 mV), followed by a bielectronic reduction (–845 mV) wave, are observed. The two consecutive monoelectronic waves correspond to the $[bipyridinium]^{2+}/[bipyridinium]^{+}$ reduction of the "alongside" unit first of all and then to the $[bipyridinium]^{2+}/[bipyridinium]^{+}$ reduction of the "inside" unit – the latter being stabilised by the π-donor ability of the sandwiching hydroquinone units. On the contrary, the subsequent $[bipyridinium]^{+}/[bipyridinium]$ reduction of the two units occurs as two simultaneous monoelectronic additions.

8. SUMMARY AND OUTLOOK

Molecules composed of two or more mechanically-interlocked macrocyclic components are termed catenanes. Their intriguing topologies have captured the imaginations of synthetic chemists and encouraged them in their quest for efficient synthetic procedures leading to their construction. Following a pioneering unsuccessful attempt to catenate cyclodextrins that was reported[19] in the literature in 1958, the first [2]catenane was synthesised two years later in very low yields by Wasserman[3]. Statistical syntheses were followed by the impressive directed syntheses devised by Schill *et al.*[1b]. However, the real breakthrough in the field came only in the early 1980s with the template-directed syntheses reported by Sauvage and his coworkers[7]. Since then, a wide number of supramolecular approaches to catenanes have been devised either by design or stumbled upon by chance by many other investigators. Indeed, nowadays it can be said that

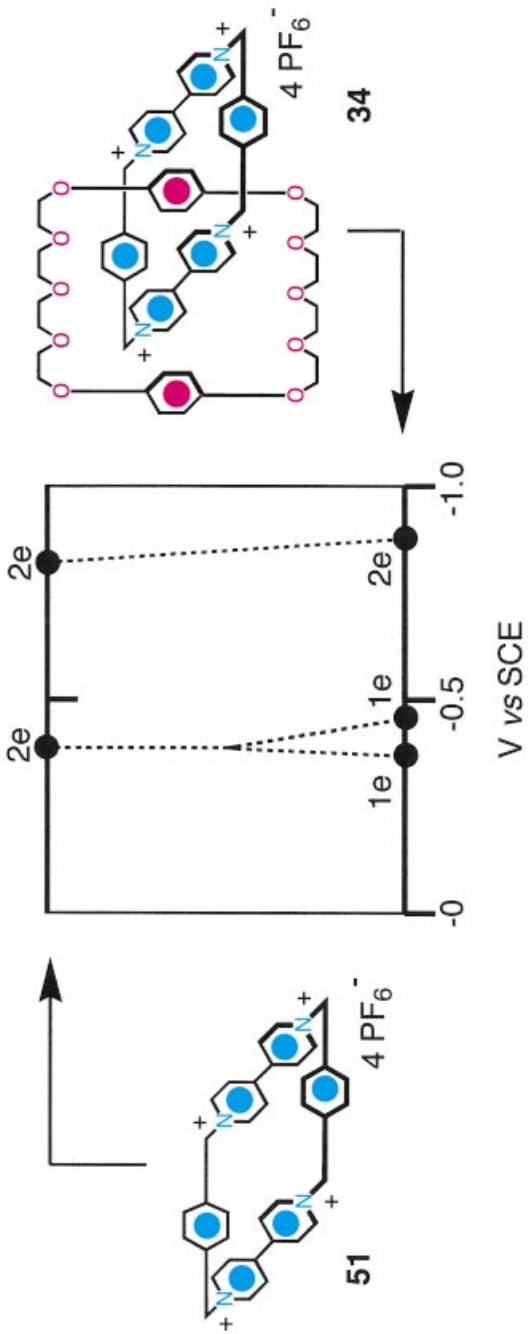


FIG. 6
Redox potentials for the reduction of the [2]catenane **34** and the tetracationic cyclophane component **51** in its free form

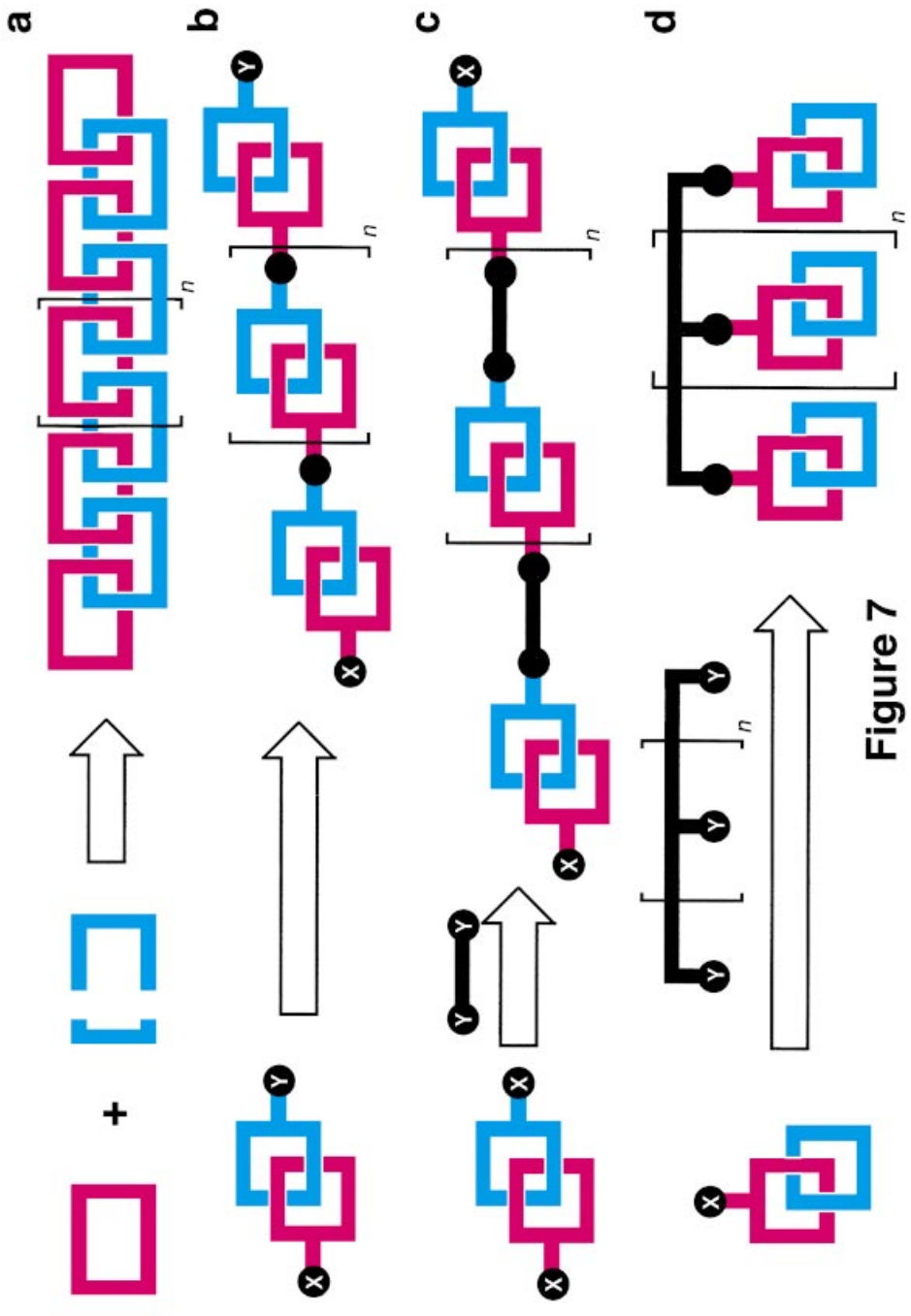


Figure 7

catenanes can be self-assembled even in quantitative yields and often from inexpensive commercially-available starting materials. Among the numerous procedures, the donor/acceptor template-directed syntheses, developed in our own research laboratories have proved to be both simple and efficient. Using this particular self-assembly approach, [*n*]catenanes incorporating up to five mechanically-interlocked rings disposed in a linear array – that is, the pentacatenane we have called Olympiadane – have been synthesised successfully. In addition, the template-directed procedures developed to synthesise catenanes have been extended successfully to the construction of [*n*]rotaxanes[30] – *i.e.*, molecules incorporating *n* macrocyclic components encircling a dumbbell-shaped component bearing bulky groups at its both ends.

The ability of the synthetic chemist to reproduce the features of mechanical-interlocking at the molecular level with a high degree of control and efficiency suggests strongly the possibility of being able to generate nanometer-scale devices[31] – the equivalents of chains and belts in the macroscopic world. Chemically-, electrochemically-, and/or photochemically-active units have already been incorporated[32] successfully within catenated compounds with the ultimate goal of controlling the relative dynamic properties of their components using external stimuli. Furthermore, extension of mechanical-interlocking to oligomers and polymers (Fig. 7) could afford a new range of materials with unusual properties. Polymerisations (**a** and **b**) and copolymerisations (**c**), and grafting of preformed catenanes onto polymeric backbones (**d**) can all be employed to generate main-chain and side-chain polycatenanes[33].

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