Interlocking of Molecular Threads: From the Statistical Approach to the Templated Synthesis of Catenands†

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I. Introduction

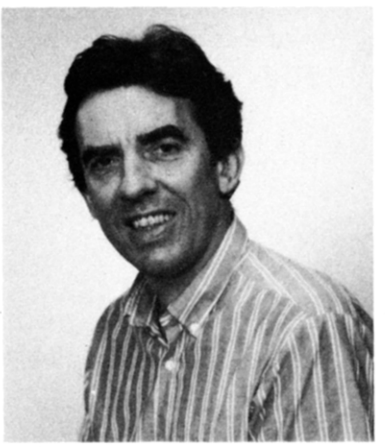
The search for aesthetically attractive molecules has been a concern going back to the origin of chemistry. The criteria for beauty have obviously changed with time, being connected to analytical and synthetic tools. The ability of synthetic chemists to build more and more complicated structures has been developing spectacularly; recently highly sophisticated molecular architectures have been achieved.

Transition metals can form molecular clusters whose arrangements are remarkably beautiful. In particular, platinum carbonyl clusters lead to geometrical figures whose regularity and harmony were completely unexpected not so long ago.[1]

Dodecahedrane[2] is another example whose importance stems both from the amount of work involved and from the cultural significance of the geometrical shape reached. This smart molecule represents the achievement of considerable efforts, and it remains today one of the most difficult patterns to be synthesized. Clearly, the imagination of the chemist is dependent on the power of the synthetic tool. As the latter becomes more and more powerful, the synthetic chemist will be able to conceive and then to construct molecules that were not envisaged previously. Concurrently, the analytical chemist becomes able to recognize molecular structures

†This review is dedicated to Professor Guy Ourisson on the occasion of his 60th birthday.

C. O. Dietrich-Buchecker was born in Strasbourg, France. She earned the Ph.D. degree from University Louis Pasteur (Strasbourg, 1973) in Prof. M. Franck-Neumann's laboratory, where she studied small rings (cyclopropanes, cyclopropenes; synthesis and reactivity) and total synthesis of chrysanthemic acids. Dr. Dietrich-Buchecker has been a member of the Centre National de la Recherche Scientifique since 1970, and she did postdoctoral work with Prof. K. B. Sharpless (MIT, Cambridge, MA, 1973–1974) on the study of new organoselenium compounds. She joined Prof. J. P. Sauvage's group in 1981, and her present research field is the synthesis of topologically novel molecules, [2]- and [3]-catenanes.



Jean-Pierre Sauvage was born in Paris and is associated with Institut de Chimie in Strasbourg. He earned the Ph.D. degree from Univerité Louis Pasteur, Strasbourg, under Prof. J. M. Lehn (cryptates) in 1971. Dr. Sauvage has been a member of the Centre National de la Recherche Scientifique since 1971, and he did postdoctoral work in organometallic chemistry in Oxford with M. L. H. Green (1973–1974). He has done research work in coordination photochemistry and in particular on the photochemical splitting of water since 1977; his current research interests cover homogeneous catalysis, electrochemical activation of CO_2, models of the natural photosynthetic apparatus, and development and use of new redox photocatalysts and chemical topology (catenands and related systems).

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whose complexity would have prohibited their discovery before. This follows from the power of analytical methods but also from the knowledge of related elaborate molecules that the synthetic chemist has made available. In this sense, a recent case is exemplary: Smalley[3] and his co-workers could detect a highly stable cluster of 60 carbon atoms formed by vaporization of graphite. The authors have proposed that the edifice has a spheroidal shape, being a soccer-ball-like cluster, whose stability is explained by the extensive delocalization of the three-dimensional system. Such an architecture, consisting of 12 pentagons and 20 hexagons, could be proposed in 1985 for the C_{60} cluster, but it would not have been easily conceived some time ago.

The aesthetic aspect of a molecule, or of any object, is closely connected to its shape in Euclidian geometry: the object is represented by points and lines, the metric properties (length of a segment, angles, etc.) being of utmost importance. In this case, the object cannot be put out of shape. However, another interesting facet of beauty rests in the topological properties of the object: the connectivity between its vertices defines the object. The latter can be deformed as much as desired, provided edges are not cleaved.

Stereochemistry and topology were linked 25 years ago in an important article by Frisch and Wasserman[4] titled "Chemical Topology". Several more recent discussions[5,6] can be found in the literature.

An important example of *topological isomers* refers to *catenanes*.[7] As shown in Figure 1, a catenane is composed of interlocked rings, the most simple case being that of [2]-catenanes. (The number in brackets corresponds to the number of interlocked cycles). The catenane (B) is a topological isomer of the set of molecules composed of the two separate rings (A). A and B are of course topologically (and chemically) distinct. It must be stressed that [2]-catenanes are normally not chiral. Topological enantiomers are obtained with directed graphs for which the edges are oriented from one vertex to another, forming *arcs*. Chiral [2]-catenanes, composed of directed rings, are represented in Figure 2. The two systems considered are topological enantiomers.

Since historically catenanes and *rotaxanes*[4,7-10] have been closely associated, it must be pointed out that these two systems are highly different from the point of view of topology. A rotaxane is formed by a ring that is threaded by a linear fragment with bulky groups on either end as shown in Figure 3. Because of restricted expansion of the cycle and limited compression of the voluminous groups, this system is isomeric to the ensemble of separate molecules: ring plus linear fragment. However, this type of isomerism is dealing with metric properties and thus originates from the shape or *topography*[11] of the system. Topologically, those two isomers are indistinguishable.

Clearly, the building of molecules displaying novel topological properties and the isolation and study of their topological isomers are challenges to synthetic chemists. In addition, we feel that a molecular object can be aesthetically appealing because of its topology. In other words, the beauty of some molecules might be independent of shape and rest only in its topological properties. We find this especially true for interlocked rings and knots.

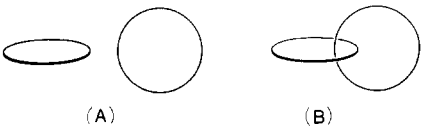
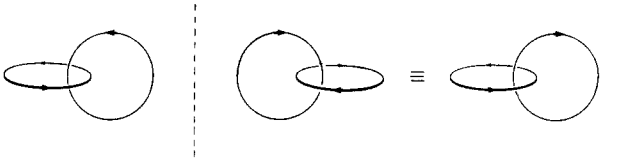


Figure 1.



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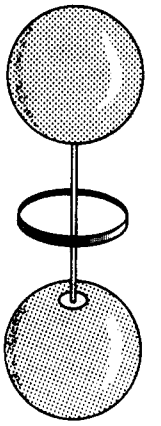

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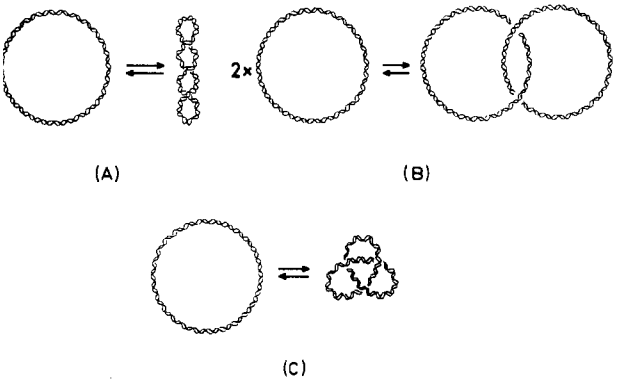


Figure 4. Duplex circular DNA: (A) supercoiled or supertwisted;[17a] (B) catenated or interlocked;[17b] (C) knotted.

DNA's Naturally Occurring Topological Stereoisomers. In contrast to organic chemistry, where only a few examples of topological isomers are known, biology offers a tremendous number of such molecules. The discovery in the early 1960s of single-stranded or double-stranded circular DNA[12,13] was the starting point of a new field of investigations that deals with what is now commonly called the "superstructures" or the topological configurations of DNA. In fact, the structure of DNA, this huge polynucleotide known to be responsible for transmission of all genetic information in living cells, "may be apprehended at three different levels."[14]

A first level of structure is given by the atoms and the covalent chemical bonds between them. Alternating sugar units and phosphate groups linked by covalent bonds constitute the backbone of each strand of DNA.

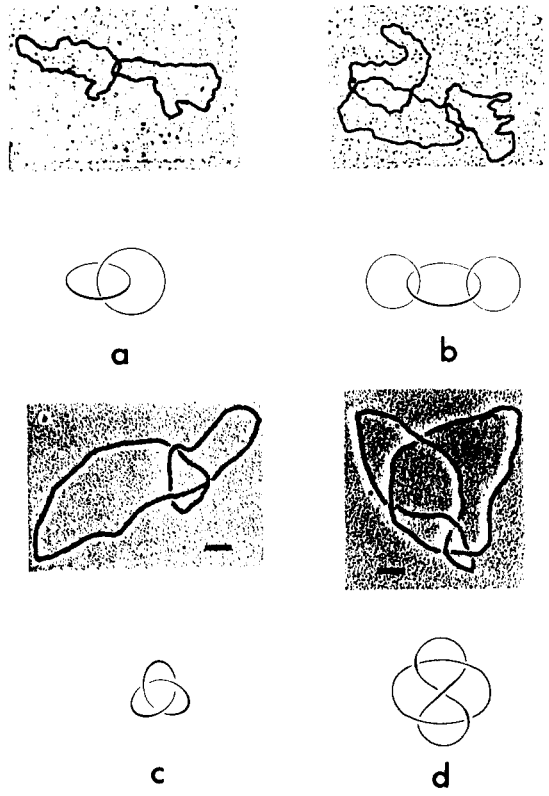


Figure 5. Electron micrographs of gyrase-produced DNA catenanes and knots: (a) [2]-catenane; (b) [3]-catenane; (c) trefoil knot; (d) figure-eight catenane. Pictures a and b are taken from ref 17c, and pictures c and d are adapted from ref 17d. For a and b, the largest edge of the rectangle is 2 μm long; for c and d the black dash is 0.1 μm long.

Each sugar unit is connected to a phosphate group by carbon 5′ on one side and to another phosphate by carbon 3′ on the other side. The backbone built up by the sugar units and the phosphates is thus naturally oriented from $C_{5'}$ to $C_{3'}$ or in reverse order (from $C_{3'}$ to $C_{5'}$). To each sugar is linked one of the four nucleotide bases A (adenine), G (guanine), C (cytosine), or T (thymine) so that these bases are almost perpendicular to the backbone.

A second level of structure arises from the hydrogen bondings between the bases of one chain and the bases of another chain. By this pairing of nucleotide bases (A with T and C with G), the two complementary chains are brought together and form the famous right-handed double B helix whose structure was first determined by Watson and Crick in 1953.[15] It has been shown[16] that the strands of this double helix make a full turn approximately every 10.0 base pairs (most stable conformation of linear double-stranded DNA). But, because of the length of DNA molecules, the axis of this double helix can itself be bent, twisted, or knotted: we reach here a third level of structure that is of utmost importance in double-stranded circular DNA.

Duplex circular DNA molecules are made up of two *closed intact* DNA rings; they are very common in bacteria and viruses. Vinograd and his co-workers[17] discovered that such molecules can appear in nature with topologically distinct stereoisomeric configurations, the most common ones being supercoils, catenanes, and knots as shown in Figures 4 and 5. All these complex molecules have a *nonplanar presentation*[18] and are defined by their *linking number*, which is "the algebraic sum of the number of supercoils and the number of double helical turns in the closed circular duplex DNA, that is, the total number of revolutions of one single strand around the other".[19] The linking number is an integer and, more important, a true topological property: it remains *invariant* as long as one or both strands of the ring are not cut, no matter how the whole molecule is distorted in space. Like organic molecules with the same connectivity but different topological properties, duplex circular DNA molecules having same molecular weight and the same base-pair sequence but different linking numbers are real topological isomers. The interconversion from one isomer into another implies a change in linking number after transient breakage of one or two strands. A whole class of enzymes effect these topological transformations perfectly: they are called *topoisomerases*. Type I topoisomerases, like the ω-protein from the bacterium *Escherichia coli*,[20] cut a single strand of DNA, whereas type II topoisomerases, like the famous bacterial enzyme gyrase discovered by Gellert and co-workers,[21] cut both strands of the double helix. Both types of enzymes work the same way: they cut the DNA strands, pass segments through the break, and reseal the cut ends.

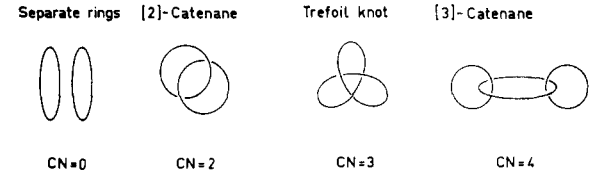
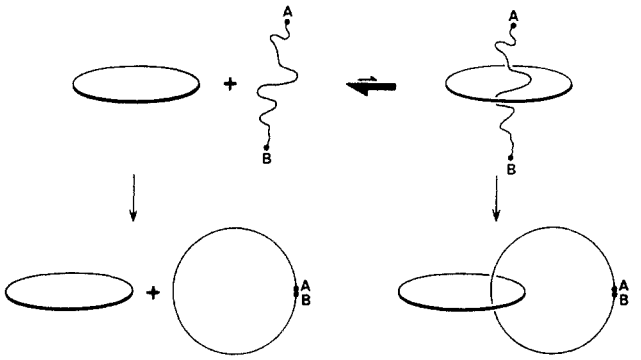


Figure 6. Increasing topological complexity of molecular graphs as defined by their *crossing number* (CN).

But if the topological complexity of a graph representing a given form of circular double-stranded DNA is described by its linking number as defined above,[19] such a definition may not be necessarily appropriate to describe the topological complexity of other molecules consisting of multiring interlocked systems. In fact, most molecules are not made up of two closed rings as is the case for circular duplex DNA, and consequently the mathematical model of a closed ribbon on which the definition of the linking number relies cannot suit these molecules. Therefore, to describe the topological complexity of any molecule (except those of double-stranded DNAs) we prefer to use the notion of a *crossing number*, which seems to be of more general use. For closed curves in a three-dimensional space, which are impossible to separate without breaking one of them, we define the crossing number as being the minimal crossing points appearing in a two-dimensional representation. With this *simplified definition*, the topological complexity of two separate rings, a [2]-catenane, a trefoil knot, or a [3]-catenane can be described by their crossing numbers, which are respectively 0, 2, 3, and 4 as shown in Figure 6.

II. Different Synthetic Routes to Catenanes

Although the existence of molecular interlocked rings was discussed as early as 1912 by Professor Willstätter,[22] it was only at the beginning of the 1960s that Frisch and Wasserman stated clearly by which routes the organic chemists could have access to such molecules:[4] "The formation of interlocking rings may be accomplished by the *statistical threading* of one ring by a linear



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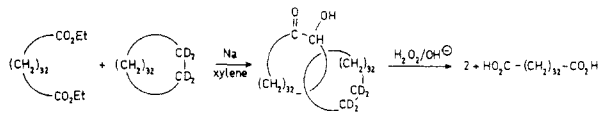


Figure 8.

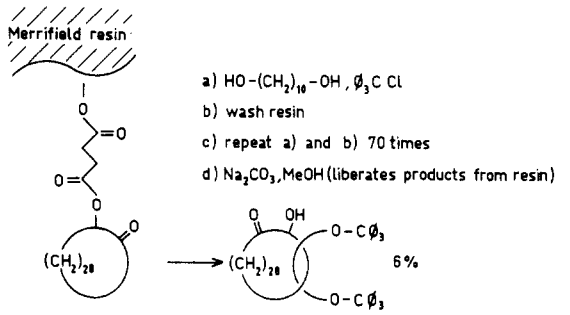
molecule which is to be formed into the second ring. Such a procedure utilizes the probability that the first ring, when sufficiently large, will take on a conformation which permits the precursor of the second to pass through. Alternatively, the two rings may be constructed about a *central core*, a procedure which should give rise to much higher yields of interlocking rings". A third approach, which may be considered a compromise between the pure statistical threading method and the directed synthesis around a central core, is the *Möbius strip approach.*

As will be shown below, all three approaches imply, at very different stages, formation of macrocycles. It is interesting to notice that good macrocyclization methods became precisely available a few years before Frisch and Wasserman conceived the different synthetical routes to catenanes. This coincidence is not a mere accident but confirms what we have already stated in the Introduction of this paper: the imagination of the chemist is dependent on the power of the synthetic tool.

A. Synthesis of Catenanes by Statistical Threading

The principle of this approach is very simple (Figure 7). A molecular thread A-B, functionalized on both ends, may enter into a macrocycle of adequate size: subsequent cyclization of A-B leads necessarily to two interlocked rings. But since the probability that cyclization occurs while the linear moleculea A-B is threaded through the macrocycle is very small, one can only expect poor yields in this kind of synthesis. Despite this fact, the first catenane ever evidenced results from such a threading process. In 1960, Wasserman[23] demonstrated that the acyloin fraction obtained by acyloin condensation of the diester **1** in the presence of the partly deuteriated cylic hydrocarbon **2** contained a small amount of catenane **3** (Figure 8).

Compound **3** could not be isolated, but the fact that the purified acyloin product still contained carbon–deuterium bonds (characteristic C–D stretches in IR) and about 1% of the deuteriated macrocycle **2** was recovered in addition to diacid **4** after oxidative cleavage



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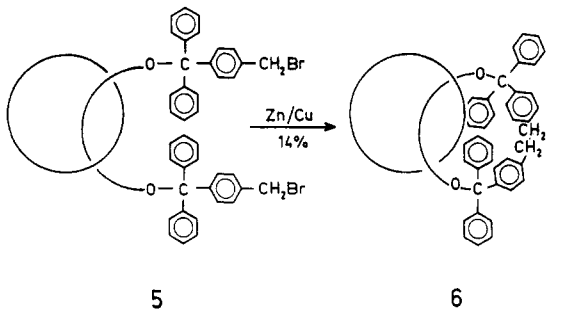

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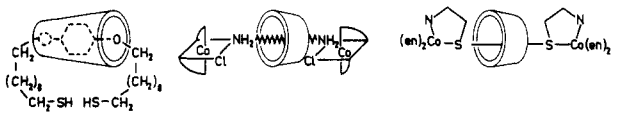
Figure 10. Double-stage catenane synthesis: statistical threading followed by intramolecular cyclization.



7 8 9

Figure 11. Threading of cyclodextrins by formation of inclusion complexes with linear molecules.

brings strong evidence for its formation.

A few years later in 1967,[8] Harrison and Harrison achieved the synthesis of a rotaxane in 6% yield by the repeated threading of linear decane-1,10-diol through a resin-bound macrocycle (Figure 9).

Even if the two previous examples have no synthetic value, historically they are of fundamental importance because they proved that Wasserman's statement[23] was not mere speculation. From a preparative point of view, statistical threading became significant with the work of Zilkha's group[10,24] (Figure 10); the rotaxane **5**, obtained with 18.5% yield by statistical threading of a "crown" polyether by poly(ethylene glycol) 400, leads to the catenane **6** after cyclization in high-dilution conditions (14% yield).

Another double-stage catenane synthesis starting from a statistically formed rotaxane was recently described by Schill and his co-workers.[25] Randomness, which is a highly limiting factor in the statistical syntheses of rotaxanes or catenanes discussed above, may become less determinant if the threading process is favored by an even weak interaction between the linear thread and the cycle. Such an attempt was described by Lüttringhaus and his co-workers[26] as early as 1958; they discuss the formation of a rotaxane like inclusion compound **7** between hydrophobic α- or β-cyclodextrin and aromatic long chain dithiols (Figure 11). Unfortunately, they could not achieve the expected ring closure that would have led to a catenane. Two other groups later utilized the same inclusion phenomenon to synthesize the first cyclodextrin ro-

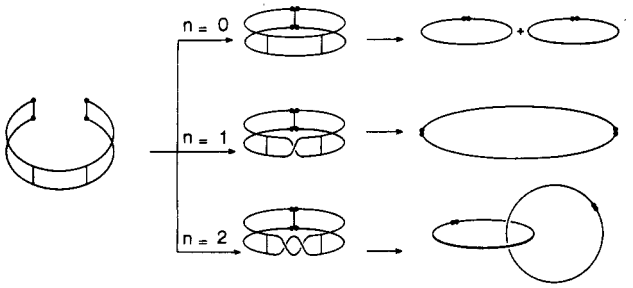


Figure 12. Principle of a catenane synthesis by preliminary construction of a Möbius strip.

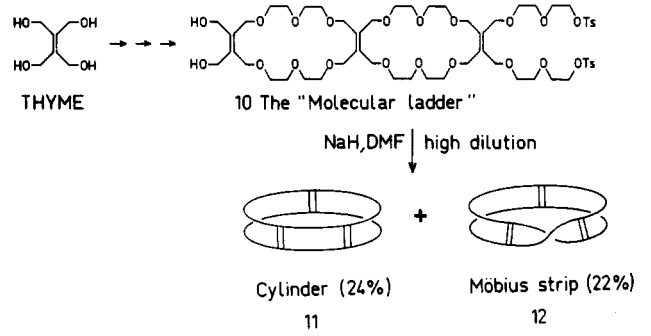


Figure 13.

taxanes 8[27] and 9[28] with yields up to 19 and 28%, respectively.

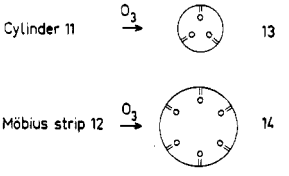
Catenane formation may also be markedly increased if cyclization, instead of occurring while a linear molecule is statistically threaded through a ring, occurs intramolecularly in a preshaped molecular edifice: such is the case with the Möbius strip approach.

B. Möbius Strip Approach

This approach, already considered by Wasserman[4] and Schill,[7] is based on a ladder-shaped molecule in which the ends are able to twist prior to bimacrocyclization. Figure 12 shows clearly that after cleavage of the vertical rungs one may have access to separate macrocycles or to a catenane, depending on the number (n = 0, 1, 2, ...) of the half-twists occurring before double-ring closure.

Recently, experimental work along this line has been performed. Walba and his co-workers achieved the synthesis of the first molecular Möbius strip in 22% yield.[29] Starting from tetrahydroxymethylethylene (THYME), they found the intermediate "molecular ladder" (compound **10** in Figure 13), submitted to cyclization, leads to an equimolecular mixture of the molecular cylinder **11** and its topological stereoisomer **12**.

The tris-THYME cylinder **11** and the racemic Möbius strip **12** could be readily separated by flash chromatography and their structures established unambiguously (single-crystal X-ray analysis for **11**, ^1H and ^{13}C NMR spectra for **12**). In addition, it was possible to demonstrate that compound **12** was chiral: addition of the Pirkle chiral solvating agent [(+)-2,2,2-trifluoro-9-anthrylethanol] allows NMR discrimination of the two enantiomers. Chemical cuttinf of the rungs was successfully achieved by selective ozonolysis[6] leading to the expected macrocycles **13** and **14** (Figure 14). Although these remarkable results are good conjecture for a catenane synthesis, achievement of the



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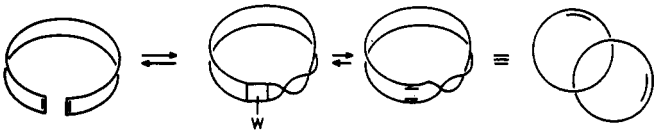

Figure 15.

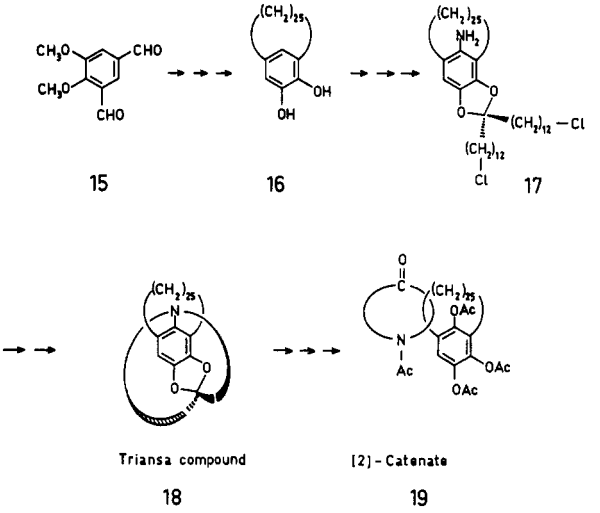

Figure 16.

latter still implies randomness; the statistical probability that the ends of a molecular ladder twist twice before cyclization, leading thus to the required single-full-twisted Möbius strip, remains quite small.

This severe restriction is also true for catenanes produced by olefin metathesis of macrocyclic polyenes. Basically, transition-metal-catalyzed cycloolefin metathesis occurs intermolecularly, leading to ring enlargement. However, when rings are large enough, an additional intramolecular metathesis process may also occur. But because of their flexibility, such large polyolefinic rings can undergo twisting prior to the metathesis as shown in Figure 15. Thus, by this process closely related to the Möbius strip approach, catenanes and knots can be formed.

The first indication that catenanes can indeed be obtained by cycloolefin metathesis was simultaneously given by Wolovsky, Wasserman, and co-workers[30] in 1970; by careful mass spectroscopy analysis, the authors could show the formation of interlocked rings during the tungsten-catalyzed metathesis of cyclododecene. Of course, the results discussed above deal with microquantities. The development of a real preparative procedure based on this principle is not to be expected.

From the preceding discussion it appears clearly that both the pure statistical threading approach and the Möbius type approach are dependent on statistical probability. Randomness may be totally excluded from a synthesis in which the different subunits, precursors of the catenane, are gathered in a rigid molecular edifice so that cyclization can only occur in a predetermined way. Such a fundamentally different route to catenanes

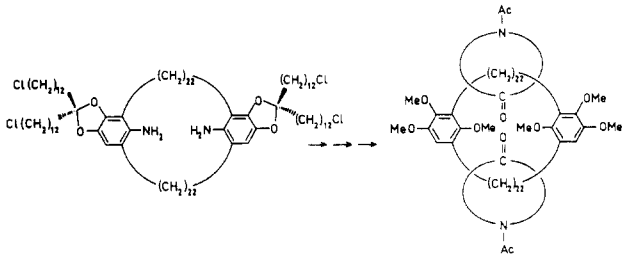

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Figure 17.

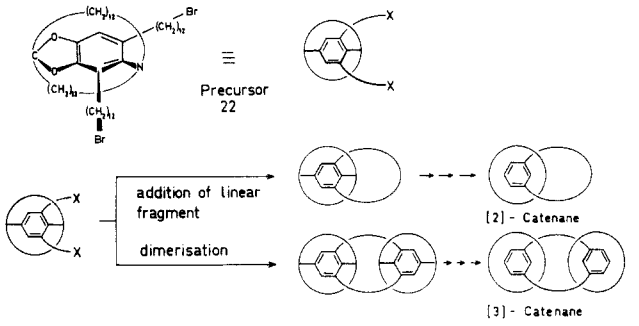

Figure 18.

was successfully developed by Schill and Lüttringhaus as early as 1964.[31]

C. Schill–Lüttringhaus Directed Catenane Synthesis

The elegant synthetic pathway conceived by these authors is given in Figure 16. In this multistep synthesis, which starts from 4,5-dimethoxy-isophthalaldehyde (**15**), compound **17** appears as a key intermediate: Euclidean geometry (bond angles, bond lengths, tetrahedral structure of the ketal carbon atom, size of the polymethylene macrocycle, length of the alkyl chloride chains) imposes intramolecular macrocyclization in a unique way. Alkylation of the amino group occurs only with the two alkyl chloride chains located one above and one below the plane central benzene ring. Selective cleavage of the aryl–nitrogen bond and hydrolysis of the ketal in triansa compound **18** leads, as expected, to [2]-catenane **19**.

A few years later the same approach allowed Schill and co-workers[32] to obtain [3]-catenane **21** in moderate yield (Figure 17). Compound **20**, a higher homologue of **17**, is now the key intermediate that ensures the topological stereocontrol during the intramolecular macrocyclization step. In order to develop the directed-synthesis approach to catenanes, rotaxanes, and knots, Schill and his group synthesized another universal precursor **22** in which the required groups are maintained in fixed positions.[33] With this precursor they could obtain either a [2]-catenane[34] or a [3]-catenane[35] by the strategies shown in Figure 18.

Whatever the precursor used, **17** or **22**, the pathways followed in the above-described syntheses ensure the formation of interlocked rings. Nevertheless, because of the numerous steps involved, large-scale preparation of catenanes via the Schill–Lüttringhaus strategy remains a highly difficult task.

From what is shown above, Schill's directed synthesis of catenanes may be considered as relying on a central

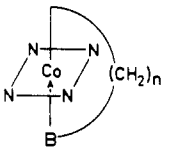

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Figure 19. Cobalt complex having a catenane structure, as conceived by Sokolov.[37] The four nitrogen atoms occupying the equatorial positions of the octahedron are supposed to be included in a ring. Sokolov noted that "the macrocycle is completed at the cobalt atom by means of a σ-bond with carbon and a donor–acceptor bond with a basic group B (e.g. phosphine or amine)".

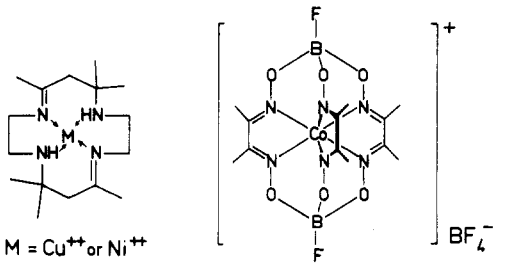

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Figure 20. 24: Curtis aliphatic Schiff base complexes of nickel(II) or copper(II). 25: Boston and Rose encapsulated cobalt(III) complex.

core, the benzo-ketal group, around which the different rings are built up.

Another central core, in the way Wasserman defined it,[4] could be a transition metal. Interestingly, such an approach, based on a template effect, was formulated twice in the past two decades.

In 1961, Wasserman stated[36] "Another interesting suggestion has been that of Closson to utilize the geometry of the ligands about a metal as a core".

In 1972, Sokolov reported[37] "Coordination compounds of metals can be used as scaffolding for building up catenoid structures". Sokolov went even further in his conjecture by imagining an amminepolymethylene complex **23** (Figure 19); its structure would be "formally of the catenane type, but (it) differs in having nitrogen–cobalt coordinate bonds between the two rings". Although only speculative, Sokolov's discussion is of high interest in chemical topology, presenting various routes to templated threading of molecules.

D. Template Synthesis of Interlocked Macrocyclic Ligands: Synthesis of [2]-Catenands

Transition metals, with their ability to gather and dispose ligands in a given predictable geometry, can induce what is generally called a "template effect". This specific property of transition metals has been widely used for the template syntheses of various single macrocycles,[38] one of the earliest examples being probably Reppe's cyclooctatetraene synthesis in which a nickel atom is supposed to bring together four acetylene molecules around it prior to cyclotetramerization.[39] Other well-known examples of early coordination template syntheses are given by the metallophthalocyanins preparations[40] as well as by the copper(II) and nickel(II) aliphatic Schiff base complexes **24** (Figure 20) first obtained and recognized by Curtis in 1961.[41] Based on analogous condensation reactions between copper(II) or nickel(II) diamine complexes and aliphatic ketones

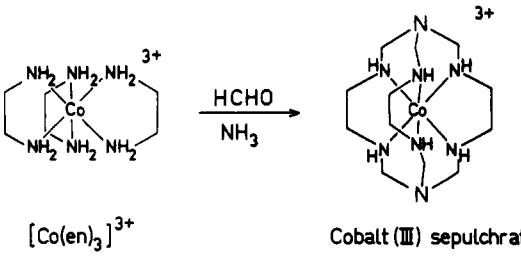


Figure 21.

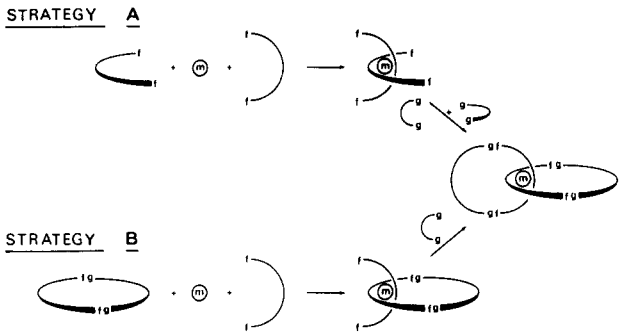


Figure 22. *Synthetic strategies based on a three-dimensional template effect induced by a transition metal.* Functions f and g react to form the links. The molecular fragment f–f interacts with a transition metal (m) bearing or not bearing auxiliary ligands. This metal disposes fragments f–f (linear or already included in a cycle) perpendicular to one another.

or aldehydes, a great variety of tetradentate macrocyclic ligands has been subsequently synthesized.[42] It is nevertheless interesting that most of the numerous template syntheses reported in the literature occur in a two-dimensional space; in contrast, there are only a very few syntheses which rely on reactions between ligands prearranged around the metal in a three-dimensional space.

An illustration of such a three-dimensional (or generalized) template effect is given by the results of Boston and Rose,[43a] who prepared the clathro chelate **25** derived from dimethylglyoxime, boron trifluoride, and cobalt(III). Soon after, Parks, Wagner, and Holm reported analogous three-dimensional macrocyclic encapsulation reactions occurring between tris[2-(oximinomethyl)-6-pyridyl]phosphine and boron trifluoride or tetrafluoroborate.[43b] Another more recent example of the generalized template effect induced by a transition metal is given by the beautiful cobalt(III) sepulchrate synthesis performed by Sargeson and his coworkers.[44] As shown in Figure 21, the reaction between $[Co(en)_3]^{3+}$, HCHO, and NH_3 leads, in one single step with 74% yield, to a macrobicyclic complex in which the ligand encapsulates completely the cobalt ion.

In recent years, efficient synthesis of interlocked macrocyclic ligands has been developed in our laboratory. For now, we are thus going to focus more on the work of our research group.

A generalized template effect may be envisaged for the building up of a catenane structure: synthesis of interlocked rings by such a route requires that the ligands set around the metallic center are adequate molecular threads which can be formed into rings in later stages. Two possible strategies for a [2]-catenane template synthesis are given in Figure 22.

In contrast to the very straightforward strategy A in which the simultaneous pairwise connection between eight reacting centers should lead to a catenane,

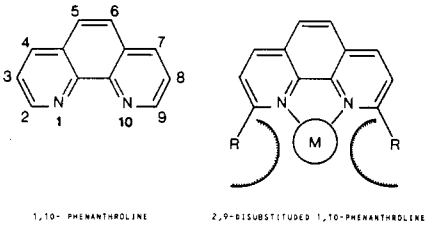


Figure 23.

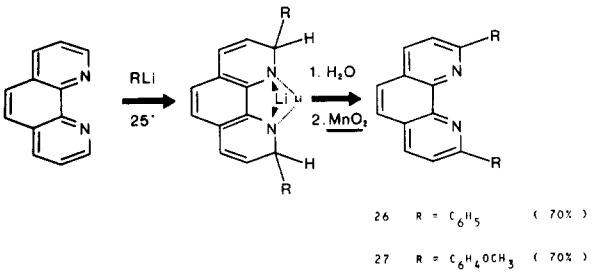


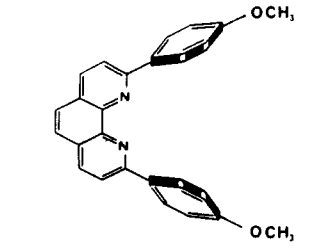
Figure 24. Synthesis of 2,9-disubstituted 1,10-phenanthroline via organolithium compounds RLi (R = CH_3, C_2H_5, n-C_4H_9, t-C_4H_9, C_6H_5, p-$C_6H_4OCH_3$).

strategy B requires the preliminary synthesis of a given macrocycle and thus, at a first look, appears less attractive. Nevertheless, this implies in counterpart that the last cyclization step leading to a catenane structure will only involve connection of four reacting centers. From a statistical point of view, strategy B should thus be more favorable than A. To decide which strategy should be tried first is difficult but, in fact, not crucial; much more important is the choice of the different subunits: nature of the coordinating fragment f–f, nature of the transition metal, length of the link g–g.

By the time we started this work we were already involved in the synthesis of 2,9-disubstituted 1,10-phenanthrolines (Figure 23) and their transition-metal complexes. Earlier studies had shown that rhodium or iridium complexes of such ligands are efficient catalysts in the water gas shift reaction:[45] bulky substituents α to nitrogen, in other words, close to the coordination sites, favor unsaturation on the metal and consequently allow fixation and activation of small molecules. But since such ligands were not readily available, (2,9-diphenyl-1,10-phenanthroline (**26**), for example, is prepared by a tedious Skraup reaction with less than 1% yield),[46] we developed an efficient synthetic method that allows easy preparation of various 2,9-disubstituted phenanthrolines in good yields.[47] Our method, based on a direct nucleophilic attack of 1,10-phenanthroline by a lithio derivative followed by hydrolysis and rearomatization, proved to be very general and is depicted in Figure 24.

Due to the now easy access to this class of ligands we were able to study their coordination chemistry. In particular, we could show that in the presence of copper(I) the 2,9-dianisyl-1,10-phenanthroline (**27**) forms a very stable pseudotetrahedral complex 28^+ in which the two ligands "fit-in" around the metallic center as shown in Figure 25. The very special topography of this type of copper(I) complex could be evidenced by an extensive NMR study.[48]

At the same time it became clear to us that copper(I) complexes with such topography could be the perfect precursors or "building-blocks" for a templated catenane synthesis as described in Figure 26, the only re-



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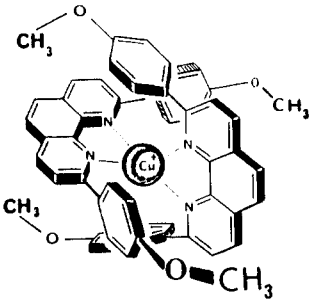


28^+

Figure 25. In the copper(I) complex 28^+, the two highly rigid coordinating subunits **27** fit together while encaging the metal atom.

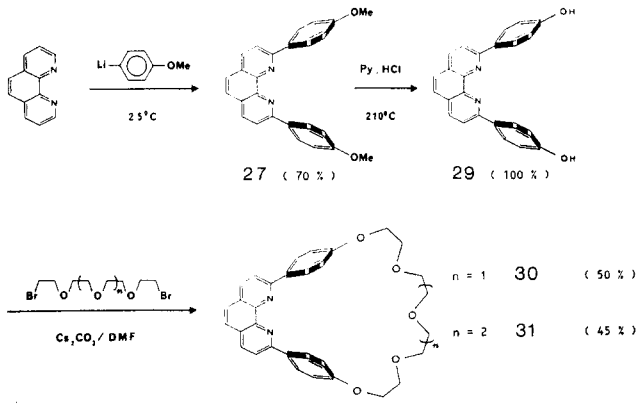


Figure 26.

quirement being functionalization of the ligands beyond the coordination sites; 2,9-dianisyl-1,10-phenanthroline (**27**) appeared to be a most suitable precursor for the fragment f–f.

Although strategy B is longer than strategy A, it offered the advantage to proceed step by step. In other words, it appeared to us to be the less risky route, and for this reason we tried it first.

1. Template Synthesis of Catenate 33^+ via Strategy B

The functionalized ligand 2,9-bis(*p*-hydroxyphenyl)-1,10-phenanthroline (**29**), precursor of all our catenanes syntheses, is prepared by addition of lithioanisole to 1,10-phenanthroline, leading to 2,9-dianisyl-1,10-phenanthroline (**27**), which is subsequently deprotected with pyridinium chlorhydrate. In the presence of a large excess of cesium carbonate in dimethylformamide (DMF) and under high-dilution conditions, **29** reacts either with 1,11-dibromo-3,6,9-trioxaundecane or with 1,14-diiodo-3,6,9,12-tetraoxatetradecane, providing the preliminary macrocycles **30** or **31** (respectively 27 and 30 atoms in the cycle) as depicted in Figure 26.[49]

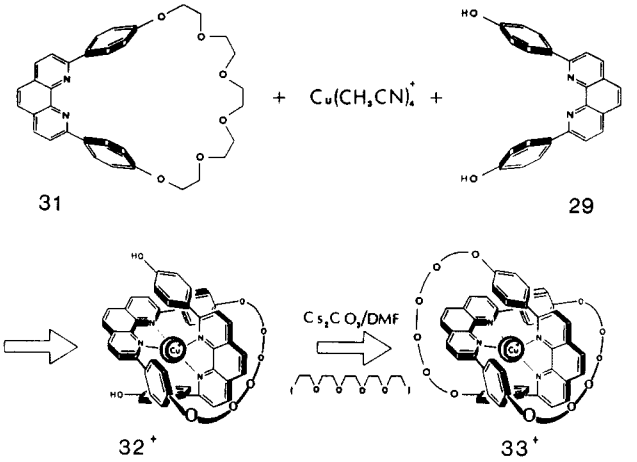


Figure 27. Template synthesis of the copper(I) catenate 33^+ via strategy B.

Because it turned out that macrocycle **30** was too small to allow efficient interlocking following a synthetic procedure analogous to that described in Figure 27, we used afterward exclusively **31**. The stable precursor 32^+ (Figure 27) is obtained quantitatively by mixing stoichiometric amounts of **31**, $Cu(CH_3CN)_4^+ \cdot BF_4^-$, and **29**. The final cyclization step is done by adding an equimolar mixture of 32^+ and a diiodo derivative of pentaethylene glycol on a large excess of Cs_2CO_3 in DMF. After workup, 33^+ (made of two interlocked 30-atom rings and a central copper(I) atom) is obtained as nice dark red needles in a 42% yield with respect to **31**. Because of the topography (ligands fit in together around copper(I)) and the symmetry properties of the molecules, it was possible, by high-resolution NMR, to identify, step by step, all the intermediates produced along the synthetical pathway described in Figures 26 and 27 and thus gain first evidence of the catenane structure of $33.^+$.[50] Due to the catenane topology of the ligand part of 33^+ and to its nature as a transition-metal complex, we propose to name compounds like 33^+ *catenates*.

2. One-Pot Template Synthesis of Catenate 33^+ via Strategy A

After this first very encouraging result, we tried also to prepare catenate 33^+ by strategy A. In the presence of $Cu(CH_3CN)_4^+ \cdot BF_4^-$, two ligands **29** fit together by forming the very stable copper(I) complex 34^+. The latter reacts with two g–g chains; with g–g being the diiodo derivative of pentaethylene glycol we obtain, by this very simple procedure, the expected catenate 33^+ in a 27% yield.[51] Besides 33^+, about 20% of macrocycle **31** as well as open-chain compounds of high molecular weight are formed; surprisingly, we could not detect formation of a complexed dimeric macrocycle 35^+ (Figure 28). When the overall yields starting from commercial 1,10-phenanthroline are considered, strategy A (3 steps, 20% yield) appears superior to strategy B (4 steps, 14% yield). Henceforth, gram-scale preparation of catenate 33^+ will be done by this most convenient one-pot synthesis. The longer strategy B remains interesting, nevertheless, for the synthesis of mixed catenanes, i.e., catenanes in which the two interlocked rings differ by size or nature, as exemplified later.

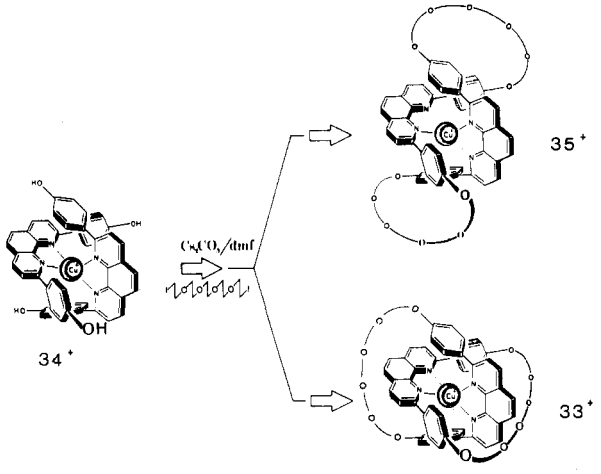


Figure 28. One-pot template synthesis of 33^+ (strategy A).

3. Demetalation of Catenate 33^+: Obtention of the Free Ligand 36

Shortly after we achieved the synthesis of catenate 33^+ arose the crucial puzzling question: will it be possible to disentangle the molecular edifice built around the copper(I) and get rid of it without destroying the entire catenane structure? Such a problem was encountered by Sargeson and co-workers when they tried to take the Co(III) out of their cobalt(III) sepulchrate.

Complex 33^+ could be quantitatively decomplexed by treatment with potassium cyanide, affording the free ligand **36** (Figure 29). The catenane structure of the free ligand thus prepared was primarily determined by NMR and mass spectroscopy.[51] Both techniques brought very interesting and complementary information, showing that the new ligand obtained still contains two interlocked macrocycles. We therefore proposed the name *catenand* for this new class of coordinating molecules.

Mass spectra (Figure 30) show that, except for the molecular ion peak at M 1132, no fragmentation occurs until the molecular peak of the monomeric ring **31** (566) is reached. This means that after the first fragmentation the mechanical link between the two subunits no longer exists; the linear part is threaded out from the intact remaining ring, and both species undergo further fragmentations. Such a pattern is characteristic of a catenane structure as already reported by Schill and his co-workers.[52] On the other hand, ^{1}H NMR studies evidence a complete conformational change that occurs during the decomplexation process. The two coordinating 2,9-diphenyl-1,10-phenanthroline (dpp) subunits, which fit in together while encaging the metal atom in the catenate 33^+, disentangle completely and stay far apart one from the other in the free ligand. This detailed NMR analysis constituted the first proof of the catenand structure of **36**. Molecular structures for both catenate 33^+ and free ligand **36** as jointly given by NMR and mass spectroscopy could later be fully confirmed by crystallographic studies.[53] These structures (Figure 31) show that the respective molecular shapes of 33^+ and **36** are totally different despite the fact that both molecules present identical bond connectivity in their organic skeleton; made up each of two interlocked rings, they have the same molecular topology but exhibit different shapes.

In 33^+ entwining of the dpp subunits by complexation to copper(I) leads to a relatively compact molecular edifice in which the coordination polyhedron is highly distorted as compared to tetrahedral geometry. This strong distortion might originate from charge-transfer interactions between the phenanthroline nucleus of one macrocyclic subunit and the phenyl groups of the other; it makes the metallic center easily accessible by small chemical species like CN^-. The strikingly different molecular arrangement of the free ligand with its two dpp subunits fully disentangled and its two virtual coordinating sites ca. 11.2 Å apart supposes that during decomplexation the two interlocked rings glide freely through one another.

This gliding, responsible for the conformational changes discussed above, might be totally inhibited if one of the macrocyclic subunits bears bulky substituents. Such a catenane would have an additional rotaxane character and could lead to isomers as shown in Figure 32. If the fragments (a) and (b) are different, compounds **37** and **38** will be distinct and cannot interconvert, provided the R groups are too bulky to pass through the ring. These isomers, topologically indistinguishable (same bond connectivity and same crossing number) but topographically distinct (different shapes in Euclidian geometry) are best described as "translational" isomers. Syntheses of translationally isomeric [3]-catenanes[32b] and rotaxanes[25] has been recently reported by Schill and his co-workers.

4. Synthesis of a Rigid Catenand

Following strategy B of Figure 22, we achieved the synthesis of a new catenate 44^+ and its corresponding free ligand **45** whose molecular structures are both equivalent to **38**. The starting compounds and the synthetic pathway used are described in Figure 33. Compound **39**, prepared with an 80% yield by reaction of lithioanisole with 4,7-diphenyl-1,10-phenanthroline, is, after deprotection, submitted to cyclization, under conditions similar to those previously described.[47,49] Macrocycle **42** is thus obtained in 53% yield. Stepwise addition of $Cu(CH_3CN)_4^+ \cdot BF_4^-$ and **29** to a solution of **42** gives quantitatively the precursor 43^+. The latter

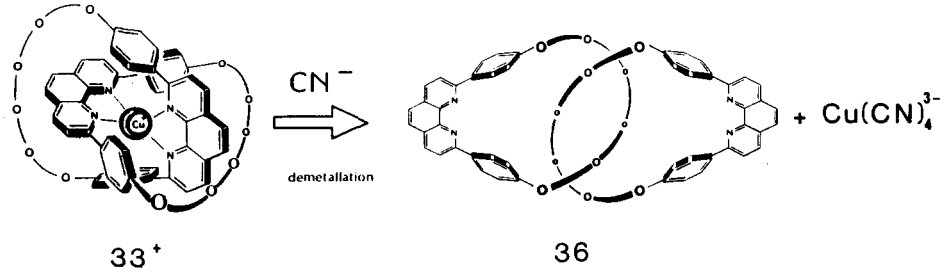


Figure 29. Demetalation of 33^+, leading to the [2]-catenand **36**.

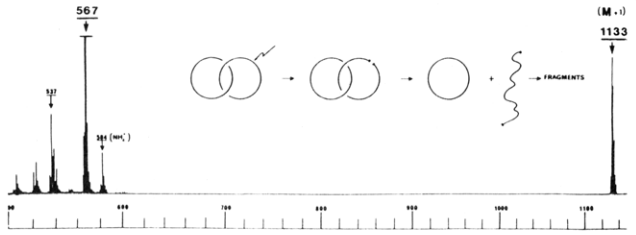
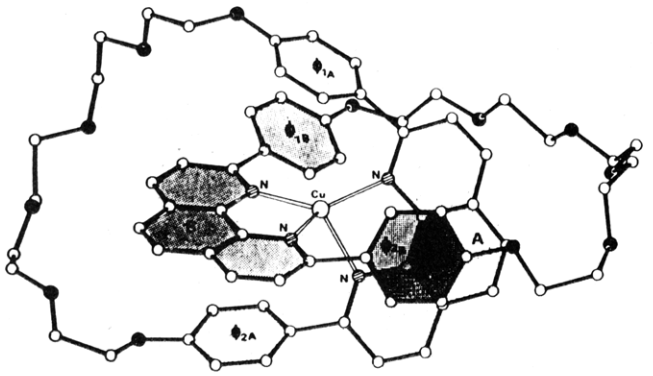


Figure 30. Mass spectrum of **36**; chemical ionization; carrier gas NH_3.



33^+

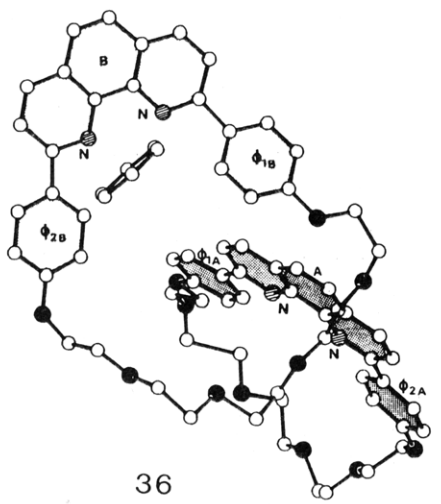


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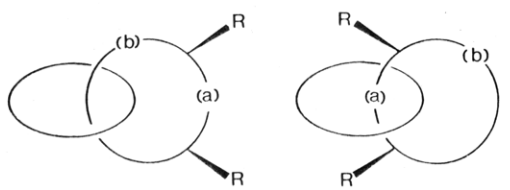
Figure 31. Molecular structures of the copper(I) catenate 33^+ and its corresponding free ligand **36**.



37 38

Figure 32.

reacts with the diiodo derivative **41** under conditions analogous to those earlier described.[50] After workup, the catenate 44^+ is isolated as its BF_4^- salt in 7% yield. This poor yield is accounted for by the steric hindrance encountered by the poly(oxyethylene) chain that has to pass between two phenyl groups in 43^+ in the last cyclization step. The free catenand **45** (Figure 34) is obtained by demetalation in the presence of KCN. This decomplexation reaction is much slower that the one observed for catenate 33^+. The decrease in the dissociation rate reflects the effect of the two phenyl rings introduced in the rear of one phenanthroline: the relative mobility of the two macrocyclic subunits is highly reduced if one poly(oxyethylene) chain is confined between the two phenyl nuclei (**38** in Figure 32). Such a situation allows only limited conformational changes and, as a consequence, makes copper(I) decomplexation particularly unfavorable.

An extended NMR study[54] confirms the restricted mobility of the catenand **45**. In the latter, the two dpp fragments are still entwined, although no gathering transition metal is present. This situation is drastically different from that observed when there are no phenyl rings in the back of one phenanthroline: in the catenand **36** the two dpp fragments are fully disentangled both in solution[50,51] and in the solid state.[53] In the rigid catenand **45**, predisposition of the coordination site should lead to novel complexing properties with respect to flexible catenands.

E. Extension of the Templated Strategy to Multiring Interlocked Coordinating Systems

1. Early Approach with Poly(oxyethylene) Links

Later on we tried to generalize our synthetic strategy based on the templating effect of copper(I) in 1,10-phenanthroline molecular systems in order to prepare [3]-catenanes, which are topologically more complex than [2]-catenanes (crossing number = 4 instead of 2). The principle of our strategy is represented in Figure 35. As it appears clearly in Figure 35, dimerization leading to a [3]-catenate may only occur if the linking fragment used in the cyclization step is too short to allow intramolecular ring formation. Such a prerequisite could be fulfilled by short chains like dibromo derivatives of tri- or tetraethylene glycol (**46** or **47**). Reaction of precursor 32^+ with **46** or **47** under high-dilution conditions, in the presence of Cs_2CO_3, affords poor yields of the expected dinuclear [3]-catenates 48^{2+} (6%) or 49^{2+} (2%) as shown in Figure 36.[55] Demetalation of 48^{2+} or 49^{2+} by KCN leads respectively to the [3]-catenands **50** (15%) or **51** (82%) (Figure 37).

These results point out the importance of the size of the central ring, both during the cyclization step and for demetalation. [3]-Catenate 48^{2+} contains a 48-membered central ring, which is more easily formed than the 54-membered cycle of 49^{2+}, as reflected by their respective yields of preparation. On the other hand, since the latter [3]-catenate is more flexible than 48^{2+}, it is more readily demetalated. The high rigidity of 48^{2+} is due to the relatively small size of the central ring that surrounds two copper atoms and two 1,10-phenanthroline subunits. Such a stretched arrangement prevents the three cycles from sliding freely one into the other, as required during the decomplexation process.

2. [3]-Catenane Synthesis by Acetylenic Oxidative Coupling

Poor yields and very tedious reaction workups for the preceding discussed [3]-catenates syntheses led us to develop a new and highly efficient method of preparation of [3]-catenates based on acetylenic oxidative

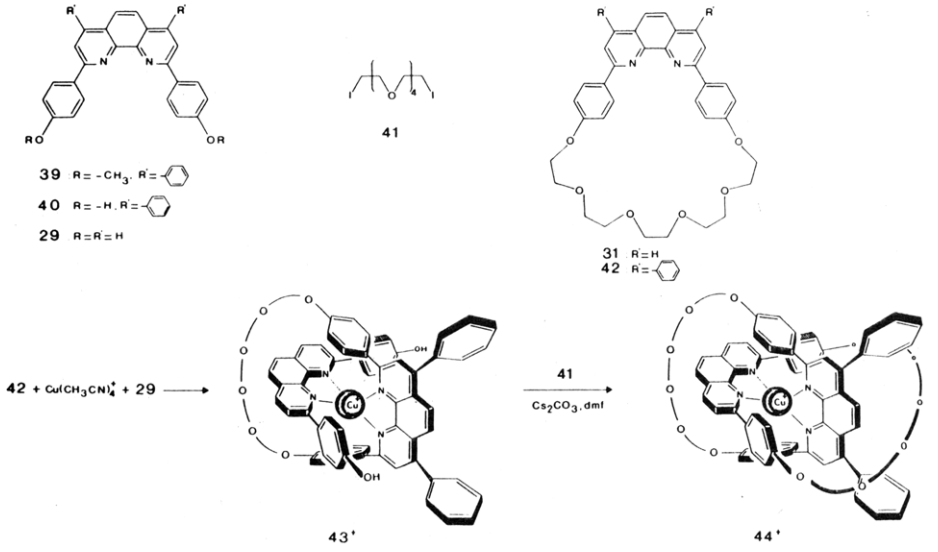


Figure 33.

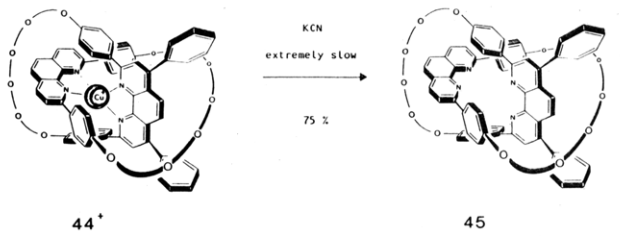


Figure 34. Catenand **45** has an entwined topography, analogous to that of the catenate 44^+.

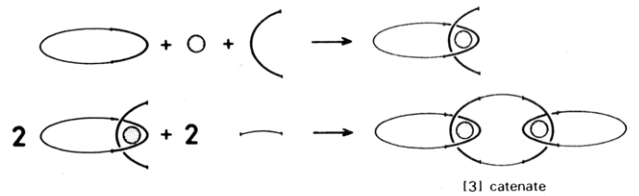


Figure 35. Principle of templated synthesis of a [3]-catenate. The transition metal disposes the two coordinating fragments (thick line) perpendicular to one another. The cyclization step involves two additional short linear links (thin line): it requires the participation of 8 reacting centers.

coupling. The strategy corresponds to a true cyclodimerization, involving four reacting centers only, in contrast to the above synthesis that required eight centers to be linked. The principle of this synthesis is given in Figure 38.

Oxidative coupling of terminal acetylenes (Glaser reaction) has been applied to diyne systems for many years. By intramolecular coupling, macrocyclic diynes have been obtained, whereas tetraacetylenes are formed by oxidative cyclodimerization.[56,57] The latter reaction has been taken advantage of for making rigid paracyclophanes designed as molecular receptors.[58] Furthermore, cyclodimerization of a triacetylenic compound has recently been carried out with a surprisingly high yield.[59]

The precursors used and the reaction scheme are represented in Figure 39. The open-chain diacetylene **52** was prepared in 80% yield from the diphenol **29** and propargyl bromide in the presence of Cs_2CO_3. Diacetylenic precatenate $\mathbf{53}^+$ was obtained from macrocycle **31**, $Cu(CH_3CN)_4^+ \cdot BF_4^-$, and **52**. The oxidatively coupling leading to $\mathbf{54}^{2+}$ was performed in DMF in the presence of CuCl, $CuCl_2$, and air. After reaction workup, the dinuclear [3]-catenate $\mathbf{54}^{2+}$ is obtained in 58% yield. This strikingly high yield allows gram-scale preparation of the latter compound.[60]

Demetalation of $\mathbf{54}^{2+}$ afforded the free ligand **55** in 75% yield (Figure 40). Its ^1H NMR spectrum clearly shows the disentangling of the dpp fragments.

The unexpected high efficiency of the above-described [3]-catenate synthesis allows us to foresee various other interesting, from a preparative point of view, applications. This acetylenic oxidative coupling method should give much easier access to [2]-catenanes in high yields and will possibly also allow the synthesis of topologically more complex molecules. On the other hand, the easy access to [3]-catenand **55** will facilitate

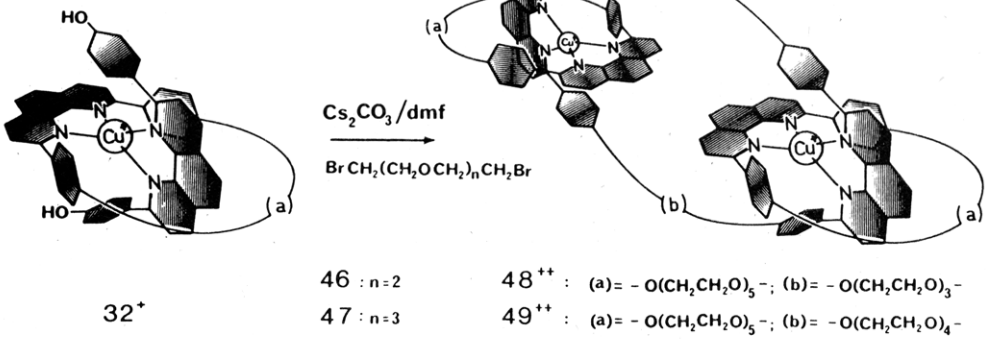
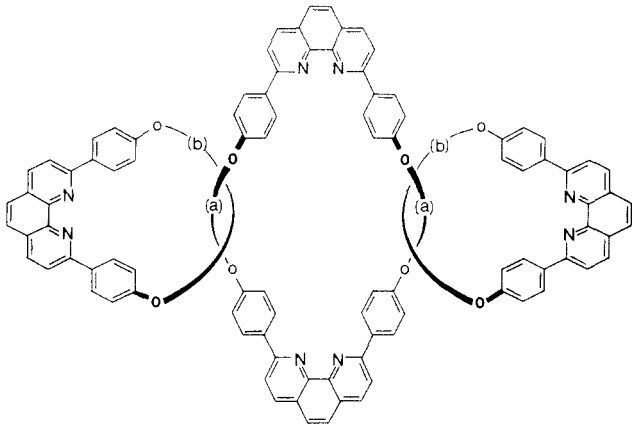


Figure 36.



50 (a)= $-O(CH_2CH_2O)_5-$; (b)= $-O(CH_2CH_2O)_3-$

51 (a)= $-O(CH_2CH_2O)_5-$; (b)= $-O(CH_2CH_2O)_4-$

Figure 37.

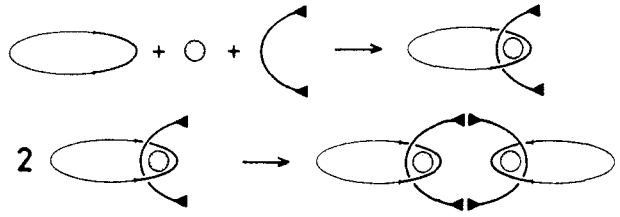


Figure 38. Principle of a [3]-catenate template synthesis based on an acetylenic oxidative coupling. The dark triangles represent the anchoring points.

studies concerned with the specific properties of this new ligand; [3]-catenand **55** may be well adapted to the preparation of heterobinuclear complexes or to the investigation of electron-transfer reactions.

III. Catenands, a New Class of Coordinating Molecules

Owing to the interlocking of coordinating macrocyclic subunits, catenands form a new class of ligands displaying very special coordinating properties. In the following discussion, we shall always try to separate factors originating from the special *shape* of the coordination polyhedron around the transition metal, namely, its *topography*, from those due to the *catenane nature* of the ligand, i.e., its *topology*.

Having at our disposal open-chain ligands like 2,9-dimethyl-1,10-phenanthrolines **56** and **27** as well as some of the monocyclic subunits that constitute the catenands, we have also studied their coordinating properties. By comparison, it is relatively easy to extract specific factors attached to topography or topology from the overall coordinating properties of the various systems. The very general trend of catenands is to bind transition metals and other cationic species, forming catenates. The latter belong to the broad family of cage complexes such as cryptates,[6] although the association phenomenon between the ligand and the cation to be complexed is highly different in principle. As will be discussed below, catenands do not possess a preformed and hollow binding site but must reorganize completely their structure in order to adapt themselves to the complexed species. The formation of catenates has been observed by NMR studies as well as by preparative methods. In view of the surprising stabilization of transition metals in their lowest oxidation states, electrochemical studies have also been performed and will be discussed. In addition, some kinetic properties of the complexes obtained have been studied and compared to those of the corresponding complexes formed with acyclic ligands.

A. Formation of Catenates from Various Cationic Species

Catenates are easily prepared from the catenand and the appropriate metal salt.[62] For instance, catenates prepared from **36** and Li^+, Zn^{2+}, Cd^{2+}, Ag^+, Ni^{2+}, Co^{2+}, etc. could be synthesized. At the moment, preparative studies have been restricted to the catenates of **36**, but it is clear that other ligands such as **45** or multiring systems like **55** should also be investigated in the future. ^1H NMR spectroscopy turns out to be a highly con-

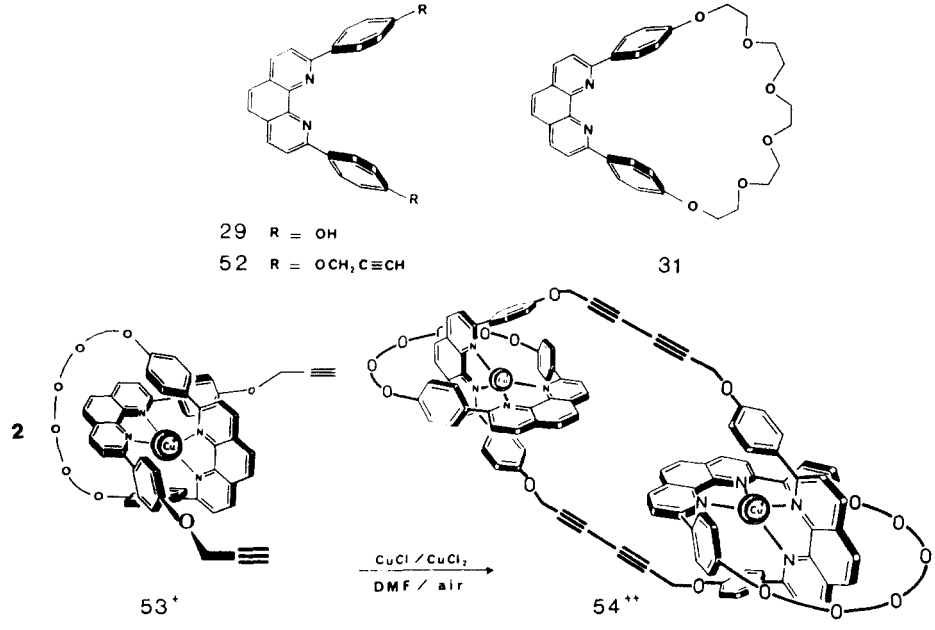
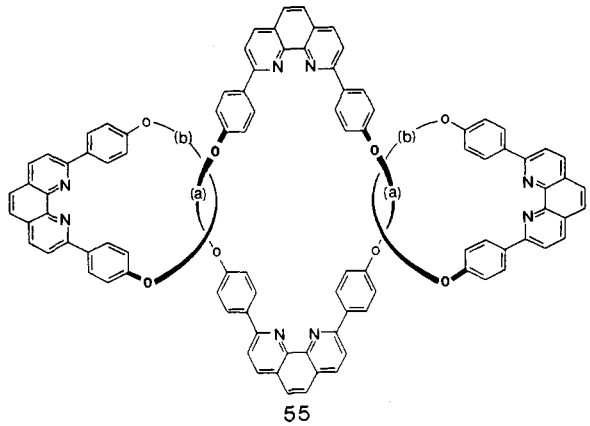


Figure 39.



55

(a) : $-CH_2-C\equiv C-C\equiv C-CH_2-$

(b) : $-CH_2CH_2(O-CH_2CH_2)_4-$

Figure 40.

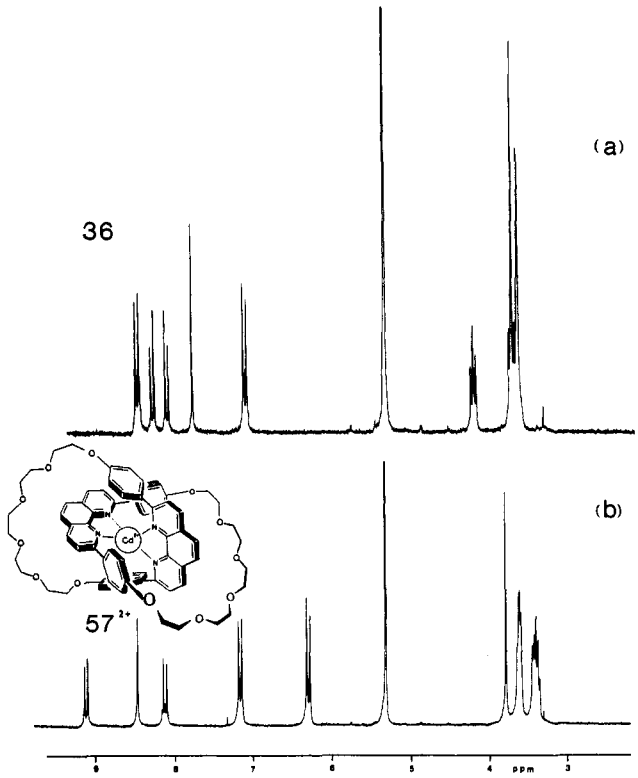


Figure 41. 200-MHz ^1H NMR spectra of (a) the free ligand **36** and (b) the Cd^{2+} catenate $\mathbf{57}^{2+}$ in CD_2Cl_2.

venient method for observing the formation of catenates.[51] This is due to the special topography of the molecular system and to the important geometrical changes accompanying the complexation phenomenon. In particular, several protons show a characteristic variation of their chemical shift, owing to the highly different environment on going from the catenand to its complexes. An example is given in Figure 41.

The two dpp fragments fit together in the cadmium complex $\mathbf{57}^{2+}$, whereas in the catenand **36** the two phenanthroline subunits are completely separate. This difference has a profound effect on the ^1H NMR spectra. Before complexation, the chemical shifts for Ho, Hm, and $CH_{2\alpha}$ have normal values (Figure 41a); once the Cd^{2+} catenate is formed, due to the intense ring-current effect of the phenanthroline nucleus, Ho, Hm, and $CH_{2\alpha}$ resonance signals appear at abnormally

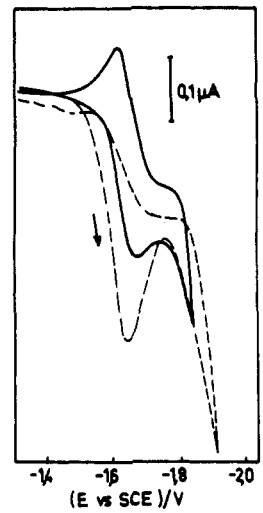


Figure 42. Cyclic voltammograms of $\mathbf{33}^+$ (full line) and $\mathbf{28}^+$ (dashed line) in DMF; 0.1 M $N(n\text{-}C_4H_9)_4^+ \cdot ClO_4^-$; room temperature; mercury cathode; scan rate = 10 mV/s.

high field (Figure 41b). The particular topography of the ligand **36** in its complexes is expected to highly favor a (distorted) tetrahedral geometry around the metal center. In addition, due to the interlocking of the two coordinating macrocyclic subunits, highly stable complexes are expected. In this respect, it is interesting to compare the complexing power of the catenand **36** to that of its open-chain analogue **27**. For several cases, it is impossible to prepare complexes of **27** due to their favored dissociation, whereas the corresponding catenates seem to be perfectly stable under identical conditions.

B. Stabilization of Low-Oxidation States: Electrochemical Studies

As mentioned above, the catenand **36** is almost ideally adapted to pseudotetrahedral geometries. On the other hand, the formation of octahedral complexes with participation of the four nitrogen sites of **36** plus two additional ligands seems to be virtually impossible. Such a situation is expected to strongly destabilize complexes whose metal is in a high-oxidation state. As a consequence, reduced states will be apparently unusually stable. A detailed electrochemical study of several catenates has been carried out,[62] amply demonstrating strong stabilization of low-oxidation states in catenates, but we shall only consider two spectacular cases in the present paper.

1. A Highly Reduced Copper Complex: Solution Preparation of a Formally Copper(0) Catenate

The copper(I) catenate $\mathbf{33}^+$ can be electrochemically reduced without demetalation.[51] At first, this was evidenced by cyclic voltammetry, as shown in Figure 42. At −1.7 V vs. SCE in DMF, the open-chain copper(I) complex $\mathbf{28}^+$ is first reduced to **28** followed by rapid dissociation to copper metal and **27**. In contrast, reduction of $\mathbf{33}^+$ under the same conditions is perfectly reversible, with no indication of **33** decomposition. Furthermore, the formally copper(0) complex **33** can be electrogenerated from $\mathbf{33}^+$. The dark blue solution obtained is stable for days at room temperature under argon. Complex **33** is probably a copper(I) stabilized radical anion, the electron being located on a dpp sub-

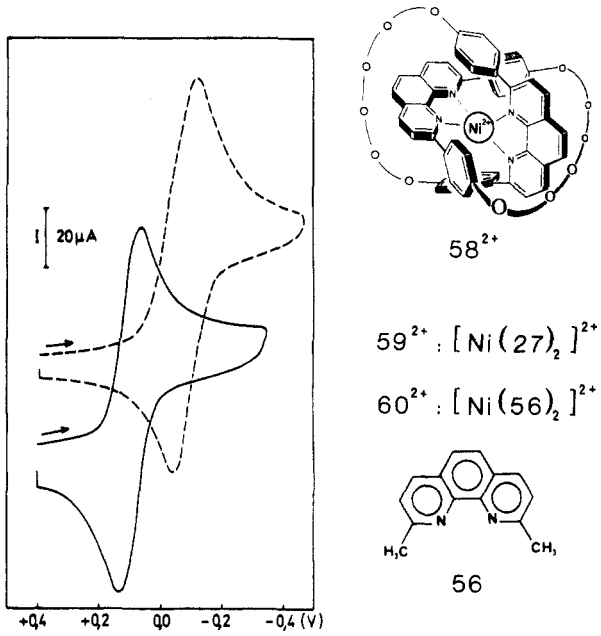


Figure 43. Cyclic voltammograms of 58^{2+} (full line), 59^{2+} (superimposable to that of 58^{2+}), and 60^{2+} (dashed line) in CH_2Cl_2; 0.1 M $N(n\text{-}C_4H_9)_4^+ \cdot ClO_4^-$; room temperature; reference electrode $Ag/Ag_3I_4^-$; mercury cathode; scan rate = 50 mV/s.

unit. In this respect, **33** is somewhat similar to $Ru(bpy)_3^{+}$[63] (bpy = 2,2′-bipyridine): the +1 oxidation state of the ruthenium atom is only formal. The situation is more properly described as a d^6 ruthenium complex (oxidation state of +2), one of the ligands having a radical anion character (bpy^-).

It is extremely unusual that copper complexes survive in such a highly electron-rich environment as **33**. It is the special combination of topology and topography of the catenate that prevents the system from dissociating to copper metal and free ligand.

2. An Air-Stable d^9 Nickel(I) Catenate

Nickel(I) complexes with nitrogen ligands are mainly restricted to tetraaza macrocyclic compounds.[64-68] In general, the complexes have a very high reducing power.[65-68] The +1 oxidation state is expected to be preferred by ligands that force a tetrahedral geometry. As already mentioned, such an arrangement strongly disfavors the +2 oxidation state, the difficulty now arising from the too low affinity of Ni^{II} for such hypothetical ligands, precluding preparation of their corresponding complexes. The catenand **36** seems to fulfill perfectly the prerequisites, due to its topology and to the expected geometry of its complexes. Indeed, the nickel(I) catenate 58^+ (Figure 43) can readily be made by electrochemical reduction of its Ni^{II} analogue.[69] Due to the topology of the ligand and despite the unfavorable topography of the divalent complex, 58^{2+} is stable enough to be crystallized and studied in solution. In contrast, the use of **56** or **27** instead of the catenand leads to no isolable complex, demonstrating the importance of the topological catenand effect. However, 59^{2+} and 60^{2+} (see Figure 43) are sufficiently stable in solution to be studied by electrochemical methods.

The electrochemical properties[69] of the nickel complexes have been studied by cyclic voltammetry, as shown in Figure 43. The Ni^{II}/Ni^{I} couple is reversible for the three complexes. In addition, controlled potential electrolysis of 58^{2+} yields 58^+, the nickel(I) complex of **36**.

The ESR spectrum of 58^+ displays characteristic features of a d^9 Ni^I complex.[67,70-72] It is striking that such easily reducible nickel(II) complexes, involving diimine ligands, lead to d^9 species by reduction and not to nickel(II) stabilized radical anions, as previously observed for unsaturated macrocyclic complexes.[67,73] Such behavior stresses the important contribution of the tetrahedral arrangement in stabilizing Ni^I. This geometrical effect is also estimated in comparing the complexes formed with **56** and **27**: whereas the nickel(I) complex of the less bulky **56** ligand could not be obtained in solution, 59^+ is perfectly stable under argon.

The relatively low reactivity of 59^+ and the inertness of 58^+ with respect to their reoxidation by O_2 are also remarkable. The corresponding bimolecular rate constants k_{O_2}, in CH_2Cl_2 at 20 °C, are as follows: for 59^+, $k_{O_2} \sim 2$ mol^{-1} L s^{-1}, whereas 58^+ can hardly be reoxidized, even in O_2-saturated CH_2Cl_2 solution for days ($k_{O_2} < 10^{-5}$ mol^{-1} L s^{-1}). Although 59^+ solutions are reoxidized by air in minutes, even this complex displays unusually low reactivity with O_2: one of the most stable Ni^I complexes ever reported with nitrogen donors reacts with O_2 several orders of magnitude faster than does 59^+.[69] The comparison between the topographically similar species 59^+ and 58^+ provides a direct measure of the catenand effect: the reaction with O_2 is more than 10^5 times slower for 58^+ than for its acyclic analogue 59^+, in spite of the strictly identical electrochemical properties of both compounds. This large factor is of purely topological origin (interlocking of the two rings). Here again it is the conjunction of topographical and topological properties that allows exceptional stabilization of low-valent transition metals like d^9 nickel(I).

C. Unusual Kinetic Inertness of Catenates

A kinetic study of the decomplexation by CN^- of 33^+ and of other related complexes has been carried out[74] in order to demonstrate a catenand effect. In addition, separation of the effects of topology from those of topography (two entwined dpp units) has demonstrated the relative importance of these different geometrical contributions in decomplexation kinetics.

It is of interest to evaluate the size of various factors such as the catenane nature of the ligand, the rigidity and cagelike character of the system formed by the two entwined dpp's, and the stacking between phenyl rings borne by one phenanthroline and the other phenanthroline nucleus within a given complex. In order to reach those individual contributions and for the purposes of comparison with acyclic compounds, the copper(I) complexes Cu(2,9-dimethyl-1,10-phenanthroline)$_2^+$ 61^+ and 28^+ were also studied. Because CN^- is known to form very stable complexes with copper(I), this decomplexing agent, previously used for preparative purposes,[56] was chosen. The overall reaction is

$$Cu^I \text{ complex}^+ + 4CN^- \rightarrow Cu(CN)_4^{3-} + \text{free ligand}$$

$$v = \frac{d[Cu^I \text{ complex}^+]}{dt} = k_{obsd}[Cu^I \text{ complex}]$$

where k_{obsd} is the observed first-order rate constant.

TABLE I. Demetalation of Copper(I) Complexes—Kinetic Parameters

	61^+	28^+	33^+	$k\ (61^+)/k\ (28^+)^a$	$k\ (28^+)/k\ (33^+)^b$
k_D (s^{-1})	5	5×10^{-1}	2×10^{-4}	10	2500
k_{CN} (mol^{-1} L s^{-1})	8×10^2	6.5	1.6×10^{-1}	120	40

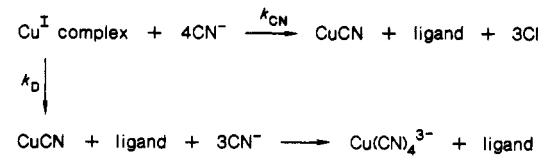
[a] Substituent effect. [b] Topological factors.

The same rate law has been obtained, in the presence of an excess of cyanide, for the various complexes studied

$$k_{obsd} = k_D + k_{CN}[CN^-]$$

where k_D (s^{-1}) is the direct dissociation rate constant and k_{CN} (mol^{-1} L s^{-1}) is the CN^--assisted dissociation rate constant.

The rate law found supports two possible pathways: a pathway related to the intrinsic inertness of the complex in the absence of CN^- (k_D) and a second pathway corresponding to a first-order attack of CN^- on the complex (k_{CN}).



The two sets of rate constants measured are collected in Table I.

In order to discuss the results, it is convenient to take into account two separate effects relating respectively to the nature of the substituents borne by the phenanthroline ligands (molecular shape) and to the catenane nature of 33^+. Steric effects may be evaluated by comparing results for 61^+ and 28^+. Whereas the intrinsic dissociation process does not strongly depend on the size of substituents α to the nitrogen atoms of phenanthroline, the bimolecular reaction, involving CN^- attack, is highly disfavored as the hindering character of the substituents increases: 28^+ dissociates 120 times more slowly via a bimolecular process than 61^+. This difference is due to the pronounced encaged character of 28^+, making the copper(I) center noticeably more protected than for 61^+ and thus rendering more difficult any nucleophilic attack on the copper atom.

The catenate 33^+ dissociates several orders of magnitude more slowly than the acyclic complexes 61^+ and 28^+, as evidenced by Table I. Clearly, this effect indicates great difficulty in disengaging the two interlocked cycles. This is the catenand effect, characteristic of the particular topology of the ligand **36**. It is directly related to the difficulty encountered by the two rings in disengaging from a given molecular arrangement while remaining interlocked during the unraveling process. The steric hindrance around the copper atom is probably not significantly greater in 33^+ than in 28^+, making the comparison between the two systems a direct measure of the topological factor. The latter can be taken as the rate constants ratio for 28^+ and 33^+ respectively 2500 for the k_D's and 40 for the bimolecular process.

IV. Outlook

The interest in catenanes and related systems originates to a large extent in their aesthetic appeal. In this respect, graphic arts and chemistry find a link.

In addition to the challenge of making topologically novel molecular systems, fundamental properties of general interest can be studied. In particular, it should be possible to determine the characteristics attached to the interlocking of cycles or, more generally, to known which specific effect is due to the interlacing of molecular threads.

Long ago, it was stated that polymers consisting of multiinterlocked rings might display very special mechanical and rheological properties.[75,76] For instance, the elastomeric properties of polysiloxanes were supposed to originate from the presence of catenanes in the polymer network.[76] Even if these statements were only highly speculative and if no real proof exists concerning the relationship between the presence of interlocked rings and elasticity, it would be of interest to develop synthetic methods allowing preparation of large molecules containing multicatenanes. It is conceivable that a templated synthesis based on transition metals might permit in the future preparation of catenated polymers.

The coordinating properties of catenands are also of interest. The copper(I) catenate 33^+ is probably one of the most stable copper(I) complexes formed with a neutral ligand. In view of the intense color of 33^+ and of its photoemitter character, the ligand **36** and its derivatives might find interesting analytical applications. Clearly, the particular stabilization of low-oxidation states like nickel(I), for instance, might also lead to analytical or electrochemical applications. In addition, the synthesis of multicatenates containing different transition metals should be possible. With such systems, it is hoped that a good control over the distance and respective orientations of the metallic centers will be had in order to study electron-transfer processes.

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