

Molecular Machines

VINCENZO BALZANI,[†]
MARCOS GÓMEZ-LÓPEZ,[‡] AND
J. FRASER STODDART^{*,‡}

*Dipartimento di Chimica "G. Ciamician",
Università di Bologna, via Selmi 2, I-40126 Bologna, Italy,
and Department of Chemistry and Biochemistry,
University of California at Los Angeles,
405 Hilgard Avenue, California 90095*

Received December 2, 1997

Introduction

The incessant demand for increasingly sophisticated technologies is encouraging scientists to think more intently on the nanometer scale¹ in the quest for more efficient ways of writing, storing, processing, reading, and transferring information than they can boast presently. The scientific community is growing increasingly conscious of the fact that the lithographic techniques² used in today's production of miniaturized silicon-based transistors may be reaching their limit, and that a fundamentally new approach is needed for the rapid handling of vast amounts of information on the nanometer scale. By proposing a "bottom-up" approach, starting from atoms and molecules, to meet this challenge, Richard Feynman³ was the first person who dared to think so small back in the 1960s. With the advent in the 1970s and 1980s of *supramolecular chemistry*⁴—a discipline which exploits fundamental concepts such as self-assembly,⁵ self-organization,⁶ and self-replication,⁷ that are central to nature's forms and functions—it is now in the 1990s becoming feasible to construct large and intricate, yet highly ordered, functioning molecular and supramolecular entities⁸ by recognizing the importance of *mechanical*⁹ as well as

Vincenzo Balzani was born in Italy in 1936. He received his "laurea" in Chemistry from the University of Bologna, Italy, in 1960. After a few years as an Assistant Professor at the University of Ferrara, he joined the Faculty of Science of the University of Bologna in 1969, where he has remained to this day, becoming Professor in 1972. His current research interests include photochemistry, photophysics, electrochemistry, supramolecular chemistry, and molecular-level devices.

Marcos Gómez-López was born in Basque Country, Spain, in 1970. He received his degrees from the University of the Basque Country, Spain (B.Sc., 1993), and the University of Birmingham, U.K. (Ph.D., 1997), where he investigated the self-assembly of molecular species with potential device-like applications under the supervision of Professor Fraser Stoddart. He continued his work on molecular assemblies in UCLA as a postdoctoral researcher. Dr. Gómez-López is currently a postdoctoral fellow with Prof. Dr. François Diederich at the ETH, Zürich, where he is studying the incorporation of fullerenes into molecular assemblies and supramolecular arrays.

J. Fraser Stoddart was born in the U.K. in 1942. He received all of his degrees from the University of Edinburgh, U.K. (B.Sc., 1964; Ph.D., 1966; D.Sc., 1980). After a seven-year spell as the Professor of Organic Chemistry at the University of Birmingham, U.K., Professor Stoddart has recently moved to the Saul Winstein Chair of Organic Chemistry at UCLA. His current research interests are concerned with transporting well-established biological principles, such as self-assembly, from the life sciences into chemistry—with one aim being to produce materials with device-like properties to them.

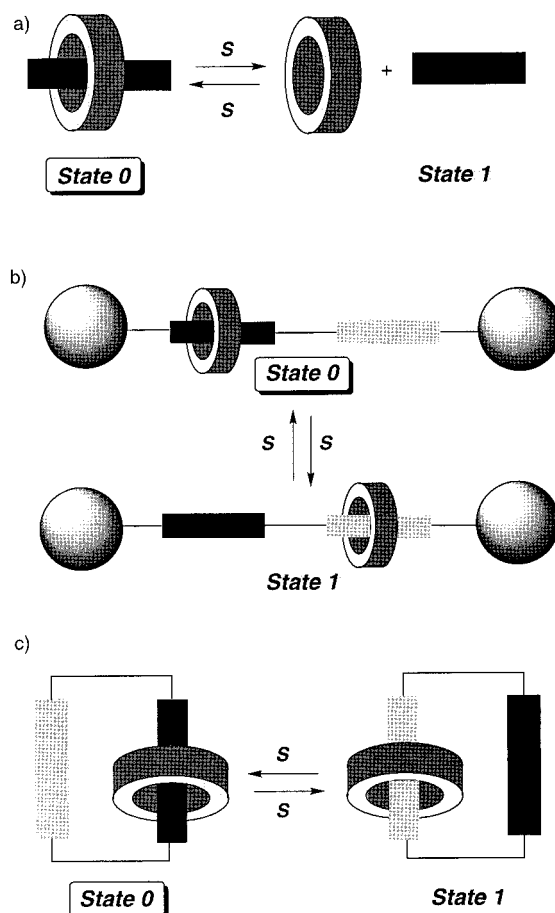


FIGURE 1. Schematic representations of the mechanical movements relating two states (0 and 1) in (a) pseudorotaxanes, (b) rotaxanes, and (c) catenanes: the stimulus (*S*) can be chemical or electrochemical energy, or it can be light.

noncovalent and, of course, covalent bonds. Pseudorotaxanes, rotaxanes, and catenanes (Figure 1) are appealing examples¹⁰ of such entities, particularly since the relative positions of their component parts can be induced to change as a result of some external stimulus. Hence, they may be considered as particular types of molecular-level switches.¹¹ In most cases, such mechanical movements occur between two different well-defined states and are accompanied by on/off switching of some observable property expressed in their NMR or electronic absorption spectra or by luminescence. Chemical or electrical energy and light have been used to induce the mechanical movements, opening up the way to process information at the molecular level. In this Account, we will call mainly on the investigations performed by our research groups on pseudorotaxanes, rotaxanes, and catenanes.¹²

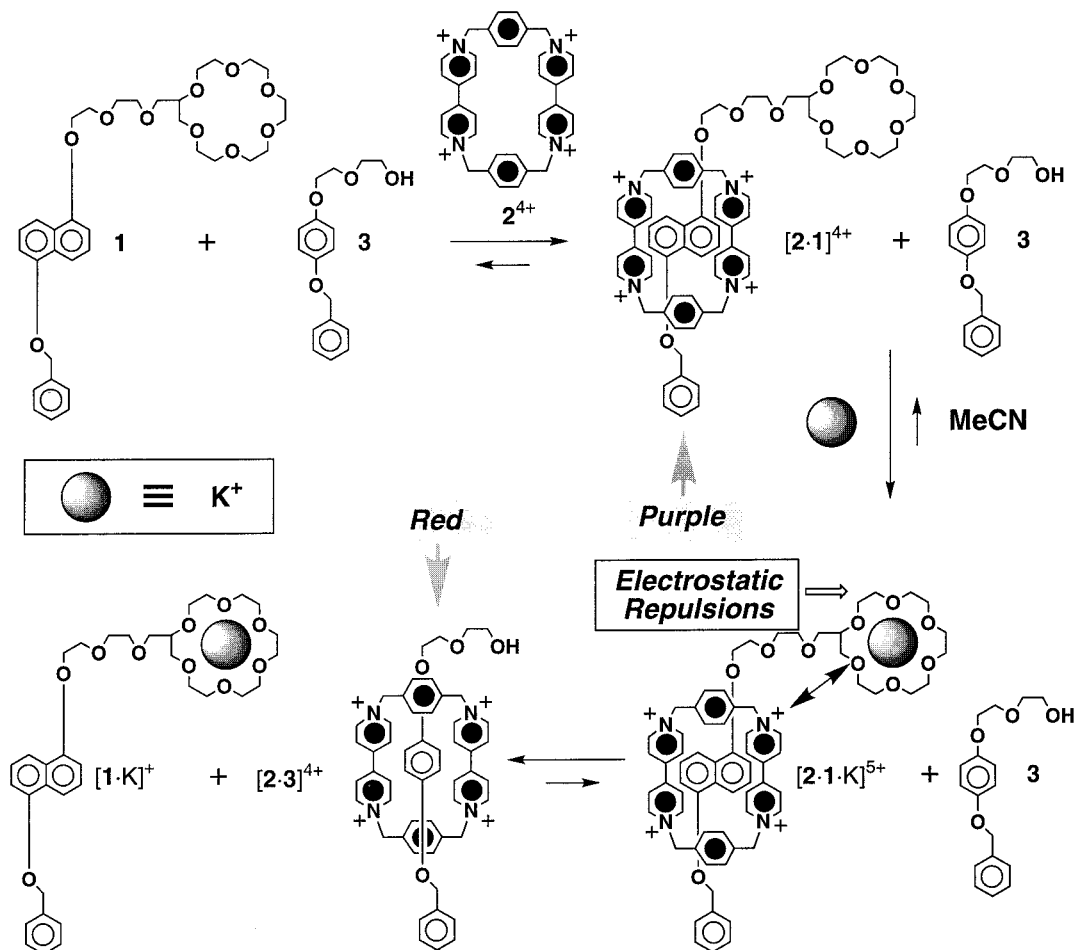
Pseudorotaxanes and Self-Complexing Compounds

In the past few years, we have designed¹³ a series of complexes with pseudorotaxane geometries in which a

[†] Università di Bologna.

[‡] University of California at Los Angeles.

Scheme 1. A Chemically Driven Chromophoric Molecular Switch Based on the Competitive Formation of Two [2]Pseudorotaxanes



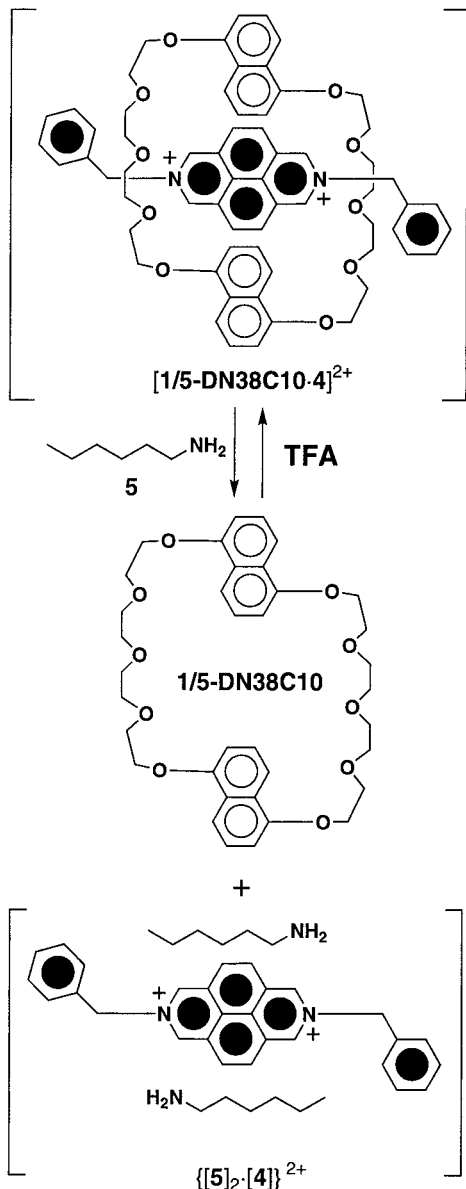
π -electron-rich linear component, e.g., **1**, threads (Scheme 1) through the cavity of the π -electron-deficient cyclophane cyclobis(paraquat-*p*-phenylene), 2^{4+} . The complexes are stabilized by a combination of electrostatic and dispersive forces, in particular, (1) charge-transfer, face-to-face, and edge-to-face [C–H $\cdots\pi$] interactions and (2) [C–H \cdots O] hydrogen bonds. Perturbation of these non-covalent bonding interactions using an external stimulus leads to dethreading of the pseudorotaxane complexes: when the stimulus is removed, allowing the components to regain their original characters, they self-assemble to form pseudorotaxanes once again.

Chemical Switching. The 18-crown-6 derivative **1**, carrying a 1,5-dioxynaphthalene ring system, is ditopic¹⁴ and so can act as a host for alkali-metal cations, as well as a guest for the cyclophane 2^{4+} to form (Scheme 1) the [2]pseudorotaxane $[2\cdot 1]^{4+}$. Upon addition of K^+ ions to a MeCN solution of $[2\cdot 1]^{4+}$, the [2]pseudorotaxane disassembles, presumably as a result of the electrostatic repulsions between the bound K^+ ion and the 2^{4+} tetracation. The cavity of the tetracationic cyclophane is then free to complex with the neutral hydroquinone-containing threadlike compound **3**, thus forming the [2]pseudorotaxane $[2\cdot 3]^{4+}$. Since the exchange of the guest is accompanied by a color change from purple to red, the system behaves as a chromophoric molecular switch.

Another family of pseudorotaxanes contains π -electron-deficient unit(s) in the threadlike component and π -electron-rich units in the macrocycle. For example (Scheme 2), the diazapyrenium dication 4^{2+} threads itself¹⁵ through the cavity of 1,5-dinaphtho-38-crown-10 (**1/5-DN38C10**). Since 4^{2+} forms adducts, e.g., $\{[5]_2\cdot[4]\}^{2+}$, with aliphatic amines, addition of hexylamine (**5**) induces dethreading of the [2]pseudorotaxane $[1/5\text{-DN38C10}\cdot 4]^{2+}$. This process is reversible quantitatively on addition of trifluoroacetic acid (TFA).

The hydrogen bond—as a result of its mutually discerning and moderately directional nature—has been employed^{4,5} in exceedingly imaginative ways for the self-assembly of a myriad of different supramolecular systems. With the main reliance on [N⁺–H \cdots O] and [C–H \cdots O] hydrogen bonding for stabilization, suitably sized crown ethers can form¹⁶ pseudorotaxane complexes with appropriate secondary dialkylammonium ions ($R^1R^2NH_2^+$). In this knowledge, the anthracene-containing $R^1R^2NH_2^+$ ion **6–H**⁺ was added¹⁷ to dibenzo-24-crown-8 (**DB24C8**), and the [2]pseudorotaxane $[\text{DB24C8}\cdot 6\text{-H}]^+$ was formed (Scheme 3). Treatment of $[\text{DB24C8}\cdot 6\text{-H}]^+$ with base deprotonates the $-\text{NH}_2^+$ center in the $R^1R^2NH_2^+$ ion, thereby destroying the hydrogen bonding principally responsible for holding the 1:1 complex together. The dethreading process can be reversed upon reprotonation

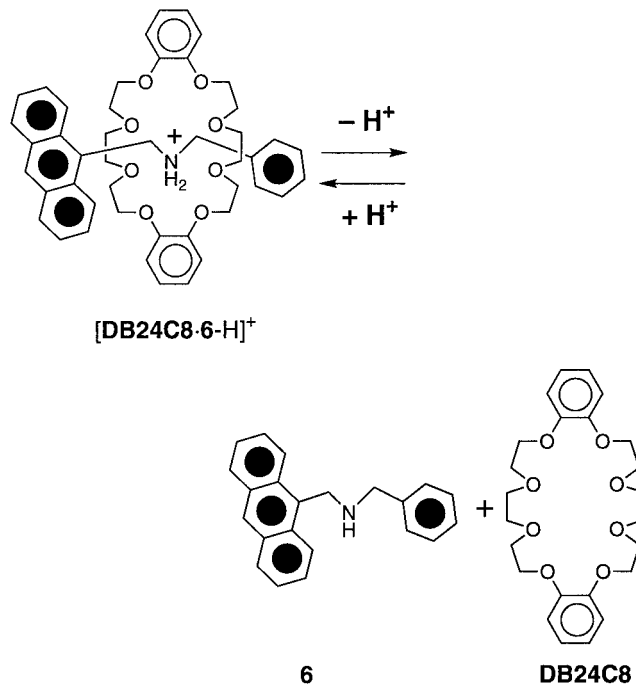
Scheme 2. A Molecular Switch Based on the Competition between a [2]Pseudorotaxane and a Ternary Complex



of the amino group in **6** with TFA. Since the fluorescent excited state of the catechol rings in **DB24C8** is deactivated by energy transfer to the anthracene unit of the protonated amine when it is held in close proximity to the crown ether as a result of hydrogen bonding, the anthracene unit behaves¹⁸ as a luminescent sensor.

Photochemical Switching. When the threadlike compound **7** is added^{19,20} to the tetracationic cyclophane **2**⁴⁺ as its tetrachloride salt, it forms (Scheme 4) the [2]-pseudorotaxane [2·7]⁴⁺ in aqueous solution. Then, if the deoxygenated solution of the [2]pseudorotaxane is irradiated in the presence of a photosensitizer (9-anthracene-carboxylic acid) and a sacrificial reductant (triethanolamine), photoreduction of one of the bipyridinium units in the tetracation occurs. As a consequence, the π - π stacking interactions which hold the 1:1 complex together are seriously impaired and dethreading occurs. This process can be monitored by the disappearance of the

Scheme 3. Acid/Base-Controlled Threading and Dethreading of a [2]Pseudorotaxane



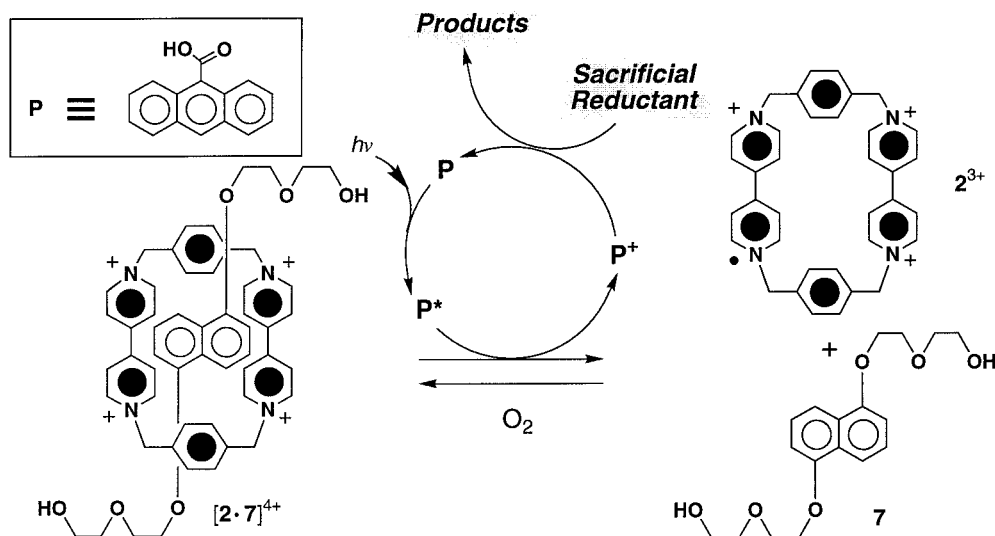
charge-transfer absorption band and the appearance of the fluorescence of the 1,5-dioxynaphthalene ring system in “free” **7**. Thereafter, if oxygen is allowed to enter the aqueous solution, the reduced cyclophane is reoxidized and the [2]pseudorotaxane is re-formed.

Electrochemical Switching. The self-complexing macrocycle **8**⁴⁺, shown in Scheme 5, has a linear polyether thread, intercepted by a 1,5-dioxynaphthalene ring system, attached covalently to one of the *p*-phenylene spacers of the tetracationic cyclophane by means of an ester linkage.²⁰ This fascinating molecule behaves as an electrochemically driven molecular switch. After one-electron reductions of each bipyridinium unit, the 1,5-dioxynaphthalene-containing side chain is ejected out of the cyclophane cavity of **8**²⁺. This dramatic conformational change is reversible upon electrochemical oxidation.²¹

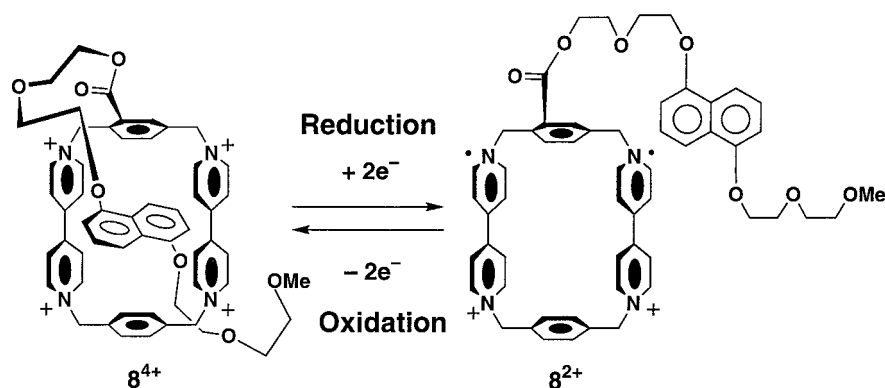
Rotaxanes

Rotaxanes⁹ consist of a dumbbell-shaped component—which incorporates one or more recognition sites in its rod section and is terminated by bulky “stoppers”—encircled by one or more ring components (Figure 1b). On account of their abacus-like geometry, rotaxanes have attracted²² our attention as potential switches since the first molecular shuttle (Scheme 6) was described in the literature in 1991. In the [2]rotaxane **9**⁴⁺, the tetracationic cyclophane moves back and forth between the two degenerate hydroquinone recognition sites on the dumbbell-shaped component approximately 500 times a second in CD₃COCD₃ at room temperature. Despite the fact that the molecular shuttle **9**⁴⁺ cannot act as a switch itself because of its degenerate nature, its well-defined dynamic behavior, as revealed by variable temperature NMR spectroscopy, made possible the next stage of develop-

Scheme 4. Light-Induced Dethreading of a Pseudorotaxane



Scheme 5. Electrochemically Induced Dethreading/Rethreading of a Self-Complexing Macrocyclic



1/5-Dioxynaphthalene "inside"

ment—namely, the self-assembly of a series of desymmetrized molecular shuttles,²³ containing two nondegenerate recognition sites in the dumbbell-shaped component. Then, we argued it should be possible to control the switching actions of such molecular shuttles.²⁴

Electrochemical Switching. Although the [2]rotaxane 10^{4+} , shown in Scheme 7, contains the same ring component as that present in the "original" molecular shuttle (Scheme 6), its dumbbell-shaped component incorporates two *different* recognition sites, one a benzidine and the other a biphenol unit.²⁵ As expected, 10^{4+} exhibits *translational isomerism*,²⁶ with the tetracationic cyclophane located preferentially (84:16 in CD_3CN at $-44^\circ C$) on the more π -electron-rich benzidine unit. However, electrochemical oxidation of the benzidine unit converts it to the monocationic radical state, and presumably, as a result of repulsive electrostatic interactions, the cyclophane, with its four formal positive charges, moves to the biphenol unit in 10^{5+} . This redox system is completely reversible since electrochemical reduction of 10^{5+} reinstates the [2]rotaxane 10^{4+} .

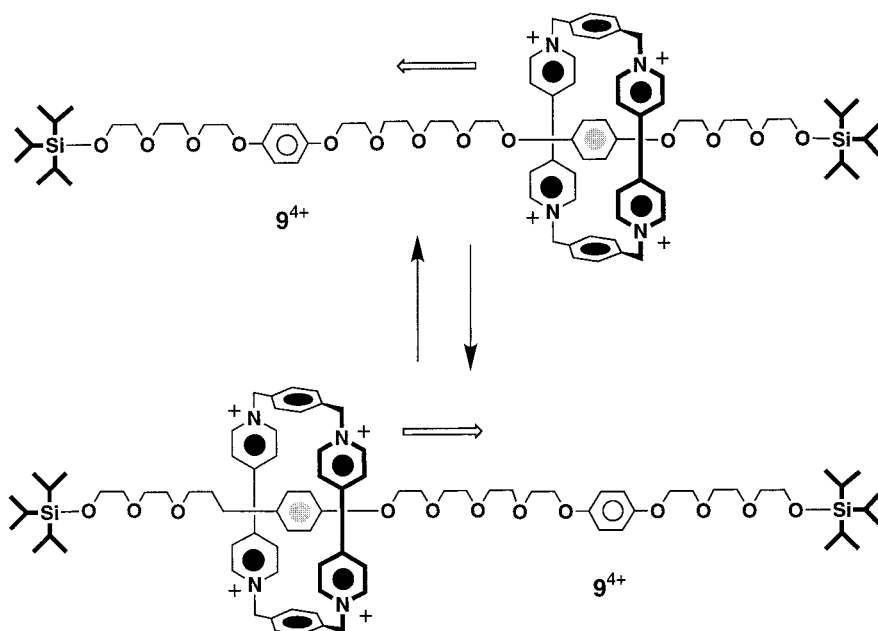
Chemical Switching. 1H NMR spectroscopy has revealed²⁵ that 10^{4+} can also be switched (Scheme 7) in

1/5-Dioxynaphthalene "outside"

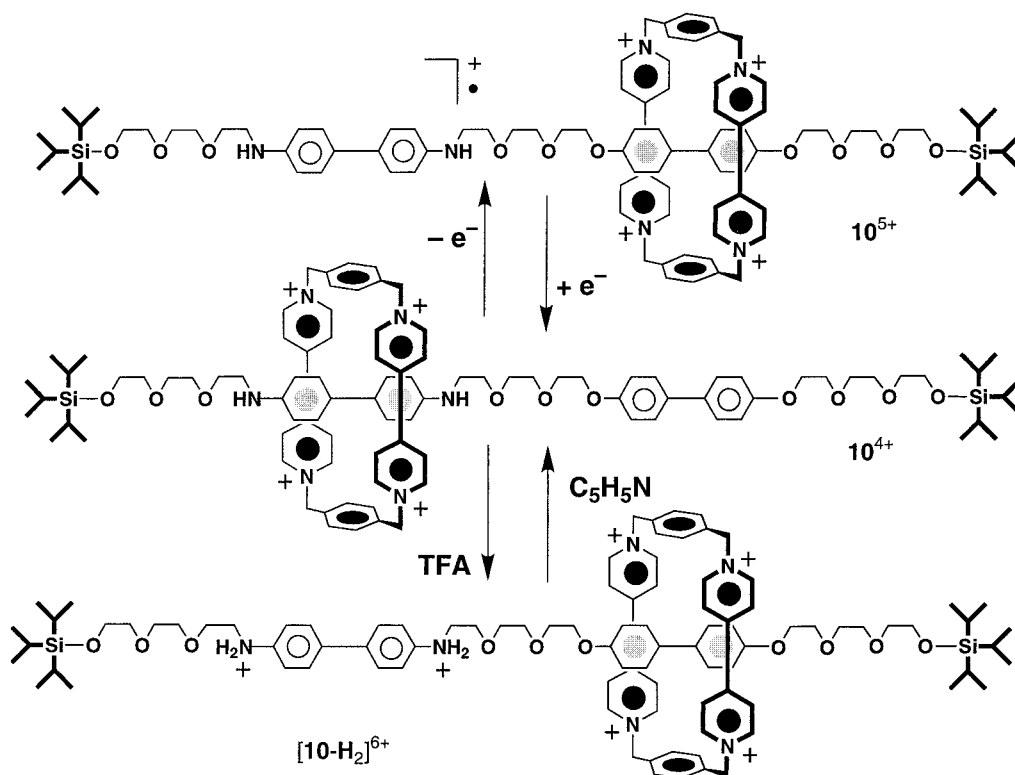
CD_3CN solution by its protonation (TFA) to give the diprotonated species $[10-H_2]^{6+}$ which can subsequently be deprotonated (C_6H_5N), re-forming 10^{4+} .

The fact that **DB24C8** forms strong complexes with $R^1R^2NH_2^+$ ions,¹⁶ yet rather weak complexes with bipyridinium dication,²⁷ prompted²⁸ the template-directed synthesis of the [2]rotaxane $[11-H]^3+$, where the dumbbell-shaped component contains both an $-NH_2^+$ center and a bipyridinium unit (Scheme 8). The **DB24C8** ring component resides *exclusively* on the $-NH_2^+$ center in $[11-H]^3+$. However, addition of the base *i*-PrNEt₂ to a CD_3COCD_3 solution—as indicated by 1H NMR spectroscopy—effects deprotonation, breaking the strong hydrogen-bonding interactions between the $-CH_2NH_2^+CH_2-$ fragment and the polyether oxygen atoms in **DB24C8**, thus inducing the ring component to move to the bipyridinium recognition site where its catechol rings can become involved in weak donor/acceptor interactions in 11^{2+} . The shuttling process, which is reversible on addition of TFA, is 100% controllable in the direction of both $[11-H]^3+$ and 11^{2+} : as far as we can tell, in its two states, the switch is an all-or-nothing one.

Scheme 6. The First Molecular Shuttle



Scheme 7. An Electrochemically and Chemically Controllable Molecular Shuttle



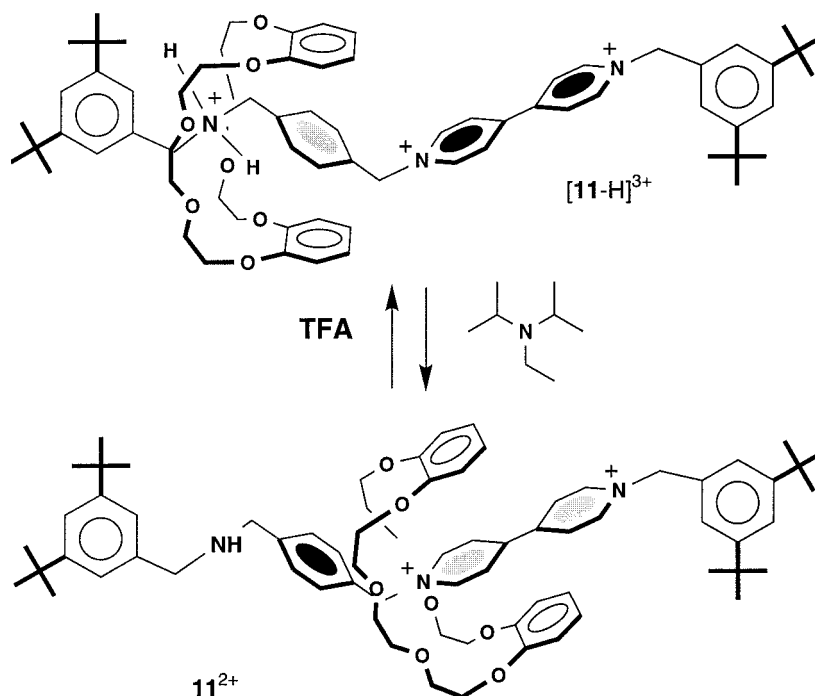
Catenanes

Catenanes⁹ can be defined as interlocked molecular compounds in which two or more rings are joined together by a *mechanical* bond. In recent years, we have self-assembled²⁹ a large number of [2]catenanes by exploiting the cooperativity that exists between electrostatic forces, including hydrogen bonds, and aromatic–aromatic interactions. Suitably desymmetrized catenanes also undergo *translational isomerism*,²⁶ making them suitable

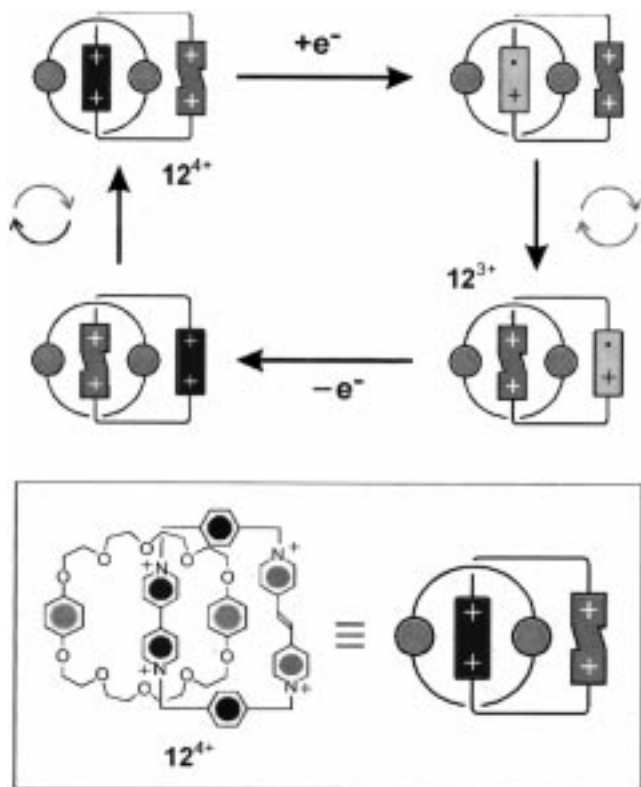
candidates for the construction of controllable switches³⁰ at the molecular level (Figure 1c).

Electrochemical Switching. Such a candidate is the [2]catenane **12**⁴⁺, portrayed in Scheme 9, in which a constitutionally dissymmetric tetracationic cyclophane containing two different recognition sites—a bipyridinium unit and a *trans*-bis(pyridinium)ethylene unit—is interlocked³¹ with the symmetrical macrocyclic polyether ring, bis(*p*-phenylene)-34-crown-10 (**BPP34C10**). ¹H NMR spec-

Scheme 8. A Chemically Controllable Molecular Shuttle



Scheme 9. Electrochemically Controlled Movements of the Ring Components in a [2]Catenane



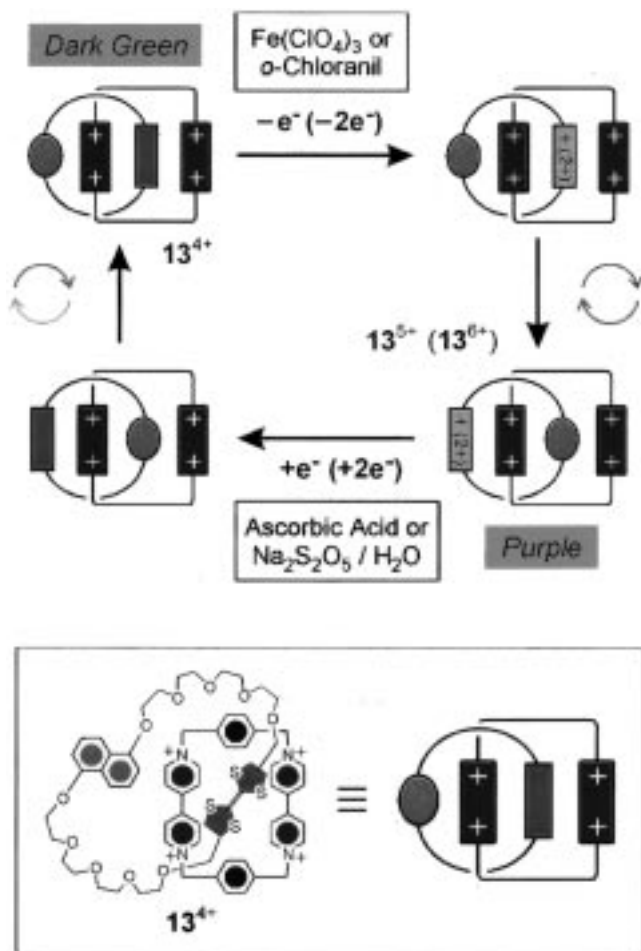
troscopy in CD_3COCD_3 shows that the bipyridinium unit resides inside the cavity of the **BPP34C10** component as a result of its high π -acidity. The first one-electron reduction of $\mathbf{12}^{4+}$ occurs preferentially at the “inside” bipyridinium unit, yielding the radical cation which, on account of its much impaired π -acidity, undergoes circumrotation of the charged component through the

BPP34C10 ring to produce $\mathbf{12}^{3+}$, wherein the now better π -acid—namely, the *trans*-bis(pyridinium)ethylene unit—is located inside the cavity of the crown ether. On oxidation, the $\mathbf{12}^{3+}$ species loses an electron and the circumrotation process is completed, affording the [2]catenane $\mathbf{12}^{4+}$ once again.

An alternative way of achieving control over the relative mechanical motions of the ring components in such catenated systems is by desymmetrizing the crown ether. The [2]catenane $\mathbf{13}^{4+}$, illustrated in Scheme 10, possesses³² a crown ether with two different π -electron-rich residues—one a disubstituted tetrathiafulvalene (TTF) unit and the other a 1,5-dioxynaphthalene ring system. In the [2]catenane’s more stable state, the TTF unit is located inside the cavity of the tetracationic cyclophane with the 1,5-dioxynaphthalene ring system lying alongside, both in the solid state and in solution. Chemical and/or electrochemical oxidation of the TTF unit in $\mathbf{13}^{4+}$ to the radical cation ($\text{TTF}^{\cdot+}$), or the TTF^{2+} dication, present in $\mathbf{13}^{5+}$ or $\mathbf{13}^{6+}$ results in a circumrotation of the crown ether ring that places the 1,5-dioxynaphthalene ring system inside the cavity of the tetracationic cyclophane. The mechanical switching action, which can be reversed chemically and/or electrochemically, is accompanied by a dramatic change in color from green—when the TTF unit is inside—to purple—when the 1,5-dioxynaphthalene ring system is inside the tetracationic cyclophane.

In an elegant piece of research, Sauvage³³ has investigated (Scheme 11) the mechanical switching action of a [2]heterocatenate $\mathbf{14}^+$ in which one of the rings possesses a bidentate chelating ligand—viz., 2,9-diphenyl-1,10-phenanthroline (dpp)—while the other one contains a dpp and a tridentate 2,2':6',2''-terpyridine (tpy) ligand. As a result, a metal ion can be coordinated tetrahedrally—with two dpp ligands—or in a 5-coordinate octahedrally dis-

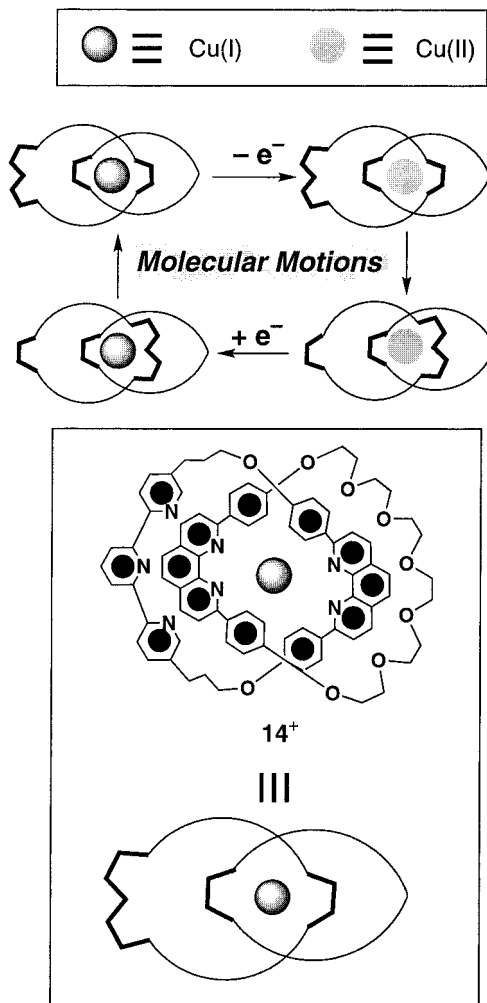
Scheme 10. Redox-Controlled Movements of the Ring Components in a [2]Catenane



torted geometry—with one dpp and one tpy ligand. Initially, the Cu(I) ion is coordinated to two dpp ligands. Electrochemical oxidation of Cu(I) to Cu(II) leads to the formation of an unstable 4-coordinate Cu(II) intermediate which rearranges to a 5-coordinate Cu(II) species—in which the metal is ligating to one dpp and one tpy ligand—following circumrotation of one ring relative to the other. The original [2]heterocatenate 14^+ can be regenerated upon reduction of Cu(II) to Cu(I).

Photochemical Switching. The first step in the cycle in Scheme 11 can also be initiated³⁴ by photoexcitation of the Cu(I) center, followed by an excited-state reaction with a suitable oxidant—viz., *p*-nitrobenzyl bromide. In principle, the back-reduction could also be driven by light. However, in this specific case, this step cannot be achieved because the 5-coordinate species is not photosensitive.

Chemical Switching. In a collaborative project, an attempt at combining the metal–ligand and donor–acceptor strategies produced the [2]catenane 15^{5+} (Scheme 12) where one ring contains a dpp ligand and a 1,5-dioxynaphthalene unit and the other ring a dpp ligand and two bipyridinium units.³⁵ This hybrid molecule possesses two very different recognition modes, namely, coordination of Cu(I) by the two dpp ligands and a donor–acceptor interaction between the 1,5-dioxynaphthalene unit and the two bipyridinium units. Since the

Scheme 11. Electrochemically Controlled Movements of the Ring Components in a [2]Catenate^a

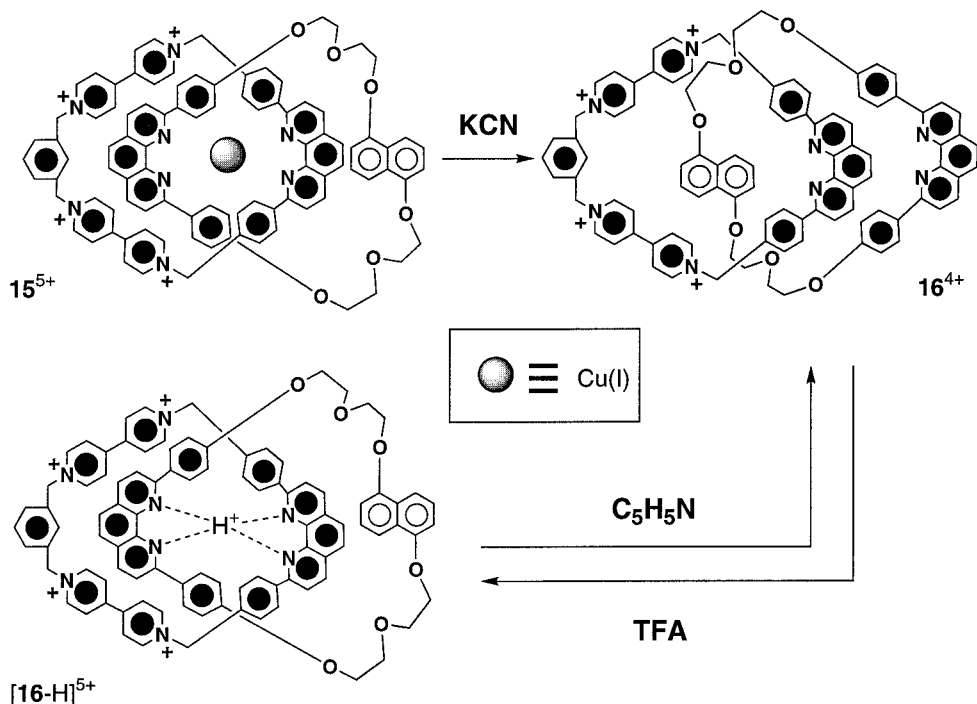
^a The first (oxidation) step can also be induced by light excitation.

coordination recognition site is the stronger, the stable state is the [2]catenane 15^{5+} in which the Cu(I) ion is complexed by the two dpp ligands in a tetrahedral coordination geometry. Removal of the Cu(I) ion, however, by addition of KCN affords the [2]catenand 16^{4+} which undergoes a dramatic topological change in order to allow its π -electron-rich 1,5-dioxynaphthalene ring system to be sandwiched between its two bipyridinium units, thus maximizing the noncovalent bonding interactions present in the demetalated system. Furthermore, the [2]catenand 16^{4+} exhibits pH dependency. In the presence of TFA, the formation of the protonated species $[16-H]^5+$ occurs such that the H^+ ion is imbedded between the two dpp ligands, forcing a considerable change on the geometry of the molecule. Subsequent treatment with base (C_5H_5N) regenerates the [2]catenand 16^{4+} in which the donor–acceptor interactions dictate the relative positioning of the rings with respect to each other.

Future Directions

Clearly, the first steps³⁶ have been taken along the pathway toward constructing simple molecular machines.

Scheme 12. Chemically Induced Movements of the Ring Components in a [2]Catenate and in Its [2]Catenand



However, the molecular shuttles and switches described in this Account relate to investigations carried out in the solution state where incoherence remains a major impediment to designing and realizing devices, based on molecular machines, that do something. It seems more than likely that, before functioning supramolecular arrays and molecular assemblies can be addressed in a practical manner, they are going to have to be multiplied and amplified by marshaling them in some manner. The next generation of molecular machines will need to be congregated on surfaces,^{37,38} or allowed to organize themselves at air–water interfaces³⁹ such that the molecules behave coherently, either in parallel or in series. These challenges are considerable ones: yet, we can start to meet them in the knowledge that nature has been “there” before and has managed to come up with some exceedingly elegant solutions to a multitude of problems, relating to machines that operate on the molecular level,⁴⁰ in the course of an evolutionary process that has spanned many billions of years. The time scale in the laboratory will be a lot less, but no one knows at this time how much less. Molecular machines⁴¹ are the forerunners of molecular computers—still an emotive term among chemists. We shall leave the last word with those who produced the so-called Pimentel Report⁴² back in 1985. We quote them verbatim:

There are those who dismiss as far-fetched the idea of man-made molecular scale computers. Only a few decades ago, however, these same individuals might have classified as science fiction a proposal that someday there would be a man on the Moon, that fertility could be controlled by taking a pill, or that we could learn the structure of DNA. But since we know that molecular computers are routine accessories of all animals from ants to zebras, it would be prudent to change the question

from *whether* there will be man-made counterparts to questions concerning *when* they will come into existence and *who* will be leading in their development. The *when* question will be answered on the basis of fundamental research in chemistry; the *who* question will depend on which countries commit the required resource and creativity to the search.

We are indebted to all members—past and present—of our research groups for their intellectual contributions and relentless efforts in inventing and producing the molecular-level switches described in this Account. Their names have been cited in the numerous references. We are also extremely grateful to Professor David J. Williams and his talented group at Imperial College for determining the X-ray crystal structure of many of the switches described herein. Much of the research was supported by the Engineering and Physical Sciences Research Council (EPSRC) in the U.K. and by the University of Bologna (Funds for Selected Research Topics) in Italy. Some of the research was carried out within the framework of the EU TMR Project FMRX-CT96-0076. Finally, we are grateful to Eusko Jaurlaritz, Unibersitate, Hezkuntza eta Ikerketa Saila in Basque Country (Spain), for a predoctoral fellowship to M.G.-L.

References

- (1) Whitesides, G. M. *Sci. Am.* **1995**, 273 (3), 114–117.
- (2) Robinson, A. L. *Science (Washington, D.C.)* **1984**, 223, 267–268.
- (3) Feynman, R. P. *Sat. Rev.* **1960**, 43, 45–47.
- (4) Lehn, J.-M. *Supramolecular Chemistry*, VCH: Weinheim, Germany, 1995.
- (5) (a) Lindsey, J. S. *New J. Chem.* **1991**, 15, 153–180. (b) Lawrence, D. S.; Jiang, T.; Levett, M. *Chem. Rev.* **1995**, 95, 2229–2260. (c) Philp, D.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1996**, 35, 1154–1196. (d) Fredericks, J. R.; Hamilton, A. D. In *Comprehensive Supramolecular Chemistry*; Atwood, J. L., Davies, J. E. D., MacNicol, D. D., Vögtle, F., Eds.; Pergamon/Elsevier: Oxford, 1996; Vol. 9, pp 565–594.

- (6) (a) Ringsdorf, H.; Schlalb, B.; Venzmer, J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 115–158. (b) Lupo, D.; Ringsdorf, H.; Schuster, A.; Seitz, M. *J. Am. Chem. Soc.* **1994**, *116*, 10498–10506. (c) Kimizika, N.; Handa, T.; Ichinose, I.; Kunitake, T. *Angew. Chem., Int. Ed. Engl.* **1994**, *33*, 2483–2485. (d) Imrie, C. T. *Trends Polym. Sci.* **1995**, *3*, 22–29.
- (7) (a) von Kiedrowski, G. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 932–935. (b) Hong, J.-I.; Feng, Q.; Rotello, V.; Rebek, J., Jr. *Acc. Chem. Res.* **1994**, *27*, 198–203. (c) Menger, F. M.; Eliseev, A. V.; Khanjin, N. A. *J. Am. Chem. Soc.* **1994**, *116*, 3613–3614. (d) Sievers, D.; von Kiedrowski, G. *Nature (London)* **1994**, *369*, 221–224. (e) Lee, D. H.; Granja, J. R.; Martínez, J. A.; Severin, K.; Ghadiri, M. R. *Science (Washington, D.C.)* **1996**, *382*, 525–527. (f) Reinhoudt, D. N.; Rudkevich, D. M.; de Long, F. *J. Am. Chem. Soc.* **1996**, *118*, 6880–6889.
- (8) (a) Walba, D. M. *Tetrahedron* **1985**, *41*, 3161–3212. (b) Dietrich-Buchecker, C. O.; Sauvage, J.-P. *Chem. Rev.* **1987**, *87*, 795–810. (c) Amabilino, D. B.; Stoddart, J. F. *Chem. Rev.* **1995**, *95*, 2725–2828. (d) Funerui, D. P.; Lehn, J.-M.; Baum, G.; Fenske, D. *Chem. Eur. J.* **1997**, *3*, 99–104. (e) Jager, R.; Vögtle, F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 930–944. (f) Amabilino, D. B.; Ashton, P. R.; Boyd, S. E.; Lee, J. Y.; Menzer, S.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 2070–2072.
- (9) When two or more integral chemical units are bound together without the assistance of any valence forces, they are said to be joined by a *mechanical bond*. See: Schill, G. *Catenanes, Rotaxanes and Knots*; Academic Press: New York, 1971.
- (10) Pseudorotaxanes result from *strict self-assembly*—which, in numerous instances, is commensurate with *supramolecular synthesis*—where stereoelectronically complementary subunits interact spontaneously to produce the final complexes under *thermodynamic control*. All the rotaxanes and catenanes mentioned in this Account are a result of *self-assembly with covalent modification*—that is, *supramolecular assistance to molecular synthesis* in this instance—to give the final compounds under kinetic control. For more details, see: Fyfe, M. C. T.; Stoddart, J. F. *Acc. Chem. Res.* **1997**, *30*, 393–401.
- (11) (a) Balzani, V.; Moggi, L.; Scandola, F. In *Supramolecular Photochemistry*; Balzani, V., Ed.; Reidel: Dordrecht, The Netherlands, 1987; pp 1–28. (b) *Molecular Electronic Devices*; Carter, F. L., Siatkowski, R. E., Wohltjen, H., Eds.; North-Holland: Amsterdam, 1988. (c) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1990**, *29*, 1304–1319. (d) Balzani, V.; Scandola, F. *Supramolecular Photochemistry*; Horwood: Chichester, 1991; Chapter 12. (e) Feringa, B. L.; Wolter, J. F.; de Lange, B. *Tetrahedron* **1992**, *49*, 8267–8309. (f) Balzani, V.; Scandola, F. In *Comprehensive Supramolecular Chemistry*; Reinhoudt, D. N., Ed.; Pergamon Press: Oxford, 1996; Vol. 10, pp 687–746. (g) Benniston, A. C. *Chem. Soc. Rev.* **1996**, *25*, 427–435. (h) de Silva, A. P.; Gunaratne, H. Q. N.; Gunnlaugsson, T.; Huxley, A. J. M.; McCoy, C. P.; Rademacher, J. T.; Rice, T. E. *Chem. Rev.* **1997**, *97*, 1515–1566.
- (12) For some publications on molecular-level machine-type systems that do not involve pseudorotaxanes, rotaxanes, or catenanes, see: (a) Iwamura, H.; Mislow, K. *Acc. Chem. Res.* **1988**, *21*, 175–182. (b) Mislow, K. *Chemtracts—Org. Chem.* **1989**, *2*, 151–174. (c) Kelly, T. R.; Bowyer, M. C.; Bhaskar, K. V.; Bebbington, D.; Gracia, A.; Lang, F.; Kim, M. H.; Jette, M. P. *J. Am. Chem. Soc.* **1994**, *116*, 3657–3658. (d) Bedard, T. C.; Moore, J. S. *J. Am. Chem. Soc.* **1997**, *117*, 10662–10671. (e) Canivet, C.; Libman, J.; Shanzer, A. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 2657–2660. (f) de Santis, G.; Fabbrizzi, L.; Iacopino, D.; Pallavicini, P.; Perotti, A.; Poggi, A. *Inorg. Chem.* **1997**, *36*, 827–832. (g) Willner, I. *Acc. Chem. Res.* **1997**, *30*, 347–356. (h) Ikeda, A.; Tsudera, T.; Shinkai, S. *J. Org. Chem.* **1997**, *62*, 3568–3574. (i) Kelly, T. R.; Tellita, I.; Sestelo, J. P. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1866–1868. (j) Deans, R.; Niemz, A.; Breinlinger, E. C.; Rotello, V. M. *J. Am. Chem. Soc.* **1997**, *119*, 10863–10864. (k) Stevens, A. N.; Richards, C. J. *Tetrahedron Lett.* **1997**, *38*, 7805–7808. (l) Malpass, J. R.; Sun, G.; Fawcett, J.; Wartenner, R. N. *Tetrahedron Lett.* **1998**, *39*, 3083–3086.
- (13) (a) Odell, B.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 1550–1553. (b) Amabilino, D. B.; Anelli, P. L.; Ashton, P. R.; Brown, G. R.; Córdova, E.; Godínez, L. A.; Hayes, W.; Kaifer, A. E.; Philp, D.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; Williams, D. J. *J. Am. Chem. Soc.* **1995**, *117*, 11142–11170.
- (14) (a) Ashton, P. R.; Iqbal, S.; Stoddart, J. F.; Tinker, N. D. *Chem. Commun.* **1996**, 479–480. (b) Asakawa, M.; Iqbal, S.; Stoddart, J. F.; Tinker, N. D. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 976–978. (c) Asakawa, M.; Ashton, P. R.; Iqbal, S.; Quick, A.; Stoddart, J. F.; Tinker, N. D.; White, A. J. P.; Williams, D. J. *Isr. J. Chem.* **1996**, *36*, 329–340.
- (15) Ballardini, R.; Balzani, V.; Credi, A.; Gandolfi, M. T.; Langford, S. J.; Menzer, S.; Prodi, L.; Stoddart, J. F.; Venturi, M.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 978–981.
- (16) (a) Kolchinski, A. G.; Busch, D. H.; Alcock, N. W. *J. Chem. Soc., Chem. Commun.* **1995**, 1289–1291. (b) Ashton, P. R.; Campbell, P. J.; Chrystal, E. J. T.; Glink, P. T.; Menzer, S.; Philp, D.; Spencer, N.; Stoddart, J. F.; Tasker, P. A.; White, A. J. P.; Williams, D. J. *Chem. Eur. J.* **1996**, *2*, 709–728. (c) Glink, P. T.; Schiavo, C.; Stoddart, J. F.; Williams, D. J. *Chem. Commun.* **1996**, 1483–1490.
- (17) Ashton, P. R.; Ballardini, R.; Balzani, V.; Gómez-López, M.; Lawrence, S. E.; Martínez-Díaz, M.-V.; Montalti, M.; Piersanti, A.; Prodi, L.; Stoddart, J. F.; Williams, D. J. *J. Am. Chem. Soc.* **1997**, *119*, 10641–10651.
- (18) Montalti, M.; Ballardini, R.; Prodi, L.; Balzani, V. *Chem. Commun.* **1996**, 2011–2012.
- (19) Ballardini, R.; Balzani, V.; Gandolfi, M. T.; Prodi, L.; Venturi, M.; Philp, D.; Ricketts, H. G.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 1301–1303.
- (20) Ashton, P. R.; Ballardini, R.; Balzani, V.; Boyd, S. E.; Credi, A.; Gandolfi, M. T.; Gómez-López, M.; Iqbal, S.; Philp, D.; Preece, J. A.; Prodi, L.; Ricketts, H. G.; Stoddart, J. F.; Tolley, M. S.; White, A. J. P.; Williams, D. J. *Chem. Eur. J.* **1997**, *3*, 152–170.
- (21) For some additional electrochemically induced switching systems involving pseudorotaxanes, see: (a) Collin, J.-P.; Gavina, R.; Sauvage, J.-P. *Chem. Commun.* **1996**, 2005–2006. (b) Mirzozian, A.; Kaifer, A. E. *Chem. Eur. J.* **1997**, *3*, 1052–1058.
- (22) Anelli, P.-L.; Spencer, N.; Stoddart, J. F. *J. Am. Chem. Soc.* **1991**, *113*, 5131–5133.
- (23) (a) Ashton, P. R.; Bissell, R. A.; Spencer, N.; Tolley, M. S. *Synlett* **1992**, 914–918. (b) Ashton, P. R.; Bissell, R. A.; Górsky, R.; Philp, D.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; *Synlett* **1992**, 919–922. (c) Ashton, P. R.; Bissell, R. A.; Spencer, N.; Stoddart, J. F.; Tolley, M. S. *Synlett* **1992**, 923–926. (d)

- Córdova, E.; Bissell, R. A.; Spencer, N.; Ashton, P. R.; Stoddart, J. F.; Kaifer, A. E. *J. Org. Chem.* **1993**, *58*, 6550–6552. (e) Anelli, P.-L.; Asakawa, M.; Ashton, P. R.; Bissell, R. A.; Clavier, G.; Górski, R.; Kaifer, A. E.; Langford, S. J.; Mattersteig, G.; Menzer, S.; Philp, D.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; Williams, D. J. *Chem. Eur. J.* **1997**, *3*, 1113–1135.
- (24) For other examples of controllable molecular shuttles, see: (a) Benniston, A. C.; Harriman, A.; Lynch, V. M. *J. Am. Chem. Soc.* **1995**, *117*, 5275–5291. (b) Collin, J.-P.; Gavina, P.; Sauvage, J.-P. *New J. Chem.* **1997**, *21*, 525–528. (c) Murakami, H.; Kawabuchi, A.; Kotoo, K.; Kunitake, M.; Nakashima, M. *J. Am. Chem. Soc.* **1997**, *119*, 7605–7606. (d) Lane, A. S.; Leigh, D. A.; Murphy, A. *J. Am. Chem. Soc.* **1997**, *119*, 11092–11093.
- (25) Bissell, R. A.; Córdova, E.; Kaifer, A. E.; Stoddart, J. F. *Nature (London)* **1994**, *369*, 133–137.
- (26) (a) Schill, G.; Rissler, K.; Fritz, H.; Vetter, W. *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 187–189. (b) Amabilino, D. B.; Ashton, P. R.; Boyd, S. E.; Gómez-López, M.; Hayes, W.; Stoddart, J. F. *J. Org. Chem.* **1997**, *62*, 3062–3075.
- (27) Ashton, P. R.; Langford, S. J.; Spencer, N.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *Chem. Commun.* **1996**, 1386–1388.
- (28) Martínez-Díaz, M.-V.; Spencer, N.; Stoddart, J. F. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 1904–1907.
- (29) (a) Ashton, P. R.; Goodnow, T. T.; Kaifer, A. E.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 1396–1399. (b) Anelli, P.-L.; Ashton, P. R.; Ballardini, R.; Balzani, V.; Delgado, M.; Gandolfi, M. T.; Goodnow, T. T.; Kaifer, A. E.; Philp, D.; Pietraszkiewicz, M.; Prodi, L.; Reddington, M. V.; Slawin, A. M. Z.; Spencer, N.; Stoddart, J. F.; Vicent, C.; Williams, D. J. *J. Am. Chem. Soc.* **1992**, *114*, 193–218. (c) Belohradsky, M.; Raymo, F. M.; Stoddart, J. F. *Collect. Czech. Chem. Commun.* **1997**, *62*, 527–557.
- (30) For some other examples of switchable catenanes, see: (a) Gunter, M. J.; Hockless, D. C. R.; Johnston, M. R.; Skelton, B. W.; White, A. H. *J. Am. Chem. Soc.* **1994**, *116*, 4810–4823. (b) Bauer, M.; Müller, M.; Müller, U.; Rissanen, K.; Vögtle, F. *Liebigs Ann. Chem.* **1995**, 649–656. (c) Cardenàs, D. J.; Livoreil, A.; Sauvage, J.-P. *J. Am. Chem. Soc.* **1996**, *118*, 11980–11981. (d) Leigh, D. A.; Moody, K.; Smart, J. P.; Watson, K. J.; Slawin, A. M. Z. *Angew. Chem., Int. Ed. Engl.* **1996**, *35*, 306–310.
- (31) (a) Ashton, P. R.; Pérez-García, L.; Stoddart, J. F.; White, A. J. P.; Williams, D. J. *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 571–574. (b) Ashton, P. R.; Ballardini, R.; Balzani, V.; Credi, A.; Gandolfi, M. T.; Menzer, S.; Pérez-García, L.; Prodi, L.; Stoddart, J. F.; Venturi, M.; White, A. J. P.; Williams, D. J. *J. Am. Chem. Soc.* **1995**, *117*, 11171–11197.
- (32) Asakawa, M.; Ashton, P. R.; Balzani, V.; Credi, A.; Hamers, C.; Mattersteig, G.; Montalti, M.; Shipway, A. N.; Spencer, N.; Stoddart, J. F.; Tolley, M. S.; Venturi, M.; White, A. J. P.; Williams, D. J. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 333–337.
- (33) Livoreil, A.; Dietrich-Buchecker, C. O.; Sauvage, J.-P. *J. Am. Chem. Soc.* **1994**, *116*, 9399–9400.
- (34) Livoreil, A.; Sauvage, J.-P.; Armaroli, N.; Balzani, V.; Flamigni, L.; Ventura, B. *J. Am. Chem. Soc.* **1997**, *119*, 12114–12124.
- (35) Amabilino, D. B.; Dietrich-Buchecker, C. O.; Livoreil, A.; Pérez-García, L.; Sauvage, J.-P.; Stoddart, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 3905–3913.
- (36) For recent reviews on topics related to molecular machines, see: (a) Stoddart, J. F. *Chem. Aust.* **1992**, *59*, 576–577. (b) Preece, J. A.; Stoddart, J. F. *Nanobiology* **1994**, *3*, 149–166. (c) Gómez-López, M.; Preece, J. A.; Stoddart, J. F. *Nanotechnology* **1996**, *7*, 183–192. (d) Ward, M. D. *Chem. Ind. (London)* **1997**, 640–645. (e) Gakh, A. A.; Sachleben, R. A.; Bryan, J. C. *Chemtech* **1997** (November), *27*, 26–33. (f) Balzani, V.; Credi, A.; Scandola, F. *Chem. Ind. (Rome)* **1997**, *79*, 751–759. (g) Chambron, J. C.; Sauvage, J.-P. *Chem. Eur. J.*, in press. (h) Sauvage, J.-P. *Acc. Chem. Res.*, in press.
- (37) For the so-called heterosupramolecular chemistry approach, see: Marguerettaz, X.; Redmond, G.; Rao, S. N.; Fitzmaurice, D. *Chem. Eur. J.* **1996**, *2*, 420–428.
- (38) For evidence of being able to build supramolecular nanostructures on surfaces using compounds similar to those described in this Account, see: Laitenberger, P.; Claessens, C. G.; Kuipers, F. M.; Raymo, F. M.; Palmer, R. E.; Stoddart, J. F. *Chem. Phys. Lett.* **1997**, *279*, 209–213.
- (39) Monolayers and Langmuir–Blodgett films can be obtained using complexes and compounds similar to those discussed in this Account. See: (a) Ahuja, R. C.; Caruso, P.-L.; Möbius, D.; Wildburg, G.; Ringsdorf, H.; Philp, D.; Preece, J. A.; Stoddart, J. F. *Langmuir* **1993**, *9*, 1534–1544. (b) Ahuja, R. C.; Caruso, P.-L.; Möbius, D.; Philp, D.; Preece, J. A.; Ringsdorf, H.; Stoddart, J. F.; Wildburg, G. *Thin Solid Films* **1996**, *284/285*, 671–677.
- (40) See, for example: (a) Finer, J. T.; Simmons, R. M.; Spudich, J. A. *Nature (London)* **1994**, *368*, 113–119. (b) Yin, H.; Wang, M. D.; Svoboda, K.; Landick, R.; Block, S. M.; Gelles, J. *Science (Washington, D.C.)* **1995**, *270*, 1653–1657. (c) Noji, H.; Yasuda, R.; Yoshida, M.; Kinoshita, K., Jr. *Nature (London)* **1997**, *386*, 299–302. (d) Howard, J. *Nature (London)* **1997**, *389*, 561–567.
- (41) Some chemical systems, including pseudorotaxanes, have been found to perform complex logic operations. See: (a) de Silva, A. P.; Gunaratne, H. Q. N.; McCoy, C. P. *Nature (London)* **1993**, *364*, 42–44. (b) Credi, A.; Balzani, V.; Langford, S. J.; Stoddart, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 2679–2681. (c) de Silva, A. P.; Gunaratne, H. Q. N.; McCoy, C. P. *J. Am. Chem. Soc.* **1997**, *119*, 7891–7892. (d) Asakawa, M.; Ashton, P. R.; Balzani, V.; Credi, A.; Mattersteig, G.; Matthews, O. A.; Montalti, M.; Spencer, N.; Stoddart, J. F.; Venturi, M. *Chem. Eur. J.* **1997**, *3*, 1992–1996.
- (42) *Opportunities in Chemistry*; National Academy of Sciences, National Academy Press: Washington, DC, 1985; p 220.

AR970340Y