Supramolecular Chemistry of Nanomaterials

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Lecture 6 – Towards the Development of Molecular Machines

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Lecture 6 - Outline

- Concepts and introduction

- Natural molecular machines
  - ATP synthase
  - Supramolecular springs

- Developing synthetic molecular machines
  - Molecular muscle
  - Molecular wires
  - Insulated molecular wires

- Current problems for the development of molecular machines

Definitions

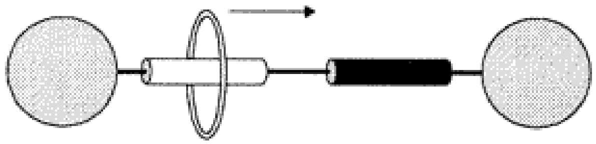
Machine: Any system, usually of rigid bodies formed and connected to alter, transmit, and direct applied forces in a predetermined manner to accomplish a specific objective such as the performance of useful work.

Motor: Device that converts any form of energy into mechanical energy. Molecular motors convert chemical energy into mechanical force and movement.

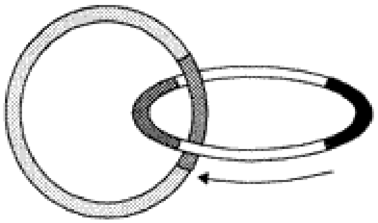
As for their macroscopic counterparts, molecular machines are characterised by:

(i) the kind of energy input supplied to make them work
(ii) the kind of movement performed by their components
(iii) the way in which their operation can be controlled
(iv) the possibility to repeat the operation at will
(v) the time scale needed to complete a cycle of operation
(vi) the function performed

Although molecular machines are widespread in Nature, the development of synthetic molecular machines is still in the very early stages. To date, several components of such potential machines have been produced, but there is still a lack of actual molecular machines. Some of such components are schematically shown in this slide:



1



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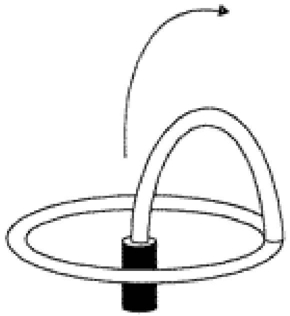

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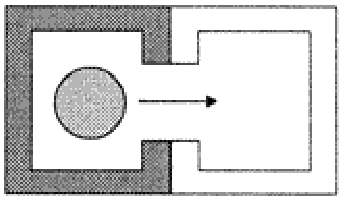
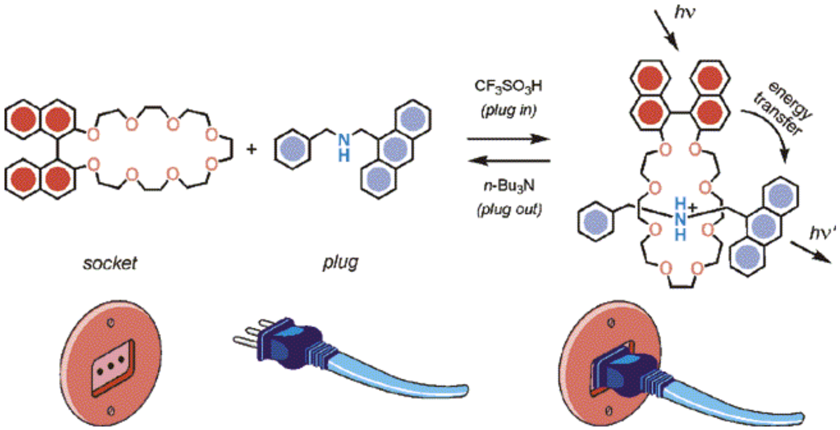


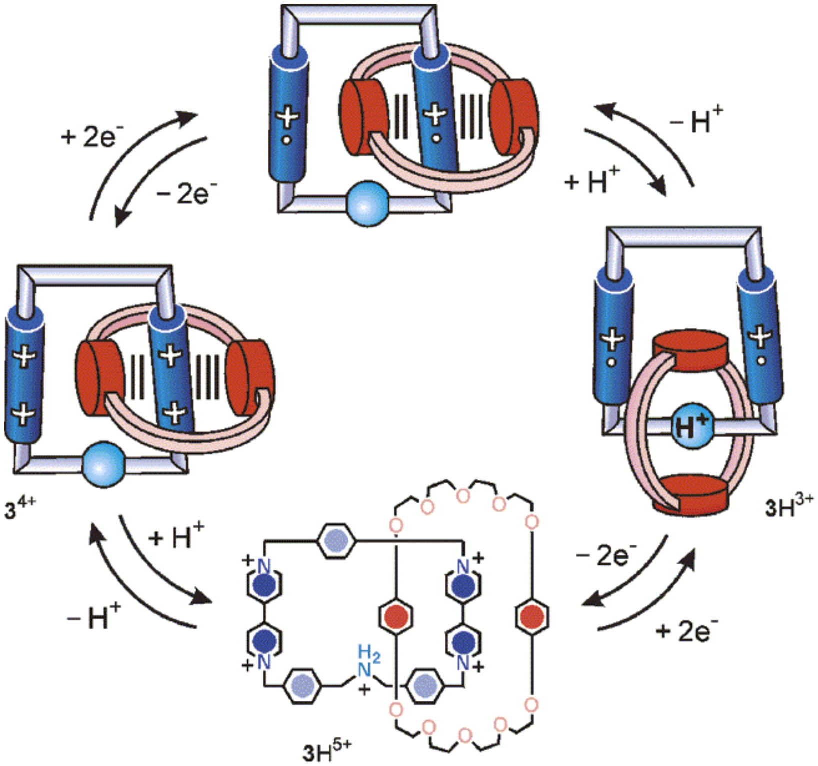
4

From previous lecture:



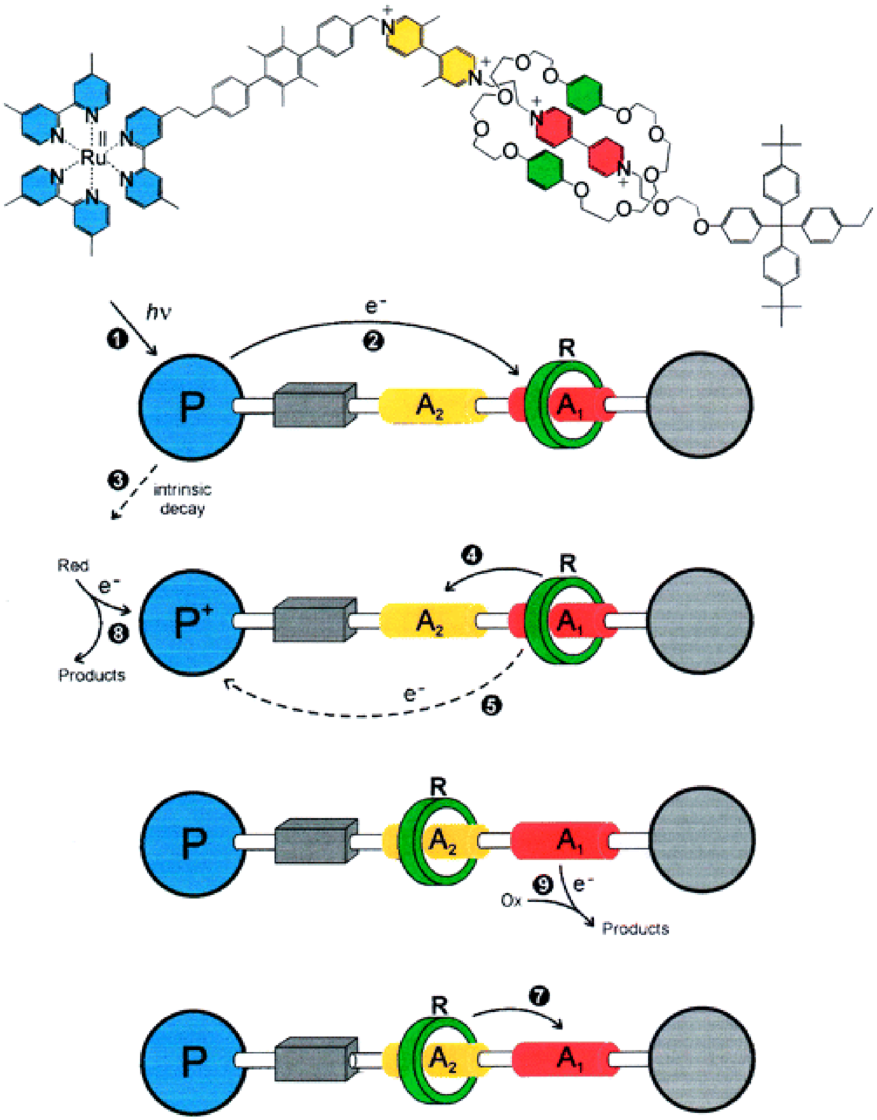
Molecular level plug

Molecular Switch (Logic Gate)



Balzani *et al. Acc. Chem. Res.*, **34** (6), 445 -455, 2001

Photocontrollable Abacus



V. Balzani, J.F.A. Stoddart, *J.Am.Chem.Soc.*, **1998**, *120*, 11190

Molecular machines in biology

The molecular machinery of nature outperforms anything that mankind currently knows how to construct with conventional manufacturing technology by many orders of magnitude.
Take few examples:

- A single cell of *E. Coli* has a digital storage capacity in its genome equivalent to that of a high-density floppy disc

- A ribosome is capable of self assembly from more that 50 proteins

- Green plants convert more energy and synthesise a greater tonnage of fine chemicals than the combined global chemical industry

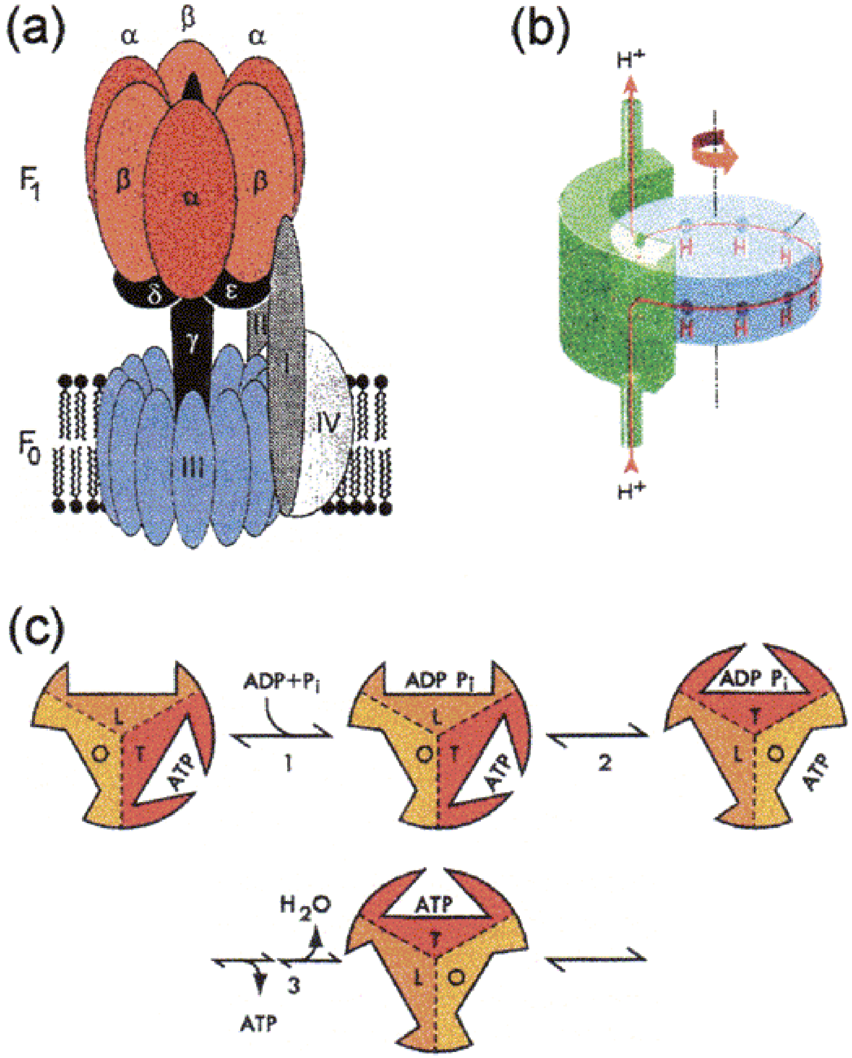
ATP synthase: an example of molecular machine at the nanometer scale

- ATP (adenosyl triphosphate) is the “energy currency” in living organisms; this small molecule is the general source of chemical energy in the cell.

- With FoF1-ATP synthase, Nature very elegantly demonstrates that devices can be constructed at a molecular scale which are not only close structural analogues of macroscopic world motors, but also represent *functional models* of their large-scale brothers.

- In this enzyme several proteins are assembled across the cell’s membrane (one of the units is held in the membrane while the other one is outside). By a concerted process of rotation, the external proteins change their conformation catalysing the formation of ATP from ADP and inorganic phosphate. The source of energy for this process is generated by a chemical potential in the form of a proton gradient.

The F_1 building block itself is a circular assembly of six domains in an alternating pattern. In an endergonic process, the subunits generate ATP from ADP and inorganic phosphate by binding the reactants in an enzyme pocket. Upon rotation of the axle by 120, the pocket changes its conformation so that ATP is formed. The next 120 degrees step again leads to conformational changes of the pocket, and ATP is released. The use of more than one active subunit has the advantage of catalytic cooperativity and allows, for example, the binding energy of ADP and phosphate gained in one pocket to support the energy consuming processes in another one.



Vogtle et al, *Acc. Chem. Res.*, 2001, **34**, 465

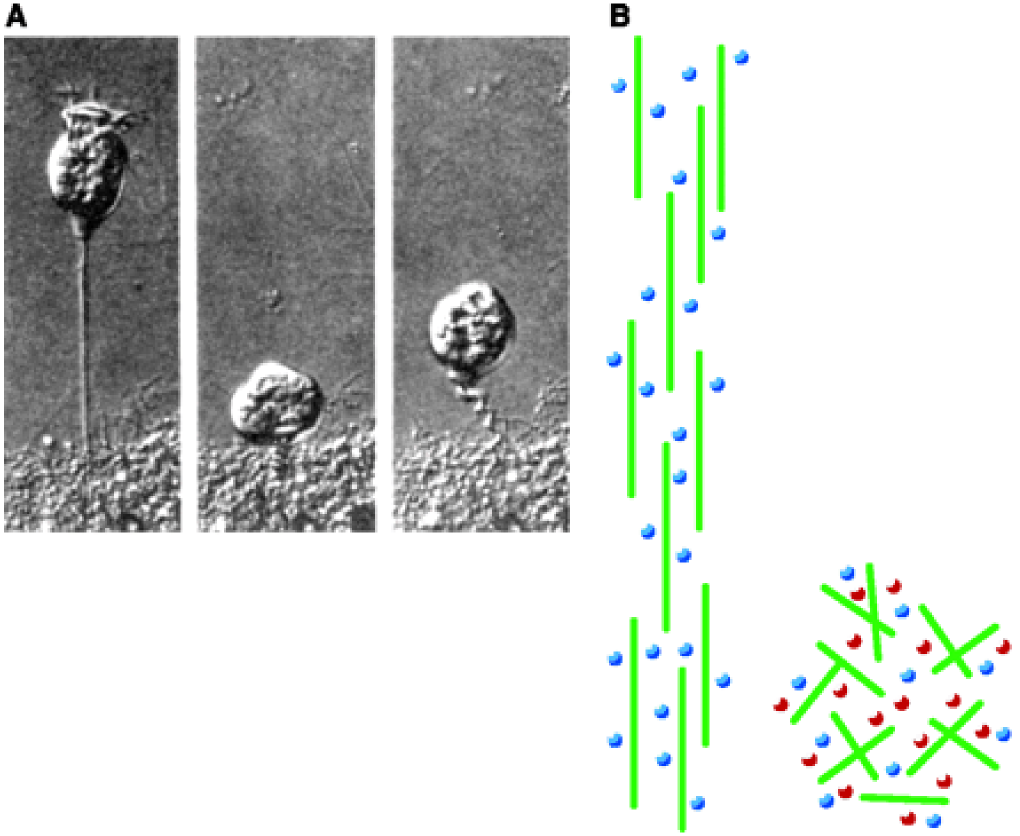
Molecular machines used for motion (motors)

There are several other actions performed by cells which are directly linked to a molecular machine. Examples of such molecular (or supramolecular) machines and motors are:

- The beating of *cilia* and *flagella*
- The movement of vesicles on microtubules
- Rotation of *flagellar* motors
- Muscle contraction
- Cellular *springs*

(A good review of such machines and motors can be found in: L. Stryer, *Biochemistry*, Chapter 15, 4th edition, 1995).

Motility Powered by Supramolecular Springs

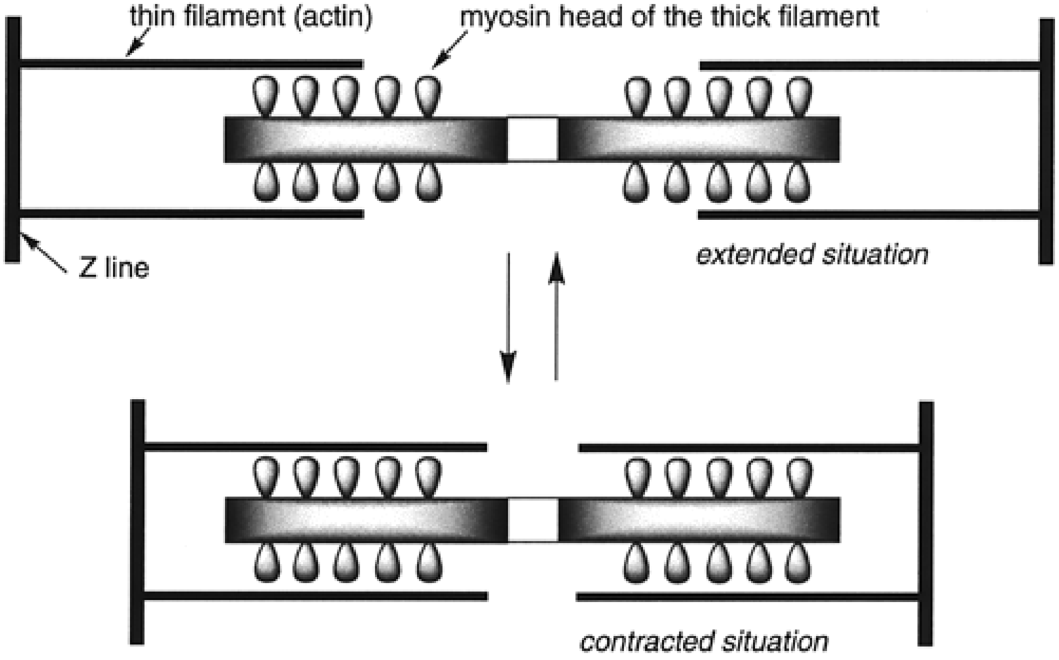


(A) The spasmoneme in *Vorticella*, shown in its fully extended (left), fully contracted (middle), and partially extended (right) states. (B) The extended state (left) consists of aligned filaments held apart by negative charges (blue). Calcium (red) neutralizes the charge, and the filaments condense (right).

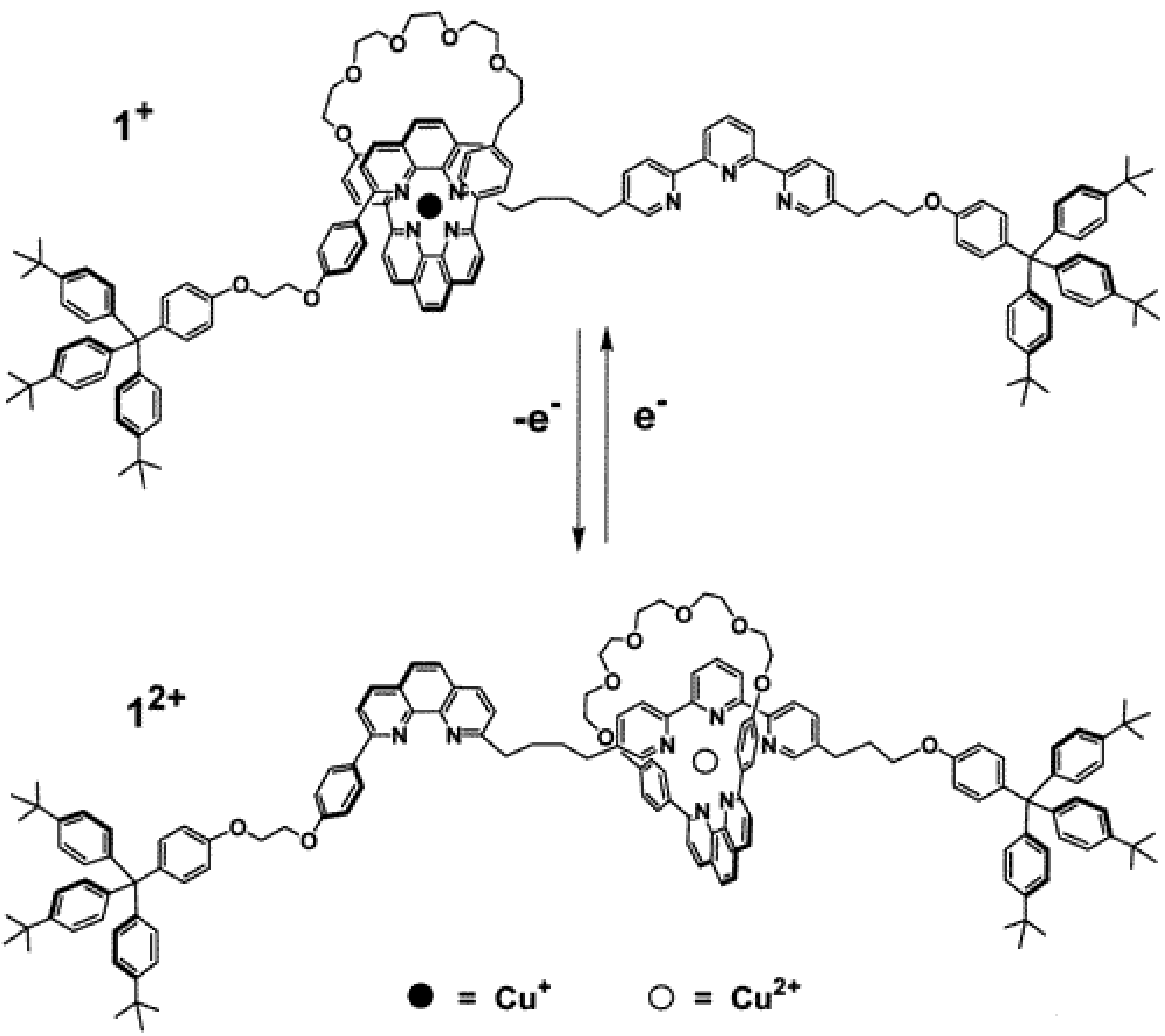
Mahadevan and Matsudaira, *Science*, 2000, **288**, 95

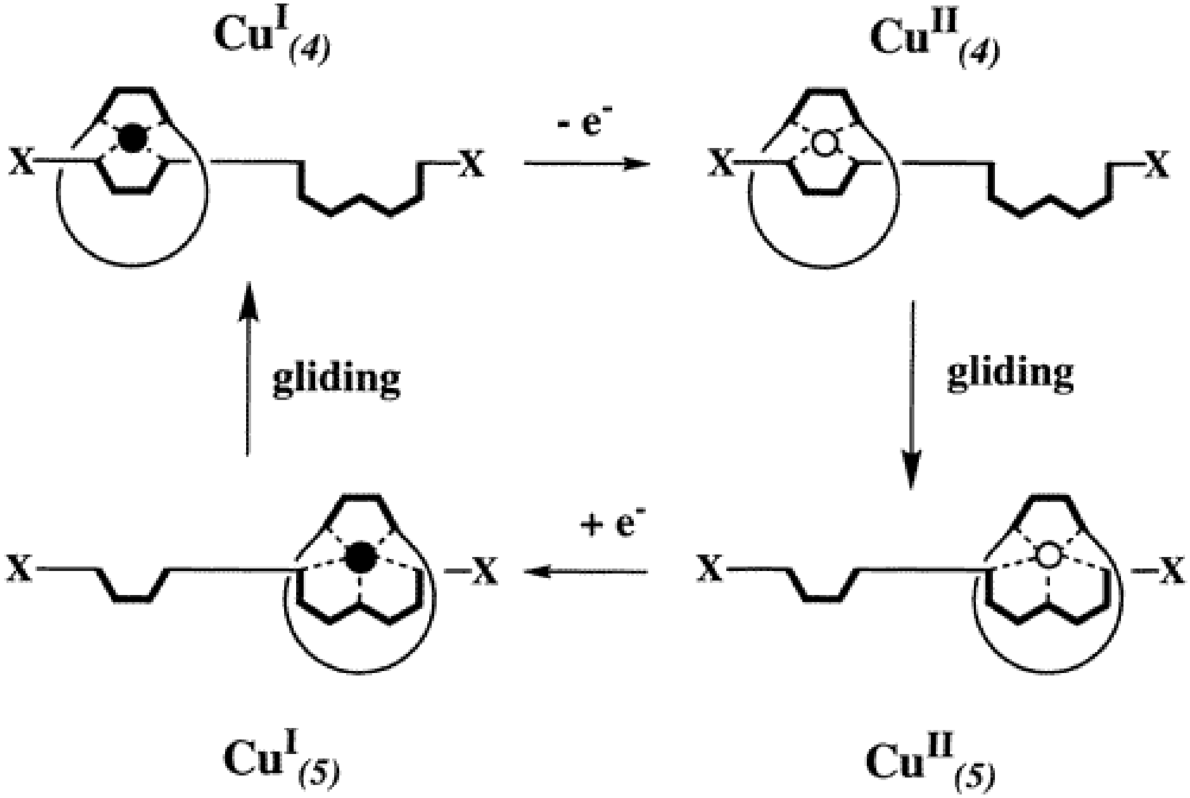
Developing synthetic molecular machines

A “molecular muscle” based on rotaxanes

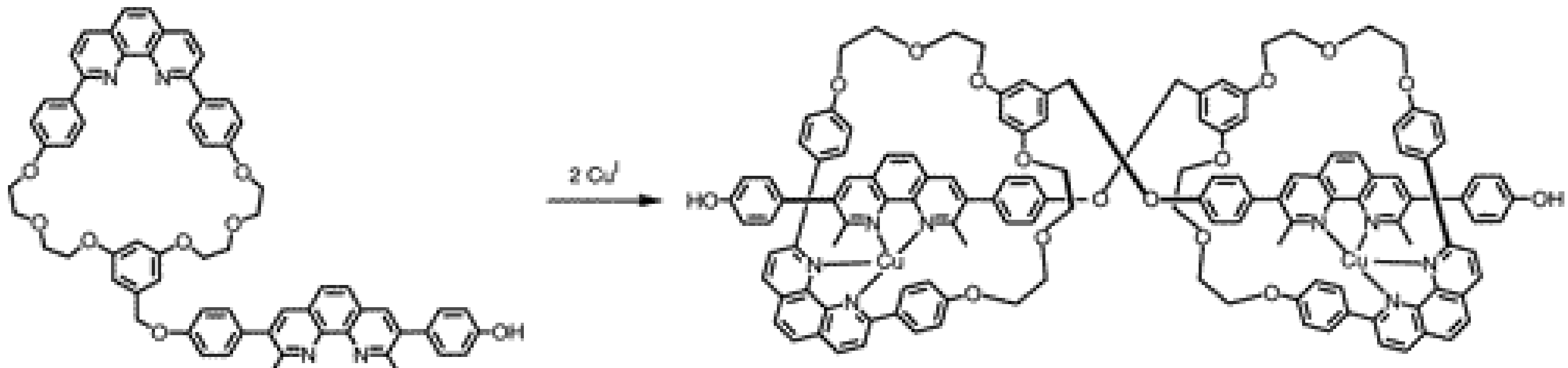


J.-P. Sauvage, *Acc.Chem.Res*, **2001**, 404, special issue on molecular motors


1+
-e-
e-
1 2+
● = Cu+
○ = Cu2+



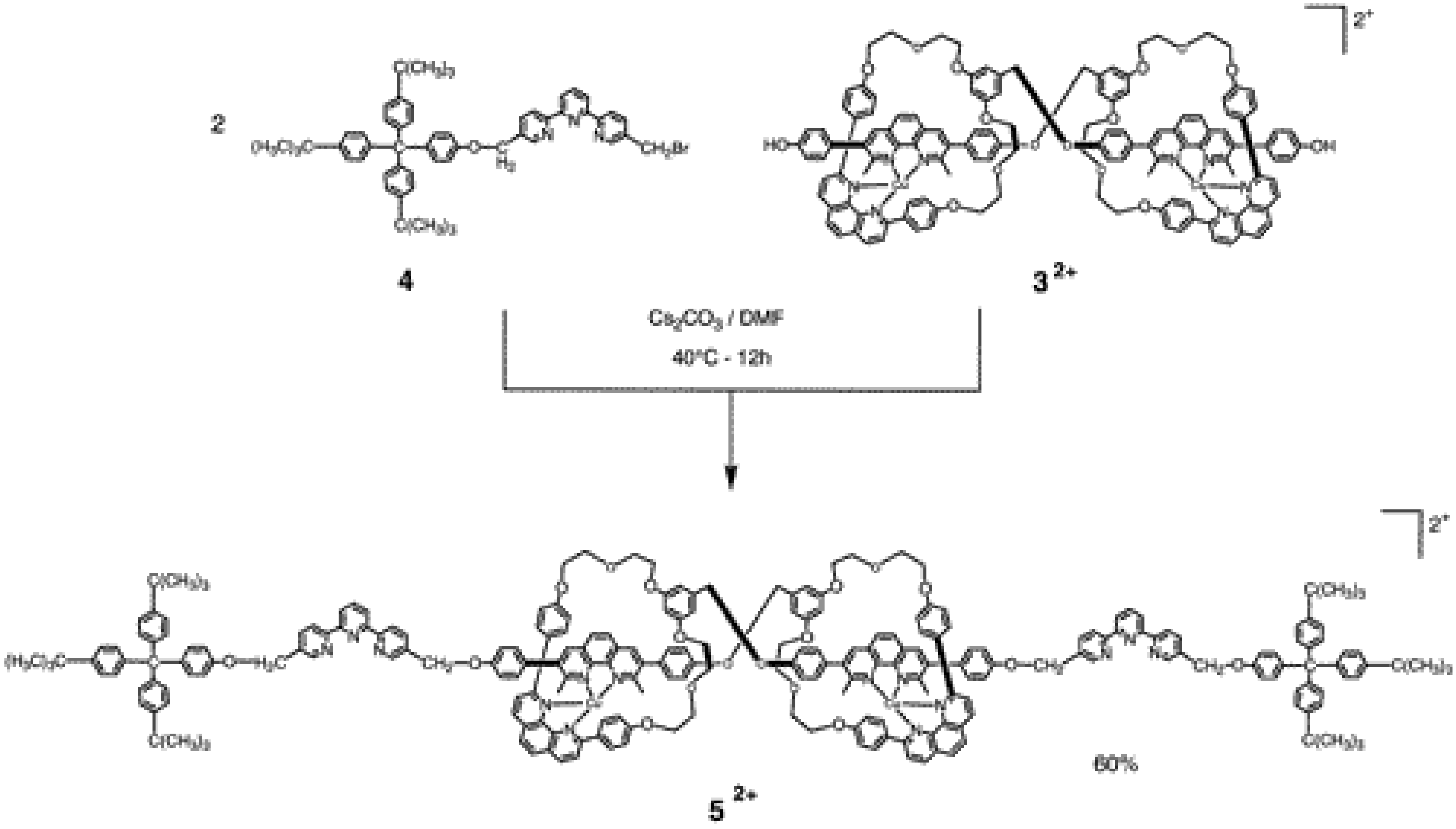
X = bulky stopper

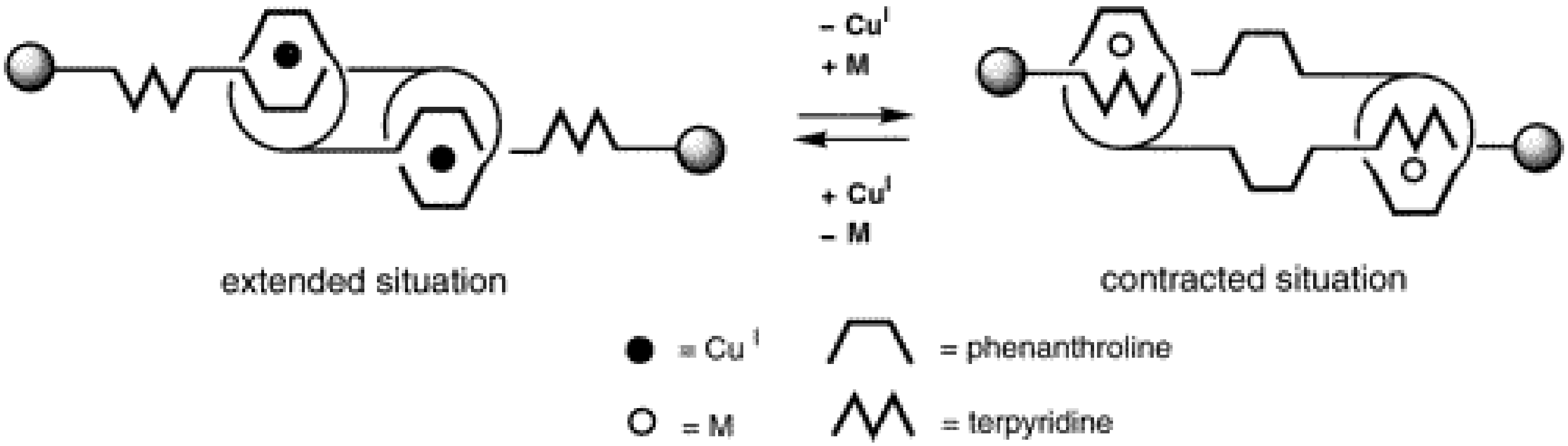


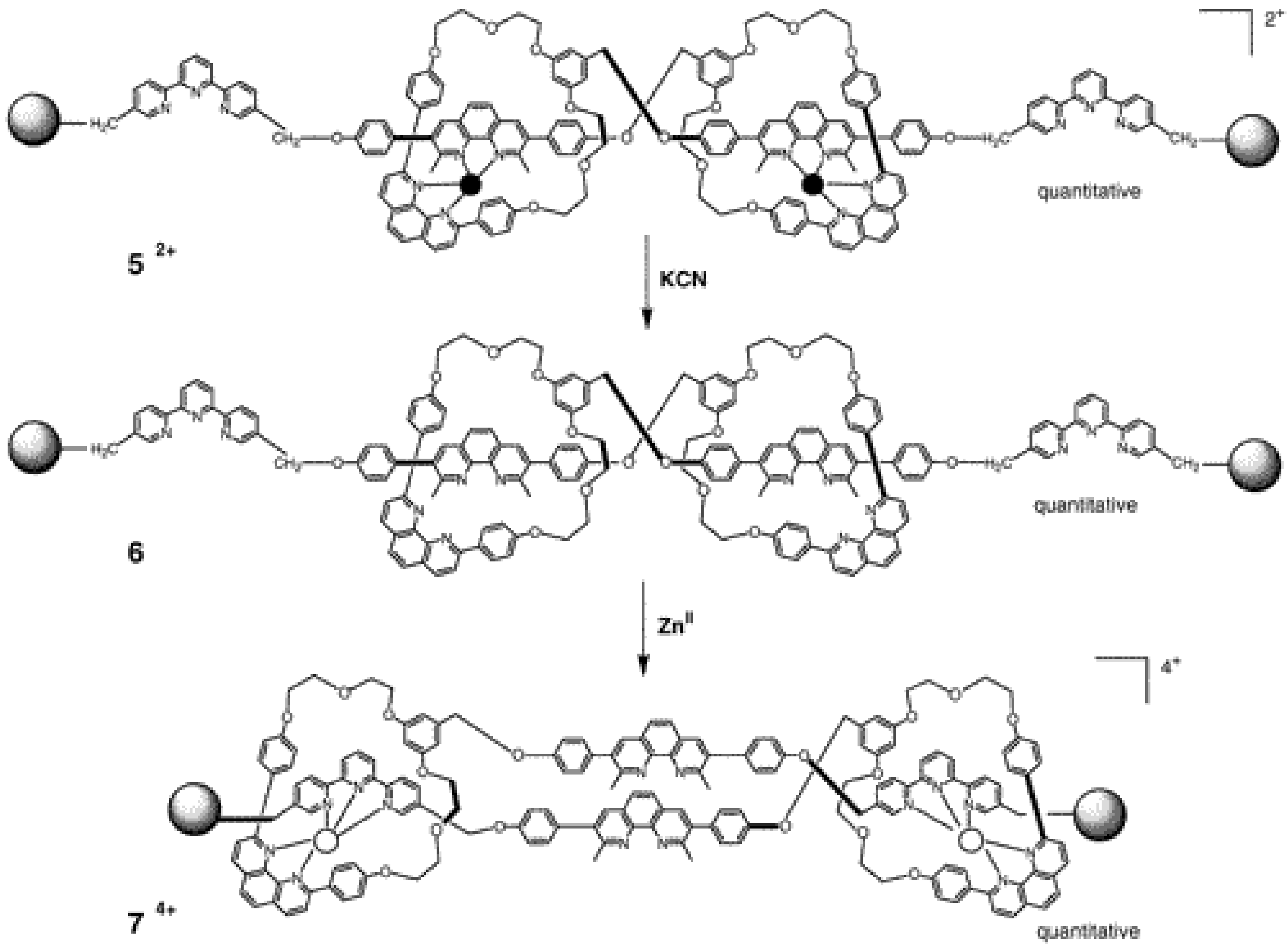
2

3^{2+}

J.-P. Sauvage, *Angew.Chem.Int.Ed.*, **2000**, *39*, 1295

2
C(CH3)3
(H3C)3C
C(CH3)3
O
C
H2
N
N
N
CH2Br
HO
Cu
OH
2+
4
3^{2+}
Cs_2CO_3 / DMF
40°C - 12h
C(CH3)3
(H3C)3C
C(CH3)3
O
H2C
N
N
N
CH2
O
Cu
Cu
O
CH2
N
N
N
CH2
O
C(CH3)3
C(CH3)3
C(CH3)3
2+
60%
5^{2+}


– Cu I
+ M
+ Cu I
– M
extended situation
contracted situation
● = Cu I
○ = M
= phenanthroline
= terpyridine

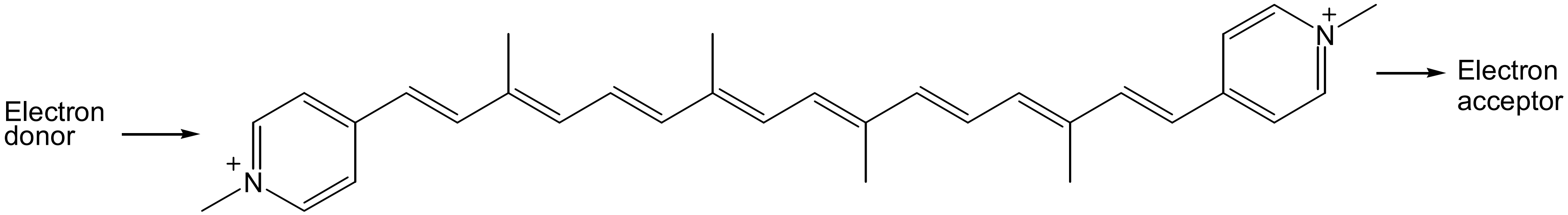


J.-P. Sauvage, *Angew.Chem.Int.Ed.*, **2000**, *39*, 3284

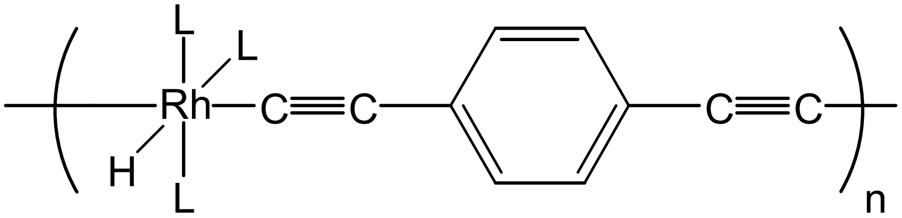
Molecular wires

The basic properties of a molecular wire are that it should connect to two components (generally an electron acceptor and an electron donor) and conduct an electrical signal or impulse between them. At a molecular level this may amount to a single electron.

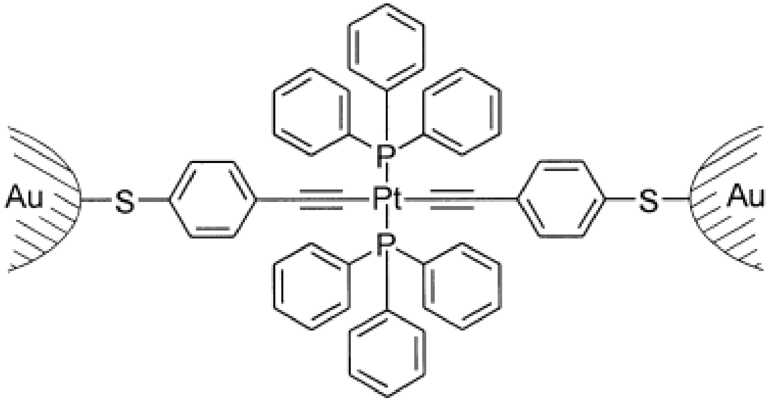
This has been achieved by using oligomeric materials with high degree of conjugation. The delocalisation of the electrons in the conjugated systems allow for the electrical impulse to be transported. Some examples are shown in the following slide.



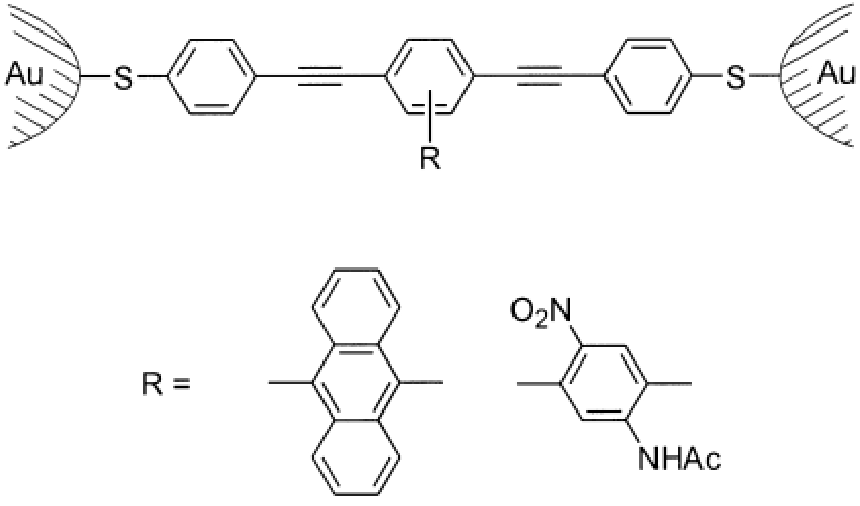
Lehn, *Proc. Nat. Acad. Sci. USA.*, 1986, **83**, 5355



One of the big challenges ahead to make these molecular wires real devices for molecular machines, is to connect them to the macroscopic world (e.g. to an electrode). Recently, some groups in Germany and the US have done experiments in which the conductivity of a single molecule has been investigated by “trapping” it between two metal tips.



1'



2' **3'**

Angew. Chem. Int. Ed. **2002***, 41*, 1183;

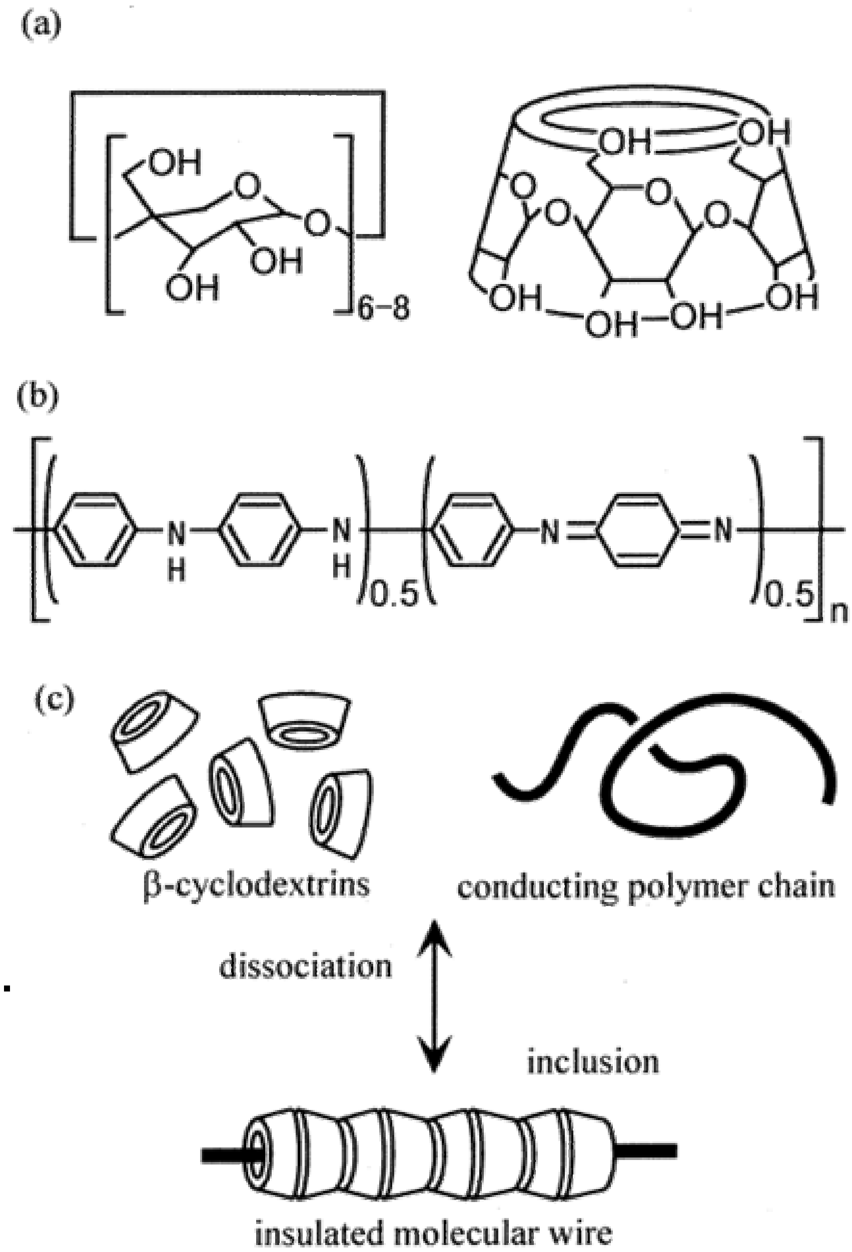
Preparation of insulated molecular-scale wires.

As will be discussed later in the lecture, one of the problems for the development of molecular machines is the stability of the molecular components. If they are to be incorporated as part of a device, they should be robust and not be easily degraded by electron transfer processes.

This is a problem with several of the current “molecular wires”; their “exposed” nature makes them vulnerable to attack by various chemicals.

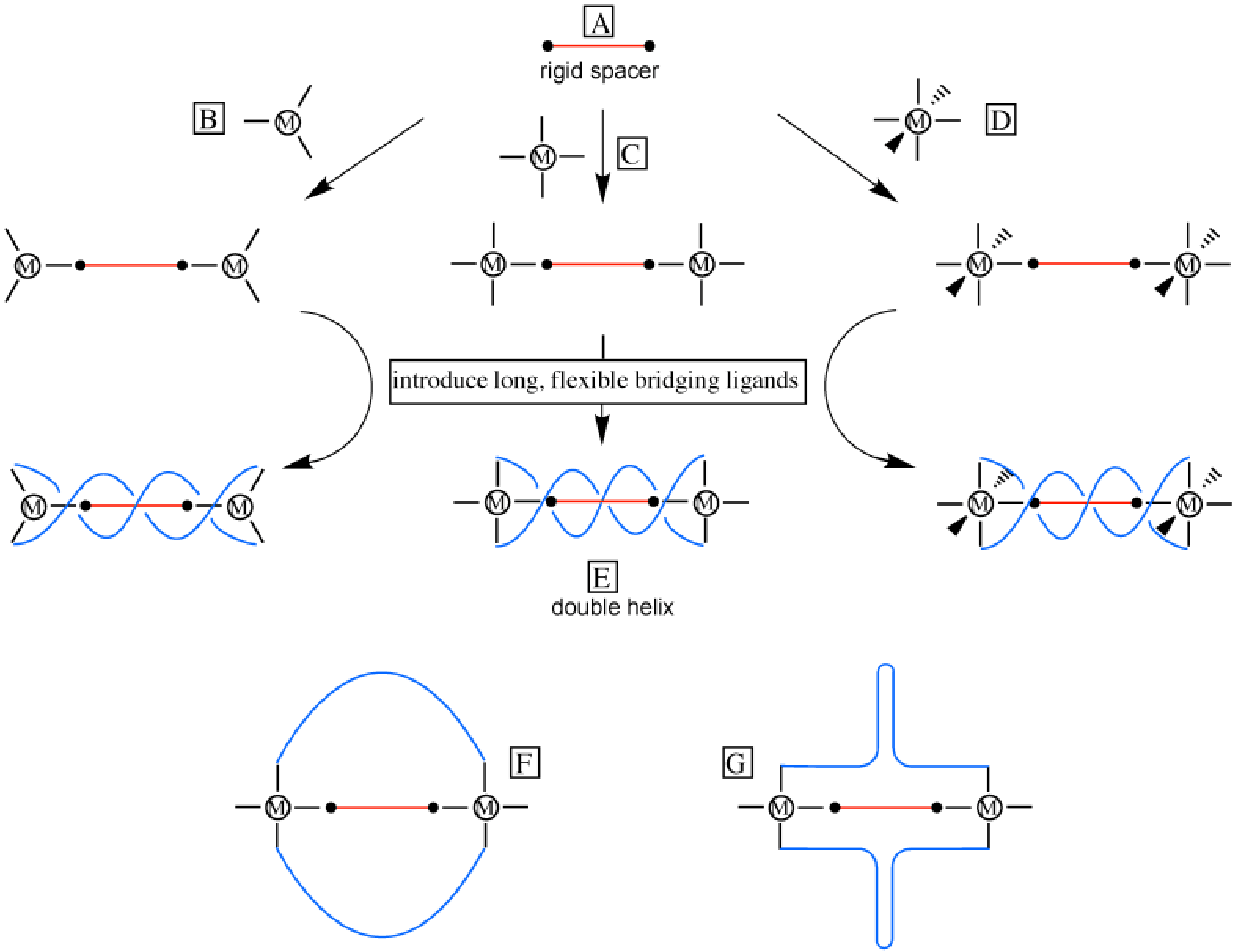
In spite of this, there are already some examples in which, by self-assembly, it has been possible to protect against chemical degradation some molecular wires.

It has been established that under the right conditions cyclodextrins can self-assembly with polymeric chains to give inclusion complexes.
By using a conducting polymer, the supramolecular necklace formed resembles an insulated molecular wire (similar to a copper wire protected by a plastic coating).



Ito, *Langmuir*, 1999, **15**, 910

More recently Gladysz has reported the following approach:



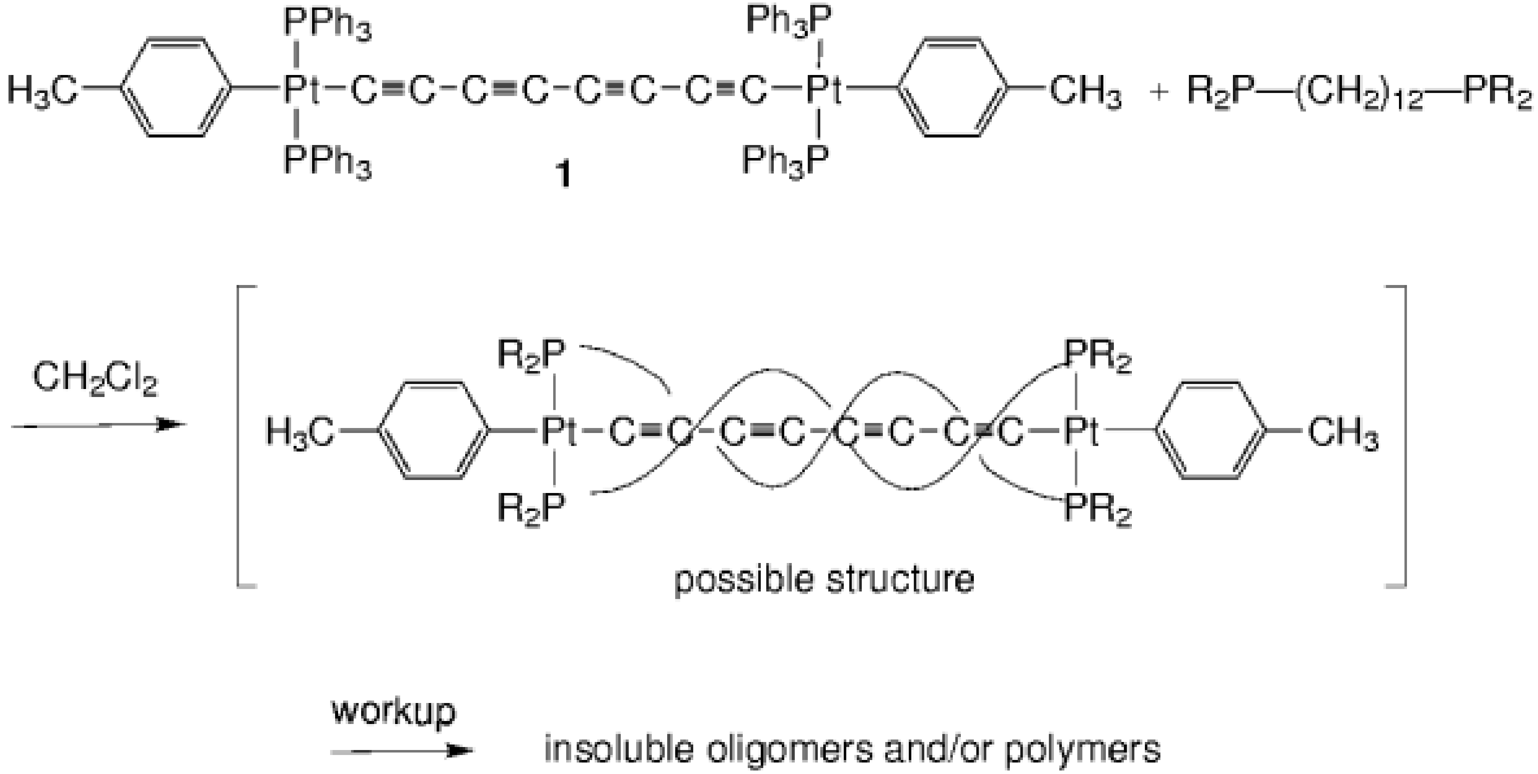
introduce long, flexible bridging ligands

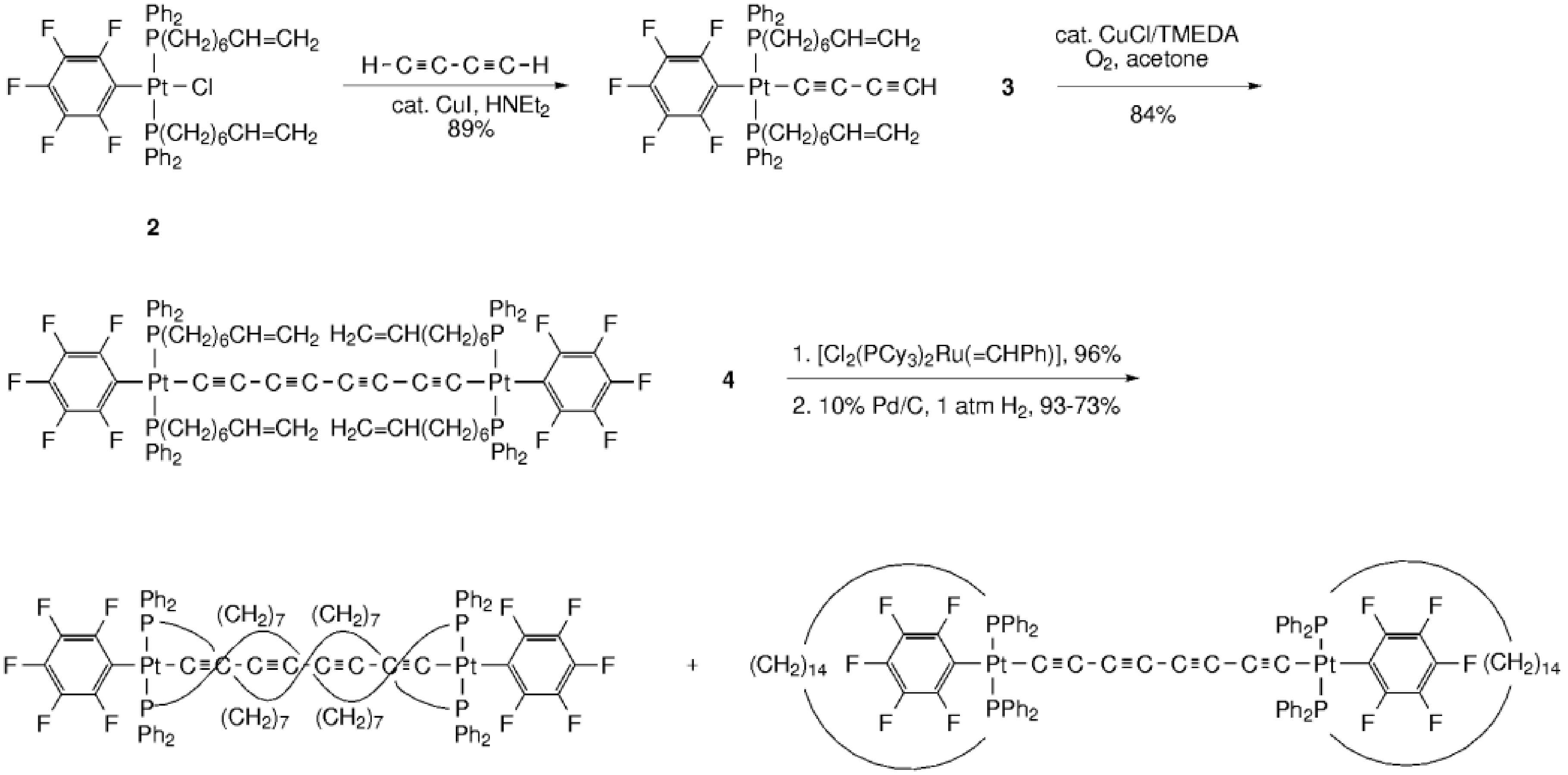
E
double helix

F
"double hole"

G
"double finger"

Gladysz, *Angew. Chem. Int. Ed.*, **2002**, *41*, 1872


1
+ R2P—(CH2)12—PR2
CH2Cl2
possible structure
workup
insoluble oligomers and/or polymers


H-C≡C-C≡C-H
cat. CuI, HNEt2
89%
cat. CuCl/TMEDA
O2, acetone
84%
1. [Cl2(PCy3)2Ru(=CHPh)], 96%
2. 10% Pd/C, 1 atm H2, 93-73%
(CH2)7
(CH2)14
+

2

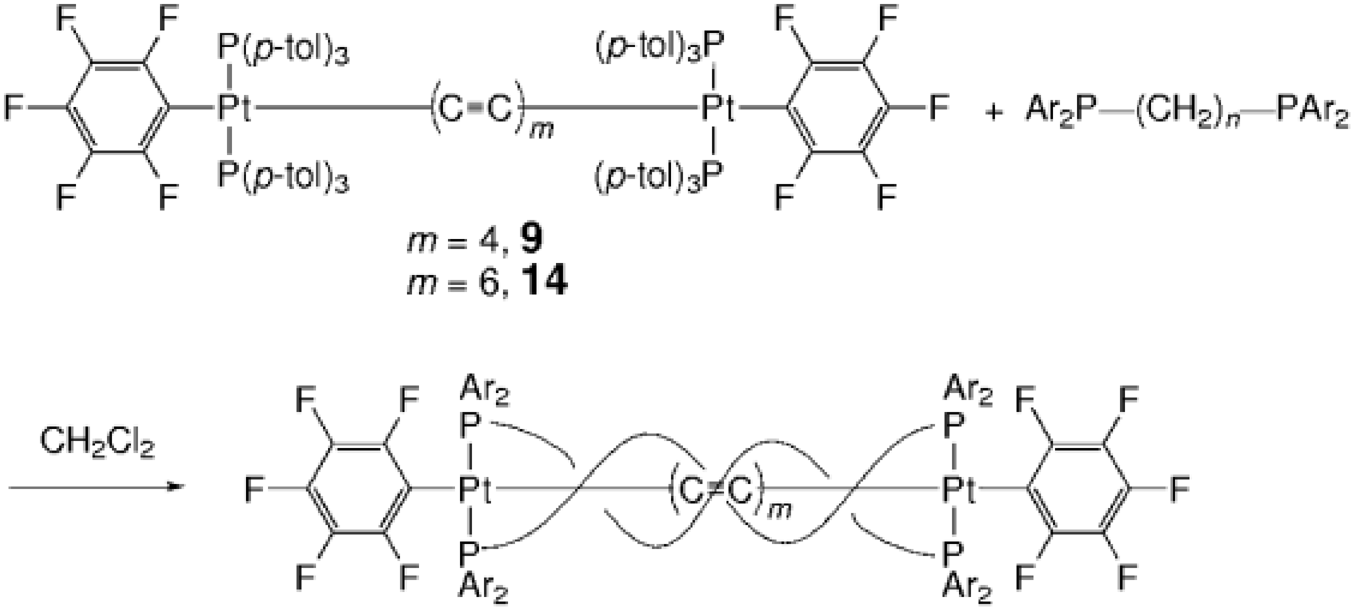
3

4

7

8

Several of such “protected” molecular wires have now been prepared; by careful variation of the length of the diphosphine spacer, it is possible to favour the formation of the desired structure:


$m = 4$, **9**
$m = 6$, **14**

Molecular machines: How far are we from practical devices?

The “bottom-up” approach is extremely attractive as it proposes
The construction of devices and circuit components through the
Rational assembly of the smallest set of building blocks available
to mankind. However, the application of these systems into actual
Circuits and devices is currently restricted by important technological
Problems such as:

-Switching rates
-Miniaturization and phase requirements
-Miniaturization and information scrambling
-Miniaturization and molecular wires
-Device stability

(Take from: Kaifer et al, *Structure and Bonding*, 2001, **99**, 141)

Switching rates: Current switching times for molecular switches based on rotaxanes and catenanes are around the millisecond regime (I.e. each molecule could support less than 1000 switching operations per second). Semiconductor-based devices switch considerably faster (within the nanosecond regime).

Miniaturization and Phase Requirements: The examples we have discussed so far represent an extraordinary high level of scale integration and miniaturization (one bit is stored in one molecule of relatively small size). The problem is that most of this systems have been studied in solution, which makes it impossible to switch a specific molecule, store one bit of info, in it and return later to read it. Information storage and processing requires the assembly of devices into 2D or 3D solid state arrays.

Miniaturization and information scrambling: If we assume the one can deposit the “switchable” molecules on a surface and that the switching occurs due to electron transfer. How can we ensure that the molecule will remain in the oxidized state for a long time? The answer will strongly depend on the distance between the deposited molecules. If there are no barriers between them, electron transfer between molecules will occur and the information will obviously be lost. This is not a trivial task.

Molecular wires: In order to address single sites in a molecular array of molecular devices, some mechanism for contacting the macroscopic world must be employed. For example, the to connect a switchable rotaxane to an electrode, molecular wires will be required. Recent studies have demonstrated that there are several factors (difficult to control) that will have enormous influence on the ability of the molecular wire to be connected to an electrode (e.g. contact geometry, contact length, stability).

Device stability: One should remember that many types of molecular residues that undergo fast and reversible electron transfer reactions (in CV timescales) undergo significant decomposition reactions in a longer time scale. Hence, the stability of the molecular devices (powered by electron transfer) known to date, would present stability problems. One could argue that other (not electron transfer mechanisms) could be used (e.g. changes in pH). This presents, not only stability problems, but the added complication of “feeding” chemicals to the reaction.