

# Stable metal–organic complexes as anion hosts

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A growing number of metal–organic complexes are being employed as anion hosts. This *tutorial review* focuses on stable, mononuclear transition metal complexes with a well defined geometry that use a combination of electrostatic attraction and hydrogen bonds for anion binding. In these hosts, the metal provides positive charge and act as a scaffold that holds the ligands containing the hydrogen-bond donor groups in the appropriate positions. Issues particular to these hosts, such as the choice of the ligands, metal center and counteranion, and the stability of the host, are discussed using examples from the recent literature. This paper is addressed to readers interested in supramolecular chemistry and coordination or organometallic chemistry.

## Introduction

Typical anion hosts are organic molecules or cations; however, a growing number of hosts incorporate metals in their structures.<sup>1,2</sup> The interaction with the guest often occurs mainly through several binding groups in the structure of the host. Metals are Lewis acids and anions are Lewis bases; therefore, metal fragments have been used as binding groups in anion hosts. When the receptor is designed to function as a sensor, metal fragments can be used as reporter units, modulating a signal, usually color, fluorescence or electrochemical potential,<sup>3</sup> as a result of the host–guest interaction. Metal fragments can bear positive charge so that the coulombic attraction between the cationic host and the anionic guest adds to other host–guest interactions at play. Hydrogen bonds are the non-covalent interactions most generally useful in host–guest chemistry because they are directional and relatively strong. For these reasons, hydrogen-bond donor groups are often used as binding groups in anion hosts. The presence of nearby electron-withdrawing metal fragments can enhance the hydrogen-

bond donor ability of those groups and, therefore, increase the strength of the host–guest interaction. Hosts are designed aiming to achieve sufficiently strong host–guest interactions. This means that, at least, the resulting host–guest adduct should be stable enough in solution so that it can be detected and, if possible, that its strength can be measured. The interaction between the guest and each individual binding group, being a non-covalent interaction, is relatively weak. As a result, several binding groups of the host must interact simultaneously with the guest. The exact number, nature and spatial disposition of the binding groups determine the affinity of the host toward a specific guest. To achieve the simultaneous interaction of the guest with several binding groups, these must be in the appropriate positions within the structure of the host. Therefore, besides the binding groups, the host must possess some group able to act as a scaffold, anchoring the binding groups in the right positions so that they can converge toward the guest. Metals can be used as scaffolds for the construction of anion hosts. This tutorial review will try to explain some key features of the simplest, mononuclear complexes of this kind. Excellent reviews appeared recently on the same topic;<sup>1,2</sup> therefore, we will concentrate on particular aspects that have been less treated.

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## A few examples

Before proceeding further, and to avoid being too abstract, let us consider a few examples.

The platinum complexes shown in Fig. 1(a), which host–guest behavior was studied by Bondy, Loeb and Gale,<sup>4</sup> possess four pyridine ligands, each bearing an amido functionality. Their N–H groups act as hydrogen-bond donor groups. The interaction between these Pt hosts and the anionic guests will be a combination of these hydrogen bonds and electrostatic attraction. The ruthenium complexes depicted in Fig. 1(b), prepared by Steed and co-workers,<sup>5</sup> are organometallic complexes featuring, besides the aminopyridine ligands (in which amino N–H groups will act as hydrogen bond donors),  $\eta^6$ -arene ligands. The rhenium compounds in Fig. 1(c), prepared by our group,<sup>6,7</sup> employ the N–H groups of three pyrazole ligands as hydrogen-bond donor groups. The coordination sphere of the Re(I) center is completed with three carbonyl ligands. Finally, the ruthenium biimidazole complex of Fig. 1(d), also studied by our group,<sup>8</sup> differ from the previous examples in that the hydrogen-bond donor groups of the host belong to the same ligand, the chelating 2,2'-biimidazole. Metal-based anion hosts containing bidentate bis(carbamoyl)bipyridine ligands have been extensively studied by Beer and co-workers (see below). In the four examples of Fig. 1, the hosts are the cationic complexes, and they are accompanied by large counteranions.

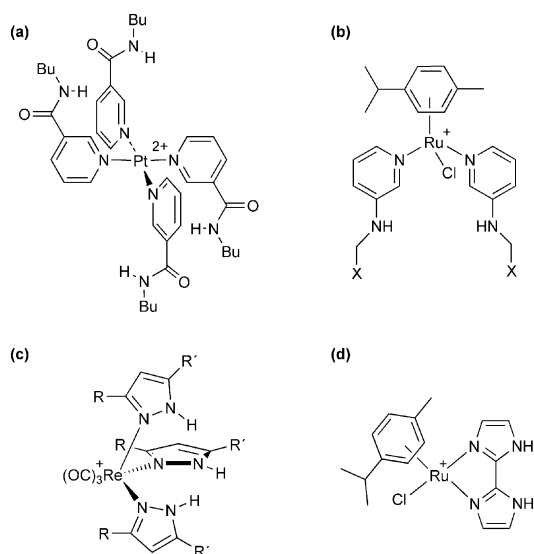


Fig. 1 Some metal complexes that have been used as anion hosts.

## Supramolecular chemistry vs. coordination chemistry

In coordination chemistry, ligands, *i.e.*, molecules or anions containing Lewis-basic sites, are used to bind metals. At first sight, using hosts that contain Lewis-acid centers as part of their structure to bind anions looks like a reverse of coordination chemistry.

It is generally considered that supramolecular chemistry begins with the invention of crown ethers and the study of their interaction with alkali-metal cations. This is an example

of host–guest chemistry, in which the cations are the guests and the crown ethers are the hosts. But the interaction between these species can also be thought of as part of the coordination chemistry of the alkali-metals. Why is the distinction important? Note that supramolecular chemistry is defined as the chemistry beyond the molecule, the chemistry of the non-covalent interactions. Pedersen's work was surprising because alkali-metal cations were not expected to be capable of forming stable coordination compounds. Alkali-metal cations have closed shell  $1s^2$  ( $Li^+$ ) or  $ns^2np^6$  valence electronic configurations and so they should not form covalent bonds with Lewis bases. Recent high-level calculations<sup>9</sup> suggest that this simple vision is quite accurate, and that the bond between alkali-metal cations and, for instance, crown ethers, can be described as essentially cation–dipole attractions, which are listed among intermolecular forces in general chemistry textbooks. At the other extreme in bond character, the transition metal–ligand bond is covalent (admittedly, with a significant ionic character) and models such as ligand field and molecular orbitals are conventionally used for its description. Therefore, the bond between a transition metal and a ligand is not a non-covalent interaction, and coordination chemistry should be considered a part of covalent chemistry (molecular chemistry, as opposed to supramolecular chemistry) such as, for instance, organic chemistry. In metal-based hosts such as those in Fig. 1, the host employs only its second coordination sphere to interact with the guest. Typically, the host–guest adducts formed by hosts of this kind are kinetically labile, *i.e.*, the anion exchange is fast in most cases. In contrast, the metal complexes that act as hosts such as most of those in Fig. 1 are kinetically inert, *i.e.*, the metal–ligand bonds remain intact over the course of the host–guest interaction.

## Host–guest vs. self-assembly

The compounds displayed in Fig. 1 are stable, isolable species. To study their interaction with anions in solution, they can be, for instance, NMR-titrated with tetraalkylammonium salts (chosen by their solubility and low ion-pairing) of the anions. Thus, the variation of the chemical shift of their anion-binding N–H groups as a function of the amount of anion added (if, as it usually happens, anion exchange is fast in the NMR timescale) can be used to estimate the strength of the host–guest interaction. If the crystallization of mixtures of the compounds in Fig. 1 and salts of the desired anion is successful, subjecting the resulting crystals to X-ray diffraction can afford information on the nature of the host–guest interaction in the solid state.

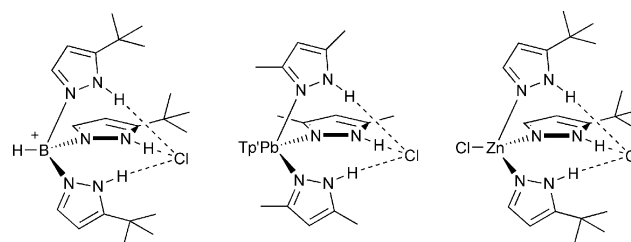


Fig. 2 Self-assembled adducts of chloride and tris(pyrazole) units.

In contrast, the compounds displayed in Fig. 2,<sup>10–12</sup> which bear an obvious structural relationship to the host–guest adducts of the rhenium compound of Fig. 1(c), are self-assembled structures, and the corresponding “free” hosts are not available. Species such as these will not be dealt with here.

## Host–guest chemistry: anionic guests vs. cationic guests

The host–guest chemistry of anionic guests is increasingly referred to as coordination chemistry of anions, which is then compared with classical coordination chemistry, that is, coordination chemistry of cations. In this vein, the slower development of the coordination chemistry of anions in comparison with that of cations is attributed to the fact that anions are larger, have higher solvation energies, their forms and protonation states are varied, *etc.* Nevertheless, one needs to be aware that the types of host–guest interactions at work in the two branches of chemistry are often completely different. Thus for cationic guests, most hosts are designed incorporating ion–dipole interactions (such as in the interactions between alkali-metal cations and crown ethers), or a combination of these with some degree of covalency, as it is the case when the guests are more polarizing cations such as  $\text{Zn}^{2+}$ ,  $\text{Hg}^{2+}$ , *etc.* Some of the hosts employed to coordinate anionic guests use the same kind of interactions; *i.e.*, Lewis base (anionic guest)–Lewis acid (incorporated into the structure of the host) interactions. However, most hosts use hydrogen bonds to bind anions, and therefore this area of host–guest chemistry is essentially different from the supramolecular chemistry of cationic guests.

## Stability of the host

As mentioned above, hosts need to be sufficiently stable. Of course, it is desirable that hosts can be handled in the air, a property shared by those compounds shown in Fig. 1, but one that limits the choices of coordination compounds. When the host contains monodentate ligands, they should be resistant to substitution; therefore kinetic stability is very important. At least some of the studies that one wants to conduct on a new host have to be done in solution; then, substitution by solvent (solvolysis) is always a concern, especially in solvents with a high coordinating ability (*e.g.*, nitriles). The anionic guest, itself a Lewis base, is another obvious possible entering ligand for the metal center. While it will never be in such large excess as the solvent (typically, NMR titrations are carried out using up to a five-fold excess of the anionic guest), when the host is cationic, such as the examples in Fig. 1, substitution of a neutral ligand, such as a pyridine or a pyrazole, by an anion, is electrostatically favored. As in every aspect of host–guest chemistry, the nature of the medium; *i.e.*, the solvent, is crucial. Hosts able to effectively bind guests in aqueous medium would be the most relevant for many purposes; however, due to the highly competitive nature of water as a solvent, this is a difficult task and most studies are carried out in organic solvents. Moreover, most metal–organic hosts such as those shown in Fig. 1(b)–(d) are more soluble in organic

solvents than in water. In organic solvents of low to moderate polarity such as those in which the behavior of most of the new hosts is studied (chloroform, dichloromethane, acetonitrile or dimethyl sulfoxide), the nucleophilicity of anions, employed as their tetrabutylammonium salts, has been found to be largely enhanced compared with aqueous medium.<sup>13</sup> Therefore, the possibility of substitution of neutral, monodentate ligands by relatively nucleophilic anionic hosts (*e.g.*, chloride) must be carefully studied.

## Design of the metal-based anion hosts

### A The choice of functional ligands

The metal-based hosts shown in Fig. 1 interact with anions through a combination of electrostatic attraction and hydrogen bonds. The latter occur between the guest and the N–H hydrogen bond donor groups present in the ligands. N–H groups are most frequently employed in anion hosts. These ligands are bifunctional molecules, possessing both the lone electron pairs that allow them to act as ligands, and the hydrogen-bond donor groups. When several of these ligands are coordinated to the metal, their hydrogen-bond donor groups must converge toward an external guest. This imposes a first restriction on the choice of the bifunctional ligands, namely, the relative positions of the metal-binding electron pairs and the hydrogen bond donor groups. Thus, whereas the N–H groups of two mutually adjacent (*cis*) pyrazole ligands can converge toward an external anion, the N–H groups of two *cis* imidazole ligands would diverge.<sup>14</sup> Such an arrangement could be useful in the synthesis of extended networks, but not in the design of discrete hosts. Analogously, the N–H groups of two *cis*-ligated 3-aminopyridines can converge towards an external anion, but those of two *cis*-positioned 4-aminopyridines would diverge.<sup>5</sup>

The bifunctional ligands must bind the metal strongly so they do not dissociate. There are metal-based dynamic systems in which this is not true, as there are purely organic dynamic systems; however, the scope of this review will be restricted to stable hosts. The stability of the host is, in fact, a major problem in the design of metal-based hosts. In what regards the choice of the functional ligands, an obvious way to improve the stability is using bidentate or polydentate ligands, such as biimidazole ( $\text{H}_2\text{biim}$ ) in Fig. 1(d).

### B The choice of the metal center

When the bifunctional ligands are monodentate, the choice of the metal center becomes crucial because the geometric preferences of the metal center will determine the geometry of the resulting host; in particular, whether or not the hydrogen bonds on the bifunctional ligands can converge toward an external guest. For polydentate ligands, in which the different donor groups are internally linked, the choice of the metal is less important: for instance, with regard to the example in Fig. 1(d), metal fragments other than areneruthenium could be used for the synthesis of biimidazole hosts.<sup>15</sup> There is another reason why the choice of the metal is crucial in the case of monodentate ligands: without the extra stabilization of the chelate effect, the stability of the host relies only in the strength

of the metal–ligand bond. Let us look at the examples in Fig. 1(a)–(c) from this perspective. In the first example, the metal center is Pt(II). The high stability of Pt(II) complexes was one of the reasons why Alfred Werner employed them in some of the studies that gave birth to the field of coordination chemistry. Re(I) and Ru(II) both possess  $d^6$  electron configurations, which are particularly stable (for instance, the  $d^6$  Co(III) center was another Werner's favorite). Besides, Re and Pt are third-row transition metals, the most kinetically inert ones. The need to employ stable metal centers is not exclusive of anion host chemistry: another example can be found in bioinorganic chemistry, where studies are often carried out in aqueous medium and in the presence of strong donors, such as serum proteins, and is not a coincidence that octahedral tricarbonyl Re(I), arene–Ru(II) and Pt(II) complexes are some of the most extensively studied metal centers in this area.

The strong preference of these transition metal centers for a given geometry makes the synthesis of receptors based on them more predictable. For more flexible metal centers, such as Cu(II), for which coordination numbers 4–6 can be accessed depending on the ligand set, the synthesis of stable anion hosts requires polydentate ligands. These provide stability and contribute to determine the geometry and the access of the anion to the metal first coordination sphere.<sup>16</sup>

### C The choice of counteranion

Many metal-based hosts are, such as those in Fig. 1, cationic complexes, because in this case coulombic attraction adds to other non-covalent interactions. The nature of the accompanying counteranion is of prime importance in what regards host solubility and stability, as well as the nature of the host–guest interaction. Anions such as  $\text{BF}_4^-$ ,  $\text{PF}_6^-$ ,  $\text{SbF}_6^-$ , *etc.*, have been the ones most often used in combination with metal-based hosts. In these anions, the single negative charge is delocalized over several highly electronegative fluorine atoms, a feature that makes them innocent in comparison with other anions having lone electron pairs on oxygen or heavier halogen atoms. However, these counteranions can undergo hydrolysis in organic solvents containing traces of water. For example, the hydrolysis of hexafluorophosphate affords difluorophosphate.<sup>5</sup> The search for innocent counteranions has been a subject of intense research in organometallic chemistry, where they are often needed to avoid the deactivation of highly electrophilic metal centers. One of the most widely used is the tetraarylborate  $\text{BAR}'_4^-$  (Fig. 3).

The ion pairing behavior of salts of organometallic cations in low-polarity solvents was investigated using NMR techniques, and it was found that the degree of ion aggregation (*i.e.*, the formation of ion pairs or, in solvents of very low relative permittivity, even quadruples), as well as the relative

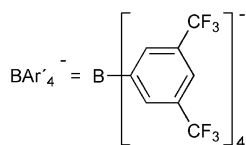


Fig. 3 Tetrakis(3,5-bis(trifluoromethyl)phenyl)borate.

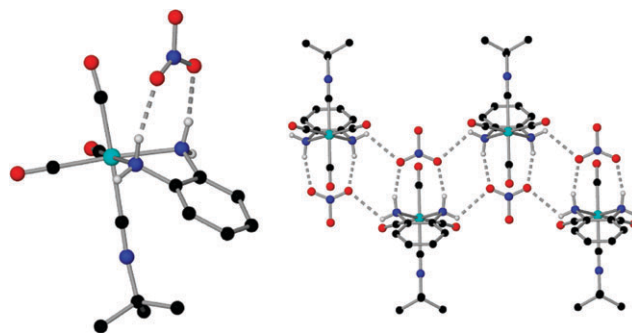


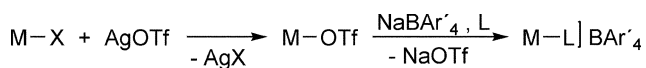
Fig. 4 Molecular structure of  $[\text{Re}(\text{CN}'\text{Bu})(\text{CO})_3(1,2\text{-(NH}_2)_2\text{-C}_6\text{H}_4)][\text{NO}_3]$ . View of the zigzag chains formed in the crystal packing.

positions of anion and cation, depend dramatically on whether the anion is the relatively small  $\text{BF}_4^-$  or  $\text{PF}_6^-$ , or the larger  $\text{BAR}'_4^-$ .<sup>17</sup> Our studies with tris(*N*-alkylimidazole) complexes in which the best hydrogen bond donors are the C–H imidazole groups showed that the strength of the host–guest interactions increased when  $\text{BAR}'_4^-$  was used as counteranion of the cationic host.<sup>14</sup> In general, the very large  $\text{BAR}'_4^-$  will interact less with the cationic host than more conventional anions such as  $\text{BF}_4^-$ ,  $\text{PF}_6^-$ ,  $\text{SbF}_6^-$ , *etc.* This leaves the host more available to interact with the guest, because for a cationic host, the measured strength of its interaction with a given guest is actually the difference between the strength of its interaction with the guest and the strength of its interaction with the counteranion. The combination of organic solvents of low solvating ability and a low-interacting counteranion such as the large, lipophilic  $\text{BAR}'_4^-$ , may allow the detection, even the measurement, of the interaction of anions with hosts that use weak hydrogen bonds. Thus, we have found that compound  $[\text{Re}(\text{CN}'\text{Bu})(\text{CO})_3(1,2\text{-(NH}_2)_2\text{C}_6\text{H}_4)]\text{BAR}'_4$  (Fig. 4) interacts with anions through a combination of electrostatic attraction and hydrogen bonding involving the N–H bonds of the coordinated *o*-phenylenediamine.<sup>18</sup>

### D Ancillary ligands: halides

Many compounds used as starting materials in coordination chemistry are halides, and a quite general way to access higher oxidation states in metal complexes is oxidative addition involving the formation of metal–halide bonds. Therefore, halide ligands are often present as ancillary ligands in metal-based hosts. On the other hand, halide abstraction is one of the most general ways to generate cationic complexes and, therefore, cationic metal-based hosts.

The presence of halide ligands in metal-based hosts can pose two different problems: first, the halide ligand can be displaced by the anionic guest, and second, it can act as hydrogen-bond acceptor. To assess whether or not the displacement of the halide  $\text{X}^-$  in an  $\text{M-X}$  host by the guest  $\text{Y}^-$  is taking place may be difficult if the compounds  $\text{M-X}$  and  $\text{M-Y}$  are not sufficiently different. For example, the IR and  $^1\text{H}$  NMR spectra of  $[\text{MoX}(\eta^3\text{-methyllyl})(\text{CO})_2(\text{H}_2\text{biim})]$  ( $\text{X} = \text{Cl}$  or  $\text{Br}$ ) hosts are very similar. We found that, in solution, partial substitution of  $\text{X} = \text{Cl}^-$  by  $\text{Br}^-$  occurs; however, the mentioned spectroscopic methods do not allow to recognize it.<sup>15</sup>



**Scheme 1** Synthesis of cationic metal complexes with  $\text{BAR}'_4^-$  counteranion.

The halide ligands in metal halide complexes have been found to be relatively good hydrogen bond acceptor groups;<sup>19</sup> in fact, metal halide complexes have been used as synthons in crystal engineering.<sup>20</sup> Therefore, if the same complex contains both halides and ligands bearing hydrogen bond donor groups, complementary intermolecular self-association can become important, reducing solubility and competing against the host-guest interaction. An obvious way to avoid these problems would be to replace the halide by a ligand that is both non-labile and devoid of hydrogen bond acceptor character. If this can be done starting from a neutral complex and employing a neutral ligand to replace the halide, it will also constitute a way to access a cationic host. As shown in Scheme 1, replacing first the halide by triflate allows to introduce the  $\text{BAR}'_4^-$  anion in a second step.<sup>15</sup>

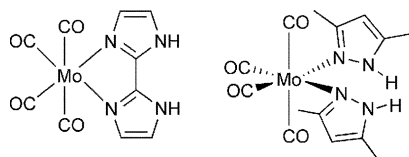
The need of passing through the intermediate triflate complex is due to the fact that in most cases, the halide ligand, unlike the triflate, is not labile enough to be directly displaced by the neutral ligand in the presence of  $\text{NaBAR}'_4$ , the most widely employed source of the  $\text{BAR}'_4^-$  anion.

### E Ancillary ligands: carbonyls

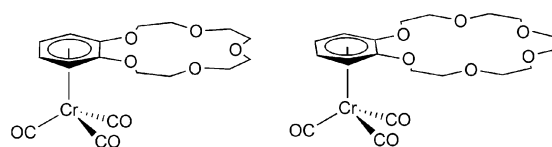
Carbonyl ligands are, in complexes such as the cationic rhenium tricarbonyl showed in Fig. 1, highly resistant to substitution, even despite the fact that the positive charge lowers the back-donation of electron density from the metal center to the CO. Carbonyl ligands in metal complexes have been found to be significant hydrogen bond acceptors, so neutral carbonyl complexes containing hydrogen bond donor groups can self-aggregate.<sup>21</sup> Such interaction is likely responsible for the low solubility of complexes such as those shown in Fig. 5.<sup>15,22</sup>

Cationic hosts as salts of the highly lipophilic counteranion  $\text{BAR}'_4^-$  can be more soluble in organic solvents than similar neutral complexes.<sup>15</sup> Both a lowering of the hydrogen bond acceptor character of ligands such as halides and carbonyls, as a result of the positive charge of the metal complex, and the interposition of the anion, can account for this counter-intuitive behavior.

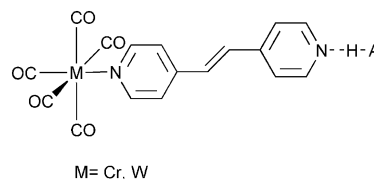
The position of the C–O stretches of  $\text{L}_n\text{M-CO}$  complexes in infrared spectroscopy is very sensitive to changes in electron density at the metal center and, therefore, in the accompanying ligands L. The idea of using these  $\nu\text{C-O}$  bands as the signal for sensing purposes is attractive because of the high sensitivity of IR spectroscopy, and because  $\nu\text{C-O}$  bands occur in a region of



**Fig. 5** Carbonyl complexes very insoluble in organic solvents.<sup>15,22</sup>



**Fig. 6** Carbonyl compounds studied by Stephenson and co-workers.<sup>23</sup>

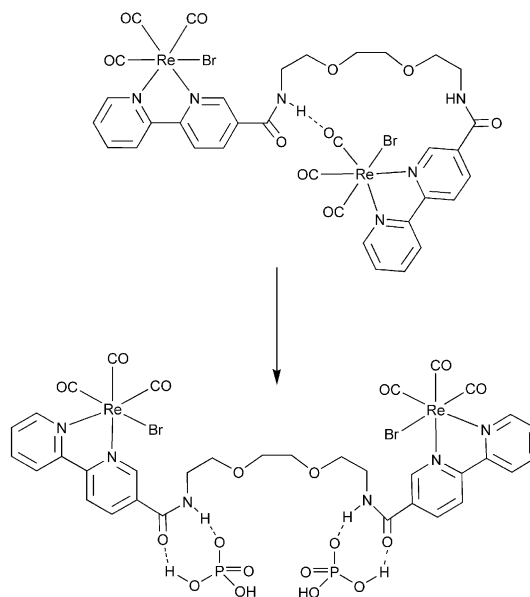


**Fig. 7** Carbonyl compounds studied by Peris *et al.*<sup>24</sup>

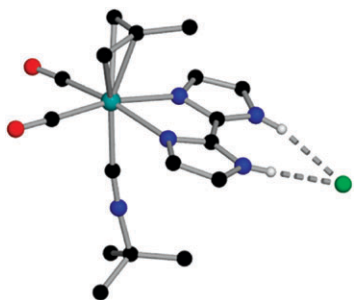
the spectrum quite clean from other bands. Stephenson and co-workers used the change in  $\nu\text{C-O}$  IR bands of the hosts depicted in Fig. 6 as a probe to detect alkali-metal cations.<sup>23</sup> Peris *et al.* studied the change in  $\nu\text{C-O}$  IR bands as a response to the formation of hydrogen bonds between the complex shown in Fig. 7 and some neutral hydrogen bond donors.<sup>24</sup>

We studied the changes in the  $\nu\text{C-O}$  bands of rhenium tricarbonyltris(pyrazole) complexes such as those shown in Fig. 1(c) when tetrabutylammonium salts of several anions were added to  $\text{BAR}'_4^-$  salts of these cationic rhenium complexes.<sup>6</sup> Although independent NMR titrations showed the host-anion interactions to be strong, changes in the IR spectra were found to be too small to be useful. Fletcher and co-workers reported recently studies of the binuclear complex shown in Fig. 8, in which the formation of the hydrogen bonds between the phosphate guest and the amido group is proposed to disrupt the intramolecular hydrogen bonding involving one amido group and one carbonyl ligand.<sup>25</sup>

In all these systems, the changes in the position of the  $\nu\text{C-O}$  bands in the IR spectrum are small; however, IR spectroscopy



**Fig. 8** Proposed interaction with phosphate.<sup>25</sup>



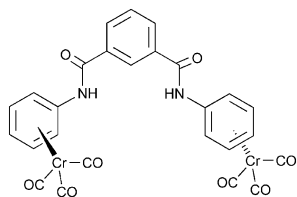
**Fig. 9** Molecular structure of the  $[\text{Mo}(\text{CN}^t\text{Bu})(\eta^3\text{-methallyl})(\text{CO})_2(\text{H}_2\text{biim})]\text{-Br}$  adduct.

in the  $\nu\text{C-O}$  region is an excellent method to detect the possible substitution of a neutral ligand by the anionic guest. It has been mentioned above that the electrostatically favored substitution of one of the neutral bifunctional ligands (those bearing the hydrogen bond donor groups, such as amino-pyridine or pyrazole) by the anionic guest is always a concern. The substitution of a neutral ancillary ligand is also undesired since it would transform the cationic host into a neutral complex, and such an event must be considered when evaluating the stability of a host. We have dealt with this problem when studying the host-guest behavior of complexes of the fragment  $\{\text{Mo}(\eta^3\text{-methallyl})(\text{CO})_2(\text{H}_2\text{biim})\}$ . In this case, IR spectroscopy ruled out the substitution of the monodentate *tert*-butylisocyanide in  $[\text{Mo}(\text{CN}^t\text{Bu})(\eta^3\text{-methallyl})(\text{CO})_2(\text{H}_2\text{biim})]^+$  (Fig. 9).<sup>15</sup>

In addition, its different timescale makes IR spectroscopy complementary of NMR in the solution studies of supramolecular hosts. A problem that received considerable attention is the distinction between full hydrogen ion transfer, *i.e.*, an acid-base reaction, and hydrogen bonding.<sup>26,27</sup> For anions such as fluoride, that are both strong hydrogen bond acceptors and strong bases, the distinction is often difficult, especially using NMR alone. In contrast, when the tricarboxyltris(pyrazole)rhenium host, shown in Fig. 1(c), was treated with less than the equimolar amount of tetrabutylammonium fluoride, the IR spectrum of the resulting solution showed the separate spectra of both the unreacted host and its deprotonation product.

Finally, carbonyl ligands are strongly  $\pi$ -acceptor ligands. Therefore, electron-withdrawing carbonyl fragments can be used to increase the polarization of hydrogen bond donor groups, as it has been elegantly exemplified by Gale and co-workers, who attached  $\text{Cr}(\text{CO})_3$  fragments *via*  $\eta^6$ -coordination to Crabtree-type isophthaloyldiamide molecular clefts (Fig. 10).<sup>21</sup>

The strong  $\pi$ -acceptor character of carbonyl ligands is also partly responsible of the coordination geometry of the



**Fig. 10**  $\{\text{Cr}(\text{CO})_3\}$  compounds studied by Gale *et al.*<sup>21</sup>

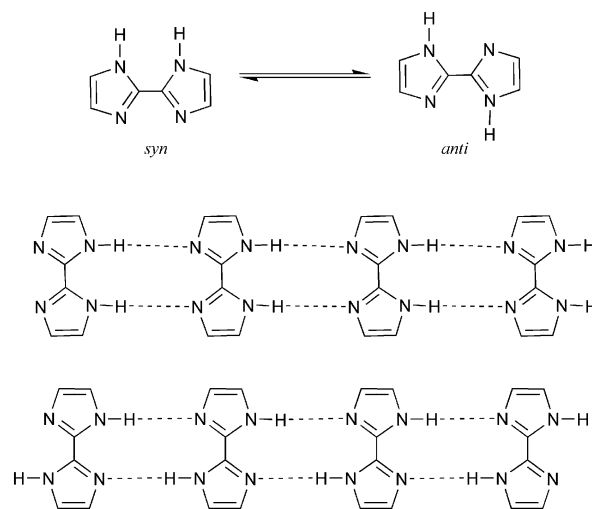
complex; this is the case in the tris(pyrazole) complexes that our group employed as hosts: on electronic grounds, the presence of the three carbonyl ligands in the coordination sphere of these octahedral complexes greatly favors the *fac*-tricarbonyl geometry over the *mer* geometry, which would be the one favored by steric factors.<sup>28</sup>

## F More on the function of the metal

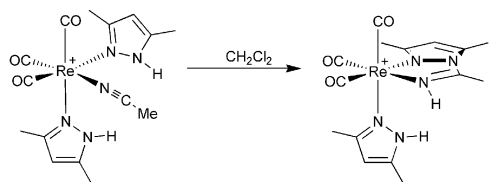
As stated in the introduction, one of the functions of the metal is to act as a scaffold, holding together the binding groups in suitable positions. The metal fragment acts, therefore, as an element of geometric organization. For bidentate ligands such as 2,2'-biimidazole<sup>8,15</sup> or Beer's bis(carbamoyl)-2,2'-bipyridines,<sup>29</sup> the precise geometrical function of the metal is to avoid the relative rotation of the two halves of the ligand. In doing so, for example, the chelated metal enforces the *syn* conformation of 2,2'-biimidazole, the one that allows the simultaneous formation of the hydrogen bonds between the anion and the two N-H groups. This simple example illustrates the notion of preorganization of the host, a central theme of supramolecular chemistry. The adoption of that particular conformation of a host that permits its interaction with a guest means that other conformations will become unavailable and, therefore, an entropic loss that opposes the binding event. Preorganization of the host will reduce the entropic price that the host must "pay" to select the particular conformation needed to bind the guest, increasing the strength of the host-guest interaction. In the complexation between the metal fragment and the organic part of the host (*e.g.*, 2,2'-biimidazole), the enthalpic gain resulting from the formation of the metal-nitrogen bonds amply overcomes the entropic loss associated to biimidazole losing its rotational freedom.

It was noted that the interaction between anions and the metal-free bis(carbamoyl)-2,2'-bipyridines was too weak to be detected.<sup>30</sup> In contrast, complexes of these ligands with several metal fragments are excellent hosts for anions.<sup>29</sup>

For 2,2'-biimidazole, there is an additional problem: it is too insoluble in low-polarity solvents.<sup>8</sup> This is a consequence of self-association as shown in Fig. 11.



**Fig. 11** Conformations and self-association of 2,2'-biimidazole.

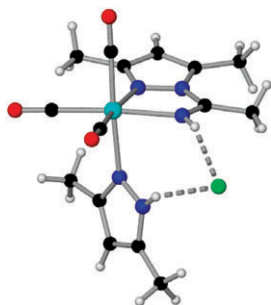


**Scheme 2**  $\{\text{Re}(\text{CO})_3\}$  mediated synthesis of a pyrazolylamidino ligand.<sup>31</sup>

Self-association is expected to occur always to some extent for bifunctional molecules possessing both hydrogen bond donor groups and Lewis basic sites, because the latter will act as hydrogen bond acceptors. For the coordination to a metal center, the bifunctional molecule employs its basic sites, which are no longer available as hydrogen bond acceptors; therefore, metal binding disrupts self-association.

The synthesis of hosts such as those discussed above involves the formation of bonds between the metal fragment, which is provided by some suitable precursor, and some pre-existing ligand (pyrazole, aminopyridine, biimidazole, *etc.*). This modular process is straightforward compared with the “total” synthesis required by many purely organic hosts and, once a successful motif is identified, it allows an easy tuning by varying both the metal fragment and the bifunctional ligands (see below).

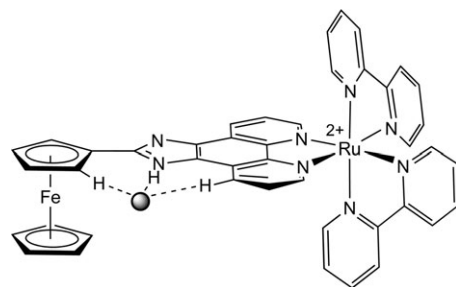
The metal can do more than binding preexisting ligands: it can help making new ones. Our group found that the rhenium tricarbonyl moiety promoted the coupling between pyrazoles and nitriles (Scheme 2), a process previously reported for other metals.<sup>31</sup> The resulting amidino chelates feature an N–H group that was able to cooperate with a proximal pyrazole ligand in binding anions. The structure of the supramolecular adduct formed between this host and chloride was determined by X-ray diffraction (Fig. 12).



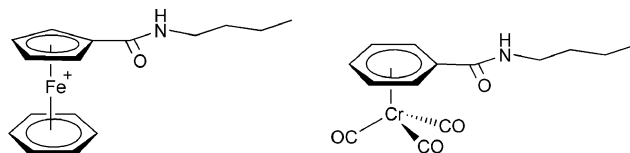
**Fig. 12** Molecular structure of the chloride adduct of the Re–amidino complex shown in Scheme 2.

### C–H groups as hydrogen bond donors in anion hosts

Hydrogen bonds in which the donors are C–H groups have attracted much attention. Theoretical studies showed that, in many cases, the strength of the hydrogen bonds formed by the C–H groups are of the same order of magnitude than those formed by, for instance, N–H groups.<sup>32</sup> The C–H groups of aryl substituents have been found to act cooperatively with N–H groups in several metal-based anion receptors. In a



**Fig. 13** An example of C–H and N–H hydrogen donor group cooperation.<sup>33</sup>

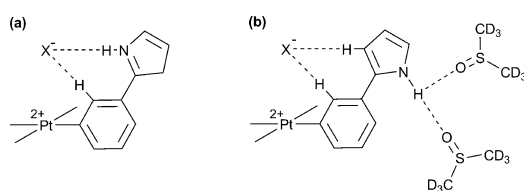


**Fig. 14** Beer's receptors featuring apparently only one hydrogen bond donor group.<sup>30</sup>

recent example, Tàrraga, Molina and co-workers found that, for the host depicted in Fig. 13, not only the N–H group, but also an aryl C–H group and one of the C–H groups of a cyclopentadienyl ring converge toward external anions, as indicated by the shifts of these groups in the  $^1\text{H}$  NMR spectra.<sup>33</sup> The similar cooperation of a C–H group from an  $\eta^5$ -cyclopentadienyl or  $\eta^6$ -arene ligand can explain why other receptors in which, at first sight, one spots only one hydrogen bond donor group, such as the complexes shown in Fig. 14, act as anion hosts.<sup>30</sup>

For  $[\text{Pt}(\text{2-phenylpyrrole})_4][\text{BF}_4]_2$ , Gale and co-workers (see Fig. 15) found that the ability of the solvent to act as a hydrogen bond acceptor (nitromethane, a poor acceptor, *vs.* dimethyl sulfoxide, a good acceptor) determines the choice by the host of either the N–H or C–H groups of the pyrrole moiety as hydrogen bond donor groups for anion binding.<sup>34</sup>

Bedford, Tucker and co-workers synthesized a palladium-based host that employs a combination of positive charge and a set of C–H hydrogen bonds to interact with anions.<sup>35</sup> The authors conclude that the interaction between the cationic host and halide anions is as shown in Fig. 16, the six *endo* C–H groups acting as hydrogen bond donors. The determination of the structure of the salt formed by the host with a  $\text{PF}_6^-$  counteranion supports the proposed mode of interaction. Note that the coordination of the 1,4,7-trithiacyclononane ligand to the metal fragment enforces that conformation of the macrocycle that allows this simultaneous hydrogen



**Fig. 15** Different binding mode of 2-phenylpyrrole in (a)  $\text{CD}_3\text{NO}_2$  or (b)  $\text{DMSO-d}_6$ .

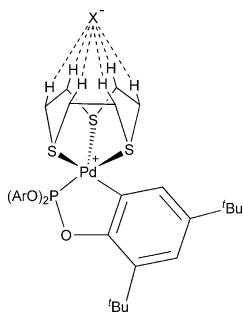


Fig. 16 Palladium anion host studied by Bedford, Tucker *et al.*<sup>35</sup>

bonding; *i.e.*, preorganizes the cyclic ligand. The macrocycle was found to be displaced by chloride and, to a lesser extent, by bromide. With iodide, for which such dissociation was not detected, a high binding constant was calculated. Notable features of this host are that it uses only C–H groups as hydrogen bond donors, and its straightforward synthesis from the commercially available trithiacyclononane.

### Platinum-based hosts: a closer look

The family of Pt hosts developed by Bondy, Gale and Loeb exemplify how a successful host design can be tuned. These authors synthesized the Pt(II) tetrakis(nicotinamide) complexes shown in Fig. 1(a) as their hexafluorophosphate salts.<sup>4</sup> An asset of the new hosts was their ease of synthesis in comparison with the multistep, low yield procedures typical of many purely organic receptors. Thus, the Pt hosts were prepared in good yield by reaction of [PtCl<sub>2</sub>(NCEt)<sub>2</sub>] with 4 equiv. of the nicotinamide and 2 equiv. of AgPF<sub>6</sub>, with filtration and crystallization as the only purification steps. The choice of *n*-butyl substituents should increase the solubility in organic solvents. Owing to free rotation around Pt–N bonds, the Pt complexes can adopt the conformations shown in Fig. 17, termed cone, partial cone, 1,3-alternate and 1,2-alternate by analogy with calix[4]arene notation.

The 1,2-alternate conformation was found in the solid state structure of the host. The PF<sub>6</sub><sup>−</sup> counteranions, each at one side of the PtN<sub>4</sub> plane, did not engage in hydrogen bonds; rather, the amido carbonyl oxygens acted as hydrogen bond acceptors to two molecules of dichloromethane. Therefore, the authors assume that PF<sub>6</sub><sup>−</sup> would not be competitive for binding of the guest anions studied. Spectroscopic titrations were used to calculate binding constants and indicated the

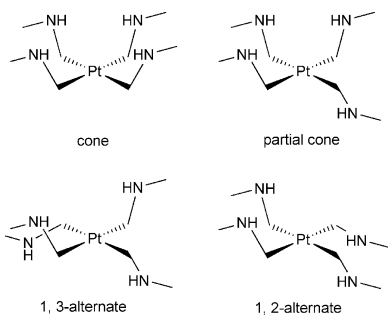


Fig. 17 Conformations of the tetrakis(nicotinamide) complexes.<sup>4</sup>

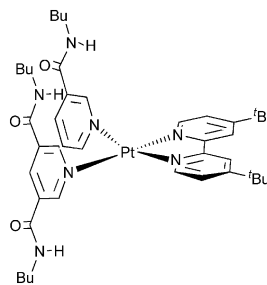


Fig. 18 *cis*-[Pt(N–N)N<sub>2</sub>][PF<sub>6</sub>]<sub>2</sub> studied by Bondy *et al.*<sup>36</sup>

formation of 1 : 2 adducts between the cationic Pt complex and planar anions such as nitrate and acetate. For the latter anion, *K*<sub>2</sub> (the second association constant) was found to be larger than *K*<sub>1</sub>. This behavior, very unusual, especially for cationic hosts, indicated that binding of the first anion has a positive allosteric effect, favoring the binding of the second. This was attributed to a pre-organization of the receptor in the 1,2-alternate conformation as the result of the binding of the first anion. In contrast, the shape mismatch between the host and the tetrahedral perchlorate anion led to 1 : 1 as the only measurable adduct formation. Based on these results, the authors prepared *cis*-[Pt(N–N)N<sub>2</sub>][PF<sub>6</sub>]<sub>2</sub> (N–N = 4,4'-*t*Bu-2,2'-bipy; N = 3,5-di-*n*-butylamidopyridine), a host designed to be pre-organized for the 1,2-alternate conformation (Fig. 18).<sup>36</sup>

However, the presence of two electron withdrawing carbamoyl groups on each pyridine made these ligands labile toward some anions such as carboxylates. Besides, anion binding by the two N–H groups on the same side of the host forces the other two N–H groups to become more distant and, therefore, unable to simultaneously bind the same anion.

Finally, the same authors synthesized [PtL<sub>4</sub>][BF<sub>4</sub>]<sub>2</sub> (L = 8-(*n*-butylurea)isoquinoline) (Fig. 19), in which the two N–H groups and one of the C–H groups of each ligand act as hydrogen bond donors towards anions.<sup>37</sup> With spherical halides, 1 : 2 behavior was found in solution, and a neutral 1 : 2 adduct with a 1,2-alternate conformation of the Pt complex was found in the solid state of the chloride complex. In contrast, for the sulfate anion, the host was found to adopt the cone conformation, with all hydrogen bond donors converging on a single anion. In accord, a high association constant was calculated for sulfate binding. Moreover, NMR spectra indicated that host–sulfate binding was

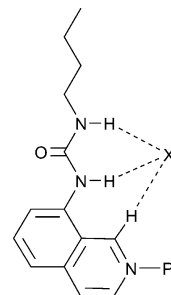


Fig. 19 Interaction of the (*n*-butylurea)isoquinoline ligand with an anion.

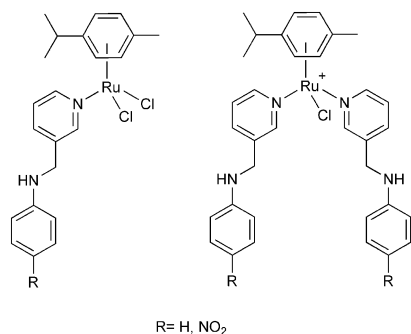


kinetically slow. Such behavior, rarely encountered for acyclic hosts, is likely a result of the multi-point interaction, the strong electrostatic attraction with the dianionic guest and the shielding from the solvent that the hosts imposes.

### Ruthenium pyridine hosts: semi-labile molecular tweezers.

Steed and co-workers prepared areneruthenium complexes with two 3-aminopyridine ligands (Fig. 1(b)).<sup>5</sup> The employment of secondary amine groups with anthracenyl or ferrocenyl substituents aimed to provide redox- or photo-active units. The failure of the attempted synthesis of the complex with two anthracenyl-substituted aminopyridine ligands was attributed to steric hindrance. Neutral hosts with a single aminopyridine ligand gave weak interactions with anions; in contrast, large binding constants were calculated for the cationic hosts with two aminopyridines and nitrate or hydrogensulfate anions. However, the authors found that nucleophilic anions, such as chloride or acetate, displaced the aminopyridine ligands. In subsequent work, they employed 3-aminomethylpyridine

ligands for the synthesis of similar areneruthenium hosts (Fig. 20). The cationic hosts were found to be much more resistant to ligand substitution, and showed strong binding of anions such as chloride or acetate.<sup>38</sup> Incorporation of *p*-nitro substitution in the pyridine ligands led to a significantly stronger binding of anions. Incorporation of a carbazole moiety allows these hosts to be used for luminescent sensing of anions.<sup>39</sup> In the NMR spectra of these complexes, the two hydrogens on the methylene group of each 3-aminomethylpyridine ligand are diastereotopic, as expected for hydrogens non-related by the mirror plane of the  $C_2$ -symmetric complexes. On addition of strongly binding anions (e.g. bromide), these diastereotopic signals collapse into singlets. This effect is more pronounced for the stronger-binding nitro-substituted hosts. Dissociation of pyridine was ruled out by NMR; therefore, the authors proposed that supramolecular anion binding could trigger a fast equilibrium between the 18-electron complex and the 16-electron complex (in which the two hydrogen atoms on each methylene group would be equivalent) resulting from chloride loss.



**Fig. 20** Areneruthenium complexes with aminomethylpyridine ligands.<sup>38</sup>

### Concluding remarks

Transition metal complexes, including organometallic complexes, can serve as anion hosts using only their second coordination sphere; *i.e.*, without direct metal–anion binding. Such hosts are synthesized easily and in a modular way, allowing the tuning of successful designs. The geometrical preferences of the metal center, the stability of the complex, in particular its resistance to ligand substitution by anionic guests in organic media, and the properties of the ancillary ligands and the accompanying counteranion, should be carefully considered.

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