Table I. Competitive Olefin Epoxidation[a]

catalyst[b]	epoxide ratio			
Mn(TPP)(OAr)	1.2	1.1	0.03	0.9
Mn(TMP)(OAr)	14.4	0.7	0.04	2.5
Mn(C_2PBP)(OAr)	0.4[c]	1.1[c]	0.05[c]	1.3[c]
Mn(C_4PBP)(OAr)	1.0[c]	2.1[c]	0.4[c]	1.8[c]
Mn(C_6PBP)(OAr)	70	67	1.7	>1000
Mn(PXYLPBP)(OAr)	29	>1000	7.0	>1000
Mn(C_8PBP)(OAr)	12.7	1.6	0.06	21.1
Mn(C_{10}PBP)(OAr)	8.8	0.2	0.04	17.9

[a] For experimental conditions, see ref 4. [b] OAr: 3,5-di-*tert*-butylphenoxide. TPP: tetraphenylporphyrin. TMP: tetramesitylporphyrin. [c] These reactions are very slow, implying that the reactions take place on the open face of the porphyrin.

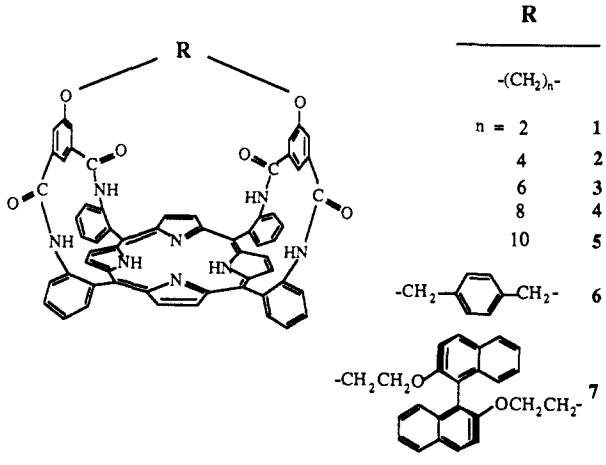

Figure 1. Picnic Basket Porphyrins.

and 1.6:1, respectively, for these two olefin pairs. The C_{10} basket, **5**, acts much more like the TMP case.

Terminal olefins are typically much less reactive in reactions with manganese porphyrin catalysts; entries showing the behavior of 1-octene versus cyclooctene for MnTPP and MnTMP illustrate this point. The C_6 basket shows a moderate reversal; 1-octene is 1.7 times more reactive. The *p*-xylyl case is more selective; the ratio is 7:1. Note, however, that in this case some reaction occurs with cyclooctene. We suppose that this slow oxidation occurs by "leaking" on the outer face during the long reaction times required by the terminal olefin.

The situation with trisubstituted olefins is very interesting; 2-methyl-2-pentene in competition with *cis*-2-octene reacts "normally" when MnTPP and MnTMP are used as the catalysts (ratios of 0.9 and 2.5, respectively). However, virtually no reaction of the trisubstituted olefin occurs within either the C_6 or *p*-xylyl baskets. The corresponding ratios are now >1000:1 for both basket catalysts. We speculate that this reactivity pattern reflects the required orientation of the Mn=O group and the olefin axis. Perhaps the alkene approaches the Mn–O bond from the side and is parallel to the porphyrin plane, as has been suggested by Groves[3a] for related iron catalysts and further discussed by Bruice.[5]

We also report a very modest case of catalytic asymmetric epoxidation when the chiral binaphthyl basket **7** is used. Styrene epoxide is formed in 13% ee as determined both by rotation ($[\alpha]_D^{20}$ = +2.8°, *c* = 1.7 in $CHCl_3$) and by NMR with a chiral shift reagent. Since the chiral site is far above the reaction locus, it is not surprising that the % ee is so small.[6] This does demonstrate that at least some (presumably all) reaction occurs within the cavity. This augurs well for the development of synthetically useful, efficient chiral catalysis.

Finally, we comment on catalyst stability. The shape-selective oxygenation can only be sustained under carefully controlled conditions. The acetonitrile solvent must be dry, and the anionic axial ligand must be present in excess. Otherwise, the blocking ligand is itself consumed by oxidation and the catalyst loses its shape selectivity as epoxidation occurs on the outer porphyrin face. In one case, we have studied the epoxidation of a 1:1 mixture of *cis*-2-octene and cyclooctene using the Mn *p*-xylyl complex, **6**; 600 turnovers/catalyst were achieved without measurable loss of shape selectivity.

We seem to be on the verge of predictable, shape-selective, catalytic oxygenation with a readily available, variable series of synthetic catalysts. For example, highly regioselective epoxidation of dienes should be possible.

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Hydrolysis of RNA by Transition-Metal Complexes

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Hydrolysis of phosphate esters has been studied extensively due to the relevance of this chemistry to biological systems. Consequently, transition-metal complexes have been examined as phosphate ester hydrolysis catalysts in an effort to model the reactions catalyzed by the ATPase and phosphatase class of enzymes. These studies have mostly employed activated *p*-nitrophenyl phosphate ester[1] or phosphate anhydrides (ATP) as substrates.[2] In addition, it is well-known that many divalent cations are capable of catalyzing the hydrolysis of RNA.[3] Examples of

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Table I. Extent of Poly(A)$_{12-18}$ Hydrolysis by Transition-Metal Complexes[a]

metal complex	% substrate hydrolyzed[b]	metal complex	% substrate hydrolyzed[b]
$Cu(trpy)^{2+}$	97	Zn(NTA)	4
$Cu(bpy)^{2+}$	61	$ZnCl_2$	72
$CuCl_2$	31	Ni-$(CR)^{2+}$ [d]	3
Zn-*N*-methyl-$(CR)^{2+}$ [c]	70	$NiCl^2$	2
control	5		

[a] Abbreviations: bpy = 2,2′-bipyridine; trpy = 2,2′,6′,2″-terpyridine; NTA = nitrilotriacetic acid; (CR) = 2,12-dimethyl-3,7,11,17-tetraazabicyclo[11.3.1]heptadeca-1(17),2,11,13,15-pentaene; *N*-methyl-(CR) = 7-(*N*-methyl)-2,12-dimethyl-3,7,11,17-tetraazabicyclo[11.3.1]heptadeca-1(17),2,11,13,15-pentaene. Experimental conditions: All reactions were run at 37 °C in 20 mM Hepes buffer pH = 7.1 for 20 h, [metal complex] = 0.160 mM, [poly(A)] = 0.06 mM. [b] The percent substrate hydrolysis was determined from the ratio of the integration of substrate peak at t = 0 h and t = 20 h. [c] Reference 6a. [d] Reference 6b.

transition-metal complexes promoting the hydrolysis of unactivated phosphate esters, such as those found in RNA, are fewer in number.[4] Transition-metal complexes capable of hydrolyzing unactivated phosphodiester bonds could find utility in probing RNA structure and as synthetic analogues of ribonucleases. In addition, artificial ribonucleases could be prepared by the covalent attachment of a transition-metal-complex hydrolysis catalyst to an oligonucleotide which binds to RNA in a sequence-specific manner.[5] Accordingly, we describe here the first example of hydrolytic cleavage of RNA oligomers by characterized transition-metal complexes at 37 °C and neutral pH.

In order to evaluate the hydrolytic activity of various metal complexes, an assay was developed by which the relative extent of RNA hydrolysis could be determined. We chose to use a mixture of adenylic acid oligomers 12 to 18 nucleotides in length, poly(A)$_{12-18}$, as the substrate for these studies. It was possible to resolve the individual cleavage products from the substrate fragments by using ion-exchange HPLC (Figure 1). The data summarized in Table I indicate that a variety of different transition-metal complexes are capable of promoting the hydrolysis of RNA at 37 °C and neutral pH. These results demonstrate that the nature of the ligand and metal ion can influence the extent to which RNA is hydrolyzed. Surprisingly, reaction of 3′,5′-ApA or 3′,5′-UpU with the complexes studied here, under the conditions described in Table I, showed no detectable hydrolysis.[7]

That the cleavage of RNA was hydrolytic in nature and not oxidative was confirmed by the following experimental results. 2,3-Cyclic AMP was detected as a product of the reactions. The HPLC traces for hydrolysis of RNA by potentially redox active metal complexes, such as $Cu(bpy)^{2+}$ or $Cu(trpy)^{2+}$, are nearly identical with those found for non-redox-active species like $ZnCl_2$ and Zn-*N*-methyl-(CR). By contrast, when poly(A)$_{12-18}$ was reacted with 1,10-phenanthroline–copper under conditions known to facilitate the oxidative cleavage of RNA,[8] a completely different product profile was generated upon HPLC analysis. Further support for a hydrolytic cleavage mechanism was also obtained by comparing the reactivity of DNA and RNA with $Cu(trpy)^{2+}$. $Cu(trpy)^{2+}$ was incubated with both poly(dA)$_{12-18}$ and poly(A)$_{12-18}$ for 14 h at 37 °C under conditions of neutral pH. Analysis of the reaction mixtures revealed that no cleavage was observed in the case of DNA, while the RNA sample showed extensive degradation. There is evidence that both RNA and DNA are oxidatively cleaved by copper 1,10-phenanthroline complexes at similar rates.[9] Thus, if the observed cleavage of RNA by $Cu(trpy)^{2+}$ was predominately oxidative in nature, significant degradation of the DNA substrate would also be expected.

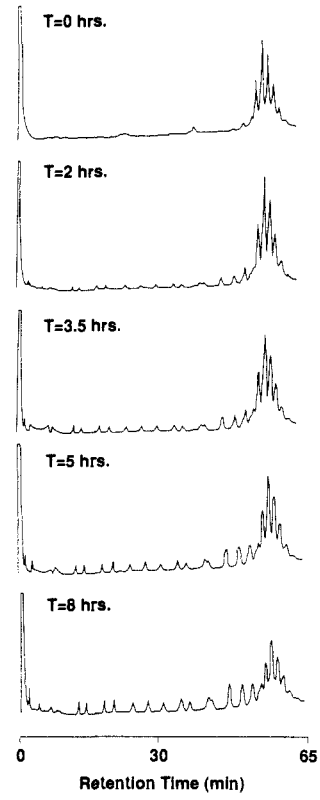

Figure 1. Ion-exchange HPLC profile of the reaction of $Cu(trpy)^{2+}$ with poly(A)$_{12-18}$ at various times. All buffers were made with diethyl pyrocarbonate treated water (0.1% v/v), and reactions were run in sterilized polypropylene tubes. Cleavage reactions run in the presence of metal complexes and excess EDTA showed no RNA degradation. Reaction conditions: 37 °C, 20 mM Hepes buffer pH = 7.1, $[Cu(trpy)^{2+}]$ = 0.06 mM, [poly(A)] = 0.06 mM. Concentration refers to amount of adenosine present in the reaction mixture. HPLC analyses were run on a 7-μm Nucleogen DEAE 60-7 column. Elution gradient: 0–15 min, 25% B; 15–45 min, 60% B; 45–60 min, 100% B. Solvent A = 20 mM KH_2PO_4, 20% acetonitrile pH = 5.5. Solvent B = solvent A + 1 M KCl.

It was possible to use the HPLC-based assay to extract kinetic data concerning the hydrolysis reaction by monitoring the decrease in integrated intensity of the substrate peaks at a low extent of substrate conversion. A typical example of the time course of hydrolysis of poly(A)$_{12-18}$ by $Cu(trpy)^{2+}$ is shown in Figure 1 (pseudo-first-order rate constant $k_{obsd} = 6.1 \times 10^{-2} \pm 0.7\ h^{-1}$).[10] We have also investigated the $Cu(trpy)^{2+}$-catalyzed hydrolysis of a single RNA strand, poly(A)$_{15}$, and found hydrolysis rates to be the same, within experimental error, as when poly(A)$_{12-18}$ was used as substrate.

The pH dependence of the $Cu(trpy)^{2+}$-catalyzed cleavage of poly(A)$_{12-18}$ was studied. A plot of pH vs k_{obsd} produced a bell-shaped curve with a rate maximum at pH = 7.8. A similar pH vs rate profile has been described for the hydrolysis of RNA by imidazole buffers, and a bifunctional mechanism was proposed which required sequential acid–base catalysis by imidazole.[11] In

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this case, the bell-shaped pH vs rate profile was determined to arise from a shift in the rate-determining step as the imidazole/imidazolium ratio was varied. On the basis of the results presented here, we propose that a bifunctional mechanism may be involved in the case of transition metal complex promoted RNA hydrolysis. In the case of $Cu(trpy)^{2+}$, a metal-bound hydroxide, or its equivalent, could function as the base while the metal center itself could act as a Lewis acid. That 2,3-cyclic AMP is detected as a product of the cleavage reactions argues against the direct attack of a metal-bound hydroxide on the phosphate center which has been proposed in the mechanism of Co(III)-promoted hydrolysis of AMP.[4] Further studies aimed at elucidating the mechanism of RNA hydrolysis by metal complexes are in progress.

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Toward Molecular Charge-Transfer Relays. A Three-Dimensional Acceptor and Its Radical Anion

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The design of molecular devices critically depends on the preparation of molecules with predictable electrical, optical, and magnetic properties.[1] An assembly of such devices within the framework of nanotechnology[1,2] is a promising new field of chemistry. Organic and organometallic materials based on charge-transfer (CT) interactions play an important role in this field.[3-5] The acceptor and donor molecules used to construct such devices (or materials) have been largely limited to flat conjugated π-systems.[3-6] As a consequence, the materials obtained are quasi one-dimensional. Here, we describe a "three-dimensional" acceptor that may serve as a relay of charge-transfer interactions between two perpendicular π-planes or two perpendicular stacks in a crystal. The radical anion of such an acceptor, $\mathbf{1}^{\bullet -}$, is shown to simultaneously delocalize its unpaired electron in two perpendicular π-planes.

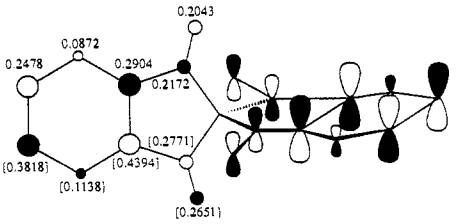
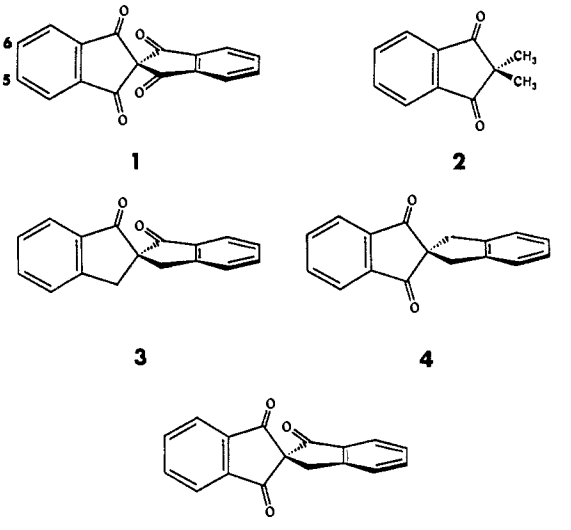


Figure 1. Coefficients (p_x or p_z) of the LUMO in **1** obtained by MNDO-PM3. The values in brackets are the corresponding LUMO coefficients for **2**.



1 **2**

3 **4**

5

Our design of CT components with increased dimensionality is based on the phenomenon of spiroconjugation.[7,8] In the case of two identical perpendicular π-networks joined by a spiro atom (as in **1**), the orbitals of the "halves" may interact only if they have the same symmetry. Such interactions lead to pairs of delocalized orbitals encompassing the entire molecule. From the point of view of CT interactions, it is essential that the frontier orbitals (LUMO for **1**) satisfy this symmetry requirement. Figure 1 shows the p_x and p_z coefficients of the LUMO in **1** obtained by MNDO-PM3 calculations.[9] This molecular orbital may be formally considered as a bonding combination of the "half-molecule" orbitals.[10] Thus, the fully delocalized LUMO of **1** should allow for simultaneous CT interactions in two perpendicular planes.

To test this prediction, we have prepared tetraone **1** and probed its LUMO by an ultimate CT interaction, i.e., full electron transfer. The synthesis[11] of **1** involved oxidation of **3**[12] with CrO_3/AcOH to afford **5** (52% yield). The dibromination of the methylene group (NBS/Br_2/$h\nu$) followed by hydrolysis with silver acetate gave the tetraone (**1**) in 53% yield. Both trione **5** and

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