need to be sulfonated in order to produce the stable polysemiquinone form of the polymer. Indeed, additional sulfonation and consequent protonation of amine nitrogen atoms would convert some of the $-(NH)-$ to $-(NH_2^+)-$ groups and hence destabilize the polymer by reducing the extent of its π conjugation. The absorption maxima at 1080, 700, and 620 cm^{-1} in the FTIR spectrum of compound IIIA,B are consistent with the presence[9] of SO_3^- groups attached to the aromatic rings. The absorption maxima at 820 and 870 cm^{-1} indicative of 1,2,4-trisubstitution of the rings are out-of-plane bending of aromatic hydrogens. These absorptions are not present in the 1,2-disubstituted emeraldine base (II), from which compound IIIA,B was synthesized.

The solubilities of compounds IIIA,B and IV differ markedly from those of the corresponding protonated and nonprotonated forms, respectively, of parent polyaniline. Compound IIIA,B dissolves appreciably in aqueous 0.1 M NH_4OH or NaOH to give the corresponding salts whereas emeraldine hydrochloride when treated in this manner is converted to the insoluble emeraldine base form (II). The anionic (SO_3^-) groups are presumably largely responsible for its solubility in water. Compound IIIA,B partly dissolves in DMSO, giving the dark green color of the protonated polyaniline, but is apparently deprotonated when it dissolves in *N*-methyl-2-pyrrolidinone (NMP), in which it has a blue-violet color, characteristic of compound IV.

The high concentration of protons in the vicinity of the polymer backbone due to the presence of the attached SO_3^- groups is not only responsible for the retention of doping of the polymer at the higher pH values, where the parent emeraldine base polymer (II) is essentially a (nondoped) insulator, but is also consistent with the observed faster electrochemical redox reactions of compound IIIA,B in aqueous media.

Acknowledgment. The authors are grateful to Prof. A. G. MacDiarmid for valuable comments and stimulating discussions. This research has been supported in part by the Defense Advanced Research Projects Agency through a grant monitored by the U.S. Office of Naval Research.

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Enantioselective Epoxidation of Unfunctionalized Olefins Catalyzed by (Salen)manganese Complexes

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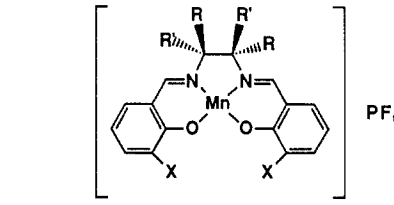
The development of catalysts that mediate enantioselective group transfer to unfunctionalized olefins is an important goal in organic chemistry.[1] Catalytic systems that are effective for *directed* epoxidation[2] and hydrogenation[3] have been discovered, but the substrates must bear specific functional groups to achieve the precoordination required for high enantioselectivity. This restriction is lifted when stereoselectivity relies solely on nonbonded interactions, and in these cases the pool of potential substrates could in principle be unlimited. We report here that manganese complexes of chiral Schiff bases catalyze epoxidation of alkyl- and aryl-substituted olefins with the highest enantioselectivities reported to date for nonenzymatic catalysts.[4]



(*S,S*)-1: R = Ph, R' = H, X = H
(*R,R*)-1: R = H, R' = Ph, X = H
(*R,R*)-2: R = H, R' = Ph, X = ^{t}Bu

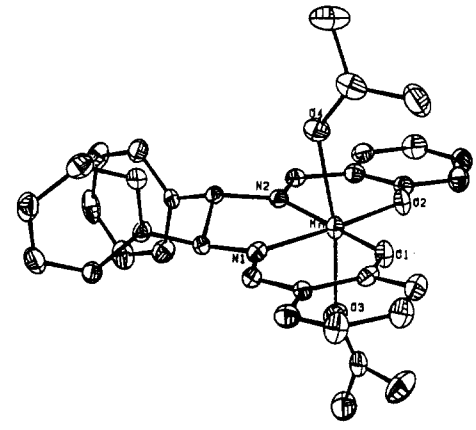


Figure 1. Structure of catalysts **1** and **2**. ORTEP view of the cation of (*S,S*)-**1**·[acetone]$_2$.

Epoxidation catalysts **1** and **2** (Figure 1) were prepared in three steps and in 68-74% overall yield from readily available (*R,R*)- or (*S,S*)-1,2-diamino-1,2-diphenylethane[5] and the appropriate salicylaldehyde derivative.[6,7] The X-ray crystal structure of the bis(acetone) adduct of (*S,S*)-**1** (ORTEP diagram included in Figure 1)[7] reveals that the tetradentate ligand adopts a near-planar geometry with the phenyl groups of the diphenylethylene unit residing in pseudoequatorial positions.

The reactions were carried out in air with iodosylmesitylene as the oxygen atom source and 1-8 mol % catalyst.[8] Our data summarized in Table I along with the best results previously

(1) Epoxidation: (a) Groves, J. T.; Myers, R. S. *J. Am. Chem. Soc.* **1983**, *105*, 5791. (b) Tani, K.; Hanafusa, M.; Otsuka, S. *Tetrahedron Lett.* **1979**, 3017. (c) Curci, R.; Fiorentino, M.; Serio, M. R. *J. Chem. Soc., Chem. Commun.* **1984**, 155. (d) Sinigalia, R.; Michelin, R. A.; Pinna, F.; Strukul, G. *Organometallics* **1987**, *6*, 728. (e) Naruta, Y.; Tani, F.; Maruyama, K. *Chem. Lett.* **1989**, 1269. (f) O'Malley, S.; Kodadek, T. *J. Am. Chem. Soc.* **1989**, *111*, 9116. Hydroboration: (g) Hayashi, T.; Matsumoto, Y.; Ito, Y. *J. Am. Chem. Soc.* **1989**, *111*, 3426. Dihydroxylation: (h) Jacobsen, E. N.; Markó, I. E.; Mungall, W. S.; Schröder, G. W.; Sharpless, K. B. *J. Am. Chem. Soc.* **1988**, *110*, 1968. (i) Wai, J. S. M.; Markó, I. E.; Svendsen, J. S.; Finn, M. G.; Jacobsen, E. N.; Sharpless, K. B. *J. Am. Chem. Soc.* **1989**, *111*, 1123. Hydrogenation: (j) Halterman, R. L.; Vollhardt, K. P. C.; Welker, M. E.; Bläser, D.; Boese, R. *J. Am. Chem. Soc.* **1987**, *109*, 8105.

(2) (a) Katsuki, T.; Sharpless, K. B. *J. Am. Chem. Soc.* **1980**, *102*, 5974. (b) Gao, Y.; Hanson, R. M.; Klunder, J. M.; Ko, S. Y.; Masamune, H.; Sharpless, K. B. *J. Am. Chem. Soc.* **1987**, *109*, 5765.

(3) (a) Takaya, H.; Ohta, T.; Sayo, N.; Kumobayashi, H.; Akutagawa, S.; Inoue, S.; Kasahara, I.; Noyori, R. *J. Am. Chem. Soc.* **1987**, *109*, 1596. (b) Hayashi, T.; Kawamura, N.; Ito, Y. *J. Am. Chem. Soc.* **1987**, *109*, 7876. (c) Koenig, K. E. In *Asymmetric Synthesis*; Morrison, J. D., Ed.; Academic: New York, 1985; Vol. 5, p 71.

(4) Reports of highly enantioselective epoxidations involving *stoichiometric* consumption of chiral reagents: (a) Davis, F. A.; Chattopadhyay, S. *Tetrahedron Lett.* **1986**, *27*, 5079. (b) Ben Hassine, B.; Gorsane, M.; Geerts-Evrard, F.; Pecher, J.; Martin, R. H.; Castelet, D. *Bull. Soc. Chim. Belg.* **1986**, *95*, 547. (c) Schurig, V.; Hintzer, K.; Leyrer, U.; Mark, C.; Pitchen, P.; Kagan, H. B. *J. Organomet. Chem.* **1989**, *370*, 81.

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(6) Achiral salen complexes have been shown previously by Kochi to be effective epoxidation catalysts: (a) Srinivasan, K.; Michaud, P.; Kochi, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 2309. (b) Samsel, E. G.; Srinivasan, K.; Kochi, J. K. *J. Am. Chem. Soc.* **1985**, *107*, 7606.

(7) Experimental procedures for the epoxidation reactions, physical and experimental data for the catalysts and their precursors, and details of the structure determination are provided as supplementary material.

(8) Preliminary studies indicate that sodium hypochlorite is also an effective oxidant. With undiluted commercial bleach, 0.3-2 mol % catalyst may be used under phase-transfer conditions with no reduction in enantioselectivity or yield. Zhang, W.; Jacobsen, E. N., work in progress.

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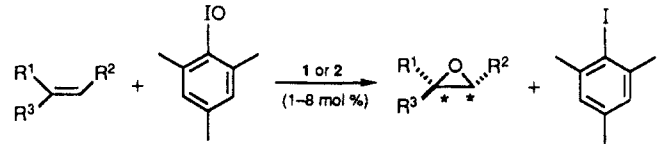
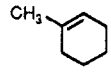
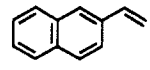
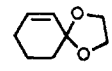
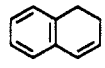
Table I. Asymmetric Epoxidation of Representative Olefins



entry	olefin[a]	catalyst[b]	yield,[c] %	ee, %	confign[d]	previous best[e]
1		(*R*,*R*)-**2**	50	59	1*R*,2*S*-(−)	12[f]
2		(*S*,*S*)-**1**[g]	63	33	*S*,*S*-(−)	
3		(*S*,*S*)-**1**	93[h]	20	1*S*,2*S*-(−)	16[i]
4		(*R*,*R*)-**2**[g]	75	57	*R*-(+)	48[i]
5		(*R*,*R*)-**2**[g]	72	67	(+)[j]	36[i]
6		(*R*,*R*)-**2**	52	93	(−)[j]	
7		(*R*,*R*)-**2**	73	84	1*R*,2*S*-(−)	40[k]
8		(*R*,*R*)-**2**	72	78	1*R*,2*S*-(+)	
9		(*R*,*R*)-**2**	36	30	*R*-(+)	

[a] Reactions were run at 25 °C unless otherwise noted. [b] Reactions with **1** were run in CH_3CN, while those with **2** were run in CH_2Cl_2. [c] Isolated yields based on olefin. [d] The sign corresponds to that of $[\alpha]_D$. Absolute configurations and ee's were established as described in the supplementary material. [e] These values correspond to the highest ee's previously reported for nonenzymatic catalysts. [f] From ref 1c. [g] Reaction run at 5 °C. [h] Based on 76% conversion of *trans*-β-methylstyrene. [i] From ref 1a. [j] Absolute configuration not ascertained. [k] From ref 1f.

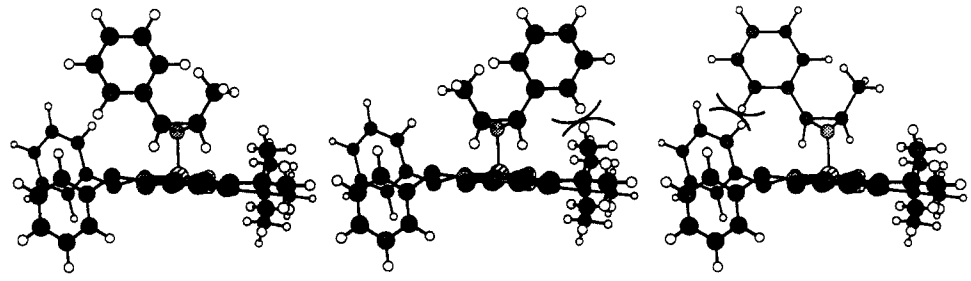


Figure 2. Proposed transition structures for the epoxidation of *cis*-β-methylstyrene mediated by **2**.

reported for nonenzymatic catalysts. Epoxidations with the chiral Mn(III) salen complexes afford higher ee's with a wide range of substrate substitution patterns, as monosubstituted (entries 4 and 5), disubstituted (entries 2, 3, and 6–9), and trisubstituted (entry 1) prochiral olefins all reacted with good or moderate selectivity.[9]

The sense and degree of enantioselection in the epoxidation of each substrate is well explained by a side-on perpendicular approach of olefin to the manganese–oxo bond of the putative Mn^V intermediate,[6a] as illustrated in structures A–C for the epoxidation of *cis*-β-methylstyrene (Figure 2).[10–12] The more hindered terminus of unsymmetrical olefins is directed away from the *tert*-butyl groups in A to avoid the unfavorable steric interactions apparent in B, and olefin approach from the opposite side of the metal–oxo bond (from behind the page) shown in transition structure C is disfavored by the dissymmetry of the catalyst. This model predicts that cis-disubstituted olefins or bulky terminal olefins should give the highest ee's with **2**, and this is borne out by entries 5–8. The aptitude for cis olefins is an attractive feature given that these substrates have been noted to afford the poorest results in several previously described highly enantioselective oxidation reactions.[1i,2,13]

The salen-based catalysts offer important advantages over known chiral porphyrin systems.[1a,e,f] Their superior enantioselectivity can be attributed to the fact that the complexes bear chirotopic carbons in the vicinity of the metal, resulting in better stereochemical communication in the epoxidation step. The synthesis of the salen catalysts is also much simpler, and their steric properties can be fine-tuned in a straightforward manner by choosing the appropriate diamine and salicylaldehyde precursors.

(9) Enantiomeric excesses of the epoxides remained invariant throughout the course of the reactions.

(10) Structures A–C were created by using the program Chem 3D based on the coordinates from the X-ray crystal structure determination of **1**.

(11) A similar model was proposed by Groves for epoxidation by chiral iron porphyrin catalysts.[1a]

(12) Either concerted oxygen transfer or a stepwise one-electron mechanism is possible within this geometry, and this model is not intended to distinguish between these mechanisms. For a sample of recent discussions on this controversial topic, see: (a) Traylor, T. G.; Miksztal, A. R. *J. Am. Chem. Soc.* **1989**, *111*, 7443; (b) **1987**, *109*, 2770. (c) Groves, J. T.; Watanabe, Y. *J. Am. Chem. Soc.* **1986**, *108*, 507. (d) Collman, J. P.; Kodadek, T.; Raybuck, S. A.; Brauman, J. I.; Papazian, L. M. *J. Am. Chem. Soc.* **1985**, *107*, 4343.

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With this latter consideration in mind, efforts are in progress to both improve selectivity and gain greater insight into the geometric constraints involved in oxygen atom transfer.

Acknowledgment. We thank Professor Thomas Kodadek for generously providing us with a preprint of ref 1f. We are also grateful to Eli Lilly for an Undergraduate Summer Scholarship to J.L.L.

Supplementary Material Available: Experimental data of the preparation and characterization of **1** and **2** and of all relevant precursors and details of the X-ray diffraction study of $\{\mathbf{1}\cdot[(CH_3)_2CO]_2\}\cdot(CH_3)_2CO$ and tables of atomic parameters, calculated hydrogen parameters, and distances and angles (22 pages). Ordering information is given on any current masthead page.

Asymmetric Synthesis of Acids by the Palladium-Catalyzed Hydrocarboxylation of Olefins in the Presence of (*R*)-(−)- or (*S*)-(+)-1,1′-Binaphthyl-2,2′-diyl Hydrogen Phosphate

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Metal complex catalyzed hydrocarboxylation (eq 1, R′ = H) and related hydroesterification reactions (eq 1, R′ = alkyl) of olefins are, together with hydroformylation, among the most extensively investigated processes in homogeneous catalysis.[1] Both

$$RCH{=}CH_2 + CO + R'OH \xrightarrow{MLn} RC(CORR)'HCH_3 + RCH_2CH_2COOR' \quad (1)$$

products of the hydrocarboxylation or hydroesterification of monoolefins are of considerable industrial value. For example, this methodology is of use in the synthesis of linear fatty acid esters, although stringent conditions are usually required.[2] Valuable representatives of branched-chain acids are 2-arylpropionic acids, which are the most important class of nonsteroidal antiinflammatory agents. A remarkably mild, completely regiospecific route to branched-chain acids was described in 1983, using palladium chloride as the catalyst under acidic conditions (eq 2).[3]

$$RCH{=}CH_2 + CO + H_2O \xrightarrow[PdCl_2,\ CuCl_2,\ HCl,\ \text{room temperature, 1 atm}]{O_2,\ THF,\ L^*} RC^*H(CH_3)COOH \quad (2)$$

While attempts have been made to achieve asymmetric hydrocarboxylation and hydroesterification, good enantioselectivity has yet to be realized.[4,5] Another problem has been the lack of regiochemical control, as these reactions are not regiospecific. Since the palladium chloride catalyzed process is regiospecific, and since the unsaturated group of the reactant is prochiral, then the use of an added chiral ligand can, in principle, result in the asymmetric synthesis of branched-chain acids. We now report the synthesis of acids in quite high optical purity, as well as good chemical yield, by the use of an appropriate chiral ligand for the palladium chloride catalyzed reaction.

Table I. Hydrocarboxylation of *p*-Isobutylstyrene (**1**) and 2-Vinyl-6-methoxynaphthalene (**2**)

substrate	L*	**1** (or **2**)/L*/$PdCl_2$	product yield,[a] %	optical yield,[b] %
1	(*S*)-BNPPA	7.7/0.38/1.0	89	83 (*S*)
	(*S*)-BNPPA	7.7/0.77/1.0	80	55 (*S*)
	(*R*)-BNPPA	7.7/0.38/1.0	81	84 (*R*)
2	(*S*)-BNPPA	4.2/0.42/1.0	46	72 (*S*)
	(*S*)-BNPPA	10/0.5/1.0	71	85 (*S*)
	(*R*)-BNPPA	4.2/0.42/1.0	48	76 (*R*)
	(*R*)-BNPPA	7.7/0.38/1.0	64	91 (*R*)

[a] Yield of pure material. [b] Determined by optical rotation measurements, relative to those for the pure enantiomers, reported in the literature[9,10] and confirmed by independent measurements of authentic pure *S*-(+) enantiomers in the authors' laboratory.

Two commercially important drugs are ibuprofen [2-(*p*-isobutylphenyl)propionic acid] and naproxen [2-(6-methoxy-2-naphthyl)propionic acid]. In both cases, it is the *S*-(+) enantiomer that is pharmacologically active.[6] The two olefinic precursors, *p*-isobutylstyrene (**1**) and 2-vinyl-6-methoxynaphthalene (**2**), were chosen as representative substrates in this investigation. The requisite olefins were easily prepared by nickel(II)-catalyzed cross coupling of a commercially available bromoarene with a Grignard reagent.[7] Specifically, treatment of *p*-bromostyrene with isobutylmagnesium chloride in the presence of (dppp)$NiCl_2$ afforded **1** in 76% yield. Similarly, 2-vinyl-6-methoxynaphthalene was isolated in 86% yield by (dmpe)$NiCl_2$-catalyzed reaction of 2-bromo-6methoxynaphthalene with vinylmagnesium bromide.

Reaction of *p*-isobutylstyrene (**1**) in tetrahydrofuran (THF) with carbon monoxide, water, oxygen, hydrochloric acid, palladium chloride, cupric chloride, and D-menthol as the added chiral ligand afforded pure ibuprofen in 94% yield, but the optical yield was only 2% (*S* configuration).[8] The ratio of **1**/D-menthol/$PdCl_2$ used was 10/3.8/1.0. Use of a 1/1 ratio of reactant to chiral ligand significantly reduced the acid yield and did not markedly affect the extent of asymmetric induction. Other chiral ligands including L-menthol, (*R*)-1,1′-bi-2-naphthol, D-diethyl tartrate (DET), and (*S*)-2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (BINAP) were of little use here, affording acids in <10% optical yield under a variety of conditions.

Effective chiral resolving agents are the atropisomeric (*R*)-(−)- and (*S*)-(+)-1,1′-binaphthyl-2,2′-diyl hydrogen phosphate (BNPPA). These compounds have been successfully employed for the resolution of a variety of pharmacologically useful organic bases[11,12] and helicenes (using HPLC).[13] It seemed conceivable that (*S*)-(+)- and (*R*)-(−)-BNPPA could function effectively in the acidic medium used for the hydrocarboxylation reaction. Indeed, use of (*S*)-(+)- and (*R*)-(−)-BNPPA as chiral ligands afford (*S*)-(+)- and (*R*)-(−)-ibuprofen, respectively, in 83–84%

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(8) General procedure: carbon monoxide was bubbled through a solution containing THF (15 mL) and $PdCl_2$ (0.07 g; 0.39 mmol). Concentrated hydrochloric acid (0.5 mL) and water (0.5 mL) were added, the mixture was stirred for 5 min, $CuCl_2$ (0.10 g, 0.74 mmol) was added, and oxygen was then bubbled through the solution (together with CO). After stirring for 10 min, the chiral ligand was added followed, 10 min later, by the substrate (see Table I for ratios of **1** (or **2**)/L*/$PdCl_2$). The reaction mixture was stirred for approximately 18 h at room temperature and 1 atm. Distilled H_2O (20 mL) was added, the product was extracted with hexane (3 × 50 mL), and the extract was dried ($MgSO_4$) and concentrated by rotary evaporation. The resulting residue was treated with 1 N NaOH, extracted with ether (3 × 50 mL), and acidified to pH 2 with concentrated HCl. Reextraction with ether (3 × 50 mL), drying ($MgSO_4$), and concentration afforded the acid. Crystallization from hexane gave pure material.
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