to be even greater. It is difficult to quantitatively predict the net effect that changing the size of the atoms in the ring will have on the strain, yet it is evident that four-membered rings containing a first-row transition-metal center have a significant amount of strain.

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Highly Enantioselective Epoxidation Catalysts Derived from 1,2-Diaminocyclohexane†

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Enantioselective epoxidation of simple olefins constitutes a challenging and important synthetic problem, and chiral salen-based complexes have recently emerged as promising catalysts for these reactions.[1] Readily available Mn(III) complexes such as **1** catalyze alkene epoxidation by bleach (NaOCl) in good yield and with higher selectivity than any other reported synthetic catalysts. However, while ee's above 70% are obtained in the epoxidation of a variety of cis olefins by **1** and related catalysts, selectivities of genuine synthetic value are not generally attainable with such 1,2-diaryldiamine-derived systems. We describe herein a new, highly enantioselective epoxidation catalyst **5** (>90% ee for several substrates, Table I), which was developed through a logical sequence of ligand modifications.

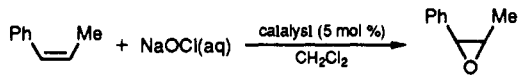
Side-on perpendicular approach of the alkene to the metal–oxo bond of a high valent intermediate has been invoked to account for both the sense and degree of enantioselectivity displayed by chiral salen and porphyrin complexes with cis olefins.[1a,2] In this context, two structural features of **1** are crucial to its selectivity: (1) the presence of bulky groups to prevent substrate approach away from the diimine bridge (approach c, Figure 1a) and (2) the dissymmetry of the diimine bridge, which disfavors attack from the side syn to the phenyl group (approach b), but leaves accessible approach anti to the phenyl group (approach a). Approach d is presumably disfavored due to the steric bulk of the diimine bridge. The enantioselectivity in the epoxidation of every cis olefin we have examined can be explained within this general model.

Axially locked substituents on the diimine bridge might lead to more effective differentiation of approaches a and b, and with this in mind we prepared catalysts from *trans*-1,2-diamino-1,2-dimethylcyclohexane.[3] Disappointingly, the corresponding salen derivative **2** exhibited only moderate enantioselectivity in the epoxidation of *cis*-β-methylstyrene (Table I, entry 2). More surprisingly, the sense of asymmetric induction proved to be the opposite of that predicted from approach a in Figure 1b. This result suggested that **2**, which is less hindered than **1** in the vicinity of the diimine bridge, might undergo competitive attack from approach d.

This was supported by the observation that **3**, which is less hindered yet, also afforded the unexpected enantiomer of *cis*-β-methylstyrene and with a higher ee than **2** (entry 3). Introduction of a second set of *tert*-butyl groups para to the salen oxygens as in **5** resulted in a further improvement in catalyst selectivity, presumably by strongly disfavoring all side-on olefin approaches with the exception of approach d. Face selectivity within the latter approach may be attributed to the larger substituent on the substrate being directed away from the axial hydrogen on the bridge.

As illustrated in Table II, catalyst **5** displays high enantioselectivity with a variety of cis-disubstituted alkenes.[4] Several

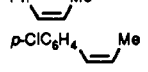
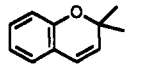
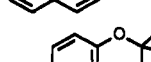
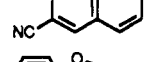
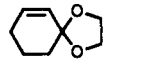
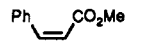
Table I. Asymmetric Epoxidation of *cis*-β-Methylstyrene with Catalysts **1–5**



entry	catalyst	yield,[a] %	ee, %	epoxide config
1	(*R*,*R*)-**1**	88	84	1*R*,2*S*-(+)
2	(*S*,*S*)-**2**	54	49	1*S*,2*R*-(−)
3	(*S*,*S*)-**3**	87	80	1*S*,2*R*-(−)
4	(*S*,*S*)-**4**	56	55	1*S*,2*R*-(−)
5	(*S*,*S*)-**5**	81	92	1*S*,2*R*-(−)

[a] Determined by GC by integration against an internal quantitative standard.

Table II. Asymmetric Epoxidation of Representative Olefins by Catalyst **5**[a]

entry	olefin	epoxide yield,[b] %	ee,[c] %	equiv of **5** required for complete reactn
1		84	92	0.04
2		67	92	0.04
3		72	98	0.02
4		96	97	0.03
5		63	94	0.15
6[d]		65[e]	89	0.10

[a] Reactions were run at 4 °C according to the general procedure outlined in ref 4. [b] Isolated yields based on olefin unless otherwise indicated. [c] Determined by analysis of the isolated epoxides by ^{1}H NMR in the presence of Eu(hfc)$_3$ and by capillary GC using a commercial chiral column (J & W Scientific Cyclodex-B column, 30 m × 0.25 mm i.d., 0.25-μm film). All reactions were run in duplicate with both enantiomers of **5**, and ee values were reproducible to ±2%. [d] Reaction carried out in the presence of 0.4 equiv of 4-phenylpyridine *N*-oxide. [e] Yield determined by GC.

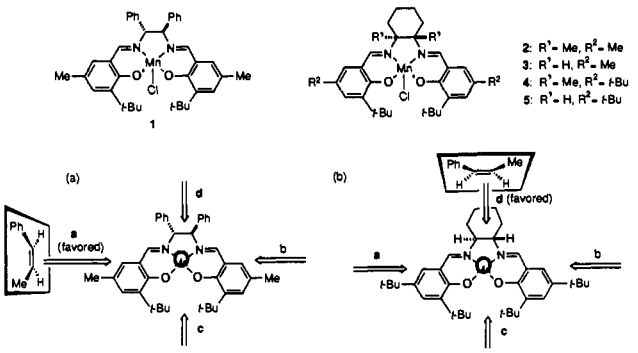


Figure 1.

† This paper is dedicated with deep respect to Professor K. Barry Sharpless on the occasion of his 50th birthday.

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interesting classes of substrates are represented in this series. Epoxidation of 2,2-dimethylchromene derivatives (entries 3 and 4) is extremely selective and provides access to important classes of biologically active compounds with high optical purity.[5] Epoxy ketals (entry 5) are versatile chiral building blocks that may be regioselectively opened to either α- or β-hydroxy ketals.[6] The epoxidation of *cis*-methyl cinnamate (entry 6) is to our knowledge the first example of epoxidation of an α,β-unsaturated carbonyl compound via oxo transfer,[7] and this methodology provides access to valuable optically active erythro-glycidic esters which are otherwise difficult to prepare.[8] For this substrate, addition of substoichiometric amounts of 4-phenylpyridine *N*-oxide was observed to improve both catalyst selectivity and turnover numbers.[9]

The use of an unhindered diamine precursor opens a quadrant to olefin approach (approach d) in which stereochemical communication between ligand and incoming substrate is maximized. High selectivity with **5** results not from a highly dissymmetric ligand, but rather from limitation of competing substrate approaches such that substrate interaction with the asymmetric environment is maximized. The effectiveness of **5** rules out the possibility (that existed with **1**) that π-stacking plays a role in directing substrate approach. Consistent with the side-on approach model, trans olefins tend to be poor substrates for this catalyst, being epoxidized slowly and with very low selectivity.[10] Terminal olefins such as styrene are generally epoxidized with higher enantioselectivities (60–75% ee) than previously reported with other catalyst systems,[11] although ee's still fall short of synthetically useful levels.[12]

Complex **5** is prepared in two simple steps in >90% overall yield from di-*tert*-butylsalicylaldehyde and 1,2-diaminocyclohexane.[13] The diamine is very inexpensive[14] and is resolved in a single crystallization with tartaric acid;[15] both pure enantiomers are also commercially available.[16] The felicitous combination of optimal catalyst design with a highly available chiral auxiliary should lead to widespread applicability of catalysts such as **5**.

Acknowledgment. This work was supported in part by the National Institutes of Health (GM-43214-01A1), a National Science Foundation PYI Award (CHE-9057740) to E.N.J., and generous contributions from the Monsanto Corporation, ICI Pharmaceuticals, Merck and Co., and Rohm and Haas.

Supplementary Material Available: Experimental and physical data for **2–5** and their precursors (4 pages). Ordering information is given on any current masthead page.

(4) The following procedure for alkene epoxidation is general. A solution of commercial household bleach (Clorox) was diluted to approximately 0.55 M in NaOCl with 0.05 M Na_2HPO_4, and the pH of the resulting buffered solution was adjusted to pH = 11.3 by addition of a 1 M NaOH solution. To this solution was added a solution of **5** (159 mg, 0.25 mmol) and 2,2-dimethylchromene (2.01 g, 12.5 mmol) in 12.5 mL of CH_2Cl_2. The two-phase mixture was stirred at 4 °C, and the reaction progress was monitored by TLC. After 6 h, 12.5 mL of CH_2Cl_2 was added to the mixture and the brown organic phase was separated, washed twice with 50 mL of H_2O and once with 50 mL of saturated NaCl solution, and then dried (Na_2SO_4). After solvent removal, the residue was purified by flash chromatography on silica gel to afford 1.59 g of pure epoxide (72% isolated yield). The ee of the product was determined to be 97.6% by GC analysis (see footnote *c* in Table II).

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(7) An alternative mechanism involving conjugate addition/cyclization appears unlikely in view of the observed selectivity.

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(11) See refs 1a and 1b and work cited therein.

(12) Diminished selectivity with terminal olefins relative to cis olefins is due to a competing epoxidation pathway. A detailed investigation of this phenomenon will be reported shortly. Zhang, W.; Jacobsen, E. N., manuscript in preparation.

(13) Experimental details are provided as supplementary material.

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(16) Aldrich Chemical Co., Milwaukee, WI.

Extended Orthogonally Fused Conducting Oligomers for Molecular Electronic Devices[1]

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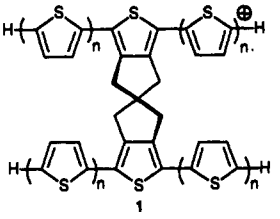
Since the time of the first room-filling computers, there has been a tremendous drive to compress the size of computing instruments. In order to bring this desire to its extreme, it was conceived that one may be able to construct single molecules that could each function as a self-contained electronic device.[3] Here we outline the convergent and flexible synthesis of two different macromolecules that approach the size necessary for molecular switch testing. Hence, the feasibility of molecular electronic devices, whether the architectures be of single molecule or ensemble arrangements, may soon be experimentally addressed.

Recently, Aviram of the IBM Corporation suggested that molecules ~50 Å long that contain a proconducting (nondoped or nonoxidized system, hence insulating) chain that is fixed at a 90° angle via a nonconjugated σ bonded network to a conducting (doped or oxidized system) chain should exhibit properties that would make them suitable for interconnection into future molecular electronic devices. These devices may be useful for the memory, logic, and amplification computing systems.[4] **1**, in doped form, is an example of a proconducting/σ/conducting molecule. To date, all experimental studies on orthogonal systems have dealt only with the spiro core of related molecules, and no synthetic approach demonstrated incorporation of the oligomeric chains.[5,6]



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(1) Presented at the 201st National Meeting of the American Chemical Society, Atlanta, GA, April 1991; Division of Polymeric Materials: Science and Engineering.

(2) Recipient of an Office of Naval Research, Young Investigator Award (1989–92) and National Science Foundation Presidential Young Investigator Award (1991–96).

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