From Highly Enantioselective Monomeric Catalysts to Highly Enantioselective Polymeric Catalysts: Application of Rigid and Sterically Regular Chiral Binaphthyl Polymers to the Asymmetric Synthesis of Chiral Secondary Alcohols

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A 1,1′-binaphthyl-based polymeric chiral catalyst with the most general enantioselectivity for the alkylzinc addition to a broad range of aldehydes has been obtained. This polymer can be easily recovered, and the recycled polymer shows the same catalytic properties as the original polymer. A highly enantioselective catalytic *diphenylzinc* addition to aldehydes has also been achieved by using the chiral binaphthyl monomer and polymer catalysts. Particularly, the excellent enantioselectivity observed for the addition of diphenylzinc to aromatic aldehydes allows the preparation of optically active diaryl carbinols that are synthetically useful but difficult to access by asymmetric catalysis. A novel asymmetric reduction of ketones catalyzed by the mono- and polybinaphthyl zinc complexes has been discovered. Our work on the asymmetric organozinc addition to aldehydes and the asymmetric reduction of ketones catalyzed by the zinc complexes of chiral binaphthyl monomer (*R*)-**12** and polybinaphthyl (*R*)-**43** has not only provided new methods to prepare optically active secondary alcohols but also demonstrated that incorporation of an enantioselective monomeric catalyst into a rigid and sterically regular polymer structure could almost completely preserve the catalytic properties of the monomeric catalyst. This strategy may find general application in converting existing highly enantioselective monomer catalysts into polymer catalysts of similar enantioselectivity provided that the catalytically active species of the monomer catalysts contain only the monomeric units rather than the aggregates of the monomers. By using this strategy, it is possible to overcome the drawbacks associated with the traditional approach to preparing polymeric chiral catalysts where the microenvironments of the catalytic sites in the polymers are often significantly altered from those in the monomeric catalysts due to the flexible and sterically irregular polymer chains.

Introduction

Extensive activities in the field of asymmetric catalysis have led to the discovery of many highly enantioselective catalysts.[1−3] A number of these catalysts have been applied to pharmaceutical and agricultural industries for the asymmetric synthesis of chiral organic molecules. Since it is often quite expensive to prepare the optically active catalysts, their easy recovery and reuse are highly desirable. Because of the significant size difference between polymers and small molecules, using polymer-based catalysts greatly simplifies both the recycle of the catalysts and purification of the products.[4−6] Heterogeneous polymer catalysts can be separated by simple filtration,[4,5] and homogeneous polymer catalysts can be separated by either membrane filtration or precipitation with a poorer solvent followed by filtration.[6] The traditional approach to constructing polymer-supported chiral catalysts involves the development of a highly enantioselective monomeric catalyst and then the attachment of this monomeric catalyst to a flexible and sterically irregular polymer backbone. Although a few enantioselective polymer catalysts have been obtained in this way, a significant drop of enantioselectivity is often observed when a monomeric chiral catalyst is attached to a polymer support due to the changes in the microenvironment of the catalytic sites.[4−6]

Recently, we have used optically active binaphthyl molecules to build novel main-chain chiral conjugated polymers[7−9] and have studied their application in asymmetric catalysis.[10−13] Polymers (*S*)-**1**,[7d] (*R*)-**2**,[7b] (*R*)-**3**,[11] and

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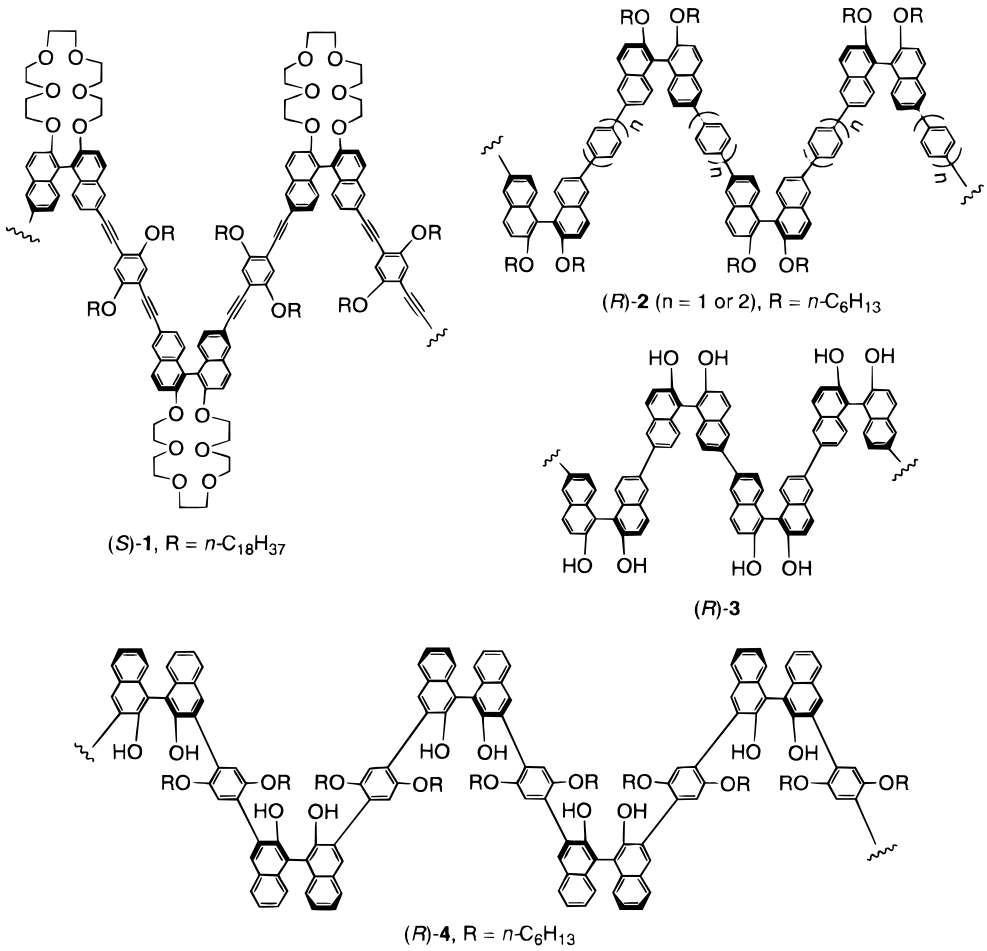

Figure 1. Examples of chiral binaphthyl polymers.

(*R*)-**4**[12] as shown in Figure 1 are examples of the optically active polybinaphthyls prepared in our laboratory. Through a systematic screening of the chiral binaphthyl polymers, we have found that polymer (*R*)-**4** exhibits very good enantioselectivity for the reaction of diethylzinc with certain aldehydes to give optically active secondary alcohols.[12] It represents a new generation of enantioselective polymeric chiral catalysts that contain a rigid and sterically regular polymer chain.

In the reactions catalyzed by (*R*)-**4**, up to 93% ee was observed for the diethylzinc addition to para-substituted benzaldehydes. However, less than 60% ee was observed for the reaction of ortho-substituted benzaldehydes.[12b] The enantioselectivity of (*R*)-**4** for aliphatic aldehydes is also limited. To improve the catalytic properties of (*R*)-**4**, we have studied its monomeric model compound. Based on the model compound study, we have designed a new binaphthyl polymer and discovered that both the monomeric model compound and the new polymer have very high enantioselectivity for the reaction of diethylzinc with a broad range of aldehydes.[14a,b] Using these new chiral ligands, we have further achieved the first highly enantioselective *diphenylzinc* addition to aldehydes.[14c] Particularly, the excellent enantioselectivity observed for the addition of diphenylzinc to aromatic aldehydes allows the preparation of optically active diaryl carbinols that are synthetically useful but difficult to obtain by asymmetric catalysis.[15]

Besides the asymmetric organozinc addition to aldehydes, the asymmetric reduction of prochiral ketones is also a very important method to synthesize chiral secondary alcohols.[16,17] We have used the mono- and polybinaphthyl-based chiral zinc complexes to catalyze the asymmetric reduction of ketones with catecholborane. Our work on the organozinc addition to aldehydes and the reduction of ketones with the binaphthyl-based

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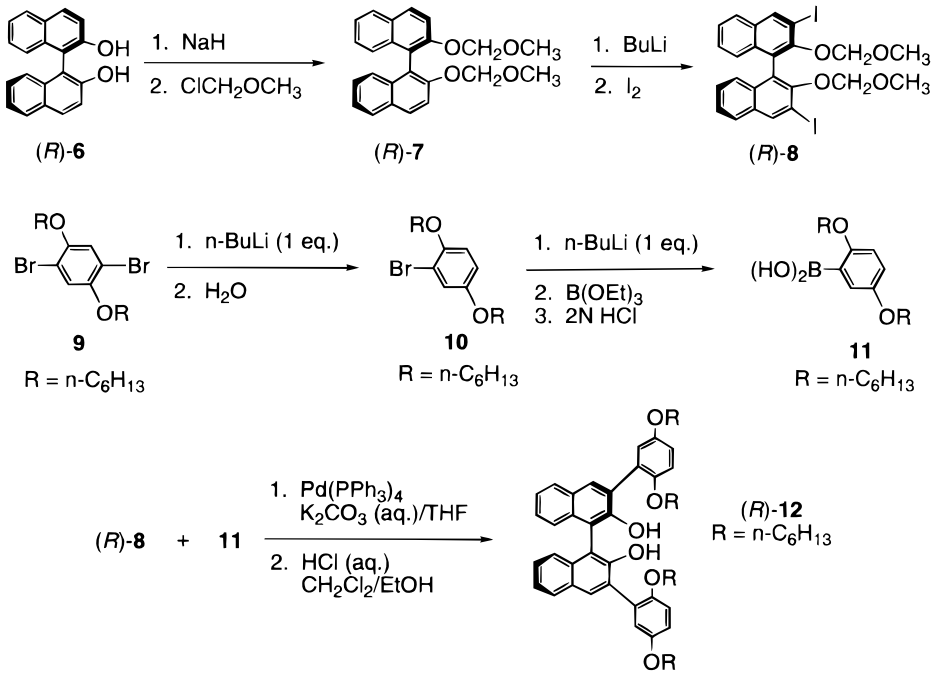
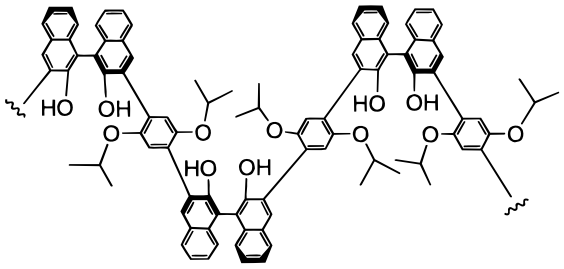
Scheme 1. Synthesis of a Monobinaphthyl Model Compound (*R*)-12



monomers and polymers demonstrates that it is possible to preserve the high enantioselectivity of a monomeric catalyst in a polymer by using the rigid and sterically regular polymers. Herein, our detailed studies on the development of novel enantioselective polymeric catalysts for the asymmetric synthesis of chiral secondary alcohols are reported.

Results and Discussion

1. Synthesis and Study of the Monomeric Model Compounds of Polybinaphthyl (*R*)-4. We have attempted to modify the catalytic properties of (*R*)-**4** by preparing polymer (*R*)-**5** that contains sterically bulkier isopropyl groups.[18] However, this polymer showed both



(*R*)-**5**

slightly lower catalytic activity and enantioselectivity than (*R*)-**4**. (*R*)-**5** catalyzed the diethylzinc addition to benzaldehyde with 89% ee and to cyclohexanecarboxaldehyde with 79% ee. This indicates that it could be difficult to further improve the catalytic properties of (*R*)-**4** by varying the size of the R groups on the alkoxyphenylene linkers alone.

To gain more understanding on the catalysis carried out by the binaphthyl polymers and to achieve more general enantioselectivity, we have synthesized (*R*)-**12** as the monomeric model compound of (*R*)-**4** (Scheme 1). Treatment of (*R*)-1,1′-bi-2-naphthol [(*R*)-**6**] with sodium hydride and then with chloromethyl methyl ether gave (*R*)-**7**.[19] Reaction of (*R*)-**7** with *n*-butyllithium followed by the addition of iodine gave (*R*)-**8**.[20] Compound **9** was synthesized by bromination and alkylation of 1,4-dihydroquinone.[21] One of the bromine atoms of **9** was removed to form **10** by using 1 equiv of *n*-butyllithium. This compound was then converted into a monoboronic acid molecule **11** by reaction with *n*-butyllithium and triethylborate.[21] The Suzuki coupling[22] of (*R*)-**8** with **11** followed by hydrolysis generated (*R*)-**12** as the monomeric model compound of polymer (*R*)-**4**. The specific optical rotation of (*R*)-**12** was $[\alpha]_D = 95.0$ ($c = 0.962$, THF). The optical purity of this compound was found to be over 99% as determined by HPLC-Chiracel-OD column.[23]

(*R*)-**12** was used to catalyze the reaction of benzaldehyde with diethylzinc in toluene at 0 °C.[24] In the presence of 5 mol % of (*R*)-**12**, the chiral alcohol product (*R*)-1-phenyl-1-propanol was obtained with over 99% ee (Scheme 2). When 0.5 mol % of (*R*)-**12** was used, the high enantioselectivity was maintained, but the reaction became much slower. The generality of this catalyst for a broad range of aldehydes was examined, and the results are summarized in Table 1. As shown in Table 1, (*R*)-**12** has high enantioselectivity for a great number of substrates including para-, ortho-, or meta-substituted aromatic aldehydes, linear or branched aliphatic aldehydes,

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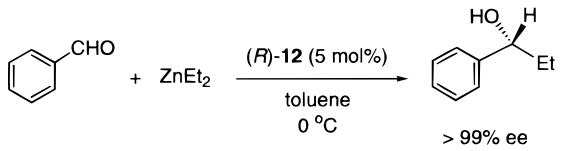
Table 1. Reaction of Aldehydes with Dialkylzincs Catalyzed by (*R*)-12

aldehyde	dialkyl-zinc	time (h)	isolated yield (%)	ee (%)	config
benzaldehyde	Et_2Zn	4	95	99[a]	*R*
p-methylbenzaldehyde	Et_2Zn	4	91	98[b]	*R*
p-anisaldehyde	Et_2Zn	6	92	97[c]	*R*
p-chlorobenzaldehyde	Et_2Zn	4	96	>99[a]	*R*
m-chlorobenzaldehyde	Et_2Zn	4	97	98[d]	*R*
m-anisaldehyde	Et_2Zn	6	95	99[a]	*R*
o-fluorobenzaldehyde	Et_2Zn	4	93	94[b]	*R*
o-anisaldehyde	Et_2Zn	8	90	94[b]	*R*
1-naphthaldehyde	Et_2Zn	6	92	>99[a]	*R*
2-naphthaldehyde	Et_2Zn	5	94	99[a]	*R*
2-furaldehyde	Et_2Zn	6	90	91[d]	*R*
hexanal	Et_2Zn	40	89	98[d]	*R*
heptanal	Et_2Zn	24	86	98[d]	*R*
nonanal	Et_2Zn	45	91	98[d]	*R*
cyclohexanecarbox-aldehyde	Et_2Zn	40	90	98[d]	*R*
isovaleraldehyde	Et_2Zn	30	73	98[e]	*R*
trans-cinnamaldehyde	Et_2Zn	24	91	92[a]	*R*
α-methyl-*trans*-cinnamaldehyde	Et_2Zn	27	86	98[d]	*R*
crotonaldehyde	Et_2Zn	18	66	91[b,f]	*R*
3-methyl-2-butenal	Et_2Zn	40	62	93[b,f,g]	*R*
trans−2-methyl-2-butenal	Et_2Zn	18	64	97[b]	*R*
2-butylacrolein	Et_2Zn	18	90	98[d]	*R*
phenylpropargyl aldehyde	Et_2Zn	15	90	93[a,h]	*R*
benzaldehyde	Me_2Zn[i]	96	90	90[a]	*R*
2-naphthaldehyde	Me_2Zn[i]	96	86	92[a]	*R*
octanal	Me_2Zn[i]	165	62	88[d]	*R*

[a] Determined by HPLC-Chiracel OD column. [b] Determined by chiral GC (*β*-Dex capillary column). [c] Determined by HPLC-Chiracel AD column. [d] Determined by analyzing the acetate derivative of the product on the GC-*β*-Dex capillary column. [e] Determined by analyzing the benzoate derivative of the product on the GC-*β*-Dex capillary column. [f] Et_2O was used as the solvent. [g] The reaction was carried out at −40 °C, and 0.3 equiv of catalyst was used. [h] 0.2 equiv of catalyst was used. The reaction was carried out in THF at −10 °C, and the aldehyde was distilled before use. [i] 2 equiv of Me_2Zn was used.

Scheme 2. Asymmetric Addition of Diethylzinc to Benzaldehyde Catalyzed by (*R*)-12



and aryl- or alkyl-substituted α,*β*-unsaturated aldehydes. (*R*)-**12** also shows high enantioselectivity for the addition of dimethylzinc to aldehydes. As observed before, the reaction of dimethylzinc is much slower than that of diethylzinc.[25] All the reactions were carried out in toluene solution at 0 °C using 5 mol % of (*R*)-**12** and 2 equiv of diethylzinc unless otherwise indicated. The racemic alcohol products were also prepared, and their HPLC or GC data were compared with those of the optically active alcohol products in order to determine the ee. The absolute configuration of all the products was found to be *R* by comparing their optical rotation values or GC data with the literature results.[24−43] (*R*)-**12** was recovered by column chromatography on silica gel and showed no change in both structure and activity.

Figure 2 lists the catalysts that are currently known to give good results for the asymmetric reaction of aldehydes with diethylzinc.[25−43] Their enantioselectivities are compared with those of (*R*)-**12** in Table 2. As shown in Table 2, most of the catalysts are good for aromatic aldehydes, but fewer are good for aliphatic aldehydes. Although the addition to α,*β*-unsaturated aldehydes is particularly useful since the resulting chiral allylic alcohols are very versatile precursors to many important organic compounds, it is very rare to find a good catalyst for the reaction of alkyl-substituted α,*β*−unsaturated aldehydes.

Among all of the previously reported catalysts, the combination of **29a** and **29b** represents the best catalyst system because of their generality.[40] However, **29a** does not show good enantioselectivity for several ortho-substituted aromatic aldehydes (ee = 62−70%). In addition, a stoichiometric amount of $Ti(O^iPr)_4$ is required most of the time when **29a** or **29b** is used. Recently, Pericàs and co-workers have reported a highly enantioselective catalyst **33** for the diethylzinc addition,[43] but it requires an α-substituent for the α,*β*-unsaturated aldehyde substrates. With a catalytic amount of (*R*)-**12**, excellent enantioselectivities are observed across the entire spectrum of the listed aldehydes. Particularly, its high enantioselectivity for various alkyl- and aryl-substituted α,*β*-unsaturated aldehydes is most remarkable.

In previous work, we found that when an ethylated 1,1′-bi-2-naphthol molecule (*R*)-**34** was used to catalyze the reaction of benzaldehyde with diethylzinc under the same conditions as in the use of (*R*)-**12**, only 72% conversion of benzaldehyde was observed in 24 h to give (*R*)-1-phenyl-1-propanol with 57% ee.[12] A dimeric complex (*R*)-**35** was produced from the reaction of (*R*)-**34** with 1 equiv of diethylzinc, and it remained mostly intact even when excess diethylzinc was added (Scheme 3). We have

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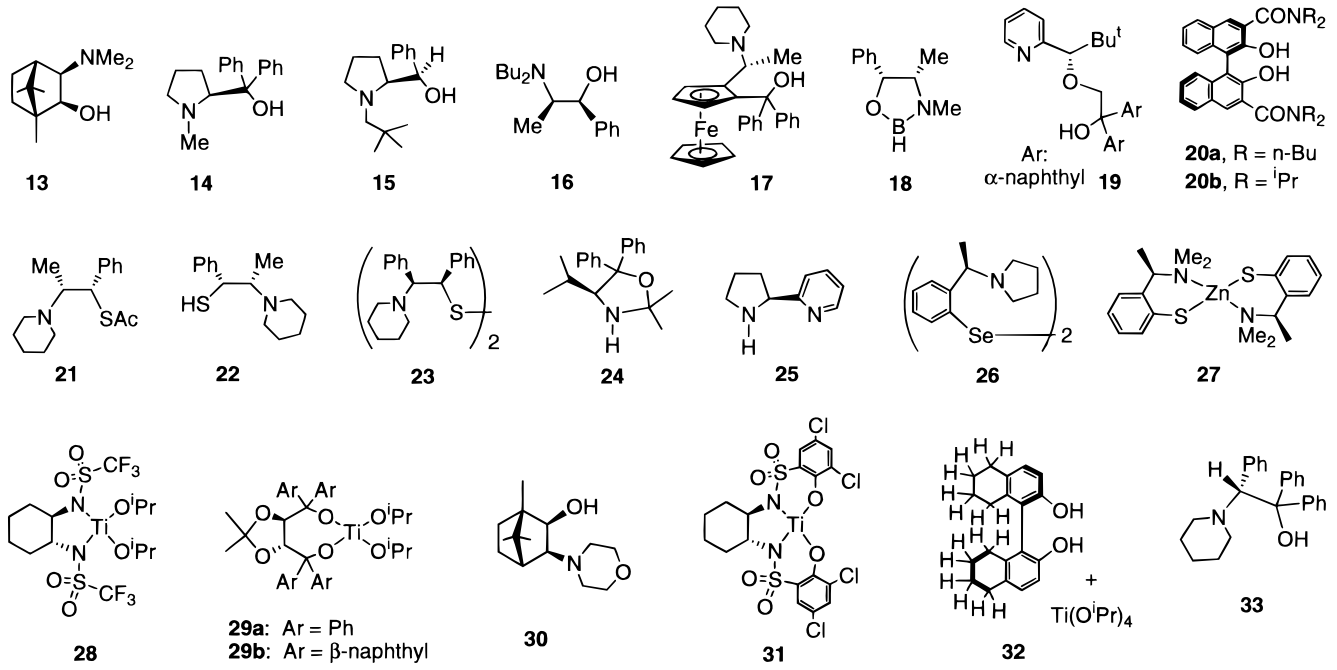


Figure 2. Currently known good catalysts for the enantioselective diethylzinc addition to aldehydes.

Table 2. Comparison of the Enantioselectivity of the Chiral Catalysts in the Reaction of Various Types of Aldehydes with Diethylzinc[a]

Catalyst	Aromatic Aldehyde[b]							Aliphatic Aldehyde			α,β-Unsaturated Aldehyde[c]					Ref
	CHO	CHO X	CHO X	CHO X	CHO	CHO	CHO O	linear	α–substituted	β–substituted	CHO Ph	OHC Me	R_2 CHO R_1	OHC Me Me	CHO Ph	
13	E	E	-	-	-	-	-	M	-	E	E	-	-	-	-	25
14	E	E	-	-	-	-	-	E	P	M or E	E	-	-	-	M	26
15	E	E	-	-	-	-	-	M	V	V	E	-	-	-	-	26a
16	E	-	E	-	-	-	-	V	M	E	-	-	-	-	-	27
17	E	E	-	-	-	E	V	P	E	M	E	-	-	-	-	28
18	E	E	-	-	-	-	M	P	-	-	-	-	-	-	-	29
19	E	E	V	-	-	-	-	G	V	G	M	-	-	-	-	30
20a	E	E	E	-	-	-	-	-	-	-	E	-	-	-	V	31
20b	E	-	-	-	-	-	-	-	E	-	-	-	-	-	E	31
21	E	E	E	-	-	E	-	-	E	-	-	-	-	-	-	32
22	E	E	E	-	E	E	-	M	E	-	M	-	-	-	-	33
23	E	E	E	-	-	E	-	V	E	-	G	-	-	-	-	34
24	E	E	E	-	E	E	-	-	P	-	-	-	-	-	-	35
25	E	E	E	-	-	-	P	M	E	M	E	-	-	-	P	36
26	E	E	E	E	E	-	-	-	-	-	-	-	-	-	-	37
27	E	E	E	-	-	-	V	-	-	M	M	-	-	-	-	38
28	E	-	-	-	-	-	-	E	-	E	E	-	-	-	-	39
29a	E	E	M or E	-	-	-	-	E	E or G	G	E	-	V	-	-	40
29b	-	-	-	-	-	-	-	E	E	E	E	E	E	-	E	40b
30	E	E	-	E	-	-	-	E	E	-	-	-	-	-	-	41
31	E	E	E,G or M	-	E	E	E	P	E or P	-	M	P	E or P	P	-	42a
32	E	E	E or V	E or V	E	E	-	-	-	-	-	-	-	-	-	42b
33	E	E	E	E	E	E	-	E	E	E	-	-	E	-	-	43
(*R*)-**12**	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	

[a] For the ee's: E = excellent, ≥90%. V = very good, 85−89%. G = good, 80−84%. M = moderate, 60−79%. P = poor, <60%. [b] X = Me, F, Cl, Br, or OMe. [c] R_1 = H, alkyl, or aryl. R_2 = alkyl.

also studied the reaction of (*R*)-**12** with 2 equiv of diethylzinc in toluene-d_8. The resulting complex gave complicated ^{1}H NMR signals, indicating the possible existence of isomeric structures. Cryoscopic analysis of the molecular weight of the complex in cyclohexane[44] suggests the formation of a monobinaphthyl dizinc complex. (*R*)-**36** is thus proposed as a possible structure for the zinc complex generated from the reaction of (*R*)-**12** with 2 equiv of diethylzinc. The calculated molecular weight for (*R*)-**36** is 1026 and the value obtained by the cryoscopic analysis is 1099. The restricted rotation of the

(44) Shoemaker, D. P.; Garland, C. W.; Nibler, J. W. *Experiments in Physical Chemistry*; 3rd ed.; The McGraw-Hill: New York, 1996; p 179.

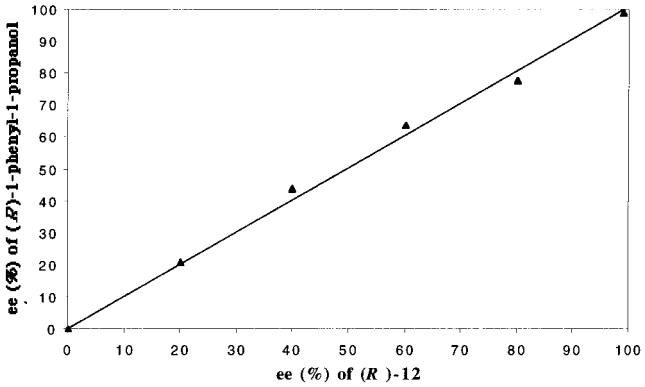
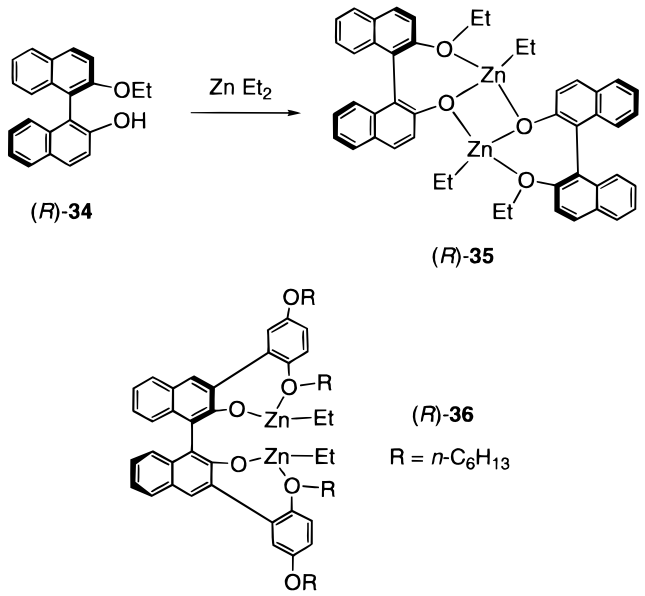


Figure 3. The correlation of the ee of the product to the ee of the monomeric catalyst for the diethylzinc addition to benzaldehyde.

Scheme 3. Reaction of (*R*)-34 with Diethylzinc

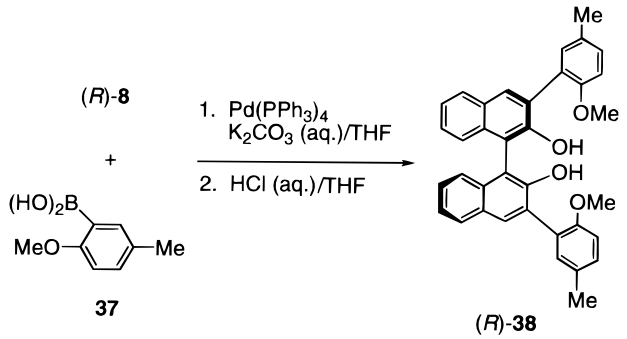


3,3′-dialkoxyphenyl substituents around the aryl−aryl single bond in (*R*)-**36** can lead to three diastereomers. In addition, a zinc center can also bridge the two 2,2′-oxygens. In the structure of the dimeric complex (*R*)-**35**, the zinc atoms are four-coordinate but in (*R*)-**36** they are only three-coordinate. The greatly enhanced catalytic activity of (*R*)-**12** over (*R*)-**34** may therefore be explained by the tendency of (*R*)-**36** to remain a monobinaphthyl structure, which leads to its coordinatively more unsaturated zinc centers and higher Lewis acidity.

We have studied the reaction of diethylzinc with benzaldehyde catalyzed by (*R*)-**12** with different enantiomeric purities, and the results are displayed in Figure 3. Unlike the nonlinear effects observed by Noyori et al. in the amino alcohol-based catalysts,[45] the ee of the alcohol product is linear with the ee of catalyst (*R*)-**12**. We also found that the ee of the alcohol product was independent of the concentration of (*R*)-**12**. These results further support the assumption that the catalytically active species in the reaction catalyzed by (*R*)-**12** contains only one binaphthyl unit.

When benzaldehyde was treated with 2 equiv of diethylzinc and 1 equiv of (*R*)-**12**, no reaction was observed. This indicates that the ethyl groups bonded to the zinc centers in (*R*)-**36** cannot migrate to the aldehyde substrate. Thus, the reaction of an aldehyde with diethylzinc may take place by transferring an ethyl group of the excess diethylzinc, probably coordinated to the oxygens of (*R*)-**36**, to the *re* face of the aldehyde to generate the corresponding *R* alcohol. Whether there are cooperative effects between the two zinc atoms in (*R*)-**36** remains undetermined.

Scheme 4. Synthesis of a Monobinaphthyl Compound (*R*)-38



Another monomeric model compound (*R*)-**38**, in which one of the alkoxy groups on each 3,3′-phenyl substituent of (*R*)-**12** was replaced with a methyl group, was also synthesized (Scheme 4). The Suzuki coupling of (*R*)-**8** with a monoboronic acid molecule **37**[46] followed by hydrolysis generated (*R*)-**38**. The specific optical rotation of (*R*)-**38** was $[\alpha]_D = 139.7$ ($c = 1.01$, CH_2Cl_2). Its 3,3′-phenyl substituents are less electron rich than those of (*R*)-**12**, and the methoxy groups are less basic. (*R*)-**38** catalyzed the diethylzinc addition to benzaldehyde with 98% ee at room temperature. Thus, the stereoselectivity of (*R*)-**38** is very similar to that of (*R*)-**12**.

With the discovery of the highly general enantioselectivity of (*R*)-**12** for the asymmetric dialkylzinc addition to aldehydes, we took on a more challenging task—the catalytic asymmetric *diphenylzinc* addition to aldehydes. Although extensive research has been carried out for the asymmetric alkylzinc addition to aldehydes, little study has been done on the asymmetric arylzinc addition to aldehydes. Only recently was the first enantioselective catalytic addition of diphenylzinc to aldehydes reported by Fu and co-workers.[47,48] In their work, a planar-chiral ligand **39** was used for the reaction of diphenylzinc with *p*-chlorobenzaldehyde (**40**) (Scheme 5).[47] This has produced a chiral diaryl alcohol **41** with 57% ee.

In the reaction of diethylzinc with aldehydes, the addition of chiral ligands not only controls the stereoselectivity but also activates diethylzinc, since diethylzinc itself does not show appreciable reaction with any aldehydes in the absence of a catalyst. However, the uncatalyzed diphenylzinc addition can become competitive even with the catalyzed reaction, which makes it more difficult

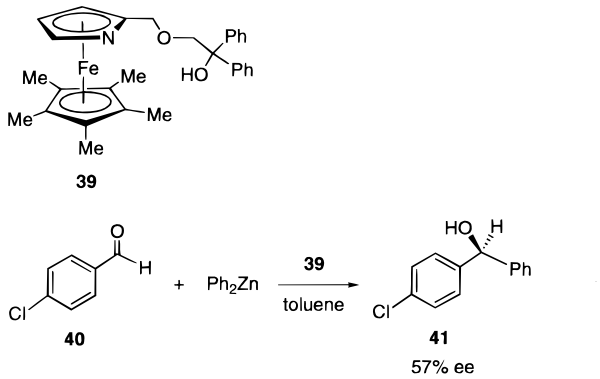
(45) Kitamura, M.; Okada, S.; Suga, S.; Noyori, R. *J. Am. Chem. Soc.* **1989**, *111*, 4028.

(46) Maruoka, K.; Murase, N.; Yamamoto, H. *J. Org. Chem.* **1993**, *58*, 8, 2938.

(47) (a) Dosa, P. I.; Ruble, J. C.; Fu, G. C. *J. Org. Chem.* **1997**, *62*, 444. (b) An asymmetric reaction of diphenylzinc with ketones was reported: Dosa, P. I.; Fu, G. C. *J. Am. Chem. Soc.* **1998**, *120*, 445.

(48) (a) An in situ generated phenylzinc reagent was added to aryl aldehydes in the presence of a stoichiometric amount of a chiral ligand: Soai, K.; Kawase, Y.; Oshio, A. *J. Chem. Soc., Perkin Trans. 1* **1991**, 1613. (b) An enantioselective catalytic diphenylzinc addition was reported shortly after our preliminary communication:[14c] Bolm, C.; Muñiz, K. *J. Chem. Soc., Chem. Commun.* **1999**, 1295.

Scheme 5. Asymmetric Diphenylzinc-Aldehyde Addition



to develop an enantioselective catalyst for the diphenylzinc addition.

We have used (*R*)-**12** to carry out the asymmetric diphenylzinc addition to aldehydes, and the results are summarized in Table 3. In the presence of 5 mol % of (*R*)-**12**, the addition of diphenylzinc to propionaldehyde gave (*S*)-1-phenyl-1-propanol with 86% ee at 0 °C (Table 3, section a, entry 1). This is the first example of a highly enantioselective catalytic diphenylzinc addition to aldehydes. The *S* configuration of the chiral alcohol product indicates that the phenyl addition occurs at the *re* face of the aldehyde. This is the same as the diethylzinc addition catalyzed by (*R*)-**12**, which, however, produces (*R*)-1-phenyl-1-propanol when reacted with benzaldehyde. Therefore, (*R*)-**12** can catalyze the formation of both the *R* and *S* enantiomers of 1-phenyl-1-propanol by either reacting diethylzinc with benzaldehyde or diphenylzinc with propionaldehyde.

The high enantioselectivity observed for the diphenylzinc addition to the aliphatic aldehyde encouraged us to launch a major effort to investigate the diphenylzinc addition to aromatic aldehydes for the asymmetric synthesis of chiral diaryl carbinols. Chiral diaryl carbinols are useful for making a number of biologically active compounds but are difficult to produce by asymmetric catalysis.[15] Preparation of secondary alcohols is normally completed by either addition of organometallic reagents to aldehydes or reduction of ketones. A chiral diarylcarbinol is difficult to form with high enantioselectivity from the asymmetric reduction of ketones because a prochiral diaryl ketone often contains two sterically and electronically very similar aryl groups. Nevertheless, using chiral oxazaborolidines as the catalysts, Corey and co-workers have accomplished a highly enantioselective reduction of ketones containing two sterically and/or electronically very different aryl groups.[15b,49] On the other hand, because of the large differences between an aryl group and a hydrogen atom in an aryl aldehyde, addition of organometallic aryl reagents to such a prochiral aldehyde in the presence of a chiral catalysts should have large chiral bias toward the two prochiral faces and should be more suitable for the asymmetric synthesis of chiral diarylcarbinols. It is a surprise to notice that very few reports on the catalytic enantioselective addition of organometallic aryl reagents to aryl aldehydes have appeared,[47,50,51] even though a large number of highly enantioselective alkyl additions have been documented.[24]

The reaction of organozinc reagents with aromatic aldehydes is normally much faster than with aliphatic aldehydes as shown in Table 1. Therefore, the catalytic asymmetric diphenylzinc addition to aromatic aldehydes is expected to be even more challenging than its addition to aliphatic aldehydes because of the faster uncatalyzed background reaction. Entry 3 in section a of Table 3 shows that the diphenylzinc addition to *p*-anisaldehyde can be completed at 0 °C even in the absence of a catalyst. We have explored the reaction conditions by carefully varying the reaction temperatures, solvents, amount of catalyst (*R*)-**12,** and concentrations of the aldehydes and by using additives such as diethylzinc and methanol. Through this study, we have achieved excellent enantioselectivity for the addition of diphenylzinc to various aromatic aldehydes and cinnamaldehyde (Table 3, entries 4−29).

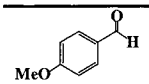
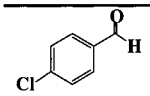
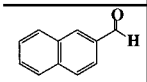
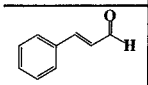
Our study shows that the enantioselectivity of the diphenylzinc addition to aldehydes are influenced by the following factors: (1) increased enantioselectivity is generally observed when chiral ligand (*R*)-**12** is pretreated with diethylzinc (e.g., Table 3, entries 4−6). Thus, the reaction of diethylzinc with (*R*)-**12** generates a better chiral zinc catalyst than the reaction of diphenylzinc with (*R*)-**12**. (2) The enantioselectivity is dramatically increased by reducing the concentration of the reaction system (e.g., Table 3, entries 13−15). This indicates that the uncatalyzed background reaction may become less competitive at low concentration. (3) In the case of cinnamaldehyde, the use of methanol as the additive greatly improves the enantioselectivity (Table 3, entries 26 and 29). In this reaction, the structure of the catalyst formed from the reaction of (*R*)-**12** with diethylzinc may be modified when treated with methanol. Previously, Fu and co-worker also observed the enhancement of enantioselectivity with the addition of methanol in their study of organozinc additions.[47b] In entries 26 and 29 of Table 3, *higher* temperature in methylene chloride solution led to higher ee. A better catalyst might have been produced at higher temperature for the reaction of diphenylzinc with *trans*-cinnamaldehye. Entries 27 and 28 of Table 3 are two attempts to improve the enantioselectivity of the diphenylzinc addition to *trans*-cinnamaldehyde by using an in situ generated optically active 1-phenyl-1-propyloxyzinc complex as the additive, since the addition of methanol in entry 26 significantly increased the enantioselectivity of the reaction. The in situ generated 1-phenyl-1-propyloxyzinc had an *R* configuration for entry 27 and an *S* configuration for entry 28. These two experiments were designed to avoid the "mismatch" of the chirality of the ligand with that of the in situ generated chiral alcohol additive. However, neither entry 27 nor entry 28 showed enhanced enantioselectivity. Instead, a significant reduction in enantioselectivity over the use of methanol additive was observed. Thus, the sterically more hindered (*R*)- or (*S*)-1-phenyl-1-propyloxyzinc additive in these experiments might have generated

(49) (a) Corey, E. J.; Helal, C. J. *Tetrahedron Lett.* **1995**, *36*, 9153. (b) Corey, E. J.; Helal, C. J. *Tetrahedron Lett.* **1996**, *37*, 5675.

(50) Weber, B.; Seebach, D. *Tetrahedron* **1994**, *50*, 7473.

(51) For the enantioselective reaction of stoichiometric or excess chiral organometallic aryl compounds with aryl aldehydes, see: (a) Seebach, D.; Beck, A. K.; Roggo, S.; Wonnacott, A. *Chem. Ber.* **1985**, *118*, 3673. (b) Noyori, R.; Suga, S.; Kawai, K.; Okada, S.; Kitamura, M. *Pure Appl. Chem.* **1988**, *60*, 1597. (c) Tomioka, K.; Nakajima, M.; Koga, K. *Chem. Lett.* **1987**, 65. (d) Kaino, M.; Ishihara, K.; Yamamoto, H. *Bull. Chem. Soc. Jpn.* **1989**, *62*, 3736. (e) Wang, J.-T.; Fan, X.; Feng, X.; Qian, Y.-M. *Synthesis* **1989**, 291. (f) Nakajima, M.; Tomioka, K.; Koga, K. *Tetrahedron* **1993**, *49*, 9751.

Table 3. Asymmetric Diphenylzinc Addition to Aldehydes Catalyzed by the Monomer (*R*)-12

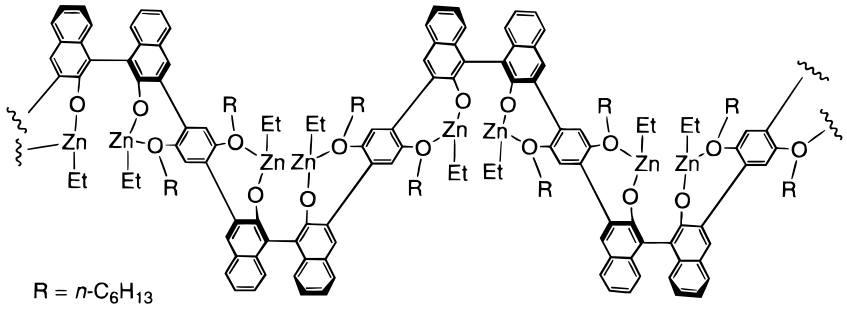
a) Aldehyde	Ph_2Zn (equiv)	(*R*)-**12** or (*R*)-**12**+Et_2Zn (mol%)	Aldehyde Concentration (mM)	Solvent	Temperature (°C)	Time (h)	Isolated Yield (%)	ee (%)	Configuration[c]	entry
	2	5	100	Toluene	0	30	93	**86**[a]	S[24]	1
	1.2	10	100	Toluene	0	20	90	**87**[a]	S	2
	1	0	50	Toluene	0	10	61	0		3
	2	5	50	Toluene	0	10	76	54[a]	R[48]	4
	1	5 + 10 Et_2Zn	50	Toluene	0	10	87	77[a]	R	5
	1	20 + 40 Et_2Zn	50	Toluene	-30	24	84	**93a**	R	6
	2	5	50	Toluene	0	4	88	15[b]	R[52]	7
	1	20 + 40 Et_2Zn	50	Toluene	-35	10	83	41[b]	R	8
	1	20 + 40 Et_2Zn	50	Toluene	r.t.	10	75	50[b]	R	9
	1	20 + 40 Et_2Zn	50	CH_2Cl_2	r.t.	10	91	54[b]	R	10
	1	20 + 40 Et_2Zn	50	Hexane	r.t.	10	80	38[b]	R	11
	1	20 + 40 Et_2Zn	50	THF	r.t.	10	35	78[b]	R	12
	1	20 + 40 Et_2Zn	50	Et_2O	r.t.	10	70	57[b]	R	13
	1	20 + 40 Et_2Zn	16	Et_2O	r.t.	10	90	**83**[b]	R	14
	1	20 + 40 Et_2Zn	5	Et_2O	r.t.	10	86	**94**[b]	R	15
b) Aldehyde	Ph_2Zn (equiv.)	(*R*)-**12**+Et_2Zn or other additive (mol%)	Aldehyde Concentration (mM)	Solvent	Temperature (°C)	Time (h)	Isolated Yield (%)	ee[a] (%)	Configuration[c]	entry
	1	20 + 40 Et_2Zn	5	Toluene	r.t.	18	82	49	R[51a]	16
	1	20 + 40 Et_2Zn	5	Et_2O	r.t.	10	89	71	R	17
	1	20 + 40 Et_2Zn	5	CH_2Cl_2	r.t.	10	84	68	R	18
	1	20 + 40 Et_2Zn	5	THF	r.t.	22	46	**82**	R	19
	1	20 + 40 Et_2Zn	5	THF	-10	96	66	**87**	R	20
	1	20 + 40 Et_2Zn	5	Toluene	-30	24	72	45	S[48]	21
	1	20 + 40 Et_2Zn	5	THF	-20	22	35	49	S	22
	1	20 + 40 Et_2Zn	5	Et_2O	-20	22	68	48	S	23
	1	20 + 40 Et_2Zn	5	Et_2O	r.t.	10	89	46	S	24
	1	20 + 40 Et_2Zn	5	CH_2Cl_2	r.t.	28	98	50	S	25
	1	20 + 80 Et_2Zn + 40 MeOH	5	CH_2Cl_2	r.t.	22	92	77	S	26
	1	20 + 80 Et_2Zn + 40 PhCHO	5	CH_2Cl_2	reflux	18	82	48	S	27
	1	20 + 40 Et_2Zn 40 Ph_2Zn + 40 EtCHO	5	CH_2Cl_2	reflux	10	66	37	S	28
	1	20 + 80 Et_2Zn + 40 MeOH	5	CH_2Cl_2	reflux	10	94	**83**	S	29

[a] Determined by HPLC-Chiracel-OD column. [b] Determined by analyzing the acetate derivative of the alcohol product by HPLC-Chiralcel-OD column. [c] Determined by comparing the optical rotation with the literature data.

a less active catalyst and allowed the uncatalyzed reaction to become more competitive.

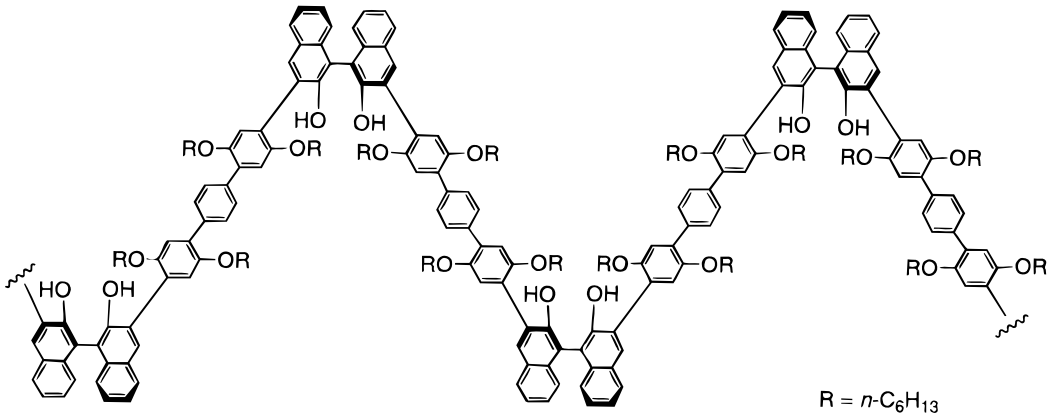
2. Converting the Highly Enantioselective Monobinaphthyl Catalyst to a Highly Enantioselective Polymeric Catalyst for the Organozinc Addition. As described in the last section, the catalytically active species generated from the reaction of (*R*)-**12** with diethylzinc in the alkyl addition to aldehydes is likely to be monomeric rather than the aggregate of the zinc complex. Therefore, it would be possible to convert this monomeric catalyst into a highly enantioselective polymeric catalyst if both the steric and electronic environments of the monomer ligand can be maintained in the resulting polymer structure. However, even though polymer (*R*)-**4** contains (*R*)-**12** as its structural units, the enantioselectivity of the polymer is much more limited. (*R*)-**42** (Chart 1) is proposed as the catalytically active species for the diethylzinc addition to aldehydes in the presence of (*R*)-**4**. In (*R*)-**42**, the two alkoxy oxygens on a phenylene spacer serve as a dual ligand to coordinate to the zinc atoms in the two adjacent binaphthyl units. Because of this interference between the neighboring units, the electronic and steric environments of the catalytic sites in (*R*)-**42** should be different from those of (*R*)-**36**, causing

Chart 1



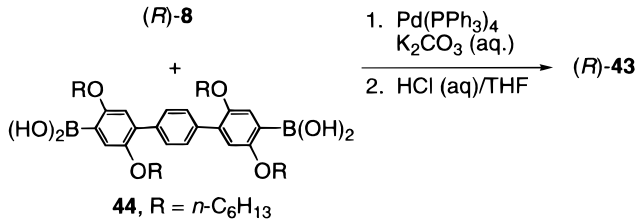
(*R*)-**42**

Chart 2

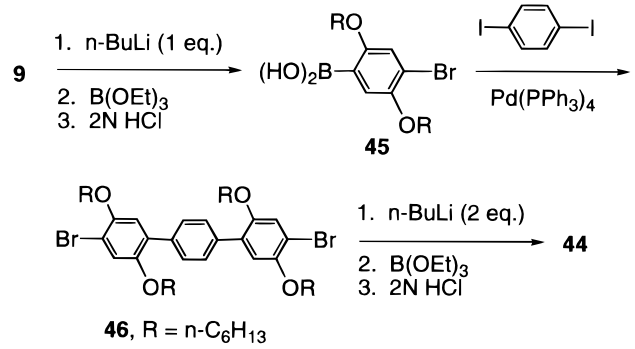


(*R*)-**43**

Scheme 6. Synthesis of the Rigid and Sterically Regular Chiral Polymer (*R*)-43



Scheme 7. Synthesis of the *p*-Triphenylene Diboronic Acid Linker 44



the observed different enantioselectivity. On the basis of this analysis, we designed a new rigid and sterically regular polymeric chiral catalyst (*R*)-**43** (Chart 2) for the asymmetric reaction of aldehydes with organozincs. Because the binaphthyl units in (*R*)-**43** are separated by long and rigid linkers, the interference between the catalytic sites in the polymer should be minimum, and the steric and electronic environments of the monomeric catalyst (*R*)-**12** should be mostly preserved. We therefore expect (*R*)-**43** to have the same catalytic properties as (*R*)-**12**.

(*R*)-**43** was obtained in 90% yield from the Suzuki coupling of (*R*)-**8** with **44** followed by hydrolysis (Scheme 6). The coupling was carried out with a slight excess of **44**. After the completion of the polymerization, 4-*tert*-butylbromobenzene was added to cap the polymer chain by consuming the boronic acid end groups. The resulting polymer (*R*)-**43** has very good solubility in THF, toluene, methylene chloride, and chloroform. Gel permeation chromatography (GPC) analysis of (*R*)-**43** showed its molecular weight as M_w = 25 800 and M_n = 14 300 (PDI = 1.8). The specific optical rotation of this chiral polymer was $[\alpha]_D = -92.9$ (c = 1.01, CH_2Cl_2). (*R*)-**43** gave well-resolved ^{1}H and ^{13}C NMR spectra consistent with a structurally well-defined polymer chain. Figure 4 is the ^{1}H NMR spectrum of the polymer in $CDCl_3$.

The diboronic acid linker **44** was obtained from **9** (Scheme 7).[21] Treatment of **9** with 1 equiv of *n*-BuLi followed by reaction with triethylborate and hydrolysis gave **45**. Because the Suzuki coupling of aryl iodide generally proceeds much faster than aryl bromide,[22] **46** was obtained from the reaction of **45** with 1,4-diiodobenzene, which was then converted to diboronic acid **44**.

When polymer (*R*)-**43** was used to catalyze the reaction of aldehydes with diethylzinc, we were very pleased to find that this polymer showed the expected high enantioselectivity for a broad range of aldehydes. Table 4 summarizes the results for the use of (*R*)-**43**. All the reactions were carried out in the presence of 5 mol % (based on the repeating unit in the polymer) of (*R*)-**43** and 2 equiv of diethylzinc in toluene solution at 0 °C unless indicated otherwise. As shown in Table 4, (*R*)-**43**

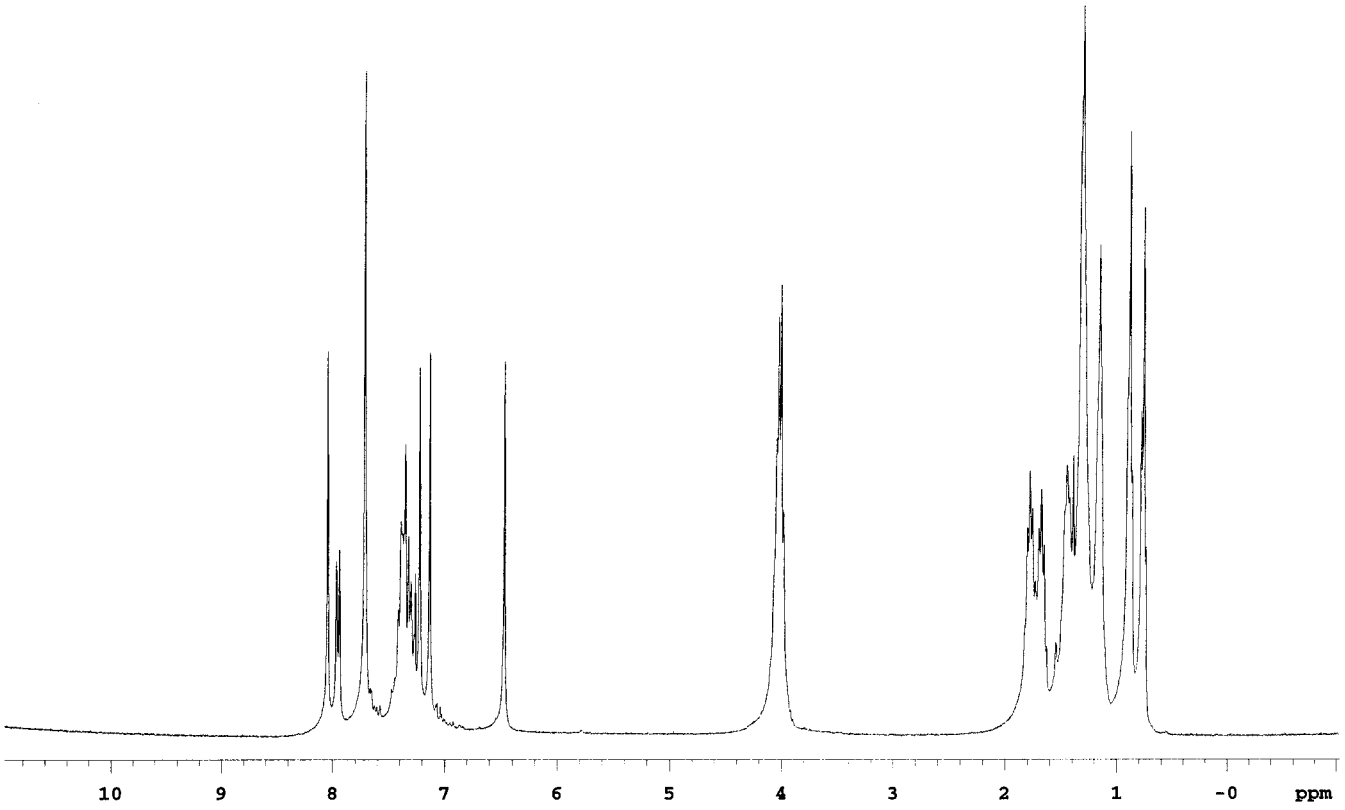


Figure 4. ^{1}H NMR spectrum of polymer (*R*)-**43**.

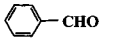
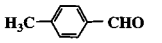
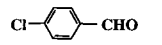
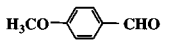
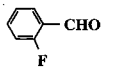
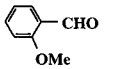
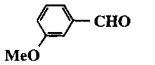
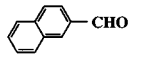
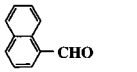
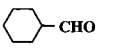
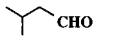
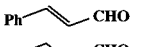
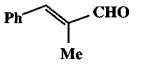
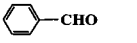
exhibits greatly enhanced enantioselectivity over (*R*)-**4**,[12] especially for the reaction of aliphatic aldehydes. This polymer was easily recovered by precipitation with methanol after workup, and the recovered (*R*)-**43** showed the same enantioselectivity as the original polymer. Previously, the best polymer-supported amino-alcohol catalyst for the reaction of *aliphatic* aldehydes gave only 69% ee.[53] Cross-linked polystyrene-supported chiral α,α,α′,α′-tetraphenyl-1,3-dioxolane-4,5-dimethanoltitanium(IV) catalysts carried out a diethylzinc addition to heptyl aldehyde with 92% ee (75% yield) and to cyclohexanecarboxaldehyde with 86% ee (57% yield), but these reactions required the use of a stoichiometric amount of $Ti(OCHMe_2)_4$ versus the aldehydes.[54] Therefore, (*R*)-**43** is the best polymeric catalyst yet obtained for the asymmetric reaction of aldehydes with diethylzinc. This polymer also showed excellent enantioselectivity for the addition of dimethylzinc to aldehydes. Since the dimethylzinc addition was a very slow reaction, more of the polymer ligand was used.

The reaction of (*R*)-**43** with diethylzinc in toluene-d_8 was studied. We found that although (*R*)-**43** was soluble in toluene, it formed an insoluble gel after treatment with 2 equiv of diethylzinc. This gel was probably produced from the cross-link of a proposed polybinaphthyl zinc complex (*R*)-**47** (Chart 3), formed from the reaction of (*R*)-**43** with 2 equiv of diethylzinc, through a very small amount of interchain coordination of the oxygen atoms to the zinc centers. The ^{1}H NMR spectrum of the reaction mixture showed the release of ethane accompanied with a complete disappearance of the polymer signal. Further addition of diethylzinc converted the gel into a homogeneous solution because excess diethylzinc might have saturated the coordination ability of the oxygen atoms in each polymer chain so that the interchain Zn−O−Zn cross-link was cleaved. Due to the broadness of the NMR signals, no structural information on (*R*)-**47** could be deduced. The behavior of (*R*)-**43** when reacted with diethylzinc is very similar to what was observed in the reaction of (*R*)-**4** with diethylzinc.[12b]

We have used polymer (*R*)-**43** to catalyze the diphenylzinc addition to propionaldehyde and p-anisaldehyde and the results are summarized in Table 5. To achieve high enantioselectivity, 0.2−0.4 equiv (based on the repeat unit) of the polymer was needed. In the presence of 0.2 equiv of the polymer, diphenylzinc reacted with propionaldehyde at 0 °C with 85% ee. For the reaction with the aromatic aldehyde, slow mixing of the reactants with the catalyst was required (Table 5, entries 3 and 4). In these experiments, two solutions were prepared, one containing (*R*)-**43**, diethylzinc, and diphenylzinc in toluene and another containing the aldehyde in toluene. Both of the solutions were simultaneously added into a flask containing toluene at −30 °C over 20 h via a syringe pump. After the addition, the reaction mixture was stirred further at −30 °C. Up to 92% ee was observed when the double slow addition technique was applied. In these reactions, the polymer was pretreated with excess diethylzinc. Since the diphenylzinc addition was much faster than the diethylzinc addition, no product from the reaction of diethylzinc was observed even though the amount of diethylzinc was 2−3 times more than diphenylzinc during the reaction. The excess diethylzinc was added in order to dissolve the gel formed from the reaction of (*R*)-**43** with 2 equiv [versus the binaphthyl unit of (*R*)-**43**] of diethylzinc.

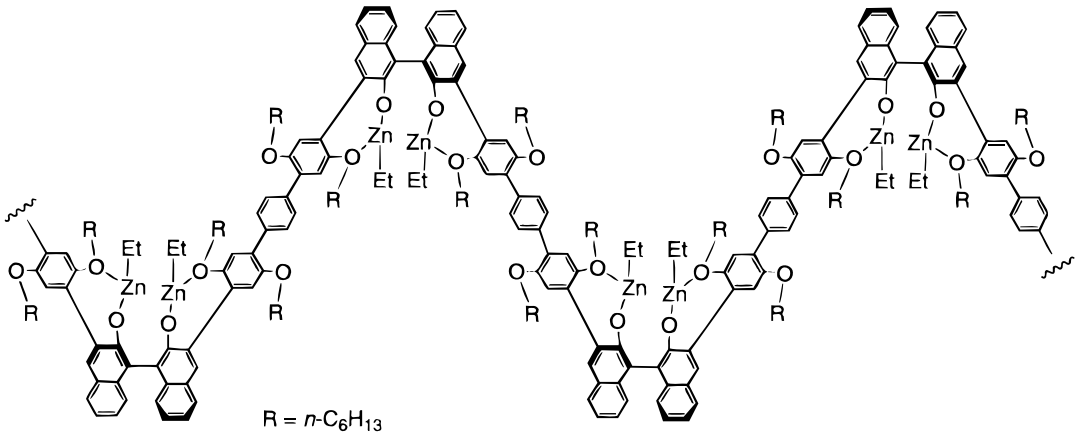
(52) Wu, B.; Mosher, H. S. *J. Org. Chem.* **1986**, *51*, 1904.
(53) Soai, K.; Watanabe, M. *Tetrahedron: Asymmetry* **1991**, *2*, 97.
(54) Seebach, D.; Marti, R. E.; Hintermann, T. *Helv. Chim. Acta* **1996**, *79*, 1710.

Table 4. Reaction of Aldehydes with Dialkylzincs in the Presence of Polymer (*R*)-43

Aldehyde	Dialkylzinc	Time(h)	Isolated Yield (%)	*ee* (%)	Configuration
	Et_2Zn	5	92	98[a]	R
	Et_2Zn	5	90	98[b]	R
	Et_2Zn	5	94	98[b]	R
	Et_2Zn	3.5	89	97[a]	R
	Et_2Zn	4	88	91[b]	R
	Et_2Zn	4	90	93[b]	R
	Et_2Zn	4	93	98[a]	R
	Et_2Zn	12	95	96[a]	R
	Et_2Zn	5	93	98[a]	R
n-C_5H_{11}CHO	Et_2Zn	20	71	98[c]	R
n-C_7H_{15}CHO	Et_2Zn	20	85	97[c]	–
n-C_8H_{17}CHO	Et_2Zn	24	88	97[c]	R
	Et_2Zn	24	81	98[d]	R
	Et_2Zn	24	65	98[e]	R
	Et_2Zn	5	93	92[a,f]	R
	Et_2Zn	6	92	97[a]	–
	Me_2Zn[g]	48	92	93[a]	R
n-C_7H_{15}CHO	Me_2Zn[g]	72	78	89[c]	R

[a] Determined by HPLC-Chiracel OD column. [b] Determined by chiral GC (β-Dex capillary column). [c] Determined by analyzing the acetate derivative of the product on the GC-β-Dex capillary column. [d] Determined by analyzing the propionate derivative of the product on the GC-β-Dex capillary column. [e] Determined by analyzing the Mosher's ester of the product on the GC-β-Dex capillary column. [f] The solvent was a 1:1 mixture of toluene/diethyl ether. [g] 3 equiv of Me_2Zn and 0.2 equiv of polymer were used.

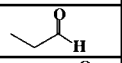
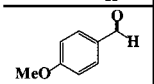
Chart 3



(*R*)-**47**

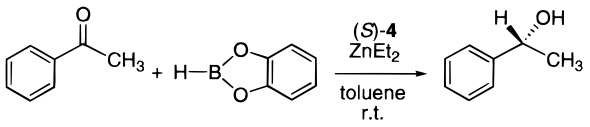
To account for the observed differences between the catalytic properties of the polymer and those of the monomer, the following explanation is proposed. Since the catalytic sites in (*R*)-**43** are almost identical to the structure of monomer (*R*)-**12**, in principle, the polymer should have the same stereoselectivity as the monomer. This is true if there is no competition from the uncatalyzed reaction as we have demonstrated for the dialkylzinc addition. However, in the diphenylzinc addition, the rate difference between the catalyzed and the uncatalyzed reactions is small. Because of the mobility differences between the polymer and the monomer, there may be less collision between the substrate and the catalytic sites in the polymer which will make the uncatalyzed

Table 5. Asymmetric Diphenylzinc Addition to Aldehydes Catalyzed by the Polymer (*R*)-43

Aldehyde	Ph_2Zn (equiv.)	(*R*)-**43** or (*R*)-**43**+Et_2Zn (mol%)	Aldehyde Concentration (mM)	Solvent	Temperature (^oC)	Time (h)	Isolated Yield (%)	ee[a] (%)	Configuration[b]	entry
	2	20	75	Toluene	0	66	82	**85**	S[24]	1
	1	20 + 40 Et_2Zn	50	Toluene	-30	20	65	76	R[48]	2
	1	20 + 200 Et_2Zn	5	Toluene	-30	40	59	**82**	R	3[c]
	1	40 + 320 Et_2Zn	5	Toluene	-30	56	72	**92**	R	4[c]

[a] Determined by HPLC-Chiracel-OD column. [b] Determined by comparing the optical rotation with the literature data. [c] Slow mixing of the catalyst, reagent, and substrate via a syringe pump.

Scheme 8. Reduction of Acetophenone with Caltecholborane in the Presence of a Chiral Polybinaphthyl−Zinc Complex



reaction even more competitive. Therefore, more of the polymer and lower concentration of the substrate are needed to suppress the competing uncatalyzed diphenylzinc addition in order to maintain the high enantioselectivity.

3. Asymmetric Reduction of Prochiral Ketones Catalyzed by the Chiral Binaphthyl Monomer and Polymer Catalysts. Asymmetric reduction of ketones is another important method for the synthesis of optically active secondary alcohols.[16,17] We have studied the use of the zinc complexes generated from the reaction of diethylzinc with the monobinaphthyl and polybinaphthyl ligands for the asymmetric reduction of prochiral ketones. Scheme 8 shows the reaction of acetophenone with catecholborane in the presence of (*S*)-**4**[12b] and diethylzinc. The molecular weight of (*S*)-**4** was M_w = 10 000 and M_n = 4600 (PDI = 2.2) as determined by GPC. The specific optical rotation of this polymer was $[\alpha]_D = -14.2$ (c = 1.01, CH_2Cl_2). (*S*)-**4** is soluble in common organic solvents such as THF, methylene chloride, chloroform, and toluene. When 5 mol % (based on the repeating unit of the polymer) of (*S*)-**4** and 10 mol % of diethylzinc were used, acetophenone was reduced to 1-phenylethanol by catecholborane in 77% yield and 54% ee at room temperature in toluene. When the reaction temperature was decreased to −30 °C, the ee of the product was raised to 67%. Lower ee's were observed when the reaction was carried out in other solvents such as methylene chloride, THF, and diethyl ether.

We have examined the use of the monobinaphthyl model compound (*R*)-**12** for this reaction. In the presence of 5 mol % of (*R*)-**12** and 10 mol % of diethylzinc, acetophenone was reduced to 1-phenylethanol in 87% yield and 81% ee at −30 °C in toluene. As expected, the absolute configuration of the product was *S*, opposite to that obtained in the presence of (*S*)-**4**. Similar to what was observed in the diethylzinc addition to aldehydes, the enantioselectivity of polymer (*S*)-**4** was significantly lower than that of monomer (*R*)-**12**, probably due to the interference of the adjacent binaphthyl units in (*S*)-**4**. The long linker polymer (*R*)-**43** was thus used for the asymmetric reduction of acetophenone. Under the same conditions as in the use of (*R*)-**12**, (*S*)-1-phenylethanol was obtained with 80% ee in the presence of (*R*)-**43**. In this reaction, the enantioselectivity of polymer (*R*)-**43** is almost the same as that of monomer (*R*)-**12**. This further demonstrates that the steric and electronic environments around the catalytic sites of (*R*)-**43** are indeed almost identical to those in (*R*)-**12**.

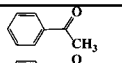
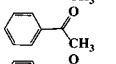
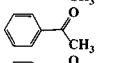
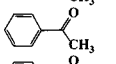
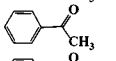
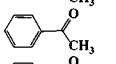
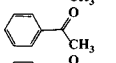
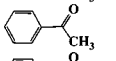
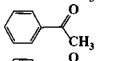
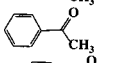
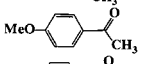
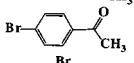
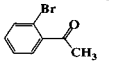
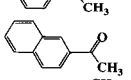
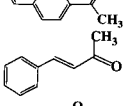
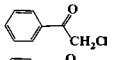
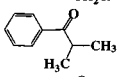
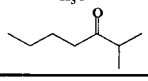
Table 6 summarizes the results obtained from the use of monomer (*R*)-**12** and polymers (*S*)-**4** and (*R*)-**43** in the asymmetric reduction of a variety of prochiral ketones. As a polymer-catalyzed asymmetric reaction, the enantioselectivity of the zinc complex of (*R*)-**43** for the reduction of the methyl aryl/vinyl ketones listed in Table 6 is considered to be quite good (Table 6, entries 10−15). However, when the methyl group of these substrates was changed to other substituents, the enantioselectivity was significantly reduced (Table 6, entries 16−18). When dimethylzinc was used in place of diethylzinc, the ee was slightly lower (Table 6, entry 7). Using $BH_3{\cdot}SMe_2$ as the reducing agent in place of catecholborane gave very low ee (Table 6, entry 8). Entry 9 of Table 6 shows that more than 2 equiv of diethylzinc versus the ligand caused a dramatic decrease of the ee of the product. This indicates that both the free and ligand-bound diethylzinc are able to catalyze the reduction of ketones with catecholborane. Polymer (*R*)-**43** was readily recovered by addition of methanol to the product mixture. After the polymer was recycled three times, it still showed 78% ee and 86% yield for the reduction of acetophenone. The specific optical rotation of this three-time-recycled polymer was $[\alpha]_D = -90.6$ (c = 0.9, CH_2Cl_2), very similar to that of the original polymer. The ^1H NMR spectrum of the recycled polymer was also very close to that of the original polymer. This demonstrates that there are almost no structural and functional changes for the polymer after repeated usage.

Summary

In summary, we have developed the most general polymeric catalyst for the highly enantioselective dialkylzinc addition to aldehydes. A catalytic asymmetric diphenylzinc addition to aldehydes by using the binaphthyl monomer and polymer catalysts has also been achieved with excellent enantioselectivity. This allows the preparation of the synthetically useful chiral diaryl carbinols that are difficult to access by asymmetric catalysis. We have further discovered that the mono- and polybinaphthyl zinc complexes can catalyze the asymmetric reduction of ketones with catecholborane.

Our work on both the asymmetric organozinc addition to aldehydes and the asymmetric reduction of ketones catalyzed by the zinc complexes of monomer (*R*)-**12** and polymer (*R*)-**43** has not only provided new methods for the synthesis of optically active secondary alcohols, but

Table 6. The Asymmetric Reduction of Ketones in the Presence of (*S*)-4, (*R*)-12, and (*R*)-43

Ketone	Ligand	Solvent	Yield (%)	ee (%)	Configuration	Entry[c]
	(*S*)-**4**	Toluene	77	54[a]	R[55]	1[d]
	(*S*)-**4**	Toluene	85	67[a]	R	2
	(*S*)-**4**	CH_2Cl_2	90	62[a]	R	3
	(*S*)-**4**	Et_2O	88	59[a]	R	4
	(*S*)-**4**	THF	51	56[a]	R	5
	(*R*)-**12**	Toluene	87	**81**[a]	S	6
	(*R*)-**12**	Toluene	88	77[a]	S	7[e]
	(*R*)-**12**	Toluene	86	14[a]	S	8[f]
	(*R*)-**12**	Toluene	90	8.5[a]	S	9[g]
	(*R*)-**43**	Toluene	89	**80**[a]	S	10
	(*R*)-**43**	Toluene	78	70[b]	S[56]	11
	(*R*)-**43**	Toluene	86	79[b]	S[57]	12
	(*R*)-**43**	Toluene	88	74[b]	S[58]	13
	(*R*)-**43**	Toluene	92	76[b]	S[59]	14
	(*R*)-**43**	Toluene	89	78[b]	S[60]	15
	(*R*)-**43**	Toluene	90	14[b]	R[61]	16
	(*R*)-**43**	Toluene	91	4.3[b]	R[62]	17
	(*R*)-**43**	Toluene	79	36[b]	S[63]	18

[a] Determined on an GC (β-Dex capillary column). [b] Determined by HPLC-Chiracel OD column. [c] The reactions were carried out at −30 °C in the presence of 5 mol % chiral ligand and 10 mol % Et_2Zn using catecholborane as the reducing agent unless otherwise specified. [d] The reaction was performed at rt. [e] 5 mol % Me_2Zn was used in place of Et_2Zn. [f] $BH_3{\cdot}SMe_2$ was the reducing agent. [g] 0.2 equiv of Et_2Zn was used.

also demonstrated that incorporation of an enantioselective monomeric catalyst into a rigid and sterically regular polymer structure could largely preserve the catalytic properties of the monomeric catalyst. This strategy may be generally applicable in converting existing highly enantioselective monomer catalysts into polymer catalysts of similar enantioselectivity provided that the catalytically active species in the monomer catalysts are monomeric rather than the monomer aggregates. By using this strategy, it is possible to overcome the drawbacks associated with the traditional approach to preparing polymeric catalysts where the microenvironment of the catalytic sites in the polymers are often significantly altered from those in the monomeric catalysts due to the flexible and sterically irregular polymer chains. The diphenylzinc addition study also reveals that the kinetics of a polymer in catalysis could be different from that of its monomeric version as a result of the large size differences. When there are competitive uncatalyzed background reactions, more of the polymer may be needed. In some cases, it may also require the modification of the polymer structure. One should be able to accomplish this since the use of the rigid and sterically regular polymers can not only maintain the steric and electronic environments of the monomeric catalysts but also allow a systematic modification of the catalytic sites in the polymer to achieve the desired catalytic property.

Experimental Section

General Data. All the solvents were dried according to the standard methods prior to use. Aldehydes, ketones and catecholborane (1 M, THF) were purchased from Aldrich and used directly. Et_2Zn, Me_2Zn, and Ph_2Zn were purchased from Strem. Molecular weights of the polymers were measured with gel permeation chromatography (GPC) by using THF eluent and polystyrene standards.

Preparation and Characterization of 2,5-Dihexyloxyphenylboronic Acid, 11. (a) Preparation of 1,4-Dihexyloxy-2-bromobenzene, 10. Under N_2, to a solution of 1,4-dihexyloxy-2,5-dibromobenzene **9** (25.92 g, 59.45 mmol) in THF (150 mL) was added *n*-BuLi (23.8 mL, 2.5 M in hexanes) at −78 °C over 30 min. After the addition, the reaction mixture was stirred at −78 °C for 1 h and was then quenched with aqueous NH_4Cl at −78 °C. Usual workup gave **10** as a pale yellow liquid (97% yield). **(b) Preparation of 11.** To a solution of **10** (10.71 g, 30 mmol) in THF (100 mL) was added *n*-BuLi (12 mL, 2.5 M in hexanes) at −78 °C over 10 min. After the addition, the reaction mixture was stirred at −78 °C for 30 min and was then cannulated into a solution of triethylborate (3 equiv, 15 mL) in THF (80 mL) at −78 °C. The mixture was stirred at −78 °C for 2 h and then at room temperature overnight. Hydrolysis of the resulting product solution with 2

N HCl at room temperature for 2 h followed by usual workup and column chromatography on silica gel (hexanes/EtOAc = 5/1) gave **11** as a pure white solid in 68% yield: mp 85−87 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.37 (d, J = 3.4 Hz, 1H), 6.95 (dd, J = 8.8, 3.0 Hz, 1H), 6.82 (d, J = 8.8 Hz, 1H), 6.53 (s, 1H), 6.44 (s, 1H), 4.01 (t, J = 6.6 Hz, 2H), 3.93 (t, J = 6.6 Hz, 2H), 1.82 (m, 2H), 1.75 (m, 2H), 1.33−1.45 (m, 12H), 0.90 (t, J = 6.8 Hz, 3H), 0.89 (t, J = 6.8 Hz, 3H); ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 158.28, 153.32, 121.34, 119.41, 112.19, 69.07, 68.67, 31.69, 31.58, 29.45, 29.38, 25.80, 25.78, 22.71, 22.62, 14.15, 14.08; FT-IR (cm^{-1}) 3462 (m), 2936 (s), 2864 (m). Anal. Calcd for $C_{18}H_{31}BO_4$: C, 67.08; H, 9.63. Found: C, 67.37; H, 9.75.

Preparation and Characterization of (*R*)-3,3′-Bis(2″,4″-dihexyloxyphenyl)-1,1′-binaphthol, (*R*)-12. (a) Preparation of (*R*)-2,2′-Bis(methoxymethoxy)-3,3′-bis(2″,4″-dihexyloxyphenyl)-1,1′-binaphthyl, A. Under N_2, to a solution of (*R*)-**8** (2.63 g, 4.21 mmol) and **11** (4.07 g, 12.63 mmol) in THF (50 mL) were added $Pd(PPh_3)_4$ (250 mg) and K_2CO_3 (aqueous 2 M, 20 mL, degassed with N_2) sequentially. The reaction mixture was heated at reflux for 22 h and then quenched with brine at room temperature. Usual workup followed by column chromatography on silica gel (hexanes/EtOAc = 10/1) gave **A** as a colorless oil in 88% yield: ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.88 (s, 2H), 7.83 (d, J = 8.0 Hz, 2H), 7.33−7.41 (m, 4H), 7.24−7.29 (m, 2H), 7.03 (d, J = 2.7 Hz, 2H), 6.88 (s, 2H), 6.86 (d, J = 2.7 Hz, 2H), 4.46 (d, J = 5.6 Hz, 2H), 4.41 (d, J = 5.6 Hz, 2H), 3.94 (t, J = 6.5 Hz, 4H), 3.89 (t, J = 6.9 Hz, 4H), 2.35 (s, 6H), 1.77 (m, 4H), 1.64 (m, 4H), 1.45 (m, 4H), 1.16−1.35 (m, 20H), 0.89 (t, J = 6.9 Hz, 6H), 0.77 (t, J = 6.9 Hz, 6H). **(b) Preparation of (*R*)-12.** To a solution of **A** (3.0 g) in a mixed solvent (10 mL of CH_2Cl_2 and 30 mL of EtOH) was added concentrated HCl (5 mL). The reaction mixture was heated at reflux under N_2 for 16 h. The volatile component was removed under reduced pressure, and the residue was purified by column chromatography on silica gel (hexanes/EtOAc = 10/1) to give (*R*)-**12** as a colorless oil in 85% yield: $[\alpha]_D$ = 95.0 (c = 0.962, THF); ^{1}H NMR (270 MHz, $CDCl_3$) δ 7.96 (s, 2H), 7.91 (d, J = 8.0 Hz, 2H), 7.25−7.38 (m, 6H), 7.12 (d, J = 2.5 Hz, 2H), 6.96 (s, 2H), 6.94 (d, J = 2.7 Hz, 2H), 6.32 (s, 2H), 3.99 (t, J = 6.5 Hz, 4H), 3.92 (t, J = 6.7 Hz, 4H), 1.81 (m, 4H), 1.63 (m, 4H), 1.49 (m, 4H), 1.33−1.40 (m, 8H), 1.21−1.28 (m, 4H), 1.11−1.26 (m, 8H), 0.93 (t, J = 6.9 Hz, 6H), 0.76 (t, J = 6.9 Hz, 6H); ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 154.10, 150.36, 149.95, 133.75, 131.02, 129.27, 129.17, 129.11, 128.26, 126.55, 124.97, 123.72, 118.52, 116.67, 115.16, 114.94, 70.75, 68.76, 31.72, 31.52, 29.47, 29.34, 25.86, 25.56, 22.74, 22.51, 14.18, 14.05; FT-IR (cm^{-1}) 3530 (m), 2930 (s), 2870 (s); MS (DIP) m/z 839 (M + H$^+$). Anal. Calcd for $C_{56}H_{70}O_6$: C, 80.19; H, 8.35. Found: C, 79.89; H, 8.80.

A Typical Experimental Procedure for the Diethylzinc Addition to Aldehydes Catalyzed by Monomer (*R*)-12. Under nitrogen, to a Schlenk flask containing toluene (10 mL, dried, and degassed with N_2) were added (*R*)-**12** (42 mg, 0.05 mmol) and Et_2Zn (0.21 mL, 2.0 mmol) at room temperature. After the colorless solution was stirred for ca. 15 min, the flask was cooled to 0 °C, and benzaldehyde (0.1 mL, 1.0 mmol) was added dropwise. The solution turned yellow, which then faded in 4 h, indicating the completion of the reaction. HCl (1 N) was added to quench the reaction at 0 °C, and the aqueous layer was extracted with the diethyl ether. The combined organic layer was washed with brine until pH = 7 and then dried over anhydrous Na_2SO_4. HPLC analysis of the crude product on a Chiracel-OD column (eluent: 2-propanol/hexane = 1/9 at 1 mL/min) showed an ee of >99%. The crude product was purified by column chromatography on silica gel with EtOAc/hexanes (1:5) to give (*R*)-1-phenyl-1-propanol as a colorless liquid (129 mg, 95%). HPLC analysis showed the same ee as that of the crude product.

A Typical Experimental Procedure for the Dimethylzinc Addition to Aldehydes Catalyzed by Monomer (*R*)-12. To a Schlenk flask were added toluene (10 mL, dried, and degassed with N_2), (*R*)-**12** (42 mg, 0.05 mmol), and Me_2Zn (0.14 mL, 2 mmol). The mixture was stirred at room temperature for 15 min and then cooled to 0 °C. 2-Naphthaldehyde (160 mg, 1 mmol) was added, and the resulting mixture was stirred at 0 °C for 80 h. Quenching the reaction with 1 N HCl followed by usual workup gave (*R*)-1-(2′-naphthyl)ethanol as a colorless liquid in 86% yield (148 mg). Analysis by HPLC-Chiracel-OD column showed an ee of 92%.

Conditions for the Analysis of the Chiral Secondary Alcohol Products from the Dialkylzinc Additions. Chiral Capillary GC: Supelco β- Dex 120 column 30 m × 0.25 mm (i.d.), 0.25 μm film. Carrier gas: He (1.05 mL/min). Detector: FID, 280 °C. Injector: 220 °C.

Chiral HPLC: Chiracel OD or Chiracel AD column, 254 nm UV detector. The solvents used were hexane/2-propanol = 9/1 at 1.0 mL/min unless indicated otherwise.

The racemic alcohol products were obtained by either addition of Et_2Zn to aldehydes in the presence of 2-pyridylcarbinol catalyst or addition of EtMgBr or MeMgBr to aldehydes. The retention times of the racemic alcohol products under the given conditions are listed below.

1-Phenyl-1-propanol: t_R = 7.45 min, t_S = 8.80 min (HPLC OD column).

1-(*p*-Methylphenyl)-1-propanol: t_R = 32.18 min, t_S = 34.11 min (GC, 100 to 150 °C, 1 °C/min).

1-(*p*-Methoxyphenyl)-1-propanol: t_R = 8.70 min, t_S = 9.48 min (HPLC AD column).

1-(*p*-Chlorophenyl)-1-propanol: t_R = 6.25 min, t_S = 7.20 min (HPLC OD column).

1-(*m*-Chlorophenyl)-1-propanol. The ee was measured by analyzing its acetate with GC. t_R = 17.46 min, t_S = 16.79 min (135 to 160 °C at 1 °C/min).

1-(*m*-Methoxyphenyl)-1-propanol: t_R = 10.00 min, t_S = 10.73 min (HPLC OD column).

1-(*o*-Fluorophenyl)-1-propanol: t_R = 26.74 min, t_S = 28.02 min (GC, 100 to 140 °C at 1 °C/min).

1-(*o*-Methoxyphenyl)-1-propanol: t_R = 45.73 min, t_S = 44.05 min (GC, 100 to 150 °C at 1 °C/min).

1-(α-Naphthyl)-1-propanol: t_R = 16.08 min, t_S = 8.83 min (HPLC OD column).

1-(*β*-Naphthyl)-1-propanol: t_R = 11.87 min, t_S = 10.40 min (HPLC OD column).

1-(2′-Furyl)-1-propanol. The ee was measured by analyzing its acetate with GC. t_R = 22.23 min, t_S = 21.31 min (80 to 120 °C at 1 °C/min).

3-Octanol. The ee was measured by analyzing its acetate with GC. t_R = 32.03 min, t_S = 30.75 min (60 to 100 °C at 1 °C/min).

3-Nonanol. The ee was measured by analyzing its acetate with GC. t_R = 33.54 min, t_S = 32.43 min (70 to 110 °C at 1 °C/min).

3-Undecanol. The ee was measured by analyzing its acetate with GC. t_R = 28.82 min, t_S = 28.07 min (100 to 140 °C at 1 °C/min).

1-Cyclohexyl-1-propanol. The ee was measured by analyzing its acetate with GC. t_R = 21.00 min, t_S = 20.34 min (100 to 130 °C at 1 °C/min).

5-Methyl-3-hexanol. The ee was measured by analyzing its benzoate with GC. t_R = 48.87 min, t_S = 47.71 min (110 to 135 °C at 0.4 °C/min).

(*E*)-1-Phenyl-1-penten-3-ol: t_R = 9.08 min, = 13.40 min (HPLC OD column).

(*E*)-1-Phenyl-2-methyl-1-penten-3-ol. The ee was measured by analyzing its acetate with GC. t_R = 33.17 min, t_S = 32.26 min (140 °C).

(*E*)-4-Hexen-3-ol: t_R = 20.42 min, t_S = 22.09 min (GC, 60 °C).

5-Methyl-4-hexen-3-ol: t_R = 11.06 min, t_S = 13.88 min (GC, 85 °C).

(*E*)-4-Methyl-4-hexen-3-ol: t_R = 22.46 min, t_S = 26.64 min (GC, 75 °C).

2-(*n*-Butyl)-1-penten-3-ol. The ee was measured by analyzing its acetate with GC. t_R = 23.04 min, t_S = 22.13 min (90 °C).

1-Phenyl-1-pentyn-3-ol: t_R = 7.27 min, t_S = 15.40 min (HPLC OD column).

1-Phenylethanol: t_R = 7.23 min, t_S = 8.08 min (HPLC OD column).

1-**(*β*-Naphthyl)ethanol:** t_R = 24.93 min, t_S = 23.82 min (HPLC OD column, 0.5 mL/min).

2-Nonanol. The ee was measured by analyzing its acetate with GC. t_R = 18.00 min, t_S = 17.20 min (100 to 120 °C at 1 °C/min).

Cryscopic Analysis of the Molecular Weight of (*R*)-36. Under N_2, to a solution of (*R*)-**12** (305 mg, 0.36 mmol) in cyclohexane (7.4 mL) was added Et_2Zn (73 μL, 0.72 mmol). After 10 min at room temperature, the produced ethane was removed by bubbling N_2 through the solution for 5 min. The resulting solution was used for the freezing point measurement. The test tube containing the solution of (*R*)-**36** under N_2 and a thermometer was placed into a beaker filled with saturated NaCl aqueous solution. The beaker was then placed into a −15 °C 2-propanol−dry ice solution. The temperature change of the (*R*)-**36** solution was recorded every 30 s. The measured frozen point is 5.5 °C. According to $\Delta T_f = k_f m$ ($T_f° = 6.7$, $k_f = 20.4$), the measured molecular weight for (*R*)-**36** is 1099.

Preparation and Characterization of (*R*)-3,3′-Bis(2′-methoxy-5′-methylphenyl)-1,1′-bi-2-naphthol, (*R*)-38. To a mixture of (*R*)-**8** (4.06 g, 6.5 mmol), compound **37** (3.00 g, 18.0 mmol), THF (25 mL), and K_2CO_3 (1 M, 35 mL) was added $Pd(PPh_3)_4$ (125 mg). The reaction was complete after reflux for 24 h as shown by ^{1}H NMR spectroscopy. The mixture was then extracted with EtOAc, and the combined organic layer was washed with brine. Evaporation of the solvent gave a solid. Hydrolysis of this solid (6 N HCl/THF, reflux for 12 h) followed by flash chromatography (hexane/ethyl acetate = 8:1) gave (*R*)-**38** as a white amorphous solid in 70% yield (2.40 g) for the two-step reaction: $[\alpha]_D$ = +139.7 (c = 1.01, CH_2Cl_2); UV−vis λ_{max} (CH_2Cl_2, nm) 254, 290, 338; fluorescence λ_{emi} (CH_2Cl_2, nm) (λ_{exc} 338 nm) 387; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.39 (s, 6H), 3.80 (s, 6H), 5.86 (s, 2H), 6.93 (d, J = 8.7 Hz, 2H), 7.21 (dd, J = 8.2, 1.5 Hz, 2H), 7.29−7.37 (m, 8H), 7.89 (d, J = 8.2 Hz, 2H), 7.97 (s, 2H); ^{13}C NMR ($CDCl_3$, 75 MHz) δ 20.74, 56.39, 115.12, 115.58, 123.92, 125.04, 126.76, 127.16, 128.42, 128.88, 129.44, 130.00, 132.96, 133.60, 150.65, 154.76; FT-IR (KBr, cm^{-1}) 3522 (s), 3050 (w), 2924 (m), 2836 (w); MS (EI) (*m*/*z*) 527 (M + H$^+$). Anal. Calcd for $C_{36}H_{30}O_4$: C, 82.11; H, 5.74. Found: C, 82.02; H, 5.88.

Diphenylzinc Addition to Propionaldehyde Catalyzed by Monomer (*R*)-12. To a Schlenk flask were added toluene (5 mL, dried, and degassed with N_2), (*R*)-**12** (42 mg, 0.05 mmol), and Ph_2Zn (132 mg, 0.6 mmol). The mixture was stirred at room temperature for 15 min and then cooled to 0 °C. Propionaldehyde (36 μL, 0.5 mmol) was added, and the resulting mixture was stirred at 0 °C for 20 h. The reaction was quenched with addition of 1 N HCl. Extraction of the aqueous layer with diethyl ether followed by washing the combined organic layer with brine and purifying on silica gel column (eluent: EtOAc/hexanes = 1:5) gave (*S*)-1-phenyl-1-propanol as a colorless liquid in 90% yield (62 mg). Analysis by HPLC-Chiracel OD column showed an ee of 87%.

Diphenylzinc Addition to *p*-Chlorobenzaldehyde Catalyzed by Monomer (*R*)-12. To a Schlenk flask were added diethyl ether (50 mL, dried, and degassed with N_2), (*R*)-**12** (42 mg, 0.05 mmol), and Et_2Zn (10 μL, 0.1 mmol). After the mixture was stirred at room temperature for 15 min, Ph_2Zn (55 mg, 0.25 mmol) was added. Stirring was continued for another 15 min, and then *p*-chlorobenzaldehyde (35 mg, 0.25 mmol) was added. The reaction mixture was stirred at room temperature for 10 h and quenched with 1 N HCl. Usual workup gave (*R*)-(*p*-chlorophenyl)phenylmethanol in 86% yield (47 mg). To a solution of the chiral alcohol (10 mg) in methylene chloride (5 mL) were added acetic anhydride (1 mL), Et_3N (1 mL), and a catalytic amount of 4-(dimethylamino)-pyridine. The mixture was stirred at room temperature for 4 h until TLC indicated the disappearance of the alcohol starting material. The reaction mixture was taken into hexanes (30 mL) and washed with 1 N HCl, brine, aqueous $NaHCO_3$, and brine successively. Evaporation of the solvent gave (*R*)-(*p*-chlorophenyl)phenylmethyl acetate, which was shown to be pure by ^{1}H NMR. Analysis by GC-chiral column showed an ee of 94%.

Diphenylzinc Addition to *trans*-Cinnamaldehyde Catalyzed by Monomer (*R*)-12 with the Addition of Methanol. To a Schlenk flask were added methylene chloride (30 mL, dried, and degassed with N_2), (*R*)-**12** (42 mg, 0.05 mmol), and diethylzinc (20 μL, 0.2 mmol). After the mixture was stirred at room temperature for 15 min, methanol (4 μL, 0.1 mmol) was added. Stirring was continued at room temperature for another 30 min, and diphenylzinc (55 mg, 0.25 mmol) was then added. The resulting solution was heated at reflux to which *trans*-cinnamaldehyde (31.5 μL, 0.25 mmol) was added. Refluxing the reaction mixture for 10 h followed by quenching with 1 N HCl at room temperature and usual workup gave (*S*)-1,3-diphenyl-2-propen-1-ol in 94% yield (49 mg). Analysis by HPLC-Chiracel-OD column showed an ee of 83%.

The Specific Optical Rotations of the Diphenylzinc Addition Products. 1-Phenyl-1-propanol: $[\alpha]_D$ = −40.82 (c = 2.52, $CHCl_3$), 86% ee, *S*.

(*p*-Methoxyphenyl)phenylmethanol: $[\alpha]_D$ = +7.94 (c = 1.63, C_6H_6), 54% ee, *R*; $[\alpha]_D$ = +13.92 (c = 1.86, C_6H_6), 93% ee, *R*.

(*p*-Chlorophenyl)phenylmethanol: $[\alpha]_D$ = −6.00 (c = 0.91, $CHCl_3$), 41% ee, *R*; $[\alpha]_D$ = −7.68 (c = 0.82, $CHCl_3$), 50% ee, *R*; $[\alpha]_D$= −13.86 (c = 0.860, $CHCl_3$), 94% ee, *R*.

(*β*-Naphthyl)phenylmethanol: $[\alpha]_D$ = +5.37 (c = 0.87, C_6H_6), 71% ee, *R*; $[\alpha]_D$= +6.22 (c = 0.76, C_6H_6), 87% ee, *R*.

1,3-Diphenyl-2-propen-1-ol: $[\alpha]_D$ = −12.33 (c = 0.80, CH_2Cl_2), 46% ee, *S*; $[\alpha]_D$ = −29.1 (c = 0.96, CH_2Cl_2), 83% ee, *S*.

Determination of the ee for the Diphenylzinc Addition Products by Chiral HPLC and GC. All ee's were determined by comparing the HPLC data of the chiral products with those of the corresponding racemic alcohols. The latter were obtained from the addition of PhMgBr to aldehydes. Chiral HPLC: Chiracel OD column, hexanes/2-propanol as eluent, 254 nm UV detector.

1-Phenyl-1-propanol: t_R = 22.30 min, t_S = 24.65 min (HPLC, hexanes/2-propanol = 97:3 at 0.5 mL/min).

(*p*-Methoxyphenyl)phenylmethanol: t_R = 15.28 min, t_S = 16.18 min (HPLC, hexanes/2-propanol = 9:1 at 1.0 mL/min).

(*p*-Chlorophenyl)phenylmethanol. The ee was measured by analyzing its acetate on HPLC: t_R = 45.05 min, t_S = 43.57 min (hexanes/2-propanol = 99:1 at 0.2 mL/min).

(*β*-Naphthyl)phenylmethanol: t_R = 21.88 min, t_S = 18.68 min (HPLC, hexanes/2-propanol = 9:1 at 1.0 mL/min).

1,3-Diphenyl-2-propen-1-ol: t_R = 24.62 min, t_S = 18.98 min (HPLC, hexanes/2-propanol = 9:1 at 1.0 mL/min).

Preparation of 4-Bromo-2,5-dihexyloxyphenylboronic Acid 45. To a solution of 1,4-dibromo-2,5-dihexyloxybenzene **9** (8.80 g, 20 mmol) in THF (100 mL) was added *n*-BuLi (8.5 mL, 21.25 mmol, 2.5 M in hexanes) at −78 °C. The mixture was stirred at this temperature for 4 h and was then cannulated to a solution of $B(OEt)_3$ (10 mL) in THF (30 mL) in 30 min at −78 °C. The mixture was allowed to warm to room temporature slowly and stirred for 18 h. A solution of 1 N HCl was then added, and the resulting mixture was extracted with EtOAc. The combined organic layer was washed with brine, saturated $NaHCO_3$, and brine. Evaporation of the solvent gave a solid that was washed with hexane. The solid was redissolved in CH_2Cl_2/EtOAc (1:1) and filtered. Removal of the solvent gave **45** as a white solid in 81% yield (6.48 g): mp 99.5−103.5 °C; UV−vis λ_{max} (CH_2Cl_2, nm) 238, 312; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.92 (m, 6H), 1.34 (m, 8H), 1.48 (m, 4H), 1.82 (m, 4H), 4.02 (t, J = 6.7 Hz, 2H), 4.03 (t, J = 6.4 Hz, 2H), 6.19 (s, 2H), 7.11 (s, 1H), 7.37 (s, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.18, 14.24, 22.72, 22.80, 25.84, 25.86, 29.38, 29.42, 31.64, 31.74, 69.55, 70.18, 116.63, 116.75, 118.54, 120.88, 150.25, 158.29; FT-IR (KBr, cm^{-1}) 3380 (s), 2940 (s), 2857 (m).

Preparation and Characterization of *p*-Triphenylene Dibromide 46. To a mixture of 4-bromo-2,5-dihexyloxyphenylboronic acid **45** (17.0 g, 42.4 mmol), 1,4-diiodobenzene (6.90 g, 21.0 mmol), THF (80 mL), and K_2CO_3 (1 M, 80 mL) was added $Pd(PPh_3)_4$ (300 mg). After being refluxed for 12 h, the reaction mixture was cooled to room temperature and extracted with EtOAc. The combined organic layer was washed with brine. Evaporation of the solvent gave a solid. Flash

chromatography (hexane/ethyl acetate = 20:1) and recrystallization (hexane/EtOAc = 100:1) gave **46** as a white crystalline solid in 60.4% yield (10.0 g): mp 99.5−101.0 °C; UV−vis λ_{max} (CH_2Cl_2, nm) 232, 274, 324; ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.88 (t, J = 7.0 Hz, 6H), 0.92 (t, J = 7.0 Hz, 6H), 1.29 (m, 8H), 1.37 (m, 12H), 1.51 (m, 4H), 1.71 (m, 4H), 1.84 (m, 4H), 3.91 (t, 6.5 Hz, 4H), 4.02 (t, J = 6.4 Hz, 4H), 6.96 (s, 2H), 7.18 (s, 2H), 7.57 (s, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.21, 14.25, 22.77, 22.81, 25.88, 29.29, 29.46, 31.60, 31.74, 69.72, 70.44, 111.50, 116.57, 118.38, 129.15, 130.66, 150.03, 150.65; FT-IR (KBr, cm^{-1}) 2940 (s), 2870 (s). Anal. Calcd for $C_{42}H_{60}Br_2O_4$: C, 63.96; H, 7.67. Found: C, 63.72; H, 7.54.

Preparation and Characterization of *p*-Triphenylene Diboronic Acid 44. To a solution of the *p*-triphenylene dibromide **46** (9.2 g, 11.7 mmol) in THF (120 mL) at −78 °C was added *n*-BuLi(15 mL, 2.5 M in hexane, 37.5 mmol). The mixture was stirred at this temperature for 2 h and was then cannulated to a solution of $B(OEt)_3$ (20 mL) in THF (50 mL). The mixture was then warmed to room temperature and stirred for another 22 h. HCl (1 N) was added. Filtration gave a white solid. The solid was washed with H_2O and EtOAc. Recrystallization from DMSO (**44** was soluble in hot DMSO, but has very low solubility in DMSO at room temperature) gave **44** as a white solid in 88% yield (7.4 g). Diboronic acid **44** was converted to its ester derivative by reaction with 2,2-dimethyl-1,3-propandiol in refluxing benzene and then characterized: mp 90.0−91.5 °C; IR (KBr, cm^{-1}) 2953 (s), 2932 (s), 2870 (s); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.90 (m, 12H), 1.07 (s, 12H), 1.29 (m, 8H), 1.36 (m, 12H), 1.50 (m, 4H), 1.70 (m, 4H), 1.79 (m, 4H), 3.81 (s, 8H), 3.96 (m, 8H), 6.93 (s, 2H), 7.25 (s, 2H), 7.61 (s, 4H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.23, 14.29, 22.14, 22.79, 22.91, 25.95, 25.97, 29.54, 29.75, 31.68, 31.87, 31.97, 69.53, 70.08, 72.61, 116.01, 120.20, 129.13, 133.73, 137.47, 150.26, 157.93; MS *m/e* (DIP) 855 ($M + H^+$).

Preparation and Characterization of Polymer (*R*)-43. To a mixture of (*R*)-**8** (5.0 g, 8.0 mmol), **44** (6.20 g, 8.6 mmol), THF (50 mL), and 1 M K_2CO_3 (50 mL) under nitrogen was added $Pd(PPh_3)_4$ (60 mg). After the mixture was heated at reflux for 36 h until the ^{1}H NMR spectrum showed the disappearance of the iodide end group signals, 4-*tert*-butylbromobenzene (0.5 mL, 2.9 mmol) was added to the mixture to cap the polymer chain by reacting with the boronic acid end groups. The mixture was heated at reflux for another 5.5 h and then cooled to room temperature. Ethyl acetate was added to extract, and the combined organic layer was washed with brine. Evaporation of the solvent gave a yellow residue that was redissolved in methylene chloride and precipitated with methanol. This procedure was repeated three times. After the residue was dried under vacuum, a polymer was obtained as a yellow solid in 94% yield (7.55 g): GPC M_w = 24 000 and M_n = 12 200 (PDI = 1.97); $[\alpha]_D$ = −140.98 (c = 1.00, CH_2Cl_2). Hydrolysis of this polymer in 6 N HCl/THF at reflux under nitrogen for 17 h gave (*R*)-**43** in 96% yield: $[\alpha]_D$ = −92.9 (c = 1.01, CH_2Cl_2); UV−vis λ_{max} (CH_2Cl_2, nm) 234, 276, 338; GPC (relative to polystyrene standard) M_w = 25 800 and M_n = 14 300 (PDI = 1.80); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.77 (t, J = 7.0 Hz, 6H), 0.89 (m, 6H), 1.17 (m, 8H), 1.32 (m, 20H), 1.46 (m, 4H), 1.68 (m, 4H), 1.79 (m, 4H), 4.01 (m, 8H), 6.49 (s, 2H), 7.14 (s, 2H), 7.23 (s, 2H), 7.31 (m, 2H), 7.38 (m, 4H), 7.72 (s, 4H), 7.96 (d, J = 8.0 Hz, 2H), 8.05 (s, 2H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.16, 14.25, 22.63, 22.81, 25.69, 25.98, 29.47, 29.50, 31.64, 31.66, 69.62, 71.00, 116.84, 117.00, 117.57, 123.94, 125.14, 126.74, 128.01, 128.39, 129.17, 129.31, 129.42, 131.17, 131.47, 133.88, 137.09, 150.04, 150.52, 151.30; IR (KBr, cm^{-1}) 3528 (s), 3055 (w), 2928 (s), 2859 (s); CD (CH_2Cl_2) $[\theta]_\lambda$ = -8.72×10^4 (343 nm), 8.59×10^3 (305 nm), -2.66×10^3 (290 nm), 1.10×10^5 (258 nm), -1.87×10^5 (235 nm), and 4.63×10^4 (221 nm). Anal. Calcd for $(C_{62}H_{72}O_6)_n$: C, 81.54; H, 7.95. Found: C, 81.40; H, 8.00.

A Typical Procedure for the Reaction of Dialkylzincs with Aldehydes in the Presence of Polymer (*R*)-43. Under nitrogen, to a solution of (*R*)-**43** (50 mg, 0.05 mmol) in toluene (4 mL) was added diethylzinc (0.21 mL, 2.0 mmol) at room temperature. After being stirred for 10 min, the solution was cooled to 0 °C, and benzaldehyde (0.10 mL, 1.0 mmol) was added. The resulting mixture was stirred for 5 h, and the reaction was monitored by TLC. A 100% conversion of benzaldehyde was observed. Then, 1 N HCl was added to quench the reaction. The mixture was extracted with diethyl ether, and the combined organic layer was washed with brine, $NaHCO_3$, and brine. After evaporation of the solvent, the residue was redissolved in methylene chloride and precipitated with methanol. The polymer was recovered by filtration, and the solution was concentrated under vacuum. The product was purified by flash chromatography on silica gel to give (*R*)-1-phenylpropanol as a colorless oil in 95% yield (120 mg). HPLC analysis of the product on an Chiracel-OD column (eluent: 2-propanol/hexane = 3:97) showed 98% ee. The recovered polymer was redissolved in methylene chloride and filtered. The solution was reprecipitated with methanol. After two more dissolution and precipitation steps and vacuum-drying, (*R*)-**43** was obtained in over 95% yield.

Diphenylzinc Addition to *p*-Anisaldehyde in the Presence of Polymer (*R*)-43. (A double slow addition technique for the polymer-catalyzed diphenylzinc addition reaction was applied). To a Schlenk flask containing toluene (15 mL, dried, and degassed with N_2) were added the polymer (*R*)-**43** (92 mg, 0.1 mmol based on the repeating unit) and diethylzinc (20 μL, 0.2 mmol). After being stirred at room temperature for 20 min, the reaction mixture turned to a gel. Diphenylzinc (55 mg, 0.25 mmol) was then added, and the above mixture became more viscous. More diethylzinc (60 μL, 0.6 mmol) was added to convert the viscous gel into a cloudy yellowish solution. Another Schlenk flask containing toluene (15 mL) was charged with *p*-anisaldehyde (35 mg, 0.25 mmol). Both the Zn−polymer complex solution and the aldehyde solution were added from two syringes simultaneously into a flask containing toluene (20 mL) at −30 °C within 20 h via a syringe pump. After the addition, stirring was continued for an additional 36 h at −30 °C. Quenching the reaction with 1 N HCl followed by usual workup gave (*R*)-(*p*-methoxyphenyl)phenylmethanol in 72% yield (39 mg). Analysis by HPLC-Chiracel-OD column showed an ee of 92%.

General Procedure for the Reduction of Ketones with Catecholborane in the Presence of Polymers (*S*)-4 and (*R*)-43 or the Monomer (*R*)-12. To a Schlenk flask containing toluene (10 mL, dried, and degassed with N_2) was added monomer (*R*)-**12** (42 mg, 0.05 mmol), polymer (*S*)-**4** (32 mg, 0.055 mmol, based on the repeating unit), or (*R*)-**43** (50 mg, 0.055 mmol) and diethylzinc (10 μL, 0.1 mmol) under N_2 at room temperature. After the mixture was stirred at room temperature for 20 min, acetophenone (0.12 mL, 1 mmol) was added. The resulting mixture was then cooled to −30 °C, and catecholborane (1.5 mmol, 1.5 mL, 1 M in THF) was added. After being stirred at this temperature for 48 h, the reaction was quenched with 1 N HCl and the aqueous layer was extracted with diethyl ether. The combined organic layer was washed with brine until pH = 7 and then dried over anhydrous Na_2SO_4. Concentration with rotary evaporator gave a yellow oil. When monomer (*R*)-**12** was used, purification by flash column chromatography on silica gel with EtOAc/hexanes (1:5) gave the product. When polymer (*S*)-**4** or (*R*)-**43** was used, precipitation by addition of methanol to the yellow oil recovered the polymer. The product was then purified by column chromatography on silica gel.

The Specific Optical Rotations of the Chiral Alcohol Products Obtained from Reduction of Ketones. (*S*)-1-Phenylethanol: $[\alpha]_D$ = −40.6 (c = 2.04, CH_2Cl_2) [lit.[55] $[\alpha]_D$ = −52.5 (c = 2.27, CH_2Cl_2), *S*].

(*S*)-1-(*p*-Methoxyphenyl)ethanol: $[\alpha]_D$ = −40.6 (c = 1.12, $CHCl_3$) [lit.[56] $[\alpha]_D$ = 52.1 (c = 1, $CHCl_3$), 87% ee, *R*].

(*S*)-1-(*p*-Bromophenyl)ethanol: $[\alpha]_D$ = −24.6 (c = 1.26, MeOH) [lit.[57] $[\alpha]_D$ = 32.9 (c = 1.39, MeOH), 99.3% ee, *R*].

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(*S*)-1-(*o*-Bromophenyl)ethanol: $[\alpha]_D = -37.8$ ($c = 1.06$, $CHCl_3$) [lit.[58] $[\alpha]_D = 54$ ($c = 1$, $CHCl_3$), *R*].

(*S*)-1-(β-Naphthyl)ethanol: $[\alpha]_D = -24.8$ ($c = 1.36$, EtOH) [lit.[59] $[\alpha]_D = 41.3$ ($c = 5.0$, EtOH), *R*].

(*S*)-4-Phenyl-3-buten-2-ol: $[\alpha]_D = -30.2$ ($c = 1.21$, $CHCl_3$) [lit.[60] $[\alpha]_D = -32.16$ ($c = 5$, $CHCl_3$), 81% ee, *S*].

(*R*)-2-Chloro-1-phenylethanol: $[\alpha]_D = -4.87$ ($c = 1.29$, cyclohexane) [lit.[61] $[\alpha]_D = 49.6$ ($c = 2.81$, cyclohexane), 96.5% ee, *S*].

(*R*)-2-Methyl-1-phenyl-1-propanol: $[\alpha]_D = 2.61$ ($c = 0.31$, Et_2O) [lit.[62] $[\alpha]_D = 47.7$ ($c = 1.0$, Et_2O), *R*].

(*S*)-2-Methyl-3-heptanol: $[\alpha]_D = -8.86$ ($c = 1.06$, EtOH) [lit.[63] $[\alpha]_D = -15.5$ ($c = 10$, EtOH), 56% ee, *S*].

GC and HPLC Analyses of the Chiral Alcohol Products from the Asymmetric Reduction of Ketones. Conditions for the GC analysis: Chiral capillary GC. Supelco β-Dex 120 column 30 m × 0.25 mm (i.d.), 0.25 mm film. Carrier gas: He (1.0 mL/min).

Conditions for the HPLC analysis: Chiracel OD column. 254 nm UV detector. Method A. Hexane/2-propanol = 9:1 at 1.0 mL/min. Method B. 0.5 mL/min.

The GC retention times of the *R* and *S* enantiomers:

1-Phenylethanol: $t_R = 20.02$ min, $t_S = 20.68$ min (100 to 150 °C at 1 °C/min).

2-Methyl-3-heptanol. The ee was determined by analyzing its acetate derivative: $t_R = 27.88$ min, $t_S = 27.46$ min (60 to 100 °C at 1 °C/min).

The HPLC retention times of the *R* and *S* enantiomers:

1-(*p*-Methoxyphenyl)ethanol: $t_R = 15.60$ min, $t_S = 16.60$ min (method B).

1-(*p*-Bromophenyl)ethanol: $t_R = 7.53$ min, $t_S = 6.95$ min (method A).

1-(*o*-Bromophenyl)ethanol: $t_R = 6.65$ min, $t_S = 6.97$ min (method A).

1-(β-Naphthyl)ethanol: $t_R = 27.35$ min, $t_S = 26.03$ min (method B).

4-Phenyl-3-buten-2-ol: $t_R = 22.01$ min, $t_S = 28.40$ min (method A).

2-Chloro-1-phenylethanol: $t_R = 8.90$ min, $t_S = 9.52$ min (method A).

2-Methyl-1-phenyl-1-propanol: $t_R = 5.97$ min, $t_S = 6.67$ min (method A).

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