Cationic BINAP-Ru(II) Halide Complexes: Highly Efficient Catalysts for Stereoselective Asymmetric Hydrogenation of α- and β-Functionalized Ketones

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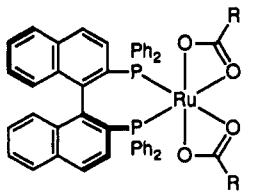
Cationic ruthenium-BINAP complexes **5**, **7**, and **10** of the formula [RuX((*S*)-BINAP)(arene)]Y, where X = Cl, Br, I; Y = Cl, Br, I, BF_4, $B(C_6H_5)_4$; arene = benzene, *p*-cymene, ethyl benzoate, and their enantiomers have been prepared by the reaction of arene-ruthenium halide complexes **4**, **6**, and **9** with (*S*)-BINAP or (*R*)-BINAP. Structures of the complexes were established by spectroscopy, conductivity, and a single-crystal X-ray analysis (**5d**: orthorhombic, $P2_12_12$; a = 20.141(2) Å, b = 18.504(1) Å, c = 12.241(1) Å, V = 4562.0(7) Å^3, Z = 4, R = 0.078 for unique 4177 reflections). BINAP derivatives with various substituents at the para and meta positions of four phenyl rings on phosphorus atoms and their cationic Ru(II) complexes have also been synthesized. These BINAP-Ru(II) complexes have been used as catalysts for the asymmetric hydrogenation of various unsaturated organic compounds such as α- and β-keto esters, allylic alcohols, and α,β-unsaturated carboxylic acids in excellent diastereo- and/or enantioselectivities. Catalytic activities and stereoselectivities depend highly on reaction conditions such as solvent, temperature, and additives. Variation of halogen ligands bound to ruthenium atom and substituents on four phenyl rings of BINAP also have exerted remarkable effects on the efficiency of the catalysis. Asymmetric hydrogenation of methyl (±)-2-(benzamidomethyl)-3-oxobutanoate catalyzed by the species derived from **9c** and 3,5-(^{t}Bu)$_2$-BINAP afforded the corresponding *syn*-(2*S*,3*R*)-**17** in 98% de and 99% ee.

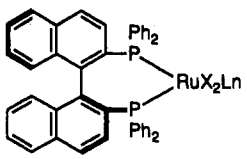
Introduction

In the course of our research in asymmetric catalysis by use of BINAP [BINAP = 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl] as a chiral chelating diphosphine ligand,[1] we found that the BINAP-Ru(II) dicarboxylate complexes of the type $Ru(OCOR)_2$(BINAP) (**1**)[2,3] are highly efficient catalysts for asymmetric hydrogenation of various olefinic substrates.[1,4] Complexes **1**, however, have almost no catalytic activity for hydrogenation of ketones at ambient temperature except for α-amino ketones. Recently, other mononuclear BINAP-Ru(II) complexes have also been reported by Genet *et al.*,[5a] Brown *et al.*,[5b] and Heiser *et al.*,[5c] but it seems that these mononuclear complexes are not always suitable as catalysts for asymmetric hydrogenation of ketones. In contrast, $Ru_2Cl_4(BINAP)_2{\cdot}NEt_3$ (**2**)[6] and complexes described by RuX_2(BINAP) (**3**)[1,7] which were prepared *in situ* by the addition of 2 equiv of HX to complex **1** have been successfully used for the catalytic asymmetric hydrogenation of α- and β-functionalized ketones. Although complexes **3** show high catalytic activity and selectivity, they are usually complicated mixtures of



(*S*)-**1**

a: R = CH_3
b: R = $C(CH_3)_3$
c: R = $C(CH_3)$=$CHCH_3$



(*S*)-**3**

$Ru_2Cl_4(BINAP)_2{\cdot}NEt_3$

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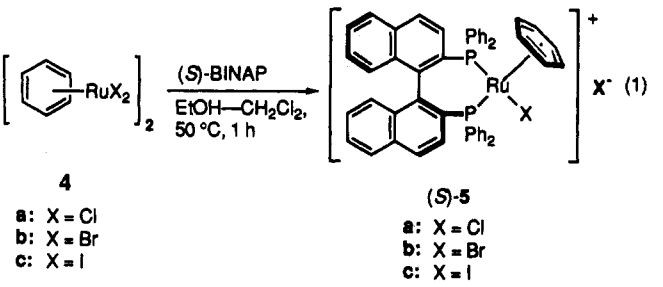
BINAP-Ru(II) species. Complex **2** has fairly low solubility in most common organic solvents. Consequently, we have started to develop a new type of BINAP-Ru(II) complexes bearing halogens bound to ruthenium which can be used conveniently as catalysts and are also suitable for mechanistic studies.[8,9] We report here the preparation and characterization of new mononuclear cationic BINAP-Ru(II)(arene) complexes (**5** and **10**), given in the formula [RuX(BINAP)(arene)]Y (X = halides, Y = anions), which serve as catalysts for asymmetric hydrogenation of *both olefinic and ketonic substrates*.[10] The present complexes can be synthesized easily in high yields and in pure forms. Moreover, these complexes are labile enough to lose the arene ligands to generate catalytically active species under mild reaction conditions. We also investigated the factors that govern catalytic activities and stereoselectivities. Reaction conditions such as solvent, temperature, additives, kind of halogen bound to ruthenium, and substituents on the four phenyl rings of BINAP are found to be all very important.[10b]

Results and Discussion

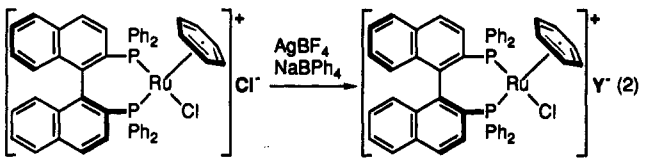
Synthesis and Characterization of Cationic BINAP-Ru(II)-arene Complexes. Treatment of $[RuCl_2(\eta^6\text{-}C_6H_6)]_2$ (**4a**)[11-13] with (*S*)-BINAP in an 8:1 mixture of ethanol-benzene afforded a reddish orange solid of cationic complex (*S*)-**5a** in 90% yield.[14] The conductivity of (*S*)-**5a** in dichloromethane indicated that the complex is monocationic. The absorption observed at δ 5.79 in the ^{1}H NMR spectrum is characteristic of the η^6-coordinated benzene moiety. The ^{31}P{^{1}H} NMR spectrum of (*S*)-**5a** displayed an AB pattern centered at δ 30.3 and 38.3 with a coupling constant (J_{PA-PB}) of 64.6 Hz assignable to the two nonequivalent phosphorus atoms of BINAP. The coordination of benzene to ruthenium makes two phosphorus atoms magnetically nonequivalent, which was further confirmed by X-ray analysis (*vide infra*).[15] When the reaction of **4a** with (*S*)-BINAP was carried out in $CDCl_3$ in the absence of alcohol, one phosphorus atom of BINAP coordinated to ruthenium, while the other remained free (^{31}P{^{1}H} NMR).[16]



4
a: X = Cl
b: X = Br
c: X = I

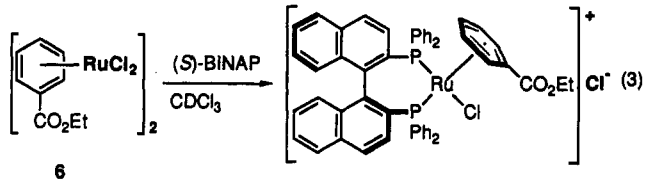
(*S*)-**5**
a: X = Cl
b: X = Br
c: X = I

Treatment of (*S*)-**5a** with $AgBF_4$ in dichloromethane afforded (*S*)-**5d** in quantitative yield. The addition of a solution of $NaBPh_4$ in methanol-benzene to the methanol solution of (*S*)-**5a** gave (*S*)-**5e**. The complex (*S*)-**1a** was also obtained by the reaction of (*S*)-**5a** with sodium acetate.



(*S*)-**5a** (*S*)-**5**
d: Y = BF_4
e: Y = BPh_4

The bromo complex (*S*)-**5b** was prepared by the reaction of **4b** and (*S*)-BINAP. In contrast, the isolation of iodo derivative (*S*)-**5c** was difficult because it released the benzene ligand easily under reaction conditions. Treatment of ruthenium-ethyl benzoate complex **6** with (*S*)-BINAP in $CDCl_3$ gave a mixture of cationic complex (*S*)-**7** and dimeric complex Ru_2Cl_4((*S*)-BINAP)$_2$(PhCOOEt) (**8**). The ^{31}P NMR spectrum of **8** was comparable with that of complex **2**. Complex **7** in $CDCl_3$ gradually decomposed at room temperature.



6 (*S*)-**7**

When ruthenium complex **9a** having *p*-cymene was used as starting complex, (*S*)-**10a** was isolated upon reaction with (*S*)-BINAP. Even the iodide complex (*S*)-**10c** could be isolated in pure form by the reaction of **9c** with (*S*)-BINAP. Complex (*S*)-**10b** was also prepared by a similar treatment of **9b** with (*S*)-BINAP. The *p*-cymene ligand of **10c** remained coordinated to ruthenium even on heating at 60 °C for 1 h.[17] The starting complex **9c** was synthesized by the metathesis reaction of **9a** in the presence of excess amounts of KI in aqueous ethanol and a catalytic amount of a crown ether. Complex **9c** could also be prepared in a mixture of dichloromethane and water (1:1) with excess KI and a catalytic amount of tetraalkylammonium salt.

(8) Recently, Consiglio and Mezzeti reported 2,2'-bis(diphenylphosphino)-6,6'-dimethylbiphenyl-$RuCl_2(PPh_3)$ which is an excellent catalyst for asymmetric hydrogenation of 1,3-diketones: Mezzeti, A.; Consiglio, G. *J. Chem. Soc., Chem. Commun.* **1991**, 1675.

(9) Recently, *in situ* preparation of BINAP-Ru(II) dichloride complexes and their use as catalysts for asymmetric hydrogenation of β-diketones have been reported: (a) See ref 5c. (b) Kitamura, M.; Tokunaga, M.; Ohkuma, T.; Noyori, R. *Tetrahedron Lett.* **1991**, *32*, 4163.

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(14) The formation of the complex (*S*)-**5a** depends on the source of the starting complex **4a**. Since the brownish yellow complex, $[Ru(\eta^6\text{-}C_6H_6)Cl_2]_n$, has poor solubility, the reaction with BINAP ligand in ethanol required a higher temperature (>70 °C) which resulted in the formation of complicated mixture (^{31}P{^{1}H} NMR). Werner, H.; Kletzin, H. *J. Organomet. Chem.* **1982**, *228*, 289.

(15) Similar magnetically nonequivalent phosphine atoms in the ^{31}P{^{1}H} NMR spectrum have been observed for the cyclopentadienyl-Ru complex CpRu(X)(chiral diphosphine). (a) Consiglio, G.; Bangerter, F.; Morandini, F. *J. Organomet. Chem.* **1985**, *293*, C29. (b) Consiglio, G.; Morandini, F. *Chem. Rev.* **1987**, *87*, 761.

(16) Similar complexes of the type $(\eta^6\text{-}C_6R^1_6)RuCl_2PR^2_3$ have been reported.[8,9,12]

(17) Thus, introduction of the electron-withdrawing group made arene labile, while the *p*-cymene moiety of $RuCl_2$(*p*-cymene)(PBu_3) can only be replaced under UV irradiation. Robertson, D. R.; Stephenson, T. A.; Arthur, T. *J. Organomet. Chem.* **1978**, *162*, 121.

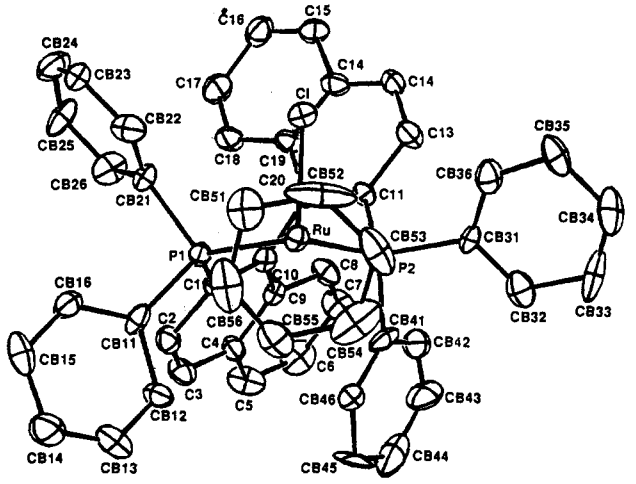


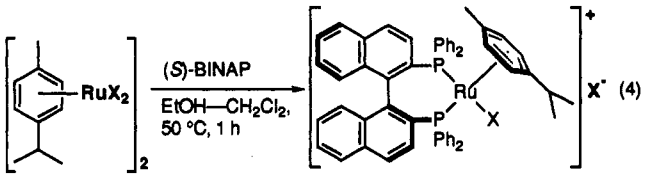
Figure 1. ORTEP drawing of complex (*S*)-**5d** with the numbering scheme.

Table 1. Selected Bond Distances (Å) and Angles (deg) of (*S*)-5d[a]

	(a) Bond Distances (Å)		
Ru-P(1)	2.379(3)	Ru-P(2)	2.334(3)
Ru-Cl	2.393(4)	Ru-C_6H_6	1.770
Ru-CB(51)	2.266(21)	Ru-CB(52)	2.264(30)
Ru-CB(53)	2.275(22)	Ru-CB(54)	2.302(27)
Ru-CB(55)	2.255(19)	Ru-CB(56)	2.278(23)
P(1)-C(1)	1.812(12)	P(1)-CB(11)	1.794(13)
P(1)-CB(21)	1.830(14)	P(2)-C(11)	1.810(12)
P(2)-CB(31)	1.836(12)	P(2)-CB(41)	1.851(14)
	(b) Angles (deg)		
P(1)-Ru-P(2)	91.4(1)	P(1)-Ru-Cl	89.1(1)
P(1)-Ru-C_6H_6	126.3	P(2)-Ru-Cl	84.9(1)
P(2)-Ru-C_6H_6	129.8	Cl-Ru-C_6H_6	122.5

[a] C_6H_6 was the centroid of the η^6-benzene ring.

The structures of **10** were determined by the comparison of the spectral data with those of complexes **5**.



9
a: X = Cl
b: X = Br
c: X = I

(*S*)-**10**
a: X = Cl
b: X = Br
c: X = I

Crystal Structure of [RuCl(C_6H_6)((*S*)-BINAP)]BF_4 [(*S*)-5d]. An ORTEP drawing of the complex (*S*)-**5d** and the labeling scheme are given in Figure 1. Bond distances and angles are given in Table 1. The crystal structure of (*S*)-**5d** consists of well-separated cation and anion with no unusual intermolecular contacts. The dissymmetry of (*S*)-BINAP ligand fixes the δ-conformation of seven-membered chelate ring of (*S*)-**5d** (Figure 2).

The crystal structure also revealed the expected pseudooctahedral geometry around ruthenium. The benzene occupies three coordination sites. The molecule has a piano-stool structure. The distance from ruthenium to the centroid of planar benzene ring is 1.770 Å, which is comparable with the reported data for [RuCl(η^6-toluene)(dppb)]PF_6 (1.772 Å)[18a] but longer than those of [Ru_2(η^6-C_6H_6)$_2$(μ-OH)$_3$]Cl•$3H_2O$ (1.651(5) and 1.638(5) Å).[18b] Bond lengths Ru-P(1) (2.379(3) Å) and Ru-P(2) (2.334(3) Å) are normal and nonequivalent to each other. The bond length Ru-Cl (2.393(4) Å) is also normal. The small deviation of angles P(1)-Ru-P(2) (91.4(1)°), P(1)-Ru-Cl (89.1(1)°), and P(2)-Ru-Cl (84.9(1)°) from 90° indicates that chloride and two phosphorus atoms hold three sites of octahedral ruthenium having *fac*-geometry.

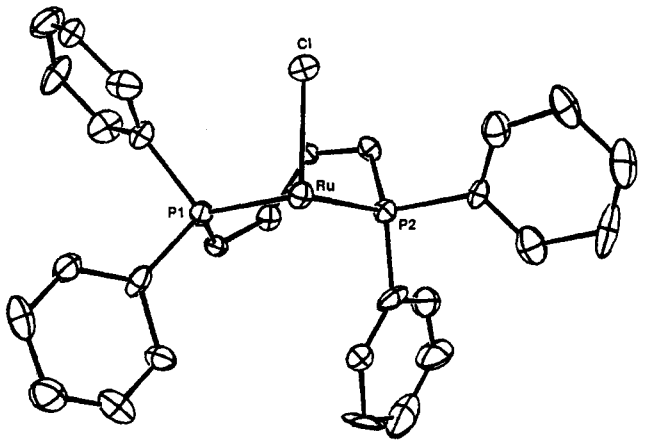
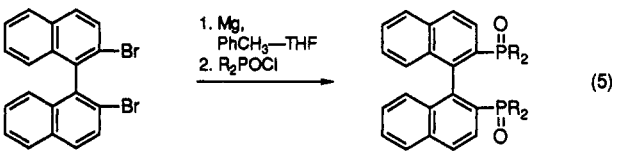


Figure 2. Schematic drawing of chelate ring of complex (*S*)-**5d**.

One of the most interesting feature is the dihedral angle (θ) between the two naphthyl planes. The value of 75.7(2)° for complex (*S*)-**5d** is comparable to those of 71.0(3)–75.5(6)° for cationic rhodium complexes,[19–21] but larger than 66° and 74° for ruthenium complexes **1b** and **1c**,[2,3] which can be ascribed to the presence of two chelating carboxylate ligands of **1**. These facts show that the BINAP ligand is flexible enough to accomodate metal ions under various environments.

Synthesis and Properties of BINAP Derivatives Having Substituents on the Four Phenyl Rings of BINAP. In order to elucidate the electronic and steric effects of substituents on four phenyl rings of BINAP, we synthesized BINAP derivatives with para or meta substituents on four phenyl groups. BINAPO derivatives **11** were prepared by the reactions as shown in eq 5.[22] Optical



(±)-**11**
a: R = 4-$CH_3OC_6H_4$ (*p*-MeO-BINAPO)
b: R = 4-$CH_3C_6H_4$ (*p*-Tol-BINAPO)
c: R = 3-$CH_3C_6H_4$ (*m*-Tol-BINAPO)
d: R = 3,5-$(CH_3)_2C_6H_3$ (3,5-Xylyl-BINAPO)
e: R = 3,5-$(^t Bu)_2C_6H_3$ (3,5-$(^t Bu)_2$-BINAPO)
f: R = 4-FC_6H_4 (*p*-F-BINAPO)
g: R = 4-ClC_6H_4 (*p*-Cl-BINAPO)
h: R = cyclohexyl (Cy-BINAPO)

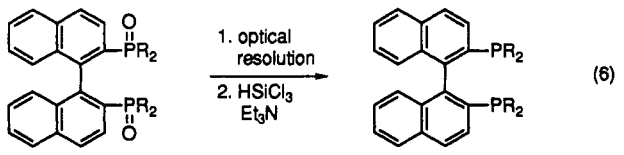
resolution by using (+)-*O,O'*-dibenzoyl-D-tartaric acid and (−)-*O,O'*-dibenzoyl-L-tartaric acid (hereafter (+)- and (−)-DBTA) or (+)-*O,O'*-di-*p*-toluoyl-D-tartaric acid and (−)-*O,O'*-di-*p*-toluoyl-L-tartaric acid (hereafter (+)- and (−)-DTTA) and the following reduction of the resolved BINAPO derivatives by trichlorosilane in the presence of triethylamine afforded almost enantiomerically pure **12a**, **12b**, and **12d–h**. Enantiomerically pure *m*-Tol-BINAP (**12c**) could not be obtained by optical resolution of its phosphine dioxide *m*-Tol-BINAPO (**11c**), but the pre-

Table 2. Asymmetric Hydrogenation of (±)-Methyl 2-(Benzamidomethyl)-3-oxobutanoate (±)-(16)[a,b]

entry	cat.	s/c[c]	solvent	time (h)	H_2 (kg/cm^2)	convn (%)	de[d] (%)	ee[e] (%)	confign
1	(*R*)-**5a**	100	CH_2Cl_2[f]	40	50	91	74	90	2*S*,3*R*
2	(*R*)-**5a**	100	CH_3OH	40	50	100	0	77	2*S*,3*R*
3	(*R*)-**5b**	100	CH_2Cl_2[f]	40	50	91	79	98	2*S*,3*R*
4	(*R*)-**5b**	100	CH_3OH	40	50	95	9	80	2*S*,3*R*
5	(*S*)-**10c**	100	CH_2Cl_2[f]	40	100	100	87	98	2*R*,3*S*
6	(*S*)-**10c**	100	CH_2Cl_2[f]	40	50	98	88	97	2*R*,3*S*
7	(*S*)-**10c**	100	CH_3OH	40	100	100	51	97	2*R*,3*S*
8	(*R*)-**10c**	1000	CH_2Cl_2–CH_3OH[g]	21	50	91	84	99	2*S*,3*R*
9	(+)-**15a**[i]	1000	CH_3OH	20	50	97	67	91	2*S*,3*R*
10	(*S*)-**15b**	1000	CH_3OH[h]	20	50	47	48	95	2*R*,3*S*
11	(−)-**15c**[i]	1000	CH_3OH	20	50	94	67	91	2*R*,3*S*
12	(−)-**15d**[i]	1000	CH_3OH	43	50	73	73	91	2*R*,3*S*
13	(−)-**15d**	1000	CH_2Cl_2–CH_3OH[g]	46	50	72	91	98	2*R*,3*S*
14	(−)-**15d**	100	CH_2Cl_2[f]	40	50	68	95	99	2*R*,3*S*
15	(−)-**15f**[i]	1000	CH_3OH[h]	20	50	20	39	94	2*R*,3*S*
16	(−)-**15g**[i]	1000	CH_3OH[i]	20	50	39	72	96	2*R*,3*S*
17	(+)-**20**[i]	1000	CH_2Cl_2–CH_3OH[g]	40	50	55	98	99	2*S*,3*R*
18	(+)-**20**[i]	500	CH_3OH	20	50	91	92	92	2*S*,3*R*

[a] Hydrogenation was carried out at 50–60 °C in an autoclave. [b] The ratio of solvent and substrate was 4 (v/w). [c] Substrate and catalyst ratio. [d] Diastereoisomeric excess was determined by HPLC analysis (Cosmosil 5SL, eluted with hexane:2-propanol = 9:1, 1 mL/min). [e] Enantiomeric excess of *syn*-17 was determined by HPLC analysis of the (+)-MTPA ester of 17 (Nucleosil 100-3A, eluted with hexane:tetrahydrofuran: methanol = 400:100:1, 1 mL/min). [f] The solvent was saturated with water at −20 °C by addition of 0.5% v/v water to stirred CH_2Cl_2 (distilled from phosphorus pentoxide). [g] The ratio of CH_2Cl_2 to methanol was 7:1. [h] Water (0.5% v/v) was added to methanol. [i] The signs (+) and (−) for the catalysts refer to the optical rotation of the ligand used.

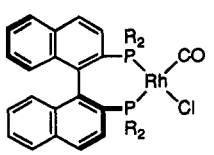
parative HPLC by use of a chiral column gave optically pure *m*-Tol-BINAPO. NMR data of BINAP derivatives are shown in the Experimental Section.



(±)-**11** (*R*)- or (*S*)-**12**

a: R = 4-$CH_3OC_6H_4$ (*p*-MeO-BINAP)
b: R = 4-$CH_3C_6H_4$ (*p*-Tol-BINAP)
c: R = 3-$CH_3C_6H_4$ (*m*-Tol-BINAP)
d: R = 3,5-$(CH_3)_2C_6H_3$ (3,5-Xylyl-BINAP)
e: R = 3,5-$(^t Bu)_2C_6H_3$ (3,5-$(^t Bu)_2$-BINAP)
f: R = 4-FC_6H_4 (*p*-F-BINAP)
g: R = 4-ClC_6H_4 (*p*-Cl-BINAP)
h: R = cyclohexyl (Cy-BINAP)

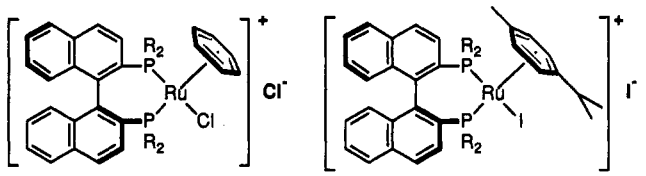
Electronic donor–acceptor properties of BINAP and its derivatives have been investigated by the IR spectral data of the carbonyl stretching frequencies of RhCl(BINAP)-(CO) complexes (**13**)[23] which were prepared by the reaction of $[RhCl(CO)_2]_2$ with BINAP and its derivatives. For comparison the corresponding complex of Cy-BINAP has also been prepared. Results are described in the Experimental Section in addition to ^{31}P and ^1H NMR data. The ν_{CO} values observed for the complexes of BINAP and its derivatives **12a,b**, and **d–g** (2004–2020 cm^{-1}) are higher than that (1990 cm^{-1}) of an alkyl-substituted diphosphine ligand such as Cy-BINAP.



(*S*)-**13**

Moderate linear relationships between the values of ν_{CO} and Hammet σ-values or Kabachnik's σ^{Ph} values[24] of BINAP derivatives were observed. The results indicate that *p*-F-BINAP (**12f**) and *p*-Cl-BINAP (**12g**) have more π-acidic character than BINAP.

Cationic Ru(II) complexes **14** and **15** of BINAP derivatives were also prepared and characterized based on NMR spectroscopy.

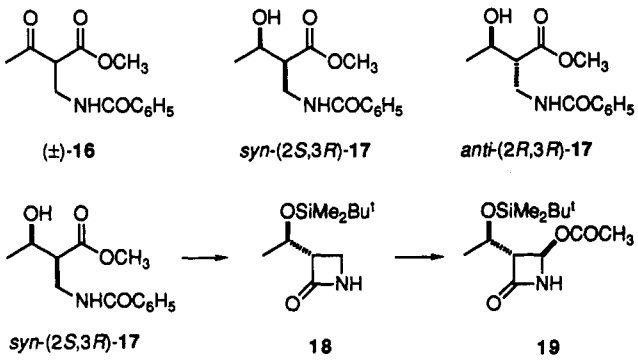


(*S*)-**14** (*S*)-**15**

Asymmetric Hydrogenation of Ketones and Olefins with Cationic BINAP–Ruthenium(II) Complexes as Catalysts. Asymmetric Hydrogenation of Methyl (±)-2-(Benzamidomethyl)-3-oxobutanoate ((±)-16). The efficiency and sense of the enantio- and diastereoselective hydrogenation of 2-substituted 3-oxocarboxylic acid esters are highly influenced by substrate structures, catalysts, and reaction conditions.[1,10a,b,25] An amide, carbamate, or amidomethyl group present in acyclic substrates exhibits high *syn* directivity in dichloromethane.[7] For instance,

(18) (a) Thorburn, I. S.; Rettig, S. J.; James, B. R. *J. Organomet. Chem.* **1985**, *296*, 103. (b) Kim, T. D.; McNeese, T. J.; Rheingold, A. L. *Inorg. Chem.* **1988**, *27*, 2554.
(19) Toriumi, K.; Ito, T.; Takaya, H.; Souchi, T.; Noyori, R. *Acta. Crystallogr.* **1982**, *B38*, 807.
(20) Tani, K.; Yamagata, T.; Tatsuno, Y.; Yamagata, Y.; Tomita, K.; Akutagawa, S.; Kumobayashi, H.; Otsuka, S. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 217.
(21) Yamagata, T.; Tani, K.; Tatsuno, Y.; Saito, T. *J. Chem. Soc., Chem. Commun.* **1988**, 466; **1989**, 67.
(22) Takaya, H.; Mashima, K.; Koyano, K.; Yagi, M.; Kumobayashi, H.; Taketomi, T.; Akutagawa, S.; Noyori, R. *J. Org. Chem.* **1986**, *51*, 629.
(23) Similar complexes have been reported: (a) Hieber, W; Kummer, R. *Chem. Ber.* **1967**, *100*, 148. (b) Sanger, A. R. *J. Chem. Soc., Dalton Trans.* **1977**, *34*, 120. (c) Grimblot, J.; Bonnele, J. P.; Mortreux, A.; Petit, F. *Inorg. Chim. Acta* **1979**, *34*, 29.
(24) Mastryukova, T. A.; Kabachnik, M. I. *Russ. Chem. Rev.* **1969**, *38*, 795.
(25) Recently, the dependence of stereoselectivity obtained by the dynamic kinetic resolution on facility of racemization of the substrates, chirality recognition ability of the catalysts, and the structures of the ketonic substrates has been discussed quantitatively: Kitamura, M.; Tokunaga, M.; Noyori, R. *J. Am. Chem. Soc.* **1993**, *115*, 144.

hydrogenation of methyl 2-(benzamidomethyl)-3-oxobutanoate (**16**) in dichloromethane catalyzed by (*R*)-**2** (substrate/catalyst = 100, 50 °C, H_2 100 kg cm^{-2}, 20 h) afforded (2*S*,3*R*)-**17** in 88% de and 98% ee. Although the reaction proceeded much faster in methanol, only less than 60% de was obtained. Since the *syn*-product, (2*S*,3*R*)-**17**, is a key intermediate to synthesize β-lactams **18** and **19**,[26] we have investigated various factors controlling the catalytic activity and the stereoselectivity of this asymmetric hydrogenation by use of pure samples of cationic BINAP–Ru(II)(arene) complexes which we have synthesized above.[10b] The results are summarized in Table 2.



Solvent effect is important for the diastereoselectivity of the present reaction. When hydrogenation of (±)-**16** was carried out by using **10c** in anhydrous dichloromethane, the reaction proceeded rather slowly (substrate/catalyst = 100, H_2 50 kg cm^{-2}, 50 °C, 40 h, 44% conversion). The presence of a small amount of water (0.5 v/v %) in dichloromethane enhanced the catalyst activity affording **17** in 88% de and 97% ee (entry 6).[27] Use of protic solvent systems, such as methanol or methanol–dichloromethane, also resulted in higher catalytic activity, but much lower diastereoselectivity.

The ratio of *syn*-**17** and *anti*-**17** also depends highly on the kinds of halogen atoms bound to ruthenium. Iodo complex **10c** was, in most cases, superior to chloro complex **5a** or bromo complex **5b** in diastereoselectivity of the reaction in any solvent (entries 1, 3, and 6 or 2, 4, and 7). When Ru(II) complexes bearing BINAP derivatives with a methyl or methoxy group at the para position were used as catalysts for hydrogenation of **16** in methanol, no remarkable changes in catalytic activity and stereoselectivity were observed (entries 9 and 10), while introduction of electronegative substituents in the para position resulted in decreased catalytic activity and stereoselectivity (entries 15 and 16). On the other hand, hydrogenation of **16** in dichloromethane–methanol or hydrous dichloromethane in the presence of a iodoruthenium complex of meta-disubstituted BINAP derivative **15d** brought about remarkable changes in diastereoselectivities, giving *syn*-**17** in 91% de (98% ee) and 95% de (99% ee), respectively (entries 13 and 14). This shows that substituents at the two meta-positions are effective for high diastereoselectivity. Thus, use of the catalytic system **9c**–3,5-(^{t}Bu)$_2$-BINAP (**20**)[28] in dichloromethane–methanol afforded the best result, giving *syn*-**17** in 98% de (99% ee) (entry 17). This procedure has been successfully applied to the industrial production of *syn*-(2*S*,3*R*)-**17** in a scale of 100 tons per year.

Table 3. Asymmetric Hydrogenation of α-Keto Esters (21)[a]

entry	substrate	cat.[b]	additive	S/C	time (h)	convn (%)	ee (%)	confign of **22**
1	**21a**	(*S*)-**5a**		580	95	100	88	*S*
2		(*S*)-**5a**	aq HBF_4	590	70	100	81	*S*
3		(*S*)-**10c**		490	90	100	50	*S*
4	**21b**	(*S*)-**5a**		150	70	100	65	*S*
5		(*S*)-**5a**	aq HBF_4	150	70	100	91	*S*
6	**21c**	(*S*)-**5a**		150	70	100	41	*S*
7		(*S*)-**5a**	aq HBF_4	150	70	100	90	*S*
8	**21d**	(*S*)-**5a**		560	94	100	79	*S*
9		(*S*)-**5a**	aq HBF_4	540	99	100	89	*S*
10		(*S*)-**5a**	H_2O	560	113	92	65	*S*
11		(*S*)-**5a**	Et_3N	520	70	45	11	*S*
12		(*S*)-**5d**		260	68	85	70	*S*
13		(+)-**14g**	aq HBF_4	180	72	100	72	*R*
14		(+)-**14f**	aq HBF_4	580	88	100	80	*R*
15		(+)-**14a**	aq HBF_4	330	90	97	85	*R*
16		(*S*)-**14b**	aq HBF_4	140	70	98	91	*S*
17		(*S*)-**14b**	aq $HClO_4$	260	83	85	90	*S*
18		(*S*)-**14b**	*p*-TsOH	250	114	96	90	*S*
19		(*S*)-**10c**		430	95	100	45	*S*
20	**21e**	(*S*)-**5a**		150	70	44	69	*S*
21		(*S*)-**5a**	aq HBF_4	150	70	82	86	*S*
22	**21f**	(*S*)-**5a**		150	70	100	83	*S*
23		(*S*)-**5a**	aq HBF_4	150	70	100	93	*S*
24	**21g**	(*S*)-**5a**		150	70	100	80	*S*
25		(*S*)-**5a**	aq HBF_4	150	70	100	93	*S*
26	**21h**	(*S*)-**5a**		150	70	100	73	*S*
27		(*S*)-**5a**	aq HBF_4	150	70	100	88	*S*

[a] Hydrogenation was carried out in an autoclave (30 °C) under the initial hydrogen pressure of 100 kg·cm^{-2} unless otherwise stated. [b] The sign (+) means that (+)-ligand was used.

Asymmetric Hydrogenation of α-Functionalized Ketones. In contrast to the fact that BINAP–iodoruthenium complexes are the most suitable catalysts for hydrogenation of **16**, use of BINAP–chlororuthenium complex **5a** afforded the best results for asymmetric hydrogenation of α-keto esters.

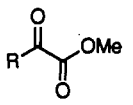
Presented in Table 3 are the results on the hydrogenation of various α-keto esters **21**. Methyl pyruvate (**21a**) was hydrogenated in the presence of (*S*)-**5a** to (*S*)-**22a** in 88% ee (entry 1). When (*S*)-**10c** was used as a catalyst, the ee of (*S*)-**22a** decreased to 50% (entry 3). When the hydrogenation of methyl benzoylformate (**21d**) was carried out by using iodoruthenium complex **10c**, rather low enantioselectivity (45% ee) was obtained (entry 19). On the other hand, hydrogenation of **21d** catalyzed by chlororuthenium complex **5a** afforded **22d** in 79% ee (entry 8).

Enantioselectivity in the hydrogenation of **21d** depended on the additives. When water was added to the catalytic system, enantioselectivity decreased to 65% ee (entry 10). Bases such as triethylamine decreased both catalytic activity and enantioselectivity. By contrast, in the presence of 10 equiv of HBF_4 with respect to the catalyst, **21d** was hydrogenated to **22d** in 89% ee (entry 9).[29] The intervention of a complex bearing a BF_4 anion seems unlikely in view of the fact that the reduction of **21d** by

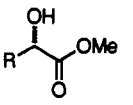
(26) Ruthenium-catalyzed oxidation of β-lactam **18** derived from *syn*-(2*S*,3*R*)-**17** is reported to afford **19** in high regio- and stereoselectivity. Murahashi, S.; Naota, T.; Kuwabara, T.; Saito, T.; Kumobayashi, H.; Akutagawa, S. *J. Am. Chem. Soc.* **1990**, *112*, 7820.

(27) Osborn and Schrock have pointed out that the presence of water in solvent effected on the hydrogenation of ketones by using cationic Rh–phosphine complexes. Schrock, R. R.; Osborn, J. A. *J. Chem. Soc., Chem. Commun.* **1970**, 567.

(28) The 1:1 complex of 3,5-(^{t}Bu)$_2$BINAP and **9c** was used as catalyst since the corresponding complex of the type **10** could not be isolated (see Experimental Section).



21

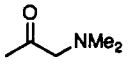


(S)-22

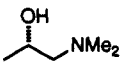
21	(S)-22
a: R = Me	a: R = Me
b: R = *i*-Pr	b: R = *i*-Pr
c: R = *c*-C_6H_{11}	c: R = *c*-C_6H_{11}
d: R = Ph	d: R = Ph
e: R = 4-MeO(C_6H_4)	e: R = 4-MeO(C_6H_4)
f: R = 4-Me(C_6H_4)	f: R = 4-Me(C_6H_4)
g: R = 4-Cl(C_6H_4)	g: R = 4-Cl(C_6H_4)
h: R = 4-NO_2(C_6H_4)	h: R = 4-NO_2(C_6H_4)

using **5d** as a catalyst gave **22d** only in 70% ee (entry 12). Acids such as $HClO_4$ and *p*-toluenesulfonic acid can also be used as additives for catalytic hydrogenation of **21d**, and high enantioselectivity (91% ee) was obtained (entries 17 and 18).

In contrast to the above observation, iodoruthenium complexes have an advantage over chloride complexes in the asymmetric hydrogenation of *N,N*-dimethylamino ketone **23**, one of the α-functionalized ketones. In the presence of (*S*)-**10c** as catalyst, hydrogenation of **23** gave (*S*)-1-(*N,N*-dimethylamino)-2-propanol ((*S*)-**24**) in 99% ee.

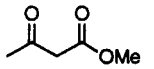


23

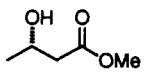


(S)-24

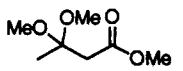
Asymmetric Hydrogenation of Other β-Functionalized Ketones. Catalytic hydrogenation of methyl 3-oxobutanoate (**25**) was also examined, and the results are summarized in Table 4. When **25** was hydrogenated in the presence of (*S*)-**5a** in methanol under hydrogen (99–100 kg/cm^2), methyl (*S*)-3-hydroxybutanoate [(*S*)-**26**] was obtained in 97–99% ee. The dimethyl acetal of methyl 3-oxobutanoate (**27**) was formed as a byproduct in 1–3% yield (entries 1 and 2). Complexes (*S*)-**5c** and (*S*)-**10c** were also employable as catalysts. In contrast, the *p*-cymene complex **10a** was inactive even at elevated temperature (60 °C) (entries 5 and 6), which might be attributed to the high stability of complex **10a** under the reaction condition. The highest enantioselectivity (99% ee) has been accomplished by use of iodide complexes (*S*)-**5c** and (*S*)-**10c** (entries 3 and 7). The formation of the dimethyl acetal of **25** was suppressed by the addition of water (5% v/v) to the reaction mixture (entry 8). Use of dichloromethane instead of methanol as solvent at higher temperature (50 °C) also prevented the formation of dimethyl acetal, giving (*S*)-**26** in 98% ee, though the presence of a trace amount of water in dichloromethane was important for the high conversions (entry 9). Hydrogenation of **25** in the presence of **10c** at much lower pressure of hydrogen (3 kg·cm^{-2}) also afforded high enantioselectivity (98% ee) (entry 10).



25

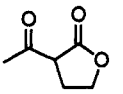


(S)-26

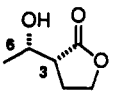


27

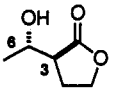
The iodoruthenium complex (*S*)-**10c** was also found to be the best catalyst for the hydrogenation of (±)-**28** and (±)-**30** (H_2 100 kg cm^{-2}, 40 h), affording *syn*-(3*R*,6*S*)-**29** (in CH_2Cl_2–MeOH, 98% de, 97% ee) and *anti*-(1*S*,2*S*)-**31** (in CH_2Cl_2 containing <1% of water, 98% de, 95% ee), respectively.[30]



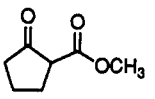
(±)-28



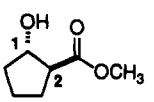
syn-(3*R*,6*S*)-29



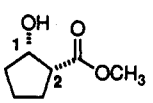
anti-(3*S*,6*S*)-29



(±)-30

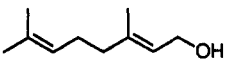


anti-(1*S*,2*S*)-31

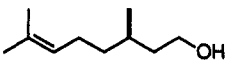


syn-(1*S*,2*R*)-31

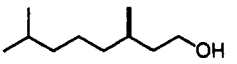
Asymmetric Hydrogenation of Olefinic Substrates. Some of the above complexes were also used as catalysts for the asymmetric hydrogenation of olefinic substrates (Table 5). Geraniol (**32**) was hydrogenated in the presence of (*S*)-**10c** to (*R*)-citronellol [(*R*)-**33**] in 96% ee, which is comparable to the results obtained with 1.[4b] (*R*)-Dihydrocitronellol [(*R*)-**34**] which arises from further reduction of the double bond at C(7) was obtained in 0.3% yield. Tiglic acid (**35**) and 2-(6-methoxy-2-naphthyl)propenoic acid (**37**) were converted to (*S*)-2-methylbutanoic acid [(*S*)-**36**] (89% ee) and (*S*)-naproxen [(*S*)-**38**] (96% ee), respectively. These results are also comparable to those given by complex **1a**.[4c]



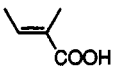
32



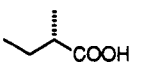
(*R*)-33



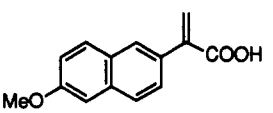
(*R*)-34



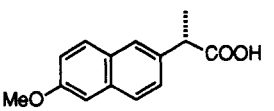
35



(*S*)-36



37



(*S*)-38

The *in Situ* Preparation and Use of the Catalytic Species Derived from Complex 9c and BINAP. A mixture of **9c** and BINAP in dichloromethane–methanol can be used, without further purification, as a catalyst for asymmetric hydrogenation of **25** (98% ee, Table 4, entry 11). This method is considered to be applicable to the asymmetric hydrogenation of various substrates.[31] Combinations of **9c** and other bidentate phosphine ligands,

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(30) Kitamura, M.; Ohkuma, T.; Tokunaga, M.; Noyori, R. *Tetrahedron: Asymmetry* **1990**, *1*,1.

(31) Review: Morrison, J. D., Ed. *Asymmetric Synthesis*; Academic Press: New York, 1985; p 5.

Table 4. Asymmetric Hydrogenation of Methyl 3-Oxobutanoate (25)

entry	cat.	solvent	s/c	H_2 (kg/cm^2)	temp (°C)	time (h)	yield (%)	ee (%)	confign
1	(*S*)-**5a**	MeOH	1950	100	55	24	100	96	*S*
2		MeOH	3000	99	20	50	73	97	*S*
3	(*S*)-**5c**	MeOH	2400	100	20	24	100	99	*S*
4	(*S*)-**5d**	MeOH	3000	89	20	92	*g*	98	*S*
5	(*S*)-**10a**	MeOH	2000	89	20	55	0		
6		MeOH	2000	101	60	22	0.4		
7	(*S*)-**10c**	MeOH	2500	100	30	35	97	99	*S*
8		MeOH–H_2O[a]	2200	100	30	48	100	98	*S*
9		CH_2Cl_2[b]	2100	100	50	48	100	98	*S*
10		MeOH–CH_2Cl_2–H_2O[c]	610	3	30	90	100	98	*S*
11	(*S*)-BINAP + **9c**[d]	MeOH–CH_2Cl_2[e]	2200	100	30	40	100	98	*S*
12	(*S,S*)-Chiraphos + **9c**[d]	MeOH–CH_2Cl_2[e]	260	90	50	40	16		
13	(*R,S*)-BPPFOH + **9c**[d]	MeOH–CH_2Cl_2[e]	270	95	30	40	60	79	*R*
14	(*S,R*)-BPPFOAc + **9c**[d]	MeOH–CH_2Cl_2[e]	110	90	30	65	53	59	*S*
15	(–)-**15a**[f]	MeOH–CH_2Cl_2[e]	1900	92	30	40	100	94	*S*
16	(*S*)-**15b**	MeOH–CH_2Cl_2[e]	2200	89	30	40	100	97	*S*
17	(+)-**15e**[f]	MeOH–CH_2Cl_2[e]	2100	100	30	39	83	93	*R*
18	(–)-**15f**[f]	MeOH–CH_2Cl_2[e]	2440	85	30	40	100	97	*S*
19	(+)-**15g**[f]	MeOH–CH_2Cl_2[e]	1400	85	30	40	81	93	*R*

[a] 5% (v/v) of water was added to methanol. [b] 5% (v/v) of water was added to CH_2Cl_2. [c] MeOH–CH_2Cl_2–H_2O (65:30:5). [d] The mixture of 2 equiv of the ligand and **9c** in MeOH–CH_2Cl_2 (3:1) was used as catalyst without further purification. Formation of the diphosphine–RuI_2 species has been confirmed by ^{31}P NMR analysis. [e] MeOH–CH_2Cl_2 (3:1). [f] The signs (+) and (–) mean that (+)- and (–)-ligands were used, respectively. [g] The yield was not determined.

Table 5. Asymmetric Hydrogenation of Olefinic Substrates 32, 35, and 37

sub.	cat.	solvent	s/c	H_2 (kg/cm^2)	temp (°C)	time (h)	yield (%)	ee (%)	confign
32	(*S*)-**10c**	MeOH–H_2O	1900	100	20	8	90	96[a]	*R*
35	(*S*)-**5d**	MeOH	1000	4	20	92	89	89[b]	*S*
37	(*S*)-**10c**	MeOH	200	116	–20	17	94	96[c]	*S*

[a] The enantiomeric excess was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:ether = 7:3, 1 mL/min) of the (+)-MTPA ester of citroneric acid derived from Jones oxidation of the product. [b] Enantiomeric excess was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:ether = 8:2, 1 mL/min) of the amide derived from condensation of the product and 1-(1-naphthyl)ethylamine. [c] Enantiomeric excess was determined by HPLC analysis (CHIRALCEL OD, eluted with hexane:2-propanol = 99:1, 1 mL/min, UV 272 nm) of the methyl ester of (*S*)-naproxen derived from the treatment of the product with diazomethane.

such as Chiraphos, BPPFOH, and BPPFOAc were also tested as catalysts for hydrogenation of **25** (Table 4). The easy preparation of catalytic species *in situ* from arene–ruthenium complexes **9** and chiral diphosphines allows us to use chiral diphosphine–Ru(II) complexes as catalysts for asymmetric reactions more conveniently than before.[32]

Conclusion

We have synthesized a series of new cationic BINAP–Ru(II) complexes of the type [RuX(BINAP)(arene)]Y which proved to be excellent catalysts for asymmetric hydrogenation of β-keto esters including methyl 2-(benzamidomethyl)-3-oxobutanoate, α-keto esters, and functionalized olefins. These complexes were also used for the elucidation of various factors controlling the catalytic activities and stereoselectivities in the asymmetric hydrogenation of ketonic substrates.

Experimental Section

General. Nuclear magnetic resonance [^1H (400 MHz and 270 MHz), ^{13}C (100 MHz and 68 MHz), and ^{31}P (161 MHz and 36 MHz) NMR] spectra were measured on JEOL JNM-GX400, JEOL EX-270, and JEOL FX-99 spectrometers. Other spectra were recorded by the use of the following instruments: IR, Hitachi 295, and Horiba FT-300; low- and high-resolution mass spectra, JEOL D300 (70 eV); gas chromatographic (GLC) analyses, Shimadzu GC-15A and Hitachi 263-30 equipped with a flame ionization detector; conductivity,[33] Horiba DS-8F; HPLC analyses, Shimadzu LC-4A and TOSOH CCPM equipped with CO-8000 injection unit and UV-8000 detector; optical rotation, JASCO DIP-360. Elemental analyses were performed at Elemental Analysis Laboratory, Institute for Molecular Science, and at Elemental Analysis Center, Kyoto University. All melting points were measured in sealed tubes and were not corrected.

2,2′-Bis(diphenylphosphino)-1,1′-binaphthyl (BINAP),[22] 2,2′-bis(dicyclohexylphosphino)-1,1′-binaphthyl (Cy-BINAP),[34a] 2,2′-bis[bis(*p*-methoxyphenyl)phosphino]-1,1′-binaphthyl (*p*-MeO-BINAP),[34b] and 2,2′-bis[di(*p*-tolyl)phosphino]-1,1′-binaphthyl (*p*-Tol-BINAP)[22] were synthesized by the method previously reported. Bis(4-chlorophenyl)phosphinic acid,[35a] bis(4-fluorophenyl)phosphinic acid,[35b] and bis(3-methylphenyl)phosphinic acid[35c] were prepared according to the previously reported methods. Methyl (4-X-phenyl)glyoxylates (X = NO_2, Cl, Me, and OMe) were prepared according to literature.[36] The complex $[RuX_2(C_6H_6)]_2$ was prepared according to the known procedure.[11] Chiraphos, (*R,S*)-BPPFOH, and (*S,R*)-BPPFOAc were obtained from Strem Chemical Inc. Silver tetrafluoroborate was obtained from Aldrich Chemical Co. Sodium tetraphenylborate was obtained from Wako Pure Chem. Ind., Ltd. 1,3-Hexadiene and *p*-mentha-1,5-diene were obtained from Tokyo Kasei Co., Ltd. All manipulations involving air- and moisture-sensitive organometallic compounds were carried out by the use of the standard Schlenk technique under argon atmosphere purified by passing through a BASF-catalyst R3-11 column. Dichloromethane, toluene, and benzene were purified by distillation under argon after drying over calcium hydride. Dichloromethane was also dried over P_2O_5. Methanol and ethanol were dried over magnesium alkoxide. THF and ether were dried over sodium benzophenone ketyl.

Preparation of [RuCl((*S*)-BINAP)(C_6H_6)]Cl [(*S*)-5a]. To a 200-mL Schlenk tube charged with (*S*)-BINAP (0.81 g, 1.3 mmol) and red brown $[RuCl_2(C_6H_6)]_2$ (0.33 g, 0.66 mmol) were added ethanol (150 mL) and benzene (20 mL). The mixture was

(32) For other examples of *in situ* preparation of chiral Ru(II) complexes, see: (a) Taber, D. F.; Silverberg, L. J.; Robinson, E. D. *J. Am. Chem. Soc.* **1991**, *113*, 6639. (b) Taber, D. F.; Silverberg, L. J. *Tetrahedron Lett.* **1991**, *32*, 4227.

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(35) (a) Doak, G. O.; Freedman, L. D. *J. Am. Chem. Soc.* **1951**, *73*, 5658. (b) Bost, R. W.; Quin, L. D.; Roe, A. *J. Org. Chem.* **1953**, *18*, 362. (c) Freedman, L. D.; Doak, G. O. *J. Org. Chem.* **1959**, *24*, 638.

(36) Muller, A. J.; Nishiyama, K.; Griffin, G. W.; Ishikawa, K.; Gibson, D. M. *J. Org, Chem.* **1982**, *47*, 2342.

stirred at 50–55 °C for 45 min. The resulting orange yellow solution was filtered through a Celite pad to remove a small amount of precipitated materials. The bright yellow filtrate was concentrated under reduced pressure to give (*S*)-**5a** as a yellow solid (1.14 g, 90% yield) which contained ethanol as crystal solvent: mp 114–125 °C dec; ^{31}P NMR ($CDCl_3$) δ 30.3 (d, J = 64.6 Hz), 38.3 (d, J = 64.6 Hz); ^{1}H NMR ($CDCl_3$) δ 5.79 (s, 6H) (signals due to aromatic protons of BINAP are omitted); ^{13}C NMR ($CDCl_3$) δ 97.0 (signals due to carbons of BINAP are omitted); Λ_0 (CH_2Cl_2) 68 S cm^2/mol (25 °C). Anal. [$C_{50}H_{38}Cl_2P_2Ru(C_2H_5OH)_2$] C, H. When complex **5a** was crystallized from a mixture of dichloromethane and hexane, it contained dichloromethane as crystal solvent.

Preparation of [RuBr((*S*)-BINAP)(C_6H_6)]Br [(*S*)-5b]. A mixture of (*S*)-BINAP (0.62 g, 1.0 mmol) and red brown [$RuBr_2(C_6H_6)]_2$ (0.37 g, 0.55 mmol) in a mixture of methanol (40 mL) and benzene (20 mL) was stirred at 50–55 °C for 40 min. A small amount of solids suspended in the orange yellow solution was removed by filtration through a Celite pad. Removal of all volatiles under reduced pressure afforded (*S*)-**5b** as a yellow solid which contained 2 mol of methanol as crystal solvent (0.94 g, 92% yield): mp 96–105 °C dec; ^{31}P NMR ($CDCl_3$) δ 29.8 (d, J = 61.0 Hz), 37.1 (d, J = 61.0 Hz); ^{1}H NMR ($CDCl_3$) δ 5.83 (s, 6H) (signals due to aromatic protons of BINAP are omitted); ^{13}C NMR ($CDCl_3$) δ 96.9 (signals due to carbons of BINAP are omitted); Λ_0 (CH_2Cl_2) 78 S cm^2/mol (25 °C). Anal. Calcd for $C_{50}H_{38}Br_2P_2Ru(CH_3OH)_2$: C, 60.89; H, 4.35. Found: C, 60.11; H, 4.38.

Preparation of [RuI((*S*)-BINAP)(C_6H_6)]I [(*S*)-5c]. To a mixture of (*S*)-BINAP (0.850 g, 1.36 mmol) and red brown [$RuI_2(C_6H_6)]_2$ (0.591 g, 1.36 mmol) placed in 80-mL Schlenk tube were added ethanol (20 mL) and dichloromethane (40 mL) at room temperature. The reaction mixture was vigorously stirred at 50 °C for 3 h. A dark red solution obtained by filtration through a Celite pad was concentrated under reduced pressure to give (*S*)-**5c** as red solids contaminated with unidentified complexes (1.11 g, 77% yield estimated as **5c**): ^{31}P NMR ($CDCl_3$) δ 28.2 (d, J = 61.0 Hz), 36.1 (d, J = 61.0 Hz); ^{1}H NMR ($CDCl_3$) δ 5.90 (s, 6H) (signals due to aromatic protons of BINAP are omitted).

Preparation of [RuCl((*S*)-BINAP)(C_6H_6)]BF_4 [(*S*)-5d]. To a suspension of $AgBF_4$ (0.14 g, 0.72 mmol) in dichloromethane (10 mL) was added a solution of [RuCl((*S*)-BINAP)(C_6H_6)]Cl (0.58 g, 0.66 mmol) in the same solvent (20 mL). The reaction mixture was stirred vigorously for 30 min at room temperature. Precipitates were removed by filtration by the aid of a Celite pad to give a clear brown solution, from which (*S*)-**5d** (0.61 g, 99% yield) was obtained as a brown yellow solid after removal of the solvent *in vacuo*, mp 171–177 °C dec; ^{31}P NMR ($CDCl_3$) δ 29.8 (d, J = 64.6 Hz), 37.8 (d, J = 64.6 Hz); ^{1}H NMR ($CDCl_3$) δ 5.59 (s, 6H) (signals due to aromatic protons of BINAP are omitted); ^{13}C NMR ($CDCl_3$) δ 96.7 (signals due to carbons of BINAP are omitted). Analytically pure sample crystallized from a mixture of dichloromethane and hexane has a dichloromethane as crystal solvent. Anal. [$C_{50}H_{38}ClBF_4P_2Ru(CH_2Cl_2)$] C, H.

Preparation of [RuCl((*S*)-BINAP)(C_6H_6)]$B(C_6H_5)_4$ [(*S*)-5e]. To a solution of $NaBPh_4$ (0.04 g, 0.12 mmol) in methanol (10 mL) and benzene (2 mL) was added a solution of [RuCl((*S*)-BINAP)(C_6H_6)]Cl (0.09 g, 0.10 mmol) in methanol (5 mL). An orange solid of the complex (*S*)-**5e** (0.09 g, 80% yield) precipitated immediately. After the supernatant liquid was removed, recrystallization of the residue from a mixture of dichloromethane and ether (1:1) gave (*S*)-**5e** (0.06 g, 51% yield) as orange crystals which contain 1 mol of dichloromethane per molecule of (*S*)-**5e** as crystal solvent: mp 162–165 °C dec; ^{31}P NMR ($CDCl_3$) δ 30.2 (d, J = 62.6 Hz), 37.9 (d, J = 62.6 Hz); ^{1}H NMR ($CDCl_3$) δ 4.96 (s, 6H) (signals due to aromatic protons of BINAP are omitted); ^{13}C NMR ($CDCl_3$) δ 96.5 (signals due to carbons of BINAP are omitted). Anal. [$C_{74}H_{58}ClBP_2Ru(CH_2Cl_2)$] C, H.

Preparation of Ru(OCOCH$_3$)$_2$((*S*)-BINAP) [(*S*)-1a] from [RuCl((*S*)-BINAP)(C_6H_6)]Cl [(*S*)-5a]. To a mixture of [RuCl((*S*)-BINAP)(C_6H_6)]Cl [(*S*)-**5a**] (0.20 g, 0.23 mmol) in THF (40 mL) was added sodium acetate (0.13 g, 1.03 mmol), and the mixture was heated at 50 °C for 12 h. All volatiles were removed under reduced pressure, and the residue was extracted with dichloromethane (15 mL, twice). Concentration of the combined extracts afforded (*S*)-**1a** (0.18 g, 95% yield) as a yellow solid which was contaminated with a small amount of RuHCl((*S*)-BINAP)$_2$ (about 5% based on ^{31}P NMR analysis). ^{31}P NMR and ^{1}H NMR spectra of (*S*)-**1a** were superimposable with those of the authentic sample.[2]

Preparation of [$RuCl_2(C_6H_5COOC_2H_5)]_2$ (6). To $RuCl_3$·hydrate (1.03 g, 3.94 mmol) in 90% ethanol (80 mL) at room temperature was added (ethoxycarbonyl)-2,5-cyclohexadiene (4.29 g, 28.2 mmol). The solution was stirred at 50 °C for a period of 6 h. Complex **6** (1.04 g, 82% yield) was obtained after the solution was allowed to stand at room temperature for 3 days: mp 160–170 °C dec; ^{1}H NMR ($CDCl_3$) δ 1.42 (t, 3H, J = 6.93 Hz), 4.47 (q, 2H, J = 6.93 Hz), 5.78 (m, 2H), 5.98 (t, 1H, J = 5.61 Hz), 6.47 (d, 2H, J = 6.27 Hz). Anal. [$(C_{18}H_{20}Cl_4O_4Ru_2)(H_2O)_2$] C, H.

Reaction of [$RuCl_2(C_6H_5COOC_2H_5)]_2$ (6) with (*S*)-BINAP. To a mixture of (*S*)-BINAP (0.18 g, 0.29 mmol) and red brown **6** (0.09 g, 0.13 mmol) placed in an 80-mL Schlenk tube were added ethanol (60 mL) and dichloromethane (20 mL). The reaction mixture was stirred at 50 °C for 40 min. The resulting orange yellow solution was filtered through a Celite pad, and then the filtrate was concentrated under reduced pressure to afford a mixture of complex (*S*)-**7** and dimeric complex **8** (0.22 g, 81% combined yield, estimated as **7**). When a solution of (*S*)-BINAP and **6** in $CDCl_3$ was kept at 50 °C for 10.5 h, only **8** was formed. ^{31}P NMR of **8** exhibited ABq and ^{1}H NMR spectrum showed the presence of two kinds of methyl protons assignable to free ethyl benzoate and the coordinated ethyl benzoate. **8**: ^{31}P NMR ($CDCl_3$) δ 59.1 (d, J = 40.3 Hz), 54.0 (d, J = 40.3 Hz); ^{1}H NMR ($CDCl_3$) δ 1.25 (t, 3H, J = 7.10 Hz), 4.40 (q, 2H, J = 7.10 Hz), 5.7–8.1 (m, 37H).

Preparation of [RuCl((*S*)-BINAP)(*p*-cymene)]Cl [(*S*)-10a]. To a mixture of (*S*)-BINAP (0.53 g, 0.85 mmol) and red brown [$RuCl_2$(*p*-cymene)]$_2$ (0.29 g, 0.47 mmol) placed in a Schlenk tube were added ethanol (60 mL) and dichloromethane (20 mL). The mixture was stirred at 50 °C for 1 h and then filtered through a Celite pad. The resulting orange yellow solution was concentrated under reduced pressure to afford (*S*)-**10a** (0.77 g, 97% yield) as a yellow brown solid which contained dichloromethane as crystal solvent: mp 120–125 °C dec; ^{31}P NMR ($CDCl_3$) δ 24.5 (d, J = 62.6 Hz), 41.2 (d, J = 62.6 Hz); ^{1}H NMR ($CDCl_3$) δ 0.99 (d, 3H, J = 7.02 Hz), 1.34 (d, 3H, J = 7.02 Hz), 1.83 (s, 3H), 3.02 (m, 1H) (signals due to aromatic protons of BINAP and *p*-cymene are omitted); ^{13}C NMR ($CDCl_3$) δ 18.9, 21.6, 22.8, 30.1, 85.7, 96.1, 104.3, 105.9, 111.1, 112.4 (signals due to carbons of BINAP are omitted); Λ_0 (CH_2Cl_2) 68 S cm^2/mol (25 °C). Anal. [$C_{54}H_{46}Cl_2P_2Ru(CH_2Cl_2)_{0.5}$] C, H.

Preparation of [RuBr((*S*)-BINAP)(*p*-cymene)]Br [(*S*)-10b]. A mixture of (*S*)-BINAP (0.23 g, 0.37 mmol) and [$RuBr_2$(*p*-cymene)]$_2$ (0.15 g, 0.38 mmol) in a mixture of ethanol (60 mL) and dichloromethane (20 mL) was stirred at 50 °C for 1 h. The bright yellow solution obtained by filtration through a Celite pad was concentrated under reduced pressure to afford (*S*)-**10b** (0.37 g, 97% yield) as a yellow brown solid: mp 88–95 °C dec; ^{31}P NMR ($CDCl_3$) δ 24.7 (d, J = 60.7 Hz), 41.0 (d, J = 60.7 Hz); ^{1}H NMR ($CDCl_3$) δ 0.98 (d, 3H, J = 7.02 Hz), 1.32 (d, 3H, J = 7.02 Hz), 1.99 (s, 3H), 3.14 (m, 1H) (signals due to aromatic protons of BINAP and *p*-cymene are omitted); ^{13}C NMR ($CDCl_3$) δ 19.1, 21.0, 23.8, 30.1, 86.3, 95.1, 104.5, 105.1, 112.0, 112.7 (signals due to carbons of BINAP are omitted); Λ_0 (CH_2Cl_2) 71 S cm^2/mol (25 °C). Anal. ($C_{54}H_{46}Br_2P_2Ru$) C, H.

Preparation of [RuI((*S*)-BINAP)(*p*-cymene)]I [(*S*)-10c]. To an 80-mL Schlenk tube charged with (*S*)-BINAP (0.27 g, 0.43 mmol) and deep brown [RuI_2(*p*-cymene)]$_2$ (0.23 g, 0.24 mmol) were added ethanol (40 mL) and dichloromethane (20 mL). The reaction mixture was stirred at 50 °C for 1 h. The resulting orange yellow solution was separated from the precipitates by filtration through a Celite pad and concentrated under reduced pressure to afford (*S*)-**10c** (0.45 g, 93% yield) as a brown solid which contains 1 mol of dichloromethane per ruthenium as crystal solvent: mp 95–105 °C dec; ^{31}P NMR ($CDCl_3$) δ 24.7 (d, J = 62.6 Hz), 41.6 (d, J = 62.6 Hz); ^{1}H NMR ($CDCl_3$) δ 0.91 (d, 3H, J = 7.02 Hz), 1.24 (d, 3H, J = 7.02 Hz), 1.92 (s, 3H), 3.28 (m, 1H) (signals due to aromatic protons of BINAP and *p*-cymene are omitted); ^{13}C NMR ($CDCl_3$) δ 20.3, 23.9, 24.5, 30.4, 87.9, 93.4, 102.0, 104.6, 111.2, 115.0 (signals due to carbons of BINAP are

Table 6. Crystal Data and Data Collection Parameters of 5d

formula	$C_{51}H_{40}BCl_3F_4P_2Ru$
formula weight	1009.06
crystl system	orthorhombic
space group	$P2_12_12$
a, Å	20.141(2)
b, Å	18.504(1)
c, Å	12.241(1)
Z	4
V, Å^3	4562.0(7)
D_{calcd}	1.469
radiation	MoKα
reflections measd	$+h, +k, +l$
crystal size, mm	0.22 × 0.48 × 0.58
abs. coeff, cm^{-1}	6.368
scan mode	2θ-θ
temp, °C	25
scan speed, deg/min	3
scan width, deg	1.2 + 0.5 tan θ
bkgd count, sec	8
$2\theta_{max}$, deg	55
unique data	5668
unique data (non-zero)	4691
unique data [$\|F_o\|>3\sigma(F_o)$]	4177
no. of variables	728
R	0.078
R_w	0.093

omitted); Λ_0 (CH_2Cl_2) 61 S cm^2/mol (25 °C). Anal. Calcd for $C_{54}H_{46}I_2P_2Ru(CH_2Cl_2)$: C, 55.22; H, 4.04. Found: C, 54.62; H, 4.04.

X-ray Structure Determination of [RuCl((*S*)-BINAP)-(C_6H_6)]BF_4·CH_2Cl_2[(*S*)-5d]. Bright orange crystals were grown from a mixture of dichloromethane and ether. The pertinent details of data collection and the final cell dimensions, which were obtained from a least-squares refinement of 2θ values of 50 independent reflections in the range of $20° < 2\theta < 30°$, are given in Table 6. The 4177 unique raw intensity data with $|F_o|>3\sigma(F_o)$ were converted to values of the structure factor by correction for Lorentz and polarization effects, and an empirical absorption correction was also applied. Inspection of the standard three reflections measured after every 50 reflections showed no systematic variation in intensity. Correction for extinction effect was not made.[37]

The systematic absence ($h00$) with h = odd and ($0k0$) with k = odd indicated the space group $P2_12_12$. The location of ruthenium atom was determined by the Patterson method. A series of standard block-diagonal least-squares refinements and Fourier syntheses revealed the remaining atoms as an anisotropic temperature factor. Atoms of BF_4 and solvated dichloromethane were located by the difference Fourier synthesis, and they had estimated occupancies because of their disorder form. All hydrogen atoms were placed by the calculated position. All non-hydrogen atoms of [RuCl((*S*)-BINAP)(C_6H_6)]$^+$ as anisotropic and atoms of BF_4, atoms of solvated dichloromethane, and hydrogen atoms as isotropic temperature factor were refined to $R = \Sigma||F_o|-|F_c||/\Sigma|F_o| = 0.078$ and $R_w = [\Sigma w(|F_o|-|F_c|)^2/\Sigma w|F_o|^2]^{1/2} = 0.093$. A weighting scheme, $1/w = \sigma_c^2 + (0.015|F_o|)^2$, was employed. The absolute configuration of the complex was determined by being correlated with the reported configuration of chiral (*S*)-BINAP ligand. Selected bond lengths and angles are listed in Table 1, and atomic positional parameters for the non-hydrogen atoms of complex **5d** are given in Table 7. Crystallographic calculations were performed on IMS Computer Center by using the UNICS-3 program system.

Preparation of Bis(3,5-dimethylphenyl)phosphinic Acid and Bis(3,5-di-*tert*-butylphenyl)phosphinic Acid. To magnesium chips (14.6 g, 0.60 mol) in THF (150 mL) was added dropwise a solution of 1-bromo-3,5-dimethylbenzene (111 g, 0.60 mol) in THF (200 mL) for 2 h. After a solution of $N(Et)_2P(O)Cl_2$ (57.0 g, 0.30 mol) in THF (60 mL) was added for 2 h, the reaction mixture was poured into an ice-cooled solution of NH_4Cl (60 g) in H_2O (1 L). The organic layer was separated, and then the crude product was treated with concd HCl (500 mL) at 80 °C. The resulting powdery product was dissolved in aqueous NaOH solution (17.8 g, 1 L of H_2O), and the aqueous layer was extracted with ether (200 mL, twice). The clear aqueous layer was acidified by the addition of 20% aqueous H_2SO_4. The precipitated phosphinic acid (62.7 g, 76% yield) was collected: mp 261–264 °C; ^{1}H NMR ($CDCl_3$) δ 2.25 (s, 12H), 7.05 (dd, 2H, J = 0.8 and 0.8 Hz), 7.32 (d, 2H, J = 0.8 Hz), 7.35 (d, 2H, J = 0.8 Hz), 12.01(s, 1H); mass spectrum m/z 274 (M^+). Anal. Calcd for $C_{16}H_{19}O_2P$: C, 70.06; H, 6.98. Found: C, 70.64; H, 7.09.

Bis(3,5-di-*tert*-butylphenyl)phosphinic acid has been prepared by similar procedures: mp 232 °C; ^{1}H NMR ($CDCl_3$) δ 1.26 (s, 36H), 7.32 (s, 1H), 7.51 (dd, 2H, J = 1.9 and 1.9 Hz), 7.62 (d, 2H, J = 1.9 Hz), 7.65 (d, 2H, J = 1.9 Hz); ^{31}P NMR ($CDCl_3$) δ 37.47 (s); mass spectrum m/z 442 (M^+). Anal. for $C_{28}H_{43}O_2P$: C, H.

Table 7. Positional Parameters of (*S*)-5d[a]

	X	Y	Z	B_{iso}[b]
Ru	2338(1)	926(1)	7983(1)	2.8
P(1)	2327(2)	−23(2)	6672(2)	2.6
P(2)	2774(2)	1733(2)	6707(3)	2.7
Cl	1282(2)	1319(2)	7313(3)	3.8
C(1)	2739(6)	58(6)	5362(10)	2.6
C(2)	2669(7)	665(6)	4671(9)	2.7
C(3)	3084(6)	704(7)	3684(10)	2.8
C(4)	3065(7)	1321(7)	3000(12)	3.8
C(5)	3498(9)	1400(9)	2089(13)	5.4
C(6)	3916(9)	829(11)	1855(12)	5.6
C(7)	3943(8)	197(10)	2532(12)	5.0
C(8)	3524(7)	135(7)	3424(11)	3.4
C(9)	3553(7)	−476(8)	4080(12)	4.0
C(10)	3149(7)	−536(7)	5004(11)	3.5
C(11)	2258(6)	1807(6)	5502(9)	2.6
C(12)	2185(5)	1230(6)	4773(9)	2.1
C(13)	1647(7)	1236(7)	4004(11)	3.2
C(14)	1505(7)	665(8)	3288(13)	4.3
C(15)	1016(9)	698(9)	2564(14)	5.2
C(16)	564(8)	1311(9)	2526(14)	5.1
C(17)	679(7)	1859(9)	3212(12)	4.2
C(18)	1223(7)	1888(8)	3960(2)	3.7
C(19)	1328(7)	2448(7)	4603(13)	4.1
C(20)	1821(8)	2429(8)	5425(12)	4.0
CB(11)	2720(7)	−799(7)	7265(10)	3.5
CB(12)	3441(7)	−802(8)	7444(12)	3.8
CB(13)	3701(9)	−1342(8)	8063(13)	5.0
CB(14)	3400(9)	−1940(10)	8391(15)	5.7
CB(15)	2683(10)	−1987(8)	8125(13)	5.5
CB(16)	2396(7)	−1434(8)	7590(12)	4.2
CB(21)	1508(7)	−370(7)	6293(11)	3.3
CB(22)	992(7)	−404(8)	7085(13)	4.5
CB(23)	413(6)	−752(7)	6829(12)	3.6
CB(24)	283(8)	−953(11)	5880(15)	5.8
CB(25)	804(9)	−1015(10)	5087(13)	5.5
CB(26)	1386(8)	−686(9)	5274(12)	4.7
CB(31)	2820(6)	2642(6)	7303(9)	2.7
CB(32)	3402(9)	3010(8)	7360(12)	4.9
CB(33)	3421(11)	3728(10)	7856(16)	7.5
CB(34)	2858(10)	4010(9)	8227(12)	6.1
CB(35)	2222(10)	3613(8)	8251(11)	5.2
CB(36)	2272(8)	2946(8)	7784(11)	4.4
CB(41)	3618(6)	1597(9)	6141(12)	3.9
CB(42)	3819(8)	1961(8)	5207(13)	4.4
CB(43)	4378(8)	1933(11)	4654(15)	6.0
CB(44)	4829(10)	1423(13)	5062(17)	8.2
CB(45)	4676(9)	992(12)	6021(27)	11.7
CB(46)	4023(7)	1104(8)	6593(15)	4.4
CB(51)	1868(10)	460(10)	9510(13)	5.6
CB(52)	1915(9)	1192(16)	9649(12)	9.5
CB(53)	2547(11)	1596(9)	9504(12)	6.5
CB(54)	3134(10)	1234(14)	9251(14)	7.9
CB(55)	3098(10)	438(9)	9118(12)	5.2
CB(56)	2498(11)	101(9)	9340(10)	6.4

[a] Positional parameters are multiplied by 10^4. [b] Isotropic temperature factor (Å^2).

(37) The author has deposited atomic coordinates for (*S*)-**5d** with the Cambridge Crystallographic Data Centre. The coordinates can be obtained, on request, from the Director, Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, CB2 1EZ, UK.

Preparation of (±)-*m*-Tol-BINAPO [(±)-11c]. In a 1-L, three-necked, round-bottomed flask equipped with a magnetic stirrer bar, a reflux condenser, and a dropping funnel were placed magnesium chips (6.33 g, 0.264 mol), and the flask was flashed with argon. To this were added iodine (10 mg) and THF (40 mL). The mixture was stirred at room temperature until the color of iodine faded, and to this was added dropwise a solution of 2,2'-dibromo-1,1'-binaphthyl (55.1 g, 0.12 mol) in a mixture of toluene (100 mL) and THF (60 mL) via the dropping funnel over a period of 2 h at 50–70 °C. The reaction mixture was further stirred at 70 °C overnight and then cooled to room temperature. To this was added dropwise a solution of bis(3-methylphenyl)-phosphinyl chloride (66.9 g, 0.25 mol) in toluene (50 mL) during 30 min, holding the temperature at 45 °C, and then water (200 mL) was added. The mixture was extracted with three 100-mL portions of dichloromethane, and the combined organic layers were washed with 10% aqueous NH_4Cl solution (200 mL, twice), 1 N NaOH solution (200 mL, twice), and water (200 mL, twice). The solvent was removed by evaporation, and the resulting residue was recrystallized from a mixture of dichloromethane and toluene (7:3) to give (±)-*m*-Tol-BINAPO [(±)-11c] as the first crop (58.5 g) and the second crop (18.1 g) (89% total yield): mp >300 °C; ^{1}H NMR ($CDCl_3$) δ 2.09 (s, 6H), 2.20 (s, 6H), 6.89–7.82 (m, 28H); ^{13}C NMR ($CDCl_3$) δ 21.28, 125.83–137.69; mass spectrum *m/z* 710 (M^+). Anal. Calcd for $C_{48}H_{40}O_2P_2$: C, 81.11; H, 5.67. Found: C, 79.92; H, 5.98.

The optical resolution of (±)-*m*-Tol-BINAPO [(±)-11c] by using chiral organic acids had been unsuccessful. Racemic *m*-Tol-BINAPO [(±)-11c] (1.0 g) was subjected to preparative HPLC with a column packed with CHIRALCEL OG and eluted with hexane:2-propanol (95:5) (0.4 mL/min) to give (+)-*m*-Tol-BINAPO [(+)-11c] (0.40 g, 80% yield). Optical purity of (+)-*m*-Tol-BINAPO [(+)-11c] was determined to be 99.9% ee by HPLC analysis (CHIRALPAK OP(+) (0.46 cm × 25 cm), MeOH, 1.0 mL/min, t_R = 8.6 min and t_S = 17.0 min).

Preparation of (+)-*m*-Tol-BINAP [(+)-12c]. To a solution of (+)-*m*-Tol-BINAPO [(+)-11c] (0.40 g, 0.56 mmol) and triethylamine (1.13 g, 11.2 mmol) in xylene (20 mL) was added trichlorosilane (1.51 g, 11.2 mmol). The reaction mixture was heated at 100 °C for 1 h, at 120 °C for 1 h, and finally at 140 °C for 1 h. After the mixture was cooled to room temperature, aqueous NaOH (30% v/v, 5 mL) was added. The solution was stirred for 30 min at 50—60 °C. The organic layer was separated, and then the solvent was removed under reduced pressure. Recrystallization from methanol afforded (+)-*m*-Tol-BINAP [(+)-12c] (0.35 g, 92% yield) as a white solid: mp 179–182 °C; $[\alpha]^{25}_D$ +234.1° (*c* 1.00, benzene); ^{1}H NMR ($CDCl_3$) δ 2.12 (s, 6H), 2.14 (s, 6H), 6.75–7.10 (m, 18H), 7.30–7.50 (m, 6H), 7.80–7.90 (m, 4H); ^{13}C NMR (CD_2Cl_2) δ 21.38, 21.49, 126.12–145.96; mass spectrum *m/z* 678 (M^+). Anal. Calcd for $C_{48}H_{40}P_2$: C, 84.93; H, 5.94. Found: C, 85.41; H, 6.22.

Preparation of (±)-3,5-Xylylene-BINAPO [(±)-11d]. Thionyl chloride (35.6 g, 0.299 mol) was added dropwise during 3 h to a suspension of bis(3,5-dimethylphenyl)phosphonic acid (63.0 g, 0.230 mol) in toluene (120 mL) at 50–55 °C. The mixure was cooled to room temperature, filtered though a pad of Celite, and stripped out of the solvent. The resulting oil was poured into hexane (300 mL), and the precipitate was collected. This crude bis(3,5-dimethylphenyl)phosphinyl chloride (51.6 g) obtained as colorless solid was used for the next reaction without further purification. In a 1-L, three-necked, round-bottomed flask equipped with a magnetic stirrer bar, a reflux condenser, and a dropping funnel were placed magnesium chips (3.14 g, 0.129 mol), and the flask was flashed with argon. To this were added 1,2-dibromoethane (0.66 g, 3.55 mmol) and THF (41 mL). The mixture was stirred at room temperature, and to this was added dropwise a solution of 2,2'-dibromo-1,1'-binaphthyl (22.0 g, 53.5 mmol) in a mixture of toluene (340 mL) via the dropping funnel over a period of 2 h at 80–85 °C. The reaction mixture was further stirred at 70 °C for 2 h and then cooled to 40 °C. To this was added dropwise a solution of bis(3,5-dimethylphenyl)-phosphinyl chloride (33.0 g, 0.113 mol) in toluene (35 mL) during 1 h, and the reaction mixture was stirred for another 15 h. Then, the reaction mixture was heated to 110 °C to remove THF. After the mixture was cooled to 60 °C, 0.47% H_2SO_4 (300 mL) was added to the mixture to make it acidic (pH 4). The mixture was stirred for another 30 min. The separated organic layer was washed with water and aqueous 5% $NaCO_3$ and dried over Na_2SO_4. Toluene was removed under reduced pressure to give crude (±)-3,5-xylylene-BINAPO [(±)-11d] (44.6 g). The crude solid was dissolved in toluene (70 mL) at reflux temperature, and to this was added hexane (700 mL). After the mixture was cooled to room temperature, the solid that separated was purified by similar operation to give (±)-3,5-xylylene-BINAPO [(±)-11d] (30.2 g, 74% yield) as a colorless solid: mp 287–290 °C; ^{1}H NMR (CD_2Cl_2) δ 2.09 (s, 12H), 2.28 (s, 12H), 6.80–6.93 (m, 4H), 6.94 (s, 2H), 7.02 (s, 2H), 7.06 (s, 2H), 7.09 (s, 2H), 7.17 (s, 2H), 7.21 (s, 2H), 7.37 (ddd, 2H, *J* = 6.7, 6.7, and 1.3 Hz), 7.51 (dd, 2H, *J* = 11.6 and 8.6 Hz), 7.78–7.82 (m, 4H); ^{13}C NMR (CD_2Cl_2) δ 21.24, 21.29, 126.02–142.83; mass spectrum *m/z* 766 (M^+). Anal. Calcd for $C_{52}H_{48}O_2P_2$: C, 81.44; H, 6.31. Found: C, 81.01; H, 6.65.

Optical Resolution of (±)-3,5-Xylylene-BINAPO [(±)-11d]. (−)-DBTA (14.1 g, 39.4 mmol) and (±)-3,5-xylylene-BINAPO [(±)-11d] (30.2 g, 39.4 mmol) were dissolved in dichloromethane (50 mL) at room temperature. The solvent was evaporated *in vacuo*, and the residue was dissolved in carbon tetrachloride at 70 °C. Ether (1350 mL) was added with stirring. After 12 h, the white solid formed was separated by filtration. The obtained solid was recrystallized from carbon tetrachloride–ether another four times. The separated solid was treated with a mixture of dichloromethane (150 mL) and 1.25 N NaOH (75 mL). The water layer was extracted with dichloromethane (50 mL), and the combined organic layer was dried over Na_2SO_4 and concentrated under reduced pressure to give optically active (−)-3,5-xylylene-BINAPO ((−)-11d, 6.82 g, 22.6%): $[\alpha]^{25}_D$ −220.8° (*c* 1.0, $CHCl_3$), 99.5% ee, determined by HPLC analysis of the phosphine oxide, CHIRALCEL OD, eluted by hexane:2-propanol = 9:1, 0.5 mL/min, t_R = 8.3 min and t_S = 11.2 min).

Preparation of (−)-3,5-Xylylene-BINAP [(−)-12d]. A mixture of (−)-3,5-xylylene-BINAPO [(−)-11d] (6.82 g, 8.89 mmol), triethylamine (19.6 g, 0.194 mol), and trichlorosilane (25 g, 0.185 mol) in xylene (80 mL) was heated gradually to 130 °C in 1 h. The mixture was stirred for another 5 h. After the mixture was cooled to 60 °C, 30% NaOH (200 mL) was added to the reaction mixture, and the mixture was stirred at 60 °C for 1 h. The separated organic layer was washed with water and dried over Na_2SO_4. The solvent was removed under reduced pressure, and the residue was purified by column chromatography (SiO_2, eluted by 9:1 mixture of hexane and ethyl acetate) to give (−)-3,5-xylylene-BINAP [(−)-12d] (3.05 g, 46% yield) as colorless solid: $[\alpha]^{25}_D$ −163.7° (*c* 1.00, $CHCl_3$); mp 286–288 °C; ^{1}H NMR (CD_2Cl_2) δ 2.08 (s, 12H), 2.13 (s, 12H), 6.66–6.71 (m, 10H), 6.83 (s, 2H), 6.87 (dd, 2H, *J* = 8.6 and 0.5 Hz), 7.02 (ddd, 2H, *J* = 6.9, 6.9, and 1.3 Hz), 7.39 (ddd, 2H, *J* = 1.3, 6.9, and 7.9 Hz), 7.52 (dd, 2H, *J* = 2.6 and 6.6 Hz), 7.86–7.89 (m, 4H); ^{13}C NMR (CD_2Cl_2) δ 21.27, 21.34, 21.38, 125.99–145.64; mass spectrum *m/z* 734 (M^+). Anal. Calcd for $C_{52}H_{48}P_2$: C, 84.99; H, 6.58. Found: C, 85.91; H, 6.27.

Preparation of (±)-3,5-(^{t}Bu)$_2$-BINAPO [(±)-11e]. Crude bis(3,5-di-*tert*-butylphenyl)phosphinyl chloride was synthesized in a similar manner as described for bis(3,5-dimethylphenyl)-phosphinyl chloride. In a 1-L, three-necked, round-bottomed flask equipped with a magnetic stirrer bar, a reflux condenser, and a dropping funnel were placed magnesium chips (2.11 g, 0.113 mol), and the flask was flashed with argon. To this were added 1,2-dibromoethane (0.574 g, 3.09 mmol) and THF (36 mL). The mixture was stirred at room temperature to make the magnesium activated, and to this was added dropwise a mixture of 2,2'-dibromo-1,1'-binaphthyl (19.2 g, 46.6 mmol) in a mixture of toluene (45 mL) via the dropping funnel over a period of 1.5 h at 80–85 °C. The reaction mixture was further stirred at 85 °C for 2 h and then cooled to 40 °C. To this was added dropwise a solution of bis(3,5-di-*tert*-butylphenyl)phosphinyl chloride (45.0 g, 98.2 mmol) in toluene (45 mL) during 1 h, holding the temperature at 40 °C. The mixture was stirred at 40 °C for 16 h and then at 110 °C (bath temperature) to remove toluene and THF (106 g). After the mixture was cooled to 60 °C, 0.5% H_2SO_4 (300 mL) was added to the reaction mixture to make the mixture acidic (pH 4), and the mixture was stirred at 60 °C for 30 min. The separated organic layer was washed with water, 5% $NaHCO_3$, and water and finally dried over $MgSO_4$. Toluene was removed under reduced pressure to give crude (±)-3,5-(^{t}Bu)$_2$-BINAPO

[(±)-11e] (57.3 g). The crude product was purified by recrystallization from ether and column chromatography (SiO_2, eluted by 6:1 mixture of hexane and ethyl acetate) to give (±)-3,5-(^{t}Bu)$_2$-BINAPO [(±)-11e] (6.39 g, 50% yield):mp 245 °C; ^{1}H NMR ($CDCl_3$) δ 1.10 (s, 36H), 1.18 (s, 36H), 6.81–6.90 (m, 4H), 7.21 (dd, 4H, J = 12.0 and 1.6 Hz), 7.31–7.36 (m, 2H), 7.39 (d, 2H, J = 1.0 Hz), 7.43 (s, 2H), 7.49 (dd, 2H, J = 11.3 and 8.6 Hz), 7.66 (dd, 4H, J = 13.1 and 1.8 Hz), 7.80–7.86 (m, 4H); ^{13}C NMR ($CDCl_3$) δ 31.32, 31.42, 34.88, 34.92, 124.8–150.2; mass spectrum m/z 1104 (M^+). Anal. Calcd for $C_{76}H_{96}O_2P_2$: C, 82.72; H, 8.77. Found: C, 83.15; H, 8.69.

Optical Resolution of (±)-3,5-(^{t}Bu)$_2$-BINAPO [(±)-11e]. (±)-2,2′-Bis[di(3,5-*tert*-butylphenyl)phosphinyl]-1,1′-binaphthyl [(±)-11e] (25.5 g, 23.1 mmol) and (+)-DBTA (8.3 g, 23.2 mmol) were resolved in dichloromethane (50 mL) at room temperature. Solvent was evaporated *in vacuo*, and the residue was dissolved in carbon tetrachloride (164 mL) at 70 °C. To this was added hexane (180 mL) with stirring, and the mixture was cooled to room temperature. After 1.5 h, the white solid formed was separated by filtration. The same operation was carried out five times. The separated solid was treated with a mixture of dichloromethane (100 mL) and 1.25 N NaOH (50 mL). The water layer was extracted with dichloromethane (50 mL), and the combined organic layer was dried over Na_2SO_4. Evaporation of the solvent under reduced pressure gave (+)-3,5-(^{t}Bu)$_2$-BINAPO [(+)-11e] (3.15 g, 12.4%): $[\alpha]^{25}_D$ +63.6° (*c* 1.0, $CHCl_3$).

Preparation of (+)-3,5-(^{t}Bu)$_2$-BINAP [(+)-12e]. A mixture of (+)-3,5-(^{t}Bu)$_2$-BINAPO [(+)-11e] (4.50 g, 4.08 mmol), triethylamine (19.6 g, 193 mmol), and trichlorosilane (25.0 g, 184 mmol) in xylene (55 mL) was heated gradually to 135 °C over a period of 5 h and then kept at this temperature for 4 h. After the mixture was cooled to 60 °C, 30% NaOH (200 mL) was added to the reaction mixture. The separated organic layer was washed with water (twice) and dried over $MgSO_4$. Xylene was removed under reduced pressure to give crude (+)-3,5-(^{t}Bu)$_2$-BINAP [(+)-12e] (3.08 g). The crude product was purified by recrystallization from a mixture of toluene (10 mL) and methanol (100 mL) to give (+)-3,5-(^{t}Bu)$_2$-BINAP [(+)-12e] (3.02 g, 69% yield) as a colorless solid: mp 211 °C; $[\alpha]^{25}_D$ +79.6° (*c* 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 1.11 (s, 36H), 1.14 (s, 36H), 6.70 (d, 2H, J = 8.4 Hz), 6.79 (m, 2H), 6.96 (m, 4H), 7.13–7.20 (m, 8H), 7.25 (m, 2H), 7.53 (dd, 2H, J = 8.5 and 2.5 Hz), 7.77 (d, 2H, J = 8.1 Hz), 7.85 (d, 2H, J = 8.5 Hz); ^{13}C NMR ($CDCl_3$) δ 31.36, 31.47, 34.93, 34.97, 124.9–153.2; mass spectrum m/z 1072 (M^+). Anal. Calcd for $C_{76}H_{96}P_2$: C, 85.19; H, 9.03. Found: C, 84.56; H, 8.78.

Preparation of (±)-*p*-F-BINAPO [(±)-11f]. In a 200-mL, three-necked, round-bottomed flask equipped with a magnetic stirrer bar, a reflux condenser, and a dropping funnel were placed magnesium chips (0.270 g, 11.1 mmol), and the flask was flushed with argon. To this were added THF (45 mL) and iodine (10 mg). The mixture was stirred at room temperature until the color of iodine faded, and then a solution of 2,2′-dibromo-1,1′-binaphthyl (2.24 g, 5.44 mmol) in THF (15 mL) was added via the dropping funnel over a period of 2 h at 50–75 °C. The reaction mixture was further stirred at 70 °C overnight and then cooled to room temperature. To the reaction mixture was added dropwise a solution of bis(4-fluorophenyl)phosphinyl chloride (3.55 g, 13.0 mmol) in THF (10 mL) during 30 min, holding the temperature at room temperature. After the addition was completed, the mixture was further stirred at 65 °C overnight. After removal of solvent, the residue was dissolved in toluene (40 mL), and to this was added water (30 mL). The organic layer was separated, washed successively with 10% aqueous NH_4Cl solution (30 mL, twice), 1 N NaOH solution (30 mL, twice), and water (30 mL, twice), and then dried over Na_2SO_4. The solvent was removed under reduced pressure, and the resulting residue was purified by column chromatography (SiO_2) eluted by a mixture of ethyl acetate, hexane, and dichloromethane (1:3:1), R_f = 0.50 (1:2 mixture of ethyl acetate and hexane). Recrystallization from toluene afforded (±)-*p*-F-BINAPO [(±)-11f] (2.86 g, 72% yield): mp > 250 °C; ^{1}H NMR ($CDCl_3$) δ 6.74 (d, 2H, J = 8.4 Hz), 6.87 (ddd, 2H, J = 1.2, 6.8, and 8.4 Hz), 6.90–7.00 (m, 8H), 7.33–7.42 (m, 8H), 7.68 (ddd, 4H, J = 5.6, 8.4, and 12.0 Hz), 7.85 (d, 2H, J = 8.0 Hz), 7.89 (dd, 2H, J = 1.8 and 8.4 Hz). Anal. ($C_{44}H_{28}F_4O_2P_2$) C, H.

Optical Resolution of (±)-*p*-F-BINAPO [(±)-11f]. A mixture of racemic *p*-F-BINAPO [(±)-11f] (2.39 g, 3.29 mmol) and (−)-DBTA monohydrate (1.24g, 3.30 mmol) in ethyl acetate (90 mL) and chloroform (150 mL) was heated at reflux for a few minutes. All volatiles were removed under reduced pressure. The resulting residue was dissolved in ethyl acetate (10 mL), and the solution was allowed to stand at room temperature. The 1:1 adduct of (−)-*p*-F-BINAPO–(−)-DBTA (2.30 g, 126% yield based on half of racemic *p*-F-BINAPO) was obtained as a colorless solid: mp 200–210 °C dec; $[\alpha]^{28}_D$ −113.6° (*c* 0.50, ethanol). Recrystallization from ethyl acetate (28 mL) gave *p*-F-BINAPO–(−)-DBTA (1.60 g, 88%): mp 202–207 °C dec; $[\alpha]^{29}_D$ −133.1° (*c* 0.52, ethanol). The solution of this complex (1.60 g) in dichloromethane (20 mL) was treated with 1 N NaOH (20 mL) and water (20 mL) and then dried over Na_2SO_4. After removal of the solvent, (−)-*p*-F-BINAPO [(−)-11f] (0.671 g, 56% yield based on half of racemic *p*-F-BINAPO) was obtained as a colorless solid: $[\alpha]^{26}_D$ −140.1° (*c* 1.09, $CHCl_3$). The enantiomeric purity of (−)-*p*-F-BINAPO [(−)-11f] was determined to be 98.9% ee by HPLC analysis (CHIRALCEL OD, eluted with hexane:2-propanol = 95:5, 0.4 mL/min, t_R = 48 min. and t_S = 33 min).

The mother liquor which contained (+)-*p*-F-BINAPO–(−)-DBTA was concentrated to give a solid (1.57 g), which was treated with 1 N NaOH (20 mL) and water (20 mL), and dried over Na_2SO_4. Evaporation of the solvent gave crude (+)-*p*-F-BINAPO [(+)-11f] (1.12 g): $[\alpha]^{27}_D$ +128.8° (*c* 1.04, $CHCl_3$). A mixture of crude (+)-*p*-F-BINAPO [(+)-11f] and (+)-DBTA monohydrate (0.552 g, 1.47 mmol) in ethyl acetate (10 mL) and chloroform (20 mL) was heated at reflux with stirring for a few minutes, and then solvents were removed by evaporation. Recrystallization of the residue from ethyl acetate (30 mL) afforded (+)-*p*-F-BINAPO–(+)-DBTA (1.55 g, 85% yield): $[\alpha]^{25}_D$ +133.5° (*c* 1.29, ethanol). This complex was treated with 1 N NaOH (60 mL), and the mixture was extracted with dichloromethane (20 mL, three times). The combined organic layer was washed with 1 N NaOH (20 mL) and water (20 mL) and then dried over Na_2SO_4. Removal of the solvent gave (+)-*p*-F-BINAPO [(+)-11f] (0.902 g, 75% yield): $[\alpha]^{25}_D$ +141.5° (*c* 1.05, $CHCl_3$). The enantiomeric purity of (+)-*p*-F-BINAPO [(+)-11f] was determined to be 99.8% ee by HPLC analysis.

Preparation of (−)-*p*-F-BINAP [(−)-12f]. A solution of (−)-*p*-F-BINAPO [(−)-11f] (0.955 g, 1.31 mmol), triethylamine (0.7 mL), and trichlorosilane (0.7 mL) in xylene (30 mL) was stirred at 150 °C in a glass pressure bottle for 2 days. After the reaction mixture was cooled to room temperature, 30% aqueous NaOH solution (20 mL) was added to the reaction mixture. The organic layer was separated. The aqueous layer was extracted with two 20-mL portions of xylene. The combined organic layer was washed with 30% aqueous NaOH (20 mL) and water (25 mL, twice) and then dried over Na_2SO_4. The solvent was removed under reduced pressure, and column chromatography (SiO_2, under argon atmosphere) of the resulting residue, eluted by dichloromethane, gave (−)-*p*-F-BINAP [(−)-12f] (0.513 g, 56% yield) as a pale yellow solid (R_f = 0.86, 1:1 mixture of ethyl acetate and hexane): mp 213 °C; $[\alpha]^{27}_D$ −90.6° (*c* 0.755, $CHCl_3$); ^{1}H NMR ($CDCl_3$) δ 6.80 (d, 2H, J = 8.6 Hz), 7.00–7.05 (m, 2H), 7.06–7.23 (m, 8H), 7.35–7.48 (m, 12H), 7.90 (d, 2H, J = 7.9 Hz), 7.95–7.98 (m, 2H); mass spectrum m/z 737 (M^+). Anal. Calcd for $C_{44}H_{28}F_4P_2$: C, 76.08; H, 4.06. Found: C, 74.63; H, 4.12.

Preparation of (±)-*p*-Cl-BINAPO [(±)-11g]. In a 500-mL, three-necked, round-bottomed flask equipped with a magnetic stirrer bar, a reflux condenser, and a dropping funnel were placed magnesium chips (1.04 g, 42.7 mmol), and the flask was flashed with argon. To this were added THF (18 mL) and iodine (25 mg). The mixture was stirred at room temperature until the color of iodine faded, and to this was added dropwise a solution of 2,2′-dibromo-1,1′-binaphthyl (8.31 g, 20.2 mmol) in THF (140 mL) via the dropping funnel over a period of 4 h at 50–75 °C. The reaction mixture was further stirred at 75 °C for 2 h and then cooled to 0 °C. To this solution was added dropwise a solution of bis(4-chlorophenyl)phosphinyl chloride (12.5 g, 41.0 mmol) in THF (15 mL) during 30 min, holding the temperature at room temperature. After the addition was completed, the mixture was further stirred at 60 °C for 2 h and then cooled to room temperature. Toluene (130 mL) and water (100 mL) were added, and the mixture was stirred at 60 °C for 10 min. The

organic layer was separated and washed successively with 10% aqueous NH_4Cl solution (100 mL, twice), 1 N NaOH solution (100 mL, twice), and water (100 mL, twice). The solvent was removed by evaporation, and the residue was purified by column chromatography (ethyl acetate:hexane:dichloromethane = 1:3:1). Recrystallization from toluene gave (±)-*p*-Cl-BINAPO [(±)-**11g**] (13.9 g, 87% yield): mp >250 °C; ^1H NMR ($CDCl_3$) δ 6.77 (d, 2H, *J* = 8.0 Hz), 6.91 (ddd, 2H, *J* = 1.2, 5.6, and 8.4 Hz), 7.20–7.31 (m, 12H), 7.36 (dd, 2H, *J* = 8.4 and 11.6 Hz), 7.43 (ddd, 2H, *J* = 1.2, 7.2, and 8.4 Hz), 7.57 (dd, 4H, *J* = 8.4 and 11.6 Hz), 7.85 (d, 2H, *J* = 8.4 Hz), 7.89 (dd, 2H, *J* = 2.8 and 8.4 Hz); mass spectrum *m/z* 680 ($M^+ - C_6H_4Cl$). Anal. ($C_{44}H_{28}Cl_4O_2P_2$), C, H.

Optical Resolution of (±)-*p*-Cl-BINAPO [(±)-11g]. (−)-DTTA (5.79 g, 15.0 mmol) and racemic *p*-Cl-BINAPO [(±)-**11g**] (11.9 g, 15.0 mmol) were dissolved in dichloromethane (100 mL) at room temperature. Solvent was evaporated *in vacuo*, and the residue was dissolved in a mixture of ethyl acetate (13 mL) and chloroform (13 mL) at 65 °C. After 12 h, the white solid formed was separated by filtration. The obtained solid was recrystallized from ethyl acetate–chloroform for four times. The combined solid was treated with a mixture of chloroform (100 mL) and 1.25 N NaOH (50 mL). The water layer was extracted with chloroform (50 mL), and the combined organic layer was dried over Na_2SO_4. Evaporation of solvents under reduced pressure gave (−)-*p*-Cl-BINAPO [(−)-**11g**] (3.87 g, 33% yield): mp 300 °C; $[\alpha]^{25}_D$ −65.9° (*c* 0.2, CH_2Cl_2).

Preparation of (+)-*p*-Cl-BINAP [(+)-12g]. A solution of (+)-*p*-Cl-BINAPO [(+)-**11g**] (1.12 g, 1.41 mmol), triethylamine (1.0 mL), and trichlorosilane (1.0 mL) in xylene (30 mL) was stirred at 150 °C in a glass pressure bottle for 2 days. To the reaction mixture was added 30% aqueous NaOH solution (20 mL) at room temperature, and then the organic layer was separated. The aqueous layer was extracted with two 20-mL portions of xylene. The combined organic layers were washed with 30% aqueous NaOH (20 mL) and water (25 mL, twice) and then dried over Na_2SO_4. The solvent was removed under reduced pressure, and the residue was purified by column chromatography (under argon atmosphere) eluted with dichloromethane to give (+)-*p*-Cl-BINAP [(+)-**12g**] as a pale yellow solid (1.05 g, 98% yield): mp 220 °C; $[\alpha]^{27}_D$ +64.6° (*c* 0.245, $CHCl_3$); ^1H NMR ($CDCl_3$) δ 6.81 (d, 2H, *J* = 8.6 Hz), 6.90–7.12 (m, 18H), 7.35–7.39 (m, 2H), 7.40–7.46 (m, 2H), 7.87 (d, 2H, *J* = 8.6 Hz), 7.90–7.93 (m, 2H); mass spectrum *m/z* 505 ($M^+ - P(C_6H_4Cl)_2$). Anal. Calcd for $C_{44}H_{28}Cl_4P_2$, C, 69.49; H. 3.71; Found, C, 68.87, H, 4.07.

Physical Data of BINAPO Derivatives 11a–11g, BINAP Derivatives 12a–12g, and Their Rh and Ru Complexes, 13a–13g, 14a–14g, and 15a–15g. ^{31}P NMR ($CDCl_3$): **11a**, δ 29.4; **11b**, 29.8; **11c**, 29.3; **11d**, 28.5; **11e**, 29.7; BINAPO, 30.7; **11f**, 27.0; **11g**, 27.4. ^{31}P NMR ($CDCl_3$): **12a**, δ −16.8; **12b**, −17.2; **12c**, −14.4; **12d**, −14.9; **12e**, −13.4; BINAP, −15.3; **12f**, −17.0; **12g**, −16.8. ^{31}P NMR ($CDCl_3$): **13a**, δ 20.0 (dd, *J* = 45.8 and 132.6 Hz), 42.7 (dd, *J* = 45.8 and 163.0 Hz); **13b**, 23.4 (dd, *J* = 43.6 and 128.2 Hz), 44.6 (dd, *J* = 43.6 and 162.6 Hz); **13d**, 23.1 (dd, *J* = 42.6 and 126.3 Hz), 47.0 (dd, *J* = 42.6 and 162.3 Hz); **13e**, 28.0 (dd, *J* = 45.1 and 131.8 Hz), 48.6 (dd, *J* = 45.1 and 162.3 Hz); RhCl(CO)((*R*)-BINAP), 25.0 (dd, *J* = 43.6 and 129.1 Hz), 46.2 (dd, *J* = 43.6 and 162.6 Hz); **13f**, 22.6 (dd, *J* = 42.8 and 127.5 Hz), 43.1 (dd, *J* = 42.8 and 160.9 Hz); **13g**, 23.4 (dd, *J* = 43.8 and 129.1 Hz), 44.2 (dd, *J* = 43.8 and 161.9 Hz); **13h**, 23.9 (broad d, *J* = 90.1 Hz), 56.6 (broad d, *J* = 167.2 Hz). IR (ν_{CO}) **13a**, 2004; **13b**, 2010; **13d**, 2011; **13e**, 2006; RhCl(CO)((*R*)-BINAP), 2013; **13f**, 2018; **13g**, 2020; **13h**, 1990 cm^{-1}. ^{31}P NMR ($CDCl_3$): **14a**, δ 26.6 (d, *J* = 63.0 Hz), 34.5 (d, *J* = 63.0 Hz); **14b**, 28.9 (d, *J* = 62.6 Hz), 36.7 (d, *J* = 62.6 Hz); **14c**, 29.8 (d, *J* = 63.0 Hz), 37.5 (d, *J* = 63.0 Hz); **14d**, 29.2 (d, *J* = 62.0 Hz), 36.4 (d, *J* = 62.0 Hz); [RuCl(C_6H_6)(BINAP)]Cl, 30.3 (d, *J* = 64.6 Hz), 38.3 (d, *J* = 64.6 Hz); **14f**, 28.1 (d, *J* = 64.0 Hz), 35.0 (d, *J* = 64.0 Hz); **14g**, 28.2 (d, *J* = 64.0 Hz), 35.6 (d, *J* = 64.0 Hz). ^{31}P NMR ($CDCl_3$): **15a**, δ 20.6 (d, *J* = 60.1 Hz), 37.6 (d, *J* = 60.1 Hz); **15b**, 22.7 (d, *J* = 59.6 Hz), 39.2 (d, *J* = 59.6 Hz); **15c**, 24.6 (d, *J* = 60.1 Hz), 40.6 (d, *J* = 60.1 Hz); **15d**, 25.5 (d, *J* = 59.1 Hz), 39.8 (d, *J* = 59.1 Hz); **15e**, 21.6; [RuI(*p*-cymene)(BINAP)]I, 24.7 (d, *J* = 60.6 Hz), 41.6 (d, *J* = 60.6 Hz); **15f**, 22.9 (d, *J* = 60.5 Hz), 38.7 (d, *J* = 60.5 Hz); **15g**, 23.7 (d, *J* = 60.1 Hz), 39.4 (d, *J* = 60.1 Hz).

Asymmetric Hydrogenation of (±)-Methyl 2-(Benzamidomethyl)-3-oxobutanoate [(±)-16]. A mixture of methyl 2-(benzamidomethyl)-3-oxobutanoate [(±)-**16**] (15.0 g, 0.06 mol) and [RuI((−)-*m*-tol-BINAP)(*p*-cymene)]I [(−)-**15c**] (170 mg, 0.06 mmol) in methanol (75 mL) was charged on an autoclave. Hydrogen was introduced (50 kg/cm^2), and the mixture was stirred at 50 °C for 20 h. After hydrogen pressure was released, removal of the solvent afforded crude products (15.1 g). Two products, *syn*- and *anti*-isomers of methyl 2-benzamido-3-hydroxybutanoate (**17**), were isolated by column chromatography on silica gel eluted by hexane–2-propanol (85:15). Conversion (94%) was determined by HPLC analysis, and the ratios of two diastereoisomers (*syn*-(2*S*, 3*R*)-**17**:*anti*-(2*R*, 3*R*)-**17** = 83.5:16.5) were determined by HPLC analysis (Cosmosil 5SL, hexane:2-propanol = 9:1).

anti-(2*R*,3*R*)-**16**: ^1H NMR ($CDCl_3$) δ 1.26 (d, 3H, *J* = 6.25 Hz), 2.60–2.64 (m, 1H), 3.57–3.62 (m, 1H), 4.00–4.03 (m, 1H), 3.73 (s, 3H), 4.08–4.14 (m, 1H), 7.27 (broad s, 1H), 7.41–7.45 (m, 2H), 7.49–7.53 (m, 1H), 7.77–7.80 (m, 1H). *syn*-(2*S*,3*R*)-**16**: ^1H NMR ($CDCl_3$) δ 1.30 (d, 3H, *J* = 6.28 Hz), 2.84–2.86 (m, 1H), 3.74 (s, 3H), 3.71–3.77 (m, 1H), 3.85–3.91 (m, 1H), 4.09–4.14 (m, 1H), 6.92 (broad s, 1H), 7.40–7.44 (m, 2H), 7.48–7.50 (m, 1H), 7.74–7.76 (m, 1H).

Preparation of the Catalytic System 9c–3,5-(^{t}Bu)$_2$-BINAP (20) and Its Use in the Asymmetric Hydrogenation of (±)-Methyl 2-(Benzamidomethyl)-3-oxobutanoate [(±)-16]. The cationic iodoruthenium complex of 3,5-(^{t}Bu)$_2$-BINAP similar to **10c** could not be prepared by the standard procedure.[10a] However, heating a 2:1 mixture of the ligand (0.42 g, 0.39 mmol) and **9c** (0.19 g, 0.19 mmol) in ethanol–CH_2Cl_2 (10 mL–10 mL) at 80 °C for 18 h under hydrogen (50 kg cm^{-2}) followed by the removal of the solvent under the reduced pressure afforded the catalytic system **9c**–(+)-3,5-(^{t}Bu)$_2$-BINAP [(+)-**20**] whose ^{31}P NMR spectrum ($CDCl_3$) showed a singlet at δ 21.6. Thus, the complex (0.11 g, 0.034 mmol of Ru atom) was used for hydrogenation. Treatment of 2-(benzamidomethyl)-3-oxobutanoate [(±)-**16**] (20 g, 80 mmol) under the same conditions as described for [RuI((−)-*m*-tol-BINAP)(*p*-cymene)]I afforded **17** in better de and ee (55% conversion, the selectivity of *syn*-(2*S*, 3*R*)-**17** was 98% de and 99% ee).

Asymmetric Hydrogenation of Methyl Pyruvate (21a). A solution of methyl pyruvate (**21a**) (0.895 g, 8.77 mmol) and (*S*)-**5a** (13.3 mg, 15.2 × 10^{-3} mmol) in methanol (6 mL) was degassed by three freeze–thaw cycles and then was charged on an autoclave. Hydrogen was introduced (100 kg/cm^2), and the reaction mixture was stirred at 30 °C for 95 h. After hydrogen pressure was released and evaporation of the solvent, the resulting residue was distilled to give methyl (*S*)-2-lactate (>99% yield). Enantioselectivity (88%) of the product was determined by HPLC analysis (Nucleosil 100–3A, eluted with hexane:ether = 9:1, 1.0 mL/min) of the (+)-MTPA ester of the product.

Asymmetric hydrogenation of all other α-keto esters was carried out under the same conditions as employed for methyl pyruvate. The results are summarized in Table 3. Methyl 3-methyl-2-hydroxybutanoate (GLC with a chiral column, CHIRADEX B-PH, 75 °C), methyl 2-hydroxy-2-cyclohexylacetate (GLC of the corresponding MTPA ester, SE 30, 180 °C), methyl 2-hydroxy-2-phenylacetate (CHIRALCEL OD, eluted with hexane:2-propanol = 975:25, 1.0 mL/min), methyl 2-hydroxy-2-(4-methoxylphenyl)acetate (CHIRALCEL OD, hexane:2-propanol = 9:1, 1.0 mL/min), methyl 2-hydroxy-2-(4-methylphenyl)acetate (CHIRALCEL OD, hexane:2-propanol = 9:1, 1.0 mL/min), methyl 2-hydroxy-2-(4-chlorophenyl)acetate (CHIRALCEL OD, hexane:2-propanol = 975:25, 1.0 mL/min), methyl 2-hydroxy-2-(4-nitrophenyl)acetate (CHIRALCEL OJ, hexane:2-propanol = 90:10, 1.0 mL/min).

Asymmetric Hydrogenation of Methyl (4-Chlorophenyl)-glyoxylate (21g) in the Presence of HBF_4. Methyl (4-chlorophenyl)glyoxylate (**21g**) (144.7 mg, 0.73 mmol) was added to a solution of **5a** (4.2 mg, 4.8 × 10^{-3} mmol) in methanol (1.0 mL) which contained HBF_4 (12.9 mM). The mixture was stirred under 100 atm of hydrogen at 30 °C for 70 h. Methyl 2-hydroxy-2-(4-chlorophenyl)acetate (**22g**) was obtained (131.3 mg, 90% yield). The configuration of the product was determined based on the optical rotation value in comparison with the reported one. The enantiomeric excess was detected by HPLC analysis (93%, CHIRALCEL OD, eluted with hexane:2-propanol = 975:25, 1.0

mL/min). Asymmetric hydrogenation of all other α-keto esters in the presence of acids were carried out under the same conditions.

Asymmetric Hydrogenation of (Dimethylamino)acetone (23). A solution of (dimethylamino)acetone (**23**) (0.878 g, 8.68 mmol) and (*S*)-**10c** (8.8 mg, 7.9×10^{-3} mmol) in a mixture of ethanol (5 mL) and dichloromethane (2 mL) was charged on an autoclave. Hydrogen was introduced (105 kg/cm²), and then the mixture was stirred at 30 °C for 40 h. After hydrogen pressure was released, the resulting oil was distilled to give (*S*)-1-(dimethylamino)-2-propanol in quantitative yield. Enantioselectivity (99.4%) of the product was determined by ^{1}H NMR analysis (400 MHz) of the (+)-MTPA ester of the product.

^{1}H NMR of the (+)-MTPA ester of (*S*)-alcohol ((*S*)-**24**): δ 1.26 (d, 3H, J = 6.4 Hz), 2.12 (s, 6H), 2.14–2.27 (m, 1H), 2.38 (dd, 1H, J = 6.3 and 13.1 Hz), 3.52 (d, 3H, J = 1.2 Hz), 5.2–5.3 (m, 1H), and 7.1–7.6 (m, 5H). ^{1}H NMR of the (+)-MTPA ester of (*R*)-alcohol ((*R*)-**24**): δ 1.16 (d, 3H, J = 6.4 Hz), 2.18 (s, 6H), 2.14–2.27 (m, 1H), 2.49 (dd, 1H, J = 8.4 and 12.9 Hz), 3.50 (d, 3H, J = 0.9 Hz), 5.2–5.3 (m, 1H), and 7.1–7.6 (m, 5H).

Asymmetric Hydrogenation of Methyl 3-Oxobutanoate (25). A solution of methyl 3-oxobutanoate (**25**) (1.61 g, 13.9 mmol) and (*S*)-**10c** (6.2 mg, 5.6×10^{-3} mmol) in methanol (1.6 mL) was degassed by three freeze–thaw cycles and then was charged on an autoclave. Hydrogen was introduced (100 kg/cm²), and the mixture was stirred at 30 °C for 35 h. After the hydrogen pressure was released, the product was distilled to give methyl (*S*)-3-hydroxybutanoate (**26**) (97%) and the dimethyl acetal of **27** (3%). The enantioselectivity (98.7%) of the product was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:ether = 8:2) of the (+)-MTPA ester of the product.

Asymmetric Hydrogenation of 3-Acetyltetrahydrofuran-2-one (28). A solution of **28** (1.05 g, 8.17 mmol), (*S*)-BINAP (6.9 mg, 11×10^{-3} mmol), and $[RuI_2(p\text{-cymene})]_2$ (5.5 mg, 5.5×10^{-3} mmol) in methanol (2.25 mL) and dichloromethane (0.75 mL), which was degassed by three freeze–thaw cycles, was transferred to a stainless steel autoclave. Hydrogen was introduced (100 kg/cm²), and the mixture was stirred at 30 °C for 40 h. After the hydrogen pressure was released, distillation gave (3*R*,6*S*)-**29** (1.08 g, 100% yield). Diastereoselectivity (98%) of (3*R*,6*S*)-3-(1-hydroxyethyl)tetrahydrofuran-2-one [*syn*-(3*R*,6*S*)-**29**] was determined by GLC analysis (PEG, 170 °C, 40 kg/cm²). Enantioselectivity (97%) was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:2-propanol = 9:1, 1.0 mL/min) of the (+)-MTPA ester of the product: ^{1}H NMR ($CDCl_3$) δ 1.27 (d, 3H, J = 6.4 Hz), 2.22–2.30 (m, 1H), 2.39 (m, 1H), 2.65 (dt, 1H, J = 3.2 and 7.2 Hz), 4.24 (dt, 1H, J = 7.2 and 8.4 Hz), 4.35–4.37 (m, 1H), 4.40 (dt, 1H, J = 3.2 and 8.4 Hz).

Asymmetric Hydrogenation of 2-(Methoxycarbonyl)-cyclopentanone (30). A solution of **30** (0.931 g, 6.55 mmol) and (*S*)-**10c** (5.2 mg, 4.8×10^{-3} mmol) in dichloromethane (6 mL) was charged on an autoclave. Hydrogen was introduced (100 kg/cm²), and then the reaction mixture was stirred at 60 °C for 40 h. After the hydrogen pressure was released, distillation of the mixture gave *anti*-(1*S*,2*S*)-**31** as the major product (95% yield). Diastereoselectivity (98%) of (1*S*,2*S*)-2-(methoxycarbonyl)cyclopentan-1-ol [*anti*-(1*S*,2*S*)-**31**] was determined by GLC analysis (PEG, 90–170 °C, 40 kg/cm²) of the product. Enantioselectivity (95%) was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:2-propanol = 10:1, 1.0 mL/min) of the (+)-MTPA ester of **31**.

Asymmetric Hydrogenation of Geraniol (32). A solution of geraniol (**32**) (1.40 g, 9.08 mmol) and (*S*)-**10c** (5.5 mg, 4.9×10^{-3} mmol) in 95% aqueous methanol (16 mL) was charged on an autoclave. Hydrogen was introduced (100 kg/cm²), and then the reaction mixture was stirred at 20 °C for 8 h. After the hydrogen pressure was released, the resulting oil was distilled *in vacuo* to give citronellol (91%) and dihydrocitronellol (0.3%). The enantioselectivity (96%) of (*R*)-citronellol was obtained by HPLC analysis (Nucleosil 100-3A, eluted with hexane:ether = 7:3, 1 mL/min) of the (+)-MTPA ester of citroneric acid derived from Jones oxidation of the product.

Asymmetric Hydrogenation of Tiglic Acid (35). A solution of tiglic acid (**35**) (0.811 g, 8.1 mmol) and **5d** (7.5 mg, 8.1×10^{-3} mmol) in methanol (8 mL) was placed in a pressure bottle. Hydrogen was introduced (4 kg/cm²), and then the mixture was stirred at 20 °C for a period of 92 h. After the hydrogen pressure was released, the resulting oil was distilled under reduced pressure to give (*S*)-2-methylbutanoic acid (0.734 g, 89% yield, bulb-to-bulb distillation, 30 °C (bath temp)/0.01 mmHg). Enantioselectivity (89%) of the product was determined by HPLC analysis (Nucleosil 100-3A, eluted with hexane:ether = 8:2) of the amide derived from condensation of the product and 1-(1-naphthyl)-ethylamine.

Asymmetric Hydrogenation of 2-(6-Methoxy-2-naphthyl)propenoic Acid (37). A solution of **37** (0.222 g, 0.973 mmol) and (*S*)-**10c** (5.7 mg, 5.1×10^{-3} mmol) in methanol (15 mL) was charged on an autoclave. Hydrogen was introduced (116 kg/cm²), and the mixture was stirred at −20 °C for 17 h. After hydrogen pressure was released, purification by column chromatography (SiO_2) gave (*S*)-naproxen (6.211 g, 94% yield, 96% ee, determined by HPLC analysis (CHIRALCEL OD, eluted with hexane:2-propanol = 99:1, 1 mL/min, UV 272 nm) of the methyl ester of (*S*)-naproxen derived from the treatment of acid with diazomethane).

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Supplementary Material Available: Figures of relations between the wave numbers of IR spectra of carbonyl ligand of RhCl(CO)(BINAPs) with Hammet's σ and Kabachnik's σ^{Ph} (5 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.