Highly Selective Hydrolytic Kinetic Resolution of Terminal Epoxides

Catalyzed by Chiral (salen)Cobalt(III)-Complexes.

Practical Synthesis of Enantioenriched Terminal Epoxides and 1,2-Diols

SUPPORTING INFORMATION

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Experimental Section

General. All reactions were conducted in glassware with magnetic stirring. Racemic epoxides were either purchased or synthesized by known procedures. Both enantiomers of the (salen)Co(II) complex **1** are commercially available from Aldrich. Tetrahydrofuran and TBME were distilled from sodium/benzophenone. Yields of the HKR are reported as a fraction of the theoretical maximum 50%. Optical rotations were measured on a Jasco DIP 370 digital polarimeter with a sodium (λ= 489 nm) lamp, and are reported as follows: $[\alpha]^{T\ ^{\circ}C}_{\lambda}$, (*c* g/100 mL, solvent). Optical rotation measurements were conducted using a Jasco DIP 370 digital polarimeter. All epoxides were purified by distillation or chromatography prior to use. Epoxides recovered from the reaction were purified by filtration through a SiO_2 plug to remove residual H_2O and concentrated by rotary evaporation to remove solvent.

Determination of Enantiomeric Purity. Enantiomeric excesses (ee's) were determined by capillary GC analysis using a Hewlett Packard 5890 Series II Gas Chromatograph with H_2 as a carrier gas or by chiral HPLC analysis using a Hewlett Packard 1050 HPLC. The following GC columns were employed: Cyclodex-B (30m x 0.25mm id x 0.25μm film; J&W Scientific) set at a column head pressure of 13 psi; Chiraldex G-TA (20m x 0.25mm id x 0.125μm film; Advanced Separation Technologies, Inc.) set at a column head pressure of 7 psi. The following HPLC columns were employed: Chiracel® OD (Chiral Technologies Inc., 24 cm x 0.46 cm i.d.), Chiralpak® AS (Chiral Technologies Inc., 24 cm x 0.46 cm i.d.), Whelk-O 1 (Regis® Technologies Inc., 25 cm x 0.46 cm i.d.), L-Leucine (Regis® Technologies Inc., 25 cm x 0.46 cm).

Representative Procedure for the Hydrolytic Kinetic Resolution of Terminal Epoxides. Pre-oxidation of Complex 1 to 1•OAc. Method A.

(*S*)-Propylene Oxide (Table 1, entry1). A 100 mL flask equipped with a stir bar was charged with (*S,S*)-**1** (242 mg, 400 μmol, 0.002 equiv). The catalyst was dissolved in 5 mL PhMe and treated with AcOH (240 μL, 4.2 mmol). The solution was allowed to stir at rt open to air for 30 min over which time the color changed from orange-red to a dark brown. The solution was concentrated *in vacuo* to leave a crude brown solid. The resulting catalyst residue was dissolved in propylene oxide (14.0 mL, 11.6 g, 200 mmol) at rt, the solution was cooled to 0 °C, and H_2O (1.98 mL, 110 mmol, 0.55 equiv) was added dropwise over 5 min. The reaction was allowed to warm to rt and stir 14 h at which time (*S*)-propylene oxide (5.35 g, 92.1 mmol, 46%) was isolated by distillation from the reaction mixture at 36 °C. The propylene diol was removed by vacuum distillation (65 °C, 0.25 torr). The catalyst was recovered by suspension in MeOH and collection by vacuum filtration. The ee of the propylene oxide was determined to be 99.7% by chiral GC analysis of the 1-azido-2-trimethylsiloxypropane derivative prepared by ring-opening of the epoxide with $TMSN_3$ (Cyclodex-B, 55 °C, isothermal, t_R(minor) = 12.29 min, t_R(major) = 12.57 min). $[\alpha]^{23}_D$ –11.6° (neat); lit.[1] $[\alpha]^{20}_D$ –18.7° (*c* 5.83, CCl_4).

Representative Procedure for the HKR of Terminal Epoxides. *In situ* Oxidation of Complex 1 to 1•OAc. Method B.

(*R*)-1,2-Epoxy-5-hexene (Table 1, entry 4). A 100 mL flask equipped with a stir bar was charged with (*R,R*)-**1** (302 mg, 500 μmol, 0.005 equiv). The catalyst was treated with (±)-1,2-epoxy-5-hexene (11.3 mL, 9.81 g, 100 mmol), AcOH (120 μL, 2.1 mmol, 0.02 equiv) and 1 mL THF. The solution was cooled to 0 °C and H_2O (1.0 mL, 55 mmol, 0.55 equiv) was added in one portion. The reaction was allowed to warm to rt and stir 16 h at which time the volatiles were separated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask. The recovered epoxide was passed through a silica plug to removed residual water and the THF was removed by rotary evaporation to yield (*R*)-1,2-epoxy-5-hexene (4.23 g, 43.1 mmol, 43%). The diol was distilled under reduced pressure (56 °C, 0.25 torr). The catalyst was recovered by suspension of the residue in MeOH and vacuum filtration. The ee of the recovered epoxide was determined to be 99.5% by chiral GC analysis of the 1-azido-2-trimethylsiloxy-5-hexene derivative (Cyclodex-B, 70 °C, isothermal, t_R(minor) = 38.00 min, t_R(major) = 39.06 min). $[\alpha]^{25}_D$ +9.36° (neat).

(*R*)-1,2-Epoxyhexane (Table 1, entry 2). Method B. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.005 equiv) was treated with (±)-1,2-epoxyhexane (9.64 mL, 8.01 g, 80 mmol) containing 2-3% AcOH (available from Aldrich). The solution was cooled to 0 °C and H_2O (0.80 mL, 44 mmol, 0.55 equiv) was added in one portion. After 16 h, (*R*)-1,2-epoxyhexane (3.44 g, 34.4 mmol, 43%) was isolated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask. The diol was distilled under reduced pressure (65 °C, 0.25 torr). The ee of the recovered epoxide was determined to be 99.5% by chiral GC analysis of the 1-azido-2-trimethylsiloxyhexane derivative (Cyclodex-B, 80 °C,

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isothermal, t_R(minor) = 20.60 min, t_R(major) = 21.02 min). $[\alpha]^{23}_D$ +14.3° (neat); lit.[2] $[\alpha]^{20}_D$ +9.6° (*c* 0.76, EtOH).

(*R*)-1,2-Epoxytetradecane (Table 1, entry 3). Method A. A solution of the catalyst ((*R,R*)-**1**, 75 mg, 125 μmol, 0.005 equiv) in 2 mL CH_2Cl_2 was treated with 75 μL AcOH. The crude catalyst residue obtained after concentration was treated with (±)-1,2-epoxytetradecane (6.28 mL, 5.31 g, 25 mmol) and 1 mL *i*-PrOH. The solution was cooled to 0 °C and treated with H_2O (450 μL, 25 mmol). After 24 h at rt, the reaction was diluted with 50 mL hexanes and filtered to remove the 1,2-diol. The filtrate was concentrated by rotary evaporation and (*R*)-1,2-epoxytetradecane (2.25 g,10.6 mmol, 42%) was obtained by vacuum distillation (86 °C, 0.25 torr). The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 °C), Chiralcel® OD, 99.5:0.5 hexanes:EtOH, 1.5 mL / min, 220 nm, t_R(minor) = 21.55 min, t_R(major) = 26.71 min). $[\alpha]^{23}_D$ +7.3° (neat); lit.[3] $[\alpha]_D$ +4.31° (*c* 1.42, $CHCl_3$).

(*R*)-(2,3-Epoxypropyl)benzene (Table 1, entry 5). Method B. The catalyst ((*R,R*)-**1**, 151 mg, 250 μmol, 0.005 equiv) was dissolved in (±)-(2,3-epoxypropyl)benzene (6.57 mL, 6.70 g, 50 mmol), AcOH (60 μL, 1.0 mmol, 0.02 equiv) and 0.5 mL THF. The solution was cooled to 0 °C and treated with H_2O (495 μL, 27.5 mmol, 0.55 equiv). After 16 h, (*R*)-(2,3-epoxypropyl)benzene (3.10 g, 23.1 mmol, 46%) was distilled (72 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of the recovered epoxide was determined to be 99% by chiral HPLC analysis ((*R,R*)-Whelk O-1, 99.5:0.5 hexanes:EtOH, 1 mL / min, 254 nm, t_R(minor) = 9.07 min, t_R(major) = 9.51 min). $[\alpha]^{23}_D$ +27.2° (neat); lit.[4] $[\alpha]^{25}_D$ +17.5° (*c* 1.94, EtOH).

(*S*)-Vinylcyclohexane oxide (Table 1, entry 6). Method B. The catalyst ((*S,S*)-**1**, 60 mg, 100 μmol, 0.005 equiv) was dissolved in (±)-vinylcyclohexane oxide[5] (2.71 mL, 2.52 g, 20 mmol), AcOH (23 μL, 0.4 mmol, 0.02 equiv) and 0.2 mL THF. The solution was cooled to 0 °C and treated with H_2O (200 μL, 11.1 mmol, 0.55 equiv). After 16 h, (*S*)-vinylcyclohexane oxide (1.12 g, 8.87 mmol, 44%) was isolated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask. The ee of the recovered epoxide was determined to be 99.9% by chiral GC analysis (G-TA, 60 °C, isothermal, t_R(minor) = 11.19 min, t_R(major) = 13.25 min). $[\alpha]^{23}_D$ +2.2° (*c* 10.5, $CHCl_3$); lit.[6] $[\alpha]^{20}_D$ +2.1° (neat).

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(*R*)-*tert*-Butyloxirane (Table 1, entry 7). Method A. A solution of the catalyst ((*R,R*)-**1**, 483 mg, 800 μmol, 0.02 equiv) in 3 mL PhMe was treated with 500 μL AcOH. The crude catalyst residue obtained after concentration was treated with (±)-*tert*-butyloxirane[7] (4.88 mL, 4.00 g, 40.0 mmol). To the reaction flask was added 1.2 mL (±)-1,2-hexane diol, the mixture was cooled to 0 °C, and H_2O (400 μL, 22 mmol, 0.55 equiv) was added in one portion. After 48 h, (*R*)-*tert*-butyloxirane (1.61 g, 16.1 mmol, 41%) was isolated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask. The recovered epoxide was determined to be 99.4% ee by chiral HPLC analysis of the 2-benzothiazolesulfide derivative (obtained by ring opening with 2-mercaptobenzothiazole in MeOH using 1 equiv TEA at 0 °C and direct analysis of the product obtained, Chiralcel® OD, 99.5:0.5 hexanes:EtOH, 1 mL / min, 230 nm, t_R(minor) = 22.61 min, t_R(major) = 27.65 min). $[\alpha]^{24}_D$ –15.2° (neat); lit.[8] $[\alpha]^{25}_D$ –18.4° (*c* 1.8, PhH, 97% ee).

(*R*)-Epichlorohydrin (Table 2, entry 1). Method A. A solution of the catalyst ((*S,S*)-**1**, 242 mg, 400 μmol, 0.005 equiv) in 5 mL CH_2Cl_2 was treated with 250 μL AcOH. The crude catalyst residue obtained after concentration was treated with (±)-epichlorohydrin (6.26 mL, 7.40 g, 80 mmol) and 0.8 mL THF. The solution was cooled to 0 °C and treated with H_2O (800 μL, 44 mmol, 0.55 equiv) and the reaction was maintained at 0 – 4 °C for 16 h. (*R*)-Epichlorohydrin (2.98 g, 32.2 mmol, 43%) was isolated by vacuum transfer (25 °C, 0.25 torr) from the reaction mixture into a cooled (-78 °C) receiving flask. The recovered epoxide was determined to be >99% ee by chiral GC analysis (G-TA, 50 °C, isothermal, t_R(minor) = 4.15 min, t_R(major) = 4.44 min). $[\alpha]_D^{26}$ –32.8° (*c* 1.27, MeOH); lit.[9] $[\alpha]_D^{22}$ –33.0° (*c* 4.22, MeOH).

(*S*)-Epifluorohydrin (Table 2, entry 3). Method A. A solution of the catalyst ((*R,R*)-**1**, 80 mg, 131 μmol, 0.005 equiv) in 2 mL PhMe was treated with 80 μL AcOH. The crude catalyst residue obtained after concentration was dissolved in (±)-epifluorohydrin (2.00 g, 26.3 mmol). The solution was cooled to 0 °C and H_2O (260 μL, 14.4 mmol, 0.55 equiv) was added to the solution. After 16 h, (*S*)-epifluorohydrin (0.810 g, 10.6 mmol, 42%) was isolated by vacuum transfer (0.25 torr) from the reaction mixture into a cooled (-78 °C) receiving flask. The recovered epoxide was determined to be >99% ee by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 °C and direct analysis of the product obtained, Chiralcel® OD, 95:5 hexanes:*i*-PrOH, 1 mL / min, 230 nm, t_R(minor) = 27.00 min, t_R(major) = 32.65 min). $[\alpha]^{25}_D$ –4.1° (*c* 3.01, $CHCl_3$); lit.[10] $[\alpha]^{16}_D$ –6.1° (*c* 2.12, MeOH).

(*S*)-1,1,1-Trifluoro-2,3-epoxypropane (Table 2, entry 4). Method A. A solution of the

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catalyst ((*R,R*)-**1**, 151 mg, 250 μmol, 0.005 equiv) in 2 mL PhMe was treated with 150 μL AcOH. The crude catalyst residue obtained after concentration was treated with (±)-1,1,1-trifluoro-2,3-epoxypropane[11] (5.60 g, 50 mmol). The solution was cooled to 0 ˚C and treated with H_2O (500 μL, 27.8 mmol, 0.55 equiv). After 16 h, (*S*)-1,1,1-trifluoro-2,3-epoxypropane (2.09 g, 18.7 mmol, 42%) was isolated by vacuum transfer (0.25 torr) from the reaction mixture into a cooled (-78 ˚C) receiving flask. The recovered epoxide was determined to be >99% ee by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 95:5 hexanes:*i*-PrOH, 1 mL / min, 230 nm, t_R(minor) = 12.85 min, t_R(major) = 15.30 min). $[\alpha]^{24}_D$ – 12.3˚ (*c* 8.40, $CHCl_3$); lit.[12] $[\alpha]^{22}_D$ –10.92˚ (*c* 5.0, $CHCl_3$, 96% ee).

(*R*)-Benzyl glycidyl ether (Table 3, entry 1). Method B. The catalyst ((*R,R*)-**1**, 151 mg, 250 μmol, 0.005 equiv) was dissolved in (±)-benzyl glycidyl ether[13] (8.20 g, 50.0 mmol), AcOH (57 μL, 1.0 mmol, 0.02 equiv) and 0.5 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (495 μL, 27.5 mmol, 0.55 equiv). After 16 h, (*R*)-benzyl glycidyl ether (3.82 g, 23.3 mmol, 48%) was isolated by vacuum distillation (82 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralcel® OD, 95:5 hexanes:*i*-PrOH, 1 mL / min, 214 nm, t_R(minor) = 11.56 min, t_R(major) = 9.72 min). $[\alpha]^{26}_D$ +10˚ (*c* 5.2, MeOH); lit.[14] $[\alpha]^{32}_D$ +9.8˚ (*c* 5.13, MeOH).

(*S*)-(*tert*-Butyldimethylsilyl) glycidyl ether (Table 3, entry 2). Method B. The catalyst ((*R,R*)-**1**, 91 mg, 150 μmol, 0.005 equiv) was dissolved in (±)-(*tert*-butyldimethylsilyl) glycidyl ether[15] (5.64 g, 30.0 mmol), AcOH (32 μL, 0.6 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (297 μL, 16.5 mmol, 0.55 equiv). After 16 h, (*S*)-(*tert*-butyldimethylsilyl) glycidyl ether (2.72 g, 14.5 mmol, 47%) was isolated by vacuum distillation (30 ˚C, 0.5 torr) into a cooled (0 ˚C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 99.25:0.75 hexanes:EtOH, 1 mL / min, 230 nm, t_R(minor) = 20.38 min, t_R(major) = 22.47 min). $[\alpha]^{25}_D$ +11˚ (*c* 3.9, C_6H_6); lit.[16] $[\alpha]^{19}_D$ +4.95˚ (*c* 1.94, C_6H_6).

(*S*)-Phenyl glycidyl ether (Table 3, entry 3). Method B. The catalyst ((*R,R*)-**1**, 151 mg, 250 μmol, 0.005 equiv) was dissolved in (±)-phenyl glycidyl ether (7.50 g, 50.0 mmol),

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AcOH (57 μL, 1.0 mmol, 0.02 equiv) and 0.5 mL THF. The solution was cooled to 0 °C and treated with H_2O (495 μL, 27.5 mmol, 0.55 equiv). After 16 h, (*R*)-phenyl glycidyl ether (3.52 g, 23.4 mmol, 47%) was isolated by vacuum distillation (80 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 214 nm, t_R(minor) = 8.38 min, t_R(major) = 11.40 min). $[\alpha]^{23}_D$ +5.2° (*c* 7.5, $CHCl_3$); lit.[17] $[\alpha]_D$ –3.6° (*c* 0.33, $CHCl_3$, (*R*)-epoxide).

(*S*)-(1-Napthyl) glycidyl ether (Table 3, entry 4). Method B. The catalyst ((*R,R*)-**1**, 30 mg, 50 μmol, 0.005 equiv) was dissolved in (±)-(1-napthyl) glycidyl ether[18] (2.00 g, 10.0 mmol), AcOH (80 μL, 1.4 mmol, 0.08 equiv) and 2 mL THF. The solution was treated with H_2O (180 μL, 10.0 mmol, 1.0 equiv). After 60 h, the reaction was concentrated *in vacuo*, the solid was suspended in 9:1 hexanes:CH_2Cl_2 and removed by filtration. The filtrate was concentrated and (*R*)-(1-napthyl) glycidyl ether (0.756 g, 3.78 mmol, 38%) was obtained by vacuum distillation (140 °C, 0.25 torr). The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 260 nm, t_R(minor) = 8.47 min, t_R(major) = 11.05 min). $[\alpha]^{26}_D$ +28.3° (*c* 1.73, $CHCl_3$); lit.[19] $[\alpha]^{25}_D$ +32.9° (*c* 1, MeOH).

(*S*)-(2-Phenylmethoxyethyl)oxirane (Table 3, entry 5). Method B. The catalyst ((*S,S*)-**1**, 151 mg, 250 μmol, 0.005 equiv) was dissolved in (±)-(2-phenylmethoxyethyl) oxirane[20] (8.90 g, 50.0 mmol), AcOH (57 μL, 1.0 mmol, 0.02 equiv) and 0.5 mL THF. The solution was cooled to 0 °C and treated with H_2O (495 μL, 27.5 mmol, 0.55 equiv). After 16 h, (*S*)-(2-phenylmethoxyethyl) oxirane (3.70 g, 20.8 mmol, 42%) was isolated by vacuum distillation (70 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralcel® OD, 99.5:0.5 hexanes:*i*-PrOH, 1 mL / min, 215 nm, t_R(minor) = 16.02 min, t_R(major) = 17.55 min). $[\alpha]^{24}_D$ –15.7° (c 4.06, $CHCl_3$); lit[21] $[\alpha]^{25}_D$ –15.1° (c 2.51, $CHCl_3$).

(*R,R*)-Butadiene diepoxide (Table 3, entry 6). Method A. The catalyst ((*S,S*)-**1**, 604 mg, 1.0 mmol, 0.01 equiv) was dissolved in 10 mL CH_2Cl_2 and 600 μL AcOH. The crude catalyst residue obtained after concentration was treated with (±)-butadiene diepoxide[22] (8.61 g, 100 mmol). The solution was treated with 17 mL THF, cooled to 0 °C and treated with H_2O (1.08 mL, 60 mmol, 0.60 equiv). After 16 h, the reaction was concentrated by rotary evaporation and (*R,R*)-butadiene diepoxide (3.07 g, 35.7 mmol, 36%) was isolated by vacuum distillation (0.25 torr, 60 °C) from the reaction mixture into a cooled (0 °C) receiving flask. The recovered epoxide was determined to be >99%

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ee by chiral HPLC analysis of the di-2-napthylsulfide derivative (obtained by ring opening with 2 equiv 2-napthalenethiol in MeOH using 2 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 8:2 hexanes:EtOH, 1 mL / min, 220 nm, t_R(minor) = 8.94 min, t_R(major) = 10.58 min). $[\alpha]^{26}_D$ –29.5˚ (*c* 2.27, $CHCl_3$); lit[23] $[\alpha]^{25}_D$ –24˚ (*c* 4, CCl_4, >98% ee).

(*S*)-Glycidyl butyrate (Table 4, entry 1). Method B. The catalyst ((*R,R*)-**1**, 91 mg, 150 μmol, 0.005 equiv) was dissolved in (±)-glycidyl butyrate[24] (4.32 g, 30.0 mmol), AcOH (32 μL, 0.6 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (297 μL, 16.5 mmol, 0.55 equiv). After 16 h, (*S*)-glycidyl butyrate (1.90 g, 13.2 mmol, 46%) was isolated by vacuum distillation (30 ˚C, 0.5 torr) into a cooled (0 ˚C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 97:3 hexanes:EtOH, 1 mL / min, 260 nm, t_R(minor) = 27.89 min, t_R(major) = 32.33 min). $[\alpha]^{23}_D$ +29˚ (*c* 8.2, $CHCl_3$); lit.[25] $[\alpha]^{20}_D$ –26.3˚ (*c* 1.0, $CHCl_3$, (*R*)-epoxide).

(*R*)-Ethyl-3,4-epoxybutyrate (Table 4, entry 2). Method B. The catalyst ((*R,R*)-**1**, 60 mg, 100 μmol, 0.005 equiv) was dissolved in (±)-ethyl-3,4-epoxybutyrate[26] (2.60 g, 20.0 mmol), AcOH (23 μL, 0.4 mmol, 0.02 equiv) and 0.2 mL THF. The solution was cooled to 0 ˚C and H_2O (200 μL, 11.1 mmol, 0.55 equiv) was added at once. After 16 h, (*R*)-ethyl-3,4-epoxybutyrate (1.19 g, 9.15 mmol, 92%) was isolated by vacuum distillation (50 ˚C, 0.5 torr) into a cooled (-78 ˚C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 280 nm, t_R(minor) = 8.9 min, t_R(major) = 11.8 min). $[\alpha]^{25}_D$ +8.4˚ (*c* 3.55, $CHCl_3$); lit.[27] $[\alpha]^{20}_D$ +24.7˚ (*c* 3.93, MeOH).

(*S*)-{[(*tert*-Butoxycarbonyl)amino]methyl}oxirane (Table 4, entry 3). Method A. The catalyst ((*S,S*)-**1**, 242 mg, 400 μmol, 0.02 equiv) in 6 mL CH_2Cl_2 was treated 240 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-{[(*tert*-butoxycarbonyl)amino]methyl} oxirane[28] (3.46 g, 20 mmol). THF (0.6 mL) was added, the solution was cooled to 0 ˚C, and then

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H_2O was added at once (200 μL, 11 mmol, 0.55 equiv). After stirring 38 h at rt, the mixture reaction was concentrated by rotary evaporation and the epoxide was recovered by flash chromatography over silica gel using 7:3 hexanes:EtOAc as the eluent. The solid obtained was recrystallized from hexanes at –20 °C to yield 1.24 g (7.18 mmol, 36%) of opaque needlelike crystals. The ee of the recovered epoxide before recrystallization was determined to be 99.3% by chiral GC analysis (Cyclodex-B, 110 °C, isothermal, t_R(minor) = 21.57 min, t_R(major) = 21.85 min). $[\alpha]^{25}_D$ –14.2° (*c* 2.26, $CHCl_3$); lit.[29] $[\alpha]^{25}_D$ +5.1° (*c* 1.4, MeOH, (*R*)-epoxide).

(*R*)-Methyl glycidate (Table 4, entry 4). Method A. The catalyst ((*S*,*S*)-**1**, 604 mg, 1.0 mmol, 0.02 equiv) in 10 mL CH_2Cl_2 was treated 600 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-methyl glycidate[30] (5.10 g, 50 mmol) and THF (2.5 mL). The solution was cooled to 0 °C and treated with H_2O (500 μL, 27.8 mmol, 0.55 equiv). After 24 h at rt, (*R*)-methyl glycidate (2.18 g, 21.4 mmol, 43%) was isolated by vacuum distillation (50 °C, 0.25 torr) into a cooled (-78 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral GC analysis (Cyclodex-B, 50 °C, isothermal, t_R(minor) = 8.38 min, t_R(major) = 8.51 min). $[\alpha]^{27}_D$ +16.4° (neat); lit.[31] $[\alpha]^{25}_D$ +10.4° (*c* 3.6, MeOH).

(*S*)-3,4-Epoxy-2-butanone (Table 4, entry 5). Method A. The catalyst ((*R*,*R*)-**1**, 480 mg, 800 μmol, 0.02 equiv) in 10 mL CH_2Cl_2 was treated 480 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3,4-epoxy-2-butanone[32] (3.44 g, 40 mmol). To the solution was added THF (0.8 mL) and AcOH (50 μL, 0.8 mmol, 0.02 equiv), the mixture was cooled to 0 °C, H_2O (500 μL, 27.8 mmol, 0.70 equiv) was added at once, and the reaction mixture was then placed under an atmosphere of O_2 (balloon pressure). After 48 h at rt, (*S*)-3,4-epoxy-2-butanone (1.41 g, 16.4 mmol, 40%) was isolated by vacuum distillation (70 °C, 53 torr) into a cooled (-78 °C) receiving flask. The ee of recovered epoxide was determined to be 99.9% by chiral GC analysis (G-TA, 40 °C, 8 min, 3 °C / min, t_R(minor) = 15.16 min, t_R(major) = 16.33 min). $[\alpha]^{24}_D$ –72° (*c* 8.35, MeOH); lit.[33] $[\alpha]^{20}_D$ –108.9° (*c* 4.69, CH_2Cl_2).

(*S*)-1,2-Epoxy-3-pentanone (Table 4, entry 6). Method A. The catalyst ((*R,R*)-**1**, 363 mg, 600 μmol, 0.02 equiv) in 6 mL CH_2Cl_2 was treated 360 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1,2-epoxy-3-pentanone[34] (3.00 g, 30 mmol) and THF (0.35 mL), the mixture cooled to 0

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˚C, and H_2O (330 μL, 18 mmol, 0.60 equiv) was added. The reaction was then placed under an atmosphere of O_2 (balloon pressure). After 16 h at rt, (*S*)-1,2-epoxy-3-pentanone (1.09 g, 10.9 mmol, 37%) was isolated by vacuum distillation (54 ˚C, 9 torr) into a cooled (0 ˚C) receiving flask. The ee of recovered epoxide was determined to be 99.7% by chiral GC analysis (G-TA, 50 ˚C, 8 min, 3 ˚C / min, t_R(minor) = 17.48 min, t_R(major) = 19.27 min). $[\alpha]^{24}_D$ –78˚ (c 8.6, $CHCl_3$); lit.[62] $[\alpha]^{20}_D$ –102.6˚ (c 4.88, MeOH).

(*R*)-Butadiene monoxide (Table 5, entry 7). Method A. The catalyst ((*R,R*)-**1**, 1.81 g, 3.0 mmol, 0.015 equiv) in 15 mL PhMe was treated with 1.8 mL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-butadiene monoxide[35] (14.0 g, 200 mmol). The solution was cooled to 0 ˚C and H_2O (2.50 mL, 140 mmol, 0.70 equiv) was added. After 72 h at rt, (*R*)-butadiene monoxide (4.96 g, 70.8 mmol, 36%) was isolated by vacuum transfer (0.25 torr) into a cooled (-78 ˚C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide derivative (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 95:5 hexanes:*i*-PrOH, 1 mL / min, 230 nm, t_R(minor) = 17.40 min, t_R(major) = 20.67 min). $[\alpha]^{24}_D$ –10.4˚ (*c* 2.97, *i*-PrOH); lit.[36] $[\alpha]^{22}_D$ –12˚ (*c* 4.9, dioxane).

(*R*)-1-(*tert*-Butyldimethylsilyl)-3,4-epoxy-1-butyne (Table 5, entry 8). Method A. The catalyst ((*R,R*)-**1**, 48 mg, 80 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated 50 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1-(*tert*-butyldimethylsilyl)-3,4-epoxy-1-butyne[37] (1.84 g, 10 mmol) and *i*-PrOH (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (100 μL, 5.5 mmol, 0.55 equiv). After 20 h at rt, (*R*)-1-(*tert*-butyldimethylsilyl)-3,4-epoxy-1-butyne (758 mg, 4.12 mmol, 41%) was isolated by vacuum distillation (36 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis of the 2-napthylsulfide (obtained by ring opening with 2-napthalenethiol in MeOH using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, L-Leucine, 99.8:0.2 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 46.49 min, t_R(major) = 40.10 min). $[\alpha]^{23}_D$ –60˚ (c 5.1, $CHCl_3$); lit.[38] $[\alpha]^{20}_D$ –72.3˚ (*c* 5.63, CH_2Cl_2).

(*R*)-Styrene oxide (Table 5, entry 1). Method A. The catalyst ((*R,R*)-**1**, 966 mg, 1.60 mmol, 0.008 equiv) in 20 mL CH_2Cl_2 was treated 1 mL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-styrene oxide (22.8 mL, 24.0 g, 200 mmol) and THF (2 mL). The solution was cooled

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to 0 °C and treated with H_2O (2.0 mL, 110 mmol, 0.55 equiv). After 72 h at rt, (*R*)-styrene oxide (10.5 g, 87.4 mmol, 44%) was isolated by vacuum distillation (27 °C, 0.25 torr) into a cooled (-78 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis ((*R*,*R*)-Whelk-O 1, 99:1 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 8.42 min, t_R(major) = 10.48 min). $[\alpha]^{23}_D$ +28.6° (neat); lit.[39] $[\alpha]^{20}_D$ +34.3° (neat).

(*R*)-4-Chlorostyrene oxide (Table 5, entry 2). Method A. The catalyst ((*R,R*)-**1**, 193 mg, 320 μmol, 0.008 equiv) in 5 mL CH_2Cl_2 was treated 200 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-4-chlorostyrene oxide[40] (6.20 g, 40 mmol) and THF (400 μL). The solution was cooled to 0 °C and treated with H_2O (400 μL, 22.2 mmol, 0.55 equiv). After 40 h at rt, (*R*)-4-chlorostyrene oxide (2.41 g, 15.5 mmol, 38%) was isolated by vacuum distillation (40 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis ((*R*,*R*)-Whelk-O 1, 99.75:0.25 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 12.56 min, t_R(major) = 16.76 min). $[\alpha]^{24}_D$ –23.8° (*c* 3.41, $CHCl_3$); lit.[69] $[\alpha]^{20}_D$ +19.3° (*c* 1.16, $CHCl_3$, (*S*)-epoxide).

(*R*)-3-Chlorostyrene oxide (Table 5, entry 3). Method A. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.008 equiv) in 5 mL CH_2Cl_2 was treated 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-chlorostyrene oxide[41] (7.75 g, 50 mmol). The solution was cooled to 0 °C and treated with H_2O (500 μL, 27.5 mmol, 0.55 equiv). After 40 h at rt, (*R*)-3-chlorostyrene oxide (3.10 g, 20.0 mmol, 40%) was isolated by vacuum distillation (55 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis ((*R*,*R*)-Whelk-O 1, 99.75:0.25 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 11.11 min, t_R(major) = 13.56 min). $[\alpha]^{26}_D$ +21° (*c* 2.9, EtOH); lit.[42] $[\alpha]_D$ 24.05° (*c* 1.24, EtOH, 95% ee).

(*R*)-2-Chlorostyrene oxide (Table 5, entry 6). Method A. The catalyst ((*R,R*)-**1**, 181 mg, 300 μmol, 0.015 equiv) in 5 mL CH_2Cl_2 was treated 200 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-2-chlorostyrene oxide[43] (3.10 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 °C and treated with H_2O (200 μL, 11 mmol, 0.55 equiv). After 40 h at rt, (*R*)-2-chlorostyrene oxide (1.16 g, 7.48 mmol, 38%) was isolated by vacuum distillation (32 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis ((*R*,*R*)-Whelk-O 1, 99.75:0.25

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hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 8.31 min, t_R(major) = 9.39 min). $[\alpha]^{26}_D$ –60.3˚ (*c* 3.22, $CHCl_3$); lit.[72] $[\alpha]^{25}_D$ +32.2˚ (*c* 1.19, $CHCl_3$, (*S*)-epoxide).

(*S*)-3-Methoxystyrene oxide (Table 5, entry 4). Method A. The catalyst ((*S*,*S*)-**1**, 97 mg, 160 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated 100 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-methoxystyrene oxide[44] (3.00 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (200 μL, 11 mmol, 0.55 equiv). After 40 h at rt, (*S*)-3-methoxystyrene oxide (1.23 g, 8.21 mmol, 41%) was isolated by vacuum distillation (28 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralpak® AS, 95:5 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 5.38 min, t_R(major) = 6.04 min). $[\alpha]^{24}_D$ +11.5˚ (*c* 2.94, $CHCl_3$).

(*R*)-3-Nitrostyrene oxide (Table 5, entry 5). Method A. The catalyst ((*R*,*R*)-**1**, 97 mg, 160 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated 100 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-nitrostyrene oxide[45] (3.30 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (200 μL, 11 mmol, 0.55 equiv). After 40 h at rt, the reaction mixture was purified by flash chromatography over silica gel using 4:1 hexanes:EtOAc as the eluent yielded (*R*)-3-nitrostyrene oxide (1.26 g, 7.64 mmol, 38%) as an opaque yellow solid. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis (Chiralpak® AS, 99:1 hexanes:*i*-PrOH, 1 mL / min, 254 nm, t_R(minor) = 22.45 min, t_R(major) = 24.97 min). $[\alpha]^{24}_D$ –2.9˚ (*c* 1.72, $CHCl_3$).

(*S*)-1,2-Hexanediol (Table 6, entry 2). Method B. The catalyst ((*R,R*)-**1**, 302 mg, 500 μmol, 0.005 equiv) was dissolved in (±)-1,2-epoxyhexane (12.1 mL, 10.0 g, 100 mmol) containing 2-3% AcOH (Aldrich). The solution was cooled to 0 ˚C and H_2O (0.810 mL, 45 mmol, 0.45 equiv) was added in one portion. After 10 h, the residual epoxide was isolated by vacuum transfer at 0.25 torr into a cooled (-78 ˚C) receiving flask and (*S*)-1,2-hexanediol (5.29 g, 44.8 mmol, 44%) was distilled under reduced pressure (65 ˚C, 0.25 torr). The ee of the product was determined to be 99.2% by chiral GC analysis of the bistrifluoroacetate (G-TA, 60 ˚C, 2 min, 1 ˚C / min, t_R(minor) = 8.98 min, t_R(major) = 10.27 min). $[\alpha]^{25}_D$ –3.9˚ (neat); lit.[46] $[\alpha]^{22}_D$ +15.2˚ (*c* 13.14, EtOH, *R*-diol).

(*S*)-1,2-Propanediol (Table 6, entry 1). Method A. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.002 equiv) in 5 mL PhMe was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-propylene oxide (14.0 mL, 11.62 g, 200 mmol). The solution was cooled to 0 ˚C and treated with H_2O (1.62 mL, 90 mmol). After 12 h, the residual propylene oxide was distilled from the reaction mixture and (*S*)-1,2-propanediol (6.81 g, 89.6 mmol, 45%)

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was isolated by vacuum distillation (50 °C, 0.25 torr). The ee of the product was determined to be 99.1% by chiral GC analysis of the bistrifluoroacetate (G-TA, 60 °C, 2 min, 1 °C / min, t_R(minor) = 3.25 min, t_R(major) = 5.04 min). $[\alpha]^{23}_D$ +17.2° (neat); lit.[47] $[\alpha]^{25}_D$ +17.48° (neat).

(*R*)-1,2-Tetradecanediol (Table 6, entry 3).[48] Method A. The catalyst ((*S,S*)-**1**, 242 mg, 400 μmol, 0.005 equiv) in 6 mL CH_2Cl_2 was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1,2-epoxytetradecane (20.1 mL, 17.0 g, 80.0 mmol) and TBME (16 mL). The solution was cooled to 0 °C and treated with H_2O (720 μL, 40.0 mmol). After 16 h at rt, the resulting heterogeneous mixture was concentrated *in vacuo*, the solid was collected by vacuum filtration and rinsed with 100 mL 95:5 hexanes:EtOAc. The powder obtained (8.28 g, 36.0 mmol, 36%) was determined to be >99% ee by HPLC analysis of the dibenzoate ester ((*S*,*S*)-Whelk-O 1, 1.5 mL / min, 98:2 hexanes:*i*-PrOH, 240 nm, t_R(minor) = 9.02 min, t_R(major) = 7.99 min). $[\alpha]^{28}_D$ –0.90° (c 1.13, $CHCl_3$).

(*S*)-5-Hexene-1,2-diol (Table 6, entry 4). Method B. The catalyst ((*R,R*)-**1**, 302 mg, 500 μmol, 0.005 equiv) was dissolved in (±)-1,2-epoxy-5-hexene (11.3 mL, 9.82 g, 100 mmol), AcOH (120 μL, 2.1 mmol, 0.02 equiv) and THF (1 mL). The solution was cooled to 0 °C and H_2O (0.810 mL, 45 mmol, 0.45 equiv) was added in one portion. After 10 h, the residual epoxide was was isolated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask and (*S*)-5-hexene-1,2-diol (5.20 g, 44.8 mmol, 44%) was distilled under reduced pressure (68 °C, 0.25 torr). The ee of the product was determined to be 99.3% by chiral GC analysis of the bistrifluoroacetate (G-TA, 60 °C, 2 min, 1 °C / min, t_R(minor) = 9.32 min, t_R(major) = 10.50 min). $[\alpha]^{23}_D$ –3.9° (neat); lit.[49] $[\alpha]_D$ –19.04° (*c* 10.0, EtOH).

(*S*)-3-Phenyl-1,2-propanediol (Table 6, entry 5). Method B. The catalyst ((*R,R*)-**1**, 30 mg, 50 μmol, 0.005 equiv) was dissolved in (±)-(2,3-epoxypropyl)benzene (1.31 mL, 1.34 g, 10 mmol), AcOH (11 μL, 0.2 mmol, 0.02 equiv) and 0.1 mL THF. The solution was cooled to 0 °C and treated with H_2O (81 μL, 4.5 mmol, 0.45 equiv). After 12 h, the reaction was diluted with 4:1 hexanes:CH_2Cl_2 and organic layer was extracted 3 X 5 mL H_2O. The aqueous layer was filtered to remove solid catalyst reside and concentrated *in vacuo* to yield (*S*)-3-phenyl-1,2-propanediol (0.611 g, 4.02 mmol, 40%). The ee of the product was determined to be 95% by chiral GC analysis of the bistrifluoroacetate (G-TA, 75 °C, 40 min, 1 °C / min, t_R(minor) = 42.80 min, t_R(major) = 45.99 min). $[\alpha]^{27}_D$ – 29.4° (*c* 1.10, EtOH); lit.[50] $[\alpha]^{18}_D$ –35.4° (*c* 1.00, EtOH).

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(*S*)-2-Cyclohexyl-1,2-ethanediol (Table 6, entry 6). Method B. The catalyst ((*R,R*)-**1**, 30 mg, 50 μmol, 0.005 equiv) was dissolved in (±)-vinylcyclohexane oxide[51] (1.35 mL, 1.26 g, 10 mmol), AcOH (11 μL, 0.2 mmol, 0.02 equiv) and 0.1 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (81 μL, 4.5 mmol, 0.45 equiv). After 12 h, the residual epoxide was removed *in vacuo* and (*S*)-2-cyclohexyl-1,2-ethanediol (0.590 g, 4.09 mmol, 41%) was isolated by vacuum distillation (84 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The ee of the product was determined to be 99.1% by chiral GC analysis of the bistrifluoroacetate (G-TA, 80 ˚C, isothermal, t_R(minor) = 12.85 min, t_R(major) = 14.61 min). $[\alpha]^{27}_D$ –2.6˚ (*c* 1.81, EtOH); lit.[52] $[\alpha]^{25}_D$ –9.4˚ (*c* 2.59, EtOH, 73% ee).

(*S*)-2-(*tert*-Butyl)-1,2-ethanediol (Table 6, entry 7). Method A. The catalyst ((*R,R*)-**1**, 120 mg, 200 μmol, 0.02 equiv) in 2 mL PhMe was treated with 120 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-*tert*-butyloxirane[53] (1.20 mL, 1.00 g, 10.0 mmol). The solution was treated with 0.5 mL *i*-PrOH, cooled to 0 ˚C and H_2O (81 μL, 4.5 mmol, 0.45 equiv). After 20 h, the residual epoxide was removed *in vacuo* (*S*)-2-(*tert*-butyl)-1,2-enthanediol (0.471 g, 4.0 mmol, 40%) was isolated by vacuum distillation (50 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask which solidified after standing. The product was determined to be 95% ee by chiral GC analysis of the bistrifluoroacetate (G-TA, 50 ˚C, 8 min, 2 ˚C / min, t_R(minor) = 9.63 min, t_R(major) = 12.62 min). $[\alpha]^{24}_D$ +28˚ (c 1.5, MeOH); lit.[54] $[\alpha]^{23}_D$ –28.5˚ (c 0.76, $CHCl_3$, (*R*)-diol).

(*R*)-3-Chloro-1,2-propanediol (Table 6, entry 8). Method A. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.005 equiv) in 6 mL CH_2Cl_2 was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-epichlorohydrin (6.25 mL, 7.40 g, 80.0 mmol). The solution was cooled to 0 ˚C treated with 2 mL THF and H_2O (650 μL, 36.0 mmol, 0.45 equiv). After 12 h at 4 ˚C, the residual epoxide was removed *in vacuo* at 20 ˚C. The residue was diluted with 100 mL 5:3 hexanes:EtOAc and 30 mL H_2O and the resulting mixture was filtered to remove solid. The layers were separated and the organic layer was extracted 2 X 30 mL H_2O. The combined aqueous layers were concentrated to yield (*R*)-3-chloro-1,2-propanediol (3.57 g, 32.3 mmol, 40%). The product was determined to be 95% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Cyclodex-B, 75 ˚C, isothermal, t_R(minor) = 6.57 min, t_R(major) = 6.80 min). $[\alpha]^{23}_D$ –1.24˚ (neat); lit.[55] $[\alpha]^{20}_D$ –6.4˚ (*c* 5.0, H_20).

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(*R*)-3-Bromo-1,2-propanediol (Table 6, entry 9). Method A. The catalyst ((*R,R*)- and stirred in air for 30 min, 1.21 g, 2.0 mmol, 0.02 equiv) in 20 mL CH_2Cl_2 was treated with 1.2 mL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-epibromohydrin (8.60 mL, 17.7 g, 100 mmol). The solution was cooled to 0 ˚C treated with 12 mL THF and H_2O (2.70 mL, 150 mmol, 1.5 equiv) portionwise over 10 min. After 48 h at 4 ˚C, the reaction was diluted with 35 mL PhMe and 25 mL H_2O. The layers were separated and the organic layer was extracted 2 X 25 mL H_2O. The combined aqueous layers were extracted 2 X 30 mL hexanes and concentrated to yield (*R*)-3-bromo-1,2-propanediol (14.0 g, 90.4 mmol, 90%). The product was determined to be 96% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 75 ˚C, isothermal, t_R(minor) = 15.47 min, t_R(major) = 16.09 min). $[\alpha]^{25}_D$ –0.69˚ (neat); lit.[56] $[\alpha]^{25}_D$ –3.94˚ (*c* 5.07, $CHCl_3$).

(*R*)-3-Fluoro-1,2-propanediol (Table 6, entry 10). Method A. The catalyst ((*R*,*R*)-**1**, 80 mg, 130 μmol, 0.005 equiv) in 2 mL PhMe was treated with 80 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-epifluorohydrin (2.00 g, 26.3 mmol). The solution was cooled to 0 ˚C and treated with H_2O (210 μL, 11.7 mmol, 0.45 equiv). After 12 h, the residual epoxide was removed in vacuo and (*R*)-3-fluoro-1,2-propanediol (0.928 g, 9.87 mmol, 38%) was isolated by vacuum distillation (55 ˚C, 0.25 torr) from the reaction mixture into a cooled (0 ˚C) receiving flask. The product was determined to be 97% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 60 ˚C, isothermal, t_R(minor) = 4.97 min, t_R(major) = 5.18 min). $[\alpha]^{24}_D$ –7.0˚ (*c* 10, H_2O); lit.[85] $[\alpha]^{11}_D$ –17.4˚ (*c* 3.05, EtOH).

(*R*)-1,1,1-Trifluoro-2,3-propanediol (Table 6, entry 11). Method A. The catalyst ((*R*,*R*)-**1**, 54 mg, 89 μmol, 0.005 equiv) in 2 mL PhMe was treated with 50 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1,1,1-trifluoro-2,3-epoxypropane[57] (2.00 g, 17.8 mmol). The solution was cooled to 0 ˚C and treated with H_2O (140 μL, 7.8 mmol, 0.45 equiv). After 16 h, the residual epoxide was was isolated by vacuum transfer (0.25 torr) from the reaction mixture into a cooled (-78 ˚C) receiving flask. The solid obtained was suspended in 9:1 hexanes:CH_2Cl_2 and collected by vacuum filtration. The hygroscopic solid obtained (0.962 g, 7.4 mmol, 42%) was determined to be >99% ee by HPLC analysis of the dibenzoate ester (Chiralcel® OD, 99.5:0.5 hexanes:i-PrOH, 1.0 mL / min, 230 nm, t_R(minor) = 9.38 min, t_R(major) = 11.06 min). $[\alpha]^{24}_D$ +12˚ (*c* 3.3, EtOH); lit.[58] $[\alpha]^{22}_D$ –10.95˚ (*c* 1.4, MeOH, *S*-diol, 96% ee).

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(58) Ramachandran, P. V.; Gong, B.; Brown, H. C. *J. Org. Chem.* **1995**, *60*, 41-46.

(*R*)-3-Benzyloxy-1,2-propanediol (Table 6, entry 12). Method B. The catalyst ((*R,R*)-**1**, 91 mg, 150 μmol, 0.005 equiv) was dissolved in (±)-benzyl glycidyl ether[59] (4.92 g, 30.0 mmol), AcOH (34 μL, 0.6 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (495 μL, 27.5 mmol, 0.45 equiv). After 12 h, the remaining epoxide was isolated by vacuum distillation (110 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask and (*R*)-3-benzyloxy-1,2-propanediol (2.21 g, 12.2 mmol, 40%) was obtained by vacuum distillation (110 ˚C, 0.25 torr) as a clear oil. The ee of the product was determined to be 95% by chiral HPLC analysis (Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 214 nm, t_R(minor) = 19.69 min, t_R(major) = 15.73 min). $[\alpha]^{23}_D$ –1.4˚ (*c* 3.31, EtOH); lit.[60] $[\alpha]_D$ –5.7˚ (neat).

(*R*)-3-(*tert*-Butyldimethylsiloxy)-1,2-propanediol (Table 6, entry 13). Method B. The catalyst ((*R,R*)-**1**, 60 mg, 100 μmol, 0.005 equiv) was dissolved in (±)-(*tert*-butyldimethylsilyl) glycidyl ether[61] (3.76 g, 20.0 mmol), AcOH (22 μL, 0.4 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (162 μL, 9.0 mmol, 0.45 equiv). After 12 h, the remaining epoxide was isolated by vacuum distillation (30 ˚C, 0.5 torr) into a cooled (0 ˚C) receiving flask and (*R*)-3-(*tert*-butyldimethylsiloxy)-1,2-propanediol (1.72 g, 8.35 mmol, 42%) was isolated by vacuum distillation (85 ˚C, 0.25 torr). The ee of the product was determined to be 98% by chiral HPLC analysis of the 1-napthylcarboxylate ester (obtained by acylation with 1-napthoyl chloride in CH_2Cl_2 using 1 equiv TEA at 0 ˚C and direct analysis of the product obtained, Chiralcel® OD, 97:3 hexanes:EtOH, 1 mL / min, 230 nm, t_R(minor) = 10.50 min, t_R(major) = 13.02 min). $[\alpha]^{26}_D$ +9.3˚ (*c* 2.92, EtOH).

(*R*)-3-Phenoxy-1,2-propanediol (Table 6, entry 14). Method B. The catalyst ((*R,R*)-**1**, 91 mg, 150 μmol, 0.005 equiv) was dissolved in (±)-phenyl glycidyl ether (4.50 g, 30.0 mmol), AcOH (34 μL, 0.6 mmol, 0.02 equiv) and 0.5 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (240 μL, 13.3 mmol, 0.45 equiv). After 12 h, the remaining epoxide was isolated by vacuum distillation (70 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The solid obtained remaining the reaction flask was suspended in 30 mL 4:1 hexanes:CH_2Cl_2 and filtered to yield to yield (*R*)-3-phenoxy-1,2-propanediol (2.07 g, 12.3 mmol, 41%) as an opaque white powder. The ee of the product was determined to be 95% by chiral HPLC analysis (Chiralcel® OD, 9:1 hexanes:EtOH, 1 mL / min, 260 nm, t_R(minor) = 14.21 min, t_R(major) = 9.10 min). $[\alpha]^{23}_D$ –10.0˚ (*c* 1.90, EtOH); lit.[62] $[\alpha]^{20}_D$ –10.8˚ (*c* 1, EtOH).

(*R*)-3-(1-Napthyloxy)-1,2-propanediol (Table 6, entry 15). Method B. The catalyst ((*R,R*)-**1**, 15 mg, 25 μmol, 0.005 equiv) was dissolved in (±)-(1-napthyl) glycidyl ether[63]

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(1.00 g, 5.0 mmol), AcOH (10 μL, 0.2 mmol, 0.04 equiv) and 0.1 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (40 μL, 2.25 mmol, 0.45 equiv). After 12 h, the reaction was concentrated *in vacuo*, the solid was suspended in 9:1 hexanes:CH_2Cl_2 and filtered to yield (*R*)-3-(1-napthyloxy)-1,2-propanediol (460 mg, 2.11 mmol, 42%) as an opaque white powder. The ee of the product was determined to be 97% by chiral HPLC analysis (Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 230 nm, t_R(minor) = 26.84 min, t_R(major) = 22.05 min). $[\alpha]^{25}_D$ –7.6˚ (*c* 1.2, EtOH); lit.[64] $[\alpha]^{25}_D$ –8.5˚ (*c* 4.5, MeOH).

(*S*)-4-Phenylmethoxy-1,2-butanediol (Table 6, entry 16). Method B. The catalyst ((*R*,*R*)-**1**, 91 mg, 150 μmol, 0.005 equiv) was dissolved in (±)-(2-phenylmethoxyethyl) oxirane[65] (5.34 g, 30.0 mmol), AcOH (35 μL, 0.6 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0˚C and treated with H_2O (240 μL, 13.3 mmol, 0.45 equiv). After 12 h, the remaining epoxide was isolated by vacuum distillation (70 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask and (*S*)-4-phenylmethoxy-1,2-butanediol (2.50 g, 12.7 mmol, 42%) was isolated by vacuum distillation (70 ˚C, 0.25 torr) to yield a clear oil. The ee of the product was determined to be 95% by chiral HPLC analysis of the 1-*tert*-butyl diphenylsilyl ether (Chiralcel® OD, 9:1 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 10.00 min, t_R(major) = 6.27 min). $[\alpha]^{23}_D$ –22.5˚ (c 1.10, EtOH); lit.[66] $[\alpha]^{20}_D$ +22.7˚ (*c* 5.6, EtOH, *R*-epoxide).

(*S,S*)-3,4-Epoxy-1,2-butanediol (Table 6, entry 17). Method A. The catalyst ((*S,S*)-**1**, 127 mg, 209 μmol, 0.01 equiv) in 3 mL CH_2Cl_2 was treated with 150 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-butadiene diepoxide[67] (1.80 g, 20.9 mmol) and THF (4 mL). The solution was cooled to 0 ˚C and treated with H_2O (150 μL, 8.4 mmol, 0.40 equiv). After 12 h, the reaction was concentrated by rotary evaporation and diluted with 30 mL 2:1 hexanes:CH_2Cl_2. The organic layer was extracted 3 X 10 mL H_2O and the combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*S*,*S*)-3,4-epoxy-1,2-butanediol (0.773 g, 7.43 mmol, 36%). The product was determined to be 96% ee by chiral HPLC analysis of the 1-*tert*-butyldiphenylsilyl ether (Chiralcel® OD, 95:5 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 10.16 min, t_R(major) = 8.44 min). $[\alpha]^{24}_D$ +13˚ (*c* 8.5, MeOH); lit.[68] $[\alpha]^{25}_D$ +1.29˚ (*c* 1, MeOH).

(*R*)-Butyryl glycerol (Table 6, entry 18). Method B. The catalyst ((*R,R*)-**1**, 60 mg, 100 μmol, 0.005 equiv) was dissolved in (±)-glycidyl butyrate[69] (2.88 g, 20.0 mmol), AcOH (24 μL, 0.4 mmol, 0.02 equiv) and 0.3 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (162 μL, 9.0 mmol, 0.45 equiv). After 12 h at rt, the reaction was

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(69) Ladner, W. E.; Whitesides, G. M. *J. Am. Chem. Soc.* **1984**, *106*, 7250-7251.

concentrated by rotary evaporation and the diol was recovered by flash chromatography over silica gel using 1:1 EtOAc:hexanes as the eluent. The clear viscous liquid obtained (1.46 g, 9.0 mmol, 45%) was determined to be 43% ee by chiral HPLC of the 1-*tert*-butyldiphenylsilyl ether (Chiralcel® OD, 98:2 hexanes:EtOH, 1 mL / min, 230 nm, t_R(minor) = 8.40 min, t_R(major) = 9.59 min). $[\alpha]^{26}_D$ –5.5° (*c* 10, pyridine); lit.[70] $[\alpha]^{24}_D$ –8.3° (*c* 10.0, pyridine).

(*R*)-Ethyl-3,4-dihydroxybutanoate (Table 6, entry 19). Method B. The catalyst ((*S,S*)-**1**, 30 mg, 50 μmol, 0.005 equiv) was dissolved in (±)-ethyl-3,4-epoxybutyrate[71] (1.30 g, 10.0 mmol), AcOH (12 μL, 0.2 mmol, 0.02 equiv) and 0.1 mL THF. The solution was cooled to 0 °C and treated with H_2O (80 μL, 4.5 mmol, 0.45 equiv). After 12 h, the reaction was concentrated *in vacuo* and the residue was dissolved in 9:1 hexanes:EtOAc. The organic layer was extracted 3 X 10 mL H_2O and the combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*R*)-ethyl-3,4-dihydroxybutanoate (0.613 g, 4.1 mmol, 41%). The ee of the recovered epoxide was determined to be 95% ee by chiral HPLC analysis of the 1-*tert*-butyldiphenylsilyl ether (Chiralcel® OD, 99.2:0.8 hexanes:EtOH, 1 mL / min, 230 nm, t_R(minor) = 12.88 min, t_R(major) = 10.75 min). $[\alpha]^{26}_D$ –9.3° (*c* 1.9, EtOH); lit.[72] $[\alpha]^{25}_D$ 6.22° (*c* 1.22, $CHCl_3$, *S*-diol).

(*S*)-*N*-*tert*-Butyloxycarbonyl-3-aminopropane-1,2-diol (Table 6, entry 20). Method A. The catalyst ((*R,R*)-**1**, 121 mg, 200 μmol, 0.02 equiv) in 5 mL CH_2Cl_2 was treated with 150 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-{[(*tert*-butoxycarbonyl)amino]methyl} oxirane[73] (1.73 g, 10 mmol). The solution was treated with 0.3 mL THF, cooled to 0 °C and treated with H_2O (80 μL, 11 mmol, 0.45 equiv). After 12 h at rt, the reaction was concentrated by rotary evaporation and the diol was recovered by flash chromatography over silica gel using 95:5 EtOAc:EtOH as the eluent. The solid obtained (680 mg, 35.6 mmol, 36%) was determined to be 78% ee by chiral HPLC of the 1-*tert*-butyldiphenylsilyl ether (Chiralcel® OD, 96:4 hexanes:*i*-PrOH, 1 mL / min, 220 nm, t_R(minor) = 7.95 min, t_R(major) = 9.74 min). $[\alpha]^{25}_D$ –6.1° (*c* 1.2, MeOH); lit.[74] $[\alpha]^{20}_D$ +13.6° (*c* 0.72, MeOH, *R*-diol).

(*R*)-Methyl-2,3-dihydroxypropanoate (Table 6, entry 21). Method A. The catalyst ((*R,R*)-**1**, 181 mg, 300 μmol, 0.02 equiv) in 3 mL CH_2Cl_2 was treated with 200 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after

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concentration was dissolved in (±)-methyl glycidate[75] (1.53 g, 15 mmol). The solution was treated with 0.4 mL THF, cooled to 0 ˚C and treated with H_2O (120 μL, 6.7 mmol, 0.45 equiv). After 12 h at rt, the reaction was diluted 30 mL 1:1 hexanes:EtOAc and the organic layer was extracted 3 X 10 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*R*)-methyl-2,3-dihydroxypropanoate (0.670 g, 5.58 mmol, 37%). The product was determined to be 97% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 95 ˚C, isothermal, t_R(minor) = 6.29 min, t_R(major) = 6.71 min). $[\alpha]^{26}_D$ +6.6˚ (*c* 4.8, $CHCl_3$); lit.[76] $[\alpha]^{31}_D$ +4.1˚ (*c* 1.7, $CHCl_3$).

(*R*)-3,4-Dihydroxy-2-butanone (Table 6, entry 22). Method A. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.02 equiv) in 5 mL CH_2Cl_2 was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3,4-epoxy-2-butanone[77] (1.72 g, 20 mmol). The solution was treated with 0.5 mL THF, cooled to 0 ˚C, treated with H_2O (160 μL, 9.0 mmol, 0.45 equiv). After 6 h at rt, the reaction was diluted 30 mL 1:1 hexanes:EtOAc and the organic layer was extracted 3 X 10 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*R*)-3,4-dihydroxy-2-butanone (0.840 g, 8.08 mmol, 40%). The product was determined to be 97% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 95 ˚C, isothermal, t_R(minor) = 4.12 min, t_R(major) = 4.37 min). $[\alpha]^{26}_D$ –70.1˚ (*c* 5.80, $CHCl_3$); lit.[78] $[\alpha]_D$ +0.3˚ (*c* 4, H_2O).

(*R*)-1,2-Dihydroxy-3-pentanone (Table 6, entry 23). Method A. The catalyst ((*R,R*)-**1**, 181 mg,300 μmol, 0.02 equiv) in 5 mL CH_2Cl_2 was treated with 180 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1,2-epoxy-3-pentanone[79] (1.50 g, 15 mmol). The solution was treated with 0.2 mL THF, cooled to 0 ˚C, treated with H_2O (120 μL, 6.7 mmol, 0.45 equiv). After 6 h at rt, the reaction was diluted 30 mL 1:1 hexanes:EtOAc and the organic layer was extracted 3 X 10 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*R*)-1,2-dihydroxy-3-pentanone (0.580 g, 4.90 mmol, 33%). The product was determined to be 96% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 95 ˚C, isothermal, t_R(minor) = 6.24 min, t_R(major) = 6.93 min). $[\alpha]^{26}_D$ –65.6˚ (*c* 4.17, $CHCl_3$).

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(*S*)-3-Butene-1,2-diol (Table 6, entry 30). Method B. The catalyst ((*R,R*)-**1**, 302 mg, 500 μmol, 0.005 equiv) was dissolved in (±)-butadiene monoxide[80] (7.0 g, 100 mmol) and AcOH (110 μL, 2 mmol, 0.02 equiv). The solution wascooled to 0 ˚C and treated with H_2O (810 μL, 45 mmol, 0.45 equiv). After 12 h at 4 ˚C, the residual epoxide was removed *in vacuo* and (*S*)-3-butene-1,2-diol (3.36 g, 38.2 mmol, 38%) was isolated by vacuum distillation (0.25 torr, 50 ˚C). The ee of the product was determined to be 97% by chiral GC analysis of the bistrifluoroacetate (G-TA, 47 ˚C, 8 min, 2 ˚C / min, t_R(minor) = 10.28 min, t_R(major) = 11.58 min). $[\alpha]^{25}_D$ –44˚ (*c* 2.5, *i*-PrOH); lit.[81] $[\alpha]^{22}_D$ –43.6˚ (*c* 4.62, *i*-PrOH).

(*S*)-1-(*tert*-Butyldimethylsilyl)-3,4-dihydroxy-1-butyne (Table 6, entry 31). Method A. The catalyst ((*R,R*)-**1**, 24 mg, 40 μmol, 0.008 equiv) in 1 mL CH_2Cl_2 was treated with 50 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-1-(*tert*-butyldimethylsilyl)-3,4-epoxy-1-butyne[82] (910 mg, 5.0 mmol). The solution was treated with 200 μL *i*-PrOH, cooled to 0 ˚C and treated with H_2O (40 μL, 2.2 mmol, 0.45 equiv). After 12 h at rt, the remaining epoxide was isolated by vacuum distillation (36 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The residue left was suspended in MeOH and the catalyst was removed by filtration. The filtrate was concentrated to yield (*S*)-1-(*tert*-butyldimethylsilyl)-3,4-dihydroxy-1-butyne (389 mg, 2.1 mmol, 41%). The product was determined to be 99% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 100 ˚C, 20 min, 5 ˚C / min, t_R(minor) = 21.78 min, t_R(major) = 22.17 min). $[\alpha]^{27}_D$ +9.8˚ (*c* 1.2, EtOH).

(*S*)-2-Phenyl-1,2-ethanediol (Table 6, entry 24). Method A. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.008 equiv) in 6 mL CH_2Cl_2 was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-styrene oxide (5.70 mL, 6.00 g, 50 mmol) and THF (0.5 mL). The solution was cooled to 0 ˚C and treated with H_2O (400 μL, 22.5 mmol, 0.45 equiv). After 12 h at rt, the residual epoxide was isolated by vacuum distillation (27 ˚C, 0.25 torr) into a cooled (-78 ˚C) receiving flask and (*S*)-2-phenyl-1,2-ethanediol (2.80 g, 20.3 mmol, 40%) was isolated by vacuum distillation (100 - 105 ˚C, 0.25 torr) and solidified upon standing. The product was determined to be 98% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 100 ˚C, isothermal, t_R(minor) = 18.77 min, t_R(major) = 20.39 min). $[\alpha]^{23}_D$ +38.4˚ (*c* 4.38, EtOH); lit.[83] $[\alpha]^{13}_D$ +39.3˚ (*c* 3.13, EtOH).

(*S*)-2-(4-Chlorophenyl)-1,2-ethanediol (Table 6, entry 25). Method A. The catalyst ((*R,R*)-**1**, 97 mg, 160 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated with 100 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after

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(80) Available in bulk from Eastman Kodak Co..

(81) Crawford, R. J.; Lutener, S. B.; Cockcroft, R. D. *Can. J. Chem.* **1976**, *54*, 3364-3376.

(82) Available by *m*-CPBA epoxidation of the corresponding alkene.

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concentration was dissolved in (±)-4-chlorostyrene oxide[84] (3.10 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (160 μL, 9.0 mmol, 0.45 equiv). After 16 h at rt, the reaction was diluted with 20 mL 95:5 hexanes:EtOAc and filtered to yield (*S*)-2-(4-chlorophenyl)-1,2-ethanediol (1.27 g, 7.36 mmol, 37%) as an opaque white solid. The product was determined to be 94% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 120 ˚C, 15 min, 5 ˚C / min, t_R(minor) = 19.53 min, t_R(major) = 20.03 min). $[\alpha]^{27}_D$ +27.4˚ (*c* 1.49, EtOH); lit.[85] $[\alpha]^{25}_D$ +30.1˚ (*c* 1.01, EtOH).

(*S*)-2-(3-Chlorophenyl)-1,2-ethanediol (Table 6, entry 26). Method A. The catalyst ((*R,R*)-**1**, 97 mg, 160 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated with 100 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-chlorostyrene oxide[86] (3.10 g, 20 mmol). The solution was cooled to 0 ˚C and treated with H_2O (160 μL, 9.0 mmol, 0.45 equiv). After 16 h at rt, the residual epoxide was isolated by vacuum distillation (55 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The residue was dissolved in 60 mL 95:5 hexanes:EtOAc and extracted 3 X 20 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*S*)-2-(3-chlorophenyl)-1,2-ethanediol (1.50 g, 8.67 mmol, 44%) as an opaque white solid. The product was determined to be 91% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 120 ˚C, 15 min, 5 ˚C / min, t_R(minor) = 19.30 min, t_R(major) = 19.89 min). $[\alpha]^{26}_D$ +21.1˚ (*c* 1.31, EtOH); lit.[87] $[\alpha]_D$ +24.05˚ (*c* 1.24, EtOH).

(*S*)-2-(2-Chlorophenyl)-1,2-ethanediol (Table 6, entry 29). Method A. The catalyst ((*R,R*)-**1**, 181 mg, 300 μmol, 0.015 equiv) in 5 mL CH_2Cl_2 was treated with 200 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-2-chlorostyrene oxide[88] (3.10 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (160 μL, 9.0 mmol, 0.45 equiv). After 16 h at rt, the remaining epoxide was isolated by vacuum distillation (32 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The residue was dissolved in 70 mL 9:1 hexanes:EtOAc and extracted 3 X 20 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*S*)-2-(2-chlorophenyl)-1,2-ethanediol (1.45 g, 8.36 mmol, 42%). The product was determined to be 94% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 110 ˚C, 15 min, 2 ˚C / min, t_R(minor) = 21.32 min, t_R(major) =

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21.49 min). $[\alpha]^{27}_{D}$ +65˚ (*c* 1.7, EtOH); lit.[89] $[\alpha]^{25}_{D}$ –56.5˚ (*c* 1.8, EtOH, 66% ee, *R*-diol).

(*S*)-2-(3-Methoxyphenyl)-1,2-ethanediol (Table 6, entry 27). Method A. The catalyst ((*R*,*R*)-**1**, 97 mg, 160 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated with 100 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-methoxystyrene oxide[90] (3.00 g, 20 mmol) and THF (200 μL). The solution was cooled to 0 ˚C and treated with H_2O (160 μL, 9.0 mmol, 0.55 equiv). After 16 h at rt, the residual epoxide was isolated by vacuum distillation (28 ˚C, 0.25 torr) into a cooled (0 ˚C) receiving flask. The residue was dissolved in 50 mL 9:1 hexanes:EtOAc and extracted 3 X 30 mL H_2O. The combined aqueous extracts were filtered and concentrated *in vacuo* to yield (*S*)-2-(3-methoxyphenyl)-1,2-ethanediol[91] (1.37 g, 8.18 mmol, 41%) as an opaque white solid. The product was determined to be 95% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 120 ˚C, 15 min, 5 ˚C / min, t_R(minor) = 21.73 min, t_R(major) = 22.08 min). $[\alpha]^{27}_{D}$ +26.9˚ (*c* 1.12, EtOH).

(*S*)-2-(3-Nitrophenyl)-1,2-ethanediol (Table 6, entry 28). Method A. The catalyst ((*R*,*R*)-**1**, 58 mg, 97 μmol, 0.008 equiv) in 3 mL CH_2Cl_2 was treated with 60 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-3-nitrostyrene oxide[92] (2.00 g, 12.1 mmol) and THF (100 μL). The solution was cooled to 0 ˚C and treated with H_2O (100 μL, 5.5 mmol, 0.45 equiv). After 16 h at rt, the reaction was diluted with 10 mL 9:1 hexanes:EtOAc and filtered to yield (*S*)-2-(3-nitrophenyl)-1,2-ethanediol (980 mg, 5.35 mmol, 44%) as an opaque white solid. The product was determined to be 99% ee by chiral GC analysis of the corresponding acetal prepared from 2,2-dimethoxypropane and catalytic TsOH (Chiraldex-B, 155 ˚C, isothermal, t_R(minor) = 22.08 min, t_R(major) = 22.88 min). $[\alpha]^{23}_{D}$ +18.0˚ (*c* 1.68, EtOH); lit.[93] $[\alpha]^{25}_{D}$ -19˚ (*c* 0.29, EtOH, *R*-diol).

Catalyst Recycling Experiments (Table 8). **Cycle 1.** (±)-Epichlorohydrin was resolved according to the experimental procedure outlined above. The catalyst ((*R,R*)-**1**, 242 mg, 400 μmol, 0.005 equiv) in 5 mL CH_2Cl_2 was treated with 250 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-epichlorohydrin (6.26 mL, 7.40 g, 80 mmol) and 0.8 mL THF. The solution was cooled to 0 ˚C and treated with H_2O (800 μL, 44 mmol, 0.55 equiv) and the reaction was maintained at 0 – 4 ˚C for 16 h. (*S*)-Epichlorohydrin (3.01 g, 32.5 mmol, 41%) was isolated by vacuum transfer (25 ˚C, 0.25 torr) from the reaction mixture into a cooled (-

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78 °C) receiving flask. The recovered epoxide was determined to be >99% ee by chiral GC analysis. The receiving flask was exchanged and the diol was distilled from the reaction flask (56 °C, 0.25 torr). The crude catalyst residue left in the flask was dissolved in 100 mL 3:1 hexanes:EtOAc and rinsed 3 X 100 mL H_2O. The organic layer was dried over Na_2SO_4, filtered and concentrated *in vacuo* to yield a crude catalyst residue that was utilized in the next cycle.

Cycle 2. (±)-Propylene oxide was resolved according to the experimental procedure described above. The catalyst (400 μmol, 0.002 equiv) was dissolved in 5 mL PhMe and treated with AcOH (240 μL, 4.2 mmol). After stirring at rt open to air for 30 min the solution was concentrated *in vacuo* to leave a crude brown solid once all of the residual AcOH had been removed. The resulting catalyst residue was dissolved in propylene oxide (14.0 mL, 11.6 g, 200 mmol) at rt, the solution was cooled to 0 °C, and H_2O (1.98 mL, 110 mmol, 0.55 equiv) was added dropwise over 5 min. The reaction was allowed to warm to rt and stir 14 h at which time (*R*)-propylene oxide (5.12 g, 88.1 mmol, 44%) was distilled from the reaction mixture at 36 °C. The ee of the propylene oxide was determined to be >99% by chiral GC analysis of the 1-azido-2-trimethylsiloxypropane. The propylene diol was removed by vacuum distillation (65 °C, 0.25 torr). The catalyst residue was used as is in cycle 3.

Cycle 3. (±)-Styrene oxide was resolved according to the experimental procedure described above. Method A. The catalyst (400 μmol, 0.008 equiv) in 50 mL CH_2Cl_2 was treated 0.5 mL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-styrene oxide (5.7 mL, 6.0 g, 50 mmol) and THF (0.5 mL). The solution was cooled to 0 °C and treated with H_2O (0.5 mL, 27.5 mmol, 0.55 equiv). After 72 h at rt, (*R*)-styrene oxide (2.47 g, 20.6 mmol, 41%) was isolated by vacuum distillation (27 °C, 0.25 torr) into a cooled (-78 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral HPLC analysis. The catalyst and diol mixture was allowed to solidify. The solid was treated with 100 mL 9:1 hexanes:EtOAc. The catalyst solution was filtered from the diol. The filtrate was rinsed 3 X 100 mL H_2O. The organic layer was dried over Na_2SO_4, filtered and concentrated *in vacuo* to yield a crude catalyst residue that was utilized in the next cycle.

Cycle 4. (±)-Methyl glycidate was resolved according to the experimental procedure described above. The catalyst (400 μmol, 0.02 equiv) in 10 mL CH_2Cl_2 was treated 400 μL AcOH and stirred in air for 30 min. The crude catalyst residue obtained after concentration was dissolved in (±)-methyl glycidate (2.04 g, 20 mmol) and THF (0.2 mL). The solution was cooled to 0 °C and treated with H_2O (200 μL, 11 mmol, 0.55 equiv). After 24 h at rt, (*R*)-methyl glycidate (0.82 g, 8.0 mmol, 40%) was isolated by vacuum distillation (50 °C, 0.25 torr) into a cooled (-78 °C) receiving flask. The ee of recovered epoxide was determined to be >99% by chiral GC analysis. The diol was distilled (60 C, 0.25 torr) into a cooled (0 °C) collection flask. The crude catalyst residue was dissolved in 100 mL 4:1 hexanes:EtOAc. The organic layer was rinsed 5 X 15 mL H_2O. The organic layer was dried over Na_2SO_4, filtered and concentrated *in vacuo* to yield a crude catalyst residue that was utilized in the next cycle.

Cycle 5. (±)-Phenyl glycidyl ether was resolved according to the experimental procedure described above. The catalyst (400 μmol, 0.005 equiv) was dissolved in (±)-phenyl glycidyl ether (12.0 g, 80.0 mmol), AcOH (90 μL, 1.6 mmol, 0.02 equiv) and 0.8 mL THF. The solution was cooled to 0 °C and dissolved in H_2O (800 μL, 44.4 mmol,

0.55 equiv). After 16 h, (*S*)-phenyl glycidyl ether (5.18 g, 34.5 mmol, 43%) was isolated by vacuum distillation (80 °C, 0.25 torr) into a cooled (0 °C) receiving flask. The ee of the recovered epoxide was determined to be >99% by chiral HPLC analysis. The catalyst and diol mixture was allowed to solidify. The solid was treated with 100 mL 4:1 hexanes:EtOAc. The diol was isolated by filtration and was rinsed 3 X 100 mL H_2O. The organic solution was dried over Na_2SO_4, filtered and concentrated *in vacuo* to yield a crude catalyst residue that was utilized in the next cycle.

Cycle 6. (±)-1,2-Epoxyhexane was resolved according to the experimental procedure described above. Method B. The catalyst (400 μmol, 0.005 equiv) was dissolved in (±)-1,2-epoxyhexane (9.6 mL, 8.0 g, 80 mmol) containing 2-3% AcOH (available from Aldrich). The solution was cooled to 0 °C and H_2O (0.80 mL, 44 mmol, 0.55 equiv) was added in one portion. After 16 h, (*R*)-1,2-epoxyhexane (3.28 g, 32.8 mmol, 41%) was was isolated by vacuum transfer at 0.25 torr into a cooled (-78 °C) receiving flask. The diol was distilled under reduced pressure (65 °C, 0.25 torr). The ee of the recovered epoxide was determined to be >99% by chiral GC analysis of the 1-azido-2-trimethylsiloxyhexane. The catalyst residue was suspended in MeOH and recovered by filtration (212 mg, 351 μmol, 88% of the amount introduced in cycle 1).