Asymmetric Synthesis of Methylenetetrahydrofurans by Palladium-Catalyzed [3+2] Cycloaddition of Trimethylenemethane with Aldehydes – A Novel Ligand Design

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Supporting Information

A. General Methods. All reactions were carried out under an argon atmosphere. All solvents were dried by passing through an Alumina column. All compounds were purchased from commercial sources unless listed. The following compounds were prepared according to known literature procedures: Pd(dba)$_2$\textsuperscript{1}, 3-acetoxy-2-trimethylsilylmethyl-1-propene\textsuperscript{2}, L$_1$-L$_4$\textsuperscript{3}, L$_5$\textsuperscript{4}, (E)-2-benzylidene-3-methylbutanal\textsuperscript{5}. Liquid aldehydes were purified by distillation immediately prior to use. 4-Chlorobenzaldehyde was purified by sublimation under reduced pressure. For TMM reactions at room temperature, toluene was degassed by bubbling argon through the solvent for 15 minutes.

Flash chromatography was performed with 0.040-0.063 µm Silica Gel. $^1$H and $^{13}$C NMR spectroscopy was performed on a Mercury NMR at 400 ($^1$H) or 100 ($^{13}$C) MHz and Unity NMR at 500 ($^1$H) or 125 ($^{13}$C) MHz. Chemical shifts are reported in ppm relative to tetramethylsilane or residual protiated solvent. All $^{13}$C NMR spectra were proton decoupled. Infrared spectroscopic data was recorded on sodium chloride plates as thin films on a Perkin-Elmer Paragon 500 FT-IR spectrometer. Chiral HPLC analysis was performed on a Thermo Separation Products Spectra Series P-100 and on an Agilent Technologies 1200 Series using Chiralcel\textsuperscript{®} columns. Optical rotations were measured on a Jasco DIP-1000 digital polarimeter using 5 cm glass cells with a Na 589 nm filter.

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B. Ligand Synthesis

**General procedure A for phosphoramidite synthesis.** To a solution of PCl$_3$ (10.8 µL, 0.124 mmol) in THF (0.5 ml) at 0 °C was added triethylamine (86 µL, 0.62 mmol) and the milky mixture was stirred for 20 minutes. To this suspension was added a solution of (2R,5R)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol)$^6$ in THF (0.2 ml) by cannula, and the reaction was stirred for 3 hours, allowing for gradual warming to ambient temperature. It was then cooled to -78 °C and a solution of the BINOL derivative (0.124 mmol) in THF (0.5 ml) was added dropwise by cannula over 2-3 minutes. The reaction was allowed to stir overnight with gradual warming to ambient temperature, concentrated and purified by flash chromatography. The purified products were concentrated from approximately 5:1 hexane/dichloromethane to yield a white powder.

**Ligand L7:** The reaction was performed according to general procedure A using (2R,5R)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and (R)-3-methyl-1,1′-binaphthyl-2,2′-diol$^7$ (37.2 mg, 0.124 mmol) and purified by flash chromatography (25% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white

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powder (53.0 mg, 66% yield, dr 9:1 as determined by the methyl resonances at $\delta 2.26$ and $\delta 1.95$ in the $^1H$ spectrum). $^1H$ NMR (400 MHz, CDCl$_3$): $\delta$ 7.87-7.77 (m, 5H), 7.71-7.68 (m, 2H), 7.62 (bs, 2H), 7.54-7.41 (m, 8H), 7.32-6.94 (m, 10H), 6.47 (d, $J = 8.4$ Hz, 0.1 H, minor), 6.27 (s, 1H), 5.91 (d, $J = 8.4$ Hz, 0.1 H, minor), 5.42 (d, $J = 6.8$ Hz, 2H, major), 5.38 (d, $J = 6.8$ Hz, 0.3H, minor) 2.71-2.66 (m, 2H), 2.26 (s, 0.35 H, minor), 1.95 (s, 3H, major), 1.93-1.90 (m, 2H). $^{13}C$ NMR (100 MHz, CDCl$_3$): $\delta$ 149.6, 149.1 (d, $J = 8.2$ Hz), 143.3 (d, $J = 3.7$ Hz), 133.6, 133.2 (d, $J = 1.5$ Hz), 132.9, 131.62, 131.56 (d, $J = 1.5$ Hz), 130.5, 130.2, 129.6, 129.3, 128.8, 128.5, 128.3, 128.2, 127.9, 127.7, 127.4, 126.7, 126.4, 126.0, 125.8, 125.7 (d, $J = 1.5$ Hz), 125.6 (d, $J = 1.5$ Hz), 124.8, 124.7, 124.2, 122.2 (d, $J = 1.6$ Hz), 120.9 (d, $J = 3.0$ Hz), 63.5 (d, $J = 12.6$ Hz), 34.4 (d, $J = 2.2$ Hz), 18.4. $^{31}P$ NMR (162 MHz): $\delta$ 149.4 (major), 143.5 (minor). IR (thin film): 3052, 2966, 1591, 1505, 1237 cm$^{-1}$. $[\alpha]_{24}^{D} = -36.6$ (c 0.52, CHCl$_3$). HRMS: calcd for (M+H$^+$) C$_{45}$H$_{35}$NO$_2$P 652.2405; found 652.2375.

Ligand L8: The reaction was performed according to general procedure A using (2$R$,5$R$)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and ($R$)-3-ethyl-1,1'-binaphthyl-2,2'-diol (38.9 mg, 0.124 mmol)$^7$ and purified by flash chromatography (25% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white powder (70.1 mg, 85% yield, dr 11:1 as determined by $^{31}P$ NMR). $^1H$ NMR (400 MHz, CDCl$_3$): $\delta$ 7.89-7.78 (m, 5H), 7.69-7.41 (m, 13H), 7.32-6.97 (m, 9H), 6.50 (d, $J = 8.8$ Hz, 0.1H, minor), 6.30 (s, 1H), 5.89 (d, $J = 8.8$ Hz, 0.1H, minor), 5.41 (d, $J = 7.2$ Hz, 2H, major), 5.37 (d, $J = 7.2$ Hz, 0.26H, minor), 2.75-2.62 (m, 3H), 1.98 (apparent sextet, $J = 7.6$ Hz, 1H), 1.90-1.88 (m, 2H), 0.88 (t, $J = 7.6$ Hz, 3H). $^{13}C$ NMR (100 MHz, CD$_2$Cl$_2$):
δ 149.9, 149.0 (d, 7.5 Hz), 143.5 (d, J = 4.5 Hz), 135.6, 133.9, 133.4 (d, J = 1.5 Hz), 133.1, 131.9, 131.6 (d, J = 1.5 Hz), 131.0, 130.5, 128.8, 128.5, 128.3, 128.3, 128.0, 127.6, 127.4, 126.63, 126.58, 126.3, 126.1, 125.6, 125.95 (d, J = 1.5 Hz), 125.1, 125.0, 124.5, 122.3 (d, J = 1.5 Hz), 121.1 (d, J = 2.5 Hz), 63.8 (d, J = 1.5 Hz), 34.6 (d, J = 2.2 Hz), 25.2, 13.8. 31P NMR (162 MHz, CDCl3): δ 149.6 (major), 144.5 (minor). IR (thin film): 3052, 2965, 1506, 1460, 1234 cm⁻¹. [α]24D = -46.9 (c 0.42, CHCl₃). HRMS: calcd for (M+H⁺) C₄₆H₃₇NO₂P 666.2562; found 666.2533.

(R)-3-isopropyl-1,1'-binaphthyl-2,2'-diol:

1. A solution of (R)-2,2'-bis(methoxymethoxy)-1,1'-binaphthyl (1.0 g, 2.68 mmol) in THF (8 ml) was cooled to -78 °C and n-butyl lithium (1.28 ml, 2.49 M in hexanes, 3.2 mmol) was added dropwise over 2 minutes. After 20 minutes at -78 °C, the mixture was allowed to warm to 0 °C and stirred for 3 hours. It was then recooled to -78 °C and acetone (0.3 ml, 4.0 mmol) was added dropwise. The reaction was stirred overnight with gradual warming to RT, then quenched by the addition of saturated NH₄Cl (10 ml) and extracted with diethyl ether (2 x 10 ml). The combined organics were washed with brine (10 ml), dried over MgSO₄, concentrated, and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (751 mg, 65% yield). ¹H NMR (400 MHz, CDCl₃): δ 8.00 (d, J = 8.8 Hz, 1H), 7.95 (s, 1H), 7.88 (dd, J = 4.0, 8.0 Hz, 2H), 7.61 (d, J = 9.2 Hz, 1H), 7.41-7.35 (m, 2H), 7.31-7.11 (m, 4H), 5.12 (d, J = 7.2 Hz, 1H), 5.09 (d, J = 7.2 Hz, 1H), 4.79 (s, 1H), 4.60 (d, J = 5.2 Hz, 1H), 4.35 (d, J = 5.2 Hz, 1H), 3.24 (s, 3H), 3.18 (s, 3H), 1.84 (s, 3H), 1.84 (s, 3H).

2. To a solution of the above adduct (376 mg, 0.87 mmol) and triethylsilane (0.43 ml, 2.69 mmol) in DCM (5 ml) was added trifluoroacetic acid (0.17 ml, 2.22 mmol). After 25 minutes, the reaction was quenched with solid K₂CO₃, filtered, and purified by chromatography (25% ethyl acetate in hexanes) to yield 2 distinct products (385 mg combined) consisting of a mixture of partially deprotected and triethylsilylated products.
The combined mixture was then dissolved in benzene (4 ml) and methanol (1 ml), and anhydrous HCl (2.0 ml, 2.0 M in diethyl ether, 4.0 mmol) was added. After stirring for 16 hours, the reaction was concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (206 mg, 76% over 2 steps). $^1$H NMR (400 MHz, CDCl$_3$): 7.99 (d, $J = 9.2$ Hz, 1H), 7.92-7.85 (m, 3H), 7.41-7.06 (m, 7H), 5.1 (bs, 2H), 3.48 (apparent quintet, $J = 6.8$ Hz, 1H), 1.41 (d, $J = 6.8$ Hz, 3H), 1.40 (d, $J = 6.8$ Hz, 3H).

$^{13}$C NMR (100 MHz, CDCl$_3$): 153.2, 151.7, 137.7, 133.8, 132.1, 131.7, 129.84, 129.82, 128.7, 128.3, 127.8, 127.1, 126.8, 124.6, 124.3, 124.23, 124.17, 118.1, 111.5, 110.7, 28.2, 22.99, 22.95 IR (thin film): 3517, 1960, 1619, 1596, 1384, 1211, 1144 cm$^{-1}$. $\alpha_{24}^D = +40.2$ (c 0.73, CHCl$_3$).

**Ligand L9:** The reaction was performed according to general procedure A using (2$R$,5$R$)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and ($R$)-3-isopropyl-1,1'-binaphthyl-2,2'-diol (40.6 mg, 0.124 mmol) and purified by flash chromatography on deactivated alumina oxide (10% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white powder (71 mg, 84% yield, dr 5:1 as determined by $^{31}$P NMR). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.93-7.72 (m, 5H), 7.68-7.63 (m, 4H), 7.56-7.53 (m, 2H), 7.74-6.92 (m, 13H), 6.76 (s, 0.82H, major), 6.54 (d, $J = 8.8$ Hz, 0.17H, minor), 5.88 (d, $J = 8.8$ Hz, 0.17H, minor), 5.33 (m, 2H), 3.10-2.97 (m, 1H), 2.64-2.52 (m, 2H), 1.99-1.82 (m, 2H), 1.01 (d, $J = 6.8$ Hz, 3H), 0.71 (d, $J = 6.8$ Hz, 3H). $^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ 149.5, 148.8 (d, $J = 8.7$ Hz), 142.5 (d, $J = 4.5$ Hz), 139.7, 133.8, 133.6, 133.3, 133.1, 132.8, 131.6 (d, $J = 9.0$ Hz), 130.6, 130.3, 128.6, 128.5, 128.19, 128.16, 128.0, 127.5, 126.7, 126.5, 126.3, 126.0, 125.8, 125.7 (d, $J = 1.4$ Hz), 124.9, 124.8 (d, $J = 4.4$ Hz), 124.3, 122.2, 121.40 (d, $J = 3.0$ Hz), 63.5 (d, $J = 11.9$ Hz), 34.6 (d, $J = 1.6$ Hz),
28.7, 24.6, 20.2. $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta$ 149.4 (major), 144.9 (minor). IR (thin film): 3052, 2961, 1232 cm$^{-1}$. $[\alpha]_{27}^D$ = -68.9 (c 0.84, CHCl$_3$).

Scheme 1 - Synthesis of BINOL precursors for ligands L10 and L11

(R)-2,2'-dimethoxy-1,1'-binaphthyl-3-ol: A solution of (R)-2,2'-dimethoxy-1,1'-binaphthyl (2.00 g, 6.36 mmol) in THF (106 ml) was prepared by gentle heating until all solids had dissolved. It was then cooled to -78 °C and n-butyl lithium (10.0 M in hexanes, 1.15 ml, 11.5 mmol) was added. The reaction was stirred for 30 minutes at -78 °C before it was warmed to 0 °C and stirred for 3 hours. The brown solution was then recooled to -78 °C and trimethyl borate (1.4 ml, 12.7 mmol) was added dropwise, during which the solution became clear. After stirring overnight with gradual warming to room temperature, the reaction was concentrated, benzene (40 ml) and H$_2$O$_2$ (2.45 ml, 30% aq.) were added, and the mixture was refluxed for 2 hours. It was finally cooled, quenched with saturated aq. NaHSO$_3$ (15 ml) and the layers were separated. The aqueous phase was extracted with ethyl acetate (2 x 20 ml) and the combined organics were washed with
brine (20 ml), dried over MgSO₄, concentrated and purified by chromatography (30% ethyl acetate in hexanes) to yield a red and white foam (1.49 g, 71% yield). ¹H NMR (400 MHz, CDCl₃): δ 8.00 (d, J = 9.2 Hz, 1H), 7.86 (d, J = 8.0 Hz, 1H), 7.73 (d, J = 8.4 Hz, 1H), 7.45-7.42 (m, 2H), 7.34-7.15 (m, 4H), 7.07-7.06 (m, 2H), 6.15 (s, 1H), 3.78 (s, 3H), 3.37 (s, 3H). ¹³C NMR (100 MHz, CDCl₃): δ 155.2, 147.9, 146.2, 134.1, 131.8, 130.4, 129.2, 129.0, 128.2, 127.1, 126.9, 125.6, 125.5, 125.4, 124.1, 124.0, 129.9, 118.5, 113.7, 110.0, 61.0, 56.8. IR (thin film): 3496, 3056, 2937, 1836, 1620, 1592, 1462 cm⁻¹. [α]₂⁶D = +20.2 (c 1.02, CHCl₃).

(R)-3-(2,2-diethoxyethoxy)-2,2'-dimethoxy-1,1'-binaphthalene: To a suspension of naphthol (3.46 g, 10.5 mmol) and Cs₂CO₃ (5.19 g, 15.9 mmol) in DMSO (49 ml) was added bromoacetaldehyde diethyl acetal (1.71 ml, 11.7 mmol). The suspension was stirred for 15 hours at 80 ºC then cooled, quenched with water (50 ml) and extracted with ethyl acetate (3 x 50 ml). The combined organics were washed with brine (50 ml), dried over MgSO₄, concentrated and purified by chromatography (20% ethyl acetate in hexanes) to yield a white solid (4.23 g, 90% yield). ¹H NMR (400 MHz, CDCl₃): δ 7.99 (d, J = 9.2 Hz, 1H), 7.86 (d, J = 8.0 Hz, 1H), 7.76 (d, J = 8.0 Hz, 1H), 7.45 (d, J = 9.2 Hz, 1H), 7.36-7.28 (m, 3H), 7.23-7.19 (m, 1H), 7.13-7.09 (m, 2H), 7.02 (d, J = 8.0 Hz, 1H), 5.02 (t, J = 5.2 Hz, 1H), 4.25 (d, J = 5.2 Hz, 2H), 3.88-3.79 (m, 2H), 3.78 (s, 3H), 3.75-3.67 (m, 2H), 3.61 (s, 3H), 1.27 (t, J = 6.8 Hz, 3H), 1.26 (t, J = 6.8 Hz, 3H). ¹³C NMR (100 MHz, CDCl₃): δ 155.0, 151.6, 147.7, 134.3, 131.4, 129.8, 129.3, 129.2, 128.1, 126.9, 126.7, 125.8, 125.5, 125.4, 124.3, 123.8, 119.2, 113.8, 108.4, 100.9, 69.2, 63.2, 63.1, 60.7, 56.8, 15.6. IR (thin film): 3056, 2973, 2933, 1593, 1507, 1463 cm⁻¹. [α]₂⁵D = +42.7 (c 0.66, CHCl₃).
(R)-4-methoxy-5-(2-methoxynaphthalen-1-yl)naphtho[2,1-b]furan: A mixture of acetal (1.75 g, 3.92 mmol), polyphosphoric acid (approximately 0.9 g) and benzene (12 ml) was refluxed for 5 hours, then cooled, concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white solid (1.33 g, 96% yield). MP 206 °C (crystallized from 15% ethyl acetate in hexanes). $^1$H NMR (400 MHz, CDCl₃): $\delta$ 8.14 (d, $J = 8.4$ Hz, 1H), 7.98 (d, $J = 9.2$ Hz, 1H), 7.86 (d, $J = 8.4$ Hz, 1H), 7.80 (d, $J = 2.1$ Hz, 1H), 7.45 (d, $J = 9.2$ Hz, 1H), 7.44 (dt, $J = 1.8$, 7.6 Hz, 1H), 7.34 (d, $J = 2.1$ Hz, 1H), 7.30 (dt, $J = 1.8$, 7.6 Hz, 1H), 7.20-7.13 (m, 4H), 3.90 (s, 3H), 3.76 (s, 3H). $^{13}$C NMR (100 MHz, CDCl₃): $\delta$ 155.4, 146.3, 144.3, 143.6, 134.6, 131.4, 129.9, 129.4, 128.2, 126.74, 126.71, 125.5, 125.4, 125.2, 125.0, 124.8, 123.8, 123.6, 120.1, 119.3, 114.0, 106.3, 60.8, 56.9. IR (thin film): 2944, 1588, 1509, 1462, 1362 cm⁻¹. [$\alpha$]$_{25}^D$ = +86.7 (c 0.57, CHCl₃).

(R)-5-(2-hydroxynaphthalen-1-yl)naphtho[2,1-b]furan-4-ol: To a room temperature solution of naphthofuran (2.87 g, 8.1 mmol) in dichloromethane (80 ml) was added BBr₃ (16.2 ml, 1.0 M in DCM, 16.2 mmol) and the dark green solution was stirred for 2.5 hours. It was carefully quenched with water (80 ml), the layers were separated, and the aqueous layer was washed with dichloromethane (80 ml). The combined organics were dried over Na₂SO₄, concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (2.60 g, 98% yield). $^1$H NMR (400 MHz, CDCl₃): $\delta$ 8.17 (dm, $J = 8.4$ Hz, 1H), 7.95 (d, $J = 8.8$ Hz, 1H), 7.87 (d, $J = 8.0$ Hz, 1H), 7.86 (d, $J = 2.0$ Hz, 1H), 7.50-7.45 (m, 1H), 7.39-7.20 (m, 6H), 7.16 (d, $J = 8.4$ Hz, 1H), 4.99 (bs, 2H).
$^{13}$C NMR (100 MHz, CDCl$_3$): $\delta$ 153.3, 145.7, 143.3, 141.3, 134.0, 131.8, 130.8, 129.8, 128.7, 127.8, 126.4, 126.4, 125.7, 124.9, 124.6, 124.3, 124.3, 124.1, 118.1, 111.1, 108.4, 106.6. IR (thin film): 3496, 3056, 1619, 1594, 1513, 1389 cm$^{-1}$. Chiral HPLC: Chiralpak IA, 0.8 mL/min, 10% i-PrOH in heptane, $\lambda$ = 254 nm, $t_{R, \text{major}}$ = 22.9 min, $t_{R, \text{minor}}$ = 34.7 min. $[\alpha]_{23}^D = +91.2$ (c 1.05, CHCl$_3$). HRMS: calcd for (M+H$^+$) C$_{22}$H$_{15}$O$_3$ 327.1021; found 327.1007.

(R)-5-(2-hydroxynaphthalen-1-yl)-1,2-dihydrannaphtho[2,1-b]furan-4-ol: To (R)-5-(2-hydroxynaphthalen-1-yl)naphtho[2,1-b]furan-4-ol (1.15 g, 3.52 mmol) was added trifluoroacetic acid (9.2 ml, 124 mmol) followed by triethylsilane (2.28 ml, 14.1 mmol). The reaction flask was sealed and the solution was stirred at 50 ºC for 18 hours. The resulting milky suspension was cooled, concentrated under vacuum and dissolved in ethyl acetate (30 ml). After washing with sat. NaHCO$_3$ (2 x 10 ml) and brine (10 ml), the organics were dried over MgSO$_4$, concentrated and purified by flash chromatography (30% ethyl acetate in hexanes) to give the product as a white solid (0.98 g, 85% yield). MP 234-236 ºC. $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.96 (d, $J$ = 9.0 Hz, 1H), 7.88 (d, $J$ = 7.6 Hz, 1H), 7.67 (d, $J$ = 7.6 Hz, 1H), 7.42-7.26 (m, 4H), 7.20-7.13 (m, 3H), 5.14 (bs, 2H), 4.92 (q, $J$ = 8.8 Hz, 1H), 4.82 (q, $J$ = 8.8 Hz, 1H), 3.73-3.59 (m, 2H). $^{13}$C NMR (100 MHz, DMSO-d$_6$): $\delta$ 153.2, 148.4, 141.0, 134.3, 129.7, 128.8, 128.1, 127.9, 125.9, 125.3, 125.2, 124.4, 123.2, 122.88, 122.85, 122.3, 119.2, 118.5, 116.9, 115.0, 71.7, 28.9. IR (thin film): 3450, 3422, 3058, 2965, 2897, 1623, 1514, 1453 cm$^{-1}$. $[\alpha]_{26}^D = +67.7$ (c 0.87, CHCl$_3$). HRMS: calcd for (M+H$^+$) C$_{22}$H$_{17}$O$_3$ 329.1177; found 329.1164.
**Ligand L10:**

1. Freshly distilled PCl₃ (3 ml, 34.0 mmol) was added to \((R)-5-(2\text{-hydroxynapthalen-1-yl})\text{naphtho}[2,1-b]\text{furan-4-ol}\) (282 mg, 0.86 mmol) followed by a single drop of N-Methyl-2-pyrrolidone. The mixture was stirred for 15 minutes at 60 °C, cooled, concentrated, and concentrated from toluene (2 x 5 ml). The residue was then dissolved in toluene (1.7 ml) to give a 0.5 M solution (assuming full conversion) as a mixture of diastereomers. \(^{31}\text{P NMR (162 MHz, CDCl}_3\): \(\delta\) 181.8, 181.7.

2. To a solution of \((2R,5R)-2,5\text{-di(naphthalen-2-yl)pyrrolidine}\) (152 mg, 0.47 mmol), triethylamine (0.33 ml, 2.34 mmol) and 4-dimethylaminopyridine (11.5 mg, 0.09 mmol) in toluene (3 ml) at -40 °C was added the above chlorophosphite solution (1.5 ml, 0.75 mmol) dropwise over 2 minutes. The solution was stirred for 16 hours with gradual warming to room temperature, then concentrated and purified by chromatography on deactivated alumina oxide (20% dichloromethane in pet ether with 1% triethylamine) to yield a white powder (309 mg, 97% yield, dr >20:1 as determined by \(^{31}\text{P NMR}). \(^1\text{H NMR (400 MHz, CDCl}_3\): \(\delta\) 8.09 (d, \(J\) = 8.4 Hz, 1H), 7.99-7.92 (m, 6H), 7.89 (d, \(J\) = 8.4 Hz, 2H), 7.60-7.39 (m, 9H), 7.32-7.28 (m, 2H), 7.24 (d, \(J\) = 2.2 Hz, 1H), 7.19-7.07 (m, 3H), 6.55 (d, \(J\) = 8.8 Hz, 1H), 5.89 (d, \(J\) = 8.8 Hz, 1H), 5.46 (d, \(J\) = 7.2 Hz, 2H), 2.62-2.51 (m, 2H), 1.89-1.77 (m, 2H). \(^{13}\text{C NMR (100 MHz, CDCl}_3\): \(\delta\) 149.7 (d, \(J\) = 10.5 Hz), 146.3 (d, \(J\) = 2.2 Hz), 145.3, 143.5 (d, \(J\) = 4.4 Hz), 137.4, 133.9, 133.2, 132.7 (d, \(J\) = 1.5 Hz), 130.3, 130.1 (d, \(J\) = 1.5 Hz), 128.71, 128.68, 128.53, 128.47, 128.3, 128.0, 127.5, 126.3, 126.0, 125.77, 125.75, 125.7, 125.6, 125.3, 124.7, 124.4, 124.0, 122.1, 121.23 (d, \(J\) = 3.7 Hz), 121.16 (d, \(J\) = 5.2 Hz), 106.3, 63.1 (d, \(J\) = 13.4 Hz), 35.5. \(^{31}\text{P NMR (162 MHz, CDCl}_3\): \(\delta\) 146.7. IR (thin film): 3052, 2967, 1462, 1367 cm\(^{-1}\). [\(\alpha\)]\(_{24}^D\) = +113.7 (c 0.97, CHCl\(_3\)). HRMS: calcd for (M+H\(^{+}\)) \(\text{C}_{46}\text{H}_{33}\text{NO}_{3}\text{P}\) 678.2198; found 678.2167.
Ligand L11:

1) Freshly distilled PCl<sub>3</sub> (1 ml, 11.3 mmol) was added to (R)-5-(2-hydroxynaphthalen-1-yl)-1,2-dihydronaphtho[2,1-b]furan-4-ol. (150 mg, 0.46 mmol) followed by N-methyl-2-pyrrolidone (5 µL). The mixture was stirred for 20 minutes at 60 ºC to give a pale yellow solution, then cooled and carefully concentrated under reduced pressure. The pale yellow foam was concentrated from toluene (2 x 1 ml) then dissolved in toluene (1.25 ml). ³¹P NMR (162 MHz, CDCl₃): δ 181.6, 178.6.

2) To a solution of (2R,5R)-2,5-di(naphthalen-2-yl)pyrrolidine (80.2 mg, 0.25 mmol), triethylamine (0.17 ml, 1.24 mmol) and 4-dimethylaminopyridine (6.1 mg, 0.05 mmol) in toluene (1.3 ml) at -40 ºC was added the above chlorophosphite solution dropwise by cannula over 3 minutes. The resulting reaction mixture was held at -40 ºC for 4 hours, then allowed to gradually warm to room temperature. After 16 hours at room temperature, the mixture was concentrated and purified by chromatography on deactivated alumina oxide (33% dichloromethane in pet ether with 1% triethylamine) to yield a white powder (110 mg, 66% yield, dr >20:1 as determined by ³¹P NMR). ¹H NMR (500 MHz, CDCl₃): δ 7.91-7.87 (m, 6H), 7.83 (d, J = 8.5 Hz, 2H), 7.55-7.49 (m, 5H), 7.45 (d, J = 8.5 Hz, 1H), 7.39 (dd, J = 1.5, 8.5 Hz, 2H), 7.31-7.25 (m, 3H), 7.15 (ddd, J = 1.2, 6.8, 8.2 Hz, 1H), 7.04 (d, J = 8.7 Hz, 1H), 6.93 (ddd, J = 1.2, 6.8, 8.2 Hz, 1H), 6.46 (d, J = 8.8 Hz, 1H), 5.89 (d, J = 8.8 Hz, 1H), 5.41 (d, J = 6.9 Hz, 2H), 4.88-4.82 (m, 1H), 4.64-4.58 (m, 1H), 3.60-3.53 (m, 1H), 3.48-3.41 (m, 1H), 2.56-2.46 (m, 2H), 1.80-1.73 (m, 2H). ¹³C NMR (125 MHz, CDCl₃): δ 151.6, 149.9 (d, J = 10.1 Hz), 143.5 (d, J = 4.6 Hz), 137.2, 133.9, 133.1, 132.6, 130.2, 128.7, 128.64, 128.56, 128.42, 128.38, 128.2, 127.9, 127.4, 126.3, 125.9, 125.70, 125.67, 125.61, 125.59, 125.43,
125.39, 124.3, 123.3, 123.2, 122.1, 121.7, 121.2 (d, \( J = 2.5 \) Hz), 72.6, 63.0 (d, \( J = 13.3 \) Hz), 33.5, 29.7.  
\(^{31}\)P NMR (162 MHz, CDCl\(_3\)): \( \delta \) 144.4. IR (thin film): 3054, 2970, 1599, 1509, 1449, 1380, 1070 cm\(^{-1}\). HRMS: calcd for (M+H\(^+\)) \( \text{C}_{46}\text{H}_{35}\text{NO}_3\text{P} \) 680.2354; found 680.2324.

C. TMM Cycloadducts

**General procedure A for the TMM cycloadditions of aldehydes with In(acac)\(_3\).** To an argon-purged vial of substrate (0.076 mmol), In(acac)\(_3\) (3.1 mg, 0.0076 mmol), \( \text{L11} \) (5.2 mg, 0.0076 mmol) and Pd(dba)\(_2\) (2.2 mg, 0.0038 mmol) was added toluene (0.5 ml) and the solution stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (25 \( \mu \)L, 0.12 mmol) was added (if the substrate was an oil, it was added immediately prior to the allyl acetate). After stirring for 3 or 24 hours (at 50\(^\circ\)C or room temperature, respectively), the solution was concentrated and purified by flash chromatography.

**General procedure B for the TMM cycloadditions of aldehydes without In(acac)\(_3\).** To an argon-purged vial of substrate (0.076 mmol), \( \text{L11} \) (5.2 mg, 0.0076 mmol) and Pd(dba)\(_2\) (2.2 mg, 0.0038 mmol) was added toluene (0.5 ml) and the solution stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (25 \( \mu \)L, 0.12 mmol) was added (if the substrate was an oil, it was added immediately prior to the allyl acetate). After stirring for 3 or 24 hours (at 50\(^\circ\)C or room temperature, respectively), the solution was concentrated and purified by flash chromatography.

(R)-4-methylene-2-(naphthalen-2-yl)tetrahydrofuran:

**Small scale:** The reaction was performed with 11.9 mg (0.076 mmol) of 2-naphthaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (11.5 mg, 72% yield).
Large scale: A mixture of 2-naphthaldehyde (154.0 mg, 1.0 mmol), Pd(dba)$_2$ (14.4 mg, 0.025 mmol) and ligand L11 (34.0 mg, 0.05 mmol) was purged with argon for 15 minutes. Toluene (3.33 ml) was added and the solution was stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (0.33 mL, 1.6 mmol) was added. The solution was immersed in a 50 ºC oil bath and stirred for 3 hours. It was then cooled and purified directly by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (165.2 mg, 80% yield). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.85-7.82 (m, 4H), 7.49-7.45 (m, 3H), 5.15 (dd, $J = 2$, 6.4 Hz, 1H), 5.05 (quintet, $J = 2.2$ Hz, 1H), 4.99 (quintet, $J = 2.2$ Hz, 1H), 4.67-4.64 (bd, $J = 13.2$ Hz, 1H), 4.49-4.44 (dm, $J = 13.2$ Hz, 1H), 3.06-3.00 (m, 1H), 2.68-2.61 (m, 1H). $^{13}$C NMR: $\delta$ 148.2, 139.6, 133.6, 133.3, 128.6, 128.3, 128.0, 126.4, 126.2, 124.9, 124.4, 104.9, 81.6, 71.8, 41.5. IR (thin film): 3056, 2910, 2846, 1667, 1602, 1329, 1055 cm$^{-1}$. $[\alpha]_{24}^{D}=+13.2$ (c 0.87, CHCl$_3$, 90% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% $i$-PrOH in heptane, $\lambda = 254$ nm, $t_{R,\text{minor}} = 9.1$ min, $t_{R,\text{major}} = 10.1$ min). HRMS: calcd for (M+Na$^+$) C$_{15}$H$_{14}$ONa 233.0942; found 233.0941.

(R)-4-methylene-2-phenyltetrahydrofuran:

Small scale: The reaction was performed with 8.1 mg (0.076 mmol) of benzaldehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (9.7 mg, 80% yield).

Large scale: A mixture of Pd(dba)$_2$ (14.4 mg, 0.025 mmol) and ligand L11 (34.0 mg, 0.05 mmol) was purged with argon for 15 minutes. Toluene (3.33 ml) was added followed by benzaldehyde (102 µL, 1.0 mmol), and the solution was stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (0.33 mL, 1.6 mmol) was added. The solution stirred for 16 hours at room temperature then purified directly by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (111.7 mg, 70% yield). Matches known characterization.$^8$ $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ 7.38-7.26

Chiral HPLC: Chiralcel OJ, 0.8 ml/min, 10% i-PrOH in heptane, $\lambda$ = 220 nm, $t_{R, \text{major}}$ = 12.7 mins, $t_{R, \text{minor}}$ = 13.6 min.

(R)-2-(4-methoxyphenyl)-4-methylenetetrahydrofuran: The reaction was performed with 10.3 mg (0.076 mmol) of $p$-anisaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (12.4 mg, 86% yield). Matches known characterization. ¹H NMR (400 MHz, CDCl₃): $\delta$ 7.30 (d, $J$ = 9.2 Hz, 2H), 6.88 (d, $J$ = 9.2 Hz, 2H), 5.03 (quintet, $J$ = 2.3 Hz, 1H), 4.95 (quintet, $J$ = 2.3 Hz, 1H), 4.91 (dd, $J$ = 6, 8.8 Hz, 1H), 4.60-4.53 (m, 1H), 4.40-4.35 (m, 1H), 3.80 (s, 3H), 2.94-2.86 (m, 1H), 2.60-2.51 (m, 1H). $[\alpha]_{24}^D = +21.1$ (c 1.10, CHCl₃, 88% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% i-PrOH in heptane, $\lambda$ = 220 nm, $t_{R, \text{major}}$ = 11.4 mins, $t_{R, \text{minor}}$ = 12.4 min.

(R)-4-methylene-2-o-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of o-tolualdehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (12.3 mg, 93% yield). ¹H NMR (400 MHz, CDCl₃): $\delta$ 7.48 (dd, $J$ = 1.6, 7.2 Hz, 1H), 7.30-7.07 (m, 3H), 5.13 (dd, $J$ = 6.4, 8.8 Hz, 1H), 5.02 (quintet, $J$ = 2.2 Hz, 1H), 4.97 (quintet, $J$ = 2.2 Hz, 1H), 4.65-4.59 (m, 1H), 4.44-4.38 (m, 1H), 3.02-2.95 (m, 1H), 2.48-2.39 (m, 1H), 2.32 (s, 3H). $^{13}$C NMR (100 MHz, CDCl₃): $\delta$ 148.4, 140.4, 134.9, 130.5, 127.6, 126.5, 125.2, 104.7, 78.7, 71.6, 40.2, 19.6. IR (thin film): 3074, 2921, 2851, 1667, 1461, 1058, 884, 753 cm⁻¹. $[\alpha]_{24}^D = +65.1$ (c 0.78, CHCl₃, 88% ee). Chiral HPLC: Chiralcel OD, 0.8 ml/min, 0.1% i-PrOH in heptane, $\lambda$ = 220 nm, $t_{R, \text{major}}$ = 31.2 mins, $t_{R, \text{minor}}$ = 32.4 min.
minor = 33.9 min. HRMS: calcd for (M+H\(^+\)) \(\text{C}_{12}\text{H}_{15}\text{O}\) 175.1123; found 175.1112.

(R)-4-methylene-2-\(m\)-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of \(m\)-tolualdehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (10.1 mg, 76% yield). \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 7.30-7.07 (m, 4H), 5.02 (quintet, \(J = 2.4\) Hz, 1H), 4.96 (quintet, \(J = 2.4\) Hz, 1H), 4.93 (dd, \(J = 6.4, 8.4\) Hz, 1H), 4.61-4.51 (m, 1H), 4.42-4.37 (m, 1H), 2.97-2.90 (m, 1H), 2.60-2.52 (m, 1H), 2.35 (s, 3H). \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \(\delta\) 148.3, 142.0, 138.4, 128.7, 128.6, 126.9, 123.3, 104.7, 81.5, 71.7, 41.5, 21.8. IR (thin film): 2920, 2851, 1706, 1650, 1610, 1431, 1360, 1057, 884, 758, 700 cm\(^{-1}\). \([\alpha]_{23}^D = +26.5\) (c 0.95, CHCl\(_3\), 81% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% \(i\)-PrOH in heptane, \(\lambda = 220\) nm, \(t_{R,\text{minor}} = 5.5\) mins, \(t_{R,\text{major}} = 6.2\) min. HRMS: calcd for (M+H\(^+\)) \(\text{C}_{12}\text{H}_{15}\text{O}\) 175.1123; found 175.1111.

(R)-4-methylene-2-\(p\)-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of \(p\)-tolualdehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (9.1 mg, 69% yield). Matches known characterization.\(^8\) \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta\) 7.28-7.24 (m, 2H), 7.17-7.14 (m, 2H), 5.04-5.01 (m, 1H), 4.97-4.91 (m, 2H), 4.60-4.54 (m, 1H), 4.42-4.36 (m, 1H), 2.96-2.88 (m, 1H), 2.59-2.51 (m, 1H), 2.34 (s, 3H). \([\alpha]_{24}^D = +25.3\) (c 0.81, CHCl\(_3\), 84% ee). Chiral HPLC: Chiralecel OJ, 0.8 ml/min, 10% \(i\)-PrOH in heptane, \(\lambda = 220\) nm, \(t_{R,\text{major}} = 11.0\) mins, \(t_{R,\text{minor}} = 12.7\) min.
**R**-2-(3,4-dimethoxyphenyl)-4-methylenetetrahydrofuran: The reaction was performed with 12.6 mg (0.076 mmol) of 3,4-dimethoxybenzaldehyde according to general procedure B and purified by flash chromatography (10% ethyl acetate in hexanes) to give a clear, colorless oil (16.7 mg, 100% yield). Matches known characterization.\(^8\) \(\text{\textsuperscript{1}H-NMR}\) (400 MHz, CDCl\(_3\)): 6.93 (d, \(J = 1.6\) Hz, 1H), 6.88 (ddd, \(J = 8.2, 2.0, 0.6\) Hz, 1H), 6.82 (d, \(J = 8.0\) Hz, 1H), 5.02 (quint, \(J = 2.3\) Hz, 1H), 4.95 (quint, \(J = 2.1\) Hz, 1H), 4.89 (dd, \(J = 8.8, 6.0\) Hz, 1H), 4.57 (d, \(J = 13.2\) Hz, 1H), 4.40-4.35 (m, 1H), 3.88 (s, 3H), 3.86 (s, 3H), 2.94-2.87 (m, 1H), 2.59-2.51 (m, 1H). \([\alpha]_{23}^D = +17.1\) (c 0.43, CHCl\(_3\), 69% ee). Chiral HPLC: Chiralcel® AD column, 10% isopropanol in heptane, 1.0 mL/min, \(\lambda = 220\) nm; \(t_R = 9.95\) (major), 11.29 (minor).

**R**-2-(4-chlorophenyl)-4-methylenetetrahydrofuran: The reaction was performed with 10.7 mg (0.076 mmol) of 4-chlorobenzaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (10.7 mg, 72% yield). Matches known characterization.\(^8\) \(\text{\textsuperscript{1}H NMR}\) (400 MHz, CDCl\(_3\)): \(\delta 7.33-7.28\) (m, 4H), 5.03 (quintet, \(J = 2.4\) Hz, 1H), 4.97 (quintet, \(J = 2.4\) Hz, 1H), 4.94 (dd, \(J = 6.4, 8.4\) Hz, 1H), 4.59-4.54 (m, 1H), 4.42-4.37 (m, 1H), 2.98-2.91 (m, 1H), 2.54-2.46 (m, 1H). \([\alpha]_{24}^D = +26.7\) (c 0.78, CHCl\(_3\), 83% ee). Chiral HPLC: Chiralpak OJ-H, 0.8 ml/min, 10% \(i\)-PrOH in heptane, \(\lambda = 220\) nm, \(t_R, \text{major} = 8.4\) min, \(t_R, \text{minor} = 9.4\) min).

**R**-4-methylene-2-(4-nitrophenyl)tetrahydrofuran: The reaction was performed with
11.5 mg (0.076 mmol) of \( p \)-nitrobenzaldehyde according to general procedure A, but using ligand L1 (4.8 mg, 0.0076 mmol). The reaction mixture was purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a pale yellow, waxy oil (9.6 mg, 62% yield). \(^1\)H NMR (400 MHz, CDCl\(_3\)): \( \delta \) 8.20 (d, \( J = 8.4 \) Hz, 2H), 7.52 (d, \( J = 8.4 \) Hz, 2H), 5.08-5.04 (m, 2H), 5.00-4.98 (m, 1H), 4.63-4.57 (m, 1H), 4.46-4.41 (m, 1H), 3.07-2.99 (m, 1H), 2.53-2.45 (m, 1H). \(^{13}\)C NMR (100 MHz, CDCl\(_3\)): \( \delta \) 149.9, 147.6, 146.8, 126.8, 124.0, 105.7, 80.3, 71.9, 41.5. IR (thin film): 3080, 2920, 2852, 1669, 1605, 1520, 1347, 1559 cm\(^{-1}\). [\( \alpha \)]\(_{25}^D\) = +30.4 (c 0.42, CHCl\(_3\), 78% ee). Chiral HPLC: Chiralcel OJ, 0.8 ml/min, 10% \( i \)-PrOH in heptane, \( \lambda = 220 \) nm, \( t_R, \) minor = 20.4 mins, \( t_R, \) major = 25.4 min. HRMS: calcd for (M+Na\(^+\)) \( \text{C}_{11}\text{H}_{11}\text{NO}_3\text{Na} \) 228.0637; found 228.0648.

\( (R) \)-2-methyl-3-(4-methylenetetrahydrofuran-2-yl)furan: The reaction was performed with 8.4 mg (0.076 mmol) of 2-methyl-3-furaldehyde\(^9\) according to general procedure A, but CpPd(\( \eta^3 \)-C\(_3\)H\(_5\)) (0.8 mg, 0.0038 mmol) was used. The reaction mixture was purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (7.8 mg, 63% yield). \(^1\)H NMR (400 MHz, CDCl\(_3\)): \( \delta \) 7.25 (d, \( J = 1.9 \) Hz, 1H), 6.34 (d, \( J = 1.9 \) Hz, 1H), 5.05 (quintet, \( J = 2.3 \) Hz, 1H), 4.96 (quintet, \( J = 2.3 \) Hz, 1H), 4.85 (dd, \( J = 6.2, 8.7 \) Hz, 1H), 4.53-4.47 (m, 1H), 4.35-4.29 (m, 1H), 2.83-2.76 (m, 1H), 2.61-2.53 (m, 1H), 2.30 (s, 3H). \(^{13}\)C NMR (125 MHz, CDCl\(_3\)): \( \delta \) 149.4, 148.5, 140.8, 119.5, 109.2, 104.6, 74.1, 71.1, 39.9, 12.1. IR (thin film): 2921, 2853, 1665, 1631, 1515, 1050 cm\(^{-1}\). [\( \alpha \)]\(_{25}^D\) = +9.62 (c 0.61, CHCl\(_3\), 83 % ee). Chiral HPLC: Chiralpak IC, 0.8 ml/min, 1% \( i \)-PrOH in heptane, \( \lambda = 220 \) nm, \( t_R, \) minor = 7.7 mins, \( t_R, \) major = 8.6 min. HRMS: calcd for (M+H\(^+\)) \( \text{C}_{10}\text{H}_{13}\text{O}_2 \) 165.0915; found 165.0904.

(R)-3-(4-methylenetetrahydrofuran-2-yl)pyridine: The reaction was performed with 8.1 mg (0.076 mmol) of 2-pyridinecarboxaldehyde according to general procedure A and purified by flash chromatography (66% ethyl acetate in hexanes) to give a clear, colorless oil (10.5 mg, 86% yield; contaminated with approximately 4% of 2-pyridinecarboxaldehyde as determined by 1H NMR). 1H NMR (400 MHz, CDCl₃): δ 8.61 (s, 1H), 8.55 (s, 1H), 7.73 (d, J = 8.0 Hz, 1H), 7.31 (dd, J = 4.8, 8.0 Hz, 1H), 5.06 (quintet, J = 2.1 Hz, 1H), 5.03-4.98 (m, 2H), 4.61-4.56 (m, 1H), 4.45-4.39 (m, 1H), 3.04-2.97 (m, 1H), 2.58-2.50 (m 1H). 13C NMR (125 MHz, CDCl₃): δ 149.3, 148.1, 147.3, 137.6, 133.8, 123.7, 105.3, 79.1, 71.7, 41.2. IR (thin film): 2919, 2851, 1680, 1578, 1427, 1056 cm⁻¹. Chiral HPLC: Chiralpak IC, 0.8 ml/min, 10% i-PrOH in heptane, λ = 220 nm, tᵣ, minor = 32.3 mins, tᵣ, major = 36.4 min. RMS: calcd for (M+H⁺) C₁₀H₁₂NO 162.0919; found 162.0907.

(R,E)-4-methylene-2-styryltetrahydrofuran: The reaction was performed with 9.6 µL (0.076 mmol) of cinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (11.0 mg, 78% yield) that was an approximately 3:1 mixture of carbonyl and olefin cycloadducts as determined by 1H NMR. Tetrahydrofuran matches known characterization. 1H NMR (tetrahydrofuran only, 400 MHz, CDCl₃): δ 7.40-7.20 (m, 5H), 6.62 (d, J = 16.2 Hz, 1H), 6.24 (dd, J = 7.0, 15.9 Hz, 1H), 5.02 (quintet, J = 2.4 Hz, 1H), 4.94 (quintet, J = 2.4 Hz, 1H), 4.57 (q, J = 6.8 Hz, 1H), 4.47 (d, J = 12.8 Hz, 1H), 4.35 (m, 1H), 2.81-2.73 (m, 1H), 2.49-2.41 (m, 1H). [α]₂⁴D = +19.3 (c 1.10, CHCl₃, 70% ee). Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% i-PrOH in heptane, λ = 254 nm, tᵣ, major = 8.7 mins, tᵣ, minor = 10.0 min.

(R,E)-4-methylene-2-(1-phenylprop-1-en-2-yl)tetrahydrofuran: The reaction was performed with 10.6 µL (0.076 mmol) of alpha-methylcinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (10.5 mg, 69% yield). ¹H NMR (400 MHz, CDCl₃): δ 7.35-7.19 (m, 5H), 6.57 (s, 1H), 5.02 (quintet, J = 2.4 Hz, 1H), 4.95 (quintet, J = 2.4 Hz, 1H), 4.54-4.46 (m, 2H), 4.38-4.42 (m, 1H), 2.79-2.71 (m, 1H), 2.56-2.47 (m, 1H), 1.87 (d, J = 1.3 Hz, 3H). ¹³C NMR: δ 148.3, 137.9, 137.7, 129.3, 128.4, 126.7, 125.9, 104.7, 84.8, 71.7, 38.0, 14.1. IR (thin film): 3079, 2915, 2855, 1667, 1600, 1494, 1444, 1050 cm⁻¹. [α]₂⁴° = + 13.42 (c 1.01, CHCl₃, 72% ee). HRMS: calcd for (M+H⁺) C₁₁H₁₁Cl₂O 201.1279; found 201.1267. Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% i-PrOH in heptane, λ = 254 nm, tᵣ, minor = 6.2 mins, tᵣ, major = 7.7 min.

(R,E)-2-(3-methyl-1-phenylbut-1-en-2-yl)-4-methylenetetrahydrofuran: The reaction was performed with 13.5 mg (13.5 µL, 0.076 mmol) of alpha-isopropylcinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (13.7 mg, 79% yield). ¹H NMR (400 MHz, CDCl₃): δ 7.34-7.29 (m, 2H), 7.23-7.19 (m, 3H), 6.71 (s, 1H), 5.01 (bs, 1H), 4.94 (bs, 1H), 4.58-4.48 (m, 2H), 4.29 (d, J = 12.9 Hz, 1H), 3.10 (septet, J = 7.0 Hz, 1H), 2.83 (dd, J 5.8, 15.7 Hz, 1H), 2.50-2.41 (m, 1H), 1.12 (d, J = 7.0 Hz, 3H), 1.03 (d, J = 7.0 Hz, 3H). ¹³C NMR: δ 148.9, 148.0, 138.4, 129.1, 128.4, 126.6, 124.1, 104.3, 78.0, 71.1, 42.2, 28.5, 22.01, 21.98. IR (thin film): 2962, 1691, 1494, 1362, 1051 cm⁻¹. [α]₂⁴° = + 39.415 (c 1.29, CHCl₃, 81% ee). HRMS: calcd for (M+H⁺) C₁₁H₁₁Cl₂O 229.1592; found 229.1580. Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% i-PrOH in heptane, λ = 254 nm, tᵣ, minor = 5.0 mins, tᵣ, major = 9.1 min.
STANDARD PROTON PARAMETERS

Archive directory: /export/home/abintole/unrepsy/data
Sample directory:

File: dab-1ili-52b
Pulse Sequence: n2p1
Solvent: CDCl3

Pulse 39.5 degrees
Acq. time 4.000 sec
WALTZ 100.6 Hz
41 repetitions
CHEBRE X1 649.7481922 MHz
DATA PROCESSING
FT size 4096
Total time 1 min

Clipar

Archive directory: /export/home/abintole/unrepsy/data
Sample directory:

File: dab-1ili-53013b
Pulse sequence: n2p1
Solvent: CDCl3
User: 1-15-97

Puls. delay 2.890 sec
Pulse 39.7 degrees
Acq. time 1.500 sec
WALTZ 100.3 Hz
41 repetitions
CHEBRE X1 649.6500111 MHz
CHEBRE X2 649.7056465 MHz
Power 43 dB
Continuously on
WALTZ16 modulated
DATA PROCESSING
Line broadening 2.0 Hz
FT size 12072
Total time 1 hr. 9 min
S-22
Arborescence directory.
Sample directory:

Pulsed sequence: alpul
Solvent: ace

Temp. 25.5°C / 298.1 K
Relax. delay 0.599 sec
Pulse 45° degrees
Acq. time 6.000 sec
Wait 5000.8 ms
16 repetitions
COMMENTS
DATA PROCESSING
FT scan 65536
Total time 1 min

Arborescence directory:
Sample directory:

Pulsed sequence: alpul
Solvent: ace

Temp. 25.5°C / 298.1 K
Relax. delay 0.599 sec
Pulse 45° degrees
Acq. time 6.000 sec
Wait 5000.8 ms
16 repetitions
COMMENTS
DATA PROCESSING
FT scan 65536
Total time 1 min
S-29
STANDARD SPECTRUM PARAMETERS

Archive directory: /export/home/dhingle/vnmrsym/data
Sample directory: 

File: sdb-mit-50
Pulse sequence: nul
Solvent: CDCl3

Pulse 90.0 degrees
Acq. time 1.000 sec
Width 5000.0 Hz
SF repetitions

OBSERVE FL 699.740773 MHz
DATA PROCESSING
PT size 50596
Total time 1 min

Clipper

Archive directory: /export/home/dhingle/vnmrsym/data
Sample directory: 

File: sdb-mit-50C13
Pulse sequence: nul
Solvent: CDCl3
User: 1-15-97

Relax. Delay 2.500 sec
Pulse 30.3 degrees
Acq. time 1.500 sec
Width 33603.3 Hz
SF repetitions

OBSERVE FL 128.6610174 MHz
DECAYFL FL 459.7505038 MHz
Power 65 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 2.0 Hz
PT size 111072
Total time 1 hr, 8 min

S-30
Sample directory:

Pulse Sequence: algp
Solvent: ocd12

Temp. 23.0 °C / 296.1 K
Relax. delay 5.560 sec
Pulse 60.0 degrees
Avg. time 8.000 sec
Width 5000.0 Hz
8 repetitions

Spectrum RL 399.7343522 MHz
DATA PROCESSING
FT size 65536
Total time 8 min