Simultaneous Control of Regioselectivity and Enantioselectivity in the Hydroxycarbonylation and Methoxycarbonylation of Vinyl arenes.

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Supporting Information

Further results on alkene carbonylation.................................................................p2
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A range of further experiments using the parent phanephos systems were carried out as mentioned in the main paper. The most informative results are presented in Tables ESI1 and ESI2.

**Table ESI 1: Hydroxycarbonylation of styrene under a range of conditions.**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst [a]</th>
<th>T (°C)</th>
<th>Time (h)</th>
<th>[LiCl] (%)</th>
<th>[acid] (%)</th>
<th>b/l</th>
<th>e.e. [b] (%)</th>
<th>Yield [c] (%)</th>
</tr>
</thead>
<tbody>
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<td>(S)-2di</td>
<td>50</td>
<td>40</td>
<td>20</td>
<td>20</td>
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<td>79(S)</td>
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</tr>
<tr>
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<td>50</td>
<td>42</td>
<td>20</td>
<td>20</td>
<td>1.1</td>
<td>69(R)</td>
<td>35</td>
</tr>
<tr>
<td>3</td>
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<td>80(S)</td>
<td>71</td>
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<tr>
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<td>(S)-2mo</td>
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<td>42</td>
<td>20</td>
<td>20</td>
<td>0.43</td>
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</tr>
<tr>
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<td>59(R)</td>
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<td>1.3</td>
<td>80(S)</td>
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<td>20</td>
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<td>81(S)</td>
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<td>63(R)</td>
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<td>0.47</td>
<td>31 (R)</td>
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<td>38(R)</td>
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<td>0.26</td>
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<td>0.25</td>
<td>16(S)</td>
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**Notes:**
- a: Reactions were carried out using 1 mol% catalyst at 30 bar CO in 1.5 mL of degassed butanone as solvent, 20 mol% LiCl and 20 mol% p-toluene sulfonic acid hydrate co-catalyst unless otherwise stated. b: e.e. determined by chiral HPLC. Absolute configuration in brackets; b/l determined by $^1$H NMR spectroscopy. c: Yield refers to yield of pure acid isolated after acid/base extraction. [d]: 20 bar of CO used.
Table ESI 2: Analysis of acidic medium and co-catalyst for the hydroxycarbonylation of styrene using shortened reaction times (5 hours).

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst [a]</th>
<th>T (°C)</th>
<th>[Co-catalyst] [b]</th>
<th>[Acid] [b]</th>
<th>Conversion (%) [c]</th>
<th>(%) Product (Yield) [d]</th>
<th>b/l [d]</th>
<th>e.e. [%]</th>
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<td>-</td>
<td>-</td>
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<td>11 (7)</td>
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<td>58(R)</td>
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<td>-</td>
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<td>8 (2)</td>
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<td>72(R)</td>
</tr>
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<td>70</td>
<td>-</td>
<td>p-TsOH</td>
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<td>12 (2)</td>
<td>0.6</td>
<td>38(R)</td>
</tr>
<tr>
<td>4</td>
<td>(R)-2di</td>
<td>70</td>
<td>LiCl</td>
<td>p-TsOH</td>
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<td>26 (9)</td>
<td>1.0</td>
<td>74(R)</td>
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<td>70</td>
<td>-</td>
<td>TFA</td>
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<td>18 (3)</td>
<td>0.8</td>
<td>53(R)</td>
</tr>
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<td>70</td>
<td>LiCl</td>
<td>TFA</td>
<td>18</td>
<td>14 (10)</td>
<td>1.0</td>
<td>69(R)</td>
</tr>
<tr>
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<td>70</td>
<td>-</td>
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<td>15 (7)</td>
<td>0.5</td>
<td>24(R)</td>
</tr>
<tr>
<td>8</td>
<td>(R)-2di</td>
<td>70</td>
<td>LiCl</td>
<td>H2SO4</td>
<td>16</td>
<td>16 (7)</td>
<td>1.0</td>
<td>64(R)</td>
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<td>70</td>
<td>-</td>
<td>H3PO4</td>
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<td>44(R)</td>
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<td>70</td>
<td>LiCl</td>
<td>H3PO4</td>
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<td>12 (5)</td>
<td>1.0</td>
<td>62(R)</td>
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<td>-</td>
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<td>LiCl</td>
<td>Al(O Tf)3</td>
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<td>17 (11)</td>
<td>1.0</td>
<td>50(R)</td>
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<td>(R)-2di</td>
<td>70</td>
<td>NaCl</td>
<td>-</td>
<td>9</td>
<td>5 (2)</td>
<td>1.1</td>
<td>56(R)</td>
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<td>70</td>
<td>NaCl</td>
<td>p-TsOH</td>
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<td>0.7</td>
<td>46(R)</td>
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<td>0.9</td>
<td>56(R)</td>
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<td>NH4Cl</td>
<td>p-TsOH</td>
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<td>10 (6)</td>
<td>0.8</td>
<td>56(R)</td>
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<td>CsCl</td>
<td>-</td>
<td>14</td>
<td>13 (8)</td>
<td>1.8</td>
<td>41(R)</td>
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<td>70</td>
<td>CsCl</td>
<td>p-TsOH</td>
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<td>28 (11)</td>
<td>1.0</td>
<td>60(R)</td>
</tr>
<tr>
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<td>70</td>
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<td>-</td>
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<td>70</td>
<td>LiBr</td>
<td>p-TsOH</td>
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<td>3 (3)</td>
<td>1.3</td>
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<td>LiBr</td>
<td>TFA</td>
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<td>1 (1)</td>
<td>1.2</td>
<td>51(R)</td>
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</table>

a: Reactions were carried out on 0.5 mmol of styrene, 1.25 mmol water, using 1 mol% catalyst (see scheme 2 of main paper for structures) at 30 bar CO in 1.5 mL of degassed butanone as solvent for 5 hours. b: 20 mol % co-catalyst and acid used. c: Conversion, (%) product and b/l determined by 1H NMR spectroscopy and comparison with an internal standard. d: e.e. determined by chiral HPLC. Absolute configuration in brackets.
Table ESI 3: Enantioselective and regioselective alkoxycarbonylation of styrene.

![Diagram: 1 mol% Pd catalyst to CO₂Me]  

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst</th>
<th>T (°C)</th>
<th>Time (h)</th>
<th>% ester [yield][c]</th>
<th>b/l [d]</th>
<th>e.e. [d]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2mo</td>
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<td>20</td>
<td>&gt;99</td>
<td>0.7</td>
<td>79</td>
</tr>
<tr>
<td>2</td>
<td>2di</td>
<td>60</td>
<td>20</td>
<td>&gt;99</td>
<td>0.7</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>3mo</td>
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<td>60</td>
<td>1.3</td>
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<tr>
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<td>49</td>
<td>32</td>
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</table>

<table>
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<th>Entry</th>
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<th>T (°C)</th>
<th>Time (h)</th>
<th>% ester [yield][c]</th>
<th>b/l [d]</th>
<th>e.e. [d]</th>
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<td>3di</td>
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<td>58</td>
<td>1.5</td>
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<td>3di [c]</td>
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<td>42</td>
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<tr>
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<td>4mo</td>
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<td>95 [83]</td>
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<td>99</td>
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<td>63</td>
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<td>22</td>
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<td>&gt;100</td>
<td>79</td>
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<td>&gt;100</td>
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<td>22</td>
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<td>7di [b]</td>
<td>60</td>
<td>22</td>
<td>&gt;99</td>
<td>23</td>
<td>61</td>
</tr>
</tbody>
</table>

a: Reactions were carried out using 1 mol% catalyst, 1 mmol styrene at 30 bar CO in 1.5 mL of MeOH, 20 mol% LiCl and 20 mol% 4-MeC₆H₄SO₃H·H₂O, unless otherwise stated. b: Reactions were carried out using 2.5 mmol MeOH in 1.5 mL of butanone. c: % ester against internal standard. d: e.e. determined by chiral HPLC or chiral GC; b/l determined by 1H NMR spectroscopy. (R) catalyst gives (R) product and vice versa. e: Dipalladium complex formed from monomer in situ. f: 0.5 mol% catalyst loading.
**Instrumentation and Chemicals**

Unless otherwise stated all reactions were carried out under inert atmosphere using standard Schlenk techniques. **NMR** All ¹H, ¹³C and ³¹P NMR spectra were recorded either on a Bruker Avance 300 spectrometer (¹H at 300 MHz, ¹³C at 75 MHz, ³¹P at 121 MHz) or Bruker Avance II 400 (¹H at 400 MHz, ¹³C at 100 MHz, ³¹P at 161 MHz) spectrometer. Chemical shift values are given in parts per million and were referenced to external standards (<sup>1</sup>H and <sup>13</sup>C were referenced to tetramethylsilane and <sup>31</sup>P spectra to phosphoric acid). All deuterated solvents were purchased from Deuterio GmbH. Proton signals multiplicities are given as s (singlet), d (doublet), t (triplet), q (quartet), m (multiplet), br s (broad singlet) or a combination of them. **EA and MS** Elemental analyses were carried out by the Elemental Analysis Service at the London Metropolitan University. Mass spectroscopy was carried out by the EPSRC National Mass Spectroscopy Service Centre, Swansea.

**Solvents** Dichloromethane, hexane, toluene and ether were dried and purified via an Innovative Technologies Puresolve 400 solvent purification system, and degassed by purging with nitrogen. Methanol was dried over CaCl₂ and tetrahydrofuran was dried over Na wires (benzophenone as indicator). Other solvents were bought and used as received without further purification other than degassing by purging with nitrogen.

**OR** Optical rotations were measured on a Perkin Elmer 341 polarimeter using a 1 mL cell with a 1 dm path length at 20 °C using the sodium d line.

**Materials** (R)- and (S)-4,12-dibromo[2.2]p-cyclophane was donated by Chirotech and used as received. 4,12-Bis(diphenylphosphino)[2.2]-paracyclophane ((R)(−)) and (S)(−)-PHANEPHOS) and 4,12-Bis(di(3,5-xylyl)phosphino)[2.2]-paracyclophane ((R)(−)) and (S)(−)- Xylyl-PHANEPHOS) were purchased from Aldrich chemical company or donated by Chirotech and used as received without further purification, after checking optical rotation data with the literature. [PdCl₂(PhCN)]₂, LiCl, PTSA monohydrate, styrene, 4-chlorostyrene and 4-tert-butylylene were obtained from Aldrich and used as received. Carbon monoxide was obtained from BOC. Flash column chromatography was performed using Davasil silica gel 40-63µm and normal grade solvents. Catalyst 1mo/di and 2mo/di were prepared as reported in literature.

**Synthesis of ligands and complexes**

(S)-(+)4,12-bis(bis(3,5-di-tert-butyl-4-methoxyphenyl)phosphino)[2.2]-para-cyclophane, L₃

(S)-(+)4,12-Dibromo-para-cyclophane (181.2 mg, 0.495 mmol) was placed in a dry Schlenk flask under inert atmosphere, Et₂O (15 ml) added and n-BuLi (0.40 ml, 0.990 mmol, 2.5 M in hexane) was slowly added. The resulting solution was stirred for 3 hours and then bis(3,5-di-tert-butyl-4-methoxyphenyl)chlorophosphine (500 mg, 0.990 mmol) was added in one portion and stirred overnight. A small sample (0.5ml) was taken and analysed by <sup>31</sup>P <sup>1</sup>H NMR spectroscopy confirming the reaction has gone to completion. MeOH (1 ml) was added and the solvent was removed under vacuum. The product was then dissolved in hexane, the precipitate filtered off and solvent removed leaving the title compound in 81% yield (456 mg, 0.3980 mmol).

<sup>1</sup>H NMR (300MHz, CD₂Cl₂) δ<sub>H</sub> 1.30 (br s, 72H), 2.5-3.00 (m, 8H), 3.58 (br s, 12H), 6.34-6.46 (m, 5H), 6.64 (d, J = 2.37, 1H), 7.18-7.26 (m, 2H), 7.39-7.56 (m, 6H). <sup>31</sup>P <sup>1</sup>H NMR (161MHz; CDCl₃) δ<sub>p</sub> 0.21 (s).

MS (Cl): m/z calcd. for C₇₆H₁₀₀O₉P₂ : 1144.76; found 1145.76. (Good agreement was found between measured and theoretical isotope patterns).

{{(S)-(−)4,12-bis[ bis(3,5-di-tert-butyl-4-methoxyphenyl)phosphino]-[2.2]-para-cyclophane]palladium(II)chloride}, 3mo}

(S)-(−)4,12-Bis[bis (3,5 di-tert-butyl-4-methoxyphenyl) phosphino]-[2.2]-para-cyclophane (142 mg, 0.124 mmol) was put under inert atmosphere and dissolved in CH₂Cl₂. One equivalent of [PdCl₂(PhCN)]_2 (48 mg, 0.124 mmol) was added. The solution was stirred overnight. A small sample was taken for ^31P {^1}H NMR confirming the reaction has gone to completion. The solvent was removed and the complex washed with hexane (3 x 20 ml). The solid obtained was dried under vacuum, yielding the desired compound as a bright yellow solid in 88% yield (144 mg, 0.109 mmol).

^1H NMR (300MHz, CDCl₃) δH 1.23 (bs, 54H), 1.38 (bs, 18H), 2.26-2.33 (m, 2H), 2.37-2.51 (m, 4H), 3.01 (s, 2H), 3.56 (s, 6H), 3.64 (s, 6H), 6.26-6.37 (m, 4H), 6.41 (s, 2H), 6.91-7.01 (m, 2H), 7.23 (d, J = 6.0 Hz, 1H), 7.87-7.91 (m, 3H), 8.53-8.58 (m, 2H). ^13C-NMR, (75MHz, CD₂Cl₂) δC 31.64 (s, CH₂), 31.88 (s, CH₃), 32.06 (s, CH₂), 32.40 (s, CH₃), 36.40 (s, CH₂), 64.66 (s, CH₂), 66.28 (s, CH₂), 124.28 (s, C₂), 124.82 (s, C₂), 127.06 (s, C₂), 130.45 (s, C₂), 134.76 (s, C₂), 136.42 (m, CH), 136.70 (m, CH), 137.49 (t, J = 8.1Hz, CH), 139.97 (t, J = 4.4Hz, C₂), 143.16 (t, J=4.0Hz, C₂), 144.60 (s, C₂), 163.14 (s, C₂), 163.22 (s, C₂). ^31P {^1}H NMR (161MHz; CDCl₃): δp 45.67 ppm (s).

MS (Cl): m/z calcd. for C₇₆H₁₀₀Cl₂O₃P₃PdCl₂O[M+NH₃]⁺: 1309.67; found 1309.67. (Good agreement was found between measured and theoretical isotope patterns).

Anal.cald. for C₇₆H₁₀₀Cl₂O₃P₃Pd: C 69.0, H 8.08 Found : C 69.14, H 8.17. [α]D=−132.3 (c = 0.655, CHCl₃). 168 °C (decomposition).

{{(S)-(−)4,12-bis[ bis(3,5-di-tert-butyl-4-methoxy-phenyl)phosphino]-[2.2]-para-cyclophane} dipalladium(II)tetrachloride}, 3di}

(S)-(−)4,12-bis[ bis(3,5 di-tert-butyl-4-methoxyphenyl) phosphino]-[2.2]-para-cyclophane (45 mg, 0.040 mmol) was weighed into a dry schlenk flask and dissolved in CH₂Cl₂ (10 ml). Two equivalents of [PdCl₂(PhCN)]_2 (30.4 mg, 0.079 mmol) added to the solution and stirred overnight. A dark brown/orange solid was formed over night. The compound was purified by removing solvent and washing with hexane (2 x 20 ml). The solution was filtered off and the precipitate dried under vacuum, giving a dark red/brown solid in 95% yield (57mg, 0.038 mmol). An attempt to dissolve a small sample was taken for ^31P {^1}H NMR spectroscopy but no signal could be found. Due to the insolubility of the compound, this could not be characterized, but MS gives the same type of spectra as the characterised dipalladium species of other ligands.

MS (Cl): m/z calcd. for C₇₆H₁₀₀Cl₄O₃P₃Pd₂ [M+NH₃]⁺: 1500.4; found 1500.6.

Literature: (R)-(−)4,12-bis(dichlorophosphine)-[2.2]-para-cyclophane[^3]

(R)-(−)4,12-dibromo-para-cyclophane (3.02 g, 8.249 mmol) was placed in a dry Schlenk flask under argon atmosphere and partly dissolved in dry Et₂O (40 ml). n-BuLi (14 ml, 35.00 mmol, 2.5 M in hexane) was added slowly under room temperature and stirred for 3 hours. Bis(di-iso-propylamino)chlorophosphine (5 g, 0.019 mol) was added in one portion and the solution stirred overnight. Anhydrous MeOH (30 ml) was
added and some solvent was removed under vacuum, until half the solvent was removed, then more MeOH (100 ml) was added. The solution was filtered off by cannula filtration and the white precipitate dried under vacuum, resulting in (R)-(−)-4, 12-bis[di-iso-propylamino]phosphino]-[2.2]-para-cyclophane in 87% yield (4.80 g, 7.172 mmol). \(^{31}P\{^{1}H\} NMR in CDCl\textsubscript{3} 72.3 ppm).

A solution of HCl in Et\textsubscript{2}O (2 M, 100 ml, 0.200 mol) was added to the solid (R)-(−)-4,12-bis[di-iso-propylamino]phosphino]-[2.2]-para-cyclophane and stirred overnight at room temperature. The solvent was removed and hexane (100 ml) was added. The solution was filtered through a cannula and the solvent removed. More hexane (100 ml) was added and the solution again filtered off and the solvent removed. Hexane (100 ml) was added and the cloudy solution was filtered again. The solvent was evaporated resulting in the product (R)-(−)-4,12-bis[dichlorophosphino]-[2.2]-para-cyclophane as a white powder in 31% yield (908 mg, 2.214 mmol). \(^{31}P\{^{1}H\} NMR in CDCl\textsubscript{3} 166.0 ppm).

**(R)-(−)-4,12-bis[3,4,5-trifluorophenyl]phosphino]-[2.2]-para-cyclophane, L4**

(R)-(−)-4, 12-bis[dichlorophosphino]-[2.2]-para-cyclophane (385.0 mg, 0.939 mmol) was dissolved in THF (5 ml) and 3,4,5 trifluorophenylimagnesiumbromide (16 ml, 4.695 mmol, 0.3 M in THF) was added slowly. After stirring for 2 hours at room temperature the solution was heated to 50 °C for one hour and cooled to room temperature. After checking the completion of the reaction using \(^{31}P\{^{1}H\} NMR MeOH (1 ml) was added and stirred, the solvent removed and hexane added and the solution was filtered off. After removing the solvent under reduced pressure, the crude product was obtained as brownish solid. The solid was dissolved in hexane (30 ml) and charcoal (spatula point) was added. The solution was filtered though celite under argon. After removing the solvent under reduced pressure the product was obtained in 33% yield (348 mg, 0.3103 mmol) as a white solid.

\(\text{[\{R\}-(−)-4,12-bis[3,4,5-trifluorophenyl]phosphino]-[2.2]-para-cyclophane]palladium(II) dichloride}, 4\text{mo}

(R)-(−)-4,12-Bis[3,4,5-trifluorophenyl]phosphino]-[2.2]-paracyclophane (103 mg, 0.130 mmol) was dissolved in DCM (10 ml) before adding one equivalent [PdCl\textsubscript{2}(PhCN)]\textsubscript{2} (50 mg, 0.130 mmol). The solution was stirred overnight. Taking a small sample (0.5 ml) for \(^{31}P\{^{1}H\} NMR spectroscopy confirmed the reaction had gone to completion. The solvent was removed under vacuum, until a few ml were left and then hexane (20 ml) was added. The yellowish precipitate was washed 3 times with hexane before dried under vacuum, yielding the palladium complex as a bright yellow powder in 70% yield (88 mg, 0.091 mmol).

\(\text{[\{R\}-(−)-4,12-bis[3,4,5-trifluorophenyl]phosphino]-[2.2]-para-cyclophane}palladium(II) dichloride, 4\text{mo}

\(\text{[\{R\}-(−)-4,12-bis[3,4,5-trifluorophenyl]phosphino]-[2.2]-para-cyclophane}palladium(II) dichloride, 4\text{mo}}\)
(R)-(−)-4,12-Bis[3,4,5-trifluorophenyl)phosphino]-[2.2]-para-cyclophane] dipalladium(II)

decachloride, 4di

(R)-(−)-4,12-Bis[3,4,5-trifluorophenyl)phosphino]-[2.2]- para-cyclophane (193 mg, 0.244 mmol) was weighed into a dry schlenk flask and put under argon. The compound was dissolved in CH_2Cl_2 (30 ml) before adding 2 equivalent of [PdCl_2(PhCN)_2] (187 mg, 0.488 mmol). The resulting solution was then stirred overnight. A small sample (0.5 ml) was taken for \(^{31}\)P \(^{1}\)H NMR spectroscopy confirming the reaction has gone to completion. Then the solvent was removed until a few ml were left and the reddish precipitate obtained washed 5 times with hexane. After cannula filtration the precipitate was dried under vacuum, yielding the title compound as an orange solid in 43% yield (126 mg, 0.110 mmol).

\(^{1}\)H NMR (300MHz, CDCl₃) δ_H 8.27-3.33 (m, 8H), 6.55 (br s, 4H), 7.04-7.13 (m, 4H), 7.38-7.44 (m, 3H), 7.52-7.61 (m, 3H). \(^{13}\)C NMR (75 MHz, CDCl₃) δ_C 33.68 (s, CH), 35.25 (s, CH₂), 115.69 (s, CH), 116.11 (s, CH), 128.29 (s, CH), 131.40 (s, CH), 131.97 (s, CH), 135.06 (d, J=2.7, CH), 139.51 (s, CH), 148.18 (s, C_qw), 151.32 (s, C_qw), 151.63 (s, C_qw). \(^{31}\)P \(^{1}\)H NMR (121MHz; CDCl₃) δ_P 36.06 (s).

MS (CI): m/z calcd. for C₄₀H₂₂Cl₄F₁₂P₂Pd₂: 1147.8; found 1147.7. (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. For C₄₀H₂₂Cl₄F₁₂P₂Pd₂: C, 41.88; H, 1.93; Found: C, 41.95; H, 1.86.

\([\alpha]_D^{25} = +691.7 (c = 0.06, CHCl₃). m.p. 172 °C (decomposition)."

(R)-(−)-4,12-bis[3,5-dimethoxyphenyl)phosphino]-[2.2]-para-cyclophane, L5

(R)-(−)-4,12-bis(dichlorophosphino)-[2.2]-para-cyclophane (600 mg, 1.463 mmol) was dissolved in THF (10 ml) and 3,5 dimethoxyphenylmagnesiumbromide (7.5 ml, 7.316 mmol, 1M in THF) slowly added. The solution was heated to 68 °C for 3 hours, then cooled to room temperature and stirred overnight. The completion of the reaction was checked using \(^{31}\)P \(^{1}\)H NMR spectroscopy. MeOH (5 ml) was added to quench the rest of the unreacted grignard. The solvent was removed, hexane added and the solution filtered via cannula filtration. After removing the solvent under reduced pressure, the product was obtained in 79% yield (943 mg, 1.154 mmol) as a white sticky solid.

\(^{1}\)H NMR (400MHz, CDCl₃) δ_H 3.67-3.76 (m, 32H), 6.38-6.45 (m, 14H), 7.11 (t, J = 8.2, 4H). \(^{31}\)P \(^{1}\)H NMR (161MHz; CDCl₃) δ_P 3.87 (s).

MS (CI): m/z calcd. for [C₄₅H₅₀O₃P₂H]+ : 817.30 found 817.30. (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. for C₄₅H₅₀O₃P₂: C, 70.58; H, 6.17; Found: C, 70.39; H 6.05.

\([\alpha]_D^{25} = -32.1 (c = 0.28, CHCl₃)."

C_qw, 152.08-152.49 (m, C_qw), 152.70-153.06 (m, C_qw). \(^{31}\)P \(^{1}\)H NMR (161 MHz; CDCl₃) δ_P 40.8 (s).

Anal. calcd. for C₄₀H₂₂Cl₄F₁₂P₂Pd₂: C, 49.54; H, 2.29; Found: C, 49.62; H 2.39,.
{(R)-(−)-4,12-bis[3,5-dimethoxyphenyl]phosphino]-[2.2]-para-cyclophane}palladium(II) dichloride], 5mo

{(R)-(−)-4,12-Bis[3,5-dimethoxyphenyl]phosphino]-[2.2]-para-cyclophane} (262 mg, 0.3208 mmol) was dissolved in CH₂Cl₂ (10 ml) and [PdCl₂(PhCN)₂] (123 mg, 0.3208 mmol) added in one portion and stirred overnight. A small sample (0.5 ml) was taken for \(^{31}P\) \(^1H\) NMR spectroscopy confirming the reaction has gone to completion. The solution was removed leaving a yellowish oily residue, which was then washed with hexane resulting in a yellow precipitate. Filtering off the solution and drying the yellow precipitate under vacuum resulted in a yellow sticky solid. In order to have the compound washed thoroughly this solid was dissolved again in CH₂Cl₂ (6 ml) and then precipitated with hexane (20 ml). About one third of the solution was removed prior to cannula filtration. The residue was dried under vacuum again leaving a yellow sticky solid in 73% yield (233.3 mg, 0.235 mmol).

\(^1\)H NMR (400MHz, CDCl₃) \(\delta\) H 3.54-3.84 (m, 32H), 6.36-6.44 (m, 6H), 6.63 (d, \(J=2.2, 4H\)), 7.09 (t, \(J=8.1, 2H\)), 7.47-7.51 (m, 2H), 7.66-7.73 (m, 4H). \(^{13}C\) NMR (75 MHz, CD₂Cl₂) \(\delta\) C 30.92 (s, CH₂), 35.10 (s, CH₂), 54.24 (s, OMe), 54.42 (s, OMe), 54.57 (s, OMe), 98.46 (s, CH), 99.50 (s, CH), 102.59 (s, CH), 103.24 (s, CH), 104.51 (s, CH), 105.40 (s, CH), 114.52 (t, \(J=5.25, CH\)), 128.86 (s, CH), 130.78 (d, \(J=11.25, C_{qu}\)), 131.50 (d, \(J=8.25, C_{qu}\)), 133.22 (d, \(J=7.5, C_{qu}\)), 133.93 (s, CH), 134.75 (d, \(J=7.5, C_{qu}\)), 135.58 (t, \(J=5.25, CH\)), 136.28 (t, \(J=11.25, CH\)), 136.66 (t, \(J=7.5, C_{qu}\)), 142.43 (s, C₉H₅), 143.10 (s, C₉H₅), 158.82 (t, \(J=7.5, C_{qu}\)), 159.55 (t, \(J=8.25, C_{qu}\)), 159.96 (s, C₉H₅). \(^{31}P\) \(^1H\) NMR (161MHz; CD₂Cl₂) \(\delta\) P 45.65 (s).

MS (EI): m/z calcd. for \([C₄₈H₅₀Cl₂O₆P₂Pd]^{-}\) : 994.1; found 994.2. (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. for C₄₈H₅₀Cl₂O₆P₂Pd : C, 57.99; H, 5.07; Found : C, 58.18; H, 4.99.

[\(\alpha\)D] = +134.3 (c = 2.69, CHCl₃).

{(R)-(−)-4,12-bis[3,5-dimethoxyphenyl]phosphino]-[2.2]-para-cyclophane}dipalladium(II) tetrachloride], 5di

{(R)-(−)-4,12-Bis[3,5-dimethoxyphenyl]phosphino]-[2.2]-para-cyclophane}palladium(II)chloride} (233 mg, 0.235 mmol) was dissolved in CH₂Cl₂ (15 ml) and [PdCl₂(PhCN)₂] (90 mg, 0.235 mmol) added and stirred overnight. A small sample (0.5ml) was taken for \(^{31}P\) \(^1H\) NMR spectroscopy confirming the reaction has gone to completion. Solvent was removed until a few ml of CH₂Cl₂ left and hexane (2 x 20 ml) added to precipitate and wash the complex. After cannula filtration the solution was dried under vacuum, leaving a red crystalline powder in 55% yield (150.2 mg, 0.129 mmol).

\(^1\)H NMR (400MHz, CDCl₃) \(\delta\) H 3.54-3.75 (m, 32H), 6.10-6.14 (m, 3H), 6.23-6.24 (m, 2H), 6.32-6.46 (m, 4H), 6.63 (d, \(J=2.32, 2H\)), 6.88-7.03 (m, 6H), 7.92-7.97 (m, 1H). \(^{13}C\) NMR (75 MHz, CD₂Cl₂) \(\delta\) C 34.78 (s, CH₂), 36.64 (s, CH₂), 55.96 (s, OMe, CH₃), 55.78 (s, OMe, CH₃), 102.49 (s, CH), 103.42 (s, CH), 110.74 (d, \(J=12.75, CH\)), 125.05 (s, C₉H₅), 125.84 (s, C₉H₅), 131.89 (s, C₉H₅), 132.75 (s, C₉H₅), 135.20 (d, \(J=9.0, CH\)), 136.83 (d, \(J=12.8, CH\)), 139.58 (s, CH), 139.85 (s, C₉H₅), 147.26 (s, C₉H₅), 160.23 (d, \(J=12.0, C_{qu}\)), 160.47 (d, \(J=12.0, C_{qu}\)). \(^{31}P\) \(^1H\) NMR (161MHz; CD₂Cl₂) \(\delta\) P 38.69 (s).
MS (Cl) (NH₃): m/z calcd. for [C₄₈H₆₀Cl₄O₆P₂Pd2][M-2Cl]⁺: 1100.04; found 1100.1; [M-3Cl]⁺ 1066.08; found 1066.07. (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. for C₄₈H₆₀Cl₄O₆P₂Pd2: C, 49.21; H, 4.30; Found: C, 49.29; H, 4.24. [α]D= +708.4 (c = 0.22, CHCl₃, 20 °C).

[(R)-(−)-4, 12-Bis(bis(3,5-trifluoromethylphenyl)phosphino)−[2,2]−para-cyclophane], L₆

(R)-(−)-4, 12-dibromo-[2,2]-para-cyclophane (185.8 mg, 0.5075 mmol) was dissolved in dry and degassed Et₂O (25 ml). n-BuLi (1.6M in hexane) (3.25 ml, 2.030 mmol) was added dropwise and the reaction stirred for 2.5 hours. Bis(3,5-di(trifluoromethyl)phenyl)chlorophosphine (500 mg, 1.015 mmol) was dissolved in Et₂O (4 ml) and added in one portion added and the reaction stirred overnight. MeOH (5 ml) was added to quench the reaction. Solvents were removed under vacuum. The crude product was washed with MeOH (2 x 20 ml). The product was then dissolved in hexane (10 ml) and degassed water (15 ml) added. The organic layer was collected and solvents removed under vacuum to give the product as an off-white solid in 52 % yield (295.7 mg, 0.2639 mmol).*

*This synthesis worked very well on several occasions but also failed on several occasions. Therefore, this compound was often prepared via the tetrachloride in a highly reproducible manner using the same procedure as given for L₇.

¹H NMR, (300 MHz, CDCl₃): δH 2.45-2.60 (m, 2H), 2.65-2.82 (m, 2H), 2.82-2.99 (m, 4H), 6.39 (d, J = 10.5, 2H), 6.67-6.74 (m, 4H), 7.86 (s, 2H), 7.91 (d, J = 7.2, 4H), 7.94-8.01 (m, 6H). ¹⁹F ¹{H} NMR (282 MHz, CDCl₃) δF -63.38 (s, 12F), -63.52 (s, 12F). ³¹P ¹{H} NMR (121 MHz, CDCl₃) δP 0.6 (s).

MS EI+ m/z 1120.1 (M⁺ requires 1120.1) (Good agreement was found between measured and theoretical isotope patterns).

[(R)-(−)-4, 12-Bis(bis(3,5-trifluoromethylphenyl)phosphino)−[2,2]−para-cyclophane]palladium[dichloride], 6mo

[(R)-(−)-4, 12-Bis(bis(3,5-trifluoromethylphenyl)phosphino)−[2,2]-paracyclophane] (143.0 mg, 0.1276 mmol) was dissolved in CH₂Cl₂ (15 ml) and [PdCl₂(PhCN)₂] (48.9 mg, 0.1276 mmol) added and stirred overnight. A sample was taken for analysis by ³¹P ¹{H} NMR to ensure that the reaction had reached completion. Solvent was removed until a few ml of CH₂Cl₂ left and hexane (2 x 20 ml) added to precipitate and wash the complex. The product was collected on a scinttered disc (pore size 4) and further washed with hexane (3 x 20 ml) leaving the product as a yellow powder in 91 % yield (146.7 mg, 0.1161 mmol).

¹H NMR, (300 MHz, CDCl₃): δH 2.56-2.80 (m, 8H), 6.64-6.76 (m, 6H), 7.05-7.14 (m, 2H), 8.01 (s, 3H), 8.17 (s, 2H), 8.37 (d, J = 9.1, 5H). ¹⁹F NMR ¹{H} (282 MHz, CDCl₃) δF -63.59 (s, 12F), -63.67 (s, 12F). ³¹P ¹{H} NMR (121 MHz, CDCl₃) δP 38.9 (s).

MS MALDI⁺ m/z 1263.0 (M-Cl⁺) requires 1263.0 (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. C₄₈H₆₀F₂₄Cl₂P₂Pd : C, 44.42; H, 2.02; Found : C, 44.52; H, 2.09. [α]D= +32.9 (c = 0.413, CHCl₃).
[(R)-(−)-4, 12-Bis(bis (3,5-trifluoromethylphenyl)phosphino)-[2,2]-para-cyclophane] dipalladium[tetrachloride], 6di

[(R)-(−)-4, 12-Bis(bis (3,5-trifluoromethylphenyl)phosphino)-[2,2]-para-cyclophane] (375.0 mg, 0.3346 mmol) was dissolved in CH₂Cl₂ (8 ml) and [PdCl₂(PhCN)₂] (256.7 mg, 0.6692 mmol) added and stirred overnight. A sample was taken for analysis by ³¹P {¹H} NMR to ensure that the reaction had reached completion. Solvent was removed until a few ml of CH₂Cl₂ left and hexane (2 x 20 ml) added to precipitate and wash the complex. The product was collected on a scinttered disc (pore size 4) and further washed with hexane (3 x 20 ml) leaving the product as a red powder in 90 % yield (444.4 mg, 0.3012 mmol).

¹H NMR, (400 MHz, CDCl₃): δH 2.84-3.11 (m, 6H), 3.32-3.47 (m, 2H), 7.19-7.25 (m, 2H), 7.41-7.57 (m, 6H), 7.59-7.82 (m, 5H) 7.87-8.02 (m, 5H). ¹³F {¹H} NMR (282 MHz, CDCl₃) δF-63.62 (s, 12F), -63.75 (s, 12F). ³¹P {¹H} NMR (161 MHz, CDCl₃) δP 35.8 (s).

MS El⁺: m/z 1475.9 (M⁺ requires 1475.8) (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd.  C, 39.04; H, 1.78; Found : C, 39.14; H, 2.00. [α]D = +113.5 (c = 0.467, CHCl₃).

[(R)-(−)-4, 12-Bis(3,5-dichlorophenyl)phosphino)-[2,2]-para-cyclophane], L7

[(R)-(−)-4, 12-dibromo-[2,2]-para-cyclophane (2 g, 5.4631 mmol) was dissolved in dry and degassed Et₂O (50 ml). n-BuLi (1.6M in hexane) (8.5 ml, 13.6788 mmol) was added dropwise and the reaction stirred for 1 hour. Bis(diisopropylamino)chlorophosphine (2.915 g, 10.9262 mmol) was added in one portion and the reaction stirred for 30 min. Anhydrous MeOH (20 ml) was added, and the Et₂O removed under vacuum. The precipitate was collected and dried under vacuum. HCl (2M in Et₂O, 50 ml) was added and the reaction stirred for 18 hours. The solvent was removed under vacuum and the solid residue suspended in Et₂O (45 ml). Salts were removed by filtration. The solvent was removed under vacuum and Et₂O (20 ml) and hexane (25 ml) added and the resulting cloudy solution filtered. The solvent was removed and hexane (40 ml) added and the reaction heated to 70 °C for 10 min. The solution was cooled to rt, filtered and the solvent removed under vacuum to give a tetrachloride species in 38 % yield (0.861 g, 2.099 mmol) as a white solid. The tetrachloride was dissolved in THF (20 ml) and 3,5-dichlorophenylmagnesium bromide solution (0.5M in THF) (16.8 ml, 8.417 mmol) was added dropwise. The reaction was heated to 50 °C and stirred for 2 hours. The reaction was cooled to rt and a sample was taken for ³¹P {¹H} NMR analysis to assure that the reaction had gone to completion. This sample was returned to the bulk reaction mixture, and the reaction was quenched with MeOH (5 ml). Solvents were removed under vacuum. Hexane (40 ml) was added and the product collected by cannula filtration. Hexane was removed to give the product as a white powder in 47 % yield (18 % overall yield) (838.6 mg, 0.984 mmol).

¹H {³¹P} NMR (400 MHz, CDCl₃) 2.57-2.77 (m, 4H), 2.84-2.97 (m, 4H), 6.37 (s, 1H), 6.48-6.62 (m, 4H), 7.14-7.24 (m, 6H), 7.30 (d, J = 1.8, 3H), 7.32-7.41 (m, 2H), 7.45-7.63 (m, 2H). ³¹P {¹H} NMR (121 MHz, CDCl₃) δP 2.2.

MS El⁺ m/z 851.9 (M⁺ requires 851.9) (Good agreement was found between measured and theoretical isotope patterns).
[(R)-(-)-4, 12-Bis(3,5-dichlorophenyl)phosphino]-[2,2]-para-cyclophane](dichloride), 7mo

[(R)-(-)-4, 12-Bis(3,5-dichlorophenyl)phosphino]-[2,2]-para-cyclophane] (377.5 mg, 0.443 mmol) was dissolved in CH₂Cl₂ (8 ml) and [PdCl₂(PhCN)₂] (170.0 mg, 0.443 mmol) added and stirred overnight. A sample was analysed by $^{31}$P $^1$H NMR to confirm completion of the reaction. Solvent was removed until a few ml of CH₂Cl₂ left and hexane (2 x 20 ml) added to precipitate and wash the complex. The product was collected on a sintered disc (pore size 4) and further washed with hexane (3 x 20 ml) leaving the product as a yellow powder in 42 % yield (191.5 mg, 0.186 mmol).

$^1$H NMR, (400 MHz, CDCl₃); δH 1.91-2.09 (m, 2H), 2.55-2.80 (m 6H), 6.50-6.71 (m, 5H), 6.99-7.08 (m, 2H), 7.45 (s, 2H) 7.62 (s, 2H), 7.77 (d, J = 9.2, 4H), 7.87-7.90 (m, 3H). $^{31}$P $^1$H NMR (121 MHz, CDCl₃) δp 40.6.

MS MALDI$: m/z 992.7 ((M-Cl)$^-$ requires 992.8) (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. C₄₀H₂₆Cl₆P₂Pd : C, 46.66; H, 2.55; Found : C, 46.44; H, 2.56. [$\alpha$]D = +79.3 (c = 0.347, CHCl₃).

[(R)-(-)-4, 12-Bis(3,5-dichlorophenyl)phosphino]-[2,2]-para-cyclophane]dipalladium[tetrachloro|de], 7di

[(R)-(-)-4, 12-Bis(3,5-dichlorophenyl)phosphino]-[2,2]-para-cyclophane] (244.6 mg, 0.287 mmol) was dissolved in CH₂Cl₂ (8 ml) and [PdCl₂(PhCN)₂] (210.1 mg, 0.574 mmol) added and stirred overnight. A $^{31}$P $^1$H NMR was taken to confirm completion of the reaction. Solvent was removed until a few ml of CH₂Cl₂ left and hexane (2 x 20 ml) added to precipitate and wash the complex. The product was collected on a sintered disc (pore size 4) and further washed with hexane (3 x 20 ml) leaving the product as a red powder in 49 % yield (116.5 mg, 0.141 mmol).

$^1$H NMR, (300 MHz, CDCl₃); δH 2.85-3.12 (m, 6H), 3.38-3.56 (m, 2H), 6.88 (d, J = 11.8, 6H), 7.09-7.19 (m, 4H), 7.24 (s, 2H), 7.39 (s, 2H), 7.51-7.61 (m, 2H), 7.94 (d, J = 16.1, 2H). $^{31}$P $^1$H NMR (121 MHz, CDCl₃) δp 35.8.

MS MALDI$: m/z 1207.6 (M$^+$ requires 1207.6) (Good agreement was found between measured and theoretical isotope patterns).

Anal. calcd. C₄₀H₂₆Cl₁₂P₂Pd₂ : C, 39.81; H, 2.17; Found : C, 40.02; H, 2.30. [$\alpha$]D = +632.9 (c = 0.353, CHCl₃).

General procedure for hydroxycarbonylation of styrene

Lithium chloride (8.4 mg, 0.20 mmol), para-toluenesulfonic acid (34.4 mg, 0.20 mmol) and [LPdCl₂] (L = diphosphine) (0.01mmol) were weighed into a Biotage 5 ml microwave vial. A magnetic stirrer bar was added and the vial was sealed with a crimp cap and put under an inert atmosphere. Styrene (114 µl, 1 mmol), degassed water (45 µl, 2.5 mmol), degassed 2-butanon (1.5 ml) and in most instances an internal standard (approximately 10µl of either tetraethylsilane or more commonly 1-methylnaphtalene) were added using a syringe. The solution was mixed before 20 µl of the solution was diluted in CDCl₃ and analysed using $^1$H NMR (to give a $t_0$ spectra that calibrates the internal standard against starting material). The caps were pierced with two needles and quickly placed in an autoclave that had previously been placed under an argon atmosphere before being opened under a flow of argon. The autoclave was sealed, purged three times with CO and then pressurised to 30 bar and heated in a preheated oil bath or heating jacket with constant magnetic stirring. After the desired time, the autoclave was cooled to room temperature and the pressure released slowly. The mixture was then analysed by taking a sample, diluting with CDCl₃ and obtaining a $^1$H NMR spectrum. The solvent was carefully removed from the reaction mixture and the residue was dissolved in toluene and extracted 3 times with saturated NaHCO₃ solution.
and the combined extracts were acidified with conc. HCl. The solution was then extracted 3 times with ethyl acetate and the combined organic layers were dried over MgSO₄, filtered and the solvent removed to give chemically pure regio-isomers 2-phenylpropanoic acid and 3-phenylpropanoic acid. The enantiomeric excess was determined by HPLC, using a Chiracel OD-H column, 250 x 4.6 mm, 5 µm with guard cartridge, 0.5 mL min⁻¹, 97:3:0.1 hexane:iso-propanol:trifluoroacetic acid, t₁₀[(+)-S] = 19 min, t₁₀[(-)-R] = 17 min, t₈[linear] = 21 min.

NMR data for catalysis products
2-phenylpropanoic acid[6]:
¹H NMR (300 MHz, CDCl₃) δ 1.45 (3H, d, J = 7.2, CH₃), 3.7 (1H, q, J = 7.2, CH), 7.2 (5H, m, ArH). ¹³C NMR (75 MHz, CDCl₃) δ 18.3, 45.5, 127.5, 127.7, 128.8, 139.8, 181.2.

3-phenylpropanoic acid[5]:
¹H NMR (300 MHz, CDCl₃) δ 2.6 (2H, t, J = 7.7, CO-CH₂), 2.9 (2H, t, J = 7.7, CH₂), 7.2 (5H, m, ArH). ¹³C NMR (75 MHz, CDCl₃) δ 30.6, 35.7, 126.4, 128.3, 128.6, 140.2, 179.6.

GC-MS: MS (EI): m/z calced. for [C₉H₁₀O₂]: 150.17; found 149.0.

General procedure for methoxycarbonylation of styrene
Lithium chloride (8.4 mg, 0.20 mmol), para-toluensulfonic acid (34.4 mg, 0.20 mmol) and [LPdCl₂] (L = diphosphine) (0.01mmol) were weighed into a Biotage 5 ml microwave vial. A magnetic stirrer bar was added and the vial was sealed with a crimp cap and put under inert atmosphere. Styrene (1 mmol), dry and degassed methanol (1.5 ml) and an internal standard (approximately 10µl of either tetraethylsilane or 1-toluene) were added using a syringe. The solution was mixed before 20 µl of the solution was diluted in CDCl₃ and analysed using ¹H NMR (to give a t₈ spectra that calibrates the internal standard against starting material). The caps were pierced with two needles and quickly placed in an autoclave that had previously been placed under an argon atmosphere before being opened under a flow of argon. The autoclave was sealed, purged three times with CO and then pressurised to 30 bar and heated in a preheated oil bath or heating jacket with constant magnetic stirring. After the desired time, the autoclave was cooled to room temperature and the pressure released slowly. The mixture was then analysed by taking a sample, diluting with CDCl₃ and obtaining a ¹H NMR spectrum. The solvent was carefully removed from the reaction mixture and the crude product was filtered through a small column packed with SiO₂ eluting with hexane: ethylacetate 8:1. The solvent was removed to give colourless chemically pure mixture of linear methyl-3-phenylpropanoate and branched methyl-2-phenylpropanoate. The enantiomeric excess was determined by HPLC, using a Chirapak AD-H, 250 x 4.6 mm, 5 µm with guard cartridge, n-hexane 100%, 0.5 mL min⁻¹, 210 µm, t₁₀[(+)-S] = 17.9 min, t₁₀[(-)-R] = 20.0 min, t₈[linear] = 25.1 min.

The absolute configuration of the ester was determined by comparison of the sign of the optical rotation with the literature values.[40] In some cases, the enantiomeric excess was determined by chiral GC, using a MEGA-DEX DMP Beta (stationary phase), 0.25 µl filmthickness, 0.25 mm internal diameter, 25 m length. Linear methyl-3 phenylpropanoate t₈[linear] = 20.00 min; branched methyl-2-phenylpropanoate t₁₀[(+)-S] = 17.24 min, t₁₀[(-)-R] = 17.38 min, t₈[linear] = 19.9 min.

NMR data for catalysis products
Methyl-2-phenylpropanoate[6]:
¹H NMR (300 MHz, CDCl₃) δ 1.42 (d, J = 9, CH₃), 3.57 (s, CH₂), 3.65 (q, J = 9 Hz, CH, 1H), 7.07-7.28 (m, ArH, 5H). ¹³C NMR (75 MHz, CDCl₃) δ 18.6, 45.5, 52.1, 127.2, 127.5, 128.7, 140.5, 175.1.

Methyl-3-phenylpropanoate[7]:
¹H NMR (300 MHz, CDCl₃) δ 2.55 ( t, J = 7.5, CH₂), 2.87 (t, J = 7.5, CH₂), 3.58 (s, OCH₃), 7.07-7.28 (m, ArH, 5H). ¹³C NMR (75 MHz, CDCl₃) δ 31.0, 35.7, 51.7, 126.3, 128.3, 128.5, 173.4.

GC-MS: MS (EI): m/z calced. for [C₁₀H₁₄O₃]: 164.20; found 164.0.

General procedure for hydroxycarbonylation of aryl-alkenes
Lithium chloride (4.2 mg, 0.10 mmol), para-toluensulfonic acid (17.2 mg, 0.10 mmol), [LPdCl₂] (L = diphosphine) (0.005 mmol) and the aryl-alkene (0.5 mmol) were weighed into a Biotage 5 ml microwave vial. A magnetic stirrer bar was added and the vial was sealed with a crimp cap and put under inert atmosphere. Degassed water (22.5 µl, 1.25 mmol), degassed 2-butanone (1.5 ml) and internal standard (approximately 10µl of 1-methylnaphtalene or tetraethylsilane) were added using a syringe. The solution was mixed before taking a crude ¹H NMR sample (for t₀ NMR approximately 20 µl of solution were
taken). The caps were pierced with two needles and placed in the autoclave that was put under inert atmosphere and opened under argon flow before quickly sealed. The autoclave was purged three times with CO and then pressurised to 30 bar and heated in a preheated oil bath or heating jacket. After the desired time, the autoclave was cooled to room temperature and the pressure released slowly. The mixture was stirred before taking another $^1$H NMR sample (for $t$ NMR approximately 20 μl of solution were taken for calculating % product). The solvent was carefully removed from the reaction mixture and the residue was dissolved in toluene and filtered to remove precipitate. The toluene filtrate was extracted three times with saturated NaHCO$_3$ solution and the combined extracts were acidified with conc. HCl. The solution was then extracted 3 times with ethyl acetate and the combined organic layers were dried over MgSO$_4$, filtered and the solvent removed to give a mixture of branched and linear acids.

2-(4-Chlorophenyl)propionic acid

$^1$H NMR (300 MHz, CDCl$_3$): δ$_H$ 1.42 (d, J = 7.2, 3H), 3.63 (q, J = 7.2, 1H), 7.17 (d, J = 8.6, 2H), 7.22 (d, J = 8.6, 2H), 11.00 (br s, 1H). $^{13}$C NMR (100 MHz, CDCl$_3$); δ$_C$ 18.1 (CH$_3$), 44.8 (CH), 128.8 (2CH), 129.0 (2CH), 133.3 (C$_{qu}$), 138.1 (CCl), 180.6 (CO$_2$H). MS Cl$^-$: m/z calcd. for $[\alpha$D$]_20 = 98.5$ (c = 4.0, CHCl$_3$, ee = 66%).

3-(4-Chlorophenyl)propionic acid

$^1$H NMR (300 MHz, CDCl$_3$): δ$_H$ 1.32 (s, 9H), 1.51 (d, J = 7.2, 3H), 3.72 (q, J = 7.2, 1H), 7.26 (d, J = 8.4, 2H), 7.36 (d, J = 8.4, 2H), 10.24 (br s, 1H). $^{13}$C NMR (100 MHz, CDCl$_3$): δ$_C$ 30.3 (CH$_3$), 35.4 (CH$_2$), 128.6 (2CH), 130.1 (2CH), 132.0 (C$_{qu}$), 139.5 (CCl), 175.0 (CO$_2$H). GC MS: MS (EI): m/z calcd. for [C$_9$H$_9$O$_2$Cl]: 184.03 found 184.0.

2-(4-tert-butylphenyl)propionic acid

$^1$H NMR (300 MHz, CDCl$_3$): δ$_H$ 1.33 (s, 9H), 2.69 (t, J = 8.0, 2H), 2.95 (t, J = 8.0, 2H), 7.21 (d, J = 8.5, 2H), 7.29 (d, J = 8.5, 2H). $^{13}$C NMR (75 MHz, CDCl$_3$): δ$_C$ 30.0 (CH$_3$), 31.4 (3CH$_3$), 34.5 (C$_{qu}$), 35.6 (CH$_2$), 125.5 (2CH), 128.0 (2CH), 137.3 (C$_{qu}$) 149.2 (C$_{qu}$), 179.6 (CO$_2$H). GC MS: MS (EI): m/z calcd. for [C$_{13}$H$_{15}$O$_2$]: 206.1 found 206.0.

para-(1-carboxy-ethyl)benzoic acid

$^1$H NMR (300 MHz, CD$_2$Cl$_2$): δ$_H$ 1.42 (d, J = 7.2, 3H), 3.70 (q, J = 7.2, 1H), 7.35 (d, J = 8.2, 2H), 7.92 (d, J = 8.2, 2H). $^{13}$C NMR (100 MHz, CD$_2$Cl$_2$): δ$_C$ 18.3 (CH$_3$), 45.4 (CH) 127.5 (2CH), 129.5 (C$_{qu}$) 130.0 (2CH), 145.9 (C$_{qu}$), 168.3 (CO$_2$H) 175.9 (CO$_2$H). MS ES$: m/z calcd. for [(M-H$^-$)]: 193.05; found 193.05. HPLC Chiralcel OD-H, 0.5 ml/min, 95:5:0.1 hexane:iso-propanol:TFA. Rs: 29 min [(S)-enantiomer], 34 min [(R)-enantiomer]. [α]$_D$ = -28.5 (c = 0.533, MeOH, ee = 66%).

* A drop of deuterated DMSO was added for solubility purposes.

para-(2-carboxy-ethyl)benzoic acid

$^1$H NMR (300 MHz, CDCl$_3$): δ$_H$ 2.54 (t, J = 7.5, 2H), 2.91 (t, J = 7.5, 2H), 7.22 (d, J = 8.1, 2H), 7.87 (d, J = 8.1, 2H). MS ES$: m/z calcd. for [(M-H$^-$)]: 193.05; found 193.05.

2-(2-Chlorophenyl)propionic acid

$^1$H NMR (300 MHz, CDCl$_3$): δ$_H$ 1.54 (d, J = 7.2, 3H), 4.28 (q, J = 7.2, 1H), 7.18-7.31 (m, 2H), 7.33-7.42 (m, 2H), 11.42 (br s, 1H). $^{13}$C NMR (100 MHz, CDCl$_3$): δ$_C$ 17.6 (CH$_3$), 42.3 (CH), 127.5 (CH), 128.8 (CH), 128.9 (CH), 130.0 (CH), 134.2 (C$_{qu}$), 137.9 (CCl), 180.7 (CO$_2$H). MS NESI: m/z calcd. for [(M-H$^-$)]: 183.02; found 183.02. HPLC Chiralpak IC, 0.5 ml/min, 100:1:0.1 hexane:iso-propanol:TFA. Rs: 29 min [(S)-enantiomer], 37 min [(R)-enantiomer]. [α]$_D$ = -32.2 (c = 1.0, CHCl$_3$, ee = 60% (R)) {lit.$^{[10]}$} [α]$_D$ = +32.8 (c = 1.31, CHCl$_3$, ee = 55% (S)}. 14
2-(3-Fluorophenyl)propionic acid

\[ ^1H \text{NMR (300 MHz, CDCl}_3\]: \delta_H 1.39 (d, J = 7.2, 3H), 3.61 (q, J = 7.2, 1H), 6.80-7.00 (m, 3H), 7.10-7.22 (m, 1H), 11.33 (br s, 1H).

\[ ^13C \text{NMR (100 MHz, CDCl}_3\]: \delta_C 18.3 (CH), 45.4 (CH), 114.9 (app. t, J = 21.3, 2CH), 123.7 (d, J = 2.8, CH), 130.5 (d, J = 8.4, CH), 142.3 (d, J = 7.4, C_\text{ar}), 163.2 (d, J = 246.4, CF), 180.8 (COOH).

MS NELSI: m/z calcd. for [(M-H\(^-\)] : 167.05; found 167.05.

HPLC Chiralcel OD-H, 0.5 ml/min; 95:5:0.1 hexane:iso-propanol:TFA. R\(_c\): 19 min [(R)-enantiomer], 24 min [(S)-enantiomer].

\[ [\alpha]_D = -29.0 (c = 0.42, CHCl_3, ee = 73\%(R)) \} \{lit.\[11\] [\alpha]_D = -68 (c = unknown, CHCl_3, ee = 97\%(R)).

2-(4-Biphenyl)propionic acid

\[ ^1H \text{NMR (300 MHz, CDCl}_3\]: \delta_H 1.57 (d, J = 7.2, 3H), 3.81 (q, J = 7.2, 1H), 7.31-7.38 (m, 1H), 7.39-7.48 (m, 4H), 7.54-7.61 (m, 4H).

\[ ^13C \text{NMR (100 MHz, CDCl}_3\]: \delta_C 18.5 (CH), 45.3 (CH), 127.4 (CH), 127.7 (CH), 128.4 (CH), 129.1 (CH), 139.1 (C_\text{ar}), 140.8 (C_\text{ar}), 141.1 (C_\text{ar}), 180.3 (COOH).

MS NELSI: m/z calcd. for [(M-H\(^-\)] : 225.09; found 225.09. HPLC Chiralcel OD-H, 0.5 ml/min; 95:5:0.1 hexane:iso-propanol:TFA. R\(_c\): 33 min [(R)-enantiomer], 40 min [(S)-enantiomer]. [\alpha]_D = -32.8 (c = 0.80, CHCl_3, ee = 62\%(R)) \} \{lit.\[12\] [\alpha]_D = +46.7 (c = 1.0, CHCl_3, ee = 91\%(S)).

Synthesis of 4-Phenylstyrlyne

4-Vinylphenylboronic acid (443.9 mg, 3 mmol), K\(_2\)CO\(_3\) (552.8 mg, 4 mmol) and [PdCl\(_2\)Phenophos] (6.0 mg, 0.008 mmol) were weighed out into a dry schlenk flask, which was placed under an inert atmosphere. Dry and degassed toluene (8 ml) was added via syringe, followed by bromobenzene (210 \(\mu\)l, 2.0 mmol). The reaction was heated to 100 °C and stirred overnight. The reaction mixture was then cooled to room temperature and concentrated under vacuum. Purification by column chromatography (hexane : EtOAc, 4:1) gave the white solid product in 80 % yield (289.2 mg, 1.60 mmol %).

\[ ^1H \text{NMR (300 MHz, CDCl}_3\]: \delta_H 5.28 (dd, J = 0.9, 10.9, 1H), 5.80 (dd, J = 0.9, 17.6, 1H), 6.77 (dd, J = 10.9, 19.6, 1H) 7.31-7.38 (m, 1H), 7.41-7.52 (m, 4H), 7.55-7.64 (m, 4H).

\[ ^13C \text{NMR (100 MHz, CDCl}_3\]: \delta_C 114.3 (CH), 127.0 (2CH), 127.3 (2CH), 127.6 (2CH), 127.7 (CH), 129.1 (2CH), 136.7 (C_\text{ar}), 136.9 (C_\text{ar}), 140.9 (C_\text{ar}), 141.0 (C_\text{ar}). MS CI\(^+: m/z\) calcd. for [(M+H\(^+\)] : 181.10; found 181.10.

References


{{(S)-(+)-4,12-bis[bis-(3,5-di-tert-butyl-4-methoxyphenyl)phosphino]-[2.2]-para-cyclophane}palladium(II)chloride}, 3mo

$^{31}$P {H} NMR

{{(R)-(−)-4,12-bis[bis-(3,4,5-trifluorophenyl)phosphino]-[2.2]-para-cyclophane}palladium(II) dichloride}, 4mo

$^{31}$P {H} NMR
$^{31}$P {H} NMR

$^{31}$P {H} NMR
\{(R)-(\_)4,12-bis\text{[bis(3,5-dimethoxyphenyl)phosphino]-[2,2]-para-cyclophane}}\text{dipalladium(II) tetrachloride}, 5di

$^{31}P\\{H\}\text{NMR}$

\{((R)-(\_)4, 12-Bis\text{[bis(3,5-trifluoromethylphenyl)phosphino]-[2,2]-para-cyclophane}}\text{palladium\text{dichloride}, 6mo}

$^{31}P\\{H\}\text{NMR}$
$[(\text{R})-(\cdot)-4, \text{12-Bis(3,5-trifluorophenyl)phosphino}-[2,2]-\text{para-cyclophane}]\text{dipalladium[tetrachloride], 6di}$

$^{31}\text{P} \{\text{H}\} \text{NMR}$

$[(\text{R})-(\cdot)-4, \text{12-Bis(3,5-dichlorophenyl)phosphino}-[2,2]-\text{para-cyclophane}]\text{palladium[dichloride], 7mo}$

$^{31}\text{P} \{\text{H}\} \text{NMR}$

$[(\text{R})-(\cdot)-4, \text{12-Bis(3,5-dichlorophenyl)phosphino}-[2,2]-\text{para-cyclophane}]\text{dipalladium[tetrachloride], 7di}$
2-(4-Chlorophenyl)propionic acid

\(^1\)H NMR

\(^{13}\)C NMR
2-(4-tert-butylphenyl)propionic acid\textsuperscript{[2]}

\( ^1H \) NMR

\( ^{13}C \) NMR
para-(1-carboxy-ethyl)benzoic acid

$^1$H NMR

$^{13}$C NMR
2-(2-Chlorophenyl)propionoic acid

$^1$H NMR

$^{13}$C NMR
2-(3-Fluorophenyl)propionic acid

$^1$H NMR

$^{13}$C NMR
2-(4-Biphenylyl)propionic acid

$^1$H NMR

$^{13}$C NMR
Example crude $^1$H NMR for determination of conversion in hydroxycarbonylation reaction of styrene.

Before CO pressurization:

After pressure release: