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Highly modular *P-OP* ligands in asymmetric allylic substitution

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ABSTRACT

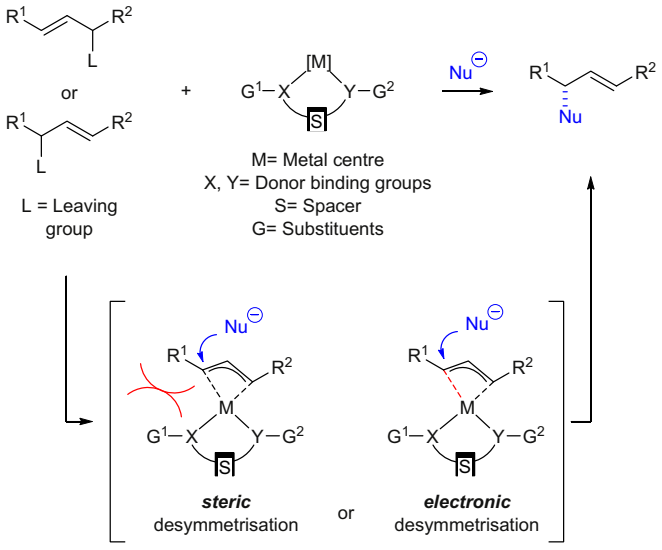
A library of highly modular *P-OP* ligands have been evaluated in Pd-catalysed allylic substitutions with C- and N-nucleophiles. Catalyst optimisation via a variation of the phosphino and phosphite substituents led to a 'lead' catalyst, which efficiently mediated the allylic substitutions when various combinations of substrates and nucleophiles were tested. Ground-state calculations were carried out and these allowed a clearer understanding of the stereochemical outcome of the reaction.

1. Introduction

Allylic alkylation is amongst the most important methodologies for the stereoselective formation of C–C bonds, enabling the creation of diverse carbon frameworks for targets ranging from natural products to non-natural organic compounds. Enantiomerically enriched alkylation products are formed from racemic substrates by differentiation of the reactivity of the two allyl termini in the intermediate π-allyl complexes. Desymmetrisation of the allyl system depends on the electronic and/or steric effects induced by the ligand bound to the metal centre.[1]

For C_2-symmetric ligands (e.g., bisoxazolines), desymmetrisation arises solely from steric interactions between the substituents of the ligand and the substrate.[1,2] On the other hand, non-steric factors may become preponderant in C_1-symmetric ligands, as for example in those containing two distinct donor groups, X and Y, that differ in their coordination to the metal centre (e.g., P,N-ligands). In this case, desymmetrisation may chiefly occur due to the different *trans*-influences of X or Y, as these may preferentially lengthen one of the two distal metal-C_{allyl} bonds (Scheme 1).[1,3]

We recently reported on the preparation of a library of highly modular *P-OP* (phosphine-phosphinite and phosphine-phosphite) ligands and their use in asymmetric hydrogenation,[4] and we felt that studying their application in allylic substitutions was the next logical step forward in assessing the utility of these ligands in asymmetric catalysis. We found that the literature precedent on the use of *P-OP* ligands in allylic substitution was scarce.[5] We reasoned that the different coordinating properties of the phosphino group and of the phosphite/phosphinite group could be efficient tools for desymmetrisation of the terminal allyl carbons. Furthermore, we envisioned that modular ligand design should enable catalyst optimisation via systematic variation of the different components of the catalytic system (G^1, G^2, X, Y or S) as differentiating tools (electronic, steric or a combination of both) for the terminal allyl carbons. Herein, we report our efforts to evaluate structurally diverse *P-OP* ligands in palladium-mediated asymmetric allylic substitutions.



Scheme 1. Metal-mediated nucleophilic allylic substitutions.

2. Results and discussion

Our initial set of ligands comprised phosphine-phosphinites **1** and phosphine-phosphites **2**–**5** (Fig. 1),[6] which we chose in order to evaluate the effect of sterically and/or electronically diverse phosphorus functionalities on the catalytic performance of their corresponding palladium complexes.

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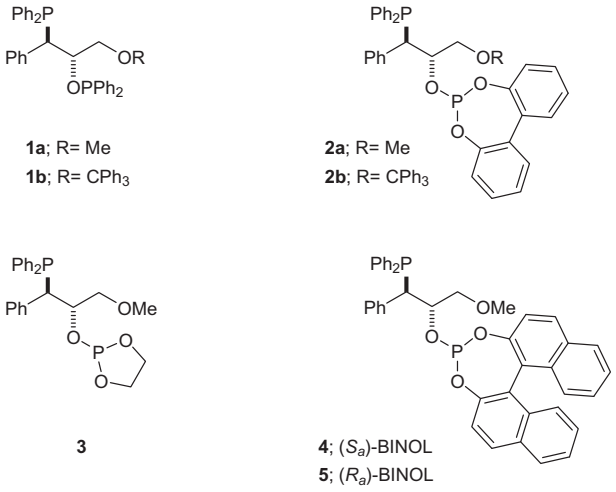
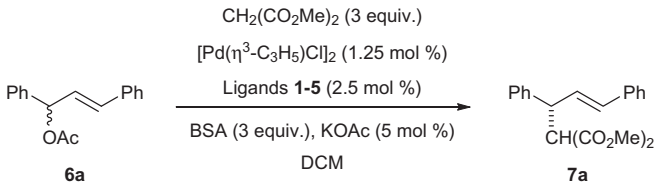


Figure 1. *P-OP* ligands.

The in situ-generated Pd-complexes between **1a** or **1b** and $[Pd(\eta^3\text{-}C_3H_5)Cl]_2$ mediated the allylic substitution of **6a** with dimethyl malonate (DMM) with high activities but poor selectivities (Table 1, entries 1 and 2). Better ee's were obtained when the diphenylphosphinite fragment was replaced with a biphenol-derived phosphite moiety (Table 1, entries 3 and 4). In this case, the size of the alkoxy group had a greater impact on enantioselectivity:[7] the smaller group (the OMe in **2a**) gave the higher ee (40%) (Table 1, entry 3). Thus, we performed all subsequent optimisation studies using the OMe group at the *R*-oxy position. Disappointingly, the Pd-complex derived from the dioxaphospholane-containing ligand **3** afforded drastically lower conversion and ee (Table 1, entry 5). As biaryl-based phosphites provided the best enantioselectivity, the (*S*)- and (*R*)-BINOL-derived ligands **4** and **5** were selected. Although the catalytic precursor-bearing ligand **4** showed only modest activity and selectivity (Table 1, entry 6), the one based on **5** achieved high conversion and the highest ee (80%, Table 1, entry 7). The incorporation of a less-coordinating counteranion into the catalytic species (PF_6^- instead of Cl^-), did not lead to an improvement of the enantioselectivity either at room temperature or at 0 °C (Table 1, entries 8 and 9).

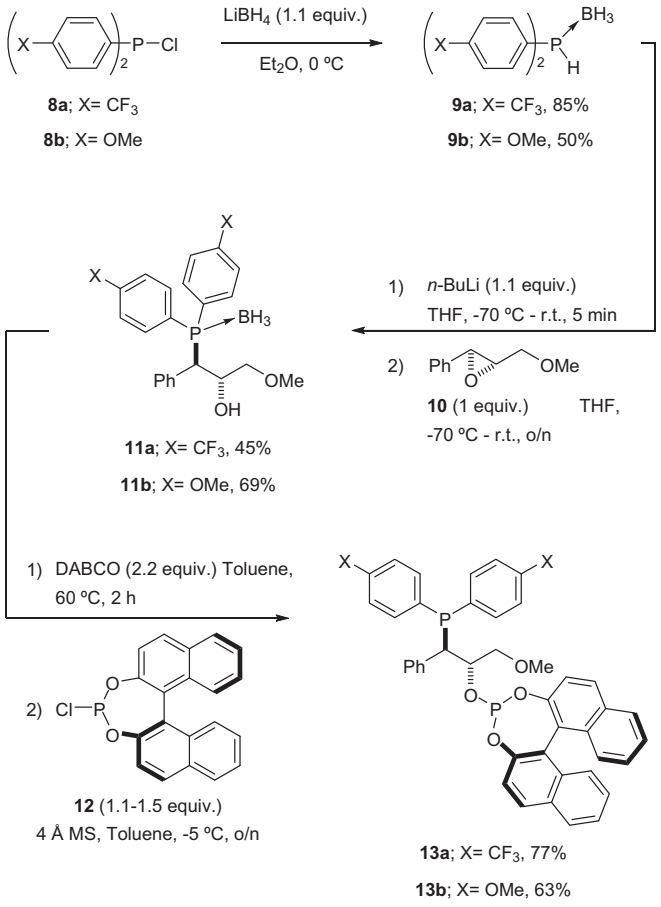
Table 1
Evaluation of **1–5** in Pd-catalysed allylic substitutions



6a **7a**

Entry	Ligand	t^a (h)	Temp (°C)	Conv.[b] (%)	ee[c] (%) (configuration)
1	**1a**	2.5	rt	>95	16 (*R*)
2	**1b**	2.5	rt	>95	21 (*R*)
3	**2a**	5	rt	>95	40 (*R*)
4	**2b**	5	rt	>95	27 (*R*)
5	**3**	24	rt	37	14 (*R*)
6	**4**	24	rt	56	56 (*S*)
7	**5**	1	rt	>95	80 (*R*)
8	**5**[d]	2	rt	>95	78 (*R*)
9	**5**[d]	2	0	>95	79 (*R*)

[a] Reaction time.
[b] Conversion was determined by ^1H NMR.
[c] Enantiomeric excess was measured by chiral HPLC and absolute configuration was assigned by comparison with published data.
[d] Preformed $[Pd(\eta^3\text{-}C_3H_5)(\mathbf{5})]PF_6$ was used as the catalyst instead of the usual catalyst (in situ-generated $[Pd(\eta^3\text{-}C_3H_5)(\mathbf{5})]Cl$).



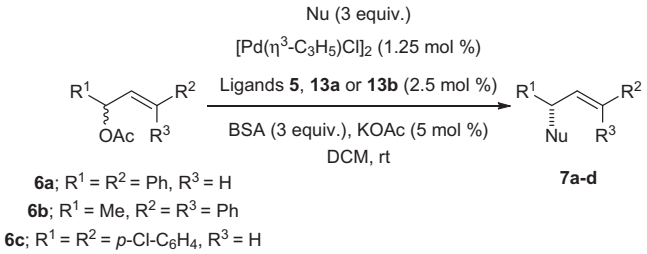
Scheme 2. Synthesis of electronically tuned *P-OP* ligands.

Our results underscore an interesting match/mismatch effect. Indeed, Pd-complexes of ligands **4** and **5** behaved rather distinctly: the former yielded the product with lower ee, whereas the latter gave the opposite enantiomer with higher ee. Thus, the (*S*)-BINOL-derived substituent on the phosphite group overrides the asymmetric induction generated by the ligand backbone, whereas the (*R*)-BINOL one enhances it.

We reasoned that a more pronounced differentiation between the two phosphorus functionalities could enhance the enantioselectivity. Thus, we wished to modulate the donor ability of the phosphino moiety in **5**, by introducing electron-withdrawing (**13a**, X = CF_3) or -donating (**13b**, X = OMe) substituents (Scheme 2). Similar variations had already been studied theoretically by Goldfuss et al.[8] on P,N-derived allylpalladium complexes and they predicted that a more electron-rich phosphine unit led to a longer bond between palladium and the allyl carbon *trans* to the phosphorus (a more pronounced *trans*-influence). Based on their results, and considering that for other phosphine-phosphites, the phosphino groups have been reported to induce a stronger *trans*-influence than the phosphite ones,[5a] we anticipated higher ee's when passing from the ligand containing the $(p\text{-}CF_3\text{–}C_6H_4)_2P$ substituent **13a**, to the one with the Ph_2P moiety **5**, and lastly, to the one with the $(p\text{-}MeO\text{–}C_6H_4)_2P$ group **13b**.

We therefore prepared the borane complexes of secondary phosphines **9a** and **9b**, with which to open the epoxy ether **10** (Scheme 2), in a single step using $LiBH_4$[9] as the reducing agent. The borane adducts of the phosphino-alcohols, **11a** and **11b**, were

Table 2
Comparative study of ligands **5**, **13a** and **13b** in Pd-catalysed allylic substitutions with C- and N-nucleophiles



Entry	Subs.	Nu[a]	Prod.	Ligand	t[b] (h)	Conv.[c] (%)	ee[d] (%) (configuration)
1	**6a**	DMM	**7a**	**13a**	1	>95	64 (*R*)
2	**6a**	DMM	**7a**	**13b**	1	>95	80 (*R*)
3	**6a**	DMM	**7a**	**13b**[e]	1	>95	78 (*R*)
4	**6b**	DMM	**7b**	**13b**[f]	90	92	34 (*R*)
5	**6c**	DMM	**7c**	**13b**	2	>95	67 (*R*)
6	**6a**	BZA	**7d**	**13a**	24	3	46 (*S*)
7	**6a**	BZA	**7d**	**5**	72	3	61 (*S*)
8	**6a**	BZA	**7d**	**13b**	24	9	81 (*S*)
9	**6a**	BZA	**7d**	**13b**[e]	17	67	81 (*S*)

[a] Nucleophile: DMM (dimethyl malonate); BZA ($PhCH_2NH_2$).
[b] Reaction time.
[c] Conversion was determined by ^1H NMR.
[d] Enantiomeric excess was measured by chiral HPLC and absolute configuration was assigned by specific rotation measurement or comparison with published data.
[e] Preformed [Pd(η^3-C_3H_5)(**13b**)]PF_6 was used as the catalyst instead of the usual catalyst (in situ-generated [Pd(η^3-C_3H_5)(**13b**)]Cl).
[f] 5 mol % of catalyst were used instead of 2.5 mol %.

obtained by stereospecific and regioselective epoxide ring-opening.[4,10] Ligands **13a–b** were finally obtained in 77% and 63% yield, respectively (Scheme 2) after borane cleavage and O-phosphorylation using DABCO as the nucleophile/base for both transformations, thereby markedly simplifying our previous[4] experimental procedure.

We then studied the Pd-complexes derived from **13** in allylic substitutions, comparing their catalytic performance to that of **5**. All of them performed similarly in the allylic alkylation of **6** with DMM, providing near total conversion of the substrate within 1 h (Table 2). As anticipated, **13a** (CF_3-substituted) gave the lowest ee, whereas **13b** (OMe-substituted) gave the same enantiomeric excess as **5** (compare Table 1, entry 7 with Table 2, entry 2).[11]

We used benzylamine (BZA) as a model nitrogen nucleophile to study the allylic substitution of **6** mediated by the Pd-complexes of **5**, **13a** and **13b** (Table 2, entries 6–9). We clearly observed the expected trend of increasing enantioselectivity with **13a** (X = CF_3; 46% ee), **5** (X = H; 61% ee), and **13b** (X = OMe; 81% ee). Conversions were low when in situ-generated [Pd(η^3-C_3H_5)(**13b**)]Cl was used as the catalyst. Conversely, they were dramatically higher when preformed [Pd(η^3-C_3H_5)(**13b**)]PF_6 was used instead (Table 2, entry 9) and the enantioselectivity remained unchanged.[12] This is the highest ee reported in the rare examples of allylic aminations with *P-OP*-based palladium complexes.

To gain further insight into the basis of the stereodirecting mechanisms,[13] the geometries of the [Pd(η^3-PhCHCHCHPh)(**5**)]$^+$ complexes **14** were optimised at the full DFT level.[14] Selected geometrical parameters are summarised in Figure 4 and Table 3. Our calculations predicted that the phosphino group was responsible for the strongest *trans*-influence on the allyl group in three of the six diastereoisomers, thus preferentially elongating the bond between the palladium and the terminal allyl carbon *trans* to the phosphino group (Pd-C_{tP}, Fig. 4) in **14**-*endo-syn-syn*, **14**-*endo-syn-anti* and **14**-*exo-syn-anti*. In the remaining [Pd(η^3-PhCHCHCHPh)(**5**)]$^+$ complexes considered **14**-*exo-syn-syn*, **14**-*endo-anti-syn* and **14**-*exo-anti-syn*, the bond between the palladium atom and the allyl carbon *trans* to the phosphite was longer (Pd-C_{tPO},

Table 3
Selected geometrical parameters for complexes **14**

Entry	Complex	Distances[a] (Å)			
		Pd–C_{tPO}	Pd–C_{tP}	PPdP–C_{tP}	PPdP–C_{tPO}
1	**14**-*endo-syn-syn*	2.27	2.33	0.58	−0.02
2	**14**-*endo-syn-anti*	2.24	2.39	0.13	0.11
3	**14**-*exo-syn-anti*	2.26	2.33	−0.04	−0.08
4	**14**-*exo-syn-syn*	2.32	2.29	−0.26	−0.36
5	**14**-*endo-anti-syn*	2.32	2.26	0.45	−0.22
6	**14**-*exo-anti-syn*	2.43	2.23	−0.26	0.11

[a] Pd–C_{tP} = Pd–(C_{allyl} *trans* to P) bond distance; Pd–C_{tPO} = Pd–(C_{allyl} *trans* to PO) bond distance; PPdPO–C_{tP} = distance between the P–Pd–PO mean plane and the C_{allyl} *trans* to P; PPdPO–C_{tPO} = distance between the P–Pd–PO mean plane and the C_{allyl} *trans* to PO.

Fig. 4). Assuming that the *trans*-influence governs the enantioselectivity by directing the nucleophile to the allyl terminus that is furthest from the palladium centre, only complexes **14**-*endo-syn-syn* and **14**-*exo-syn-syn* led to the experimentally observed stereoisomer of **7**. In contrast, all of the remaining complexes led to substituted products with a *Z*-configuration, which we did not observe. Thus, analysis of the stereochemical outcome of the reaction based merely on the differentiation of the allyl unit due to *trans*-influences leads in our case to an incongruence: none of the possible [Pd(η^3-PhCHCHCHPh)(**5**)]$^+$ complexes gives the minor enantiomer of **7**. Apparently, the electronic effects are not the only source of enantiodiscrimination in the reaction. This was confirmed by a Hammett analysis of the enantiomeric ratio (er) with respect to σ_p[15] (Fig. 2). Indeed, the log(er) data did not perfectly fit σ_p and moreover the low absolute value of the slopes, that is, of the constant ρ (<1 for DMM and BZA as nucleophiles), also suggests that the electronic effects are not the only influence on enantioselectivity.[15a]

It has been reported for analogous systems[16] that nucleophilic attack may be determined by steric effects, more precisely by the orientation of the allyl group with respect to the X-Pd-Y plane

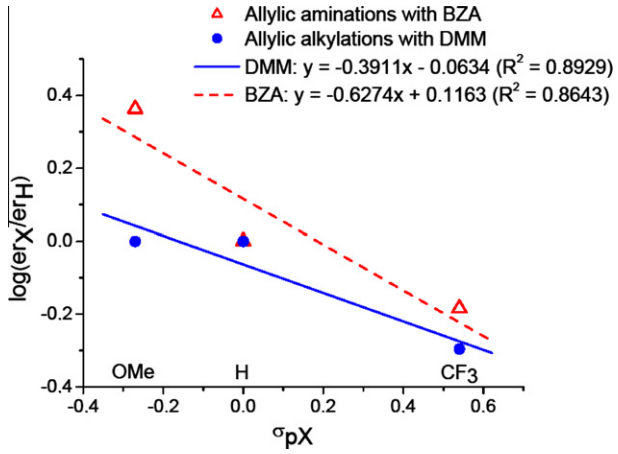


Figure 2. Hammett plot of the enantiomeric ratio of products **7a** and **7d** when using ligands **13a**, **5** and **13b**.

(X, Y = donor binding groups). When two vicinal allylic carbons tend to be aligned with that plane in the starting Pd–allyl complex, the energy barrier for allylic substitution is reduced and nucleophilic attack takes place at the allylic terminus which is furthest out of the plane (Fig. 3).[16]

In complexes **14**-*endo-syn-syn* and **14**-*endo-anti-syn*, the allyl groups present the highest degree of rotation with respect to the plane (Table 3, entries 1 and 5). Thus, attack of the nucleophile at these positionally activated allyl carbons would lead to the formation of the electronically favoured substitution product [(*R*)-**7a** for DMM and (*S*)-**7d** for BZA as nucleophiles] from **14**-*endo-syn-syn*. The formation of the electronically disfavoured stereoisomer [(*S*)-**7a** for DMM and (*R*)-**7d** for BZA as nucleophiles], which is observed in a minor amount, could be rationalised by nucleophilic attack onto **14**-*endo-anti-syn*.

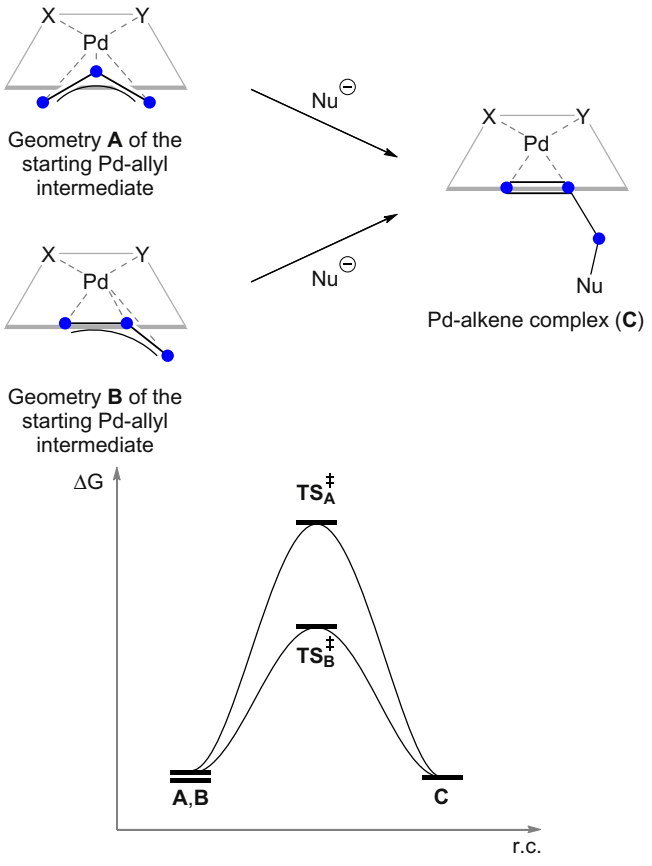


Figure 3. Influence of the geometry of the Pd-allyl intermediate on the activation barrier of the nucleophilic attack.

3. Conclusions

In conclusion, we have described an efficient synthesis of new phosphine-phosphite ligands that incorporate substituents with different electronic properties on the phosphino group. We evaluated a library of highly modular *P-OP* ligands in palladium-catalysed allylic substitutions. The first phosphine-phosphinite ligands to be tested in this reaction gave poor enantioselectivities, while catalyst optimisation via variation of the phosphine and phosphite substituents led to the development of a lead catalyst derived from **13b**, which afforded enantioselectivities ranging from low to acceptable for all combinations of substrates and nucleophiles. Lastly, a rationalisation of the stereochemical outcome of the reaction solely based on *trans*-influences on Pd-complexes **14** was unable to provide a complete picture of the stereochemical outcome of the reaction. A subtle interplay between electronic and steric effects in the [Pd(η^3-PhCHCHCHPh)(**5**)]$^+$ complexes **14** was shown to be determinant for stereochemical induction. Structure optimisation and evaluation in other transformations of Sharpless epoxide-derived *P-OP* ligands are currently underway.

4. Experimental

4.1. General

All syntheses were carried out using chemicals as purchased from commercial sources unless otherwise noted. Solvents were dried and deoxygenated prior to use. Air- and moisture-sensitive compounds were prepared under an argon atmosphere using standard Schlenk techniques. NMR spectra were recorded in $CDCl_3$ unless otherwise noted using a 400 MHz spectrometer. Chemical shifts (δ) are reported relative to residual solvent signals or tetramethylsilane as an internal reference (0.00 ppm). IR spectra were recorded using the Attenuated Total Reflection technique. Mass spectra were obtained by matrix-assisted laser desorption/ionisation time of flight (MALDI-TOF) or electrospray ionisation (ESI, HRMS). Optical rotations were measured in chloroform, dichloromethane or ethanol. Melting points were uncorrected.

4.2. Synthetic route for the preparation of *P-OP* ligands 13a and 13b

4.2.1. Bis(4-trifluoromethylphenyl)phosphine–borane complex 9a

This compound was prepared according to the procedure of Manners et al.[9] Lithium borohydride (42 mg, 1.92 mmol, 1.1 equiv) was introduced in a dry Schlenk flask equipped with a stirring bar. The flask was purged with argon three times, then diethyl ether (4.5 mL) was added. The mixture was cooled to 0 °C, then chlorobis[4-(trifluoromethyl)phenyl]phosphine **8a** (621 mg, 1.74 mmol) was added in one portion. The mixture turned cloudy white at once, and was stirred for 1.5 h at 0 °C. After evaporation of the volatiles, the residue was taken up in hexanes, filtered through Celite and concentrated, to give **9a** as an air-sensitive colourless oil (537 mg, containing ca. 4% of the corresponding phosphine oxide; 85% yield of **9a**). Due to the lability of the phosphorus–boron bond in **9a**, this compound was used shortly after preparation. ^{1}H NMR ($CDCl_3$, 400 MHz): δ (ppm) 7.89–7.71 (m, 8H), 6.43 (dq, J = 382.9, 7.2 Hz, 1H), 1.7–0.4 (m, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ (ppm) 134.2 (qd, $^2J_{C-F}$ = 32.5, $^4J_{C-P}$ = 2.3 Hz, C), 133.6 (d, $^2J_{C-P}$ =

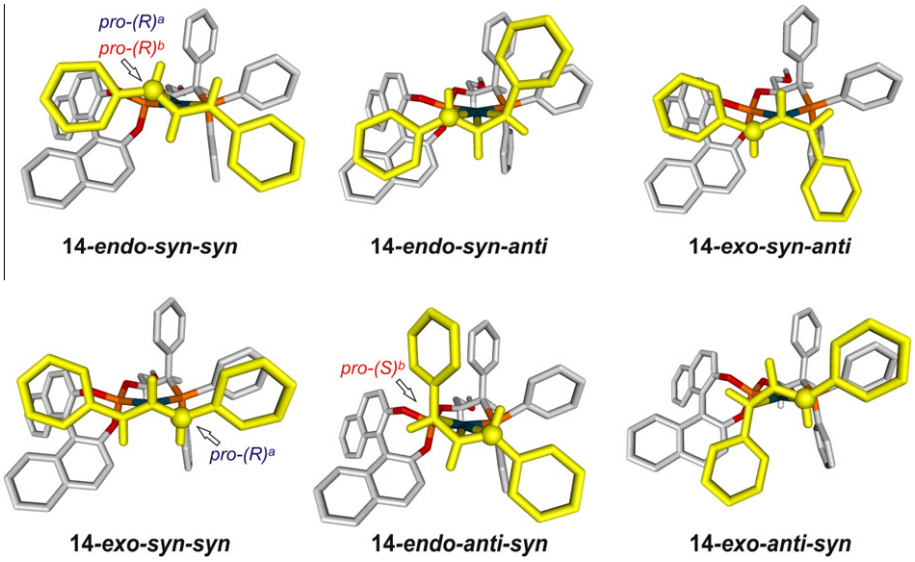


Figure 4. Calculated geometries for the diastereomeric Pd(η^3-PhCHCHCHPh) complexes derived from ligand **5**. Positions in the allyl units, whose attack by the nucleophile is favoured due to bond elongation, have been marked with a yellow sphere. [a]Attack at the '*trans*-influence'-favoured C_{allyl} leads to (*R*)-**7a** with DMM. [b]Attacks at the C_{allyl} which are furthest out of the plane with DMM lead to (*R*)-**7a** or (*S*)-**7a** as indicated.

10.0 Hz, CH), 130.3 (d, $^1J_{C-P}$ = 54.1 Hz, C), 126.3 (dq, $^3J_{C-P}$ = 10.6, $^3J_{C-F}$ = 3.3 Hz, CH), 123.5 (q, $^1J_{C-F}$ = 272.7 Hz, C). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz): δ (ppm) 6.2–4.3 (m). $^{11}B\{^1H\}$ NMR ($CDCl_3$, 128 MHz): δ (ppm) (−)40.4 (br s).

4.2.2. Bis(4-methoxyphenyl)phosphine–borane complex 9b

This compound[17] was prepared using a procedure similar to the one used for **9a**. Lithium borohydride (55 mg, 2.53 mmol, 1.26 equiv) was introduced in a dry Schlenk flask equipped with a stirring bar. The flask was purged with argon three times, then diethyl ether (8 mL) was added. The mixture was cooled to 0 °C, then chlorobis(4-methoxyphenyl)phosphine **8b** (561 mg, 2.00 mmol) was added in one portion. After stirring at 0 °C to rt for 4 h, the reaction mixture was filtered through Celite using diethyl ether as the washing eluent, and concentrated to give **9b** as an air-stable white solid (263 mg, 50% yield). ^1H NMR ($CDCl_3$, 400 MHz): δ (ppm) 7.62–7.53 (m, 4H), 7.00–6.92 (m, 4H), 6.26 (dq, *J* = 377.8, 6.8 Hz, 1H), 3.82 (s, 6H), 1.7–0.4 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ (ppm) 162.4 (d, $^4J_{C-P}$ = 2.2 Hz, C), 134.7 (d, $^2J_{C-P}$ = 10.6 Hz, CH), 117.4 (d, $^1J_{C-P}$ = 62.2 Hz, C), 114.8 (d, $^3J_{C-P}$ = 11.2 Hz, CH), 55.5 (s, CH_3). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz): δ (ppm) 3.4–(−)2.4 (m). $^{11}B\{^1H\}$ NMR ($CDCl_3$, 128 MHz): δ (ppm) (−)37–(−)43 (m). IR: ν_{max} (cm^{-1}) 3201, 2932, 2837, 2381, 2343, 1593, 1569, 1499, 1459, 1440, 1407, 1292, 1250, 1178, 1110, 1060, 1024, 903, 824, 799. HRMS (ESI): $[M+Na]^+$, calculated for $C_{14}H_{18}BO_2NaP$: 282.1072, found: 282.1071. Mp = 68–72 °C.

4.2.3. ((1*R*,2*S*)-2-Hydroxy-3-methoxy-1-phenyl-propyl)bis(4-trifluoromethylphenyl)phosphine–borane complex 11a

n-Butyllithium (2.5 M in hexanes; 0.34 mL, 0.85 mmol, 1.1 equiv) was added dropwise to a −70 °C solution of phosphine–borane complex **9a** (259 mg, 0.77 mmol) in THF (3 mL) under argon. The mixture was stirred at −70 °C for 2 min, removed from the cooling bath and was allowed to warm up for 5 min, and then cooled back to −70 °C. To this red solution was added dropwise a −70 °C solution of (2*S*,3*S*)-2-(methoxymethyl)-3-phenyloxirane **10** (127 mg, 0.77 mmol, 1 equiv) in THF (4 mL). Next, 2 × 1 mL of THF were used to rinse the equipment. The resulting yellow mixture was stirred at −70 °C for 1 h. The cryostat was then switched off, and the mixture was allowed to warm slowly to rt overnight. After the addition of 10 mL of water and 10 mL of ethyl acetate, the layers were separated and the aqueous phase was extracted with ethyl acetate (3 × 10 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, concentrated, and purified by silica gel chromatography (hexanes/ethyl acetate 80:20) to give **11a** as a white sticky foam (175 mg, 45% yield). Due to the lability of the phosphorus–boron bond in **11a**, this compound was further derivatised shortly after preparation. ^1H NMR ($CDCl_3$, 400 MHz): δ (ppm) 8.13–8.05 (m, 2H), 7.83–7.76 (m, 2H), 7.51–7.41 (m, 4H), 7.34–7.27 (m, 2H), 7.20–7.13 (m, 3H), 4.50 (tdd, ^3J = 7.2, 4.8, 4.0 Hz, 1H), 4.21 (dd, $^2J_{H-P}$ = 17.0, $^3J_{H-H}$ = 4.0 Hz, 1H), 3.23 (ddd, $^2J_{H-H}$ = 9.6, $^3J_{H-H}$ = 4.8, $^4J_{H-P}$ = 1.6 Hz, 1H), 3.16 (s, 3H), 3.13 (dd, $^2J_{H-H}$ = 9.6, $^3J_{H-H}$ = 7.2 Hz, 1H), 2.70 (br s, 1H), 1.9–0.7 (m, 3H). $^{13}C\{^1H\}$ NMR ($CDCl_3$, 100 MHz): δ (ppm) 133.9 (qd, $^2J_{C-F}$ = 32.8, $^4J_{C-P}$ = 2.7 Hz, C), 133.56 (d, $^2J_{C-P}$ = 8.9 Hz, CH), 133.53 (d, $^2J_{C-P}$ = 9.1 Hz, CH), 133.1 (qd, $^2J_{C-F}$ = 32.9, $^4J_{C-P}$ = 2.9 Hz, C), 132.6 (d, $^1J_{C-P}$ = 38.1 Hz, C), 132.1 (d, $^1J_{C-P}$ = 41.1 Hz, C), 132.0 (d, $^2J_{C-P}$ = 1.1 Hz, C), 131.2 (d, $^4J_{C-P}$ = 5.0 Hz, CH), 128.5 (d, $^3J_{C-P}$ = 1.1 Hz, CH), 128.1 (d, $^5J_{C-P}$ = 1.9 Hz, CH), 125.9 (dq, $^3J_{C-P}$ = 9.9, $^3J_{C-F}$ = 3.5 Hz, CH), 125.1 (dq, $^3J_{C-P}$ = 10.3, $^3J_{C-F}$ = 3.5 Hz, CH), 123.6 (q, $^1J_{C-F}$ = 272.7 Hz, CF_3), 123.5 (q, $^1J_{C-F}$ = 273.2 Hz, CF_3), 73.0 (d, $^3J_{C-P}$ = 8.8 Hz, CH_2), 69.2 (d, $^3J_{C-P}$ = 5.9 Hz, CH), 58.9 (s, CH_3), 44.7 (d, $^1J_{C-P}$ = 30.8 Hz, CH). $^{31}P\{^1H\}$ NMR ($CDCl_3$, 162 MHz): δ (ppm) 23.2 (br s). $^{11}B\{^1H\}$ NMR ($CDCl_3$, 128 MHz): δ (ppm) (−)39.0 (br s). $^{19}F\{^1H\}$ NMR ($CDCl_3$, 376 MHz): δ (ppm) (−)63.4 (s, 3F), (−)63.5 (s, 3F). IR: ν_{max} (cm^{-1}) 2928, 2395, 1609, 1494, 1454, 1398, 1320, 1169, 1125, 1060, 1016, 966, 833, 700. HRMS (ESI): $[M+Na]^+$, calculated for $C_{24}H_{24}BO_2F_6NaP$: 523.1409, found: 523.1401. $[\alpha]_D^{27} = -116.8$ (*c* 1.11, $CHCl_3$).

4.2.4. ((1*R*,2*S*)-2-Hydroxy-3-methoxy-1-phenylpropyl)bis(4-methoxyphenyl)phosphine–borane complex 11b

n-Butyllithium (2.5 M in hexanes; 0.34 mL, 0.85 mmol, 1.1 equiv) was added dropwise to a −70 °C solution of phosphine–borane complex **9b** (200 mg, 0.77 mmol) in THF (3 mL) under argon. The mixture was stirred at −70 °C for 2 min, removed from the cooling bath and allowed to warm up for 5 min, and cooled back to −70 °C. To this yellow-orange solution was added dropwise a −70 °C solution of (2*S*,3*S*)-2-(methoxymethyl)-3-phenyloxirane **10** (128 mg, 0.77 mmol, 1 equiv) in THF (4 mL). Next, 2 × 1 mL of THF were used to rinse the equipment. The

resulting yellow mixture was stirred at −70 °C for 1 h. The cryostat was then switched off, and the mixture was allowed to warm slowly to rt overnight. After the addition of 10 mL of water and 10 mL of ethyl acetate, the layers were separated and the aqueous phase was extracted with ethyl acetate (3 × 10 mL). The combined organic layers were washed with brine, dried over $MgSO_4$, concentrated, and purified by silica gel chromatography (hexanes/ethyl acetate 65:35) to give **11b** as a white sticky foam (224 mg, 69% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ (ppm) 7.93–7.84 (m, 2H), 7.39–7.31 (m, 2H), 7.31–7.22 (m, 2H), 7.19–7.17 (m, 3H), 7.07–6.99 (m, 2H), 6.70–6.63 (m, 2H), 4.43 (tdd, ^3J = 6.8, 5.2, 3.6 Hz, 1H), 4.03 (dd, $^2J_{H-P}$ = 16.8, $^3J_{H-H}$ = 3.6 Hz, 1H), 3.85 (s, 3H), 3.70 (s, 3H), 3.19 (ddd, $^2J_{H-H}$ = 9.5, $^3J_{H-H}$ = 5.2, $^4J_{H-P}$ = 1.6 Hz, 1H), 3.15 (s, 3H), 3.09 (dd, $^2J_{H-H}$ = 9.5, $^3J_{H-H}$ = 6.8 Hz, 1H), 2.90 (br s, 1H), 1.9–0.7 (m, 3H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ (ppm) 162.2 (d, $^4J_{C-P}$ = 2.5 Hz, C), 161.6 (d, $^4J_{C-P}$ = 2.5 Hz, C), 134.6 (d, $^2J_{C-P}$ = 9.9 Hz, CH), 134.5 (d, $^2J_{C-P}$ = 10.1 Hz, CH), 133.3 (s, C), 131.4 (d, $^4J_{C-P}$ = 4.8 Hz, CH), 128.1 (s, CH), 127.4 (d, $^5J_{C-P}$ = 2.0 Hz, CH), 119.4 (d, $^1J_{C-P}$ = 17.9 Hz, C), 118.8 (d, $^1J_{C-P}$ = 21.5 Hz, C), 114.7 (d, $^3J_{C-P}$ = 10.8 Hz, CH), 113.8 (d, $^3J_{C-P}$ = 11.1 Hz, CH), 73.3 (d, $^3J_{C-P}$ = 8.4 Hz, CH_2), 69.0 (d, $^2J_{C-P}$ = 5.7 Hz, CH), 58.9 (s, CH_3), 55.5 (s, CH_3), 55.3 (s, CH_3), 45.7 (d, $^1J_{C-P}$ = 33.2 Hz, CH). ^{31}P{^{1}H} NMR ($CDCl_3$, 162 MHz): δ (ppm) 19.1–16.2 (m). ^{11}B{^{1}H} NMR ($CDCl_3$, 128 MHz): δ (ppm) (−)38.9 (br s). IR: ν_{max} (cm^{-1}) 2897, 2377, 1595, 1569, 1501, 1455, 1291, 1255, 1181, 1106, 1062, 1027, 968, 828, 803, 703. HRMS (ESI): [M+Na]$^+$, calculated for $C_{24}H_{30}BO_4NaP$: 447.1872, found: 447.1864. $[\alpha]_D^{28} = -145.9$ (*c* 1.06, $CHCl_3$).

4.2.5. ((1*R*,2*S*)-1-(Bis(4-(trifluoromethyl)phenyl)phosphino)-3-methoxy-1-phenylpropan-2-yl) ((*R*)-1,1′-binaphthalen-2,2′-yl) phosphite 13a

Hydroxyalkylphosphine-borane **11a** (175 mg, 0.35 mmol) was introduced as a toluene solution into a dry Schlenk flask under argon. The toluene was removed in vacuo, after which the residue was then dried azeotropically twice with toluene and the flask placed under argon. Next, DABCO (86 mg, 0.77 mmol, 2.2 equiv) was added and the flask quickly purged by doing quite fast vacuum/argon cycles, in order to avoid sublimation of DABCO. Toluene (5 mL) was added, and the septum was swapped for a greased glass stopper while under a strong stream of argon. The flask was purged again with quite fast vacuum/argon cycles and dipped into a 60 °C oil bath. After 2 h, it was allowed to cool down to rt. The glass stopper was swapped back for a septum, after which the reaction mixture was cooled to −5 °C and was added dropwise via cannula onto a −5 °C solution of (*R*)-(binaphthalene-2,2′-diyl)chlorophosphite **12** (184 mg, 0.52 mmol, 1.5 equiv) in toluene (5 mL) to which had been added a few 4 Å molecular sieves. Next, 2 × 1 mL of toluene were used to rinse the equipment. The resulting cloudy mixture was stirred overnight at −5 °C. The cryostat was then switched off and the cooling bath was allowed to warm slowly to rt. After stirring at rt for another 2 h, the mixture was introduced in the glovebox and filtered through a very short pad of previously dried and deoxygenated silica (ca. 1 mL). The pad was washed with 4 × 5 mL of toluene. The filtrate was concentrated in vacuo, then purified by a short silica gel chromatography in the glovebox (*n*-hexane/THF 80:20) to give phosphine-phosphite **13a** as a white solid (217 mg, 77% yield). ^{1}H NMR ($CDCl_3$, 400 MHz): δ (ppm) 8.11–8.05 (m, 1H), 8.02–7.96 (m, 2H), 7.95–7.87 (m, 4H), 7.70–7.64 (m, 2H), 7.48–7.35 (m, 7H), 7.33–7.22 (m, 6H), 7.15–7.02 (m, 3H), 4.44–4.34 (m, 1H), 3.82 (dd, $^3J_{H-H}$ = 5.2, $^2J_{H-P}$ = 3.2 Hz, 1H), 3.20 (s, 3H), 3.19 (dd, $^2J_{H-H}$ = 9.6, $^3J_{H-H}$ = 5.2 Hz, 1H), 2.95 (dd, $^2J_{H-H}$ = 9.6, $^3J_{H-H}$ = 7.6 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz): δ (ppm) 148.6 (d, $^2J_{C-P}$ = 4.8 Hz, C), 147.6 (d, $^2J_{C-P}$ = 2.5 Hz), 141.8 (d, $^1J_{C-P}$ = 18.4 Hz, C), 140.3 (d, $^1J_{C-P}$ = 21.0 Hz, C), 135.8 (d, $^2J_{C-P}$ = 11.6 Hz, C), 135.4 (s, CH), 135.3 (s, CH), 133.3 (s, CH), 133.1 (s, CH), 133.0 (s, C), 132.8 (s, C), 132.3 (q, $^2J_{C-F}$ = 32.5 Hz, C), 131.7 (s, C), 131.4 (s, C), 130.84 (d, $^4J_{C-P}$ = 8.5 Hz, CH), 130.76 (q, $^2J_{C-F}$ = 32.4 Hz, C), 130.4 (s, CH), 129.6 (s, CH), 128.54 (s, CH), 128.46 (d, $^3J_{C-P}$ = 6.1 Hz, CH), 127.5 (d, $^5J_{C-P}$ = 1.3 Hz, CH), 127.2 (s, CH), 126.4 (s, CH), 126.3 (s, CH), 125.9 (dq, $^2J_{C-P}$ = 7.6, $^3J_{C-F}$ = 3.7 Hz, CH), 125.2 (s, CH), 125.0 (s, CH), 124.9 (dq, $^2J_{C-P}$ = 6.0, $^3J_{C-F}$ = 3.7 Hz, CH), 124.5 (d, $^3J_{C-P}$ = 5.0 Hz, C), 124.5 (q, $^1J_{C-F}$ = 272.2 Hz, C), 123.5 (q, $^1J_{C-F}$ = 272.2 Hz, C), 123.2 (d, $^3J_{C-P}$ = 2.5 Hz, C), 123.0 (d, $^4J_{C-P}$ = 6.6 Hz, CH), 121.9 (s, CH), 74.5 (dd, J_{C-P} = 16.4, 12.0 Hz, CH), 74.1 (d, $^3J_{C-P}$ = 3.4 Hz, CH_2), 58.9 (s, CH_3), 48.0 (dd, J_{C-P} = 14.5, 6.4 Hz, CH). ^{31}P{^{1}H} NMR ($CDCl_3$, 162 MHz): δ (ppm) 155.2 (br s, P–O), (−)5.7 (br s, P–C). ^{19}F{^{1}H} NMR ($CDCl_3$, 376 MHz): δ (ppm) −63.0 (s, 6F). HRMS (ESI): [M+H]$^+$, calculated for $C_{44}H_{33}O_4F_6P_2$: 801.1758, found: 801.1761. $[\alpha]_D^{24} = -180.5$ (*c* 0.5, CH_2Cl_2).

4.2.6. ((1*R*,2*S*)-1-(Bis(4-methoxyphenyl)phosphino)-3-methoxy-1-phenylpropan-2-yl) ((*R*)-1,1′-binaphthalen-2,2′-yl) phosphite 13b

Hydroxyalkylphosphine-borane **11b** (106 mg, 0.25 mmol) was introduced as a toluene solution into a dry Schlenk flask under argon. The toluene was removed in vacuo, after which the residue was then dried azeotropically twice with toluene and the flask placed under argon. DABCO (62 mg, 0.55 mmol, 2.2 equiv) was added and the flask quickly purged by doing quite fast vacuum/argon cycles, in order to avoid sublimation of DABCO. Toluene (4 mL) was added, and the septum was swapped for a greased glass stopper while under a strong stream of argon. The flask was purged again with quite fast vacuum/argon cycles and dipped into a 60 °C oil bath. After 2 h, it was allowed to cool down to rt. The glass stopper was swapped back for a septum, after which the reaction mixture was cooled to −5 °C and was added dropwise via cannula onto a −5 °C solution of (*R*)-(binaphthalene-2,2′-diyl)chlorophosphite **12** (97 mg, 0.27 mmol, 1.1 equiv) in toluene (4 mL) to which had been added a few 4 Å molecular sieves. Then, 2 × 1 mL of toluene were used to rinse the equipment. The resulting cloudy mixture was stirred overnight at −5 °C. The cryostat was then switched off and the cooling bath was allowed to warm slowly to rt. After stirring at rt for another 2 h, the mixture was introduced in the glovebox and filtered through a very short pad of previously dried and deoxygenated silica (ca. 1 mL). The pad was washed with 4 × 5 mL of toluene. The filtrate was concentrated in vacuo to give phosphine-phosphite **13b** as a white solid (114 mg, 63% yield). ^{1}H NMR ($CDCl_3$, 500 MHz): δ (ppm) 8.13–8.03 (m, 2H), 8.01–7.96 (m, 1H), 7.93–7.88 (m, 2H), 7.81–7.73 (m, 2H), 7.49–7.36 (m, 5H), 7.31–7.23 (m, 4H), 7.21–7.14 (m, 2H), 7.10–6.99 (m, 3H), 6.97–6.92 (m, 2H), 6.74–6.68 (m, 2H), 4.52–4.42 (m, 1H), 3.79 (s, 3H), 3.74–3.68 (m, 4H), 3.25 (dd, $^2J_{H-H}$ = 9.9, $^3J_{H-H}$ = 4.4 Hz, 1H), 3.22 (s, 3H), 2.92 (dd, $^2J_{H-H}$ = 9.8, $^3J_{H-H}$ = 7.9 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125 MHz): δ (ppm) 161.1 (s, C), 159.9 (s, C), 148.9 (d, $^2J_{C-P}$ = 4.2 Hz, C), 148.0 (d, $^2J_{C-P}$ = 2.1 Hz, C), 137.2 (d, $^2J_{C-P}$ = 11.4 Hz, C), 136.5 (s, CH), 136.3 (s, CH), 134.5 (s, CH), 134.3 (s, CH), 133.1 (s, C), 132.8 (s, C), 131.6 (s, C), 131.5 (s, C), 130.9 (d, $^4J_{C-P}$ = 8.0 Hz, CH), 130.1 (s, CH), 129.6 (s, C), 128.4 (s, C), 128.2 (s, C), 128.0 (d, $^1J_{C-P}$ = 13.8 Hz, C), 127.3 (s, C), 127.2 (s, C), 127.0 (d, $^1J_{C-P}$ = 15.2 Hz, C), 126.8 (s, C), 126.3 (s, C), 126.0 (s, C), 125.0 (s, C), 124.8 (s, C), 124.7 (d, $^3J_{C-P}$ = 4.7 Hz, C), 123.5 (d, $^4J_{C-P}$ = 7.9 Hz, CH), 123.1 (d, $^3J_{C-P}$ = 1.8 Hz, C), 122.1 (s, C), 114.7 (d, $^3J_{C-P}$ = 8.7 Hz, CH), 113.8 (d, $^3J_{C-P}$ = 7.3 Hz, CH), 75.2 (dd, J_{C-P} = 18.1, 12.5 Hz, CH), 74.8 (d, $^3J_{C-P}$ = 2.9 Hz, CH_2), 58.9 (s, CH_3), 55.3 (s, CH_3), 55.2 (s, CH_3), 48.8 (dd, $^1J_{C-P}$ = 14.7, $^3J_{C-P}$ = 6.6 Hz, CH). ^{31}P{^{1}H} NMR ($CDCl_3$, 202 MHz): δ (ppm) 157.0 (br s, P–O), (−)7.5 (br s, P–C). HRMS (ESI): [M+H]$^+$, calculated for $C_{44}H_{39}O_6P_2$: 725.2222, found: 725.2232. $[\alpha]_D^{25} = -248.4$ (*c* 0.5, CH_2Cl_2).

4.3. Preparation of [allylpalladium(*P-OP*)]PF_6 complexes

In a typical procedure, a solution of *P-OP* ligand in DCM was added to a suspension of allylpalladium chloride dimer (0.5 equiv) in DCM under nitrogen. The pale yellow solution was stirred at rt for 30 min, then added to a suspension of NH_4PF_6 in DCM. The mixture was stirred overnight at rt then filtered through an HPLC filter to eliminate solid residues. The final product was obtained as a 1:1 mixture of two isomers by precipitation from DCM/hexane 25:75 in 42% yield for [Pd(η^3-C_3H_5)(**5**)]PF_6, and subsequently used in catalysis. In an alternative procedure, after being stirred overnight, the mixture was allowed to stand still at −20 °C for several hours. It was allowed to reach rt again, then filtered through a plug of Celite and concentrated to give the desired [Pd(η^3-C_3H_5)(**13b**)]PF_6 complex (94% yield) as a 1:1 mixture of two isomers, which was subsequently used in catalysis.

4.3.1. [Pd(η^3-C_3H_5)(5)]PF_6

^{1}H NMR ($CDCl_3$, 400 MHz): δ (ppm) 8.34–8.23 (m, 2H), 8.15–6.91 (m, 52H), 5.91–5.75 (m, 1H), 5.75–5.58 (m, 1H), 4.95–4.83 (m, 1H), 4.83–4.63 (m, 2H), 4.51–4.34 (m, 3H), 4.20 (br s, 1H), 3.82 (br t, J = 15.1 Hz, 1H), 3.69 (br s, 1H), 3.36–2.96 (m, 13H). ^{13}C{^{1}H} NMR ($CDCl_3$, 125 MHz), selected signals: δ (ppm) 125.7 (br s, CH), 124.3 (br s, CH), 78.3 (br d, J = 43.9 Hz, CH_2), 76.0 (br s, CH), 75.0 (br d, J = 44.2 Hz, CH_2), 72.4 (br dd, J = 22.9, 6.0 Hz, CH_2), 71.9 (br d, J = 28.6 Hz, CH_2), 71.2 (br s, CH_2), 59.2 (CH_3), 42.2 (d, J = 27.4 Hz, CH), 41.0 (d, J = 27.7 Hz, CH). ^{31}P{^{1}H} NMR ($CDCl_3$, 162 MHz): δ (ppm) 141.9 (d, $^2J_{P-P}$ = 97.3 Hz, P–O), 140.7 (d, $^2J_{P-P}$ = 98.5 Hz, P–O), 21.3 (d, $^2J_{P-P}$ = 97.3 Hz, P–C), 19.8 (d, $^2J_{P-P}$ = 98.5 Hz, P–C), (−)141.1 (sept., $^1J_{P-F}$ = 713.0 Hz, PF_6^-). IR: ν_{max} (cm^{-1}) 3059, 1588, 1389, 1257, 1028, 871, 654. HRMS (ESI): [M − PF_6^-+MeOH]$^+$, calculated for $C_{46}H_{43}O_5P_2Pd^+$: 843.1621, found: 843.1639.

4.3.2. [Pd(η^3-C_3H_5)(13b)]PF_6

^{1}H NMR ($CDCl_3$, 400 MHz): δ (ppm) 8.37–8.28 (m, 2H), 8.12–8.02 (m, 2H), 7.96–7.81 (m, 6H), 7.75–7.66 (m, 2H), 7.64–7.15 (m, 22H), 6.96–6.84 (m, 4H), 6.70–6.61 (m, 4H), 5.93–5.79 (m, 1H), 5.68–5.54 (m, 1H), 4.88–4.77 (m, 1H), 4.76–4.60 (m, 2H), 4.36 (br t, J = 8.1 Hz, 1H), 4.28 (dd, J = 16.7, 13.7 Hz, 2H), 4.19–4.12 (m, 1H), 3.94 (s, 6H), 3.84 (br t, J = 15.7 Hz, 1H), 3.72 (s, 3H), 3.71 (s, 3H), 3.69–3.61 (m, 1H), 3.23–3.08 (m, 12H), 2.97 (br t, J = 12.1 Hz, 1H). ^{13}C{^{1}H} NMR ($CDCl_3$, 100 MHz), selected signals: δ (ppm) 114.3 (d, $^3J_{C-P}$ = 12.6 Hz, CH), 75.8 (br s, CH), 71.1 (br s, CH_2), 59.2 (s, CH_3), 55.9 (s, CH_3), 55.5 (s, CH_3). ^{31}P{^{1}H} NMR ($CDCl_3$, 162 MHz): δ (ppm) 142.1 (d, $^2J_{P-P}$ = 97.9 Hz, P–O), 141.0 (d, $^2J_{P-P}$ = 98.8 Hz, P–O), 18.5 (d, $^2J_{P-P}$ = 97.9 Hz, P–C), 17.1 (d, $^2J_{P-P}$ = 98.8 Hz, P–C), (−)141.1 (sept., $^1J_{P-F}$ = 713.0 Hz, PF_6^-). HRMS (ESI): [M − PF_6^-]$^+$, calculated for $C_{47}H_{43}O_6P_2Pd^+$: 871.1570, found: 871.1548.

4.4. (*P-OP*)Pd-catalysed allylic substitution reactions

In a typical procedure, 0.25 mL of a 0.005 M solution of allylpalladium chloride dimer (i.e., 0.0025 mmol of Pd, 2.5 mol %) were added to a solution of *P-OP* ligand (0.0025 mmol, 2.5 mol %) in DCM (0.15 mL) under argon. The resulting solution was stirred at rt for 20 min, then added to (±)-1,3-diphenylallyl acetate (25.2 mg, 0.1 mmol). The nucleophile (0.3 mmol, 3 equiv), *N*,*O*-bis(trimethylsilyl)acetamide (73 μL, 0.3 mmol, 3 equiv), and finally potassium acetate (0.5 mg, 0.005 mmol, 5 mol %) were added. The reaction mixture was stirred at rt and conversion followed by TLC. The reaction medium was quenched by the addition of 1 mL of water and the aqueous layer was extracted with 3 × 1 mL of DCM. The combined organic layers were passed through a plug of $MgSO_4$ and concentrated. The conversion and identity of the product were determined by ^{1}H NMR spectroscopy. The crude sample was purified if necessary, and the enantiomeric excess of the product was evaluated by chiral HPLC, or ^{1}H NMR using Eu(hfc)$_3$ as a chiral lanthanide NMR shift reagent. The absolute configuration of the major enantiomer of the product was assigned according to the literature.

4.4.1. (*E*)-Dimethyl 2-(1,3-diphenylallyl)malonate 7a[18]

The enantiomeric excess of this product was determined by chiral HPLC on a Chiralcel OD-H column (*n*-hexane/*i*-propanol 99:1, 0.4 mL/min, 216 nm): t_R = 28.9 min [major (*R*)], 31.5 min [minor (*S*)].

4.4.2. Dimethyl 2-(4,4-diphenylbut-3-en-2-yl)malonate 7b[19]

The enantiomeric excess of the product was determined by NMR spectroscopy using Eu(hfc)$_3$ (6 equiv) as a chiral shift reagent by integrating suitable signals of the diastereomeric complexes, or by chiral HPLC on a Chiralcel OD-H column (*n*-hexane/*i*-propanol 99:1, 1 mL/min, 216 nm): t_R = 10.0 min [major (*R*)], 12.5 min [minor (*S*)]. The absolute configuration of the major enantiomer of this product was ascertained to be (*R*) by specific rotation measurement:[20] $[\alpha]_D^{26} = +41.0$ (*c* 0.5, EtOH) for a 34% ee sample.

4.4.3. (*E*)-Dimethyl 2-(1,3-bis(4-chlorophenyl)-allyl)malonate 7c[14b]

The enantiomeric excess of this product was determined by chiral HPLC on a Chiralcel AD-H column (*n*-hexane/*i*-propanol 85:15, 0.8 mL/min, 254 nm): t_R = 19.1 min [major (*R*)], 28.6 min [minor (*S*)].

4.4.4. (*E*)-*N*-Benzyl-1,3-diphenylprop-2-en-1-amine 7d[21]

The enantiomeric excess of this product was determined by chiral HPLC on a Chiralcel OD-H column (*n*-hexane/*i*-propanol 99.5:0.5, 0.3 mL/min, 254 nm): t_R = 64.8 min [minor (*R*)], 68.8 min [major (*S*)].

4.5. Computational data

The geometries of complexes [Pd(η^3-PhCHCHCHPh)(**5**)]$^+$ **14** were calculated with a GAUSSIAN 03, Revision C.02,[22] using the B3LYP[23] functional. 6-31g(d) Basis set[24] was used for phosphorus, oxygen, carbon and hydrogen atoms, whereas the Stuttgart-Dresden

Table 4
Calculated bond distances of complexes **14** with B3LYP/6-31g(d) and PBE1PBE/6-31g(d) functionals

Entry	Complex	Bond distances (Å) calculated with B3LYP/6-31g(d)				Bond distances (Å) calculated with PBE1PBE/6-31g(d)			
		Pd–C_{tP}	Pd–C_{tPO}	Pd–P	Pd–PO	Pd–C_{tP}	Pd–C_{tPO}	Pd–P	Pd–PO
1	**14**-*endo-syn-syn*	2.332	2.266	2.391	2.316	2.263	2.220	2.349	2.278
2	**14**-*endo-syn-anti*	2.392	2.235	2.388	2.319	2.304	2.199	2.348	2.280
3	**14**-*exo-syn-anti*	2.331	2.260	2.381	2.317	2.262	2.215	2.343	2.280
4	**14**-*exo-syn-syn*	2.288	2.324	2.400	2.312	2.235	2.259	2.355	2.276
5	**14**-*endo-anti-syn*	2.261	2.321	2.392	2.307	2.213	2.266	2.348	2.268
6	**14**-*exo-anti-syn*	2.232	2.425	2.406	2.303	2.199	2.320	2.358	2.271

Pd–C_{tP} = Pd–(C_{allyl} *trans* to P) bond distance; Pd–C_{tPO} = Pd–(C_{allyl} *trans* to PO) bond distance; Pd–P = palladium to phosphine phosphorus bond distance; Pd–PO = palladium to phosphite phosphorus bond distance.

ECP[25] as implemented in GAUSSIAN 03, Rev. C.02 was used for palladium.

For the sake of comparison (Table 4), calculations were carried out using the PBE1PBE[26] functional, 6-31g(d) basis set for P, O, C and H and the Stuttgart-Dresden ECP for palladium. Similar conclusions could be extracted from the geometries calculated with PBE1PBE with respect to the ones calculated with B3LYP.

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11. In conditions identical to those of entry 2 in Table 2, 3-methyl-1-phenylbut-2-en-1-yl acetate was converted to (*E*)-dimethyl 2-(2-methyl-4-phenylbut-3-en-2-yl)malonate; and cyclohex-2-en-1-yl acetate gave the racemic substitution product.
12. In the case of DMM as the nucleophile, variation of the counteranion of the palladium precatalyst [Pd(η^3-C_3H_5)(**13b**)]X had little influence on the activity and enantioselectivity; all reactions proceeded with >95% conversion and with ee's of 80%, 78% and 74% for X^- = Cl^-, PF_6^- and BAr_F^-, respectively, indicating a tenuous counteranion effect.
13. ^{31}P NMR analysis of [Pd(η^3-PhCHCHCHPh)(**5**)]Cl revealed that only two diastereoisomers were present in solution. Heavy signal overlapping did not allow us to unequivocally establish the structure of the two complexes **14** present in solution.
14. Energetic and geometrical analysis at the full DFT-level of the transition structures for all possible reaction pathways is, even today, extremely time-consuming in systems of such complexity. Calculations on the geometries of the intermediate π-allyl complexes are much quicker and has allowed rationalisation of the stereochemical outcome of asymmetric allylic substitutions (see for example: (a) Kollmar, M.; Goldfuss, B.; Reggelin, M.; Rominger, F.; Helmchen, G. *Chem. Eur. J.* **2001**, *7*, 4913–4927; (b) Popa, D.; Puigjaner, C.; Gomez, M.; Benet-Buchholz, J.; Vidal-Ferran, A.; Pericàs, M. A. *Adv. Synth. Catal.* **2007**, *349*, 2265–2278). See Experimental for details on the geometry optimisation of complexes **14** at the DFT level. We did not consider the diastereoisomers **14**-*exo-anti-anti* and **14**-*endo-anti-anti* in the calculations, as nucleophilic attack on these substrates by DMM or BZA would lead to (*Z*)-alkenes **7a** or **7d**, respectively, neither of which we observed.
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