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Phosphine Effects in the Copper(I) Hydride-Catalyzed Hydrogenation of Ketones and Regioselective 1,2-Reduction of α,β-Unsaturated Ketones and Aldehydes. Hydrogenation of Decalin and Steroidal Ketones and Enones

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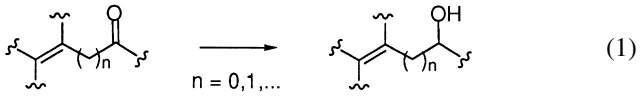
Abstract—The stereoselectivity and regioselectivity of the catalytic hydrogenation of ketones and α,β-unsaturated ketones and aldehydes using soluble copper(I) hydride catalysts have been investigated as a function of the ancillary phosphine ligand. While a relatively narrow range of aryldialkylphosphine ligands produce active hydrogenation catalysts, some ligands provide higher selectivity for 1,2-reduction of acyclic unsaturated carbonyl substrates than observed using the previously reported dimethylphenylphosphine-stabilized catalyst. The synthetic utility of this class of hydridic hydrogenation catalysts is illustrated by the hydrogenation of decalin and steroidal ketones and enones, the latter giving allylic alcohols with high selectivity.

Introduction

We recently reported that the dimethylphenylphosphine-stabilized copper(I) hydride catalyst mediates the highly chemoselective carbonyl hydrogenation of unsaturated ketone and aldehydes, including the selective 1,2-reduction of conjugated substrates (Eq. (1)).[1–3] The catalyst is remarkably chemoselective, reducing ketones and aldehydes without competitive hydrogenation or hydrogenolysis of alkenes, alkynes, dienes, or benzyl ethers, all preferentially reduced by standard hydrogenation catalysts. The regioselectivity for 1,2-reduction of α,β-unsaturated substrates is complementary to that obtained from copper(I) hydride catalysts derived from triarylphosphine ligands, which mediate highly selective conjugate reduction[4] and conjugate hydrosilylation reactions.[5] The latter have been recently extended to include efficient catalytic asymmetric conjugate reductions of α,β-unsaturated esters[6] and tandem catalytic conjugate reduction/alkylation and crossed aldol reactions.[7]



(1)

The structure, reactivity and selectivity of copper(I) hydride catalysts are a complex and subtle function of the ancillary ligand.[1,4] For the hydrogenation of isolated ketones, efficient catalysts appear to be limited to complexes stabilized by *monodentate* phosphine ligands, despite considerable effort to identify alternative ligand systems.[8] The dimethylphenylphosphine-stabilized copper(I) hydride catalyst alone leads to useful selectivity for 1,2-reduction of α,β-unsaturated aldehydes and ketones to allylic alcohols. The complex derived from the sterically and electronically similar di*ethyl*phenylphosphine ligand, for example, is a very poor catalyst for ketone hydrogenation, illustrating the exceptional sensitivity of the catalyst to structural variation in the ancillary ligand.

Despite the generally high regioselectivity observed in the hydrogenation of acyclic substrates, the dimethylphenylphosphine-derived catalyst delivers only modest selectivity for 1,2-reduction of simple cyclohexenone derivatives.[1b] In addition, dimethylphenylphosphine is achiral, providing no basis for the development of an asymmetric hydrogenation catalyst. In this report, the reactivity of copper(I) catalysts derived from an expanded range of monodentate dialkylarylphosphine ligands is described for the reduction of isolated and conjugated ketones. In addition, the selectivity of the dimethylphenylphosphine-derived catalyst toward cyclohexanone and cyclohexenone hydrogenation is further investigated for the reduction of synthetically relevant bicyclic and steroidal substrates.

Keywords: copper and compounds; hydrogenation; catalysis; carbonyl compounds.

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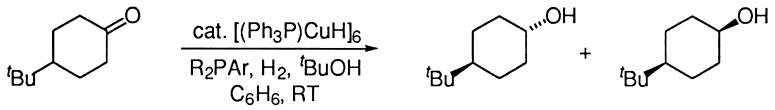
Table 1. Hydrogenation of 4-*tert*-butylcyclohexanone using dialkylarylphosphine-stabilized copper(I) hydride catalysts and hydrogen (conditions: 0.83 mol% $[(Ph_3P)CuH]_6$, 6 equiv. R_2PAr/Cu, 20–40 equiv. ^tBuOH/Cu, C_6H_6, 1 atm H_2, RT. Details in the Experimental section)



Entry	Phosphine	Reaction time	Stereoselectivity (*trans*/*cis*)	Yield (%)[a]
1[1b]	$PhPMe_2$	18	3:1	97
2	PhP(Me)Et	20	1:1	94
3	$PhP(CH_2)_4$[b]	24	2.5:1	92
4	PhP(Me)Cy	24	1:2	71[c]

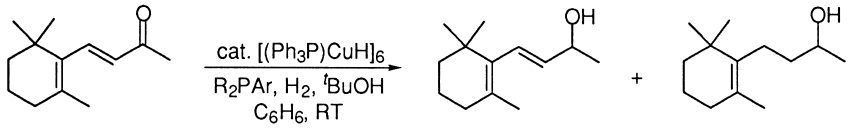
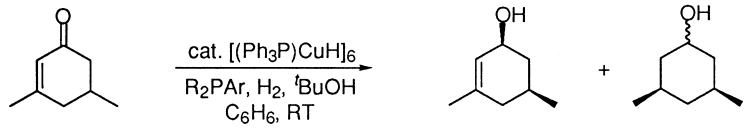
[a] Yields refer to isolated purified products, stereochemical assignments by comparison to authentic materials.
[b] Phenylphospholane.
[c] Conversion; remaining material is unconverted substrate (29%).

Results and Discussion

Catalytic ketone hydrogenation mediated by dialkylarylphosphine copper(I) hydride derivatives

To assess the dramatic differences in the reactivity of the dimethylphenylphosphine and diethylphenylphosphine catalysts, the reactivity of three analogous dialkylphenylphosphine ligands was investigated for the reduction of the conformationally unambiguous and sterically unbiased substrate 4-*tert*-butylcyclohexanone (Table 1). The catalysts were prepared in situ by phosphine exchange starting with the commercially available triphenylphosphine complex, $[(Ph_3P)CuH]_6$,[9] and the hydrogenation reactions were conducted at atmospheric pressure. While none of the phosphine ligands provided significantly enhanced performance, several observations are noteworthy. The catalyst derived from ethylmethylphenylphosphine, sterically 'halfway' between the dimethylphenylphosphine and diethylphenylphosphine ligands, is surprisingly effective, although unselective stereochemically (entry **2**). Constraining the ethyl groups of diethylphenylphosphine into cyclic form is also effective: the phenylphospholane [1-(phenyl)phosphacyclopentane] ligand also provides a functional catalyst, although the rate of the reduction is significantly attenuated (entry **3**). While no catalyst gave higher stereoselectivity for axial hydride addition than that obtained from dimethylphenylphosphine (entry **1**),[10] the catalyst derived from the sterically larger cyclohexylmethylphenylphosphine ligand provides inverted stereoselectivity, leading to preferential equatorial addition of the hydride (entry **3**).

Table 2. Hydrogenation of α,β-unsaturated ketones using phosphine-stabilized copper(I) hydride catalysts and hydrogen (conditions: 0.83 mol% $[(Ph_3P)CuH]_6$, 6 equiv. R_2PAr/Cu, 40 equiv. ^tBuOH/Cu, C_6H_6, 500 psi H_2, RT. Details in the Experimental section)

Entry	Phosphine	Reaction time	Regioselectivity[a]	Yield (%)[b]
				
1	$^nBu_3P$	18	4:1	[c]
2[1b]	$PhPMe_2$	26	49:1	97
3	PhP(Me)Et	21	>50:1	95
4	$PhP(CH_2)_4$[d]	21	19:1	84
5	PhP(Me)Cy	24	20:1	87
				
6	$^nBu_3P$	18	1 (3:1)[e]:5 (1:1)	85
7[1b]	$PhPMe_2$	30	2.7 (12:1):1[f]	90
8[1b]	$PhPMe_2$[g]	25	4.4 (12:1):1[f]	92
9	PhP(Me)Et	20	3 (7.3:1):1[f]	89
10	$PhP(CH_2)_4$[d]	20	1[f]:2[f]	[c]
11	PhP(Me)Cy	24	3 (4.9:1):1[f]	88

[a] Products identified by comparison to authentic materials prepared by unambiguous synthesis. See Experimental section.
[b] Isolated yield after purification by chromatography.
[c] Complete conversion; isolated yield not determined.
[d] Phenylphospholane.
[e] Major allylic alcohol stereoisomer as indicated; minor isomer epimeric at hydroxyl center.
[f] Stereochemical ratio not determined.
[g] Catalyst derived from CuCl (5 mol%) and NaO^{t}Bu (5 mol%) in the presence of Me_2PPh (6 equiv./Cu).

Catalytic hydrogenation of α,β-unsaturated ketones and aldehydes using dialkylarylphosphine copper(I) hydride derivatives

To compare the regioselectivity of dialkylphenylphosphine catalysts for the reduction of α,β-unsaturated ketones, the hydrogenation of one acyclic and one cyclic substrate was evaluated under standard conditions[1b] (ambient temperature, 500 psi H_2). The reduction of β-ionone proceeds with high regioselectivity for all three phosphines (Table 2, entries **3**–**5**), although only the ethylmethylphenylphosphine-derived catalyst (entry **3**) provides improved selectivity over the dimethylphenylphosphine catalyst (entry **2**). For comparison, the catalyst derived from tri-*n*-butylphosphine (entry **1**) provides only a 4:1 ratio favoring the 1,2-reduction product and the use of stoichiometric $[(Ph_3P)CuH]_6$ leads, as expected, to exclusive conjugate reduction.[11]

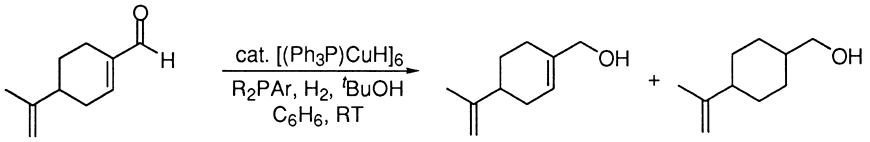
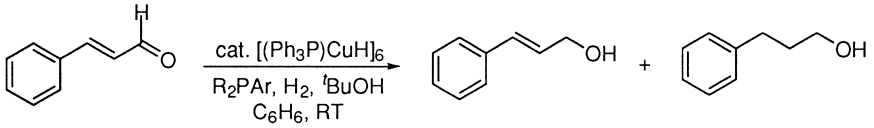
As anticipated, the regioselectivity obtained in the hydrogenation of 3,5-dimethylcyclohexenone was notably attenuated. While both ethylmethylphenylphosphine (entry **9**) and cyclohexylmethylphenylphosphine (entry **11**) provide regioselectivity equivalent to that obtained from dimethylphenylphosphine (entry **7**), the phenylphospholane ligand surprisingly favors conjugate reduction (entry **10**), although not to the same extent as the tri-*n*-butylphosphine catalyst (entry **6**) or $[(Ph_3P)CuH]_6$ itself, which provides complete selectivity.[4] As observed for the hydrogenation of *tert*-butylcyclohexanone, the dimethylphenylphosphine-derived catalyst is the most stereoselective, again favoring pseudo-axial delivery of the hydride. In contrast to the dimethylphenylphosphine catalyst (cf. entry **8**), no further improvement in regioselectivity is obtained using catalyst formulations free of residual triphenylphosphine.[1b] For the reduction of unsaturated aldehydes (Table 3), the selectivity of the phenylphospholane-derived catalyst *exceeds* the already high selectivity obtained from the dimethylphenylphosphine catalyst, a result not easily reconciled with the low selectivity obtained in the reduction of α,β-unsaturated ketones using this catalyst.

Two further dialkylarylphosphine ligands were evaluated, both previously unreported monodentate axially chiral binaphthyl derivatives analogous to Hayashi's 'MOP' ligands.[12] The compounds were prepared by palladium-catalyzed monophosphinylation of the (racemic) 2,2′-bis(trifluoromethanesulfonyloxy)-1,1′-binaphthyl (**1**) under modified conditions, which gives a mixture of the 2′-hydroxylated dimethylphosphinyl derivative **2** and the deoxygenated dimethylphosphinyl compound **3** after basic hydrolysis. After separation by chromatography, deoxygenation under standard conditions gave the air-sensitive 2-(dimethylphosphino)-1,1′-binaphthyl ligands **4** and **5** in good yields. Inexplicably, however, copper(I) hydride complexes of neither ligand function as hydrogenation catalysts for ketone reduction (Scheme 1).

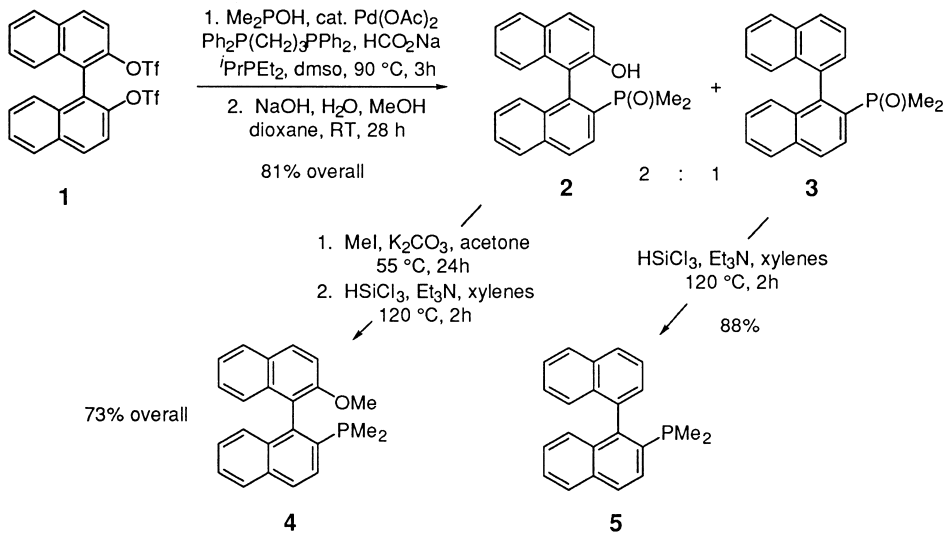
Catalytic reduction of cyclohexanone and cyclohexenone substrates. Hydrogenation of decalin and steroidal derivatives

The relatively modest stereoselectivity and regioselectivity obtained in the reduction of sterically unbiased cyclohexanone and cyclohexenone substrates prompted further investigation. Using the catalyst derived from dimethylphenylphosphine, the hydrogenation of a series of *trans*- and *cis*-fused decalin and steroidal ketones was evaluated (Table 4). Greater stereoselectivity is observed in the hydrogenation of *trans*-fused substrates (entries **1**–**3**), with the major products resulting from preferential axial hydride addition to the conformationally defined ring systems.[13] In the *cis*-fused series, reduction of the decalone system (entry **4**) proceeds with poor selectivity and unexpectedly returns the β-hydroxydecalin as the major product, in contrast to the preferential formation of the α-hydroxy epimer from both

Table 3. Hydrogenation of α,β-unsaturated aldehydes using phosphine-stabilized copper(I) hydride catalysts and hydrogen (conditions: 0.83 mol% $[(Ph_3P)CuH]_6$, 6 equiv. R_2PAr/Cu, 40 equiv. ^tBuOH/Cu, C_6H_6, 500 psi H_2, RT. Details in the Experimental section)

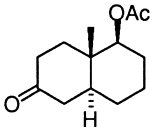
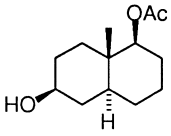
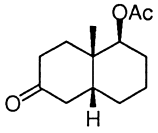
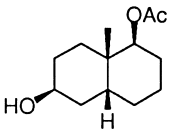
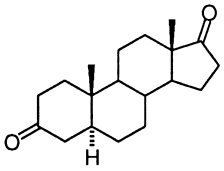
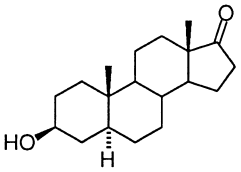
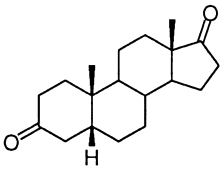
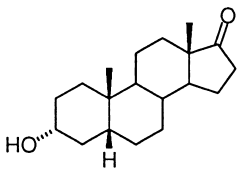
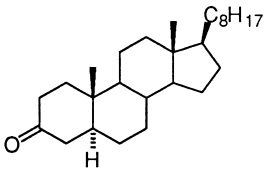
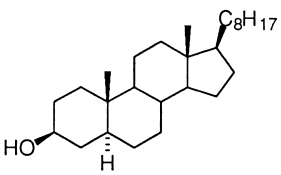
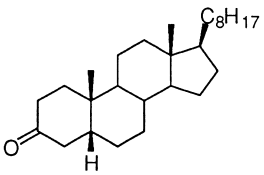
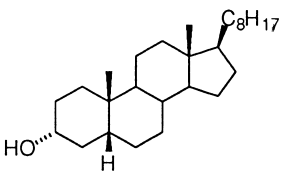
Entry	Phosphine	Reaction time	Regioselectivity[a]	Yield (%)[b]
				
1[1b]	$PhPMe_2$	18	32:1[c]	95
2	$PhP(CH_2)_4$[d]	18	38:1[c]	83
				
3[1b]	$PhPMe_2$	4	32:1	94
4	$PhP(CH_2)_4$[d,e]	18	80:1	89

[a] Products identified by comparison to authentic materials prepared by unambiguous synthesis. See Experimental section.
[b] Isolated yield after purification by chromatography.
[c] Stereochemical ratio not determined.
[d] Phenylphospholane.
[e] 70 psi H_2.

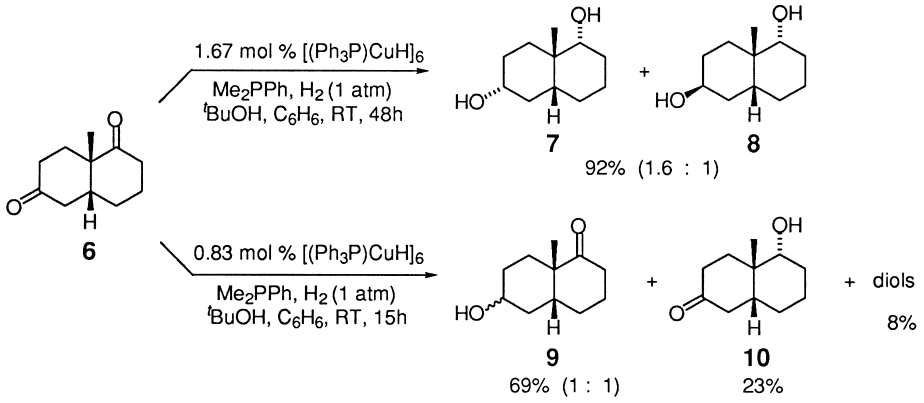


Scheme 1.

Table 4. Catalytic reduction of decalin and steroidal ketones using Me_2PPh-stabilized copper(I) hydride and hydrogen

trans-Series				*cis*-Series			
Substrate/ Entry	Conditions.[a]	Time (h)	Product(s)/ Yield (%)[b,c]	Substrate/ Entry	Conditions.[a]	Time (h)	Product(s)/ Yield (%)[b,c]
 **1**[1b]	A	27	 93 (16 : 1)	 **4**	C	48	 82 (1.8 : 1)
 **2**	B	24	 93 (6 : 1)	 **5**	C	30	 85 (2.5 : 1)[d]
 **3**	B	28	 100 (5 : 1)	 **6**	B	24	 100 (3.5 : 1)

[a]Reaction conditions. A: 0.83 mol% $[(Ph_3P)CuH]_6$ (5 mol% Cu), $PhPMe_2$ (8 equiv./Cu), 1 atm H_2, C_6H_6 (0.4–0.8 M in substrate), *tert*-butanol (10–20 equiv./Cu), RT. B: as A, except $PhPMe_2$ (6 equiv./Cu). C: as A, except $PhPMe_2$ (10 equiv./Cu).
[b]Major product indicated; minor product is epimeric alcohol. Product ratio is given in parentheses.
[c]Isolated yields after purification by chromatography. Products identified by comparison with authentic materials prepared by unambiguous synthesis (see the Experimental section).
[d]6% diols also isolate as a mixture of stereoisomers.



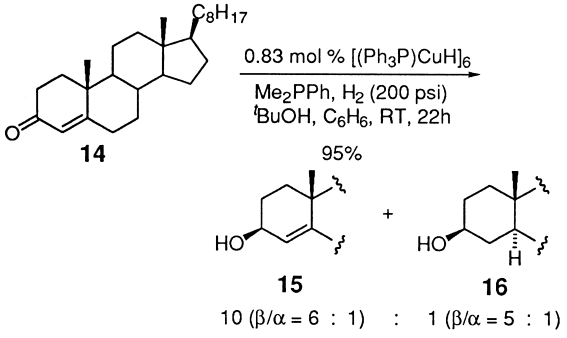
Scheme 2.

steroid substrates (entries **5**, **6**). Although this stereochemical reversal is difficult to rationalize, we note that the conformationally mobile decalone substrate preferentially adopts the non-steroid conformation,[14] based on the equatorial disposition of the acetate methine hydrogen.[15] In this conformation, axial addition of the hydride leads to the observed major product. A consistent preference for axial hydride delivery also accounts for the major product obtained from the *cis*-fused steroid substrates.[16]

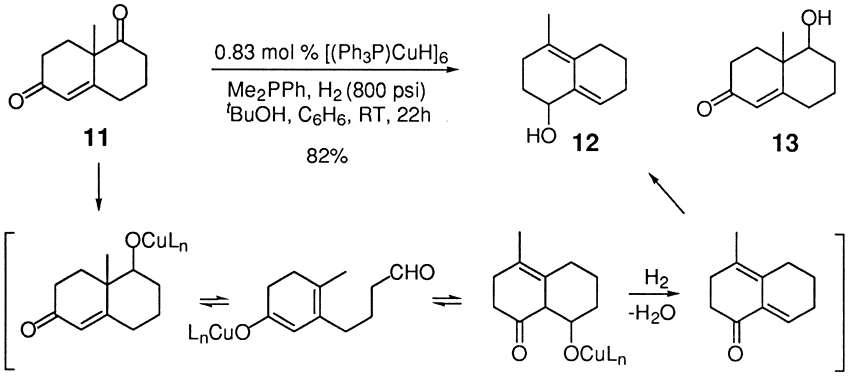
Catalytic hydrogenation of the *cis*-fused diketone **6** (Scheme 2) leads to the isolation of the stereoisomeric diols **7** and **8** in high yield, the product of highly stereoselective reduction of the B-ring ketone, but nonselective reduction in the A-ring. To determine the relative rates of hydrogenation of the two carbonyl groups, partial reduction was obtained by using a lower catalyst loading and shorter reaction time, providing a high yield of the isomeric ketoalcohols **9** and **10** in a 3:1 ratio favoring reduction of the A-ring ketone.

Finally, the regioselectivity of the hydrogenation of polycyclic α,β-unsaturated ketones was evaluated. The reduction of the Wieland–Miescher ketone **11**, however, was accompanied by molecular rearrangement, providing the unexpected alcohol **12** exclusively in high yield (Scheme 3). The structure of the product was unambiguously determined by one- and two-dimensional NMR spectroscopic analysis (Experimental section). The rearrangement is readily rationalized by proposing kinetic hydrometallation of the B-ring ketone, followed by retro-aldol fragmentation of the intermediate copper(I) alkoxide complex. Subsequent aldol condensation and base-catalyzed elimination provides the rearranged α,β-unsaturated ketone, which then undergoes highly selective 1,2-reduction to give the observed product (Scheme 3). This mechanistic rationale is supported by the isolation of the known hydroxy enone **13**[17] from reductions run to partial conversion.

The catalytic hydrogenation of 4-cholesten-3-one **14**, in contrast, proceeds as anticipated to give a mixture of four products, two allylic alcohol stereoisomers **15** and two stereoisomeric saturated alcohols **16** (Eq. (2)). The reaction is substantially more regioselective than corresponding reductions of simple cyclohexenone substrates, promoting 1,2-reduction over conjugate reduction by a factor of 10:1.



(2)



Scheme 3.

Conclusions

An expanded range of copper(I) catalysts has been developed for the chemoselective hydrogenation of isolated ketones and for the difficult problem of regioselective catalytic 1,2-reduction of α,β-unsaturated aldehydes and ketones. While a number of structurally similar dialkylarylphosphine ligands can be used, the catalyst derived from dimethylphenylphosphine combines useful levels of selectivity with the convenience of using a commercially available phosphine ligand. The catalyst can be generated in situ either by phosphine exchange from the thermally stable $[(Ph_3P)CuH]_6$ or, less expensively, by direct synthesis from copper(I) chloride, sodium *tert*-butoxide, and the phosphine under hydrogen.[1b]

Experimental

General experimental

Unless otherwise noted, all manipulations were performed under an inert atmosphere using standard Schlenk line or glove box techniques (≤5 ppm O_2). Reactions run under hydrogen pressure were performed in a magnetically stirred, glass-lined, Parr stainless steel autoclave (75–1500 psi) equipped with Swagelok Quick-connects and pressure gauges. All solvents, reagents and commercial substrates were purified by standard methods. Toluene, benzene, diethyl ether, hexanes, pentane and tetrahydrofuran were dried and deoxygenated by distillation from sodium or potassium benzophenone ketyl. Product purifications were performed by flash chromatography[18] using E. Merck Kieselgel 60, 230–400 mesh.

Materials

tert-Butanol was distilled from sodium, deaerated and stored under N_2. $[(Ph_3P)CuH]_6$,[9c] 1-Phenylphospholane,[19] ethylmethylphenylphosphine,[20] cyclohexylmethylphenylphosphine,[20] 2,2′-bis(trifluoromethanesulfonyloxy)-1,1′-binaphthyl,[12] 5α-androstane-3,17-dione (Table 4, entry **2**),[21] 5α-cholestane-3-one (Table 4, entry **3**),[22] 1β-acetoxy-8aβ-methyl-1,2,3,4,4aβ,5,8,8a-octahydronaphthalene-6(7*H*)-one (Table 4, entry **4**),[23] 5β-androstane-3,17-dione (Table 4, entry **5**),[24] 5β-cholestane-3-one (Table 4, entry **6**),[22] and 8aβ-methyl-3,4,4aβ,5,8,8a-hexahydronaphthalene-1,6(2*H*,7*H*)-dione (**6**)[25] were prepared according to previously published procedures. Cinnamaldehyde, perillaldehyde, β-ionone, 4-*tert*-butylcyclohexanone, 3,5-dimethyl-2-cyclohexenone, 3,4,8,8a-tetrahydro-8a-methyl-1,6(2*H*,7*H*)-naphthalenedione (Wieland–Miescher ketone, **11**), 4-androstene-3,17-dione, and (+)-4-cholesten-3-one (**14**) were purchased from commercial suppliers.

Product identification

Reaction products were identified spectroscopically and compared to authentic materials prepared by unambiguous synthesis. Isolated alcohols were prepared by standard ketone reduction using $NaBH_4$ in methanol or $LiAlH_4$ in diethyl ether. Allylic alcohols were prepared from α,β-unsaturated aldehydes and ketones by treatment with $NaBH_4/CeCl_3$ in methanol.[26] Fully reduced alcohols were prepared by catalytic hydrogenation of the allylic alcohols using Pd/C and H_2 (1 atm)[27] or, in the case of α,β-unsaturated aldehydes, by reduction using stoichiometric $[(Ph_3P)CuH]_6$ (0.4–0.5 equiv.).[28]

General procedure for reduction of saturated ketones using $[(Ph_3P)CuH]_6$ and tertiary phosphine

In the glove box, $[(Ph_3P)CuH]_6$ (5 mol% Cu), the phosphine (6 equiv./Cu) and *tert*-butanol (10–40 equiv./Cu) were combined in a Schlenk flask and dissolved in benzene. To this solution was added a solution of the substrate (20 equiv./Cu) in benzene (0.4–0.8 M in substrate). The flask was sealed and placed under a slight positive pressure of hydrogen after one freeze–pump–thaw degassing cycle. The resulting yellow-orange homogeneous solution was allowed to stir until complete by TLC analysis. The reaction mixture was exposed to air, diluted with ether, and treated with a small amount of silica gel. This mixture was stirred in the air for ≥0.5 h prior to filtration, concentration in vacuo, and purification by flash chromatography. When the polarity of the product was similar to that of the residual phosphine, the crude mixture was treated with sodium hypochlorite (5% aqueous solution) and filtered through silica gel/$MgSO_4$ prior to chromatography.

Reduction of 4-*tert*-butylcyclohexanone; ethylmethylphenylphosphine (Table 1, entry **2**). Using the general procedure, 4-*tert*-butylcyclohexanone (49 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.2 mg, 0.0027 mmol), *tert*-butanol (0.048 g, 0.65 mmol), and ethylmethylphenylphosphine (15 mg, 0.098 mmol) were combined and hydrogenated (1 atm) for 20 h, giving 4-*tert*-butylcyclohexanol (47 mg, 94%, 1:1 *trans*:*cis*) after flash chromatography. The products were identified by comparison to commercial samples.

Reduction of 4-*tert*-butylcyclohexanone; 1-phenylphospholane (Table 1, entry **3**). Using the general procedure, 4-*tert*-butylcyclohexanone (49 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.2 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and 1-phenylphospholane (16 mg, 0.097 mmol) were combined and hydrogenated (1 atm) for 24 h, giving 4-*tert*-butylcyclohexanol (46 mg, 92%, 2.5:1 *trans*:*cis*).

Reduction of 4-*tert*-butylcyclohexanone; cyclohexylmethylphenylphosphine (Table 1, entry **4**). Using the general procedure, 4-*tert*-butylcyclohexanone (49 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.2 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and cyclohexylmethylphenylphosphine (20 mg, 0.097 mmol) were combined and hydrogenated (1 atm) for 24 h, giving starting material (29%) and 4-*tert*-butylcyclohexanol (34 mg, 70%, 1:2 *trans*:*cis*).

Reduction of 5α-androstane-3,17-dione (Table 4, entry **2**). Using the general procedure, 5α-androstane-3,17-dione (75 mg, 0.26 mmol), $[(Ph_3P)CuH]_6$ (4.2 mg, 0.0021 mmol), *tert*-butanol (9.6 mg, 0.13 mmol), and dimethylphenylphosphine (13 mg, 0.078 mmol) were combined and hydrogenated (1 atm) for 24 h, giving an inseparable mixture of 3β-hydroxy-5α-androstan-17-one[21]

and 3α-hydroxy-5α-androstan-17-one[21] (70 mg, 93%, 3β/3α=6:1) after flash chromatography (2:1 hexanes/EtOAc).

Reduction of 5α-cholestane-3-one (Table 4, entry **3**). Using the general procedure, 5α-cholestane-3-one (75 mg, 0.19 mmol), $[(Ph_3P)CuH]_6$ (3.2 mg, 0.0016 mmol), *tert*-butanol (7.2 mg, 0.097 mmol), and dimethylphenylphosphine (8.0 mg, 0.058 mmol) were combined and hydrogenated (1 atm) for 28 h, giving a mixture of 3β-hydroxy-5α-cholestanol[22] and 3α-hydroxy-5α-cholestanol[22] (75 mg, 100%, 3β/3α=5:1) after flash chromatography (5:1 hexanes/EtOAc).

Reduction of 1β-acetoxy-8aβ-methyl-1,2,3,4,4aβ,5,8,8a-octahydronaphthalene-6(7*H*)-one (Table 4, entry **4**). Using the general procedure, 1β-acetoxy-8aβ-methyl-1,2,3,4,4aβ,5,8,8a-octahydronaphthalene-6(7*H*)-one (38 mg, 0.17 mmol), $[(Ph_3P)CuH]_6$ (2.8 mg, 0.0014 mmol), *tert*-butanol (13 mg, 0.17 mmol), and dimethylphenylphosphine (14 mg, 0.102 mmol) were combined and hydrogenated (1 atm) for 48 h, giving 1β-acetoxy-6β-hydroxy-8aβ-methyl-1,2,3,4,4aβ,5,6,7,8,8a-decahydronaphthalene (20 mg, 53%) and 1β-acetoxy-6α-hydroxy-8aβ-methyl-1,2,3,4,4aβ,5,6,7,8,8a-decahydronaphthalene (11 mg, 29%) after separation by flash chromatography (5:1 hexanes/EtOAc). Major 6β-isomer: TLC R_f=0.33 (1:1 hexanes/EtOAc); IR ($CHCl_3$, cm^{-1}) 3620, 3450, 2940, 2870, 1725, 1470, 1445, 1375, 1260, 1175, 1130; ^1H NMR (500 MHz, $CDCl_3$) δ 5.00 (1H, bs), 4.04 (1H, bs), 2.04 (3H, s), 1.89 (1H, m), 1.84–1.64 (4H, m), 1.63–1.20 (9H, m), 1.01 (3H, s); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 170.8, 66.7, 36.6, 36.3, 34.5, 29.7, 28.5, 26.9, 26.6, 21.9, 21.2, 20.2. HRMS (CI) calcd for $C_{13}H_{23}O_3$=227.1648 (M^++1), found=227.1664; Minor 6α-isomer: TLC R_f=0.29, (1:1 hexanes/EtOAc); mp=105–107°C; IR ($CHCl_3$, cm^{-1}) 3610, 3450, 2940, 2870, 1725, 1470, 1445, 1375, 1260, 1070, 1050, 1030, 970; ^1H NMR (500 MHz, $CDCl_3$) δ 5.21 (1H, dd, *J*=5.0, 10.7 Hz), 3.61 (1H, tt, *J*=4.4, 10.8 Hz), 2.03 (3H, s), 1.85–1.45 (10H, m), 1.43 (1H, bs), 1.25 (2H, m), 1.04 (1H, dt, *J*=3.8, 14.0 Hz), 0.99 (3H, s); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 170.8, 71.3, 70.9, 41.9, 36.6, 36.0, 31.0, 29.7, 27.4, 26.6, 21.6, 21.2, 20.3; HRMS (CI) calcd for $C_{13}H_{23}O_3$=227.1648 (M^++1), found=227.1636.

Reduction of 5β-androstane-3,17-dione (Table 4, entry **5**). Using the general procedure, 5α-androstane-3,17-dione (0.065 g, 0.23 mmol), $[(Ph_3P)CuH]_6$ (0.0037 g, 0.0019 mmol), *tert*-butanol (0.010 g, 0.14 mmol), and dimethylphenylphosphine (0.016 g, 0.11 mmol) were combined and hydrogenated (1 atm) for 30 h, giving 3α-hydroxy-5β-androstane-17-one[29] (0.040 g, 61%), 3β-hydroxy-5β-androstan-17-one[29] (0.016 g, 24%), and 5β-androstane-3,17β-diol (3α/3β mixture, 0.004 g, 6%) after chromatography (5:1 hexanes/EtOAc). Major 3α-isomer: TLC R_f=0.23, (1:1 hexanes/EtOAc); mp=148.0–150.0°C, lit. mp=150.0–151.0°C; IR ($CDCl_3$, cm^{-1}) 3600, 2930, 2880, 2860, 1730, 1445, 1045, 1025; Partial ^1H NMR (500 MHz, $CDCl_3$) δ 3.64 (1H, tt, *J*=4.7, 11.0 Hz), 0.95 (3H, s), 0.85 (3H, s). Minor 3β-isomer: TLC R_f=0.33, (1:1 hexanes/EtOAc); mp=150.5–152.0°C, lit. mp= 151.0–152.0°C; IR ($CDCl_3$, cm^{-1}) 3610, 2930, 2880, 2855, 1730,1445, 1045, 1025; Partial ^1H NMR (500 MHz, $CDCl_3$) δ 4.11 (1H, bm), 0.98 (3H, s), 0.85 (3H, s). Trace diols: TLC R_f=0.16, (1:1 hexanes/EtOAc); Partial ^1H NMR (500 MHz, $CDCl_3$) δ 3.63 (overlapping multiplets), 0.93 (s), 0.72 (s).

Reduction of 5β-cholestane-3-one (Table 4, entry **6**). Using the general procedure, 5β-cholestane-3-one (75 mg, 0.19 mmol), $[(Ph_3P)CuH]_6$ (3.2 mg, 0.0016 mmol), *tert*-butanol (7.2 mg, 0.097 mmol), and dimethylphenylphosphine (8.0 mg, 0.058 mmol) were combined and hydrogenated (1 atm) for 24 h, giving an inseparable mixture of 3α-hydroxy-5β-cholestanol[22] and 3β-hydroxy-5β-cholestanol[22] (75 mg, 100%, 3α/3β=3.5:1) after flash chromatography (10:1 hexanes/EtOAc). Major 3α-isomer: ^1H NMR (500 MHz, $CDCl_3$, partial data only) δ 3.62 (1H, tt, *J*=4.7, 11.0 Hz). Minor 3β-isomer: ^1H NMR (500 MHz, $CDCl_3$, partial data only) δ 4.10 (1H, bm).

Reduction of 8aβ-methyl-3,4,4aβ,5,8,8a-hexahydronaphthalene-1,6 (2*H*,7*H*)-dione (6). Using the general procedure, 8aβ-methyl-3,4,4aβ,5,8,8a-hexahydronaphthalene-1,6 (2*H*,7*H*)-dione (50 mg, 0.27 mmol), $[(Ph_3P)CuH]_6$ (9.1 mg, 0.0046 mmol), *tert*-butanol (4.1 mg, 0.56 mmol), and dimethylphenylphosphine (46 mg, 0.33 mmol) were combined and hydrogenated (1 atm) for 48 h, giving 1α,6α-dihydroxy-8aβ-methyl-1,2,3,4,4aβ,5,6,7,8a-decahydronaphthalene[30] **7** (28.5 mg, 57%) and 1α,6β-dihydroxy-8aβ-methyl-1,2,3,4,4aβ,5,6,7,8a-decahydronaphthalene[30] **8** (17.5 mg, 35%) after separation by flash chromatography (2:1 hexanes/EtOAc). Major 6α-isomer **7**: TLC R_f=0.18 (1:1 hexanes/EtOAc); mp=108–110°C; IR ($CDCl_3$, cm^{-1}) 3610, 2980, 2930, 2860, 1465, 1380, 1090, 1030, 1010; ^1H NMR (500 MHz, $CDCl_3$) δ 4.00 (1H, bs), 3.34 (1H, dd, *J*=2.9, 10.0 Hz), 1.97–1.67 (7H, m), 1.63–1.42 (3H, m), 1.37–1.27 (3H, m), 1.26–1.17 (2H, m), 1.05 (3H, s); Difference NOE spectrum (400 MHz, $CDCl_3$): Irr. at δ 3.34 (C1-methine) ↔ δ 1.05 (1.8%, 8a-methyl), Irr. at 1.05 ↔ δ 3.34 (7.8%); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$) δ 79.1, 67.8, 39.9, 37.7, 34.7, 30.7, 29.8, 29.7, 23.9, 22.9, 22.8; HRMS (CI) calcd for $C_{11}H_{21}O_2$=185.1542 (M^++1), found=185.1523. Minor 6β-isomer **8**: TLC R_f=0.12 (1:1 hexanes/EtOAc); mp=158–160°C; IR ($CDCl_3$, cm^{-1}) 3620, 2990, 2930, 2860, 1470, 1380, 1250, 1100, 1050; ^1H NMR (500 MHz, $CDCl_3$) δ 3.86 (1H, apparent septet (tt), $J_{observed}$=5.0 Hz), 3.36 (1H, dd, *J*=4.3, 11.6 Hz), 1.89 (1H, m), 1.75–1.23 (14H, m), 1.16 (3H, s); $^{13}C\{^1H\}$ NMR (100 MHz, $CDCl_3$) δ 79.9, 67.3, 41.9, 37.7, 36.5, 31.2, 30.2, 28.1, 24.3, 23.5, 22.6; HRMS (CI) calcd for $C_{11}H_{21}O_2$=185.1542 (M^++1), found= 185.1556.

Partial reduction of 8aβ-methyl-3,4,4aβ,5,8,8a-hexahydronaphthalene-1,6 (2*H*,7*H*)-dione (6). Using the general procedure, 8aβ-methyl-3,4,4aβ,5,8,8a-hexahydronaphthalene-1,6 (2*H*,7*H*)-dione (50 mg, 0.27 mmol), $[(Ph_3P)CuH]_6$ (4.5 mg, 0.0023 mmol), *tert*-butanol (21 mg, 0.28 mmol), and dimethylphenylphosphine (23 mg, 0.17 mmol) were combined and hydrogenated (1 atm) for 15 h, giving a mixture containing 6-hydroxy-8aβ-methyl-3,4,4aβ,5,6,7,8,8a-octahydronaphthalene-1(2*H*)-one[30] **9** (6α/6β=1:1), 1α-hydroxy-8aβ-methyl-1,2,3,4,4aβ,5,8,8a-octahydronaphthalene-6(7*H*)-one **10**, and diols **7** and **8** (as a mixture) in quantitative yield (51 mg, 100%, **9**/**10**/**7**+**8**=69:23:8). Partial ^1H NMR data (500 MHz, $CDCl_3$) **9** (6α): δ 4.06 (quintet, *J*=4.6 Hz); **9** (6β): δ 3.60 (tt, *J*=4.0, 11.2 Hz).

General procedure for reduction of α,β-unsaturated ketones and aldehydes using $[(Ph_3P)CuH]_6$ and tertiary phosphine

In the glove box, $[(Ph_3P)CuH]_6$ (5 mol% Cu), Me_2PPh (6 equiv./Cu) and *tert*-butanol (40 equiv./Cu) were dissolved in benzene. The substrate (20 equiv./Cu) was added and the resulting solution was rapidly transferred to a steel autoclave equipped with a stirbar (total volume: 0.4–0.8 M in substrate). The apparatus was sealed and connected to a tank of pre-purified hydrogen. After pressurizing and releasing several times to flush the apparatus, the vessel was charged to the desired pressure and stirred for the indicated reaction time. After releasing the pressure, the contents were exposed to air, stirred several minutes, and filtered through celite. The solvent was removed in vacuo and the crude mixture analyzed by ^1H NMR spectroscopy (integration at long pulse delay) to determine product ratios. Purification and isolation of the product(s) was accomplished by flash chromatography on silica gel.

Reduction of β-ionone; tri-*n*-butylphosphine (Table 2, entry **1**). Using the general procedure, β-ionone (62 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and tri-*n*-butylphosphine (19 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 18 h, giving complete conversion to a 3.9:1 mixture of the inseparable allylic alcohol and saturated alcohol. The products were identified by comparison to authentic samples.[1b]

Reduction of β-ionone; ethylmethylphenylphosphine (Table 2, entry **3**). Using the general procedure, β-ionone (62 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and ethylmethylphenylphosphine (15 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 21 h, giving a >50:1 mixture of the allylic alcohol and saturated alcohol (60 mg, 95%) after flash chromatography.

Reduction of β-ionone; 1-phenylphospholane (Table 2, entry **4**). Using the general procedure, β-ionone (62 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and 1-phenylphospholane (16 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 21 h, giving a 19:1 ratio of the allylic alcohol and saturated alcohol products (53 mg, 84%) after flash chromatography.

Reduction of β-ionone; cyclohexylmethylphenylphosphine (Table 2, entry **5**). Using the general procedure, β-ionone (62 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and cyclohexylmethylphenylphosphine (20 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 24 h, giving a 20:1 mixture of the allylic and saturated alcohols (55 mg, 87%) after purification.

Reduction of 3,5-dimethyl-2-cyclohexenone; tri-*n*-butylphosphine (Table 2, entry **6**). Using the general procedure, 3,5-dimethyl-2-cyclohexenone (40 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and tri-*n*-butylphosphine (19 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 18 h, giving an inseparable 1:5 mixture of the allylic alcohol (*cis*/*trans*=3:1) and saturated alcohol. The products were purified by flash chromatography and identified by spectroscopic comparison to authentic samples; details have been previously discussed.[1b]

Reduction of 3,5-dimethyl-2-cyclohexenone; ethylmethylphenylphosphine (Table 2, entry **9**). Using the general procedure, 3,5-dimethyl-2-cyclohexenone (40 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and ethylmethylphenylphosphine (15 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 20 h, giving a 3:1 mixture of the allylic alcohol (*cis*/*trans*=7.3:1) and saturated alcohol (36 mg, 90%) after flash chromatography.

Reduction of 3,5-dimethyl-2-cyclohexenone; 1-phenylphospholane (Table 2, entry **10**). Using the general procedure, 3,5-dimethyl-2-cyclohexenone (40 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and 1-phenylphospholane (16 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 20 h, giving complete conversion to a 1:2 ratio of the allylic alcohol and saturated alcohol products.

Reduction of 3,5-dimethyl-2-cyclohexenone; cyclohexylmethylphenylphosphine (Table 2, entry **11**). Using the general procedure, 3,5-dimethyl-2-cyclohexenone (40 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol), and cyclohexylmethylphenylphosphine (20 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 21 h, giving a 3:1 mixture of the allylic alcohol (*cis*/*trans*=4.9:1) and saturated alcohols (35 mg, 88%) after flash chromatography.

Reduction of perillaldehyde; 1-phenylphospholane (Table 3, entry **2**). Using the general procedure, (*S*)-(−)-perillaldehyde (49 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol) and 1-phenylphospholane (16 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 18 h, giving (*S*)-(−)-perillyl alcohol and 1-hydroxymethyl-4-isopropenyl-1-cyclohexane[31] in a ratio of 38:1 (41 mg, 83%) after flash chromatography.

Reduction of cinnamaldehyde; 1-phenylphospholane (Table 3, entry **4**). Using the general procedure, *trans*-cinnamaldehyde (43 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol) and 1-phenylphospholane (16 mg, 0.097 mmol) were combined and hydrogenated (500 psi) for 18 h, giving cinnamyl alcohol and 3-phenyl-1-propanol in a ratio of 80:1 (38 mg, 89%) after chromatography.

Reduction of Wieland–Miescher ketone (11). Using the general procedure, Wieland–Miescher ketone (58 mg, 0.32 mmol), $[(Ph_3P)CuH]_6$ (5.3 mg, 0.0027 mmol), *tert*-butanol (48 mg, 0.65 mmol) and dimethylphenylphosphine (13 mg, 0.097 mmol) were combined and hydrogenated (800 psi) for 18 h, giving 4-methyl-1,2,3,5,6,7-hexahydronaphthalen-1-ol **12** (44 mg, 82%) after flash chromatography (4:1 hexanes/EtOAc). FTIR (KCl) 3100–3600 (br s), 2924 (s), 1644 (m), 1372 (m), 1357 (w), 1340 (w), 1163 (w),

1093 (s), 1020 (w), 925 (w), 878 (w), 865 (w), 801 (w) cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 5.71 (t, J=4.0 Hz, 1H), 4.19 (t, J=3.6 Hz, 1H), 2.30 (m, 3H), 2.15 (m, 3H), 1.80 (m, 2H), 1.70 (m, 6H); $^{13}C\{^1H\}$ NMR (75 MHz, $CDCl_3$, APT) δ 137.5, 128.2, 125.4, 122.8, 70.2, 30.5, 28.6, 26.1, 25.5, 22.8, 19.0; INAPT (75 MHz, C_6D_6) irradiate δ=5.71↔δ 125.4, 70.1, 25.5, 22.8; irradiate δ=4.19↔δ 137.4, 125.4, 122.8, 30.4, 28.6; HMQC (300 MHz, $CDCl_3$, selected data only) δ 122.8↔δ 5.71; δ 70.2↔δ 4.19; HMBC (300 MHz, $CDCl_3$, selected data only) δ 4.19↔δ 137.4, 125.4, 122.8, 28.6; δ 5.71↔δ 125.4, 70.1, 25.5, 22.8; HRMS calcd m/z for $C_{11}H_{16}O$ 164.12012, found 164.12120.

Reduction of 4-cholesten-3-one (14). Using the general procedure, 4-cholesten-3-one (62 mg, 0.16 mmol), $[(Ph_3P)CuH]_6$ (2.7 mg, 0.0014 mmol), *tert*-butanol (0.5 mL, excess used to solubilize the cholestenone) and dimethylphenylphosphine (7.0 mg, 0.048 mmol) were combined and hydrogenated (200 psi) for 22 h, giving an inseparable 10:1 mixture of stereoisomeric 4-cholesten-3-ols (3β/3α=6:1) and stereoisomeric cholestan-3-ols (3β/3α=5:1) after flash chromatography (59 mg, 95%). The products were identified spectroscopically by comparison to authentic samples prepared by unambiguous synthesis.[22,32]

2-Dimethylphosphinyl-2′-hydroxy-1,1′-binaphthyl (2) and 2-dimethylphosphinyl-1,1′-binaphthyl (3). Into a 50 mL Schlenk flask containing a stirbar were added 2,2′-bis-(trifluoromethanesulfonyloxy)-1,1′-binaphthyl **1** (1.25 g, 2.26 mmol), DMSO (5 mL), dimethylphosphine oxide (0.35 g, 4.52 mmol, prepared according to the literature[33]), diisopropylethylamine (1.16 g, 9.04 mmol), and sodium formate (31 mg, 0.46 mmol). $Pd(OAc)_2$ (52 mg, 0.23 mmol), 1,3-bis(diphenylphosphino)propane (95 mg, 0.23 mmol), and DMSO (3 mL) were combined and transferred to the Schlenk flask, rinsing with an additional 0.5 mL of DMSO. The reaction mixture was placed under nitrogen, stirred, and heated to 90–100°C for 3 h. After cooling, the solution was concentrated in vacuo and the residue diluted with ethyl acetate (30 mL), washed with water (3×40 mL) and brine, and dried over sodium sulfate. The solvent was evaporated in vacuo and the residue purified by flash chromatography, giving a light yellow solid (0.95 g), which consisted of two compounds by ^{31}P NMR spectroscopy (δ 43.8 and 37.5). To this mixture (0.800 g), dissolved in dioxane (10 mL) and methanol (5 mL), was added an aqueous solution of NaOH (3N, 22.5 mL). The resulting solution was stirred at room temperature for 8 h, followed by heating to 80°C for 2 h until complete by TLC analysis. The solution was cooled to room temperature, acidified with concentrated HCl (to pH 1), and extracted with several portions of ethyl acetate. The combined extracts were dried over sodium sulfate and concentrated in vacuo. The residue was purified by flash chromatography (20:1 chloroform/methanol), to afford a mixture of 2-dimethylphosphinyl-2′-hydroxy-1,1′-binaphthyl **2** (0.36 g) as a white solid, along with 2-dimethylphosphinyl-1,1′-binaphthyl **3** (0.18 g) as a yellow solid (81% combined yield). Data for **2**: R_f 0.2 ($CHCl_3$/MeOH 20:1); FTIR (KBr) 2400–3400 (br s), 1622 (m), 1584 (w), 1502 (m), 1434 (m), 1365 (s), 1299 (m), 1275 (w), 1166 (s), 1066 (w), 976 (s), 908 (s), 865 (s) cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.05 (m, 2H), 7.95 (m, 2H), 7.85 (m, 1H), 7.57 (m, 2H), 7.30 (m, obscured by solvent), 7.15 (m, 2H), 6.67 (m, 1H), 1.40 (m, 3H), 1.20 (m, 3H); ^{31}P NMR (81 MHz, $CDCl_3$) δ 47.2; HRMS calcd for $C_{22}H_{19}O_2P$ 346.11227, found 346.11208. Data for **3**: R_f 0.35 ($CHCl_3$/MeOH 20:1); FTIR (KBr) 3439 (br w), 3053 (w), 1504 (w), 1383 (w), 1298 (w), 1176 (s), 1027 (w), 950 (s), 903 (m), 862 (m), 820 (m), 774 (m), 748 (m), 708 (m) cm^{-1}; ^1H NMR (300 MHz, $CDCl_3$) δ 8.15 (m, 1H), 8.05 (m, 1H), 7.95 (m, 2H), 7.40–7.65 (m, 6H), 7.31 (m, 1H), 7.15 (m, 1H), 7.05 (m, 1H), 1.51 (d, J=11.6 Hz, 3H), 1.00 (d, J=11.6 Hz, 3H); ^{31}P NMR (81 MHz, $CDCl_3$) δ 43.7; HRMS calcd for $C_{22}H_{19}OP$ 330.11734, found 330.11661.

2-Dimethylphosphino-2′-methoxy-1,1′-binaphthyl (4). To a solution of 2-dimethylphosphinyl-2′-hydroxy-1,1′-binaphthyl **2** (0.346 g, 1.0 mmol) in acetone (15 mL) were added potassium carbonate (0.552 g, 4.0 mmol) and methyl iodide (0.568 g, 4 mmol). The resulting solution was heated to reflux for 16 h, after which additional methyl iodide (0.568 g, 4 mmol) was added to the reaction mixture. After heating to reflux for an additional 8 h, the solution was cooled to room temperature, filtered, and the residue washed with diethyl ether (5 mL). The ether washes were combined with the filtrate and concentrated in vacuo. The residue was purified by flash chromatography (chloroform/methanol 10:1) to afford 2-dimethylphosphinyl-2′-methoxy-1,1′-binaphthyl (0.340 g, 94%) as a pale yellow solid. R_f 0.6 (10:1 $CHCl_3$/MeOH). To a cold (0°C) solution of this material (0.210 g, 0.58 mmol) and triethylamine (1.172 g, 11.6 mmol) in xylenes (10 mL) was added trichlorosilane (0.405 g, 3 mmol, 0°C) dropwise. The resulting solution was warmed to room temperature, followed by heating to 120°C for 2 h. After cooling, the reaction mixture was diluted with diethyl ether (10 mL) and quenched with 5 mL saturated sodium bicarbonate. The resulting mixture was filtered through celite and the organic layer was dried over sodium sulfate. The solvent was evaporated in vacuo and the residue purified by flash chromatography under a nitrogen atmosphere (10:1 hexanes/ethyl acetate), giving 2-dimethylphosphino-2′-methoxy-1,1′-binaphthyl **4** (150 mg, 78%) as a white solid. R_f 0.4 (10:1 hexanes/ EtOAc); FTIR (KBr) 3052 (w), 3004 (w), 2954 (w), 2932 (w), 2835 (w), 1620 (w), 1508 (s), 1414 (w), 1331 (s), 1215 (w), 1118 (s), 907 (m), 784 (s), 703 (s), 674 (w) cm^{-1}; ^1H NMR (300 MHz, C_6D_6) δ 7.70–7.85 (m, 5H), 7.45 (m, 1H), 7.18 (m, obscured by solvent), 6.90–7.11 (m, 4H), 3.25 (s, 3H), 1.12 (d, J=3.7 Hz, 3H), 0.92 (d, J=3.7 Hz, 3H); ^{31}P NMR (162 MHz, C_6D_6) δ −55.3; HRMS calcd for $C_{23}H_{21}OP$ 3344.13300, found 344.13277.

2-Dimethylphosphino-2′-methoxy-1,1′-binaphthyl (5). Using the procedure described above, 2-dimethylphosphinyl-1,1′-binaphthyl **3** (0.150 g, 0.46 mmol), triethylamine (0.919 g, 9 mmol), xylenes (10 mL), and trichlorosilane (0.310 g, 2.3 mmol) were combined and the resulting solution warmed to room temperature and then heated at 120°C for 2 h. After work-up, 2-dimethylphosphino-1,1′-binaphthyl **5** was obtained as a pale yellow solid (0.126 g, 88%). R_f 0.7 (10:1 hexanes/ethyl acetate); FTIR (KBr) 3053 (m), 3006 (w), 2955 (m), 2925 (m), 2898 (m), 1591 (w), 1554 (w), 1414 (m), 1316 (m), 1232 (m), 1137 (m), 1042 (m), 962 (s), 703 (s), 673 (s) cm^{-1}; ^1H

NMR (360 MHz, C_6D_6) δ 7.82 (m, 1H), 7.61–7.75 (m, 4H), 7.35 (m, 4H), 7.19 (m, 2H, obscured by solvent), 6.98 (m, 2H), 1.04 (d, J=4.8 Hz, 3H), 0.83 (d, J=4.8 Hz, 3H); ^{31}P NMR (162 MHz, C_6D_6) δ −57.6; HRMS calcd for $C_{22}H_{19}P$ 314.12244, found 314.12108.

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