Preparation and Reactions of Diorganozincs from Dienic Silyl Enol Ethers

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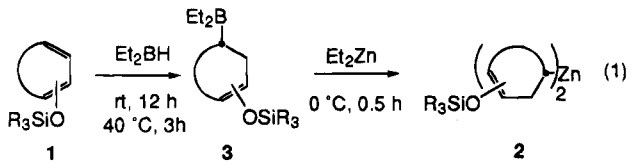
The hydroboration of the dienic silyl enol ethers **1a–d** with Et_2BH produces organoboranes which are readily converted under mild conditions by a treatment with Et_2Zn to the corresponding dialkylzincs **2a–d**. These organometallics react after transmetalation with CuCN·2LiCl with various electrophiles affording polyfunctional silyl enol ethers of type **4**. In the presence of the chiral catalyst (1*R*,2*R*)-bis(trifluoromethanesulfonamido)cyclohexane **6**, the dialkylzinc **2b** was added to various aldehydes leading to hydroxy silyl enol ethers of type **8** in satisfactory yields (45–77%) and excellent enantioselectivities (85 to >96 % ee). The chiral products **8** can be oxidatively cyclized using t-BuOOH and catalytic amounts of $VO(acac)_2$ furnishing trisubstituted tetrahydropyrans like **9a,b** with high diastereoselectivity. An iodoalkoxylation of **8a** affords after HI elimination and Jones oxidation the unsaturated valerolactone **13**.

Recently, we have shown that functionalized olefins can be readily converted into functionalized diorganozincs via hydroboration with Et_2BH followed by transmetalation with Et_2Zn. This method allows the preparation of dialkylzincs in high yields (ca. 70–80% overall yield). It proceeds under mild conditions (0–25 °C, 0.5–2 h) and tolerates a broad range of functional groups.[1] Furthermore, it avoids the preparation of expensive and often sensitive alkyl iodides as starting materials[2] (Scheme 1). It is also a reaction displaying a good atom economy[3] since the only byproducts are Et_2Zn (added in excess) and BEt_3 which can be recovered by distillation from the crude reaction mixture. This "halide free" synthesis certainly has a potential for the large scale or industrial preparation of dialkylzincs. All these features make the boron–zinc exchange reaction[1,4] the most convenient method for the preparation of functionalized primary dialkylzincs starting from terminal olefins. The use of internal olefins is possible in some cases; however, regioselectivity and reactivity problems are encountered.[1]

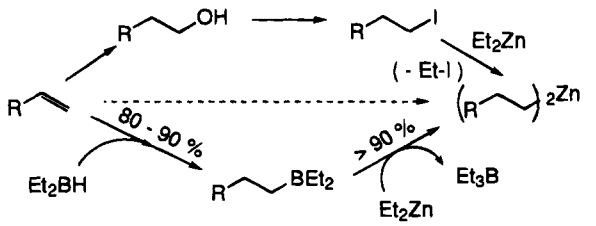
In this work, we wish to report the preparation of functionalized diorganozincs using dienic silyl enol ethers of type **1** as precursors and show that this approach allows a unique preparation of functionalized diorganozincs of type **2** via the corresponding boranes **3** (eq 1). The synthetic utility of these zinc organometallics will be briefly demonstrated.

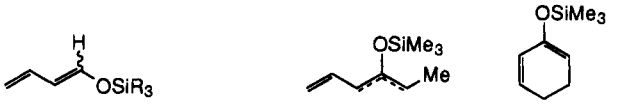


Results and Discussion

The dienic silyl enol ethers **1a–d** were prepared from the corresponding unsaturated aldehydes using literature methods (see Experimental Section).[5–8] Interestingly, whereas 1-(trimethylsiloxy)butadiene (**1a**) is obtained as a *E*:*Z* mixture (87:13),[6] the corresponding 1-(triisopropylsiloxy)butadiene (**1b**) is obtained as the pure *E*-isomer.[7,8] The hydroboration of these dienes is performed with excellent regioselectivity using Et_2BH.[9] This reagent is conveniently prepared by mixing BH_3·Me_2S and Et_3B in the ratio 1:2 and is stable for several months at 4 °C without decomposition.[10] The hydroboration with Et_2BH is usually complete after 12 h at rt and 3 h at 40 °C affording, after evaporation of methyl sulfide, the pure diethyl boranes **3a–d** in >90% crude yield. The boron–zinc exchange reaction is performed by adding Et_2Zn (2 equiv) at 0 °C. After 0.5 h, the excess Et_2Zn and formed Et_3B are pumped off under vacuum leading to the dialkylzinc reagents **2a–d** in 75–95% crude yield. The transmetalation of these zinc species with CuCN·2LiCl[11]

Scheme 1





1a : R = Me (E : Z 87:13)
1b : R = i-Pr (100 % E)

1c : mixture of regioisomers

1d

[⊗] Abstract published in *Advance ACS Abstracts,* May 1, 1995.

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(3) Trost, B. M. *Science* **1991**, *254*, 1471.

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(6) Jung, M. E.; Gardiner, J. M. *J. Org. Chem.* **1991**, *56*, 2614.

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(8) The diene **1b** may find interesting applications in Diels–Alder reactions.

(9) Köster, R.; Griasnow, G.; Larbig, W.; Binger, P. *Liebigs Ann. Chem.* **1964**, *627*, 1.

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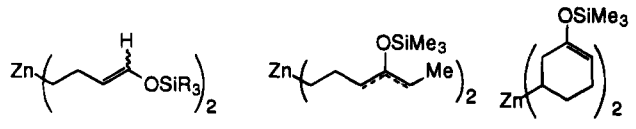
produces intermediate copper reagents which react with

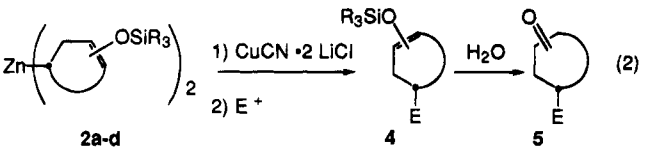


2a : R = Me (E : Z 87:13)
2b : R = i-Pr (100 % E)

2c : mixture of regioisomers

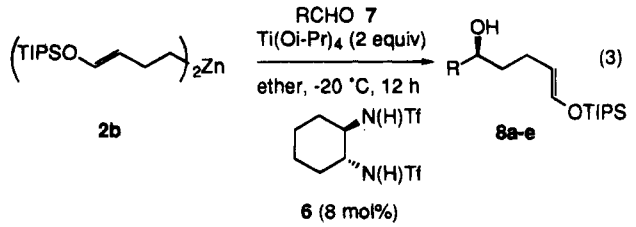
2d

several electrophiles (allylic halides, acid chlorides, alkylidenemalonates, 3-iodo-2-cyclohexen-1-one, ethyl propiolate) affording polyfunctional silyl enol ethers of type **4** or after hydrolysis carbonyl compounds of type **5** in satisfactory yields (eq 2 and Table 1). 1-(Trimethylsiloxy)butadiene (**1a**) can be readily converted to the zinc reagent **2a**; however, the trimethylsilyl enol ethers



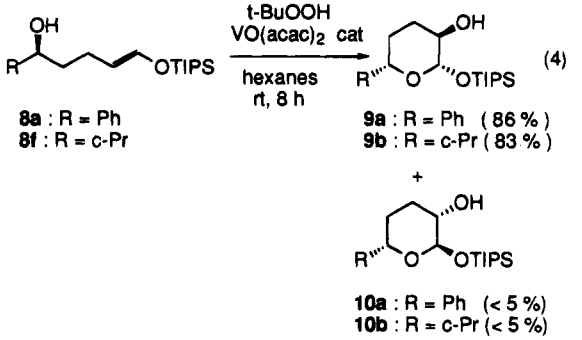
2a-d **4** **5** (2)

formed after reaction with electrophiles were found to be very sensitive toward a chromatographic purification and have to be distilled. Alternatively, the corresponding aldehydes can be prepared by performing an acidic workup (see entries 1–3 of Table 1). In order to avoid this limitation, the corresponding 1-(triisopropylsiloxy)-butadiene (**1b**) was used. In this case, TIPS enol ethers[12] **4b–g** were obtained which survived the chromatographic purification procedure allowing the preparation of a range of polyfunctional (*E*)-TIPS enol ethers. Silyl enol ethers derived from ketones like **1c** can also be converted to the corresponding dialkylzinc **2c** and reacted with various electrophiles providing after hydrolysis of the silyl enol ether the polyfunctional ketones **5c–f**. Finally, the secondary zinc reagent **2d** obtained from 2-(trimethylsiloxy)-1,3-cyclohexadiene (**1d**) reacts after transmetalation with CuCN·2LiCl with ethyl 2-(bromomethyl)-acrylate or benzoyl chloride providing the cyclic silyl enol ether **4h** (84% yield; entry 14) or after a acidic aqueous workup the ketones **5g** and **5h** (83 and 75% yield; entries 15 and 16). The dialkylzinc **2b** can also be added with high enantioselectivity to various aldehydes **7** in the presence of catalytic amounts of (1*R*,2*R*)-bis(trifluoromethanesulfonamido)cyclohexane (**6**) (8 mol %)[2b,13] and $Ti(Oi\text{-}Pr)_4$ (2 equiv) in ether (−20 °C, 12 h; 85 to >96% ee) producing the hydroxy-TIPS enol ethers **8a–e**. Aromatic, α,β-unsaturated, and aliphatic aldehydes react with similar high enantioselectivity; however, high yields are obtained only with the more reactive aromatic aldehydes (Table 2 and eq 3). Products of type **8** can be cyclized under oxidative conditions. Thus, treatment of **8a** and **8f** with *tert*-butyl hydroperoxide (2 equiv) and vanadyl acetylacetonate ($VO(acac)_2$; 5 mol %)[14] produces



2b **8a-e** **6** (8 mol%) (3)

with very high regio- and stereoselectivity the cyclized β-hydroxytetrahydropyran derivatives **9a** and **9b**, respectively, in 86 and 83% isolated yield. The crude reaction mixture is contaminated with less than 5% of the isomers **10a,b** formed by a diastereotopic attack of the epoxidation agent. Epoxidation with MCPBA instead of $VO(acac)_2$ is unselective in the case of **8a** leading to a 1:1 mixture of **9a** and **10a** (eq 4). The relative stereochem-

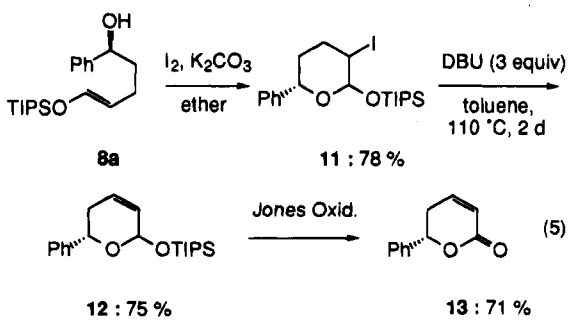


8a : R = Ph
8f : R = c-Pr

9a : R = Ph (86 %)
9b : R = c-Pr (83 %)

10a : R = Ph (< 5 %)
10b : R = c-Pr (< 5 %) (4)

istry of compounds **9** and **10** has been established by performing NOESY and COSY experiments (Tables 3 and 4). The relevant NOESY correlations used for the attribution of the relative stereochemistry are shown in Figure 1. The iodocyclization of **8a** (I_2, K_2CO_3, ether, −78 °C, 2 h) is regiospecific, but proceeds with moderate stereoselectivity producing the iodotetrahydropyran **11** in 78% yield as a mixture of stereoisomers. Elimination of HI with DBU (3 equiv, toluene, 110 °C, 2 d) produces the dihydropyran **12** as a *cis:trans* mixture (80:20) in 75% yield. Oxidation of **12** with Jones reagent affords in a stereoconvergent way the optically active lactone **13** in 71% yield and 90% ee (eq 5).



8a **11** : 78 %

12 : 75 % **13** : 71 % (5)

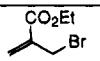
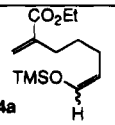
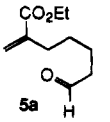
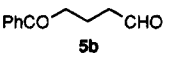
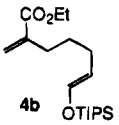
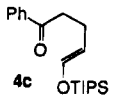
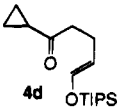
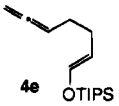
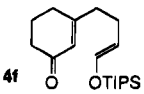
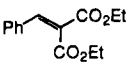
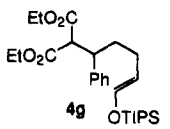
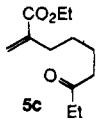
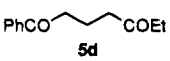
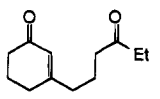
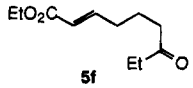
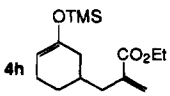
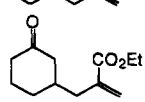
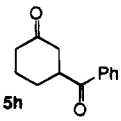
In summary, we have developed a direct conversion of dienic silyl enol ethers to functionalized homoallylic zinc reagents. Their reaction with electrophiles in the presence of CuCN·2LiCl allows a simple preparation of polyfunctional silyl enol ethers, whereas their addition to aldehydes in the presence of the chiral catalyst **6** produces new secondary alcohols bearing a valuable TIPS enol ether function with excellent enantioselectivity. The stereoselective cyclization of these adducts has been briefly investigated.

(12) (a) Magnus, P.; Lacour, J. *J. Am. Chem. Soc.* **1992**, *114*, 767, 3993. (b) Magnus, P.; Evans, A.; Lacour, J. *Tetrahedron Lett.* **1992**, *33*, 2933. (c) Magnus, P.; Rigollier, P.; Lacour, J.; Tobler, J. *J. Am. Chem. Soc.* **1993**, *115*, 12629.

(13) (a) Rozema, M. J.; Eisenberg, C.; Lütjens, H.; Ostwald, R.; Belyk, K.; Knochel, P. *Tetrahedron Lett.* **1993**, *34*, 3115. (b) Knochel, P.; Brieden, W.; Rozema, M. J.; Eisenberg, C. *Tetrahedron Lett.* **1993**, *34*, 5881. (c) Brieden, W.; Ostwald, R.; Knochel, P. *Angew. Chem., Int. Ed. Engl.* **1993**, *32*, 582. (d) Vettel, S.; Knochel, P. *Tetrahedron Lett.* **1994**, *35*, 5849. (e) Eisenberg, C.; Knochel, P. *J. Org. Chem.* **1994**, *59*, 3760. (f) Ostwald, R.; Chavant, P.-Y.; Stadtmüller, H.; Knochel, P. *J. Org. Chem.* **1994**, *59*, 4143.

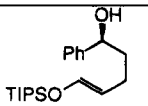
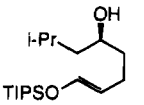
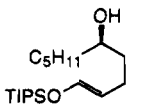
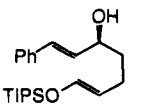
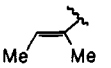
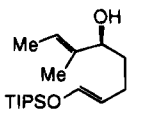
(14) (a) Sharpless, K. B.; Michaelson, R. C. *J. Am. Chem. Soc.* **1973**, *95*, 6136. For an excellent review, see: Hoveyda, A. H.; Evans, D. A.; Fu, G. C. *Chem. Rev.* **1993**, *93*, 1307.

Table 1. Silyl Enol Ethers 4a–h and Carbonyl Derivatives 5a–h Obtained by the Reaction of the Functionalized Zinc Reagents 2a–d with an Electrophile in the Presence of CuCN·2LiCl

entry	zinc reagent of type 2	electrophile	product of type 4 or 5	yield (%)[a]
1	**2a**		 **4a**	66
2	**2a**		 **5a**	65
3	**2a**	PhCOCl	 **5b**	68
4	**2b**		 **4b**	71
5	**2b**	PhCOCl	 **4c**	73
6	**2b**		 **4d**	72
7	**2b**	HC≡C-CH_2OTs	 **4e**	68
8	**2b**		 **4f**	81
9	**2b**		 **4g**	75
10	**2c**		 **5c**	70
11	**2c**	PhCOCl	 **5d**	74
12	**2c**		 **5e**	76
13	**2c**	HC≡C-CO_2Et	 **5f**	69
14	**2d**		 **4h**	84
15	**2d**		 **5g**	83
16	**2d**	PhCOCl	 **5h**	75

[a] Isolated yield of analytically pure product.

Table 2. Chiral Hydroxy-TIPS Enol Ethers of Type 8 Obtained by the Catalytic Enantioselective Addition of the Dialkylzinc 2b to Aldehydes 7 in the Presence of the Catalyst 6

entry	aldehyde 7 R	product 8	yield (%)[a]	ee (%)[b]
1	Ph-	 **8a**	77	> 96
2	*i*-Bu-	 **8b**	60	92
3	C_5H_{11}-	 **8c**	66	91
4	Ph-CH=CH-	 **8d**	55	85
5		 **8e**	45	> 96

[a] Isolated yield of analytically pure product. [b] Determined by preparing the corresponding *O*-acetylmandelates using (*S*)-(+)-*O*-acetylmandelic acid. In each case, a calibration sample using (±)-*O*-acetylmandelic acid was prepared (ref 19).

Table 3. ^{1}H-NMR Assignments for 9a

proton	^{1}H-NMR of **9a**	^{1}H–^{1}H COSY	^{1}H–^{1}H NOESY
1	4.64 (d, 7.3)	2	5, 8, 10
2	3.40–3.44 (m)	1,(4), 5	3, (4), 7
3	2.24 (d, 1.7)	–	2
4	2.10–2.13 (m)	(2), 5, 7	2, 5
5	1.58–1.67 (m)	2, 4, 6, 7	
6	1.89–1.92 (m)	5, 7	5, 7, (8)
7	1.58–1.67 (m)	4, 5, 6, 8	
8	4.47 (dd, 10.7, 2.4)	7	1, 5, 6, 9
9	7.23–7.33 (m)	–	8
10	1.03–1.16 (m)	–	1

Table 4. ^{1}H-NMR Assignments for 10a

proton	^{1}H-NMR of **10a**	^{1}H–^{1}H COSY	^{1}H–^{1}H NOESY
1	5.18 (s)	–	2, 3, 10
2	3.63–3.65 (m)	3, 4, (5)	1, 3, 4, 5
3	2.04 (d, 9.1)	2	1, 2, (7)
4	1.77–1.82 (m)	2, 5, 6, 7	2, 5
5	2.19–2.25 (m)	(2), 4, 6, 7	2, 4, 8
6	1.66–1.70 (m)	5, 7, (8)	7, (8)
7	1.84–1.89 (m)	4, 5, 6, 8	(3), 6
8	5.01 (dd 11.8, 2.5)	(6), 7	5, 6, 10
9	7.22–7.35 (m)	–	8
10	0.99–1.15 (m)	–	1, 8

Experimental Section

General Methods. Unless otherwise indicated all reactions were carried out under Ar. Solvents (THF, ether, toluene) were dried and freshly distilled from sodium/benzophenone. Dichloromethane was freshly distilled over CaH_2. Reactions were monitored by gas chromatography (GC) or thin layer chromatography (TLC) analysis of worked up reaction aliquots. The NOESY and COSY measurements were performed on a 500 MHz NMR instrument.

Starting Materials. The following starting materials were prepared according to literature procedures: 1-(trimethylsi-

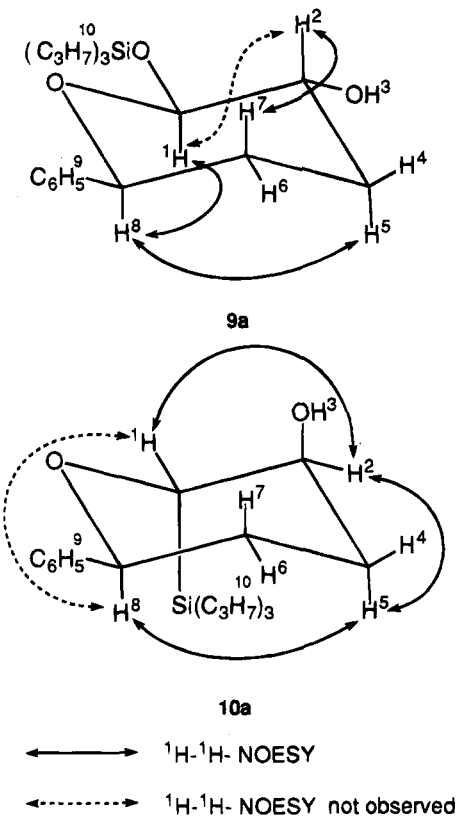


Figure 1. NOESY correlations for compounds **9a** and **10a**.

loxy)-1,3-butadiene (**1a**),[6] 2-(trimethylsiloxy)-1,3-cyclohexadiene (**1d**),[5] ethyl (2-bromomethyl)acrylate,[15] propargyl tosylate,[16] 3-iodo-2-cyclohexen-1-one,[17] triisopropylsilyl triflate.[7]

Preparation of (*E*)-1-(Triisopropylsiloxy)-1,3-butadiene (1b). To a solution of (*E*)-2-butenal (4.73 g; 5.6 mL; 67.5 mmol) and triethylamine (13 mL; 9.1 g; 90 mmol) in toluene (40 mL) was added TIPS-OTf[7] (11.7 g; 38.2 mmol) within 10 min. A slightly exothermic reaction took place, and the reaction mixture became inhomogeneous. After 2 h of further stirring, the upper layer was separated and the lower layer extracted with hexanes (3 × 30 mL). The combined organic phase was washed with brine and dried ($MgSO_4$), and the solvents were evaporated. The residue was distilled through a 20 cm column affording the diene **1b** (6.9 g; 30.5 mmol; 80% yield as a clear liquid, $bp_{0.7}$ = 47–49 °C). IR (neat): 3090 (w), 3030 (w), 2940 (vs), 1640 (s), 1600 (w), 1185 (vs, br). ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 6.64 (d, 1H, *J* = 11.8 Hz); 6.21 (dt, 1H, *J* = 16.9, 10.6 Hz); 5.74 (t, 1H, *J* = 11.4 Hz); 4.97 (dd, 1H, *J* = 16.9, 1.9 Hz); 4.79 (dd, 1H, *J* = 10.3, 1.8 Hz); 1.37-1.09 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 145.8, 133.4, 113.9, 111.5, 17.6 (6C), 11.9 (3C). EI-MS (70 eV): 226 (M^+, 51), 183 (67), 141 (55), 113 (100), 99 (26). Anal. Calcd for $C_{13}H_{26}OSi$: C, 68.96; H, 11.57. Found: C, 68.72; H, 11.61.

Preparation of 4-(Trimethylsiloxy)-1,3-hexadiene (1c) (contains 38% of 4-(trimethylsiloxy)-1,4-hexadiene). 5-Hexen-3-one[18] (4.9 g, 50 mmol) was added dropwise to a 1:1 THF–ether solution (50 mL) of LDA (52 mmol) at 0 °C. After stirring for 10 min, a 1:1 THF–ether solution (25 mL) of Et_3N (2.2 g, 22 mmol) and TMSCl (9.2 g, 85 mmol) was added. The reaction mixture was stirred at 0 °C for 15 min and at rt for 30 min. The resulting mixture was diluted with hexanes (100 mL), washed with ice cold 5% $NaHCO_3$ solution (2 × 30 mL), cold water (2 × 30 mL), and brine (2 × 25 mL), and dried (Na_2SO_4). Distillation of the crude residue obtained after evaporation of the solvents gave a mixture of **1c** and 4-(trimethylsiloxy)-1,4-hexadiene (62:38; bp_{20} = 65 °C) as a clear liquid (7.23 g, 85% yield). IR (neat): 3087 (w), 3044 (w), 2965 (m), 1646 (s), 1596 (w), 1254 (s), 1209 (s), 845 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 300 MHz): δ 6.57–6.29 (m, 2H), 5.26 (q, 1H, *J* = 10.0 Hz), 4.91 (t, 1H, *J* = 15.8 Hz), 4.74 (t, 1H, *J* = 8.9 Hz), 2.16 (q, 2H, *J* = 7.5 Hz), 2.03 (q, 1H, *J* = 7.4 Hz), 0.99 (q, 2H, *J* = 7.0 Hz), 0.16 (s, 9H). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 157.3, 154.9, 132.8, 131.8, 111.6, 111.2, 109.3, 109.1, 29.6, 25.0, 11.8, 11.5, 0.6, 0.4. MS (EI): 170 (M^+, 22), 155 (27), 141 (9). Anal. Calcd for $C_9H_{18}OSi$: C, 63.47; H, 10.65. Found: C, 62.95; H, 11.06.

Typical One-Pot Hydroboration, Successive Boron–Zinc, Zinc–Copper Transmetalation and Reaction with an Electrophile. Preparation of (*E*)-5-Phenyl-1-(triisopropylsiloxy)-1-penten-5-one 4c (entry 5 of Table 1). The diene **1b** (1.67 g, 7.4 mmol) was cooled to 0 °C, Et_2BH (7.4 mmol) was slowly added via syringe, and the mixture was stirred for 12 h at rt and then 3 h at 40 °C. Methyl sulfide was removed under vacuum (1 mmHg, 0 °C, 0.5 h, and then rt, 4 h) affording the desired crude diethyl(alkyl)borane **3b** (2.1 g, 7 mmol, ca. 95% crude yield). The organoborane **3b** was cooled to 0 °C and Et_2Zn (14 mmol) was added. After 30 min at 0 °C, the excess of Et_2Zn and formed BEt_3 were pumped off (1 mmHg, 0 °C, 1 h, and then rt, 3 h). The resulting crude oil of the zinc reagent **2b** was diluted with THF (6 mL) and cooled to −78 °C, and a THF (10 mL) solution of CuCN·2LiCl prepared from CuCN (0.63 g, 7 mmol) and LiCl (0.59 g, 14 mmol) was added. The reaction mixture was warmed to 0 °C and immediately cooled back to −50 °C. Benzoyl chloride (0.84 g, 6 mmol) was added, and the reaction mixture was warmed to −20 °C and was stirred for 6 h at this temperature. After dilution with ether (200 mL), the reaction mixture was poured in saturated aqueous NH_4Cl solution (200 mL). The aqueous layer was extracted with ether (2 × 50 mL), the combined organic layer was washed successively with water (2 × 30 mL) and brine (2 × 20 mL) and dried ($MgSO_4$), and the solvents were evaporated. The crude residue was purified by column chromatography (hexanes:t-BuOMe 97:3) affording pure **4c** (1.45 g, 73% yield).

Analytical Data of the Products 4a–h and 5a–h of Table 1. Ethyl 2-[5-(trimethylsiloxy)-4-pentenyl]acrylate (4a): yield (2.0 g, 66%). Prepared using ethyl (2-bromomethyl)-acrylate[15] (2.3 g, 12 mmol) and the zinc reagent **2a** (ca. 14 mmol). Reaction conditions: −78 °C to 25 °C, 3 h; (bp_1 = 95–100 °C). IR (neat): 3104 (w), 2956 (vs), 1719 (vs), 1664 (s), 1632 (w), 1445 (m), 1369 (m), 1090 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 6.12–6.02 (m, 2H), 5.41–5.39 (m, 1H), 4.92–4.83 (m, 1H), 4.09 (q, 2H, *J* = 7.1 Hz), 2.19 (t, 2H, *J* = 7.4 Hz), 1.82 (q, 2H, *J* = 7.4 Hz), 1.45–1.32 (m, 2H), 1.19 (t, 3H, *J* = 7.1 Hz), 0.07 (s, 9H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 167.6, 141.5, 140.3, 138.6, 124.8, 111.8, 111.3, 61.0, 31.9, 31.8, 29.7, 28.9, 27.4, 23.6, 14.7, −0.1. MS (EI): 256 (M^+, 1), 183 (4), 167 (7), 142 (12), 129 (30), 116 (16). Exact mass calcd for $C_{13}H_{24}O_3Si$: 256.15017. Found: 256.15016.

Ethyl 2-[5-(triisopropylsiloxy)-4-pentenyl]acrylate (4b): yield (1.2 g, 71%). Prepared using ethyl (2-bromomethyl)-acrylate[15] (0.96 g, 5 mmol) and **2b** (ca. 5.8 mmol). Reaction conditions: −78 °C to −20 °C, 3 h. Purification by column chromatography (hexanes:EtOAc 95:5). IR (neat): 3104 (w), 3035 (w), 2944 (vs), 2896 (m), 1720 (vs), 1663 (s), 1632 (w), 1464 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 300 MHz) δ 6.24 (d, 1H, *J* = 11.8 Hz), 6.04 (s, 1H), 5.41 (s, 1H), 4.96–4.87 (m, 1H), 4.12 (q, 2H, *J* = 7.1 Hz), 2.22 (t, 2H, *J* = 7.7 Hz), 1.84 (q, 2H, *J* = 7.3 Hz), 1.47–1.34 (m, 2H), 1.22 (t, 3H, *J* = 7.1 Hz), 1.16–0.94 (m, 21H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 167.1, 141.0, 140.9, 124.1, 110.5, 60.4, 31.2, 29.2, 26.8, 17.7, 14.1, 12.2. MS (EI): 340 (M^+, 3), 297 (23), 223 (100), 131 (16), 103 (16), 75 (20), 61 (16). Anal. Calcd for $C_{19}H_{36}O_2$: C, 67.00; H, 10.65. Found: C, 66.97; H, 10.90.

5-Phenyl-1-(triisopropylsiloxy)-1-penten-5-one (4c): yield (1.45 g, 73%). Prepared using benzoyl chloride (0.84 g, 6 mmol) and **2b** (ca. 7 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −20 °C, 6 h. Purification by column chromatography (hexanes:t-BuOMe 97:3). IR (neat): 3038 (w), 2944 (vs), 2867 (m), 1688 (vs), 1663 (vs), 1598 (w) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz) δ 7.86–7.81 (m, 2H), 7.44–7.33 (m, 3H), 6.32 (d, 1H, *J* = 11.8 Hz), 5.04–4.90 (m, 1H), 2.89 (t, 2H, *J* = 7.3 Hz), 2.30–2.19 (m, 2H), 1.08–0.92 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 199.8, 141.9, 137.3, 133.1, 128.7, 128.2,

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109.7, 39.8, 22.6, 18.0, 12.2. MS (EI): 332 (M^+, 1), 289 (87), 233 (96), 205 (14), 131 (66), 105 (100). Anal. Calcd for $C_{20}H_{32}O_2Si$: C, 72.23; H, 9.70. Found: C, 72.17; H, 9.73.

1-Cyclopropyl-5-(triisopropylsiloxy)-4-penten-1-one (4d): yield (1.70 g, 72%). Prepared using cyclopropylcarbonyl chloride (0.84 g, 8 mmol) and the zinc reagent **2b** (ca. 8 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −20 °C, 8 h. Purification by column chromatography (hexanes:EtOAc 92:8). IR (neat): 3038 (w), 3010 (w), 2944 (vs), 2893 (s), 1702 (vs), 1664 (vs) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz) δ 6.33 (d, 1H, J = 10.7 Hz), 5.02−4.93 (m, 1H), 2.57 (t, 2H, J = 7.3 Hz), 2.19 (q, 2H, J = 7.3 Hz), 1.92−1.88 (m, 1H), 1.16−1.05 (m, 21H), 1.01−0.97 (m, 2H), 0.86−0.81 (m, 2H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 210.0, 141.4, 109.3, 44.1, 21.9, 20.3, 17.6, 11.9, 10.3. MS (EI): 296 (M^+, 1), 253 (100), 197 (27), 155 (52), 127 (30), 113 (27), 103 (11). Anal. Calcd for $C_{17}H_{32}O_2Si$: C, 68.86; H, 10.88. Found: C, 68.91; H, 11.09.

1-(Triisopropylsiloxy)-1,5,6-heptatriene (4e): yield (0.90 g, 68%). Prepared using propargyl tosylate[16] (1.1 g, 5 mmol) and **2b** (ca. 6 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −30 °C, 6 h. Purification by column chromatography (hexanes). IR (neat): 3036 (w), 2944 (vs), 1957 (s), 1664 (vs) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 6.30 (d, 1H, J = 11.7 Hz), 5.07−4.93 (m, 2H), 4.62−4.58 (m, 2H), 2.03−1.93 (m, 4H), 1.17−0.97 (m, 21H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 208.5, 141.1, 110.1, 89.4, 74.6, 29.3, 27.0, 17.7, 12.0. MS (EI): 267 (M + 1, 4), 223 (4), 214 (2), 181 (14), 158 (39), 115 (60). Anal. Calcd for $C_{16}H_{30}OSi$: C, 72.11; H, 11.35. Found: C, 71.99; H, 11.54.

3-[4-(Triisopropylsiloxy)-3-butenyl]-2-cyclohexen-1-one (4f): yield (1.56 g, 81%). Prepared using 3-iodo-2-cyclohexen-1-one[17] (1.33 g, 6 mmol) and **2b** (ca. 7 mmol). Reaction conditions: −78 °C to −30 °C, 1 h, and then −30 °C, 4 h. Purification by column chromatography (hexanes:EtOAc 90:10). IR (neat): 3035 (m), 2944 (vs), 2893 (s), 1665 (vs), 1627 (w), 1465 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz) δ 6.21 (d, 1H, J = 10.6 Hz), 5.71 (s, 1H), 4.85−4.76 (m, 1H), 2.21−1.79 (m, 10H), 1.05−0.89 (m, 21H). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 199.1, 165.2, 141.4, 125.9, 109.0, 38.8, 37.2, 29.6, 24.8, 22.5, 17.5, 11.8. MS (EI): 322 (M^+, 1), 279 (8), 223 (12), 213 (7), 157 (6). Anal. Calcd for $C_{19}H_{34}O_2Si$: C, 70.75; H, 10.62. Found: C, 70.89; H, 10.51.

Diethyl 2-[1-phenyl-5-(triisopropylsiloxy)-4-pentenyl]-malonate (4g): yield (1.96 g, 75%). Prepared using diethyl benzylidenemalonate (1.36 g, 5.5 mmol) and **2b** (ca. 6.5 mmol). Reaction conditions: −78 °C to −30 °C, 1 h, and then −30 °C, 5 h. Purification by column chromatography (hexanes:EtOAc 90:10). IR (neat): 3063 (w), 3031 (w), 2944 (vs), 2867 (m), 1756 (vs), 1736 (vs), 1663 (s), 1603 (w), 1465 (m), 1175 (vs), 701 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz) δ 7.20−7.07 (m, 5H), 6.10 (d, 1H, J = 11.8 Hz), 4.86−4.78 (m, 1H), 4.13 (q, 2H, J = 7.1 Hz), 3.77 (q, 2H, J = 7.1 Hz), 3.53 (d, 1H, J = 10.8 Hz), 3.33−3.29 (m, 1H), 1.65−1.56 (m, 4H), 1.20 (t, 3H, J = 7.1 Hz), 1.09−0.91 (m, 21 H), 0.86 (t, 3H, J = 7.0 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 168.3, 167.7, 141.0, 140.7, 128.4, 128.2, 126.8, 110.0, 61.3, 60.9, 58.9, 45.0, 34.6, 24.8, 17.7, 14.0, 13.6, 12.0. MS (EI): 433 (2), 359 (1), 255 (1), 119 (8). Anal. Calcd for $C_{27}H_{44}O_5Si$: C, 68.03; H, 9.30. Found: C, 67.77; H, 9.49.

Ethyl 2-[(3′-(trimethylsiloxy)-3′-cyclohexenyl)methyl]-acrylate (4h): yield (3.08 g, 84%). Prepared using ethyl (2-bromomethyl)acrylate[15] (2.5 g, 13 mmol) and the zinc reagent **2d** (15 mmol). Reaction conditions: −78 °C to 25 °C, 3 h. Purification by distillation (bp_1 = 110 °C). IR (neat): 3101 (w), 3045 (w), 2934 (s), 1719 (vs), 1663 (w), 1630 (w), 1252 (s), 1178 (s), 910 (m), 844 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz) δ 6.09 (s, 1H), 5.43 (s, 1H), 4.76 (t, 1H, J = 3.5 Hz), 4.12 (q, 2H, J = 7.1 Hz), 2.78 (dd, 1H, J = 13.6, 3.5 Hz), 2.21−1.90 (m, 4H), 1.60−1.28 (m, 4H), 1.22 (t, 3H, J = 7.2 Hz), 0.11 (s, 9H). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 167.0, 152.4, 139.6, 125.5, 104.0, 60.2, 37.6, 34.8, 27.3, 23.9, 19.4, 14.0, 0.0. MS (EI): 282 (M^+, 18), 237 (8), 169 (43), 119 (15). Exact mass calcd for $C_{15}H_{26}O_3Si$: 282.16623. Found: 282.16623.

Ethyl 2-(5-oxopentyl)acrylate (5a): yield (0.42 g, 65%). Prepared using ethyl (2-bromomethyl)acrylate[15] (0.67 g, 3.5 mmol) and the zinc reagent **2a** (ca. 4 mmol). Reaction conditions: −78 °C to 25 °C, 3 h. Purification by column chromatography (hexanes:t-BuOMe 4:1). IR (neat): 3105 (w), 2939 (s), 2722 (w), 1720 (vs, br), 1632 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz) δ 9.68 (s, 1H), 6.06 (s, 1H), 5.46 (s, 1H), 4.12 (q, 2H, J = 7.1 Hz), 2.39 (td, 2H, J = 7.2, 1.6 Hz), 2.25 (t, 2H, J = 7.4 Hz), 1.59−1.43 (m, 4H), 1.22 (t, 3H, J = 7.2 Hz). ^{13}C-NMR ($CDCl_3$, 50 MHz) δ 202.4, 167.2, 140.5, 124.8, 60.7, 43.7, 31.7, 28.0, 21.7, 14.3. MS (EI): 155 (8), 14 (36), 138 (53). Anal. Calcd for $C_{10}H_{16}O_3$: C, 65.20; H, 8.75. Found: C, 64.92; H, 8.96.

5-Oxo-5-phenylpentanal (5b): yield (0.83 g, 68%). Prepared using benzoyl chloride (0.98 g, 7 mmol) and the zinc reagent **2a** (ca. 8 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −20 °C, 6 h. Purification by column chromatography (hexanes:t-BuOMe 4:1). IR (neat): 3062 (w), 2939 (m), 2827 (m), 2726 (m), 1723 (vs), 1684 (vs), 1597 (m), 1449 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz) δ 9.66 (s, 1H), 7.83−7.80 (m, 2H), 7.43−7.33 (m, 3H), 2.91 (t, 2H, J = 7.0 Hz), 2.43 (t, 2H, J = 7.1 Hz), 2.00−1.85 (m, 2H). ^{13}C-NMR ($CDCl_3$, 75 MHz) δ 201.9, 199.4, 136.9, 133.2, 128.7, 128.1, 43.1, 37.4, 16.7. MS (EI): 176 (M^+, 5), 148 (18), 120 (21), 105 (100). Anal. Calcd for $C_{11}H_{12}O_2$: C, 74.98; H, 6.86. Found: C, 74.72; H, 7.00.

Ethyl 2-(5-oxoheptyl)acrylate (5c): yield (0.67 g, 70%). Prepared using ethyl (2-bromomethyl)acrylate[15] (0.86 g, 4.5 mmol) and the zinc reagent **2c** (ca. 5.2 mmol). Reaction conditions: −78 °C to 25 °C, 3 h. Purification by column chromatography (hexanes:t-BuOMe 9:1). IR (neat): 2939 (s), 1715 (vs), 1632 (m), 1369 (w) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 5.99 (s, 1H), 5.39 (s, 1H), 4.06 (q, 2H, J = 7.2 Hz), 2.29 (q, 4H, J = 6.9 Hz), 2.17 (t, 2H, J = 7.1 Hz), 1.52−1.28 (m, 4H), 1.16 (t, 3H, J = 7.1 Hz), 0.91 (t, 3H, J = 7.4 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 210.9, 166.8, 140.4, 124.1, 60.2, 41.7, 35.5, 31.4, 27.7, 23.1, 13.9, 7.5. MS (EI): 212 (M^+, 15), 167 (19), 141 (48). Anal. Calcd for $C_{12}H_{20}O_3$: C, 67.89; H, 9.50. Found: C, 67,79; H, 9.70.

1-Phenyl-1,5-heptadione (5d): yield (0.75 g, 74%). Prepared using benzoyl chloride (0.70 g, 5 mmol) and the zinc reagent **2c** (ca. 5.6 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −20 °C, 6 h. Purification by column chromatography (hexanes:EtOAc 85:15). IR (neat): 3060 (w), 2965 (m), 1708 (vs), 1675 (vs), 1448 (s), 1270 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 7.87−7.84 (m, 2H), 7.45−7.35 (m, 3H), 2.91 (t, 2H, J = 7.1 Hz), 2.44 (t, 2H, J = 7.1 Hz), 2.32 (q, 2H, J = 7.3 Hz), 1.96−1.86 (m, 2H), 0.95 (t, 3H, J = 7.3 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 210.9, 199.6, 136.8, 132.9, 128.5, 127.9, 41.1, 37.4, 35.8, 18.3, 7.7. MS (EI): 204 (M^+, 11), 147 (13), 120 (27), 105 (100). Anal. Calcd for $C_{13}H_{16}O_2$: C, 76.44; H, 7.89. Found: C, 76.74; H, 8.12.

3-(4-Oxohexyl)-2-cyclohexen-1-one (5e): yield (0.96 g, 76%). Prepared using 3-iodo-2-cyclohexen-1-one[17] (1.44 g, 6.5 mmol) and the zinc reagent **2c** (ca. 7.3 mmol). Reaction conditions: −78 °C to −30 °C, 1 h, and then −30 °C, 4 h. Purification by column chromatography (hexanes:EtOAc 4:1). IR (neat): 2939 (s), 1713 (s), 1669 (vs), 1625 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 5.78 (s, 1H), 2.40−2.12 (m, 10H), 1.96−1.87 (m, 2H) 1.78−1.68 (m, 2H), 0.98 (t, 3H, J = 7.3 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 210.6, 199.7, 165.5, 126.0, 41.2, 37.3, 36.0, 29.5, 22.7, 20.8, 7.8. MS (EI): 194 (M^+, 24), 137 (13), 123 (100), 110 (24). Anal. Calcd for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.24; H, 9.60.

Ethyl 7-oxo-2-nonenoate (5f): yield (0.95 g, 69%). Prepared using ethyl propiolate (0.69 g, 7 mmol) and the zinc reagent **2c** (ca. 8 mmol). Reaction conditions: −78 °C to −30 °C, 1 h, and then −30 °C, 5 h. Purification by column chromatography (hexanes:t-BuOMe 4:1). IR (neat): 2939 (m), 1717 (vs), 1655 (s), 1368 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 6.86−6.76 (m, 1H), 5.70 (d, 1H, J = 15.7 Hz), 4.06 (q, 2H, J = 7.1 Hz), 2.32 (q, 4H, J = 8.1 Hz), 2.14−2.05 (m, 2H), 1.70−1.60 (m, 2H), 1.18 (t, 3H, J = 6.9 Hz), 0.94 (t, 3H, J = 7.3 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 210.4, 166.2, 147.8, 121.8, 59.9, 40.9, 35.7, 31.2, 21.8, 14.0, 7.5. MS (EI): 198 (M^+, 5), 187 (15), 152 (29), 114 (17). Anal. Calcd for $C_{11}H_{18}O_3$: C, 66.64; H, 9.15. Found: C, 66.64; H, 9.35.

Ethyl 2-[(3′-oxocyclohexyl)methyl]acrylate (5g): yield (1.22 g, 83%). Prepared using ethyl 2-(bromomethyl)acrylate[15] (1.34 g, 7 mmol) and the zinc reagent **2d** (ca. 8 mmol). Reaction conditions: −78 °C to 25 °C, 3 h. Purification by

column chromatography (hexanes:t-BuOMe (90:10). IR (neat): 3104 (w), 2935 (vs), 1712 (vs, br), 1629 (s), 1448 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 6.04 (s, 1H), 5.42 (s, 1H), 4.04 (q, 2H, J = 7.1 Hz), 2.79–2.73 (m, 1H), 2.44–2.42 (m, 1H), 2.24–2.16 (m, 3H), 2.00–1.90 (m, 3H), 1.71–1.70 (m, 1H), 1.54–1.48 (m, 2H), 1.17 (t, 3H, J = 7.2 Hz). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 211.6, 166.8, 138.6, 126.4, 60.4, 49.2, 42.0, 33.5, 31.9, 27.9, 24.9, 14.0. MS (EI): 210 (M^+, 16), 164 (84), 136 (100), 122 (28). Anal. Calcd for $C_{12}H_{18}O_3$: C, 68.55; H, 8.63. Found: C, 68.32; H, 8.60.

3-Benzoylcyclohexanone (5h): yield (1.06 g, 75%). Prepared using benzoyl chloride (0.98 g, 7 mmol) and the zinc reagent **2d** (ca. 8 mmol). Reaction conditions: −78 °C to −20 °C, 1 h, and then −20 °C, 6 h. Purification by column chromatography (hexanes:EtOAc 9:1). IR (neat): 3060 (w), 2936 (m), 1710 (vs), 1675 (vs), 1597 (w), 1444 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz): δ 7.85–7.80 (m, 2H), 7.49–7.37 (m, 3H), 4.34–4.27 (m, 1H), 2.48–1.56 (m, 8H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 208.8, 197.8, 136.8, 133.5, 128.9, 59.0, 42.5, 30.2, 27.5, 23.3. MS (EI): 202 (M^+, 41), 174 (10), 105 (100). Anal. Calcd for $C_{13}H_{14}O_2$: C, 77.20; H, 6.98. Found: C, 77.25; H, 6.93.

Catalytic Asymmetric Addition of Bis[(3*E*)-4-(triisopropylsiloxy)-3-butenyl]zinc (2b) to Various Aldehydes. Typical Procedure. (*S*)-(*E*)-5-Phenyl-1-(triisopropylsiloxy)-1-penten-5-ol (8a) (entry 1 of Table 2). (a) Hydroboration. A 50 mL two-necked flask equipped with an argon inlet and a rubber septum was charged under argon with (*E*)-1-(triisopropylsiloxy)-1,3-butadiene (**1b**) (1.13 g; 5.0 mmol). Diethylborane (0.52 g; 5.6 mmol) was added at 0 °C over 10 min. The reaction mixture was warmed to 35 °C and stirred for 6 h at this temperature. The volatiles were evaporated under vacuum (0.7 mmHg) affording the crude hydroboration product.

(b) Boron–Zinc Exchange. To the organoborane prepared above was added diethylzinc (1.0 mL; 10 mmol) at 0 °C. After 20 min, the excess diethylzinc and formed triethylborane were evaporated (0.7 mmHg, rt, 10 h). The resulting dialkylzinc **2b** was diluted with ether (3 mL) and was ready to use for the next step.

(c) Asymmetric Addition. The catalyst (1*R*,2*R*)-1,2-bis(trifluoromethanesulfonamido)cyclohexane (**6**) (30 mg; 0.08 mmol) was dissolved in a mixture of ether (1 mL) and titanium(IV) isopropoxide (0.57 g; 2.0 mmol), and the solution was cooled to −60 °C. The dialkylzinc **2b** prepared above was added via syringe within 15 min. After stirring the green reaction mixture at −60 °C for 20 min, it was warmed to −20 °C and stirred an additional 10 min. Benzaldehyde (120 mg; 1.13 mmol) was added and allowed to react for 10 h. Aqueous workup (brine, 30 mL), extraction, drying, and evaporation of the solvent afforded the crude product which was purified by chromatography (hexanes–ether 8:1) leading to the analytically pure secondary alcohol **8a** (291 mg; 0.87 mmol; 77%) as a clear oil. The enantiomeric excess was determined by preparing the corresponding *O*-acetylmandelate using (*S*)-(+)-*O*-acetylmandelic acid.[19]

$[\alpha]_D$ = −6.6 (*c* = 2.74, $CHCl_3$). IR (neat): 3360 (m, br), 3030 (w), 2920 (vs), 1660 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz): δ 7.30–7.21 (m, 5H); 6.30 (d, 1H, J = 11.8 Hz); 4.97 (dt, 1H, J = 11.8, 7.3 Hz); 4.62 (t, 1H, J = 5.4 Hz); 2.22 (s, br, 1H); 1.95–1.50 (m, 4H); 1.20–1.00 (m, 21 H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 144.7, 141.1, 128.3 (2C), 127.4, 125.8 (2C), 110.1, 73.8, 39.6, 23.7, 17.7 (6C), 11.9 (3C). EI-MS (70 eV): 291 (50), 187 (17), 131 (100). Anal. Calcd for $C_{20}H_{34}O_2Si$: C, 71.80; H, 10.24. Found: C, 71.79; H, 10.37. (*S*)-(+)-*O*-Acetylmandelate derivative: the doublet at 6.28 ppm was integrated against the doublet at 6.03 ppm. Ratio >98:<2.

(*S*)-(*E*)-7-Methyl-1-(triisopropylsiloxy)-1-octen-5-ol (8b): prepared from (*E*)-1-(triisopropylsiloxy)-1,3-butadiene (**1b**) (1.09 g; 4.81 mmol) and 3-methylbutanal (79 mg; 0.92 mmol). Yield: 174 mg, 60% (clear oil). Chromatography solvent: hexanes–ether 8:1. $[\alpha]_D$ = +5.5 (*c* = 3.08, $CHCl_3$). IR (neat): 3360 (m, br), 3030 (w), 2930 (vs), 1660 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz): δ 6.32 (d, 1H, J = 11.8 Hz); 4.98 (dt, 1H, J = 11.8, 7.5 Hz); 3.70–3.50 (m, 1H); 2.00–1.00 (m, 29H); 0.88 (d, 3H, J = 6.8 Hz), 0.87 (d, 3H, J = 6.5 Hz). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 140.9, 110.5, 69.3, 46.7, 38.6, 24.5, 23.6, 23.5, 22.0, 17.7 (6C), 11.9 (3C). EI-MS (70 eV): 271 (65), 187 (22). Anal. Calcd for $C_{18}H_{38}O_2Si$: C, 68.73; H, 12.17. Found: C, 68.73; H, 12.19. (*S*)-(+)-*O*-Acetylmandelate derivative: the doublet at 6.28 ppm was integrated against the doublet at 5.98 ppm. Ratio 96:4.

(*R*)-(*E*)-1-(Triisopropylsiloxy)-1-decen-5-ol (8c): prepared from (*E*)-1-(triisopropylsiloxy)-1,3-butadiene (**1b**) (1.09 g; 4.81 mmol) and hexanal (86 mg; 0.86 mmol). Yield: 186 mg, 66% (clear oil). Chromatography solvent: hexanes–ether 8:1. $[\alpha]_D$ = 0.0 (*c* = 3.12, $CHCl_3$). IR (neat): 3320 (m, br), 2930 (vs), 1660 (m) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz): δ 6.32 (d, 1H, J = 11.8 Hz); 4.98 (dt, 1H, J = 11.8, 7.5 Hz); 3.57 (s, br, 1H); 2.04–1.87 (m, 2H); 1.50–1.00 (m, 32H); 0.86 (t, br, 3H, J = 6.4 Hz). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 140.9, 110.5, 71.4, 38.0, 37.4, 31.9, 25.3, 23.6, 22.6, 17.7 (6C), 14.0, 12.0 (3C). EI-MS (70 eV): 285 (72), 187 (21), 131 (100). Anal. Calcd for $C_{19}H_{40}O_2Si$: C, 69.45; H, 12.27. Found: C, 69.31; H, 12.49. (*S*)-(+)-*O*-Acetylmandelate derivative: the doublet at 6.24 ppm was integrated against the doublet at 5.98 ppm. Ratio 95.5:4.5.

(*S*)-(1*E*,6*E*)-1-Phenyl-7-(triisopropylsiloxy)-1,6-heptadien-3-ol (8d): prepared from (*E*)-1-(triisopropylsiloxy)-1,3-butadiene (**1b**) (1.15 g; 5.08 mmol) and (*E*)-3-phenyl-2-propenal (126 mg; 0.95 mmol). Only 426 mg (1.50 mmol, 1.5 equiv instead of 2 equiv as usual) $Ti(Oi\text{-}Pr)_4$ was used in the addition step. Yield: 190 mg, 55% (clear oil). Chromatography solvent: hexanes–ether 8:1. $[\alpha]_D$ = +20.3 (*c* = 3.99, $CHCl_3$). IR (neat): 3320 (m, br), 3025 (w), 2930 (vs), 1660 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 200 MHz): δ 7.27–7.11 (m, 5H); 6.44 (d, 1H, J = 16.0 Hz); 6.24 (d, 1H, J = 12.0 Hz); 6.12 (dd, 1H, J = 15.8, 6.6 Hz); 4.90 (dt, 1H, J = 11.8, 7.4 Hz); 4.20–4.16 (m, 1H); 1.90 (q, br, 2H, J = 8.1 Hz); 1.68 (d, 1H, J = 3.4 Hz); 1.65–1.50 (m, 2H); 1.09–0.93 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 141.1, 136.7, 132.4, 130.2, 128.5 (2C), 127.6, 126.4 (2C), 110.1, 72.4, 37.9, 23.4, 17.7 (6C), 11.9 (3C). EI-MS (70 eV): 360 (M^+, 1), 317 (35), 169 (18), 131 (100), 103 (52). Anal. Calcd for $C_{22}H_{36}O_2Si$: C, 73.28; H, 10.06. Found: C, 73.41; H, 10.09. (*S*)-(+)-*O*-Acetylmandelate derivative: the multiplet at 4.97 ppm was integrated against the multiplet at 4.81 ppm. Ratio 92.5:7.5.

(*S*)-(1*E*,6*E*)-6-Methyl-1-(triisopropylsiloxy)-1,6-octadien-5-ol (8e): prepared from (*E*)-1-(triisopropylsiloxy)-1,3-butadiene (**1b**) (0.98 g; 4.34 mmol) and (*E*)-2-methyl-2-butenal (86 mg; 1.00 mmol). Yield: 140 mg, 45% (clear oil). Chromatography solvent: hexanes–ether 8:1. $[\alpha]_D$ = 0.0 (*c* = 1.54, $CHCl_3$). IR (neat): 3330 (m, br), 3030 (w), 2940 (vs), 1660 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 6.31 (dt, 1H, J = 11.8, 1.2 Hz); 5.47–5.40 (m, 1H); 4.98 (dt, 1H, J = 11.8, 7.5 Hz); 3.99 (t, 1H, J = 6.7 Hz); 1.85–1.80 (m, 2H); 1.60–1.51 (m, 8H); 1.45 (s, br, 1H); 1.17–1.01 (m, 21H). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 141.0, 137.9, 120.7, 110.4, 77.3, 35.6, 23.7, 17.7 (6C), 13.0, 12.0 (3C), 10.9. EI-MS (70 eV): 294 (5), 269 (21), 251 (10), 157 (28), 131 (100), 103 (74). Anal. Calcd for $C_{18}H_{36}O_2Si$: C, 69.17; H, 11.61. Found: C, 68.96; H, 11.46. (*S*)-(+)-*O*-Acetylmandelate derivative: the doublet at 6.26 ppm was integrated against the doublet at 6.03 ppm. Ratio >98:<2.

Preparation of Racemic 8a and 8b by Reduction of 4c and 4d. Typical Procedure. (±)-(*E*)-5-Phenyl-1-(triisopropylsiloxy)-1-penten-5-ol (8a). An ether (5 mL) solution of the ketone **4c** (0.67 g, 2.0 mmol) was added dropwise to a suspension of lithium aluminum hydride (40 mg, 1 mmol) in ether (10 mL) at rt. The reaction mixture was kept at reflux for 4 h and worked up as usual affording after evaporation of the solvents a crude residue which was purified by column chromatography (hexanes:EtOAc 85:15) providing the alcohol **8a** (560 mg, 84% yield).

(±)-(*E*)-5-Cyclopropyl-1-(triisopropylsiloxy)-1-penten-5-ol (8f). Obtained as described above (460 mg, 77% yield) by the reduction of ketone **4d** (590 mg, 2.0 mmol) with lithium aluminum hydride (40 mg, 1 mmol). IR (neat): 3379 (bs), 3005 (m), 2944 (s), 1663 (s), 1465 (s) cm^{-1}. ^1H-NMR ($CDCl_3$, 300 MHz): δ 6.28 (d, 1H, J = 11.8 Hz), 4.98–4.89 (m, 1H), 2.83–2.76 (m, 1H), 2.00–1.95 (m, 2H), 1.60–1.52 (m, 2H), 1.10–0.96 (m, 21H), 0.84–0.78 (m, 1H), 0.46–0.40 (m, 2H), 0.18–0.14 (m, 2H). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 140.8, 110.5, 76.1,

(19) Parker, D. J. *Chem. Soc., Perkin Trans.* 2 **1983**, 83.

37.8, 23.5, 17.8, 17.6, 11.9, 2.6, 2.4. MS (EI): 298 (M^+, 5), 255 (60), 187 (21), 131 (100), 103 (59), 81 (19). Anal. Calcd for $C_{17}H_{34}O_2Si$: C, 68.40; H, 11.48. Found: C, 68.48; H, 11.49.

Oxidative Cyclization of the Alcohols 8a,b to the Tetrahydropyrans 9a,b. Typical Procedure. (−)-3(*R*)-Hydroxy-6(*S*)-phenyl-2(*S*)-(triisopropylsiloxy)tetrahydropyran (9a). A suspension of vanadyl acetylacetonate (13 mg, 0.05 mmol) and the alcohol **8a** (0.34 g, 1 mmol) in dry hexanes (10 mL) was stirred at rt for 5 min. *tert*-Butyl hydroperoxide (0.61 mL, 3.3 M solution in toluene, 2 mmol) was added, and the resulting dark red solution was stirred for 8 h and then treated with an 5% aqueous solution of $Na_2S_2O_3$ (10 mL). The organic layer was separated, and the aqueous layer was extracted with ether (2 × 20 mL). The combined organic layer was washed with water (15 mL) and brine (25 mL) and dried (Na_2SO_4), and the solvents were evaporated. The crude residue was purified by column chromatography (hexanes:EtOAc 4:1) affording two separable products: the tetrahydropyran **9a** (300 mg, 86% yield) and the diastereomeric tetrahydropyran **10a** (5.3 mg; 1.5% yield). By performing the oxidative ring closure using MCPBA (2 mmol) in dichloromethane a 1:1 mixture of **9a** and **10a** is obtained.

Analytical Data of the Tetrahydropyrans 9a,b and 10a. (−)-3(*R*)-Hydroxy-6(*S*)-phenyl-2(*S*)-(triisopropylsiloxy)tetrahydropyran (9a): $[\alpha]^{25}_D$ = −89.8 (*c* = 6.09, $CHCl_3$). IR (neat): 3473 (m, br) 3031 (w), 2944 (vs), 1463 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 7.26−7.16 (m, 5H), 4.59 (d, 1H, *J* = 7.2 Hz), 4.42 (dd, 1H, *J* = 10.7, 2.4 Hz), 3.40−3.35 (m, 1H), 2.27 (s, 1H), 2.11−2.09 (m, 1H), 1.90−1.86 (m, 1H), 1.62−1.57 (m, 2H), 1.12−0.95 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 142.1, 128.6, 127.6, 126.0, 100.9, 78.3, 72.5, 33.8, 29.9, 18.4, 18.3, 12.7. MS (EI): 307 (20), 187 (35), 159 (49), 117 (86), 104 (100). Anal. Calcd for $C_{20}H_{34}O_3Si$: C, 68.52; H, 9.78. Found: C, 68.62; H, 9.89.

3(*S*)-Hydroxy-6(*S*)-phenyl-2(*R*)-(triisopropylsiloxy)tetrahydropyran (10a): IR (neat): 3360 (s, br), 3031 (w), 2939 (s), 1605 (w), 1495 (m), 1463 (m) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 7.31−7.15 (m, 5H), 5.12 (s, 1H), 4.95 (dd, 1H, *J* = 11.6, 2.6 Hz), 3.60−3.56 (m, 1H), 2.32−2.00 (m, 2H), 1.95−1.72 (m, 3H), 1.08−0.94 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 142.9, 128.7, 127.7, 126.4, 95.2, 70.5, 67.8, 27.4, 25.5, 18.3, 12.4. MS (EI): 307 (23), 289 (26), 187 (31), 159 (58), 131 (37), 117 (88), 104 (100). Anal. Calcd for $C_{20}H_{34}O_3Si$: C, 68.52; H, 9.78. Found: C, 68.41; H, 9.68.

3(*S)-Hydroxy-6(*R**)-cyclopropyl-2(*R**)-(triisopropylsiloxy)tetrahydropyran (9b):** obtained as described above (260 mg, 83% yield) by using alcohol **8f** (300 mg, 1.0 mmol), vanadyl acetylacetonate (13 mg, 0.05 mmol), TBHP (0.61 mL, 3.3 M solution in toluene, 2 mmol) in dry hexanes. Reaction conditions: 8 h, rt. Purification by column chromatography (hexanes:t-BuOMe 4:1). IR (neat): 3476 (s, br), 3082 (w), 2943 (vs), 1465 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 300 MHz): δ 4.32 (d, 1H, *J* = 7.3 Hz), 3.27−3.22 (m, 1H), 2.73−2.66 (m, 1H), 2.15 (d, 1H, *J* = 1.6 Hz), 1.93−1.83 (m, 1H), 1.78−1.67 (m, 1H), 1.50−1.46 (m, 2H), 1.11−0.96 (m, 21H), 0.85−0.80 (m, 1H), 0.42−0.36 (m, 2H), 0.22−0.12 (m, 2H). ^{13}C-NMR ($CDCl_3$, 75 MHz): δ 99.9, 80.1, 72.2, 30.3, 29.0, 17.6, 15.2, 12.2, 2.8, 1.8. MS (EI): 271 (54), 203 (33), 187 (44), 159 (94), 131 (49). Anal. Calcd for $C_{17}H_{34}O_3Si$: C, 64.92; H, 10.89. Found: C, 64.92; H, 10.86.

Iodocyclization of the Alcohol 8a. Preparation of 3-Iodo-6(*S*)-phenyl-2-(triisopropylsiloxy)tetrahydropyran (11). An ether solution (5 mL) of the alcohol **8a** (670 mg, 2 mmol) was added dropwise to a suspension of iodine (530 mg, 2.1 mmol) and K_2CO_3 (550 mg, 4 mmol) in ether (10 mL) at −78 °C. After 1.5 h of stirring at −78 °C, the reaction mixture was quenched with an aqueous solution (5%) of $Na_2S_2O_3$ (15 mL). The organic layer was separated, and the aqueous layer was extracted with ether (2 × 20 mL). The combined organic layer was washed with brine and dried (Na_2SO_4), and the solvents were evaporated. The crude residue was purified by chromatography (hexanes:t-BuOMe 95:5) affording the iodide **11** (720 mg, 78% yield) as a mixture of diastereomers (4:1). IR (neat): 3031 (w), 2943 (vs), 2892 (s), 1605 (w), 1463 (s) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 7.26−7.14 (m, 5H), 4.94 (d, 1H, *J* = 8.4 Hz), 4.50 (dd, 1H, *J* = 9.8, 3.7 Hz), 3.98−3.85 (m, 1H), 2.54−2.41 (m, 1H), 2.33−2.27 (m, 1H), 1.63−1.58 (m, 2H), 1.09−0.95 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 142.8, 141.9, 128.8, 127.8, 126.8, 126.0, 100.6, 95.8, 78.9, 71.5, 37.6, 37.5, 33.3, 32.7, 29.9, 27.7, 18.6, 18.2, 12.8, 12.5. MS (EI): 417 (95), 291 (46), 159 (31), 131 (55), 117 (82), 104 (100). Anal. Calcd for $C_{20}H_{33}O_2ISi$: C, 52.17; H, 7.22. Found: C, 52.40; H, 7.46.

Preparation of 6(*S*)-Phenyl-2-(triisopropylsiloxy)-5,6-dihydro-2*H*-pyran (12). The iodide **11** (0.46 g, 1 mmol) and DBU (0.46 g, 3 mmol) were dissolved in toluene (10 mL). The reaction mixture was refluxed for 2 d, poured into hexanes (50 mL), washed with H_2O (20 mL) and brine (20 mL), and dried ($MgSO_4$), and the solvents were evaporated. The crude residue was purified by column chromatography (hexanes:t-BuOMe 95:5) affording **12** (250 mg, 75% yield) as a *cis*:*trans* mixture (ca. 7:3). IR (neat): 3065 (w), 3039 (m), 2961(s), 1604 (w), 1657 (w) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 7.30−7.14 (m, 6H), 5.72−5.56 (m, 3H), 4.74−4.34 (m, 1H), 2.23−2.15 (m, 2H), 1.11−0.95 (m, 21H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 142.9, 142.6, 131.0, 128.6, 128.0, 127.6, 127.4, 126.4, 125.8, 94.0, 90.1, 74.5, 68.7, 33.3, 33.0, 18.4, 18.3, 12.8, 12.6. MS (EI): 289 (100), 183 (66), 141 (28), 113 (24). Anal. Calcd for $C_{20}H_{32}O_2Si$: C, 72.23; H, 9.70. Found: C, 71.98; H, 9.80.

(−)-6(*S*)-Phenyl-5,6-dihydro-2*H*-pyran-2-one (13). To a solution of **12** (0.33 g, 1 mmol) in acetone (5 mL) was added at 0 °C the Jones reagent (3 mL; prepared from $Na_2Cr_2O_7$ (5.4 g), concd H_2SO_4 (9.5 mL) and H_2O (38 mL) at 0 °C). The reaction mixture was stirred for 1.5 h at 0 °C and treated with i-PrOH (5 mL). The upper layer was decanted, and the green residue was washed with acetone (2 × 10 mL). The combined organic phase was poured into water (50 mL) and washed with diluted aqueous $NaHCO_3$ solution until pH = 7 was reached. The aqueous layer was extracted with $CHCl_3$ (2 × 40 mL). The combined organic phase was washed with brine and dried ($MgSO_4$), and the solvents were evaporated. The crude residue was purified by bulb to bulb distillation (bp_1 = 110 °C) affording the pure lactone **13** (120 mg, 71% yield). $[\alpha]^{25}_D$ = −210 (*c* = 3.50, $CHCl_3$). IR (neat): 3064 (w), 3036 (w), 2924 (s), 1720 (vs), 1635 (w), 1604 (w) cm^{-1}. ^{1}H-NMR ($CDCl_3$, 200 MHz): δ 7.37−7.31 (m, 5H), 6.91−6.89 (m, 1H), 6.11−6.05 (m, 1H), 5.44−5.36 (m, 1H), 2.62−2.55 (m, 2H). ^{13}C-NMR ($CDCl_3$, 50 MHz): δ 164.5, 145.4, 138.9, 129.0, 126.5, 122.0, 79.7, 32.1. MS (EI): 174 (M^+, 7), 105 (5). Anal. Calcd for $C_{11}H_{10}O_2$: C, 75.85; H, 5.79. Found: C, 75.76; H, 5.93.

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Supplementary Material Available: Copies of ^{1}H and ^{13}C NMR spectra of all compounds (67 pages). This material is contained in libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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