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Articles

Stereoselective Synthesis of (*Z*)- and (*E*)-Allylic Silanes by Copper-Mediated Substitution Reactions of Allylic Carbamates with Grignard Reagents

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Both (*Z*)- and (*E*)-allylic silanes were prepared with high stereoselectivity by the copper-mediated substitution of allylic carbamates by organometallic reagents. The reaction of alkylmagnesium reagents with (*E*)-allylic carbamates provides (*Z*)-allylic silanes, whereas both alkylmagnesium and alkyllithium reagents react with (*Z*)-allylic carbamates to afford (*E*)-allylic silanes. Because Grignard reagents are often more facile to prepare than alkyllithium species, these reagents are the optimal nucleophiles for the synthesis of both (*Z*)- and (*E*)-allylic silanes. This method also allows readily available nonracemic allylic carbamates to be converted to chiral, nonracemic (*Z*)- and (*E*)-allylic silanes with high stereoselectivity.

Introduction

Allylic silanes are important reagents for the stereoselective construction of carbon−carbon bonds.[1] The Hosomi−Sakurai allylation reaction[2,3] and annulation reactions (both [3 + 2][4−6] and [2 + 2][7−9]) provide access to acyclic and cyclic products, respectively, with control of stereochemistry. The structure of the allylic silane determines the course of the reaction and the stereochemistry of the product. The nature of the silicon group controls whether the silyl group is eliminated from an intermediate β-silyl carbocation (leading to allylation) or whether the silicon group is retained (resulting in annulation).[4,10] Annulation reactions can be stereospecific with respect to the olefin geometry of the allylic silane, with (*E*)- and (*Z*)-allylic silanes leading to diastereomeric products.[9,11,12] Because allylic silane structure is closely related to the efficiency and stereochemistry of annulation reactions, the syntheses of these compounds must be flexible to permit optimization of annulation processes. Although many syntheses of allylic silanes have been

(1) For a review discussing the use of chiral allylsilanes in synthesis, see: Masse, C. E.; Panek, J. S. *Chem. Rev.* **1995**, *95*, 1293−1316.
(2) Hosomi, A.; Sakurai, H. *Tetrahedron Lett.* **1976**, *17*, 1295−1298.
(3) Fleming, I.; Dunogues, J.; Smithers, R. *Org. React.* **1989**, *37*, 57−574 and references therein.
(4) For a review on [3 + 2] annulation reactions of allyltriisopropylsilane, see: Knölker, H.-J. *J. Prakt. Chem.* **1997**, *339*, 304−314.
(5) Groaning, M. D.; Brengel, G. P.; Meyers, A. I. *J. Org. Chem.* **1998**, *63*, 5517−5522.
(6) Akiyama, T.; Yamanaka, M. *Tetrahedron Lett.* **1998**, *39*, 7885−7888.
(7) Akiyama, T.; Kirino, M. *Chem. Lett.* **1995**, 723−724.
(8) Akiyama, T.; Yamanaka, M. *Synlett* **1996**, 1095−1096.
(9) Knölker, H.-J.; Baum, E.; Schmitt, O. *Tetrahedron Lett.* **1998**, *39*, 7705−7708.
(10) Akiyama, T.; Ishikawa, K.; Ozaki, S. *Chem. Lett.* **1994**, 627−630.
(11) Danheiser, R. L.; Takahashi, T.; Bertók, B.; Dixon, B. R. *Tetrahedron Lett.* **1993**, *34*, 3845−3848.
(12) Roberson, C. W.; Woerpel, K. A. *J. Org. Chem.* **1999**, *64*, 1434−1435.
(13) For a review of methods for the synthesis of allylsilanes, see: Sarkar, T. K. *Synthesis* **1990**, 969−983. Sarkar, T. K. *Synthesis* **1990**, 1101−1111.
(14) For a method to prepare enantiomerically enriched (*E*)-allylic silanes, see: Suginome, M.; Matsumoto, A.; Ito, Y. *J. Am. Chem. Soc.* **1996**, *118*, 3061−3062.

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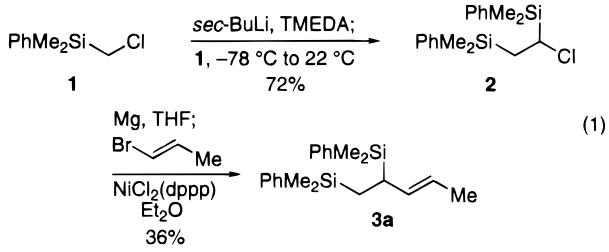
reported,[13,14] a general route that permits facile variation of the structure (including the nature of the silyl substituent, olefin geometry, and absolute stereochemistry) is lacking.

As part of our program investigating the [3 + 2] annulation reactions of allylic silanes,[12] we required a stereo- and regioselective synthesis of silylmethyl-substituted allylic silanes. Our initial experiments revealed that standard methods for the synthesis of allylic silanes gave low yields when applied to these structures. The copper-mediated allylic displacement of carbamates by organometallic reagents,[15,16] however, proved to be a general route for the synthesis of these compounds. The reaction of alkylmagnesium reagents with (*E*)-allylic carbamates provided (*Z*)-allylic silanes, whereas both alkylmagnesium and alkyllithium reagents reacted with (*Z*)-allylic carbamates to afford (*E*)-allylic silanes. We report here the details of our allylic displacement method, which can be applied to the synthesis of chiral, nonracemic (*Z*)-[17] and (*E*)-allylic silanes with high enantioselectivity.

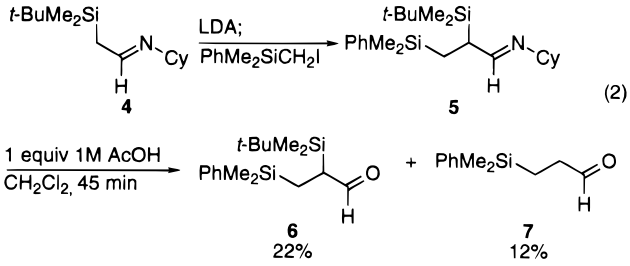
Results and Discussion

Initial Approaches to Silylmethyl-Substituted Allylic Silanes. Our first approach to silylmethyl-substituted allylic silanes such as **3** relied upon Hayashi−Kumada coupling of Grignard reagents with vinyl halides (eq 1).[18,19] This route was attractive because both (*E*)- and (*Z*)-allylic silanes would be available by choice of the appropriate vinyl halide coupling partner. Nickel and palladium couplings of (silylmethyl)methylmagnesium halides with vinyl halides have been used successfully for the synthesis of unsubstituted allyl- and crotylsilanes,[20,21] and the coupling of secondary silyl-substituted Grignard reagents by the Hayashi protocol has been demonstrated in a few examples.[19,22,23]

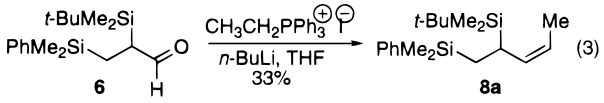
The metal-catalyzed coupling reaction was unsuccessful for the formation of the desired allylic silanes. Chloride **2**, the Grignard precursor, was prepared by deprotonation of (chloromethyl)dimethylphenylsilane (**1**) with *sec*-butyllithium[24] followed by addition of a second equivalent of **1** (eq 1). Treatment of the Grignard reagent generated from chloride **2** with *trans*-3-bromopropene in the presence of a nickel catalyst afforded the coupling product **3a** in low yield (eq 1). The other products of the reaction arose from protonation of the Grignard reagent and from β-hydride elimination after transmetalation of the Grignard reagent from magnesium to nickel. All attempts to increase the yield by varying catalyst, temperature, and solvent failed.



We next focused on the synthesis of allylic silanes by a Wittig reaction of an α-silylaldehyde,[25] which was prepared from imine **4**[26] (eq 2). Deprotonation of **4** with LDA followed by addition of (iodomethyl)dimethylphenylsilane gave disilylimine **5**, which was separated from lower boiling impurities by bulb-to-bulb distillation and subjected to hydrolysis without further purification (eq 2). Upon hydrolysis[26] of **5**, a mixture of the desired aldehyde **6** and α-desilylated aldehyde **7** was obtained. Extensive variation of hydrolysis conditions did not increase the yield of **6** above 22%.



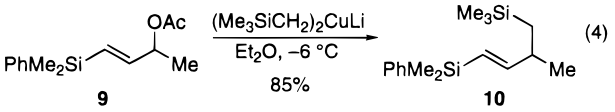
Addition of aldehyde **6** to a solution of the ylide generated from ethyltriphenylphosphonium iodide afforded the allylic silane **8a** in low yield (33%) with high (*Z*)-selectivity (*E*/*Z* = 4:96, eq 3). Considering the low yield obtained upon imine hydrolysis, the Wittig reaction was not optimized, and production of allylic silanes by this route was abandoned.



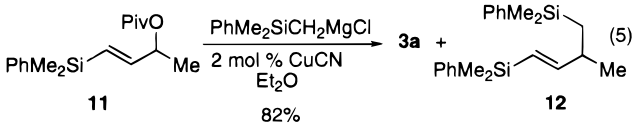
Development of the Allylic Displacement Route. The copper-mediated substitution of allylic derivatives has been used for the synthesis of (*E*)-allylic silanes[27,28] and appeared to be a viable route to **3**. Inspection of the requisite vinyl silane **9** (eq 4), however, revealed a potential problem. Allylic acetate **9** bears a methyl group α to the leaving group and a bulky silyl-group at the γ-position. Reaction of **9** would be expected to occur with delivery of the nucleophile to the less hindered allylic terminus,[29] which in this case is the α-position. Indeed,

(15) Gallina, C.; Ciattini, P. G. *J. Am. Chem. Soc.* **1979**, *101*, 1035−1036.
(16) Goering, H. L.; Kantner, S. S.; Tseng, C. C. *J. Org. Chem.* **1983**, *48*, 715−721.
(17) Smitrovich, J. H.; Woerpel, K. A. *J. Am. Chem. Soc.* **1998**, *120*, 12998−12999.
(18) Tamao, K.; Sumitani, K.; Kiso, Y.; Zembayashi, M.; Fujioka, A.; Kodama, S.; Nakajima, I.; Minato, A.; Kumada, M. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 1958−1969.
(19) Hayashi, T.; Konishi, M.; Okamoto, Y.; Kabeta, K.; Kumada, M. *J. Org. Chem.* **1986**, *51*, 3772−3781.
(20) Hayashi, T.; Kabeta, K.; Hamachi, I.; Kumada, M. *Tetrahedron Lett.* **1983**, *24*, 2865−2868.
(21) Organ, M. G.; Murray, A. P. *J. Org. Chem.* **1997**, *62*, 1523−1526.
(22) Hayashi, T.; Konishi, M.; Ito, H.; Kumada, M. *J. Am. Chem. Soc.* **1982**, *104*, 4962−4963.
(23) Tamao, K.; Iwahara, T.; Kanatani, R.; Kumada, M. *Tetrahedron Lett.* **1984**, *25*, 1909−1912.
(24) This procedure was developed by van Boom et al.: van Delft, F. L.; de Kort, M.; van der Marel, G. A.; van Boom, J. H. *J. Org. Chem.* **1996**, *61*, 1883−1885.
(25) Bhushan, V.; Lohray, B. B.; Enders, D. *Tetrahedron Lett.* **1993**, *34*, 5067−5070.
(26) Hudrlik, P. F.; Kulkarni, A. K. *J. Am. Chem. Soc.* **1981**, *103*, 6251−6253.
(27) Tanigawa, Y.; Fuse, Y.; Murahashi, S.-I. *Tetrahedron Lett.* **1982**, *23*, 557−560.
(28) Fleming, I.; Higgins, D.; Lawrence, N. J.; Thomas, A. P. *J. Chem. Soc., Perkin Trans. 1* **1992**, 3331−3349.
(29) Kang, J.; Cho, W.; Lee, W. K. *J. Org. Chem.* **1984**, *49*, 1838−1840.

treatment of acetate **9** with bis[(trimethylsilyl)methyl]-cuprate afforded vinylsilane **10** arising from α-substitution (eq 4). The desired allylsilane obtained from γ-substitution could not be detected by ^{1}H NMR spectroscopic analysis.

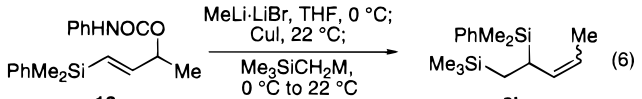


Several methods for selective γ-substitution of biased substrates have been developed, and these procedures were investigated. Goering demonstrated that the regiochemistry of copper-catalyzed addition of Grignard reagents to allylic esters can be controlled by the choice of the copper salt, with CuCN giving selective γ-alkylation.[30] Reaction of pivalate ester[31] **11** with (dimethylphenylsilyl)-methylmagnesium chloride in the presence of catalytic CuCN provided a 61:39 mixture of the desired γ-substitution product **3a** (*E*/*Z* = 40:60) and the α-substitution product **12** (eq 5). Bäckvall determined that slow addition of the Grignard reagent to a mixture of substrate and catalytic copper salts further increases γ-selectivity.[32] Addition of (phenyldimethylsilyl)methylmagnesium chloride over 3 h to a solution of acetate **9** and 10 mol % CuCN also afforded a mixture of the desired γ-product (*E*/*Z* = 64:36) and α-product in a 42:58 ratio. These results demonstrate that α-substitution distal to the silane moiety is competitive with γ-substitution of esters **9** and **11**.



The poor γ-selectivity observed for the copper-mediated allylic displacement reactions may also be overcome by the use of allylic carbamates, which react with exclusive γ-substitution and (*E*)-selectivity.[15,16,28] This modification proved to be successful for our purposes. Deprotonation of carbamate **13a** followed by complexation with CuI and subsequent addition of (trimethylsilyl)methyllithium produced the (*E*)-allylic silane **3b** with modest selectivity (*E*/*Z* = 60:40, eq 6). By simply changing the nucleophile to the organomagnesium reagent, the allylic silane **3b** was obtained in higher yield, with high γ-selectivity and, most notably, *with high (Z)-selectivity* (*E*/*Z* = 5:95).[33]

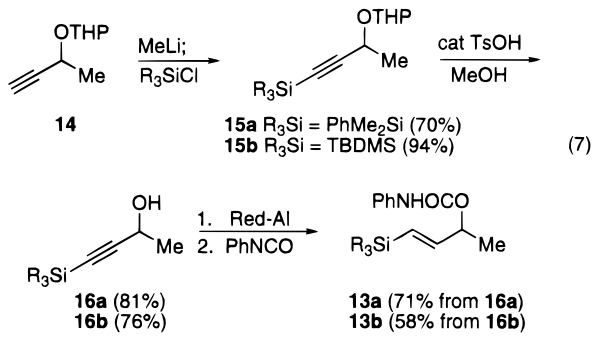
The observation of high (*Z*)-selectivity upon the first attempt to optimize the copper-mediated displacement reaction was not anticipated. Allylic substitution reactions, including both the traditional S_N2' reaction and the copper-mediated processes, generally provide (*E*)-alkenes.[34] The (*Z*)-selectivity was of interest to us because it provided a route to allylic silanes that would otherwise be difficult to access. We also felt that this transformation



M	*E* : *Z*	yield (%)
Li	60 : 40	52
MgCl	5 : 95	82

would provide valuable insight into the mechanism of copper-mediated allylic displacement reactions. We launched a systematic study of this reaction not only to enhance the synthetic utility but also to investigate the effect of reaction conditions on the control of alkene geometry. Optimization of selectivity and yield was accomplished by investigating the effects of copper salt, equivalents of Grignard reagent, and nucleophile. The reactions of both trans- and cis-allylic carbamates were investigated. We also sought to use this method for the synthesis of chiral, nonracemic (*Z*)- and (*E*)-allylic silanes with high enantioselectivity.

Preparation of Allylic Carbamates. A synthesis of the requisite allylic carbamates that would permit variation of the silyl group was desired. Alkyne starting materials were attractive because both the (*E*)- and (*Z*)-alkenes would be available by selective reduction of the alkyne. The (*E*)-isomer was prepared from the THP ether of 3-butyn-2-ol (**14**). Deprotonation of **14** with MeLi, followed by treatment with 1 equiv of chlorosilane, afforded propargylic derivatives **15a** and **15b**, in 70% and 94% yields, respectively (eq 7).[35] After cleavage of the THP ether, propargyl alcohols **16a** and **16b** were selectively reduced to trans-allylic alcohols by Red-Al (*E*/*Z* = 98:2 by capillary GC).[36] Treatment of the alcohols with phenyl isocyanate gave the carbamates **13a** and **13b** in good yield. The incorporation of the silyl group via the silyl chloride allows easy variation of this substituent to permit tuning of allylic silane reactivity.



The selective synthesis of the cis-allylic carbamate was more challenging than that of its trans counterpart. Semi-hydrogenation[37] of propargylic alcohol **16a** occurred slowly and provided an inseparable mixture of the desired (*Z*)-allylic alcohol, the (*E*)-isomer, and alkane. Successful production of **18a** with high (*Z*)-selectivity was achieved by hydroboration[38,39] of acetate **17** with dicyclohexyl-

(30) Tseng, C. C.; Paisley, S. D.; Goering, H. L. *J. Org. Chem.* **1986**, *51*, 2884−2891.

(31) Pivalate esters have been employed in the copper-catalyzed allylic substitution reaction to disfavor attack of the Grignard reagent on the carbonyl.

(32) Bäckvall, J.-E.; Sellén, M.; Grant, B. *J. Am. Chem. Soc.* **1990**, *112*, 6615−6621.

(33) Alkene geometries were assigned by analysis of ^{1}H NMR coupling constants, by comparison of spectral data to reported data, or by comparison to reference materials.

(34) Magid, R. M. *Tetrahedron* **1980**, *36*, 1901−1930.

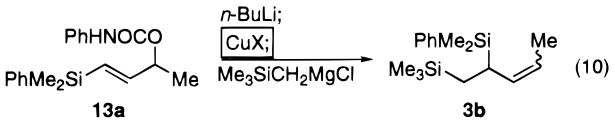
(35) This reaction sequence was adapted from that reported for the synthesis of 3-(*tert*-butyldimethylsilyl)-2-propyn-1-ol: Myers, A. G.; Zheng, B. *Org. Synth.* **1998**, *76*, 178−188.

(36) Denmark, S. E.; Jones, T. K. *J. Org. Chem.* **1982**, *47*, 4595−4597.

(37) Panek, J. S.; Clark, T. D. *J. Org. Chem.* **1992**, *57*, 4323−4326.

(38) Brown, H. C. *Organic Synthesis via Boranes*; Wiley: New York, 1975; pp 178−179.

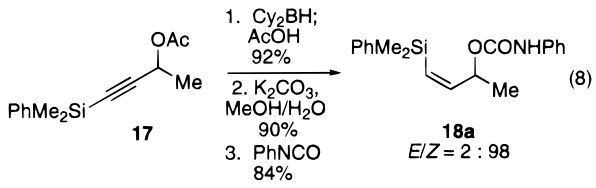
Table 1. Screen of Copper Salts (Eq 10)

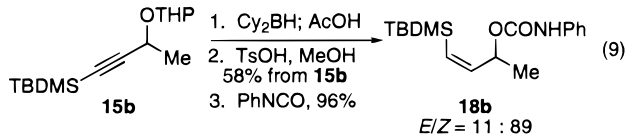


entry	CuX	*E*/*Z*[a]	yield[b] (%)
1	CuI	4:96	63
2[c]	CuBr·SMe_2	9:91	74
3	CuCN·2LiCl	22:78	62
4	CuI·2LiCl	6:94	82

[a] Determined by GC analysis of the unpurified reaction mixture. [b] Yields reported for material isolated after column chromatography. [c] MeLi−LiBr was employed as the base.

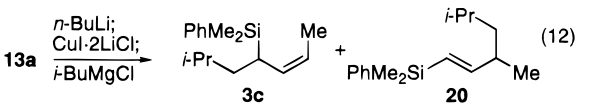
borane[38] and protonolysis with acetic acid (eq 8).[40] Deprotection of the acetate followed by treatment with neat phenyl isocyanate provided the allylic carbamate **18a**. It was later found that the THP ether **15b** could be submitted to the hydroboration/protonolysis procedure to obtain the (*Z*)-alkene (eq 9), obviating the need for manipulation of the protecting group.





Optimization of Copper-Mediated Substitution. Before the generality of the (Z)-selective allylic displacement described in eq 6 could be probed, optimization of the procedure was required. The most serious problem encountered was that of reproducibility. Upon addition of the deprotonated carbamate to a suspension of CuI in THF at 0 °C, reduction of Cu(I) to Cu(0), which appeared as a black suspension, occasionally occurred, and upon addition of the nucleophile, starting material was recovered. House reported a similar reduction of copper during the formation of dialkylcuprates.[41] He found that the use of the more soluble CuBr·SMe_2 complex avoided reduction. A screen of copper salts was undertaken to determine if soluble salts would be less susceptible to reduction (eq 10, Table 1). Of the copper sources investigated, the soluble salt CuI·2LiCl,[42,43] prepared by stirring 1 equiv of CuI and 2 equiv of LiCl in THF at 22 °C, gave reproducibly high yields and eliminated the reduction of the copper(I). The presence of the additional 2 equiv of lithium introduced by the lithium chloride did not significantly diminish the (*Z*)-selectivity (compare entries 1 and 4).

Table 2. Effect of Equivalents of Grignard Reagent (Eq 12)

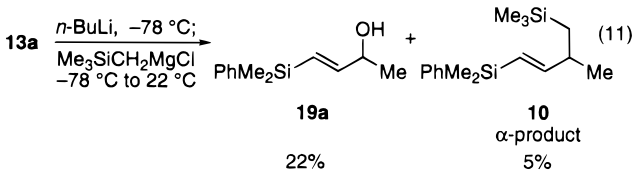


entry	equiv of *i*-BuMgCl	*E*/*Z* of **3c**[a]	**3c**:**20**[a]	yield[b] (%)
1	1.1	9:91	99:1	55
2	1.2	7:93	≥95:5	69
3	1.3	8:92	95:5	70
4	1.4	7:93	93:7	71
5	2.0	6:94	88:12	77

[a] Determined by GC analysis of the unpurified reaction mixture. [b] Yields reported for mixture of **3c** and **20** isolated after column chromatography.

The use of the soluble salt CuI·2LiCl also permitted the formation of the copper-carbamate complex to be conducted at lower temperatures. With copper iodide, the complex did not form at −78 °C, and warming to 0 °C was necessary for complete formation of the complex (as indicated by a homogeneous reaction mixture).[16] Reactions carried out from 0 °C to 22 °C, however, produced 10% of the unprotected alcohol corresponding to **13a** (i.e., alcohol **19a**). The conjugate base of the carbamate could be complexed to CuI·2LiCl at −78 °C, which minimized formation of **19a**.

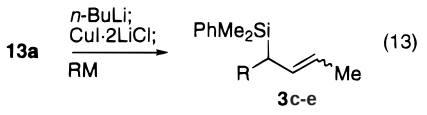
The use of a stoichiometric amount of copper is necessary to obtain high γ-selectivity. In the absence of copper, the allylic carbamate **13a** was recovered (71%) along with alcohol **19a** (22%) and the vinylsilane **10** (5%) arising from S_N2 reaction of the Grignard reagent (eq 11). No γ-substitution products were produced. The use of a catalytic amount of copper results in loss of γ-selectivity. The addition of 10 mol % CuI·2LiCl to a cooled −78 °C solution of the deprotonated carbamate, followed by addition of 1 equiv of (trimethylsilyl)methylmagnesium chloride afforded the vinylsilane **10** as the major product (58%, γ/α = 19:81). Presumably, the vinylsilane is produced by reaction of the dialkylcuprate, which delivers the nucleophile to the less-hindered allylic terminus.[32] Therefore, the γ-substitution product cannot be obtained in the presence of catalytic copper.



The number of equivalents of Grignard reagent employed in the reaction influences γ-selectivity and, to a lesser extent, (*Z*)-selectivity. As the amount of the Grignard reagent was increased, the amount of **20** arising from α-substitution also increased (eq 12, Table 2). In the presence of excess Grignard reagent, the dialkylcuprate may be formed, leading to the α-substitution product.[32] The (*Z*)-selectivity of the γ-substitution product also increased slightly as the equivalents of Grignard reagent increased. Titration[44] of the Grignard reagent prior to use is critical for maintaining both high (*Z*)- and γ-selectivity. The use of 1.2 equiv of Grignard reagent provides optimal (*Z*)- and γ-selectivity (entry 2).

(39) Miller, R. B.; Reichenbach, T. *Tetrahedron Lett.* **1974**, *15*, 543−546.
(40) Brown, H. C.; Zweifel, G. *J. Am. Chem. Soc.* **1961**, *83*, 3834−3840.
(41) House, H. O.; Chu, C.-Y.; Wilkins, J. M.; Umen, M. J. *J. Org. Chem.* **1975**, *40*, 1460−1469.
(42) For the introduction of CuCN·2LiX, see: Knochel, P.; Yeh, M. C. P.; Berk, S. C.; Talbert, J. *J. Org. Chem.* **1988**, *53*, 2390−2392.
(43) Lipshutz, B. H.; Segi, M. *Tetrahedron* **1995**, *51*, 4407−4420.
(44) Voskuil, W.; Arsens, J. F. *Organic Syntheses*; Wiley: New York, 1963; Collect. Vol. V, pp 211−214.

Table 3. Reaction of 13a with Other Metals (Eq 13)



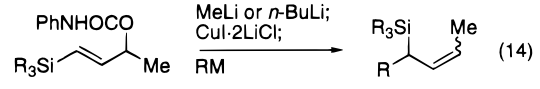
entry	RM	product	*E*/*Z*[a]	γ/α[a]	yield[b] (%)
1	$Me_2Ti(O\text{-}i\text{-}Pr)_3Li$	**3d**	89:11	99:1	82
2	Et_2Zn	**3e**	90:10	>99:1	77
3	$AlMe_3$	**3d**	76:24	>99:1	76
4	$Al(i\text{-}Bu)_3$	**3c**	48:52	>99:1	73
5	$allylSnBu_3$				NR

[a] Determined by GC analysis of the unpurified reaction mixture. [b] Yields reported for material isolated after column chromatography.

We were curious as to whether other organometallic nucleophiles would exhibit a strong preference for alkene stereochemistry and if the selectivities would be higher than those observed for either lithium or magnesium reagents. The metal used as the nucleophilic component of the reaction with carbamate **13a** was varied and the (*E*/*Z*) ratio was determined (eq 13, Table 3). As with alkyllithium reagents, dimethyltriisopropoxytitanate[45] and diethylzinc[46] both favored formation of the (*E*)-alkene (entries 1 and 2) with selectivities comparable to that of alkyllithium species. Trimethylaluminum[47] exhibited lower (*E*)-selectivity (76:24), while triisobutylaluminum was unselective (entries 3 and 4). Allyltributyltin did not react with the carbamate. The γ-selectivity was high in all cases, but none of these alkylmetal reagents favored formation of the (*Z*)-alkene. Grignard reagents appear to be unique in their selectivity.

Reaction of Trans-Allylic Carbamates with Grignard and Alkyllithium Reagents. The reversal of selectivity observed with alkyllithium versus alkylmagnesium reagents is a general phenomenon with trans-allylic carbamate **13a** as substrate. Upon changing only the metal in the nucleophile, in all cases alkyllithium reagents showed (*E*)-selectivity, whereas use of alkylmagnesium reagents resulted in (*Z*)-selectivity (eq 14, Table 4). Furthermore, γ/α-selectivity (S_N2'/S_N2) was consistently high for both lithium and magnesium reagents. Methylmagnesium chloride gave the crotylsilane **3d** with modest (*Z*)-selectivity (entry 1), but all other alkylmagnesium chlorides exhibited high (*Z*)-selectivity. Of the Grignard reagents examined, only phenylmagnesium chloride afforded the (*E*)-isomer as the major product, albeit with low selectivity (entry 8). This modest (*E*)-selectivity is not due to the steric bulk of the nucleophile, because *tert*-butylmagnesium chloride affords the (*Z*)-allylic silane **3g** with high selectivity (entry 7). The presence of the bulkier *t*-$BuMe_2Si$ group on carbamate **13b** does not diminish either (*Z*)- or γ/α-selectivity as compared to carbamate **13a** (entries 3 and 4). Thus, the synthesis of (*Z*)-allylic silanes with primary, secondary, and tertiary alkyl groups adjacent to silicon is possible by this method.

Table 4. Comparison of the Reactions of *trans*-13a,b with Grignard and Alkyllithium Reagents (Eq 14)



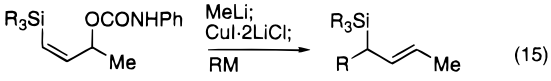
R_3Si = $PhMe_2Si$, **13a**; *t*-$BuMe_2Si$, **13b**

R_3Si = $PhMe_2Si$, **3a-h**; *t*-$BuMe_2Si$, **8b,c**

entry	substrate	RM	product	*E*/*Z*[a]	γ/α[a]	yield[b] (%)
1	**13a**	MeMgCl	**3d**	26:74	>99:1	80
2[c]		*i*-BuMgCl	**3c**	6:94	95:5	90
3	**13b**		**8b**	7:93	97:3	95
4		Me_3SiCH_2MgCl	**8c**	6:94	>99:1	78
5	**13a**	$PhMe_2SiCH_2MgCl$	**3a**	4:96	99:1	68
6		*i*-PrMgCl	**3f**	13:87	>99:1	71
7		*t*-BuMgCl	**3g**	7:93	100:0	54
8		PhMgCl	**3h**	58:42	97:3	57
9		MeLi	**3d**	92:8	94:6	72
10		*i*-BuLi	**3c**	91:9	99:1	69
11	**13b**		**8b**	91:9	>99:1	77
12		Me_3SiCH_2Li	**8c**	76:24	>99:1	75
13[d]	**13a**	$PhMe_2SiCH_2Li$	**3a**	72:28	>99:1	68

[a] Determined by GC analysis of the unpurified reaction mixture. [b] Yields reported for material isolated after column chromatography. [c] Enantiomerically enriched **13a** was employed (see eq 18). [d] CuI was used, and the reaction was performed at 0−22 °C.

Table 5. Comparison of the Reaction *cis*-18a,b with Grignard and Alkyllithium Reagents (Eq 15)



R_3Si = $PhMe_2Si$, **18a**; *t*-$BuMe_2Si$, **18b**

R_3Si = $PhMe_2Si$, **3**; *t*-$BuMe_2Si$, **8**

entry	carbamate	RM	product	*E*/*Z*[a]	γ/α[a]	yield[b] (%)
1[c]	**18a**[d]	*i*-BuMgCl	**3c**	97:3	98:2	93
2[e]		Me_3SiCH_2MgCl	**3b**	93:7	>99:1	78
3	**18b**[f]	*i*-PrMgCl	**8d**	90:10	>99:1	85
4		MeLi	**3d**	100:0	>99:1	73
5[c]	**18a**	*i*-BuLi	**3c**	>99:1	100:0	93
6		PhLi	**3h**	>99:1	>99:1	55
7	**18b**[f]	Me_3SiCH_2Li	**8c**	98:2	>99:1	91

[a] Determined by GC analysis of the unpurified reaction mixture. [b] Yields reported for material isolated after column chromatography. [c] Enantiomerically enriched **18a** was employed. [d] The (*E*/*Z*)-ratio of **18a** was 2:98 unless otherwise indicated. [e] The (*E*/*Z*)-ratio of **18a** was 4:96. [f] The (*E*/*Z*)-ratio of **18b** was 11:89.

Reaction of Cis-Allylic Carbamates. To investigate whether the (*Z*)-selectivity exhibited by Grignard reagents would change upon reaction with cis-allylic carbamates, the reaction of *cis*-**18** with both Grignard and alkyllithium reagents (eq 15, Table 5) was compared to the reactions with the trans carbamate (eq 14, Table 4). The copper-mediated reaction of lithium reagents with cis-allylic carbamates is known to occur with higher (*E*)-selectivity than that of trans-allylic carbamates.[28] As expected, the reaction of **18a** with isobutyllithium afforded the (*E*)-allylic silane **3c** with high selectivity (*E*/*Z* > 99:1, entry 5). The reaction of **18a** with the corresponding Grignard reagent also afforded (*E*)-**3c** with high selectivity (*E*/*Z* = 97:3, entry 1). With alkylmagnesium reagents as nucleophiles, the degree of stereochemical purity of the starting carbamates was preserved in the products (entries 1−3). Comparison of the data in Tables

(45) For the copper-catalyzed reactions of terminal and cyclic allylic phosphates and chlorides with titanate reagents, see: Arai, M.; Nakamura, E.; Lipshutz, B. H. *J. Org. Chem.* **1991**, *56*, 5489−5491. Arai, M.; Lipshutz, B. H.; Nakamura, E. *Tetrahedron* **1992**, *48*, 5709−5718.

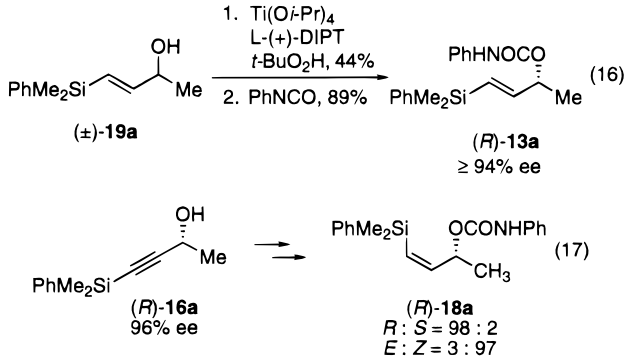
(46) For the copper-catalyzed reactions of allylic chlorides and phosphates with organozinc reagents, see: (a) Sekiya, K.; Nakamura, E. *Tetrahedron Lett.* **1988**, *29*, 5155−5156. (b) Nakamura, E.; Sekiya, K.; Arai, M.; Aoki, S. *J. Am. Chem. Soc.* **1989**, *111*, 3091−3093. (c) Zhu, L.; Wehmeyer, R. M.; Rieke, R. D. *J. Org. Chem.* **1991**, *56*, 1445−1453.

(47) For the copper-catalyzed reactions of allylic phosphates and halides with trialkylaluminum reagents, see: Flemming, S.; Kabbara, J.; Nickisch, K.; Westermann, J.; Mohr, J. *Synlett* **1995**, 183−185.

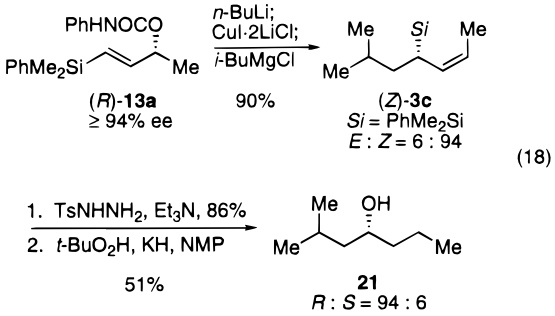
4 and 5 indicates that, in all cases, the reactions of cis-allylic carbamates lead to higher (*E*)-selectivity than reactions of the trans-isomers.

Stereochemistry. The products of the copper-mediated substitution of allylic carbamates with alkylmetal nucleophiles possess two stereochemical features: the geometry of the olefin and the stereochemistry of the newly formed allylic center. Goering[16] and Fleming[28] have demonstrated that the reactions of alkyllithium and silyllithium reagents with acyclic allylic carbamates produce (*E*)-alkenes and (*E*)-allylsilanes, respectively, by addition of the nucleophile syn to the carbamate moiety. This observation contrasts to the reaction of allylic esters,[48] halides,[46] and phosphates,[46] which undergo anti substitution.[49] We have demonstrated that alkylmagnesium reagents are unlike alkyllithium species in their reactions with trans-allylic carbamates in that Grignard reagents selectively afford (*Z*)-alkenes, whereas with cis-substrates, both reagents give the (*E*)-isomer.

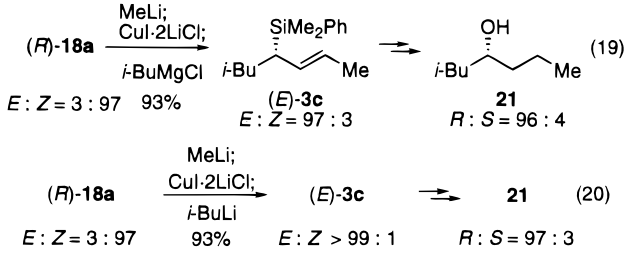
To determine the stereochemical relationship between the carbamate leaving group and the incoming nucleophile (i.e., syn or anti), nucleophilic substitutions on nonracemic *trans*-**13a** and *cis*-**18a** were conducted. The optically active carbamate (*R*)-**13a** was obtained in ≥ 94% ee by Sharpless kinetic resolution[50,51] of racemic allylic alcohol **19a** followed by treatment with phenyl isocyanate (eq 16). Nonracemic *cis*-allylic carbamate (*R*)-**18a** (eq 17) was prepared from nonracemic propargylic alcohol **16a** (obtained in 96% ee by asymmetric transfer hydrogenation of the corresponding ketone using Noyori's ruthenium catalyst[52,53]) as previously described for the racemic compound.



These nonracemic carbamates were submitted to copper-mediated substitution reactions, and the enantiomeric ratios of the product crotylsilanes were determined. Reaction of *trans*-(*R*)-**13a** with isobutylmagnesium chloride afforded (*Z*)-allylic silane **3c** with an *E*/*Z* ratio of 6:94 in 90% yield (eq 18).[17] Chemical correlation allowed the stereochemistry of the newly formed allylic center to be elucidated. Tosylhydrazide reduction[54] of **3c** to the alkylsilane was followed by oxidation of the C−Si bond[55] to afford the known alcohol **21** ([α]$_D$ = −11.9, lit.[56] [α]$_D$ = −11.9). Since the oxidation of the C−Si bond occurs with retention of configuration,[55,57] these data indicate that the alcohol **21** has predominately the (*R*)-configuration. Analysis of the carbamate obtained from treatment of alcohol **21** with (*R*)-(α-methyl)benzyl isocyanate by capillary GC indicated a 94:6 ratio of diastereomers, which is consistent with the ratio of alkene isomers of **3c**. Thus, reaction of *trans*-(*R*)-**13a** with alkylmagnesium chlorides affords the (*S*)-enantiomer of (*Z*)-allylic silane (eq 18).



This process was repeated for cis-carbamate (*R*)-**18a**. Reaction of (*R*)-**18a** with isobutylmagnesium chloride afforded (*E*)-**3c** with an (*E*/*Z*)-ratio of 97:3 in 93% yield (eq 19). Analysis of alcohol **21**, obtained as described previously, indicated that the (*R*)-isomer predominated with an enantiomeric ratio of 96:4, which compares favorably to the (*E*/*Z*)-ratio of (*E*)-**3c**. Isobutyllithium also gives (*E*)-**3c** (*E*/*Z* > 99:1, 93% yield) upon reaction with (*R*)-**18a** (eq 20). Therefore, reaction of *cis*-**18a** with both alkylmagnesium chlorides and alkyllithium reagents gives the (*S*)-enantiomer of the (*E*)-crotylsilane.



These results indicate that the reactions of readily available nonracemic trans- and cis-allylic carbamates with alkylmagnesium reagents occur with high stereochemical fidelity. The requisite allylic carbamates can be prepared from propargylic and allylic alcohols, for which numerous methods for asymmetric syntheses have been reported.[50,52,58] Thus, the allylic carbamates are attractive precursors of both nonracemic (*Z*)- and (*E*)-allylic silanes.

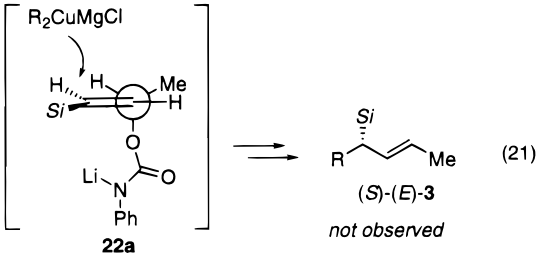
Mechanism. Because the mechanism proposed by Goering to explain the (*E*)-selective displacement reactions of (*E*)-allylic carbamates with alkyllithiums did not

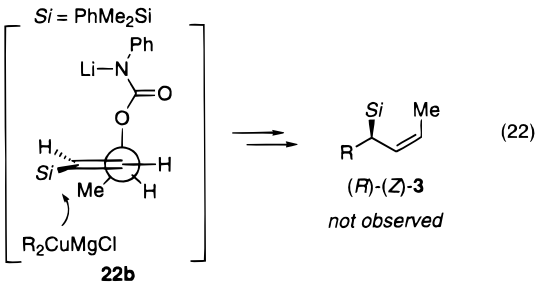
(48) Goering, H. L.; Kantner, S. S. *J. Org. Chem.* **1984**, *49*, 422−426.
(49) Corey, E. J.; Boaz, N. W. *Tetrahedron Lett.* **1984**, *25*, 3063−3066.
(50) Gao, Y.; Hanson, R. M.; Klunder, J. M.; Ko, S. Y.; Masamune, H.; Sharpless, K. B. *J. Am. Chem. Soc.* **1987**, *109*, 5765−5780.
(51) Kitano's procedure for Sharpless kinetic resolution of γ-silyl allylic alcohols was followed: Kitano, Y.; Matsumoto, T.; Sato, F. *Tetrahedron* **1988**, *44*, 4073−4086.
(52) Matsumura, K.; Hashiguchi, S.; Ikariya, T.; Noyori, R. *J. Am. Chem. Soc.* **1997**, *119*, 8738−8739.
(53) Haack, K.-J.; Hashiguchi, S.; Fujii, A.; Ikariya, T.; Noyori, R. *Angew. Chem., Int. Ed. Engl.* **1997**, *36*, 285−288.
(54) Suginome, M.; Iwanami, T.; Matsumoto, A.; Ito, Y. *Tetrahedron: Asymmetry* **1997**, *8*, 859−862.
(55) Smitrovich, J. H.; Woerpel, K. A. *J. Org. Chem.* **1996**, *61*, 6044−6046.
(56) Takenaka, M.; Takikawa, H.; Mori, K. *Liebigs Ann.* **1996**, 1963−1964.
(57) Tamao, K.; Ishida, N.; Tanaka, T.; Kumada, M. *Organometallics* **1983**, *2*, 1694−1696.
(58) For a review of methods available for the enantioselective reduction of ketones, see: Singh, V. K. *Synthesis* **1992**, 605−617.

include a critical role of the counterion, it was not clear why these reactions should be (*Z*)-selective when lithium was exchanged with magnesium. Insight into these reactions can be gained by consideration of both alkene stereochemistry and the configuration at the allylic stereocenter of the products.

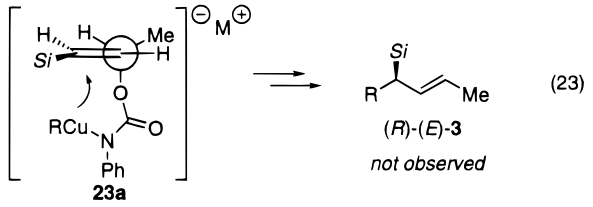
The copper-mediated substitution reactions of allylic derivatives can occur by two modes of oxidative addition of copper: either anti[49] or syn[15,16,59] to the leaving group. In turn, each of these types of addition can occur through two rotamers. Inspection of these four possible scenarios for the reaction of (*E*)-allylic carbamate (*R*)-**13a** with an organomagnesium reagent indicates that only one leads to the observed (*S*)-enantiomer of the (*Z*)-allylic silane.

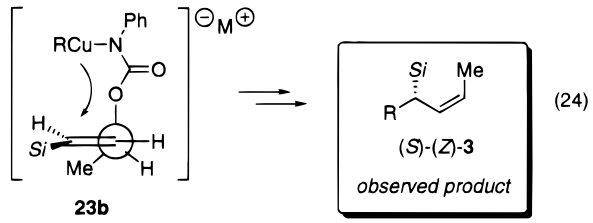
Analysis of the two possible manners for oxidative addition of the magnesiocuprate anti to the carbamate group demonstrates that neither mode would provide the observed product. Anti oxidative addition of copper to rotamer **22a** followed by reductive elimination would afford (*S*)-(*E*)-**3**, which is not observed (eq 21). Addition of the copper reagent anti to the carbamate moiety in rotamer **22b** would provide the (*Z*)-allylic silane, but the stereocenter would have the (*R*)-configuration, opposite to what is observed (eq 22). Since neither mode of addition accounts for the formation of (*S*)-(*Z*)-**3**, the reaction cannot be occurring by addition of copper anti to the carbamate moiety.



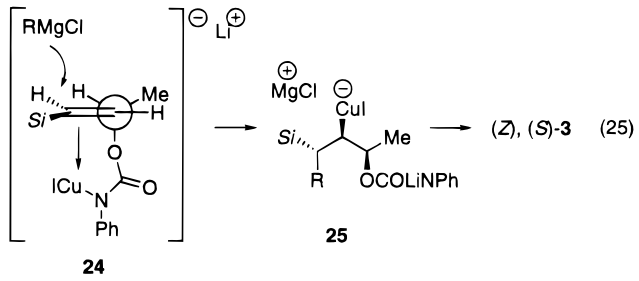


The observed stereochemistry of the reaction of allylic carbamates with Grignard reagents can be understood by consideration of syn attack. Goering proposed that trans-allylic carbamates react with alkyllithium reagents to provide (*E*)-alkenes by a directed intramolecular oxidative addition of copper syn to the carbamate moiety.[16] If this mechanism were also operative for organomagnesium reagents, then addition of the magnesium reagent to the carbamate copper complex followed by transmetalation from magnesium to copper would afford **23** (eq 23). Intramolecular oxidative addition via the lower energy conformer **23a** followed by reductive elimination would lead to (*R*)-(*E*)-**3**, which is not observed for organomagnesium reagents (eq 23). Formation of the observed (*S*)-enantiomer of the (*Z*)-alkene by a syn oxidative addition would require that the higher energy rotamer **23b** leads to the major product (eq 24). This analysis requires the reactivity of the reactant conformation to be a function of the organometallic reagent.





Since the relationship between the reactivity of the two rotamers and the counterion of the cuprate was not obvious, we originally proposed that the allylic displacement with alkylmagnesium reagents to form (*Z*)-alkenes proceeded by a fundamentally different mechanism than that with organolithium nucleophiles.[17] The alternative model relied on anti carbometalation followed by anti elimination (eq 25). If formation of the alkyl cuprate of **24** with organomagnesium reagents were disfavored, carbometalation by the Grignard reagent anti to the carbamate moiety of the copper complex, in its lower energy conformer **24**, becomes an alternative pathway (eq 25). Anti-elimination from this acyclic intermediate **25** would afford the observed (*Z*)-alkene.

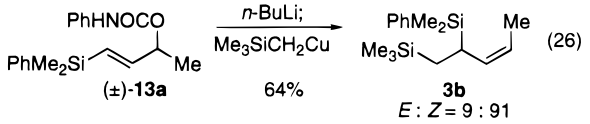


Since we first presented the carbometalation pathway shown in eq 25,[17] we have accumulated evidence that argues against it. To determine if the Grignard reagent transmetalates to copper prior to addition to the allylic carbamate, a preformed alkylcopper complex was used as the nucleophile. Addition of the deprotonated carbamate to a solution of (trimethylsilyl)methylcopper,[60] prepared by addition of (trimethylsilyl)methylmagnesium chloride to a solution of CuI·2LiCl, afforded the allylic silane **3b** with high (*Z*)-selectivity (64%, *E*/*Z* = 9:91, eq 26). This ratio is comparable to that obtained by the standard protocol (*E*/*Z* = 4:96). This result suggests that the alkyl group is coordinated to copper prior to addition to the carbamate and rules out an intermolecular attack of alkylmagnesium reagent on the olefin (i.e., eq 25). Therefore, the reaction of alkylmagnesium reagents with

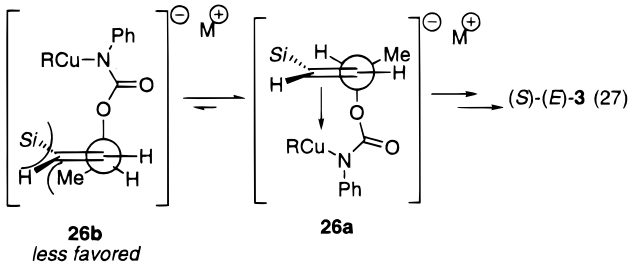
(59) Goering, H. L.; Tseng, C. C. *J. Org. Chem.* **1985**, *50*, 1597−1599.

(60) Foulon, J. P.; Bourgain-Commerçon, M.; Normant, J. F. *Tetrahedron* **1986**, *42*, 1389−1397.

allylic carbamates likely occurs by transmetalation of the Grignard reagent to copper followed by oxidative addition of copper in rotamer **23b** (eq 24). The enhanced reactivity via the higher energy rotamer may be the result of aggregation.



The syn-oxidative addition mechanism is further supported by the reaction of the nonracemic cis-allylic carbamate **18a**. The stereochemical studies revealed that both alkylmagnesium reagents and alkyllithiums afford the same enantiomer of the (*E*)-allylic silane. In the case of the cis-allylic carbamate, the less favored rotamer **26b** suffers from such severe $A^{1,3}$ strain[61] that this rotamer is prohibitively high in energy. Oxidative addition must occur through the more favored rotamer **26a**, leading to the (*E*)-alkene as the (*S*)-enantiomer (eq 27) with *both* alkyllithium and alkylmagnesium reagents.



Conclusion

The copper-mediated substitution of allylic carbamates by organometallic reagents provides a versatile method for the synthesis of allylic silanes. The reaction of alkylmagnesium reagents with (*E*)-allylic carbamates provides (*Z*)-allylic silanes, whereas both alkylmagnesium and alkyllithium reagents react with (*Z*)-allylic carbamates to afford (*E*)-allylic silanes with high selectivity. When an alkylmagnesium reagent was used as the nucleophile, the stereoselectivity of the starting alkene was transferred faithfully to the product. Considering that Grignard reagents are often more facile to prepare than alkyllithium species, Grignard reagents are the preferred nucleophiles for the synthesis of both (*Z*)- or (*E*)-allylic silanes with high selectivity. Furthermore, the reaction of readily available nonracemic allylic carbamates with alkylmagnesium reagents occurs in a highly stereoselective fashion, affording chiral, nonracemic (*Z*)- and (*E*)-allylic silanes.

Experimentals

General Methods. All reactions were carried out under an atmosphere of nitrogen in glassware that had been flame-dried under a stream of nitrogen. THF was purified by filtration through activated alumina according to the method of Grubbs.[62] Diisopropylamine and *N*-methylpyrrolidinone were distilled from CaH_2. CuI was purified by a published method.[63,64] LiCl was dried at 150 °C at 0.05 mmHg for 8 h and then stored in an Innovative Technologies nitrogen atmosphere drybox. KH (26% dispersion in mineral oil) was purchased from Aldrich, washed with hexanes, dried at 22 °C at 0.05 mmHg, and then stored in an Innovative Technologies nitrogen atmosphere drybox. Alkyllithium reagents were purchased from Aldrich or were prepared by lithium−iodine exchange of the corresponding alkyl iodide[65,66] and were titrated using diphenylacetic acid as an indicator. Grignard reagents were purchased from Aldrich or were prepared from the corresponding alkyl chlorides and were titrated with 2-butanol (1.00 M in xylenes) using *o*-phenanthroline as an indicator.[44]

Copper-Mediated Reaction of Allylic Carbamate 13a Using CuI: (±)-(*E*)-2-(Dimethylphenylsilyl)-1-(trimethylsilyl)-3-pentene [(*E*)-3b]. To a cooled (0 °C) solution of carbamate **13a** (1.58 g, 4.85 mmol) in 16 mL of THF was added dropwise by syringe MeLi·LiBr (1.2 M solution in hexanes, 4.1 mL, 4.8 mmol). After 5 min, the clear yellow-orange reaction mixture was added dropwise by cannula to a suspension of CuI (932 mg, 4.9 mmol). After 20 min, the brown reaction mixture was cooled to 0 °C, and (trimethylsilyl)methyllithium (1.0 M solution in Et_2O/pentane, 4.9 mL, 4.9 mmol) was added dropwise by syringe. The reaction mixture was allowed to warm to 22 °C without removing the cold bath. After 16 h, 50 mL of 9:1 saturated aqueous NH_4Cl/NH_4OH and 75 mL of methyl *tert*-butyl ether were added, and the mixture was stirred until the aqueous layer became transparent blue. The layers were separated, and the aqueous layer was extracted with 3 × 50 mL of methyl *tert*-butyl ether. The combined organic layers were washed with 50 mL of brine, dried ($MgSO_4$), filtered, and concentrated in vacuo to afford a golden oil. Purification by flash chromatography (hexanes) provided **3b** as a colorless oil (695 mg, 52%) with an *E*/*Z* ratio of 60:40 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer (*E*)-**3b** was assigned as the (*E*)-alkene by the value of the coupling constant of the olefinic protons (J = 15.2 Hz). (*E*)-**3b**: GC t_R 5.2 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 300 MHz) δ 7.47−7.52 (m, 2H), 7.33−7.36 (m, 3H), 5.18 (m, 2H), 1.73 (m, 1H), 1.62 (d, J = 4.6 Hz, 3H), 0.49 (m, 2H), 0.24 (s, 3H), 0.22 (s, 3H), −0.08 (s, 9H); ^{1}H NMR (C_6D_6, 500 MHz) δ 7.50−7.52 (m, 2H), 7.22−7.33 (m, 3H), 5.27 (ddq, J = 15.2, 9.1, 1.2 Hz, 1H), 5.19 (dq, J = 15.2, 5.8 Hz, 1H), 1.83 (ddd, J = 12.1, 9.5, 2.2 Hz, 1H), 1.60 (d, J = 6.2 Hz, 3H), 0.69 (dd, J = 14.8, 2.3 Hz, 1H), 0.60 (dd, J = 14.8, 12.2 Hz, 1H), 0.28 (s, 3H), 0.27 (s, 3H), 0.01 (s, 9H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.3, 134.2, 133.5, 128.7, 127.5, 120.3, 27.2, 18.0, 15.2, −0.8, −4.6, −5.5; IR (thin film) 3008, 2954 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{16}H_{28}Si_2$ (M^+) 276.1729, found 276.1729. Anal. Calcd for $C_{16}H_{28}Si_2$: C, 69.49; H, 10.20. Found: C, 69.34; H, 10.25.

(±)-(*Z*)-2-(Dimethylphenylsilyl)-1-(trimethylsilyl)-3-pentene [(*Z*)-3b]. The procedure given for (*E*)-**3b** was followed, except that the Grignard reagent was employed. The product **3b** was provided, after purification by flash chromatography (pentane), as a colorless oil (136 mg, 82%) with an *E*/*Z* ratio of 5:95 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer (*Z*)-**3b** was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons (J = 10.8 Hz): GC t_R 5.9 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.51−7.53 (m, 2H), 7.35−7.36 (m, 3H), 5.29 (dq, J = 10.8, 6.7 Hz, 1H), 5.12 (m, 1H), 2.11 (m, 1H), 1.46 (dd, J = 6.8, 1.6 Hz, 3H), 0.65 (dd, J = 14.7, 2.0 Hz, 1H), 0.48 (dd, J = 14.7, 11.9 Hz, 1H), 0.28 (s, 3H), 0.25 (s, 3H), −0.07 (s, 9H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.1, 134.1, 133.9, 128.7, 127.4, 120.3, 22.4, 16.0, 13.2, −1.0, −4.8, −5.6; IR (thin film) 3005, 2954, 1642 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{16}H_{28}Si_2$ (M^+) 276.1729, found 276.1724. Anal. Calcd for $C_{16}H_{28}Si_2$: C, 69.49; H, 10.20. Found: C, 69.71; H, 10.22.

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(±)-2-[3-(Dimethylphenylsilyl)-1-methyl-2-propynyloxy]tetrahydropyran (15a).[35] To a cooled (−78 °C) solution of **14**[67] (5.85 g, 37.9 mmol) in 38 mL of THF was added MeLi (1.1 M solution in Et_2O, 36.0 mL, 40 mmol) dropwise by addition funnel. After 10 min, the mixture was allowed to warm to 0 °C. Chlorodimethylphenylsilane (6.6 mL, 40 mmol) was added dropwise. The ice/H_2O bath was removed, and after 15 min, 100 mL of brine and 100 mL of hexanes were added to the reaction mixture. The layers were separated, and the aqueous layer was extracted with 3 × 100 mL of hexanes. The combined organic layers were dried (Na_2SO_4), filtered, and concentrated in vacuo to provide a golden oil. Purification by distillation (0.05 mmHg, 121−129 °C) provided **15a** as a colorless oil (7.71 g, 70%). ^{1}H NMR spectroscopic analysis indicated that the product was a 3:1 mixture of epimers: ^{1}H NMR ($CDCl_3$, 500 MHz) major isomer δ 7.61−7.64 (m, 2H), 7.37−7.38 (m, 3H), 4.96 (m, 1H), 4.59 (q, J = 6.7 Hz, 1H), 3.83 (m, 1H), 3.51 (m, 1H), 1.54−1.84 (m, 6H), 1.48 (d, J = 6.7 Hz, 3H), 0.41 (s, 6H); minor isomer: δ 7.61−7.64 (m, 2H), 7.37−7.38 (m, 3H), 4.81 (m, 1H), 4.49 (q, J = 6.7 Hz, 1H), 4.00 (m, 1H), 3.51 (m, 1H), 1.54−1.84 (m, 6H), 1.46 (d, J = 6.7 Hz, 3H), 0.41 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) major isomer δ 136.9, 133.6, 129.33, 127.5, 107.4, 95.9, 87.0, 62.4, 61.7, 30.5, 25.4, 22.0, 19.4, −0.9; minor isomer (characteristic peaks): δ 137.0, 133.7, 129.27, 127.7, 108.4, 97.2, 86.1, 63.1, 62.0, 19.0; IR (thin film) 3049, 2941, 2169 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{17}H_{25}O_2Si$ (M + H)$^+$ 289.1623, found 289.1624.

(±)-2-[3-(*tert*-Butyldimethylsilyl)-1-methyl-2-propynyloxy]tetrahydropyran (15b). The procedure given for **15a** was followed, except that the *tert*-butyldimethylsilyl chloride was employed and the reaction mixture was stirred at 22 °C for 1 h following the addition of *tert*-butyldimethylsilyl chloride. Purification by distillation (0.05 mmHg, 83−93 °C) provided **15b** as a colorless oil (4.69 g, 94%). ^{1}H NMR spectroscopic analysis indicated that the product was a 3:1 mixture of epimers: ^{1}H NMR ($CDCl_3$, 500 MHz) major isomer δ 4.95 (m, 1H), 4.54 (q, J = 6.7 Hz, 1H), 3.82 (m, 1H), 3.51 (m, 1H), 1.51−1.87 (m, 6H), 1.45 (d, J = 6.7 Hz, 3H), 0.93 (s, 9H), 0.10 (s, 6H); minor isomer δ 4.80 (m, 1H), 4.34 (m, 1H), 4.00 (m, 1H), 3.51 (m, 1H), 1.51−1.87 (m, 6H), 1.42 (d, J = 6.7 Hz, 3H), 0.93 (s, 9H), 0.10 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) major isomer δ 106.0, 95.9, 87.2, 62.5, 61.2, 30.5, 26.0, 22.0, 19.5, 16.4, −4.7, minor isomer (characteristic peaks) δ 107.1, 97.0, 86.4, 63.0, 62.0, 25.4, 22.1, 19.0, 16.5; IR (thin film) 2951, 2169 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{15}H_{29}O_2Si$ (M + H)$^+$ 269.1937, found 269.1927. Anal. Calcd for $C_{15}H_{28}O_2Si$: C, 67.11; H, 10.51. Found: C, 66.91; H, 10.66.

(±)-4-(Dimethylphenylsilyl)-3-butyn-2-ol (16a). To a solution of **15a** (925 mg, 3.21 mmol) in 12 mL of MeOH was added TsOH (16 mg, 0.08 mmol). The reaction mixture was stirred for 12 h and then concentrated in vacuo. The resultant yellow oil was diluted with 50 mL of Et_2O and washed with 25 mL of saturated aqueous $NaHCO_3$. The layers were separated, and the aqueous layer was extracted with 3 × 50 mL of Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated in vacuo. Purification by flash chromatography (2:98 to 10:90 EtOAc/pentane) provided **16a** as a colorless oil (528 mg, 81%). Spectral data were identical to those reported in the literature:[37,68] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.61−7.63 (m, 2H), 7.36−7.40 (m, 3H), 4.56 (m, 1H), 1.83 (d, J = 5.3 Hz, 1H), 1.48 (d, J = 6.6 Hz, 3H), 0.42 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 136.6, 133.6, 129.4, 127.9, 109.4, 86.4, 58.7, 24.1, −1.0.

(±)-4-(*tert*-Butyldimethylsilyl)-3-butyn-2-ol (16b). Using the procedure given for **16a** with **15b** provided **16b**, after purification by flash chromatography (2:98 to 10:90 EtOAc/pentane), as a colorless oil (524 mg, 76%): ^{1}H NMR ($CDCl_3$, 500 MHz) δ 4.52 (m, 1H), 1.78 (d, J = 5.3 Hz, 1H), 1.45 (d, J = 6.6 Hz, 3H), 0.93 (s, 9H), 0.10 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 108.4, 86.5, 58.7, 26.0, 24.3, 16.4, −4.7; IR (thin film) 3330, 2175 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{10}H_{20}OSi$ (M$^+$) 184.1283, found 184.1281. Anal. Calcd for $C_{10}H_{20}OSi$: C, 65.15; H, 10.94. Found: C, 64.91; H, 11.02.

(±)-(*E*)-1-(Dimethylphenylsilyl)-1-buten-3-ol (19a). To a cooled (−20 °C) solution of Red-Al (65% weight solution in toluene, 23.6 mL, 78.6 mmol) in 30 mL of Et_2O was added a solution of **16a** (10.7 g, 52.4 mmol) in 20 mL of Et_2O dropwise by cannula. The reaction temperature was maintained at −25 to −15 °C over the course of the addition and was then allowed to increase to 22 °C. After 3.5 h, the reaction mixture was cooled to 0 °C, and H_2SO_4 (3.6 M, 30 mL, 108 mmol) was cautiously added. The reaction mixture was diluted with 200 mL of Et_2O. The layers were separated, and the aqueous layer was extracted with 3 × 200 mL of Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated in vacuo to provide a golden oil. Purification by flash chromatography (hexanes to 20:80 EtOAc/hexanes) provided **19a** as a colorless oil (9.45 g, 87%). Capillary GC revealed that the product was formed as a 98:2 (*E*/*Z*) mixture of alkene isomers. The spectral data were identical to that reported in the literature:[69] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.50−7.53 (m, 2H), 7.34−7.37 (m, 3H), 6.17 (dd, J = 18.7, 4.8 Hz, 1H), 5.97 (dd, J = 18.7, 1.1 Hz, 1H), 4.32 (m, 1H), 1.56 (d, J = 3.2 Hz, 1H), 1.28 (d, J = 6.5 Hz, 3H), 0.35 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 151.4, 133.8, 129.0, 127.8, 125.9, 105.4, 70.4, 22.9, −2.8.

(±)-(*E*)-1-(*tert*-Butyldimethylsilyl)-1-buten-3-ol (19b). Using the procedure given for **19a** with alcohol **15b** provided **19b**, after purification by flash chromatography (10:90 EtOAc/hexanes), as a yellow oil (7.1 g, 100%). Only one stereoisomer was formed as determined using ^{1}H and ^{13}C NMR spectroscopy: ^{1}H NMR ($CDCl_3$, 500 MHz) δ 6.10 (dd, J = 18.5, 5.1 Hz, 1H), 5.83 (dd, J = 18.8, 1.4 Hz, 1H), 4.30 (m, 1H), 1.49 (br s, 1H), 1.27 (d, J = 6.5 Hz, 3H), 0.87 (s, 9H), 0.03 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 151.1, 125.2, 70.6, 26.4, 23.0, 16.4, −6.2; IR (thin film) 3333, 2953, 1620 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{10}H_{22}OSi$ (M$^+$) 186.1440, found 186.1440. Anal. Calcd for $C_{10}H_{22}OSi$: C, 64.45; H, 11.90. Found: C, 64.40; H, 11.94.

(±)-1-(*E*)-(Dimethylphenylsilyl)-1-buten-3-ol *N*-Phenylcarbamate (13a).[70] Phenyl isocyanate (0.875 mL, 8.0 mmol) was added to neat alcohol **19a** (1.66 g, 8.05 mmol). After the mixture was stirred for 24 h, the resultant off-white solid was diluted with hot hexanes, and the slurry was filtered. The filtrate was concentrated in vacuo to provide an orange-yellow oil. Purification by flash chromatography (2:98 to 5:95 EtOAc/hexanes) provided **13a** as a pale yellow oil that solidified on standing (2.14 g, 82%): mp 56−57 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.50−7.52 (m, 2H), 7.26−7.49 (m, 7H), 7.02−7.04 (m, 1H), 6.71 (br s, 1H), 6.12 (dd, J = 18.8, 4.6 Hz, 1H), 6.04 (dd, J = 18.8, 1.2 Hz, 1H), 5.39 (m, 1H), 1.36 (d, J = 6.4 Hz, 3H), 0.34 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.8, 146.7, 138.2, 137.9, 133.8, 129.05, 129.01, 128.3, 127.8, 123.3, 118.6, 73.0, 20.0, −2.7; IR (thin film) 3321, 3068, 2957, 1706 cm^{-1}; HRMS (CI/NH_3) *m*/*z* calcd for $C_{19}H_{27}N_2O_2Si$ (M + NH_4)$^+$ 343.1842, found 343.1845. Anal. Calcd for $C_{19}H_{23}NO_2Si$: C, 70.11; H, 7.12; N, 4.30. Found: C, 70.06; H, 7.21; N, 4.29.

(±)-1-(*E*)-(*tert*-Butyldimethylsilyl)-1-buten-3-ol *N*-Phenylcarbamate (13b). Using the procedure given for **13a** with alcohol **19b** provided **13b**, after purification by flash chromatography (2:98 to 5:95 EtOAc/hexanes), as a white solid (6.15 g, 58%): mp 103−104 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.35−7.39 (m, 2H), 7.28−7.32 (m, 2H), 7.04−7.07 (m, 1H), 6.54 (br s, 1H), 6.07 (dd, J = 18.9, 5.0 Hz, 1H), 5.90 (dd, J = 18.9, 1.4 Hz, 1H), 5.36 (m, 1H), 1.37 (d, J = 6.5 Hz, 3H), 0.87 (s, 9H), 0.39 (s, 3H), 0.37 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.8, 146.2, 138.0, 129.0, 127.8, 123.3, 118.6, 73.3, 26.4, 20.2, 16.4, −6.3; IR (thin film) 3296, 2952, 1702 cm^{-1}; HRMS (CI/NH_3) *m*/*z* calcd for $C_{17}H_{27}NO_2Si$ (M$^+$) 305.1811, found 305.1819.

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(69) Panek, J. S.; Sparks, M. A. *Tetrahedron*: *Asymmetry* **1990**, *1*, 801−816.

(70) McElvain's procedure for carbamate preparation was followed: McElvain, S. M. *The Characterization of Organic Compounds*; MacMillan: New York, 1953; p 199.

Anal. Calcd for $C_{17}H_{27}NO_2Si$: C, 66.84; H, 8.91; N, 4.58. Found: C, 66.63; H, 8.98; N, 4.59.

(±)-(*Z*)-3-[1-(Dimethylphenylsilyl)-1-butenyl] Acetate (27). To a cooled (0 °C) solution of BH_3·SMe_2 (0.340 mL, 3.58 mmol) in 3.6 mL of THF was added cyclohexene (0.725 mL, 7.16 mmol). The reaction mixture was allowed to warm to 22 °C and gradually became milky white. After 2.5 h, the reaction mixture was cooled to 0 °C, and a solution of propargylic acetate **17**[37] (586 mg, 2.38 mmol) in 2 mL of THF was added dropwise. The reaction mixture was allowed to warm to 22 °C and gradually became clear and colorless. After 3.5 h, the reaction mixture was cooled to 0 °C, and AcOH (glacial, 0.340 mL, 5.94 mmol) was added dropwise. The reaction mixture was allowed to warm to 22 °C. After 20 h, the reaction mixture was poured into 20 mL of saturated aqueous $NaHCO_3$ and diluted with 50 mL of Et_2O. The layers were separated, and the aqueous layer was extracted with 3 × 50 mL of Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated in vacuo. Purification by flash chromatography (5:95 EtOAc/pentane) provided **27** as a colorless oil (543 mg, 92%) with an *E*/*Z* ratio of 2:98 as indicated by capillary GC analysis of the unpurified reaction mixture. The spectral data were identical to that reported in the literature:[37] GC t_R 4.2 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.49−7.56 (m, 2H), 7.34−7.37 (m, 3H), 6.30 (dd, J = 14.4, 8.8 Hz, 1H), 5.82 (dd, J = 14.4, 0.8 Hz, 1H), 5.37 (dqd, J = 8.8, 6.4, 0.8 Hz, 1H), 1.95 (s, 3H), 1.15 (d, J = 6.4 Hz, 3H), 0.41 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 170.0, 147.7, 138.7, 133.7, 130.1, 129.0, 127.8, 21.2, 20.5, −1.0, −1.3.

(±)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-ol (28a). A solution of **27** (540 mg, 2.17 mmol) in 10 mL of MeOH was treated with K_2CO_3 (saturated, 2:1 MeOH/H_2O, 1.2 mL). The resultant mixture was stirred for 3 h. The reaction mixture was concentrated in vacuo to an orange slurry that was diluted with 50 mL of Et_2O. The mixture was washed with 25 mL of saturated aqueous NH_4Cl. The layers were separated, and the aqueous layer was washed with 3 × 50 mL of Et_2O. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated in vacuo to provide a yellow oil. Purification by flash chromatography (10:90 EtOAc/hexanes) provided **28a** as a colorless oil (404 mg, 90%). The spectral data were identical to that reported in the literature:[37] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.51−7.56 (m, 2H), 7.35−7.38 (m, 3H), 6.36 (dd, J = 14.1, 8.6 Hz, 1H), 5.76 (dd, J = 14.1, 0.7 Hz, 1H), 4.30 (m, 1H), 1.36 (br s, 1H), 1.14 (d, J = 6.3 Hz, 3H), 0.40 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.7, 139.3, 133.5, 129.1, 128.2, 128.0, 68.5, 22.8, −0.7, −0.8.

(±)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-ol *N*-Phenylcarbamate (18a). Using the procedure given for **13a** with allylic alcohol **28a** provided **18a**, after purification by flash chromatography (5:95 to 10:90 EtOAc/hexanes), as a white solid (330 mg, 84%): mp 40 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.56−7.58 (m, 2H), 7.35−7.38 (m, 3H), 7.28−7.32 (m, 4H), 7.02−7.05 (m, 1H), 6.37 (dd, J = 14.5, 8.2 Hz, 1H), 6.28 (br s, 1H), 5.85 (d, J = 14.4 Hz, 1H), 5.40 (m, 1H), 1.23 (d, J = 6.4 Hz, 3H), 0.48 (s, 3H), 0.43 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.5, 147.9, 139.0, 137.9, 133.7, 129.8, 129.0, 128.9, 127.9, 123.2, 118.5, 71.9, 20.8, −0.97, −1.02; IR (thin film) 3292, 3050, 2958, 1725 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{19}H_{23}NO_2Si$ (M^+) 325.1498, found 325.1493. Anal. Calcd for $C_{19}H_{23}NO_2Si$: C, 70.11; H, 7.12; N, 4.30. Found: C, 70.35; H, 7.15; N, 4.40.

(±)-(*Z*)-1-(*tert*-Butyldimethylsilyl)-1-buten-3-ol (28b). To a cooled (0 °C) solution of BH_3·SMe_2 (3.0 mL, 31.6 mmol) in 30 mL of THF was added cyclohexene (6.5 mL, 64.2 mmol). The reaction mixture was allowed to warm to 22 °C and gradually became milky white. After 2.5 h, the reaction mixture was cooled to 0 °C, and **15b** (5.74 g, 21.4 mmol) was added dropwise. The reaction mixture was allowed to warm to 22 °C and gradually became clear and colorless. After 3.5 h, the reaction mixture was cooled to 0 °C and AcOH (glacial, 3.1 mL, 54.2 mmol) was added dropwise. The reaction mixture was allowed to warm to 22 °C. After 20 h, the reaction mixture was poured into 100 mL of saturated aqueous $NaHCO_3$ and diluted with 100 mL of Et_2O. The layers were separated, and the aqueous layer was extracted with 3 × 100 mL of Et_2O. The combined organic layers were washed with brine, dried (Na_2SO_4), filtered, and concentrated in vacuo. The resultant pale yellow slurry was diluted with 70 mL of MeOH, and TsOH (81 mg, 0.43 mmol) was added. The reaction mixture was stirred for 12 h and then concentrated in vacuo. The resultant yellow oil was diluted with 100 mL of Et_2O and washed with 50 mL of saturated aqueous $NaHCO_3$. The layers were separated, and the aqueous layer was extracted with 3 × 100 mL of Et_2O. The combined organic layers were washed with brine, dried (Na_2SO_4), filtered, and concentrated in vacuo. Purification by flash chromatography (10:90 EtOAc/pentane) provided **28b** as a colorless oil (2.3 g, 58%) with an *E*/*Z* ratio of 11:89 as indicated by capillary GC analysis of the unpurified reaction mixture: GC t_R 7.3 min (DB-1, 60−150 °C at 5 °C/min, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 6.33 (dd, J = 14.3, 9.1 Hz, 1H), 5.61 (dd, J = 14.3, 0.7 Hz, 1H), 4.42 (m, 1H), 1.40 (br s, 1H), 1.26 (d, J = 6.2 Hz, 3H), 0.89 (s, 9H), 0.12 (s, 3H), 0.11 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.1, 127.6, 68.5, 26.3, 23.0, 16.5, −3.9, −4.0; IR (thin film) 3341, 1613 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_6H_{13}OSi$ ($M - CMe_3$)$^+$ 129.0731, found 129.0733.

(±)-(*Z*)-1-(*tert*-Butyldimethylsilyl)-1-buten-3-ol *N*-Phenylcarbamate (18b). Using the procedure given for **13a** with allylic alcohol **28b** provided **18b**, after purification by flash chromatography (5:95 to 10:90 EtOAc/hexanes), as a white solid (1.90 g, 96%): mp 98−99 °C; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.37−7.40 (m, 2H), 7.28−7.31 (m, 2H), 7.03−7.07 (m, 1H), 6.54 (br s, 1H), 6.35 (dd, J = 14.5, 9.2 Hz, 1H), 5.73 (d, J = 14.5 Hz, 1H), 5.48 (m, 1H), 1.36 (d, J = 6.3 Hz, 3H), 0.90 (s, 9H), 0.18 (s, 3H), 0.17 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 152.7, 147.2, 138.0, 129.7, 129.0, 123.2, 118.6, 72.1, 26.3, 20.1, 16.5, −4.2, −4.5; IR (thin film) 3292, 2952, 1697 cm^{-1}; HRMS (LSIMS) *m*/*z* calcd for $C_{17}H_{28}NO_2Si$ ($M + H$)$^+$ 306.1889, found 306.1884. Anal. Calcd for $C_{17}H_{27}NO_2Si$: C, 66.84; H, 8.91; N, 4.58. Found: C, 66.99; H, 8.98; N, 4.63.

Copper-Mediated Reaction of Allylic Carbamate 13a Using CuI·2LiCl: (±)-(*Z*)-2-(Dimethylphenylsilyl)-1-(trimethylsilyl)-3-pentene [(*Z*)-3b]. To a cooled (−78 °C) solution of carbamate **13a** (150 mg, 0.46 mmol) in 1.2 mL of THF was added dropwise by syringe *n*-BuLi (1.30 M solution in hexanes, 0.355 mL, 0.46 mmol). After 5 min, the transparent yellow-orange reaction mixture was added dropwise by cannula to a cooled (−78 °C) solution of CuI·2LiCl [prepared by stirring CuI (90 mg, 0.47 mmol) and LiCl (39 mg, 0.92 mmol) in 2.3 mL of THF at 22 °C for 10 min]. After 30 min, (trimethylsilyl)methylmagnesium chloride (0.69 M solution in THF, 0.670 mL, 0.46 mmol) was added dropwise by syringe, and the reaction mixture was allowed to warm to 22 °C without removing the cold bath. After 16.5 h, the reaction mixture was submitted to aqueous workup as described for the reaction of **13a** using CuI. Purification by flash chromatography (pentane) provided (*Z*)-**3b** as a colorless oil (105 mg, 82%) with an *E*/*Z* ratio of 6:94 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was identical to a sample of (*Z*)-**3b** prepared from **13a** using CuI by ^{1}H and ^{13}C NMR spectroscopic analyses (vide supra).

Reaction of 13a with (Trimethylsilyl)methylmagnesium Chloride in the Absence of Copper(I). To a cooled (−78 °C) solution of carbamate **13a** (254 mg, 0.78 mmol) in 3 mL of THF was added dropwise by syringe *n*-BuLi (1.34 M solution in hexanes, 0.582 mL, 0.78 mmol). After 5 min, (trimethylsilyl)methylmagnesium chloride (1.1 M solution in THF, 0.730 mL, 0.8 mmol) was added dropwise by syringe, and the reaction mixture was allowed to warm to 22 °C without removing the cold bath. After 20 h, the reaction mixture was submitted to aqueous workup as described for the reaction of **13a** using CuI. Purification by flash chromatography (pentane to 10:90 EtOAc/hexanes) provided vinylsilane **10** (11 mg, 5%), recovered **13a** (181 mg, 71%), and alcohol **19a** (35 mg, 22%). **Vinylsilane 10:** GC t_R 6.6 min (DB-1, 175 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.52−7.54 (m, 2H), 7.35−7.36 (m, 3H), 6.05 (dd, J = 18.5, 7.0 Hz, 1H), 5.68 (dd, J = 18.7, 1.2 Hz,

1H), 2.38 (m, 1H), 1.05 (d, $J = 6.8$ Hz, 3H), 0.70 (dd, $J = 14.5$, 7.4 Hz, 1H), 0.59 (dd, $J = 14.5$, 7.0 Hz, 1H), 0.33 (s, 6H), 0.01 (s, 9H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 157.0, 139.4, 133.8, 128.8, 127.7, 123.0, 37.0, 24.7, 23.6, −0.6, −2.4; IR (thin film) 3069, 2955, 1612 cm^{-1}; HRMS (CI/isobutane) *m/z* calcd for $C_{16}H_{28}Si_2$ (M^+) 276.1729, found 276.1723. Anal. Calcd for $C_{16}H_{28}Si_2$: C, 69.49; H, 10.20. Found: C, 69.40; H, 10.26.

Optimized Procedure for the Copper-Mediated Reaction of Allylic Carbamate 13a: (±)-(*Z*)-4-(Dimethylphenylsilyl)-2-methyl-5-heptene [(*Z*)-3c]. To a cooled (−78 °C) solution of carbamate **13a** (254 mg, 0.78 mmol) in 1.5 mL of THF was added dropwise by syringe *n*-BuLi (1.26 M solution in hexanes, 0.620 mL, 0.78 mmol). After 5 min, the transparent yellow-orange reaction mixture was added dropwise by cannula to a cooled (−78 °C) solution of CuI·2LiCl [prepared by stirring CuI (151 mg, 0.79 mmol) and LiCl (67 mg, 1.6 mmol) in 3 mL of THF at 22 °C for 10 min]. After 30 min, isobutylmagnesium chloride (0.87 M solution in THF, 1.08 mL, 0.94 mmol) was added dropwise by syringe, and the reaction mixture was allowed to warm to 22 °C without removing the cold bath. After 16.5 h, the reaction mixture was submitted to aqueous workup as described for the reaction of **13a** using CuI. Purification by flash chromatography (pentane) provided (*Z*)-**3c** as a colorless oil (133 mg, 69%) with an *E*/*Z* ratio of 7:93 as indicated by capillary GC analysis of the unpurified reaction mixture. The γ/α ratio was determined to be ≥95:5 by the ^{1}H NMR spectroscopic analysis of the unpurified reaction mixture. The major isomer was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons ($J = 10.9$ Hz): GC t_R 4.5 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.47−7.51 (m, 2H), 7.32−7.36 (m, 3H), 5.37 (dq, $J = 10.9$, 6.7 Hz, 1H), 5.11 (m, 1H), 2.15 (app dt, $J = 11.6$, 2.7 Hz, 1H), 1.53 (m, 1H), 1.46 (dd, $J = 6.8$, 1.7 Hz, 3H), 1.30 (m, 1H), 1.12 (ddd, $J = 13.4$, 10.4, 2.9 Hz, 1H), 0.82 (d, $J = 6.6$ Hz, 3H), 0.76 (d, $J = 6.6$ Hz, 3H), 0.27 (s, 3H), 0.25 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.1, 134.1, 132.2, 128.8, 127.5, 121.5, 38.8, 26.8, 25.5, 23.8, 20.7, 13.1, −4.4, −5.2; IR (thin film) 3050, 2954, 1644 cm^{-1}; HRMS (EI-GCMS) *m/z* calcd for $C_{16}H_{26}Si$ (M^+) 246.1803, found 246.1805. Anal. Calcd for $C_{16}H_{26}Si$: C, 78.29; H, 10.27. Found: C, 78.01; H, 10.56.

(±)-(*Z*)-2-(Dimethylphenylsilyl)-3-pentene [(*Z*)-3d]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and methylmagnesium chloride provided (*Z*)-**3d**, after purification by flash chromatography (pentane), as a colorless oil (163 mg, 80%) with an *E*/*Z* ratio of 26:74 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. Spectral data of the major isomer was identical to that reported in the literature for the (*Z*)-isomer:[28] GC t_R 4.6 min (DB-1, 125 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.48−7.53 (m, 2H), 7.32−7.37 (m, 3H), 5.33 (dqd, $J = 10.7$, 6.7, 0.8 Hz, 1H), 5.20 (tq, $J = 10.8$, 1.7 Hz, 1H), 2.10 (dqd, $J = 10.9$, 7.2, 0.6 Hz, 1H), 1.47 (dd, $J = 6.7$, 1.7 Hz, 3H), 1.00 (d, $J = 7.2$ Hz, 3H), 0.27 (s, 3H), 0.26 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.0, 134.0, 133.6, 128.8, 127.5, 120.6, 21.2, 15.2, 13.1, −4.7, −5.5.

(±)-(*E*)-2-(Dimethylphenylsilyl)-3-pentene [(*E*)-3d]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and methyllithium provided (*E*)-**3d**, after purification by flash chromatography (pentane), as a colorless oil (182 mg, 72%) with an *E*/*Z* ratio of 92:8 and a γ/α ratio of 94:6 as indicated by capillary GC analysis of the unpurified reaction mixture. Spectral data of the major isomer (*E*)-**3d** was identical to that reported in the literature for the (*E*)-isomer:[28] GC t_R 4.4 min (DB-1, 125 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.47−7.49 (m, 2H), 7.29−7.34, (m, 3H), 5.42 (dd, $J = 15.1$, 8.0 Hz, 1H), 5.21 (dq, $J = 15.1$, 6.4 Hz, 1H), 1.74 (m, 1H), 1.64 (d, $J = 6.4$ Hz, 3H), 1.00 (d, $J = 7.2$ Hz, 3H), 0.24 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.2, 134.0, 133.4, 128.8, 127.5, 121.3, 25.5, 18.2, 13.9, −4.8, −5.4.

(±)-(*Z*)-1,2-Bis(dimethylphenylsilyl)-3-pentene [(*Z*)-3a]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and (dimethylphenylsilyl)methylmagnesium chloride provided (*Z*)-**3a**, after purification by flash chromatography (pentane), as a colorless oil (136 mg, 68%) with an *E*/*Z* ratio of 4:96 and a γ/α ratio of 99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons ($J = 10.8$ Hz): GC t_R 6.6 min (DB-1, 200 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.44−7.46 (m, 2H), 7.39−7.41 (m, 2H), 7.30−7.34 (m, 6H), 5.25 (dqd, $J = 10.7$, 6.8, 0.8 Hz, 1H), 5.09 (app tq, $J = 10.8$, 1.7 Hz, 1H), 2.07 (m, 1H), 1.34 (dd, $J = 6.8$, 2.0 Hz, 3H), 0.90 (dd, $J = 14.7$, 2.0 Hz, 1H), 0.68 (dd, $J = 14.9$, 12.1 Hz, 1H), 0.24 (s, 3H), 0.21 (s, 3H), 0.20 (s, 3H), 0.18 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 139.8, 138.0, 134.1, 133.7, 133.6, 128.8, 128.6, 127.6, 127.5, 120.7, 22.3, 15.3, 13.2, −1.8, −3.0, −4.7, −5.7; IR (thin film) 3006, 2955 cm^{-1}; HRMS (CI/isobutane) *m/z* calcd for $C_{21}H_{30}Si_2$ (M^+) 338.1886, found 338.1880. Anal. Calcd for $C_{21}H_{30}Si_2$: C, 74.48; H, 8.93. Found: C, 74.60; H, 8.96.

(±)-(*E*)-1,2-Bis(dimethylphenylsilyl)-3-pentene [(*E*)-3a]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and (dimethylphenylsilyl)methyllithium provided (*E*)-**3a**, after purification by flash chromatography (pentane), as a colorless oil (105 mg, 68%) with an *E*/*Z* ratio of 72:28 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was assigned as the (*E*)-alkene by comparison of ^{1}H NMR spectroscopic and capillary GC data to that of the reference compound prepared by Hayashi−Kumada coupling using *trans*-bromopropene:[71] GC t_R 5.9 min (DB-1, 200 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.42−7.46 (m, 2H), 7.35−7.40 (m, 2H), 7.29−7.34 (m, 6H), 5.12 (m, 2H), 1.74 (m, 1H), 1.57 (d, $J = 4.9$ Hz, 3H), 0.82 (dd, $J = 14.9$, 2.2 Hz, 1H), 0.72 (dd, $J = 14.9$, 12.3 Hz, 1H), 0.22 (s, 3H), 0.20 (s, 3H), 0.19 (s, 3H), 0.18 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 140.1, 138.1, 134.1, 133.6, 133.3, 128.7, 128.5, 127.53, 127.49, 122.4, 27.1, 17.9, 14.4, −1.8, −2.7, −4.6, −5.7; IR (thin film) 3010, 2956 cm^{-1}; HRMS (EI-GCMS) *m/z* calcd for $C_{21}H_{30}Si_2$ (M^+) 338.1886, found 338.1892. Anal. Calcd for $C_{21}H_{30}Si_2$: C, 74.48; H, 8.93. Found: C, 74.63; H, 8.83.

(±)-(*E*)-4-(Dimethylphenylsilyl)-2-methyl-5-heptene [(*E*)-3c]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and isobutyllithium provided (*E*)-**3c**, after purification by flash chromatography (pentane), as a colorless oil with an *E*/*Z* ratio of 91:9 and a γ/α ratio of 99:1 as indicated by capillary GC analysis of the unpurified reaction mixture (77 mg, 69%). The major isomer was assigned as the (*E*)-alkene by the value of the coupling constant of the olefinic protons ($J = 15.2$ Hz): GC t_R 4.2 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.47−7.51 (m, 2H), 7.32−7.36 (m, 3H), 5.22 (dq, $J = 15.2$, 5.9 Hz, 1H), 5.19 (ddq, $J = 15.2$, 8.9, 1.1 Hz, 1H), 1.77 (ddd, $J = 12.1$, 9.1, 2.9 Hz, 1H), 1.64 (d, $J = 5.4$ Hz, 3H), 1.57 (m, 1H), 1.32 (ddd, $J = 13.5$, 12.3, 3.6 Hz, 1H), 1.04 (ddd, $J = 13.5$, 10.3, 3.1 Hz, 1H), 0.82 (d, $J = 6.7$ Hz, 3H), 0.74 (d, $J = 6.5$ Hz, 3H), 0.24 (s, 3H), 0.23 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 138.3, 134.1, 131.9, 128.7, 127.5, 122.9, 38.0, 30.2, 26.3, 23.9, 20.6, 18.1, −4.3, −5.1; IR (thin film) 3050, 2954, 1657 cm^{-1}; HRMS (EI-GCMS) *m/z* calcd for $C_{16}H_{26}Si$ (M^+) 246.1803, found 246.1798. Anal. Calcd for $C_{16}H_{26}Si$: C, 78.29; H, 10.27. Found: C, 78.01; H, 10.54.

(±)-(*Z*)-3-(Dimethylphenylsilyl)-2-methyl-4-hexene [(*Z*)-3f]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and isopropylmagnesium chloride provided (*Z*)-**3f**, after purification by flash chromatography (pentane), as a colorless oil (142 mg, 71%) with an *E*/*Z* ratio of 13:87 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. Spectral data of the major isomer were identical to those reported in the literature for the (*Z*)-isomer:[72] GC t_R 4.0 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.51−7.53 (m, 2H), 7.32−7.34 (m, 3H), 5.49 (dq, $J = 11.0$, 6.6 Hz, 1H), 5.35 (m, 1H), 2.01 (dd, $J = 11.9$, 5.1 Hz, 1H), 1.84 (m, 1H), 1.45 (dd, $J = 6.7$, 1.7 Hz, 3H), 0.84 (d, $J = 2.3$ Hz, 3H), 0.82 (d, $J = 2.4$ Hz, 3H), 0.30 (s, 3H), 0.27 (s,

(71) Details are provided as Supporting Information.

(72) Fleming, I.; Gil, S.; Sarkar, A. K.; Schmidlin, T. *J. Chem. Soc., Perkin Trans. 1* **1992**, 3351−3361.

3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 139.2, 133.9, 128.8, 128.7, 127.5, 123.0, 35.0, 28.9, 23.9, 20.6, 13.0, −2.9, −3.7.

(±)-(*Z*)-3-(Dimethylphenylsilyl)-2,2-dimethyl-4-hexene [(*Z*)-3g]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and *tert*-butylmagnesium chloride provided (*Z*)-**3g**, after purification by flash chromatography (pentane), as a colorless oil (135 mg, 54%) with an *E*/*Z* ratio of 7:93 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons (J = 11.0 Hz): GC t_R 4.9 min (DB-1, 150 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.50−7.55 (m, 2H), 7.30−7.32 (m, 3H), 5.46 (dq, J = 11.0, 6.3 Hz, 1H), 5.41 (m, 1H), 2.02 (d, J = 9.9 Hz, 1H), 1.37 (d, J = 5.0 Hz, 3H), 0.86 (s, 9H), 0.36 (s, 3H), 0.30 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 140.2, 134.1, 129.8, 128.5, 127.4, 123.0, 40.3, 34.0, 30.5, 12.8, −1.4, −1.6; IR (thin film) 3010, 2955, 1642 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{16}H_{26}Si$ (M^+) 246.1804, found 246.1815.

(±)-1-(Dimethylphenylsilyl)-1-phenyl-2-butene (3h). Using the optimized procedure given for (*Z*)-**3c** with carbamate **13a** and phenylmagnesium chloride provided **3h**, after purification by flash chromatography (pentane), as a colorless oil (151 mg, 57%) with an *E*/*Z* ratio of 58:42 and a γ/α ratio of 97:3 as indicated by capillary GC analysis of the unpurified reaction mixture. Spectral data were identical to that reported in the literature for the (*E*)-isomer[28] and (*Z*)-isomer:[72] GC (*E*)-**3h**: t_R 7.9 min, (*Z*)-**3h**: t_R 8.1 min (DB-1, 5 min at 150 °C then ramped at 20 °C/min to 250 °C, 16 psi).

(±)-(*Z*)-4-(*tert*-Butyldimethylsilyl)-2-methyl-5-heptene [(*Z*)-8b]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13b** and isobutylmagnesium chloride provided (*Z*)-**8b**, after purification by flash chromatography (pentane), as a colorless oil (140 mg, 95%) with an *E*/*Z* ratio of 7:93 and a γ/α ratio of 97:3 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons (J = 10.8 Hz): GC t_R 3.4 min (DB-1, 125 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 5.32 (dq, J = 10.8, 6.7 Hz, 1H), 5.17 (m, 1H), 2.09 (m, 1H), 1.59 (d, J = 6.6 Hz, 3H), 1.51 (m, 1H), 1.33 (m, 1H), 1.20 (m, 1H), 0.91 (s, 9H), 0.86 (d, J = 6.5 Hz, 3H), 0.81 (d, J = 6.5 Hz, 3H), −0.07 (s, 3H), −0.09 (s, 3H);^{13}C NMR ($CDCl_3$, 125 MHz) δ 133.5, 120.6, 39.9, 27.4, 26.7, 24.1, 23.5, 20.8, 17.7, 13.3, −7.0, −7.3; IR (thin film) 2954, 1645 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{14}H_{30}Si$ (M^+) 226.2117, found 226.2115. Anal. Calcd for $C_{14}H_{30}Si$: C, 74.25; H, 13.35. Found: C, 74.29; H, 13.39.

(±)-(*E*)-4-(*tert*-Butyldimethylsilyl)-2-methyl-5-heptene [(*E*)-8b]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13b** and isobutyllithium provided (*E*)-**8b**, after purification by flash chromatography (pentane), as a colorless oil (175 mg, 77%) with an *E*/*Z* ratio of 91:9 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture: GC t_R 3.1 min (DB-1, 125 °C, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 5.20 (m, 2H), 1.71 (m, 1H), 1.64 (d, J = 4.8 Hz, 3H), 1.57 (m, 1H), 1.34 (m, 1H), 1.10 (m, 1H), 0.89 (s, 9H), 0.86 (d, J = 6.7 Hz, 3H), 0.78 (d, J = 6.5 Hz, 3H), −0.09 (s, 3H), −0.10 (s, 3H);^{13}C NMR ($CDCl_3$, 125 MHz) δ 133.2, 122.3, 39.0, 28.7, 26.1, 24.1, 20.5, 18.0, 17.7, −7.1; IR (thin film) 2956, 1659 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{14}H_{30}Si$ (M^+) 226.2117, found 226.2122. Anal. Calcd for $C_{14}H_{30}Si$: C, 74.25; H, 13.35. Found: C, 74.41; H, 13.44.

(±)-(*Z*)-2-(*tert*-Butyldimethylsilyl)-1-(trimethylsilyl)-3-pentene [(*Z*)-8c]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13b** and (trimethylsilyl)methylmagnesium provided (*Z*)-**8c**, after purification by flash chromatography (pentane), as a colorless oil (198 mg, 78%) with an *E*/*Z* ratio of 6:94 and a γ:α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture: GC t_R 6.0 min (DB-1, 100 °C to 250 °C at 5 °C/min, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 5.21 (m, 2H), 2.10 (m, 1H), 1.59 (d, J = 5.0 Hz, 3H), 0.91 (s, 9H), 0.73 (dd, J = 14.8, 2.0 Hz, 1H), 0.54 (dd, J = 14.8, 12.0 Hz, 1H), −0.03 (s, 9H), −0.07 (s, 3H), −0.10 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 135.4, 119.3, 27.6, 20.6, 17.9, 17.6, 13.6, −0.9, −7.2, −7.4; IR (thin film) 2929, 1643 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd $C_{14}H_{32}Si_2$ (M^+) 256.2042, found 256.2043. Anal. Calcd for $C_{14}H_{32}Si_2$: C, 65.54; H, 12.57. Found: C, 65.27; H, 12.41.

(±)-(*E*)-2-(*tert*-Butyldimethylsilyl)-1-(trimethylsilyl)-3-pentene [(*E*)-8c]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **13b** and (trimethylsilyl)methyllithium provided (*E*)-**8c**, after purification by flash chromatography (pentane), as a colorless oil (192 mg, 75%) with an *E*/*Z* ratio of 76:24 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. The major isomer was assigned as the (*Z*)-alkene by the value of the coupling constant of the olefinic protons (J = 15.1 Hz): GC t_R 5.4 min (DB-1, 100 °C to 250 °C at 5 °C/min, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 5.23 (m, 1H), 5.19 (dd, H = 15.1, 5.8 Hz, 1H), 1.71 (ddd, J = 11.8, 9.1, 2.7 Hz, 1H), 1.62 (d, J = 5.1 Hz, 3H), 0.89 (s, 9H), 0.63 (dd, J = 14.9, 2.6 Hz, 1H), 0.56 (dd, J = 14.8, 11.9 Hz, 1H), −0.04 (s, 9H), −0.09 (s, 3H), −0.10 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 135.1, 121.4, 27.5, 25.9, 17.9, 17.8, 16.5, −0.7, −7.2, −7.6; IR (thin film) 2929, 1643 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd $C_{14}H_{32}Si_2$ (M^+) 256.2042, found 256.2044. Anal. Calcd for $C_{14}H_{32}Si_2$: C, 65.54; H, 12.57. Found: C, 65.56; H, 12.74.

(±)-1-(Dimethylphenylsilyl)-1-phenyl-4-butene [(*E*)-3h]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **18a** and phenyllithium provided (*E*)-**3h**, after purification by flash chromatography (pentane), as a colorless oil (121 mg, 55%) with an *E*/*Z* ratio of >99:1 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture. ^{1}H NMR and ^{13}C NMR spectral data were identical to that of a sample of **3h** prepared from **13a** and to that reported in the literature[28] for the (*E*)-isomer: ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.26−7.36 (m, 5H), 7.15−7.18 (m, 2H), 7.05−7.07 (m, 1H), 6.90−6.95 (m, 2H), 5.71−5.81 (m, 1H), 5.33 (m, 1H), 3.06 (d, J = 9.8 Hz, 1H), 1.66 (dd, J = 6.4, 1.0 Hz, 3H), 0.24 (s, 3H), 0.22 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 142.4, 137.1, 134.3, 129.9, 129.0, 128.1, 127.4, 124.5, 124.0, 42.5, 18.1, −4.3, −4.7.

(±)-(*E*)-3-(*tert*-Butyldimethylsilyl)-2-methyl-4-hexene [(*E*)-8d]. Using the optimized procedure given for (*Z*)-**3c** with carbamate **18b** (11:89 = *E*:*Z*) and isopropylmagnesium chloride provided (*E*)-**8d**, after purification by flash chromatography (pentane), as a colorless oil (180 mg, 85%) with an *E*/*Z* ratio of 90:10 and a γ/α ratio of >99:1 as indicated by capillary GC analysis of the unpurified reaction mixture: GC t_R 2.7 min (DB-1, 5 min at 125 °C then ramped to 250 °C at 10 °C/min, 16 psi); ^{1}H NMR ($CDCl_3$, 500 MHz) δ 5.32 (m, 1H), 5.25 (dq, J = 14.9, 5.9 Hz, 1H), 1.91 (m, 1H), 1.67 (d, J = 5.8 Hz, 3H), 1.56 (dd, J = 10.6, 3.3 Hz, 1H), 0.85−0.88 (m, 15H), −0.02 (s, 3H), −0.05 (s, 3H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 129.3, 125.3, 37.6, 28.5, 27.2, 23.9, 19.8, 18.1, 17.7, −5.7, −6.0; IR (thin film) 2856, 1472 cm^{-1}; HRMS (EI-GCMS) *m*/*z* calcd for $C_{13}H_{28}Si$ (M^+) 212.1960, found 212.1964. Anal. Calcd for $C_{13}H_{28}Si$: C, 73.50; H, 13.28. Found: C, 73.77; H, 13.36.

(*R*)-(*E*)-1-(Dimethylphenylsilyl)-1-buten-3-ol [(*R*)-19a].[50,51] To a cooled (−23 °C) suspension of 4 Å molecular sieves (crushed, 1.2 g) in 13 mL of CH_2Cl_2 was added Ti(O-*i*-Pr)$_4$ (1.23 mL, 4.20 mmol) followed by L-(+)-diisopropyl tartrate (1.05 mL, 5.0 mmol). The resultant mixture was stirred for 30 min at −23 °C. A solution of (±)-**19a** (4.3 g, 20.8 mmol) in 13 mL of CH_2Cl_2 (this solution was kept over molecular sieves for 1 h prior to addition to the reaction mixture) was added to the reaction mixture dropwise by cannula. After being stirred for 1 h at −23 °C, the mixture was cooled to −40 °C, and *tert*-butylhydroperoxide (4.55 M solution in CH_2Cl_2, 2.75 mL, 12.5 mmol) was added dropwise. The reaction mixture was allowed to warm to −25 °C and stirred for 7 h. Dimethyl sulfide (0.920 mL, 12.5 mmol) was added, and the reaction mixture was stirred for 30 min and then allowed to warm to 22 °C. Saturated aqueous potassium sodium tartrate (2.4 mL), Et_2O (2.4 mL), sodium fluoride (14.5 g), and Celite (8.3 g) were added sequentially, and the resultant slurry was stirred for 30 min. The slurry was filtered and washed with 100 mL of CH_2Cl_2. The filtrate was concentrated in vacuo to provide a yellow oil. Purification by flash chromatography (5:95 to 20:80 EtOAc/hexanes) provided (*R*)-**19a** as a pale yellow oil (1.89 g, 44%,

≥94% ee by ^{1}H NMR spectroscopic analysis of the Mosher ester).[71] The spectral data were identical to that reported in the literature:[69] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.51−7.54 (m, 2H), 7.34−7.37 (m, 3H), 6.14 (dd, J = 18.7, 4.9 Hz, 1H), 5.97 (d, J = 18.7 Hz, 1H), 4.32 (m, 1H), 1.55 (d, J = 4.4 Hz, 1H), 1.28 (d, J = 6.5 Hz, 3H), 0.36 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 151.4, 138.5, 133.8, 129.0, 127.8, 125.9, 70.4, 22.9, −2.6; $[\alpha]^{23}_D$ −5.3 (*c* 0.8, $CHCl_3$).

(*R*)-1-(Dimethylphenylsilyl)-1-butene-3-ol *N*-phenylcarbamate [(*R*)-13a]. Using the procedure given for (±)-**13a** with (*R*)-**19a** (1.64 g, 8.0 mmol) and phenyl isocyanate (0.910 mL, 8.7 mmol) provided (*R*)-**13a** as a pale yellow oil (2.32 g, 89%). (*R*)-**13a** was identical to (±)-**13a** by ^{1}H NMR and ^{13}C NMR spectroscopic analyses: $[\alpha]^{23}_D$ +36.8 (*c* 1.0, $CHCl_3$).

(*S*)-(*Z*)-4-(Dimethylphenylsilyl)-2-methyl-5-heptene [(*S*)-(*Z*)-3c]. Using the optimized procedure given for (*Z*)-**3c** with carbamate (*R*)-**13a** (1.23 g, 3.78 mmol), MeLi (1.3 M solution in hexanes, 2.9 mL, 3.8 mmol), CuI (720 mg, 3.78 mmol), LiCl (321 mg, 7.57 mmol), and isobutylmagnesium chloride (1.1 M solution in THF, 4.3 mL, 4.7 mmol) provided (*Z*)-**3c**, after purification by flash chromatography (pentane), as a colorless oil (834 mg, 90%) with an *E*/*Z* ratio of 6:94 and a γ:α ratio of 95:5 as indicated by capillary GC analysis of the unpurified reaction mixture. The ^{1}H and ^{13}C NMR spectroscopic data matched that of a sample of racemic material: $[\alpha]^{23}_D$ +85.1 (*c* 1.02, $CHCl_3$).

(*R*)-2-Methyl-4-(dimethylphenylsilyl)heptane [(*R*)-29]. To a solution of (*S*)-(*Z*)-**3c** (728 mg, 2.95 mmol) in 15 mL of dioxane were added tosylhydrazide (5.5 g, 29.5 mmol) and triethylamine (4.1 mL, 29.4 mmol). The reaction mixture was heated at reflux for 11 h. After the reaction mixture was cooled to 23 °C, additional tosylhydrazide (1.4 g, 7.5 mmol) and triethylamine (1.0 mL, 7.2 mmol) were added, and the reaction mixture was heated to reflux. After 14 h, the reaction mixture was allowed to cool to 22 °C and was diluted with 50 mL of Et_2O. The mixture was washed with saturated aqueous Na_2CO_3. The layers were separated, and the aqueous layer was washed with 3 × 50 mL of Et_2O. The combined organic layers were washed with H_2O and brine, dried (Na_2SO_4), filtered, and concentrated in vacuo. ^{1}H NMR analysis of the unpurified reaction mixture indicated that the reaction was incomplete. The reaction mixture was submitted to flash chromatography (pentane) to remove the sulfur containing impurities, and the recovered material was resubmitted to the hydrogenation conditions using the same amount of reagents listed above. After being heated at reflux for 30 h, the reaction mixture was allowed to cool to 22 °C and was worked up as described above. Purification by flash chromatography provided (*R*)-**29** as a colorless oil (663 mg, 86%): ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.49−7.51 (m, 2H), 7.32−7.34 (m, 3H), 1.55 (m, 1H), 1.15−1.38 (m, 6H), 0.87 (m, 1H), 0.81 (m, 6H), 0.77 (d, J = 6.5 Hz, 3H), 0.25 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 139.4, 133.9, 128.6, 127.6, 39.5, 32.8, 26.7, 23.4, 22.4, 22.3, 21.9, 14.6, −3.8, −3.9; IR (thin film) 3069, 2956 cm^{-1}; $[\alpha]^{23}_D$ +8.0 (*c* 1.01, $CHCl_3$); HRMS (EI-GCMS) *m*/*z* calcd for $C_{15}H_{25}Si$ $(M - CH_3)^+$ 233.1725, found 233.1725. Anal. Calcd for $C_{16}H_{28}Si$: C, 77.34; H, 11.36. Found: C, 77.50; H, 11.28.

(*R*)-2-Methyl-4-heptanol [(*R*)-21]. To a cooled (0 °C) solution of *tert*-butylhydroperoxide (90%, 1.6 mL, 14.4 mmol) in 1.5 mL of *N*-methylpyrrolidinone was added KH (powder, 580 mg, 14.5 mmol) cautiously in five portions.[55] To the resultant foamy reaction mixture was added by syringe a solution of (*R*)-**29** (627 mg, 2.52 mmol) in 1.5 mL of *N*-methylpyrrolidinone. The reaction mixture was allowed to warm to 22 °C and was heated at 90 °C for 16 h. After the reaction mixture was allowed to cool to 22 °C, $Na_2S_2O_3$ (anhydrous, 4.5 g, 27.0 mmol) and 1.0 mL of H_2O were added. After being stirred for 1 h, the reaction mixture was filtered through a pad of SiO_2, washing with 200 mL of 20:80 Et_2O/pentane. The filtrate was washed with 50 mL of 1 M NaOH, dried (Na_2SO_4), filtered, and concentrated in vacuo. Purification by flash chromatography (10:90 Et_2O/pentane) provided **21** as a colorless, volatile oil (172 mg, 51%, 88% ee by ^{1}H NMR spectroscopic analysis of the α-methylbenzylcarbamate).[71] Spectral data were identical to that reported in the literature:[56] ^{1}H NMR ($CDCl_3$, 500 MHz) δ 3.71 (m, 1H), 1.8 (m, 1H), 1.34−1.50 (m, 5H), 1.26 (m, 2H), 0.95 (m, 9H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 69.7, 46.8, 40.3, 24.6, 23.5, 22.0, 18.8, 14.1; $[\alpha]^{23}_D$ −11.9 (*c* 1.04, CH_3OH); literature:[56] $[\alpha]^{23}_D$ −11.9 (*c* 1.04, CH_3OH).

(*R*)-3-[1-(Dimethylphenylsilyl)-1-butynyl] acetate [(*R*)-17]. To a solution of (*R*)-**16a** (2.4 g, 11.7 mmol) in 12 mL of CH_2Cl_2 were added pyridine (0.093 mL, 1.15 mmol), 4-(*N*,*N*-dimethylamino)pyridine (1 mg, 0.008 mmol), and acetic anhydride (0.108 mL, 1.15 mmol). After 12 h, 25 mL of saturated aqueous NH_4Cl and 25 mL of CH_2Cl_2 were added. The layers were separated, and the aqueous layer was washed with 3 × 25 mL of CH_2Cl_2. The combined organic layers were washed with brine, dried ($MgSO_4$), filtered, and concentrated in vacuo to afford a yellow oil. Purification by flash chromatography (5:95 EtOAc/hexanes) provided (*R*)-**17** as a colorless liquid (2.68 g, 93%). The spectral data were identical to that reported in the literature:[37] $[\alpha]^{23}_D$ +104 (*c* 1.46, CH_2Cl_2) [lit.[37] $[\alpha]^{23}_D$ +61.0 (*c* 1.45, CH_2Cl_2)]; ^{1}H NMR ($CDCl_3$, 500 MHz) δ 7.60−7.62 (m, 2H), 7.36−7.39 (m, 3H), 5.51 (q, J = 6.7 Hz, 1H), 2.12 (s, 3H), 1.51 (d, J = 6.9 Hz, 3H), 0.42 (s, 6H); ^{13}C NMR ($CDCl_3$, 125 MHz) δ 169.7, 136.5, 133.6, 129.5, 127.9, 105.3, 87.4, 60.6, 21.4, 21.1, −1.0; IR (thin film) 3070, 2982, 2179, 1748 cm^{-1}; HRMS (CI/isobutane) *m*/*z* calcd for $C_{14}H_{18}O_2Si$ (M^+) 246.1076, found 246.1068. Anal. Calcd for $C_{14}H_{18}O_2Si$: C, 68.25; H, 7.36. Found: C, 68.37; H, 7.37.

(*R*)-(*Z*)-3-[1-(Dimethylphenylsilyl)-1-butenyl] Acetate [(*R*)-27]. Using the procedure given for (±)-**27** with propargylic acetate (*R*)-**17** provided (*R*)-**27** as a colorless liquid (2.41 g, 90%) with an *E*/*Z* ratio of 7:93 as indicated by capillary GC analysis of the unpurified reaction mixture. The product was identical to (±)-**27** by ^{1}H NMR and ^{13}C NMR spectroscopic analyses (vide supra).

(*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-ol [(*R*)-28a]. Using the procedure given for (±)-**28a** with allylic acetate (*R*)-**27** provided (*R*)-**28a**, after two successive purifications with 6% $AgNO_3/SiO_2$, as a colorless liquid (1.35 g, 78%) with an *E*/*Z* ratio of 3:97 as indicated by capillary GC analysis. The product was identical to (±)-**28a** by ^{1}H NMR and ^{13}C NMR spectroscopic analysis: $[\alpha]^{23}_D$ +4.2 (*c* 1.45, $CHCl_3$) [lit.[37] $[\alpha]^{23}_D$ +2.76 (*c* 1.45, $CHCl_3$)].

(*R*)-(*Z*)-1-(Dimethylphenylsilyl)-1-buten-3-ol *N*-Phenylcarbamate [(*R*)-18a]. Using the procedure given for (±)-**13a** with alcohol (*R*)-**28a** provided (*R*)-**18a** as a white solid (1.80 g, 88%). The product was identical to (±)-**18a** by ^{1}H NMR and ^{13}C NMR spectroscopic analyses (vide supra): $[\alpha]^{23}_D$ −76.1 (*c* 1.02, $CHCl_3$).

(*S*)-(*E*)-4-(Dimethylphenylsilyl)-2-methyl-5-heptene [(*S*)-(*E*)-3c]. Using the optimized procedure given for (*Z*)-**3c** with carbamate (*R*)-**18a** (850 mg, 2.61 mmol), MeLi (1.1 M solution in Et_2O, 2.4 mL, 2.6 mmol), CuI (500 mg, 2.6 mmol), LiCl (223 mg, 5.3 mmol), and isobutylmagnesium chloride (1.0 M solution in THF, 2.6 mL, 2.6 mmol) provided (*S*)-(*E*)-**3c**, after purification by flash chromatography (pentane), as a colorless oil (600 mg, 93%) with an *E*/*Z* ratio of 3:97 and a γ/α ratio of 98:2 as indicated by capillary GC analysis of the unpurified reaction mixture. The product was identical to a sample of (±)-(*E*)-**3c** prepared from (±)-**18a** by ^{1}H and ^{13}C NMR spectroscopic analysis (vide supra): $[\alpha]^{23}_D$ +28.3 (*c* 1.03, $CHCl_3$).

(*R*)-2-Methyl-4-(dimethylphenylsilyl)-heptane [(*R*)-29]. To a solution of (*S*)-(*E*)-**3c** (570 mg, 2.31 mmol) in 23 mL of dioxane was added tosylhydrazide (4.3 g, 23.1 mmol) and triethylamine (3.2 mL, 23.0 mmol).[54] The reaction mixture was heated at reflux for 24 h. After the reaction mixture was cooled to 23 °C, additional tosylhydrazide (2.2 g, 11.5 mmol) and triethylamine (1.6 mL, 11.5 mmol) were added, and the reaction mixture was heated to reflux. After 10 h, the reaction mixture was allowed to cool to 22 °C and was diluted with 75 mL of Et_2O. The mixture was washed with saturated aqueous $NaHCO_3$ (20 mL). The layers were separated and the aqueous layer was extracted with 3 × 50 mL of hexanes. The combined organic layers were washed with H_2O and brine (20 mL each), dried (Na_2SO_4), filtered, and concentrated in vacuo. Purification by flash chromatography (pentane) provided **29** as a colorless liquid (556 mg, 97%). The product was identical to a

sample of **29** prepared from (*S*)-(*Z*)-**3c** by ^{1}H and ^{13}C NMR spectroscopic analyses (vide supra): $[\alpha]^{23}_D$ +13.2 (*c* 1.01, $CHCl_3$).

(*R*)-2-Methyl-4-heptanol [(*R*)-21]. Using the procedure given for (*R*)-**21** derived from carbamate (*R*)-**13a** with silane (*R*)-**29** provided the product as a colorless, volatile oil (127 mg, 45%, 92% ee by ^{1}H NMR spectroscopic analysis of the α-methylbenzylcarbamate).[71] ^{1}H and ^{13}C NMR spectral data were identical to that reported in the literature[56] and to that of a sample of (*R*)-**21** derived from allylic carbamate (*R*)-**13a**: $[\alpha]^{23}_D$ −10.6 (*c* 1.03, CH_3OH).

(*S*)-(*E*)-4-(Dimethylphenylsilyl)-2-methyl-5-heptene [(*S*)-(*E*)-3c]. The optimized procedure given for (*Z*)-**3c** with carbamate (*R*)-**18a** (793 mg, 2.44 mmol), MeLi (1.3 M solution in Et_2O, 1.9 mL, 2.5 mmol), CuI (465 mg, 2.4 mmol), LiCl (210 mg, 5.0 mmol), and isobutyllithium (0.5 M solution in Et_2O/pentane, 4.9 mL, 2.5 mmol) was used. The product (*S*)-(*E*)-**3c** was obtained, after purification by flash chromatography (pentane), as a colorless oil (561 mg, 93%) with an *E*/*Z* ratio of >99:1 and a γ/α ratio of 100:0 as indicated by capillary GC analysis of the unpurified reaction mixture. The product was identical to (±)-(*E*)-**3c** prepared from (±)-**18a** by ^{1}H NMR and ^{13}C NMR spectroscopic analyses (vide supra): $[\alpha]^{23}_D$ +33.7 (*c* 1.03, $CHCl_3$).

(*R*)-2-Methyl-4-(dimethylphenylsilyl)heptane [(*R*)-29]. The procedure described for the previous synthesis of (*R*)-**29** was used on the sample of (*S*)-(*E*)-**3c** prepared in the previous procedure. Purification by flash chromatography (pentane) provided (*R*)-**29** as a colorless liquid (518 mg, 97%). The product was identical to a sample of (*R*)-**29** prepared from allylic silane (*S*)-(*Z*)-**3c** by ^{1}H and ^{13}C NMR spectroscopic analyses (vide supra): $[\alpha]^{23}_D$ +15.3 (*c* 1.01, $CHCl_3$).

(*R*)-2-Methyl-4-heptanol [(*R*)-21]. Using the procedure given for (*R*)-**21** derived from carbamate (*R*)-**13a** with silane (*R*)-**29** provided the product as a colorless, volatile oil (131 mg, 63%, 94% ee by ^{1}H NMR spectroscopic analysis of the α-methylbenzylcarbamate).[71] ^{1}H and ^{13}C NMR spectral data were identical to that reported in the literature and to that of a sample of (*R*)-**21** derived from allylic carbamate (*R*)-**12a** (vide supra): $[\alpha]^{23}_D$ −11.4 (*c* 1.05, CH_3OH).

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Supporting Information Available: Full experimental and analytical data for the nickel-coupling and Wittig routes; experimental details for reactions with allylic carboxylates and for reactions described in Table 3; preparations of Grignard and alkyllithium reagents; details of the determination of enantiomeric ratios for reactions of nonracemic carbamates; and ^{1}H NMR data for select compounds; GC traces used to determine stereoisomer ratios. This material is available free of charge via the Internet at http://pubs.acs.org.

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