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**Development of New Catalytic Reactions
with Organoboron Compounds**

**Kazunori Nagao
2016**

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General Introduction

Boron chemistry is located in the center of the current organic synthesis. Herbert C. Brown and Akira Suzuki received a Nobel Prize in this field. Generally, organoboron compounds are important organometallic reagents due to stability in air and water, ease of handling, and availability. As represented by Suzuki–Miyaura coupling, transition-metal catalyzed transformations of organoboron compounds enable breakthrough in synthetic organic chemistry. However, these reactions mainly relied on rare metals such as palladium and rhodium. Therefore, researchers in organic synthesis must realize “rare metal free organic synthesis” to contribute to sustainable society. To achieve the aim, the author used copper and simple organic molecules as catalysts for transformation of organoboron compounds.

1. Copper Catalysis in Boron Chemistry

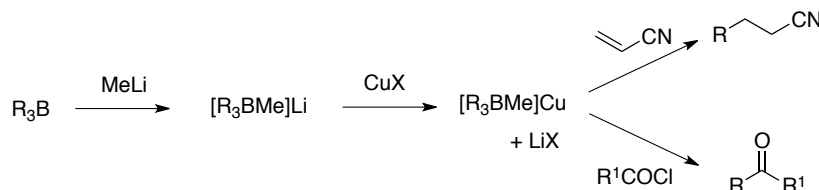
1.1. Introduction

Copper, one of base metals, is an earth-abundant, inexpensive and low-toxic transition metal. Organocopper reagents are useful synthetic reagents due to the ease of handling and to the high chemo-, regio- and stereoselectivities in C–C bond formations.¹ They are generally prepared by transmetalation of basic organometallic reagents such as organolithium and Grignard reagents to a copper salt. Therefore, they suffer from low functional group compatibility. Organoboron compounds are attractive as alternative organometallic reagents due to broad functional group tolerance.

1.2. Stoichiometric Reaction

Transmetalation of organoboron to a copper salt has been investigated.² Direct transmetalation is difficult due to similar electron negativities. Boron (2.04) is more electronegative than copper(I) (1.90) in Pauling’s scale. In 1977, Miyaura and Suzuki overcame this problem by formation of borates (Scheme 1).³ Addition of methyl lithium to trialkylborane gave the lithium tetraalkylborate, which reacted with a copper salt to form a copper borate. The copper borate reacted with various electrophiles. Brown found sodium methoxide promoted the transmetalation of alkenylboranes to a copper salt (Scheme 2).⁴ He demonstrated the synthesis of symmetrical conjugated dienes through this methodology.

Scheme 1. Reactions with Copper Borates



Scheme 2. Transmetalation between Sodium Trialkyl(alkoxo)borate and Copper Salt



Although the transmetalation of organoborons to a copper salt has been reported about 40 years ago, copper-catalyzed transformation of organoborons has not developed until recent times.

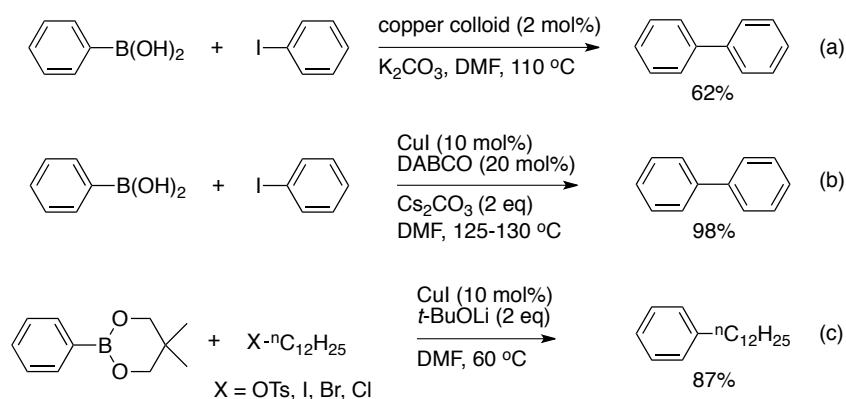
1.3. Copper-Catalyzed Transformation of Organoborons

1.3.1. Aryl-, Alkenyl- and Allylborons

In early times, copper-catalyzed transformation of alkenyl-, aryl- and allylboronates has been mainly developed because transmetalation from these organoborons to a copper salt in the aid of base is relatively facile. The reactions are divided into 3 types: 1) cross coupling 2) addition 3) substitution.

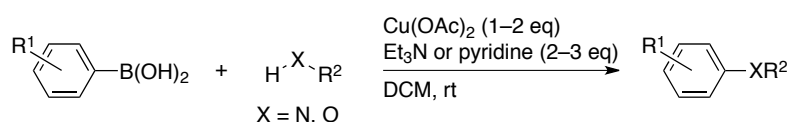
First, cross coupling with organoborons under copper catalysis was shown. Since 1979, Suzuki–Miyaura coupling became one of the most reliable method to construct $\text{C}(\text{sp}^2)\text{--C}(\text{sp}^2)$ bonds.⁵ Most of them mainly relied on palladium and nickel.⁶ Copper-catalyzed Suzuki–Miyaura coupling for biaryl synthesis has been also developed.⁷ In 2002, Rothenberg and co-workers reported copper or copper-contained nanocolloid catalyzed cross coupling between phenylboronic acid and various aryl halides (Scheme 3a).^{7a} Homogeneous copper catalysis has been reported by Li's group (Scheme 3b).^{7b} They showed CuI/DABCO-catalyzed cross coupling between arylboronic acids and aryl halides. The role of DABCO would be a ligand for a copper. However, the substrate scope was narrow and high temperature was required. Recently, Liu and co-workers developed copper catalyzed aryl–alkyl coupling between arylboronates and primary alkyl halides and pseudohalides (Scheme 3c).^{7g} This reaction proceeds under relatively mild conditions.

Scheme 3. Copper-Catalyzed Suzuki–Miyaura Coupling with Arylborons



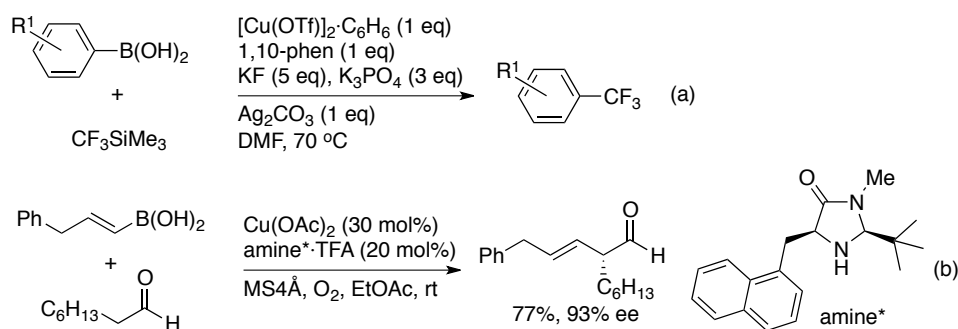
As mentioned above, Suzuki–Miyaura coupling is the powerful tool for carbon–carbon (C–C) bond formations. Chan–Lam–Evans coupling is that copper-mediated transformation of carbon–boron (C–B) bond to carbon–heteroatom (C–X, where X = O, N, S, Se, Te, Cl, Br, I) bond (Scheme 4).⁸ Although most of the reactions require stoichiometric amounts of copper salt, these transformations are attractive for synthesis of aryl ether, aniline and aryl sulfide derivatives from available arylboronic acids. Additionally, they are compatible with mild conditions, for example, room temperature, weak base and ambient atmosphere.

Scheme 4. Chan–Lam–Evans Coupling



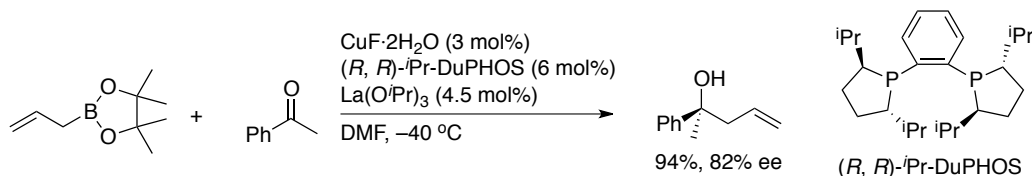
Recently, some groups could apply the Chan–Lam–Evans coupling to C–C bond formations.⁹ In 2010, Qing and Chu developed that the stoichiometric amounts of copper/1,10-phen promoted oxidative trifluoromethylation of arylboronic acids (Scheme 5a).^{9a} MacMillan and co-workers demonstrated copper(II)/chiral amine co-catalyzed enantioselective coupling between aldehydes and alkenylboronic acids (Scheme 5b).^{9b} Both reports provide attractive moieties for medicinal chemistry.

Scheme 5. Oxidative C–C Coupling

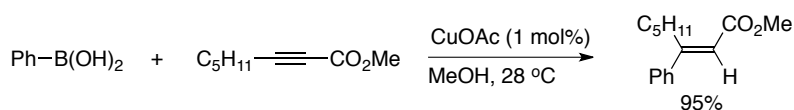


Next, addition reactions of organoborons to various unsaturated compounds were developed. In 2004, Kanai and Shibasaki disclosed copper-catalyzed enantioselective 1,2-addition of allylboronates to ketones in the presence of a lanthanide salt as additive (Scheme 6).¹⁰ The Lewis acidity of $La(O^iPr)_3$ would increase the reactivity by the acceleration of the transmetalation step. Yamamoto and co-workers reported copper-catalyzed conjugate addition of arylboronic acids to alkynoates (Scheme 7).¹¹ Only *syn*-hydroarylation products were obtained. Interestingly, the any ligands such as 2,2'-bipyridine and N-heterocyclic carbenes did not increase the reactivity. Recently, Shintani and Hayashi developed enantioselective conjugate addition of organoboronates to alkylidene cyanoacetates by use of copper/chiral NHC catalyst (Scheme 8).¹² They proposed the reaction mechanism involving only neutral copper(I) species on the basis of the stoichiometric reactions. Iwasawa^{13a} and Hou^{13b} independently reported copper-catalyzed carboxylation of aryl- and alkenylboronates with carbon dioxide (Scheme 9).

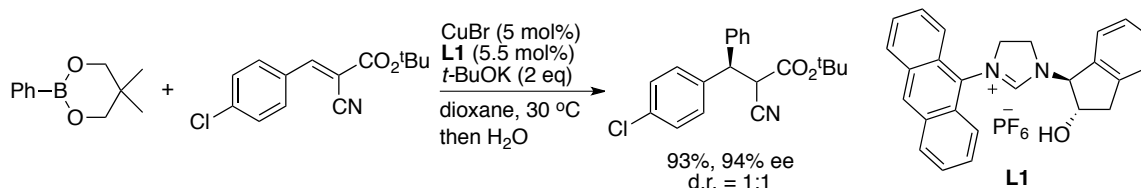
Scheme 6. Cu/La(OTf)₃-Catalyzed Enantioselective Allylation of Ketones



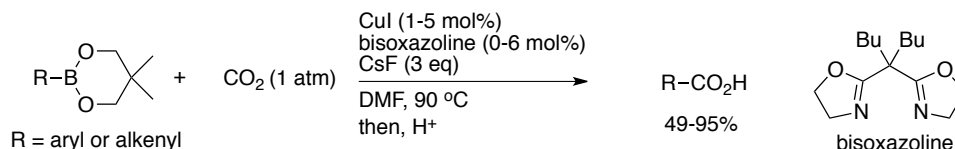
Scheme 7. Conjugate Addition to Alkynoate



Scheme 8. Enantioselective Conjugate Addition

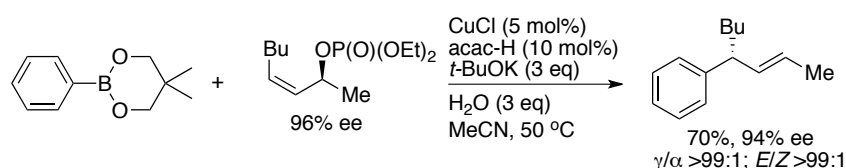


Scheme 9. Carboxylation

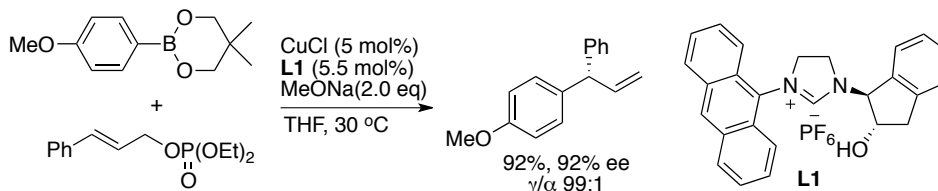


Transition-metal-catalyzed allylic substitution is one of the most powerful tools for carbon-carbon bond formation. However, there are problems with the control of regioselectivity and stereoselectivity. In 2010, Ohmiya and Sawamura developed copper-catalyzed allylic substitution of allylic phosphates with arylboronates (Scheme 10).¹⁴ This reaction achieved excellent γ -selectivity and 1,3-*anti* stereoselectivity. Shintani and Hayashi reported the development of asymmetric allylic substitution of allylic phosphates with aryl- and alkenylboronates (Scheme 11).¹⁵ Construction of quaternary carbon stereocenters was also shown. Recently, Hoveyda's group developed asymmetric allylic substitution of allylic phosphates with alkenyl-, allenyl- and propargylboronates.¹⁶

Scheme 10. Copper-Catalyzed Allyl-Aryl Coupling.



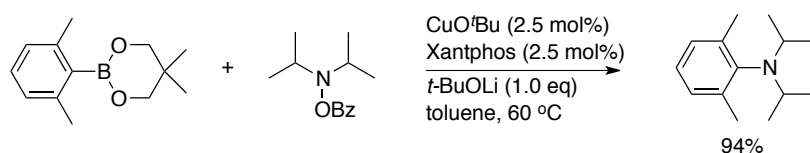
Scheme 11. Enantioselective Allylic Substitution with Ary- and Alkenylboronates



In 2012, Lalic and co-workers described electrophilic amination of arylboronates catalyzed by copper/Xantphos complex (Scheme 12).¹⁷ Although this transformation was similar to

Chan-Lam-Evans coupling, they used the benzoyloxyamine as introduction of amino group without another oxidant. Various functional group and steric hindrance are tolerated in arylboronic esters and benzoyloxyamines.

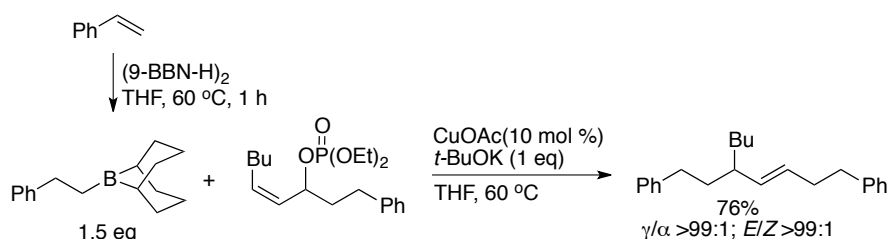
Scheme 12. Electrophilic Amination



1.3.2. Alkylborons

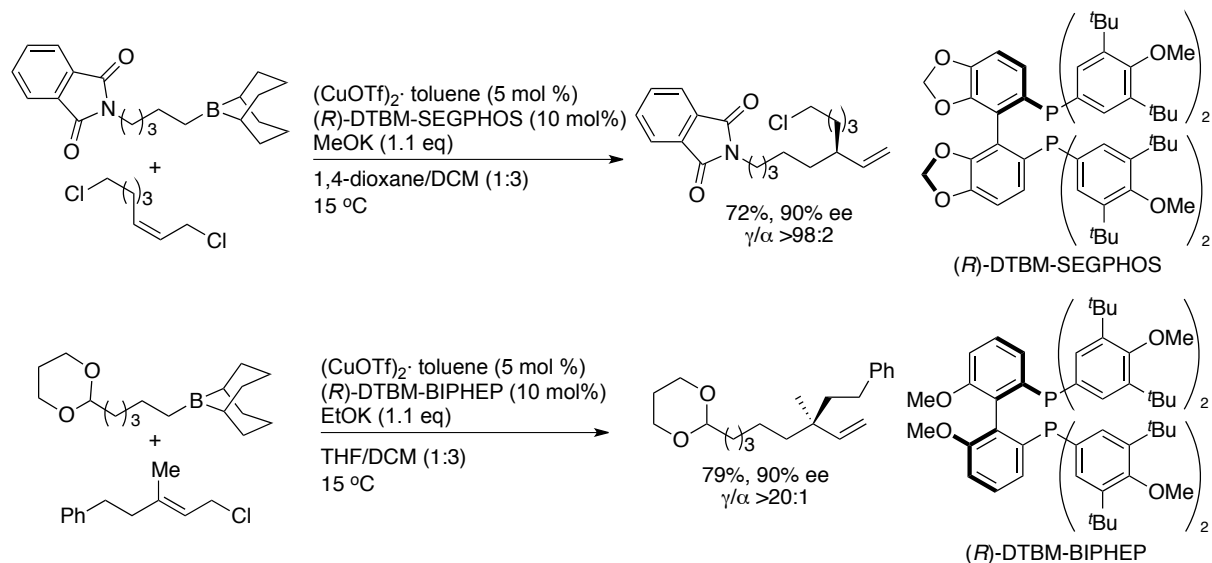
On the other hand, copper-catalyzed transformations with alkylborons have not been explored. In 2010, Ohmiya and Sawamura developed copper-catalyzed γ -selective allyl–alkyl coupling between allylic phosphates and alkylboranes (Scheme 13).¹⁸ This is first example of copper-catalyzed transformation of alkylboron compounds. This reaction proceeds with complete γ - and *E*-selectivities. The alkyl-9-BBN is prepared by hydroboration of terminal alkenes and used to the coupling without isolation. The various functional groups are tolerated in both the allylic phosphates and the alkylborons.

Scheme 13. Copper-Catalyzed γ -Selective Allyl–Alkyl Coupling

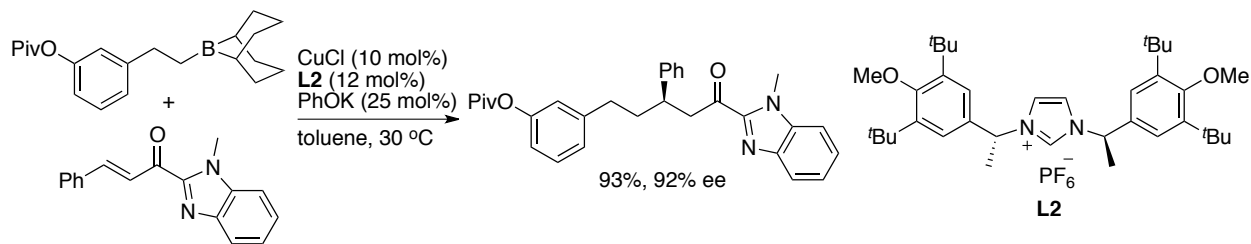


After this report, the chemistry of alkylcopper with alkylborons has been extended rapidly. Then, Ohmiya and Sawamura developed enantioselective allylic substitutions with alkylborons to construct the tertiary or quaternary carbon centers (Scheme 14).¹⁹ The chiral bulky bisphosphines would be effective for the formation of active monomeric copper complexes in the view of reactivity and stereoselectivity. They also synthesized the chiral *N*-heterocyclic carbene (NHC) ligand and developed copper-catalyzed enantioselective conjugate addition of alkylboranes to imidazol-2-yl α,β -unsaturated ketones (Scheme 15).²⁰ These are the first examples of asymmetric allylic substitution or conjugate addition of alkylboranes.

Scheme 14. Copper-Catalyzed Enantioselective Allylic Substitutions

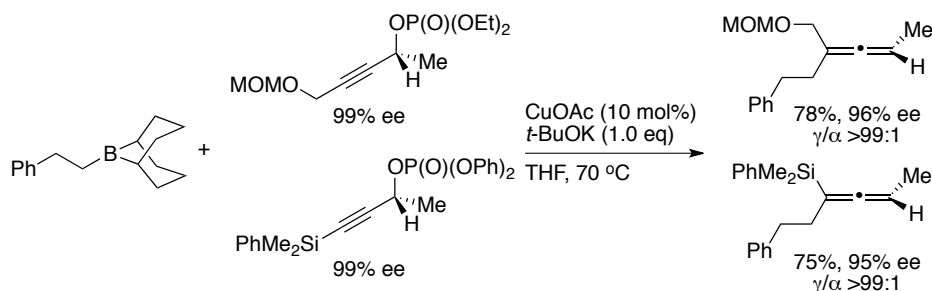


Scheme 15. Copper-Catalyzed Enantioselective Conjugate Addition

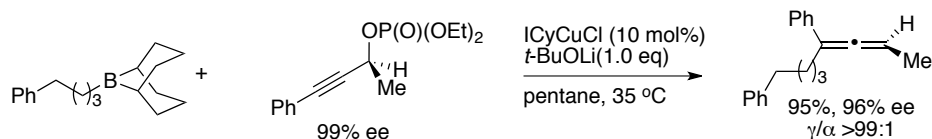


They demonstrated the synthesis of chiral allenes and allenylsilanes through copper-catalyzed stereospecific alkylation of chiral propargylic phosphates with alkyl-9-BBN (Scheme 16).²¹ Shortly thereafter, Lalic and co-workers reported the same reaction with copper NHC complex (Scheme 18).²² Hou's group and Sawamura's group independently reported the carboxylation of alkylboranes with copper catalysts (Schemes 18 and 19).²³ Hou's reaction system shows higher catalytic activity than Sawamura's one. This difference would come from the ligand for a copper. Hou's group succeeded in isolation of some intermediates and stoichiometric reactions.

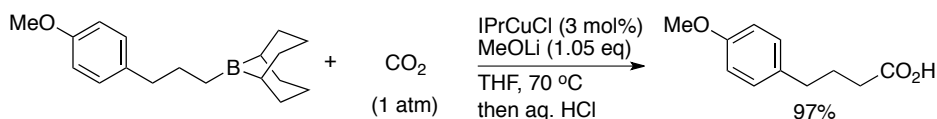
Scheme 16. Synthesis of Chiral Allenes and Allenylsilanes (reported by Ohmiya and Sawamura)



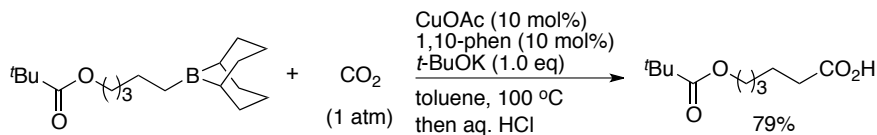
Scheme 17. Synthesis of Chiral Allenes (reported by Lalic)



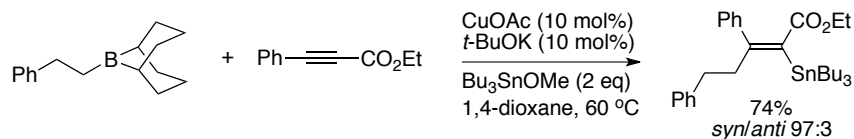
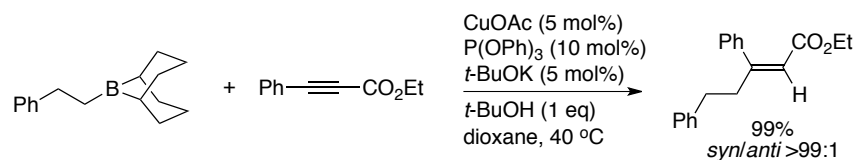
Scheme 18. Carboxylation of Alkylboranes (reported by Hou)



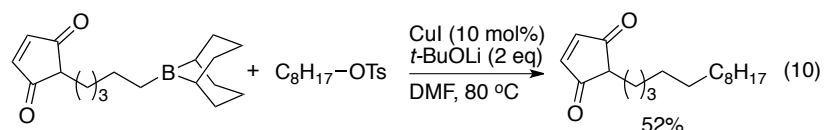
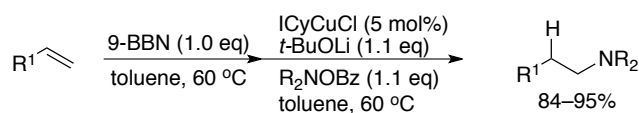
Scheme 20. Carboxylation of Alkylboranes (reported by Ohmiya and Sawamura)



Copper-catalyzed three-component coupling of alkylboranes with alkynoates and alkoxytannanes has been developed (Scheme 20).²⁴ This reaction, alkylstannylation of alkynes, is straightforward stereoselective synthesis of trisubstituted alkenylstannanes which are important scaffolds for synthesis of tetrasubstituted alkenes. Instead of alkoxytannanes, alcohol is also a suitable electrophile (Scheme 21).²⁵

Scheme 20. Alkylstannylation of Alkynoates with Alkylboranes**Scheme 21.** Hydroalkylation of Alkynoates with Alkylboranes

Many other groups reported copper-catalyzed transformations of alkylboranes. Liu demonstrated alkyl–alkyl Suzuki–Miyaura coupling between alkylboranes and alkyltosylates (Scheme 22).^{7g} Lalic combined alkene hydroboration with copper-catalyzed electrophilic amination to realize a formal *anti*-Markovnikov hydroamination of alkenes (Scheme 23).²⁶

Scheme 22. Copper-Catalyzed Alkyl–Alkyl Suzuki–Miyaura coupling**Scheme 23.** Formal *Anti*-Markovnikov Hydroamination of Terminal Alkenes

2. Organocatalysis in Boron Chemistry

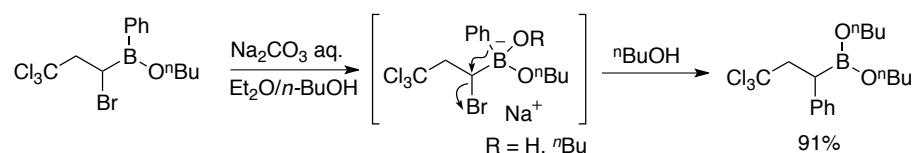
2.1. Introduction

Since “organocatalysis” has been established 15 years ago, this field has been developed rapidly. The concept of “organocatalysis” is that small organic molecules catalyzed organic transformations. Organocatalysis has the greater advantages of ease of handling in the atmosphere, low cost, non-toxicity and availability of catalysts compared with transition-metal catalysis. Therefore, organocatalytic transformation of organoborons is expected to be one of the ideal reactions. Generally, this mechanism is based on the migration of boron substituent.

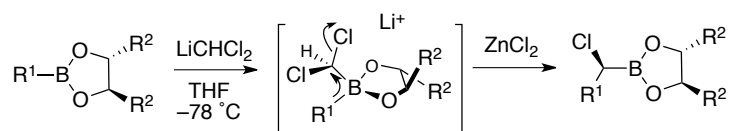
2.2. Migration in Borate

In 1963, Matteson first reported 1,2-migration of an organic group on boron atom to α -carbon in α -haloalkylborate (Scheme 24).²⁷ Then, he applied this methodology to homologation reaction of chiral organoboronates with α -dihaloalkyllithium to afford the various chiral alkylboronates (Scheme 25).²⁸ Recently, Aggarwal established the synthesis of chiral organoboron compounds combined with organoborons and chiral lithium carbenoids (Scheme 26).²⁹ The iterative lithiation-borylation method offered the stereoselective construction of consecutive carbon stereogenic centers.

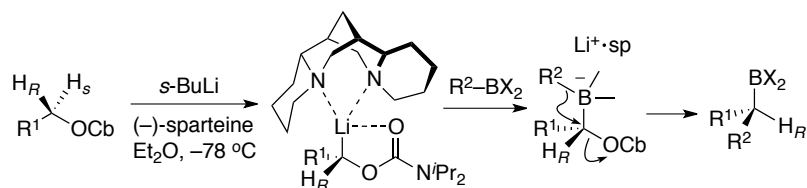
Scheme 24. First 1,2-Migration in α -Haloalkylborate



Scheme 25. Homologation of Organoborons through 1,2-Migration

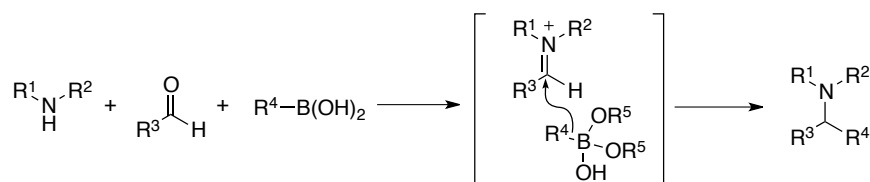


Scheme 26. Synthesis of Chiral Organoborons via Lithiation-Borylation

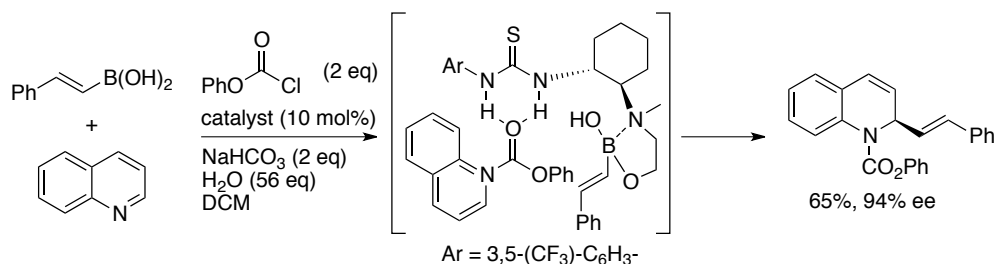


Petasis reported Mannich reaction with an amine, aldehyde and aryl- or alkenylboronic acid in 1993 (Scheme 27).³⁰ This multicomponent reaction is named as Petasis-borono Mannich reaction (Petasis reaction). In the proposed mechanism, the organic group R^4 in borates transferred to the iminium species. Recently, Takemoto and co-workers reported first catalytic enantioselective petasis type alkenylation of quinolines (Scheme 28).³¹ This reaction achieved the high reactivity and enantioselectivity by use of a chiral bifunctional thiourea catalyst containing an aminoalcohol moiety.

Scheme 27. Petasis Reaction



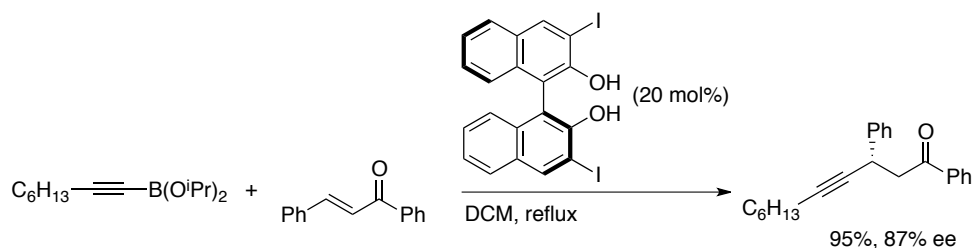
Scheme 28. Enantioselective Petasis Type Reaction



2.3. Catalytic Transformations

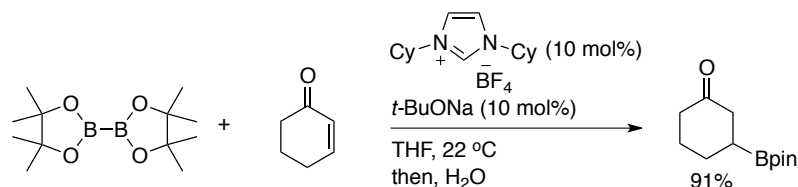
The facile carbon–boron (C–B) bond activation depends on Lewis acidity of boron. In 2005, Chong reported BINOL-catalyzed enantioselective alkynylboration of enones (Scheme 30).³² BINOL worked as an exchangeable chiral ligand for alkynylboronates. Electron-withdrawing groups in 3,3'-positions of the catalyst increased the lewis acidity of boron atom. This concept is applied to alkenylboration and arylboration of enones and allylboration of imines and ketones.³³

Scheme 29. BINOL-Catalyzed Asymmetric Alkynylation of Enones

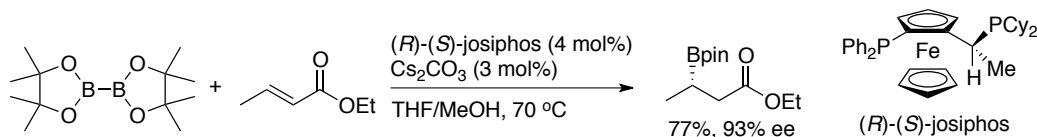


In contrast, Hoveyda developed the new field of Lewis base catalyzed transformation of boron compounds. He reported N-heterocyclic carbenes (NHC) catalyzed conjugate additions of diboron or silylboron to α,β -unsaturated carbonyl compounds (Scheme 30).³⁴ NHC activates the diboron or silylboron as Lewis base to generate formal boryl- or silyl anions. Moreover, he developed the transition-metal free boration or silylation into asymmetric reaction by using chiral carbenes. Subsequently, Fernandez found that organophosphine was also effective for the same reaction (Scheme 31).³⁵ Simple alkoxide bases are also catalysts for diboration and silaboration of alkenes (Scheme 32).³⁶ Recently, Morken demonstrated the stereoselective synthesis of various 1,2-diols through the alkoxide base-catalyzed diboration of alkenyl alcohols.

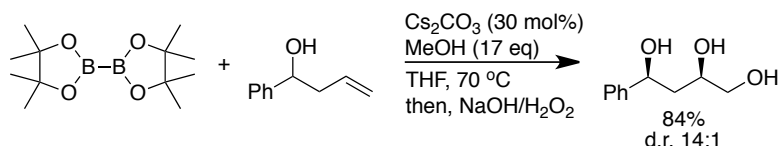
Scheme 30. NHC-Catalyzed Conjugate Addition of Diboron to Enone



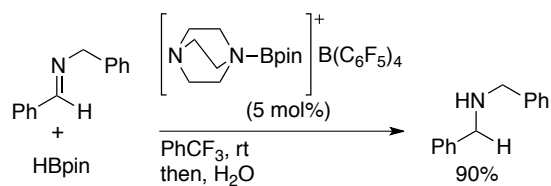
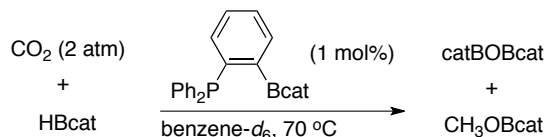
Scheme 31. Phosphine-Catalyzed Enantioselective Conjugate Addition of Diboron to Enone



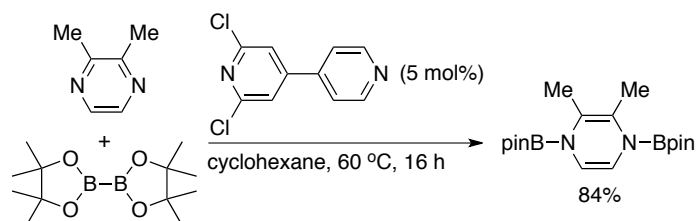
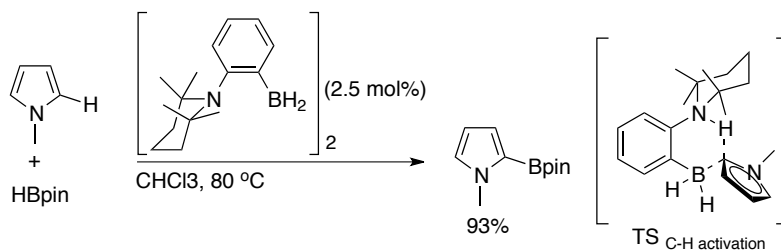
Scheme 32. Alkoxide base-Catalyzed Diboration of Enones



In the recent decade, the chemistry of Lewis acid-base pair has been developed. In boron chemistry, Lewis acid-base pairs were used as catalysts for reduction of unsaturated compounds with pinacolborane. Crudden reported borenium ion catalyzed reduction of imine with pinacolborane in 2012 (Scheme 33).³⁷ Maron and Fontaine synthesized the phosphine-borane molecule and used it as catalyst for reduction of carbon dioxide to methanol.³⁸ In both examples, catalysts initially activated the substrates such as imines and CO₂ followed by hydride reduction from HBpin (Scheme 34).

Scheme 33. Borenium Cation Catalyzed Reduction of Imines**Scheme 34.** Reduction of CO₂ by Phosphine–Borane Organocatalyst

In some cases, organocatalysis in activation of unactivated bond showed unprecedented features. Sugimoto and Ohmura discovered diboration of pyrazines through “reductive addition” of diborons to 4,4’-bipyridine catalyst (Scheme 35).³⁹ The Lewis pair combined with TMP and borane moieties activated a carbon-hydrogen bond of heteroarenes like CMD process in transition-metal catalysis (Scheme 36).⁴⁰ These reactions indicate that organocatalysis has a potential to cleave unactivated bonds.

Scheme 35. Organocatalytic Diboration of Pyrazine Derivatives**Scheme 36.** Metal-Free Catalytic C–H Borylation of Heteroarenes

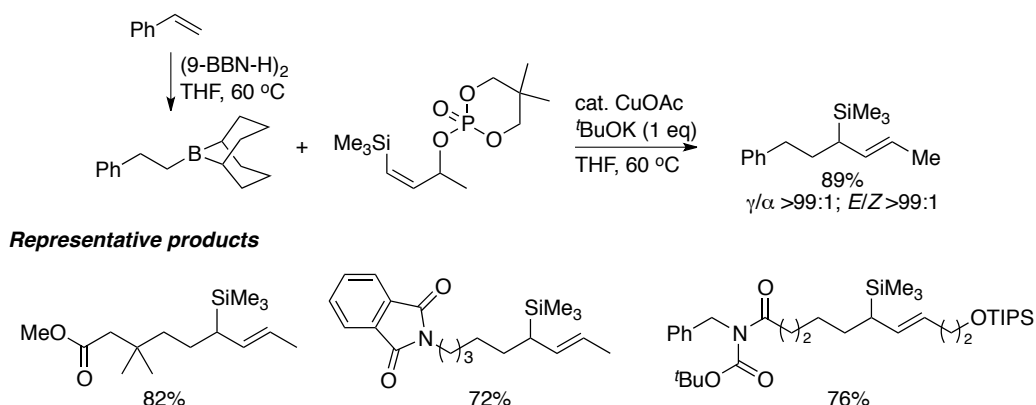
3. Overview of This Thesis

The author developed the transformations of organoborons with copper catalysis or organocatalysis. In Chapters 1 and 2, advancement of copper-catalyzed allyl–alkyl coupling with alkylboranes: synthesis of functionalized allylsilanes (Chapter 1) and discovery of stereodivergency (Chapter 2) are described. In Chapters 3–5, the author shows the development of stereoselective synthesis of multisubstituted alkenylborons through organocatalysis. In Chapters 3 and 4, he describes the phosphine-catalyzed *anti*-selective vicinal carboboration, silaboration and diboration of alkynoates. In Chapter 5, Brønsted base catalyzed geminal diboration of terminal alkynes is described. These organocatalysis formally cleave the C–B, Si–B and B–B bonds to introduce them into C–C triple bonds of alkynes with unprecedented regio- and stereoselectivity.

3.1. Functional Group Tolerable Synthesis of Allylsilanes through Copper-Catalyzed γ -Selective Allyl–Alkyl Coupling between Allylic Phosphates and Alkylboranes (Chapter 1)

Allylsilanes are known as versatile organometallic reagents for stereoselective C–C bond formations. In chapter 1, the author developed the synthesis of allylsilanes through copper-catalyzed γ -selective allyl–alkyl coupling between γ -silylated allylic phosphates and alkylboranes (Scheme 37). This reaction allowed a preparation of highly functionalized allylsilanes possessing ester, methoxy, silylether, phthalimide, acetal, thiophene, bromoarene and amide groups.

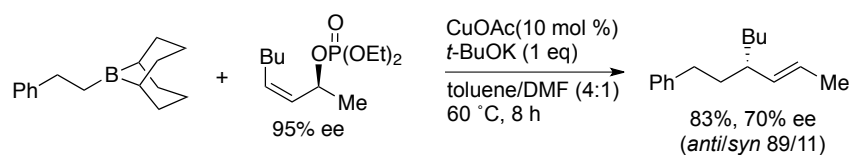
Scheme 37. Synthesis of Allylsilanes through Copper-catalyzed Allyl–Alkyl Coupling



3.2. Reversible 1,3-*anti/syn*-Stereochemical Courses in Copper-Catalyzed γ -Selective Allyl-Alkyl Coupling between Chiral Allylic Phosphates and Alkylboranes (Chapter 2)

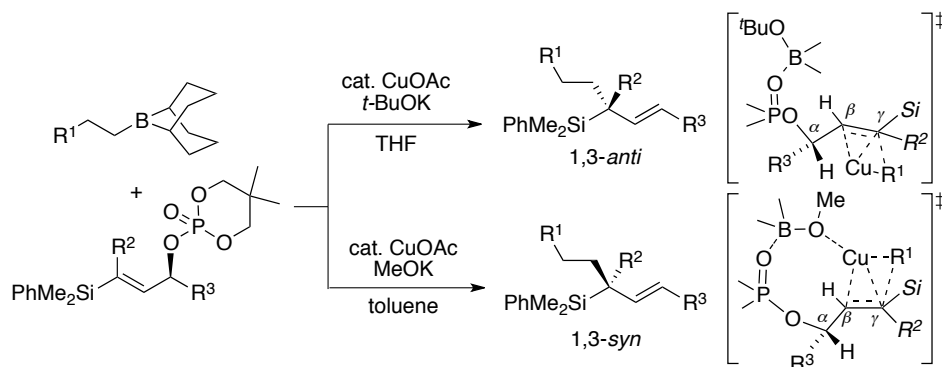
In 2010, the author's laboratory also showed the reaction between chiral acyclic allylic phosphates and alkylboranes (Scheme 38). The reaction occurred preferentially with 1,3-*anti* stereochemistry, however, the stereoselectivity was sensitive for reaction conditions.

Scheme 38. Allyl-Alkyl Coupling between Chiral Allylic Phosphate and Alkylborane



The author tried to change the stereochemical course from *anti* to *syn* by the choice of reaction conditions. In Chapter 2, he describes the novel stereochemical switch of copper-catalyzed γ -selective allyl-alkyl coupling between chiral allylic phosphates and alkylboranes by the choice of solvents and achiral alkoxide bases with different steric demands (Scheme 39).

Scheme 39. Stereodivergent Allyl-Alkyl Coupling

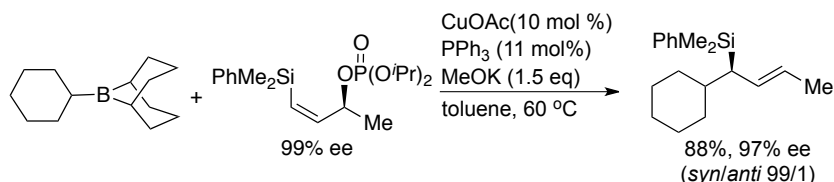


The protocols allow the stereoselective conversion of silicon-substituted allylic phosphates into enantioenriched chiral allylsilanes with tertiary or quaternary carbon stereogenic centers. Thus, both enantiomers of the allylsilanes with high enantiomeric purities are readily available from one enantiomer of the substrate. Cyclic and acyclic bimodal participation of alkoxyborane species in an organocopper addition-elimination sequence is proposed to account for the phenomenon of the *anti/syn* stereochemical reversal.

Based on the discovery of 1,3-*syn* stereochemical pathway, the authors laboratory succeeded in development of allyl-alkyl coupling with secondary alkylboranes (Scheme 40).⁴¹ In addition to

1,3-*syn* conditions, a monodentate phosphine ligand is essential. (This is not included in this thesis).

Scheme 40. Allyl–Alkyl Coupling with Secondary Alkylboranes

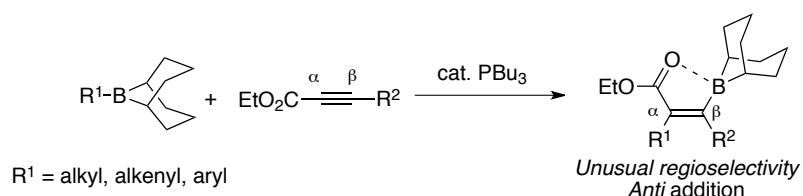


3.3. Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates with Alkyl-, Alkenyl-, and Arylboranes (Chapter 3)

Carboboration of internal alkynes with organoboron compounds via C–B bond cleavage is one of the most challenging difunctionalization reactions. Suginome and co-workers reported transition-metal-catalyzed cyanoboration and alkynylboration of internal alkynes.⁴² However these methodologies are limited to only organoborons possessing a C(sp)–B bond.

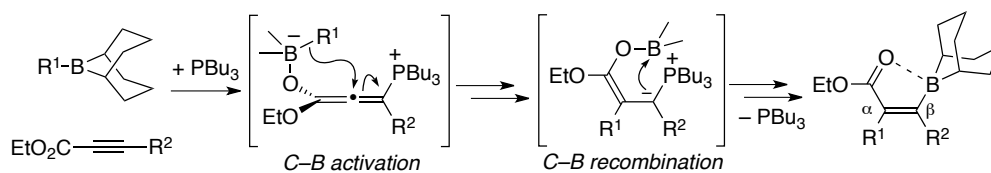
In Chapter 3, the author demonstrates *anti*-carboboration of alkynoates with alkyl-, alkenyl-, and arylboranes through phosphine organocatalysis (Scheme 41). The regioselectivity of the carboboration across the polar C–C triple bond exhibited inverse electronic demands. The less electronegative B atom was introduced to the positively charged β carbon atom of alkynoates. The complete *anti* stereochemistry was achieved in contrast to transition-metal catalysis.

Scheme 41. Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates



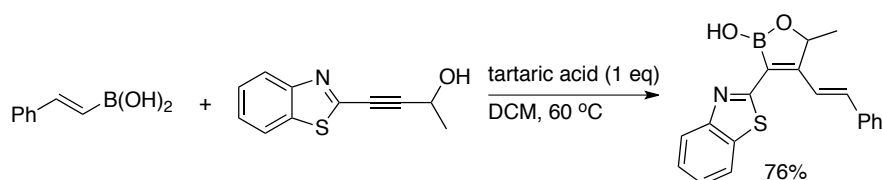
Possible mechanism is shown in Scheme 42. The role of tributylphosphine would be a nucleophilic catalyst. The phosphine would activate a C–B bond through conjugate addition to an alkynoate. After conformation change, C–B bond recombination occurred to give carboboration product.

Scheme 42. Possible Mechanism



After his report, Csaky reported direct *anti*-carboboration of electron-deficient heteroarene conjugated terminal propargyl alcohols with aryl- and alkenylboronic acids (Scheme 43).⁴³ Stoichiometric amounts of tartaric acid were required for increasing the electrophilicity of the boron atom to promote the carboboration reaction.

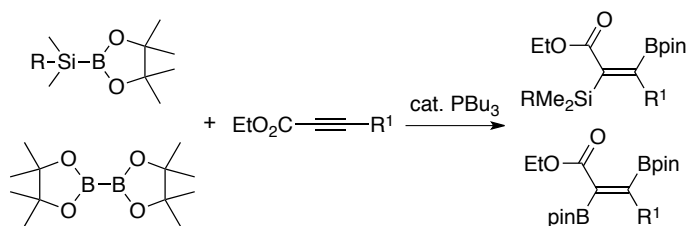
Scheme 43. Anti-Carboboration of Electron-deficient Heteroarene derived Propargyl Alcohols



3.4. Anti-Selective Vicinal Silaboration and Diboration of Alkynoates thorough Oranocatalysis (Chapter 4)

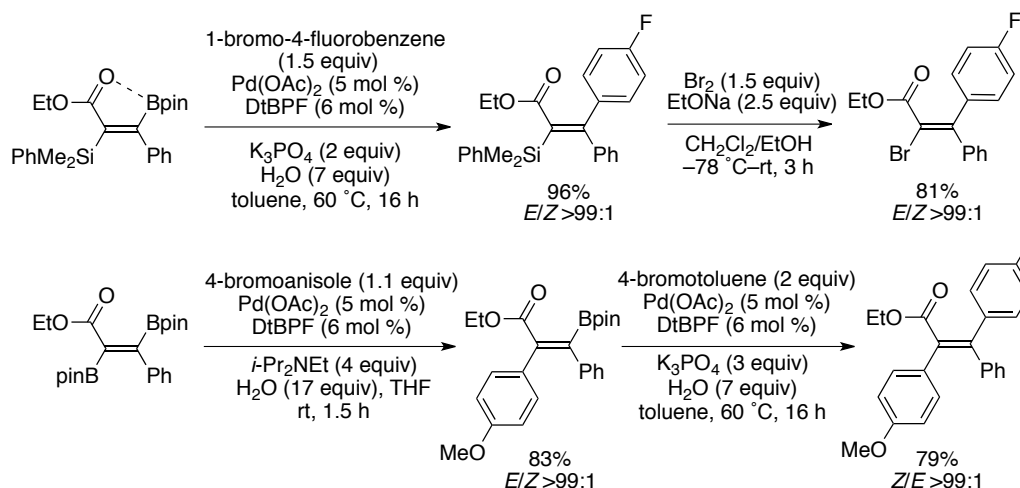
In Chapter 4, the author shows that phosphine-catalyzed carboboration protocol is applicable to *anti*-selective silaboration and diboration of alkynoates (Scheme 44). These reactions provided the efficient method for the synthesis of β -bory- α -silyl acrylates and α, β -diboryl acrylates. The *anti* selectivity was complete regardless of substrate structures. Various functional groups were tolerated in alkynotes.

Scheme 44. Phosphine-Catalyzed Anti-Silaboration and Diboration of Alkynoates



The two vicinally installed heteroatom substituents of the β -boryl- α -silylacrylates and α,β -diborylacrylates could be differentiated and transformed in a stepwise manner, allowing the synthesis of a diverse array of unsymmetrical tetrasubstituted alkenes (Scheme 45). This stepwise functionalization enabled the synthesis of *anti*-functionalized (*Z*)-tamoxifen derivatives.

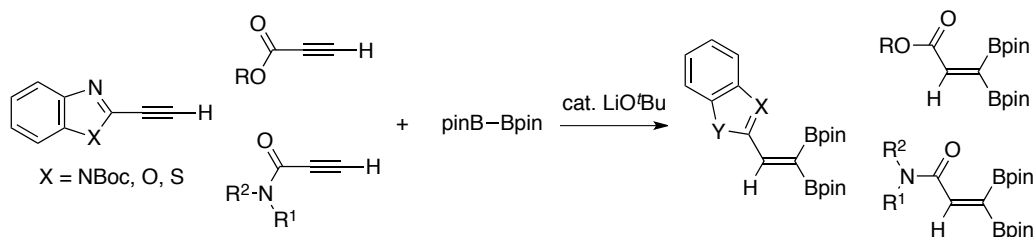
Scheme 45. Chemoselective Transformations



3.5. Synthesis of 1,1-Diborylalkenes through a Brønsted Base Catalyzed Reaction between Terminal Alkynes and Bis(pinacolato)diboron (Chapter 5)

In Chapter 5, he describes Brønsted base catalyzed geminal diboration of terminal alkynes with bis(pinacolato)diboron (Scheme 46). Propiolates, propiolamides and 2-ethynylazoles are suitable terminal alkynes for this reaction. The phosphine catalysis in Chapter 3 and 4 are not applicable to the geminal diboration of terminal alkynoate and didn't afford the corresponding vicinal diboration product. The obtained β -diborylacrylates are converted to the corresponding β -diarylacrylates through stepwise Suzuki–Miyaura couplings.

Scheme 46. Synthesis of 1,1-Diborylalkene by Brønsted Base Catalysis



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Chapter 1

Functional Group Tolerable Synthesis of Allylsilanes through Copper-Catalyzed γ -Selective Allyl–Alkyl Coupling between Allylic Phosphates and Alkylboranes

A copper-catalyzed γ -selective allyl–alkyl coupling between γ -silylated allylic phosphates and alkylboron compounds (alkyl-9-BBN, prepared by hydroboration of alkenes with 9-BBN-H) produced allylsilanes. The reaction tolerated various functional groups in both the alkylboranes and the allylic phosphates, and afforded functionalized allylsilanes.

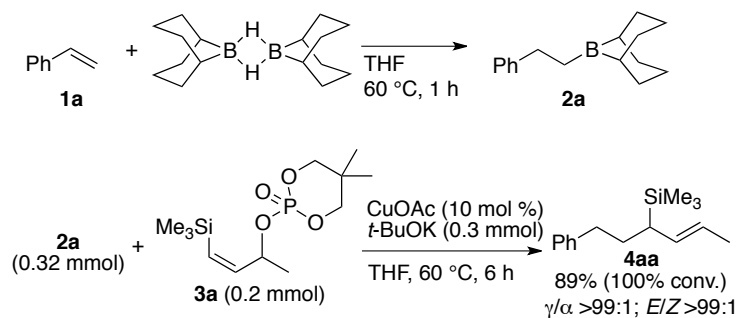
Introduction

Allylsilanes are versatile synthetic intermediates in organic synthesis.¹ The development of facile and efficient methods for the synthesis of allylsilanes is important. Among the available methods for accessing to allylsilanes,^{2–14} two types of the S_N2' displacement strategies, γ -substitutions of γ -silylated allylic alcohol derivatives with organocuprate reagents^{15,16} and silylations of allylic alcohol derivatives with silylcuprate reagents,^{17,18} are particularly useful because the substrates and the reagents are readily available and the reactions are highly reliable in terms of product yield and selectivity.

Previously the author's laboratory developed the copper-catalyzed allyl–alkyl coupling reaction between allylic phosphates and alkylboranes (alkyl-9-BBN) that proceeds with excellent γ - and *E*-selectivities.^{19a} In this chapter, the author reports that this copper-catalyzed protocol is applicable to the reaction between γ -silylated allylic phosphates and alkylboranes (alkyl-9-BBN), which appeared to be a straightforward, functional group-tolerable approach to allylsilanes.^{19–22} The wide availability of alkylboranes via the established alkene hydroboration reaction is an attractive feature of this transformation.

Results and Discussion

Scheme 1. Allyl–Alkyl Coupling between **2a** and **3a**

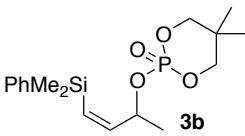
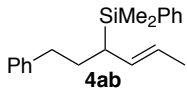
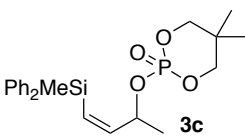
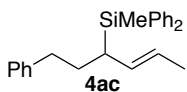
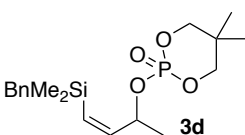
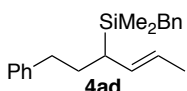
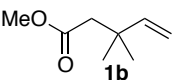
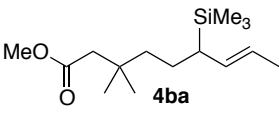


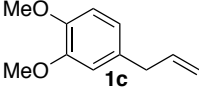
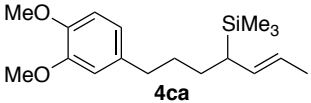
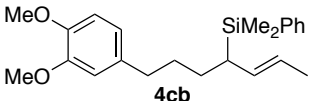
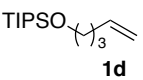
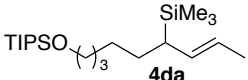
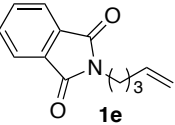
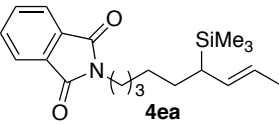
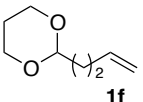
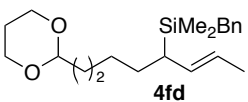
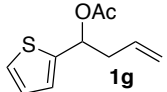
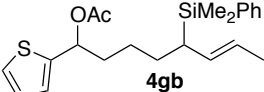
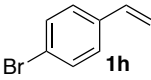
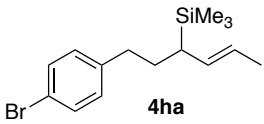
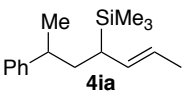
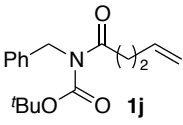
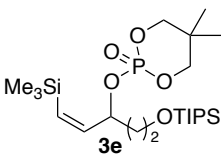
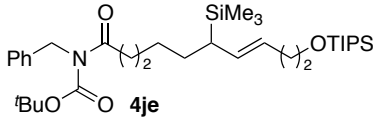
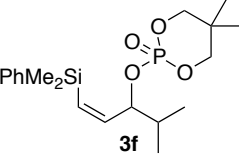
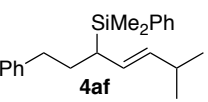
Alkylborane **2a** (0.32 mmol), which was prepared via hydroboration of styrene (**1a**) with 9-borabicyclo[3.3.1]nonane (9-BBN-H) dimer, and γ -trimethylsilyl allylic substrates **3a** (0.2 mmol) bearing a cyclic phosphate leaving group were subjected to the standard reaction conditions for the copper-catalyzed allyl–alkyl coupling (**2a/3a**/CuOAc/*t*-BuOK 1.6:1:0.1:1.5, THF, 60°C) (Scheme 1).^{19a} The reaction afforded allylsilane **4aa** in 89% yield (based on **3a**; 100% convn of **3a**) with complete γ - and *E*-selectivities. The use of a diethyl phosphate as a leaving group gave a slightly decreased product yield compared to the cyclic phosphate (80% yield). The reaction of (*E*)-**3a** proceeded with significantly decreased *E*-selectivity (*E/Z* 71:29) (data not shown).²³

The hydroboration–coupling one-pot protocol affords a variety of allylsilanes (Table 1). Allylic phosphates **3b–d** with other silyl substituents such as PhMe₂Si, Ph₂MeSi and BnMe₂Si instead of Me₃Si at the γ-position were also converted to the corresponding allylsilanes derivatives **4ab**, **ac**, **ad** in high yields (entries 1–3). The reaction tolerates a variety of functional groups including ester, methoxy, silyl ether, phthalimide, acetal, thiophene, bromo and amide moieties in alkenes and allylic phosphates (entries 4–13).

The tolerance of the reaction toward steric demand in both the alkylboranes (**2**) and allylic phosphates (**3**) is also shown in Table 1. The sterically more demanding alkylborane **2b**, which was derived from an alkene (**1b**) bearing a tertiary alkyl substituent, served as a substrate to afford the corresponding allylsilanes **4ba** in high yield (entry 4). The reaction of the β-branched alkylborane (**2i**), which was prepared from α-methylstyrene (**1i**), was also successful to give **4ia** as a 1:1 diastereomeric mixture (entry 12). Unfortunately, however, the use of secondary alkylborane reagents prepared from internal alkenes resulted in no reaction (data not shown). The allylic phosphate **3e** with a CH₂CH₂OTIPS group instead of α Me group at the α-position underwent the reaction (entry 13). A sterically more demanding α-substituent such as an ⁱPr group was also tolerated (entry 14).

Table 1. Synthesis of Allylsilanes^a

entry	alkene	phosphate	product	yield (%) ^{b,c}
1	1a	 3b	 4ab	94
2	1a	 3c	 4ac	92
3	1a	 3d	 4ad	94
4	 1b	3a	 4ba	82

5		3a		81
6	1c	3b		87
7		3a		78
8		3a		72
9		3d		79
10		3b		73 ^d
11		3a		88
12		3a		79 ^d
13				76
14	1a			92

^a The reaction was carried out with **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %) and *t*-BuOK (0.3 mmol, 1 M in THF) in THF at 60 °C for 6 h. Alkylborane **2** was prepared in advance by hydroboration of **1** with 9-BBN dimer in THF at 60 °C for 1 h and used without purification. ^b Isolated yield based on **3**. ^c Isomeric ratios ($\gamma/\alpha > 99:1$, $E/Z > 99:1$). Determined by ¹H NMR or GC of the crude product. ^d Diastereomeric ratio (1:1).

Conclusion

In conclusion, the author has developed a versatile, functional group-tolerable approach to allylsilanes through a copper-catalyzed γ -selective cross-coupling reaction between γ -silylated allylic phosphates and alkylboranes.

Experimental Section

Instrumentation and Chemical

NMR spectra were recorded on a Varian Gemini 2000 spectrometer, operating at 300 MHz for ^1H NMR and 75.4 MHz for ^{13}C NMR. Chemical shift values for ^1H and ^{13}C are referenced to Me_4Si and the residual solvent resonances, respectively. Chemical shifts are reported in δ ppm. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TZ at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Elemental analysis was performed at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Melting point was measured on a Yanaco MP-500D apparatus. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Kanto Chemical Co., Silica gel 60 N, spherical, neutral) and aluminum oxide (Nacalai Tesuque, Alumina Activated 200) were used for column chromatography. Gas chromatographic (GLC) analyses were conducted on a Shimadzu GC-14B equipped with a flame ionization detector. Gel permeation chromatography (GPC) was performed by LC-908 (Japan Analytical Industry Ltd., two in-line JAIGEL-2H, CHCl_3 , 3.5 mL/min, UV and RI detectors).

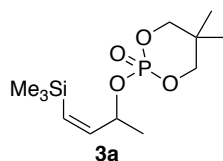
All reactions were carried out under nitrogen or argon atmosphere. Materials were obtained from commercial suppliers or prepared according to standard procedures unless otherwise noted. *t*-BuOK (1.0 M THF solution) and CuOAc were purchased from Aldrich Chemical Co., stored under nitrogen, and used as it is. Tetrahydrofuran (THF) was purchased from Kanto Chemical Co., stored under argon. Alkenes **1a–j** were well known compounds. Allylsilane **4ab** was found in literature.¹⁴

Preparation of γ -Silylated Allylic Phosphates **3a–d**

THP-protection of commercially available 3-butyne-2-ol followed by silylations gave γ -silylated propargylic alcohol derivatives. Next, DIBAL-H reduction followed by deprotection afforded γ -silylated allylic alcohols. Finally, allylic phosphates **3a–d** were prepared by the phosphorylation of the γ -silylated allylic alcohols (*vide infra* for the product yield of the phosphorylation).

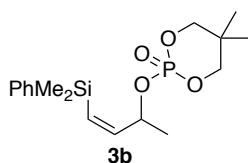
The phosphorylation of (Z)-4-(dimethylphenylsilyl)-3-buten-2-ol to **3b** is representative. To a solution of (Z)-4-(dimethylphenylsilyl)-3-buten-2-ol (413 mg, 2.0 mmol) in THF (16.0 mL) and TMEDA (4.0 mL), ⁿBuLi (1.3 mL, 1.63 M, 2.1 mmol) was added at –78 °C. After being stirred at –78 °C for 45 min, 2-chloro-5,5-dimethyl-1,3,2-dioxaphosphinane 2-oxide (Aldrich Chemical Co., 480 mg, 2.6 mmol) was added to the reaction mixture. The reaction mixture was stirred for an additional 5 minutes at –78 °C, then warmed to room temperature, and stirred for 3 hours. The resulting solution was quenched with saturated NH₄Cl aq. Aqueous layer was extracted with ethyl acetate. The organic layers were combined and washed with brine, dried over MgSO₄, filtered, and concentrated under vacuum to leave an oil. After passing through a short plug of aluminum oxide with diethyl ether, an eluent was concentrated, and the residue was purified with GPC to provide **3b** in 73% yield (517 mg, 1.46 mmol).

(Z)-5,5-Dimethyl-2-[[4-(trimethylsilyl)-3-buten-2-yl]oxy]-1,3,2-dioxaphosphinane 2-Oxide (3a)



The product **3a** was purified by GPC. White solid. **M.p.** 45.6–45.8 °C. ¹H NMR (300 MHz, CDCl₃) δ 0.17 (s, 9H), 0.87 (s, 3H), 1.25 (s, 3H), 1.44 (d, *J* = 5.1 Hz, 3H), 3.78–4.11 (m, 4H), 5.13 (dq, *J* = 9.0, 5.1 Hz, 1H), 5.71 (d, *J* = 14.1 Hz, 1H), 6.29 (dd, *J* = 14.1, 9.0 Hz, 1H). ¹³C NMR (75.4 MHz, CDCl₃) δ –0.20, 20.21 (d, *J* = 1.1 Hz), 21.55, 22.59 (d, *J* = 4.6 Hz), 31.91 (d, *J* = 5.7 Hz), 75.14 (d, *J* = 5.1 Hz), 77.36 (d, *J* = 6.8 Hz), 77.75 (d, *J* = 6.8 Hz), 132.39, 146.26 (d, *J* = 5.7 Hz). **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₁₂H₂₅O₄PSiNa, 315.11574; found, 315.11519.

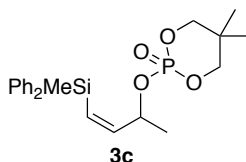
(Z)-2-[[4-(Dimethylphenylsilyl)-3-buten-2-yl]oxy]-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3b)



The product **3b** was purified by GPC. Colorless oil. ¹H NMR (300 MHz, CDCl₃) δ 0.44 (s, 3H),

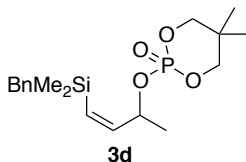
0.48 (s, 3H), 0.84 (s, 3H), 1.23 (s, 3H), 1.28 (d, $J = 6.3$ Hz, 3H), 3.69–4.04 (m, 4H), 5.04 (dq, $J = 9.0, 6.3$ Hz, 1H), 5.86 (d, $J = 14.2$ Hz, 1H), 6.38 (dd, $J = 14.2, 9.0$ Hz, 1H), 7.26–7.37 (m, 3H), 7.54–7.56 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ -1.54, -1.27, 20.26 (d, $J = 4.0$ Hz), 21.58, 22.19 (d, $J = 4.0$ Hz), 31.92 (d, $J = 5.7$ Hz), 75.18 (d, $J = 5.1$ Hz), 77.35 (d, $J = 6.8$ Hz), 77.73 (d, $J = 6.8$ Hz), 128.00, 129.24, 130.37, 133.75, 138.54, 147.67 (d, $J = 5.7$ Hz). HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{17}\text{H}_{27}\text{O}_4\text{PSiNa}$, 377.44290; found, 377.13084.

(Z)-5,5-Dimethyl-2-[[4-(methyldiphenylsilyl)-3-buten-2-yl]oxy]-1,3,2-dioxaphosphinane 2-Oxide (3c)



The product **3c** was purified by GPC. Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 0.78 (s, 3H), 0.81 (s, 3H), 1.19 (d, $J = 6.3$ Hz, 3H), 1.21 (s, 3H), 3.66–3.98 (m, 4H), 4.93 (dq, $J = 9.0, 6.3$ Hz, 1H), 6.08 (d, $J = 14.4$ Hz, 1H), 6.53 (dd, $J = 14.4, 9.0$ Hz, 1H), 7.33–7.39 (m, 6H), 7.53–7.58 (m, 4H). ^{13}C NMR (75.4 MHz, CDCl_3) δ -2.57, 20.26 (d, $J = 1.1$ Hz), 21.53, 21.88 (d, $J = 4.0$ Hz), 31.88 (d, $J = 5.7$ Hz), 75.20 (d, $J = 5.1$ Hz), 77.34 (d, $J = 6.8$ Hz), 77.64 (d, $J = 6.8$ Hz), 128.04, 128.10, 128.14, 129.49, 129.60, 134.61, 134.75, 136.30, 136.68, 149.30 (d, $J = 6.3$ Hz). HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{29}\text{O}_4\text{PSiNa}$, 439.14704; found, 439.14649.

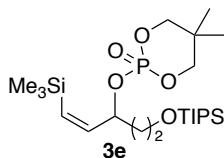
(Z)-2-[[4-(Benzyldimethylsilyl)-3-buten-2-yl]oxy]-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3d)



The product **3d** was purified by GPC. Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 0.16 (s, 3H), 0.17 (s, 3H), 0.87 (s, 3H), 1.24 (s, 3H), 1.37 (d, $J = 6.3$ Hz, 3H), 2.19 (s, 2H), 3.76–4.09 (m, 4H), 5.08 (dq, $J = 9.0, 6.3$ Hz, 1H), 5.68 (d, $J = 14.4$ Hz, 1H), 6.32 (dd, $J = 14.4, 9.0$ Hz, 1H), 7.00–7.10 (m, 3H), 7.19–7.24 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ -2.05, -2.00, 20.25, 21.55, 22.51 (d, $J = 4.6$ Hz), 26.17, 31.94 (d, $J = 5.7$ Hz), 75.20 (d, $J = 5.1$ Hz), 77.38 (d, $J = 6.8$ Hz), 77.75 (d, $J = 6.8$ Hz), 124.19, 128.22, 128.28, 130.46, 139.51, 147.16 (d, $J = 5.7$ Hz). HRMS-ESI (m/z):

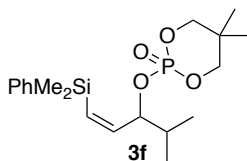
$[M+Na]^+$ calcd for $C_{18}H_{29}O_4PSiNa$, 391.14704; found, 391.14649.

(Z)-5,5-Dimethyl-2-[[5-(triisopropylsilyloxy)-1-(trimethylsilyl)-1-penten-3-yl]oxy]-1,3,2-dioxaphosphinane 2-Oxide (3e)



THP-protection of 5-[(triisopropylsilyl)oxy]-1-pentyn-3-ol followed by silylation gave γ -silylated propargylic alcohol derivative. Next, DIBAL-H reduction followed by deprotection afforded γ -silylated allylic alcohol. Finally, the phosphorylation of the γ -silylated allylic alcohol (2.0 mmol) provided allylic phosphate **3e** in 50% (171 mg, 1.0 mmol). The product **3a** was purified by GPC. Colorless oil. ^1H NMR (300 MHz, $CDCl_3$) δ 0.18 (s, 9H), 0.88 (s, 3H), 1.06–1.14 (m, 21H), 1.23 (s, 3H), 1.81–1.91 (m, 1H), 1.96–2.07 (m, 1H), 3.82–3.94 (m, 4H), 4.01–4.10 (m, 2H), 5.13 (m, 1H), 5.76 (d, J = 14.4 Hz, 1H), 6.34 (dd, J = 14.4, 9.3 Hz, 1H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ -0.15, 11.77, 17.88, 20.35, 21.57, 31.95 (d, J = 5.7 Hz), 39.71 (d, J = 6.3 Hz), 59.03, 76.04 (d, J = 5.7 Hz), 77.39 (d, J = 5.1 Hz), 77.58 (d, J = 6.9 Hz), 133.44, 145.14 (d, J = 2.7 Hz). HRMS-ESI (m/z): $[M+Na]^+$ calcd for $C_{22}H_{47}O_5PSi_2Na$, 501.25973; found, 501.25919.

(Z)-2-[[1-(Dimethylphenylsilyl)-4-methyl-1-penten-3-yl]oxy]-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3f)



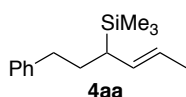
THP-protection of 4-methyl-1-pentyn-3-ol followed by silylation gave γ -silylated propargylic alcohol derivative. Next, DIBAL-H reduction followed by deprotection afforded γ -silylated allylic alcohol. Finally, the phosphorylation of the γ -silylated allylic alcohol (2.0 mmol) provided allylic phosphate **3f** in 59% (451 mg, 1.18 mmol). The product **3f** was purified by GPC. White solid; **M.p.** 91.5–91.7 °C. ^1H NMR (300 MHz, $CDCl_3$) δ 0.46 (s, 3H), 0.50 (s, 3H), 0.81 (d, J = 6.6 Hz, 3H), 0.85 (s, 3H), 0.89 (d, J = 6.6 Hz, 3H), 1.24 (s, 3H), 1.77 (sext, J = 6.6 Hz, 1H), 3.71–4.06 (m, 4H), 4.68–4.76 (m, 1H), 5.95 (d, J = 14.4 Hz, 1H), 6.37 (dd, J = 14.4, 9.6 Hz, 1H), 7.34–7.37 (m, 3H), 7.57–7.58 (m, 2H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ -1.43, -1.31, 17.15, 17.99, 20.34 (d, J = 1.1

Hz), 21.63, 31.92 (d, $J = 5.7$ Hz), 33.47 (d, $J = 5.7$ Hz), 77.27 (d, $J = 6.3$ Hz), 77.68 (d, $J = 6.8$ Hz), 82.59 (d, $J = 6.3$ Hz), 127.95, 129.18, 132.94, 133.90, 138.69, 144.54 (d, $J = 2.9$ Hz). **HRMS–ESI** (m/z): $[M+Na]^+$ calcd for $C_{19}H_{31}O_4NaPSi$, 405.16269; found, 405.16241.

Typical Procedure for Synthesis of Allylsilanes

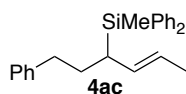
The preparation of **4aa** is representative (Scheme 1). In a grove box, (9-BBN-H)₂ (40.3 mg, 0.165 mmol), THF (0.06 mL) and styrene (**1a**) (0.041 mL, 0.36 mmol) were sequentially placed in a screw-top test tube containing a magnetic stirring bar. Also in the glove box, CuOAc (2.5 mg, 0.02 mmol) was placed in another vial containing a magnetic stirring bar. The two vials were then each sealed with a cap equipped with a Teflon-coated silicon rubber septum, and were removed from the glove box. After the mixture in THF was stirred at 60 °C for 1 h to prepare alkylborane **2a**, *t*-BuOK (1 M in THF, 0.3 mL, 0.3 mmol) was added to **2a** prepared in advance at 25 °C. Next, the mixture was transferred to the vial containing the Cu salt. Finally, allylic phosphate **3a** (56.1 mg, 0.2 mmol) was added. After 6 h stirring at 60 °C, CH₂Cl₂ was added to the mixture. Then, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether. After the solvent was removed under reduced pressure, flash chromatography on silica gel (hexane) provided **4aa** (41.5 mg, 0.178 mmol) in 89% yield.

(*E*)-Trimethyl(1-phenyl-4-hexen-3-yl)silane (**4aa**)



The product **4aa** was purified by flash chromatography on silica gel (hexane). Colorless oil. ¹H NMR (300 MHz, CDCl₃) δ −0.05 (s, 9H), 1.40–1.46 (m, 1H), 1.52–1.78 (m, 2H), 1.71 (d, $J = 4.8$ Hz, 3H), 2.43 (ddd, $J = 13.5, 9.6, 6.9$ Hz, 1H), 2.77 (ddd, $J = 13.5, 9.3, 4.5$ Hz, 1H), 5.23 (dd, $J = 15.0, 7.8$ Hz, 1H), 5.30 (dq, $J = 15.0, 4.8$ Hz, 1H), 7.15–7.19 (m, 3H), 7.25–7.30 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ −3.37, 18.11, 31.08, 32.71, 35.59, 123.16, 125.60, 128.29, 128.59, 132.17, 143.18. **Anal.** Calcd for C₁₅H₂₄Si: C, 77.51; H, 10.41%. Found: C, 77.70; H, 10.76%.

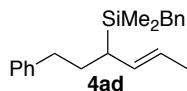
(*E*)-Methyldiphenyl(1-phenyl-4-hexen-3-yl)silane (**4ac**)



The product **4ac** was purified by flash chromatography on silica gel (hexane). Colorless oil. ¹H NMR (300 MHz, CDCl₃) δ 0.48 (s, 3H), 1.59–1.71 (m, 1H), 1.66 (d, $J = 4.2$ Hz, 3H), 1.78–1.86 (m,

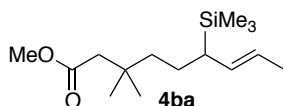
1H), 2.05–2.10 (m, 1H), 2.45 (dt, $J = 13.8, 8.4$ Hz, 1H), 2.76 (ddd, $J = 13.8, 9.0, 4.8$ Hz, 1H), 5.27–5.29 (m, 2H), 7.07–7.49 (m, 15H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –5.82, 18.09, 30.21, 30.96, 35.04, 124.89, 125.65, 127.63, 127.76, 128.25, 128.73, 129.08, 129.20, 130.97, 135.07, 135.10, 135.84, 136.40, 142.62. **Anal.** Calcd for $\text{C}_{25}\text{H}_{28}\text{Si}$: C, 84.21; H, 7.91%. Found: C, 83.88; H, 7.95%.

(*E*)-Benzyldimethyl(1-phenyl-4-hexen-3-yl)silane (4ad)



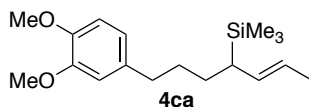
The product **4ad** was purified by flash chromatography on silica gel (hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ –0.12 (s, 3H), –0.10 (s, 3H), 1.48–1.80 (m, 3H), 1.72 (d, $J = 5.1$ Hz, 3H), 2.06 (s, 2H), 2.42 (ddd, $J = 13.5, 9.0, 7.2$ Hz, 1H), 2.77 (ddd, $J = 13.5, 9.6, 4.2$ Hz, 1H), 5.25 (dd, $J = 16.2, 8.4$ Hz, 1H), 5.31 (dq, $J = 16.2, 5.1$ Hz, 1H), 6.93–6.95 (m, 2H), 7.03–7.08 (m, 1H), 7.15–7.21 (m, 5H), 7.26–7.31 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –5.40, –5.29, 18.12, 23.69, 31.14, 31.31, 35.41, 123.91, 123.93, 125.67, 128.20, 128.27, 128.33, 128.62, 131.69, 140.37, 142.96. **Anal.** Calcd for $\text{C}_{21}\text{H}_{28}\text{Si}$: C, 81.75; H, 9.15%. Found: C, 81.53; H, 9.40%.

(*E*)-Methyl 3,3-Dimethyl-6-(trimethylsilyl)-7-nonenoate (4ba)



The product **4ba** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ –0.05 (s, 9H), 0.98 (s, 6H), 1.04–1.26 (m, 3H), 1.42–1.47 (m, 2H), 1.66 (d, $J = 4.8$ Hz, 3H), 2.19 (s, 2H), 3.65 (s, 3H), 5.15 (dd, $J = 15.3, 7.8$ Hz, 1H), 5.21 (dq, $J = 15.3, 4.8$ Hz, 1H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –3.26, 18.02, 23.04, 27.12, 27.22, 33.24, 33.47, 42.34, 45.77, 51.01, 122.49, 132.51, 173.09. **Anal.** Calcd for $\text{C}_{15}\text{H}_{30}\text{O}_2\text{Si}$: C, 66.61; H, 11.18%. Found: C, 66.59; H, 11.20%.

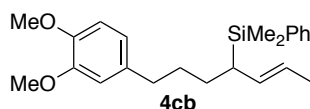
(*E*)-[7-(3,4-Dimethoxyphenyl)-2-hepten-4-yl]trimethylsilane (4ca)



The product **4ca** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ –0.06 (s, 9H), 1.26–1.54 (m, 4H), 1.65 (d, $J = 4.8$ Hz,

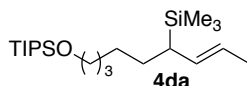
3H), 1.71–1.78 (m, 1H), 2.46 (ddd, $J = 15.0, 8.1, 6.6$ Hz, 1H), 2.58 (ddd, $J = 15.0, 9.6, 5.1$ Hz, 1H), 3.86 (s, 3H), 3.87 (s, 3H), 5.17 (dd, $J = 15.3, 7.2$ Hz, 1H), 5.24 (dq, $J = 15.3, 4.8$ Hz, 1H), 6.70–6.72 (m, 2H), 6.77–6.80 (m, 1H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –3.34, 18.01, 28.42, 31.34, 32.75, 35.23, 55.68, 55.82, 111.08, 111.69, 120.14, 122.59, 132.34, 135.69, 146.99, 148.75. **Anal.** Calcd for $\text{C}_{18}\text{H}_{30}\text{O}_2\text{Si}$: C, 70.53; H, 9.87%. Found: C, 70.52; H, 10.02%.

(*E*)-[7-(3,4-Dimethoxyphenyl)-2-hepten-4-yl]dimethyl(phenyl) silane (4cb)



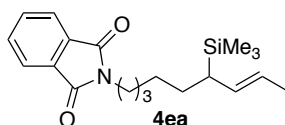
The product **4cb** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 0.22 (s, 3H), 0.24 (s, 3H), 1.28–1.70 (m, 5H), 1.64 (d, $J = 4.8$ Hz, 3H), 2.38 (ddd, $J = 14.4, 8.4, 6.0$ Hz, 1H), 2.51 (ddd, $J = 14.4, 9.3, 4.5$ Hz, 1H), 3.84 (s, 3H), 3.85 (s, 3H), 5.18 (dd, $J = 15.3, 7.5$ Hz, 1H), 5.22 (dq, $J = 15.3, 4.8$ Hz, 1H), 6.63–6.66 (m, 2H), 6.74–6.77 (m, 1H), 7.30–7.38 (m, 3H), 7.38–7.49 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –5.37, –4.39, 18.01, 28.47, 31.22, 32.28, 35.10, 55.68, 55.83, 111.09, 111.68, 120.12, 123.37, 127.60, 128.86, 131.77, 134.12, 135.63, 138.33, 146.99, 148.75. **Anal.** Calcd for $\text{C}_{23}\text{H}_{32}\text{O}_2\text{Si}$: C, 74.95; H, 8.75%. Found: C, 75.11; H, 8.77%.

(*E*)-Triisopropyl[(6-(trimethylsilyl)-7-nonen-1-yl)oxy]silane (4da)



The product **4da** was purified by flash chromatography on silica gel (hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ –0.06 (s, 9H), 1.05–1.07 (m, 21H), 1.15–1.57 (m, 9H), 1.65 (d, $J = 4.8$ Hz, 3H), 3.66 (t, $J = 13.2$ Hz, 2H), 5.16 (dd, $J = 14.7, 6.9$ Hz, 1H), 5.23 (dq, $J = 14.7, 4.8$ Hz, 1H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –3.32, 11.90, 17.92, 18.02, 25.56, 28.81, 29.08, 32.88, 32.89, 63.50, 122.35, 132.63. **HRMS–APCI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{21}\text{H}_{46}\text{OSi}_2$, 370.3087; found, 370.3083.

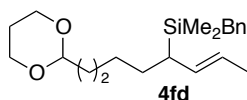
(*E*)-2-[6-(Trimethylsilyl)-7-nonen-1-yl]isoindoline-1,3-dione (4ea)



The product **4ea** was purified by flash chromatography on silica gel (0–20% EtOAc/hexane).

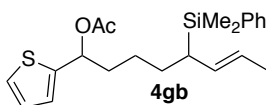
White solid. **M.p.** 54.2–54.4 °C. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ –0.08 (s, 9H), 1.14–1.49 (m, 9H), 1.63 (d, J = 5.1 Hz, 3H), 3.67 (t, J = 7.2 Hz, 2H), 5.13 (dd, J = 15.0, 6.9 Hz, 1H), 5.20 (dq, J = 15.0, 5.1 Hz, 1H), 7.71 (m, 2H), 7.85 (m, 2H). $^{13}\text{C NMR}$ (75.4 MHz, CDCl_3) δ –3.35, 17.80, 26.70, 28.48, 28.65, 28.90, 32.85, 38.06, 122.47, 123.20, 132.26, 132.42, 133.90, 168.63. Anal. Calcd for $\text{C}_{20}\text{H}_{29}\text{NO}_2\text{Si}$: C, 69.92; H, 8.51; N, 4.08%. Found: C, 70.14; H, 8.68; N, 3.99%.

(*E*)-[9-(1,3-Dioxan-2-yl)-2-nonen-4-yl](benzyl)dimethylsilane (4fd)



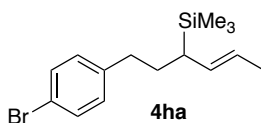
The product **4fd** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ –0.11 (s, 3H), –0.10 (s, 3H), 1.16–1.63 (m, 12H), 1.66 (d, J = 4.8 Hz, 3H), 2.02–2.16 (m, 1H), 2.06 (s, 2H), 3.76 (td, J = 12.3, 2.1 Hz, 2H), 4.10 (dd, J = 10.8, 5.1 Hz, 2H), 4.50 (t, J = 5.1 Hz, 1H), 5.16 (dd, J = 15.3, 7.8 Hz, 1H), 5.21 (dq, J = 15.3, 4.8 Hz, 1H), 6.97–7.00 (m, 2H), 7.03–7.08 (m, 1H), 7.18–7.23 (m, 2H). $^{13}\text{C NMR}$ (75.4 MHz, CDCl_3) δ –5.32, –5.28, 18.02, 23.75, 23.82, 25.74, 28.77, 29.08, 29.24, 31.70, 35.17, 66.86, 102.47, 123.09, 123.86, 128.14, 128.29, 132.08, 140.49. Anal. Calcd for $\text{C}_{22}\text{H}_{36}\text{O}_2\text{Si}$: C, 73.28; H, 10.06%. Found: C, 73.21; H, 10.33%.

(*E*)-5-(Dimethylphenylsilyl)-1-(thiophen-2-yl)-6-octen-1-yl Acetate (4gb)



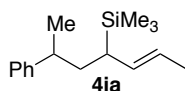
The product **4gb** was purified by flash chromatography on silica gel (0–15% EtOAc/hexane). Colorless oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ 0.22 (s, 3H), 0.23 (s, 3H), 1.07–1.50 (m, 5H), 1.62 (d, J = 4.8 Hz, 1.5H), 1.63 (d, J = 4.8 Hz, 1.5H), 1.79–1.93 (m, 2H), 2.02 (s, 3H), 5.07–5.24 (m, 2H), 5.94 (t, J = 7.2 Hz, 0.5H), 5.95 (t, J = 7.2 Hz, 0.5H), 6.92–6.98 (m, 2H), 7.23–7.26 (m, 1H), 7.34–7.35 (m, 3H), 7.44–7.48 (m, 2H). $^{13}\text{C NMR}$ (75.4 MHz, CDCl_3) δ –5.46, –5.41, –4.46, –4.42, 17.97 ($\times 2\text{C}$), 21.09 ($\times 2\text{C}$), 24.87, 25.00, 28.29, 28.31, 32.02, 32.24, 35.68, 35.90, 71.09, 71.30, 123.56, 123.62, 125.11, 125.20, 125.77, 125.91, 126.50, 126.52, 127.63, 127.65, 128.91, 131.43, 131.49, 134.09, 134.11, 138.15, 138.19, 143.64, 143.84, 170.41, 170.44. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{30}\text{O}_2\text{SSiNa}$, 409.16335; found, 409.16280.

(E)-[1-(4-Bromophenyl)-4-hexen-3-yl]trimethylsilane (4ha)



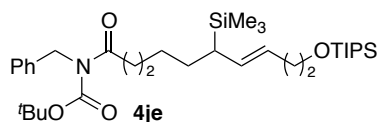
The product **4ha** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ –0.07 (s, 9H), 1.35–1.42 (m, 1H), 1.49–1.73 (m, 2H), 1.70 (d, J = 5.1 Hz, 3H), 2.40 (ddd, J = 13.5, 9.0, 7.2 Hz, 1H), 2.71 (ddd, J = 13.5, 9.3, 4.5 Hz, 1H), 5.20 (dd, J = 15.6, 8.1 Hz, 1H), 5.26 (dq, J = 15.6, 5.1 Hz, 1H), 7.02–7.05 (m, 2H), 7.36–7.40 (m, 2H). $^{13}\text{C NMR}$ (75.4 MHz, CDCl_3) δ –3.40, 18.09, 30.83, 32.47, 34.84, 119.27, 123.39, 130.40, 131.32, 131.95, 142.02. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{15}\text{H}_{23}\text{BrSi}$, 310.0752; found, 310.0752.

(E)-Trimethyl(6-phenyl-2-hepten-4-yl)silane (4ia)



The product **4ia** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ –0.13 (s, 4.5H), –0.06 (s, 4.5H), 1.09–1.27 (m, 1H), 1.15 (d, J = 6.9 Hz, 1.5H), 1.21 (d, J = 6.9 Hz, 1.5H), 1.44–1.64 (m, 2H), 1.68 (d, J = 5.1 Hz, 1.5H), 1.69 (d, J = 5.1 Hz, 1.5H), 2.71–2.87 (m, 1H), 5.03–5.34 (m, 2H), 7.11–7.15 (m, 1H), 7.17–7.21 (m, 2H), 7.26–7.32 (m, 2H). $^{13}\text{C NMR}$ (75.4 MHz, CDCl_3) δ –3.53, –3.40, 18.08, 19.12, 23.60, 30.52, 30.66, 37.27, 37.46, 38.03, 38.40, 122.96, 123.03, 125.73, 125.76, 126.97, 127.48, 128.24, 128.35, 131.85, 132.23, 147.11, 149.29. **Anal.** Calcd for $\text{C}_{16}\text{H}_{26}\text{Si}$: C, 77.97; H, 10.63%. Found: C, 78.09; H, 10.89%.

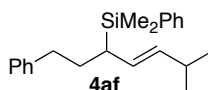
(E)-tert-Butyl Benzyl{10-[(triisopropylsilyl)oxy]-6-(trimethyl silyl)-7-decenoyl}carbamate (4je)



The product **4je** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ –0.06 (s, 9H), 1.06 (s, 21H), 1.12–1.70 (m, 7H), 1.41 (s, 9H), 2.25 (d, J = 6.9 Hz, 2H), 2.88 (td, J = 7.8, 2.1 Hz, 2H), 3.65 (t, J = 6.9 Hz, 2H), 4.88 (s, 2H),

5.21–5.24 (m, 2H), 7.23–7.32 (m, 5H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –3.37, 11.86, 17.91, 24.98, 27.78, 28.58, 28.85, 32.92, 36.80, 38.21, 47.21, 64.03, 82.99, 124.36, 127.10, 127.60, 128.33, 133.52, 138.53, 153.25, 176.45. HRMS–ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{34}\text{H}_{61}\text{NO}_4\text{Si}_2\text{Na}$, 626.40368; found, 626.40313.

(*E*)-Dimethyl(6-methyl-1-phenyl-4-hepten-3-yl)(phenyl)silane (4af)



The product **4af** was purified by flash chromatography on silica gel (hexane). Colorless oil. ^1H NMR (300 MHz, CDCl_3) δ 0.22 (s, 3H), 0.24 (s, 3H), 0.96 (d, J = 6.6 Hz, 3H), 0.98 (d, J = 6.6 Hz, 3H), 1.50–1.78 (d, J = 6.6 Hz, 3H), 2.22–2.34 (m, 1H), 2.36–2.44 (m, 1H), 2.67–2.76 (m, 1H), 5.15 (dd, J = 15.3, 7.8 Hz, 1H), 5.22 (dd, J = 15.3, 6.0 Hz, 1H), 7.08–7.10 (m, 2H), 7.13–7.18 (m, 1H), 7.22–7.27 (m, 2H), 7.30–7.34 (m, 3H), 7.42–7.45 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ –5.34, –4.53, 22.87, 23.03, 30.81, 31.41, 31.70, 35.18, 125.58, 127.29, 127.60, 128.25, 128.63, 128.89, 134.18, 137.17, 138.07, 142.89. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{22}\text{H}_{30}\text{Si}$, 322.21168; found, 322.2115.

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- (22) For an approach to allenylsilanes by the Rh-catalyzed coupling between propargylic carbonates and a silylboronate, see: Ohmiya, H.; Ito, H.; Sawamura, M. *Org. Lett.* **2009**, *11*, 5618.
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Chapter 2

Reversible 1,3-*anti/syn*-Stereochemical Courses in Copper-Catalyzed γ -Selective Allyl-Alkyl Coupling between Chiral Allylic Phosphates and Alkylboranes

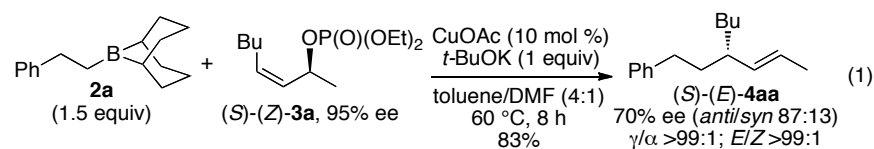
The stereochemical courses of the copper-catalyzed allyl-alkyl coupling between enantioenriched chiral allylic phosphates and alkylboranes were switchable between 1,3-*anti* and 1,3-*syn* selectivities by the choice of solvents and achiral alkoxide bases with different steric demands. The reactions with γ -silylated allylic phosphates allow efficient synthesis of enantioenriched chiral allylsilanes with tertiary or quaternary carbon stereogenic centers. Cyclic and acyclic bimodal participation of alkoxyborane species in an organocopper addition-elimination sequence is proposed to account for the phenomenon of the *anti/syn* stereochemical reversal.

Introduction

Copper-mediated allylic substitutions of enantioenriched chiral allylic alcohol derivatives with organometallic reagents are powerful tools for constructing stereogenic carbon centers.¹ Typically, the reaction occurs with an 1,3-*anti* stereochemistry (*anti*-S_N2') to deliver a new stereogenic center at the γ -position. In contrast, a switch of the stereochemical course from *anti* to *syn* is possible by employing reagent-directing leaving groups, such as benzothiazoles and carbamates (*syn*-S_N2').²⁻⁴ Breit and co-workers introduced the *ortho*-diphenylphosphanyl benzoate (*o*-DPPB) group as a new reagent-directing leaving group,^{5a-f} and furthermore realized the stereoselective conversion of chiral allylic substrates by employing the switchable *o*-DPPB/*o*-DPPB oxide leaving groups.^{5g,h}

In Chapter 2, the author describes a new case for the reversibility of 1,3-*anti*/*syn* stereochemical courses in allylic substitution, where the stereochemical courses are switchable by the choice of solvents and achiral alkoxide bases with different steric demands. The reactions allow efficient synthesis of enantioenriched chiral allylsilanes with tertiary or quaternary carbon stereogenic centers.⁶⁻¹¹ He notes that examples of stereoselective conversion of one enantiomer of a substrate to both enantiomers of a product are still rare despite their usefulness in organic synthesis.¹²

Earlier, the author's laboratory reported the copper-catalyzed γ -selective allyl-alkyl coupling between allylic phosphates and alkylboranes (alkyl-9-BBN).^{13,14} This reaction occurred preferentially with 1,3-*anti* stereochemistry, but the efficiency of the stereoselectivity was only moderate with acyclic allylic substrates (eq. 1).^{13a} The sensitivity of the *anti*/*syn* stereochemistry prompted him to explore the possibility of reversing the stereochemical course from *anti* to *syn* by the choice of reaction conditions.¹⁵

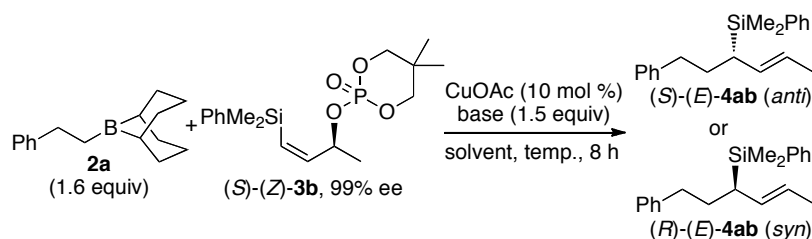


Results and Discussion

His initial study was focused on the reaction producing allylsilanes, because γ -silylated allylic phosphates appeared to be more suitable substrates in terms of the stereoselectivity compared with allylic phosphates having a hydrocarbon backbone (see eq. 1, Table 4). Alkylborane **2a**, which was prepared via hydroboration of styrene (**1a**) with 9-borabicyclo[3.3.1]nonane (9-BBN-H) dimer, and γ -silylated allylic phosphate (*S*)-(*Z*)-**3b** (99% ee) bearing a cyclic phosphate leaving group¹⁶ were subjected to the standard reaction conditions for the copper-catalyzed allyl-alkyl coupling (**2a/3b**/CuOAc/*t*-BuOK 1.6:1:0.1:1.5, THF, 40°C) (Table 1, entry 1; conditions A).^{13a} The reaction afforded allylsilane (*S*)-(*E*)-**4ab** in 94% yield with complete γ - and *E*-selectivities. The absolute configuration of (*S*)-(*E*)-**4ab** indicated that the reaction took place with 1,3-*anti* stereochemistry and the enantiomeric excess was 94% ee (*anti/syn* 97.5:2.5).¹⁷

As shown in Table 1, entries 2–5, the natures of a base and a solvent have marked impacts on the *anti/syn* selectivity. When *t*-BuOLi was used instead of *t*-BuOK in conditions A, the yield was low and the *anti* selectivity decreased to 61% (entry 2). More pronounced effect on the stereoselectivity was observed when *t*-BuOK was changed to sterically less demanding EtOK: under otherwise same conditions, the stereochemical outcome was reversed to *syn* selectivity, giving the *R* isomer of **4ab** with 56% ee (*anti/syn* 22:78) in 86% yield (entry 3). The *syn* selectivity was further increased to 80% by the use of even smaller base MeOK (entry 4). Changing the solvent (THF) in conditions A to toluene also caused the *anti*-to-*syn* reversal although the yield and the *syn* selectivity were low (28% yield, *anti/syn* 38:62, Table 1, entry 5). The *syn* selectivity was increased to 90.5% and 91.5% by the use of EtOK and MeOK, respectively, in place of *t*-BuOK (entries 6 and 7). Use of the smaller bases had a marked impact also on the increase in the yield. He was delighted to find that, when the reaction temperature was increased to 80 °C, the *syn* selectivity became as high as 97.5% and the yield was excellent (entry 8; conditions B).

Table 1. Effect of Reaction Conditions on the *Anti/Syn* Stereoselectivity of the Coupling between **2a** and γ -Silylated Allylic Phosphate (*S*)-(*Z*)-**3b**^a



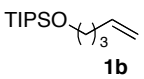
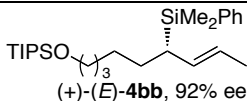
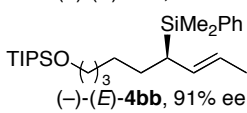
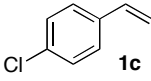
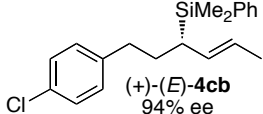
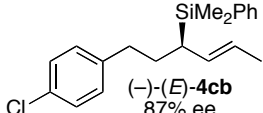
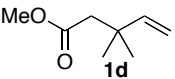
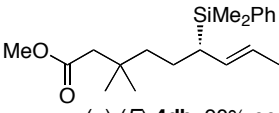
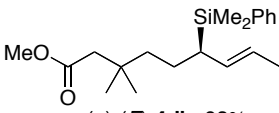
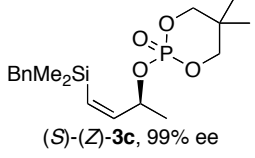
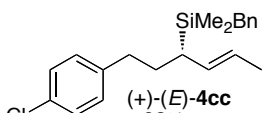
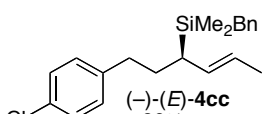
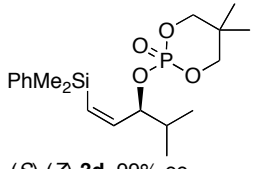
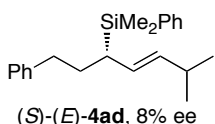
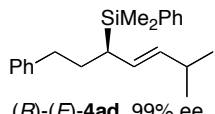
entry	base	solvent	temp (°C)	yield (%) ^{b,c}	ee (%) ^d	<i>anti/syn</i>
1	<i>t</i> -BuOK	THF (conditions A)	40	94	94 (<i>S</i>)	97.5:2.5
2	<i>t</i> -BuOLi	THF	40	14	22 (<i>S</i>)	61:39
3	EtOK	THF	40	86	56 (<i>R</i>)	22:78
4	MeOK	THF	40	99	59 (<i>R</i>)	20:80
5	<i>t</i> -BuOK	toluene	40	28	23 (<i>R</i>)	38:62
6	EtOK	toluene	40	90	80 (<i>R</i>)	9.5:90.5
7	MeOK	toluene	40	92	82 (<i>R</i>)	8.5:91.5
8	MeOK	toluene (conditions B)	80	95	94 (<i>R</i>)	2.5:97.5

^aThe reaction was carried out with (*S*)-(*Z*)-**3b** (0.2 mmol), **2a** (0.32 mmol), CuOAc (10 mol %) and base (0.3 mmol) for 8 h.

^bYield of the isolated product based on (*S*)-(*Z*)-**3b**. ^cIsomeric ratios ($\gamma/\alpha > 99:1$, $E/Z > 99:1$). Determined by ¹H NMR or GC of the crude product. ^dThe enantiomeric excess was determined by HPLC analysis.

Various enantioenriched allylsilanes can be synthesized through the either 1,3-*anti*- or 1,3-*syn*-selective allyl-alkyl coupling reactions (Table 2). The alkylboranes (**2b–d**) bearing silyl ether, chloroaryl or ester moieties underwent the reactions with excellent stereoselectivity (Table 2, entries 1–6). The PhMe₂Si group at the γ -position of **3b** could be replaced with BnMe₂Si groups, affording the corresponding *R* and *S* isomers with excellent stereoselectivities (entries 7 and 8). For the reaction of (*S*)-(*Z*)-**3d** (99% ee), which has an α -*i*-Pr substituent using conditions A, the *anti* and *syn* stereochemical courses were comparable (entry 9). In contrast, conditions B resulted in a higher *syn* selectivity than those with the other substrates (entry 10). This suggests that the bulkiness of the α -*i*-Pr substituent prompted the reactions toward the 1,3-*syn* selectivity (*vide infra* for discussion).

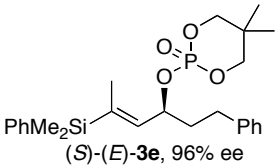
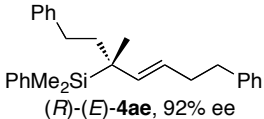
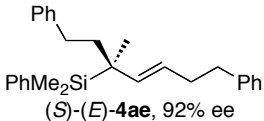
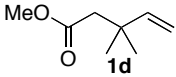
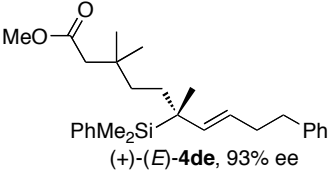
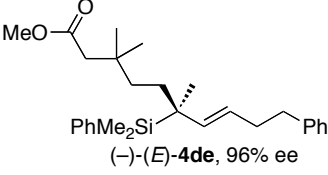
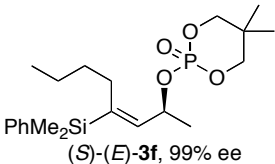
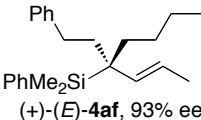
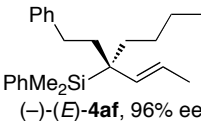
Table 2. Synthesis of Various Enantioenriched Allylsilanes with a Tertiary Carbon Stereogenic Center^{a,b}

entry	alkene	phosphate	conditions	product	yield (%) ^{c,d}	anti/syn ^e
1		(<i>S</i>)-(Z)- 3b 99% ee	A	 (+)-(E)- 4bb , 92% ee	89	96.5:3.5
2	1b	(<i>S</i>)-(Z)- 3b 99% ee	B	 (-)-(E)- 4bb , 91% ee	99	4:96
3		(<i>S</i>)-(Z)- 3b 99% ee	A	 (+)-(E)- 4cb 94% ee	91	97.5:2.5
4	1c	(<i>S</i>)-(Z)- 3b 99% ee	B	 (-)-(E)- 4cb 87% ee	99	6:94
5		(<i>S</i>)-(Z)- 3b 99% ee	A	 (+)-(E)- 4db , 90% ee	69	95.5:4.5
6	1d	(<i>S</i>)-(Z)- 3b 99% ee	B	 (-)-(E)- 4db , 93% ee	94	3:97
7	1c	 (<i>S</i>)-(Z)- 3c , 99% ee	A	 (+)-(E)- 4cc 92% ee	92	96.5:3.5
8	1c	(<i>S</i>)-(Z)- 3c 99% ee	B	 (-)-(E)- 4cc 90% ee	95	4.5:95.5
9	1a	 (<i>S</i>)-(Z)- 3d , 99% ee	A	 (<i>S</i>)-(E)- 4ad , 8% ee	96	54:46
10	1a	(<i>S</i>)-(Z)- 3d 99% ee	B	 (<i>R</i>)-(E)- 4ad , 99% ee	95	1:>99

^a Conditions A: **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), *t*-BuOK (0.3 mmol, 1 M in THF), THF, 40 °C, 8 h. Conditions B: **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), MeOK (0.3 mmol), toluene, 80 °C, 8 h. ^b Alkylborane **2** was prepared in advance by hydroboration of **1** with 9-BBN dimer in THF (conditions A) or toluene (conditions B) at 60 °C for 1 h and used without purification. ^c Yield of the isolated product based on **3**. ^d Isomeric ratios (γ/α >99:1, *E/Z* >99:1). Determined by ¹H NMR or GC of the crude product. ^e The enantiomeric excess was determined by HPLC analysis.

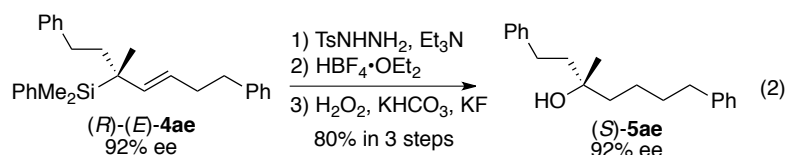
The copper-catalyzed, 1,3-*anti*- and 1,3-*syn*-selective allyl–alkyl couplings can be extended to the synthesis of enantioenriched allylsilanes with a quaternary stereogenic center. The results are summarized in Table 3. He used γ,γ -disubstituted *E* allylic phosphates, which are easier to prepare than the corresponding *Z* isomers.¹⁸ The reaction of γ,γ -disubstituted allylic phosphate (*S*)-(*E*)-**3e** (96% ee) using either conditions A or B afforded the corresponding quaternary chiral allylsilanes (*R*)-(*E*)-**4ae** (92% ee, *anti/syn* 98:2) and (*S*)-(*E*)-**4ae** (92% ee, *anti/syn* 2:98), respectively (entries 1 and 2).¹⁹ The synthetic methods were compatible with an ester moiety in the alkenic (alkylborane) substrate (entries 3 and 4). The reactions of allylic phosphate (*S*)-(*E*)-**3f** (99% ee) with a Bu group instead of the Me group at the γ -position by using either conditions A or B afforded (–)-(*E*)-**4af** (93% ee, *anti/syn* 97:3) and (+)-(*E*)-**4af** (96% ee, *anti/syn* 1.5:98.5), respectively (entries 5 and 6).

Table 3. Synthesis of Enantioenriched Allylsilanes with a Quaternary Carbon Stereogenic Center^{a,b}

entry	alkene	phosphate	conditions	product	yield (%) ^{c,d}	anti/syn ^e
1	1a	 (<i>S</i>)-(-)- 3e , 96% ee	A	 (<i>R</i>)-(-)- 4ae , 92% ee	86	98:2
2	1a	(<i>S</i>)-(-)- 3e 96% ee	B	 (<i>S</i>)-(-)- 4ae , 92% ee	67	2:98
3	 1d	(<i>S</i>)-(-)- 3e 96% ee	A	 (+)-(-)- 4de , 93% ee	93	98.5:1.5
4	1d	(<i>S</i>)-(-)- 3e 96% ee	B	 (-)-(-)- 4de , 96% ee	81	1:>99
5	1a	 (<i>S</i>)-(-)- 3f , 99% ee	A	 (+)-(-)- 4af , 93% ee	70	97:3
6 ^f	1a	(<i>S</i>)-(-)- 3f 99% ee	B	 (-)-(-)- 4af , 96% ee	56	1.5:98.5

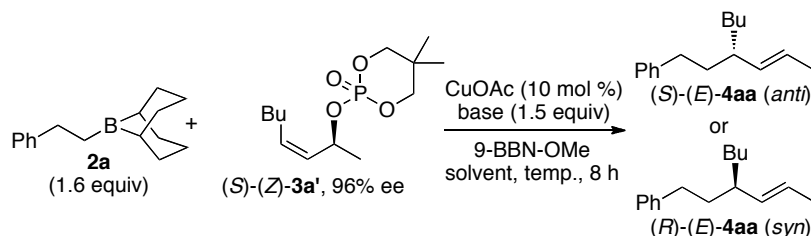
^a Conditions A: **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), *t*-BuOK (0.3 mmol, 1 M in THF), THF, 40 °C, 18 h. Conditions B: **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), MeOK (0.3 mmol), toluene, 80 °C, 8 h. ^b Alkylborane **2** was prepared in advance by hydroboration of **1** with 9-BBN dimer in THF (conditions A) or toluene (conditions B) at 60 °C for 1 h and used without purification. ^c Yield of the isolated product based on **3**. ^d Isomeric ratios (γ/α >99:1, *E/Z* >99:1). Determined by ¹H NMR or GC of the crude product. ^e The enantiomeric excess was determined by HPLC analysis. ^f The reaction was carried out in toluene/DCE (3:1) solvent.

The α -quaternary allylsilane (*R*)-(*E*)-**4ae** (92% ee) was readily derivatized to the chiral tertiary carbinol **5ae** (92% ee) by alkene reduction followed by Fleming–Tamao oxidation with retention of configuration (eq. 2).²⁰



The phenomenon of *anti/syn* stereochemical reversal is not limited to cases with silylated allylic phosphates (Table 4). For instance, the reaction between the allylic phosphate (*S*)-(*Z*)-**3a'** (96% ee) and **2a** under conditions A occurred with 97% 1,3-*anti* selectivity (entry 1). In contrast, the copper-catalyzed reaction of the same substrate pair under conditions B proceeded with 85% *syn* selectivity, giving (*R*)-(*E*)-**4aa** with 66% ee in 31% yield (entry 2). The addition of 9-BBN-OMe (1.5 equiv to **3a'**) increased the *syn* selectivity to 89% and the product yield to 55% (entry 3) (see section 5 for the role of 9-BBN-OMe). The use of 9-BBN-OMe in a larger quantity (3 eq) improved the yield to 74% (entry 4; conditions C).

Table 4. Effect of Reaction Conditions on the *Anti/Syn* Stereoselectivity of the Coupling between **2a** and Allylic Phosphate (*S*)-(*Z*)-**3a'**^a



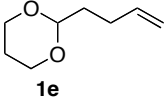
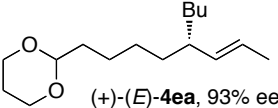
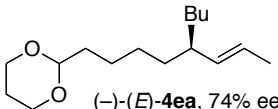
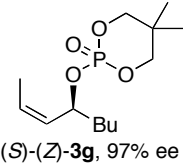
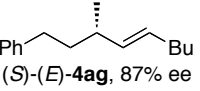
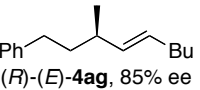
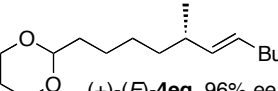
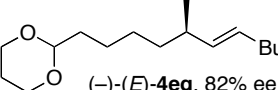
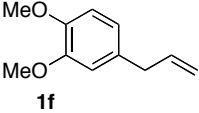
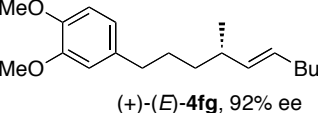
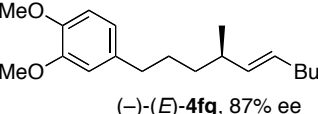
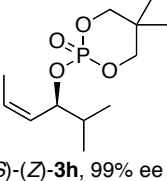
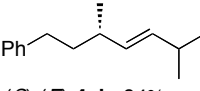
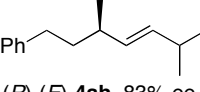
entry	base	solvent	9-BBN-OMe (equiv)	temp (°C)	yield (%) ^{b,c}	ee (%) ^d	<i>anti/syn</i>
1	<i>t</i> -BuOK	THF	none (conditions A)	40	87	90 (<i>S</i>)	97:3
2	MeOK	toluene	none (conditions B)	80	31	66 (<i>R</i>)	15:85
3	MeOK	toluene	1.5	80	55	74 (<i>R</i>)	11:89
4	MeOK	toluene	3.0 (conditions C)	80	74	74 (<i>R</i>)	11:89

^aThe reaction was carried out with (*S*)-(*Z*)-**3a'** (0.2 mmol), **2a** (0.32 mmol), CuOAc (10 mol %) and MeOK (0.3 mmol) for 8 h.

^bYield of the isolated product based on (*S*)-(*Z*)-**3a'**. ^cIsomeric ratios ($\gamma/\alpha > 99:1$, $E/Z > 99:1$). Determined by ¹H NMR or GC of the crude product. ^dThe enantiomeric excess was determined by HPLC analysis.

Various combinations of allylic phosphates having a hydrocarbon backbone and alkylboranes were examined, and the results are summarized in Table 5. The 1,3-*anti* selectivity was generally high with conditions A (*anti/syn* >95:5) (entries 1, 3, 5, 7 and 9). Although the efficiency of 1,3-*syn* selectivity under conditions C was relatively low with the phosphates (*S*)-(*Z*)-**3a'**, which has a Me group at the α -position (entry 2, *anti/syn* 11:89), higher *syn* selectivities (92–95%) were observed when the steric demand of the α -substituent is larger than the Me group (entries 4, 6, 8 and 10). The selectivity trend biased toward the 1,3-*syn* stereochemical course by the bulkiness of the α -substituent is similar to that observed in the reaction with γ -silylated allylic substrates. The reactions were compatible with acetal or 3,4-dimethoxyphenyl moieties in the alkenic (alkylborane) substrates (entries 1, 2 and 5–8).

Table 5. Scope on Stereospecific Allyl–Alkyl Coupling^{a,b}

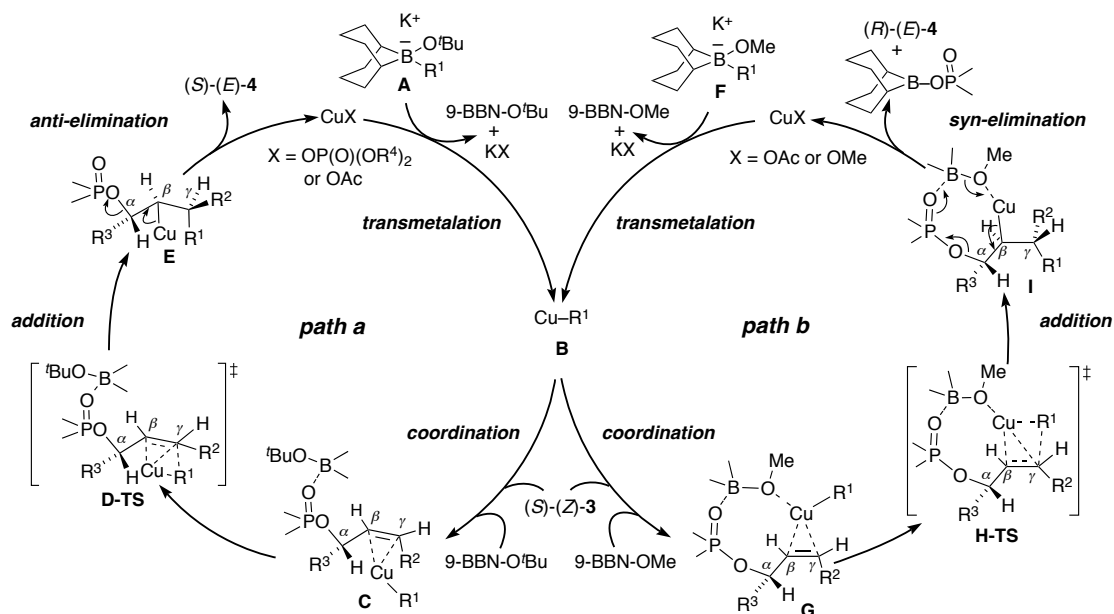
entry	alkene	phosphate	conditions	product	yield (%) ^{c,d}	anti/syn ^e
1		(<i>S</i>)-(Z)- 3a' 96% ee	A	 (+)-(E)- 4ea , 93% ee	65	98.5:1.5
2	1e	(<i>S</i>)-(Z)- 3a' 96% ee	C	 (-)-(E)- 4ea , 74% ee	67	11:89
3	1a	 (<i>S</i>)-(Z)- 3g , 97% ee	A	 (<i>S</i>)-(E)- 4ag , 87% ee	70	95:5
4	1a	(<i>S</i>)-(Z)- 3g 97% ee	C	 (<i>R</i>)-(E)- 4ag , 85% ee	74	6:94
5	1e	(<i>S</i>)-(Z)- 3g 97% ee	A	 (+)-(E)- 4eg , 96% ee	80	99.5:0.5
6	1e	(<i>S</i>)-(Z)- 3g 97% ee	C	 (-)-(E)- 4eg , 82% ee	84	8:92
7		(<i>S</i>)-(Z)- 3g 97% ee	A	 (+)-(E)- 4fg , 92% ee	74	97.5:2.5
8	1f	(<i>S</i>)-(Z)- 3g 97% ee	C	 (-)-(E)- 4fg , 87% ee	95	5:95
9 ^f	1a	 (<i>S</i>)-(Z)- 3h , 99% ee	A	 (<i>S</i>)-(E)- 4ah , 94% ee	29	97.5:2.5
10 ^f	1a	(<i>S</i>)-(Z)- 3h 99% ee	C	 (<i>R</i>)-(E)- 4ah , 83% ee	70	8:92

^a Conditions A (entries 1, 3, 5, 7, 9): **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), *t*-BuOK (0.3 mmol, 1 M in

THF), THF, 40 °C, 8 h. Conditions C (entries 2, 4, 6, 8, 10): **3** (0.2 mmol), alkylborane **2** (0.32 mmol), CuOAc (10 mol %), MeOK (0.3 mmol), 9-BBN-OMe (0.6 mmol), toluene, 80 °C, 8 h. ^b Alkylborane **2** was prepared in advance by hydroboration of **1** with 9-BBN dimer in THF (conditions A) or toluene (conditions C) at 60 °C for 1 h and used without purification. ^c Yield of the isolated product based on **3**. ^d Isomeric ratios ($\gamma/\alpha > 99:1$, $E/Z > 99:1$). Determined by ¹H NMR or GC of the crude product. ^e The enantiomeric excess was determined by HPLC analysis. ^f The reaction was carried out for 18 h.

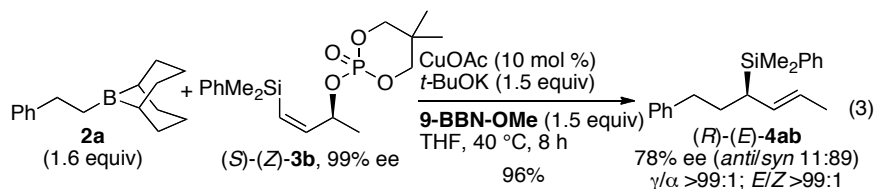
As his laboratory proposed in the previous report, it is conceivable that the copper-catalyzed allyl–alkyl coupling proceeds through the addition–elimination mechanism of a neutral organocopper species.^{13a} The generality and completeness of the γ -regioselectivity (>99:1) strongly supports this assumption. On the basis of this assumption, the 1,3-*anti* stereochemical outcome, which was preferred under conditions A, can be rationalized by the mechanism involving B/Cu transmetalation between trialkyl(alkoxy)borate **A** and CuX [X = OP(O)(OR⁴)₂ or OAc], and the addition of alkylcopper(I) species **B** across the C–C double bond of **3** followed by *anti*- β -elimination from alkylcopper complex **E** (Figure 1, path a). In contrast, the 1,3-*syn* stereochemical outcome, which was preferred under conditions B and C, can be attributed to the pathway involving the addition of alkylcopper species **B** with *syn* stereochemistry with respect to the leaving group followed by *syn*- β -elimination (Figure 1, path b).

Figure 1. Possible pathways for the copper-catalyzed allyl–alkyl coupling between allylic phosphates and alkylboranes.



The switch of the selectivity would likely rely on the nature of the alkoxyboranes (9-BBN-OR, R = *t*-Bu or Me), which are derived from the transmetalation between CuX [X = OMe, OP(O)(OR⁴)₂ or OAc] and the alkylborates (**A** or **F**). Regardless of the R groups, the alkoxyboranes would play a role in activating the phosphate leaving group through their Lewis-acidic character at the boron atom.^{21,22} When the R group in the alkoxyborane is compact enough (R = Me), the alkoxy oxygen would be able to coordinate to the copper atom, enabling path b, which proceeds through a cyclic transition state **H-TS** (**G** → **H-TS** → **I**). This results in 1,3-*syn* stereochemistry. In contrast, when the R group is bulky as the *t*-Bu group, steric factors would prevent the coordination of the alkoxy oxygen to the copper atom. Accordingly, the acyclic mechanism as in path a is preferred (**C** → **D-TS** → **E**). Use of a potentially coordinating solvent such as THF may also render the O–Cu coordination less favorable.

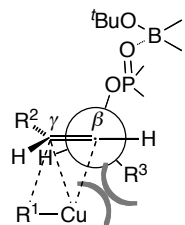
The assumed participation of 9-BBN-OMe in the 1,3-*syn* allylic substitution was strongly supported by an additional experiment that used an external 9-BBN-OMe reagent (eq. 3). Thus, the *anti*-to-*syn* reversal occurred upon adding 9-BBN-OMe (1.5 equiv) to the reaction between **2a** and (*S*)-(*Z*)-**3b** under otherwise 1,3-*anti* reaction conditions.



The proposed acyclic and cyclic mechanisms for the 1,3-*anti* and 1,3-*syn* stereochemical courses may be consistent with the general observation that the sterically more demanding α -substituents in the allylic phosphates biased the reaction toward 1,3-*syn* stereoselectivity. Thus, assuming the stereodifferentiating transition state **D-TS** for the *anti* stereochemical course so that the Cu–C(β) bond and the C(α)–O bond is antiperiplanar as illustrated in Figure 2a, a steric repulsion between the organocopper moiety and the bulky α -substituent (R³) would be significant. On the other hand, such a steric repulsion could be avoided in the cyclic transition state **H-TS** leading to the 1,3-*syn* stereochemical outcome as shown in Figure 2b.

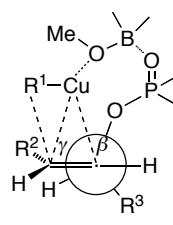
Figure 2. Stereoelectronic effect models.

a) acyclic mode (*anti*)



favored under conditions A

b) cyclic mode (*syn*)



favored under conditions B and C

Conclusion

In summary, the author demonstrated a new case of the reversibility of 1,3-*anti/syn* stereochemical courses in allylic substitution, where the stereochemical courses are switchable by the choice of solvents and achiral alkoxide bases with different steric demands. The protocols allowed the stereoselective conversion of silicon-substituted allylic phosphates into enantioenriched chiral allylsilanes with tertiary or quaternary carbon stereogenic centers. Thus, both enantiomers of the allylsilanes with high enantiomeric purities are readily available from one enantiomer of the substrate. The protocols are versatile and useful for the synthesis of functionalized allylsilanes because alkylboranes are widely available via *in situ* alkene hydroboration with a broad functional compatibility.²³ Furthermore, the use of secondary allylic alcohol derivatives as substrates is advantageous to the preparation of allylsilanes that are substituted at the alkene terminus.^{6–11} The reversible nature of the *anti/syn* stereoselectivity provides clues to understanding the mechanism of the copper-catalyzed allyl–alkyl coupling reactions. Although elucidation of the mechanism must await further detailed studies aided by theoretical calculations, the experimental results obtained in the present study strongly suggest the critical participation of alkoxyboranes in acyclic and cyclic modes during the organocopper addition–elimination pathways.

Experimental Section

Instrumentation and Chemical

NMR spectra were recorded on a Varian Gemini 2000 spectrometer, operating at 300 MHz for ^1H NMR and 75.4 MHz for ^{13}C NMR. Chemical shift values for ^1H and ^{13}C are referenced to Me_4Si and the residual solvent resonances, respectively. Chemical shifts are reported in δ ppm. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TZ at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Elemental analysis was performed at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Melting points were measured on a Yanaco MP-500D apparatus. HPLC analyses were conducted on a HITACHI ELITE LaChrom system with a HITACHI L-2455 diode array detector. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Kanto Chemical Co., Silica gel 60 N, spherical, neutral) and aluminum oxide (Nacalai Tesuque, Alumina Activated 200) were used for column chromatography. Gas chromatographic (GLC) analyses were conducted on a Shimadzu GC-14B equipped with a flame ionization detector. Gel permeation chromatography (GPC) was performed by LC-908 (Japan Analytical Industry Ltd., two in-line JAIGEL-2H, CHCl_3 , 3.5 mL/min, UV and RI detectors).

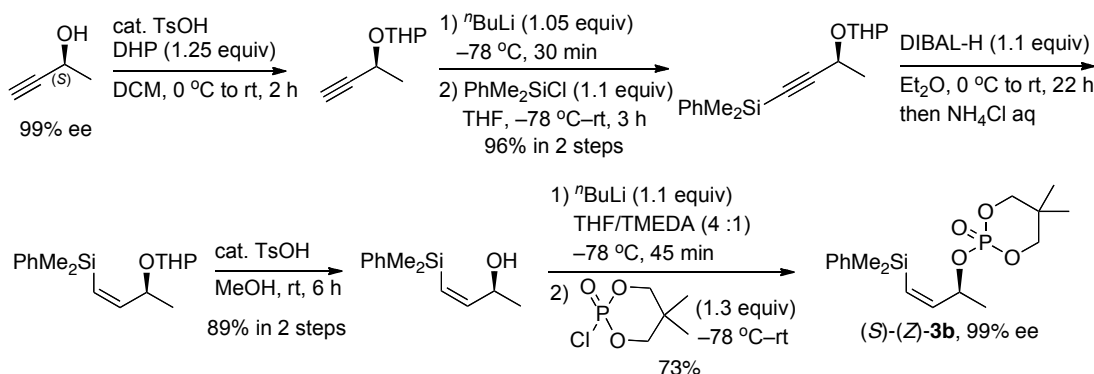
All reactions were carried out under nitrogen or argon atmosphere. Materials were obtained from commercial suppliers or prepared according to standard procedures unless otherwise noted. *t*-BuOK (1.0 M THF solution), MeOK, CuOAc and 9-BBN-OMe were purchased from Aldrich Chemical Co., stored under nitrogen, and used as it is. Tetrahydrofuran (THF) and toluene were purchased from Kanto Chemical Co., stored under argon. Alkenes **1a–f** were well known compounds.

Preparation of Allylic Phosphates

Preparation of γ -Silylated Allylic Phosphates (S)-(E)-3b and (S)-(E)-3c (Scheme 1, Synthesis of (S)-(Z)-3b is representative). THP-protection of commercially available (S)-3-butyne-2-ol (99% ee) followed by silylation gave γ -silylated propargylic alcohol derivatives. Next, DIBAL-H reduction followed by deprotection afforded γ -silylated allylic alcohols.²⁶ Finally, allylic substrates were prepared by the phosphorylation of the γ -silylated allylic alcohols.

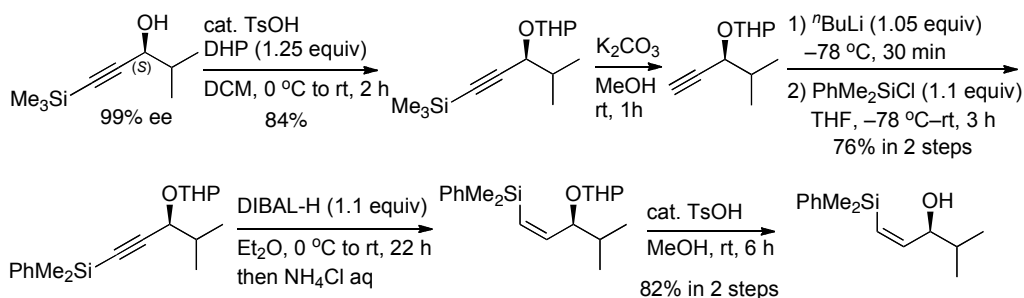
The phosphorylation of (*S*)-(Z)-4-(dimethylphenylsilyl)-3-buten-2-ol to (*S*)-(Z)-**3b** is representative. To a solution of (*S*)-(Z)-4-(dimethylphenylsilyl)-3-buten-2-ol (413 mg, 2.0 mmol) in THF (16.0 mL) and TMEDA (4.0 mL), ⁿBuLi (1.3 mL, 1.63 M, 2.1 mmol) was added at –78 °C. After being stirred at –78 °C for 45 min, 2-chloro-5,5-dimethyl-1,3,2-dioxaphosphinane 2-oxide (480 mg, 2.6 mmol) was added to the reaction mixture. The reaction mixture was stirred for an additional 5 minutes at –78 °C, then warmed to room temperature, and stirred for 3 hours. The resulting solution was quenched with saturated NH₄Cl aq. Aqueous layer was extracted with ethyl acetate, and the combined organic layer was washed with brine, dried over MgSO₄, filtered, and concentrated under vacuum to leave an oil. After passing through a short plug of aluminum oxide with diethyl ether, an eluent was concentrated, and the residue was purified with GPC to provide (*S*)-(Z)-**3b** in 73% yield (517 mg, 1.46 mmol).

Scheme 1.



Preparation of γ -Silylated Allylic Phosphate (*S*)-(E)-3d** (Scheme 2).** (*S*)-4-Methyl-1-trimethylsilyl-1-pentyn-3-ol (99% ee) was prepared by the asymmetric reduction of the corresponding ketone according to the reported procedure.^{8,24} THP-protection of the propargylic alcohol derivative, desilylation followed by silylation with dimethylphenylsilyl chloride gave γ -silylated propargylic alcohol derivative. Next, DIBAL-H reduction followed by deprotection afforded γ -silylated allylic alcohol²⁶ Finally, allylic substrate (*S*)-(E)-**3d** was prepared by the phosphorylation of the γ -silylated allylic alcohol. The absolute configuration of (*S*)-(Z)-**3d** was determined by optical rotation of the precursor compound, 4-methyl-1-trimethylsilyl-1-pentyn-3-ol.²⁴

Scheme 2.



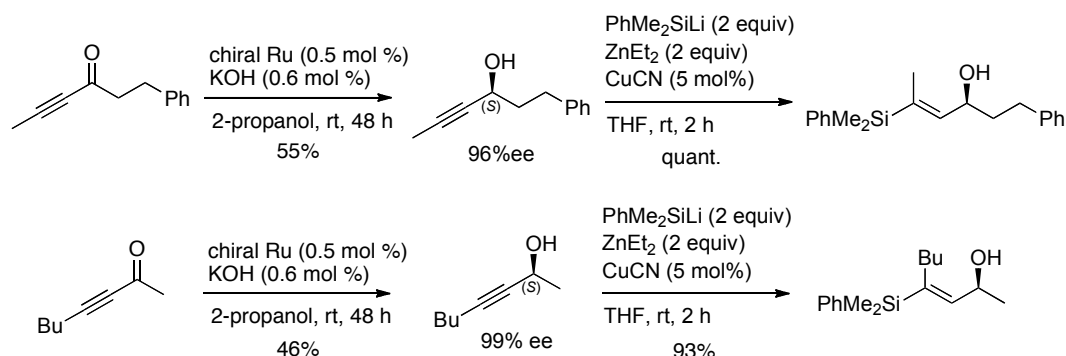
Preparation of γ -Silylated Allylic Phosphates (*S*)-(*E*)-3e** and (*S*)-(*E*)-**3f** (Scheme 3).**

(*S*)-1-Phenyl-4-hexyn-3-ol and (*S*)-3-octyn-2-ol were prepared by the asymmetric reduction of the corresponding ketones according to the reported procedure.²⁴ Copper-catalyzed silylzincation¹⁹ of propargylic alcohols followed by phosphorylation gave (*S*)-(*E*)-**3e** and (*S*)-(*E*)-**3f**.

The ee values of (*S*)-(*E*)-**3e** and (*S*)-(*E*)-**3f** were determined by chiral HPLC analysis. (*S*)-(*E*)-**3e** (96% ee): The ee value was determined by chiral HPLC analysis of **3e** [CHIRALCEL[®] OD-3 column, 4.6 mm $\times$ 250 mm, Daicel Chemical Industries, 2-propanol/hexane 5/95, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 20.8 min for the *R* isomer and 30.5 min for the *S* isomer]. (*S*)-(*E*)-**3f** (99% ee): The ee value was determined by chiral HPLC analysis of the *p*-nitrobenzoate derivative of (*S*)-3-octyn-2-ol [CHIRALCEL[®] OD-3 column, 4.6 mm $\times$ 250 mm, Daicel Chemical Industries, 2-propanol/hexane 1/99, 0.5 mL/min, 40 °C, 254 nm UV detector, retention time = 16.4 min for the *S* isomer and 17.7 min for the *R* isomer].

The absolute configuration of (*S*)-(*E*)-**3e** was confirmed by the alternative synthesis²⁷ of (*S*)-1-phenyl-4-hexyn-3-ol from (2*S*, 3*S*)-2,3-epoxy-5-phenylpentan-1-ol. The absolute configuration of (*S*)-(*E*)-**3f** was determined by optical rotation of the precursor compound, 3-octyn-2-ol.²⁴

Scheme 3.



Preparation of Allylic Phosphate (S)-(Z)-3a'. (S)-3-Octyn-2-ol was prepared by the asymmetric reduction of 3-octyn-2-one according to the reported procedure.²⁴ (S)-3-Octyn-2-ol was reduced with Cp₂TiCl₂/*i*-BuMgBr according to the reported procedure,²⁵ producing (S)-(Z)-3-octen-2-ol, which was then converted to the corresponding allylic phosphate (S)-(Z)-3a'.

The phosphorylation of (S)-(Z)-3-octen-2-ol to (S)-(Z)-3a' is representative. To a solution of (S)-(Z)-3-octen-2-ol (256.3 mg, 2.0 mmol) in THF (16.0 mL) and TMEDA (4.0 mL), ⁿBuLi (1.32 mL, 1.67 M in hexane, 2.2 mmol) was added at -78 °C. After being stirred at -78 °C for 45 min, 2-chloro-5,5-dimethyl-1,3,2-dioxaphosphinane 2-oxide (Aldrich Chemical Co., 553.6 mg, 3 mmol) was added to the reaction mixture. The reaction mixture was stirred for an additional 5 minutes at -78 °C, then warmed to room temperature, and stirred for 3 hours. The resulting solution was quenched with saturated NH₄Cl aq. Aqueous layer was extracted with ethyl acetate, and the combined organic layer was washed with brine, dried over MgSO₄, filtered, and concentrated under vacuum to leave an oil. After passing through a short plug of aluminum oxide with diethyl ether, an eluent was concentrated, and the residue was purified with GPC to provide (S)-(Z)-3a' in 71% yield (398.4 mg, 1.42 mmol).

The ee value of (S)-(Z)-3a' (96% ee) was determined by HPLC analysis of the *p*-nitrobenzoate derivative of (S)-(Z)-3-octen-2-ol (CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daicel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 254 nm UV detector, retention time = 32.8 min for the *R* isomer and 34.3 min for the *S* isomer). The absolute configuration of (S)-(Z)-3a' was determined by optical rotation of the precursor compound, 3-octyn-2-ol.²⁴

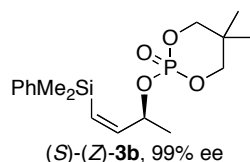
Preparation of Allylic Phosphate (S)-(Z)-3g. (S)-2-Octyn-4-ol was prepared by the asymmetric reduction of 2-octyn-4-one according to the reported procedure.²⁴ (S)-2-Octyn-4-ol

was reduced with $\text{Cp}_2\text{TiCl}_2/i\text{-BuMgBr}^2$ to (*S*)-(*Z*)-2-octen-4-ol, which was then converted to the corresponding allylic phosphate (*S*)-(*Z*)-**3g**. The ee value of (*S*)-(*Z*)-**3g** (97% ee) was determined by HPLC analysis of the *p*-nitrobenzoate derivative of (*S*)-(*Z*)-2-octen-4-ol (CHIRALCEL[®] OD-3 column, 4.6 mm $\times$ 250 mm, Daicel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 254 nm UV detector, retention time = 32.7 min for *S* isomer and 35.2 min for *R* isomer). The absolute configuration of (*S*)-(*Z*)-**3g** was determined by optical rotation of the precursor compound, 2-octyn-4-ol.^{13g}

Preparation of Allylic Phosphate (*S*)-(*Z*)-3h**.** (*S*)-2-Methyl-4-hexyn-3-ol was prepared by the asymmetric reduction of 2-methyl-4-hexyn-3-one according to the reported procedure.²⁴ (*S*)-2-Methyl-4-hexyn-3-ol was reduced with $\text{Cp}_2\text{TiCl}_2/i\text{-BuMgBr}^2$ to (*S*)-(*Z*)-2-methyl-4-hexen-3-ol, which was then converted to the corresponding allylic phosphate (*S*)-(*Z*)-**3h**. The ee value of (*S*)-(*Z*)-**3h** (99% ee) was determined by chiral HPLC analysis of the *p*-nitrobenzoate derivative of (*S*)-(*Z*)-2-methyl-4-hexen-3-ol (CHIRALCEL[®] OJ-H column, 4.6 mm $\times$ 250 mm, Daicel Chemical Industries, hexane/2-propanol = 99.5:0.5, 0.5 mL/min, 40 °C, 254 nm UV detector, retention time = 16.2 min for *R* isomer and 20.8 min for *S* isomer). The absolute configuration of (*S*)-(*Z*)-**3h** was determined by optical rotation of the precursor compound, (*Z*)-2-methyl-4-hexen-3-ol.²⁸

Characterization Data for Allylic Phosphates

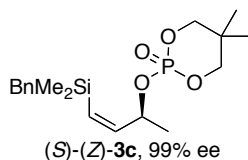
(*S*)-(*Z*)-2-(4-Dimethylphenylsilyl-3-buten-2-yloxy)-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (**3b**)



The product **3b** was purified by GPC. Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.44 (s, 3H), 0.48 (s, 3H), 0.84 (s, 3H), 1.23 (s, 3H), 1.28 (d, *J* = 6.3 Hz, 3H), 3.69–4.04 (m, 4H), 5.04 (dq, *J* = 9.0, 6.3 Hz, 1H), 5.86 (d, *J* = 14.4 Hz, 1H), 6.38 (dd, *J* = 14.4, 9.0 Hz, 1H), 7.26–7.37 (m, 3H), 7.54–7.56 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ -1.54, -1.27, 20.26 (d, *J* = 4.0 Hz), 21.58, 22.19 (d, *J* = 4.0 Hz), 31.92 (d, *J* = 5.7 Hz), 75.18 (d, *J* = 5.1 Hz), 77.35 (d, *J* = 6.8 Hz), 77.73 (d, *J* = 6.8 Hz), 128.00, 129.24, 130.37, 133.75, 138.54, 147.67 (d, *J* = 5.7 Hz). HRMS-ESI (*m/z*):

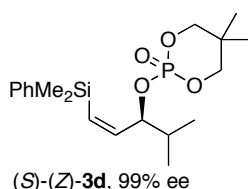
$[M+Na]^+$ calcd for $C_{17}H_{27}O_4PSiNa$, 377.1308; found, 377.1311. $[\alpha]_D^{24} +62.4$ (c 1.03, $CHCl_3$).

(S)-(Z)-2-(4-Benzyltrimethylsilyl-3-buten-2-yloxy)-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3c)



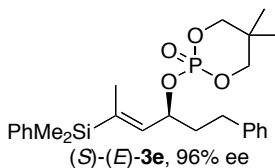
The product **3c** was purified by GPC. Oil. ^1H NMR (300 MHz, $CDCl_3$) δ 0.16 (s, 3H), 0.17 (s, 3H), 0.87 (s, 3H), 1.24 (s, 3H), 1.37 (d, $J = 6.3$ Hz, 3H), 2.19 (s, 2H), 3.76–4.09 (m, 4H), 5.08 (dq, $J = 9.0, 6.3$ Hz, 1H), 5.68 (d, $J = 14.4$ Hz, 1H), 6.32 (dd, $J = 14.4, 9.0$ Hz, 1H), 7.00–7.10 (m, 3H), 7.19–7.24 (m, 2H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ -2.05, -2.00, 20.25, 21.55, 22.51 (d, $J = 4.6$ Hz), 26.17, 31.94 (d, $J = 5.7$ Hz), 75.20 (d, $J = 5.1$ Hz), 77.38 (d, $J = 6.8$ Hz), 77.75 (d, $J = 6.8$ Hz), 124.19, 128.22, 128.28, 130.46, 139.51, 147.16 (d, $J = 5.7$ Hz). HRMS-ESI (m/z): $[M+Na]^+$ calcd for $C_{18}H_{29}O_4PSiNa$, 391.1465; found, 391.1467. $[\alpha]_D^{23} +42.7$ (c 0.87, $CHCl_3$).

(S)-(Z)-2-(1-Dimethylphenylsilyl-4-methyl-1-penten-3-yloxy)-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3d)



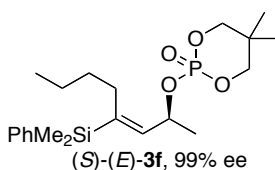
The product **3d** was purified by GPC. White solid. **M.p.** 91.5–91.7 °C. ^1H NMR (300 MHz, $CDCl_3$) δ 0.46 (s, 3H), 0.50 (s, 3H), 0.81 (d, $J = 6.6$ Hz, 3H), 0.85 (s, 3H), 0.89 (d, $J = 6.6$ Hz, 3H), 1.24 (s, 3H), 1.77 (sextet, $J = 6.6$ Hz, 1H), 3.71–4.06 (m, 4H), 4.68–4.76 (m, 1H), 5.95 (d, $J = 14.4$ Hz, 1H), 6.37 (dd, $J = 14.4, 9.6$ Hz, 1H), 7.34–7.37 (m, 3H), 7.55–7.58 (m, 2H). ^{13}C NMR (75.4 MHz, $CDCl_3$) δ -1.43, -1.31, 17.15, 17.99, 20.34 (d, $J = 1.1$ Hz), 21.63, 31.92 (d, $J = 5.7$ Hz), 33.47 (d, $J = 5.7$ Hz), 77.27 (d, $J = 6.3$ Hz), 77.68 (d, $J = 6.8$ Hz), 82.59 (d, $J = 6.3$ Hz), 127.95, 129.18, 132.94, 133.90, 138.69, 144.54 (d, $J = 2.9$ Hz). HRMS-ESI (m/z): $[M+Na]^+$ calcd for $C_{19}H_{31}O_4NaPSi$, 405.1621; found, 405.1624. $[\alpha]_D^{25} +68.8$ (c 0.93, $CHCl_3$).

(S)-(Z)-2-(5-Dimethylphenylsilyl-1-phenyl-4-hexen-3-yloxy)-5,5-dimethyl-1,3,2-dioxaphosphinane 2-Oxide (3e)



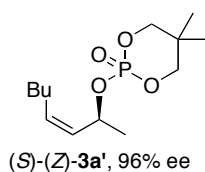
The product **3e** was purified by GPC. Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.36 (s, 6H), 0.83 (s, 3H), 1.23 (s, 3H), 1.74 (d, *J* = 1.5 Hz, 3H), 1.82–1.95 (m, 1H), 2.07–2.20 (m, 1H), 2.61–2.78 (m, 2H), 3.67–4.07 (m, 4H), 5.27–5.37 (m, 1H), 5.78 (dd, *J* = 8.7, 1.5 Hz, 1H), 7.17–7.20 (m, 2H), 7.26–7.31 (m, 3H), 7.33–7.38 (m, 3H), 7.47–7.51 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ –3.88, –3.86, 15.30, 20.29 (d, *J* = 1.1 Hz), 21.58, 31.06, 31.88 (d, *J* = 5.7 Hz), 37.48 (d, *J* = 6.3 Hz), 74.31 (d, *J* = 6.3 Hz), 77.14 (d, *J* = 6.3 Hz), 77.79 (d, *J* = 6.9 Hz), 126.00, 127.89, 128.43, 128.47, 129.22, 133.97, 137.43, 138.21 (d, *J* = 2.9 Hz), 140.33, 141.35. HRMS–ESI (*m/z*): [M+Na]⁺ calcd for C₂₅H₃₅O₄PSiNa, 481.1934; found, 481.1940. [α]_D²³ +1.52 (*c* 0.72, CHCl₃).

(S)-(E)-2-(4-Dimethylphenylsilyl-3-octen-2-yloxy)-5,5-dimethyl-1,3,2-dioxaphosphinane 2-oxide (3f)



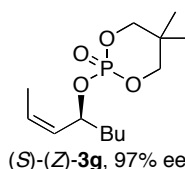
The product **3f** was purified by GPC. Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.38 (s, 6H), 0.81 (t, *J* = 7.2 Hz, 3H), 0.83 (s, 3H), 1.11–1.34 (m, 4H), 1.23 (s, 3H), 1.42 (d, *J* = 6.3 Hz, 3H), 2.03–2.13 (m, 1H), 2.24–2.34 (m, 1H), 3.67–4.08 (m, 4H), 5.40 (dq, *J* = 8.4, 6.3 Hz, 1H), 5.77 (d, *J* = 8.4 Hz, 1H), 7.32–7.37 (m, 3H), 7.48–7.51 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ –3.02, –2.91, 13.69, 20.29 (d, *J* = 1.1 Hz), 21.62, 22.53 (d, *J* = 5.1 Hz), 22.84, 29.87, 31.91 (d, *J* = 5.7 Hz), 32.46, 71.25 (d, *J* = 5.7 Hz), 77.25 (d, *J* = 6.3 Hz), 77.79 (d, *J* = 6.9 Hz), 127.82, 129.12, 134.01, 138.12, 140.17 (d, *J* = 4.6 Hz), 143.33. HRMS–ESI (*m/z*): [M+Na]⁺ calcd for C₂₁H₃₅O₄PSiNa, 433.1934; found, 433.1937. [α]_D²⁴ +30.2 (*c* 0.96, CHCl₃).

(S)-(Z)-5,5-Dimethyl-2-(3-octen-2-yloxy)-1,3,2-dioxaphosphinane 2-Oxide (3a')



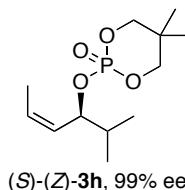
The product **3a'** was purified by GPC. Oil. **¹H NMR** (300 MHz, CDCl₃) δ 0.87 (s, 3H), 0.90 (t, *J* = 6.3 Hz, 3H), 1.25 (s, 3H), 1.31–1.36 (m, 4H), 1.42 (d, *J* = 6.6 Hz, 3H), 2.13 (dt, *J* = 7.2, 6.6 Hz, 2H), 3.78–4.11 (m, 4H), 5.36 (dq, *J* = 8.7, 6.6 Hz, 1H), 5.46 (dd, *J* = 10.5, 8.7 Hz, 1H), 5.55 (dt, *J* = 10.5, 7.2 Hz, 1H). **¹³C NMR** (75.4 MHz, CDCl₃) δ 13.75, 20.25 (d, *J* = 1.1 Hz), 21.60, 22.10, 22.66 (d, *J* = 4.6 Hz), 27.19, 31.44, 31.93 (d, *J* = 5.7 Hz), 71.12 (d, *J* = 5.7 Hz), 77.30 (d, *J* = 6.9 Hz), 77.71 (d, *J* = 6.3 Hz), 129.32 (d, *J* = 5.1 Hz), 133.58. **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₁₃H₂₅O₄PNa, 299.1383; found, 299.1384. [α]_D²³ +71.5 (*c* 1.01, CHCl₃).

(S)-(Z)-5,5-Dimethyl-2-(2-octen-4-yloxy)-1,3,2-dioxaphosphinane 2-Oxide (3g)



The product **3g** was purified by GPC. Oil. **¹H NMR** (300 MHz, CDCl₃) δ 0.87 (s, 3H), 0.89 (t, *J* = 6.9 Hz, 3 H), 1.23 (s, 3H), 1.27–1.34 (m, 4H), 1.50–1.65 (m, 1H), 1.73 (dd, *J* = 7.2, 1.5 Hz, 3H), 1.77–1.87 (m, 1H), 3.77–4.10 (m, 4H), 5.20 (dq, *J* = 10.2, 7.2 Hz, 1H), 5.44 (td, *J* = 10.2, 1.5 Hz, 1H), 5.70 (dq, *J* = 10.2, 7.2 Hz, 1H). **¹³C NMR** (75.4 MHz, CDCl₃) δ 13.23, 13.79, 20.29, 21.60, 22.30, 26.72, 31.92 (d, *J* = 5.7 Hz), 35.79 (d, *J* = 5.7 Hz), 74.33 (d, *J* = 5.8 Hz), 77.19 (d, *J* = 6.3 Hz), 77.71 (d, *J* = 6.9 Hz), 128.87, 129.19 (d, *J* = 4.0 Hz). **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₁₃H₂₅O₄PNa, 299.13827; found, 299.13850. [α]_D²³ +45.1 (*c* 1.00, CHCl₃)

(S)-(Z)-5,5-Dimethyl-2-(2-methyl-4-hexen-3-yloxy)-1,3,2-dioxaphosphinane 2-Oxide (3h)



The product **3h** was purified by GPC. Oil. **¹H NMR** (300 MHz, CDCl₃) δ 0.88 (s, 3H), 0.93 (d, *J* = 6.9 Hz, 3H), 0.98 (d, *J* = 6.9 Hz, 3H), 1.24 (s, 3H), 1.74 (dd, *J* = 6.9, 1.8 Hz, 3H), 1.96 (sextet, *J* = 6.9 Hz, 1H), 3.77–4.12 (m, 4H), 4.99 (dt, *J* = 9.3, 6.9 Hz, 1H), 5.46 (m, 1H), 5.77 (dq, *J* = 11.1, 6.9 Hz, 1H). **¹³C NMR** (125.8 MHz, CDCl₃) δ 13.40, 17.18, 17.96, 20.35, 21.64, 31.94 (d, *J* = 6.0 Hz), 33.43 (d, *J* = 6.0 Hz), 77.11 (d, *J* = 6.0 Hz), 78.54 (d, *J* = 6.0 Hz), 126.92 (d, *J* = 2.4 Hz), 129.15. **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₁₂H₂₃O₄PNa, 285.1226; found, 285.1225. [α]_D²⁵ +72.7 (*c* 0.98, CHCl₃).

Procedures for Copper-Catalyzed Allyl–Alkyl Coupling

Typical Procedure for Synthesis of Allylsilanes with Conditions A (Table 1, entry 1). The preparation of (*S*)-(*E*)-**4ab** is representative. In a grove box, (9-BBN-H)₂ (40.3 mg, 0.165 mmol), THF (0.06 mL) and styrene (**1a**) (0.041 mL, 0.36 mmol) were sequentially placed in a screw-top test tube containing a magnetic stirring bar. Also in the glove box, CuOAc (2.5 mg, 0.02 mmol) was placed in another vial containing a magnetic stirring bar. The two vials were then each sealed with a cap equipped with a Teflon-coated silicon rubber septum, and were removed from the glove box. After the mixture in THF was stirred at 60 °C for 1 h to prepare alkylborane **2a**, *t*-BuOK (1 M in THF, 0.3 mL, 0.3 mmol) was added to **2a** prepared in advance at 25 °C. Next, the mixture was transferred to the vial containing the Cu salt. Finally, allylic phosphate (*S*)-(Z)-**3b** (70.9 mg, 0.2 mmol) was added. After 8 h stirring at 40 °C, CH₂Cl₂ was added to the mixture. Then, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether. After the solvent was removed under reduced pressure, flash chromatography on silica gel (hexane) provided (*S*)-(*E*)-**4ab** (55.4 mg, 0.188 mmol) in 94% yield.

Typical Procedure for Synthesis of Allylsilanes with Conditions B (Table 1, entry 8). The preparation of (*R*)-(*E*)-**4ab** is representative. In a grove box, (9-BBN-H)₂ (40.3 mg, 0.165 mmol), toluene (0.06 mL) and styrene (**1a**) (0.041 mL, 0.36 mmol) were sequentially placed in a screw-top test tube containing a magnetic stirring bar. Also in the glove box, CuOAc (2.5 mg, 0.02 mmol) and MeOK (21.0 mg, 0.3 mmol) were placed in another vial containing a magnetic stirring bar. The two vials were then each sealed with a cap equipped with a Teflon-coated silicon rubber septum, and were removed from the glove box. After the mixture in toluene was stirred at 60 °C for 1 h to prepare alkylborane **2a**, toluene (0.3 mL) was added to **2a** prepared in advance at 25 °C. Next, the alkylborane was transferred to the vial containing the Cu salt. Finally, allylic phosphate (*S*)-(Z)-**3b** (70.9 mg, 0.2 mmol) was added. After 8 h stirring at 80 °C, CH₂Cl₂ was added to the mixture. Then, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether. After the solvent was removed under reduced pressure, flash chromatography on silica gel (hexane) provided (*R*)-(*E*)-**4ab** (56.1 mg, 0.19 mmol) in 95% yield.

Typical Procedure for 1,3-*syn* Selective Allyl–Alkyl Coupling with Conditions C (Table 4, entry 4). In a grove box, (9-BBN-H)₂ (40.3 mg, 0.165 mmol), toluene (0.06 mL) and styrene (**1a**) (0.041 mL, 0.36 mmol) were sequentially placed in a screw-top test tube containing a

magnetic stirring bar. Also in the glove box, CuOAc (2.5 mg, 0.02 mmol) and MeOK (21.0 mg, 0.3 mmol) were placed in another vial containing a magnetic stirring bar. The two vials were then each sealed with a cap equipped with a Teflon-coated silicon rubber septum, and were removed from the glove box. After the mixture in toluene was stirred at 60 °C for 1 h to prepare alkylborane **2a**, toluene (0.3 mL) was added to **2a** prepared in advance at 25 °C. Next, the alkylborane was transferred to the vial containing the Cu salt. Finally, 9-BBN-OMe (1 M in Hexane, 0.3 mL, 0.6 mmol) and allylic phosphate (*S*)-(Z)-**3a** (58.5 mg, 0.2 mmol) were added. After 8 h stirring at 80 °C, CH₂Cl₂ was added to the mixture. Then, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether. After the solvent was removed under reduced pressure, flash chromatography on silica gel (hexane) provided (*R*)-(E)-**4aa** (32.0 mg, 0.148 mmol) in 74% yield.

Addition of 9-BBN-OMe under 1,3-*anti* Reaction Conditions (eq. 3). In a grove box, (9-BBN-H)₂ (40.3 mg, 0.165 mmol), THF (0.06 mL) and styrene (**1a**) (0.041 mL, 0.36 mmol) were sequentially placed in a screw-top test tube containing a magnetic stirring bar. Also in the glove box, CuOAc (2.5 mg, 0.02 mmol) was placed in another vial containing a magnetic stirring bar. The two vials were then each sealed with a cap equipped with a Teflon-coated silicon rubber septum, and were removed from the glove box. After the mixture in THF was stirred at 60 °C for 1 h to prepare alkylborane **2a**, *t*-BuOK (1 M in THF, 0.3 mL, 0.3 mmol) was added to **2a** prepared in advance at 25 °C. Next, the mixture was transferred to the vial containing the Cu salt. Finally, 9-BBN-OMe (1 M in Hexane, 0.3 mL, 0.3 mmol) and allylic phosphate (*S*)-(Z)-**3b** (70.9 mg, 0.2 mmol) were added. After 8 h stirring at 40 °C, CH₂Cl₂ was added to the mixture. Then, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether. After the solvent was removed under reduced pressure, flash chromatography on silica gel (hexane) provided (*R*)-(E)-**4ab** (56.5 mg, 0.192 mmol) in 96% yield.

Synthesis of Chiral Tertiary Carbinol (*S*)-5ae** (eq. 2).** *p*-Toluenesulfonyl hydrazide (346 mg, 1.86 mmol) was placed in a screw-top test tube. Allylsilane (*S*)-(E)-**4ae** (74.2 mg, 0.186 mmol), 1,4-dioxane (1.86 mL) and triethylamine (0.26 mL, 1.86 mmol) were sequentially added to the test tube at 25 °C. The resulting mixture was stirred at reflux for 24 h (monitored by TLC). After the mixture was cooled to 25 °C, water was added. The aqueous layer was extracted with hexane (three times). The combined organic layer was washed with water and brine, and then was dried and concentrated. The crude product was purified by flash column chromatography

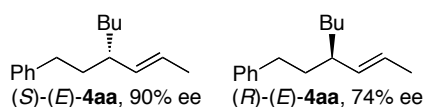
(5% EtOAc/hexane) to yield the hydrogenated product as a colorless oil (68.5 mg, 0.171 mmol, 92%).

A vial containing the reduced compound (68.5 mg, 0.169 mmol) was filled with argon. CH₂Cl₂ (1.6 mL) and HBF₄•OEt₂ (0.4 mL, 0.24 mmol) were sequentially added at 25 °C. After 1.5 h stirring at 25 °C, the mixture was quenched with water. The aqueous layer was extracted with hexane (three times). The combined organic layer was washed with water and brine, and then was dried and concentrated to provide the fluorinated product (57.4 mg, 0.169 mmol, quant.)

The fluorinated compound (28.9 mg, 0.085 mmol) was placed in a screw-top test tube. THF (0.3 mL), MeOH (0.6 mL), KF (19.8 mg, 0.34 mmol), KHCO₃ (85.1 mg, 0.85 mmol), 30% H₂O₂ aq (96.3 mg, 1.69 mmol) were sequentially added at 25 °C. After being stirred at 40 °C for 24 h, the mixture was quenched with Na₂S₂O₃ aq. The aqueous layer was extracted with ethyl acetate (three times). The combined organic layer was washed with water and brine, and then was dried and concentrated. The crude product was purified by flash column chromatography (5–20% EtOAc/hexane) to yield the alcohol as a colorless oil (20.8 mg, 0.074 mmol, 87%).

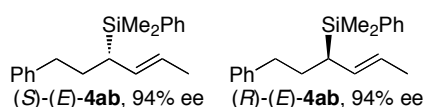
Characterization Data for Coupling Products

(*E*)-4-(2-Phenylethyl)-2-octene (**4aa**)



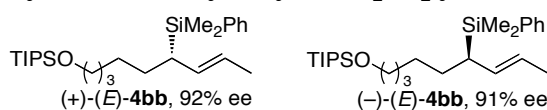
The product **4aa** was purified by flash chromatography on silica gel (hexane). NMR data were described previously.^{13a} The ee values were determined by chiral HPLC analysis of (*E*)-**4aa** [CHIRALCEL® OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 8.7 min for the *S* isomer and 9.2 min for the *R* isomer]. The absolute configuration of (*E*)-**4aa** was confirmed by comparison of the optical rotation with the literature data. *S* isomer: $[\alpha]_D^{25} +0.9$ (*c* 1.17, CHCl₃), *R* isomer: $[\alpha]_D^{26} -0.87$ (*c* 0.93, CHCl₃), [lit^{13a}, *S* isomer, 70% ee, $[\alpha]_D^{24} +1.0$ (*c* 0.8, CHCl₃)].

(*E*)-Dimethylphenyl(1-phenyl-4-hexen-3-yl)silane (**4ab**)^{10f}



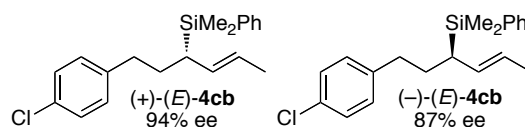
The product **4ab** was purified by flash chromatography on silica gel (hexane). The ee values were determined by chiral HPLC analysis of (*E*)-**4ab** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.3 mL/min, 40 °C, 220 nm UV detector, retention time = 17.8 min for the *R* isomer and 18.4 min for the *S* isomer]. The absolute configuration of (*E*)-**4ab** was confirmed by comparison of the optical rotations with the literature data. *S* isomer: $[\alpha]_D^{23} +11.1$ (*c* 1.03, CHCl₃), *R* isomer: $[\alpha]_D^{24} -12.4$ (*c* 1.26, CHCl₃), {lit^{10f}, *S* isomer, 94% ee, $[\alpha]_D^{23} +8.0$ (*c* 1.6, CHCl₃)}.

(*E*)-[(6-Dimethylphenylsilyl-7-nonen-1-yl)oxy]triisopropylsilane (4bb**)**



The product **4bb** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.22 (s, 3H), 0.24 (s, 3H), 0.97–1.49 (m, 9H), 1.05 (s, 21H), 1.64 (d, *J* = 5.1 Hz, 3H), 3.62 (t, *J* = 13.5 Hz, 2H), 5.15 (dd, *J* = 15.0, 7.2 Hz, 1H), 5.19 (dq, *J* = 15.0, 5.1 Hz, 1H), 7.33–7.35 (m, 3H), 7.46–7.49 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ –5.29, –4.40, 11.87, 17.91, 18.00, 25.42, 28.80, 28.95, 32.36, 32.83, 63.45, 123.13, 127.58, 128.81, 132.01, 134.14, 138.48. **Anal.** Calcd for C₂₆H₄₈O₂Si₂: C, 72.15; H, 11.18%. Found: C, 72.20; H, 11.29%. (+) isomer: $[\alpha]_D^{23} +3.98$ (*c* 1.01, CHCl₃). (–) isomer: $[\alpha]_D^{25} -3.64$ (*c* 1.01, CHCl₃). The ee values were determined by chiral HPLC analysis of the *p*-nitrobenzoate derivative obtained by desilylation followed by bezoylation from (*E*)-**4bb** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 0.5/99.5, 0.5 mL/min, 40 °C, 250 nm UV detector, retention time = 27.2 min for the (+) isomer and 28.5 min for the (–) isomer].

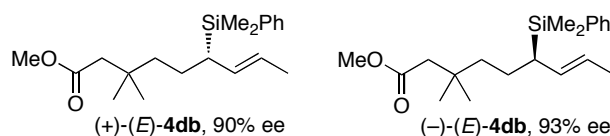
(*E*)-[1-(4-Chlorophenyl)-4-hexen-3-yl]dimethylphenylsilane (4cb**)**



The product **4cb** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.21 (s, 3H), 0.23 (s, 3H), 1.50–1.70 (m, 3H), 1.69 (d, *J* = 4.8 Hz, 3H), 2.36 (m, 1H), 2.66 (ddd, *J* = 13.5, 9.3, 4.3 Hz, 1H), 5.20 (dd, *J* = 15.6, 6.9 Hz, 1H), 5.23 (dq, *J* = 15.0, 4.8 Hz, 1H), 6.98–7.00 (m, 2H), 7.17–7.20 (m, 2H), 7.30–7.35 (m, 3H), 7.41–7.44 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ –5.48, –4.41, 18.08, 30.72, 31.84, 34.51, 124.09, 127.66, 128.30, 128.96, 129.96, 131.23, 131.44, 134.11, 137.97, 141.21. **Anal.** Calcd for C₂₀H₂₅ClSi: C, 73.20; H, 7.44%; Cl, 19.36%. Found: C, 73.15; H, 7.48%; Cl, 19.31%.

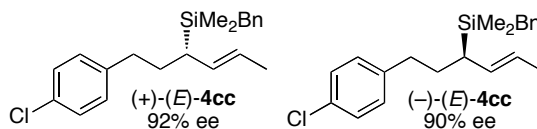
7.73%. Found: C, 73.02; H, 7.66%. (+) isomer: $[\alpha]_D^{23} +11.2$ (c 0.95, CHCl_3). (–) isomer: $[\alpha]_D^{25} -10.7$ (c 1.00, CHCl_3). The ee values were determined by chiral HPLC analysis of (*E*)-**4cb** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 10.3 min for the (–) isomer and 10.8 min for the (+) isomer].

(*E*)-Methyl 6-(Dimethylphenylsilyl)-3,3-dimethyl-7-nonenoate (4db)



The product **4db** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. ¹H NMR (300 MHz, CDCl_3) δ 0.23 (s, 3H), 0.25 (s, 3H), 0.91 (s, 6H), 1.12–1.26 (m, 1H), 1.37–1.51 (m, 3H), 1.64 (d, J = 4.8 Hz, 3H), 2.12 (s, 3H), 3.60 (s, 3H), 5.14 (dd, J = 14.1, 6.9 Hz, 1H), 5.20 (dq, J = 14.1, 4.8 Hz, 1H), 7.33–7.35 (m, 3H), 7.46–7.49 (m, 2H). ¹³C NMR (75.4 MHz, CDCl_3) δ –5.17, –4.37, 18.01, 23.15, 27.06, 27.15, 32.99, 33.18, 42.25, 45.72, 50.95, 123.25, 127.61, 128.86, 131.11, 134.11, 138.35, 173.02. HRMS–ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{20}\text{H}_{32}\text{O}_2\text{Si}$, 355.2064; found, 355.2063. (–) isomer: $[\alpha]_D^{25} -0.30$ (c 1.00, CHCl_3). The ee values were determined by chiral HPLC analysis of (*E*)-**4db** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 13.1 min for the (–) isomer and 13.6 min for the (+) isomer].

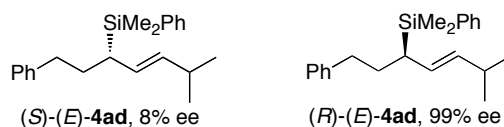
(*E*)-Benzyl[1-(4-chlorophenyl)-4-hexen-3-yl]dimethylsilane (4cc)



The product **4cc** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl_3) δ –0.11 (s, 3H), –0.09 (s, 3H), 1.43–1.72 (m, 3H), 1.71 (d, J = 5.1 Hz, 3H), 2.05 (s, 2H), 2.40 (ddd, J = 16.2, 13.5, 8.1 Hz, 1H), 2.72 (ddd, J = 13.7, 9.0, 4.8 Hz, 1H), 5.21 (dd, J = 15.6, 8.1 Hz, 1H), 5.29 (dq, J = 15.6, 5.1 Hz, 1H), 6.92–6.94 (m, 2H), 7.02–7.08 (m, 3H), 7.16–7.26 (m, 4H). ¹³C NMR (75.4 MHz, CDCl_3) δ –5.40, –5.27, 18.11, 23.66, 30.93, 31.02, 34.59, 123.98, 124.10, 128.25, 128.39, 130.00, 131.33, 131.49, 142.20, 141.28, 142.89. **Anal.** Calcd for $\text{C}_{21}\text{H}_{27}\text{ClSi}$: C, 73.54; H, 7.93%. Found: C, 73.93; H, 7.85%. (+) isomer: $[\alpha]_D^{21}$

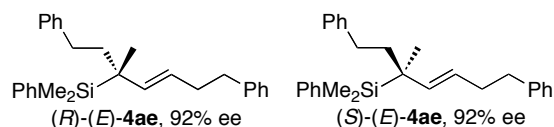
+21.5 (*c* 0.98, CHCl₃). (–) isomer: [α]_D²⁵ –20.0 (*c* 0.99, CHCl₃). The ee values were determined by chiral HPLC analysis of (*E*)-**4cc** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 0.5/99.5, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 10.0 min for the (–) isomer and 10.8 min for the (+) isomer].

(*E*)-Dimethyl(6-methyl-1-phenyl-4-hepten-3-yl)phenylsilane (4ad)



The product **4ad** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.22 (s, 3H), 0.24 (s, 3H), 0.96 (d, *J* = 6.6 Hz, 3H), 0.98 (d, *J* = 6.6 Hz, 3H), 1.50–1.78 (d, *J* = 6.6 Hz, 3H), 2.22–2.34 (m, 1H), 2.36–2.44 (m, 1H), 2.67–2.76 (m, 1H), 5.15 (dd, *J* = 15.3, 7.8 Hz, 1H), 5.22 (dd, *J* = 15.3, 6.0 Hz, 1H), 7.08–7.10 (m, 2H), 7.13–7.18 (m, 1H), 7.22–7.27 (m, 2H), 7.30–7.34 (m, 3H), 7.42–7.45 (m, 2H). ¹³C NMR (75.4 MHz, CDCl₃) δ –5.34, –4.53, 22.87, 23.03, 30.81, 31.41, 31.70, 35.18, 125.58, 127.29, 127.60, 128.25, 128.63, 128.89, 134.18, 138.07, 142.89. HRMS–EI (*m/z*): [*M*]⁺ calcd for C₂₂H₃₀Si, 322.2116; found, 322.2115. *R* isomer: [α]_D²⁴ –15.6 (*c* 1.01, CHCl₃). The ee values were determined by chiral HPLC analysis of (*E*)-**4ad** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 9.4 min for the *R* isomer and 10.1 min for the *S* isomer]. The absolute configuration of (*R*)-(*E*)-**4ad** was determined by transforming it to chiral homoallylic alcohol by the established TiCl₄-mediated addition of allylsilanes to aldehydes (TiCl₄, *i*-PrCHO, CH₂Cl₂, –78 °C, 2 h),⁸ followed by Mosher's NMR spectroscopic method.²⁹

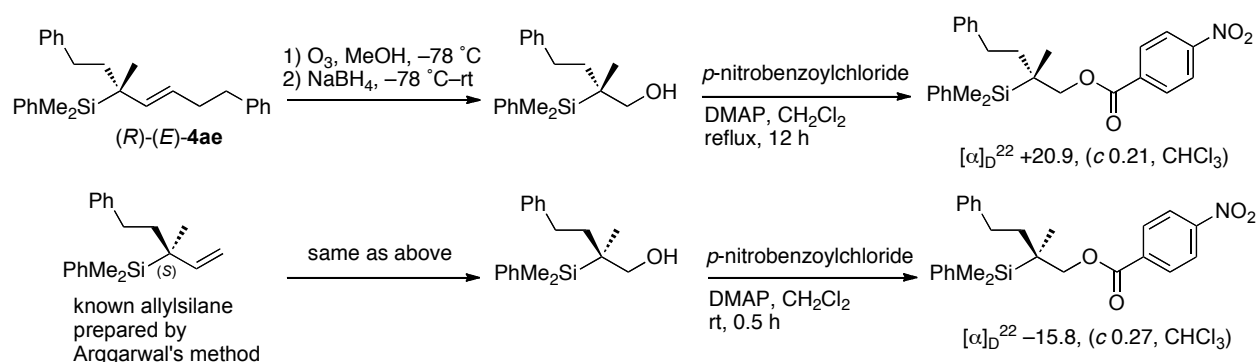
(*E*)-Dimethyl(3-methyl-1,7-diphenyl-4-hepten-3-yl)phenylsilane (4ae)



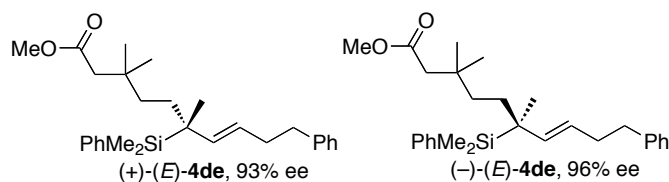
The product **4ae** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.22 (s, 3H), 0.22 (s, 3H), 1.05 (s, 3H), 1.56–1.75 (m, 2H), 2.24–2.34 (m, 1H), 2.37–2.44 (m, 3H), 2.67–2.72 (m, 2H), 5.15 (dt, *J* = 15.8, 6.6 Hz, 1H), 5.39 (d, *J* = 15.8 Hz, 1H), 7.06–7.43 (m, 15H). ¹³C NMR (75.4 MHz, CDCl₃) δ –6.23, –6.19, 17.67, 29.30, 29.80, 34.95, 36.47, 38.05, 125.51, 125.78, 126.53, 127.42, 128.30, 128.34, 128.50, 128.59, 128.92,

134.85, 136.58, 137.10, 142.22, 143.71. **Anal.** Calcd for $C_{28}H_{34}Si$: C, 84.36; H, 8.60%. Found: C, 84.73; H, 8.80%. *R* isomer: $[\alpha]_D^{21} +47.8$ (*c* 0.98, $CHCl_3$). *S* isomer: $[\alpha]_D^{25} -38.1$ (*c* 0.95, $CHCl_3$). The ee values were determined by chiral HPLC analysis of (*E*)-**4ae** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 42.4 min for the *S* isomer and 50.2 min for the *R* isomer]. The *R* absolute configuration of **4ae** was determined as follows; **4ae** was converted into the *p*-nitrobenzoate derivative by the ozonolysis, reduction with $NaBH_4$ followed by benzoylation (Scheme S4). An alternative synthesis of the *p*-nitrobenzoate derivative (*S* isomer) from a known allylsilane,^{10f} which was prepared with Aggarwal's method confirmed the absolute configuration of **4ae**.

Scheme 4.



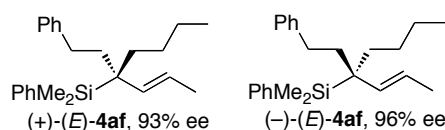
(*E*)-Methyl 6-(Dimethylphenylsilyl)-3,3,6-trimethyl-10-phenyl-7-decenoate (4de**)**



The product **4de** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Oil. ¹H NMR (300 MHz, $CDCl_3$) δ 0.22 (s, 3H), 0.22 (s, 3H), 0.89 (s, 6H), 0.91 (s, 3H), 0.99 (td, *J* = 12.9, 3.9 Hz, 1H), 1.14 (td, *J* = 12.9, 4.5 Hz, 1H), 1.27 (td, *J* = 12.6, 3.9 Hz, 1H), 1.40 (td, *J* = 12.6, 4.5 Hz, 1H), 2.10 (s, 2H), 2.35 (td, *J* = 7.5, 6.6 Hz, 2H), 2.65 (td, *J* = 2.66 Hz, 2H), 3.59 (s, 3H), 5.05 (dt *J* = 15.6, 6.6 Hz, 1H), 5.27 (d, *J* = 15.6 Hz, 1H), 7.16–7.20 (m, 3H), 7.25–7.37 (m, 5H), 7.41–7.44 (m, 2H). ¹³C NMR (75.4 MHz, $CDCl_3$) δ –6.15, –6.13, 17.58, 27.00, 27.13, 28.31, 29.35, 32.91, 34.89, 35.23, 45.62, 50.95, 125.75, 126.20, 126.20, 127.36, 128.31, 128.54,

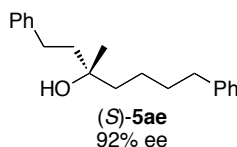
128.86, 134.78, 136.75, 137.32, 142.26, 173.00. **Anal.** Calcd for $C_{28}H_{40}O_2Si$: C, 77.01; H, 9.23%. Found: C, 76.74; H, 9.12%. (+) isomer: $[\alpha]_D^{21} +5.48$ (c 1.07, $CHCl_3$). (–) isomer: $[\alpha]_D^{26} -4.97$ (c 0.98, $CHCl_3$). The ee values were determined by chiral HPLC analysis of (*E*)-**4de** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 0.5/99.5, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 12.0 min for the (–) isomer and 12.6 min for the (+) isomer].

(*E*)-Dimethyl(4-phenethyl-2-octen-4-yl)phenylsilane (4af)



The product **4af** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, $CDCl_3$) δ 0.30 (s, 6H), 0.89 (t, J = 6.9 Hz, 3H), 1.18–1.33 (m, 4H), 1.40–1.50 (m, 1H), 1.59–1.68 (m, 2H), 1.71 (dd, J = 6.3, 1.2 Hz, 3H), 1.83 (ddd, J = 13.8, 9.6, 7.8 Hz, 1H), 2.45 (dd, J = 9.6, 7.8 Hz, 2H), 5.10 (dq, J = 15.6, 6.3 Hz, 1H), 5.32 (dd, J = 15.6, 1.2 Hz, 1H), 7.10–7.14 (m, 2H), 7.16–7.19 (m, 1H), 7.24–7.29 (m, 2H), 7.34–7.38 (m, 3H), 7.47–7.50 (m, 2H). ¹³C NMR (75.4 MHz, $CDCl_3$) δ –4.49, –4.36, 14.03, 18.48, 23.62, 26.48, 30.66, 32.08, 33.08, 34.95, 121.42, 125.61, 127.39, 128.37 (2C), 128.82, 134.81, 137.65, 138.22, 143.74. **Anal.** Calcd for $C_{24}H_{34}Si$: C, 84.36; H, 8.60%. Found: C, 84.73; H, 8.80%. (–) isomer: $[\alpha]_D^{24} -9.9$ (c 0.82, $CHCl_3$). The ee values were determined by chiral HPLC analysis of (*E*)-**4af** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, hexane, 0.5 mL/min, 40 °C, 220 nm UV detector, retention time = 9.1 min for the (–) isomer and 9.7 min for the (+) isomer].

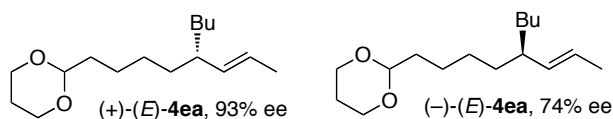
(*S*)-3-Methyl-1,7-diphenylheptan-3-ol (5ae)



The product **5ae** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. ¹H NMR (300 MHz, $CDCl_3$) δ 1.23 (s, 3H), 1.36–1.50 (m, 2H), 1.53–1.60 (m, 3H), 1.65 (t, J = 7.2 Hz, 2H), 1.75 (m, 2H), 2.63 (t, J = 4.8 Hz, 2H), 2.66 (t, J = 7.2 Hz, 2H), 7.11–7.35 (m, 10H). ¹³C NMR (75.4 MHz, $CDCl_3$) δ 23.49, 26.83, 30.23, 31.89, 35.79, 41.71, 43.64, 72.64, 125.74, 125.80, 128.36, 128.39, 128.45, 128.47, 142.61, 142.65. **HRMS–FI** (m/z): $[M-OH_2]^+$

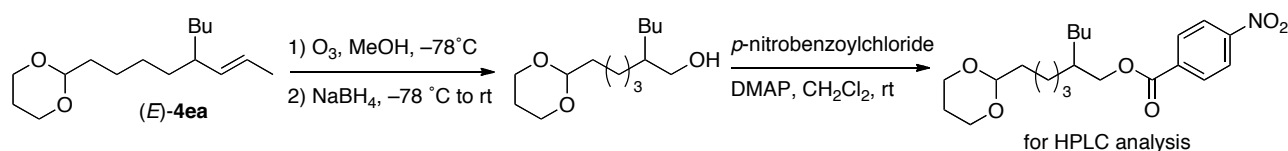
calcd for C₂₀H₂₄, 264.1878; found, 264.1874. [α]_D²⁴ –1.01 (c 1.04, CHCl₃). The ee value was determined by chiral HPLC analysis of the *p*-nitrobenzoate derivative obtained by benzylation from **5ae** [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 3/97, 0.5 mL/min, 40 °C, 250 nm UV detector, retention time = 30.7 min for the *S* isomer and 39.3 min for the *R* isomer].

(*E*)-2-[5-(1-propenyl)nonan-1-yl]-1,3-dioxane (4ea**)**

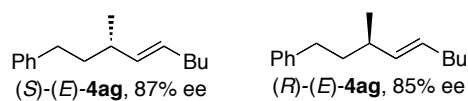


The product **4ea** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.87 (t, *J* = 7.2 Hz, 3 H), 1.17–1.36 (m, *J* = 12H), 1.54–1.58 (m, 3H), 1.65 (dd, *J* = 6.3, 1.5 Hz, 3H), 1.78–1.90 (m, 1H), 2.01–2.14 (m, 1H), 3.76 (td, *J* = 12.0, 2.4 Hz, 2H), 4.10 (dd, *J* = 10.5, 5.1 Hz, 2H), 4.50 (t, *J* = 5.1, 1H), 5.10 (ddd, *J* = 15.0, 8.7, 1.5 Hz, 1H), 5.27–5.34 (m, 1H). ¹³C NMR (75.4 MHz, CDCl₃) δ 14.01, 17.83, 22.74, 23.99, 25.75, 26.95, 29.39, 35.13, 35.16, 35.23, 42.55, 66.87, 102.50, 124.24, 136.32. HRMS–ESI (*m/z*): [M+H]⁺ calcd for C₁₆H₃₁O₂, 255.2324; found, 255.2327. (+) isomer: [α]_D²² +2.31 (c 0.83, CHCl₃), (–) isomer: [α]_D²⁴ –1.72 (c 1.15, CHCl₃). The ee values were determined by chiral HPLC analysis of corresponding *p*-nitrobenzoate derivatives prepared by ozonolysis, reduction with NaBH₄ followed by benzylation sequence (Scheme S5), [CHIRALCEL[®] OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 1/99, 0.5 mL/min, 40 °C, 250 nm UV detector, retention time = 42.5 min for the (–) isomer and 44.6 min for the (+) isomer].

Scheme 5.



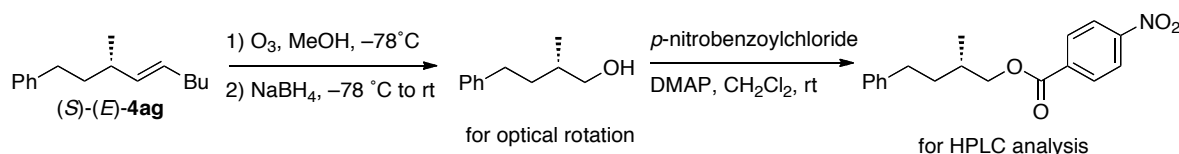
(*E*)-(3-methyl-4-nonen-1-yl)benzene (4ag**)**



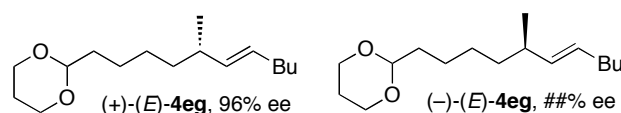
The product **4ag** was purified by flash chromatography on silica gel (hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.90 (t, *J* = 6.9 Hz, 3 H), 0.99 (t, *J* = 6.9 Hz, 3 H), 1.32–1.37 (m, 4H),

1.48–1.70 (m, 2H), 1.99 (dt, $J = 6.6, 6.3$ Hz, 2H), 2.10 (m, 1H), 2.57 (m, 2H), 5.28 (dd, $J = 15.3, 7.5$ Hz, 1H), 5.40 (dt, $J = 15.3, 6.6$ Hz, 1H), 7.14–7.19 (m, 3H), 7.25–7.30 (m, 2H). ^{13}C NMR (75.4 MHz, CDCl_3) δ 13.85, 20.92, 22.07, 31.79, 32.20, 33.63, 36.36, 38.91, 125.59, 128.31, 128.49, 129.31, 135.95, 143.12. **Anal.** Calcd for $\text{C}_{16}\text{H}_{24}$: C, 88.82; H, 11.18%. Found: C, 88.75; H, 11.16%. *S* isomer: $[\alpha]_{\text{D}}^{21} +13.9$ (c 1.00, CHCl_3), *R* isomer: $[\alpha]_{\text{D}}^{24} -11.5$ (c 1.06, CHCl_3). The ee values were determined by chiral HPLC analysis of corresponding *p*-nitrobenzoate derivatives prepared by ozonolysis, reduction with NaBH_4 followed by benzylation sequence (Scheme S6), [CHIRALCEL[®] OD-3 column, 4.6 mm $\times$ 250 mm, Daisel Chemical Industries, 2-propanol/hexane 1/99, 0.5 mL/min, 40 $^\circ\text{C}$, 250 nm UV detector, retention time = 40.7 min for the *S* isomer and 47.1 min for the *R* isomer]. The *S* absolute configuration of (*E*)-**4ag** was determined by comparison of the optical rotation of the corresponding alcohol (Scheme S6) with the literature data. $[\alpha]_{\text{D}}^{25} -18.7$ (c 0.70, CHCl_3), [lit³⁰, *S* isomer, >99% ee, $[\alpha]_{\text{D}}^{20} -18.1$ (c 1.03, CHCl_3), *R* isomer, 99% ee, $[\alpha]_{\text{D}}^{23} +20.0$ (c 1.5, CHCl_3)].

Scheme 6.



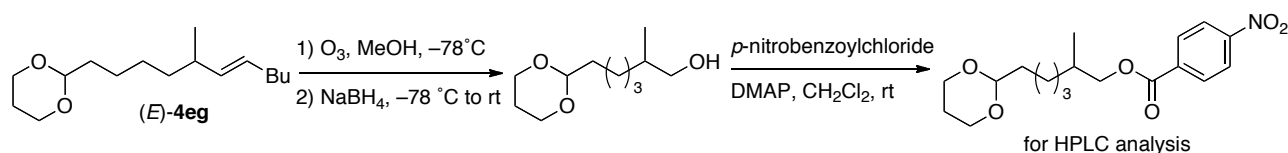
(*E*)-2-(5-methyl-6-undecen-1-yl)-1,3-dioxane (**4eg**)



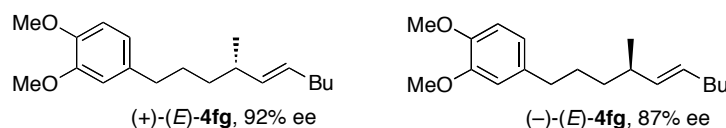
The product **4eg** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Oil. ^1H NMR (300 MHz, CDCl_3) δ 0.88 (t, $J = 7.2$ Hz, 3 H), 0.92 (d, $J = 6.9$ Hz, 3 H), 1.24–1.36 (m, 11H), 1.54–1.61 (m, 2H), 1.96 (dt, $J = 6.6, 6.3$ Hz, 2H), 2.01–2.15 (m, 2H), 3.76 (td, $J = 11.7, 2.4$ Hz, 2H), 4.09 (dd, $J = 11.7, 3.9$ Hz, 2H), 4.50 (t, $J = 5.1$, 1H), 5.22 (dd, $J = 15.3, 7.2$ Hz, 1H), 5.34 (dt, $J = 15.3, 6.3$ Hz, 1H). ^{13}C NMR (75.4 MHz, CDCl_3) δ 13.83, 20.82, 22.03, 23.94, 25.74, 27.03, 31.76, 32.15, 35.14, 36.48, 36.93, 66.86, 102.45, 128.58, 136.38. **Anal.** Calcd for $\text{C}_{16}\text{H}_{30}\text{O}_2$: C, 75.54; H, 11.89%. Found: C, 75.38; H, 11.68%. (+) isomer: $[\alpha]_{\text{D}}^{22} +14.3$ (c 1.02, CHCl_3), (–) isomer: $[\alpha]_{\text{D}}^{24} -11.5$ (c 1.13, CHCl_3). The ee values were determined by chiral HPLC analysis of corresponding *p*-nitrobenzoate derivatives prepared by ozonolysis, reduction with NaBH_4 followed by benzylation sequence (Scheme S7), [CHIRALCEL[®] OD-3

column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 0.5/99.5, 0.5 mL/min, 40 °C, 250 nm UV detector, retention time = 115.5 min for the (+) isomer and 123.4 min for the (–) isomer].

Scheme 7.

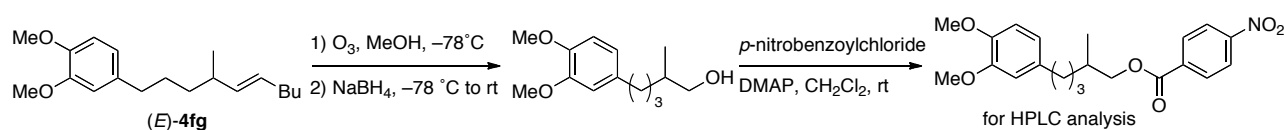


(*E*)-1,2-dimethoxy-4-(4-methyl-5-decen-1-yl)benzene (**4fg**)

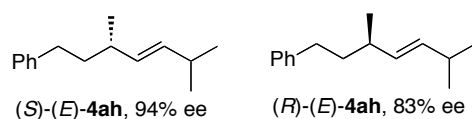


The product **4fg** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. ¹H NMR (300 MHz, CDCl₃) δ 0.88 (t, *J* = 7.2 Hz, 3 H), 0.94 (d, *J* = 6.9 Hz, 3 H), 1.24–1.34 (m, 6H), 1.51–1.61 (m, 2H), 1.96 (dt, *J* = 6.6, 6.3 Hz, 2H), 2.03–2.12 (m, 1H), 2.53 (t, *J* = 6.9 Hz, 2H), 3.86 (s, 3H), 3.88 (s, 3H), 5.23 (dd, *J* = 15.3, 7.5 Hz, 1H), 5.35 (*J* = 15.3, 6.6 Hz, 1H), 6.70–6.73 (m, 2H), 6.78–6.81 (m, 1H). ¹³C NMR (75.4 MHz, CDCl₃) δ 13.83, 20.88, 22.04, 29.36, 31.76, 32.14, 35.51, 36.55, 36.67, 55.68, 55.81, 111.08, 111.68, 120.13, 128.75, 135.65, 136.20, 147.02, 148.76. **Anal.** Calcd for C₁₉H₃₀O₂: C, 78.57; H, 10.41%. Found: C, 78.48; H, 10.37%. (+) isomer: [α]_D²² +13.1 (*c* 1.00, CHCl₃). (–) isomer: [α]_D²⁴ –12.3 (*c* 1.13, CHCl₃). The ee values were determined by chiral HPLC analysis of corresponding *p*-nitrobenzoate derivatives prepared by ozonolysis, reduction with NaBH₄ followed by benzylation sequence (Scheme S8), [CHIRALCEL® OD-3 column, 4.6 mm × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 2/98, 0.5 mL/min, 40 °C, 250 nm UV detector, retention time = 76.3 min for the (–) isomer and 78.4 min for the (+) isomer].

Scheme 8.

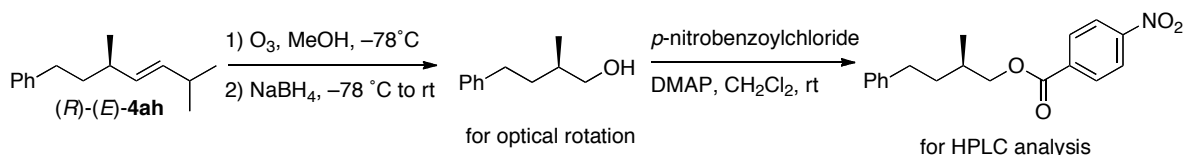


(*E*)-(3,6-Dimethylhept-7-en-1-yl)benzene (**4ah**)



The product **4ah** was purified by flash chromatography on silica gel (hexane). Oil. $^1\text{H NMR}$ (300 MHz, CDCl_3) δ 0.96–1.01 (m, 9H), 1.50–1.63 (m, 2H), 2.08 (m, 1H), 2.25 (m, 1H), 2.51–2.64 (m, 2H), 5.23 (dd, $J = 15.3, 8.1$ Hz, 1H), 5.36 (dd, $J = 15.3, 6.9$ Hz, 1H), 7.13–7.18 (m, 3H), 7.23–7.29 (m, 2H). $^{13}\text{C NMR}$ (125.8 MHz, CDCl_3) δ 21.04, 22.79, 31.03, 33.68, 36.30, 39.00, 125.51, 128.22, 128.41, 132.68, 136.47, 143.01. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{15}\text{H}_{22}$, 202.1722; found, 202.1723. (*S*) isomer: $[\alpha]_{\text{D}}^{24} +16.9$ (c 0.88, CHCl_3). (*R*) isomer: $[\alpha]_{\text{D}}^{24} -13.0$ (c 0.90, CHCl_3). The ee values were determined by chiral HPLC analysis of corresponding *p*-nitrobenzoate derivatives prepared by ozonolysis, reduction with NaBH_4 followed by benzylation sequence (Scheme S9), [CHIRALCEL[®] OD-3 column, 4.6 mm $\times$ 250 mm, Daisel Chemical Industries, 2-propanol/hexane 1/99, 0.5 mL/min, 40 $^\circ\text{C}$, 250 nm UV detector, retention time = 40.7 min for the (*R*) isomer and 46.5 min for the (*S*) isomer]. The *R* absolute configuration of (*E*)-**4ah** was determined by comparison of the optical rotation of the corresponding alcohol (Scheme S9) with the literature data. $[\alpha]_{\text{D}}^{25} +10.6$ (c 0.88, CHCl_3). [lit³⁰, *S* isomer, >99% ee, $[\alpha]_{\text{D}}^{20} -18.1$ (c 1.03, CHCl_3), *R* isomer, 99% ee, $[\alpha]_{\text{D}}^{23} +20.0$ (c 1.5, CHCl_3)].

Scheme 9.



References and Notes

- (1) For reviews on Cu-mediated allylic substitutions, see: (a) *Modern Organocopper Chemistry*; Krause, N., Ed.; Wiley-VCH: Weinheim, Germany, 2002. (b) Hoveyda, A. H.; Hird, A. W.; Kacprzynski, M. A. *Chem. Commun.* **2004**, 1779. (c) Yorimitsu, H.; Oshima, K. *Angew. Chem. Int. Ed.* **2005**, *44*, 4435. (d) Falciola, C. A.; Alexakis, A. *Eur. J. Org. Chem.* **2008**, 3765. (e) Alexakis, A.; Bäckvall, J. E.; Krause, N.; Pàmies, O.; Diéguez, M. *Chem. Rev.* **2008**, *108*, 2796. (f) Harutyunyan, S. R.; den Hartog, T.; Geurts, K.; Minnaard, A. J.; Feringa, B. L. *Chem. Rev.* **2008**, *108*, 2824.
- (2) For a review on directed reactions of organocopper reagents, see: Breit, B.; Schmidt, Y. *Chem. Rev.* **2008**, *108*, 2928.
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Chapter 3

Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates with Alkyl-, Alkenyl-, and Arylboranes

The author found that trialkylphosphine organocatalysts promoted unprecedented *anti*-carboboration of alkynoates with alkyl-, alkenyl-, or arylboranes to form β -borylacrylates. The regioselectivity of the carboboration across the polar C–C triple bond exhibited inverse electronic demand, with the less electronegative B atom being delivered to the positively charged β carbon atom. The regioselectivity and the *anti* stereoselectivity were both complete and robust. In addition, the substrate scope was broad with excellent functional group compatibility.

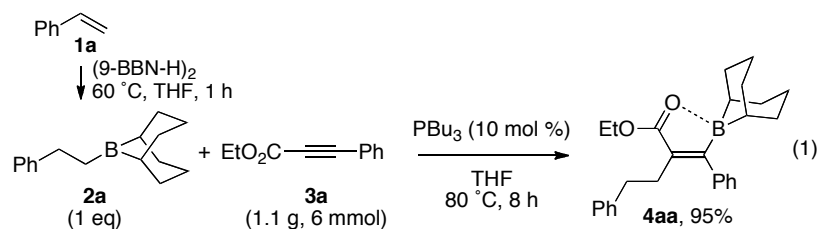
Introduction

Carboboration of internal alkynes with organoboron compounds offers an efficient strategy for the synthesis of trisubstituted alkenylboron derivatives, which can be utilized as precursors to tetrasubstituted alkenes.^{1,2} Suginome and co-workers reported the palladium- and nickel-catalyzed carboborations of internal alkynes with cyano-^{1a-d} and alkynylboron^{1e} derivatives. These reactions introduced carbon and boron atoms with *syn* stereochemistry. However, alkyne carboboration has not yet been expanded to the use of more common organoboron compounds such as alkyl-, alkenyl-, or arylboron compounds.³ This is mainly due to resistance of the C–B bond in these compounds against oxidative addition to transition metals.⁴

In the author's study on copper-catalyzed transformations of organoboron compounds (Chapters 1 and 2),⁵ he unexpectedly found that an alkylborane (**2a**) reacted with an alkynoate (**3a**) in the presence of a catalytic amount of tributylphosphine (PBU₃) in a carboboration mode to give a β -borylacrylate derivative (**4aa**) with a B–O coordination bond.⁶⁻⁸ Interestingly, the carboboration exhibited an inverse electronic demand with regard to regioselectivity: the less electronegative B atom was introduced at the positively charged β carbon of the α,β -unsaturated ester (alkynoate), with the more electronegative C atom at the electron-neutral α carbon. Another interesting feature of this reaction is the *anti* stereochemistry of the C–B bond addition. Both regio- and stereoselectivities are exclusive and robust irrespective of substrate structures. Although this study was mostly focused on the reaction of alkyl-9-BBN reagents (9-BBN: 9-borabicyclo[3.3.1]nonane) due to the convenience of their preparation, alkenyl or aryl-9-BBN reagents also worked as suitable substrates.

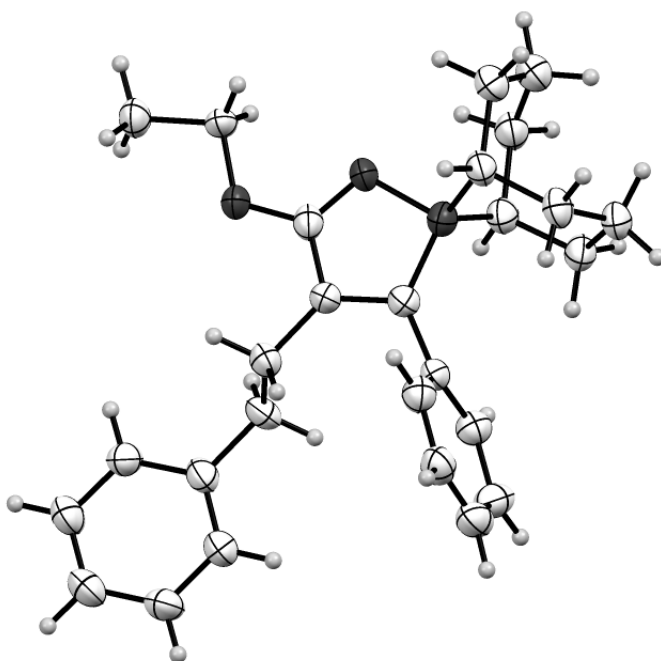
Results and Discussion

Specifically, a solution of alkylborane **2a** (6 mmol) was first prepared through hydroboration of styrene (**1a**) with 9-borabicyclo[3.3.1]nonane dimer [(9-BBN-H)₂] (3 mmol) in THF (24 mL) at 60 °C (**1a**/B 1.05:1). Subsequently, PBU₃ (10 mol%) and ethyl 3-phenylpropionate (**3a**) (1.1 g, 6 mmol) were added, and the mixture was heated at 80 °C over 8 h for complete conversion of **3a**. Evaporation of volatiles followed by purification by recrystallization gave trisubstituted alkenylborane **4aa** in an isomerically pure form in 95% yield (based on **3a**).



Single-crystal X-ray diffraction analysis of **4aa** confirmed that the alkyl group and the B atom were bound at the α and β positions of the alkynoate, respectively, and that the carbonyl oxygen coordinated to the boron atom (Figure 1). Thus, the C–B bond addition across the C–C triple bond was completely *anti*-stereoselective.

Figure 1. The molecular structure of **4aa** was confirmed by single-crystal X-ray diffraction analysis.



Presuming the role of PBu_3 as a nucleophilic catalyst,⁹ he examined various potential nucleophiles as catalysts for the reaction between **2a** and **3a**, and PBu_3 was found to be the most effective (Table 1). The use of sterically less demanding PMe_3 or PEt_3 instead of PBu_3 under otherwise identical conditions resulted in significantly decreased substrate conversions and product yields (entries 3 and 4). Bulkier trialkylphosphines such as PCy_3 and P^tBu_3 were ineffective (entries 5 and 6). The weaker electron-donors such as PPh_3 or P(OPh)_3 also resulted in no reaction (entries 7 and 8). DPPE

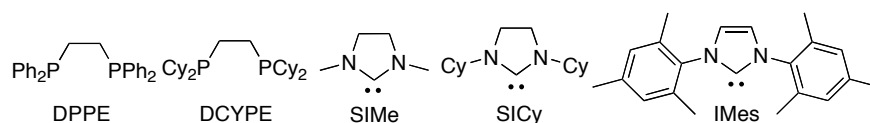
or DCYPE bisphosphines showed a slight catalytic activity (entries 9 and 10). These results can be summarized as follows. Electron-donating natures of the P-alkyl substituents favored the phosphine catalysis, while bulkiness around the P center inhibited the reaction probably due to a decrease in nucleophilicity of the phosphine molecules. No reaction occurred with *N*-heterocyclic carbenes (NHCs) or amines (DABCO, DBU, DMAP and NBu_3) with different steric and electronic natures (entries 11–17). The PBu_3 loading could be reduced to 5 mol % without affecting the yield of **4aa** (95%) (entry 2).

The use of (2-phenylethyl)boronic acid and its pinacolate ester instead of the alkyl-9-BBN reagents resulted in no reaction. As alkynic substrates, the corresponding conjugated amides, aldehydes, or ketones as well as nonpolar internal alkenes showed no reactivity under similar conditions. The carboboration did not occur with C–C double bonds in conjugated enone or enoate derivatives.

Table 1. Catalyst effects in carboboration of **3a** with **2a**.^a

entry	catalyst	yield (%) ^b	entry	catalyst	yield
1	PBu_3 (eq 1)	99 (95)	10	DCYPE	7
2	PBu_3 (5 mol%)	99 (95)	11	SIMe	0
3	PMe_3	48	12	SICy	0
4	PEt_3	29	13	IMes	0
5	PCy_3	0	14	DABCO	0
6	P^tBu_3	0	15	DBU	0
7	PPh_3	0	16	DMAP	0
8	P(OPh)_3	0	17	NBu_3	0
9	DPPE	0			

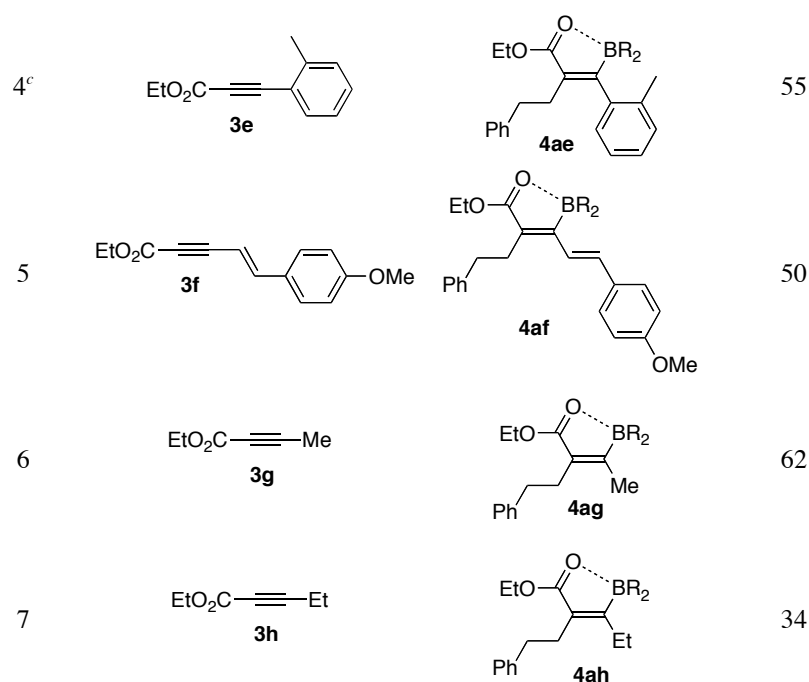
^aConditions of hydroboration: **1a**, 0.315 mmol; (9-BBN-H)₂, 0.15 mmol (1/B 1.05:1); THF, 60 °C, 1 h. **2a** (0.3 mmol) was used without purification. Conditions of carboboration reaction: **3a**, 0.3 mmol; **2a**, 0.3 mmol; PBu_3 , 10 mol %; THF, 80 °C, 8 h. ^b¹H NMR yield. Yield of the isolated product is in parentheses.



Various alkynoates with different substituents at the β -position were subjected to the carboboration of **2a** with the PBU_3 catalyst (Table 2). Methoxy and fluoro groups were tolerated at the *para*-position of the aromatic β -substituent of the alkynoate (entries 1 and 2). The 2-thienyl-substituted alkynoate **3d** underwent the carboboration in high yield (entry 3). The reaction of the *o*-tolyl-substituted alkynoate **3e** proceeded at 100 °C (1,4-dioxane) with 20 mol % catalyst loading to give a sterically congested alkenylborane (**4ae**) in moderate yield (entry 4).¹⁰ The reaction of 1,3-enyne derivative **3f** occurred regioselectively to afford a conjugated 2,4-dienoate (**4af**) (entry 5).¹⁰ The carboboration protocol was applicable to aliphatic alkynoates such as 2-butynoate (**3g**) and 2-pentynoate (**3h**) although the yields were lower than the reaction of the Ph-substituted alkynoate (**3a**) (entries 6 and 7).¹⁰

Table 2. Scope of alkynoates.^a

entry	alkynoate	product	yield (%) ^b
1	 3b	 4ab	89
2	 3c	 4ac	91
3	 3d	 4ad	87



^aConditions of hydroboration: **1**, 0.315 mmol; (9-BBN-H)₂, 0.15 mmol (1/B 1.05:1); THF, 60 °C, 1 h. **2a** (0.3 mmol) was used without purification. Conditions of carboboration reaction: **3**, 0.3 mmol; **2a**, 0.3 mmol; PBu₃, 10 mol % (entries 1–3, 5 and 6) or 20 mol % (entries 4 and 7); THF, 80 °C, 8 h. ^bYield of the isolated product (silica gel chromatography). ^cReaction was carried out in 1,4-dioxane at 100 °C.

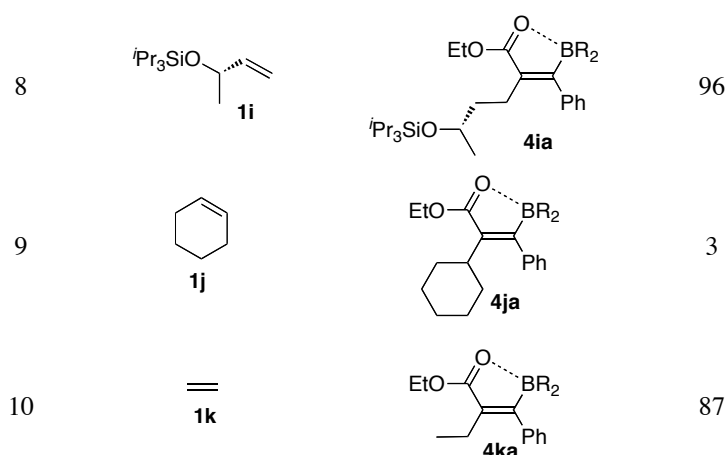
Various terminal alkenes were subjected to 9-BBN-hydroboration and were used for carboboration of **3a** (Table 3). The reaction tolerated functional groups such as chloro and methoxy groups on aromatic rings as well as acetal, phthalimide, ester, carbamate, and silyl ether moieties in aliphatic chains of alkylboranes (entries 1–8).

The tolerance toward steric demand in the alkylboranes (**2**) was also evaluated and the results are shown in Table 3. The sterically more demanding alkylborane **2g**, which was derived from a terminal alkene **1g** bearing a tertiary alkyl substituent, served as a substrate to afford the corresponding product in high yield (entry 6). However, the use of secondary alkylborane **2j** prepared from cyclohexene resulted in low conversion and poor yield (entry 9).

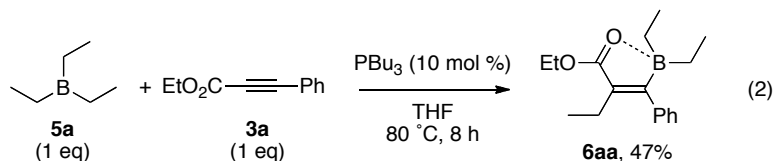
Ethyl-9-BBN (**2k**), which was derived from hydroboration of ethylene (**1k**), was a suitable substrate (Table 3, entry 10). This reaction delivered an ethyl group to the α carbon atom of the alkynoate in high yield (87%). However, the carboboration with Et₃B resulted in a lower product yield (47%) (eq 2).

Table 3. Scope of alkylboranes.^a

entry	alkene	product	yield (%) ^b
1			87
2			80
3			80
4			87
5			98
6			96
7			94



^aConditions of hydroboration: **1**, 0.315 mmol; (9-BBN-H)₂, 0.15 mmol (**1**/B 1.05:1); THF, 60 °C, 1 h. **2** (0.3 mmol) was used without purification. Conditions of carboboration reaction: **3a**, 0.3 mmol; **2**, 0.3 mmol; PBu₃, 10 mol %; THF, 80 °C, 8 h. ^bYield of the isolated product (silica gel chromatography).



The phosphine-catalyzed carboboration was also possible with alkenyl- and arylboranes, allowing the introduction of sp² carbons to the α carbon atom of the alkynoate (Table 4). For instance, the carboboration with β-borylstyrene **2l**, which was prepared in advance through hydroboration of phenylacetylene (**1l**), occurred to afford the 1,3-dienylborane derivative **4la** (entry 1). Alkyl-substituted alkenylborane **2m** was also a suitable substrate (entry 2).

The reaction of phenyl-9-BBN (**2n**) with **3a** proceeded efficiently, giving the corresponding tetrasubstituted alkenylborane **4na** (Table 4, entry 3). The reactions of aryl-9-BBN derivatives with electron-donating (**2o**: *p*-MeO) or withdrawing (**2p**: *p*-F) substituents afforded the corresponding products (entries 4 and 5).

Table 4. Scope of alkenyl- and arylboranes.^a

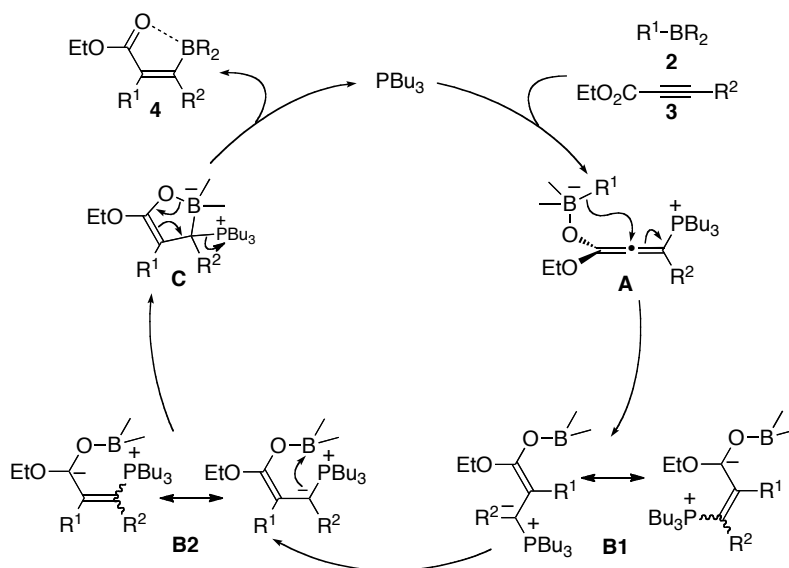
entry	organoborane	product	yield (%) ^b
1	 2l	 4la	34 (75) ^c
2	 2m	 4ma	64
3	 2n	 4na	93
4	 2o	 4oa	64
5	 2p	 4pa	91

^aConditions of carboboration reaction: **3a**, 0.3 mmol; **2**, 0.3 mmol; PBu₃, 10 mol % (entries 1–3 and 5) or 20 mol % (entry 4); THF, 80 °C, 8 h. ^bYield of the isolated product (silica gel chromatography). ^c¹H NMR yield is in parentheses. ^dThe isolated yield was significantly reduced as compared with the ¹H NMR yield because of the material loss during silica gel chromatography.

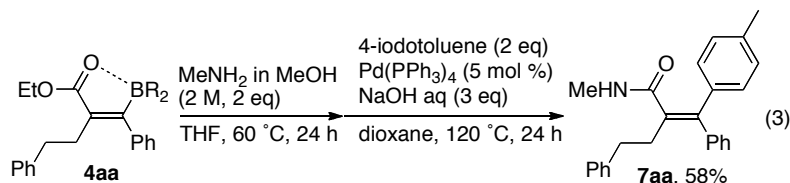
Phosphine catalysis triggered by conjugate addition of the P center of the phosphine to the alkynoate is known in the literature.⁹ On the basis of this knowledge, he proposes a catalytic mechanism as shown in Figure 2, which involves the conjugate addition of PBu₃ to the alkynoate **3**

with the assistance of Lewis-acidic activation of the carbonyl group with the organoborane **2** to form a zwitterionic allenolate intermediate (**A**). The *B*-substituent (R^1) in **A** migrates to the *sp*-hybridized central carbon of the allene moiety to form a phosphonium ylide (**B1**).¹¹ After conversion of **B1** to its geometrical isomer **B2**, the ylide carbon forms a bond with the proximal boron atom to afford cyclic borate **C**. Finally, elimination of Bu_3P associated with B–O bond cleavage affords the alkenylborane **4**. The B–O interaction in **C** and the concerted nature of the final elimination step is responsible for the *anti* stereochemistry of the carboboration.

Figure 2. A possible catalytic cycle.



The trisubstituted alkenylborane obtained by the phosphine-catalyzed carboboration was used to demonstrate the synthetic utility (eq 3). Although attempts at direct Suzuki–Miyaura coupling with **4aa** were unsuccessful, the conversion of the ester group into a secondary amide gave an organoboron derivative suitable for Pd-catalyzed coupling with 4-iodotoluene to afford tetrasubstituted alkene **7aa**.¹²



Conclusion

In conclusion, the author have found phosphine-catalyzed *anti*-selective carboboration of alkynoates with alkyl-, alkenyl-, or arylboranes. Interestingly, the carboboration across the polar C–C triple bond occurred with inverse electronic demand with regard to the regioselectivity, with the less electronegative B atom being delivered to the positively charged β carbon atom. The regioselectivity and *anti* stereoselectivity were both complete and robust. In addition, a broad substrate scope with excellent functional group compatibility was confirmed. Accordingly, this phosphine-catalyzed protocol provides a new and efficient strategy for organic synthesis mediated by organoboron compounds.

Experimental Section

Instrumentation and Chemicals

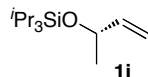
NMR spectra were recorded on a JEOL ECX-400, operating at 400 MHz for ^1H NMR, 100.5 MHz for ^{13}C NMR and 128 MHz for ^{11}B NMR. Chemical shift values for ^1H and ^{13}C are referenced to Me_4Si , the residual solvent resonances and $\text{BF}_3\cdot\text{OEt}_2$, respectively. Chemical shifts are reported in δ ppm. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TZ at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Elemental analysis was performed at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Optical rotations were measured on a JASCO P-2200. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Kanto Chemical Co., Silica gel 60 N, spherical, neutral) was used for column chromatography. IR spectra were measured with a Perkin-Elmer Spectrum One. Melting points were measured on a Yanaco MP-500D apparatus.

All reactions were carried out under nitrogen or argon atmosphere. Materials were obtained from commercial suppliers or prepared according to standard procedures unless otherwise noted. 9-Borabicyclo[3,3,1]nonane dimer (9-BBN-H)₂ was purchased from Kanto Chemical Co., stored under nitrogen, and used as it is. PBU_3 was purchased from Kanto Chemical Co., stored under nitrogen, and used as it is. THF was purchased from Kanto Chemical Co., stored under argon.

Alkynoates **3b**, **3c**, **3d** and **3e** are known compounds.^{5h} These alkynoates were prepared by the reaction between the corresponding lithium acetylides and ethyl chloroformate. Alkynoates **3a**, **3g** and **3h** were purchased from TCI Chemical Co., stored under nitrogen, and used as it is. Alkenes **1a–h**, **1j** and **1k** are known compounds.¹³ Alkene **1i** was prepared from ethyl (–)-lactate through silylation, reduction followed by Wittig reaction. Alkenyllborane **2l** was prepared in advance through hydroboration of **1l** with (9-BBN-H)₂ at 60 °C (1 h) and used without purification. Alkenyllborane **2m**¹⁴ and aryllboranes **2n–p**¹⁵ were prepared according to the reported procedure and purified by distillation. Triethylborane (1.0 M in THF) was purchased from Aldrich Chemical Co., stored under nitrogen, and used as it is.

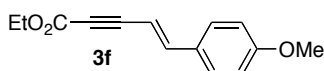
Characterization Data for Substates

(*S*)-(3-Buten-2-yloxy)triisopropylsilane (**1i**)



Colorless Oil. IR (neat) 761, 881, 919, 989, 1091, 1154, 1257, 1368, 1464, 2867, 2893, 2944 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 1.06–1.09 (m, 21H), 1.24 (d, $J = 6.4$ Hz, 3H), 4.38 (qdt, $J = 6.4$, 5.6, 1.6 Hz, 1H), 4.98 (dt, $J = 10.0$, 1.6 Hz, 1H), 5.17 (dt, $J = 16.4$, 1.6 Hz, 1H), 5.87 (ddd, $J = 16.4$, 10.0, 5.6 Hz, 1H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 12.30, 18.06, 24.68, 69.62, 112.29, 142.25. $[\alpha]_{\text{D}}^{23} +4.16$ (c 0.45, CHCl_3). HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{13}\text{H}_{28}\text{OSi}$, 229.19822; found, 229.19861.

(*E*)-Ethyl 5-(4-Methoxyphenyl)-4-penten-2-ynoate (**3f**)



Yellow oil. IR (neat) 812, 1028, 1089, 1173, 1247, 1366, 1510, 1599, 1697, 2200, 2839, 2937, 2982 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 1.34 (t, $J = 7.6$ Hz, 3H), 3.83 (s, 3H), 4.26 (q, $J = 7.6$ Hz, 2H), 6.05 (d, $J = 16.4$ Hz, 1H), 6.87–6.89 (m, 2H), 7.20 (d, $J = 16.4$ Hz, 1H), 7.36–7.38 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 13.99, 55.25, 61.79, 81.85, 86.58, 101.81, 114.20, 127.76, 128.39, 147.36, 154.07, 161.05. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{14}\text{H}_{14}\text{O}_3$, 230.09429; found, 230.09417.

Procedures for Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates with Organoboranes.

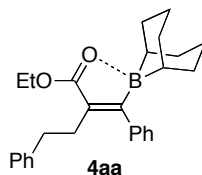
Typical Procedure for Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates with Alkylboranes. The reaction in Table 2, entry 1 is representative. Styrene (**1a**) (36.0 μL , 0.315 mmol) and (9-BBN-H)₂ (36.6 mg, 0.3 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. THF (1.2 mL) was added to the vial, and then the mixture was stirred at 60 °C for 1 h to prepare an alkylborane. PBU_3 (7.4 μL , 0.03 mmol) and alkynoate (**3b**) (61.2 mg, 0.3 mmol) were added to the vial. After 8 h stirring at 80 °C, the mixture was evaporated under reduced pressure. The residue was dissolved in toluene (abt. 1 mL) and the resulting solution was put on a silica gel column. Chromatography with 0–10% EtOAc/hexane provided **4ab** (114.4 mg, 0.267 mmol) in 89% yield.

A Gram Scale Reaction of 2a and 3a. The reaction in eq. 1 is representative. Styrene (**1a**) (720 μ L, 6.3 mmol) and (9-BBN-H)₂ (732 mg, 3 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. THF (24 mL) was added to the vial, and then the mixture was stirred at 60 °C for 1 h to prepare an alkylborane. PBu₃ (148 μ L, 0.6 mmol) and ethyl 3-phenylpropionate (**3a**) (1.1 g, 6 mmol) were added to the vial. After 8 h stirring at 80 °C, the mixture was evaporated under reduced pressure. The residue was purified by recrystallization with CH₂Cl₂/EtOH to afford **4aa** in 95% yield (2.28 g, 5.70 mmol).

Typical Procedure for Phosphine-Catalyzed *Anti*-Carboboration of Alkynoates with Alkenyl- or Arylboranes. The reaction in Table 4, entry 5 is representative. To a vial sealed with a Teflon[®]-coated silicon rubber septum was added arylborane (**2p**) (64.8 mg, 0.3 mmol),¹⁵ THF (1.2 mL), PBu₃ (7.4 mL, 0.03 mmol) and ethyl 3-phenylpropionate (**3a**) (52.3 mg, 0.3 mmol) in this order under argon. After 8 h stirring at 80 °C, the mixture was evaporated under reduced pressure. The residue was dissolved in toluene (abt. 1 mL) and the resulting solution was put on a silica gel column. Chromatography with 0–5% EtOAc/hexane provided **4pa** in 91% yield (107.7 mg, 0.273 mmol).

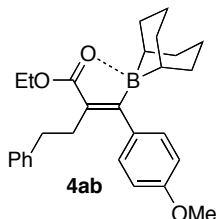
Characterization Data for β -Borylacrylates

(*E*)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-4-phenylbutanoate (**4aa**)



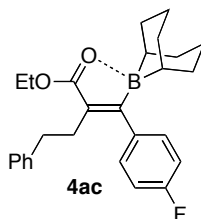
The product **4aa** was purified by recrystallization with CH₂Cl₂/EtOH. White solid. **M.p.** 131–132 °C. **IR** (neat) 698, 749, 1017, 1112, 1198, 1290, 1353, 1386, 1444, 1520, 1589, 2831, 2843, 2863, 2915, 2979 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 0.82 (s, 2H), 1.12 (m, 1H), 1.44 (t, *J* = 7.6 Hz, 3H), 1.50–1.79 (m, 8H), 1.86–2.01 (m, 3H), 2.28 (dd, *J* = 9.2, 7.2 Hz, 2H), 2.60 (dd, *J* = 9.2, 7.2 Hz, 2H), 4.53 (q, *J* = 7.6 Hz, 2H), 6.74–6.76 (m, 2H), 6.93–6.98 (m, 2H), 7.12–7.27 (m, 5H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 14.14, 24.67, 25.90, 26.15, 32.03, 32.99, 35.44, 66.09, 124.16, 125.33, 125.58, 125.86, 127.67, 128.15, 128.64, 141.29, 143.17, 178.74. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 12.4. **HRMS–EI** (*m/z*): [*M*]⁺ calcd for C₂₇H₃₃BO₂, 400.25736; found, 400.25750.

(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(4-methoxyphenyl)methylene}-4-phenylbutanoate (4ab)



The product **4ab** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). White solid. **M.p.** 121–122 °C. **IR** (neat) 831, 1018, 1245, 1280, 1347, 1387, 1452, 1476, 1528, 1595, 1736, 2843, 2861, 2918 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.80 (s, 2H), 1.16 (m, 1H), 1.44 (t, $J = 7.2$ Hz, 3H), 1.50–1.80 (m, 8H), 1.86–2.00 (m, 3H), 2.29 (t, $J = 7.2$ Hz, 2H), 2.60 (t, $J = 7.2$ Hz, 2H), 3.82 (s, 3H), 4.52 (q, $J = 7.2$ Hz, 2H), 6.66–6.68 (m, 2H), 6.81–6.84 (m, 2H), 6.98–7.00 (m, 2H), 7.16–7.24 (m, 3H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.12, 24.67, 24.70, 25.95, 26.10, 32.04, 33.03, 35.41, 55.10, 65.99, 113.17, 125.47, 125.54, 125.84, 128.15, 128.65, 135.37, 141.36, 157.57, 178.82. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 12.6. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{28}\text{H}_{35}\text{BO}_3$, 430.26792; found, 430.26764.

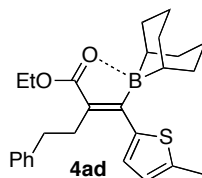
(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(4-fluorophenyl)methylene}-4-phenylbutanoate (4ac)



The product **4ac** was purified by flash chromatography on silica gel (0–2% EtOAc/hexane). White solid. **M.p.** 134–136 °C. **IR** (neat) 700, 750, 835, 1018, 1290, 1354, 1389, 1445, 1476, 1500, 1525, 1592, 2837, 2863 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.80 (s, 2H), 1.14 (m, 1H), 1.46 (t, $J = 6.8$ Hz, 3H), 1.48–1.80 (m, 8H), 1.85–2.00 (m, 3H), 2.27 (t, $J = 7.6$ Hz, 2H), 2.60 (t, $J = 7.6$ Hz, 2H), 4.55 (q, $J = 6.8$ Hz, 2H), 6.61–6.65 (m, 2H), 6.93–6.97 (m, 4H), 7.17–7.23 (m, 3H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.10, 24.61, 24.63, 25.89, 26.17, 32.03, 32.96, 35.25, 66.23, 114.64 (d, $J_{\text{C-F}} = 21.0$ Hz), 125.75 (2C), 125.88 (d, $J_{\text{C-F}} = 10.5$ Hz), 128.20, 128.69, 138.81 (d, $J_{\text{C-F}} = 2.8$ Hz), 141.09, 161.09 (d, $J_{\text{C-F}} = 243.3$ Hz), 178.69. A signal for the sp^2 -carbon directly attached to the

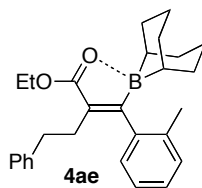
boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.4. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{27}\text{H}_{32}\text{BFO}_2$, 418.24794; found, 418.24804.

(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(5-methylthiophen-2-yl)methylene}-4-phenyl butanoate (4ad)



The product **4ad** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). White solid. **M.p.** 109–112 °C. **IR** (neat) 697, 796, 1015, 1218, 1352, 1387, 1444, 1474, 1521, 1592, 1736, 2831, 2847, 2917 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.76 (s, 2H), 1.41 (t, J = 6.8 Hz, 3H), 1.42 (m, 1H), 1.55–1.68 (m, 5H), 1.79–1.99 (m, 6H), 2.49 (s, 3H), 2.60 (dd, J = 10.4, 8.8 Hz, 2H), 2.72 (dd, J = 10.4, 8.8 Hz, 2H), 4.48 (q, J = 6.8 Hz, 2H), 6.64–6.70 (m, 2H), 7.11–7.27 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.09, 15.26, 24.43, 24.66, 26.13, 26.75, 31.81, 33.52, 35.55, 66.02, 125.46, 125.88, 125.90, 126.18, 128.22, 128.55, 139.91, 140.53, 141.53, 178.33. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.4. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{33}\text{BO}_2\text{S}$, 420.22943; found, 420.22893.

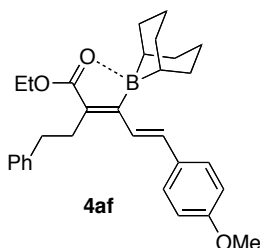
(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(*o*-tolyl)methylene}-4-phenylbutanoate (4ae)



The product **4ae** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). White solid. **M.p.** 122–123 °C. **IR** (neat) 700, 751, 1017, 1211, 1350, 1385, 1443, 1472, 1524, 1593, 1736, 2829, 2849, 2923 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.81–0.90 (m, 2H), 1.12 (m, 1H), 1.42 (m, 1H), 1.45 (t, J = 6.8 Hz, 3H), 1.53–1.80 (m, 7H), 1.88–2.00 (m, 3H), 2.05 (s, 3H), 2.11 (dt, J = 13.6, 6.8 Hz, 1H), 2.31 (dt, J = 13.6, 6.4 Hz, 1H), 2.57 (dd, J = 6.8, 6.4 Hz, 2H), 4.53 (q, J = 6.8 Hz, 2H), 6.62 (m, 1H), 6.95–6.97 (m, 2H), 7.07–7.25 (m, 6H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.10, 19.85, 24.63, 26.18, 26.53, 31.52, 31.96, 32.47, 33.26, 34.89, 66.10, 124.37, 124.88, 125.31, 125.70, 125.84, 128.19, 128.51, 129.55, 131.23, 141.44, 142.37, 178.46. A signal

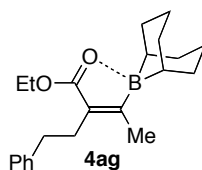
for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.8. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{28}\text{H}_{35}\text{BO}_2$, 414.27301; found, 414.27319.

(2*E*,4*E*)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-5-(4-methoxyphenyl)-2-phenethyl-2,4-pentadienoate (4af)



The product **4af** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). White solid. **M.p.** 150–152 °C. **IR** (neat) 697, 822, 970, 1023, 1170, 1250, 1341, 1383, 1427, 1505, 1574, 1603, 1736, 2881, 2914, 2972, 3023 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.64 (s, 2H), 1.42 (t, $J = 7.2$ Hz, 3H), 1.59–1.79 (m, 6H), 1.88–2.10 (m, 6H), 2.70 (dd, $J = 10.4, 8.4$ Hz, 2H), 2.80 (dt, $J = 10.4, 8.4$ Hz, 2H), 3.83 (s, 3H), 4.49 (q, $J = 7.2$ Hz, 2H), 6.51 (d, $J = 16.4$ Hz, 1H), 6.88–6.90 (m, 2H), 7.09 (d, $J = 16.4$ Hz, 1H), 7.15–7.37 (m, 7H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.15, 24.53, 24.88, 25.69, 26.51, 31.60, 33.18, 35.56, 55.32, 65.76, 114.13, 122.86, 125.96, 126.70, 128.18, 128.30, 128.64, 130.14, 132.21, 141.53, 159.63, 178.79. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 11.5. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{30}\text{H}_{37}\text{BO}_3$, 456.28357; found, 456.28373.

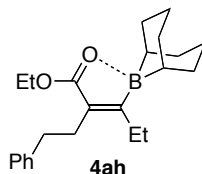
(*E*)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-2-phenethyl-2-butenate (4ag)



The product **4ag** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). White Solid. **M.p.** 98–100 °C. **IR** (neat) 700, 750, 1014, 1347, 1444, 1521, 1601, 1737, 2844, 2920 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.56 (s, 2H), 1.36 (t, $J = 7.2$ Hz, 3H), 1.53–1.61 (m, 2H), 1.62–1.70 (m, 2H), 1.70–1.80 (m, 2H), 1.85–1.97 (m, 6H), 2.00 (s, 3H), 2.49 (t, $J = 7.2$ Hz, 2H), 2.66 (t, $J = 7.2$ Hz, 2H), 4.41 (q, $J = 7.2$ Hz, 2H), 7.09–7.26 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.11, 19.64, 24.57, 24.94, 25.21, 25.43, 31.67, 32.93, 35.24, 65.41, 123.45, 125.85, 128.16, 128.74, 141.45, 178.65. A signal for the sp^2 -carbon directly attached to the boron atom was

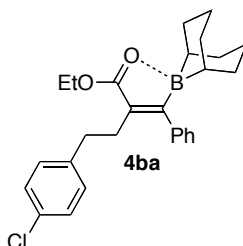
not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 11.5. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{22}\text{H}_{31}\text{BO}_2$, 338.24171; found, 338.24149.

(E)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-2-phenethyl-2-pentenoate (4ah)



The product **4ah** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). White Solid. **M.p.** 84–86 °C. **IR** (neat) 697, 751, 1018, 1234, 1351, 1385, 1441, 1476, 1520, 1599, 1737, 2851, 2923, 2973 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.62 (s, 2H), 0.96 (t, $J = 7.6$ Hz, 3H), 1.41 (t, $J = 7.2$ Hz, 3H), 1.57–1.67 (m, 4H), 1.73–1.80 (m, 2H), 1.88–1.99 (m, 6H), 2.48 (dd, $J = 10.0, 7.2$ Hz, 2H), 2.53 (q, $J = 7.6$ Hz, 2H), 2.71 (dd, $J = 10.0, 7.2$ Hz, 2H), 4.46 (q, $J = 7.2$ Hz, 2H), 7.15–7.29 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 12.68, 14.16, 24.76, 24.87, 24.96, 25.76, 32.07, 33.07, 35.55, 65.48, 123.55, 125.92, 128.26, 128.56, 141.77, 178.99. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 11.3. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{23}\text{H}_{33}\text{BO}_2$, 352.25736; found, 352.25666.

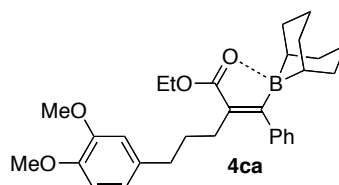
(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-4-(4-chlorophenyl)butanoate (4ba)



The product **4ba** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). White solid. **M.p.** 94–96 °C. **IR** (neat) 703, 759, 811, 1089, 1226, 1350, 1385, 1439, 1526, 1593, 1737, 2838, 2858, 2981 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.81 (s, 2H), 1.12 (m, 1H), 1.44 (t, $J = 6.8$ Hz, 3H), 1.50–1.79 (m, 8H), 1.85–2.00 (m, 3H), 2.25 (t, $J = 7.6$ Hz, 2H), 2.55 (t, $J = 7.6$ Hz, 2H), 4.52 (q, $J = 6.8$ Hz, 2H), 6.76–6.78 (m, 2H), 6.87–6.89 (m, 2H), 7.16–7.29 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.08, 24.63, 25.93, 26.02, 32.01, 32.96, 34.81, 66.20, 124.07, 124.94, 125.66, 127.73, 128.20, 129.98, 131.60, 139.73, 143.06, 178.64. A signal for the sp^2 -carbon directly

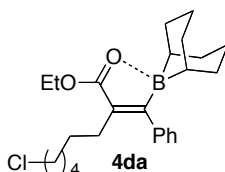
attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 13.1. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{27}\text{H}_{32}\text{BClO}_2$, 434.21839; found, 434.21830.

(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-5-(3,4-dimethoxyphenyl)pentanoate (4ca)



The product **4ca** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Colorless oil. IR (neat) 751, 1155, 1258, 1346, 1384, 1430, 1515, 1590, 1736, 2837, 2932 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.82 (s, 2H), 1.13 (m, 1H), 1.46–1.79 (m, 10H), 1.48 (t, $J = 7.2$ Hz, 3H), 1.86–1.98 (m, 3H), 2.04 (t, $J = 8.0$ Hz, 2H), 2.40 (t, $J = 8.0$ Hz, 2H), 3.83 (s, 3H), 3.84 (s, 3H), 4.58 (q, $J = 7.2$ Hz, 2H), 6.56–6.58 (m, 2H), 6.72 (m, 1H), 6.91–6.93 (m, 2H), 7.18 (m, 1H), 7.28–7.32 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.15, 23.82, 24.62, 24.64, 25.94, 30.86, 32.02, 32.98, 35.05, 55.73, 55.87, 66.08, 111.00, 111.52, 119.91, 124.33, 125.60, 126.00, 127.71, 134.70, 143.35, 146.97, 148.62, 178.84. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 13.0. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{30}\text{H}_{39}\text{BO}_4$, 474.29414; found, 474.29313.

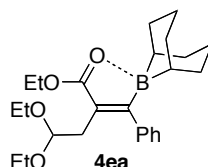
(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-8-chlorooctanoate (4da)



The product **4da** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). Colorless oil. IR (neat) 702, 760, 1012, 1276, 1346, 1384, 1429, 1525, 1590, 1736, 2842, 2922, 2981 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.81 (s, 2H), 1.10–1.19 (m, 3H), 1.24–1.34 (m, 4H), 1.48–1.80 (m, 10H), 1.50 (t, $J = 6.8$ Hz, 3H), 1.90–2.00 (m, 5H), 3.45 (t, $J = 6.8$ Hz, 2H), 4.59 (q, $J = 6.8$ Hz, 2H), 6.91–6.93 (m, 2H), 7.18 (m, 1H), 7.29–7.33 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.17, 23.79, 24.64, 24.65, 25.92, 26.34, 28.30, 28.80, 32.04, 32.36, 33.00, 45.04, 66.09, 124.37, 125.60, 126.20, 127.70, 143.42, 178.90. A signal for the sp^2 -carbon directly attached to the

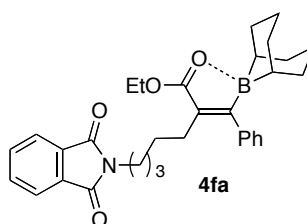
boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.4. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{36}\text{BClO}_2$, 414.24969; found, 414.24842.

(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-4,4-diethoxybutanoate (4ea)



The product **4ea** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. IR (neat) 702, 757, 1011, 1062, 1111, 1219, 1281, 1346, 1384, 1431, 1527, 1591, 2842, 2875, 2921, 2976 cm^{-1} . ^1H NMR (400 MHz, CD_2Cl_2) δ 0.82 (s, 2H), 1.05 (t, $J = 7.2$ Hz, 6H), 1.10 (m, 1H), 1.48 (t, $J = 6.8$ Hz, 3H), 1.52–1.81 (m, 10H), 1.86–2.05 (m, 5H), 3.30 (dq, $J = 9.2$, 7.2 Hz, 2H), 3.41 (dq, $J = 9.2$, 7.2 Hz, 2H), 4.28 (t, $J = 5.6$ Hz, 1H), 4.59 (q, $J = 6.8$ Hz, 2H), 6.95–6.97 (m, 2H), 7.20 (m, 1H), 7.31–7.35 (m, 2H). ^{13}C NMR (100.5 MHz, CD_2Cl_2) δ 14.32, 15.39, 19.77, 25.03, 25.10, 26.22, 32.42, 33.08, 33.30, 60.66, 66.79, 102.26, 124.79, 126.00, 126.39, 128.15, 143.81, 179.34. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CD_2Cl_2) δ 12.4. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{39}\text{BO}_4$, 426.29414; found, 429.29377.

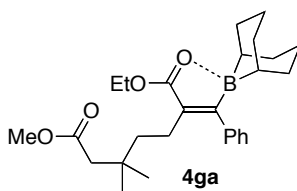
(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-7-(1,3-dioxisoindolin-2-yl)heptanoate (4fa)



The product **4fa** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). Colorless oil. IR (neat) 703, 717, 1011, 1346, 1394, 1430, 1526, 1590, 1709, 1773, 2840, 2921, 2980 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.77 (s, 2H), 1.09–1.20 (m, 3H), 1.31–1.38 (m, 2H), 1.49 (t, $J = 6.8$ Hz, 3H), 1.47–1.75 (m, 10H), 1.89–2.00 (m, 5H), 3.61 (t, $J = 6.8$ Hz, 2H), 4.59 (q, $J = 6.8$ Hz, 2H), 6.89–6.91 (m, 2H), 7.15 (m, 1H), 7.26–7.29 (m, 2H), 7.69–7.71 (m, 2H), 7.81–7.84 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.14, 23.89, 24.64, 25.88, 26.29, 28.17, 28.52, 32.00,

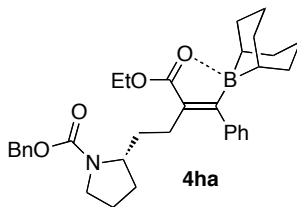
32.97, 37.76, 66.11, 123.10, 124.33, 125.54, 125.96, 127.69, 132.04, 133.83, 143.33, 168.39, 178.83. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 13.0. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{32}\text{H}_{38}\text{BNO}_4$, 511.28939; found, 511.29001.

(*E*)-1-Ethyl 7-Methyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-5,5-dimethyl heptanedioate (4ga)



The product **4ga** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). White solid. **M.p.** 54–56 °C. **IR** (neat) 703, 756, 1009, 1195, 1346, 1385, 1435, 1473, 1529, 1591, 1733, 2841, 2873, 2931 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.83 (s, 8H), 1.14 (m, 1H), 1.28–1.32 (m, 2H), 1.50 (t, J = 6.8 Hz, 3H), 1.48–1.80 (m, 8H), 1.86–1.96 (m, 5H), 2.05 (s, 2H), 3.59 (s, 3H), 4.59 (q, J = 6.8 Hz, 2H), 6.91–6.93 (m, 2H), 7.18 (m, 1H), 7.29–7.33 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.11, 18.97, 24.62, 24.66, 25.89, 26.53, 32.04, 32.95, 33.07, 41.84, 45.49, 51.05, 66.06, 124.28, 125.65, 126.48, 127.70, 143.27, 172.51, 178.75. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.2. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{27}\text{H}_{39}\text{BO}_4$, 438.29414; found, 438.29448.

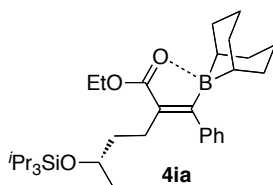
(*R*)-Benzyl 2-[(*E*)-4-(9-Borabicyclo[3.3.1]nonan-9-yl)-3-(ethoxycarbonyl)-4-phenyl-3-buten-1-yl]pyrrolidine-1-carboxylate (4ha)



The product **4ha** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). Colorless Oil. **IR** (neat) 697, 751, 1010, 1096, 1188, 1217, 1346, 1432, 1528, 1591, 1697, 2842, 2874, 2921 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.81 (s, 1H), 0.83 (s, 1H), 1.14 (m, 1H), 1.24–1.32 (m, 2H), 1.36–1.40 (m, 2H), 1.47–1.59 (m, 5H), 1.59–1.78 (m, 8H), 1.84–2.04 (m, 5H), 3.27–3.39 (m, 2H), 3.66 (m, 1H), 4.45 (m, 1H), 4.58 (m, 1H), 5.04–5.12 (m, 2H), 6.86–6.99 (m, 2H), 7.12–

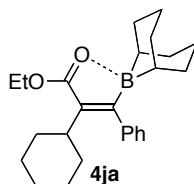
7.35 (m, 8H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.08, 20.88, 22.76, 23.53, 24.62, 25.87, 29.25, 29.96, 32.04, 32.94, 33.08, 33.86, 46.08, 46.48, 56.68, 57.43, 66.11, 66.15, 66.28, 66.49, 124.25, 124.29, 125.61, 125.64, 125.68, 125.93, 127.64, 127.73, 127.76, 128.39, 137.03, 137.09, 143.17, 143.33, 154.60, 154.84, 178.62, 178.72. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 13.7. $[\alpha]_{\text{D}}^{23}$ -42.5 (c 1.00, CHCl_3). HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{33}\text{H}_{42}\text{BNO}_4$, 527.32069; found, 527.31949.

(*S,E*)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-5-(triisopropylsilyloxy)hexanoate (4ia)



The product **4ia** was purified by flash chromatography on silica gel (0–2% EtOAc/hexane). Colorless oil. IR (neat) 757, 882, 1013, 1218, 1285, 1347, 1432, 1526, 1592, 2844, 2865, 2922 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.80 (s, 8H), 0.83 (s, 1H), 0.96 (d, J = 6.0 Hz, 3H), 0.99 (s, 21H), 1.14 (m, 1H), 1.39–1.79 (m, 10H), 1.48 (t, J = 6.8 Hz, 3H), 1.86–2.05 (m, 5H), 3.73 (m, 1H), 4.58 (t, J = 6.8 Hz, 2H), 6.90–6.92 (m, 2H), 7.17 (m, 1H), 7.26–7.31 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 12.34, 14.12, 18.08, 18.10, 20.15, 22.91, 24.66, 24.68, 25.85, 25.98, 32.04, 32.08, 33.00, 39.42, 66.06, 67.97, 124.32, 125.64, 126.28, 127.75, 143.30, 178.87. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.5. $[\alpha]_{\text{D}}^{23}$ -17.4 (c 1.15, CHCl_3). HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{32}\text{H}_{53}\text{BO}_3\text{Si}$, 524.38570; found, 524.38537.

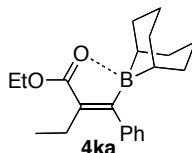
(*E*)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-2-cyclohexyl-3-phenylacrylate (4ja)



The product **4ja** was purified by flash chromatography on silica gel (hexane). White solid. **M.p.** 175–177 °C. IR (neat) 703, 776, 891, 1010, 1241, 1345, 1427, 1522, 1585, 2847, 2929 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.79 (s, 2H), 1.03–1.14 (m, 4H), 1.43–1.76 (m, 18H), 1.85–1.97 (m, 3H), 2.04 (tt, J = 14.0, 4.0 Hz, 1H), 4.59 (q, J = 7.2 Hz, 2H), 6.89–6.90 (m, 2H), 7.19 (m, 1H), 7.26–7.32 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.17, 24.65, 25.82, 25.91, 26.51, 31.03,

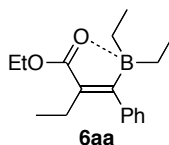
31.92, 33.06, 35.99, 66.03, 124.37, 125.46, 127.61, 130.84, 143.70, 178.90. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 10.8. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{35}\text{BO}_2$, 378.27301; found, 378.27169.

(E)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}butanoate (4ka)



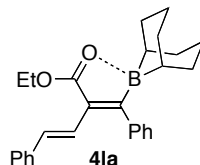
The product **4ka** was purified by flash chromatography on silica gel (0–2% EtOAc/hexane). White solid. **M.p.** 106–107 °C. **IR** (neat) 700, 753, 1005, 1347, 1380, 1428, 1530, 1591, 1736, 2845, 2871, 2919, 2970 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.81 (s, 2H), 0.89 (t, J = 7.6 Hz, 3H), 1.13 (m, 1H), 1.49 (t, J = 7.2 Hz, 3H), 1.51–1.79 (m, 8H), 1.85–2.01 (m, 3H), 1.99 (q, J = 7.2 Hz, 2H), 4.59 (q, J = 7.6 Hz, 2H), 6.91–6.94 (m, 2H), 7.18 (m, 1H), 7.29–7.33 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.18, 17.58, 24.67, 24.68, 25.90, 32.06, 33.00, 66.04, 124.38, 125.57, 127.72, 127.92, 143.49, 178.91. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 12.3. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{21}\text{H}_{29}\text{BO}_2$, 324.22606; found, 324.22576.

(E)-Ethyl 2-{(Diethylboryl)(phenyl)methylene}butanoate (6aa)



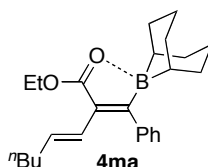
The product **6aa** was purified by flash chromatography on silica gel (0–3% EtOAc/hexane). Colorless oil. **IR** (neat) 701, 741, 1179, 1263, 1347, 1384, 1431, 1523, 1605, 1703, 2876, 2938, 2967, 3217 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.63 (t, J = 7.6 Hz, 3H), 0.81 (dq, J = 14.8, 7.6 Hz, 1H), 0.99 (m, 1H), 0.94 (t, J = 7.6 Hz, 3H), 1.05 (t, J = 7.6 Hz, 3H), 1.48 (t, J = 7.2 Hz, 3H), 2.26 (q, J = 7.6 Hz, 2H), 2.40 (q, J = 7.6 Hz, 1H), 2.41 (q, J = 7.6 Hz, 1H), 4.59 (q, J = 7.2 Hz, 2H), 7.11–7.24 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 9.53, 12.46, 14.12, 14.27, 16.82, 23.96, 66.14, 125.46, 126.87, 127.21, 130.88, 181.74. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 11.2. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{17}\text{H}_{25}\text{BO}_2$, 272.19476; found, 272.19402].

(2*E*,3*E*)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-4-phenyl-3-butenolate (4la)



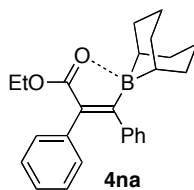
The product **4la** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Yellow solid. **M.p.** 164–166 °C. **IR** (neat) 689, 739, 965, 1009, 1350, 1384, 1435, 1448, 1568, 1736, 2841, 2871, 2922 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.91 (s, 2H), 1.17 (m, 1H), 1.53–1.78 (m, 8H), 1.61 (t, $J = 7.2$ Hz, 3H), 1.88–2.04 (m, 3H), 4.74 (q, $J = 7.2$ Hz, 2H), 6.39 (d, $J = 16.8$ Hz, 1H), 7.00–7.02 (m, 3H), 7.15–7.28 (m, 6H), 7.34–7.38 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.19, 24.56, 24.61, 26.05, 31.90, 32.90, 66.97, 118.51, 123.39, 124.64, 126.15, 126.24, 127.44, 128.01, 128.48, 129.82, 137.69, 142.92, 177.73. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 12.3. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{27}\text{H}_{31}\text{BO}_2$, 398.24171; found, 398.24154.

(2*E*,3*E*)-Ethyl 2-{9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene}-3-octenoate (4ma)



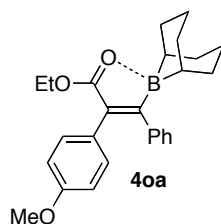
The product **4ma** was purified by flash chromatography on silica gel (0–2% EtOAc/hexane). White solid. **M.p.** 164–166 °C. **IR** (neat) 701, 972, 1011, 1264, 1346, 1384, 1429, 1512, 1575, 1692, 2843, 2921 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.84 (t, $J = 7.2$ Hz, 3H), 0.85 (s, 2H), 1.14 (m, 1H), 1.20–1.30 (m, 4H), 1.52–1.80 (m, 8H), 1.54 (t, $J = 6.8$ Hz, 3H), 1.86–2.20 (m, 5H), 4.65 (q, $J = 6.8$ Hz, 2H), 5.65 (dt, $J = 16.4, 1.2$ Hz, 1H), 6.06 (dt, $J = 16.4, 7.2$ Hz, 1H), 6.94–6.97 (m, 2H), 7.21 (m, 1H), 7.32–7.36 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 13.87, 14.13, 22.14, 24.60, 24.62, 25.91, 31.53, 31.91, 32.94, 33.39, 66.60, 119.41, 123.47, 124.62, 125.77, 127.86, 133.10, 143.28, 177.94. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 11.8. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{35}\text{BO}_2$, 378.27301; found, 378.27313.

(*E*)-Ethyl 3-(9-Borabicyclo[3.3.1]nonan-9-yl)-2,3-diphenylacrylate (4na)



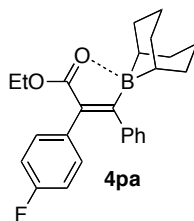
The product **4na** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). White solid. **M.p.** 133–135 °C. **IR** (neat) 693, 1017, 1343, 1385, 1422, 1527, 1541, 1572, 1588, 1609, 1736, 2842, 2870, 2922 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.97 (s, 2H), 1.19 (m, 1H), 1.49 (t, J = 7.2 Hz, 3H), 1.54–1.85 (m, 8H), 1.91–2.08 (m, 3H), 4.64 (q, J = 7.2 Hz, 2H), 6.91–7.22 (m, 10H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.11, 24.60, 26.11, 31.94, 33.10, 66.70, 125.10, 125.77, 126.50, 126.89, 127.61, 127.65, 129.69, 131.94, 142.79, 177.64. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 13.1. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{29}\text{BO}_2$, 372.22606; found, 372.22520.

(E)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-2-(4-methoxyphenyl)-3-phenylacrylate (4oa)



The product **4oa** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). White solid. **M.p.** 116–119 °C. **IR** (neat) 704, 836, 1028, 1252, 1344, 1385, 1436, 1506, 1586, 1743, 2833, 2853, 2931 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.95 (s, 2H), 1.18 (m, 1H), 1.49 (t, J = 6.8 Hz, 3H), 1.52–1.83 (m, 8H), 1.91–2.08 (m, 3H), 3.72 (s, 3H), 4.63 (q, J = 6.8 Hz, 2H), 6.67–6.70 (m, 2H), 6.92–7.02 (m, 4H), 7.07–7.26 (m, 3H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.13, 24.61, 26.10, 31.95, 33.11, 55.00, 66.66, 113.11, 124.26, 125.15, 125.68, 126.00, 127.65, 130.81, 143.04, 158.25, 177.86. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 12.9. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{31}\text{BO}_3$, 402.23662; found, 402.23659.

(E)-Ethyl 3-{9-Borabicyclo[3.3.1]nonan-9-yl}-2-(4-fluorophenyl)-3-phenylacrylate (4pa)



The product **4pa** was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). White solid. **M.p.** 116–118 °C. **IR** (neat) 703, 838, 1012, 1219, 1343, 1383, 1434, 1504, 1581, 1735, 2834, 2855, 2913 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.96 (s, 2H), 1.18 (m, 1H), 1.49 (t, J = 7.2 Hz, 3H), 1.55–1.84 (m, 8H), 1.91–2.06 (m, 3H), 4.64 (q, J = 7.2 Hz, 2H), 6.82–6.86 (m, 2H), 6.90–6.92 (m, 2H), 6.97–7.04 (m, 2H), 7.11 (m, 1H), 7.19–7.23 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.11, 24.57, 26.10, 31.93, 33.07, 66.82, 114.70 (d, $J_{\text{C-F}}$ = 21.1 Hz), 125.01, 125.53, 125.90, 127.72, 127.88 (d, $J_{\text{C-F}}$ = 3.9 Hz), 131.34 (d, $J_{\text{C-F}}$ = 7.7 Hz), 142.63, 161.58 (d, $J_{\text{C-F}}$ = 246.3 Hz), 177.49. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 12.8. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{28}\text{BFO}_2$, 390.21664; found, 390.21664.

Procedure for the Synthesis of Tetrasubstituted Alkenes (eq 3)

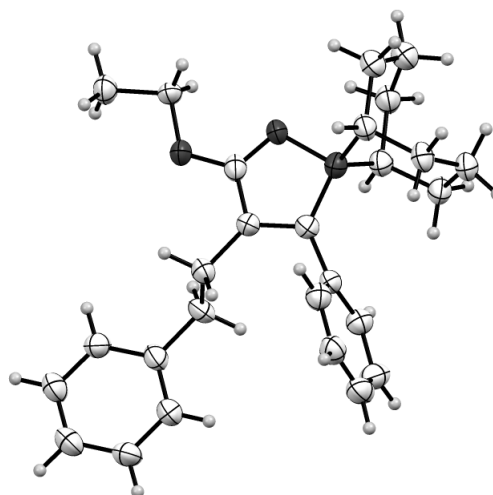
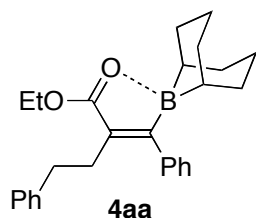
To a solution of **4aa** (40 mg, 0.1 mmol) in THF (0.5 mL) was added MeNH_2 (2 M in MeOH, 100 μL , 0.2 mmol) at room temperature. After being stirred at 60 °C for 24 h, the mixture was evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (0–20% EtOAc/hexane) to give the corresponding secondary amide (38.1 mg, 0.099 mmol) quantitatively. White solid. **M.p.** 159–162 °C. **IR** (neat) 701, 758, 1201, 1354, 1414, 1599, 1737, 2841, 2932, 3456 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.76 (s, 2H), 1.12 (m, 1H), 1.50–1.80 (m, 8H), 1.85–2.05 (m, 3H), 2.21 (t, J = 7.2 Hz, 2H), 2.55 (t, J = 7.2 Hz, 2H), 2.82 (d, J = 4.0 Hz, 3H), 5.12 (d, J = 4.0 Hz, 1H), 6.88–6.90 (m, 2H), 7.04–7.06 (m, 2H), 7.13–7.23 (m, 2H), 7.25–7.30 (m, 4H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.93, 26.41, 26.90, 28.24, 32.20, 32.93, 36.30, 124.58, 124.88, 125.16, 126.43, 127.68, 128.56, 128.70, 141.45, 144.18, 175.45. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 10.7. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{32}\text{BNO}_2$, 385.25756; found, 385.25769.

To a suspension of **4aa** (38.1 mg, 0.099 mmol), $\text{Pd}(\text{PPh}_3)_4$ (6.4 mg, 0.005 mmol) and NaOH aq (3 M, 100 μL , 0.3 mmol) in 1,4-dioxane (0.4 mL) was added 4-iodotoluene (32.3 mg, 0.2 mmol) at room temperature. After being stirred at 120 °C for 24 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH_4Cl aq. The aqueous layer was extracted with EtOAc, and

the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO_4 , filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (5–25% EtOAc/hexane) to give the corresponding coupling product **7aa** (20.6 mg, 0.058 mmol) in 58% yield. **7aa**: White solid. **M.p.** 184 °C (decomp.). **IR** (neat) 699, 823, 1200, 1409, 1494, 1556, 1610, 1736, 3026, 3238 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 2.30 (s, 3H), 2.60 (d, $J = 4.8$ Hz, 3H), 2.62 (dd, $J = 9.2, 5.6$ Hz, 2H), 2.78 (dd, $J = 9.2, 5.6$ Hz, 2H), 5.15 (d, $J = 4.8$ Hz, 1H), 6.93–6.96 (m, 2H), 7.03–7.10 (m, 6H), 7.17 (m, 1H), 7.22–7.31 (m, 5H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 21.15, 26.44, 34.35, 34.93, 125.90, 127.32, 128.15, 128.26, 128.58, 128.70, 128.89, 128.94, 136.57, 137.48, 138.25, 140.99, 141.44, 142.51, 171.97. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{25}\text{NO}$, 355.19361; found, 355.19203.

X-ray Crytallographic Analysis

Data were collected on a Rigaku Mercury CCD diffractometer with graphite monochromated Mo-K α radiation ($\lambda = 0.71075$ Å) at 150 K, and processed using the CrystalClear software.¹⁶ Structures were solved by a direct method using SIR2004,¹⁷ and refined by full-matrix least-square method using SHELXL-97.¹⁸ Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were located on the calculated positions and refined using a riding model. All calculations were performed using the CrystalStructure software package.¹⁹ The supplementary crystallographic data for this paper can be obtained free of charge from the Cambridge Crystallographic Data Centre *via* www.ccdc.cam.ac.uk/data_request/cif.



Crystal data for **4aa** (CCDC 1008035; recrystallization from $\text{CH}_2\text{Cl}_2/\text{EtOH}$). $\text{C}_{27}\text{H}_{33}\text{BO}_2$, $M = 400.37$, triclinic, space group $P\bar{1}$ (#2), $a = 10.023(14)$ Å, $b = 10.902(17)$ Å, $c = 11.848(17)$ Å, $\alpha = 108.72(3)^\circ$, $\beta = 92.751(3)^\circ$, $\gamma = 109.02(3)^\circ$, $V = 1142(3)$ Å³, $Z = 2$, density (calc.) = 1.164, total

reflections collected = 8405, unique reflections = 4414 ($R_{\text{int}} = 0.0697$), GOF = 0.990, $R_1 = 0.0831$ ($I > 2\sigma(I)$), $wR_2 = 0.2592$.

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Chapter 4

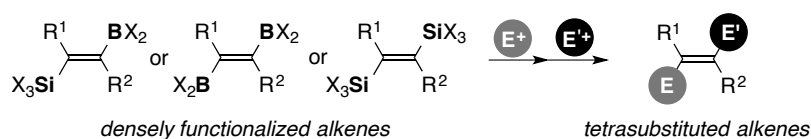
***Anti*-Selective Vicinal Silaboration and Diboration of Alkynoates through Phosphine Organocatalysis**

Trialkylphosphine organocatalysts have enabled *anti*-selective vicinal silaboration and diboration of the C–C triple bond in alkynoates to produce β -boryl- α -silylacrylates and α,β -diborylacrylates, respectively. The *anti* stereoselectivity was complete and robust. A variety of functional groups were tolerated in the alkynoates. The two vicinally installed heteroatom substituents of the β -boryl- α -silylacrylates and α,β -diborylacrylates could be differentiated and transformed in a stepwise manner, allowing the synthesis of a diverse array of unsymmetrical tetrasubstituted alkenes.

Introduction

Alkenylborons and alkenylsilanes are useful synthetic intermediates in organic synthesis because of their chemical stability and their applicability toward various transformations.¹ 1-Boryl-2-silyl-, 1,2-diboryl-, and 1,2-disilylalkenes are thus likely to represent platforms for the synthesis of various tetrasubstituted alkenes that are found in many important pharmaceuticals and bioactive natural compounds (Figure 1).² Addition of interelement compounds such as silylborens (Si–B), diborens (B–B), or disilanes (Si–Si) across carbon–carbon triple bonds is the most straightforward and attractive method for formation of densely functionalized alkenes.³ Most of the reported alkyne silaborations, diborations and disilylations occurred in *syn* addition mode.^{4–8} *anti*-Selective additions were also reported, but they were rare. For example, Suginome and co-workers reported the palladium-catalyzed *anti*-selective silaboration of terminal alkynes with silylboronates, but the stereoselectivity was not complete.^{9a} Recently, Uchiyama, Hirano, and co-workers reported the completely *anti*-selective diboration of the C–C triple bond in propargylic alkoxide anions.^{9b}

Figure 1. Synthesis of tetrasubstituted alkenes



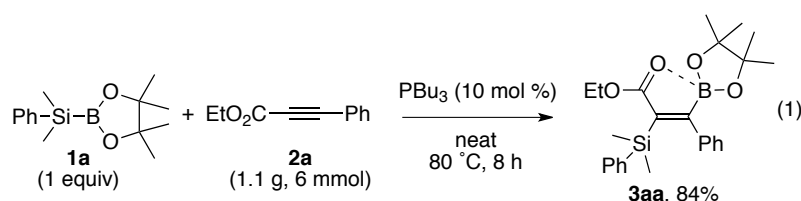
In Chapter 3, the author described a nucleophilic phosphine catalysis that promoted *anti*-selective carboboration of alkynoates with alkyl-, alkenyl-, or arylboranes to form β -borylacrylate derivatives.¹⁰ In this Chapter, he reports that similar protocols were applicable to the silaboration and diboration of alkynoates, providing a versatile and efficient approach to densely functionalized alkenes such as β -boryl- α -silylacrylates and α,β -diborylacrylates.¹¹ The *anti*-stereoselectivity was exclusive and robust irrespective of substrate structures. The regioselectivity of the silaboration across the polar C–C triple bond exhibited inverse electronic demand, with the intrinsically electrophilic B atom being delivered to the positively charged β carbon atom of the α,β -unsaturated ester (alkynoate). A variety of functional groups were tolerated in the alkynoates. Importantly, the two vicinally installed heteroatom substituents of the β -boryl- α -silylacrylates and α,β -diborylacrylates could be differentiated and transformed in a stepwise manner, allowing the use of these densely functionalized alkenes as a platform for the synthesis of a diverse array of

unsymmetrical tetrasubstituted alkenes. The potential of this strategy was demonstrated by molecular transformations toward the synthesis of tamoxifen-type compounds.

It should be noted that bis(pinacolato)diboron and a silylboron reagent $\text{PhMe}_2\text{SiB}(\text{pin})$ have been used as reagents for protoboration or protosilylation of electron-deficient alkenes under metal-free Lewis-base-catalyzed conditions.¹² More recently, the chemistry of the Lewis-base-catalyzed transformation of the interelement compounds has been extended to diboration and silaboration of the C–C double bonds in styrenes and allylic alcohols.¹³ Importantly, however, the vicinal difunctionalization of alkynes under transition metal free conditions is still limited to the Uchiyama's diboration of the propargylic alkoxide anions discussed above.^{9b}

Results and Discussion

The reaction of ethyl 3-phenylpropiolate (**2a**) (1.1 g, 6 mmol) with $\text{PhMe}_2\text{SiB}(\text{pin})$ (**1a**) (1.57 g, 6 mmol) in the presence of PBu_3 (10 mol %) without a solvent at 80 °C over 8 h gave β -boryl- α -silylacrylate **3aa** in isomerically pure form in 84% isolated yield (based on **2a**; 99% NMR yield; complete conversion of **2a**) (eq 1). The Si–B bond addition was completely regioselective and *anti*-stereoselective. The ^{11}B NMR spectrum of **3aa** indicated that the carbonyl oxygen was coordinated with the boron atom.



The result of other catalyst screening was shown in Table 1. It revealed that sterically less hindered trialkylphosphines, PMe_3 and PEt_3 were useful, PBu_3 being the most effective (Table 1, entries 1, 3 and 4). Bulkier trialkylphosphines such as PCy_3 and P^tBu_3 were ineffective (entries 5 and 6). The weaker electron-donors such as PPh_3 or $\text{P}(\text{OPh})_3$ and bisphosphines also resulted in no reaction (entries 7-10). No reaction occurred with *N*-heterocyclic carbenes (NHCs) or amines (DABCO, DBU, DMAP and NBu_3) with different steric and electronic natures (entries 11-17). The PBu_3 loading could be reduced to 5 mol % without affecting the yield of **3aa** (99%) (entry 2)

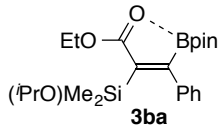
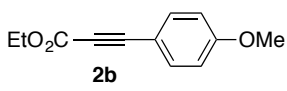
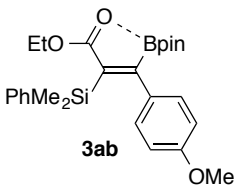
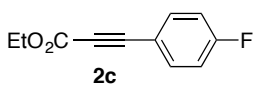
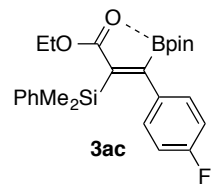
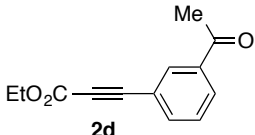
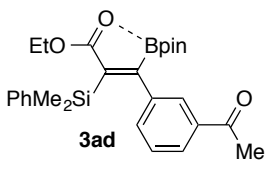
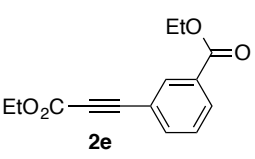
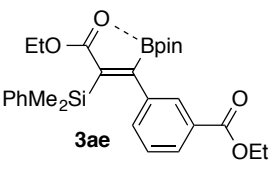
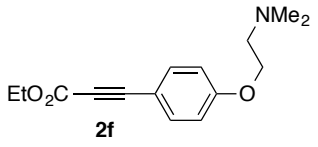
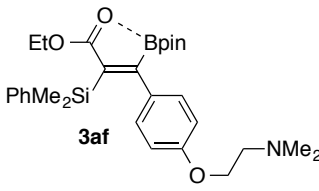
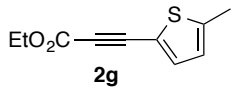
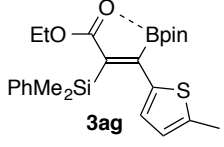
Table 1. Catalyst effects in silaboration of **1a** with **2a**.^a

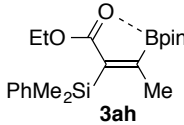
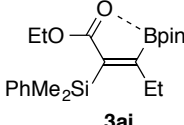
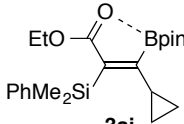
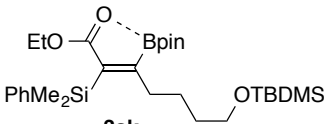
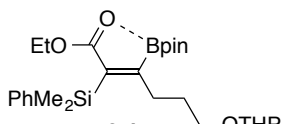
entry	catalyst	yield (%) ^b
1	PBu ₃	99
2	PBu ₃ (5 mol%)	99
3	PMe ₃	20
4	PEt ₃	25
5	PCy ₃	0
6	P ^t Bu ₃	0
7	PPh ₃	0
8	P(OPh) ₃	0
9	DPPE	0
10	DCYPE	0
11	SIMe	0
12	SICy	0
13	IMes	0
14	DABCO	0
15	DBU	0
16	DMAP	0
17	NBu ₃	0

^aConditions of silaboration reaction: **2a**, 0.3 mmol; **1a**, 0.3 mmol; catalyst, 10 mol %; 80 °C, 8 h. ^b¹H NMR yield.

The scope of the phosphine-catalyzed silaboration is shown in Table 2. The reaction of (*i*-PrO)Me₂SiB(pin) (**1b**) with **2a** occurred cleanly without touching the potentially sensitive Si–O bond to give β-boryl-α-alkoxysilylacrylate **3ba** in excellent yield (Table 2, entry 1). Substituted phenylpropiolates (**2b–f**) with a methoxy, fluoro, ketone, ester, or 2-(dimethylamino)ethoxy group at the *meta*- or *para*-position of the aromatic β-substituent and 2-thienyl-substituted alkynoate (**2g**) reacted with PhMe₂SiB(pin) (**1a**) in high yields (entries 2–7). Alkyl-substituted alkynoates **2h–l** also underwent efficient silaboration (entries 8–12).¹⁴

Table 2. Phosphine-catalyzed silaboration^a

$\text{RMe}_2\text{Si}-\text{Bpin}$ 1 (1 equiv) $+$ $\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{R}^1$ 2 (1 equiv) cat. PBU_3 neat 80°C, 8 h $\text{EtO}-\text{C}(=\text{O})-\text{O}-\text{Bpin}$ RMe_2Si R^1 3				
entry	silylboron	alkynoate	product	yield (%) ^b
1	$(\text{iPrO})\text{Me}_2\text{Si}-\text{Bpin}$ 1b	2a	 3ba	96
2	1a	 2b	 3ab	99
3	1a	 2c	 3ac	92
4	1a	 2d	 3ad	77
5	1a	 2e	 3ae	76
6	1a	 2f	 3af	76 ^c
7	1a	 2g	 3ag	94

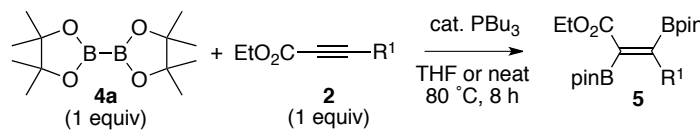
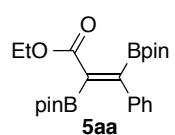
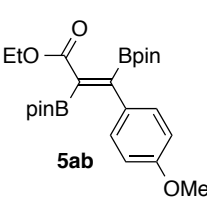
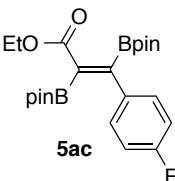
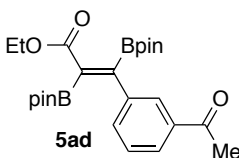
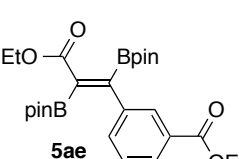
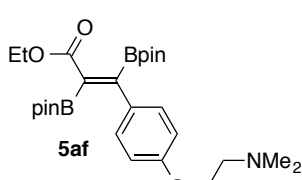
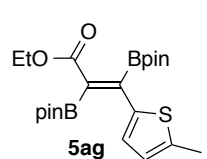
8	1a	$\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{Me}$ 2h	 3ah	70
9 ^d	1a	$\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{Et}$ 2i	 3ai	84
10	1a	$\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{Cyclopropyl}$ 2j	 3aj	90
11	1a	$\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{CH}_2\text{CH}_2\text{CH}_2\text{OTBDMS}$ 2k	 3ak	71
12	1a	$\text{EtO}_2\text{C}-\text{C}\equiv\text{C}-\text{CH}_2\text{CH}_2\text{OTHP}$ 2l	 3al	75

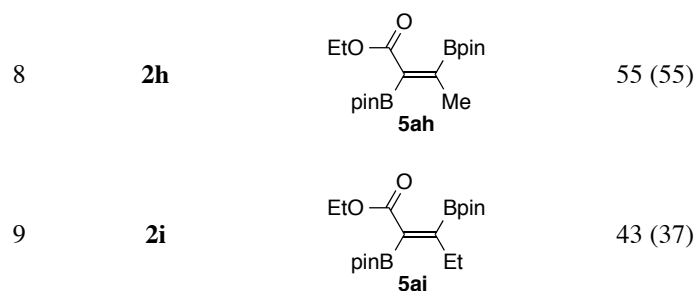
^aConditions of silaboration reaction: **2**, 0.3 mmol; **1**, 0.3 mmol; PBu_3 , 10 mol %; 80 °C, 8 h. ^bYield of the isolated product (silica gel chromatography). ^c¹H NMR yield. ^d**2i** (0.45 mmol) was used.

The diboration was possible by using a symmetrical diboron compound bis(pinacolato)diboron (**4a**) as a reagent, allowing the selective preparation of *trans*- α,β -diborylacrylate derivatives (Table 3). For instance, the phosphine-catalyzed diboration of **2a** with **4a** occurred with complete *anti* stereoselectivity to afford the corresponding α,β -diborylacrylate **5aa** (entry 1). Neither B atom in **5aa** had an interaction with the carbonyl oxygen as indicated by ¹¹B NMR spectroscopy. The use of bis(neopentylglycolato)diboron or bis(catecholato)diboron instead of **4a** resulted in no reaction (data not shown).

Functional groups such as methoxy, fluoro, ketone, ester, and 2-(dimethylamino)ethoxy moieties were tolerated at the *meta*- or *para*-position of the β -substituent in the alkynoates (Table 3, entries 2–6). The thiophene-substituted propiolate **2g** was a suitable substrate (entry 7). The reaction of alkyl-substituted propiolates such as 2-butyne **2h** and 2-pentyne **2i** gave alkyl-substituted alkenylboranes **5ah** and **5ai**, respectively, in good yields (entries 8 and 9).¹⁴

Table 3. Phosphine-catalyzed diboration^a

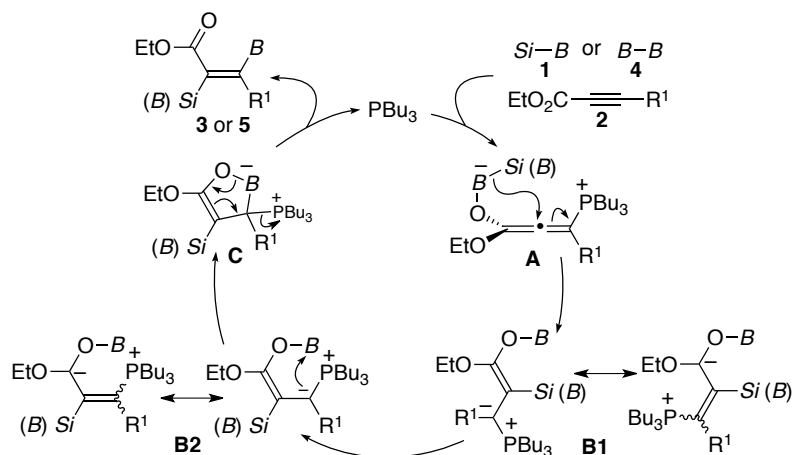
			
entry	alkynoate	product	yield (%) ^{b,c}
1 ^d	2a	 5aa	97 (64)
2	2b	 5ab	99 (82)
3	2c	 5ac	99 (70)
4	2d	 5ad	71 (56)
5	2e	 5ae	83 (70)
6 ^e	2f	 5af	93 (78)
7	2g	 5ag	99 (68)



^aConditions of diboration reaction: **2**, 0.3 mmol; **4a**, 0.3 mmol; PBu_3 , 10 mol %; THF (0.05 mL, entries 2–5 and 7) or neat (entries 8 and 9), 80 °C, 8 h. ^b ^1H NMR yield. Yield of the isolated product is in parentheses (silica gel chromatography; entries 1–5 and 7–9, recrystallization; entry 6). ^cThe isolated yield was significantly lower than the ^1H NMR yield due to material loss during silica gel chromatography or recrystallization. ^dReaction at 6 mmol scale. ^eReaction at 0.9 mmol scale.

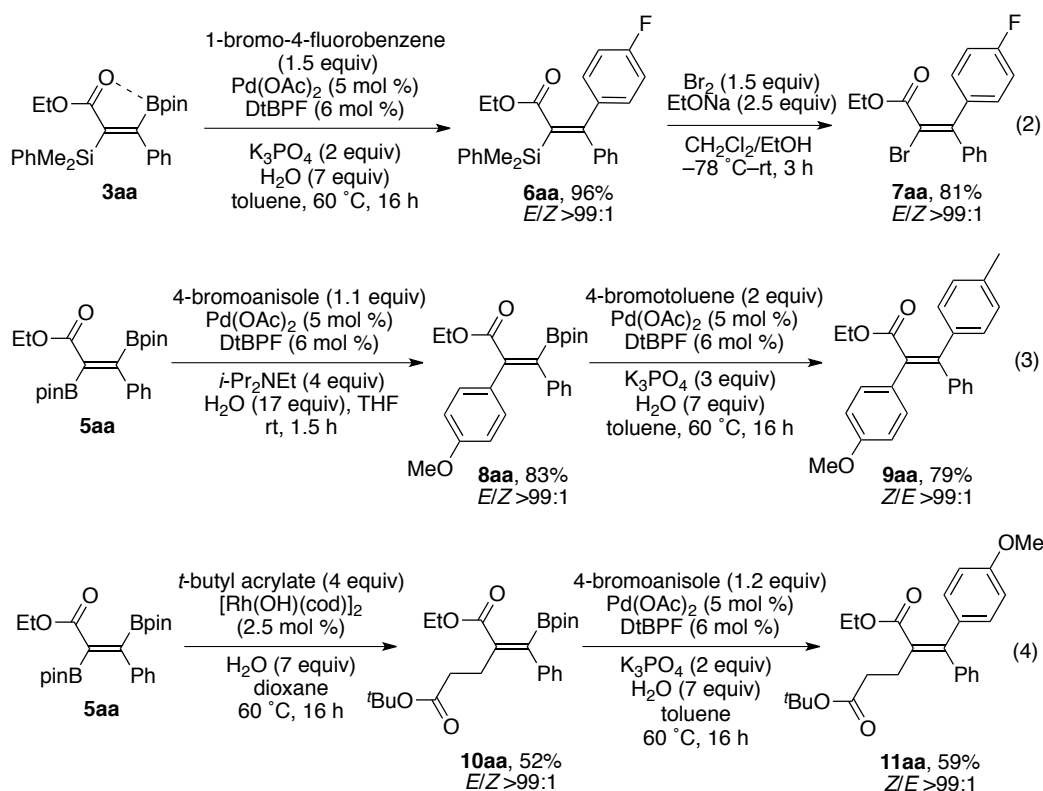
A possible catalytic cycle for the silaboration and diboration is illustrated in Figure 2. As proposed for the carboboration of alkynoates with organoboranes,¹⁰ the phosphine catalysis should be initiated by the conjugate addition of PBu_3 to the alkynoate **2** with the assistance of Lewis-acidic activation of the carbonyl group to form a zwitterionic allenolate intermediate (**A**).¹⁵ The B atom of the silylboronate (**1**) or diboron (**4**) should be a Lewis-acid center in the present case. The terminal silyl or boryl groups migrate to the *sp*-hybridized central carbon of the allene moiety to form ylide intermediates (**B1/B2**).¹⁶ Next, the ylide carbon of **B2** attacks the B atom bound to the enolate oxygen to form cyclic borate **C**. Finally, elimination of Bu_3P associated with B–O cleavage affords **3** or **5**.

Figure 2. A possible catalytic cycle.



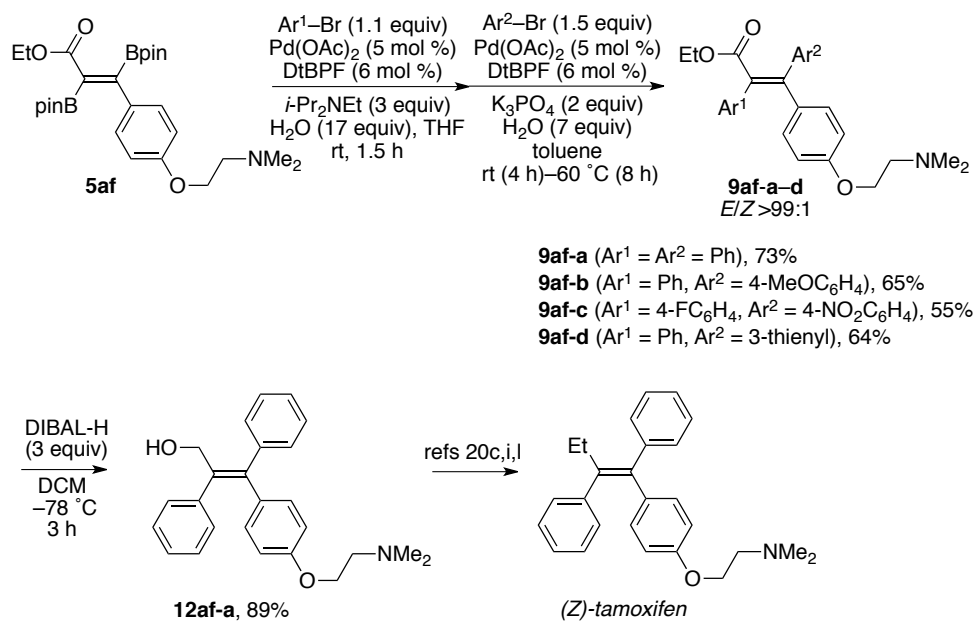
The two vicinally installed heteroatom substituents of the β -boryl- α -silylacrylates and α,β -diborylacrylates could be differentiated and transformed in a stepwise manner (eqs 2–4). For example, β -boryl- α -silylacrylate **3aa** underwent Suzuki–Miyaura coupling with 1-bromo-4-fluorobenzene at the boron site [$\text{Pd}(\text{OAc})_2$ –DtBPF (1,1'-bis(di-*tert*-butylphosphino)ferrocene) catalyst/ K_3PO_4] to afford the corresponding trisubstituted alkenylsilane **6aa** with excellent yield and complete *E* selectivity; the C–Si bond remained untouched (eq 2). The obtained **6aa** could be derivatized to the trisubstituted alkenyl bromide **7aa** without *E/Z* isomerization.¹⁷

He was delighted to find that the two boron sites in **5aa** could be efficiently differentiated for a stepwise twofold cross-coupling. Thus, the cross-coupling between the α,β -diborylacrylate **5aa** and 4-bromoanisole under the influence of a $\text{Pd}(\text{OAc})_2$ –DtBPF catalyst and *i*-Pr₂NEt base occurred selectively at the α -boron site to give alkenylboronate **8aa** (83%, *E/Z* > 99:1), and no diarylation occurred (eq 3).¹⁸ The second arylation with 4-bromotoluene (*Z/E* > 99:1) was possible by subjecting **8aa** to the coupling conditions using the $\text{Pd}(\text{OAc})_2$ /DtBPF/ K_3PO_4 system: isomerically pure tetrasubstituted alkene **9aa** was obtained in good yield (eq 3). The site-selectivity in the first cross-coupling favoring C(α)–B bond transformation is likely due to the electron-withdrawing resonance effect of the ester group rendering C(β) less nucleophilic. Additionally, the α,β -diborylacrylate **5aa** underwent site-selective Rh-catalyzed conjugate addition to *tert*-butyl acrylate followed by Pd-catalyzed cross-coupling with 4-bromoanisole to produce tetrasubstituted alkene **11aa** (eq 4). Overall, these transformations (eqs 2–4) demonstrated the usefulness of the β -boryl- α -silylacrylates and α,β -diborylacrylates as precursors to a diverse array of unsymmetrical tetrasubstituted alkenes.



The author then used this strategy for molecular transformations toward the synthesis of (*Z*)-tamoxifen, an antiestrogenic anticancer drug, and its analogues (Scheme 1).¹⁹ The Pd-catalyzed α -selective cross-coupling of the α,β -diborylacrylate **5af** with an aryl bromide (Ar¹-Br) followed by a second coupling with the same or different (hetero)aryl bromide (Ar²-Br) afforded the diarylated products **9af-a-d** in isomerically pure forms. The reduction of the ester group in **9af-a** (Ar¹ = Ar² = Ph) with DIBAL-H produced the alcohol **12af-a**. The synthesis of (*Z*)-tamoxifen from **12af-a** was reported previously.^{19c, i, 1} Thus, a formal total synthesis of (*Z*)-tamoxifen was achieved.

Scheme 1. Synthesis of tamoxifen-type compounds.



Conclusion

In summary, the author has developed phosphine-catalyzed *anti*-selective silaboration and diboration of the C–C triple bond in alkynoates to produce β -boryl- α -silylacrylates and α,β -diborylacrylates, respectively. The *anti*-stereoselectivity was exclusive and robust irrespective of substrate structures. The silaboration across the polar C–C triple bond occurred with inverse electronic demand with regard to the regioselectivity, with the intrinsically electrophilic B atom being delivered to the positively charged β carbon atom. A variety of functional groups were tolerated in the alkynoates. Importantly, the two vicinally installed heteroatom substituents of the β -boryl- α -silylacrylates and α,β -diborylacrylates could be differentiated and transformed in a stepwise manner, allowing the use of these densely functionalized alkenes as a platform for the synthesis of a diverse array of unsymmetrical tetrasubstituted alkenes. The power of this strategy was demonstrated by molecular transformations toward the synthesis of tamoxifen-type compounds.

Experimental Procedure

Instrumentation and Chemicals

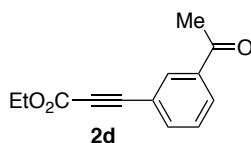
NMR spectra were recorded on a JEOL ECX-400, operating at 400 MHz for ^1H NMR, 100.5 MHz for ^{13}C NMR and 128 MHz for ^{11}B NMR. Chemical shift values for ^1H and ^{13}C are referenced to Me_4Si , the residual solvent resonances and $\text{BF}_3\cdot\text{OEt}_2$, respectively. Chemical shifts are reported in δ ppm. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TZ at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Elemental analysis was performed at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Kanto Chemical Co., Silica gel 60 N, spherical, neutral) was used for column chromatography. IR spectra of neat samples were measured with a Perkin-Elmer Frontier FT-IR equipped with a universal diamond ATR sampling accessory. Melting points were measured on a Yanaco MP-500D apparatus. Melting points were measured on a Yanaco MP-500D apparatus.

All reactions were carried out under nitrogen or argon atmosphere. Materials were obtained from commercial suppliers or prepared according to standard procedures unless otherwise noted. Bis(pinacolato)diboron was purchased from AllyChem Co., Ltd., and recrystallized from pentane before use, stored under nitrogen, and used as it is. PBU_3 was purchased from Kanto Chemical Co., stored under nitrogen, and used as it is. THF and toluene were purchased from Kanto Chemical Co., stored under argon. Dichloromethane (DCM) was purchased from Kanto Chemical Co., stored over 4Å molecular sieves under nitrogen.

Alkynoates **2b**²⁰, **2c**²⁰, **2g**²⁰ and **2l**²¹ are known compounds. Alkynoates **2f**, **2j** and **2k** were prepared by the reaction between the corresponding lithium acetylides and ethyl chloroformate. Alkynoates **2d** and **2e** were prepared by Sonogashira coupling with the corresponding aryl iodides and ethyl propiolate. Alkynoates **2a** and **2i** were purchased from Aldrich Chemical Co., stored under nitrogen, and used as it is. Alkynoate **2h** was purchased from TCI Chemical Co., stored under nitrogen, and used as it is. Silylborons **1a**²² and **1b**²³ were synthesized by the reported method.

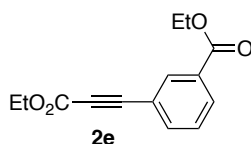
Characterization Data for Alkynoates

Ethyl 3-(3-Acetylphenyl)propiolate (**2d**)



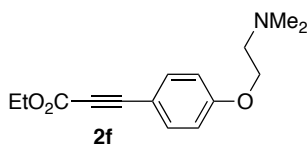
Yellow solid. **M.p.** 66–68 °C. **IR** (neat) 683, 748, 800, 1023, 1167, 1186, 1248, 1294, 1354, 1424, 1594, 1682, 1695, 2222, 2996 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.37 (t, $J = 7.2$ Hz, 3H), 2.62 (s, 3H), 4.32 (q, $J = 7.2$ Hz, 2H), 7.50 (t, $J = 8.0$, 1H), 7.76 (dd, $J = 8.0$, 1.6 Hz, 1H), 8.04 (dd, $J = 8.0$, 1.6 Hz, 1H), 8.16 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.02, 26.57, 62.25, 81.30, 84.50, 120.27, 129.00, 129.97, 132.88, 136.88, 137.29, 153.71, 196.60. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{13}\text{H}_{12}\text{O}_3$, 216.07864; found, 216.07825.

Ethyl 3-(3-Ethoxy-3-oxoprop-1-yn-1-yl)benzoate (2e)



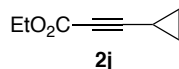
Colorless oil. **IR** (neat) 682, 750, 1019, 1103, 1164, 1182, 1250, 1295, 1367, 1706, 2221, 2983 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.37 (t, $J = 6.8$ Hz, 3H), 1.41 (t, $J = 7.2$ Hz, 3H), 4.31 (q, $J = 6.8$ Hz, 2H), 4.39 (q, $J = 7.2$ Hz, 2H), 7.47 (t, $J = 8.0$, 1H), 7.75 (dt, $J = 8.0$, 1.2 Hz, 1H), 8.12 (dt, $J = 8.0$, 1.2 Hz, 1H), 8.27 (t, $J = 1.2$ Hz, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 13.98, 14.17, 61.32, 62.14, 81.12, 84.54, 119.96, 128.67, 131.01, 131.40, 133.90, 136.62, 153.67, 165.17. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{14}\text{H}_{14}\text{O}_4$, 246.08921; found, 246.08849.

Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}propiolate (2f)



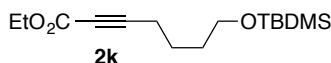
White solid. **M.p.** 36–37 °C. **IR** (neat) 747, 835, 1022, 1170, 1198, 1287, 1513, 1601, 1692, 2199, 2771, 2815, 2970 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.35 (t, $J = 7.2$ Hz, 3H), 2.33 (s, 6H), 2.73 (t, $J = 5.6$ Hz, 2H), 4.08 (t, $J = 5.6$ Hz, 2H), 4.28 (q, $J = 7.2$ Hz, 2H), 6.88–6.92 (m, 2H), 7.51–7.54 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.09, 45.89, 58.07, 61.87, 66.17, 80.11, 86.87, 111.40, 114.79, 134.85, 154.30, 160.73. **HRMS–ESI** (m/z): $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{15}\text{H}_{20}\text{NO}_3$, 262.14377; found, 262.14384.

Ethyl 3-Cyclopropylpropiolate (**2j**)



Colorless oil. **IR** (neat) 749, 859, 886, 1026, 1127, 1182, 1252, 1369, 1702, 2222, 2985 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.88–0.97 (m, 4H), 1.30 (t, $J = 7.6$ Hz, 3H), 1.37 (m, 1H), 4.20 (q, $J = 7.6$ Hz, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ -0.74, 9.07, 13.95, 61.57, 68.43, 92.94, 153.71. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_8\text{H}_{10}\text{O}_2$, 138.06808; found, 138.06798.

Ethyl 6-[(*tert*-Butyldimethylsilyl)oxy]hex-2-ynoate (**2k**)



Colorless oil. **IR** (neat) 661, 712, 74, 834, 1075, 1094, 1245, 1464, 1712, 2236, 2858, 2931, 2954 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.05 (s, 6H), 0.91 (s, 9H), 1.31 (t, $J = 7.2$ Hz, 3H), 1.58–1.71 (m, 4H), 2.37 (t, $J = 6.0$ Hz, 2H), 3.63 (t, $J = 6.0$ Hz, 2H), 4.21 (q, $J = 7.2$ Hz, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ -5.38, 14.01, 18.27, 18.45, 24.09, 25.90, 31.74, 61.72, 62.31, 73.25, 89.17, 153.80. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{15}\text{H}_{28}\text{O}_3\text{NaSi}$, 307.16999; found, 307.17011.

Procedures for Phosphine-Catalyzed *Anti*-selective Silaboration and Diboration of Alkynoates

Typical Procedure for Phosphine-Catalyzed *Anti*-Silaboration of Alkynoates. The reaction in Table 2, entry 2 is representative. Silylboronate **1a** (78.7 mg, 0.30 mmol) and ethyl 3-(4-methoxyphenyl)propiolate (**2b**) (61.2 mg, 0.30 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. PBu_3 (7.4 μL , 0.03 mmol) was added to the vial. After 8 h stirring at 80 $^\circ\text{C}$, the mixture was put on a silica gel column. Chromatography with 3–15% EtOAc/hexane provided **3ab** (139.5 mg, 0.299 mmol) in 99% yield.

A Gram Scale Reaction of 2a. The reaction in eq. 1 is representative. Silylboronate **1a** (1.57 g, 6.00 mmol) and ethyl 3-phenylpropiolate (**2a**) (1.05 g, 6.00 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. PBu_3 (148 μL , 0.60 mmol) was added to the vial. After 8

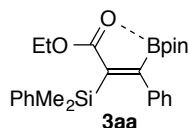
h stirring at 80 °C, the mixture was put on a silica gel column. Chromatography with 3–15% EtOAc/hexane provided **3aa** (2.20 g, 5.04 mmol) in 84% yield.

Typical Procedure for Phosphine-Catalyzed *Anti*-Diboration of Alkynoates. The reaction in Table 3, entry 2 is representative. Bis(pinacolato)diboron (**4a**) (76.2 mg, 0.30 mmol) and ethyl 3-(4-methoxyphenyl)propiolate (**2b**) (61.2 mg, 0.30 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. THF (50 μ L) and PBu₃ (7.4 mL, 0.03 mmol) were added to the vial. After 8 h stirring at 80 °C, the mixture was evaporated under reduced pressure. The residue was put on a silica gel column. Chromatography with 0–10% EtOAc/hexane provided **5ab** in 82% yield (112.1 mg, 0.244 mmol).

Procedure for Phosphine-Catalyzed *Anti*-Diboration of **2f.** The reaction in Table 3, entry 6 is representative. Bis(pinacolato)diboron (**4a**) (228.6 mg, 0.90 mmol) and **2f** (235.2 mg, 0.9 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. THF (150 μ L) and PBu₃ (22.2 μ L, 0.09 mmol) were added to the vial. After 8 h stirring at 80 °C, the mixture was evaporated under reduced pressure. The residue was diluted with pentane and filtered thorough a Celite[®] pad. The filtrate was evaporated under reduced pressure. The residue was purified by recrystallization with pentane at 0 °C to afford **5af** in 78% yield (363.0 mg, 0.70 mmol).

Characterization Data for β -Boryl- α -silylacrylates and α,β -Diborylacrylates

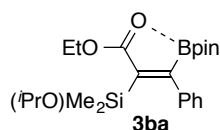
(*Z*)-Ethyl 2-(Dimethylphenylsilyl)-3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3aa**)



The product **3aa** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Yellow oil. **IR** (neat) 699, 732, 785, 814, 843, 968, 1013, 1059, 1111, 1142, 1234, 1319, 1371, 1693, 2977 cm^{-1} . **¹H NMR** (400 MHz, CDCl₃) δ 0.07 (s, 6H), 1.15–1.25 (m, 15H), 4.28 (q, *J* = 7.2 Hz, 2H), 7.14–7.16 (m, 2H), 7.21–7.23 (m, 2H), 7.26–7.28 (m, 3H), 7.43–7.45 (m, 2H). **¹³C NMR** (100.5 MHz, CDCl₃) δ –1.27, 13.86, 24.81, 63.33, 82.61, 126.72, 127.35, 127.45, 127.54, 128.68, 133.70, 136.88, 138.71, 140.45, 176.77. A signal for the sp^2 -carbon directly attached to the boron

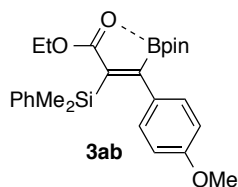
atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 24.0. HRMS–EI (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{33}\text{BO}_4\text{Si}$, 436.22412; found, 436.22441. The regio- and stereochemistries were determined by transforming it to **6aa** and **7aa** (eq 2).

(Z)-Ethyl 2-(Isopropoxydimethylsilyl)-3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3ba)



The product **3ba** was purified by flash chromatography on silica gel (0–12% EtOAc/hexane). Colorless oil. IR (neat) 700, 789, 844, 968, 1022, 1062, 1142, 1233, 1319, 1369, 1698, 2975 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ –0.07 (s, 6H), 1.05 (d, J = 6.4 Hz, 6H), 1.21 (s, 12H), 1.39 (t, J = 6.8 Hz, 3H), 3.97 (sept, J = 6.4 Hz, 1H), 4.42 (q, J = 6.8 Hz, 2H), 7.26–7.32 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 0.64, 14.06, 24.86, 25.51, 63.47, 65.24, 82.52, 126.94, 127.53, 137.01, 140.43, 177.13. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 23.6. HRMS–ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{35}\text{BO}_5\text{NaSi}$, 441.22434; found, 441.22417. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

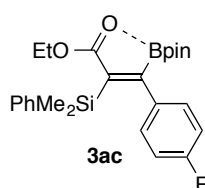
(Z)-Ethyl 2-(Dimethylphenylsilyl)-3-(4-methoxyphenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3ab)



The product **3ab** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Yellow oil. IR (neat) 731, 752, 845, 1110, 1141, 1174, 1241, 1371, 1506, 1605, 1687, 2977 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.12 (s, 6H), 1.18–1.27 (m, 15H), 3.78 (s, 3H), 4.29 (q, J = 7.2 Hz, 2H), 6.73–6.75 (m, 2H), 7.10–7.12 (m, 2H), 7.23–7.31 (m, 3H), 7.43–7.45 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ –0.99, 13.90, 24.96, 55.11, 63.32, 82.53, 112.97, 127.47, 128.53, 128.62,

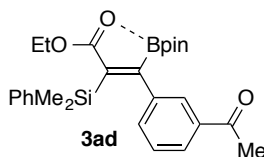
132.80, 133.72, 135.70, 139.00, 159.39, 177.09. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 23.2. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{35}\text{BO}_5\text{Si}$, 466.23468; found, 466.23442. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 2-(Dimethylphenylsilyl)-3-(4-fluorophenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3ac)



The product **3ac** was purified by flash chromatography on silica gel (0–8% EtOAc/hexane). Colorless solid. M.p. 55–56 °C. **IR** (neat) 700, 731, 813, 846, 1012, 1060, 1141, 1217, 1371, 1503, 1600, 1697, 2978 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.12 (s, 6H), 1.19 (s, 12H), 1.25 (t, $J = 7.6$ Hz, 3H), 4.32 (q, $J = 7.6$ Hz, 2H), 6.86–6.91 (m, 2H), 7.08–7.11 (m, 2H), 7.22–7.32 (m, 3H), 7.32–7.41 (m, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ –1.20, 13.87, 24.85, 63.68, 82.57, 114.52 (d, $J_{\text{C-F}} = 21.0$ Hz), 127.52, 128.50 (d, $J_{\text{C-F}} = 7.2$ Hz), 128.77, 133.65, 136.20 (d, $J_{\text{C-F}} = 3.0$ Hz), 137.00, 138.31, 162.35 (d, $J_{\text{C-F}} = 246.2$ Hz), 177.15. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 23.9. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{32}\text{BFO}_4\text{Si}$, 454.21469; found, 454.21030. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

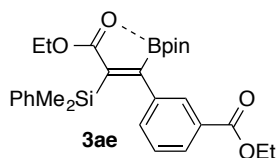
(Z)-Ethyl 3-(3-Acetylphenyl)-2-(dimethylphenylsilyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3ad)



The product **3ad** was purified by flash chromatography on silica gel (2–20% EtOAc/hexane). Yellow oil. **IR** (neat) 708, 731, 913, 968, 1018, 1060, 1110, 1235, 1320, 1687, 2977 cm^{-1} . ^1H NMR

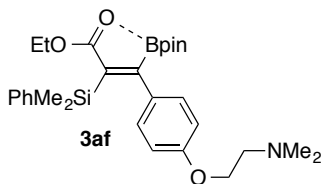
(400 MHz, CDCl₃) δ 0.13 (s, 6H), 1.20 (s, 12H), 1.30 (t, J = 7.2 Hz, 3H), 2.36 (s, 3H), 4.37 (q, J = 7.2 Hz, 2H), 7.19–7.40 (m, 7H), 7.62 (m, 1H), 7.80 (m, 1H). ¹³C NMR (100.5 MHz, CDCl₃) δ -1.13, 13.92, 24.86, 26.40, 63.82, 82.67, 126.98, 127.30, 127.59, 127.94, 128.86, 131.28, 133.63, 136.27, 137.84, 138.17, 140.57, 177.06, 197.84. A signal for the sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 23.3. HRMS–EI (m/z): [M]⁺ calcd for C₂₇H₃₅BO₅Si, 478.23468; found, 478.23369. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 3-[2-(Dimethylphenylsilyl)-3-ethoxy-3-oxo-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1-propen-1-yl]benzoate (3ae)



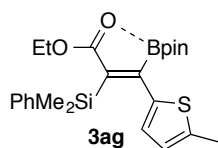
The product **3ae** was purified by flash chromatography on silica gel (5–25% EtOAc/hexane). Yellow oil. IR (neat) 701, 785, 815, 835, 1017, 1060, 1107, 1141, 1204, 1235, 1369, 1718, 2978 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) δ 0.14 (s, 6H), 1.19 (s, 12H), 1.25 (t, J = 7.2 Hz, 3H), 1.36 (t, J = 7.2 Hz, 3H), 4.30–4.36 (m, 4H), 7.18–7.38 (m, 7H), 7.84–7.89 (m, 2H). ¹³C NMR (100.5 MHz, CDCl₃) δ -1.19, 13.86, 14.23, 24.84, 60.81, 63.73, 82.61, 127.44, 127.61, 128.13, 128.64, 128.73, 129.73, 131.05, 133.64, 137.54, 137.98, 140.29, 166.32, 177.09. A signal for the sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 23.4. HRMS–ESI (m/z): [M+Na]⁺ calcd for C₂₈H₃₇BO₆NaSi, 531.23500; found, 531.23502. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 2-(Dimethylphenylsilyl)-3-{4-[2-(dimethylamino)ethoxy]phenyl}-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3af)



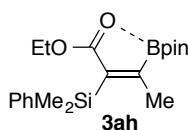
The product **3af** was characterized without further purification and contaminated with a trace amount of an unidentified material. Yellow oil. **IR** (neat) 732, 845, 1110, 1141, 1235, 1371, 1459, 1505, 1605, 1692, 2771, 2821, 2976 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.12 (s, 6H), 1.19–1.25 (m, 15H), 2.34 (s, 6H), 2.71 (t, $J = 5.6$ Hz, 2H), 4.03 (t, $J = 5.6$ Hz, 2H), 4.29 (q, $J = 6.8$ Hz, 2H), 6.74–6.77 (m, 2H), 7.08–7.11 (m, 2H), 7.23–7.29 (m, 3H), 7.42–7.46 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ -1.02, 13.86, 24.91, 45.89, 58.24, 63.25, 65.82, 82.49, 113.60, 127.43, 128.45, 128.57, 132.85, 133.68, 135.67, 138.98, 158.64, 177.02. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 23.8. **HRMS–ESI** (m/z): $[\text{M}+\text{H}]^+$ calcd for $\text{C}_{29}\text{H}_{43}\text{BNO}_5\text{Si}$, 524.30036; found, 524.29969. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 2-(Dimethylphenylsilyl)-3-(5-methylthiophen-2-yl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3ag)



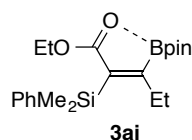
The product **3ag** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Yellow oil. **IR** (neat) 700, 732, 812, 834, 967, 1009, 1110, 1140, 1220, 1307, 1370, 1698, 2977 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.28 (s, 6H), 1.22 (t, $J = 7.2$ Hz, 3H), 1.30 (s, 12H), 2.42 (s, 3H), 4.33 (q, $J = 7.2$ Hz, 2H), 6.52 (m, 1H), 6.71 (m, 1H), 7.26–7.29 (m, 3H), 7.47–7.49 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ -0.86, 13.85, 15.44, 25.40, 63.73, 82.51, 125.33, 127.52, 128.57, 128.64, 133.67, 134.21, 138.99, 139.05, 143.44, 177.90. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 21.9. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{24}\text{H}_{33}\text{BO}_4\text{SSi}$, 530.23810; found, 530.23862. The regiochemistry was assigned by consideration of the reaction pathway. The stereochemistry was determined by NOESY experiments.

(Z)-Ethyl 2-(Dimethylphenylsilyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-butenate (3ah)



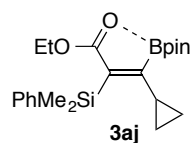
The product **3ah** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Colorless oil. **IR** (neat) 701, 732, 785, 834, 965, 1041, 1125, 1247, 1315, 1371, 1714, 2976 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.46 (s, 6H), 1.23 (t, $J = 7.2$ Hz, 3H), 1.28 (s, 12H), 1.93 (s, 3H), 4.29 (q, $J = 7.2$ Hz, 2H), 7.27–7.34 (m, 3H), 7.49–7.51 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ –0.92, 13.81, 19.48, 24.95, 63.86, 81.87, 127.68, 128.93, 133.01, 133.68, 138.20, 178.85. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 21.4. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{20}\text{H}_{31}\text{BO}_4\text{Si}$, 374.20847; found, 374.20826. The regio- and stereochemistries were determined by NOESY experiments and the comparison of the NMR data with the reported isomers.^{5k}

(Z)-Ethyl 2-(Dimethyl(phenyl)silyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-pentenoate (3ai)



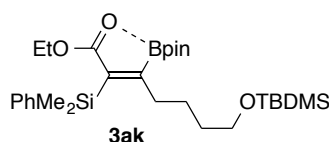
The product **3ai** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Colorless oil. **IR** (neat) 659, 701, 732, 818, 967, 1039, 1132, 1240, 1315, 1347, 1371, 1711, 2976 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.46 (s, 6H), 0.95 (t, $J = 7.6$ Hz, 3H), 1.21 (t, $J = 7.2$ Hz, 3H), 1.29 (s, 12H), 2.30 (q, $J = 7.6$ Hz, 2H), 4.23 (q, $J = 7.2$ Hz, 2H), 7.29–7.33 (m, 3H), 7.50–7.53 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ –0.70, 13.05, 13.88, 25.01, 26.93, 63.12, 82.29, 127.63, 128.91, 133.71, 134.34, 138.50, 177.57. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 23.4. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{21}\text{H}_{33}\text{BO}_4\text{Si}$, 388.22412; found, 388.22313. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 3-Cyclopropyl-2-(dimethylphenylsilyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3aj)



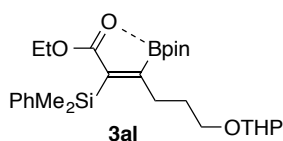
The product **3aj** was purified by flash chromatography on silica gel (0–8% EtOAc/hexane). Colorless oil. **IR** (neat) 700, 731, 814, 833, 965, 1015, 1110, 1138, 1247, 1300, 1370, 1698, 2977 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.47 (s, 6H), 0.72–0.78 (m, 2H), 1.23 (t, $J = 7.2$ Hz, 3H), 1.26–1.28 (m, 14H), 1.78 (m, 1H), 4.25 (q, $J = 7.2$ Hz, 2H), 7.29–7.32 (m, 3H), 7.53–7.55 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ –0.26, 9.86, 13.90, 19.24, 25.81, 63.41, 82.10, 127.61, 128.76, 130.21, 133.79, 138.82, 178.53. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 20.7. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{22}\text{H}_{33}\text{BO}_4\text{Si}$, 400.22412; found, 400.22325. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 6-(*tert*-Butyldimethylsilyloxy)-2-(dimethylphenylsilyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-hexenoate (3ak)



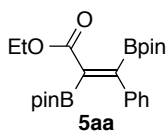
The product **3ak** was purified by flash chromatography on silica gel (0–8% EtOAc/hexane). Colorless oil. **IR** (neat) 701, 774, 834, 966, 1099, 1129, 1247, 1314, 1711, 2857, 2930, 2954 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ –0.00 (s, 6H), 0.44 (s, 6H), 0.86 (s, 9H), 1.21 (t, $J = 7.2$ Hz, 3H), 1.26 (s, 12H), 1.26–1.39 (m, 4H), 2.19–2.23 (m, 2H), 3.44 (t, $J = 6.4$ Hz, 2H), 4.23 (q, $J = 7.2$ Hz, 2H), 7.27–7.32 (m, 3H), 7.49–7.51 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ –5.34, –0.79, 13.88, 18.08, 25.01, 25.21, 25.93, 33.34, 33.83, 62.92, 63.19, 82.23, 127.65, 128.94, 133.75, 134.47, 138.54, 177.65. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 23.6. **HRMS–EI** (m/z): $[\text{M}-t\text{Bu}]^+$ calcd for $\text{C}_{25}\text{H}_{42}\text{BO}_5\text{Si}_2$, 489.26638; found, 489.26594. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(Z)-Ethyl 2-(Dimethylphenylsilyl)-6-(tetrahydro-2H-pyran-2-yloxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-hexenoate (3al)



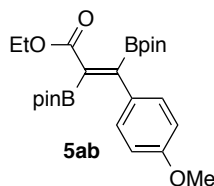
The product **3a** was purified by flash chromatography on silica gel (0–15% EtOAc/hexane). Colorless oil. **IR** (neat) 660, 701, 815, 840, 986, 1033, 1115, 1230, 1246, 1314, 1370, 1710, 2942 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.47 (s, 6H), 1.21 (t, $J = 7.2$ Hz, 3H), 1.28 (s, 12H), 1.42–1.60 (m, 4H), 1.60–1.72 (m, 3H), 1.78 (m, 1H), 2.30–2.44 (m, 2H), 3.19 (dt, $J = 10.0, 5.6$ Hz, 1H), 3.45 (m, 1H), 3.53 (dt, $J = 10.0, 5.6$ Hz, 1H), 3.77 (m, 1H), 4.25 (q, $J = 7.2$ Hz, 2H), 4.50 (m, 1H), 7.28–7.33 (m, 3H), 7.50–7.53 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ –0.79, 13.85, 19.24, 25.03, 25.46, 28.81, 30.55, 30.82, 61.76, 63.33, 67.09, 82.23, 98.25, 127.64, 128.93, 133.74, 134.57, 138.47, 177.82. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 23.0. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{27}\text{H}_{43}\text{BO}_6\text{SiNa}$, 525.28199.; found, 525.28142. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

(E)-Ethyl 3-Phenyl-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5aa)



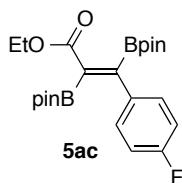
The product **5aa** was purified by flash chromatography on silica gel (10–25% EtOAc/hexane). White solid. M.p. 147–149 °C. **IR** (neat) 670, 707, 772, 845, 969, 1062, 1138, 1238, 1315, 1371, 1700, 2979 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.15 (s, 12H), 1.23–1.34 (m, 15H), 4.26 (q, $J = 7.2$ Hz, 2H), 7.26–7.32 (m, 3H), 7.41–7.44 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.06, 24.42, 24.85, 61.34, 83.57, 83.75, 127.50, 128.11, 128.16, 140.13, 170.55. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.6 ($\times 2\text{B}$). **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{23}\text{H}_{34}\text{B}_2\text{O}_6$, 428.25415; found, 428.25483. The stereochemistry was determined by transforming it to **9aa** (eq 3).

(E)-Ethyl 3-(4-Methoxyphenyl)-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5ab)



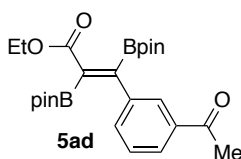
The product **5ab** was purified by flash chromatography on silica gel (10–25% EtOAc/hexane). Yellow solid. M.p. 103–105 °C. **IR** (neat) 846, 971, 1022, 1141, 1177, 1247, 1308, 1370, 1510, 1604, 1688, 2981 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.19 (s, 12H), 1.28 (t, $J = 7.2$ Hz, 3H), 1.32 (s, 12H), 3.80 (s, 3H), 4.26 (q, $J = 7.2$ Hz, 2H), 6.83–6.85 (m, 2H), 7.40–7.43 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.06, 24.48, 24.95, 55.19, 61.35, 83.41, 83.70, 113.52, 129.21, 132.63, 159.91, 171.14. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.5. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{24}\text{H}_{36}\text{B}_2\text{O}_7$, 458.26471; found, 458.26504. The stereochemistry was determined by NOESY experiments.

(E)-Ethyl 3-(4-Fluorophenyl)-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5ac)



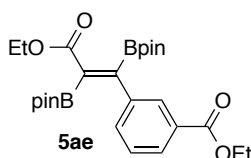
The product **5ac** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). White solid. M.p. 111–113 °C. **IR** (neat) 747, 846, 971, 1065, 1141, 1219, 1248, 1319, 1600, 1701, 2982 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.16 (s, 12H), 1.26–1.32 (m, 15H), 4.26 (q, $J = 6.8$ Hz, 2H), 6.97–7.02 (m, 2H), 7.40–7.44 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.05, 24.44, 24.86, 61.54, 83.60, 83.86, 115.06 (d, $J_{\text{C-F}} = 22.0$ Hz), 129.41 (d, $J_{\text{C-F}} = 8.6$ Hz), 136.11 (d, $J_{\text{C-F}} = 2.9$ Hz), 162.87 (d, $J_{\text{C-F}} = 271.4$ Hz), 170.73. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.6. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{23}\text{H}_{33}\text{B}_2\text{FO}_6$, 446.24473; found, 446.24483. The stereochemistry was assigned by consideration of the reaction pathway.

(E)-Ethyl 3-(3-Acetylphenyl)-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5ad)



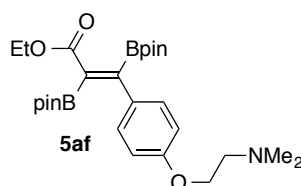
The product **5ad** was purified by flash chromatography on silica gel (5–30% EtOAc/hexane). White solid. M.p. 168–170 °C. **IR** (neat) 807, 845, 967, 1062, 1139, 1195, 1241, 1318, 1683, 1702, 2981 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.12 (s, 12H), 1.29–1.33 (m, 15H), 2.60 (s, 3H), 4.29 (q, J = 7.2 Hz, 2H), 7.42 (m, 1H), 7.64 (m, 1H), 7.90 (m, 1H), 8.02 (m, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.05, 24.40, 24.86, 26.61, 61.67, 83.68, 83.94, 127.72, 127.99, 128.47, 132.05, 136.91, 140.45, 170.63, 197.82. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.1. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{25}\text{H}_{36}\text{B}_2\text{O}_7$, 470.26471; found, 470.26456. The stereochemistry was assigned by consideration of the reaction pathway.

(E)-Ethyl 3-(3-Ethoxy-3-oxo-1,2-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1-propen-1-yl)benzoate (5ae)



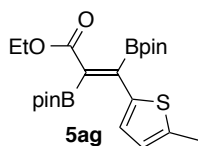
The product **5ae** was purified by flash chromatography on silica gel (3–20% EtOAc/hexane). White solid. M.p. 84–86 °C. **IR** (neat) 845, 902, 975, 1074, 1105, 1140, 1204, 1249, 1315, 1698, 1722, 2982 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.14 (s, 12H), 1.29–1.33 (m, 15H), 1.38 (t, J = 7.2 Hz, 3H), 4.28 (q, J = 7.2 Hz, 2H), 4.36 (q, J = 7.2 Hz, 2H), 7.39 (m, 1H), 7.64 (m, 1H), 7.98 (m, 1H), 8.13 (m, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.05, 14.29, 24.41, 24.85, 60.89, 61.61, 83.67, 83.89, 128.20, 128.84, 129.40, 130.41, 131.85, 140.21, 166.32, 170.70. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.1. **HRMS–EI** (m/z): $[\text{M}]^+$ calcd for $\text{C}_{26}\text{H}_{38}\text{B}_2\text{O}_8$, 500.27528; found, 500.27493. The stereochemistry was assigned by consideration of the reaction pathway.

(E)-Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5af)



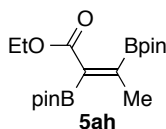
The product **5af** was purified by recrystallization with pentane. White solid. M.p. 106–108 °C. **IR** (neat) 830, 1140, 1247, 1321, 1370, 1458, 1510, 1603, 1693, 2777, 2822, 2929, 2978 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.18 (s, 12H), 1.28 (t, *J* = 7.2 Hz, 3H), 1.32 (s, 12H), 2.33 (s, 6H), 2.71 (t, *J* = 5.6 Hz, 2H), 4.06 (t, *J* = 5.6 Hz, 2H), 4.25 (q, *J* = 7.2 Hz, 2H), 6.84–6.86 (m, 2H), 7.39–7.41 (m, 2H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 14.08, 24.50, 24.96, 45.91, 58.23, 61.34, 65.94, 83.42, 83.70, 114.19, 129.18, 132.72, 159.22, 171.12. Two signals for the sp²-carbons directly attached to the boron atoms were not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 29.3. **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₇H₄₄B₂NO₇, 516.33079; found, 516.33038. The stereochemistry was determined by transforming it to **12af-a** (Scheme 1).

(*E*)-Ethyl 3-(5-Methylthiophen-2-yl)-2,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (5ag**)**



The product **5ag** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). Yellow solid. M.p. 161–162 °C. **IR** (neat) 800, 845, 968, 1045, 1137, 1215, 1239, 1318, 1457, 1577, 1694, 2928, 2978 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.26–1.32 (m, 15H), 1.31 (s, 12H), 2.47 (d, *J* = 1.2 Hz, 3H), 4.28 (q, *J* = 7.2 Hz, 2H), 6.67 (m, 1H), 7.22 (m, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 14.03, 15.65, 24.69, 25.44, 62.00, 83.23, 83.87, 126.04, 130.33, 140.35, 143.89, 172.98. Two signals for the sp²-carbons directly attached to the boron atoms were not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 26.8. **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₂₂H₃₄B₂O₆SNa, 471.21625; found, 471.21603. The stereochemistry was assigned by consideration of the reaction pathway.

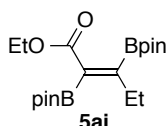
(*E*)-Ethyl 2,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-butenate (5ah**)**



The product **5ah** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). White solid. M.p. 142–143 °C. **IR** (neat) 668, 692, 782, 844, 860, 965, 1028, 1135, 1239, 1316, 1702, 2979 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.26–1.28 (m, 15H), 1.30 (s, 12H), 2.08 (s, 3H), 4.25 (q, *J*

= 7.2 Hz, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.02, 19.87, 24.62, 24.81, 61.85, 82.85, 83.43, 172.99. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 29.7. HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{18}\text{H}_{32}\text{B}_2\text{O}_6\text{Na}$, 389.22838; found, 389.22791. The stereochemistry was assigned by consideration of the reaction pathway.

(*E*)-Ethyl 2,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-pentenoate (5ai**)**



The product **5ai** was purified by flash chromatography on silica gel (5–20% EtOAc/hexane). White solid. M.p. 140–142 °C. IR (neat) 667, 754, 847, 858, 967, 1048, 1136, 1232, 1311, 1336, 1702, 2978 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 1.09 (t, J = 7.6 Hz, 3H), 1.25–1.32 (m, 27H), 2.39 (q, J = 7.6 Hz, 2H), 4.20 (q, J = 7.2 Hz, 2H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 13.41, 14.03, 24.57, 24.88, 28.01, 61.18, 83.15, 83.47, 171.53. Two signals for the sp^2 -carbons directly attached to the boron atoms were not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 29.4. HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{19}\text{H}_{34}\text{B}_2\text{O}_6$, 403.24407; found, 403.24376. The stereochemistry was assigned by consideration of the reaction pathway.

Procedure for Synthesis of Tetrasubstituted Alkenes (eqs 2–4)

Procedure for the Synthesis of Trisubstituted Alkenyl Bromide **7aa (eq 2).** To a suspension of $\text{Pd}(\text{OAc})_2$ (1.1 mg, 5.0 μmol) and DtBPF (2.8 mg, 6.0 μmol) in toluene (0.6 mL) was added K_3PO_4 (42.4 mg, 0.2 mmol), H_2O (12.6 μL), 1-bromo-4-fluorobenzene (26.3 mg, 0.15 mmol) and **3aa** (43.6 mg, 0.1 mmol) at room temperature. After being stirred at 60 °C for 16 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH_4Cl aq. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO_4 , filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (0–8% EtOAc/hexane) to give **6aa** (38.9 mg, 0.096 mmol) in 96% yield. The ratio of *E/Z* selectivity was determined by GC analysis.

To a solution of **6aa** (38.9 mg, 0.096 mmol) in DCM (0.5 mL) was added Br_2 (0.15 mL, 0.15 mmol, 1 M DCM solution) at –78 °C, and then the mixture was stirred –78 °C for 3 min. Next, EtONa (17.4 mg, 0.256 mmol) and EtOH (0.26 mL) were added at –78 °C. The reaction mixture was

allowed to warm slowly to rt, stirred for another 3 h, quenched with H₂O. The aqueous layer was extracted with Et₂O, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (0–3% EtOAc/hexane) to give **7aa** (27.2 mg, 0.078 mmol) in 81% yield.²⁴ The ratio of *E/Z* selectivity was determined by GC analysis.

Procedure for the synthesis of 8aa (eq 3). To a suspension of Pd(OAc)₂ (1.1 mg, 5.0 μmol) and DtBPF (2.8 mg, 6.0 μmol) in THF (0.2 mL) was added *i*-Pr₂NEt (69 μL, 0.4 mmol), H₂O (30.0 μL), 4-bromoanisole (14.0 μL, 0.11 mmol) and **5aa** (42.3 mg, 0.1 mmol) at room temperature. After being stirred at rt for 1.5 h, the reaction mixture was diluted with Et₂O. The mixture was filtrated through a short plug of silica gel with Et₂O as an eluent. The mixture was evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (3–15% EtOAc/hexane) to give **8aa** (33.8 mg, 0.083 mmol) in 83% yield. The ratio of *E/Z* selectivity was determined by GC analysis.

To a suspension of Pd(OAc)₂ (0.9 mg, 4.2 μmol) and DtBPF (2.3 mg, 5.0 μmol) in toluene (600 μL) was added K₃PO₄ (35.2 mg, 0.17 mmol), H₂O (10.5 μL), 4-bromotoluene (12.3 μL, 0.10 mmol) and **8aa** (33.8 mg, 0.083 mmol) at room temperature. After being stirred at 60 °C for 16 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH₄Cl aq. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (0–12% EtOAc/hexane) to give the corresponding coupling product **9aa** (24.4 mg, 0.066 mmol) in 79% yield. The ratio of *E/Z* selectivity was determined by GC analysis.

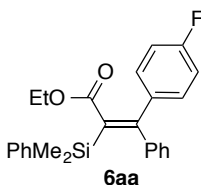
Procedure for synthesis of 11aa (eq 4). To solution of [Rh(OH)(cod)]₂ (1.1mg, 2.5 μmol), *tert*-butyl acrylate (58 μL, 0.4 mmol), 1,4-dioxane (1 mL) and H₂O (12.6 μL, 0.7 mmol) was added **5aa** (42.3 mg, 0.1 mmol). After being stirred at 60 °C for 16 h, the mixture was evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (3–15% EtOAc/hexane) to give **10aa** (22.4 mg, 0.052 mmol) in 52% yield. The ratio of *E/Z* selectivity was determined by GC analysis.

To a suspension of Pd(OAc)₂ (0.06 mg, 2.6 μmol) and DtBPF (1.5 mg, 3.1 μmol) in toluene (300 μL) were added K₃PO₄ (22.0 mg, 0.10 mmol), H₂O (6.6 μL, 0.36 mmol), 4-bromoanisole (9.7 μl,

0.078 mmol) and **10aa** (22.4 mg, 0.52 mmol) at room temperature. After being stirred at 60 °C for 16 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH₄Cl aq. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (0–15% EtOAc/hexane) to give **11aa** (12.7 mg, 0.031 mmol) in 59% yield.

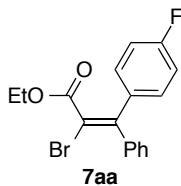
Characterization Data for Tetrasubstituted Alkenes

(*E*)-Ethyl 2-[Dimethyl(phenyl)silyl]-3-(4-fluorophenyl)-3-phenylacrylate (**6aa**)



The product **6aa** was purified by flash chromatography on silica gel (0–8% EtOAc/hexane). Colorless oil. **IR** (neat) 699, 779, 815, 835, 1041, 1112, 1157, 1217, 1505, 1602, 1709, 2978 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 0.12 (s, 6H), 1.02 (t, *J* = 6.8 Hz, 3H), 3.92 (q, *J* = 6.8 Hz, 2H), 6.89–6.94 (m, 2H), 6.99–7.01 (m, 2H), 7.11–7.19 (m, 2H), 7.19–7.28 (m, 3H), 7.28–7.36 (m, 3H), 7.44–7.46 (m, 2H). **¹³C NMR** (100.5 MHz, CDCl₃) δ -1.65, 13.96, 60.37, 114.74 (d, *J*_{C-F} = 21.1 Hz), 127.62, 127.83, 127.90, 128.92, 128.95, 130.01 (d, *J*_{C-F} = 7.6 Hz), 133.77, 136.55, 138.41 (d, *J*_{C-F} = 3.8 Hz), 138.61, 141.64, 155.89, 162.21 (d, *J*_{C-F} = 247.2 Hz), 171.73. **HRMS–EI** (*m/z*): [*M*]⁺ calcd for C₂₅H₂₅FO₂Si, 404.16078; found, 404. 16012. The stereochemistry was determined by NOESY experiments.

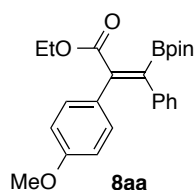
(*E*)-Ethyl 2-Bromo-3-(4-fluorophenyl)-3-phenylacrylate (**7aa**)



The product **7aa** was consistent with the the literature data.²⁴ Colorless oil. **¹H NMR** (400 MHz, CDCl₃) δ 1.04 (t, *J* = 7.2 Hz, 3H), 4.07 (q, *J* = 7.2 Hz, 2H), 6.97–7.01 (m, 2H), 7.14–7.18 (m, 2H),

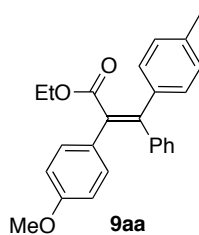
7.27–7.32 (m, 2H), 7.34–7.39 (m, 3H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 13.60, 62.13, 110.59, 115.31 (d, $J_{\text{C-F}} = 22.0$ Hz), 128.01, 128.69, 129.25, 130.48 (d, $J_{\text{C-F}} = 8.6$ Hz), 136.42 (d, $J_{\text{C-F}} = 2.9$ Hz), 140.30, 148.40, 162.75 (d, $J_{\text{C-F}} = 249.1$ Hz), 165.68.

(E)-Ethyl 2-(4-Methoxyphenyl)-3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (8aa)



The product **8aa** was purified by flash chromatography on silica gel (3–15% EtOAc/hexane). Yellow oil. IR (neat) 700, 753, 833, 1047, 1141, 1243, 1298, 1370, 1509, 1611, 1693, 2977 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 1.27 (t, $J = 7.2$ Hz, 3H), 1.34 (s, 12H), 3.75 (s, 3H), 4.33 (q, $J = 7.2$ Hz, 2H), 6.70–6.72 (m, 2H), 6.95–6.97 (m, 2H), 7.10–7.14 (m, 5H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 14.11, 25.02, 55.01, 62.85, 83.26, 113.17, 126.80, 127.22, 127.79, 128.69, 131.57, 136.53, 138.32, 158.60, 171.92. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 27.1. HRMS–ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{24}\text{H}_{29}\text{O}_5\text{BNa}$, 431.20046; found, 431.20038. The stereochemistry was determined by NOESY experiments.

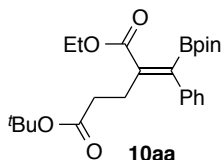
(Z)-Ethyl 2-(4-Methoxyphenyl)-3-phenyl-3-(p-tolyl)acrylate (9aa)



The product **9aa** was purified by flash chromatography on silica gel (0–8% EtOAc/hexane). White solid. M.p. 141–143 $^{\circ}\text{C}$. IR (neat) 757, 818, 833, 1024, 1039, 1151, 1178, 1220, 1249, 1269, 1511, 1604, 1717 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 1.00 (t, $J = 7.2$ Hz, 3H), 2.35 (s, 3H), 3.75 (s, 3H), 4.04 (q, $J = 7.2$ Hz, 2H), 6.69–6.71 (m, 2H), 7.00–7.03 (m, 4H), 7.09–7.16 (m, 7H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 13.73, 21.25, 55.09, 60.81, 113.56, 127.36, 127.79, 128.75, 129.05, 129.99, 130.92, 131.07, 132.83, 137.73, 139.74, 141.00, 144.86, 158.62, 170.92. HRMS–EI (m/z): $[\text{M}]^+$ calcd for

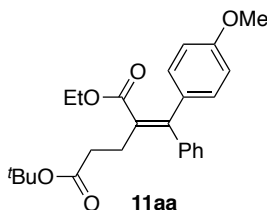
$C_{25}H_{24}O_3$, 372.17254; found, 372.17172. The regio- and stereochemistries were determined by transforming it to the known allylic alcohol derivative with DIBAL-H reduction.⁷ Allylic alcohol: White solid. M.p. 147–149 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 2.37 (s, 3H), 3.75 (s, 3H), 4.47 (d, J = 2.8 Hz, 2H), 6.72–6.74 (m, 2H), 6.91–6.94 (m, 2H), 7.03–7.08 (m, 3H), 7.11–7.14 (m, 2H), 7.15–7.18 (m, 2H), 7.18–7.22 (m, 2H). ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 21.21, 55.12, 65.04, 113.69, 126.26, 127.56, 128.94, 129.56, 130.67, 131.04, 132.35, 136.92, 137.64, 139.50, 142.12, 142.65, 158.36.

(*E*)-5-*tert*-Butyl 1-Ethyl-2-[phenyl(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)methylene]pentanedioate (10aa)



The product **10aa** was purified by flash chromatography on silica gel (5–15% EtOAc/hexane). Yellow oil. IR (neat) 703, 761, 854, 972, 1024, 1140, 1268, 1294, 1339, 1368, 1702, 1729, 2977 cm^{-1} . ^1H NMR (400 MHz, $CDCl_3$) δ 1.27 (s, 12H), 1.34 (t, J = 7.2 Hz, 3H), 1.39 (s, 9H), 2.30–2.35 (m, 2H), 2.53–2.57 (m, 2H), 4.34 (q, J = 7.2 Hz, 2H), 7.23–7.28 (m, 3H), 7.34–7.37 (m, 2H). ^{13}C NMR (100.5 MHz, $CDCl_3$) δ 14.19, 22.90, 24.76, 28.02, 35.01, 62.14, 80.24, 83.35, 127.32, 127.35, 128.27, 135.63, 138.42, 170.92, 172.06. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, $CDCl_3$) δ 27.0. HRMS–ESI (m/z): $[M+Na]^+$ calcd for $C_{24}H_{35}O_6BNa$, 453.24233; found, 453.24195. The stereochemistry was determined by NOESY experiments.

(*Z*)-5-*tert*-Butyl 1-Ethyl 2-[(4-methoxyphenyl)(phenyl)methylene]pentanedioate (11aa)



The product **11aa** was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). White solid. M.p. 56–58 °C. **IR** (neat) 701, 767, 840, 1103, 1147, 1243, 1368, 1509, 1605, 1710, 1727, 2976 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 0.97 (t, J = 7.2 Hz, 3H), 1.42 (s, 9H), 2.38–2.42 (m, 2H), 2.62–2.66 (m, 2H), 3.78 (s, 3H), 3.99 (q, J = 7.2 Hz, 2H), 6.77–6.79 (m, 2H), 7.03–7.05 (m, 2H), 7.15–7.17 (m, 2H), 7.29–7.37 (m, 3H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 13.76, 27.59, 28.04, 34.56, 55.19, 60.51, 80.31, 113.27, 127.69, 128.26, 129.01, 129.91, 130.79, 134.70, 140.77, 146.57, 159.09, 170.63, 171.79. **HRMS–ESI** (m/z): [M+Na]⁺ calcd for C₂₅H₃₀O₅Na, 433.19855; found, 433.19806. The regio- and stereochemistries were determined by NOESY experiments.

Procedure for Synthesis of Tamoxifen-type compounds (Scheme 1)

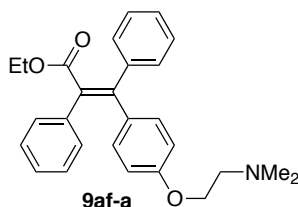
The synthesis of **12af-a** is representative. To a suspension of Pd(OAc)₂ (1.1 mg, 5 μ mol) and DtBPF (2.8 mg, 6 μ mol) in THF (0.2 mL) was added *i*-Pr₂NEt (52 μ L, 0.3 mmol), H₂O (30.0 μ L), bromobenzene (11.5 μ L, 0.11 mmol) and **5af** (51.0 mg, 0.10 mmol) at room temperature. After being stirred at rt for 1.5 h, the reaction mixture was evaporated under reduced pressure. The residue was diluted with Et₂O and filtered with a Celite[®] pad. The filtrate was evaporated under reduced pressure to give the corresponding monophenylated compound.

To a suspension of Pd(OAc)₂ (1.1 mg, 5 μ mol) and DtBPF (2.8 mg, 6 μ mol) in toluene (0.6 mL) was added K₃PO₄ (42.4 mg, 0.2 mmol), H₂O (12.6 μ L, 0.7 mmol), bromobenzene (12.5 μ L, 0.12 mmol) and the monophenylated compound at room temperature. After being stirred at rt for 4 h and at 60 °C for 8 h, the reaction mixture was filtered with a Celite[®] pad. The filtrate was evacuated under reduced pressure. The residue was purified by flash column chromatography on silica gel (Et₃N/acetone/hexane 1:1:10–1:2:10) to give **9af-a** (30.2 mg, 0.073 mmol) in 73% yield.

To a solution of the diarylated compound **9af-a** (30.2 mg, 0.073 mmol) in DCM (730 μ l) was added DIBAL-H (219 μ l, 0.219 mmol, 1.00 M toluene solution) at –78 °C. After being stirred at –78 °C for 2 h, 1M HCl aq. was added. The mixture was extracted with DCM. The combined organic layers were dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (Et₃N/acetone/hexane 1:1:10–1:3:10) to give **12af-a** (24.3 mg, 0.065 mmol) in 89% yield.

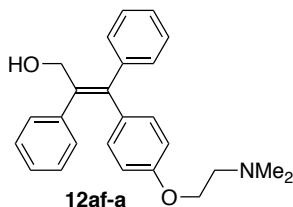
Characterization Data for Tamoxifen-type compounds

(E)-Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}-2,3-diphenylacrylate (9af-a)



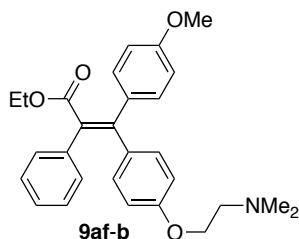
The product **9af-a** was purified by flash chromatography on silica gel (1/1/10–1/2/10 Et₃N/acetone/hexane). White solid. M.p. 106–107 °C. **IR** (neat) 700, 814, 1021, 1151, 1221, 1248, 1510, 1603, 1712, 2770, 2821, 2940, 2977, 3048 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 0.93 (t, *J* = 7.2 Hz, 3H), 2.30 (s, 6H), 2.67 (t, *J* = 5.6 Hz, 2H), 3.98 (t, *J* = 5.6 Hz, 2H), 3.99 (q, *J* = 7.2 Hz, 2H), 6.65–6.67 (m, 2H), 6.88–6.98 (m, 2H), 7.11–7.23 (m, 5H), 7.25–7.33 (m, 5H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 13.62, 45.90, 58.23, 60.76, 65.79, 113.73, 127.15, 127.93, 128.00, 128.18, 129.18, 129.87, 132.32, 132.64, 132.84, 137.91, 142.80, 145.92, 158.34, 170.68. **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₇H₃₀O₃N, 416.22202; found, 416.22166.

(E)-3-{4-[2-(Dimethylamino)ethoxy]phenyl}-2,3-diphenyl-2-propen-1-ol (12af-a)



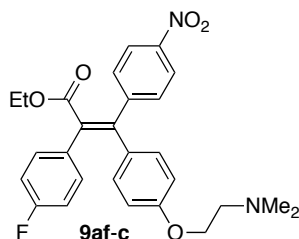
The product **12af-a** was consistent with the the literature data.²⁰¹ White solid. M.p. 117–119 °C. **¹H NMR** (400 MHz, CDCl₃) δ 2.29 (s, 6H), 2.65 (t, *J* = 5.6 Hz, 2H), 3.93 (t, *J* = 5.6 Hz, 2H), 4.45 (s, 2H), 6.57–6.61 (m, 2H), 6.78–6.83 (m, 2H), 7.16 (m, 1H), 7.20–7.23 (m, 4H), 7.27–7.38 (m, 5H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 45.83, 58.19, 65.11, 65.64, 113.51, 126.68, 127.21, 128.18, 128.28, 129.68, 129.88, 131.85, 134.58, 137.56, 140.57, 142.30, 142.46.34, 157.33.

(E)-Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}-3-(4-methoxyphenyl)-2-phenylacrylate (9af-b)



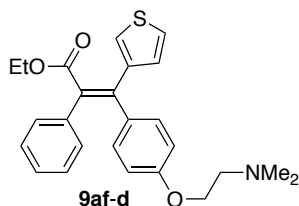
The product **9af-b** was purified by flash chromatography on silica gel (1:1:10–1:2.5:10 Et₃N/acetone/hexane). Yellow solid. M.p. 101–103 °C. **IR** (neat) 886, 1036, 1174, 1218, 1241, 1457, 1509, 1604, 1715, 2770, 2818, 2846, 2935 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.01 (t, *J* = 7.2 Hz, 3H), 2.31 (s, 6H), 2.68 (t, *J* = 5.6 Hz, 2H), 3.82 (s, 3H), 3.98 (t, *J* = 5.6 Hz, 2H), 4.04 (q, *J* = 7.2 Hz, 2H), 6.65–6.67 (m, 2H), 6.83–6.87 (m, 2H), 6.87–6.92 (m, 2H), 7.08–7.11 (m, 2H), 7.11–7.22 (m, 5H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 13.82, 45.90, 55.22, 58.24, 60.74, 65.79, 113.44, 113.69, 126.98, 128.15, 129.88, 130.58, 131.81, 132.44, 133.12, 135.22, 138.17, 145.61, 158.33, 159.51, 170.99. **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₈H₃₂O₄N, 446.23258; found, 446.23232.

(E)-Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}-2-(4-fluorophenyl)-3-(4-nitrophenyl)acrylate (9af-c)



The product **9af-c** was purified by flash chromatography on silica gel (1:1:10–1:2.5:10 Et₃N/acetone/hexane). Brown solid. M.p. 148–150 °C. **IR** (neat) 837, 1032, 1150, 1223, 1256, 1347, 1506, 1514, 1594, 1712, 2770, 2821, 2946 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.00 (t, *J* = 7.2 Hz, 3H), 2.32 (s, 6H), 2.69 (t, *J* = 5.6 Hz, 2H), 4.00 (t, *J* = 5.6 Hz, 2H), 4.02 (q, *J* = 7.2 Hz, 2H), 6.69–6.71 (m, 2H), 6.81–6.85 (m, 2H), 6.85–6.94 (m, 2H), 7.06–7.13 (m, 2H), 7.40–7.46 (m, 2H), 8.18–8.21 (m, 2H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 13.70, 45.91, 58.18, 61.26, 65.92, 114.24, 115.47 (d, *J*_{C-F} = 22.0 Hz), 123.39, 130.00, 131.45, 131.65 (d, *J*_{C-F} = 7.6.0 Hz), 132.10, 133.09 (d, *J*_{C-F} = 3.8 Hz), 133.45, 144.25, 147.33, 149.39, 158.85, 162.04 (d, *J*_{C-F} = 246.9 Hz), 169.56. **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₇H₂₈O₅N₂F, 479.19768; found, 479.19702.

(Z)-Ethyl 3-{4-[2-(Dimethylamino)ethoxy]phenyl}-2-phenyl-3-(thiophen-3-yl)acrylate (9af-d)



The product **9af-d** was purified by flash chromatography on silica gel (1:0.5:10–1:2.5:10 Et₃N/acetone/hexane). White solid. M.p. 95–97 °C. **IR** (neat) 713, 859, 1026, 1180, 1222, 1249, 1302, 1462, 1509, 1605, 1712, 2770, 2821, 2951 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.08 (t, *J* = 7.2 Hz, 3H), 2.32 (s, 6H), 2.69 (t, *J* = 6.0 Hz, 2H), 3.99 (t, *J* = 6.0 Hz, 2H), 4.11 (q, *J* = 7.2 Hz, 2H), 6.66–6.69 (m, 2H), 6.91–6.95 (m, 3H), 7.09–7.13 (m, 2H), 7.15–7.22 (m, 3H), 7.24–7.28 (m, 2H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 13.85, 45.55, 57.95, 61.02, 65.31, 113.75, 124.93, 125.06, 127.22, 128.21, 128.60, 129.69, 132.08, 132.35, 132.43, 137.31, 139.19, 142.92, 158.12, 170.88. **HRMS-ESI** (*m/z*): [M+H]⁺ calcd for C₂₅H₂₈NO₃S, 422.17844; found, 422.17831.

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Chapter 5

Synthesis of 1,1-Diborylalkenes through a Brønsted-base-catalyzed Reaction between Terminal Alkynes and Bis(pinacolato)diboron

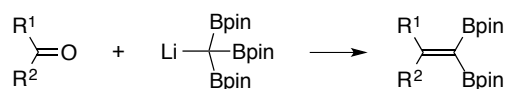
A new method for the synthesis of 1,1-diborylalkenes through a Brønsted-base-catalyzed reaction between terminal alkynes and bis(pinacolato)diboron has been developed. The protocol allows direct synthesis of functionalized 1,1-diborylalkenes from various terminal alkynes including propiolates, propiolamides and 2-ethynylazoles.

Introduction

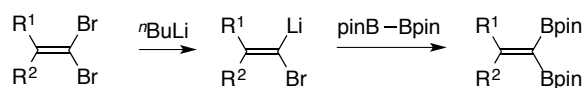
1,1-Diborylalkenes have gained increasing attention as versatile intermediates in organic synthesis due to their applicability toward various transformations. For example, the two geminal boron substituents can be differentiated and transformed in a stepwise manner, allowing the synthesis of a diverse array of multisubstituted alkenes.¹ Several synthetic methods for accessing 1,1-diborylalkenes have been developed.¹⁻⁴ Specifically, more than 40 years ago, Matteson reported the synthesis of 1,1-diborylalkenes through an addition reaction of triborylmethyl lithium to carbonyl compounds (Scheme 1a).² Recently, Shimizu, Hiyama and co-workers reported a reaction between bis(pinacolato)diboron and 1-bromo-1-lithioalkenes, which were prepared from 1,1-dibromoalkenes *via* Br–Li exchange (Scheme 1b).¹ Marder and Iwasawa reported the use of rhodium and palladium catalyst systems for dehydrogenative geminal diboration of terminal alkenes (Scheme 1c).³

Scheme 1. Synthesis of 1,1-diborylalkenes

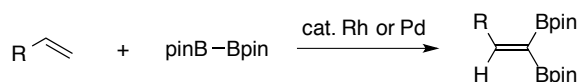
a) Addition of triborylmethyl lithium to carbonyl compounds



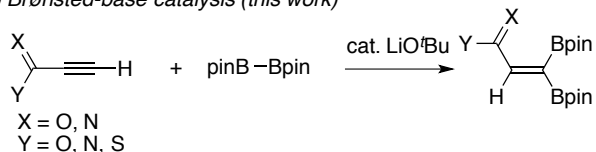
b) Reaction between 1-bromo-1-lithioalkenes and diboron



c) Dehydrogenative geminal diboration of alkenes



d) Brønsted-base catalysis (this work)



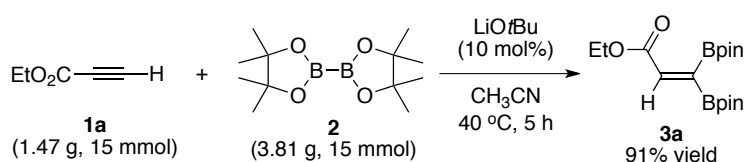
In Chapter 5, the author describes a new and efficient approach to the synthesis of 1,1-diborylalkenes through a Brønsted-base catalyzed reaction between terminal alkynes and bis(pinacolato)diboron (Scheme 1d).⁵⁻⁷ The protocol allows direct synthesis of functionalized 1,1-diborylalkenes from various terminal alkynes including propiolates, propiolamides and

2-ethynylazoles. The mild and transition-metal-free reaction conditions are attractive features of this method.

Results and Discussion

The reaction between ethyl propiolate (**1a**) (1.47 g, 15 mmol) and bis(pinacolato)diboron (**2**) (3.81 g, 15 mmol) in the presence of LiOtBu (10 mol%) in CH₃CN (30 mL) at 40 °C over 5 h gave β,β-diborylacrylate **3a** (4.81 g, 13.7 mmol) in 91% yield (based on **1a**; 99% NMR yield; complete conversion of **1a**) (Scheme 2). The boron atoms of **3a** showed no interaction with the carbonyl oxygen, as indicated by ¹¹B NMR spectroscopy.

Scheme 2. Brønsted-base catalyzed reaction between **1a** and **2**



Screening of base catalysts for the reaction between **1a** and **2** identified LiOtBu as the most effective (Table 1, entry 1). NaOtBu, KOtBu and LHMDS were also effective, but gave slightly lower product yields (74–79% yields, entries 2–4), while weaker bases such as LiOMe, DABCO, DMAP and PBu₃ were much less effective (15–33% yields, entries 5–8). No reaction occurred in the absence of base (entry 9). Aprotic solvents such as hexane, toluene, THF and dichloromethane could also be used, but gave slightly lower yields (89%, 71%, 74%, and 78%). Significant reductions in yield were observed for the reactions with protic solvents such as *t*BuOH (54%).

Table 1. Catalyst effects in reaction between **1a** and **2**^a

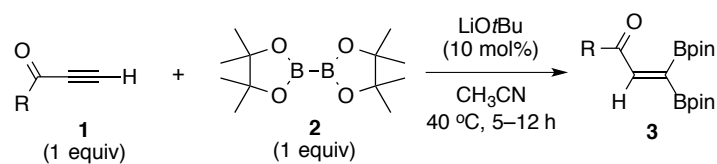
entry	catalyst	yield (%) ^b
1	LiOtBu	91
2	NaOtBu	79
3	KOtBu	78
4	LHMDS	74
5	LiOMe	3
6	DABCO	17
7	DMAP	15
8	PBu ₃	33
9	none	0

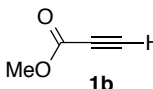
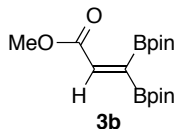
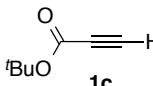
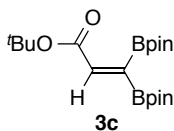
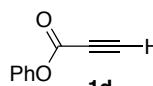
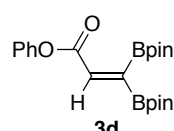
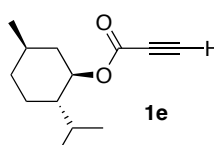
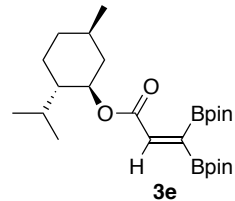
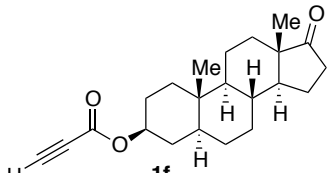
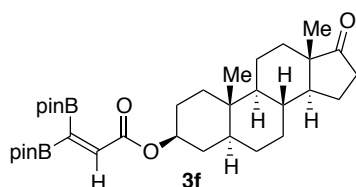
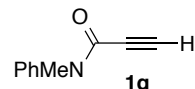
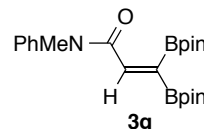
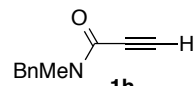
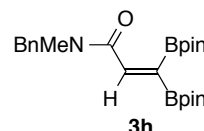
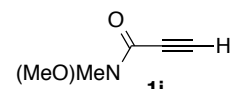
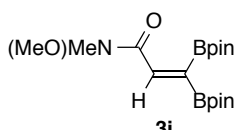
^aConditions: **1**, 0.2 mmol; **2a**, 0.2 mmol; catalyst, 10 mol%; CH₃CN, 40 °C, 5 h. ^bYield of isolated product.

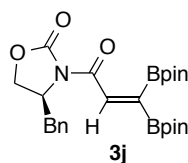
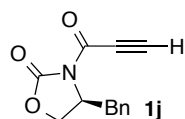
The optimal protocol was applicable to various alkynoates (Table 2, entries 1–5). The ethoxy carbonyl group of **1a** could be replaced with a methoxy carbonyl group with only a slight reduction in the product yield (entry 1). More sterically demanding alkoxy carbonyl substituents such as *t*-butoxy-, phenoxy- or menthoxy groups were tolerated (entries 2–4). The steroidal alkynoate **1f**, which was prepared from *trans*-androsterone, was also found to be a suitable substrate (entry 5).

The reaction of propiolamides **1g–j** furnished the corresponding 1,1-diborylalkenes (Table 2, entries 6–9). For example, *N*-phenyl-*N*-methanamide, *N*-benzyl-*N*-methyl- or Weinreb amide derivatives reacted with **2** efficiently (entries 6–8). The imide **1j**, prepared from chiral oxazolidinone, also participated in the reaction (entry 9). However, propiolaldehyde showed no reactivity under similar conditions.

Table 2. Reaction Scope: Terminal Alkynes^a



entry	alkyne	product	yield (%) ^b
1	 1b	 3b	83
2	 1c	 3c	81
3	 1d	 3d	88
4	 1e	 3e	89
5	 1f	 3f	84
6	 1g	 3g	75 ^c
7	 1h	 3h	63
8	 1i	 3i	63

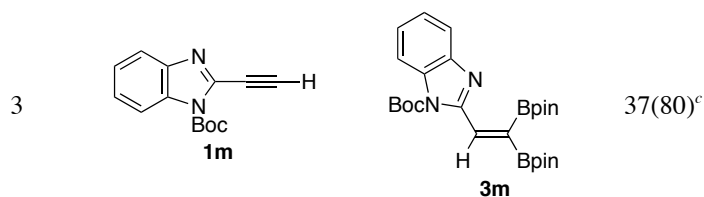


^aConditions: **2**, 0.2 mmol; **1**, 0.2 mmol; LiOtBu, 10 mol%; CH₃CN, 40 °C, 5 h (entries 1–4) or 12 h (entries 5–9). ^bYield of isolated product. ¹H NMR yield is in parentheses. ^cThe reaction was carried out on a 5.0 mmol scale.

2-Ethynylazoles were also suitable substrates (Table 3).⁸ For example, the reaction of 2-ethynylbenzoxazole derivatives, with an increased catalyst loading (20 mol% LiOtBu), proceeded efficiently and cleanly, giving the corresponding 1,1-diborylalkenes (entry 1). Benzothiazole and benzimidazole were also tolerated as azole groups (entries 2 and 3), but the use of phenylacetylene or 2-ethynylpyridine resulted in no reaction.

Table 3. Reaction scope: 2-Ethynylazoles^a

entry	alkyne	product	yield (%) ^b
1	1k	3k	88
2	1l	3l	78

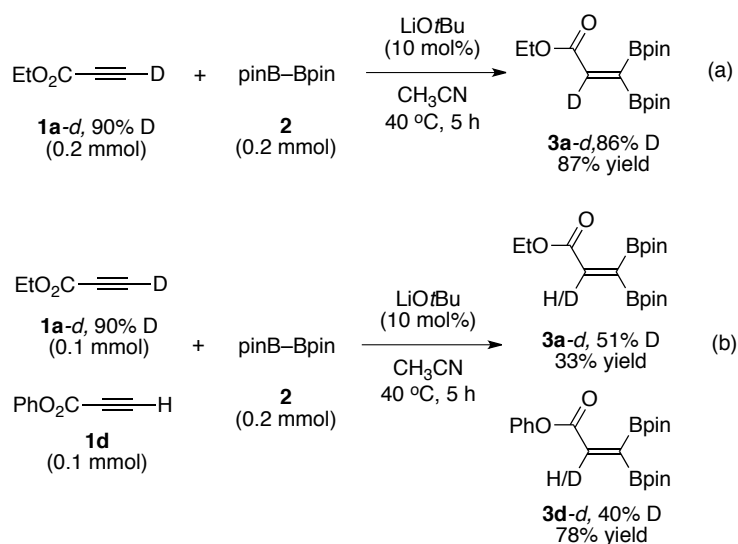


^aConditions: **1**, 0.2 mmol; **2**, 0.2 mmol; LiOtBu, 20 mol%; CH₃CN, 40 °C, 5 h. ^bYield of isolated product. ¹H NMR yield is in parentheses. ^cA loss of material occurred during purification because **3m** was unstable. As a result, the isolated yield was significantly reduced as compared with the ¹H NMR yield.

To gain insight into the mechanism of the LiOtBu-catalyzed reaction between terminal alkynes and the diboron, a deuterium labeling experiment was conducted (Scheme 3a). The reaction with C3-deuterated ethyl propiolate **1a-d** (90% D) instead of **1a** under optimum conditions afforded the C2-deuterated product **3a-d** with 86% deuterium incorporation. This result indicated that the H atom in **3** stemmed from the terminal C(sp)–H bond of the alkyne substrate **1**.

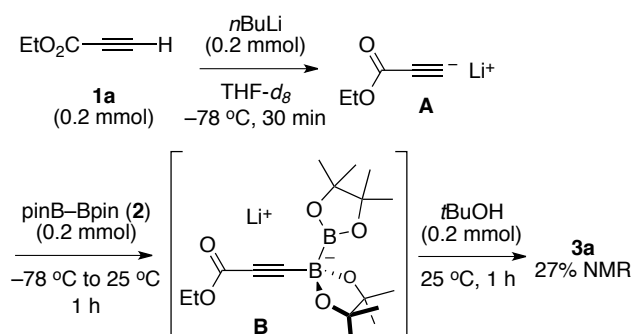
A deuterium-labeled crossover experiment between **1a-d** (90% D) and **1d** resulted in nearly complete H/D scrambling in both products (**3a-d** and **3d-d**) (Scheme 3b). Based on this observation, intramolecular 1,2-H-migration should be ruled out.

Scheme 3. Deuterium labeling experiments



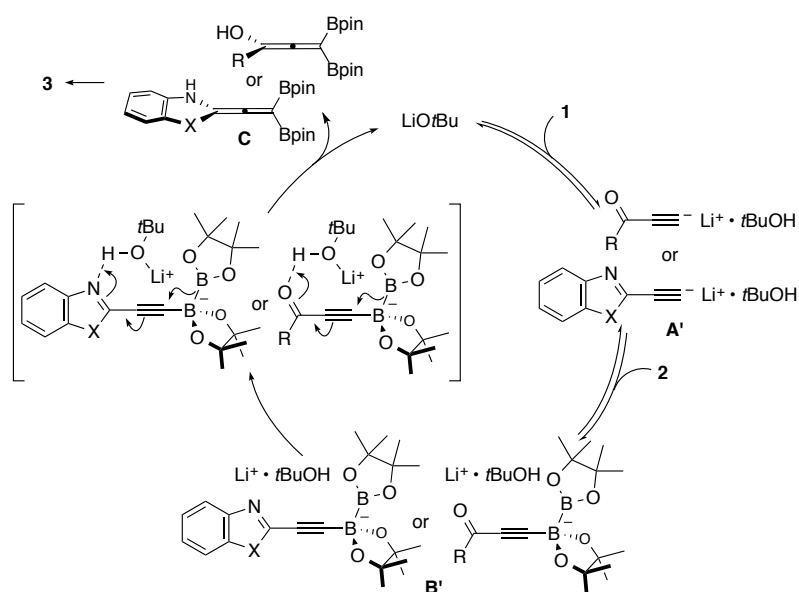
The screening of base catalysts discussed above found LHMDs to be effective regardless of its extreme steric demand (see Table 1, entry 4). Based on this observation, a mechanism involving conjugate addition of the base catalyst to the terminal alkyne, as in the cases of phosphine-catalyzed 1,2-carboboration and 1,2-diboration of alkynoates (Chapters 3 and 4), was ruled out.^{6b,c} Instead, a Brønsted-base mechanism involving acetylide formation is conceivable. To test this possibility, the stoichiometric reaction using *n*BuLi instead of the catalytic LiOtBu base was conducted (Scheme 4). Thus, a lithium acetylide (**A**) was first prepared and was reacted with the diboron **2**. We assumed the formation of an alkynyl borate species (**B**), while signal assignment in the NMR spectroscopy was unsuccessful due to the complexity of spectra. Subsequent addition of one equiv of *t*BuOH and standing the mixture at 25 °C for 1 h gave **3a** in 27% NMR yield.⁹

Scheme 4. Stoichiometric Reaction



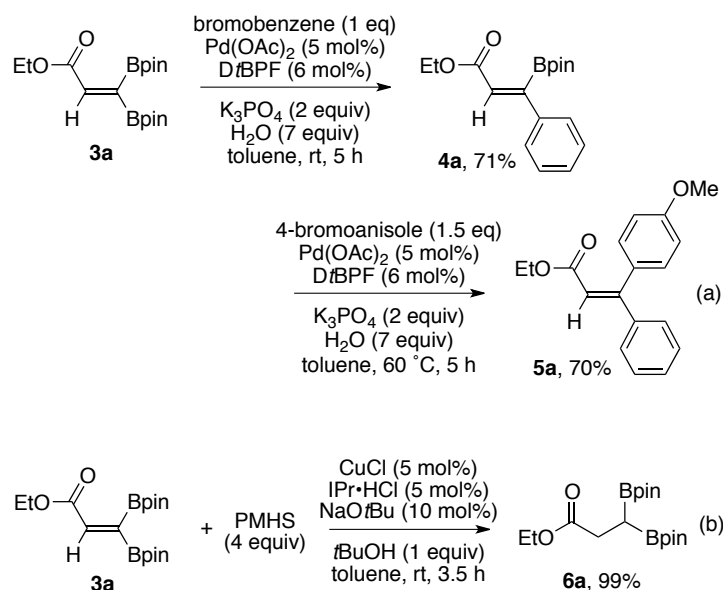
Taking into account the results of the deuterium labeling experiments and the stoichiometric reaction with *n*BuLi, a mechanism described in Figure 1 is proposed. A catalytic cycle is initiated by deprotonation of the terminal alkyne of **1** with LiOtBu to form a lithium acetylide (**A'**) coordinated with *t*BuOH in an equilibrium. Then, **A'** reacts with diboron **2** to form an alkynyl borate intermediate (**B'**). Migration of the terminal boryl group in **B'** to the *sp*-hybridized carbon atom of the alkyne moiety associated with protonation of the carbonyl oxygen atom or azole nitrogen atom of **1** with the Li⁺-coordinated *t*BuOH gave an allenol or allenamine intermediate (**C**), which immediately isomerized to **3**. This B-migration-protonation reaction regenerates LiOtBu.

Figure 1. Possible catalytic cycle.



It was found that the two geminally-installed boron substituents of the 1,1-diborylalkenes could be differentiated and transformed in a stepwise manner (Scheme 5a). For example, Suzuki–Miyaura coupling between β,β -diborylacrylate **3a** and bromobenzene under the influence of a $\text{Pd}(\text{OAc})_2$ –DtBPF (1,1'-bis(di-*tert*-butylphosphino)ferrocene) catalyst and K_3PO_4 as a base occurred selectively at the boron site *trans* to the ester group to give alkenylboronate **4a** (71%, *E/Z* > 99:1) with the formation of a small amount of diphenylated product (10%). This stereoselectivity is probably due to the steric effect of the ester group (Note that no interaction exists between the B atoms and the ester O atom in **3a**: *vide supra*). The second cross-coupling of **4a** with 4-bromoanisole produced isomerically pure trisubstituted alkene **5a** in good yield (*Z/E* > 99:1). Copper-catalyzed conjugate reduction of **3a** with poly(methylhydrosiloxane) (PMHS) afforded a functionalized geminal diborylalkane (**6a**) in quantitative yield with the two C–B bonds remaining untouched (Scheme 5b).¹⁰

Scheme 5. Derivatization of **3a**



Conclusion

In summary, the author has developed a new method for the synthesis of 1,1-diborylalkenes through a Brønsted-base-catalyzed reaction between terminal alkynes and bis(pinacolato)diboron. The protocol allows direct synthesis of functionalized 1,1-diborylalkenes from various terminal alkynes including propiolates, propiolamides and 2-ethynylazoles. The functionalized β,β -diborylacrylates and β,β -diborylacrylamides reported here are difficult to obtain by other methods (Schemes 1a–c).^{1–4} Importantly, the two geminally installed boron substituents of the 1,1-diborylalkenes were differentiated and transformed in a stepwise manner, showing the potential of the new 1,1-diborylalkenes as versatile intermediates in organic synthesis.

Experimental Procedure

Instrumentation and Chemicals

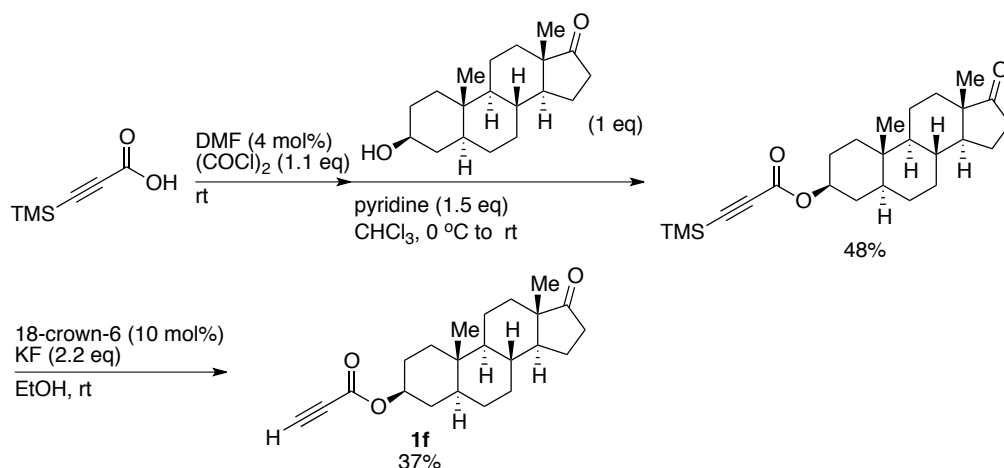
NMR spectra were recorded on a JEOL ECX-400, operating at 400 MHz for ^1H NMR, 100.5 MHz for ^{13}C NMR and 128 MHz for ^{11}B NMR. Chemical shift values for ^1H and ^{13}C are referenced to Me_4Si , the residual solvent resonances and $\text{BF}_3\cdot\text{OEt}_2$, respectively. Chemical shifts are reported in δ ppm. Natural quartz NMR sample tubes from NORELL[®] were used for ^{11}B NMR spectroscopy. Mass spectra were obtained with Thermo Fisher Scientific Exactive, JEOL JMS-T100LP or JEOL JMS-700TZ at the Instrumental Analysis Division, Equipment Management Center, Creative Research Institution, Hokkaido University. Optical rotations were measured on a JASCO P-2200. TLC analyses were performed on commercial glass plates bearing 0.25-mm layer of Merck Silica gel 60F₂₅₄. Silica gel (Kanto Chemical Co., Silica gel 60 N, spherical, neutral) was used for column chromatography. IR spectra of neat samples were measured with a Perkin-Elmer Frontier FT-IR equipped with a universal diamond ATR sampling accessory. Melting points were measured on a Yanaco MP-500D apparatus. Melting points were measured on a Yanaco MP-500D apparatus.

All reactions were carried out under nitrogen or argon atmosphere. Materials were obtained from commercial suppliers or prepared according to standard procedures unless otherwise noted. Acetonitrile and toluene were purchased from Kanto Chemical Co., stored under argon. LiOtBu , was purchased from Aldrich Chemical Co., stored under nitrogen, and used as it is. Bis(pinacolato)diboron (**2**) was purchased from AllyChem Co., Ltd., and recrystallized from pentane before use, stored under nitrogen, and used as it is. Propiolates **1a–c** were purchased from Tokyo Kasei Kogyo Co., Ltd., stored under nitrogen, and used as it is. Alkynes **1d**^{11,12}, **1e**^{11,13}, **1g**¹⁴, **1i**¹⁵, **1j**¹⁶ and **1l**¹⁷ are known compounds. **1a–d** was prepared according to reported procedures¹⁸.

Preparation of Terminal Alkynes

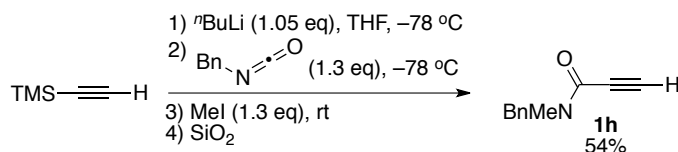
Preparation of 1f (Scheme 6). Substrate **1f** was prepared in 2 steps from 3-(trimethylsilyl)propionic acid according to the scheme shown below.

Scheme 6



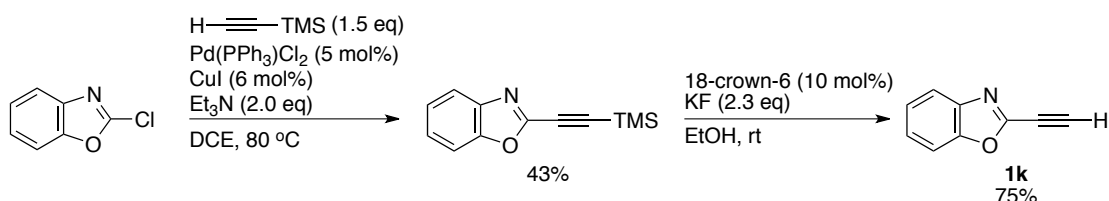
Preparation of 1h (Scheme 7). Substrate **1h** was prepared through the addition of trimethylsilylacetylene to benzyl isocyanate, followed by methyl trapping according to reported procedures¹⁹. The deprotection of TMS group occurred by treatment with silica gel.

Scheme 7.



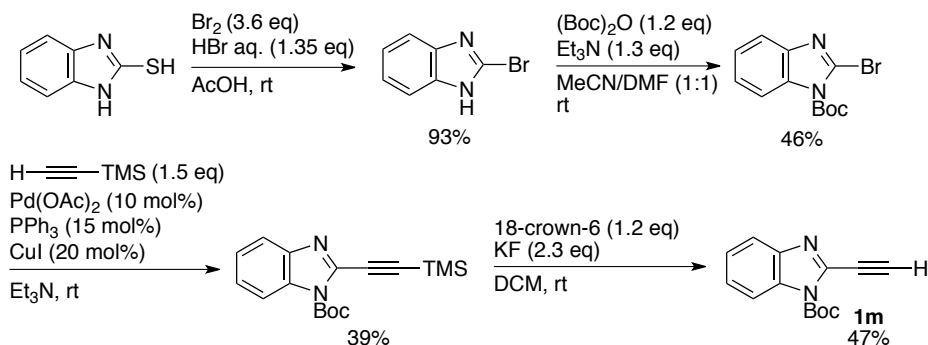
Preparation of 1k (Scheme 8). Substrate **1k** was prepared in 2 steps from 2-chlorobenzoxazole according to reported procedures¹⁷. 2-Chlorobenzoxazole was coupled with trimethylsilylacetylene through the Sonogashira coupling. Deprotection of the obtained alkyne afforded **1k**.

Scheme 8.



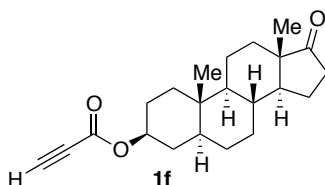
Preparation of 1m (Scheme 9). Substrate **1m** was prepared in four steps from 2-mercaptobenzimidazole according to reported procedures²⁰. Bromination, protection, Sonogashira coupling and deprotection of 2-mercaptobenzimidazole afforded **1m**.

Scheme 9.



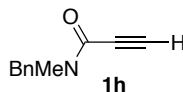
Characterization Data for Terminal Alkynes

Epiandrosterone Propiolate (**1f**)



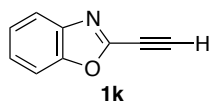
White solid. M.p. 187–189 °C. **IR** (neat) 1227, 1366, 1453, 1706, 1732, 2108, 2862, 2919, 2955 cm^{-1} . **¹H NMR** (400 MHz, CDCl_3) δ 0.71 (m, 1H), 0.86 (s, 6H), 0.93–1.08 (m, 2H), 1.16–1.37 (m, 6H), 1.42–1.58 (m, 3H), 1.60–1.72 (m, 3H), 1.75–1.83 (m, 3H), 1.85–1.97 (m, 2H), 2.07 (dt, $J = 19.2, 8.8$ Hz, 1H), 2.44 (dd, $J = 19.2, 4.0$ Hz, 1H), 2.87 (s, 1H), 4.82 (tt, $J = 11.6, 4.8$ Hz, 1H). **¹³C NMR** (100.5 MHz, CDCl_3) δ 12.2, 13.8, 20.4, 21.7, 27.1, 28.2, 30.7, 31.4, 33.5, 35.0, 35.6, 35.8, 36.6, 44.6, 47.7, 51.3, 54.2, 74.2, 75.0, 76.0, 152.2, 221.2. **HRMS-ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{30}\text{O}_3\text{Na}$, 365.20872; found, 365.20869. $[\alpha]_D^{24} +22.2$ (c 0.73, CHCl_3).

N-Benzyl-N-methylpropiolamide (**1h**)



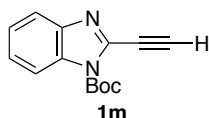
Yellow oil. Signal for the rotamers were given. **IR** (neat) 1238, 1398, 1426, 1495, 1621, 2099, 2927, 3032, 3187 cm^{-1} . **¹H NMR** (400 MHz, CDCl_3) δ 2.88 and 3.13 (rotamer) (s, 3H), 3.14 and 3.17 (rotamer) (s, 1H), 4.62 and 4.80 (rotamer) (s, 2H), 7.24–7.27 (m, 2H), 7.29–7.40 (m, 3H). **¹³C NMR** (100.5 MHz, CDCl_3) δ 31.7, 35.7, 49.7, 54.7, 75.7, 75.7, 79.0, 79.4, 127.3, 127.7, 128.0, 128.1, 128.7, 128.8, 135.7, 135.8, 153.4, 153.5. **HRMS-ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{11}\text{H}_{11}\text{ONNa}$, 196.07329; found, 196.07355.

2-Ethynylbenzo[d]oxazole (1k)



Red oil. **IR** (neat) 1162, 1237, 1447, 1532, 1602, 1785, 2123, 3062, 3191, 3279 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 3.39 (s, 1H), 7.38–7.45 (m, 2H), 7.53 (m, 1H), 7.76 (m, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 71.7, 81.7, 110.7, 120.7, 125.2, 126.7, 140.4, 146.3, 150.1. **HRMS–ESI** (m/z): $[\text{M}+\text{H}]^+$ calcd for $\text{C}_9\text{H}_6\text{ON}$, 144.04439; found, 144.04475.

tert-Butyl 2-Ethynyl-1*H*-benzo[d]imidazole-1-carboxylate (2j)



Purple solid. M.p. 107–109 °C. **IR** (neat) 1120, 1151, 1225, 1331, 1447, 1494, 1758, 2111, 2985, 3166 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.73 (s, 9H), 3.52 (s, 1H), 7.36–7.45 (m, 2H), 7.75 (m, 1H), 7.98 (m, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 28.0, 74.5, 83.5, 86.5, 114.9, 120.5, 124.9, 126.3, 131.9, 134.7, 142.4, 147.6. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{14}\text{H}_{14}\text{O}_2\text{N}_2\text{Na}$, 265.09475; found, 265.09499.

Procedures for Brønsted-Base-Catalyzed Reaction

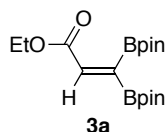
A Gram Scale Reaction of 1a. The reaction in Scheme 2 is representative. Bis(pinacolato)diboron (**2**) (3.81 g, 15 mmol) was placed in a Schlenk flask containing a magnetic stirring bar. The flask was evacuated and filled with argon. Acetonitrile (30 mL), ethyl propiolate (**1a**) (1.47 g, 15 mmol) and LiOtBu (120 mg, 1.5 mmol) were sequentially added to the flask. After 5 h stirring at 40 °C, the mixture was filtered through a short plug of silica gel with diethyl ether. The solvent was removed under reduced pressure to give pure **3a** (4.81 g, 13.7 mmol, 91% yield).

Typical Procedure for LiOtBu -Catalyzed Reaction. The reaction in Table 1, entry 1 is representative. Bis(pinacolato)diboron (**2**) (50.8 mg, 0.2 mmol) was placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. Acetonitrile (300 μL), ethyl propiolate (**1a**) (19.6 mg, 0.2 mmol) and LiOtBu (1.6 mg, 0.02 mmol) dissolved in acetonitrile (100 μL) were sequentially added

to the vial. After 5 h stirring at 40 °C, the mixture was filtered through a short plug of silica gel, which was then washed with diethyl ether. The solvent was removed under reduced pressure to give pure **3a** (64.1 mg, 0.182 mmol, 91% yield).

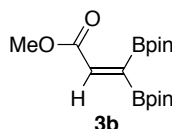
Characterization Data for 1,1-Diborylalkenes

Ethyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3a**)



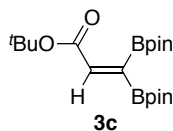
The product **3a** was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow solid. **IR** (neat) 1016, 1139, 1189, 1325, 1381, 1469, 1617, 1718, 2934, 2979 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.25 (s, 12H), 1.26 (t, $J = 7.2$ Hz, 3H), 1.36 (s, 12H), 4.21 (q, $J = 7.2$ Hz, 2H), 6.78 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.1, 24.5, 24.7, 60.6, 83.7, 83.8, 141.6, 166.7. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 29.5 ($\times 2\text{B}$). **HRMS-ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{17}\text{H}_{30}\text{O}_6\text{B}_2\text{Na}$, 375.21262; found, 375.21270.

Methyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3b**)



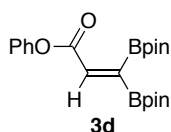
The product **3b** was purified by filtration through a short plug of silica gel with diethyl ether. Colorless oil. **IR** (neat) 1138, 1199, 1308, 1327, 1372, 1382, 1436, 1723, 2933, 2979 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.25 (s, 12H), 1.36 (s, 12H), 3.75 (s, 3H), 6.77 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.6, 24.7, 51.9, 83.8, 83.9, 141.0, 167.2. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 30.5 ($\times 2\text{B}$). **HRMS-ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{16}\text{H}_{28}\text{O}_6\text{B}_2\text{Na}$, 361.19697; found, 361.19701.

tert-Butyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3c**)



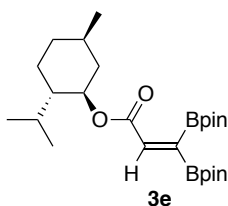
The product **3c** was purified by filtration through a short plug of silica gel with diethyl ether. White solid. M.p. 143–145 °C. **IR** (neat) 1134, 1212, 1326, 1368, 1388, 1473, 1623, 1713, 2934, 2980 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.24 (s, 12H), 1.35 (s, 12H), 1.45 (s, 9H), 6.73 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.6, 24.7, 28.0, 80.6, 83.6, 83.6, 144.1, 166.1. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 30.3 ($\times 2\text{B}$). **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{19}\text{H}_{34}\text{O}_6\text{B}_2\text{Na}$, 403.24392; found, 403.24407.

Phenyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3d**)



The product **3d** was purified by filtration through a short plug of silica gel with diethyl ether. White solid. M.p. 115–117 °C. **IR** (neat) 1131, 1164, 1195, 1314, 1326, 1373, 1382, 1488, 1741, 2934, 2981 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.28 (s, 12H), 1.30 (s, 12H), 6.99 (s, 1H), 7.10–7.12 (m, 2H), 7.21 (m, 1H), 7.35–7.38 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.7, 24.8, 84.0, 84.1, 121.6, 125.8, 129.3, 140.7, 150.6, 164.7. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 30.2 ($\times 2\text{B}$). **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{21}\text{H}_{30}\text{O}_6\text{B}_2\text{Na}$, 423.21262; found, 423.21283.

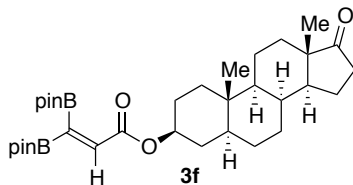
(1*R*,2*S*,5*R*)-2-Isopropyl-5-methylcyclohexyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**3e**)



The product **3e** was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow oil. **IR** (neat) 1139, 1192, 1268, 1320, 1388, 1457, 1714, 2871, 2930, 2958, 2977 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 0.72 (d, $J = 7.2$ Hz, 3H), 0.85 (d, $J = 7.2$ Hz, 3H), 0.87 (m, 1H), 0.89 (d, $J = 6.4$ Hz, 3H), 0.91–1.09 (m, 2H), 1.24 (s, 12H), 1.30 (m, 1H), 1.35 (s, 12H), 1.48 (m, 1H), 1.63–1.68 (m, 2H), 1.85 (m, 1H), 2.01 (m, 1H), 4.73 (td, $J = 10.6, 4.4$ Hz, 1H), 6.78 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 16.1, 20.8, 22.0, 23.2, 24.6, 24.7 ($\times 2\text{C}$), 24.8, 25.9, 31.3, 34.2, 40.7, 47.2, 74.5, 83.7, 83.8, 142.4, 166.3. A signal for the sp^2 -carbon directly attached to the boron atom was not

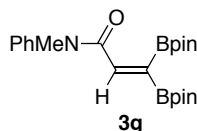
observed. ^{11}B NMR (128 MHz, CDCl_3) δ 30.3 ($\times 2\text{B}$). HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{25}\text{H}_{44}\text{O}_6\text{B}_2\text{Na}$, 485.32217; found, 485.32251. $[\alpha]_{\text{D}}^{25} -11.2$ (c 1.18, CHCl_3).

Epiandrosteron 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (3f)



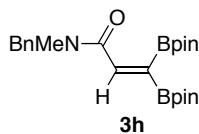
The product **3f** was purified by filtration through a short plug of silica gel with diethyl ether. White solid. M.p. 119–121 °C. IR (neat) 1140, 1191, 1269, 1324, 1372, 1457, 1716, 1740, 2932, 2976 cm^{-1} . ^1H NMR (400 MHz, CDCl_3) δ 0.70 (m, 1H), 0.84 (s, 3H), 0.86 (s, 3H), 0.91–1.08 (m, 2H), 1.16–1.41 (m, 7H), 1.24 (s, 12H), 1.36 (s, 12H), 1.44–1.56 (m, 3H), 1.58–1.68 (m, 3H), 1.71–1.84 (m, 3H), 1.89–1.96 (m, 1H), 2.07 (dt, $J = 19.2, 8.8$ Hz, 1H), 2.44 (dd, $J = 19.2, 8.8$ Hz, 1H), 4.77 (tdd, $J = 10.4, 5.6, 4.8$ Hz, 1H), 6.76 (s, 1H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 12.2, 13.8, 20.4, 21.74, 24.6, 24.8, 27.3, 28.2, 30.8, 31.5, 33.9, 35.0, 35.6, 35.8, 36.6, 44.5, 47.8, 51.3, 54.3, 73.6, 83.8, 83.8, 142.3, 166.3, 221.4. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 30.2 ($\times 2\text{B}$). HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{34}\text{H}_{54}\text{B}_2\text{O}_7\text{Na}$, 619.39533; found, 619.39510. $[\alpha]_{\text{D}}^{25} +22.1$ (c 1.22, CHCl_3).

N-Methyl-N-phenyl-3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylamide (3g)



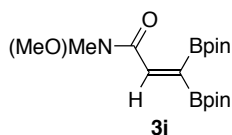
The product **3g** was purified by recrystallization with CH_2Cl_2 /hexane. Pale yellow solid. M.p. 157–159 °C. IR (neat) 1123, 1143, 1318, 1371, 1463, 1497, 1590, 1638, 2931, 2981 cm^{-1} . Signals for the rotamers were given in the NMR spectra. ^1H NMR (400 MHz, CDCl_3) δ 1.20 (s, 12H), 1.33 (s, 12H), 3.44 (s, 3H), 6.46 (s, 1H), 7.16–7.18 (m, 2H), 7.38–7.45 (m, 3H). ^{13}C NMR (100.5 MHz, CDCl_3) δ 24.7, 25.0, 38.9, 81.3, 83.2, 126.6, 128.3, 129.8, 130.1, 141.3, 170.4. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. ^{11}B NMR (128 MHz, CDCl_3) δ 22.0 and 30.4 (rotamer) ($\times 2\text{B}$). HRMS-ESI (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{22}\text{H}_{33}\text{B}_2\text{NO}_5\text{Na}$, 436.24425; found, 436.24449.

N-Benzyl-N-methyl-3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylamide (3h)



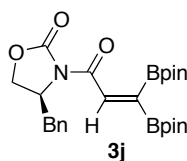
The product **3h** was purified by filtration through a short plug of silica gel with diethyl ether. Yellow oil. **IR** (neat) 1014, 1116, 1140, 1323, 1372, 1456, 1577, 1629, 2930, 2976 cm^{-1} . Signals for the rotamers were given in the NMR spectra. **^1H NMR** (400 MHz, CDCl_3) δ 1.26 and 1.27 (rotamer) (s, 12H), 1.30 and 1.31 (rotamer) (s, 12H), 3.04 and 3.07 (rotamer) (s, 3H), 4.65 and 4.70 (rotamer) (s, 2H), 7.01 and 7.07 (rotamer) (s, 1H), 7.17 (m, 1H), 7.28–7.38 (m, 4H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.9 ($\times 2\text{C}$), 25.2, 25.2, 34.5, 35.1, 53.2, 53.3, 80.9, 81.0, 83.4 ($\times 2\text{C}$), 127.2, 128.1, 128.4, 128.5, 128.8, 129.0, 132.2, 133.2, 134.3, 135.1, 171.3, 172.0. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 19.1 and 30.8 (rotamer) ($\times 2\text{B}$). **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{23}\text{H}_{35}\text{B}_2\text{NO}_5\text{Na}$, 450.25990; found, 450.26017.

***N*-Methoxy-*N*-methyl-3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylamide (**3i**)**



The product **3i** was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow solid. M.p. 116–118 $^{\circ}\text{C}$. **IR** (neat) 1140, 1283, 1312, 1371, 1379, 1467, 1606, 1641, 2935, 2975 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.27 (s, 12H), 1.34 (s, 12H), 3.29 (s, 3H), 3.73 (s, 3H), 7.23 (s, 1H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 24.7, 24.8, 32.8, 62.1, 82.8, 83.5, 137.0, 167.5. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 30.2 ($\times 2\text{B}$). **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{17}\text{H}_{31}\text{O}_6\text{NB}_2\text{Na}$, 390.22352; found, 390.22360.

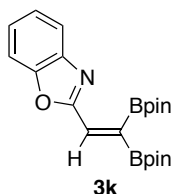
(*S*)-4-Benzyl-3-[3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acryloyl]oxazolidin-2-one (3j**)**



The product **3j** was purified by recrystallization with CH_2Cl_2 /hexane. Pale yellow solid. M.p. 191–3 $^{\circ}\text{C}$. **IR** (neat) 1109, 1141, 1228, 1259, 1298, 1334, 1388, 1484, 1611, 1660, 1784, 2932, 2980 cm^{-1} .

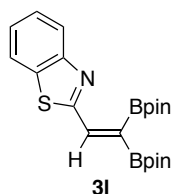
¹H NMR (400 MHz, CDCl₃) δ 1.27 (s, 12H), 1.39 (s, 12H), 2.80 (dd, *J* = 13.2, 9.6 Hz, 1H), 3.32 (dd, *J* = 13.2, 3.2 Hz, 1H), 4.15–4.23 (m, 2H), 4.72 (m, 1H), 7.19–7.21 (m, 2H), 7.29 (m, 1H), 7.32–7.35 (m, 2H), 8.03 (s, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 24.5, 24.7, 24.8, 24.8, 37.6, 55.3, 66.2, 83.7, 83.9, 127.3, 128.9, 129.4, 135.3, 139.7, 152.8, 165.5. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 30.7 (× 2B). **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₂₅H₃₅O₇NB₂Na, 506.24973; found, 506.25007. [α]_D²⁶ +15.9 (c 1.01, CHCl₃).

2-[2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl]benzo[d]oxazole (3k)



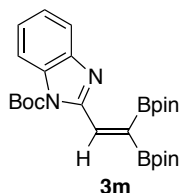
The product **3k** was purified by filtration through a short plug of silica gel with diethyl ether. Yellow oil. **IR** (neat) 1138, 1243, 1313, 1372, 1451, 1523, 1596, 1626, 2932, 2978 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.29 (s, 12H), 1.44 (s, 12H), 7.29–7.35 (m, 2H), 7.46 (m, 1H), 7.48 (s, 1H), 7.71 (m, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 24.7, 24.8, 83.8, 84.2, 110.5, 120.5, 124.5, 125.6, 136.8, 142.1, 150.6, 162.6. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 30.4 (× 2B). **HRMS–ESI** (*m/z*): [M+Na]⁺ calcd for C₂₁H₂₉B₂NO₅Na, 420.21295; found, 420.21316.

2-[2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl]benzo[d]thiazole (3l)



The product **3l** was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow oil. **IR** (neat) 1115, 1138, 1257, 1308, 1330, 1370, 1389, 1458, 1599, 2931, 2977 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.29 (s, 12H), 1.45 (s, 12H), 7.35 (m, 1H), 7.45 (m, 1H), 7.64 (s, 1H), 7.86 (m, 1H), 7.97 (m, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 24.8, 24.8, 83.7, 83.9, 121.8, 123.3, 125.1, 126.2, 136.2, 142.8, 153.8, 165.82. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 30.2 (× 2B). **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₁H₃₀O₄NB₂S, 414.20817; found, 414.20838.

***tert*-Butyl 2-[2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl]-1*H*-benzo[*d*]imidazole-1-carboxylate (**3m**)**



The product **3l** was purified by gel permeation chromatography (CHCl₃). Pale yellow solid. M.p. 145–147 °C. **IR** (neat) 1096, 1119, 1140, 1293, 1346, 1511, 1602, 1736, 2935, 2975 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) δ 1.27 (s, 12H), 1.41 (s, 12H), 1.69 (s, 9H), 7.27–7.33 (m, 2H), 7.64 (m, 1H), 7.99 (m, 1H), 8.13 (s, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 24.7, 24.9, 28.0, 83.4, 83.7, 85.6, 115.2, 119.8, 124.2, 124.8, 133.7, 140.9, 142.4, 148.6, 151.9. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 29.5 (× 2B). **HRMS–ESI** (*m/z*): [M+H]⁺ calcd for C₂₆H₃₉B₂N₂O₆, 497.29942; found, 497.30034.

Procedure for Synthesis of Trisubstituted Alkene (Scheme 5a)

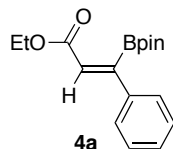
To a suspension of Pd(OAc)₂ (5.6 mg, 0.025 mol) and DtBPF (14.2 mg, 0.030 mol) in toluene (3 mL) was added K₃PO₄ (212.3 mg, 1.0 mmol), H₂O (63 μL), bromobenzene (52.7 μL, 0.5 mmol) and **3a** (176 mg, 0.5 mmol) at room temperature. After being stirred at rt for 5 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH₄Cl aq. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (1–8% EtOAc/hexane) to give the corresponding coupling product **4a** (107.3 mg, 0.36 mmol) in 71% yield. The ratio of *E/Z* selectivity was determined by GC analysis. A diphenylated product (12.6 mg, 0.05 mmol) was also obtained in 10% yield.

To a suspension of Pd(OAc)₂ (1.1 mg, 5.0 μmol) and DtBPF (2.8 mg, 6.0 μmol) in toluene (600 μL) was added K₃PO₄ (42.5 mg, 0.2 mmol), H₂O (12.6 μL), 4-bromoanisole (18.7 μL, 0.15 mmol) and **4a** (30.2 mg, 0.1 mmol) at room temperature. After being stirred at 60 °C for 5 h, the reaction mixture was diluted with EtOAc and quenched with saturated NH₄Cl aq. The aqueous layer was extracted with EtOAc, and the combined organic layer was washed with brine. The mixture was dried over anhydrous MgSO₄, filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (1–10% EtOAc/hexane) to give the

corresponding coupling product **5a** (19.5 mg, 0.069 mmol) in 69% yield. The ratio of *E/Z* selectivity was determined by GC analysis.

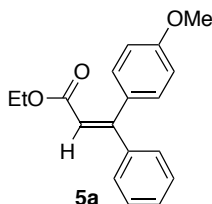
Characterization Data for Cross-Coupling Product

(*E*)-Ethyl 3-Phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylate (**4a**)



Colorless oil. **IR** (neat) 1030, 1137, 1180, 1210, 1302, 1377, 1606, 1705, 2933, 2978 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.31 (t, $J = 7.2$ Hz, 3H), 1.42 (s, 12H), 4.25 (q, $J = 7.2$ Hz, 2H), 6.43 (s, 1H), 7.30–7.38 (m, 3H), 7.48–7.50 (m, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.2, 25.0, 60.8, 84.3, 126.0, 127.1, 128.7, 129.0, 138.6, 168.1. A signal for the sp^2 -carbon directly attached to the boron atom was not observed. **^{11}B NMR** (128 MHz, CDCl_3) δ 30.3. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{17}\text{H}_{23}\text{O}_4\text{BNa}$, 325.15871; found, 325.15847.

(*Z*)-Ethyl 3-(4-Methoxyphenyl)-3-phenylacrylate (**5a**)



The product **5a** was consistent with the the literature data.²¹

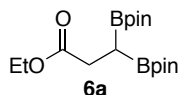
Procedure for Copper-Catalyzed Conjugate Reduction (Scheme 5b)

Procedure for synthesis of 6a. CuCl (1.0 mg, 0.01 mol), NaOtBu (1.0 mg, 0.01 mmol) and 1,3-bis(2,6-diisopropylphenyl)imidazolium chloride (4.3 mg, 0.01 mmol) were placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. Toluene (400 μL) was added and the resulting solution was stirred for 10 min. PMHS (48.1 mg, 0.8 mmol) and *t*BuOH (19.0 μL , 0.2 mmol) were added, the reaction mixture was stirred for another 10 min, followed by addition of **3a** (70.4 mg, 0.2 mmol) dissolved in toluene (400 μL). After stirring at rt for 3.5 h, the mixture was filtered through a short plug of silica gel, which was washed with diethyl ether, and the solvent was removed under

reduced pressure. The residue was purified by flash column chromatography on silica gel (0–10% EtOAc/hexane) to give the corresponding product **6a** (70.1 mg, 0.198 mmol) in 99% yield.

Characterization Data for Geminal Diborylalkane

Ethyl 3,3-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate (**6a**)



Colorless oil. **IR** (neat) 1137, 1166, 1187, 1269, 1310, 1369, 1468, 1734, 2934, 2978 cm^{-1} . **^1H NMR** (400 MHz, CDCl_3) δ 1.08 (t, J = 8.8 Hz, 1H), 1.22 (s, 12H), 1.24 (s, 12H), 1.24 (t, J = 7.2 Hz, 3H), 2.56 (d, J = 8.8 Hz, 2H), 4.10 (q, J = 7.2 Hz, 2H). **^{13}C NMR** (100.5 MHz, CDCl_3) δ 14.3, 24.4, 24.8, 30.5, 60.2, 83.1, 174.9. **^{11}B NMR** (128 MHz, CDCl_3) δ 34.0. **HRMS–ESI** (m/z): $[\text{M}+\text{Na}]^+$ calcd for $\text{C}_{17}\text{H}_{32}\text{O}_6\text{B}_2\text{Na}$, 377.22827; found, 377.22835.

Reaction between Ethyl Propiolate (**1a**) and **2** in the Presence of Stoichiometric Amount of $n\text{BuLi}$

Ethyl propiolate (**1a**) (19.6 mg, 0.2 mmol) was placed in a vial containing a magnetic stirring bar. The vial was sealed with a Teflon[®]-coated silicon rubber septum and the vial was evacuated and filled with argon. THF- d_8 (0.4 mL) and $n\text{BuLi}$ (130 μL , 0.2 mmol, 1.63 M hexane) were sequentially added to the vial at -78°C . After stirring for 30 min at -78°C , bis(pinacolato)diboron (**2**) (50.8 mg, 0.2 mmol) in THF- d_8 (0.3 mL) was added, and the mixture was warmed to 25°C with stirring for 1 h. The mixture was then transferred to NMR tube (signal assignment in ^1H and ^{11}B NMR spectroscopy was unsuccessful due to complexity of spectra). Subsequently, one equiv of $t\text{BuOH}$ was added, and then the resulting mixture was kept standing at 25°C for 1 h. The mixture was filtered through a short plug of silica gel, which was then washed with diethyl ether. The solvent was removed under reduced pressure to give a pale red oil. The yield of **3a** was determined to be 27% by ^1H NMR analysis using 1,1,2,2-tetrachloroethane as an internal standard.

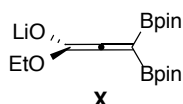
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(9) The addition of Me₃SiCl or aldehydes to a solution containing **B** did not give the corresponding coupling products but gave **3a** after work-up. These results are incompatible to the formation of a lithium allenolate intermediate (**X**) as a precursor to **3a**.



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Publication List

I. Parts of the present thesis have been published in the following journals

- Chapter 1** Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura
Synthesis **2012**, 44, 1535.
- Chapter 2** Kazunori Nagao, Umi Yokobori, Yusuke Makida, Hirohisa Ohmiya, and Masaya Sawamura
J. Am. Chem. Soc. **2012**, 134, 8982.
- Chapter 3** Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura
J. Am. Chem. Soc. **2014**, 136, 10605.
- Chapter 4** Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura
Org. Lett. **2015**, 17, 1304.
- Chapter 5** Akira Morinaga, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura
Angew. Chem. Int. Ed. **2015**, 54, 15859.

II. Other Publications not included in this thesis

- (1) Synthesis of Trisubstituted Alkenylstannanes through Copper-Catalyzed Three-Component Coupling with Alkylboranes, Alkynoates, and Tributyltin Methoxide
Takamichi Wakamatsu, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura.
Angew. Chem. Int. Ed. **2013**, 52, 11620.
- (2) Copper(I)-Catalyzed Intramolecular Hydroalkoxylation of Unactivated Alkenes
Hiroaki Murayama, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura
Org. Lett. **2015**, 17, 2038.
- (3) Copper-Catalyzed γ -Selective and Stereospecific Allylic Cross-Coupling with Secondary Alkylboranes
Yuto Yasuda, Yoshinori Shido, Kazunori Nagao, Seiji Mori, Hirohisa Ohmiya, and Masaya Sawamura
Chem. Eur. J. **2015**, 21, 9666.
- (4) Copper-Catalyzed Enantioselective Allylic Cross-Coupling with Alkylboranes
Kentaro Hojoh, Yoshinori Shido, Kazunori Nagao, Seiji Mori, Hirohisa Ohmiya, and Masaya Sawamura.
Tetrahedron, **2015**, 71, 6519.
- (5) Copper-Catalyzed Stereoselective Conjugate Addition of Alkylboranes to Alkynoates
Takamichi Wakamatsu, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura.
Beilstein J. Org. Chem. **2015**, 11, 2444.

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