Development of New Catalytic Reactions
with Organoboron Compounds

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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. 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. 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). 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). He demonstrated the synthesis of symmetrical conjugated dienes through this methodology.
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 C(sp²)–C(sp²) bonds. Most of them mainly relied on palladium and nickel. Copper-catalyzed Suzuki–Miyaura coupling for biaryl synthesis has been also developed. In 2002, Rothenberg and co-workers reported copper or copper-contained nanocolloid catalyzed cross coupling between phenylboronic acid and various aryl halides (Scheme 3a). Homogeneous copper catalysis has been reported by Li’s group (Scheme 3b). They showed Cul/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). This reaction proceeds under relatively mild conditions.
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.

Recently, some groups could apply the Cham-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).\textsuperscript{10} The Lewis acidity of La(O\textit{Pr})\textsubscript{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).\textsuperscript{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).\textsuperscript{12} They proposed the reaction mechanism involving only neutral copper(I) species on the basis of the stoichiometric reactions. Iwasawa\textsuperscript{13a} and Hou\textsuperscript{13b} independently reported copper-catalyzed carboxylation of aryl- and alkenylboronates with carbon dioxide (Scheme 9).

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

Scheme 7. Conjugate Addition to Alkynoate
Scheme 8. Enantioselective Conjugate Addition

\[
\text{Ph-B} + \text{Ph-CO}_2\text{Bu} \xrightarrow{\text{CuBr (5 mol%), L1 (5.5 mol%), t-BuOK (2 eq), dioxane, 30 °C, then H}_2\text{O}} \quad \text{Ph-CO}_2\text{Bu}
\]

Scheme 9. Carboxylation

\[
\text{R-B} + \text{CO}_2(1 \text{ atm}) \xrightarrow{\text{Cul (1-5 mol%), bisoxazoline (0-6 mol%), CsF (3 eq), DMF, 90 °C, then, H}^+} \quad \text{R-CO}_2\text{H}
\]

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). This reaction achieved excellent \(\gamma\)-selectivity and 1,3-\textit{anti} stereoselectivity. Shintani and Hayashi reported the development of asymmetric allylic substitution of allylic phosphates with aryl- and alkenylboronates (Scheme 11). Construction of quaternary carbon stereocenters was also shown. Recently, Hoveyda's group developed asymmetric allylic substitution of allylic phosphates with alkenyl-, allenyl- and propargylboronates.

Scheme 10. Copper-Catalyzed Allyl–Aryl Coupling.

\[
\text{MeO-B} + \text{BuOP(O)(OEt)}_2 \xrightarrow{\text{CuCl (5 mol%), aca-H (10 mol%), t-BuOK (3 eq), MeCN, 50 °C, H}_2\text{O (3 eq)}} \quad \text{Me}
\]

Scheme 11. Enantioselective Allylic Substitution with Aryl and Alkenylboronates

\[
\text{Ph-OP(O)(OEt)}_2 + \text{MeONa (2.0 eq), THF, 30 °C} \xrightarrow{\text{CuCl (5 mol%), L1 (5.5 mol%), MeONa (2.0 eq), THF, 30 °C}} \quad \text{Ph}
\]

In 2012, Lalic and co-workers described electrophilic amination of arylboronates catalyzed by copper/Xantphos complex (Scheme 12). 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).\(^\text{18}\) 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 alkylborans.

**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).\(^\text{19}\) 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).\(^\text{20}\) These are the first examples of asymmetric allylic substitution or conjugate addition of alkylboranes.
They demonstrated the synthesis of chiral allenes and allenylsilanes through copper-catalyzed stereospecific alkylation of chiral propargylic phosphates with alkyl-9-BBN (Scheme 16).\textsuperscript{21} Shortly thereafter, Lalic and co-workers reported the same reaction with copper NHC complex (Scheme 18).	extsuperscript{22} Hou's group and Sawamura's group independently reported the carboxylation of alkylboranes with copper catalysts (Schemes 18 and 19).	extsuperscript{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)

\[
\begin{align*}
&\text{Ph-} - \text{B} - \text{Ph} + \text{OP(O)(OEt)}_2 \rightarrow \text{MOMO-} \text{Me} - \text{Ph} \\
&\text{CuOAc (10 mol%) t-BuOK (1.0 eq)} \\
&\text{THF, 70 °C} \\
&\text{78%, 96% ee} \\
&\gamma/\alpha > 99:1
\end{align*}
\]

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

\[
\begin{align*}
&\text{Ph-} \text{B} - \text{Bu} + \text{OP(O)(OPh)}_2 \rightarrow \text{MOMO-} \text{Me} - \text{Me} \\
&\text{ICyCuCl (10 mol%) t-BuOLi(1.0 eq)} \\
&\text{pentane, 35 °C} \\
&\text{95%, 96% ee} \\
&\gamma/\alpha > 99:1
\end{align*}
\]

Scheme 18. Carboxylation of Alkylboranes (reported by Hou)

\[
\begin{align*}
&\text{MeO-} \text{B} - \text{Ph} + \text{CO}_2 \rightarrow \text{MeO-} \text{CO}_2\text{H} \\
&\text{THF, 70 °C} \\
&\text{97%}
\end{align*}
\]

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

\[
\begin{align*}
&\text{tBuO-} \text{B} - \text{tBu} + \text{CO}_2 \rightarrow \text{tBuO-} \text{CO}_2\text{H} \\
&\text{toluene, 100 °C} \\
&\text{79%}
\end{align*}
\]

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

\[
\text{PhB} + \text{PhCO}_2\text{Et} \xrightarrow{\text{CuOAc (10 mol%), t-BuOK (10 mol%), Bu}_3\text{SnOMe (2 eq), 1,4-dioxane, 60 °C}} \text{PhCO}_2\text{Et} + \text{SnBu}_3
\]

Scheme 21. Hydroalkylation of Alkynoates with Alkylboranes

\[
\text{PhB} + \text{PhCO}_2\text{Et} \xrightarrow{\text{CuOAc (5 mol%), P(OPh)_3 (10 mol%), t-BuOK (5 mol%), t-BuOH (1 eq), dioxane, 40 °C}} \text{PhCO}_2\text{Et} + \text{H}
\]

Many other groups reported copper-catalyzed transformations of alkylboranes. Liu demonstrated alkyl–alkyl Suzuki–Miyaura coupling between alkylboranes and alkyltosylates (Scheme 22).\(^7\) Lalic combined alkene hydroboration with copper-catalyzed electrophilic amination to realize a formal anti-Markovnikov hydroamination of alkenes (Scheme 23).\(^2^6\)

Scheme 22. Copper-Catalyzed Alkyl–Alkyl Suzuki–Miyaura coupling

\[
\text{Ph}_3\text{B} + \text{C}_9\text{H}_{17}-\text{OTs} \xrightarrow{\text{CuI (10 mol%), t-BuOLi (2 eq), DMF, 80 °C}} \text{C}_9\text{H}_{17}\text{C}(=\text{O})(\text{OTs})(\text{Ph})_3 \quad 52\%
\]

Scheme 23. Formal Anti-Markovnikov Hydroamination of Terminal Alkenes

\[
\text{R}^1\text{H} \xrightarrow{9\text{-BBN (1.0 eq), toluene, 60 °C}} \xrightarrow{\text{ICyCuCl (5 mol%), t-BuOLi (1.1 eq), R}_3\text{NOBz (1.1 eq), toluene, 80 °C}} \text{R}^1\text{NR}_2 \quad 84–95\%
\]
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).\(^2^7\) Then, he applied this methodology to homologation reaction of chiral organoboronates with α-dihaloalkyllithium to afford the various chiral alkylboronates (Scheme 25).\(^2^8\) Recently, Aggarwal established the synthesis of chiral organoboron compounds combined with organoborons and chiral lithium carbenoids (Scheme 26).\(^2^9\) The iterative lithiation-borylation method offered the stereoselective construction of consecutive carbon stereogenic centers.

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

\[
\begin{align*}
\text{Scheme 25.} & \text{ Homologation of Organoborons through 1,2-Migration} \\
\text{Scheme 26.} & \text{Synthesis of Chiral Organoborons via Lithiation-Borylation}
\end{align*}
\]
Petasis reported Mannich reaction with an amine, aldehyde and aryl- or alkenylboronic acid in 1993 (Scheme 27). 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). This reaction achieved the high reactivity and enantioselectivity by use of a chiral bifunctional thiourea catalyst containing an aminoalcohol moiety.

**Scheme 27. Petasis Reaction**

\[
R^1R^2NH + R^3CHO + R^4\text{B(OH)}_2 \rightarrow R^1^+R^2^+R^3^+R^4\text{B(OH)}_2 \rightarrow R^1^+R^2^+R^3^+R^4\text{NOR^5B(OH)}_2
\]

**Scheme 28. Enantioselective Petasis Type Reaction**

\[
\text{Ph} = \text{B(OH)}_2 + \text{PhO}_2\text{Cl} \text{(2 eq)} \quad \text{NaHCO}_3 \text{(2 eq)} \quad \text{H}_2\text{O} \text{(66 eq)} \quad \text{DCM}
\]

\[
\text{Ar} = 3,5-(\text{CF}_3)-\text{C}_6\text{H}_3^-
\]

**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). 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.

**Scheme 29. BINOL-Catalyzed Asymmetric Alkynylation of Enones**

\[
\text{C}_6\text{H}_{13} = \text{B(OPh)}_2 + \text{Ph}_2\text{CHOH} \quad \text{DCM, reflux}
\]

95%, 87% ee
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 $\alpha,\beta$-unsaturated carbonyl compounds (Scheme 30). 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). Simple alkoxide bases are also catalysts for diboration and silaboration of alkenes (Scheme 32). Recently, Morken demonstrated the stereoselective synthesis of various 1,2-diols through the alkoxide base-catatalyzed diboration of alkenyl alcohols.

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

\[
\begin{align*}
\text{Cy} & \text{-N} \text{N-Cy (10 mol\%)} \\
\text{t-BuONa (10 mol\%)} \\
\text{THF, 22 °C then, H}_2\text{O}
\end{align*}
\]

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

\[
\begin{align*}
\text{(R)-(S)-josiphos (4 mol\%)} \\
\text{Cs}_2\text{CO}_3 (3 mol\%) \\
\text{THF/MeOH, 70 °C}
\end{align*}
\]

**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). Maron and Fontaine synthesized the phosphine-borane molecule and used it as catalyst for reduction of carbon dioxide to methanol. In both examples, catalysts initially activated the substrates such as imines and CO$_2$ followed by hydride reduction from HBpin (Scheme 34).
**Scheme 33.** Borenium Cation Catalyzed Reduction of Imines

\[
\text{Ph}^+ + \text{N}^+\text{N}^-\text{Bpin} \xrightarrow{\text{PhCF}_3, \text{rt then, } \text{H}_2\text{O}} \text{Ph}^- + \text{N}^-\text{Ph}
\]

**Scheme 34.** Reduction of CO\(_2\) by Phosphine–Borane Organocatalyst

\[
\begin{align*}
\text{CO}_2 (2 \text{ atm}) + \text{HBcat} & \xrightarrow{\text{Ph}_3\text{P} \text{Bcat}, 1 \text{ mol%}} \text{catBOBcat} + \text{CH}_3\text{OBcat} \\
\text{biphenyl, } 70 \degree \text{C} & \xrightarrow{\text{benzene-}d_6} \text{PhCF}_3, \text{ rt then, } \text{H}_2\text{O} \\
\text{Ph}^- + \text{N}^-\text{Ph} & \xrightarrow{\text{B(C}_6\text{F}_5)_4, 5 \text{ mol%}} \text{Ph}^+ + \text{N}^+\text{N}^-\text{Bpin}
\end{align*}
\]

In some cases, organocatalysis in activation of unactivated bond showed unprecedented features. Suginome 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

\[
\begin{align*}
\text{Me-N-N-Me} & \xrightarrow{\text{Cl-N-N-Cl}, 5 \text{ mol%}} \text{Me-N-N-Bpin}
\end{align*}
\]

**Scheme 36.** Metal-Free Catalytic C–H Borylation of Heteroarenes

\[
\begin{align*}
\text{N}^-\text{H} + \text{HBpin} & \xrightarrow{\text{CHCl}_3, 80 \degree \text{C}, 2.5 \text{ mol%}} \text{N}^-\text{Bpin}
\end{align*}
\]
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 Torelable Synthesis of Allylsilanes through Copper-Catalyzed \( \gamma \)-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 \( \gamma \)-selective allyl–alkyl coupling between \( \gamma \)-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). In addition to
1,3-syn conditions, a monodentate phophine ligand is essential. (This is not included in this thesis).

**Scheme 40.** Allyl–Alkyl Coupling with Secondary Alkylboranes

![Scheme 40](image)

### 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. 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

![Scheme 41](image)

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](image)
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).\textsuperscript{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 Herteroarene derived Propargyl Alcohols

3.4. Anti-Selective Vicinal Silaboration and Diboration of Alkynoates through 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-boryl-α-silyl acrylates and α,β-diboryl acrylates. The anti selectivity was complete regardless of substrate structures. Various functional groups were tolerated in alkynoates.

Scheme 44. Phosphine–Catalyzed Anti-Silaboration and Diboration of Alkynoates
The two vicinally installed heteroatom substituents of the $\beta$-boryl-$\alpha$-silylacrylates and $\alpha,\beta$-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, propiolamindes and 2-ethynylazoles are suitable terminal alkynes for this reaction. The phospine 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 $\beta$-diborylacrylates are converted to the corresponding $\beta$-diarylacrylates through stepwise Suzuki–Miyaura couplings.

**Scheme 46.** Synthesis of 1,1-Diborylalkene by Brønsted Base Catalysis
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Chem. Soc. 2015, 137, 8948.


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. The development of facile and efficient methods for the synthesis of allylsilanes is important. Among the available methods for accessing to allylsilanes, two types of the SN2’ displacement strategies, γ-substitutions of γ-silylated allylic alcohol derivatives with organocuprate reagents and silylations of allylic alcohol derivatives with silylcuprate reagents 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. 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. 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). 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).
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 a 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

<table>
<thead>
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<th>entry</th>
<th>alkene</th>
<th>phosphate</th>
<th>product</th>
<th>yield (%)</th>
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<tr>
<td>1</td>
<td>1a</td>
<td>3b</td>
<td>4ab</td>
<td>94</td>
</tr>
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<td>2</td>
<td>1a</td>
<td>3c</td>
<td>4ac</td>
<td>92</td>
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<tr>
<td>3</td>
<td>1a</td>
<td>3d</td>
<td>4ad</td>
<td>94</td>
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<tr>
<td>4</td>
<td>1b</td>
<td>3a</td>
<td>4ba</td>
<td>82</td>
</tr>
</tbody>
</table>
The reaction was carried out with \(3 (0.2 \text{ mmol})\), alkylborane \(2 (0.32 \text{ mmol})\), 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. Isolated yield based on \(3\). Isomeric ratios \((\gamma/\alpha > 99:1, E/Z > 99:1)\). Determined by \(^1\)H NMR or GC of the crude product. Diasteremeric 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 13C NMR. Chemical shift values for 1H and 13C are referenced to Me2Si 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 Tesque, 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, CHCl3, 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 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-butyln-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)

![Structure of 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 C₁₂H₂₅O₅PSiNa, 315.11574; found, 315.11519.

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

![Structure of 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): [M+Na]$^+$ calcd for C$_{17}$H$_{27}$O$_4$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. $^1$H 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 −2.05, −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$_{22}$H$_{29}$O$_4$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. $^1$H 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$_4$PSiNa, 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. $^1$H 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$_5$Si$_2$Na, 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. $^1$H 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$_4$NaPSi, 405.16269; found, 405.16241.

**Typical Procedure for Synthesis of Allylsilanes**

The preparation of 4aa is representative (Scheme 1). In a glove 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, CH$_2$Cl$_2$ 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. $^1$H NMR (300 MHz, CDCl$_3$) 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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) δ −3.37, 18.11, 31.08, 32.71, 35.59, 123.16, 125.60, 128.29, 128.59, 132.17, 143.18. **Anal.** Caled for C$_{15}$H$_{24}$Si: 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. $^1$H NMR (300 MHz, CDCl$_3$) δ 0.48 (s, 3H), 1.59–1.71 (m, 1H), 1.66 (d, $J = 4.2$ Hz, 3H), 1.78–1.86 (m,
(E)-Benzyltrimethyl(1-phenyl-4-hexen-3-yl)silane (4ad)

The product 4ad was purified by flash chromatography on silica gel (hexane). Colorless oil. \(^{1}H\) NMR (300 MHz, CDCl\(_3\)) \(\delta \) 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\(_3\)) \(\delta \) 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 C\(_{25}\)H\(_{28}\)Si: C, 84.21; H, 7.91%. Found: C, 83.88; H, 7.95%.

(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. \(^{1}H\) NMR (300 MHz, CDCl\(_3\)) \(\delta \) 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\(_3\)) \(\delta \) –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 C\(_{15}\)H\(_{30}\)O\(_2\)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. \(^{1}H\) NMR (300 MHz, CDCl\(_3\)) \(\delta \) 0.06 (s, 9H), 1.26–1.54 (m, 4H), 1.65 (d, \(J = 4.8\) Hz, 3H).
$^{13}$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.

Analytical Calcd for C$_{18}$H$_{30}$O$_2$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. $^1$H 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. Analytical Calcd for C$_{23}$H$_{32}$O$_2$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. $^1$H 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): [M]$^+$ calcd for C$_{21}$H$_{46}$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. $^1$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). $^{13}$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, 132.62, 132.26, 133.90, 168.63. Anal. Calcd for C$_{20}$H$_{29}$NO$_2$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](benzyldimethylsilane (4fd)*

The product 4fd was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). Colorless oil. $^1$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, 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). $^{13}$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 C$_{22}$H$_{36}$O$_2$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. $^1$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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) δ −5.46, −5.41, −4.46, −4.42, 17.97 (×2C), 21.09 (×2C), 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): [M+Na]$^+$ calcd for C$_{22}$H$_{30}$O$_2$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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ –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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ –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): [M]$^+$ calcd for C$_{15}$H$_{23}$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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ –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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ –3.53, –3.40, 18.09, 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. Caled for C$_{16}$H$_{26}$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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ –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), 35
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): [M+Na]$^+$ calcd for C$_{34}$H$_{61}$NO$_4$Si$_2$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. $^1$H 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): [M]$^+$ calcd for C$_{22}$H$_{30}$Si, 322.21168; found, 322.2115.

References and Notes


(23) For the concept of allylic 1,3-strain in acyclic stereocontrol, see: Hoffmann, R. W. Chem. Rev. 1989, 89, 1841.
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. Typically, the reaction occurs with an 1,3-anti stereochemistry \((anti-S_N^2')\) to deliver a new stereogenic center at the \(\gamma\)-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 \((syn-S_N^2')\). Breit and co-workers introduced the ortho-diphenylphosphanyl benzoate \((o\text{-DPPB})\) group as a new reagent-directing leaving group, and furthermore realized the stereoselective conversion of chiral allylic substrates by employing the switchable \(o\text{-DPPB}/o\text{-DPPB oxide}\) leaving groups. 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. 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.

Earlier, the author's laboratory reported the copper-catalyzed \(\gamma\)-selective allyl–alkyl coupling between allylic phosphates and alkylboranes \((\text{alkyl-9-BBN})\). This reaction occurred preferentially with 1,3-anti stereochemistry, but the efficiency of the stereoselectivity was only moderate with acyclic allylic substrates (eq. 1). 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. 

\[
\begin{align*}
\text{Ph} & \quad \text{B} \\
2a & \quad (1.5 \text{ equiv}) \\
\text{Bu} & \quad \text{OP(O)(OEt)}_2 \\
(S)-(Z)-3a, 95\% \text{ ee} & \\
\text{CuOAc} \, (10 \text{ mol } \%) & \quad \text{t-BuOK} \, (1 \text{ equiv}) \\
\text{toluene/DMF} \, (4:1) & \quad 60 \degree C, 8 \text{ h} \\
\gamma\text{-}\alpha > 99:1; \ E/Z > 99:1 & \\
\end{align*}
\]

\[
\begin{align*}
\text{Ph} & \quad \text{B} \\
2a & \quad (1.5 \text{ equiv}) \\
\text{Bu} & \quad \text{OP(O)(OEt)}_2 \\
(S)-(Z)-3a, 95\% \text{ ee} & \\
\text{CuOAc} \, (10 \text{ mol } \%) & \quad \text{t-BuOK} \, (1 \text{ equiv}) \\
\text{toluene/DMF} \, (4:1) & \quad 60 \degree C, 8 \text{ h} \\
\gamma\text{-}\alpha > 99:1; \ E/Z > 99:1 & \\
\end{align*}
\]
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 group\textsuperscript{16} 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).\textsuperscript{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).\textsuperscript{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

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

abc The 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.

dYield of the isolated product based on (S)-(Z)-3b. cIsomeric ratios (γ/α>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-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-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\textsuperscript{a,b}

<table>
<thead>
<tr>
<th>entry</th>
<th>alkene</th>
<th>phosphate</th>
<th>conditions</th>
<th>product</th>
<th>yield (%)	extsuperscript{c,d}</th>
<th>anti/syn\textsuperscript{e}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>TIPSO\textsubscript{3}+\textsubscript{3}</td>
<td>(S)-(Z)-3b</td>
<td>A</td>
<td>TIPSO\textsubscript{3}+\textsubscript{3}</td>
<td>89</td>
<td>96.5:3.5</td>
</tr>
<tr>
<td>2</td>
<td>1b</td>
<td>(S)-(Z)-3b</td>
<td>B</td>
<td>TIPSO\textsubscript{3}+\textsubscript{3}</td>
<td>99</td>
<td>4.96</td>
</tr>
<tr>
<td>3</td>
<td>Cl-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>99% ee</td>
<td>A</td>
<td>(+)-(E)-4bc</td>
<td>91</td>
<td>97.5:2.5</td>
</tr>
<tr>
<td>4</td>
<td>1c</td>
<td>(S)-(Z)-3b</td>
<td>B</td>
<td>Cl-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>99</td>
<td>6:94</td>
</tr>
<tr>
<td>5</td>
<td>MeO-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>99% ee</td>
<td>A</td>
<td>MeO-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>99</td>
<td>95.5:4.5</td>
</tr>
<tr>
<td>6</td>
<td>1d</td>
<td>(S)-(Z)-3b</td>
<td>B</td>
<td>MeO-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>94</td>
<td>3:97</td>
</tr>
<tr>
<td>7</td>
<td>1c</td>
<td>(S)-(Z)-3b</td>
<td>A</td>
<td>Cl-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3b</td>
<td>92</td>
<td>96.5:3.5</td>
</tr>
<tr>
<td>8</td>
<td>1c</td>
<td>(S)-(Z)-3c</td>
<td>B</td>
<td>Cl-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3c</td>
<td>95</td>
<td>4.5:95.5</td>
</tr>
<tr>
<td>9</td>
<td>1a</td>
<td>(S)-(Z)-3d</td>
<td>A</td>
<td>Ph-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3d</td>
<td>96</td>
<td>54:46</td>
</tr>
<tr>
<td>10</td>
<td>1a</td>
<td>(S)-(Z)-3d</td>
<td>B</td>
<td>Ph-C\textsubscript{6}H\textsubscript{4} \textsubscript{C}H &amp; (S)-(Z)-3d</td>
<td>95</td>
<td>1:99</td>
</tr>
</tbody>
</table>
Conditions A: \(3 (0.2 \text{ mmol}), \text{alkylborane } 2 (0.32 \text{ mmol}), \text{CuOAc} (10 \text{ mol } \%), \text{t-BuOK} (0.3 \text{ mmol}, 1 \text{ M in THF}), \text{THF}, 40 \degree \text{C}, 8 \text{ h.}\)

Conditions B: \(3 (0.2 \text{ mmol}), \text{alkylborane } 2 (0.32 \text{ mmol}), \text{CuOAc} (10 \text{ mol } \%), \text{MeOK} (0.3 \text{ mmol}), \text{toluene}, 80 \degree \text{C}, 8 \text{ h.}\)

Alkylborane 2 was prepared in advance by hydroboration of 1 with 9-BBN dimer in THF (conditions A) or toluene (conditions B) at 60 \degree \text{C} for 1 h and used without purification. * Yield of the isolated product based on 3. † Isomeric ratios \((\gamma/\alpha > 99:1, E/Z > 99:1)\). Determined by \(^1\text{H} \text{NMR or GC of the crude product.} ‡ \text{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 \(\gamma,\gamma\)-disubstituted \(E\) allylic phosphates, which are easier to prepare than the corresponding \(Z\) isomers. § The reaction of \(\gamma,\gamma\)-disubstituted allylic phosphate \((S)-(E)-3\) (96% ee) using either conditions A or B afforded the corresponding quaternary chiral allylsilanes \((R)-(E)-4\) (92% ee, \text{anti/syn } 98:2) and \((S)-(E)-4\) (92% ee, \text{anti/syn } 2:98), respectively (entries 1 and 2). ¶ The synthetic methods were compatible with an ester moiety in the alkenic (alkylborane) substrate (entries 3 and 4). The reactions of allylic phosphate \((S)-(E)-3\) (99% ee) with a Bu group instead of the Me group at the \(\gamma\)-position by using either conditions A or B afforded \((-)-(E)-4\) (93% ee, \text{anti/syn } 97:3) and \((+)-(E)-4\) (96% ee, \text{anti/syn } 1.5:98.5), respectively (entries 5 and 6).
Table 3. Synthesis of Enantioenriched Allylsilanes with a Quaternary Carbon Stereogenic Center

<table>
<thead>
<tr>
<th>entry</th>
<th>alkene</th>
<th>phosphate</th>
<th>conditions</th>
<th>product</th>
<th>yield (%)</th>
<th>anti/syn&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1a</td>
<td>(S)-(E)-3e</td>
<td>A</td>
<td>PhMe₂Si-(S)-(E)-4ae, 92% ee</td>
<td>86</td>
<td>98:2</td>
</tr>
<tr>
<td>2</td>
<td>1a</td>
<td>(S)-(E)-3e</td>
<td>B</td>
<td>PhMe₂Si-(S)-(E)-4ae, 92% ee</td>
<td>67</td>
<td>2:98</td>
</tr>
<tr>
<td>3</td>
<td>MeO⁻alley-1d</td>
<td>(S)-(E)-3e</td>
<td>A</td>
<td>PhMe₂Si-(+)-(E)-4de, 93% ee</td>
<td>93</td>
<td>98.5:1.5</td>
</tr>
<tr>
<td>4</td>
<td>1d</td>
<td>(S)-(E)-3e</td>
<td>B</td>
<td>PhMe₂Si-(−)-(E)-4de, 96% ee</td>
<td>81</td>
<td>1:&gt;99</td>
</tr>
<tr>
<td>5</td>
<td>1a</td>
<td>(S)-(E)-3f</td>
<td>A</td>
<td>PhMe₂Si-(+)-(E)-4af, 93% ee</td>
<td>70</td>
<td>97:3</td>
</tr>
<tr>
<td>6&lt;sup&gt;f&lt;/sup&gt;</td>
<td>1a</td>
<td>(S)-(E)-3f</td>
<td>B</td>
<td>PhMe₂Si-(−)-(E)-4af, 96% ee</td>
<td>56</td>
<td>1.5:98.5</td>
</tr>
</tbody>
</table>

<sup>a</sup>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. <sup>b</sup>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. <sup>c</sup>Yield of the isolated product based on 3. <sup>d</sup>Isomeric ratios (γ/α>99:1, E/Z >99:1). Determined by <sup>e</sup>1H NMR or GC of the crude product. <sup>f</sup>The enantiomeric excess was determined by HPLC analysis. <sup>f</sup>The reaction was carried out in toluene/DCE (3:1) solvent.
The \( \alpha \)-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).

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*:

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

*a The 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.

*b Yield of the isolated product based on (S)-(Z)-3a’.
*c Isomeric ratios (γ/α >99:1, E/Z >99:1). Determined by 1H NMR or GC of the crude product.
*d The 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$^a,b$

<table>
<thead>
<tr>
<th>entry</th>
<th>alkene</th>
<th>phosphate</th>
<th>conditions</th>
<th>product</th>
<th>yield (%)$^c,d$</th>
<th>anti/syn$^e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="alkene" /></td>
<td><img src="image2" alt="phosphate" /></td>
<td>A</td>
<td><img src="image3" alt="product" /></td>
<td>65</td>
<td>98.5:1.5</td>
</tr>
<tr>
<td>2</td>
<td>1e</td>
<td><img src="image2" alt="phosphate" /></td>
<td>C</td>
<td><img src="image3" alt="product" /></td>
<td>67</td>
<td>11:89</td>
</tr>
<tr>
<td>3</td>
<td><img src="image1" alt="alkene" /></td>
<td><img src="image2" alt="phosphate" /></td>
<td>A</td>
<td><img src="image3" alt="product" /></td>
<td>70</td>
<td>95:5</td>
</tr>
<tr>
<td>4</td>
<td>1a</td>
<td><img src="image2" alt="phosphate" /></td>
<td>C</td>
<td><img src="image3" alt="product" /></td>
<td>74</td>
<td>6:94</td>
</tr>
<tr>
<td>5</td>
<td>1e</td>
<td><img src="image2" alt="phosphate" /></td>
<td>A</td>
<td><img src="image3" alt="product" /></td>
<td>80</td>
<td>99.5:0.5</td>
</tr>
<tr>
<td>6</td>
<td>1e</td>
<td><img src="image2" alt="phosphate" /></td>
<td>C</td>
<td><img src="image3" alt="product" /></td>
<td>84</td>
<td>8:92</td>
</tr>
<tr>
<td>7</td>
<td><img src="image1" alt="alkene" /></td>
<td><img src="image2" alt="phosphate" /></td>
<td>A</td>
<td><img src="image3" alt="product" /></td>
<td>74</td>
<td>97.5:2.5</td>
</tr>
<tr>
<td>8</td>
<td>1f</td>
<td><img src="image2" alt="phosphate" /></td>
<td>C</td>
<td><img src="image3" alt="product" /></td>
<td>95</td>
<td>5:95</td>
</tr>
<tr>
<td>9$'$</td>
<td>1a</td>
<td><img src="image2" alt="phosphate" /></td>
<td>A</td>
<td><img src="image3" alt="product" /></td>
<td>29</td>
<td>97.5:2.5</td>
</tr>
<tr>
<td>10$'$</td>
<td>1a</td>
<td><img src="image2" alt="phosphate" /></td>
<td>C</td>
<td><img src="image3" alt="product" /></td>
<td>70</td>
<td>8:92</td>
</tr>
</tbody>
</table>

$^a$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
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. 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)(OR)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)(OR)\(_2\) 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 \( \text{H-TS} (G \rightarrow \text{H-TS} \rightarrow I) \). 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 \( \rightarrow \) D-TS \( \rightarrow \) 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 \( a\)-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(\( \beta\)) bond and the C(\( \alpha\))–O bond is antiperiplanar as illustrated in Figure 2a, a steric repulsion between the organocopper moiety and the bulky \( \alpha\)-substituent (R\(^3\)) would be significant. On the other hand, such a steric repulsion could be avoided in the cyclic transition state \( \text{H-TS} \) leading to the 1,3-syn stereochemical outcome as shown in Figure 2b.
Figure 2. Stereoelectronic effect models.

a) acyclic mode (anti)  
b) cyclic mode (syn)

favoured under conditions A  
favoured 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. Furthermore, the use of secondary allylic alcohol derivatives as substrates is advantageous to the preparation of allylsilanes that are substituted at the alkene terminus. 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 $^1$H NMR and 75.4 MHz for $^{13}$C NMR. Chemical shift values for $^1$H and $^{13}$C are referenced to Me₄Si and the residual solvent resonances, respectively. Chemical shifts are reported in d 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 Tesque, 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, CHCl₃, 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-butyn-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. 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), n-BuLi (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-dioxygenophosphinane 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 g-silylated allylic alcohol. 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
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.\textsuperscript{24} Copper-catalyzed silylzincation\textsuperscript{19} 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\textsuperscript{®} OD-3 column, 4.6 mm × 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\textsuperscript{®} OD-3 column, 4.6 mm × 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 synthesis\textsuperscript{27} of (S)-1-phenyl-4-hexyn-3-ol from (2S, 3S)-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.\textsuperscript{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.\textsuperscript{24} (S)-3-Octyn-2-ol was reduced with Cp\textsubscript{2}TiCl\textsubscript{2}/i-BuMgBr according to the reported procedure,\textsuperscript{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), "BuLi (1.32 mL, 1.67 M in hexane, 2.2 mmol) was added at –78 °C. After being stirred at –78 °C for 45 minutes at –78 °C, then warmed to room temperature, and stirred for 3 hours. The resulting solution was quenched with saturated NH\textsubscript{4}Cl aq. Aqueous layer was extracted with ethyl acetate, and the combined organic layer was washed with brine, dried over MgSO\textsubscript{4}, 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\textsuperscript{®} 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.\textsuperscript{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.\textsuperscript{24} (S)-2-Octyn-4-ol
was reduced with Cp₂TiCl₂/i-BuMgBr² 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 × 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.¹³

**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 Cp₂TiCl₂/i-BuMgBr² 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 × 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)

![PhMe₂Si-OP-O-P(O)(O)CH₂](image)

(S)/(Z)-3b, 99% ee

The product 3b was purified by GPC. Oil.¹¹H 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$_4$PSiNa, 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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ –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$_4$PSiNa, 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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ –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$_4$NaPSi, 391.1645; found, 391.1647. $[\alpha]_D^{25} +42.7$ (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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ –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), 77.25 (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 C$_{25}$H$_{35}$O$_4$PSiNa, 481.1934; found, 481.1940. $[\alpha]_b^{23}$ +1.52 (c 0.72, CHCl$_3$).

(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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ –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 C$_{21}$H$_{35}$O$_4$PSiNa, 433.1934; found, 433.1937. $[\alpha]_b^{24}$ +30.2 (c 0.96, CHCl$_3$).

(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. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ 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 C$_{13}$H$_{25}$O$_4$PNa, 299.1383; found, 299.1384. $\left[\alpha\right]_D^{23} +71.5$ (c 1.01, CHCl$_3$).

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

The product 3g was purified by GPC. Oil. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 0.87 (s, 3H), 0.89 (t, $J = 6.9$ Hz, 3H), 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 (tt, $J = 10.2$, 1.5 Hz, 1H), 5.70 (dq, $J = 10.2$, 7.2 Hz, 1H). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ 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 C$_{13}$H$_{25}$O$_4$PNa, 299.13827; found, 299.13850. $\left[\alpha\right]_D^{23} +45.1$ (c 1.00, CHCl$_3$).

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

The product 3h was purified by GPC. Oil. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (125.8 MHz, CDCl$_3$) $\delta$ 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 C$_{13}$H$_{25}$O$_4$PNa, 285.1226; found, 285.1225. $\left[\alpha\right]_D^{25} +72.7$ (c 0.98, CHCl$_3$).
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. CH$_2$Cl$_2$ (1.6 mL) and HBF$_4$•OEt$_2$ (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), KHCO$_3$ (85.1 mg, 0.85 mmol), 30% H$_2$O$_2$ 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 Na$_2$S$_2$O$_3$ 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. 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, CHCl$_3$), R isomer: $[\alpha]_D^{26}$ −0.87 (c 0.93, CHCl$_3$), [lit$^{13a}$, S isomer, 70% ee, $[\alpha]_D^{24}$ +1.0 (c 0.8, CHCl$_3$)].

*(E)-Dimethylphenyl(1-phenyl-4-hexen-3-yl)silane (4ab)*

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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: [α]D +11.1 (c 1.03, CHCl₃), R isomer: [α]D –12.4 (c 1.26, CHCl₃). {lit¹⁰, S isomer, 94% ee, [α]D +8.0 (c 1.6, CHCl₃}).

(E)-[(6-Dimethylphenyloxylsilyl-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, 32.85, 32.36, 32.83, 36.45, 123.13, 127.58, 128.81, 132.01, 134.14, 138.48. Anal. Calcd for C₂₅H₄₈O₂Si₂: C, 72.15; H, 11.18%. Found: C, 72.20; H, 11.29%. (+) isomer: [α]D +3.98 (c 1.01, CHCl₃). (–) isomer: [α]D –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 (dd, 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 –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,
7.73%. 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)

![Chemical Structure](image)

The product 4db was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. $^1$H 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, $J = 14.1$, 5.1 Hz, 1H), 5.20 (dq, $J = 14.1$, 4.8 Hz, 1H), 7.33–7.35 (m, 3H), 7.46–7.49 (m, 2H). $^{13}$C 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): [M+Na]$^+$ calcd for C$_{25}$H$_{33}$O$_2$Si, 355.2064; found, 355.2063. (-) isomer: $[\alpha]_D^{23} - 0.30$ (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)

![Chemical Structure](image)

The product 4cc was purified by flash chromatography on silica gel (hexane). Oil. $^1$H 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 (ddd, $J = 15.6$, 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). $^{13}$C 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 C$_{21}$H$_{27}$ClSi: C, 73.54; H, 7.93%. Found: C, 73.93; H, 7.85%. (+) isomer: $[\alpha]_D^{21}$

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+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, hexane, 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]D⁹⁴ −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), followed by Mosher’s NMR spectroscopic method.

**(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,\textsuperscript{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-decanoate (4de)

The product 4de was purified by flash chromatography on silica gel (0–5% EtOAc/hexane). OIl. $^1$H NMR (300 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (75.4 MHz, CDCl$_3$) $\delta$ –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.** Caled for C_{28}H_{40}O_{2}Si: C, 77.01; H, 9.23%. Found: C, 76.74; H, 9.12%. (+) isomer: [α]_{D}^{21} +5.48 (c 1.07, CHCl_{3}). (−) isomer: [α]_{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)**

![Chemical structure](image)

The product 4af was purified by flash chromatography on silica gel (hexane). Oil. \(^1\)H NMR (300 MHz, CDCl\(_3\)) \(\delta\): 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), 7.0–7.14 (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). \(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)) \(\delta\): 93% ee

**HRMS–FI (m/z): [M–OH]⁺**

\(\text{PhMe}_3\text{Si} \quad \text{PhMe}_3\text{Si} \quad \text{Ph} \quad \text{PhMe}_3\text{Si} \quad \text{Ph} \quad \text{PhMe}_3\text{Si} \quad \text{Ph} \quad \text{PhMe}_3\text{Si} \quad \text{Ph} \quad \text{PhMe}_3\text{Si} \quad \text{Ph}

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

![Chemical structure](image)

The product 5ae was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. \(^1\)H NMR (300 MHz, CDCl\(_3\)) \(\delta\): 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). \(^{13}\)C NMR (75.4 MHz, CDCl\(_3\)) \(\delta\): 92% ee

**HRMS–FI (m/z): [M–OH]⁺**
calcd for C_{20}H_{33}, 264.1878; found, 264.1874. \([\alpha]_D^{24} = 1.01\) (c 1.04, CHCl\(_3\)). The ee value was determined by chiral HPLC analysis of the \(p\)-nitrobenzoate derivative obtained by benzylation from 5ae [CHIRALCEL\textsuperscript{®} OD-3 column, 4.6 mm \(\times\) 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. \(^1\text{H NMR}\) (300 MHz, CDCl\(_3\)) \(\delta\) 0.87 (t, \(J = 7.2\) Hz, 3 H), 1.17–1.36 (m, \(J = 12\) H), 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, \(J = 5.1, 1\) H), 5.10 (dd, \(J = 15.0, 8.7, 1.5\) Hz, 1H), 5.27–5.34 (m, 1H). \(^{13}\text{C NMR}\) (75.4 MHz, CDCl\(_3\)) \(\delta\) 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. \(\text{HRMS–ESI (m/z): [M+H]}^+\) calcd for C\(_{16}\)H\(_{23}\)O\(_2\), 255.2324; found, 255.2327. (+) isomer: \([\alpha]_D^{24} = 2.31\) (c 0.83, CHCl\(_3\)), (−) isomer: \([\alpha]_D^{24} = 1.72\) (c 1.15, 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 S5), [CHIRALCEL\textsuperscript{®} OD-3 column, 4.6 mm \(\times\) 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].

\textbf{Scheme 5.}

\((E)-(3\text{-methyl-4-nonen-1-yl})\text{benzene (4ag)}\)

The product 4ag was purified by flash chromatography on silica gel (hexane). Oil. \(^1\text{H NMR}\) (300 MHz, CDCl\(_3\)) \(\delta\) 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). ^13C 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 C$_{16}$H$_{24}$: C, 88.82; H, 11.18%. Found: C, 88.75; H, 11.16%. S isomer: [α]$_D^{21}$ +13.9 (c 1.00, CHCl$_3$), R isomer: [α]$_D^{24}$ -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$^\text{®}$ 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 = 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. [α]$_D^{25}$ $-$18.7 (c 0.70, CHCl$_3$), [lit$^3$] $S$ isomer, >99% ee, [α]$_D^{20}$ $-$18.1 (c 1.03, CHCl$_3$), R isomer, 99% ee, [α]$_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. $^1$H 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 C$_{16}$H$_{30}$O$_2$: C, 75.54; H, 11.89%. Found: C, 75.38; H, 11.68%. (+) isomer: [α]$_D^{22}$ +14.3 (c 1.02, CHCl$_3$), (−) isomer: [α]$_D^{24}$ -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$^\text{®}$ 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.

\[ \textbf{(E)-1,2-dimethoxy-4-(4-methyl-5-decen-1-yl)benzene (4fg)} \]

The product 4fg was purified by flash chromatography on silica gel (0–10% EtOAc/hexane). Oil. \(^1\)H 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). \(^13\)C 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 C₁₉H₂₀O₂: C, 78.57; H, 10.41%. Found: C, 78.48; H, 10.37%. (+) isomer: [α]\(^D\)\(+\)13.1 (c 1.00, CHCl₃). (−) isomer: [α]\(^D\)\(^−\)12.3 (c 1.13, CHCl₃). The ee values were determined by chiral HPLC analysis of corresponding p-nitrobenzoyl derivatives prepared by ozonolysis, reduction with NaBH₄ followed by benzoylation 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.

\[ \textbf{(E)-(3,6-Dimethylhept-7-en-1-yl)benzene (4ah)} \]
The product 4ah was purified by flash chromatography on silica gel (hexane). Oil. \(^1\text{H NMR}\) (300 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 21.04, 22.79, 31.03, 33.68, 36.30, 39.00, 125.51, 128.22, 128.41, 132.68, 136.47, 143.01. \textbf{HRMS–EI} (m/z): [M]\(^+\) calcd for C\(_{15}\)H\(_{22}\), 202.1722; found, 202.1723. (S) isomer: [\(\alpha\)]\(_D\)\(^{24}\) +16.9 (c 0.88, CHCl\(_3\)). (R) isomer: [\(\alpha\)]\(_D\)\(^{24}\) –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 × 250 mm, Daisel Chemical Industries, 2-propanol/hexane 1/99, 0.5 mL/min, 40 °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. [\(\alpha\)]\(_D\)\(^{25}\) +10.6 (c 0.88, CHCl\(_3\)). [lit\(^{30}\), S isomer, >99% ee, [\(\alpha\)]\(_D\)\(^{21}\) –18.1 (c 1.03, CHCl\(_3\)), R isomer, 99% ee, [\(\alpha\)]\(_D\)\(^{23}\) +20.0 (c 1.5, CHCl\(_3\))].

\textbf{Scheme 9.}
References and Notes


(7) For Cu-catalyzed enantioselective allylic substitutions of prochiral γ-silylated primary allylic alcohol derivatives with organozinc or organoaluminum reagents, giving allylsilanes with a terminal alkene moiety, see: (a) Kacprzynski, M. A.; May, T. L.;
For allylic substitutions of chiral $\gamma$-silylated secondary allylic alcohol derivatives with organocopper reagents, giving allylsilanes that are substituted at the alkene terminus, see: refs 3c and d. For palladium-catalyzed allylic substitutions of enantioenriched $\gamma$-silylated secondary allylic alcohol derivatives with organoboronic acids, giving allylsilanes that are substituted at the alkene terminus, see: Li, D.; Tanaka, T.; Ohmiya, H.; Sawamura, M. Org. Lett. 2010, 12, 3344.


For a paper on the synthesis of racemic allylsilanes through the copper-catalyzed coupling between $\gamma$-silylated allylic phosphates and alkylboranes, see: Nagao, K.; Ohmiya, H.; Sawamura, M. Synthesis 2012, 44, 1535.

For the selective conversion of one enantiomer of secondary alcohols into both enantiomers of tertiary alcohols, see: (a) Stymiest, J. L.; Bagutski, V.; French, R. M.; Aggarwal, V. K. Nature 2008, 456, 778. For the Suzuki–Miyaura-type coupling of chiral $\alpha$-(acetylamino)benzylboronic esters, which allows selective conversion of one enantiomer of substrates to both enantiomers, see: (b) Awano, T.; Ohmura, T.; Suginome, M. J. Am. Chem. Soc. 2011, 133, 20738.


(16) The use of a cyclic phosphate as a leaving group markedly improved the efficacy of the 1,3-anti selectivity.

(17) The reaction of (S)-(E)-3b proceeded with significantly decreased E-selectivity (E/Z 71:29) in consistent with the concept of allylic 1,3-strain in acyclic stereocontrol. See: Hoffmann, R. W. Chem. Rev. 1989, 89, 1841.

(18) When the alkene geometry of (S)-(E)-3e was changed to Z [(S)-(Z)-3e, 98% ee], the reactions proceeded with 1,3-syn selectivity to afford (R)-(E)-4ae regardless of which
conditions were used (conditions A, 93% yield, *anti/syn* 18:82; conditions B, 83% yield, *anti/syn* 1.5:98.5). A reason for the biased 1,3-*syn* selectivity is not clear at present.


(22) For discussions on the participation of Lewis acids in enantioselective allylic substitutions catalyzed by copper/N-heterocyclic carbene complexes, see: refs 7b and 13e.


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. Suginome and co-workers reported the palladium- and nickel-catalyzed carboborations of internal alkynes with cyano-1a-d and alkynylboron1e 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. This is mainly due to resistance of the C–B bond in these compounds against oxidative addition to transition metals.

In the author’s study on copper-catalyzed transformations of organoboron compounds (Chapters 1 and 2), 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. 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 PBu₃ as a nucleophilic catalyst, he examined various potential nucleophiles as catalysts for the reaction between 2a and 3a, and PBu₃ was found to be the most effective (Table 1). The use of sterically less demanding PMe₃ or PEt₃ instead of PBu₃ under otherwise identical conditions resulted in significantly decreased substrate conversions and product yields (entries 3 and 4). Bulkier trialkylphosphines such as PCy₃ and P'BU₃ were ineffective (entries 5 and 6). The weaker electron-donors such as PPh₃ 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 NBu₃) with different steric and electronic natures (entries 11–17). The PBu₃ 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 alkylic 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

<table>
<thead>
<tr>
<th>entry</th>
<th>catalyst</th>
<th>yield (%)ᵇ</th>
<th>entry</th>
<th>catalyst</th>
<th>yield</th>
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<tr>
<td>1</td>
<td>PBu₃ (eq 1)</td>
<td>99 (95)</td>
<td>10</td>
<td>DCYPE</td>
<td>7</td>
</tr>
<tr>
<td>2</td>
<td>PBu₃ (5 mol%)</td>
<td>99 (95)</td>
<td>11</td>
<td>SIMe</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>PMe₃</td>
<td>48</td>
<td>12</td>
<td>SiCy</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>PEt₃</td>
<td>29</td>
<td>13</td>
<td>IMes</td>
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<tr>
<td>5</td>
<td>PCy₃</td>
<td>0</td>
<td>14</td>
<td>DABCO</td>
<td>0</td>
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<tr>
<td>6</td>
<td>PBu₃</td>
<td>0</td>
<td>15</td>
<td>DBU</td>
<td>0</td>
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<tr>
<td>7</td>
<td>PPh₃</td>
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<td>16</td>
<td>DMAP</td>
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<tr>
<td>8</td>
<td>P(OPh)₃</td>
<td>0</td>
<td>17</td>
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</tr>
<tr>
<td>9</td>
<td>DPPE</td>
<td>0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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; PBu₃, 10 mol %; THF, 80 °C, 8 h. ¹H 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 PBu₃ 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). The reaction of 1,3-enyne derivative 3f occurred regioselectively to afford a conjugated 2,4-dienoate (4af) (entry 5). 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).

Table 2. Scope of alkynoates.

<table>
<thead>
<tr>
<th>entry</th>
<th>alkynoate</th>
<th>product</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>EtO₂C≡C≡O₃Me</td>
<td>4ab</td>
<td>89</td>
</tr>
<tr>
<td>2</td>
<td>EtO₂C≡C≡F</td>
<td>4ac</td>
<td>91</td>
</tr>
<tr>
<td>3</td>
<td>EtO₂C≡C≡S</td>
<td>4ad</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>EtO₂C≡C≡O₃Me</td>
<td>4ae</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EtO₂C≡C≡F</td>
<td>4af</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EtO₂C≡C≡S</td>
<td>4ad</td>
<td></td>
</tr>
</tbody>
</table>
Various terminal alkenes were subjected to 9-BBN-hydroboration and were used for carboxoboration 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 a carbon atom of the alkyne in high yield (87%). However, the carboxoboration with Et₃B resulted in a lower product yield (47%) (eq 2).
Table 3. Scope of alkylboranes.\textsuperscript{a}

\begin{tabular}{llll}
\hline
entry & alkene & product & yield \\
\hline
1 & Cl-1b & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 87 \\
2 & MeO-1c & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 80 \\
3 & Cl-1d & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 80 \\
4 & EtO-1e & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 87 \\
5 & N-1f & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 98 \\
6 & MeO-1g & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 96 \\
7 & BnO-1h & \begin{tikzpicture}
  \node at (0,0) {\includegraphics[width=0.5\textwidth]{alkene.png}};
\end{tikzpicture} & 94 \\
\hline
\end{tabular}

\textsuperscript{a} Reactions performed in THF, 80 °C, 1 h, or THF, 80 °C, 8 h with cat. PBu$_3$.
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.\(^a\)

<table>
<thead>
<tr>
<th>entry</th>
<th>organoborane</th>
<th>product</th>
<th>yield (%)(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2l</td>
<td>4la</td>
<td>34 (75)(^c)</td>
</tr>
<tr>
<td>2</td>
<td>2m</td>
<td>4ma</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>2n</td>
<td>4na</td>
<td>93</td>
</tr>
<tr>
<td>4</td>
<td>2o</td>
<td>4oa</td>
<td>64</td>
</tr>
<tr>
<td>5</td>
<td>2p</td>
<td>4pa</td>
<td>91</td>
</tr>
</tbody>
</table>

\(^a\)Conditions of carboboration reaction: 3a, 0.3 mmol; 2, 0.3 mmol; PBu\(_3\), 10 mol % (entries 1–3 and 5) or 20 mol % (entry 4); THF, 80 °C, 8 h. \(^b\)Yield of the isolated product (silica gel chromatography). \(^c\)\(^{1}\)H NMR yield is in parentheses. \(^c\)The isolated yield was significantly reduced as compared with the \(^{1}\)H 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 PBu\(_3\) 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') 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$_3$P 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 \textit{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 $^1$H NMR, 100.5 MHz for $^{13}$C NMR and 128 MHz for $^{11}$B NMR. Chemical shift values for $^1$H and $^{13}$C are referenced to Me$_4$Si, the residual solvent resonances and BF$_3$•OEt$_2$, respectively. Chemical shifts are reported in $\delta$ 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 60F$_{254}$. 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 is. PBu$_3$ was purchased from Kanto Chemical Co., stored under nitrogen, and used as is. THF was purchased from Kanto Chemical Co., stored under argon. Alkynoates $3_b$, $3_c$, $3_d$ and $3_e$ are known compounds.$^5$ These alkynoates were prepared by the reaction between the corresponding lithium acetylides and ethyl chloroformate. Alkynoates $3_a$, $3_g$ and $3_h$ were purchased from TCI Chemical Co., stored under nitrogen, and used as it is. Alkenes $1_a$–$h$, $1_j$ and $1_k$ are known compounds.$^{13}$ Alkene $1_l$ was prepared from ethyl (−)-lactate through silylation, reduction followed by Wittig reaction. Alkenyllborane $2_l$ was prepared in advance through hydroboration of $1_l$ with (9-BBN-H)$_2$ at 60 °C (1 h) and used without purification. Alkenyllborane $2_m$$^{14}$ and arylboranes $2_n$–$p$$^{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

\((S)-(3-\text{Buten}-2-\text{yloxy})\text{triisopropylsilane (1i)\)}

\[
\text{Pr}_3\text{SiO} = \bullet
\]

Colorless Oil. IR (neat) 761, 881, 919, 989, 1091, 1154, 1257, 1368, 1464, 2867, 2893, 2944 cm\(^{-1}\). \(\text{^1}H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(\text{^13}C\) NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 12.30, 18.06, 24.68, 69.62, 112.29, 142.25. 

\[\alpha\]\(_D\)\(^{23}\) +4.16 (c 0.45, CHCl\(_3\)). HRMS–EI (m/z): [M]\(^+\) calcd for C\(_{13}\)H\(_{28}\)OSi, 229.19822; found, 229.19861.

\((E)-\text{Ethyl 5-(4-Methoxyphenyl)-4-penten-2-ynoate (3f)}\)

Yellow oil. IR (neat) 812, 1028, 1089, 1173, 1247, 1366, 1510, 1599, 1697, 2200, 2839, 2937, 2982 cm\(^{-1}\). \(\text{^1}H\) NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(\text{^13}C\) NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 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): [M]\(^+\) calcd for C\(_{14}\)H\(_{14}\)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\(^\circledR\)-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 µL, 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. PBu_3 (148 µL, 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 CH_2Cl_2/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), PBu_3 (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 CH_2Cl_2/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, CDCl_3) 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, CDCl_3) 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, CDCl_3) δ 12.4. HRMS–EI (m/z): [M]^+ calcd for C_{23}H_{33}BO_2, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) δ 14.12, 24.67, 24.70, 25.95, 26.10, 32.04, 33.03, 35.41, 55.10, 113.17, 125.47, 125.54 125.84, 128.15, 128.65, 135.37, 141.36, 157.57, 178.82. A signal for the sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 12.6. HRMS–EI (m/z): [M]⁺ calcd for C₂₈H₃₅BO₃, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) δ 14.10, 24.61, 24.63, 25.89, 26.17, 32.03, 32.96, 35.25, 66.23, 114.64 (d, J_C–F = 21.0 Hz), 125.75 (2C), 125.88 (d, J_C–F = 10.5 Hz), 128.20, 128.69, 138.81 (d, J_C–F = 2.8 Hz), 141.09, 161.09 (d, J_C–F = 243.3 Hz), 178.69. A signal for the sp²-carbon directly attached to the
boron atom was not observed. $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 12.4. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{27}$H$_{32}$BF$_2$O$_2$, 418.24794; found, 418.24804.

**(E)-Ethyl 2-(9-Borabicyclo[3.3.1]nonan-9-yl(5-methylthiophen-2-yl)methylene)-4-phenylbutanoate (4ad)**

![Chemical Structure](image)

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, 1444, 1474, 1521, 1592, 1736, 2831, 2847, 2917 cm$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 0.76 (s, 2H), 1.41 (t, $J = 6.8$ Hz, 3H), 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$_3$) $\delta$ 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$_3$) $\delta$ 12.4. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{26}$H$_{33}$BO$_2$S, 420.22943; found, 420.22893.

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

![Chemical Structure](image)

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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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): [M]$^+$ calcd for C$_{28}$H$_{35}$BO$_2$, 414.27301; found, 414.27319.

**$(2E,4E)$-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$^{-1}$. $^1$H 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): [M]$^+$ calcd for C$_{30}$H$_{37}$BO$_3$, 456.28357; found, 456.28373.

**$(E)$-Ethyl 3-{(9-Borabicyclo[3.3.1]nonan-9-yl)-2-phenethyl-2-butenoate (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$^{-1}$. $^1$H 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): [M]$^+$ calcd for C$_{22}$H$_{31}$BO$_2$, 338.24171; found, 338.24149.

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

![Structural diagram for 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$^{-1}$. $^1$H 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): [M]$^+$ calcd for C$_{23}$H$_{33}$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)

![Structural diagram for 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$^{-1}$. $^1$H 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. \(^{11}\text{B NMR}\) (128 MHz, CDCl\(_3\)) \(\delta\) 13.1. \textit{HRMS–EI (m/z)}: [M]\(^+\) calecd for C\(_{27}\)H\(_{32}\)BClO\(_2\), 434.21839; found, 434.21830.

\((E)\)\textsuperscript{-}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. \textit{IR} (neat) 751, 1155, 1258, 1346, 1384, 1430, 1515, 1590, 1736, 2837, 2932 cm\(^{-1}\). \(^{1}\text{H NMR}\) (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^{13}\text{C NMR}\) (100.5 MHz, CDCl\(_3\)) \(\delta\) 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. \(^{11}\text{B NMR}\) (128 MHz, CDCl\(_3\)) \(\delta\) 13.0. \textit{HRMS–EI (m/z)}: [M]\(^+\) calecd for C\(_{30}\)H\(_{39}\)BO\(_4\), 474.29414; found, 474.29313.

\((E)\)\textsuperscript{-}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. \textit{IR} (neat) 702, 760, 1012, 1276, 1346, 1384, 1429, 1525, 1590, 1736, 2842, 2922, 2981 cm\(^{-1}\). \(^{1}\text{H NMR}\) (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^{13}\text{C NMR}\) (100.5 MHz, CDCl\(_3\)) \(\delta\) 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$_3$) $\delta$ 12.4. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{25}$H$_{36}$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, 1346, 1384, 1431, 1527, 1591, 2842, 2875, 2921, 2976 cm$^{-1}$. $^1$H NMR (400 MHz, CD$_2$Cl$_2$) $\delta$ 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$_2$Cl$_2$) $\delta$ 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$_2$Cl$_2$) $\delta$ 12.4. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{26}$H$_{39}$BO$_4$, 426.29414; found, 429.29377.

(E)-Ethyl 2-(9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene)-7-(1,3-dioxoisindolin-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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 14.14, 23.89, 24.64, 25.88, 26.29, 28.17, 28.52, 32.00,
A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 13.0. **HRMS–EI (m/z):** [M]⁺ calcd for C₃₂H₃₈BNO₄, 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)**

![Image of 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, CDCl₃) 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). **¹³C NMR** (100.5 MHz, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 12.2. **HRMS–EI (m/z):** [M]⁺ calcd for C₂₇H₃₉BO₄, 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)**

![Image of 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, CDCl₃) 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$_3$) $\delta$ 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$_3$) $\delta$ 13.7. [$\alpha$]$_D^{23}$ –42.5 (c 1.00, CHCl$_3$). HRMS–EI (m/z): [M]$^+$ calcd for C$_{33}$H$_{42}$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, 1347, 1432, 1526, 1592, 2844, 2865, 2922 cm$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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$_3$) $\delta$ 12.5. [$\alpha$]$_D^{23}$ –17.4 (c 1.15, CHCl$_3$). HRMS–EI (m/z): [M]$^+$ calcd for C$_{52}$H$_{62}$BO$_3$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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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 sp²-carbon directly attached to the boron atom was not observed. $^{11}$B NMR (128 MHz, CDCl₃) δ 10.8. HRMS–EI (m/z): [M]$^{+}$ calcd for C₂₅H₃₅BO₂, 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. $^1$H NMR (400 MHz, CDCl₃) 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, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. $^{11}$B NMR (128 MHz, CDCl₃) δ 12.3. HRMS–EI (m/z): [M]$^{+}$ calcd for C₂₁H₂₉BO₂, 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. $^1$H NMR (400 MHz, CDCl₃) 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, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. $^{11}$B NMR (128 MHz, CDCl₃) δ 11.2. HRMS–EI (m/z): [M]$^{+}$ calcd for C₁₇H₂₅BO₂, 272.19476; found, 272.19402.
(2E,3E)-Ethyl 2-(9-Borabicyclo[3.3.1]nonan-9-yl(phenyl)methylene)-4-phenyl-3-butenoate (4ia)

The product 4ia 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, 1435, 1448, 1568, 1736, 2841, 2871, 2912 cm⁻¹. \( ^1H \) NMR (400 MHz, CDCl₃) \( \delta \) 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). \( ^13C \) NMR (100.5 MHz, CDCl₃) \( \delta \) 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, CDCl₃) \( \delta \) 12.3. HRMS–EI (m/z): [M]+ calcd for C₂₇H₃₁BO₂, 398.24171; found, 398.24154.

(2E,3E)-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, CDCl₃) \( \delta \) 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). \( ^13C \) NMR (100.5 MHz, CDCl₃) \( \delta \) 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, CDCl₃) \( \delta \) 11.8. HRMS–EI (m/z): [M]+ calcd for C₂₅H₃₅BO₂, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 13.1. HRMS–EI (m/z): [M]+ calcd for C₂₅H₂₉BO₂, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 12.9. HRMS–EI (m/z): [M]+ calcd for C₂₆H₃₁BO₃, 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, 1434, 1504, 1581, 1735, 2834, 2855, 2913 cm⁻¹. \(^1\)H NMR (400 MHz, CDCl₃) 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), 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, CDCl₃) δ 14.11, 24.57, 26.10, 31.93, 33.07, 66.82, 114.70 (d, J_C-F = 21.1 Hz), 125.01, 125.53, 125.90, 127.72, 127.88 (d, J_C-F = 3.9 Hz), 131.34 (d, J_C-F = 7.7 Hz), 142.63, 161.58 (d, J_C-F = 246.3 Hz), 177.49. A signal for the sp²-carbon directly attached to the boron atom was not observed. \(^{11}\)B NMR (128 MHz, CDCl₃) δ 12.8. HRMS–EI (m/z): [M]⁺ calcd for C₂₅H₂₈BFO₂, 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 MeNH₂ (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. \(^1\)H NMR (400 MHz, CDCl₃) 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, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. \(^{11}\)B NMR (128 MHz, CDCl₃) δ 10.7. HRMS–EI (m/z): [M]⁺ calcd for C₂₅H₃₂BNO₂, 385.25756; found, 385.25769.

To a suspension of 4aa (38.1 mg, 0.099 mmol), Pd(PPh₃)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 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 (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, 3238 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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): [M]⁺ calcd for C₂₅H₂₅NO, 355.19361; found, 355.19203.

**X-ray Crystallographic Analysis**

Data were collected on a Rigaku Mercury CCD diffractometer with graphite monochromated Mo-Kα radiation (λ = 0.71075 Å) at 150 K, and processed using the CrystalClear software. Structures were solved by a direct method using SIR2004, and refined by full-matrix least-square method using SHELXL-97. 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. 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 CH₂Cl₂/EtOH). C₂₇H₃₃BO₂, M = 400.37, triclinic, space group P1 (#2), a = 10.023(14) Å, b = 10.902(17) Å, c = 11.848(17) Å, α = 108.72(3), β = 92.751(3), γ = 109.02(3), V = 1142(3) Å³, Z = 2, density (calc.) = 1.164, total
reflections collected = 8405, unique reflections = 4414 ($R_{int} = 0.0697$), GOF = 0.990, $R_1 = 0.0831$ ($I>2\sigma(I)$), $wR_2 = 0.2592$. 
References and Notes


(2) For a review on the synthesis of multisubstituted alkenes, see: Flynn, A. B.; Ogilvie, W. W. Chem. Rev. 2007, 107, 4698.


(4) For a proposed C–B oxidative addition to Ni(0) in the hydroarylation of internal alkynes with arylboronates, see: Shirakawa, E.; Takahashi, G.; Tsuchimoto, T.; Kawakami, Y. Chem. Commun. 2001, 2688.


(7) For Cu-catalyzed carboborations of internal alkynes with bis(pinacolato) diboron and carbon electrophiles, see: (a) Alfaro, R.; Parra, A.; Alemán, J.; Ruano, J. L. G.; Tortosa, M. J. Am.


For Table 2, entries 4 and 5, unreacted alkynoate was detected in the crude materials. For Table 2, entries 6 and 7, the conversion of 3g and 3h was 100% with unidentified compounds observed in the crude materials.


(18) G. M. Sheldrick, SHELX97, University of Göttingen, Germany, 1997.

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 silylborons (Si–B), diborons (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.\(^9\)\(^a\) Recently, Uchiyama, Hirano, and co-workers reported the completely anti-selective diboration of the C–C triple bond in propargylic alkoxide anions.\(^9\)\(^b\)

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 PhMe₂SiB(pin) have been used as reagents for protoboration or protosilylation of electron-deficient alkenes under metal-free Lewis-base-catalyzed conditions. 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. 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.

Results and Discussion

The reaction of ethyl 3-phenylpropionate (2a) (1.1 g, 6 mmol) with PhMe₂SiB(pin) (1a) (1.57 g, 6 mmol) in the presence of PBu₃ (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 ¹¹B NMR spectrum of 3aa indicated that the carbonyl oxygen was coordinated with the boron atom.

![Equation 1](attachment:image.png)

The result of other catalyst screening was shown in Table 1. It revealed that sterically less hindered trialkylphosphines, PMe₃ and PEt₃ were useful, PBu₃ being the most effective (Table 1, entries 1, 3 and 4). Bulkier trialkylphosphines such as PCy₃ and P’Bu₃ were ineffective (entries 5 and 6). The weaker electron-donors such as PPh₃ or P(OPh)₃ and bisp phosphines also resulted in no reaction (entries 7-10). No reaction occurred with N-heterocyclic carbenes (NHCs) or amines (DABCO, DBU, DMAP and NBu₃) with different steric and electronic natures (entries 11-17). The PBu₃ 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.\textsuperscript{a}

<table>
<thead>
<tr>
<th>entry</th>
<th>catalyst</th>
<th>yield (%)\textsuperscript{b}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PBu\textsubscript{3}</td>
<td>99</td>
</tr>
<tr>
<td>2</td>
<td>PBu\textsubscript{3} (5 mol%)</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>PMe\textsubscript{3}</td>
<td>20</td>
</tr>
<tr>
<td>4</td>
<td>PEt\textsubscript{3}</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>PCy\textsubscript{3}</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>P′Bu\textsubscript{3}</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>PPh\textsubscript{3}</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>P(OPh)\textsubscript{3}</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>DPPE</td>
<td>0</td>
</tr>
<tr>
<td>10</td>
<td>DCYPE</td>
<td>0</td>
</tr>
<tr>
<td>11</td>
<td>SIMe</td>
<td>0</td>
</tr>
<tr>
<td>12</td>
<td>SICy</td>
<td>0</td>
</tr>
<tr>
<td>13</td>
<td>IMes</td>
<td>0</td>
</tr>
<tr>
<td>14</td>
<td>DABCO</td>
<td>0</td>
</tr>
<tr>
<td>15</td>
<td>DBU</td>
<td>0</td>
</tr>
<tr>
<td>16</td>
<td>DMAP</td>
<td>0</td>
</tr>
<tr>
<td>17</td>
<td>NBu\textsubscript{3}</td>
<td>0</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Conditions of silaboration reaction: 2a, 0.3 mmol; 1a, 0.3 mmol; catalyst, 10 mol %; 80 °C, 8 h. \textsuperscript{b}\textsuperscript{1}H NMR yield.

The scope of the phosphine-catalyzed silaboration is shown in Table 2. The reaction of (i-PrO)Me\textsubscript{2}SiB(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 PhMe\textsubscript{2}SiB(pin) (1a) in high yields (entries 2–7). Alkyl-substituted alkynoates 2h–l also underwent efficient silaboration (entries 8–12).\textsuperscript{14}
Table 2. Phosphine-catalyzed silaboration

<table>
<thead>
<tr>
<th>entry</th>
<th>silylboron</th>
<th>alkynoate</th>
<th>product</th>
<th>yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(PrO)Me₂Si-Bpin</td>
<td>2a</td>
<td>3ba</td>
<td>96</td>
</tr>
<tr>
<td>2</td>
<td>1a</td>
<td>2b</td>
<td>3ab</td>
<td>99</td>
</tr>
<tr>
<td>3</td>
<td>1a</td>
<td>2c</td>
<td>3ac</td>
<td>92</td>
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<td>4</td>
<td>1a</td>
<td>2d</td>
<td>3ad</td>
<td>77</td>
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<td>5</td>
<td>1a</td>
<td>2e</td>
<td>3ae</td>
<td>76</td>
</tr>
<tr>
<td>6</td>
<td>1a</td>
<td>2f</td>
<td>3af</td>
<td>76&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>7</td>
<td>1a</td>
<td>2g</td>
<td>3ag</td>
<td>94</td>
</tr>
</tbody>
</table>
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 $^{11}$B 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-butynoate 2h and 2-pentynoate 2i gave alkyl-substituted alkenylboranes 5ah and 5ai, respectively, in good yields (entries 8 and 9).
Table 3. Phosphine-catalyzed diboration

<table>
<thead>
<tr>
<th>entry</th>
<th>alkynoate</th>
<th>product</th>
<th>yield (%)&lt;sup&gt;b,c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;d&lt;/sup&gt;</td>
<td>2a</td>
<td><img src="image" alt="Product 5aa" /></td>
<td>97 (64)</td>
</tr>
<tr>
<td>2</td>
<td>2b</td>
<td><img src="image" alt="Product 5ab" /></td>
<td>99 (82)</td>
</tr>
<tr>
<td>3</td>
<td>2c</td>
<td><img src="image" alt="Product 5ac" /></td>
<td>99 (70)</td>
</tr>
<tr>
<td>4</td>
<td>2d</td>
<td><img src="image" alt="Product 5ad" /></td>
<td>71 (56)</td>
</tr>
<tr>
<td>5</td>
<td>2e</td>
<td><img src="image" alt="Product 5ae" /></td>
<td>83 (70)</td>
</tr>
<tr>
<td>6&lt;sup&gt;e&lt;/sup&gt;</td>
<td>2f</td>
<td><img src="image" alt="Product 5af" /></td>
<td>93 (78)</td>
</tr>
<tr>
<td>7</td>
<td>2g</td>
<td><img src="image" alt="Product 5ag" /></td>
<td>99 (68)</td>
</tr>
</tbody>
</table>
A possible catalytic cycle for the silaboration and diboration is illustrated in Figure 2. As proposed for the carboxylation of alkynoates with organoboranes, the phosphine catalysis should be initiated by the conjugate addition of PBU₃ to the alkynoate 2 with the assistance of Lewis-acidic activation of the carbonyl group to form a zwitterionic allenolate intermediate (A). 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). Next, the ylide carbon of B2 attacks the B atom bound to the enolate oxygen to form cyclic borate C. Finally, elimination of Bu₃P associated with B–O cleavage affords 3 or 5.

Figure 2. A possible catalytic cycle.
The two vicinally installed heteroatom substituents of the $\beta$-boryl-$\alpha$-silylacrylates and $\alpha,\beta$-diborylacrylates could be differentiated and transformed in a stepwise manner (eqs 2–4). For example, $\beta$-boryl-$\alpha$-silylacrylate $3\text{aa}$ underwent Suzuki–Miyaura coupling with 1-bromo-4-fluorobenzene at the boron site [Pd(OAc)$_2$–DtBPF (1,1′-bis(di-tert-butylphosphino)ferrocene) catalyst/K$_3$PO$_4$] to afford the corresponding trisubstituted alkenylsilane $6\text{aa}$ with excellent yield and complete $E$ selectivity; the C–Si bond remained untouched (eq 2). The obtained $6\text{aa}$ could be derivatized to the trisubstituted alkenyl bromide $7\text{aa}$ without $E/Z$ isomerization.\textsuperscript{17}

He was delighted to find that the two boron sites in $5\text{aa}$ could be efficiently differentiated for a stepwise twofold cross-coupling. Thus, the cross-coupling between the $\alpha,\beta$-diborylacrylate $5\text{aa}$ and 4-bromoanisole under the influence of a Pd(OAc)$_2$–DtBPF catalyst and $i$-Pr$_2$NEt base occurred selectively at the $\alpha$-boron site to give alkenylboronate $8\text{aa}$ ($83\%$, $E/Z > 99:1$), and no diarylation occurred (eq 3).\textsuperscript{18} The second arylation with 4-bromotoluene ($Z/E > 99:1$) was possible by subjecting $8\text{aa}$ to the coupling conditions using the Pd(OAc)$_2$/DtBPF/K$_3$PO$_4$ system: isomerically pure tetrasubstituted alkene $9\text{aa}$ was obtained in good yield (eq 3). The site-selectivity in the first cross-coupling favoring C($\alpha$)–B bond transformation is likely due to the electron-withdrawing resonance effect of the ester group rendering C($\beta$) less nucleophilic. Additionally, the $\alpha,\beta$-diborylacrylate $5\text{aa}$ underwent site-selective Rh-catalyzed conjugate addition to tert-butyl acrylate followed by Pd-catalyzed cross-coupling with 4-bromoanisole to produce tetrasubstituted alkene $11\text{aa}$ (eq 4). Overall, these transformations (eqs 2–4) demonstrated the usefulness of the $\beta$-boryl-$\alpha$-silylacrylates and $\alpha,\beta$-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).

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–d in isomerically pure forms. The reduction of the ester group in 9af (Ar1 = Ar2 = Ph) with DIBAL-H produced the alcohol 12af-a. The synthesis of (Z)-tamoxifen from 12af-a was reported previously. Thus, a formal total synthesis of (Z)-tamoxifen was achieved.
Scheme 1. Synthesis of tamoxifen-type compounds.

**Scheme Diagram**

- **5af**
  - DIBAL-H (3 equiv)
  - DCM
  - -78 °C
  - 3 h
  - 12af-a, 89%

- **ref 20c,i,l**

- **9af-a**
  - Ar^1-Br (1.1 equiv)
  - Pd(OAc)_2 (5 mol %)
  - DiBPF (6 mol %)
  - i-Pr_2NEt (3 equiv)
  - H_2O (17 equiv), THF
  - rt, 1.5 h
  - 9af-a, 73%

- **9af-b**
  - (Ar^1 = Ph, Ar^2 = 4-MeOC_6H_4), 65%

- **9af-c**
  - (Ar^1 = 4-FC_6H_4, Ar^2 = 4-NO_2C_6H_4), 55%

- **9af-d**
  - (Ar^1 = Ph, Ar^2 = 3-thienyl), 64%

**9af-a-d**

**EtO**

**PinB**

**Ar**

**O**

**NMe_2**

**E/Z >98:1**

**Scheme Text**

- **5af**
  - DIBAL-H (3 equiv)
  - DCM
  - -78 °C
  - 3 h
  - 12af-a, 89%

- **ref 20c,i,l**

- **9af-a**
  - Ar^1-Br (1.1 equiv)
  - Pd(OAc)_2 (5 mol %)
  - DiBPF (6 mol %)
  - i-Pr_2NEt (3 equiv)
  - H_2O (17 equiv), THF
  - rt, 1.5 h
  - 9af-a, 73%

- **9af-b**
  - (Ar^1 = Ph, Ar^2 = 4-MeOC_6H_4), 65%

- **9af-c**
  - (Ar^1 = 4-FC_6H_4, Ar^2 = 4-NO_2C_6H_4), 55%

- **9af-d**
  - (Ar^1 = Ph, Ar^2 = 3-thienyl), 64%
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 $^1$H NMR, 100.5 MHz for $^{13}$C NMR and 128 MHz for $^{11}$B NMR. Chemical shift values for $^1$H and $^{13}$C are referenced to Me$_4$Si, the residual solvent resonances and BF$_3$•OEt$_2$, respectively. Chemical shifts are reported in $\delta$ 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 60F$_{254}$. 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 2i$^{21}$ 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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 1.37 (t, \(J = 7.2\) Hz, 3H), 2.62 (s, 3H), 4.32 (q, \(J = 7.2\) Hz, 2H), 7.50 (t, \(J = 8.0\) Hz, 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\(_3\)) \(\delta\) 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 \((m/z)\): [M]\(^+\) calcd for C\(_{13}\)H\(_{12}\)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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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, \(J = 8.0\) Hz, 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\(_3\)) \(\delta\) 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 \((m/z)\): [M]\(^+\) calcd for C\(_{14}\)H\(_{14}\)O\(_4\), 246.08921; found, 246.08849.

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

White solid. M.p. 36–37 °C. IR (neat) 747, 835, 1022, 1170, 1198, 1287, 1513, 1601, 1692, 2199, 2771, 2815, 2970 cm\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 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 \((m/z)\): [M+H]\(^+\) calcd for C\(_{15}\)H\(_{20}\)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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) –0.74, 9.07, 13.95, 61.57, 68.43, 92.94, 153.71. HRMS–EI (m/z): [M]\(^+\) calcd for C\(_8\)H\(_{10}\)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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) –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): [M+Na]\(^+\) calcd for C\(_{15}\)H\(_{28}\)O\(_3\)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\(^\circledR\)-coated silicon rubber septum and the vial was evacuated and filled with argon. PBu\(_3\) (7.4 \(\mu\)L, 0.03 mmol) was added to the vial. After 8 h stirring at 80 °C, the mixture was 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\(^\circledR\)-coated silicon rubber septum and the vial was evacuated and filled with argon. PBu\(_3\) (148 \(\mu\)L, 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 µL) and P Bu₃ (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 µL) and P Bu₃ (22.2 µL, 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)

![Chemical Structure](image)

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 sp²-carbon directly attached to the boron
atom was not observed. $^{11}$B NMR (128 MHz, CDCl$_3$) $\delta$ 24.0. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{25}$H$_{33}$BO$_4$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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ –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$_3$) $\delta$ 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$_3$) $\delta$ 23.6. HRMS–ESI ($m/z$): [M+Na]$^+$ calcd for C$_{22}$H$_{35}$BO$_5$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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ –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$_3$) $\delta$ 23.2. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{26}$H$_{35}$BO$_5$Si, 466.23468; found, 466.23442. The regio- and stereochemistries were assigned by consideration of the reaction pathway.

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

![Diagram of 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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ –1.20, 13.87, 24.85, 63.68, 82.57, 114.52 (d, $J_{C\text{-F}} = 21.0$ Hz), 127.52, 128.50 (d, $J_{C\text{-F}} = 7.2$ Hz), 128.77, 133.65, 136.20 (d, $J_{C\text{-F}} = 3.0$ Hz), 137.00, 138.31, 162.35 (d, $J_{C\text{-F}} = 246.2$ 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$_3$) $\delta$ 23.9. HRMS–EI ($m/z$): [M]$^+$ calcd for C$_{25}$H$_{32}$BFO$_4$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)

![Diagram of 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$^{-1}$. $^1$H 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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^1\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) –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. \(^1\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 23.8. HRMS–ESI (m/z): [M+H]\(^+\) calcd for C\(_{29}\)H\(_{43}\)BNO\(_5\)Si, 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)**

![Structure of 3ag](image)

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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^1\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) –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. \(^1\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 21.9. HRMS–EI (m/z): [M]’ calcd for C\(_{24}\)H\(_{33}\)BO\(_4\)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-butenoate (3ah)**

![Structure of 3ah](image)
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, CDCl3) 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). 13C NMR (100.5 MHz, CDCl3) 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 sp2-carbon directly attached to the boron atom was not observed. 11B NMR (128 MHz, CDCl3) δ 21.4. HRMS–EI (m/z): [M]+ calcd for C20H31BO4Si, 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.3k

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

![Diagram of 3ai](image)

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, CDCl3) 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). 13C NMR (100.5 MHz, CDCl3) 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 sp2-carbon directly attached to the boron atom was not observed. 11B NMR (128 MHz, CDCl3) δ 23.4. HRMS–EI (m/z): [M]+ calcd for C21H33BO4Si, 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)

![Diagram of 3aj](image)
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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) –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\(_3\)) \(\delta\) 20.7. HRMS–EI (m/z): [M]\(^+\) calcld for C\(_{22}\)H\(_{33}\)BO\(_3\)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)

![3ak](image)

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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) –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\(_3\)) \(\delta\) –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\(_3\)) \(\delta\) 23.6. HRMS–EI (m/z): [M–’Bu]\(^+\) calcld for C\(_{25}\)H\(_{42}\)BO\(_5\)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-ylxyloxy)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-2-hexenoate (3al)

![3al](image)
The product 3al 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 23.0. HRMS–ESI (m/z): [M+Na]⁺ calcd for C₂₇H₄₃BO₆SiNa, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbons directly attached to the boron atoms were not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 29.6 (× 2B). HRMS–EI (m/z): [M⁺] calcd for C₂₃H₃₄B₂O₆, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) δ 14.06, 24.48, 24.95, 55.19, 83.41, 83.70, 113.52, 129.21, 132.63, 159.91, 171.14. Two signals for the sp²-carbons directly attached to the boron atoms were not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 29.5. HRMS–EI (m/z): [M]+ calcd for C₂₄H₃₆B₂O₇, 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)

![Structure of 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) δ 14.05, 24.44, 24.86, 61.54, 83.60, 83.86, 115.06 (d, J_C-F = 22.0 Hz), 129.41 (d, J_C-F = 8.6 Hz), 136.11 (d, J_C-F = 2.9 Hz), 162.87 (d, J_C-F = 271.4 Hz), 170.73. Two signals for the sp²-carbons directly attached to the boron atoms were not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 29.6. HRMS–EI (m/z): [M]+ calcd for C₂₃H₃₃B₂FO₆, 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)

![Structure of 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, 1363, 1402, 1432, 1502, 1574, 1682, 1702, 2981 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbons directly attached to the boron atoms were not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 29.1. HRMS–EI (m/z): [M]+ calcd for C₂₅H₃₆B₂O₇, 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, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) δ 14.05, 14.29, 24.41, 24.85, 26.61, 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 sp²-carbons directly attached to the boron atoms were not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 29.1. HRMS–EI (m/z): [M]+ calcd for C₂₆H₃₈B₂O₈, 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. H 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). IR (neat) 830, 1140, 1247, 1321, 1370, 1458, 1510, 1603, 1693, 2777, 2822, 2929, 2978 cm⁻¹. H 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, 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 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)

![Image](image.png)

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. H 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-butenoate (5ah)

![Image](image.png)

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. H NMR (400 MHz, CDCl₃) δ 1.26–1.28 (m, 15H), 1.30 (s, 12H), 2.08 (s, 3H), 4.25 (q, J
C NMR (100.5 MHz, CDCl$_3$) $\delta$ 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. B NMR (128 MHz, CDCl$_3$) $\delta$ 29.7. HRMS–ESI (m/z): [M+Na]$^+$ calcd for C$_{18}$H$_{32}$B$_2$O$_6$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$^{-1}$. H NMR (400 MHz, CDCl$_3$) $\delta$ 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). C NMR (100.5 MHz, CDCl$_3$) $\delta$ 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. B NMR (128 MHz, CDCl$_3$) $\delta$ 29.4. HRMS–ESI (m/z): [M+Na]$^+$ calcd for C$_{19}$H$_{34}$B$_2$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 Pd(OAc)$_2$ (1.1 mg, 5.0 µmol) and DtBPF (2.8 mg, 6.0 µmol) in toluene (0.6 mL) was added K$_3$PO$_4$ (42.4 mg, 0.2 mmol), H$_2$O (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$_4$Cl 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. 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 (1.1 mg, 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)

![Structure of 6aa](image)

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)

![Structure of 7aa](image)

The product 7aa was consistent with the literature data.**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$_3$) $\delta$ 13.60, 62.13, 110.59, 115.31 (d, $J_{C,F} = 22.0$ Hz), 128.01, 128.69, 129.25, 130.48 (d, $J_{C,F} = 8.6$ Hz), 136.42 (d, $J_{C,F} = 2.9$ Hz), 140.30, 148.40, 162.75 (d, $J_{C,F} = 249.1$ 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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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$_3$) $\delta$ 27.1. HRMS–ESI (m/z): [M+Na]$^+$ calcd for C$_{24}$H$_{29}$O$_5$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 °C. IR (neat) 757, 818, 833, 1024, 1039, 1151, 1178, 1220, 1249, 1269, 1511, 1604, 1717 cm$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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): [M]$^+$ calcd for
C$_{25}$H$_{35}$O$_6$, 372.17254; found, 372.17172. The regio- and stereochemistries were determined by transforming it to the known allylic alchol derivative with DIBAL-H reduction. Allylic alcohol: White solid. M.p. 147–149 °C. $^1$H 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$^{-1}$. $^1$H 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. $^{13}$B NMR (128 MHz, CDCl$_3$) δ 27.0. HRMS–ESI (m/z): [M+Na]$^+$ calcd for C$_{25}$H$_{35}$O$_6$Na, 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\(^{-1}\). **\(^1\)H NMR** (400 MHz, CDCl\(_3\)) \(\delta\) 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).

**\(^{13}\)C NMR** (100.5 MHz, CDCl\(_3\)) \(\delta\) 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 C\(_{25}\)H\(_{30}\)O\(_5\)Na, 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 µmol) and DtBPF (2.8 mg, 6 µmol) in THF (0.2 mL) was added \(i\)-Pr\(_2\)NEt (52 µL, 0.3 mmol), H\(_2\)O (30.0 µL), bromobenzene (11.5 µL, 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 Et\(_2\)O and filtered with a Celite\textsuperscript{®} 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 µmol) and DtBPF (2.8 mg, 6 µmol) in toluene (0.6 mL) was added K\(_3\)PO\(_4\) (42.4 mg, 0.2 mmol), H\(_2\)O (12.6 µL, 0.7 mmol), bromobenzene (12.5 µL, 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\textsuperscript{®} pad. The filtrate was evacuated under reduced pressure. The residue was purified by flash column chromatography on silica gel (Et\(_3\)N/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 µL) was added DIBAL-H (219 µL, 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 MgSO\(_4\), filtered, and evaporated under reduced pressure. The residue was purified by flash column chromatography on silica gel (Et\(_3\)N/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 Et<sub>3</sub>N/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<sup>-1</sup>.<sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ 0.93 (t, <i>J</i> = 7.2 Hz, 3H), 2.30 (s, 6H), 2.67 (t, <i>J</i> = 5.6 Hz, 2H), 3.98 (t, <i>J</i> = 5.6 Hz, 2H), 3.99 (q, <i>J</i> = 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). <sup>13</sup>C NMR (100.5 MHz, CDCl<sub>3</sub>) 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]<sup>+</sup> calcd for C<sub>27</sub>H<sub>30</sub>O<sub>3</sub>N, 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.<sup>20</sup> White solid. M.p. 117–119 °C. <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>) δ 2.29 (s, 6H), 2.65 (t, <i>J</i> = 5.6 Hz, 2H), 3.93 (t, <i>J</i> = 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). <sup>13</sup>C NMR (100.5 MHz, CDCl<sub>3</sub>) 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, 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 Et$_3$N/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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) 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). $^{13}$C NMR (100.5 MHz, CDCl$_3$) δ 13.82, 45.90, 58.24, 65.79, 113.44, 113.69, 126.98, 128.15, 129.88, 130.18, 131.22, 132.22, 132.15, 134.17, 145.61, 158.33, 159.51, 170.99. HRMS–ESI (m/z): [M+H]$^+$ calcd for C$_{28}$H$_{32}$O$_4$N, 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 Et$_3$N/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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) 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). $^{13}$C NMR (100.5 MHz, CDCl$_3$) 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, $J_{C,F} = 7.6$ Hz), 132.10, 133.09 (d, $J_{C,F} = 246.9$ Hz), 169.56. HRMS–ESI (m/z): [M+H]$^+$ calcd for C$_{27}$H$_{28}$O$_5$N$_2$F, 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 Et$_3$N/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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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). $^{13}$C NMR (100.5 MHz, CDCl$_3$) $\delta$ 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 C$_{25}$H$_{28}$NO$_3$S, 422.17844; found, 422.17831.
References and Notes


(2) For a review on the synthesis of multisubstituted alkenes, see: Flynn, A. B.; Ogilvie, W. W. Chem. Rev. 2007, 107, 4698.


(14) For Table 2, entries 8–12 and Table 3, entries 8 and 9, unreacted alkynoate was detected in the crude materials.


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 triborylmethyllithium 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 triborylmethyllithium to carbonyl compounds

\[
\begin{align*}
R^1 & + \text{Li}_2\text{Bpin} \rightarrow R^1\text{Bpin} \\
R^2 & + \text{Li}_2\text{Bpin} \rightarrow R^2\text{Bpin}
\end{align*}
\]

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

\[
\begin{align*}
\text{BuLi} & \rightarrow \text{LiBpin} \\
\text{Br} & \rightarrow \text{pinBpin}
\end{align*}
\]

c) Dehydrogenative geminal diboration of alkenes

\[
\begin{align*}
\text{R} & \rightarrow \text{Bpin} \\
\text{cat. Rh or Pd} & \rightarrow \text{Bpin}
\end{align*}
\]

d) Brønsted-base catalysis (this work)

\[
\begin{align*}
\text{X} & = O, N \\
\text{Y} & = O, N, S
\end{align*}
\]

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 LiO\textsubscript{t}Bu (10 mol%) in CH\textsubscript{3}CN (30 mL) at 40 °C over 5 h gave \( \beta,\beta \)-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 \(^{11}\text{B} \) NMR spectroscopy.

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

Screening of base catalysts for the reaction between 1a and 2 identified LiO\textsubscript{t}Bu as the most effective (Table 1, entry 1). NaO\textsubscript{t}Bu, KO\textsubscript{t}Bu 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 PBu\textsubscript{3} 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 tBuOH (54%).

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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-methylamide, 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, propionaldehyde showed no reactivity under similar conditions.

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

<table>
<thead>
<tr>
<th>entry</th>
<th>catalyst</th>
<th>yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LiOrBu</td>
<td>91</td>
</tr>
<tr>
<td>2</td>
<td>NaOrBu</td>
<td>79</td>
</tr>
<tr>
<td>3</td>
<td>KOOrBu</td>
<td>78</td>
</tr>
<tr>
<td>4</td>
<td>LHMDS</td>
<td>74</td>
</tr>
<tr>
<td>5</td>
<td>LiOMe</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
<td>DABCO</td>
<td>17</td>
</tr>
<tr>
<td>7</td>
<td>DMAP</td>
<td>15</td>
</tr>
<tr>
<td>8</td>
<td>PBu₃</td>
<td>33</td>
</tr>
<tr>
<td>9</td>
<td>none</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup>Conditions: 1, 0.2 mmol; 2a, 0.2 mmol; catalyst, 10 mol%; CH₃CN, 40 °C, 5 h. <sup>b</sup>Yield of isolated product.
**Table 2. Reaction Scope: Terminal Alkynes**

<table>
<thead>
<tr>
<th>entry</th>
<th>alkyne</th>
<th>product</th>
<th>yield (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MeO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1b&lt;/sub&gt;</td>
<td>MeO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3b&lt;/sub&gt;</td>
<td>83</td>
</tr>
<tr>
<td>2</td>
<td>tBuO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1c&lt;/sub&gt;</td>
<td>tBuO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3c&lt;/sub&gt;</td>
<td>81</td>
</tr>
<tr>
<td>3</td>
<td>PhO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1d&lt;/sub&gt;</td>
<td>PhO&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3d&lt;/sub&gt;</td>
<td>88</td>
</tr>
<tr>
<td>4</td>
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<td>1&lt;sub&gt;e&lt;/sub&gt;</td>
<td>89</td>
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<td>5</td>
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</tr>
<tr>
<td>6</td>
<td>PhMeN&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1g&lt;/sub&gt;</td>
<td>PhMeN&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3g&lt;/sub&gt;</td>
<td>75&lt;sup&gt;c&lt;/sup&gt;</td>
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<td>7</td>
<td>BnMeN&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1h&lt;/sub&gt;</td>
<td>BnMeN&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3h&lt;/sub&gt;</td>
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<td>8</td>
<td>(MeO)&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;1i&lt;/sub&gt;</td>
<td>(MeO)&lt;sub&gt;2&lt;/sub&gt;C≡H&lt;sub&gt;3i&lt;/sub&gt;</td>
<td>63</td>
</tr>
</tbody>
</table>
2-Ethynylazoles were also suitable substrates (Table 3). For example, the reaction of 2-ethynylbenzoxazole derivatives, with an increased catalyst loading (20 mol% LiO\textsubscript{t}Bu), 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

<table>
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<th>product</th>
<th>yield (%)\textsuperscript{b}</th>
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<td><img src="154.png" alt="3k" /></td>
<td>88</td>
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<td>2</td>
<td><img src="154.png" alt="1l" /></td>
<td><img src="154.png" alt="3l" /></td>
<td>78</td>
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</table>
To gain insight into the mechanism of the LiO\textsubscript{t}Bu-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**

\[ \text{EtO}_2\text{C} \equiv \text{H} + \text{pinB–Bpin} \xrightarrow{\text{LiO\textsubscript{t}Bu (10 mol\text{%)}}\text{, CH}_2\text{CN, 40 °C, 5 h}} \text{EtO}_2\text{C} \equiv \text{D} \]

(a) 87% yield

(b) 33% yield
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. Instead, a Brønsted-base mechanism involving acetylide formation is conceivable. To test this possibility, the stoichiometric reaction using nBuLi 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 tBuOH and standing the mixture at 25 °C for 1 h gave 3a in 27% NMR yield.

**Scheme 4. Stoichiometric Reaction**

Taking into account the results of the deuterium labeling experiments and the stoichiometric reaction with nBuLi, 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 tBuOH 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 tBuOH 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 Pd(OAc)$_2$–DtrBPF (1,1'-bis(di-tert-butylphosphino)ferrocene) catalyst and K$_3$PO$_4$ 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).
**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). 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 $^1$H NMR, 100.5 MHz for $^{13}$C NMR and 128 MHz for $^{11}$B NMR. Chemical shift values for $^1$H and $^{13}$C are referenced to Me$_4$Si, the residual solvent resonances and BF$_3$•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 60F$_{254}$. 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. LiOrBu, 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, 1e, 1g, 1i, 1j and 1l are known compounds. 1a–d was prepared according to reported procedures.

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 procedures. 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 procedures. 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 procedures. 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 3218 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) 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, CDCl₃) 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): [M+Na]⁺ calcd for C₇₂H₇₂O₃Na, 365.20872; found, 365.20869. [α]D²⁴ +22.2 (c 0.73, CHCl₃).

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, CDCl₃) 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), 7.42, 74.2, 75.0, 76.0, 152.2, 221.2. HRMS–ESI (m/z): [M+Na]⁺ calcd for C₁₁H₁₄ONa, 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$^{-1}$. **$^1$H NMR** (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 71.7, 81.7, 110.7, 120.7, 125.2, 126.7, 140.4, 146.3, 150.1. **HRMS–ESI (m/z):** [M+H]$^+$ calcd for C$_9$H$_6$ON, 144.04439; found, 144.04475.

**tert-Butyl 2-Ethynyl-1H-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$^{-1}$. **$^1$H NMR** (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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):** [M+Na]$^+$ calcd for C$_{14}$H$_{14}$O$_2$N$_2$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 LiOrBu (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 LiOrBu-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 $\mu$L), ethyl propiolate (1a) (19.6 mg, 0.2 mmol) and LiOrBu (1.6 mg, 0.02 mmol) dissolved in acetonitrile (100 $\mu$L) 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)**

![Structure of 3a](image)

The product 3a was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow solid. **IR** (neat) 1016, 1139, 1289, 1325, 1361, 1469, 1617, 1718, 2934, 2979 cm⁻¹. **¹H NMR** (400 MHz, CDCl₃) 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). **¹³C NMR** (100.5 MHz, CDCl₃) δ 14.1, 24.5, 24.7, 60.6, 83.7, 83.8, 141.6, 166.7, A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 29.5 (x 2B). **HRMS–ESI** (m/z): [M+Na]⁺ calcd for C₁₇H₃₀O₆B₂Na, 375.21262; found, 375.21270.

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

![Structure of 3b](image)

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, CDCl₃) δ 1.25 (s, 12H), 1.36 (s, 12H), 3.75 (s, 3H), 6.77 (s, 1H). **¹³C NMR** (100.5 MHz, CDCl₃) δ 24.6, 24.7, 51.9, 83.8, 83.9, 141.0, 167.2. A signal for the sp²-carbon directly attached to the boron atom was not observed. **¹¹B NMR** (128 MHz, CDCl₃) δ 30.5 (x 2B). **HRMS–ESI** (m/z): [M+Na]⁺ calcd for C₁₆H₂₈O₆B₂Na, 361.19697; found, 361.19701.

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

![Structure of 3c](image)
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, 1388, 1473, 1623, 1713, 2934, 2980 cm\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 1.24 (s, 12H), 1.35 (s, 12H), 1.45 (s, 9H), 6.73 (s, 1H). \(^{13}\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 30.3 (\(\times\) 2B). HRMS–ESI (m/z): [M+Na\(^+\)] calcd for C\(_{19}\)H\(_{34}\)O\(_6\)B\(_2\)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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 30.2 (\(\times\) 2B). HRMS–ESI (m/z): [M+Na\(^+\)] calcd for C\(_{21}\)H\(_{30}\)O\(_6\)B\(_2\)Na, 423.21262; found, 423.21283.

(1R,2S,5R)-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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 16.1, 20.8, 22.0, 23.2, 24.6, 24.7 (\(\times\) 2C), 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$_3$) $\delta$ 30.3 ($\times$ 2B). HRMS–ESI ($m/z$): \([\text{M+Na}]^+ \text{ calcd for } C_{25}H_{44}O_6B_2Na, 485.32217; \text{ found}, 485.32251. [\alpha]_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)**

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

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$^{-1}$. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 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$_3$) $\delta$ 30.2 ($\times$ 2B). HRMS–ESI ($m/z$): \([\text{M+Na}]^+ \text{ calcd for } C_{34}H_{54}B_2O_7Na, 619.39533; \text{ found}, 619.39510. [\alpha]_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)**

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

The product 3g was purified by recrystallization with CH$_2$Cl$_2$/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. $^1$H NMR (400 MHz, CDCl$_3$) $\delta$ 1.20 (s, 12H), 1.33 (s, 12H), 3.44 (s, 12H), 6.46 (s, 1H), 7.16–7.18 (m, 2H), 7.38–7.45 (m, 3H). $^{13}$C NMR (100.5 MHz, CDCl$_3$) $\delta$ 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$_3$) $\delta$ 22.0 and 30.4 (rotamer) ($\times$ 2B). HRMS–ESI ($m/z$): \([\text{M+Na}]^+ \text{ calcd for } C_{22}H_{33} B_2NO_5Na, 436.24425; \text{ found}, 436.24449.

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

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The product \textbf{3h} was purified by filtration through a short plug of silica gel with diethyl ether. Yellow oil. \textbf{IR} (neat) 1014, 1116, 1140, 1323, 1372, 1456, 1577, 1629, 2930, 2976 cm\(^{-1}\). Signals for the rotamers were given in the NMR spectra. \textbf{\textsuperscript{1}H NMR} (400 MHz, CDCl\(_3\)) \(\delta\) 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). \textbf{\textsuperscript{13}C NMR} (100.5 MHz, CDCl\(_3\)) \(\delta\) 24.9 (\(\times\) 2C), 25.2, 25.2, 34.5, 35.1, 53.2, 53.3 80.9, 81.0, 83.4 (\(\times\) 2C), 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. \textbf{\textsuperscript{11}B NMR} (128 MHz, CDCl\(_3\)) \(\delta\) 19.1 and 30.8 (rotamer) (\(\times\) 2B). \textbf{HRMS–ESI} (m/z): [M+Na]\(^+\) calcd for C\(_{23}\)H\(_{35}\)B\(_2\)NO\(_5\)Na, 450.25990; found, 450.26017.

\textit{N-Methoxy-N-methyl-3,3-bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)acrylamide (3i)}

The product \textbf{3i} was purified by filtration through a short plug of silica gel with diethyl ether. Pale yellow solid. M.p. 116–118 °C. \textbf{IR} (neat) 1140, 1283, 1312, 1371, 1379, 1467, 1606, 1641, 2935, 2975 cm\(^{-1}\). \textbf{\textsuperscript{1}H NMR} (400 MHz, CDCl\(_3\)) \(\delta\) 1.27 (s, 12H), 1.34 (s, 12H), 3.29 (s, 3H), 3.73 (s, 3H), 7.23 (s, 1H). \textbf{\textsuperscript{13}C NMR} (100.5 MHz, CDCl\(_3\)) \(\delta\) 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. \textbf{\textsuperscript{11}B NMR} (128 MHz, CDCl\(_3\)) \(\delta\) 30.2 (\(\times\) 2B). \textbf{HRMS–ESI} (m/z): [M+Na]\(^+\) calcd for C\(_{17}\)H\(_{31}\)O\(_6\)NB\(_2\)Na, 390.22352; found, 390.22360.

\textit{(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 \textbf{3j} was purified by recrystallization with CH\(_2\)Cl\(_2\)/hexane. Pale yellow solid. M.p. 191–3 °C. \textbf{IR} (neat) 1109, 1141, 1228, 1259, 1298, 1334, 1388, 1484, 1611, 1660, 1784, 2932, 2980 cm\(^{-1}\).
\(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^1\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 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 sp\(^2\)-carbon directly attached to the boron atom was not observed. \(^1\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 30.7 (\(\times\) 2B). HRMS–ESI (m/z): [M+Na]\(^+\) calcd for C\(_{25}\)H\(_{35}\)O\(_7\)NB\(_2\)Na, 506.24973; found, 506.25007. \(\left[\alpha\right]_{D}\) +15.9 (c 1.01, CHCl\(_3\)).

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

![Diagram of 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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^1\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 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 sp\(^2\)-carbon directly attached to the boron atom was not observed. \(^1\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 30.4 (\(\times\) 2B). HRMS–ESI (m/z): [M+Na]\(^+\) calcd for C\(_{21}\)H\(_{29}\)B\(_2\)NO\(_5\)Na, 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)**

![Diagram of 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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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). \(^1\)C NMR (100.5 MHz, CDCl\(_3\)) \(\delta\) 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 sp\(^2\)-carbon directly attached to the boron atom was not observed. \(^1\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 30.2 (\(\times\) 2B). HRMS–ESI (m/z): [M+H]\(^+\) calcd for C\(_{21}\)H\(_{30}\)O\(_4\)NB\(_2\)S, 414.20817; found, 414.20838.
**tert-Butyl 2-[2,2-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)vinyl]-1H-benzo[d]imidazole-1-carboxylate (3m)**

![Diagram](image)

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)

![Structure of 4a]

Colorless oil. IR (neat) 1030, 1137, 1180, 1210, 1302, 1377, 1606, 1705, 2933, 2978 cm⁻¹. ¹H NMR (400 MHz, CDCl₃) 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). ¹³C NMR (100.5 MHz, CDCl₃) 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 sp²-carbon directly attached to the boron atom was not observed. ¹¹B NMR (128 MHz, CDCl₃) δ 30.3. HRMS–ESI (m/z): [M+Na]⁺ calcd for C₁₇H₂₃O₄BNa, 325.15871; found, 325.15847.

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

![Structure of 5a]

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

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

Procedure for synthesis of 6a. CuCl (1.0 mg, 0.01 mol), NaOrBu (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 tBuOH (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\(^{-1}\). \(^1\)H NMR (400 MHz, CDCl\(_3\)) \(\delta\) 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\(_3\)) \(\delta\) 14.3, 24.4, 24.8, 30.5, 60.2, 83.1, 174.9. \(^{11}\)B NMR (128 MHz, CDCl\(_3\)) \(\delta\) 34.0. **HRMS–ESI** (\(m/z\)): [M+Na]\(^+\) calcd for C\(_{17}\)H\(_{32}\)O\(_6\)B\(_2\)Na, 377.22827; found, 377.22835.

**Reaction between Ethyl Propiolate (1a) and 2 in the Presence of Stoichiometric Amount of nBuLi**

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 \(n\)BuLi (130 \(\mu\)L, 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 \(^1\)H and \(^{11}\)B NMR spectroscopy was unsuccessful due to complexity of spectra). Subsequently, one equiv of \(t\)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 \(^1\)H NMR analysis using 1,1,2,2-tetrachloroethane as an internal standard.
References and Notes


(2) Matteson, D. S. Synthesis 1975, 147.


(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.


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

Chapter 3  Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura

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
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.

(2) Copper(I)-Catalyzed Intramolecular Hydroalkoxylation of Unactivated Alkenes
Hiroaki Murayama, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura

(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

(4) Copper-Catalyzed Enantioselective Allylic Cross-Coupling with Alkylboranes
Kentaro Hojoh, Yoshinori Shido, Kazunori Nagao, Seiji Mori, Hirohisa Ohmiya, and Masaya Sawamura.

(5) Copper-Catalyzed Stereoselective Conjugate Addition of Alkylboranes to Alkynoates
Takamichi Wakamatsu, Kazunori Nagao, Hirohisa Ohmiya, and Masaya Sawamura.
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