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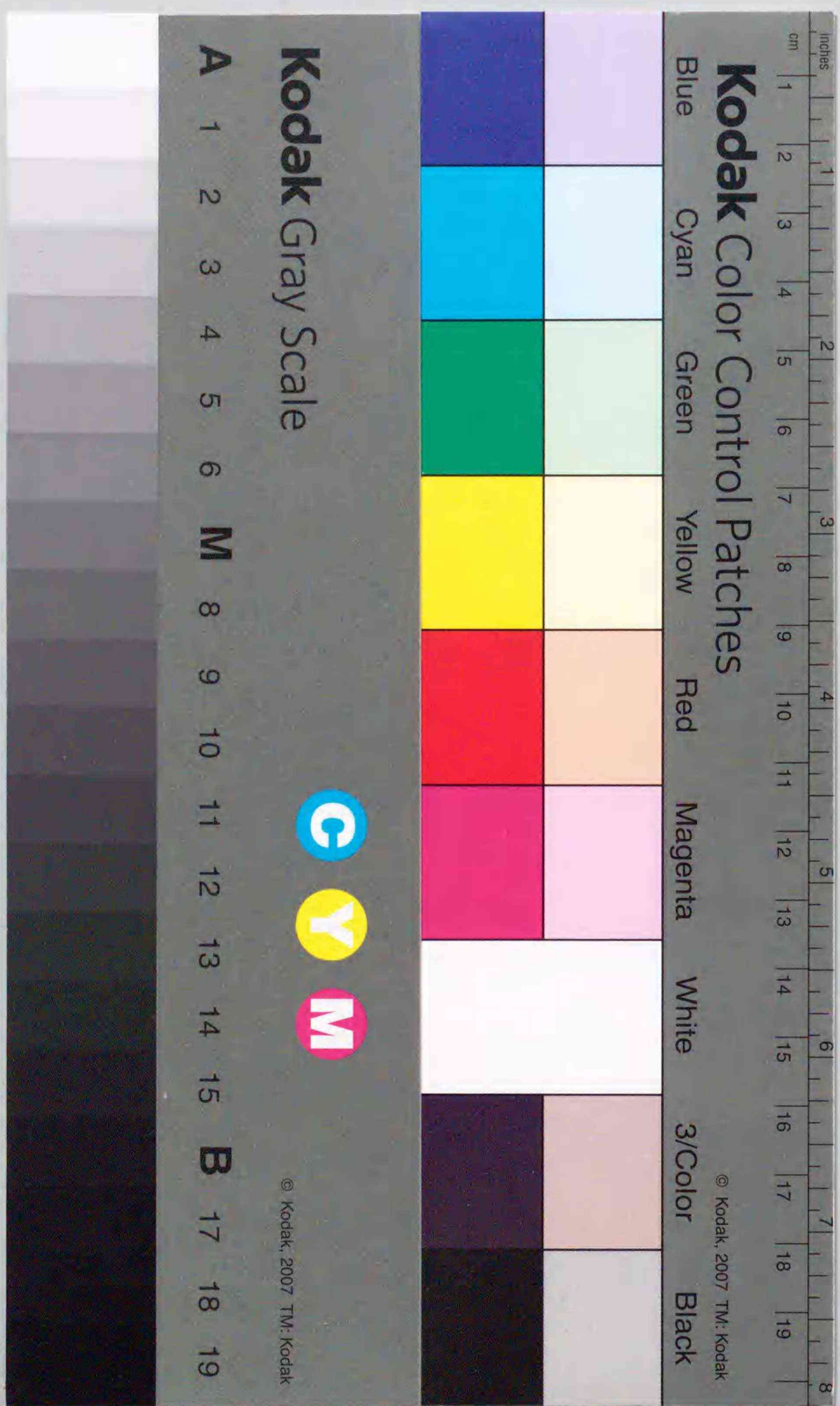


博士論文

Syntheses of
Organometallic Compounds of Group 13 and 14 Elements
by Transition Metal-Catalyzed
Carbon-Metal Bond-Forming Reactions

Naoki Mizuta

2000



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Syntheses of
Organometallic Compounds of Group 13 and 14 Elements
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2000

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Chapter 1.

Introduction

Understanding functions ranging from material science to biology occurs increasingly at the molecular level. Thus, synthesis in the molecular level is an important science. A key in synthesis is efficiency, which may be defined as the ability to convert readily available building blocks into the target molecule in relatively few synthetic operations that require minimal quantities of raw materials and produce minimal waste. Synthetic efficiency may be divided into three categories, chemo-, regio-, and stereoselectivity.

Recently, for the organic synthesis, stoichiometric or catalytic amount of metal compounds is widely utilized as catalyst, reagent, and building block. Because, it has been recognized that there is a remarkable advantage of the reaction using metal reagents. Namely, metal compounds achieve the selectivity which is often high, and the reaction which needed multiple stages so far may be able to be done by one step. Today the organometallic compounds are indispensable in putting together the molecular edifice.

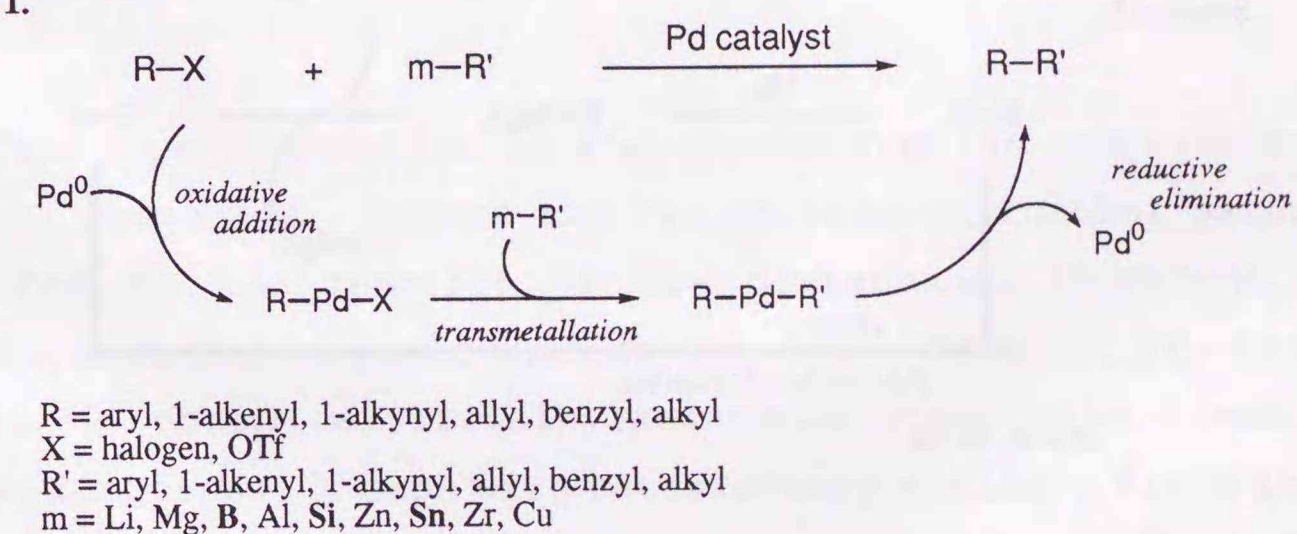
The organic metal compound which has more complicated structure should be more necessary from such circumstances. This thesis concerns the novel transition metal-catalyzed reaction of introducing a metal element in organic molecules by using bimetallic reagents and metal hydrides. It aimed at the simple and easy preparation of organoboron, -silicon and -tin compounds from organic halides or unsaturated hydrocarbons.

The transition metal-catalyzed cross-coupling reactions of organometallic compounds.

The palladium-catalyzed cross-coupling reaction of alkyl, aryl, alkenyl, allyl, and benzyl compounds of main group elements with organic electrophiles offers powerful bond-forming methods and is very useful in organic synthesis (Scheme 1).¹ Aryl- or alkenylpalladium halide complexes formed by the oxidative addition undergo transmetalation with organometallic compounds of the main group metals, and then carbon-carbon bond formation takes place by reductive elimination as a final step.

From the chronological point of view, the reaction using the Grignard reagent and a nickel catalyst was the first example of such a cross-coupling reaction as reported in 1972 independently by the Kumada-Tamao group² and the Corriu group.³ Since then, many organometallic reagents of lithium,⁴ boron,⁵ aluminium,⁶ zirconium,^{6c, 7} zinc,^{6c, 8} copper,⁹ silicon,¹⁰ and tin¹¹ were found to undergo this type of carbon-carbon bond formation, and various palladium catalysts were employed more conveniently than nickel.

Scheme 1.



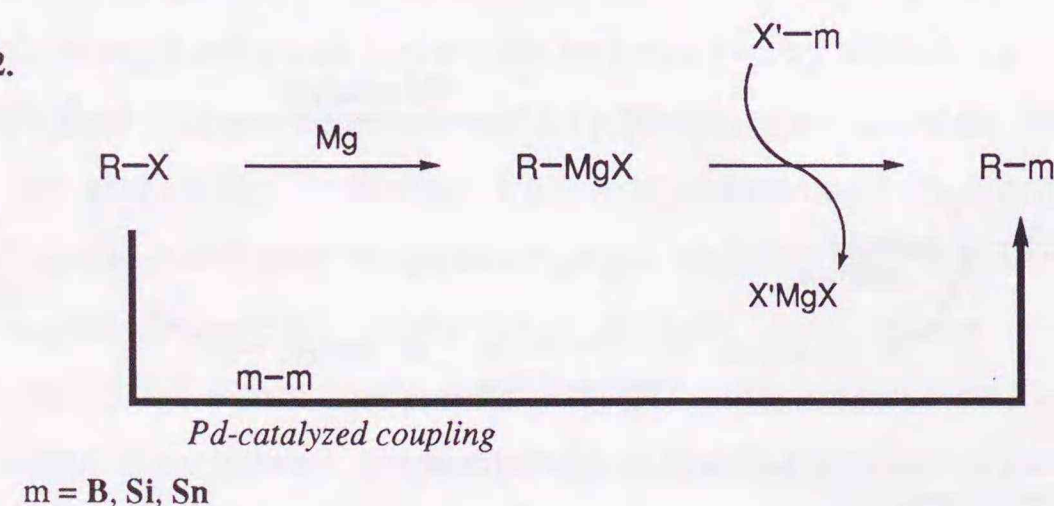
Organolithium and Grignard reagents are widely used in organic synthesis, but neither tolerates a wide variety of functional groups on either coupling partner, and often homo-coupling of the organic halides is observed.

Although organometallic reagents containing metals of

intermediate electropositive character generally lead to higher yields of the coupled products and fewer side-reactions, these organometallic reagents tolerate a wide range of functional groups in either or both of the coupling partners. From these standpoints, organoboron, -tin, and -silicon compounds are particularly useful and convenient reagents.

The coupling reaction by means of organoboron reagents in the presence of a base is known as the Suzuki-Miyaura reaction and is now applied widely to industrial-scale synthesis.⁵ The coupling reaction by means of organotin reagents is called the Migita-Kosugi-Stille coupling or simply the Stille reaction, and is convenient for laboratory-scale synthesis.¹¹ Hiyama and Hatanaka have found that the coupling reaction by means of organosilicon reagents was achieved with the aid of fluoride ion.¹⁰ Since these compounds containing group 13 or 14 elements, such as boron, silicon, and tin, are thermally stable and generally not susceptible to oxygen or moisture in the air, they can be handled by all the usual chromatographic and spectroscopic techniques, with some exceptions.

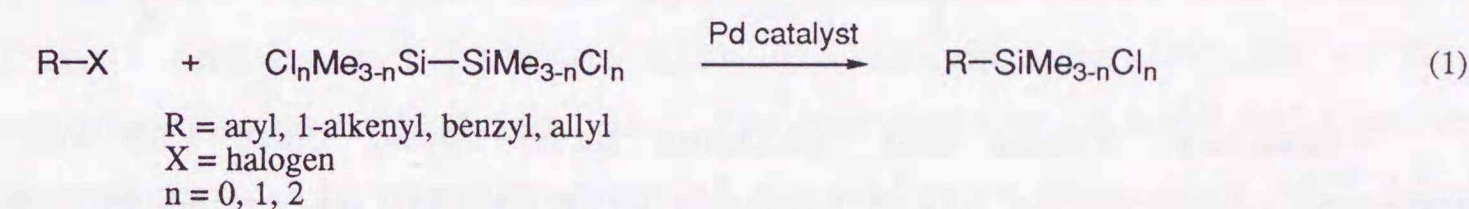
Scheme 2.



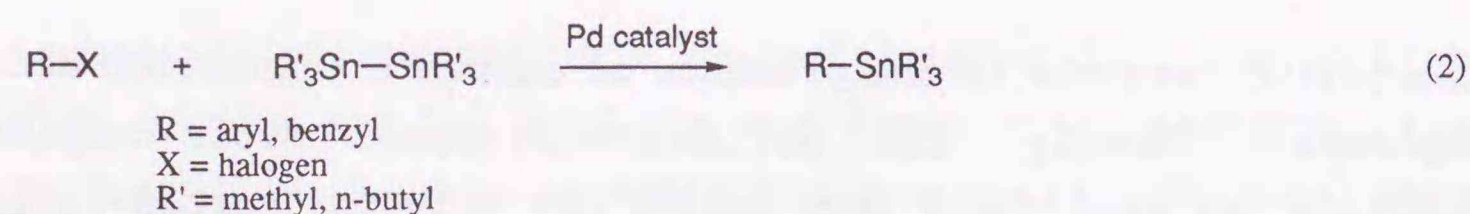
The most important method of forming these elements-carbon bonds involves the reaction of carbanion including organolithium or Grignard reagents with metal halides or alkoxides of group 13 or 14 elements (Scheme 2). Numerous other methods are now available, however, and can be of value in special circumstances, and one such is based on the reaction between organic electrophiles and

bimetallic reagents in the presence of suitable transition metal complexes. Namely, the palladium-catalyzed cross-coupling technique has been found very useful not only for carbon-carbon bond formation but also for metal-carbon bond formation.

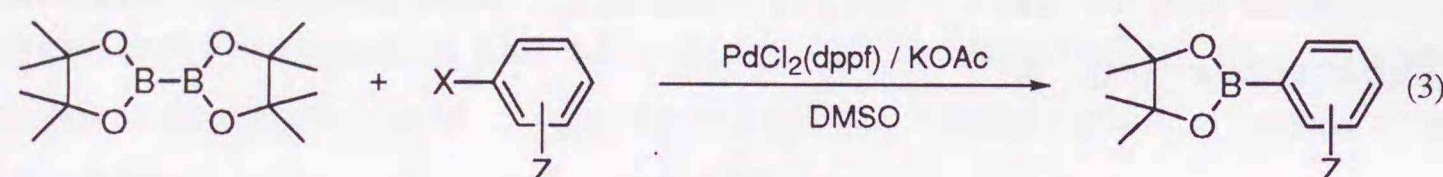
It was shown by Atwell and Bokermann in 1973 that some organic halides react with disilanes in the presence of some transition metal complexes to give organosilanes compounds, the reaction being especially effective for allyl halides.¹² Matsumoto, Nagai and their co-workers later found that aryl bromides react with hexamethyldisilane in toluene or similar solvents in the presence of $\text{Pd}(\text{PPh}_3)_4$ to give aryltrimethylsilanes,¹³ thus providing an important new route to such compounds, especially those in which the aryl group bears a reactive functional substituent and so could not be attached to silicon by methods involving Grignard or organolithium reagents. This method was later extended the reaction to use of aryl,¹⁴ allyl,¹⁵ benzyl,¹⁶ and 1-alkenyl halides¹⁷ as substrates (eq. 1).



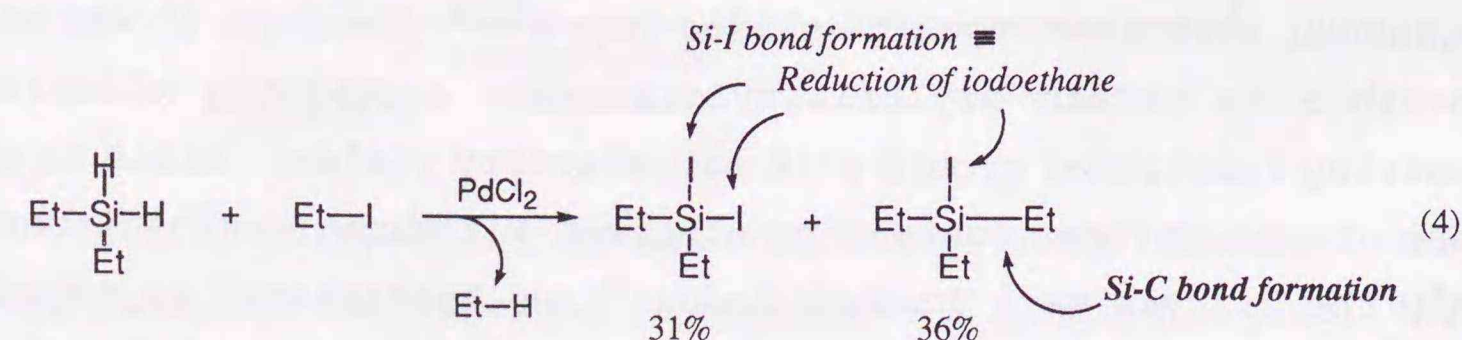
This type of reaction is also useful for the preparation of organotin compounds. Eaborn and his colleagues further extended the method to the reaction of the distannanes $\text{Me}_3\text{SnSnMe}_3$ and $\text{Bu}_3\text{SnSnBu}_3$ with some organic halides (eq. 2).¹⁸ However, it was only possible to obtain aryltrialkylstannanes containing electron-donating functional groups with satisfactory yields. Since in the case of aryl halides containing electron-withdrawing substituents only the biaryls were formed, Kosugi¹⁹ and Beletskaya²⁰ reported a useful variant independently.



Although the cross-coupling reaction of disilanes or distannanes has been extensively studied, the lack of suitable boron nucleophiles has limited this protocol. In chapter 2, a palladium-catalyzed coupling reaction of bis(pinacolato)diboron and aryl halides, which represents the first one-step procedure for preparing arylboronic esters from aryl halides, is described (eq. 3). Such diborons should be useful as a boron nucleophile for the cross-coupling reaction with organic halides due to thermally stability. The reaction was catalyzed by $\text{PdCl}_2(\text{dppf})$ at 80 °C in the presence of KOAc in DMSO and available with various functional groups.



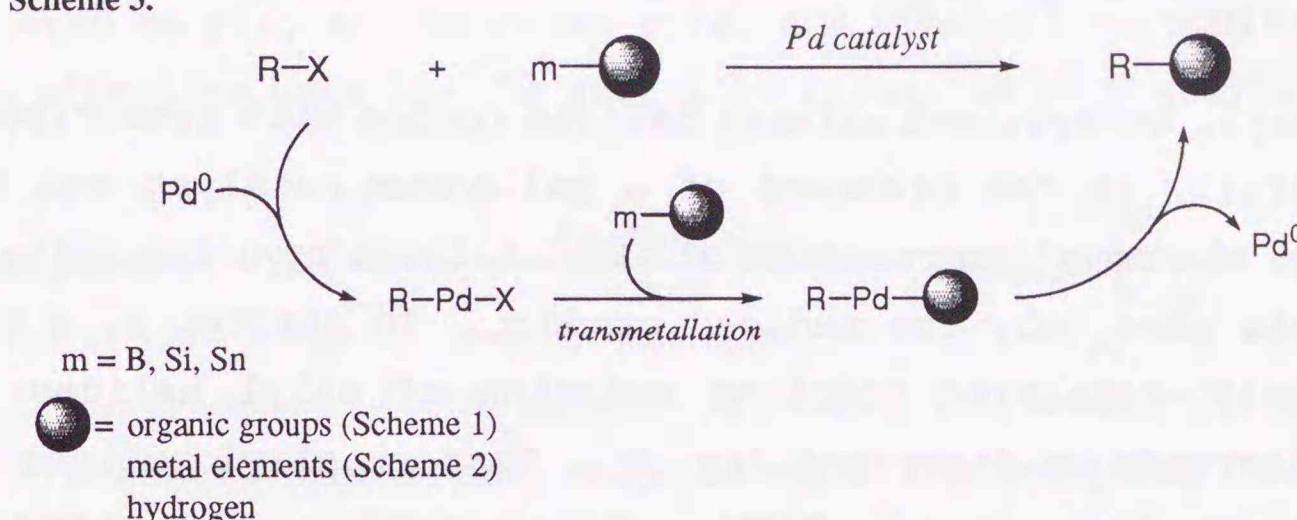
Recently, Kunai and Ishikawa have found that the PdCl_2 -catalyzed reaction of alkyl iodides with Et_2SiH_2 afforded $\text{Et}_2\text{ISi-R}$ to some extent,²¹ indicating the potential use of metal hydride as an alternative metalating reagent for the palladium-catalyzed metalations of organic electrophiles (eq. 4).



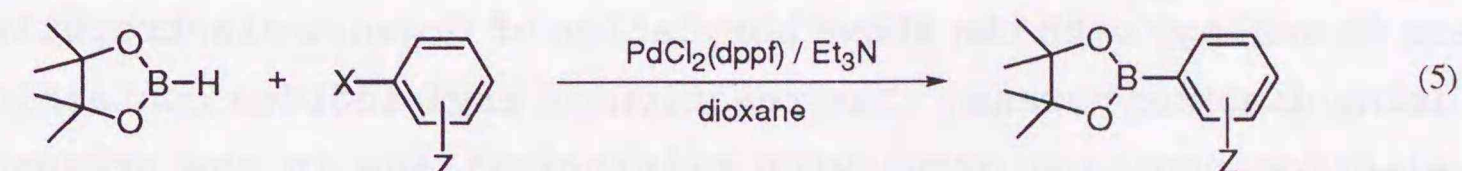
However, in the presence of a palladium catalyst, such metal hydrides greatly facilitate the hydrogenolysis of organic electrophiles,²² as organic electrophiles is generally substituted

by atomic groups on the metal element in a similar manner as Scheme 1 and 2 (Scheme 3). Thus, it has been very difficult to achieve palladium-catalyzed metalations of organic electrophiles using metal hydrides with high chemical selectivity, although Kunai's report is very unique.

Scheme 3.

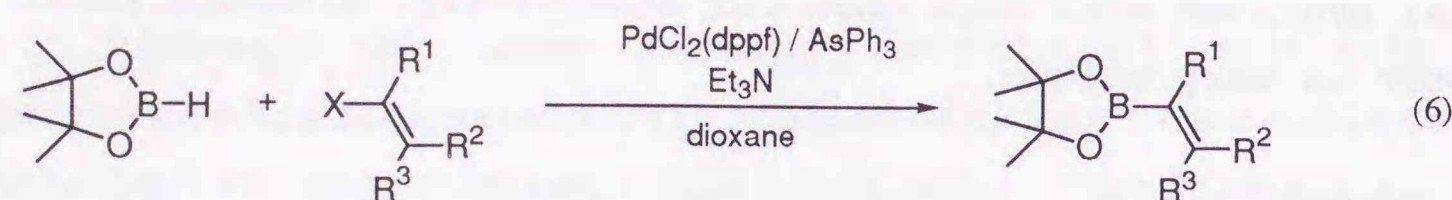


The author gave attention to the slow transmetalation of boron compounds in the absence of a base or in the presence of weak bases. In chapter 3, the first success of a palladium-catalyzed metalation of aryl and benzyl halides with dialkoxyborane $(\text{RO})_2\text{BH}$ as metal hydrides is described (eq. 5). The borylation of aryl halides with pinacolborane in the presence of a catalytic amount of $\text{PdCl}_2(\text{dppf})$ together with a base provided arylboronates in high yields. The product distributions were strongly dependent on the base employed, and the tertiary amine, especially Et_3N , was effective for the selective formation of the boron-carbon bond.

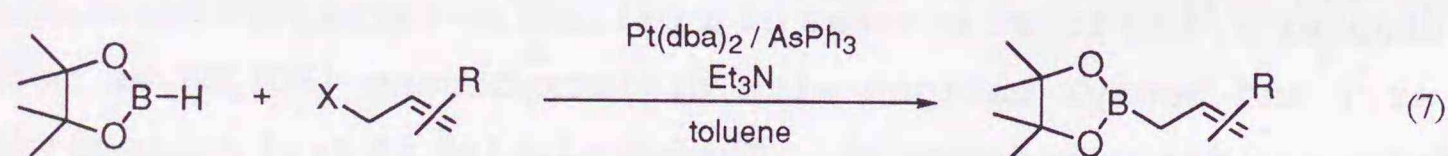


In chapter 4, a direct borylation of alkenyl electrophiles with dialkoxyborane is described (eq. 6). Various cycloalkenyl iodides and triflates were borylated with pinacolborane in the presence of Et_3N and a catalytic amount of $\text{PdCl}_2(\text{dppf})$ and AsPh_3 to afford the corresponding alkenylboronates in good yields. In the

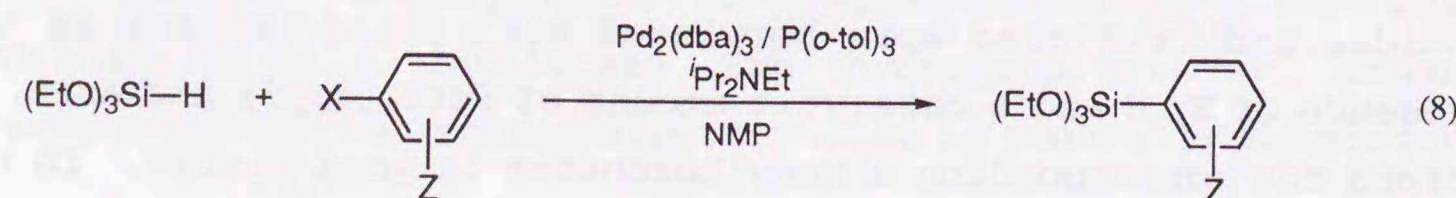
absence of AsPh_3 , which weakly coordinated palladium complexes, the borylation of alkenyl triflates resulted in low conversion, while the catalyst was decomposed during the reaction.



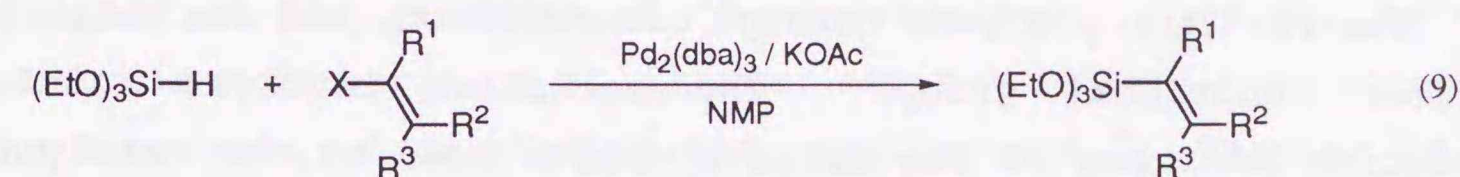
Aryl, benzyl, and alkenyl halides couple with pinacolborane successfully in the presence of a palladium catalyst and Et_3N . However, the coupling reaction of allyl halides by using palladium catalysts gave only the reduced product. In chapter 5, a novel platinum(0)-catalyzed coupling reaction of allyl halides with pinacolboranes is described (eq. 7). Various allyl halides were borylated in the presence of NEt_3 and a catalytic amount of $\text{Pt}(\text{dba})_2$ and AsPh_3 to afford the corresponding regio- and stereodefined allylboranes in good yields.



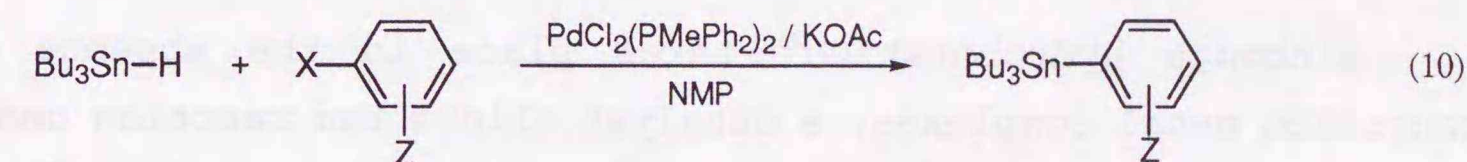
The selective metalation of organic electrophiles using metal hydrides was extended to a reaction of the hydrosilanes. In chapter 6, an advantageous example of a specific silylation of aryl halides with hydrosilanes as a silicon source is described (eq. 8). This silylation was achieved with the aid of palladium catalysts and bases in analogy with the above borylation of organic electrophiles by using dialkoxyborane. The reaction of aryl iodides containing an electron-donating group with triethoxysilane in the presence of $^i\text{Pr}_2\text{NEt}$ and catalytic amounts of $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ and $\text{P}(\text{o-tol})_3$ provides the corresponding arylsilanes in high yield.



In chapter 7, a palladium(0)-catalyzed selective silylation of alkenyl iodides with hydrosilanes is described (eq. 9). Alkenyl iodides were silylated in the presence of KOAc and a catalytic amount of $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ to afford the corresponding regio- and stereodefined (*E*)-alkenylsilanes in high yields. The base appeared to play an important role, and KOAc was recognized to be most effective base for the selective formation of alkenylsilanes.



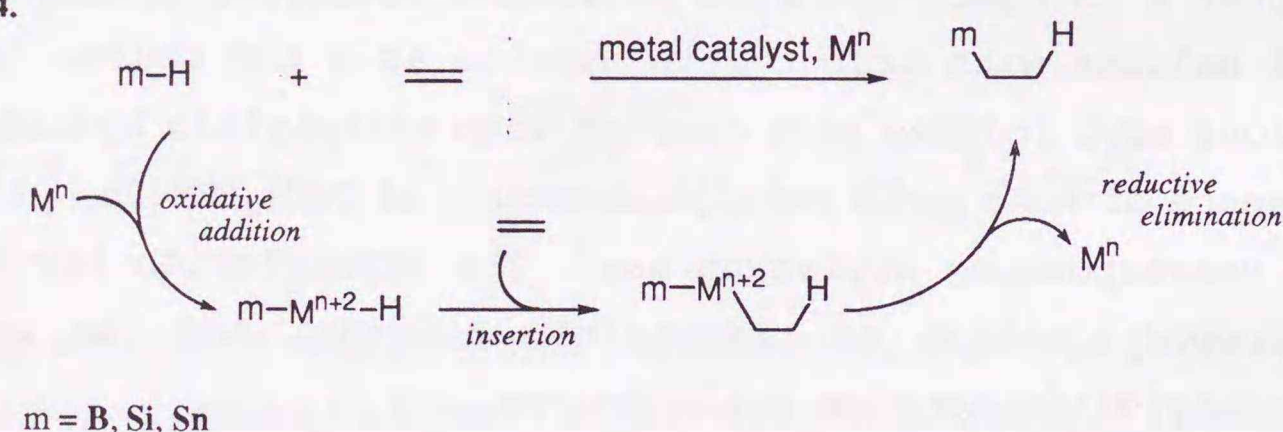
Further, since not only bimetallic reagents but metal hydrides are considered now available metalating reagents for the palladium-catalyzed metalations of organic electrophiles, Chapter 8 is concerned with palladium-catalyzed stannylation of aryl halides with tributyltin hydride as a tin source (eq. 10). Various aryl iodides were coupled with tributyltin hydride in the presence of KOAc and a catalytic amount of $\text{PdCl}_2(\text{PMePh}_2)_2$ to afford the corresponding arylstannanes. The stannylation involves the disproportionation of tributyltin hydride, and the resultant hexabutylditin acts as a tin source.



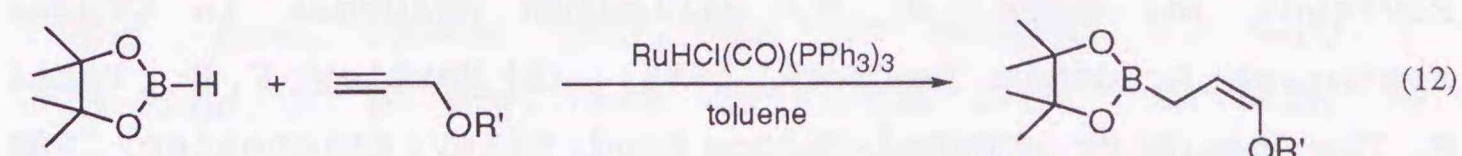
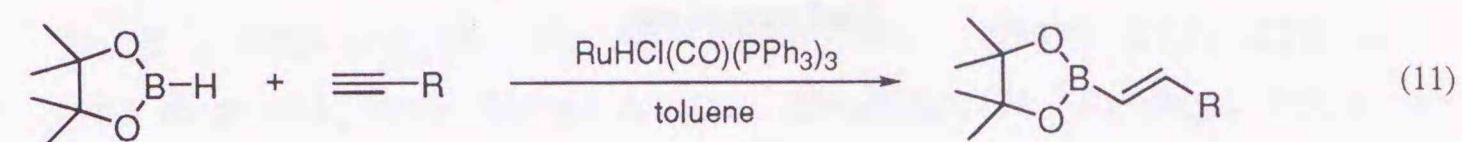
The transition metal-catalyzed addition reactions of organo-metallic compounds.

The transition metal-catalyzed addition of organometallic reagents including group 13 or 14 elements to carbon-carbon multiple bonds has proven to be a versatile method for synthesizing stereodefined and functionalized organometallic compounds.²³ Among others, the addition of metal hydrides, such as $R_3SiH^{23c, d}$ and R_3SnH^{23f-h} (hydrometalation), has been extensively studied (Scheme 4). The reaction proceeds through *cis*-addition, and can tolerate various functional groups. The mechanism involves initial oxidative addition of the metal-hydrogen bond to the catalyst, followed by insertion into the transition metal-hydrogen bond. Reductive elimination then liberates the adduct and regenerates the catalyst.

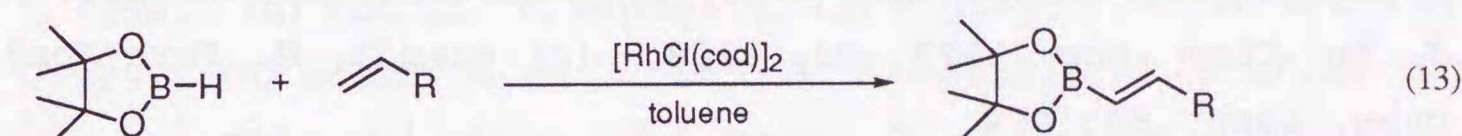
Scheme 4.



Although hydroboration²⁴ takes place in the absence of transition metal complexes, a catalyst allows the reaction under very mild conditions and often can direct the course of addition of borane to a different selectivity than the uncatalyzed reaction.²⁵ In chapter 9, a new catalytic system for hydroboration of alkynes by using a ruthenium complex is described (eq. 11). Among the ruthenium catalysts, $RuHCl(CO)(PPh_3)_3$ gave the best result. It is interesting to note that $RuHCl(CO)(PPh_3)_3$ -catalyzed hydroboration of propargyl ethers involved carbon-carbon double bond isomerization to afford (*Z*)- γ -alkoxyallylboronates (eq. 12).



The rhodium-catalyzed hydroboration of alkenes has been applied for the preparation of alkylboranes. However, in the catalytic hydroboration of alkenes, several authors have observed the formation of dehydrogenated vinylboranes.²⁶ Chapter 10 is concerned with a rhodium-catalyzed selective dehydrogenative borylation of vinylarenes. Dehydrogenative borylation by using pinacolborane in the presence of a phosphine-free rhodium catalyst proceeded predominantly over hydroboration (eq. 13).



References

1. Reviews: (a) Heck, R. F. *Palladium Reagents in Organic Syntheses*; Academic: New York, 1985. (b) Hartley, F. R.; Patai, S. *The Chemistry of Metal-Carbon Bond*; Wiley: Chichester, 1985; Vol. 3. (c) Tamao, K. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Pattenden, G., Eds.; Pergamon: Oxford, 1991; Vol. 3, p. 435. (d) Knight, D. W. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Pattenden, G., Eds.; Pergamon: Oxford, 1991; Vol. 3, p. 481. (e) Tsuji, J. *Palladium Reagents and Catalysts*; Wiley: Chichester, 1996. (f) Diederich, F.; Stang, P. J. *Metal-catalyzed Cross-coupling Reactions*; Wiley: Weinheim, 1998.
2. (a) Tamao, K.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc.* **1972**, *94*, 4374. (b) Tamao, K.; Kiso, Y.; Sumitani, K.; Kumada, M. *J. Am. Chem. Soc.* **1972**, *94*, 9268. (c) Kumada, M. *Pure Appl. Chem.* **1980**, *52*, 669.
3. Corriu, R. J. P.; Masse, J. P. *J. Chem. Soc., Chem. Commun.* **1972**, 144.
4. Murahashi, S.; Yamamura, M.; Yanagisawa, K.; Mita, N.; Kondo, K. *J. Org. Chem.* **1979**, *44*, 2408.
5. (a) Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc.* **1985**, *107*, 972. (b) Miyaura, N.; Yanagi, T.; Suzuki, A. *Synth. Commun.* **1981**, *11*, 513. (c) Suzuki, A. *Acc. Chem. Res.* **1982**, *15*, 178; *Pure Appl. Chem.* **1985**, *57*, 1749; **1991**, *63*, 419; **1994**, *66*, 213. (d) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457.
6. (a) Negishi, E.; Baba, S. *J. Chem. Soc., Chem. Commun.* **1976**, 596. (b) Baba, S.; Negishi, E. *J. Am. Chem. Soc.* **1976**, *98*, 6729. (c) Negishi, E. *Pure Appl. Chem.* **1981**, *53*, 2333; *Acc. Chem. Res.* **1982**, *15*, 340.
7. (a) Negishi, E.; Van Horn, D. E. *J. Am. Chem. Soc.* **1977**, *99*, 3168. (b) Van Horn, D. E.; Negishi, E. *J. Am. Chem. Soc.* **1978**, *100*, 2252. (c) Negishi, E.; Takahashi, T.; Baba, S.; Van Horn, D. E.; Okukado, N. *J. Am. Chem. Soc.* **1987**, *109*, 2393.
8. (a) Negishi, E.; King, A. O.; Okukado, N. *J. Org. Chem.* **1977**, *42*, 1821. (b) King, A. O.; Okukado, N.; Negishi, E. *J. Chem. Soc., Chem. Commun.* **1977**, 683. (c) Negishi, E.; King, A. O.; Okukado, N. *J. Org. Chem.* **1977**, *42*, 1821. (d) King, A. O.; Negishi, E. *J. Org. Chem.* **1978**, *43*, 358.
9. Alexakis, N. J. A.; Normant, J. F. *Tetrahedron Lett.* **1981**, *22*, 959.
10. (a) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1988**, *53*, 918. (b) Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1989**, *54*, 268. (c) Hatanaka, Y.; Matsui, K.; Hiyama, T. *Tetrahedron Lett.* **1989**, *30*, 2403. (d) Hatanaka, Y.; Hiyama, T. *J. Am. Chem. Soc.* **1990**, *112*, 7793. (e) Hatanaka, Y.; Hiyama, T. *Synlett* **1991**, 845.
11. (a) Kosugi, M.; Simizu, Y.; Migita, T. *Chem. Lett.* **1977**, 1423. (b) Milstein, D.; Stille, J. K. *J. Am. Chem. Soc.* **1979**, *101*, 4992. (c) Kosugi, M.; Hagiwara, I.; Migita, T. *Chem. Lett.* **1983**, 839. (d) Scott, W. J.; Crisp, G. T.; Stille, J. K. *J. Am. Chem. Soc.* **1984**, *106*, 4630. (e) Scott, W. J.; Stille, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 3033. (f) Echavarren, A. M.; Stille, J. K. *J. Am. Chem. Soc.* **1987**, *109*, 5478. (g) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508.
12. Atwell, W. H.; Bokerman, G. U.S. Patent 3,772,347 (1973).
13. (a) Matsumoto, H.; Nagashima, S.; Yoshihiro, K.; Nagai, Y. *J. Organomet. Chem.* **1975**, *85*, C1. (b) Matsumoto, H.; Yoshihiro, K.; Nagashima, S.; Watanabe, H.; Nagai, Y. *J. Organomet. Chem.* **1977**, *128*, 409.
14. (a) Azarian, D.; Dua, S. S.; Eaborn, C.; Walton, D. R. M. *J. Organomet. Chem.* **1976**, *117*, C55. (b) Matsumoto, H.; Shono, K.; Nagai, Y. *J. Organomet. Chem.* **1981**, *208*, 145. (c) Eaborn, C.; Griffiths, R. W.; Pidcock, A. *J. Organomet. Chem.* **1982**, *225*, 331.
15. (a) Matsumoto, H.; Yako, T.; Nagashima, S.; Motegi, T.; Nagai, Y. *J. Organomet. Chem.* **1978**, *148*, 97. (b) Lefort, M.; Simmonet, C.; Birot, M.; Dereris, G.; Dunogues, J.; Calas, R. *Tetrahedron*

- Lett. 1980, 21, 1857. (c) Tsuji, Y.; Funato, M.; Ozawa, M.; Ogiyama, H.; Kajita, S.; Kawamura, T. *J. Org. Chem.* 1996, 61, 5779.
16. (a) Matsumoto, H.; Kasahara, M.; Matsubara, I.; Takahashi, M.; Nakano, T.; Nagai, Y. *Chem. Lett.* 1982, 399. (b) Nakano, T.; Takahashi, M.; Ashizawa, T.; Arai, T.; Seki, S.; Matsumoto, H.; Nagai, Y. *Chem. Lett.* 1982, 613. (c) Matsumoto, H.; Kasahara, M.; Matsubara, I.; Takahashi, M.; Arai, T.; Hasegawa, M.; Nakano, T.; Nagai, Y. *J. Organomet. Chem.* 1983, 250, 99.
17. (a) Matsumoto, H.; Nagashima, S.; Kato, T.; Nagai, Y. *Angew. Chem., Int. Ed. Engl.* 1978, 17, 279. (b) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* 1987, 28, 4715.
18. (a) Azarian, D.; Dua, S. S.; Eaborn, C.; Walton, D. R. M. *J. Organomet. Chem.* 1976, 117, C55. (b) Azizian, H.; Eaborn, C.; Pidcock, A. *J. Organomet. Chem.* 1981, 215, 49.
19. Kosugi, M.; Shimizu, K.; Ohtani, A.; Migita, T. *Chem. Lett.* 1981, 829.
20. (a) Kashin, A. N.; Bumagina, I. G.; Bumagin, N. A.; Bakunin, V. N.; Beletskaya, I. P. *J. Org. Chem. USSR* 1981, 17, 905. (b) Bumagin, N. A.; Bumagina, I. G.; Beletskaya, I. P. *Dokl. Acad. Nauk SSSR* 1984, 274, 1103.
21. Kunai, A.; Sakurai, T.; Toyoda, E.; Ishikawa, M.; Yamamoto, Y. *Organometallics* 1994, 13, 3233.
22. For examples, see: (a) Four, P.; Guibe, F. *J. Org. Chem.* 1982, 46, 4439. (b) Boukherroub, R.; Chatgililoglu, C.; Manuel, G. *Organometallics* 1996, 15, 1508. (c) Lipshutz, B. H.; Buzard, D. J.; Vivian, R. W. *Tetrahedron Lett.* 1999, 40, 6871.
23. B-H: (a) Burgess, K.; Ohlmeyer, M. J. *Chem. Rev.* 1991, 91, 1179. B-B: (b) Ishiyama, T.; Miyaura, N. *J. Synth. Org. Chem. Jpn.* 1999, 57, 503. Si-H: (c) Ojima, I. *The Chemistry of Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, 1989; p 1479. (d) Hiyama, T.; Kasumoto, T. *Comprehensive Organic Synthesis*; Trost, B. M., Fleming, I., Pattenden, G., Eds.; Pergamon: Oxford, 1991; Vol. 8, Chapter 3.12. Si-Si: (e) Horn, K. A. *Chem. Rev.* 1995, 95, 1317. Sn-H: (f) Kikukawa, K.;

- Umekawa, H.; Wada, F.; Matsubara, T. *Chem. Lett.* 1988, 881. (g) Zhang, H. X.; Guibe, F.; Balavoine, G. *J. Org. Chem.* 1990, 55, 1857. (h) Magriotis, P. A.; Brown, J. T.; Scott, M. E. *Tetrahedron Lett.* 1991, 38, 5047. Sn-Sn: (i) Mitchell, T. N. *Synthesis* 1992, 803.
24. Reviews: (a) Brown, H. C. *Organic Syntheses via Boranes*; Wiley: Chichester, 1975. (b) Pelter, A.; Smith, K.; Brown, H. C. *Borane Reagents*; Academic: London, 1988.
25. For examples, see: (a) Männig, D.; Nöth, H. *Angew. Chem., Int. Ed. Engl.* 1985, 24, 878. (b) Evans, D. A.; Fu, G. C.; Hovayda, A. H. *J. Am. Chem. Soc.* 1988, 110, 6917. (c) Satoh, M.; Miyaura, N.; Suzuki, A. *Tetrahedron Lett.* 1989, 30, 3789. (d) Nomoto, Y.; Miyaura, N.; Suzuki, A. *Synlett* 1992, 727. (e) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *Organometallics* 1993, 12, 589.
26. (a) Lynch, A. T.; Sneddon, L. G. *J. Am. Chem. Soc.* 1989, 111, 6201. (b) Burgess, K.; van der Donk, W. A.; Westcott, S. A.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. *J. Am. Chem. Soc.* 1992, 114, 9350. (c) Brown, J. M.; Lloyd-Jones, G. C. *J. Am. Chem. Soc.* 1994, 116, 866. (d) Pereira, S.; Srebnik, M. *Tetrahedron Lett.* 1996, 37, 3283.

Chapter 2.

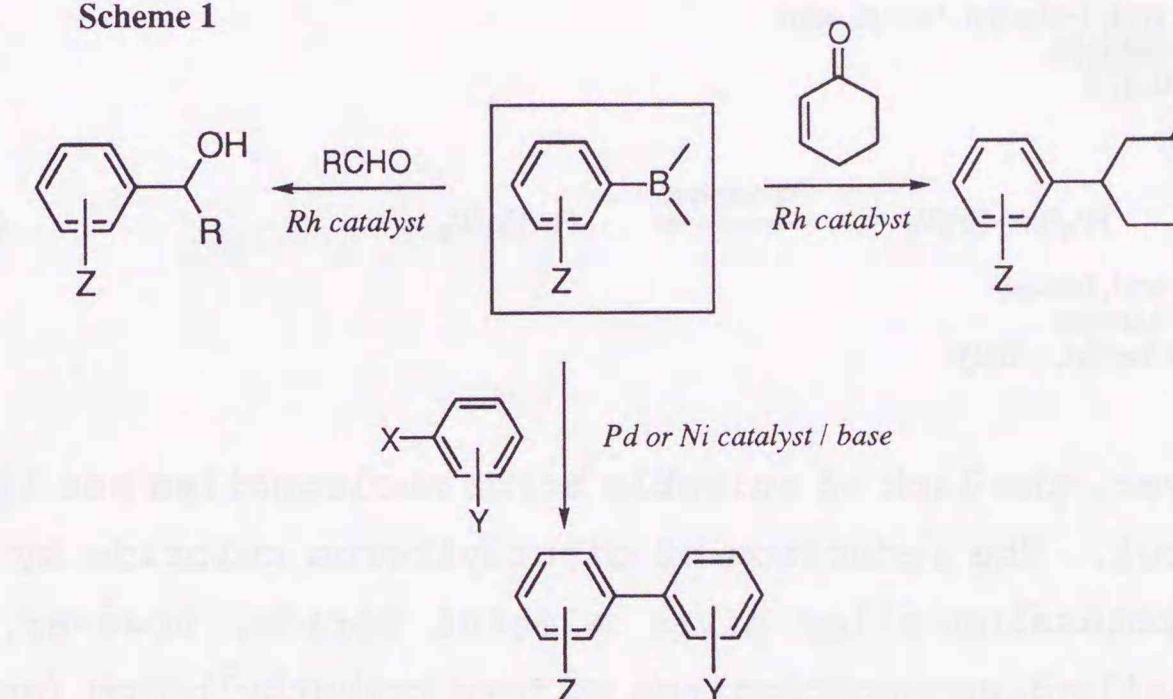
Palladium(0)-Catalyzed Cross-Coupling Reaction of Alkoxydiboron with Haloarenes: A Direct Procedure for Arylboronic Esters

The palladium-catalyzed cross-coupling reaction of bis(pinacolato)diboron ($\text{Me}_4\text{C}_2\text{O}_2$) $\text{BB}(\text{O}_2\text{C}_2\text{Me}_4)$ with haloarenes gave a direct procedure for arylboronic esters from aryl halides in a range of 60-98%. The reaction was catalyzed by $\text{PdCl}_2(\text{dppf})$ (3 mol%) at 80 °C in the presence of KOAc (3 equiv) in DMSO and available with various functional groups such as nitro, cyano, ester, and carbonyl groups. The *trans*- $\text{ArPd}^{\text{II}}(\text{OAc})(\text{PPh}_3)_2$ intermediate was isolated and characterized to propose the catalytic cycle involving the transmetalation between the phenylpalladium(II) acetate complex and bis(pinacolato)diboron.

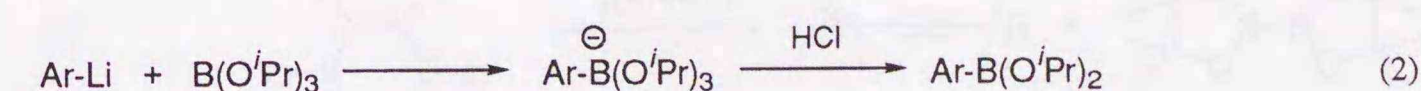
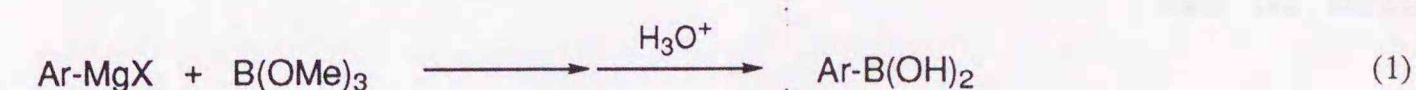
Introduction

Considerable attention has recently been paid to arylboronic acids and esters due to their usefulness in organic synthesis (Scheme 1),¹⁻³ their biological activity,⁴ and their molecular recognition properties.⁵

Scheme 1

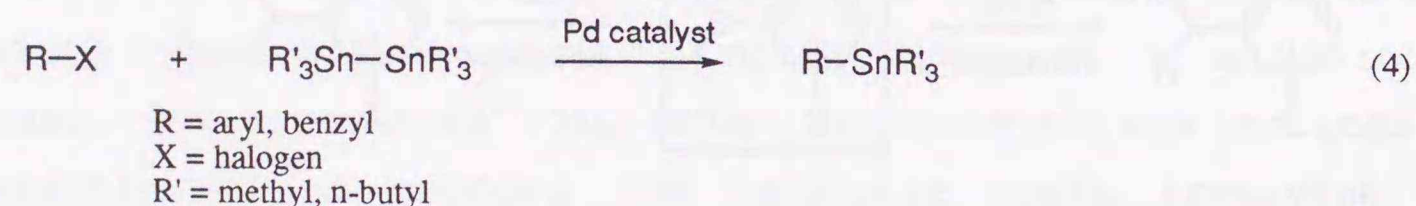
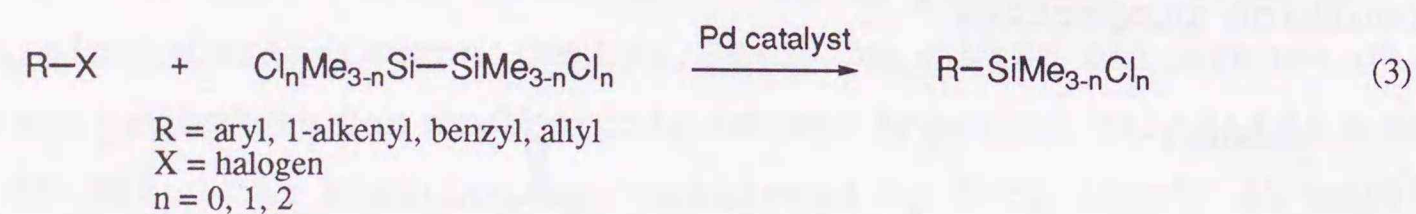


Several syntheses of boronic acids have been reported, but the best methods are based on the reaction of trialkyl borates with Grignard or lithium reagents (eq. 1 and 2).⁶ In particular, the reaction of aryllithium reagents and triisopropyl borate affords arylboronic esters in high yield, often over 90%, without contamination of multiple alkylation products.

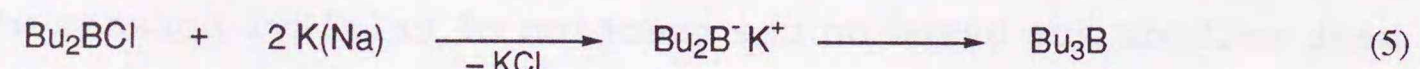


The transition-metal-catalyzed cross-coupling reaction of boron nucleophiles with aryl electrophiles is an alternative and convenient route to such boronic acids and esters.

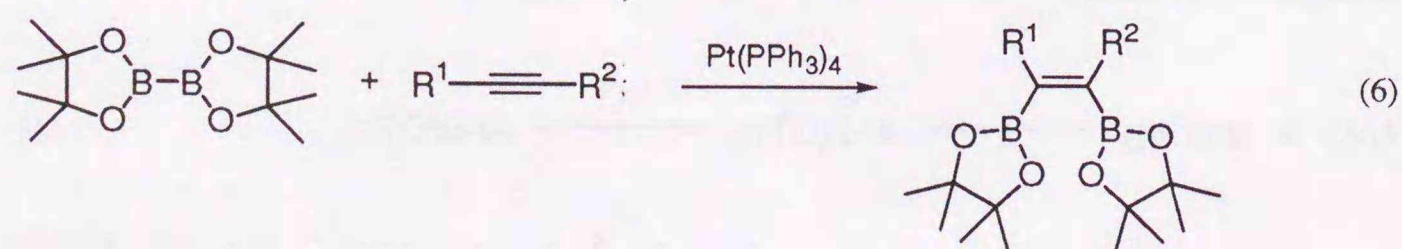
The cross-coupling reaction of disilanes⁷ or distannanes⁸ has been extensively studied. Matsumoto and Nagai found that some organic halides react with methylchlorosilanes $\text{Me}_n\text{Cl}_{6-n}\text{Si}_2$ in the presence of palladium catalyst to give the corresponding organosilanes (eq. 3).^{7c, d} Further, Eaborn and his colleagues extended the method to the reaction of the distannanes $\text{Me}_3\text{SnSnMe}_3$ and $\text{Bu}_3\text{SnSnBu}_3$ with some organic halides (eq. 4).^{8b, c}



However, the lack of suitable boron nucleophiles has limited this protocol. The reduction of dibutylboron chloride by means of sodium-potassium alloy gives a metal boride, however, such compound easily disproportionates to form tributylboron (eq. 5).⁹ Diboron tetrahalides reported by Schlesinger are also unstable.¹⁰

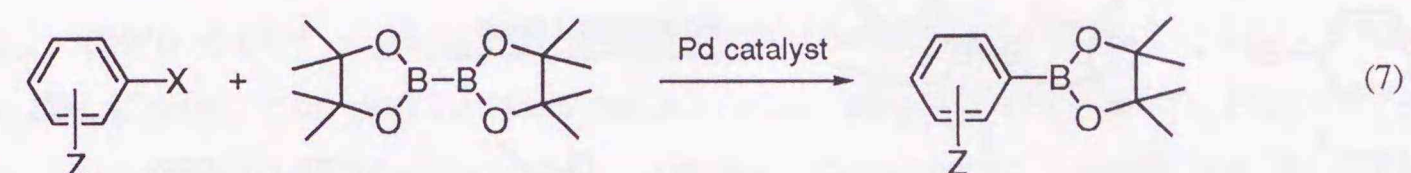


Recently, we found that the addition of tetraalkoxydiboron to alkynes to give *cis*-diborylalkenes is catalyzed by platinum(0) complexes (eq. 6).¹¹ Such diborons are thermally stable and easily handled in air.



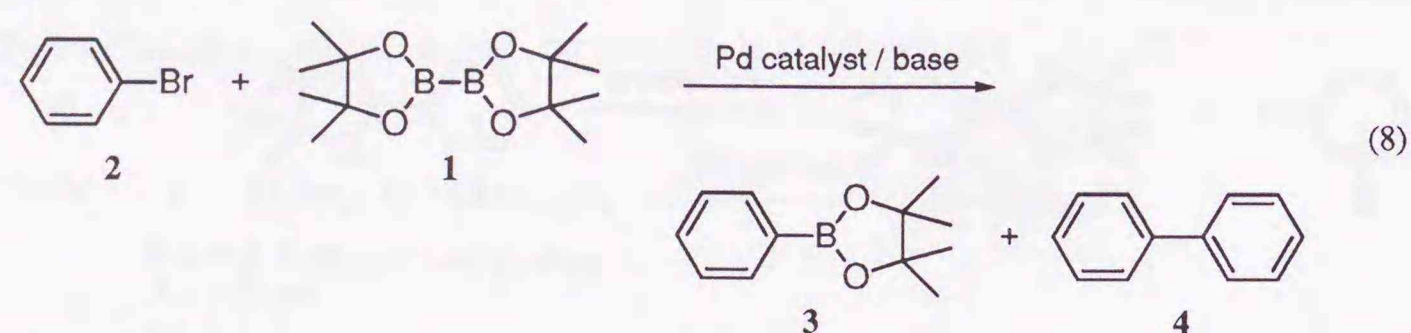
Thus, the alkoxydiborons should be useful as a boron

nucleophile for the cross-coupling reaction with organic halides. In this chapter, the palladium-catalyzed coupling reaction of the pinacol ester of diboron¹² and aryl halides, which represents the first one-step procedure for preparing arylboronic esters from aryl halides, is described (eq 7).



Results and Discussion

Reaction conditions.



The reaction conditions were optimized at 80 °C using bis(pinacolato)diboron 1 and bromobenzene 2 as a substrate (eq. 8, Table 1). We previously reported that the cross-coupling reaction of organoboron reagents with organic halides smoothly proceeds in the presence of base and a palladium catalyst.^{1, 13} A suitable base is also essential for the cross-coupling reaction of 1. Although very weak bases such as KOAc generally did not accelerate the cross-coupling reaction of organoboron compounds,

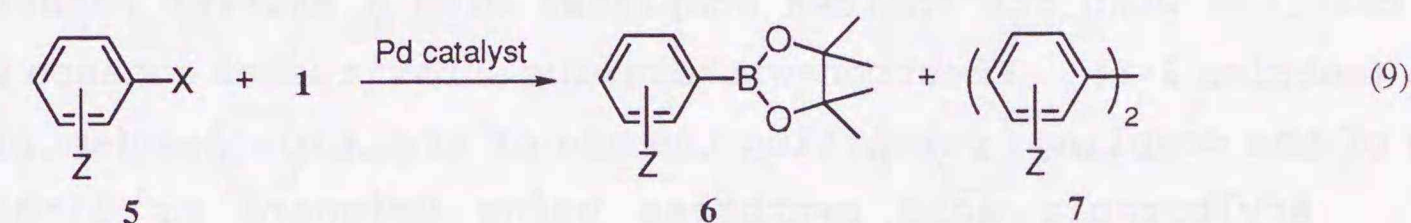
Table 1. Reaction condition for cross-coupling of 1 with bromobenzene^a

entry	catalyst	base	solvent	yield (%) ^b	
				3	4
1	PdCl ₂ (dppf)	none	DMSO	1	0
2	PdCl ₂ (dppf)	KOAc	DMSO	98	0
3	Pd(PPh ₃) ₄	KOAc	DMSO	43	0
4	Pd(OAc) ₂	KOAc	DMSO	16	8
5	Pt(PPh ₃) ₄	KOAc	DMSO	3	0
6	Ni(PPh ₃) ₄	KOAc	DMSO	0	0
7	RhCl(PPh ₃) ₃	KOAc	DMSO	3	0
8	PdCl ₂ (dppf)	K ₃ PO ₄	DMSO	25	60
9	PdCl ₂ (dppf)	K ₂ CO ₃	DMSO	56	36
10	PdCl ₂ (dppf)	KF	DMSO	66	28
11	PdCl ₂ (dppf)	Et ₃ N	DMSO	6	0
12	PdCl ₂ (dppf)	KOAc	DMF	94	0
13	PdCl ₂ (dppf)	KOAc	dioxane	78	0
14	PdCl ₂ (dppf)	KOAc	toluene	67	0

^a All reactions were carried out at 80 °C by using bromobenzene (1.0 mmol), diboron (1.1 mmol), catalyst (0.03 mmol), base (3 mmol), and solvent (6 mL). ^b GLC yield based on bromobenzene.

it was unexpectedly the best base to achieve high yields and high selectivity (entry 2). Stronger bases, such as K₃PO₄ and K₂CO₃, promoted the further reaction of 3 with bromobenzene, resulting in contamination by a substantial amount of biphenyl 4 (entries 8 and 9). The solvent also plays an important role in the rate of the cross-coupling. The reaction is accelerated in polar solvents: e.g., DMSO ≥ DMF > dioxane > toluene (entries 2 and 12-14). As for the catalyst, the palladium catalysts, especially PdCl₂(dppf), gave the best results (entry 2). Other catalysts, such as Ni(PPh₃)₄, Pt(PPh₃)₄, and RhCl(PPh₃)₃, did not catalyze the reaction at all (entries 5-7).

Effect of phosphine ligand.



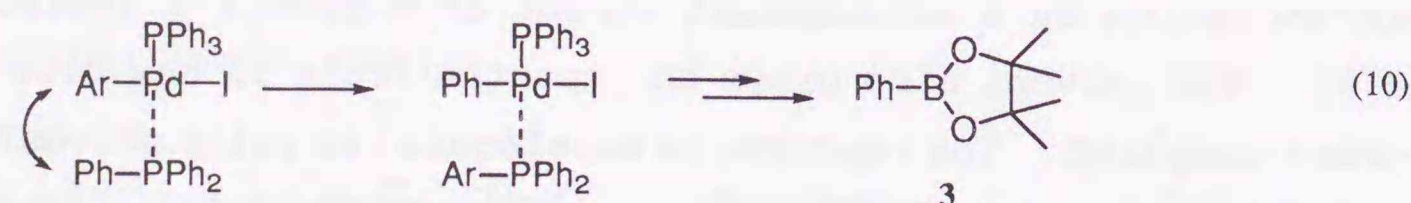
As for the catalyst, PdCl₂(dppf) gave the best results for haloarenes 5 having either an electron-withdrawing or -donating group (eq. 9, Table 2). The Pd(PPh₃)₄-catalyzed reaction of 4-bromoanisole with 1 gave 62% of (4-methoxyphenyl)boronate together with an 8% yield of phenylboronate 3. The contamination by this unexpected byproduct, arising from the coupling with a phenyl group

Table 2. Effect of ligand on the reaction (eq. 9)^a

Z	catalyst	yield (%) ^b		
		6	7	3
OMe	PdCl ₂ (dppf)	44	0	2
	Pd(PPh ₃) ₄	62	0	8
CO ₂ Me	PdCl ₂ (dppf)	86	0	0
	Pd(PPh ₃) ₄	28	0	0

^a All reactions were carried out at 80 °C by using aryl bromide (1.0 mmol), diboron (1.1 mmol), catalyst (0.03 mmol), KOAc (3 mmol), and DMSO (6 mL). ^b GLC yield based on aryl bromide.

on triphenylphosphine (eq 10),¹⁴ was also observed in the reaction with 4-(dimethylamino)bromobenzene.



Cross-coupling reaction of bis(pinacolato)diboron with representative haloarenes.

The results of the $\text{PdCl}_2(\text{dppf})$ -catalyzed cross-coupling of 1 with representative haloarenes are summarized in Table 3. The cross-coupling reaction of haloarenes having electron-donating groups, such as NMe_2 or OMe , is slow when using the bromides, but the reaction with the iodides completes with a shorter reaction time (entries 2-5). Electron-withdrawing substituents enhance the rate of the coupling, permitting the use of aryl bromides (entries 6-9). Arylboronic acid syntheses using Grignard or lithium reagents require the protection of functional groups sensitive to these reagents, but the present reaction is tolerated by various functional groups, e.g., CO_2Me , COMe , and CN . Sterically hindered halides such as iodomesitylene (entry 10) and heteroaromatic halides (entries 11 and 12) also gave the corresponding arylboronates in high yields. The coupling with the C-I bond is adequately faster than with the C-Br bond that the selective synthesis of (4-bromophenyl)boronate was accomplished (entry 13). The reaction of p-dibromobenzene with 2 equiv of 1 directly gave an 86% yield of diboronic ester, which has been used extensively for the synthesis of poly(p-phenylene) (entry 14).¹⁵

Reaction mechanism.

A mixture of 1 (0.5 mmol) and $\text{Pd}(\text{PPh}_3)_4$ (0.05 mmol) in toluene (4 mL) was heated at 100 °C for 1 h in an NMR tube. ^{31}P NMR analysis did not give any signal corresponding to the oxidative adducts. Thus, the mechanism involving a palladium(IV) intermediate

Table 3. Cross-coupling of 1 and haloarenes^a

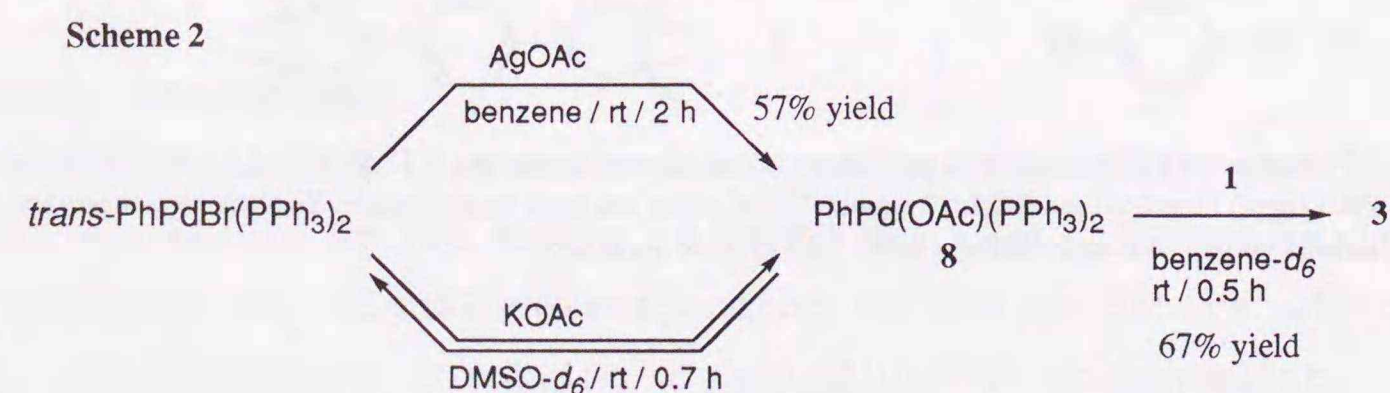
entry	aryl halide	time (h)	product 3	yield (%) ^b
1		2		98
2		6		90
3		24		23
4		2		82
5		24		69
6		1		86
7		1		(80)
8		1		(76)
9		2		(86)
10		24		(86)
11		4		(76)
12		4		(86)
13		1		(86) ^c
14		2		(76) ^d

^a Reactions of 1 (1.1 mmol) with aryl halide (1.0 mmol) were carried out in DMSO (4 mL) at 80 °C by using $\text{PdCl}_2(\text{dppf})$ (3 mol %) and KOAc (3 mmol). ^b GLC yields are based on aryl halide. Yields in parentheses are isolated yields. ^c 1.0 equiv of 1 was used. ^d 2.2 equiv of 1 was used.

generated by the stepwise double-oxidative additions of 1 and 2 to the palladium(0) complex can be excluded because the oxidative addition of 1 did not proceed under the given reaction conditions.

This transformation may result from a catalytic cycle¹⁶ that involves the oxidative addition of a haloarene to the palladium(0) complex to give a ArPd(II)X adduct, the transmetalation between 1 and ArPd(II)X to provide a ArPd(II)B(OR)_2 intermediate, and the reductive elimination of 3 to regenerate the palladium(0) complex.

For the present cross-coupling reaction, the use of KOAc is essential not only to accelerate the reaction but also to prevent the formation of biaryl byproducts. Although oxidative addition and reductive elimination sequences are reasonably well understood and are fundamentally common processes to all cross-coupling reactions of organometallics,^{16, 17} less is known about the transmetalation step since the process is highly dependent on the organometallics or the conditions used for the couplings. The role of the base is thought to be the acceleration of the transmetalation rate, similar to the related cross-coupling reaction of organoboron compounds.¹³ In general, the effect of bases on the cross-coupling reaction of organoboron compounds can be best understood in terms of the following two mechanisms. The first mechanism involves the coordination of a negatively charged base to the boron atom to increase its nucleophilicity for transmetalation to the palladium halide. By the second mechanism, the base first displaces the palladium halide to give an alkoxo-, hydroxo-, or acetoxypalladium(II) species¹⁸ in solution, these being known to transmetalate with organoboron compounds under neutral conditions.^{13, 19} However, ¹¹B NMR analysis of a mixture of 1 and KOAc



in $\text{DMSO-}d_6$ gave no evidence of the coordination of the acetoxo anion to the boron atom, thus suggesting that the latter mechanism, which gives an acetoxypalladium(II) species, is predominant.

The treatment of trans- $\text{PhPdBr(PPh}_3)_2$ with AgOAc (1.1 equiv) in benzene at room temperature gave a thermally unstable pale yellow solid, $\text{PhPd(OAc)(PPh}_3)_2$ (8) (Scheme 1).²⁰ The complex can be trans-coordinated, since the ³¹P NMR spectrum exhibited one singlet at 21.39 ppm and the ¹³C NMR signal due to the phenyl C(1) carbon occurred at 148.60 ppm. Strong absorptions at 1600 and 1430 cm^{-1} are characteristic for the trans-coordination of an acetoxo ligand. The quantitative formation of the same complex under the conditions used for the cross-coupling was immediately observed by ¹H NMR analysis of a trans- $\text{PhPdBr(PPh}_3)_2$ and KOAc (10 equiv) mixture in $\text{DMSO-}d_6$. The isolated complex 8 exhibited high reactivity toward 1 giving a 67% yield of 3 ($\text{Ar} = \text{Ph}$) at room temperature. Although the cross-coupling reaction proceeded at 80 °C, the above two reactions (which involve three steps: the ligand exchange with acetoxo anion, the transmetalation with 1, and the reductive elimination of 3) easily occurred at room temperature. On the basis of these results, the mechanism must be comprised of a catalytic cycle entailing the transmetalation between 1 and the acetoxypalladium(II) intermediate, as outlined in Figure 2.

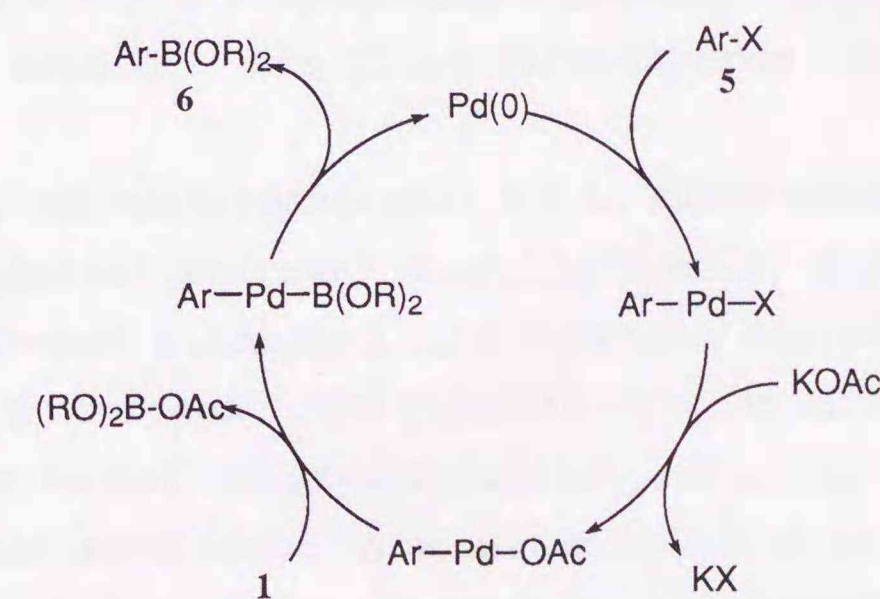


Figure 1. Catalytic Cycle

The high reactivity of oxopalladium complexes toward transmetalation with organoboron compounds can be attributed to both the high reactivity of the Pd-O bond, which consists of a soft acid and a hard base combination, and the high oxophilicity of the boron center. The kinetic study reflects the transmetalation process taking place. first the coordination of the alkoxy ligand to the boron atom followed by the transfer of the organic group on boron to the palladium atom. A similar high reactivity of RO-Pd complexes toward transmetalation with organosilicon compounds has recently been reported by Hiyama.²¹ Thus, it is reasonable to anticipate a similar effect of base on the other cross-coupling reactions of less reactive organometallics.

Experimental Section

General. All the experiments were carried out under a nitrogen atmosphere. IR spectra were taken with a Hitachi Perkin-Elmer Model 125 spectrometer. ¹H and ¹³C NMR spectra were recorded on a JEOL EX-400 spectrometer (¹H, 400 MHz; ¹³C, 100 MHz). Chemical shifts of ¹H and ¹³C NMR signals reported δ ppm referenced to CHCl₃ (7.26 and 77.0) or an internal SiMe₄. ¹¹B and ³¹P NMR spectra were recorded with a Bruker MSL-400 (128 or 162 MHz) using BF₃•OEt₂ or H₃PO₄ as an external standard. Mass spectra were obtained with a Finnigan ITD 800 for the GC-MS analysis and a JEOL JMS-DX303 for the high-resolution analysis. GLC analyses were carried out with a Hitachi 263 equipped with a glass column (OV-17 on Uniport B, 2 m).

Materials and reagents. Solvents were distilled before use from either sodium (toluene, dioxane) or CaH₂ (DMSO, DMF). PdCl₂(dppf),²² PdCl₂(PPh₃)₂,²³ and Pd(PPh₃)₄²⁴ were prepared by the established methods. PhPdBr(PPh₃)₂ was obtained from bromobenzene and Pd(PPh₃)₄.²⁵ All aryl iodides and bromides were commercial products except for 3-iodobenzothiophene,²⁶ which was prepared by the known method. Bis(pinacolato)diboron was synthesized as follows.¹²

Bis(pinacolato)diboron. A 2 L, three-necked flask equipped with a mechanical stirrer, dropping funnel, and a dry ice-cooled reflux condenser connected to a nitrogen source and a bubbler is flushed with nitrogen. The flask is charged with 800 mL of pentane and 218 g (4.84 mol) of dimethylamine, and cooled to ca. -30°C with a dry ice-methanol bath. A solution of 201 g (0.801 mol) of boron tribromide in 400 mL of pentane is added dropwise through the addition funnel over 3 h to the vigorously stirred solution while maintaining the bath-temperature at -20°C to -10°C. As soon as the addition is begun, a white precipitate of dimethylamine

hydrobromide appears. The temperature is allowed to rise to ambient temperature without removing the cooling bath, and the slurry is stirred for 16 h at room temperature. The precipitate is removed by filtration through a Celite pad on a glass-fitted filter funnel. The flask and filter cake are rinsed three times with 60 mL of pentane. The pentane solution is distilled to give 92.7 g (81%) of tris(dimethylamino)borane as a colorless liquid, bp 44-45°C (12 mm). A 500 mL, two-necked flask equipped with a magnetic stirring bar, dropping funnel, and a distillation apparatus connected to a nitrogen source and a bubbler is flushed with nitrogen. The flask is charged with 100 mL of pentane and 92.7 g (0.648 mol) of tris(dimethylamino)borane, and cooled to -40°C (external bath temperature) with a dry ice-methanol bath. A solution of 81.3 g (0.324 mol) of boron tribromide in 80 mL of pentane is added dropwise to the stirred solution over a period of 1.5 h maintaining the external bath temperature at -40°C. The cooling bath is removed and the solution is stirred at room temperature for 30 min. Distillation affords 172.8 g (99%) of bromobis(dimethylamino)borane as a colorless liquid, bp 56-58°C (12 mm), lit.²⁷ bp 20-28°C (0.5 mm). A 500 mL, three-necked flask equipped with an airtight mechanical stirrer, a dropping funnel, and a reflux condenser connected to a nitrogen source and a bubbler is flushed with nitrogen. The flask is charged with 78 mL of toluene and 22.3 g (0.97 g-atom) of sodium. The mixture is brought to reflux with an oil bath and the sodium is finely pulverized by vigorous stirring. A solution of 135.6 g (0.758 mol) of bromobis(dimethylamino)borane in 55 mL of toluene is added dropwise at a rate sufficient to maintain a gentle reflux over 45 min. Shortly after the addition is begun, a deep-blue precipitate appears. The suspension is heated at reflux for an additional 2.5 h. The slurry is cooled to room temperature, and filtered through a Celite pad on a sintered-glass funnel. The flask and filter cake are rinsed three times with 50 mL of toluene. The yellow filtrate is concentrated under reduced pressure, and the residual oil is distilled under reduced pressure to give 54 g (72%) of

tetrakis(dimethylamino)diboron as a colorless liquid, bp 92°C (12 mm), lit.²⁷ bp 55-57°C (2.5 mm). A 2 L, three-necked flask fitted with a mechanical stirrer, dropping funnel, and a reflux condenser connected to a nitrogen source and a bubbler is flushed with nitrogen. To the flask are added 53.7 g (0.271 mol) of tetrakis(dimethylamino)diboron and 510 mL of toluene, and then a solution of 64.4 g (0.545 mol) of pinacol in 340 mL of toluene. The flask is immersed in an ice-water bath and a 5.4 M ethereal solution of hydrogen chloride (203 mL, 1.10 mol) is added dropwise during 2 h. As soon as the addition is started, a white precipitate of dimethylamine hydrochloride appears. The slurry is stirred at room temperature for an additional 4 h. The precipitate is removed by filtration in a Büchner funnel with suction, and the filtrate is concentrated on a rotary evaporator to give a white solid. The solid is dissolved in ca. 700 mL of pentane and the remaining solid is again removed by filtration. The filtrate is washed three times with 500 mL of water and dried over anhydrous magnesium sulfate. The drying agent is removed by filtration and the filtrate is concentrated to ca. 150 mL. The flask is heated to dissolve the resulting precipitate, allowed to cool to room temperature, and then thoroughly chilled in a freezer (-30°C). The first crop is collected by filtration and washed twice with 30 mL of cold pentane. The mother liquor is again concentrated to give another crop of crystals. The procedure is repeated two additional times. The combined crystals are dried under reduced pressure (0.1 mm) for 16 h at room temperature to give 54.3 g (79%) of bis(pinacolato)diboron as colorless plates, mp 138 °C, lit.¹² mp 138 °C.

Typical procedure for arylboronates. A flask charged with palladium catalyst (0.03 mmol), KOAc (294 mg, 3.0 mmol), and diboron (279 mg, 1.1 mmol) was flushed with nitrogen. DMSO (6 mL) and haloarene (1.0 mmol) were then added. After being stirred at 80 °C for an appropriate period, the product was extracted with benzene, washed with water, and dried over anhydrous magnesium sulfate.

Kugelrohr distillation in vacuo gave the arylboronates.

The following compounds were prepared by the above procedure.

(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzene (Table 3, entry 1): n_D^{20} 1.4971; IR (neat) 3000, 1600, 1510, 1370, 1150, 1100, 1040 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.35 (s, 12 H), 7.36 (t, $J = 7.6$ Hz, 2 H), 7.45 (d, $J = 7.6$ Hz, 1 H), 7.81 (d, $J = 7.6$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.89, 83.78, 127.72, 131.25, 134.77; ^{11}B NMR (CDCl_3) δ 26.67; MS (m/z) 205 (38), 189 (100), 161 (37), 118 (93), 105 (74); HRMS for $\text{C}_{12}\text{H}_{17}\text{O}_2\text{B}$ calcd 204.1321, found 204.1320.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)anisole (Table 3, entry 4): n_D^{20} 1.5051; IR (neat) 1600, 1360, 1240, 1140, 1030 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.33 (s, 12 H), 3.82 (s, 3 H), 6.89 (d, $J = 8.1$ Hz, 2 H), 7.75 (d, $J = 8.1$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.87, 55.10, 83.56, 113.33, 136.52, 162.18; ^{11}B NMR (CDCl_3) δ 30.75; MS (m/z) 234 (M^+ , 100), 219 (12), 191 (5), 148 (15), 135 (5); HRMS for $\text{C}_{13}\text{H}_{19}\text{O}_3\text{B}$ calcd 234.1427, found 234.1438.

Methyl 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)benzoate (Table 3, entry 6): mp 78 $^\circ\text{C}$; IR (Nujol) 1730, 1360, 1270, 1130, 1110 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.36 (s, 12 H), 3.92 (s, 3 H), 7.87 (d, $J = 8.3$ Hz, 2 H), 8.02 (d, $J = 8.3$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.91, 52.18, 84.22, 128.62, 132.35, 134.69, 167.17; ^{11}B NMR (CDCl_3) δ 30.60; MS (m/z) 263 (100), 247 (33), 231 (25), 176 (54), 145 (35); HRMS for $\text{C}_{14}\text{H}_{19}\text{O}_4\text{B}$ calcd 262.1376, found 262.1385.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-*N,N*-dimethylaniline (Table 3, entry 2): mp 116 $^\circ\text{C}$; IR (Nujol) 1600, 1360, 1140 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.32 (s, 12 H), 2.98 (s, 6 H), 6.69 (d, $J = 8.8$ Hz, 2 H), 7.69 (d, $J = 8.8$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.85, 40.14, 83.18, 111.28, 136.16, 152.56; ^{11}B NMR (CDCl_3) δ 30.92; MS (m/z) 247 (M^+ , 100), 174 (6), 146 (12); HRMS for $\text{C}_{14}\text{H}_{22}\text{O}_2\text{NB}$ calcd 247.1744, found 247.1737.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)acetophenone (Table 3, entry 7): mp 63 $^\circ\text{C}$; IR (Nujol) 1680, 1500, 1350, 1140, 1090 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.36 (s, 12 H), 2.62 (s, 6 H), 7.91 (q, $J = 8.3$ Hz, 4 H); ^{13}C NMR (CDCl_3) δ 24.89, 26.78, 84.22, 127.30, 134.93, 139.03, 198.46; ^{11}B NMR (CDCl_3) δ 30.66; MS (m/z) 247 (100), 231 (41),

161 (5), 145 (12); HRMS for $\text{C}_{14}\text{H}_{19}\text{O}_3\text{B}$ calcd 246.1406, found 246.1427.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzonitrile (Table 3, entry 8): mp 97 $^\circ\text{C}$; IR (Nujol) 2230, 1400, 1270, 1140, 1090 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.35 (s, 12 H), 7.64 (d, $J = 8.3$ Hz, 2 H), 7.88 (d, $J = 8.3$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.87, 84.51, 114.58, 118.89, 131.14, 135.11; ^{11}B NMR (CDCl_3) δ 30.46; MS (m/z) 230 (51), 214 (100), 172 (3), 143 (59); HRMS for $\text{C}_{13}\text{H}_{16}\text{O}_2\text{NB}$ calcd 229.1274, found 229.1288.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)nitrobenzene (Table 3, entry 9): mp 111 $^\circ\text{C}$; IR (Nujol) 1600, 1510, 1400, 1350, 1150, 1090 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.37 (s, 12 H), 7.96 (d, $J = 8.8$ Hz, 2 H), 8.19 (d, $J = 8.8$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.89, 84.64, 122.42, 135.68, 149.87; ^{11}B NMR (CDCl_3) δ 30.33; MS (m/z) 250 (53), 234 (100), 163 (42); HRMS for $\text{C}_{12}\text{H}_{16}\text{O}_4\text{NB}$ calcd 249.1172, found 249.1185.

(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)mesitylene (Table 3, entry 10): n_D^{20} 1.4898; IR (neat) 3010, 1610, 1330, 1290, 1140, 1070 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.38 (s, 12 H), 2.24 (s, 3 H), 2.36 (s, 6 H), 6.77 (s, 2 H); ^{13}C NMR (CDCl_3) δ 21.25, 22.20, 24.96, 83.47, 127.45, 138.94, 142.15; ^{11}B NMR (CDCl_3) δ 32.18; MS (m/z) 246 (M^+ , 100), 189 (15), 145 (11); HRMS for $\text{C}_{15}\text{H}_{23}\text{O}_2\text{B}$ calcd 246.1791, found 246.1810.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)quinoline (Table 3, entry 11): mp 58 $^\circ\text{C}$; IR (Nujol) 1620, 1600, 1570, 1300, 1120, 1090 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.40 (s, 12 H), 7.54 (t, $J = 8.3$ Hz, 1 H), 7.75 (t, $J = 8.3$ Hz, 1 H), 7.84 (d, $J = 8.3$ Hz, 1 H), 8.12 (d, $J = 8.3$ Hz, 1 H), 8.63 (s, 1 H), 9.20 (s, 1 H); ^{13}C NMR (CDCl_3) δ 24.93, 84.35, 126.48, 127.58, 128.42, 129.37, 130.54, 144.28, 149.45, 154.81; ^{11}B NMR (CDCl_3) δ 30.77; MS (m/z) 255 (M^+ , 100), 169 (11), 156 (11); HRMS for $\text{C}_{15}\text{H}_{18}\text{O}_2\text{NB}$ calcd 255.1431, found 255.1459.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzo[b]thiophene (Table 3, entry 12): mp 76 $^\circ\text{C}$; IR (Nujol) 1330, 1160 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.38 (s, 12 H), 7.3-7.4 (m, 2H), 7.88 (d, $J = 8.3$ Hz, 1 H), 8.07 (s, 1 H), 8.37 (d, $J = 8.3$

Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.95, 83.58, 122.15, 124.12, 124.30, 125.42, 139.03, 140.75, 142.81; ^{11}B NMR (CDCl_3) δ 24.87; MS (m/z) 260 (M^+ , 100), 245 (3), 217 (14), 203 (1), 187 (2), 174 (32); HRMS for $\text{C}_{14}\text{H}_{17}\text{O}_2\text{SB}$ calcd 260.1043, found 260.1031.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)bromobenzene
(Table 3, entry 13): mp 70 $^\circ\text{C}$; IR (Nujol) 1590, 1350, 1230, 1080 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.34 (s, 12 H), 7.50 (d, J = 8.1 Hz, 2 H), 7.66 (d, J = 8.1 Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.87, 84.05, 126.24, 130.96, 136.32; ^{11}B NMR (CDCl_3) δ 30.81; MS (m/z) 283 (43), 269 (100), 239 (17), 198 (44), 183 (12); HRMS for $\text{C}_{12}\text{H}_{16}\text{O}_2\text{BBr}$ calcd 284.0406, found 284.0392.

1,4-Bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)benzene
(Table 3, entry 14): IR (Nujol) 1510, 1250, 1210, 1130, 1090 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.35 (s, 24 H), 7.80 (s, 4 H); ^{13}C NMR (CDCl_3) δ 24.89, 83.85, 133.91; ^{11}B NMR (CDCl_3) δ 31.16; MS (m/z) 330 (M^+ , 10), 315 (49), 287 (12), 273 (41), 244 (100), 231 (53); HRMS for $\text{C}_{18}\text{H}_{28}\text{O}_4\text{B}_2$ calcd 330.2174, found 330.2148.

Reaction of $\text{PhPdBr}(\text{PPh}_3)_2$ with acetoxo anion. Preparation of $\text{PhPd}(\text{OAc})(\text{PPh}_3)_2$.

To a flask were added $\text{PhPdBr}(\text{PPh}_3)_2$ (0.30 mmol), AgOAc (0.32 mmol), and benzene (4.5 mL). After being stirred at room temperature for 2 h, the precipitate of AgBr was removed by filtration. Evaporation of solvent gave a pale yellow solid which was recrystallized from benzene-ether at lower than room temperature to give 57% of $\text{PhPd}(\text{OAc})(\text{PPh}_3)_2$ 8: IR (KBr) 3050, 1600 (s), 1580, 1560, 1480, 1430 (s), 1370 (s), 1320 (s), 1090 (s), 740, 720, 680 cm^{-1} ; ^1H NMR ($\text{DMSO}-d_6$) δ 0.77 (br s, 3 H), 6.25 (t, 2 H, J = 6.9 Hz), 6.35-6.55 (m, 3 H), 7.2-7.5 (m, 30 H); ^1H NMR (C_6D_6) δ 1.41 (br s, 3 H), 6.41 (t, 2 H, J = 7.6 Hz), 6.58 (t, 1 H, J = 7.3 Hz), 6.9-7.1 (m, 20 H), 7.70 (br s, 12 H); ^{13}C NMR (C_6D_6) δ 24.18, 122.21, 127.46, 128.56, 129.94, 131.26, 135.11, 138.45, 148.60, 175.50; ^{31}P NMR (C_6D_6) δ 21.39.

The ^1H NMR analysis of a mixture of $\text{PhPdBr}(\text{PPh}_3)_2$ and KOAc (10 equiv) in $\text{DMSO}-d_6$ gave the same spectrum with 8, except there was

a large signal corresponding to KOAc at 1.57 ppm.

Reaction of $\text{PhPd}(\text{OAc})(\text{PPh}_3)_2$ with bis(pinacolato)diboron.

A mixture of $\text{PhPd}(\text{OAc})(\text{PPh}_3)_2$ 8 (0.039 mmol) and diboron 1 (0.035 mmol) in C_6D_6 (0.5 mL) was stirred at room temperature for 30 min. The ^1H NMR analysis indicated the formation of phenylboronate 3 in a 67% yield.

References

- For reviews, see: (a) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457. (b) Suzuki, A. *Pure Appl. Chem.* **1994**, *66*, 213-222. (c) Suzuki, A. *Pure Appl. Chem.* **1991**, *63*, 419-422. (d) Matteson, D. S. *Tetrahedron* **1989**, *45*, 1859-1885. (e) Suzuki, A. *Pure Appl. Chem.* **1985**, *57*, 1749-1758.
- (a) Sakai, M.; Hayashi, H.; Miyaura, N. *Organometallics* **1997**, *16*, 4229. (b) Takaya, Y.; Ogasawara, M.; Hayashi, T.; Sakai, M.; Miyaura, N. *J. Am. Chem. Soc.* **1998**, *120*, 5579.
- Sakai, M.; Ueda, M.; Miyaura, N. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 3279.
- (a) Reetz, M. T.; Huff, J.; Rudolph, J.; Töllner K.; Deege A.; Goddard, R. *J. Am. Chem. Soc.* **1994**, *116*, 11588-11589. (b) Paugam, M.-F.; Valencia, L. S.; Boggess, B.; Smith, B. D. *J. Am. Chem. Soc.* **1994**, *116*, 11203-11204. (c) Groziak, M. P.; Ganguly, A. D.; Robinson, P. D. *J. Am. Chem. Soc.* **1994**, *116*, 7597-7605. (d) Hamachi, I.; Tajiri, Y.; Shinkai, S. *J. Am. Chem. Soc.* **1994**, *116*, 7437-7438.
- (a) London, R. E.; Gabel, S. A. *J. Am. Chem. Soc.* **1994**, 2562-2569. (b) Sandanayake, K. R. A. S.; Nakashima, K.; Shinkai, S. *J. Chem. Soc., Chem. Commun.* **1994**, 1621-1622. (c) Sandanayake, K. R. A. S.; Shinkai, S. *J. Chem. Soc., Chem. Commun.* **1994**, 1083-1084.
- (a) Matteson, D. S. In *The Chemistry of the Metal-Carbon Bond*; Hartley, F. R., Patai, S., Eds.; Wiley: New York, 1987; Vol. 4, pp 307-499. (b) Nesmeyanov, A. N.; Sokolik, R. A. *Methods of Elemento-Organic Chemistry*; North-Holland: Amsterdam, The Netherlands, 1967; Vol. 1.
- (a) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1987**, *28*, 4715-4718. (b) Eaborn, C.; Griffiths, R. W.; Pidcock, A. *J. Organomet. Chem.* **1982**, *225*, 331-341. (c) Matsumoto, H.; Shono, K.; Nagai, Y. *J. Organomet. Chem.* **1981**, *208*, 145-152. (d) Matsumoto, H.; Yoshihiro, K.; Nagashima, S.; Watanabe, H.; Nagai, Y. *J. Organomet. Chem.* **1977**, *128*, 409-413.
- (a) Bumagin, N. A.; Bumagina, I. G.; Beletskaya, I. P. *Dokl. Acad. Nauk SSSR* **1984**, *274*, 1103-1106. (b) Azizian, H.; Eaborn, C.; Pidcock, A. *J. Organomet. Chem.* **1981**, *215*, 49-58. (c) Azarian, D.; Dua, S. S.; Eaborn, C.; Walton, D. R. M. *J. Organomet. Chem.* **1976**, *117*, C55-C57.
- (a) Nöth, H.; Schwerthöffer, R. *Chem. Ber.* **1981**, *114*, 3056-3062. (b) Kennedy, J. D.; McFarlane, W.; Wrackmeyer, B. *Inorg. Chem.* **1976**, *15*, 1299-1302. (c) Smith, K.; Swaminathan, K. *J. Chem. Soc., Chem. Commun.* **1975**, 719-720. (d) Parsons, T. D.; Baker, E. D.; Burg, A. B.; Juvinall, G. L. *J. Am. Chem. Soc.* **1961**, *83*, 250-251. (e) Auten, R. W.; Kraus, C. A. *J. Am. Chem. Soc.* **1952**, *74*, 3398-3401.
- (a) Urry, G.; Wartik, T.; Moore, R. E.; Schlesinger, H. I. *J. Am. Chem. Soc.* **1954**, *76*, 5293. (b) Ceron, P.; Finch, A.; Frey, J.; Kerrigan, J.; Parsons, T.; Urry, G.; Schlesinger, H. I. *J. Am. Chem. Soc.* **1959**, *81*, 6368-6371.
- (a) Ishiyama, T.; Matsuda, N.; Miyaura, N.; Suzuki, A. *J. Am. Chem. Soc.* **1993**, *115*, 11018-11019. (b) Ishiyama, T.; Matsuda, N.; Murata, M.; Ozawa, F.; Suzuki, A.; Miyaura, N. *Organometallics* **1996**, *15*, 713.
- Nöth, H. *Z. Naturforsch.* **1984**, *39b*, 1463-1466.
- (a) Miyaura, N.; Ishiyama, T.; Sasaki, H.; Ishikawa, M.; Satoh, M.; Suzuki, A. *J. Am. Chem. Soc.* **1989**, *111*, 314-321. (b) Miyaura, N.; Yamada, K.; Suginome, H.; Suzuki, A. *J. Am. Chem. Soc.* **1985**, *107*, 972-980.
- For aryl-phenyl scrambling during the cross-coupling, see: (a) Segelstein, B. E.; Butler, T. W.; Chenard, B. L. *J. Org. Chem.* **1995**, *60*, 12-13. (b) O'Keefe, D. F.; Dannock, M. C.; Marcuccio, S. M. *Tetrahedron Lett.* **1992**, *33*, 6679-6680. (c) Kong, K.-C.; Cheng, C.-H. *J. Am. Chem. Soc.* **1991**, *113*, 6313-6315.
- (a) Lamba, J. J. S.; Tour, J. M. *J. Am. Chem. Soc.* **1994**, *116*, 11723-11736. (b) Goldfinger, M. B.; Swager, T. M. *J. Am. Chem. Soc.* **1994**, *116*, 7895-7896. (c) Tour, J. M.; Lamba, J. J. S. *J. Am. Chem. Soc.* **1993**, *115*, 4935-4936. (d) Rehahn, M.; Schlüter,

- A.-D.; Wegner, G.; Feast, W. J. *Polymer* 1989, 30, 1060-1062. (e) Rehahn, M.; Schlüter, A.-D.; Wegner, G.; Feast, W. J. *Polymer* 1989, 30, 1054-1059.
16. Aliprantis, A. O.; Canary, J. W. *J. Am. Chem. Soc.* 1994, 116, 6985-6986.
 17. (a) Hegedus, L. S. In *Organometallics in Synthesis*; Schlosser, M., Ed.; Wiley: New York, 1994; pp 383-459. (b) Stille, J. K. In *The Chemistry of the Metal-Carbon Bond*; Hartley, F. R., Patai, S., Eds.; Wiley: New York, 1985; Vol. 2, pp 625-787. (c) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* 1986, 25, 508-524.
 18. Grushin, V. V.; Alper, H. *Organometallics* 1993, 12, 1890-1901.
 19. Moriya, T.; Miyaura, N.; Suzuki, A. *Synlett* 1994, 149-151.
 20. (a) Amatore, C.; Jutand, A.; M'Barki, M. A. *Organometallics* 1992, 11, 3009. (b) Amatore, C.; Jutand, A.; M'Barki, M. A. *Organometallics* 1995, 14, 1818. (c) For a related complex, $\text{EtPd}(\text{OAc})(\text{PMe}_3)_2$, see: Kawataka, F.; Kayaki, Y.; Shimizu, I.; Yamamoto, A. *Organometallics* 1994, 13, 3517-3524.
 21. Matsushashi, H.; Hatanaka, Y.; Kuroboshi, M.; Hiyama, T. *Tetrahedron Lett.* 1995, 36, 1539-1540.
 22. Hayashi, T.; Konishi, M.; Kobori, M.; Kumada, M.; Higuchi, T.; Hirotsu, K. *J. Am. Chem. Soc.* 1984, 106, 158.
 23. Heck, R. F. *Palladium Reagents in Organic Syntheses*; Academic: New York, 1985; p. 18.
 24. Coulson, D. R. *Inorg. Synth.* 1972, 13, 121.
 25. Fitton, P.; Rick, E. A. *J. Organomet. Chem.* 1971, 28, 287.
 26. Gaertner, R. J. *Am. Chem. Soc.*, 1952, 74, 4950.
 27. Brotherton, R. J.; McCloskey, A. L.; Petterson, L. L., Steinberg, H. J. *Am. Chem. Soc.* 1960, 82, 6242.

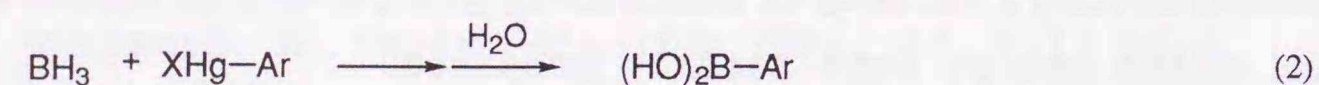
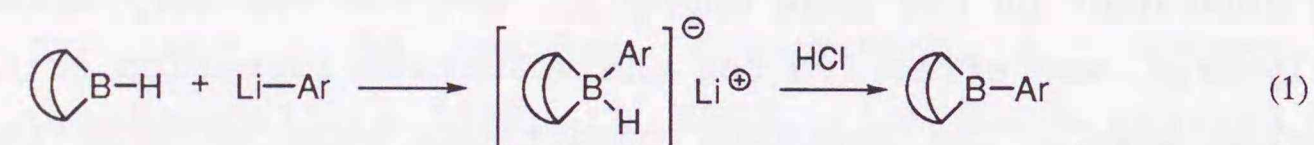
Chapter 3.

Novel Palladium(0)-Catalyzed Coupling Reaction of Dialkoxyborane with Aryl Halides: A Facile Synthetic Route to Arylboronates

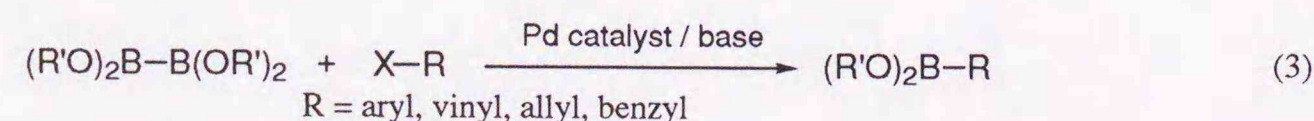
A direct borylation of aryl halides or triflates with dialkoxyborane was investigated. The coupling reaction of pinacolborane with aryl halides or triflates in the presence of a catalytic amount of $\text{PdCl}_2(\text{dppf})$ together with a base provided arylboronates in high yields. The product distributions were strongly dependent on the base employed, and the tertiary amine, especially Et_3N , was effective for the selective formation of the boron-carbon bond. The reaction conditions were so mild that arylboronates having a variety of functional groups such as carbonyl, cyano, and nitro groups were readily prepared.

Introduction

Arylboronic acids and their esters are valuable reagents in organic synthesis,¹⁻³ and much attention has been paid to them in biology,⁴ and in the study of molecular recognition.^{5,6} Ordinarily, arylboron compounds can be prepared by the transmetalation between arylmagnesium or -lithium reagents and boron compounds which have good leaving groups such as the halogen or alkoxy group.⁷ In a few cases, this synthesis has been conducted by the use of boron compounds containing a boron-hydrogen bond (eq. 1 and 2).^{8,9}

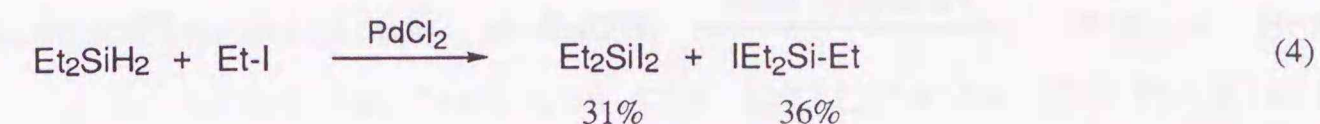


On the one hand, the direct borylation of aryl halides or pseudo-halides has been expected to be a more convenient procedure for preparing arylboronates. Thus, Miyaura and co-workers reported on a palladium-catalyzed cross-coupling reaction of tetraalkoxydiboron, which provided a one-step procedure for deriving organoboronates from organic electrophiles, including aryl, 1-alkenyl, allyl, benzyl halides and pseudo-halides (eq. 3).¹⁰ Arylboronic acid syntheses using Grignard or lithium reagents require the protection of functional groups sensitive to these reagents, but the palladium-catalyzed cross-coupling reaction is tolerated by various functional groups, e.g., CO₂Me, COMe, and CN.

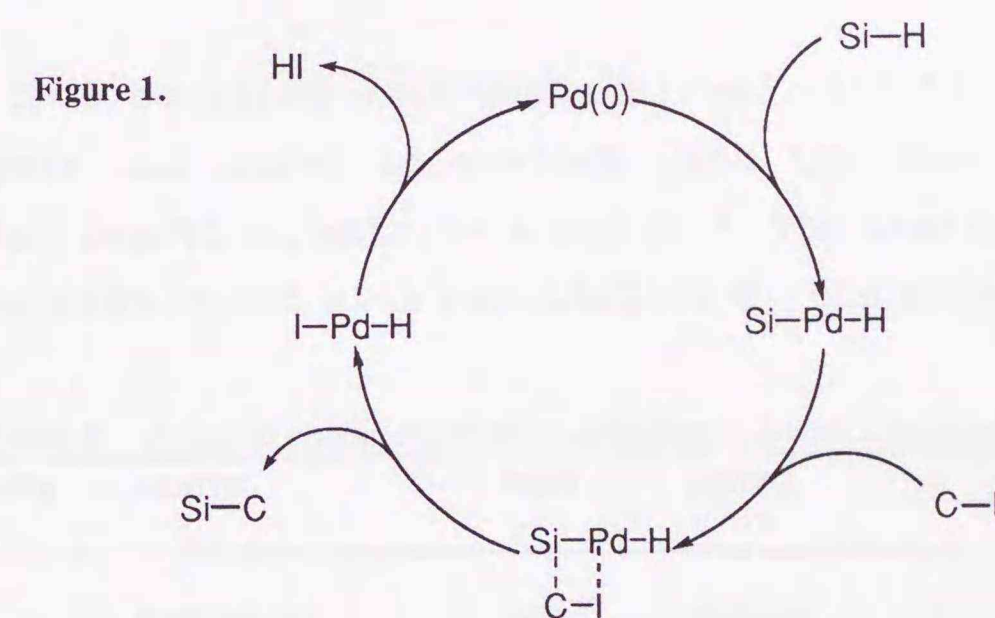


Recently, Kunai and his colleague have found that the PdCl₂-catalyzed reaction of alkyl iodides with Et₂SiH₂ afforded

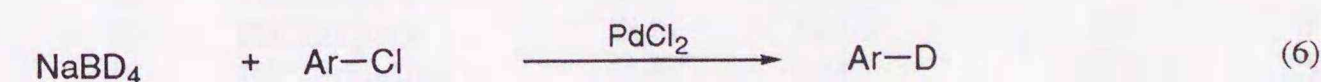
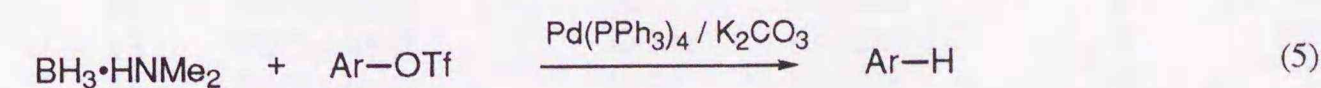
Et₂ISi-R to some extent,¹¹ indicating the potential use of metal hydride as a metalating reagent in the presence of a palladium catalyst (eq. 4).



Bearing in mind the character of hydrosilanes as hydride, Kunai's report is very unique. A mechanism which involved the first oxidative addition of hydrosilane to a Pd catalyst followed by a σ-bond metathesis between an Si-Pd bond and a C-I bond, has been postulated (Figure 1).

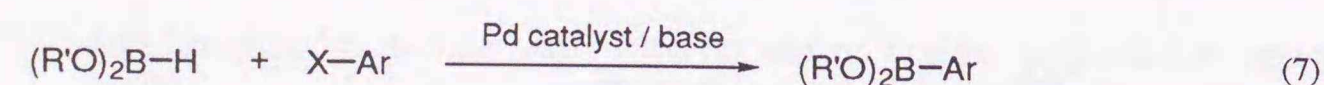


To our knowledge, however, there has been no report of a catalytic reaction using hydroboranes as a boron source. Generally, in the presence of a palladium catalyst, such hydroboranes as BH₃,¹² and NaBH₄¹³ greatly facilitate the hydrogenolysis of organic electrophiles (eq. 5 and 6).



In this chapter, a novel palladium-catalyzed coupling reaction of dialkoxyhydroborane with aryl halides in the presence

of a base and affording the corresponding arylboronates are described (eq 7). It can be seen that the low nucleophilicity of the hydride suppresses the above hydrogenolysis.

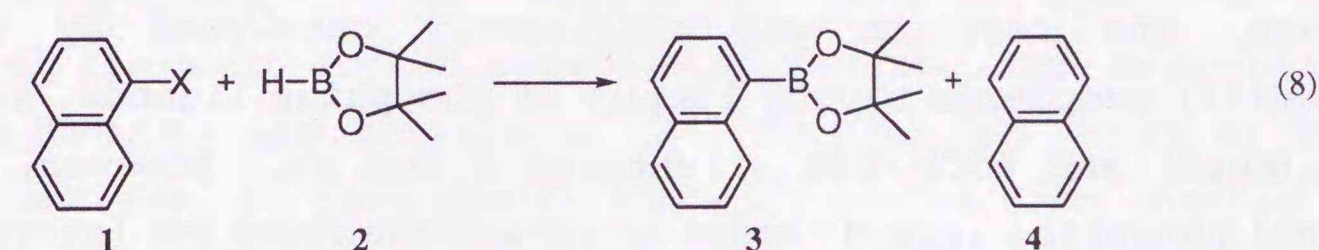


Dialkoxyboranes are more readily available than the diboron reagents, and the borylation using dialkoxyboranes is an atom economical manner. In addition, pinacolborane tolerates various functional groups and pinacolboronates are insensitive to air, moisture, and chromatography.¹⁴ Thus, the present borylation-methodology possesses several great advantages to allow for a wide range of arylboronates.

Results and Discussion

Reaction conditions.

In order to disclose the aptitude of the borylation, the reaction of 1-iodonaphthalene (1, X = I) with pinacolborane 2 was carried out under various conditions (eq.8, Table 1).



This coupling work was achieved with the aid of palladium catalysts and bases in analogy with the Suzuki-Miyaura cross-coupling reaction (entries 1 and 2).¹ The desired products tended to be contaminated with naphthalene 4, the normal cross-coupling

Table 1. Reaction condition for cross-coupling of 2 with 1-iodonaphthalene^a

entry	catalyst	base	solvent	yield (%) ^b	
				3	4
1	PdCl ₂ (dppf)	none	dioxane	0	3
2	PdCl ₂ (dppf)	Et ₃ N	dioxane	89	6
3	PdCl ₂ (PPh ₃) ₂	Et ₃ N	dioxane	75	13
4	PdCl ₂ (PPh ₃) ₂ /2PPh ₃	Et ₃ N	dioxane	0	0
5	Pd(PPh ₃) ₄	Et ₃ N	dioxane	10	1
6	Pd(OAc) ₂	Et ₃ N	dioxane	34	6
7	Pt(PPh ₃) ₄	Et ₃ N	dioxane	1	0
8	NiCl ₂ (PPh ₃) ₂	Et ₃ N	dioxane	11	3
9	RhCl(PPh ₃) ₃	Et ₃ N	dioxane	1	4
10	PdCl ₂ (dppf)	pyridine	dioxane	12	47
11	PdCl ₂ (dppf)	^t Pr ₂ NEt	dioxane	64	29
12	PdCl ₂ (dppf)	KF	dioxane	2	4
13	PdCl ₂ (dppf)	KOAc	dioxane	6	82
14	PdCl ₂ (dppf)	Et ₃ N	toluene	79	7
15	PdCl ₂ (dppf)	Et ₃ N	CH ₂ ClCH ₂ Cl	81	7
16	PdCl ₂ (dppf)	Et ₃ N	MeCN	83	8
17	PdCl ₂ (dppf)	Et ₃ N	DMF	27	23

^a All reactions were carried out at 80 °C for 2 h by using 1-iodonaphthalene (1.0 mmol), pinacolborane (1.5 mmol), catalyst (0.03 mmol), base (3 mmol), and solvent (4 mL).

^b GLC yield based on 1-iodonaphthalene.

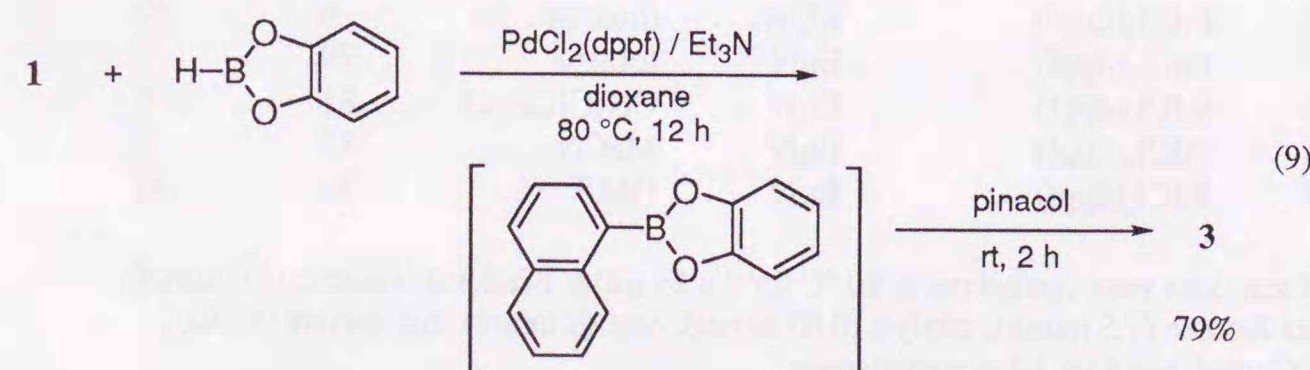
like product, in each case as a result of the behavior of pinacolborane as a hydride source. However, this situation was greatly improved by the choice of a suitable base. Thus, the tertiary amine, especially Et_3N , which was generally known not to contribute to the coupling reaction of boron compounds, was recognized to be most effective for the selective formation of **3** (entries 2 and 11).¹⁵ In the presence of other weak bases, the formation of undesirable **4** unexpectedly predominated (entries 10, 12 and 13).

Then, the reaction was efficiently catalyzed by the palladium(II) complexes having 2 equiv of phosphine ligands, such as $\text{PdCl}_2(\text{dppf})$ and $\text{PdCl}_2(\text{PPh}_3)_2$ (entries 2 and 3). However, an additional phosphine ligand tended to retard the reaction (entries 4 and 5). Other catalysts, such as $\text{NiCl}_2(\text{PPh}_3)_2$, $\text{Pt}(\text{PPh}_3)_4$, and $\text{RhCl}(\text{PPh}_3)_3$, did not catalyze the reaction (entries 7-9).

In testing the four solvents, dioxane, toluene, MeCN, and $\text{CH}_2\text{ClCH}_2\text{Cl}$, it was found that these did not play a distinguished role in the present reaction (entries 2 and 14-16). However, the use of the polar solvent, DMF, caused both a low yield and selectivity due to a decomposition of dialkoxyborane to diborane B_2H_6 (entry 17).¹⁶

Borylation of iodonaphthalene with catecholborane.

Also, the procedure could be applied for catecholborane (eq. 9). Although the resulting catechol esters are insecure to moisture and chromatography unlike inert pinacol esters **3**, they moderately favor the transesterification with other diols.¹⁷ Thus, the borylation of 1-iodonaphthalene with 1.5 equiv of



catecholborane at 80 °C for 12 h, followed by transesterifying with pinacol, gave an 79% yield of **3** along with naphthalene **4** (18%).

Borylation of aryl bromides and triflates with pinacolborane.

In Table 2, the reaction of 1-bromonaphthalene (**1**, $\text{X} = \text{Br}$) and 1-naphthyl trifluoromethanesulfonate ($\text{X} = \text{OSO}_2\text{CF}_3$) with pinacolborane **2** under various conditions are summarized (eq. 8). These electrophiles are more readily available than the corresponding iodides. Especially, from the synthetic point of view, the use of aryl fluoroalkanesulfonates, such as aryl triflates ($\text{X} = \text{OSO}_2\text{CF}_3$) and nonaflates ($\text{X} = \text{OSO}_2(\text{CF}_2)_3\text{CF}_3$, entry 4) has some advantages, in part due to the easy access from phenols.¹⁸

At 80 °C, the aryl bromide and triflate were not so reactive as the corresponding iodides, requiring a more elevated temperature (entries 1-4, 7, and 8). 1-Bromonaphthalene smoothly borylated with **2** at 100 °C in the presense of $\text{PdCl}_2(\text{PPh}_3)_2$ or $\text{PdCl}_2(\text{dppf})$ catalyst (entries 2 and 4). However, the phosphine ligand of palladium catalyst affected the borylation of triflates markedly; that is, $\text{PdCl}_2(\text{PPh}_3)_2$ -catalyzed reaction of 1-naphthyl triflate gave 43% of **3**, along with 52% of **4** (entry 9), whereas $\text{PdCl}_2(\text{PPh}_3)_2$ could

Table 2. Reaction condition for cross-coupling of **1** ($\text{X} = \text{Br}, \text{OTf}$) with **2**^a

entry	X=	catalyst	base	solvent	yield (%) ^b	
					3	4
1 ^c	Br	$\text{PdCl}_2(\text{dppf})$	Et_3N	dioxane	33	14
2		$\text{PdCl}_2(\text{dppf})$	Et_3N	dioxane	75	18
3 ^c		$\text{PdCl}_2(\text{PPh}_3)_2$	Et_3N	dioxane	66	17
4		$\text{PdCl}_2(\text{PPh}_3)_2$	Et_3N	dioxane	77	19
5		$\text{PdCl}_2(\text{PPh}_3)_2$	pyridine	dioxane	0	92
6		$\text{PdCl}_2(\text{PPh}_3)_2$	Et_3N	toluene	54	17
7 ^c	OTf ^d	$\text{PdCl}_2(\text{dppf})$	Et_3N	dioxane	6	11
8		$\text{PdCl}_2(\text{dppf})$	Et_3N	dioxane	82	18
9		$\text{PdCl}_2(\text{PPh}_3)_2$	Et_3N	dioxane	43	52
10		$\text{PdCl}_2(\text{dppf})$	pyridine	dioxane	3	19
11		$\text{PdCl}_2(\text{dppf})$	KOAc	dioxane	7	81
12		$\text{PdCl}_2(\text{dppf})$	Et_3N	toluene	42	54

^a All reactions were carried out at 100 °C for 2 h by using **1** (1.0 mmol), **2** (1.5 mmol), catalyst (0.03 mmol), base (3 mmol), and solvent (4 mL). ^b GLC yield based on **1**. ^c At 80 °C, for 16 h. ^d For 4 h.

be used satisfactorily for the borylation of aryl halides. As for the solvent, 1,4-dioxane was the most suitable, but the reaction taken place in toluene resulted in low selectivity (entries 6 and 12).

In the case of 1-naphthyl triflate, the addition of metal halides, which have been used for palladium-catalyzed reaction of aryl and alkenyl triflates, was less effective (Table 3). However, metal halides appeared to play an important role in swaying the selectivity (entries 2-4). Although the complete control of selectivity was unsuccessful, the addition of LiI was recognized to be most effective for the selective formation of 3 (entry 2). Presumably, LiI should displace OTf of Ar-Pd^{II}-OTf to give a palladium(II) iodide complex and play a critical role to preventing a transmetalation of the hydride (eq. 10).¹⁹

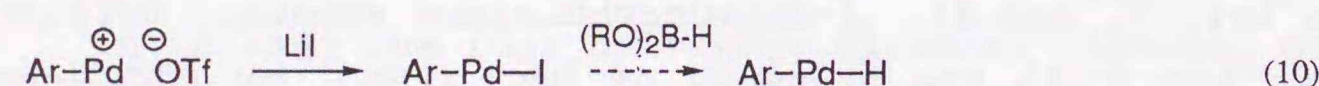


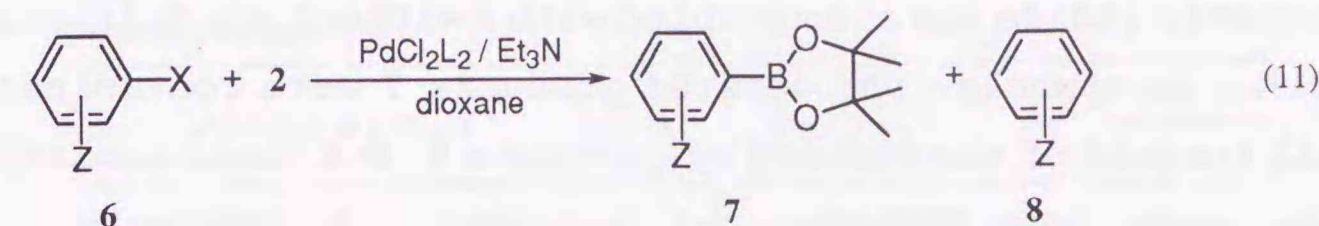
Table 3. Effect of metal halides^a

entry	metal halides	conv. (%) ^b	yield (%) ^c	
			3	4
1	none	43	32	60
2	LiI	52	85	15
3	LiBr	36	58	28
4	LiCl	38	42	50

^a All reactions were carried out at 80 °C for 18 h by using naphthyl triflate (1.0 mmol), 2 (1.5 mmol), PdCl₂(dppf) (0.03 mmol), Et₃N (3 mmol), metal halide (1.1 mmol), and dioxane (4 mL). ^b Conversion of naphthyl triflate. ^c GLC yield based on the conversion.

Borylation of representative aryl halides and sulfonates.

On the basis of the typical result obtained above, subsequent experiments with a considerable number of representative aryl halides or sulfonates 6 were carried out to give the corresponding products 7 (eq. 11). They are summarized in Table 4.

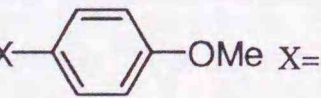
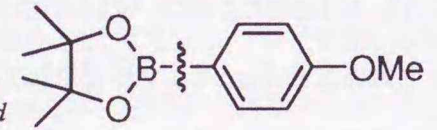
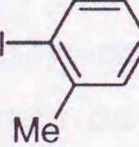
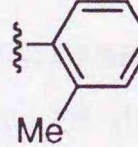
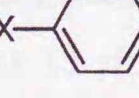
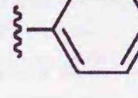
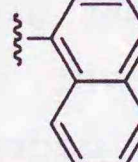
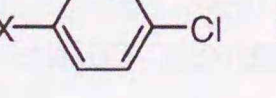
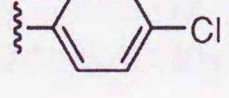
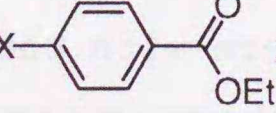
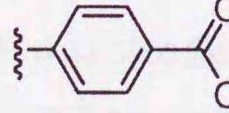
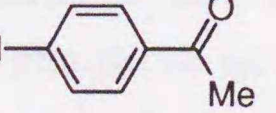
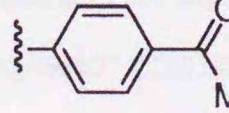


Generally, aryl iodides exhibited higher reactivity than aryl bromides or fluoroalkanesulfonates in the present reaction. Besides, in the case of aryl iodides or triflates having an electron-donating group such as OMe and Me, the reaction proceeded smoothly at 80 °C similarly to that above (entries 1 and 5). The presence of powerful electron-withdrawing substituents such as NO₂ are known to induce the reductive dehalogenation of 6;¹⁹ nevertheless, the differences in the yields and on the selectivity among aryl iodides having electron-donating or -withdrawing groups were not particularly large (entries 1, 7, 15, and 18-19). As in the case of aryl iodides, the product yields of the borylation of aryl triflates also were not substantially affected by their substituent moieties of 6, but the reaction of those having electron-withdrawing groups was sluggish at 80 °C, requiring a more elevated temperature (100 °C) (entries 3, 9, 17 and 25). On the whole, the reactivity of aryl bromides was not favorable when compared with that of aryl iodides or triflates. Besides, the borylation of aryl bromides having electron-donating groups proceeded smoothly at 100 °C (entries 2 and 22); however, the presence of electron-withdrawing substituents remarkably decreased the yield of 7 (entries 14 and 16).

The presence of functional groups, such as CO₂Et (entries 15-17), COMe (entries 18 and 25), CN (entries 19 and 26), and NHAc (entry 24), in the starting 6 did not interfere with the outcome of the present reaction at 80-100 °C. As this, the present procedure tolerates various functional groups owing to the inertness of 2 to these.¹⁵ In contrast, the previous methods via Grignard reagents or organolithiums⁷ require the protection of functional groups frequently. Then, both of the yield and the selectivity are almost independent of the steric requirement (entries 6, and 10-12). A

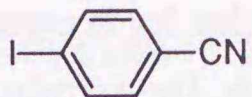
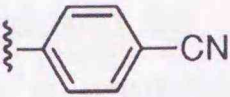
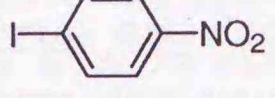
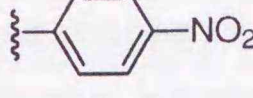
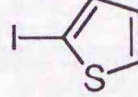
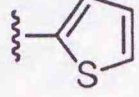
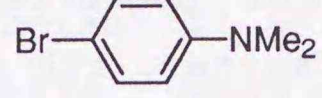
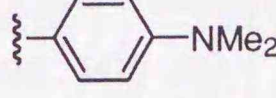
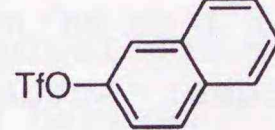
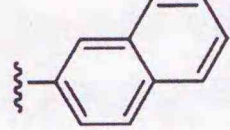
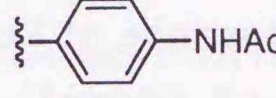
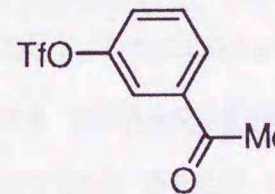
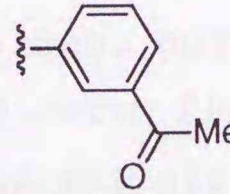
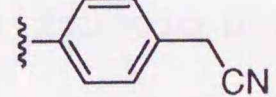
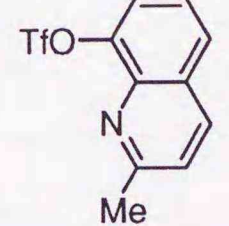
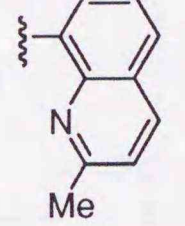
heteroaromatic iodide was also coupled with **2** without any difficulty (entry 21). As a whole, the desired products **7** were contaminated with small amounts of the reduced by-products **8**, but their isolation were very easy (see Experimental Section). Accordingly, the present reaction provides a simple and available procedure for synthesizing arylboronates **7**.

Table 4. Reaction of Representative **1** with **2**^a

entry	aryl halide or triflate 1	time (h)	product 3	yield (%) ^b	
				3	4
1	X-  -OMe X=I	1		77	16
2	Br	3 ^{c,d}		77	11
3	OTf ^e	4		81	12
4	ONf ^f	4		74	18
5	I-  -Me	1		(79)	
6	I-  -Me	5		(78)	
7	X-  X=I	2		84	
8	Br	6 ^c		67	
9	OTf	4		93	
10	X-  X=I	2		89	6
11	Br	6 ^c		75	18
12	OTf	4 ^c		82	18
13	X-  -Cl X=I	3		(83)	
14	Br	4 ^{c,d}		(49)	
15	X-  -CO ₂ Et X=I	2		79	17
16	Br	18 ^{c,d}		43	20
17	OTf	2 ^c		77	21
18	I-  -CO ₂ Me	4		(74)	

(continued)

Table 4. (continued)

entry	aryl halide or triflate 1	time (h)	product 3	yield (%) ^b	
				3	4
19	I-  -CN	4		(73)	
20	I-  -NO ₂	4		(84)	
21	I- 	4		(80)	
22	Br-  -NMe ₂	2 ^{c,d}		(79)	
23	TfO- 	4		(73)	
24	TfO-  -NHAc	4		(77)	
25	TfO-  -CO ₂ Me	4 ^{c,g}		(55)	
26	TfO-  -CH ₂ CN	6 ^c		(73)	
27	TfO- 	4		(63)	

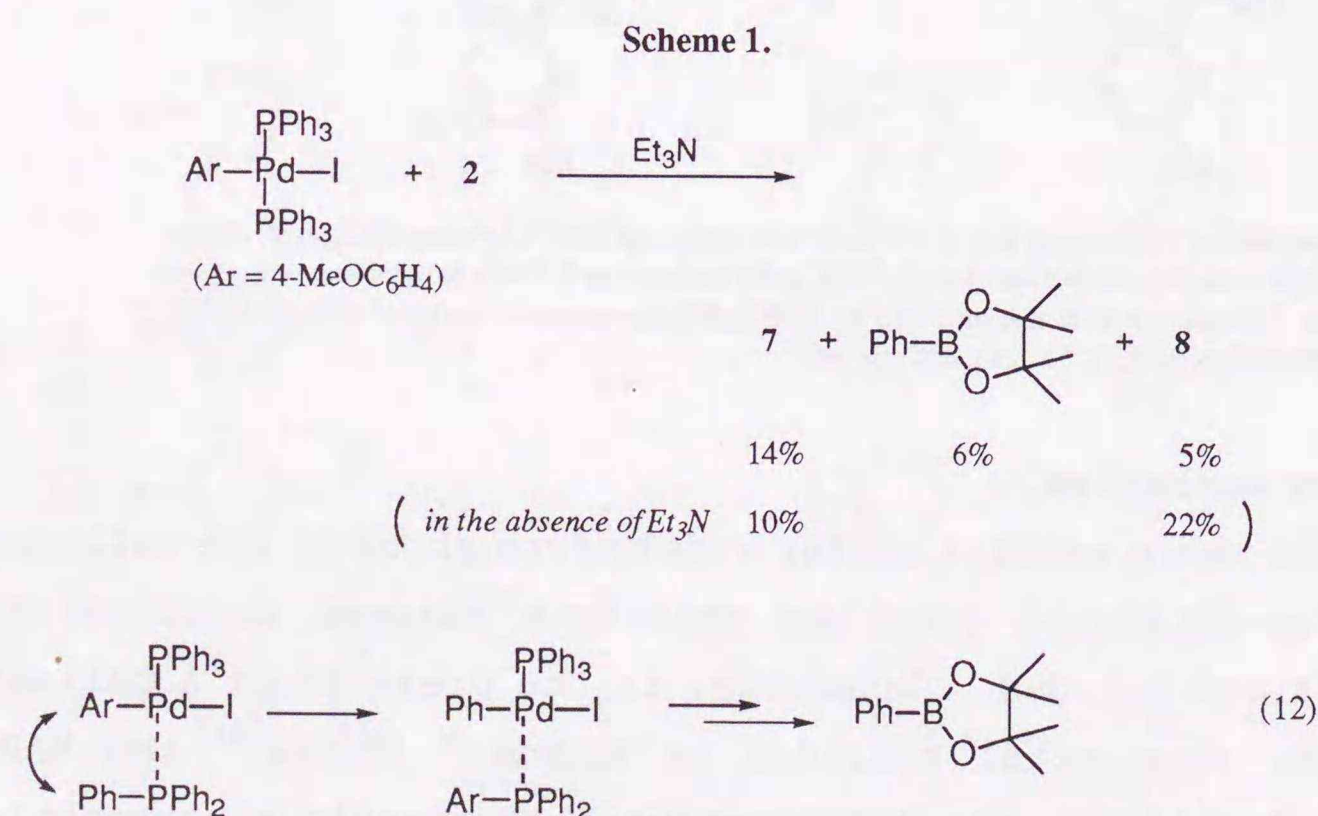
^a Reactions of **1** (1.0 mmol) with **2** (1.5 mmol) were carried out at 80 °C by using PdCl₂(dppf) (3 mol %), Et₃N (3 mmol), and dioxane (4 mL). ^b GLC yields are based on **1**. Yields in parentheses are isolated yields. ^c Reactions were carried out at 100 °C. ^d PdCl₂(PPh₃)₂ was used as catalyst. ^e OTf= OSO₂CF₃. ^f ONf= OSO₂(CF₂)₃CF₃. ^g 3 mmol of **2** was used.

Reaction mechanism.

The above results differ widely from those of the well-known palladium-catalyzed coupling reactions between organometallic reagents and halides. Generally, in the presence of a palladium catalyst, such metal hydrides as Bu₃SnH,²⁰ Et₃SiH,²¹ and NaBH₄¹³ greatly facilitate the hydrogenolysis of organic electrophiles. Thus, it is recognized that this common process involves a sequence of oxidative addition of the electrophiles to Pd⁰ giving an R-Pd^{II}-X

species, transmetalation with the hydride forming an $R-Pd^{II}-H$, and reductive elimination of the $R-H$. It now can be seen that, under the present conditions, the slow transmetalation with 2 due to the low nucleophilicity of the hydride suppresses the hydrogenolysis, which appears to produce a small amount of the by-product 4.

Also, the organometallic reagents such as arylmercury compounds are known to react with borane to give the arylboronic acids.⁹ Very recently, Iverson and Smith have reported that a phenyliridium complex reacted with 2 to yield the corresponding phenylboronate.²² On the analogy of these matter, the $Ar-Pd^{II}-X$ species generated by the oxidative addition of 1 to Pd^0 may react with 2 to form the B-C bond in the present process. Actually, the treatment of the authentically isolated $(4-MeO-C_6H_4)PdI(PPh_3)_2$ with 2 at 80 °C in the presence of Et_3N gave the corresponding arylboronate 3 (yield, 14%) and phenylboronate (6%), together with 4 (5%), although the reaction conditions were not optimized (Scheme 1). The phenyl group will drive from PPh_3 used as a ligands (eq. 12).²³ On the one hand, a similar treatment without a base decreased the yield of borylation product (3, 10%) and increased the reduced one 4 (22%).



Thus, for the present reaction, Et_3N appeared to play an important role in not only preventing the production of 4 but also facilitating the B-C bond formation. In related Et_3N -metal hydrides systems, Benkeser postulated that a silyl anion species was generated by the Et_3N -hydrosilane combination.²⁴ With the above effect of Et_3N in mind, a mechanism involving a boryl anion analog generated by the Et_3N -dialkoxyborane combination is proposed and then a reasonable catalytic cycle for the borylation with dialkoxyborane 2, as following Figure 2. Initially, the aryl electrophile 1 would add oxidatively to the palladium catalyst to give arylpalladium(II) species $Ar-Pd^{II}-X$. Then, the ligand exchange between X of $Ar-Pd^{II}-X$ and the boryl anion analog would produce $Ar-Pd^{II}-B(OR)_2$ intermediate and $Et_3NH^+X^-$, and the subsequent reductive elimination would furnish the arylboronate 3 along with the regeneration of the catalyst.

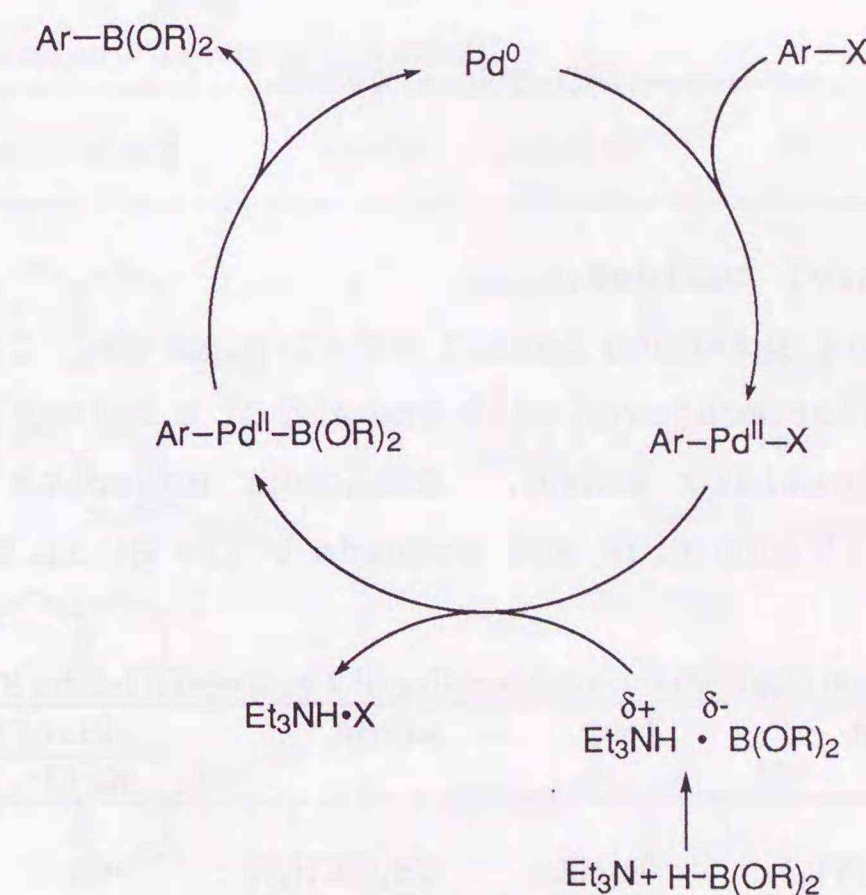


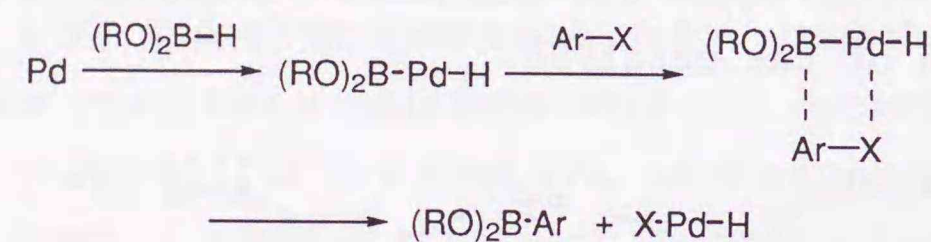
Figure 2.

However, bearing in mind the previously described result,²⁵ it seems also possible that dialkoxyborane 2 first added oxidatively to the palladium(0) complexes. This is because in the $PdCl_2$ -catalyzed silylation of alkyl iodides, such a mechanism which

involved the first oxidative addition of hydrosilane to a Pd catalyst followed by a σ -bond metathesis between an Si-Pd bond and a C-I bond, has been postulated.¹¹ Accordingly, at present, the mechanism involving the oxidative addition of dialkoxyborane 2 cannot necessarily be ruled out.

As shown by Scheme 2, it may be possible that the borane first adds to the palladium(0) and then the metathesis of the boryl-palladium complex with aryl halides takes place. However, NMR analysis of a mixture of 2 (0.2 mmol) and Pd(PPh₃)₄ (0.02 mmol) in C₆D₆ (0.5 mL) did not exhibit any signal corresponding to H-Pd^{II}-B(OR)₂ species, presumably due to a thermodynamic preference for the formation of B-H bond rather than the oxidative adduct.

Scheme 2.



Borylation of benzyl halides.

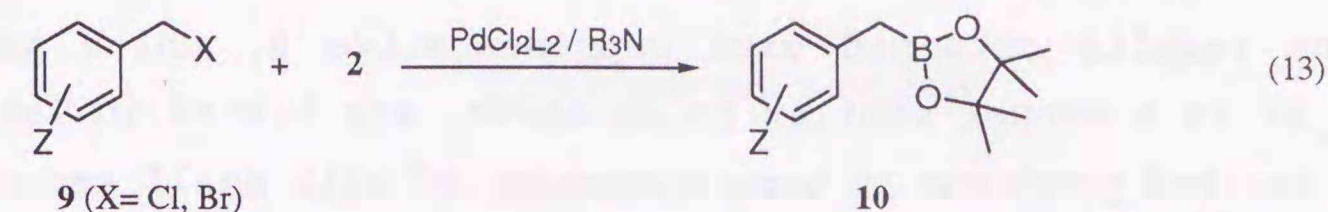
The study was extended benzyl substrates (eq. 13, Table 5). The reaction was also achieved with the aid of a suitable palladium catalyst and a tertiary amine. Although moderate yields were obtained for benzyl chloride and bromide 9 (Z = H) in the presence

Table 5. Reaction condition for cross-coupling of 2 with benzyl halides 9^a

entry	catalyst	base	solvent	yield of 10 (%) ^b	
				X = Cl	Br
1	PdCl ₂ (PPh ₃) ₂	ⁱ Pr ₂ NEt	CH ₂ ClCH ₂ Cl	96	79
2	PdCl ₂ (dppf)	ⁱ Pr ₂ NEt	CH ₂ ClCH ₂ Cl	8	8
3	Pd(PPh ₃) ₄	ⁱ Pr ₂ NEt	CH ₂ ClCH ₂ Cl	77	84
4	PdCl ₂ (PPh ₃) ₂	Et ₃ N	CH ₂ ClCH ₂ Cl	48	28
5	PdCl ₂ (PPh ₃) ₂	ⁱ Pr ₂ NEt	dioxane	96	62
6	PdCl ₂ (PPh ₃) ₂	ⁱ Pr ₂ NEt	toluene	90	54

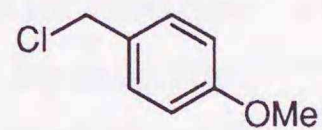
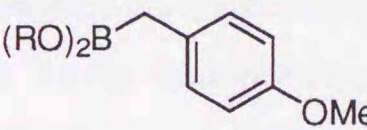
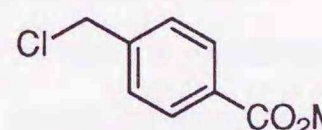
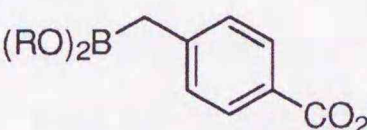
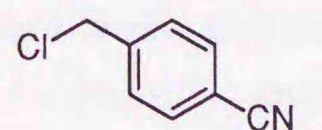
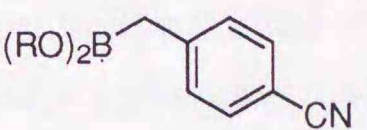
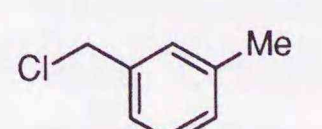
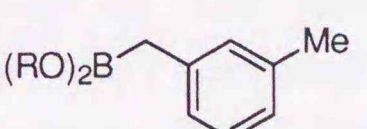
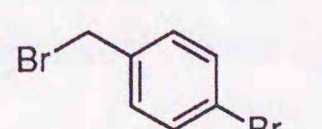
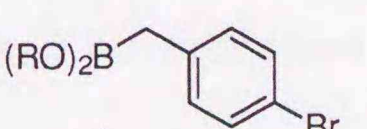
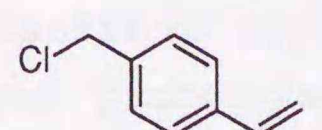
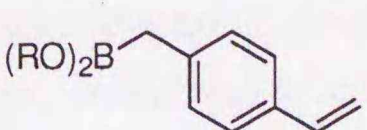
^a All reactions were carried out at 80 °C for 6 h by using benzyl halides (1.0 mmol), pinacolborane (1.5 mmol), catalyst (0.03 mmol), base (3 mmol), and solvent (4 mL).

^b GLC yield based on benzyl halides.



of Et₃N, which contributed to the borylation of aryl substrates, ⁱPr₂NEt was recognized to be most effective for the formation of benzylboronates 10 (entries 10, 12 and 13). Then, the reaction was efficiently catalyzed by the palladium complexes having a monodentate phosphine ligand, such as PdCl₂(PPh₃)₂ and Pd(PPh₃)₄ (entries 2 and 3). The phosphine ligand of palladium catalyst affected the borylation markedly; that is, PdCl₂(dppf)-catalyzed reaction of benzyl halides 9 resulted in low yield, whereas PdCl₂(dppf) could be used satisfactorily for the borylation of aryl halides. CH₂ClCH₂Cl was the most suitable for the solvent, although it was found that the solvent did not play an important role in

Table 6. Reaction of Representative 9 with 2^a

entry	benzyl halide 9	time (h)	product 10	yield (%) ^b	
				10	11
1		6		77	18
2		8		83	15
3		8		(70)	
4		6		(73)	
5		4		(72)	
6		4		(74)	

^a Reactions of 9 (1.0 mmol) with 2 (1.5 mmol) were carried out at 80 °C by using PdCl₂(PPh₃)₂ (3 mol %), ⁱPr₂NEt (3 mmol), and CH₂ClCH₂Cl (4 mL).

the present reaction.

The results obtained with representative 9, which gave product 10 in a manner similar to as above, are listed in Table 6. The desired products 10 were contaminated with small amounts of the reduced by-products ArCH_3 , 11 in each case. The present reaction is tolerated by various functional groups, e.g., CO_2Me and CN (entries 2 and 3). And then, both of the yield and the selectivity are almost independent of functional groups (entries 1 and 2). Since aryl bromides were not so reactive at 80 °C, 4-bromobenzyl bromide was preferentially borylated at benzylic position under the present condition (entry 5). Interestingly, the carbon-carbon double bond was inert to hydroboration in the presence of $\text{PdCl}_2(\text{PPh}_3)_2$ and $^i\text{Pr}_2\text{NEt}$, whereas pinacolborane 2 has been widely recognized as a potent hydroboration reagent (entry 6).¹⁴

Experimental Section

General. All the experiments were carried out under an argon atmosphere using oven-dried (120 °C) glassware. IR spectra were taken with a PERKIN-ELMER System 2000 FT-IR spectrometer. NMR spectra were recorded on a JNM-A500 spectrometer (^1H , 500 MHz; ^{13}C , 125 MHz) or a JNM-FX-200 spectrometer (^1H , 200 MHz; ^{13}C , 50 MHz). Chemical shifts of ^1H NMR and ^{13}C NMR signals reported δ ppm referenced to CHCl_3 (7.26 and 77.0) or an internal SiMe_4 . Mass spectra were obtained at an ionization potential of 70 eV with a JEOL JMS-SX102 spectrometer. GLC analyses were carried out with a Shimadzu GC-14B equipped with a glass column (OV-17 on Chromosorb W, 2 m) and with a capillary column (DB-1, 0.53 mm I.D., 30 m). GLC yields were determined using suitable hydrocarbons as internal standards.

Materials and reagents. Solvents were distilled before use from either sodium benzophenone ketyl (toluene, dioxane) or CaH_2 (DMF). All amines were commercial products and dried over potassium hydroxide. The salts from commercial sources were used without purification or drying. $(4\text{-MeO-C}_6\text{H}_4)\text{PdI}(\text{PPh}_3)_2$ was obtained from 4-iodoanisole and $\text{Pd}(\text{PPh}_3)_4$.²⁶ Other palladium catalysts were prepared as described in chapter 2. All aryl iodides and bromides were purchased from Tokyo Kasei Kogyo Co. except for 4-iodobenzonitrile and 4-iodoacetophenone, which were prepared from the corresponding bromides by the known method.²⁷ Aryl triflates were obtained from the corresponding phenols and trifluoromethanesulfonic anhydride.²⁸ Pinacolborane^{14a} and catecholborane²⁹ were synthesized as reported previously.

Synthesis of arylboronates. Typical procedure (Table 1-4). The general procedure for the synthesis of arylboronates is illustrated by the synthesis of 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)naphthalene. To a solution of $\text{PdCl}_2(\text{dppf})$ (22 mg,

0.03 mmol) in dioxane (4 mL) was added 1-iodonaphthalene (250 mg, 0.98 mmol), Et₃N (0.42 mL, 3.0 mmol), and pinacolborane (0.22 mL, 1.5 mmol). After being stirred for 2 h at 80 °C, the mixture was extracted with benzene. The extract was washed with water, dried over MgSO₄, and concentrated. The residue was purified by Kugelrohr distillation to give 212 mg (85 % yield) of the corresponding arylboronate: IR (Nujol) 2924, 1578, 1509, 1464, 1339, 1298, 1257, 1207, 1136 cm⁻¹; ¹H NMR (CDCl₃) δ 1.43 (s, 12 H), 7.4-7.6 (m, 3 H), 7.82 (d, *J* = 9.3 Hz, 1 H), 7.92 (d, *J* = 8.2 Hz, 1 H), 8.07 (d, *J* = 7.0 Hz, 1 H), 8.76 (d, *J* = 8.2 Hz, 1 H); ¹³C NMR (CDCl₃) δ 24.96, 83.72, 124.93, 125.46, 126.27, 128.31, 128.47, 131.57, 133.28, 135.64, 136.98; MS (*m/z*) 254 (49, M⁺), 239 (9), 210 (10), 196 (9), 181 (13), 168 (20), 154 (100), 128 (8); HRMS for C₁₆H₁₉O₂B calcd 254.1426, found 254.1452.

The following compounds were prepared by the above procedure.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)anisole (Table 4, entries 1-4): IR (neat) 2978, 1606, 1518, 1467, 1361, 1278, 1248, 1215, 1144, 1092 cm⁻¹; ¹H NMR (CDCl₃) δ 1.33 (s, 12 H), 3.83 (s, 3 H), 6.89 (d, *J* = 8.9 Hz, 2 H), 7.75 (d, *J* = 8.9 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.80, 54.94, 83.42, 113.24, 136.33, 162.11; MS (*m/z*) 234 (52, M⁺), 219 (28), 176 (6), 161 (6), 148 (38), 134 (100); HRMS for C₁₃H₁₉O₃B calcd 234.1428, found 234.1456.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)toluene (Table 4, entry 5): IR (neat) 2978, 1612, 1517, 1446, 1360, 1266, 1213, 1143, 1089 cm⁻¹; ¹H NMR (CDCl₃) δ 1.34 (s, 12 H), 2.36 (s, 3 H), 7.19 (d, *J* = 7.8 Hz, 2 H), 7.70 (d, *J* = 7.8 Hz, 2 H); ¹³C NMR (CDCl₃) δ 21.71, 24.83, 83.59, 128.50, 134.19, 141.37; MS (*m/z*) 218 (27, M⁺), 203 (33), 161 (5), 145 (4), 132 (48), 119 (100); HRMS for C₁₃H₁₉O₃B calcd 218.1478, found 218.1463.

2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)toluene (Table 4, entry 6): IR (neat) 2979, 1602, 1442, 1347, 1274, 1214, 1146, 1073 cm⁻¹; ¹H NMR (CDCl₃) δ 1.34 (s, 12 H), 2.54 (s, 3 H), 7.1-7.2 (m, 2 H), 7.31 (t, *J* = 7.5 Hz, 1 H), 7.75 (d, *J* = 7.5 Hz, 1 H); ¹³C NMR (CDCl₃) δ 22.19, 24.87, 83.38, 124.68, 129.75, 130.76, 135.83, 144.81; MS (*m/z*) 218 (20, M⁺), 203 (31), 161 (71), 145 (4), 132 (11),

119 (100); HRMS for C₁₃H₁₉O₂B calcd 218.1478, found 218.1466.

(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzene (Table 4, entries 7-9): IR (neat) 2979, 1605, 1450, 1439, 1360, 1325, 1275, 1144, 1027 cm⁻¹; ¹H NMR (CDCl₃) δ 1.35 (s, 12 H), 7.3-7.5 (m, 3 H), 7.80 (d, *J* = 7.9 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.88, 83.76, 127.66, 131.20, 134.74; MS (*m/z*) 204 (22, M⁺), 189 (45), 147 (5), 118 (54), 105 (100); HRMS for C₁₂H₁₇O₂B calcd 204.1321, found 204.1304.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)chlorobenzene (Table 4, entries 13 and 14): IR (Nujol) 2980, 1721, 1614, 1562, 1510, 1361, 1270, 1109, 1022 cm⁻¹; ¹H NMR (CDCl₃) δ 1.34 (s, 12 H), 7.34 (d, *J* = 8.3 Hz, 2 H), 7.73 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.85, 84.00, 127.99, 136.11, 137.52; MS (*m/z*) 238 (25, M⁺), 223 (69), 195 (4), 181 (6), 152 (50), 139 (100); HRMS for C₁₂H₁₆O₂B³⁵Cl calcd 238.0932, found 238.0950.

Ethyl 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)benzoate (Table 4, entries 15-16): IR (neat) 2980, 1721, 1614, 1562, 1510, 1361, 1270, 1109, 1022 cm⁻¹; ¹H NMR (CDCl₃) δ 1.36 (s, 12 H), 1.40 (t, *J* = 7.1 Hz, 3 H), 4.39 (q, *J* = 7.1 Hz, 2 H), 7.82 (d, *J* = 8.3 Hz, 2H), 8.03 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 14.29, 24.89, 61.00, 84.13, 128.51, 132.71, 134.62, 166.68; MS (*m/z*) 276 (22, M⁺), 261 (68), 231 (30), 190 (86), 177 (100), 149 (25), 131 (19); HRMS for C₁₅H₂₁O₄B calcd 276.1533, found 276.1542.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)acetophenone (Table 4, entry 18): IR (Nujol) 2972, 1693, 1508, 1461, 1362, 1264, 1144, 1095 cm⁻¹; ¹H NMR (CDCl₃) δ 1.36 (s, 12 H), 2.62 (s, 3 H), 7.89 (d, *J* = 8.3 Hz, 2 H), 7.93 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.86, 26.77, 84.20, 127.30, 134.93, 139.03, 198.44; MS (*m/z*) 246 (16, M⁺), 231 (100), 203 (7), 189 (9), 160 (30), 147 (78), 131 (21); HRMS for C₁₄H₁₉O₃B calcd 246.1427, found 246.1445.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzonitrile (Table 4, entry 19): IR (Nujol) 2971, 2227, 1609, 1556, 1508, 1459, 11374, 1271, 1143 cm⁻¹; ¹H NMR (CDCl₃) δ 1.35 (s, 12 H), 7.64 (d, *J* = 8.3 Hz, 2H), 7.88 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.86, 84.49, 114.55, 118.89, 131.13, 135.09; MS (*m/z*) 229 (15, M⁺), 214 (100), 186 (11), 172 (8), 143 (84), 130 (66); HRMS for C₁₃H₁₆O₂NB calcd

229.1274, found 229.1233.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)nitrobenzene
(Table 4, entry 20): IR (Nujol) 2971, 1597, 1526, 1457, 1376, 1279, 1146, 1088, 857 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.37 (s, 12 H), 7.96 (d, J = 8.8 Hz, 2 H), 8.19 (d, J = 8.8 Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.88, 84.64, 122.41, 135.66, 149.87; MS (m/z) 249 (7, M^+), 234 (100), 206 (9), 192 (5), 163 (76), 150 (37); HRMS for $\text{C}_{12}\text{H}_{16}\text{O}_4\text{NB}$ calcd 249.1172, found 249.1188.

2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)thiophene
(Table 4, entry 21): IR (Nujol) 1520, 1425, 1362, 1302, 1210, 1139, 1057, 1019 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.38 (s, 12 H), 7.21 (dd, J = 4.6, 3.4 Hz, 1 H), 7.62 (d, J = 4.6 Hz, 1H), 7.66 (d, J = 3.4 Hz, 1H); ^{13}C NMR (CDCl_3) δ 24.75, 84.07, 128.20, 132.35, 137.14; MS (m/z) 210 (47, M^+), 195 (43), 167 (6), 152 (10), 124 (57), 111 (100); HRMS for $\text{C}_{10}\text{H}_{15}\text{O}_2\text{SB}$ calcd 210.0886, found 210.0900.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-*N,N*-dimethylaniline (Table 4, entry 22): IR (Nujol) 2930, 1607, 1532, 1466, 1364, 1271, 1198, 1142, 1089 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.32 (s, 12 H), 2.98 (s, 6 H), 6.69 (d, J = 8.8 Hz, 2 H), 7.69 (d, J = 8.8 Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.83, 40.14, 83.18, 111.26, 136.16, 152.56; MS (m/z) 247 (100, M^+), 232 (7), 189 (35), 174 (30), 162 (9), 148 (45); HRMS for $\text{C}_{14}\text{H}_{22}\text{O}_2\text{NB}$ calcd 247.1744, found 247.1764.

2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)naphthalene
(Table 4, entry 23): IR (KBr) 2980, 1628, 1599, 1479, 1353, 1299, 1145, 1132 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.39 (s, 12H), 7.4-7.5 (m, 2H), 7.7-7.9 (m, 4H), 8.37 (s, 1H); ^{13}C NMR (CDCl_3) δ 24.92, 83.91, 125.76, 126.95, 127.69, 128.64, 130.37, 132.79, 135.01, 136.22; MS (m/z) 254 (31, M^+), 239 (6), 211 (2), 196 (3), 168 (69), 154 (100), 128 (12); HRMS for $\text{C}_{16}\text{H}_{19}\text{O}_2\text{B}$ calcd 254.1478, found 254.1487.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)acetanilide
(Table 4, entry 24): IR (KBr) 3306, 2982, 1668, 1595, 1532, 1399, 1359, 1316, 1144, 1092 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.33 (s, 12H), 3.59 (s, 3H), 7.24 (s, 1H), 7.52 (d, 2H, J = 8.1 Hz), 7.63 (d, 2H, J = 8.1 Hz); ^{13}C NMR (CDCl_3) δ 24.83, 83.70, 118.49, 135.76, 140.57, 168.33; MS (m/z), 261 (44, M^+), 219 (59), 204 (13), 162 (38), 146

(8), 133 (22), 119 (100); HRMS for $\text{C}_{14}\text{H}_{20}\text{O}_3\text{NB}$ calcd 261.1536, found 261.1513.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)acetophenone
(Table 4, entry 25): IR (KBr) 3306, 2982, 1668, 1595, 1532, 1399, 1359, 1316, 1144, 1092 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.37 (s, 12H), 2.64 (s, 3H), 7.47 (t, 1H, J = 7.6 Hz), 8.00 (d, 1H, J = 7.6 Hz), 8.06 (d, 1H, J = 7.6 Hz), 8.37 (s, 1H); ^{13}C NMR (CDCl_3) δ 24.83, 26.71, 30.88, 84.12, 128.00, 130.72, 134.78, 136.45, 139.37, 198.41; MS (m/z), 246 (32, M^+), 231 (100), 203 (54), 146 (23), 131 (22); HRMS for $\text{C}_{14}\text{H}_{19}\text{O}_3\text{B}$ calcd 246.1427, found 246.1379.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)benzyl cyanide
(Table 4, entry 26): IR (KBr) 2985, 2248, 1615, 1517, 1363, 1214, 1143, 1090, 1023 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.35 (s, 12H), 3.77 (s, 2H), 7.34 (d, 2H, J = 7.8 Hz), 7.82 (d, 2H, J = 7.8 Hz); ^{13}C NMR (CDCl_3) δ 23.74, 24.83, 83.97, 117.60, 127.18, 132.76, 135.50; MS (m/z) 243 (13, M^+), 228 (60), 200 (6), 186 (5), 157 (100), 144 (84), 117 (43); HRMS for $\text{C}_{14}\text{H}_{18}\text{O}_2\text{NB}$ calcd 243.1430, found 243.1418.

2-Methy-8-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-quinoline (Table 4, entry 27): IR (KBr) 2980, 1609, 1562, 1501, 1354, 1291, 1203, 1137 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.50 (s, 12H), 2.72 (s, 3H), 7.23 (d, 1H, J = 8.5 Hz), 7.44 (t, 1H, J = 7.3 Hz), 7.77 (d, 1H, J = 8.5 Hz), 7.89 (d, 1H, J = 7.3 Hz), 7.97 (d, 1H, J = 8.5 Hz); ^{13}C NMR (CDCl_3) δ 24.88, 25.57, 30.90, 84.01, 121.58, 125.00, 125.73, 134.60, 135.90, 158.81; MS (m/z), 269 (15, M^+), 254 (5), 199 (5), 184 (5), 170 (100), 154 (4), 143 (40); HRMS for $\text{C}_{16}\text{H}_{20}\text{O}_2\text{NB}$ calcd 269.1587, found 269.1569.

Coupling reaction of catecholborane (eq. 9). To a solution of $\text{PdCl}_2(\text{dppf})$ (22 mg, 0.03 mmol) in dioxane (4 mL) was added 1-iodonaphthalene (250 mg, 0.98 mmol), Et_3N (0.42 mL, 3.0 mmol), and catecholborane (0.16 mL, 1.5 mmol). After being stirred for 12 h at 80 $^\circ\text{C}$. The reaction mixture was added pinacol (200 mg, 1.7 mmol) and was stirred for 2 h at room temperature. GLC analysis indicated that the corresponding 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)naphthalene was formed in 79% yield.

Reaction of arylpalladium complex with pinacolborane (Scheme 1). A mixture of (4-MeO-C₆H₄)PdI(PPh₃)₂ (0.050 mmol), **2** (0.098 mmol), and Et₃N (0.30 mmol) in dioxane (1 mL) was stirred at 80 °C for 6 h. A GLC analysis of the reaction mixtures indicated formations of phenylboronate (yield, 6%), 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)anisole (14%), and anisole (5%).

Synthesis of benzylboronates. Typical procedure (Table 5 and 6). To a solution of PdCl₂(PPh₃)₂ (22 mg, 0.03 mmol) in dichloroethane (4 mL) was added benzylhalides (1.0 mmol), ⁱPr₂NEt (0.52 mL, 3.0 mmol), and pinacolborane (0.22 mL, 1.5 mmol). After being stirred for 4-8 h at 80 °C, the mixture was extracted with benzene. The extract was washed with brine, dried over MgSO₄, and concentrated. The residue was purified by Kugelrohr distillation to give the corresponding benzylboronates.

The following compounds were prepared by the above procedure.

[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]benzene (Table 5): IR (neat) 2979, 1144 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (s, 12 H), 2.29 (s, 2 H), 7.1-7.3 (m, 5 H); ¹³C NMR (CDCl₃) δ 24.69, 83.38, 124.79, 128.22, 128.96, 138.61; MS (m/z) 218 (38, M⁺), 203 (22), 118 (100), 91 (52), 83 (58); HRMS (m/z) for C₁₃H₁₉O₂B calcd 218.1478, found 218.1457.

4-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]anisole (Table 6, entry 1): IR (neat) 2978, 1246, 1144 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (s, 12 H), 2.22 (s, 2 H), 3.77 (s, 3 H), 6.79 (d, J = 8.8 Hz, 2 H), 7.09 (d, J = 8.8 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.73, 55.22, 83.36, 113.76, 129.81, 130.49, 157.12; MS (m/z) 248 (87, M⁺), 233 (20), 148 (68), 121 (100); HRMS (m/z) for C₁₄H₂₁O₃B calcd 248.1584, found 248.1590.

Methyl 4-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-methyl]benzoate (Table 6, entry 2): IR (neat) 2991, 1717, 1327, 1140, 1110 cm⁻¹; ¹H NMR (CDCl₃) δ 1.22 (s, 12 H), 2.35 (s, 2 H), 3.89 (s, 3 H), 7.24 (d, J = 8.4 Hz, 2 H), 7.91 (d, J = 8.4 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.69, 51.89, 83.638, 126.90, 128.94, 129.64, 144.73, 167.32; MS (m/z) 276 (37, M⁺), 261 (20), 245 (19), 176 (27), 149

(11), 145 (52), 118 (100), 117 (23); HRMS (m/z) for C₁₅H₂₁O₄B calcd 276.1533, found 276.1514.

4-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]-benzonitrile (Table 6, entry 3): IR (neat) 2983, 2226, 1143 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (s, 12 H), 2.35 (s, 2 H), 7.23 (d, J = 8.3 Hz, 2 H), 7.52 (d, J = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.70, 108.69, 119.35, 129.70, 132.06, 145.01; MS (m/z) 243 (53, M⁺), 228 (52), 143 (63), 127 (14), 116 (27), 117 (84), 83 (100); HRMS (m/z) for C₁₄H₁₈O₂B₁N calcd 243.1430, found 243.1434.

3-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]toluene (Table 6, entry 4): IR (neat) 2979, 1144 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (s, 12 H), 2.25 (s, 2 H), 7.6-7.0 (m, 3 H), 7.12 (t, J = 7.5 Hz, 1 H); ¹³C NMR (CDCl₃) δ 21.38, 24.69, 83.35, 125.57, 125.94, 128.11, 129.84, 137.69, 138.45; MS (m/z) 232 (59, M⁺), 217 (24), 133 (36), 132 (100), 117 (10), 105 (51), 91 (22); HRMS (m/z) for C₁₄H₂₁O₂B calcd 232.1634, found 232.1642.

4-Bromo-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]-benzene (Table 6, entry 5): IR (neat) 2981, 1210, 1141, 677 cm⁻¹; ¹H NMR (CDCl₃) δ 1.22 (s, 12 H), 2.23 (s, 2 H), 7.10 (d, J = 8.3 Hz, 2 H), 7.34 (d, J = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 24.72, 83.57, 118.56, 130.74, 131.25, 137.71; MS (m/z) 296 (36, M⁺), 281 (15), 217 (86), 117 (76), 90 (20), 83 (100); HRMS (m/z) for C₁₃H₁₈O₂B₁Br calcd 296.0583, found 296.0564.

4-[(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)methyl]styrene (Table 6, entry 6): IR (neat) 2979, 1477, 1457, 1331, 983, 968 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (s, 12 H), 2.28 (s, 2 H), 5.15 (dd, J = 10.8, 1.1 Hz, 1 H), 5.67 (dd, J = 17.5, 1.1 Hz, 1 H), 6.68 (dd, J = 17.5, 10.8 Hz, 1 H), 7.14 (d, J = 7.9 Hz, 2 H), 7.29 (d, J = 7.9 Hz, 2 H); ¹³C NMR (CDCl₃) δ 22.87, 81.59, 110.54, 124.32, 127.25, 134.44, 134.98, 136.92; MS (m/z) 244 (80, M⁺), 229 (17), 145 (33), 144 (98), 117 (100); HRMS (m/z) for C₁₅H₂₁O₂B calcd 244.1634, found 244.1629.

References

1. (a) Miyaura, N.; Yanagi, T.; Suzuki, A. *Synth. Commun.* 1981, 11, 513. (b) Watanabe, T.; Miyaura, N.; Suzuki, A. *Synlett* 1992, 207. (c) Huth, A.; Beetz, I.; Schumann, I. *Tetrahedron* 1989, 45, 6679. (d) Fu, J.-m.; Snieckus, V. *Tetrahedron Lett.* 1990, 31, 1665. (e) Shieh, W. -C.; Carlson, J. A. *J. Org. Chem.* 1992, 57, 379. (f) Oh-e, T.; Miyaura, N.; Suzuki, A. *J. Org. Chem.* 1993, 58, 2201. (g) Ishiyama, T.; Kizaki, H.; Hayashi, T.; Suzuki, A.; Miyaura, N. *J. Org. Chem.* 1998, 63, 4726. (h) For a recent review for palladium-catalyzed cross-coupling reaction of arylboronates, see: Miyaura, N.; Suzuki, A. *Chem. Rev.* 1995, 95, 2457.
2. (a) Percec, V.; Bae, J. -Y.; Hill, D. H. *J. Org. Chem.* 1995, 60, 1060. (b) Kobayashi, Y.; Mizojiri, R. *Tetrahedron Lett.* 1996, 37, 8531. (c) Saito, S.; Oh-tani, S.; Miyaura, N. *J. Org. Chem.* 1997, 62, 8024. (d) Ueda, M.; Saito, A.; Miyaura, N. *Tetrahedron* 1998, 54, 13079.
3. (a) Ishihara, K.; Mouri, M.; Gao, Q.; Maruyama, T.; Furuta, K.; Yamamoto, H. *J. Am. Chem. Soc.* 1993, 115, 11490. (b) Ishihara, K.; Kurihara, H.; Yamamoto, H. *J. Am. Chem. Soc.* 1996, 118, 3049. (c) Ishihara, K.; Ohara, S.; Yamamoto, H. *J. Org. Chem.* 1996, 61, 4196. (d) Ishihara, K.; Inanaga, K.; Kondo, S.; Funahashi, M.; Yamamoto, H. *Synlett* 1998, 1053.
4. For a recent review for boron neutron capture therapy, see: Soloway, A. H.; Tjarks, W.; Barnum, B. A.; Rong, F. -G.; Barth, R. F.; Wyzlic, I. M.; Wilson, J. G. *Chem. Rev.* 1998, 98, 1515.
5. (a) Wulff, C.; Heide, B.; Helfmeier, G. *J. Am. Chem. Soc.* 1986, 108, 1089. (b) Nagai, Y.; Kobayashi, K.; Toi, H.; Aoyama, Y. *Bull. Chem. Soc. Jpn.* 1993, 66, 2965. (c) Mohler, L. H.; Czarnik, A. W. *J. Am. Chem. Soc.* 1993, 115, 2998. (d) Westmark, P. R.; Smith, B. D. *J. Am. Chem. Soc.* 1994, 116, 9343. (e) James, T. D.; Sandnayake, K. R. A. S.; Iguchi, R.; Shinkai, S. *J. Am. Chem. Soc.* 1995, 117, 8982. (f) For a recent review for boronic acid receptors for saccharides, see: James, T. D.; Linnane, P.; Shinkai, S. *Chem. Commun.* 1996, 281.
6. (a) Reetz, M. T.; Niemer, C. M.; Harmes, M.; Goddard, R. *Angew. Chem., Int. Ed. Engl.* 1992, 31, 1017. (b) Nozaki, K.; Tsutsumi, T.; Takaya, H. *J. Org. Chem.* 1995, 60, 6668. (c) Nozaki, K.; Yoshida, M.; Takaya, H. *Bull. Chem. Soc. Jpn.* 1996, 69, 2043.
7. (a) Matteson, D. S. In *The Chemistry of the Metal-Carbon Bond*; Hartley, F. R.; Patai, S., Eds.; Wiley: New York, 1987; Vol. 4, p 307. (b) Vaultier, M.; Carboni, B. In *Comprehensive Organometallic Chemistry II*; Abel, E. W.; Stone, F. G. A.; Wilkinson, G., Eds.; Pergamon: Oxford, 1995; Vol. 11, p 191. (c) Miyaura, N.; Maruoka, K. In *Synthesis of Organometallic Compounds*; Komiya, S., Ed.; Wiley: New York, 1997; p 345.
8. Brown, H. C.; Rogic, M. M. *J. Am. Chem. Soc.* 1969, 91, 4304.
9. Breuer, S. W.; Thorpe, F. G.; Podestá, J. C. *Tetrahedron Lett.* 1974, 3719.
10. (a) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* 1995, 60, 7508. (b) Ishiyama, T.; Itoh, Y.; Kitano, T.; Miyaura, N. *Tetrahedron Lett.* 1997, 38, 3447. (c) Ishiyama, T.; Ahiko, T.-a.; Miyaura, N. *Tetrahedron Lett.* 1996, 37, 6889. (d) Ahiko, T.-a.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* 1997, 811.
11. Kunai, A.; Sakurai, T.; Toyoda, E.; Ishikawa, M.; Yamamoto, Y. *Organometallics* 1994, 13, 3233.
12. Lipshutz, B. H.; Buzard, D. J.; Vivian, R. W. *Tetrahedron Lett.* 1999, 40, 6871.
13. (a) Egli, R. A. *Helv. Chim. Acta* 1968, 51, 2090. (b) Hutchins, R. O.; Learn, K. *J. Org. Chem.* 1982, 47, 4380.
14. (a) Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* 1992, 57, 3482. (b) Pereira, S.; Srebnik, M. *Organometallics* 1995, 14, 3127. (c) Pereira, S.; Srebnik, M. *J. Am. Chem. Soc.* 1996, 118, 909. (d) Pereira, S.; Srebnik, M. *Tetrahedron Lett.* 1996, 37, 3283. (e) Murata, M.; Watanabe, S.; Masuda, Y. *Tetrahedron Lett.* 1999, 40, 2585.
15. The abnormal cross-coupling reaction of 1-alkenylboronates with

- aryl iodides in the presence of Et_3N has been reported. See: (a) Miyaura, N.; Suzuki, A. *J. Organomet. Chem.* 1981, 213, C53. (b) Hunt, A. R.; Stewart, S. K.; Whiting, A. *Tetrahedron Lett.* 1993, 34, 3599.
16. Garrett, C. E.; Fu, G. C. *J. Org. Chem.* 1996, 61, 3224.
17. (a) Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* 1982, 21, 555. (b) Burgess, K.; van der Donk, W. A.; Westcott, S. A.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. *J. Am. Chem. Soc.* 1992, 114, 9350.
18. (a) Rottlander, M.; Knochel, P. *J. Org. Chem.* 1998, 63, 203. (b) For a recent review for synthetic transformation of aryl triflates, see: Ritter, K. *Synthesis* 1993, 735.
19. Echavarrene, A. M.; Stille, J. K. *J. Am. Chem. Soc.* 1988, 110, 1557.
20. (a) Four, P.; Guibe, F. *J. Org. Chem.* 1982, 46, 4439. (b) Baillargeon, V. P.; Stille, J. K. *J. Am. Chem. Soc.* 1986, 108, 452. (c) Uenishi, J.; Kawahama, R.; Shiga, Y.; Yonemitsu, O.; Tsuji, J. *Tetrahedron Lett.* 1996, 37, 6759.
21. Boukherroub, R.; Chatgililoglu, C.; Manuel, G. *Organometallics* 1996, 15, 1508 and references cited therein.
22. Iverson, C. N.; Smith, M. R., III *J. Am. Chem. Soc.* 1999, 121, 7696.
23. For an aryl-phenyl exchange reaction of $\text{ArPdX}(\text{PPh}_3)_2$, see: (a) Kong, K. -C.; Cheng, C. -H. *J. Am. Chem. Soc.* 1991, 113, 6313. (b) Herrmann, W. A.; Brossmer, C.; Priermeier, T.; Öfele, K. *J. Organomet. Chem.* 1994, 481, 97. (c) Segelstein, B. E.; Butler, T. W.; Chenard, B. L. *J. Org. Chem.* 1995, 60, 12. (d) Sakamoto, M.; Shimizu, I.; Yamamoto, A. *Chem. Lett.* 1995, 1101.
24. Benkeser, R. A.; Gaul, J. M.; Smith, W. E. *J. Am. Chem. Soc.* 1969, 91, 3666.
25. (a) Satoh, M.; Nomoto, Y.; Miyaura, N.; Suzuki, A. *Tetrahedron Lett.* 1989, 30, 3789. (b) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *Organometallics* 1993, 12, 589. (c) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *J. Org. Chem.* 1993, 58, 5351. (d) For a recent review for the transition-metal-catalyzed hydroboration, see:

- Burgess, K.; Ohlmeyer, M. J. *Chem. Rev.* 1991, 91, 1179.
26. Coulson, D. R. *Inorg. Synth.* 1972, 13, 121.
27. Takagi, K.; Hayama, N.; Okamoto, T. *Chem. Lett.* 1978, 191.
28. Stang, P. J.; Hanack, M.; Subramanian, L. R. *Synthesis* 1982, 85.
29. Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* 1971, 93, 1816.

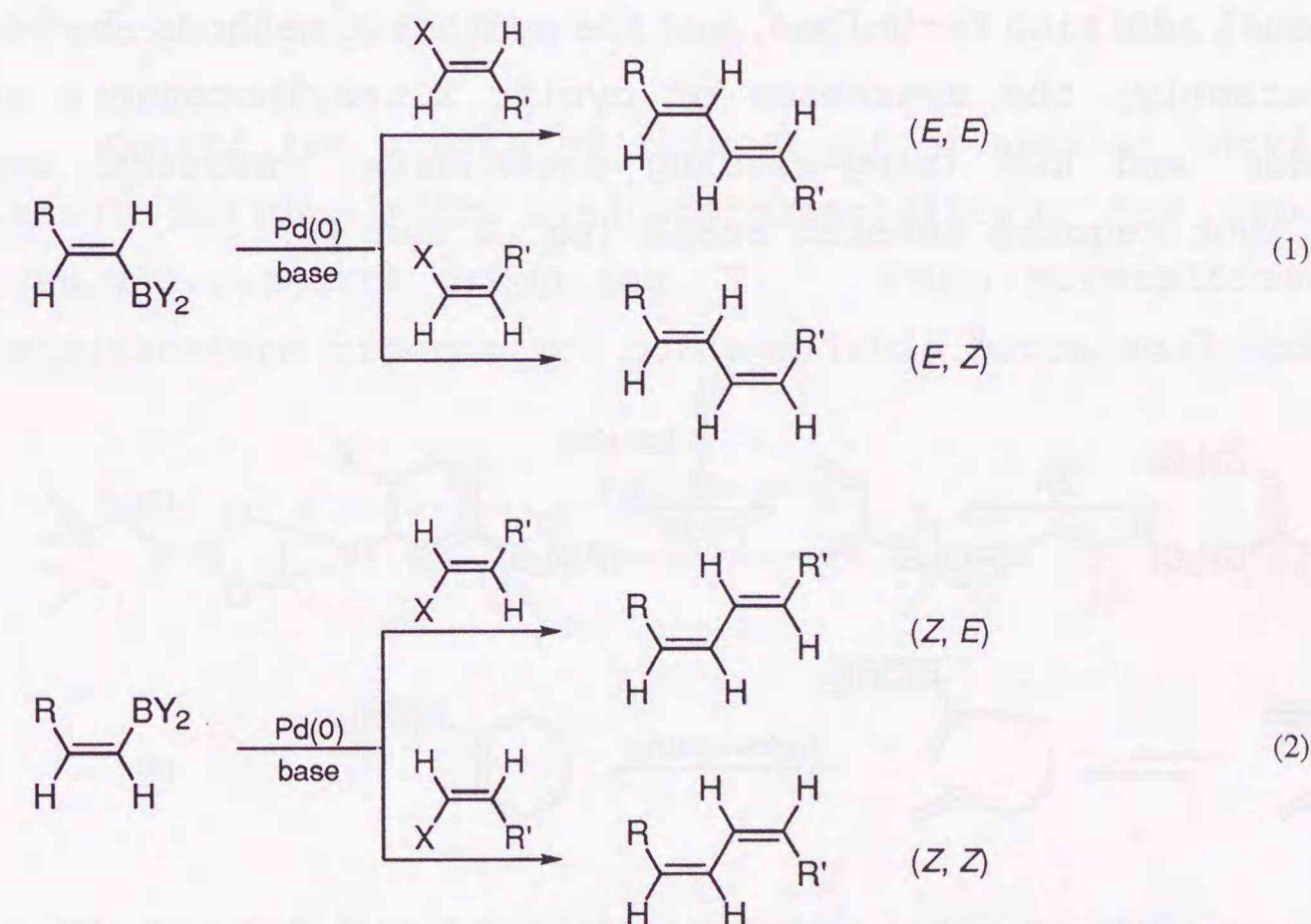
Chapter 4.

Synthesis of Alkenylboronates via Palladium-Catalyzed Borylation of Alkenyl Triflates with Pinacolborane

A direct borylation of alkenyl electrophiles with dialkoxyborane was investigated. Various cycloalkenyl iodides and triflates were borylated with pinacolborane in the presence of Et_3N and a catalytic amount of $\text{PdCl}_2(\text{dppf})$ and AsPh_3 to afford the corresponding alkenylboronates in good yields. The product distributions were strongly dependent on the base employed, and the tertiary amine, especially Et_3N , was effective for the selective formation of the boron-carbon bond.

Introduction

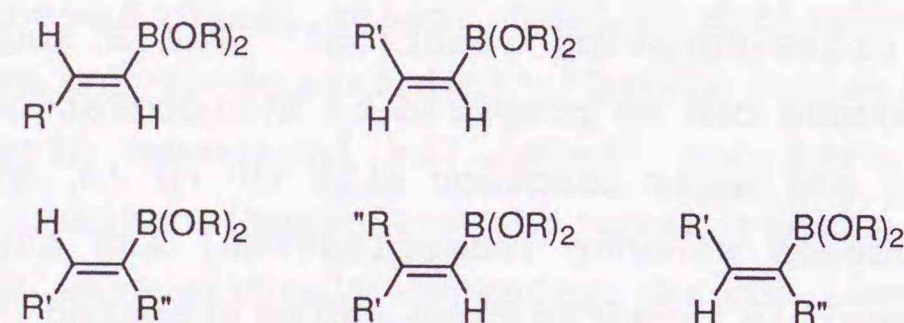
Alkenylboronates have been shown to be versatile intermediates in organic synthesis, particularly in that involving carbon-carbon bond formation through the palladium-catalyzed Suzuki-Miyaura cross-coupling reaction.¹ The *E* and *Z* forms of vinylboron compounds can be prepared by hydroboration of alkynes and haloalkynes, and their reaction with (*E*) or (*Z*)-vinyl iodides or bromides proceeds without isomerization, and the conjugated dienes of four possible isomeric forms can be prepared in high purity (eq. 1 and 2).



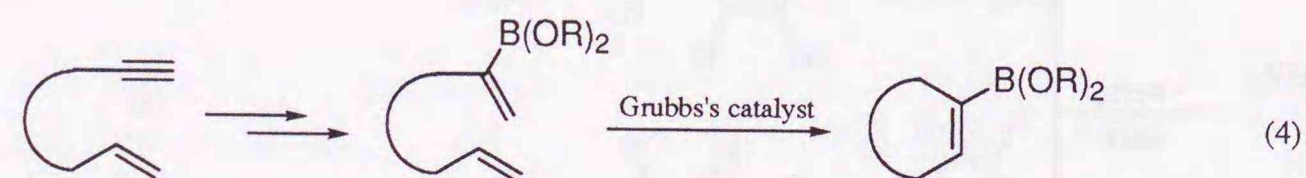
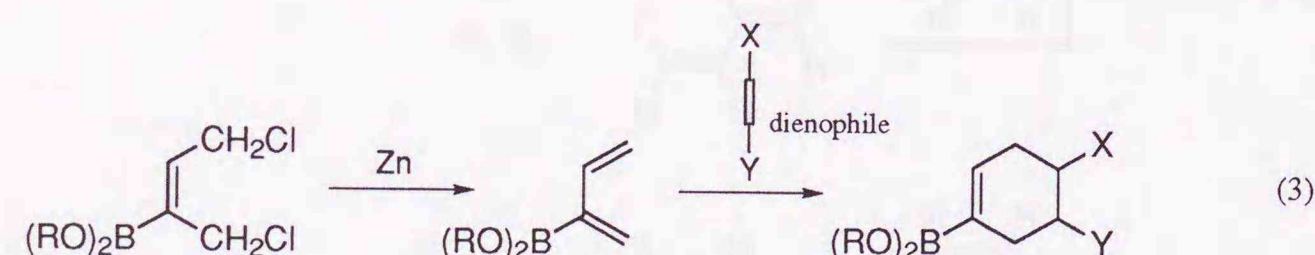
This method of diene formation with definite *E* and *Z* structure has wide synthetic applications, particularly for the syntheses of natural products with conjugated polyene structures.² In the total synthesis of the naturally occurring big molecule of palytoxin, which has numerous labile functional groups, this coupling is the most useful for the creation of *E*, *Z*-conjugated diene part.^{2a}

The (*E*)-alkenylboronates can be prepared by several methods, one of which is hydroboration of alkynes.³ Also, (*Z*)-isomers and trisubstituted alkenylboranes can be prepared by the addition technique, such as hydroboration of haloalkynes,⁴ haloboration of alkynes,⁵ and diboration of alkynes.⁶

Figure 1.

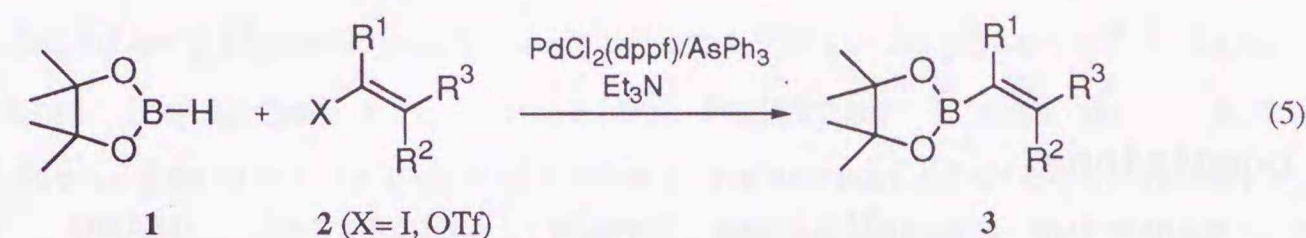


However, cyclic alkenylboronates are not available by the conventional addition technique, and the synthetic methods are very rare. Recently, the syntheses of cyclic alkenylboronates via Diels-Alder⁷ and RCM (ring-closing metathesis) reaction⁸ were reported, but require several steps (eq. 3 and 4).

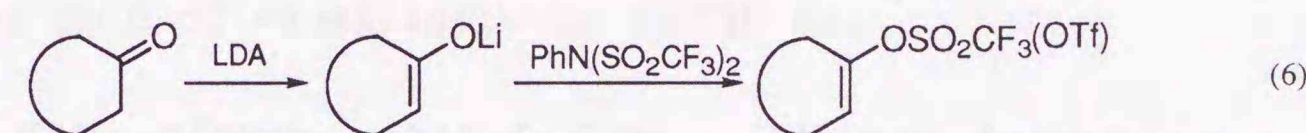


The transition-metal-catalyzed direct borylation of alkenyl electrophiles should be a convenient route to a wide range of boronic esters. In chapter 3, a novel boron-carbon bond formation utilizing dialkoxyboranes was described.⁹ This chapter is concerned with the synthesis of alkenylboronates. Thus, the author here mainly report a palladium-catalyzed borylation of cyclic alkenyl halides or triflates 2 with pinacolborane 1 to provide a new and available synthetic route for the corresponding

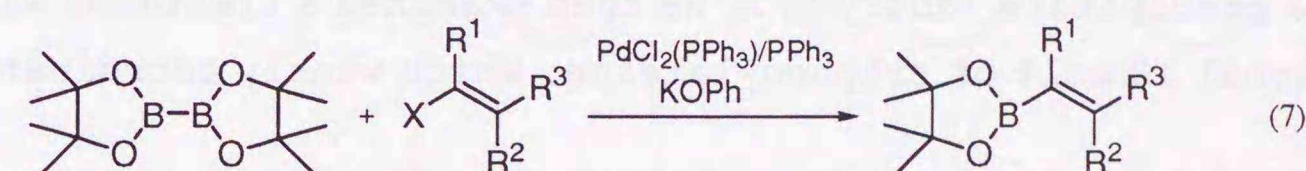
cycloalkenylboronates 3 (eq. 5).



Alkenyl triflates are especially valuable as alkenyl electrophiles, in part due to the easy access from carbonyl enolates (eq. 6).¹⁰ Particularly, ready availability of cycloalkenyl triflates from cyclic ketones is of greater advantage than the synthesis of corresponding halides.



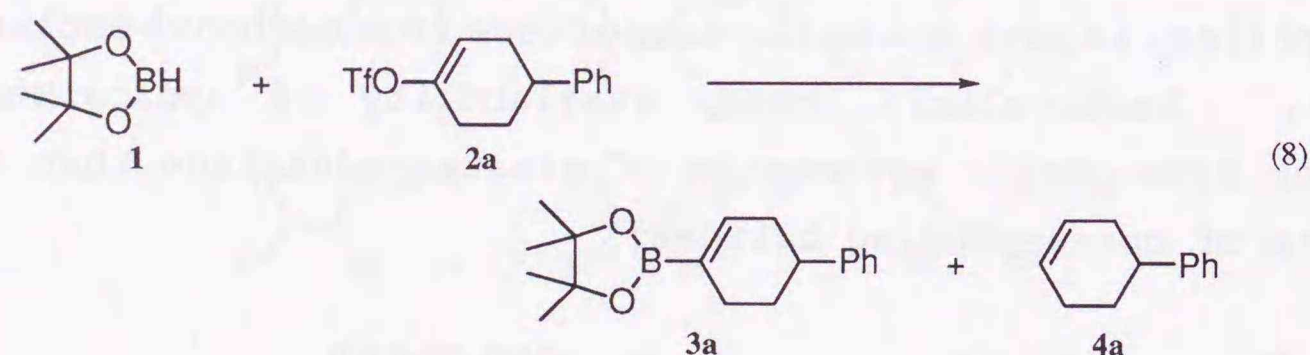
During the course of this study, a similar borylation of alkenyl halides with bis(pinacolato)diboron was reported by Miyaura's research group (eq. 7).¹¹ Thus, pinacolborane 1 and bis(pinacolato)diboron are now available boron nucleophiles.



Results and Discussion

Reaction conditions.

The reaction conditions were optimized using 4-phenylcyclohexenyl triflate (**2a**) as a substrate (eq. 8, Table 1).



As we reported recently, aryl halides couple with **1** successfully in the presence of 3 mol% of $\text{PdCl}_2(\text{dppf})$ and 3 equiv of Et_3N in dioxane to give arylboronates.⁶ Under these conditions, the borylation of **2a** gave the corresponding **3a** together with 4-phenylcyclohexene (**4a**), resulting in low conversion, while the catalyst was decomposed during the reaction, liberating palladium black as a precipitate (entry 1). We then examined a treatment with an additional 12 mol% of triphenylarsine, which weakly coordinated

Table 1. Reaction of 4-phenylcyclohexenyl triflate under various conditions^a

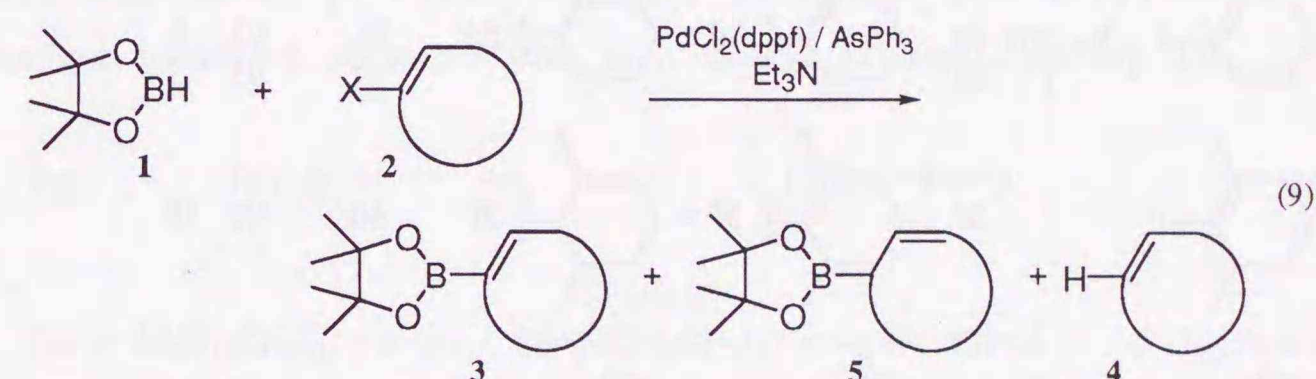
entry	catalyst	base	solvent	yield (%) ^b	
				3a	4a
1	$\text{PdCl}_2(\text{dppf})^c$	Et_3N	dioxane	47	14
2	$\text{PdCl}_2(\text{dppf})/4\text{AsPh}_3$	Et_3N	dioxane	83	7
3	$\text{PdCl}_2(\text{dppf})/2\text{PPh}_3$	Et_3N	dioxane	51	14
4	$\text{PdCl}_2(\text{dppf})/\text{dppf}$	Et_3N	dioxane	53	11
5	$\text{PdCl}_2(\text{dppf})/4\text{AsPh}_3$	pyridine	dioxane	23	68
6	$\text{PdCl}_2(\text{dppf})/4\text{AsPh}_3$	KOAc	dioxane	2	98
7	$\text{PdCl}_2(\text{dppf})/4\text{AsPh}_3$	Et_3N	toluene	81	9

^a Reactions of 4-phenylcyclohexenyl triflate **2a** (1.0 mmol) with **1** (1.5 mmol) were carried out at 80 °C for 4 h in 4 mL of solvent by using 3 mol % of catalyst and base (3 mmol). ^b GLC yields based on **2a** used. ^c DPPF is 1,1'-bis(diphenylphosphino)ferrocene.

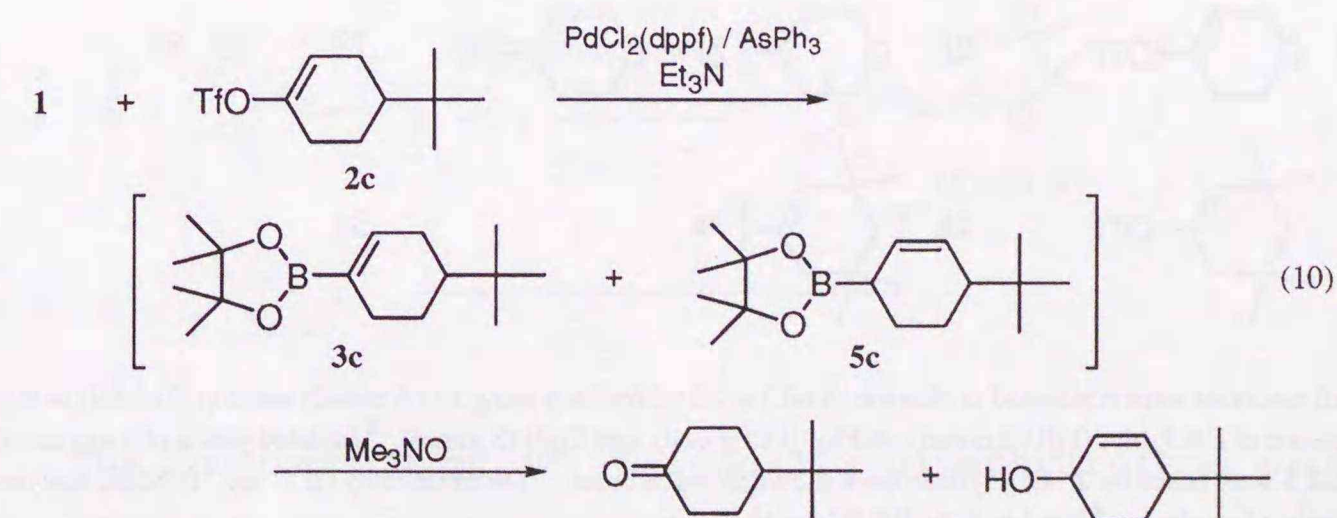
palladium complexes to stabilize the catalyst,¹² and the borylation proceeded considerably (entry 2). In addition, the use of excess phosphine ligand, such as dppf and PPh_3 , in place of triphenylarsine rather retarded the reaction (entries 3 and 4). Although the desired product **3a** tended to be contaminated with reduced by-product **4a** in each case as a result of the behavior of **1** as a hydride source,¹³ this was no matter in practice.

The base played an important role in swaying the yields and the selectivity. Among bases that were effective the tertiary amine, Et_3N , was recognized to be the most effective for the selective formation of **3**. In contrast, the use of potassium acetate caused the reductive cleavage of the C-O bond of **2a** to form the C-H bond of **4a** exclusively (entry 6).

Borylation of representative cyclic alkenyl halides or triflates.

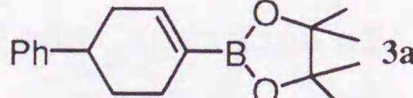
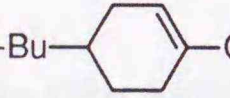
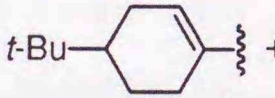
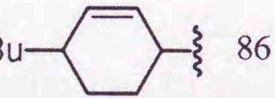
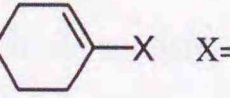
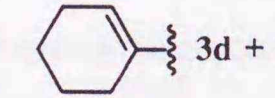
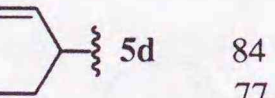
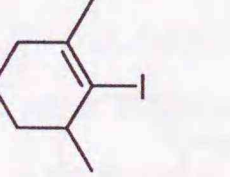
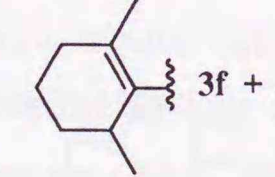
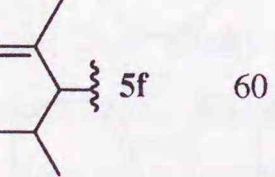
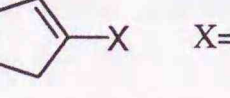
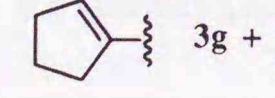
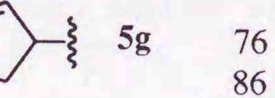
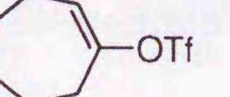
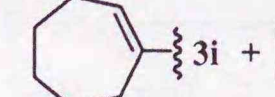
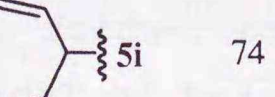
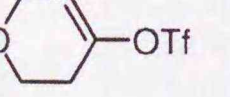
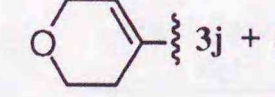
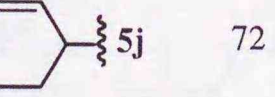
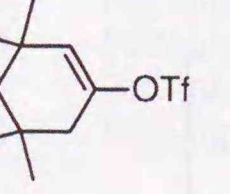
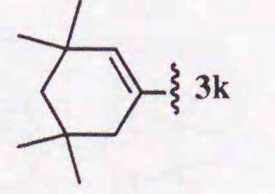


The results obtained with representative **2** (the triflates and/or the iodides), which gave product **3** in a manner similar to as above, are listed in Table 2 (eq. 9).



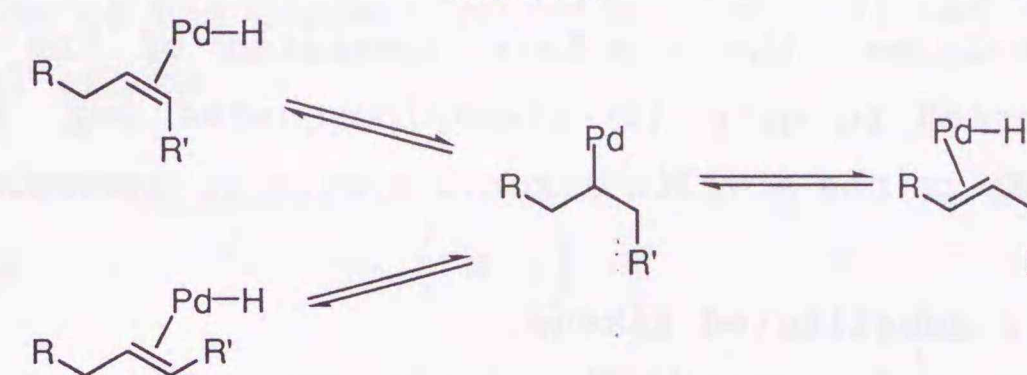
As shown, the reaction of **2**, excepting 4-phenylcyclohexenyl triflate and iodide, afforded two borylation products, the major alkenylboronates **3**, and a small amount of their isomeric allylboronates **5** (entries 3-10).¹⁰ The reaction of **2c** with **1**, followed by *in situ* treatment with an excess of trimethylamine oxide at 80 °C for 18 h, provided 4-*t*-butylcyclohexanone in 45% yield

Table 2. Borylation of Representative **2** with **1** (Eq 8)^a

entry	substrate 2	product	yield (%) of boronates ^b	ratio (%) ^c 3 5	yield (%) of 4 ^b
1 ^d	Ph- 	Ph-  3a	(83)	>99 <1	(7)
2 ^d	X=OTf 2a I 2b		(82)	>99 <1	(14)
3	<i>t</i> -Bu- 	2c <i>t</i> -Bu-  3c + <i>t</i> -Bu-  5c	86	90 10	(11)
4		X=OTf 2d  3d +  5d	84	92 8	
5		I 2e	77	95 5	
6 ^e		2f  3f +  5f	60	82 18	
7		X=OTf 2g  3g +  5g	76	95 5	
8		I 2h	86	95 5	
9		2i  3i +  5i	74	90 10	
10		2j  3j +  5j	72	19 81	
11		2k  3k	31		

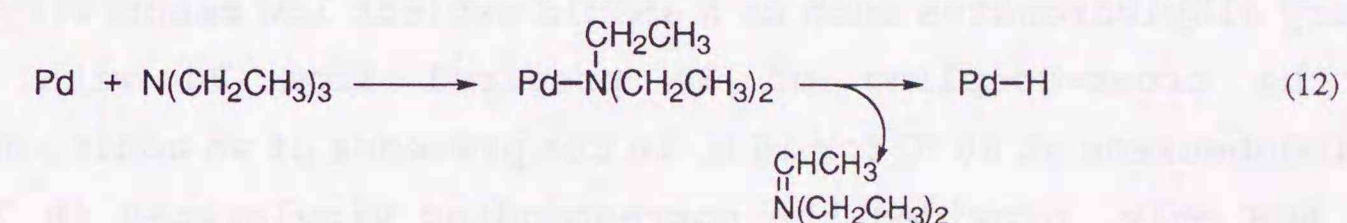
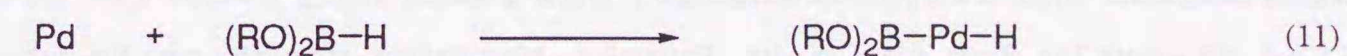
^a All reactions were conducted in dioxane (4 mL) at 80 °C for 16 h using **1** (1.5 mmol) and **2** (1.0 mmol) in the presence of PdCl₂(dppf) (0.03 mmol), AsPh₃ (0.12 mmol), and Et₃N (3 mmol). ^b Isolated yields of a mixture of **3** and **5** were based on **2**. GLC yields were shown in parentheses. ^c Determined by GLC and ¹H NMR analysis of isolated products. ^d For 4 h. ^e At 100 °C for 48 h.

Scheme 1.

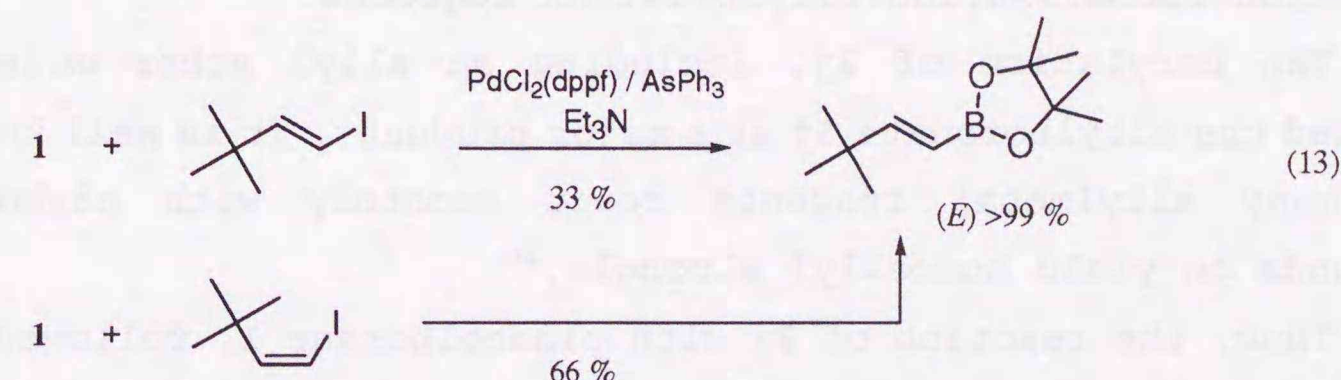


together with 4-*t*-butyl-2-cyclohexen-1-ol (8%) (eq. 10).

This product ratio of boronates was affected by the substrates employed and not by the bases and/or other reaction conditions. It is likely that the present borylation partially involved the carbon-carbon double bond isomerization of the desired **3**¹⁴ (Scheme 1) due to the participation of a palladium hydride species that formed in the presence of dialkoxyborane¹⁵ (eq. 11) and/or trialkylamine¹⁶ (eq. 12). Interestingly, the borylation of **2j**, including an allyl ether moiety, afforded the allylboronate **5j** as a major product due to the n- π conjugation (entry 10).¹⁷



Borylation of acyclic alkenyl halides.

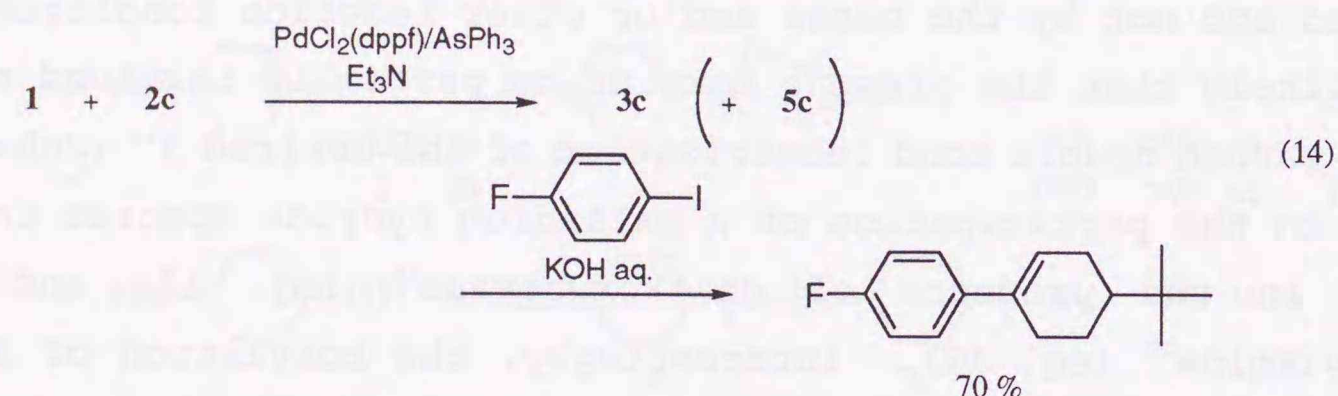


The borylation of (*E*)-1-iodo-3,3-dimethylbutene proceeded with retention of starting geometry to provide the corresponding

(*E*)-alkenylboronate in 33% yield. In the case of using acyclic (*Z*)-alkenyl halides, the complete inversion of the starting geometry occurred to give (*E*)-alkenylboronates (eq. 13). Our synthetic study on the acyclic alkenyl system is uncompleted yet.

Synthesis of a substituted alkene.

The potential versatility of the present borylation was demonstrated by the one-pot synthesis of a substituted alkene (eq. 14).



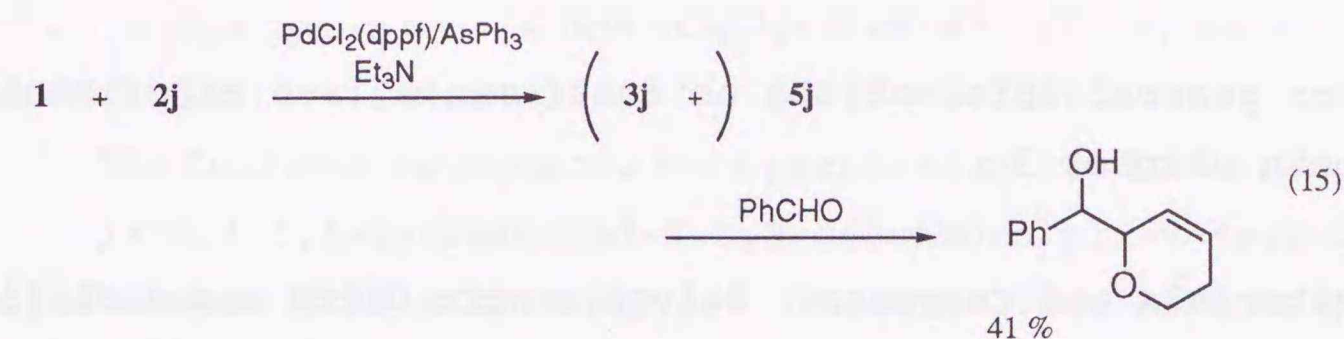
Although the borylation of **2** provided a mixture of alkenylboronates and allylboronates, the resulting solution could be applied directly for the next Suzuki-Miyaura reaction in which secondary alkylboronates such as **5** should exhibit low reactivity.¹⁸ Thus, the cross-coupling of **3c** prepared from **2c** with 4-fluoriodobenzene at 80 °C for 16 h, in the presence of an additional 3M aq. KOH only, provided the corresponding vinylarenes in 70% isolated yield based on the iodoarene employed.

Borylation-isomerization-allylboration sequence.

The borylation of **2j**, including an allyl ether moiety, afforded the allylboronate **5j** as a major product. It is well known that many allylmetal reagents react smoothly with carbonyl compounds to yield homoallyl alcohols.¹⁹

Thus, the reaction of 2j with pinacolborane 1, followed by *in situ* treatment with an excess of benzaldehyde at room temperature provided the corresponding homoallylic alcohol in 41% isolated yield (eq. 15). The presence of alkenylboronate 3j did not interfere with

the outcome of the present reaction, since 3j was inert to many functional groups.



Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. Solvents were dried and distilled before use (see, chapter 3). All amines were commercial products and dried over potassium hydroxide. The palladium catalysts were prepared as described in chapter 2. The ligands (AsPh₃, PPh₃, dppf) from commercial sources were used without purification. All cycloalkenyl iodides²⁰ and triflates⁷ were obtained from the corresponding cyclic ketones by the known method. Pinacolborane was synthesized as reported previously.²¹

Synthesis of alkenylboronates. Typical Procedure. The general procedure for the synthesis of alkenylboronates is illustrated by the synthesis of 1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-4-phenylcyclohexene. To a solution of PdCl₂(dppf) (22 mg, 0.03 mmol) and AsPh₃ (36 mg, 0.12 mmol) in dioxane (4 ml), Et₃N (0.42 mL, 3.0 mmol), pinacolborane (0.22 mL, 1.5 mmol), and 4-phenylcyclohexenyl triflate (304 mg, 0.99 mmol) were added. After being stirred for 4 h at 80 °C, the mixture was extracted with ether. The extract was washed with water, dried over MgSO₄, and concentrated. The residue was purified by column chromatography on a silica gel (hexane/ether = 10/1) to give 201 mg (71% yield) of the corresponding alkenylboronate 3a along with the reduced product 4a.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-4-phenylcyclohexene: IR (KBr) 2976, 2930, 1141 cm⁻¹; ¹H NMR (CDCl₃) δ 1.28 (s, 12 H), 1.6-1.7 (m, 1 H), 1.9-2.0 (m, 1 H), 2.2-2.4 (m, 4 H), 2.7-2.8 (m, 1 H), 6.66 (dd, *J* = 3.9, 1.7 Hz, 1 H), 7.1-7.2 (m, 3 H), 7.30 (t, *J* = 7.5 Hz); ¹³C NMR (CDCl₃) δ 24.80, 27.01, 29.76, 34.88, 39.76, 83.13, 125.95, 126.85, 128.34, 142.25, 147.25; MS (*m/z*) 284

(16, M⁺), 269 (3), 227 (5), 184 (4), 157 (3), 104 (100); HRMS (*m/z*) for C₁₈H₂₅O₂B calcd 284.1947, found 284.1946. **4-Phenylcyclohexene:** ¹H NMR (CDCl₃) δ 1.7-2.3 (m, 6 H), 2.7-2.9 (m, 1 H), 5.77 (br. s, 2 H), 7.1-7.4 (m, 5 H); ¹³C NMR (CDCl₃) δ 25.89, 29.73, 33.40, 40.16, 125.95, 126.77, 126.89, 126.97, 128.35, 147.35.

The following compounds were prepared by the above procedure.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-4-tert-butyl-1-cyclohexene (Table 2, entry 3): IR (KBr) 2964, 1146 cm⁻¹; ¹H NMR (CDCl₃) δ 0.85 (s, 9 H), 1.0-1.1 (m, 1 H), 1.26 (s, 12 H), 1.3-1.4 (m, 1 H), 1.8-1.9 (m, 2 H), 2.0-2.1 (m, 2 H), 2.3-2.4 (m, 1 H), 6.59 (t, *J* = 2.1 Hz, 1 H); ¹³C NMR (CDCl₃) δ 23.91, 24.76, 27.08, 27.79, 28.42, 32.20, 43.73, 82.98, 143.43; MS (*m/z*) 264 (6, M⁺), 249 (7), 207 (12), 164 (5), 207 (12), 101 (21); HRMS (*m/z*) for C₁₆H₂₉O₂B calcd 264.2261, found 264.2279.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-cyclohexene (Table 2, entry 4): IR (neat) 2978, 2928, 1147 cm⁻¹; ¹H NMR (CDCl₃) δ 1.26 (s, 12 H), 1.5-1.6 (m, 4 H), 2.0-2.1 (m, 4 H), 6.57 (t, *J* = 1.7 Hz, 1 H); ¹³C NMR (CDCl₃) δ 22.17, 22.54, 24.81, 26.10, 26.61, 82.99, 142.94; MS (*m/z*) 208 (9, M⁺), 193 (2), 124 (5), 108 (48), 84 (100); HRMS (*m/z*) for C₁₂H₂₁O₂B calcd 208.1635, found 208.1627.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2,6-dimethyl-1-cyclohexene (Table 2, entry 6): IR (neat) 2977, 2927, 1147 cm⁻¹; ¹H NMR (CDCl₃) δ 0.99 (d, *J* = 6.7 Hz, 3 H), 1.1-1.2 (s, 1 H), 1.29 (s, 12 H), 1.5-1.7 (m, 4 H), 1.85 (s, 3 H), 1.9-2.0 (m, 1 H); ¹³C NMR (CDCl₃) δ 19.61, 21.83, 23.39, 25.16, 30.29, 31.24, 32.78, 82.79, 146.50; MS (*m/z*) 236 (22, M⁺), 221 (25), 164 (2), 148 (1), 121 (37), 108 (100), 84 (73), 79 (12); HRMS (*m/z*) for C₁₄H₂₅O₂B calcd 236.1947, found 236.1943.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-cyclopentene (Table 2, entry 7): IR (neat) 2978, 1145 cm⁻¹; ¹H NMR (CDCl₃) δ 1.27 (s, 12 H), 1.8-1.9 (m, 2 H), 2.4-2.5 (m, 4 H), 6.55 (t, *J* = 4.6 Hz, 1 H); ¹³C NMR (CDCl₃) δ 23.90, 24.78, 34.50, 34.76, 83.04, 147.56; MS (*m/z*) 194 (19, M⁺), 179 (25), 164 (6), 137 (4), 108 (100), 94 (25); HRMS (*m/z*) for C₁₁H₁₉O₂B calcd 194.1478, found 194.1475.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-cycloheptene

(Table 2, entry 9): IR (neat) 2978, 2920, 1145 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.26 (s, 12 H), 1.4-1.5 (m, 4 H), 1.7-1.8 (m, 2 H), 2.2-2.3 (m, 4 H), 6.77 (t, $J = 6.3$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.83, 26.47, 27.36, 29.56, 30.56, 32.74, 83.14, 148.62; MS (m/z) 222 (7, M^+), 207 (11), 165 (33), 122 (22), 84 (100); HRMS (m/z) for $\text{C}_{13}\text{H}_{23}\text{O}_2\text{B}$ calcd 222.1791, found 222.1792.

4-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-5,6-dihydro-2H-pyran (Table 2, entry 10): IR (neat) 2977, 2929, 1145 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.25 (s, 12 H), 1.9-2.0 (m, 2 H), 2.2-2.3 (m, 1 H), 4.70 (dd, $J = 6.1, 3.7$ Hz, 1 H), 6.37 (dd, $J = 6.1, 2.4$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.16, 24.61, 24.69, 65.62, 83.31, 101.08, 142.96; MS (m/z) 210 (66, M^+), 195 (16), 153 (19), 110 (60), 84 (100), 83 (90); HRMS (m/z) for $\text{C}_{11}\text{H}_{19}\text{O}_3\text{B}$ calcd 210.1427, found 210.1444.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-3,3,5,5-tetramethyl-1-cyclohexene (Table 2, entry 11): IR (KBr) 2953, 1146 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.92 (s, 6 H), 1.01 (s, 6 H), 1.27 (s, 12 H), 1.32 (s, 2 H), 1.85 (s, 2 H), 6.27 (s, 1 H); ^{13}C NMR (CDCl_3) δ 24.83, 29.94, 39.65, 49.82, 83.00, 151.33; MS (m/z) 264 (17, M^+), 249, (60), 180 (6), 137 (22), 121 (100), 101 (56), 107 (46); HRMS (m/z) for $\text{C}_{16}\text{H}_{29}\text{O}_2\text{B}$ calcd 264.2261, found 264.2225.

(E)-1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-3,3-dimethyl-1-butene (eq. 13): IR (neat) 2978, 1147 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.02 (s, 9 H), 1.27 (s, 12 H), 5.35 (d, $J = 18.5$ Hz, 1 H), 6.64 (d, $J = 18.5$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.78, 28.77, 34.99, 82.98, 164.41; MS (m/z) 210 (8, M^+), 195 (16), 153 (36), 110 (25), 101 (100), 83 (61); HRMS (m/z) for $\text{C}_{12}\text{H}_{23}\text{O}_2\text{B}$ calcd 210.1755, found 210.1751.

Oxidation of alkenylboronate (eq. 10). To the solution of 3c, prepared *in situ* from 2c (141 mg, 1.0 mmol), similarly to as above, trimethylamine oxide (375 mg, 5 mmol) was added, and the resulting mixture was stirred at 80 $^\circ\text{C}$ for 16 h. The products, the parent ketone and the allyl alcohol, were isolated by column chromatography on a silica gel (hexane/ether).

4-t-butyl-2-cyclohexen-1-ol: ^1H NMR (CDCl_3) δ 1.3-2.0 (m, 5 H), 4.10 (br.s, 1 H), 5.7-6.0 (m, 2 H); ^{13}C NMR (CDCl_3) δ 18.36, 27.28,

31.14, 46.29 ($\text{CH}-^t\text{Bu}$), 63.39 ($\text{CH}-\text{OH}$), 128.94 ($=\text{CH}$), 134.03 ($=\text{CH}$). DEPT and H-C COSY analysis indicated methine protons at 4.10 ppm ($\text{CH}-\text{OH}$) and at 1.79 ppm ($\text{CH}-^t\text{Bu}$). H-H COSY analysis indicated vinyl protons coupled with the methine protons.

Cross-coupling of alkenylboronate with iodoarene (eq.14).

To the solution of 3c, prepared *in situ* from 2c (212 mg, 1.5 mmol), aqueous 3M KOH (1 mL, 3 mmol) and 4-fluoriodobenzene (218 mg, 0.98 mmol) were added. After stirring at 80 $^\circ\text{C}$ for 18 h. The mixture was diluted with ether, washed with water, and dried (MgSO_4). The coupling product, 1-(4-tert-butyl-1-cyclohexenyl)-4-fluorobenzene, was isolated by column chromatography on a silica gel (hexane) to give a 70% yield (159 mg): IR (neat) 2960, 1231 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.91 (s, 9 H), 1.2-1.4 (m, 2 H), 1.9-2.0 (m, 2 H), 2.2-2.3 (m, 1 H), 2.4-2.5 (m, 2 H), 6.0-6.1 (m, 1H), 6.9-7.0 (m, 2 H), 7.2-7.3 (m, 2 H); ^{13}C NMR (CDCl_3) δ 24.35, 27.20, 27.42, 28.99, 32.19, 43.73, 114.78, 114.95, 124.79, 126.32, 135.42, 162.71; MS (m/z) 232 (27, M^+), 217 (3), 175 (35), 148 (100), 108 (3), 96 (5); HRMS (m/z) for $\text{C}_{16}\text{H}_{21}\text{F}$ calcd 232.1628, found 234.1642.

Synthesis of 2-phenylmethanol-5,6-dihydro-2H-pyran (eq. 15).

To the solution of 3j, prepared *in situ* from 2j (1.0 mmol), benzaldehyde (1.5 mmol) was added, and the resulting mixture was stirred at room temperature for 24 h. After addition of triethanolamine (0.1 mL), the mixture stirred for 24 h. The mixture was diluted with ether, washed with water, and dried (MgSO_4). 2-Phenylmethanol-5,6-dihydro-2H-pyran was isolated by Kugelrohr distillation to give a 41% yield (78 mg): IR (KBr) 2975, 2924, 1334, 1149, 1088 cm^{-1} ; ^1H NMR (CDCl_3) δ 2.0-2.1 (m, 1 H), 2.2-2.3 (m, 1 H), 3.15 (d, $J = 1.8$ Hz, 1 H), 3.7-3.8 (m, 1 H), 4.0-4.1 (m, 1 H), 4.1-4.2 (m, 1 H), 4.55 (dd, $J = 7.9, 1.8$ Hz, 1 H), 5.3-5.4 (m, 1 H); ^{13}C NMR (CDCl_3) δ 25.15, 62.62, 76.40, 78.04, 125.80, 126.82, 127.33, 128.07, 128.37, 139.82; MS (m/z) 190 (1, M^+), 173 (24), 107 (39), 109 (100), 83 (13); HRMS (m/z) for $\text{C}_{12}\text{H}_{14}\text{O}_2$ calcd 190.0994, found 190.1039.

References

- For a recent review, see: Miyaura, N.; Suzuki, A. *Chem. Rev.* 1995, 95, 2457.
- For examples, see: (a) Uenishi, J.; Beau, J.-M.; Armstrong, R. W.; Kishi, Y. *J. Am. Chem. Soc.* 1987, 109, 4756. (b) Roush, W.; Riva, R. *J. Org. Chem.* 1988, 53, 710. (c) Nicolaou, K. C.; Ramphal, J. Y.; Palazon, J. M.; Spanevello, R. A. *Agew. Chem., Int. Ed. Engl.* 1989, 28, 587. (d) Potter, G. A.; McCague, R. *J. Org. Chem.* 1990, 55, 6184. (e) Kobayashi, Y.; Shimazaki, T.; Taguchi, H.; Sato, F. *J. Org. Chem.* 1990, 55, 5324. (f) Uemura, M.; Nishimura, H.; Minami, T.; Hayashi, Y. *J. Am. Chem. Soc.* 1991, 113, 5402.
- (a) Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* 1975, 97, 5249. (b) For a review, see: Lane, C. F.; Kabalka, G. W. *Tetrahedron* 1976, 32, 981.
- (a) Brown, H. C.; Imai, T. *Organometallics* 1984, 3, 1392. (b) Brown, H. C.; Imai, T.; Bhat, N. G. *J. Org. Chem.* 1986, 51, 5277. (c) Moriya, T.; Miyaura, N.; Suzuki, A. *Chem. Lett.* 1993, 1429.
- Satoh, Y.; Serizawa, H.; Miyaura, N.; Hara, S.; Suzuki, A. *Tetrahedron Lett.* 1988, 29, 1811.
- Ishiyama, T.; Yamamoto, M.; Miyaura, N. *Chem. Lett.* 1996, 1117.
- Kamabuchi, A.; Miyaura, N.; Suzuki, A. *Tetrahedron Lett.* 1993, 34, 4827.
- Renaud, J.; Ouellet, S. G. *J. Am. Chem. Soc.* 1998, 120, 7995.
- (a) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* in press.
- For a recent review, see: Stang, P. J.; Hanack, M.; Subramanian, L. R. *Synthesis* 1982, 85.
- Takahashi, K.; Takagi, J.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* 2000, 126.
- Farina, V.; Krishnan, B. *J. Am. Chem. Soc.* 1991, 113, 9585.
- (a) Egli, R. A. *Helv. Chim. Acta* 1968, 51, 2090. (b) Hutchins, R. O.; Learn, K. *J. Org. Chem.* 1982, 47, 4380. (c) Lipshutz, B. H.; Buzard, D. J.; Vivian, R. W. *Tetrahedron Lett.* 1999, 40, 6871.
- For a review of the palladium-catalyzed carbon-carbon double bond isomerization, see; Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic: New York, 1985; p. 19.
- (a) Satoh, M.; Nomoto, Y.; Miyaura, N.; Suzuki, A. *Tetrahedron Lett.* 1989, 30, 3789. (b) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *Organometallics* 1993, 12, 589. (c) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *J. Org. Chem.* 1993, 58, 5351.
- (a) Murahashi, S.-I.; Watanabe, T. *J. Am. Chem. Soc.* 1979, 101, 7429. (b) Hagiwara, H.; Eda, Y.; Morohashi, K.; Suzuki, T.; Ando, M.; Ito, N. *Tetrahedron Lett.* 1998, 39, 4055.
- (a) Moriya, T.; Suzuki, A.; Miyaura, N. *Tetrahedron Lett.* 1995, 36, 1887. (b) Yamamoto, Y.; Miyairi, T.; Miyaura, N. *J. Org. Chem.* 1999, 64, 296.
- Miyaura, N.; Ishiyama, T.; Sasaki, H.; Ishikawa, M.; Satoh, M.; Suzuki, A. *J. Am. Chem. Soc.* 1989, 111, 314.
- (a) Hoffmann, R. W. *Agew. Chem., Int. Ed. Engl.* 1982, 21, 555. (b) Yamamoto, Y.; Yatagai, H.; Maruyama, K. *J. Am. Chem. Soc.* 1981, 103, 1969. (c) Sato, K.; Kira, M.; Sakurai, H. *J. Am. Chem. Soc.* 1989, 111, 6429. (d) Kira, M.; Hino, T.; Sakurai, H. *Tetrahedron Lett.* 1989, 30, 1099. (e) Masuyama, Y.; Takahara, J. P.; Kurusu, Y. *J. Am. Chem. Soc.* 1988, 110, 4473.
- Pross, A.; Sternhell, S. *Aust. J. Chem.* 1970, 23, 989.
- Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* 1992, 57, 3482.

Chapter 5.

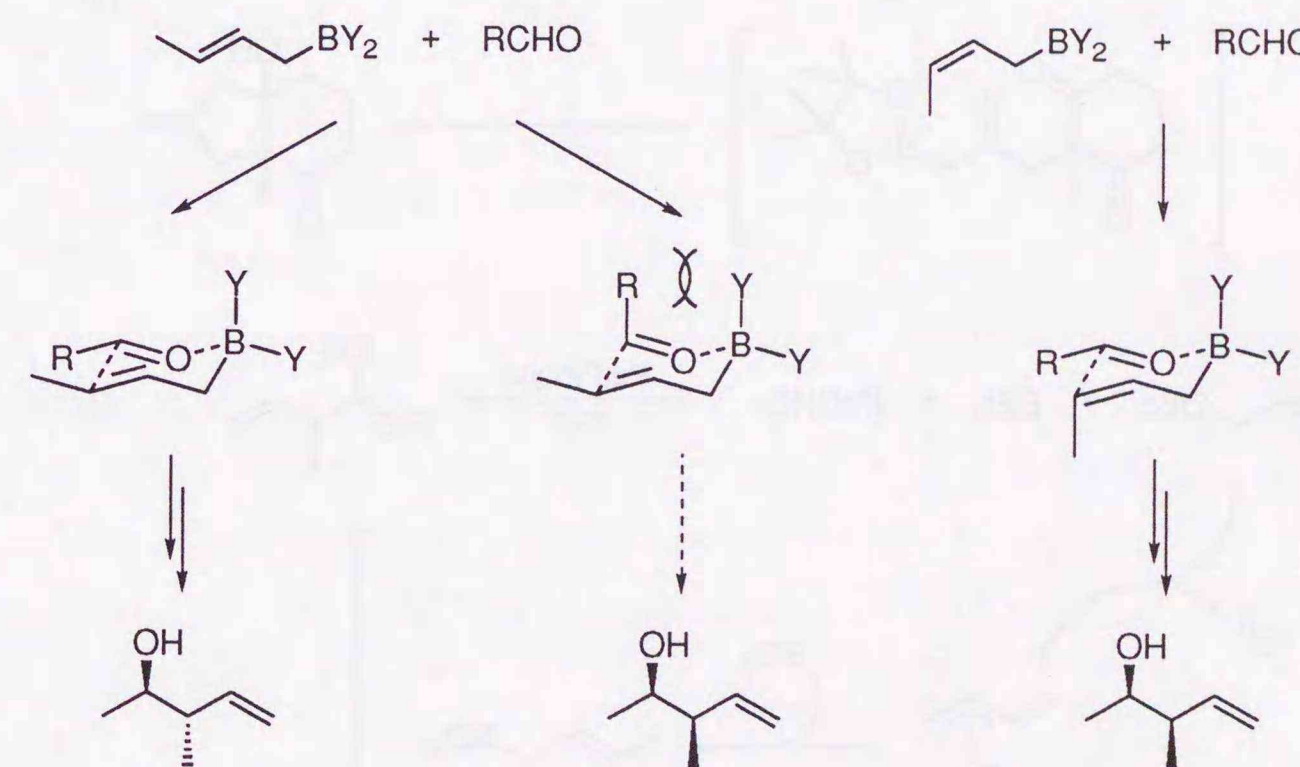
Regio- and Stereoselective Synthesis of Allylboranes via Platinum(0)-Catalyzed Borylation of Allyl Halides with Pinacolborane

Various allyl halides were borylated with pinacolboranes in the presence of NEt_3 and a catalytic amount of $\text{Pt}(\text{dba})_2$ and AsPh_3 to afford the corresponding regio- and stereodefined allylboranes in good yields. The reaction was applied to the one-pot synthesis of homoallyl alcohols via allylboration.

Introduction

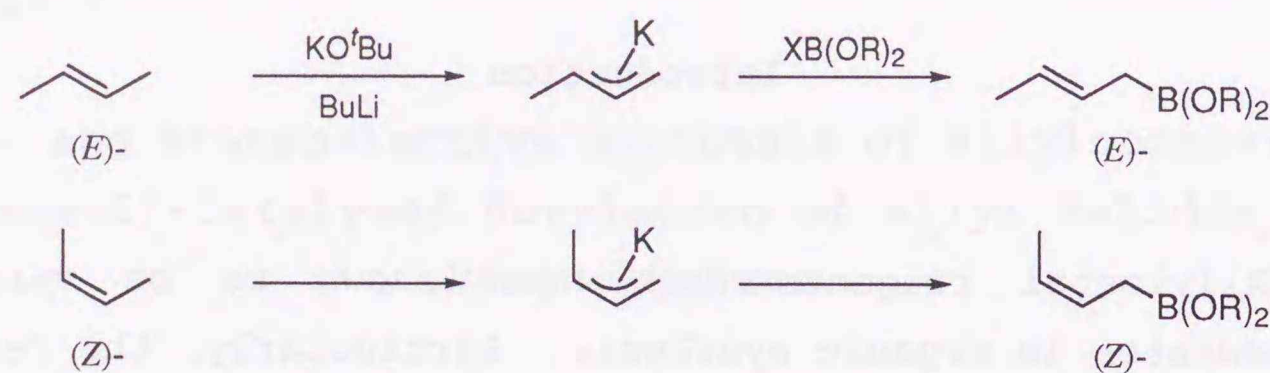
Allylmetal reagents have been shown to be versatile intermediates in organic synthesis. Particularly, the reaction with carbonyl compounds affords homoallyl alcohol derivatives. Among other reagents, the reaction of allylboranes proceeds diastereospecifically due to the formation of a cyclic six-membered transition state (Figure 1).¹ (*E*)- and (*Z*)-allylboranes provide *anti*- and *syn*-homoallyl alcohols, respectively. Thus, allylboranes are one of the most useful reagents for a carbon-carbon bond formation under controlling the stereochemistry. Furthermore, such reaction are highly important in current research on asymmetric synthesis.²

Figure 1.

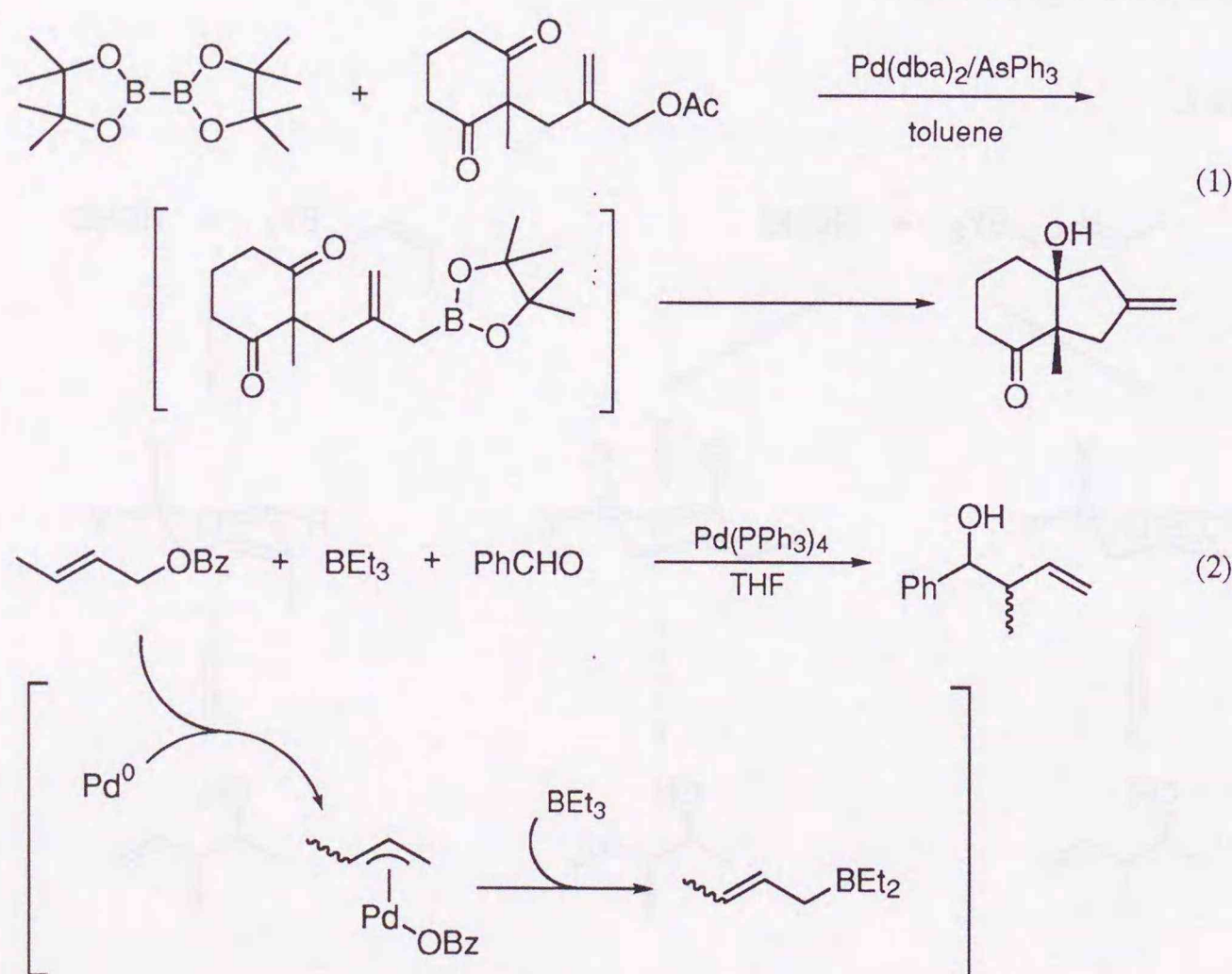


Accordingly, much attention has been paid to the stereoselective synthesis of allylboranes.³ Schlosser reported on a stereoselective synthesis of allylboronates from allylpotassium reagents (Scheme 1).^{3a} However, this method requires several steps.

Scheme 1.

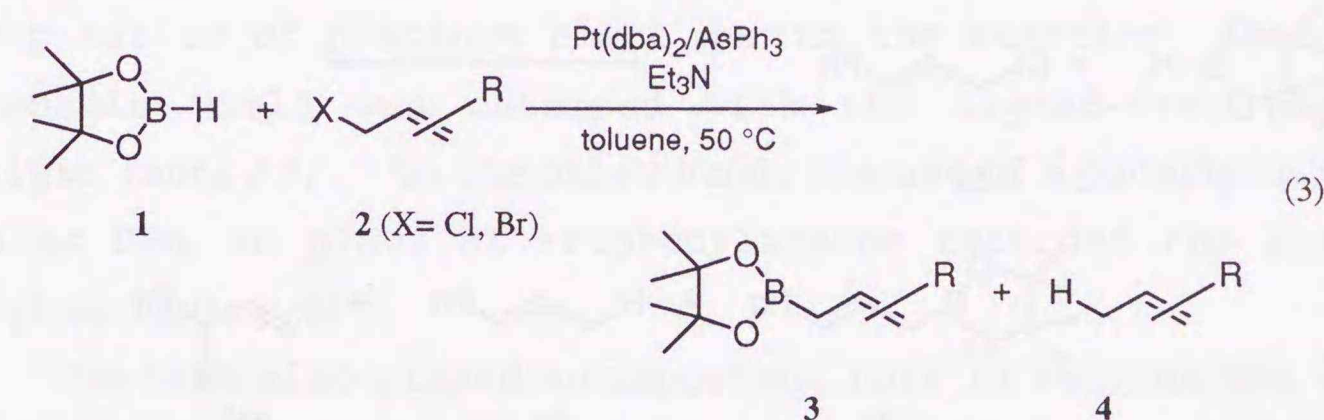


On the other hand, the transition-metal-catalyzed direct borylation of organic electrophiles is a convenient route to boronic esters. Recently, palladium-catalyzed coupling reactions of allyl electrophiles with tetraalkoxydiboron (eq. 1)⁴ and triethylborane (eq. 2)⁵ were reported, respectively. Since these reactions tolerate various functional groups such as carbonyl group, provided a one-step procedure for deriving homoallyl alcohols.



The author gave attention to dialkoxyboranes as metalating reagents in the presence of palladium(0) complexes and tertiary amine. In chapter 3 and 4, a boron-carbon bond formation utilizing

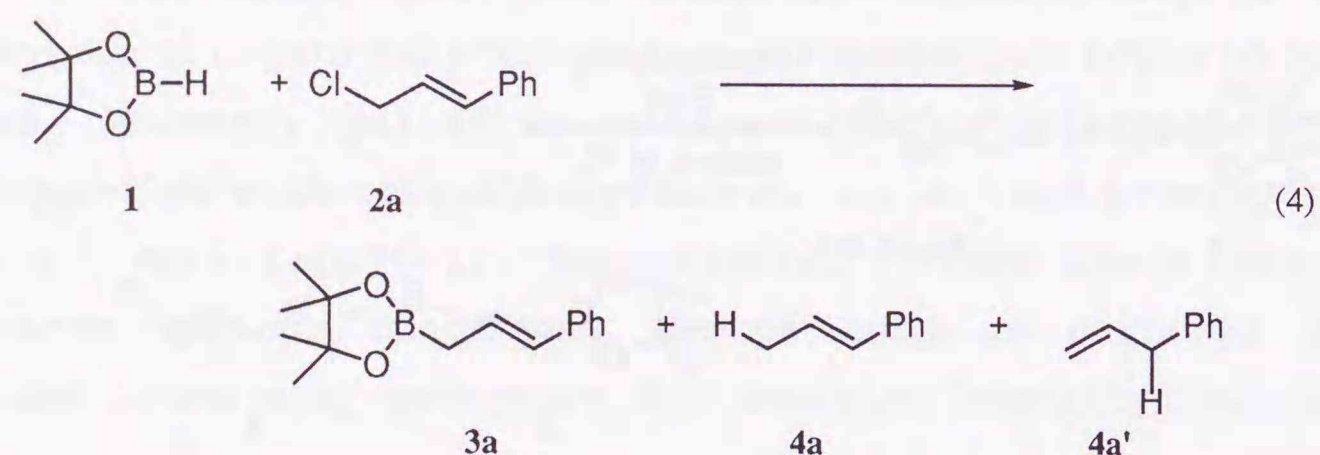
pinacolborane was described.⁶ However, the palladium-catalyzed reaction of allylelectrophiles with pinacolborane gave no allylboronates. This chapter is concerned with a stereoselective and available synthetic route to allylboranes. Herein, a novel platinum(0)-catalyzed coupling reaction of allyl halides 2 with pinacolboranes 1 to provide the corresponding allylboranes 3 is described (eq 3).



Results and Discussion

Reaction conditions.

The reaction conditions were optimized using cinnamyl chloride (2a) as a substrate (eq. 4, Table 1).



At 50 °C in toluene, the reaction of 2a with 1.5 equiv of pinacolborane 1 in the presence of $\text{Pt}(\text{dba})_2$ (dba = dibenzylideneacetone), AsPh_3 , and Et_3N gave the corresponding (*E*)-cinnamylboronate 3a (79% GLC yield based on 2a) regio- and stereoselectively together with a small amount of β -methylstyrene

Table 1. Reaction of cinnamyl chloride 2a with pinacolborane 1^a

entry	catalyst	ligand	base	solvent	yield / % ^b		
					3a	4a	4a'
1	$\text{Pt}(\text{dba})_2$	AsPh_3	Et_3N	toluene	72	6	21
2	$\text{Pd}(\text{dba})_2$	AsPh_3	Et_3N	toluene	0	24	44
3	$\text{Ni}(\text{cod})_2$	AsPh_3	Et_3N	toluene	0	0	0
4	$[\text{RuCl}_2(\text{cod})]_n$	AsPh_3	Et_3N	toluene	0	3	2
5	$[\text{IrCl}(\text{cod})]_2$	AsPh_3	Et_3N	toluene	37	4	30
6	$[\text{RhCl}(\text{cod})]_2$	AsPh_3	Et_3N	toluene	12	3	47
7	$\text{Pt}(\text{dba})_2$	none	Et_3N	toluene	59	20	20
8	$\text{Pt}(\text{dba})_2$	PPh_3	Et_3N	toluene	0	9	28
9	$\text{Pt}(\text{dba})_2$	AsPh_3	pyridine	toluene	0	20	30
10	$\text{Pt}(\text{dba})_2$	AsPh_3	KOAc	toluene	9	17	52
11	$\text{Pt}(\text{dba})_2$	AsPh_3	Et_3N	$\text{CH}_2\text{ClCH}_2\text{Cl}$	66	6	16
12	$\text{Pt}(\text{dba})_2$	AsPh_3	Et_3N	dioxane	52	6	25

^a Reactions of 3-chloro-1-phenyl-1-propene 2a (1.0 mmol) with 1 (1.5 mmol) were carried out at 50 °C for 16 h in 4 mL of solvent by using 3 mol % of catalyst and base (3 mmol). ^b GLC yields based on 2a used.

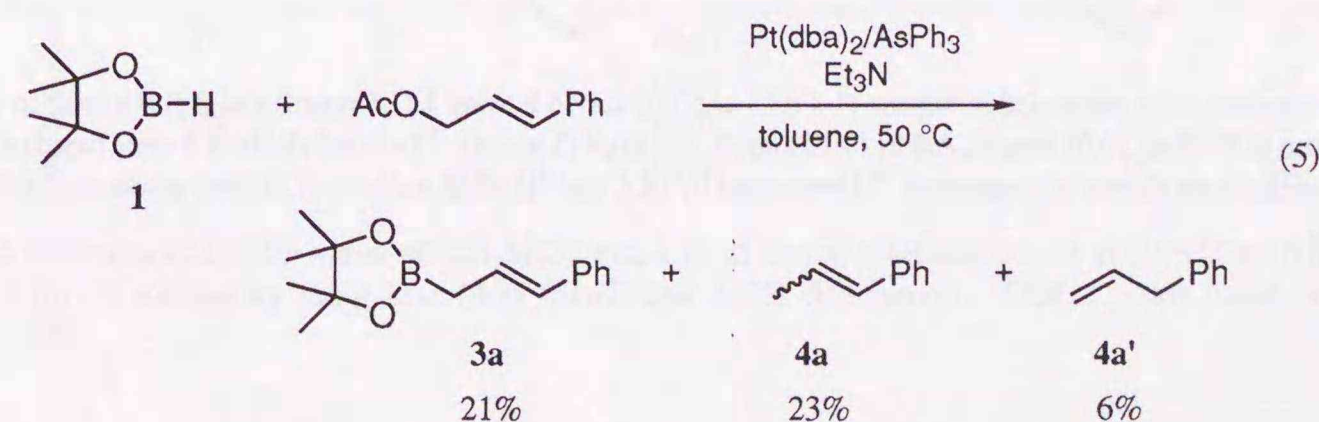
4a (2%) and allylbenzene 4a' (6%) (entry 1).

With regard to catalysts, a variety of transition metal complexes were examined. As we reported recently, aryl halides couple with 1 successfully in the presence of a palladium catalyst and Et_3N to give arylboronates.⁵ However, the coupling reaction of 2a by using $\text{Pd}(\text{dba})_2$ catalyst gave only the corresponding reduced product 4 (entry 2).⁷ Triphenylarsine, which weakly coordinated with transition metals,⁸ stabilized the complex to prevent the precipitation of platinum black during the reaction, although a reasonable yield was obtained with the ligand-free platinum catalyst (entry 7). On the other hand, the use of a phosphine ligand such as PPh_3 in place of triphenylarsine retarded the intended reaction (entry 8).

The base also played an important role in swaying the yields and the selectivity. Among bases that were effective, the tertiary amine, Et_3N , was recognized to be the most effective for the selective formation of 3. In contrast, the use of potassium acetate caused the reductive cleavage of the C-Cl bond of 2a to form the C-H bond of 4a exclusively (entry 10).

Borylation of representative allyl electrophiles.

The results of $\text{Pt}(\text{dba})_2$ -catalyzed borylation of representative allyl halides 2 are summarized in Table 2. The differences in yields and in selectivity from the nature of halides were not very significant (entries 2 and 3); however, allyl acetates were less reactive toward the borylation. Under the present conditions, the borylation of cinnamyl acetate gave only 21% yield of 3a along with 4a and 4a' (eq. 5).



Although the starting crotyl chloride **2e** was a mixture of (*E*)- and (*Z*)-isomer, the borylation of such aliphatic allyl electrophiles proceeded regio- and stereoselectively to give (*E*)-crotylboronates **3e** exclusively (entry 5). Also, 3-chloro-1-butene **2f** afforded the same product **3e** (entry 6), suggesting a process via π -allyl platinum intermediacy. It is interesting to note that the present platinum-catalyzed borylation afforded regio- and stereodefined allylboronates, whereas the palladium-catalyzed borylation of such aliphatic allyl electrophiles proceeded in modest stereoselectivity.⁴ Alicyclic allyl halides **2h** also afforded the corresponding boronates **3h** in high yield (entry 8).

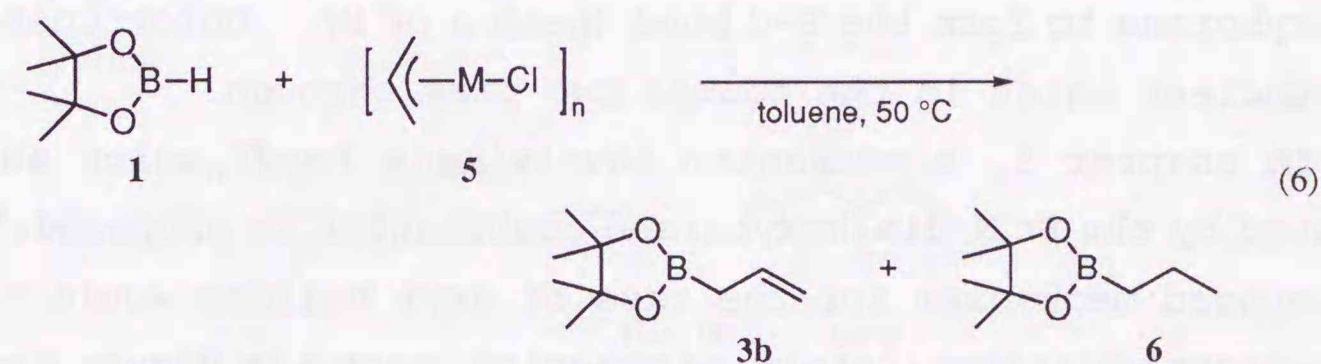
Table 2. Borylation of representative **2** with **1**^a

entry	substrate 2	product	yield ^b (%)	<i>E/Z</i> ^c
1			(72)	>99
2			(70)	—
3			(77)	—
4			78	—
5			67	>99
6			78	>99
7			49	—
8			81	—

^a All reactions were conducted in toluene (1–4 mL) at 50 °C for 16 h using **1** (1.5 mmol) and **2** (1.0 mmol) in the presence of Pt(dba)₂ (0.03 mmol), AsPh₃ (0.12 mmol), and Et₃N (3 mmol). ^b Isolated yields of **3** were based on **2**. GLC yields were shown in parentheses. ^c Determined by GLC and ¹H NMR analysis of isolated products. ^d *E/Z* = 87/13.

Reaction mechanism.

Organometallic reagents such as an iridium complex are known to react with dialkoxyborane to give the organoboronates.⁹ Analogous to this reaction, the π - and/or σ -allylplatinum species generated by the oxidative addition of **2** to Pt⁰ may react with pinacolborane **1** to form the B–C bond in the present process. The results of stoichiometric reaction of π -allyl complexes **5** with pinacolborane **1** are summarized in Table 3 (eq. 6).



The treatment of the authentically isolated [$(\eta^3\text{-C}_3\text{H}_5)\text{PtCl}$]₄¹⁰ with pinacolborane **1** at 50 °C in the presence of Et₃N gave the corresponding allylboronate **3b** (yield, 6%), although the reaction conditions were not optimized (entry 1).¹² On the one hand, a similar treatment without a base gave not **3b** but propylboronate **6** unexpectedly (entry 2). The use of Et₃N is essential not only for catalytic borylation but also for stoichiometric reaction. In the case of the palladium complex, the reaction also afforded propylboronate **6** in the absence of the base, although this situation was greatly improved by Et₃N (entry 3 and 4). Although the formation

Table 3. Reaction of π -allyl complexes **5** with pinacolborane **1** (eq. 6)^a

entry	M	n	base	yield / % ^b	
				3b	6
1	Pt	4	Et ₃ N	6	0
2			none	0	40
3	Pd	2	Et ₃ N	0	0
4			none	0	92

^a Reactions of **5** (0.05 mmol of C₃H₅MCl) with **1** (0.25 mmol) were carried out at 50 °C for 16 h in 2 mL of toluene by using base (0.25 mmol) and AsPh₃ (0.1 mmol). ^b GLC yields based on **5** used.

of propylboronate 6 was not detected in the catalytic borylation, 6 may be produced by hydroboration of the reduced alkene 4b (path C in Figure 2). Thus, for the present reaction, Et₃N appeared to play an important role in preventing the production of reduced by-product 4.

A reasonable, although unproven, catalytic cycle for the borylation via π -allyl platinum intermediacy is outlined in Figure 2. In the presence of Et₃N, the allylplatinum species generated by the oxidative addition of allyl halides may react with dialkoxyborane to form the B-C bond (path A or B). Unfortunately, it is unclear which in the course two pass through.

In chapter 3, a mechanism involving a boryl anion analog generated by the Et₃N-dialkoxyborane combination is proposed.⁶ As the proposed mechanism for the case of aryl halides would refer to the present platinum-catalyzed reaction, path A in Figure 2 would be favored. Investigations on further mechanistic aspects are currently in progress.

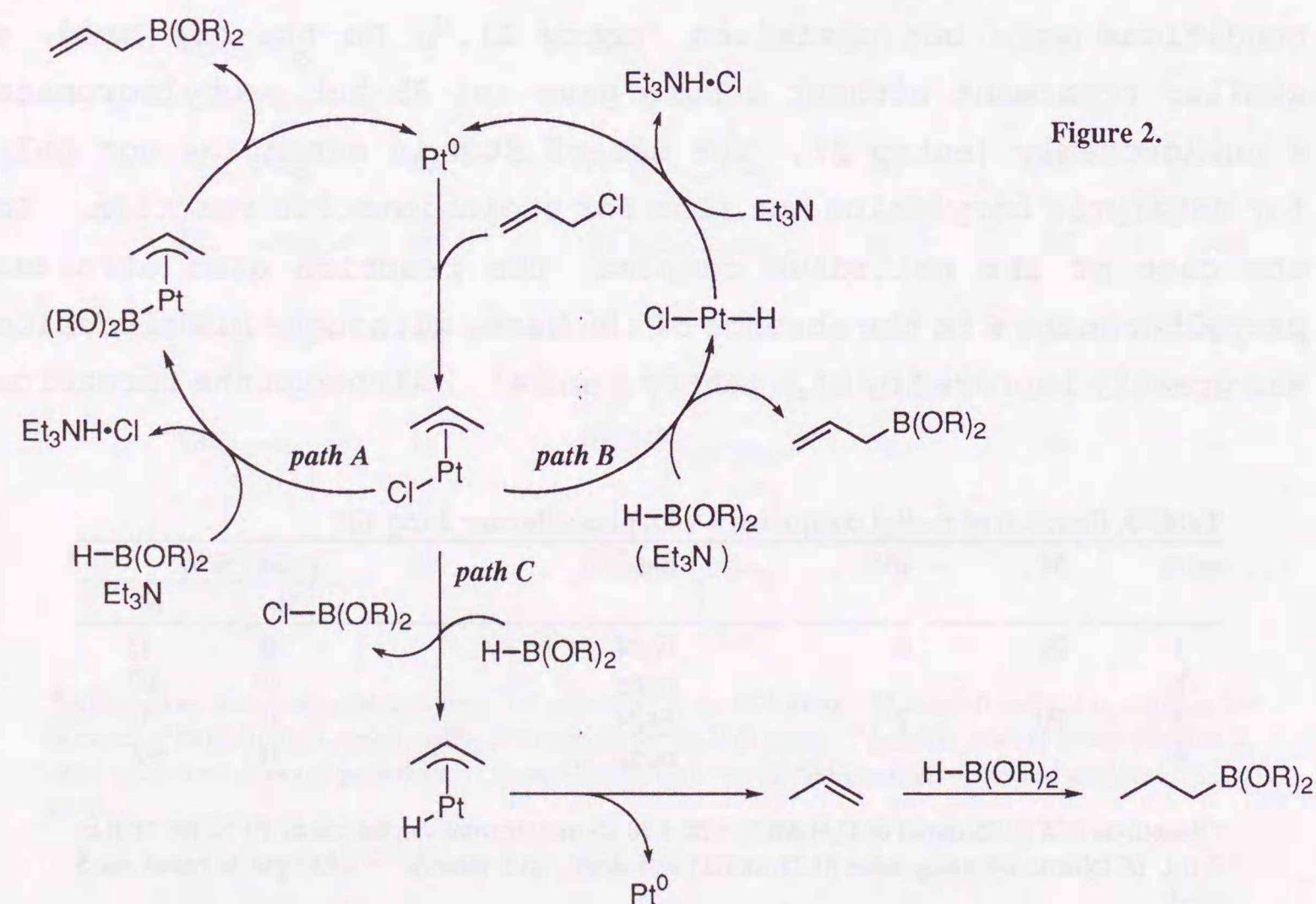
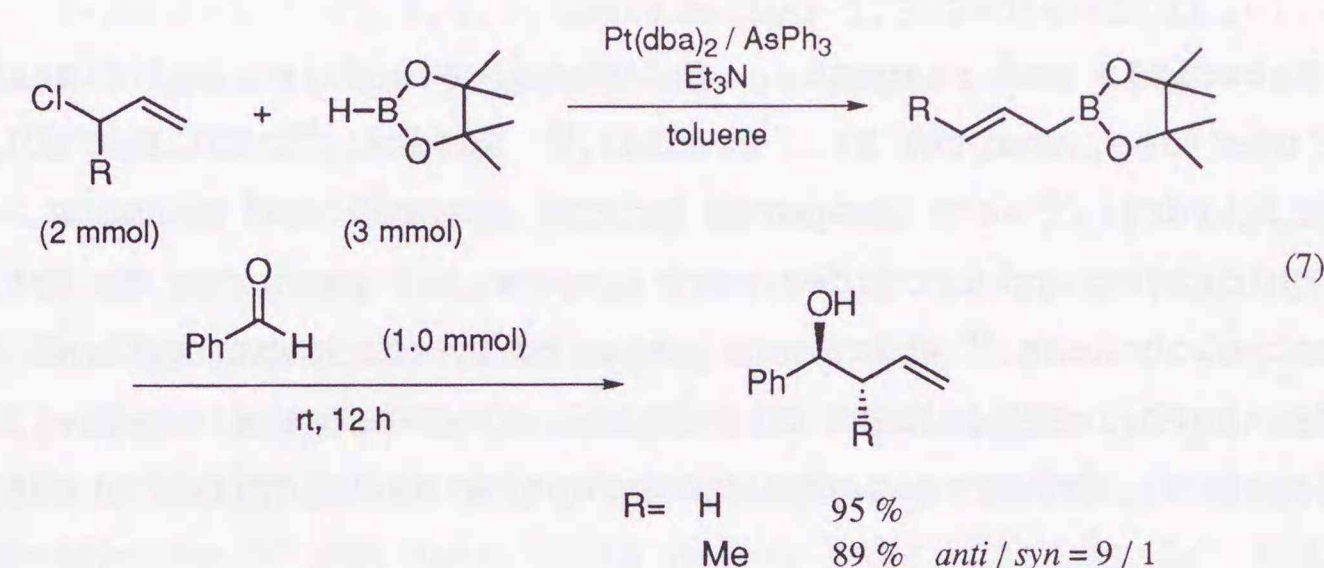


Figure 2.

One-pot synthesis of homoallyl alcohols.

The potential versatility of the present borylation was demonstrated by the one-pot synthesis of homoallyl alcohols (eq. 7).



The reaction of 2b with pinacolborane 1, followed by *in situ* treatment with benzaldehyde at room temperature provided the corresponding homoallylic alcohol in 95% isolated yield based on benzaldehyde.

Also, (*E*)-crotylboronates 3e, prepared *in situ* from 2f, afforded in 89% yield of the corresponding alcohol with modest diastereoselectivity, whereas it is well known that allylboration proceeds diastereospecifically.¹ The platinum catalyst and/or triethylamine may prevent the formation of a cyclic six-membered transition state.

Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. Solvents were dried and distilled before use (see, chapter 3). $\text{Pt}(\text{dba})_2^{11}$, $\text{Pd}(\text{dba})_2^{12}$, $[(\text{C}_3\text{H}_5)\text{PtCl}]_4^{10}$ and $[(\text{C}_3\text{H}_5)\text{PdCl}]_2^{13}$ were prepared by the established methods. All allyl chlorides and bromides were commercial products except for 2-bromocyclohexene,¹⁴ which was prepared by the known method. The ligands (AsPh_3 , PPh_3) from commercial sources were used without purification. Other reagents were prepared as described in chapter 3.

Synthesis of allylboronates. Typical Procedure.

A flask was charged with $\text{Pt}(\text{dba})_2$ (0.03 mmol), AsPh_3 (0.12 mmol), toluene (1-4 ml), and Et_3N (3 mmol) under an argon flow. Pinacolborane 1 (1.5 mmol) and allyl halide 2 (1.0 mmol) were added successively, and the mixture was stirred at 50 °C for 16 h. The reaction mixture was diluted with toluene, washed with water, and dried over MgSO_4 . The solvent was evaporated, and product 3 was isolated by distillation with Kugelrohr.

The following compounds were prepared by the above procedure.

(E)-3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-phenylpropene (Table 2, entry 1): IR (neat) 2979, 1371, 1328, 1145, 966, 745, 695 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.25 (s, 12 H), 1.87 (d, J = 7.1 Hz, 2 H), 6.28 (dt, J = 15.9, 7.1 Hz, 1 H), 6.37 (d, J = 15.9 Hz, 1 H), 7.1-7.3 (m, 5 H); ^{13}C NMR (CDCl_3) δ 24.78, 83.37, 125.80, 126.27, 126.47, 128.35, 130.22, 138.18; MS (m/z) 244 (61, M^+), 229 (12), 144 (29), 128 (21), 117 (100), 103 (9), 77 (11); HRMS for $\text{C}_{15}\text{H}_{21}\text{O}_2\text{B}$ calcd 244.1635, found 244.1645.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-propene (Table 2, entry 2 and 3): IR (neat) 2980, 1637, 1355, 1145, 970,

847 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.25 (s, 12 H), 1.73 (d, J = 7.5 Hz, 2 H), 4.93 (dd, J = 10.1, 2.1 Hz, 1 H), 5.00 (dd, J = 17.1, 2.1 Hz, 1 H), 5.87 (ddt, J = 17.1, 10.1, 7.5 Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.83, 83.26, 114.86, 134.04; MS (m/z) 168 (20, M^+), 153 (49), 129 (100), 111 (10), 84 (17), 68 (19); HRMS for $\text{C}_9\text{H}_{17}\text{O}_2\text{B}$ calcd 168.1483, found 168.1303.

2-Methyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-1-propene (Table 2, entry 4): IR (neat) 2980, 1648, 1326, 1145, 846 cm^{-1} , ^1H NMR (CDCl_3) δ 1.26 (s, 12 H), 1.72 (s, 2 H), 1.77 (s, 3 H), 4.6-4.7 (m, 2 H); ^{13}C NMR (CDCl_3) δ 24.45, 24.72, 83.24, 110.16, 142.85; MS (m/z) 182 (14, M^+), 167 (28), 125 (100), 82 (44), 55 (61); HRMS for $\text{C}_{10}\text{H}_{19}\text{O}_2\text{B}$ calcd 182.1478, found 182.1468.

(E)-1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2-butene (Table 2, entry 5 and 6). The assignment of configuration was determined by ^{13}C NMR data.¹⁵ IR (neat) 2980, 1356, 1326, 1145, 967 cm^{-1} , ^1H NMR (CDCl_3) δ 1.25 (s, 12 H), 1.6-1.7 (m, 5 H), 5.4-5.5 (m, 2 H); ^{13}C NMR (CDCl_3) δ 18.06, 24.76, 83.14, 125.31, 125.84; MS (m/z) 182 (6, M^+), 167 (20), 140 (5), 125 (34), 83 (100), 82 (30), 55 (45); HRMS for $\text{C}_{10}\text{H}_{19}\text{O}_2\text{B}$ calcd 182.1478, found 182.1457.

3-Methyl-1-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-2-butene (Table 2, entry 7): IR (neat) 2980, 1648, 1340, 1147, 850 cm^{-1} , ^1H NMR (CDCl_3) δ 1.24 (s, 12 H), 1.5-1.6 (m, 5 H), 1.69 (s, 3 H), 5.23 (t, J = 7.8 Hz, 1 H); ^{13}C NMR (CDCl_3) δ 17.62, 24.74, 25.68, 83.06, 118.48, 131.47; MS (m/z) 196 (21, M^+), 181 (12), 139 (42), 96 (32), 84 (100), 69 (70), 55 (34); HRMS for $\text{C}_{11}\text{H}_{21}\text{O}_2\text{B}$ calcd 196.1634, found 196.1629.

3-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)cyclohexene (Table 2, entry 8): IR (neat) 2980, 2929, 1361, 1317, 1145, 738, 656, cm^{-1} , ^1H NMR (CDCl_3) δ 1.24 (s, 12 H), 1.6-1.8 (m, 5 H), 1.9-2.0 (m, 2 H), 5.6-5.7 (m, 2 H); ^{13}C NMR (CDCl_3) δ 22.50, 24.08, 24.63, 24.96, 83.10, 126.01, 127.56; MS (m/z) 208 (6, M^+), 193 (13), 151 (7), 108 (20), 84 (100), 81 (40); HRMS for $\text{C}_{12}\text{H}_{21}\text{O}_2\text{B}$ calcd 208.1635, found 208.1656.

Reaction of allylplatinum complex with pinacolborane (eq. 6).

A mixture of $[(C_3H_5)_3PtCl]_4$ (0.0125 mmol), $AsPh_3$ (0.1 mmol), **2** (0.25 mmol), and Et_3N (0.25 mmol) in toluene (1 ml) was stirred at 50 °C for 16 h. GLC analysis of the reaction mixture indicated formation of the corresponding allylboronate **3b**.

Synthesis of homoallyl alcohols (eq. 7).

To the solution of allylboronate **3**, prepared *in situ* from **2** (2.0 mmol), benzaldehyde (1.0 mmol) was added, and the resulting mixture was stirred at room temperature for 24 h. After addition of triethanolamine (1.5 mmol), the mixture stirred for 12 h. The mixture was diluted with ether, washed with water, and dried ($MgSO_4$). The product was isolated by Kugelrohr distillation.

The following compounds were prepared by the above procedure.

4-Phenyl-1-propen-4-ol: IR (neat) 3393, 2361, 1456, 1048, 916, 758, 700 cm^{-1} ; 1H NMR ($CDCl_3$) δ 2.07 (d, $J = 2.9$ Hz, 1 H), 2.5-2.6 (m, 2 H), 4.73 (ddd, $J = 8.1, 5.2, 2.9$ Hz, 1 H), 5.1-5.2 (m, 2 H), 5.7-5.8 (m, 1 H), 7.3-7.4 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 43.81, 74.27, 118.39, 125.78, 127.52, 128.39, 134.43, 143.84; MS (m/z) 148 (1, M^+), 131 (2), 117 (1), 107 (100), 104 (1), 90 (1), 77 (51); HRMS for $C_{10}H_{12}O$ calcd 148.0888, found 148.0852.

(3S*, 4S*)-4-Hydroxy-3-methyl-4-phenylbutene: 1H NMR ($CDCl_3$) δ 0.87 (d, $J = 7.0$ Hz, 3 H), 2.16 (s, 1 H), 2.4-2.5 (m, 1 H), 4.36 (d, $J = 7.6$ Hz, 1 H), 5.1-5.2 (m, 2 H), 5.81 (ddd, $J = 18.3, 10.1, 8.2$ Hz, 1 H), 7.2-7.4 (m, 5 H); ^{13}C NMR ($CDCl_3$) δ 43.81, 74.27, 118.39, 125.78, 127.52, 128.39, 134.43, 143.84. The assignment of configuration and isomeric purity were determined by 1H NMR data.¹⁵ **(3R*, 4S*)**-isomer showed a doublet of the methyl proton at 0.98 ppm (d, $J = 7.0$ Hz).

References

1. (a) Hoffmann, R. W.; Zeiss, H. -J. *Angew. Chem., Int. Ed. Engl.* 1979, 18, 306. (b) For a review, see: Hoffmann, R. W. *Angew. Chem., Int. Ed. Engl.* 1982, 21, 555.
2. (a) Brown, H. C.; Bhat, K. S.; Randad, R. S. *J. Org. Chem.* 1989, 54, 1570. (b) Roush, W. R.; Banfi, L.; Park, J. C.; Hoong, L. K. *Tetrahedron Lett.* 1989, 30, 6457. (c) Roush, W. R.; Walts, A. E.; Hoong, L. K. *J. Am. Chem. Soc.* 1985, 107, 8186. (d) Roush, W. R.; Palkowitz, A. D.; Ando, K.; *J. Am. Chem. Soc.* 1990, 112, 6348.
3. For examples, see: (a) Schlosser, M.; Rauchschwalb, G. *J. Am. Chem. Soc.* 1978, 100, 3258. (b) Brown, H. C.; DeLue, N. R.; Yamamoto, Y.; Maruyama, K.; Kasahara, T.; Murahashi, S. -I. *J. Org. Chem.* 1977, 42, 4088. (c) Watanabe, T.; Miyaura, N.; Suzuki, A. *J. Organomet. Chem.* 1993, 444, C1.
4. (a) Ishiyama, T.; Ahiko, T. -a.; Miyaura, N. *Tetrahedron Lett.* 1996, 37, 6889. (b) Ahiko, T. -a.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* 1997, 811.
5. Kimura, M.; Kiyama, I.; Tomizawa, T.; Horino, Y.; Tanaka, S.; Tamaru, Y. *Tetrahedron Lett.* 1999, 40, 6795.
6. (a) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 2000, 65, 164. (c) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *Synthesis* in press.
7. For the palladium-catalyzed reduction of organic halides, see: (a) Egli, R. A. *Helv. Chim. Acta* 1968, 51, 2090. (b) Hutchins, R. O.; Learn, K. *J. Org. Chem.* 1982, 47, 4380. (c) Lipshutz, B. H.; Buzard, D. J.; Vivian, R. W. *Tetrahedron Lett.* 1999, 40, 6871.
8. Farina, V.; Krishnan, B. *J. Am. Chem. Soc.* 1991, 113, 9585.
9. (a) Parks, D. J.; von h. Spence, R. E.; Piers, W. E. *Angew. Chem., Int. Ed. Engl.* 1995, 34, 809. (b) Iverson, C. N.;

- Smith, M. R., III *J. Am. Chem. Soc.* 1999, 121, 7696.
10. Lukas, J.; Blom, J. E. *J. Organomet. Chem.* 1971, 26, C25.
 11. Cherwinski, W. J.; Johnson, B. F. G.; Lewis, J. J. *Chem. Soc., Dalton Trans.* 1974, 1405.
 12. Ukai, T.; Kawazura, H.; Ishii, Y. *J. Organomet. Chem.* 1974, 65, 253.
 13. Sakakibara, M.; Takahashi, Y.; Sakai, S.; Ishii, Y. *J. Chem. Soc., Chem. Commun.* 1969, 396.
 14. Ford, M. C.; Waters, W. A. *J. Chem. Soc.* 1952, 2240.
 15. Hoffman, R. W.; Zeib, H.-J. *J. Org. Chem.* 1981, 46, 1309.

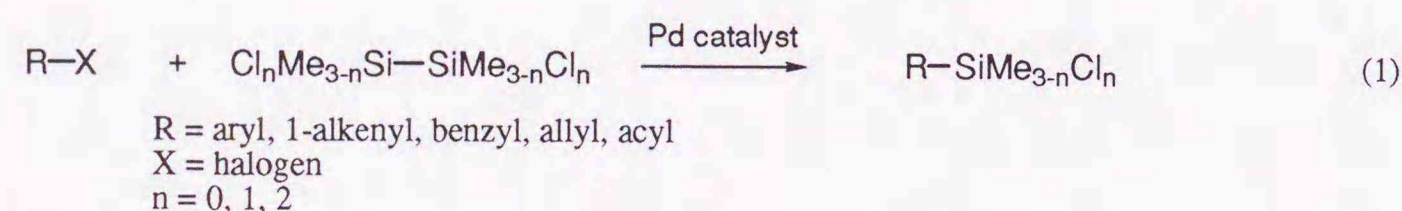
Chapter 6.

Palladium(0)-Catalyzed Silylation of Aryl Halides with Hydrosilane: Selective Formation of Carbon-Silicon Bond

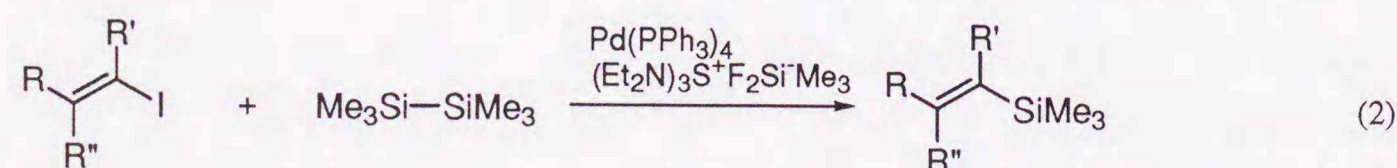
The specific silylation of aryl halides and triflates containing an electron-donating group (4-Cl, 4-Me, 4-MeO, 4-AcO, 4-AcNH, 4-Me₂N) with hydrosilanes in the presence of *i*-Pr₂NEt and catalytic amounts of Pd₂(dba)₃•CHCl₃ and P(*o*-tol)₃ provides the corresponding arylsilanes in high yield. The silylation of aryl bromides and triflates was achieved with the aid of additional KI.

Introduction

Organosilicon compounds are valuable intermediates in organic synthesis and materials science. Accordingly, much attention has been paid to their synthesis.¹ Among others, the catalytic cross-coupling reaction of organic electrophiles using disilanes as a silyl anion equivalent has proven to be a versatile method for synthesizing functionalized organosilanes as arylsilanes,² vinylsilanes,³ allylsilanes,⁴ benzylsilanes,⁵ and acylsilanes⁶ (eq. 1). However, the low reactivity of disilanes requires usually drastic conditions and therefore limited its synthetic application.

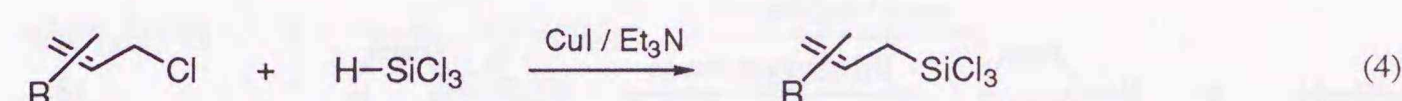
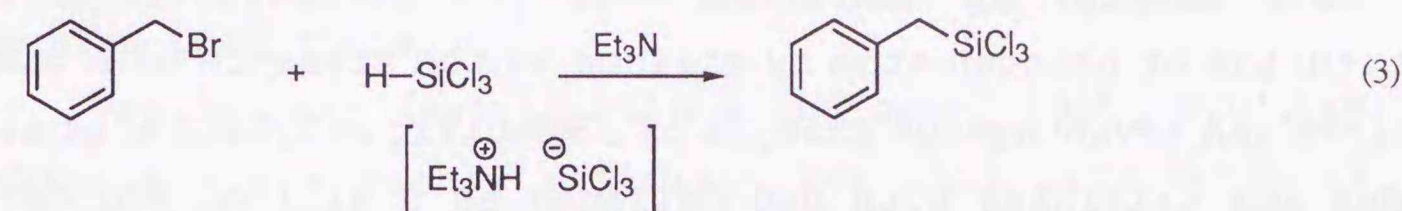


Hiyama and his colleagues have found that fluoride ion induces the cleavage of Si-Si bond of hexamethyldisilane under extremely mild conditions to produce metal-free silyl anion species.⁷ They developed the palladium-catalyzed silylation of vinyl halides by using tris(diethylamino)sulfonium difluoro(trimethyl)silicate TASF (eq. 2).⁸ However, it was only possible to obtain vinylsilanes.

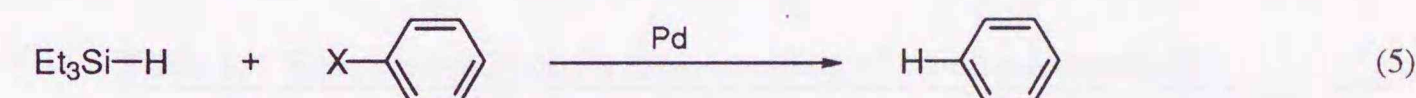


In related silyl anion systems, Benkeser postulated that a silyl anion species $\text{Cl}_3\text{Si}^-\bullet\text{Et}_3\text{NH}^+$ was generated by the Et_3N -hydrosilane combination.⁹ It is known that the $\text{Cl}_3\text{SiH-Et}_3\text{N}$ combination greatly facilitates the silylation of allyl¹⁰ or benzyl

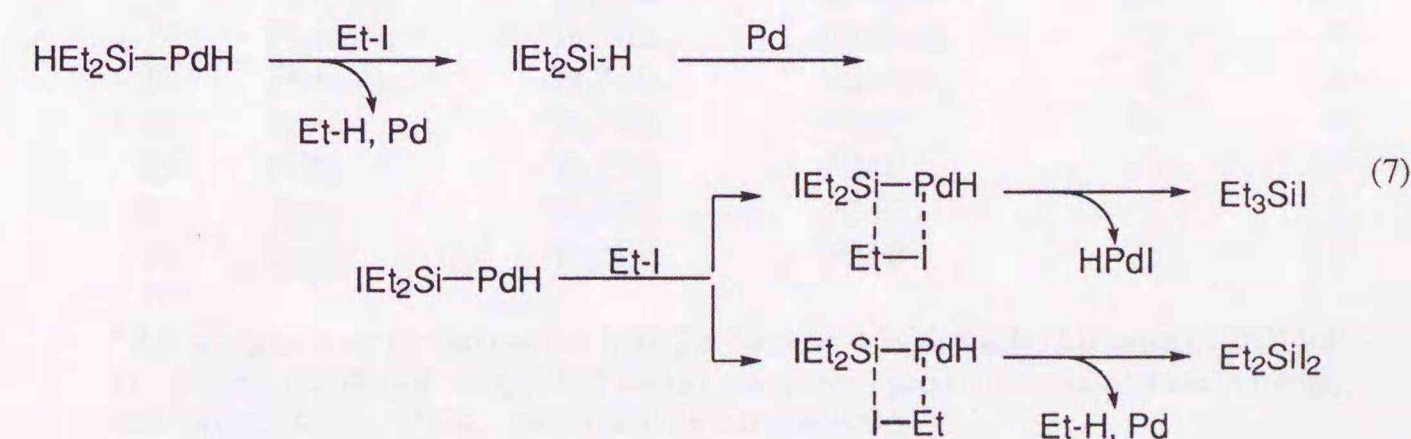
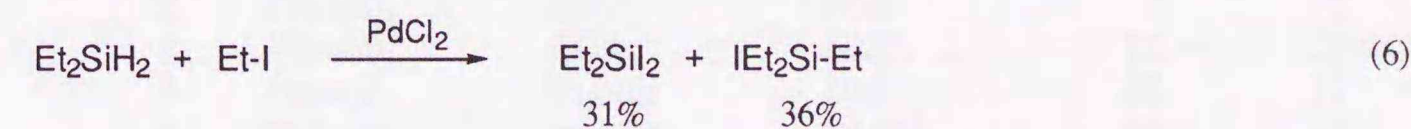
chlorides (eq. 3 and 4).⁹ However, it is impossible to obtain aryl- or vinylsilanes with satisfactory yields because nucleophilic substitutions proceed so slowly at an sp^2 carbon.



It is well-known that palladium complexes are highly effective catalyst of an aromatic substitution of aryl halides with nucleophiles. To our knowledge, however, there has been no report of palladium-catalyzed silicon- sp^2 carbon bond formation using hydrosilane derivatives with high chemical selectivity. Generally, in the presence of a palladium catalyst, such hydrosilanes greatly facilitate the hydrogenolysis of organic electrophiles (eq. 5).¹¹

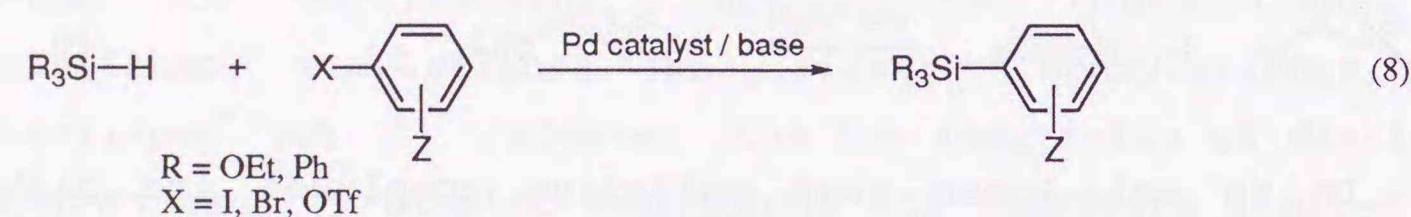


However, Kunai has recently reported on a PdCl_2 -catalyzed Si-H / C-I exchange reaction that formed an Si-I bond as well as an Si-C bond (eq. 6),¹² indicating the potential use of hydrosilanes not



only as reductant but also as silylating reagents in the presence of palladium catalyst. A mechanism which involved not a silicon nucleophile but a σ -bond metathesis between an Si-Pd bond and a C-I bond, has been postulated (eq. 7), though.

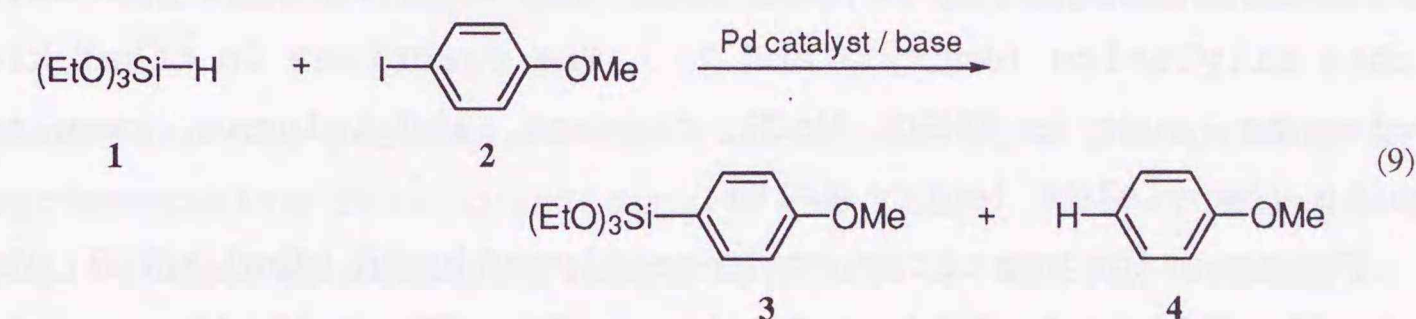
This chapter is concerned with the palladium-catalyzed substitution of halogen atom by silicon in the presence of a base. The first and advantageous example of a specific silylation of aryl halides and triflates with hydrosilanes as a silicon source is described (eq. 8).



Results and Discussion

Reaction Conditions.

Preliminary investigations indicated that $(\text{EtO})_3\text{SiH}$ 1 as hydrosilane was highly efficient for this silylation of aryl iodides.



The results of the reaction of 4-iodoanisole 2 with 1.5 equiv of $(\text{EtO})_3\text{SiH}$ 1 for 1 h at room temperature under various conditions are listed in Table 1. The products were contaminated with the normal cross-coupling product,¹² anisole 4, in each case as a result of a hydridic behavior of 2. Although we were unable to completely

Table 1. Reaction condition for cross-coupling of 1 with 4-iodoanisole^a

entry	ligand	base	solvent	yield (%) ^b	
				3	4
1	P(<i>o</i> -tol) ₃	none	NMP	5	4
2	P(<i>o</i> -tol) ₃	Et ₃ N	NMP	88	6
3	P(<i>o</i> -tol) ₃	^t Pr ₂ NEt	NMP	92	7
4	P(<i>o</i> -tol) ₃	pyridine	NMP	4	5
5	P(<i>o</i> -tol) ₃	DBU	NMP	0	2
6	P(<i>o</i> -tol) ₃	KOAc	NMP	72	23
7	P(<i>o</i> -tol) ₃	^t Pr ₂ NEt	DMF	82	17
8	P(<i>o</i> -tol) ₃	^t Pr ₂ NEt	DMSO	31	19
9	P(<i>o</i> -tol) ₃	^t Pr ₂ NEt	dioxane	5	4
10	P(<i>o</i> -tol) ₃	^t Pr ₂ NEt	toluene	6	5
11	none	^t Pr ₂ NEt	NMP	89	8
12	PPh ₃	^t Pr ₂ NEt	NMP	76	19
13	dppe	^t Pr ₂ NEt	NMP	0	1
14	dppf	^t Pr ₂ NEt	NMP	25	11

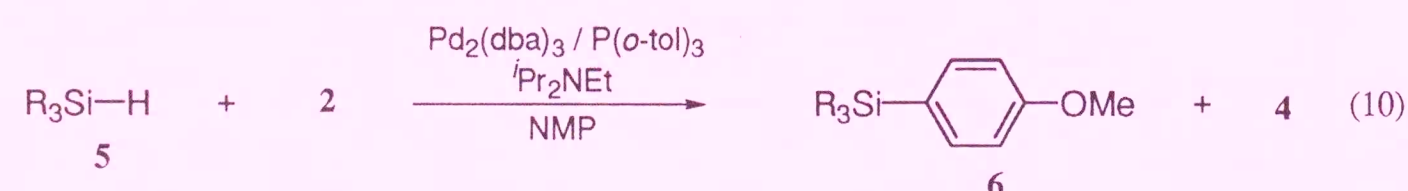
^a All reactions were carried out at r. t. for 2 h by using 4-iodoanisole (1.0 mmol), $(\text{EtO})_3\text{SiH}$ (1.5 mmol), $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (0.015 mmol), phosphine ligand (0.06 mmol), base (3 mmol), and solvent (4 mL). ^b GLC yield based on 4-iodoanisole.

control the selectivity of the products, the $(\text{EtO})_3\text{SiH}$ -base combination provided the predominant formation of 4-triethoxysilylanisole 3. As for the base, the tertiary amines, such as Et_3N and $i\text{-Pr}_2\text{NEt}$, proved to be highly effective (entry 2 and 3). In the absence of a base or in the presence of other types of bases, the reactions occurred insufficiently (entry 1, 4-6), even though the cited simultaneous silylation and reduction of alkyl iodides using Et_2SiH_2 was caused in the absence of base.¹¹ The use of amide solvents, such as NMP, DMF, and DMA, is also essential for this silylation (entry 3 and 7). The reactions in other kind of solvents, such as DMSO, MeCN, dioxane, and toluene, resulted in quite low yields (entry 8-10).

The reaction was efficiently catalyzed by $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ with 2 equiv (for Pd atom) of $\text{P}(o\text{-tol})_3$ (entry 3). The palladium complex having bulky phosphines may effectively accelerate the oxidative addition step by ready formation of a coordinatively unsaturated species.¹³ The ratio of $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ to a phosphine ligand affected the rate of the silylation; that is, more than 2 equiv of $\text{P}(o\text{-tol})_3$ slowed down the reaction rate extremely. And the monodentate phosphine ligand was recognized to be more effective than the bidentate ligand (entry 13 and 14).

Silylation of 4-iodoanisole with representative hydrosilanes.

It is known that the $\text{Cl}_3\text{SiH-Et}_3\text{N}$ combination greatly facilitates the silylation of allyl¹⁰ or benzyl chlorides.⁹ However, the present use of Cl_3SiH was not suitable in the presence of palladium complex, under which condition it merely recovered the starting aryl halide.



It is well-known that the reactivity of hydrosilane strongly is dependent on substituents on the silicon atom. Table 2

Table 2. Silylation of 2 with trialkylsilanes^a

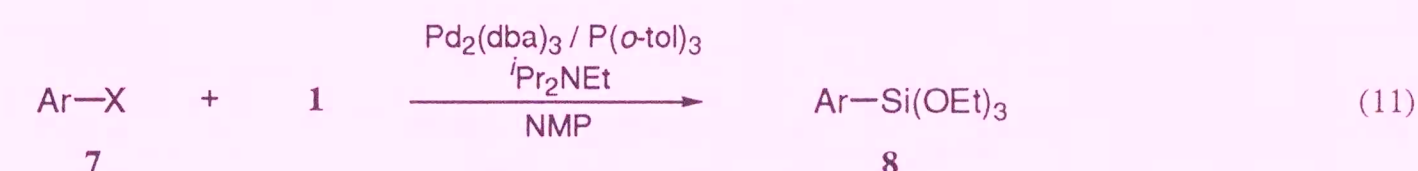
entry	5	yield (%) ^b	
		6	4
1	Et_3SiH (5a)	44	46
2	Me_2PhSiH (5b)	(34)	57
3	MePh_2SiH (5c)	(79)	18
4	Ph_3SiH (5d)	(64)	33

^a All reactions were carried out at r. t. for 2 h by using 4-iodoanisole (1.0 mmol), hydrosilanes (1.5 mmol), $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (0.015 mmol), $\text{P}(o\text{-tol})_3$ (0.06 mmol), $i\text{Pr}_2\text{NEt}$ (3 mmol), and NMP (4 mL). ^b GLC yields are based on 2. Yields in parentheses are isolated yields.

summarizes the results of the silylation of 4-iodoanisole 2 with representative trialkylsilanes 5 (eq. 10). The trialkylsilanes usually used as reducing reagents, such as Et_3SiH , tended to form a C-H bond in preference to a C-Si bond (entry 1).^{11, 12} The phenyl group on the silicon atom affected the selectivity. The silylation of 4-iodoanisole 2 using diphenylmethyilsilane Ph_2MeSiH 5c occurred predominately over reduction of 2 (entry 3).

Silylation of representative aryl halides with $(\text{EtO})_3\text{SiH}$.

Table 3 summarizes the results of the silylation of representative aryl halides 7 with 1, which was conducted in a manner similar to that above (eq. 11). Since the desired 3 and reduced arenes were purely and easily separated by bulb-to-bulb distillation, although the 8 were contaminated with arenes in each case, the present reaction should provide a simple and available procedure for synthesizing arylsilanes 8.



The rate of the silylation was also affected by the sort of aryl halides used; that is, aryl iodides 7 usually exhibited higher reactivity than aryl bromides (entry 1 and 2). The presence of functional groups such as MeCO_2 in the starting 7 did not interfere

with the outcome of the present reaction, since the reactants were inert to many functional groups (entry 5). However, although both aryl iodides **7** having electron-donating groups and heteroaromatic iodides were very readily silylated with **1** (entries 1, 3-7, 10, and 11), the presence of electron-withdrawing groups significantly decreased the yields and the selectivity of this silylation (entry 8 and 9). Namely, aryl iodides having the latter groups had a strong tendency to produce competitively reduced arenes (52 and 60%, GLC yields) as a result of the respective acceleration both of the oxidative addition to form an $\text{Ar-Pd}^{\text{II}}\text{-X}$ and the following

Table 3. Reaction of Representative **7** with **1**^a

entry	aryl halide 7	time (h)	product 8	yield (%) ^b
1		1		83
2		16		9 ^c
3		1		(81)
4		1		(72)
5		1		(77)
6		1		(82)
7		4		(72)
8		16		23
9		16		20
10		1		(84)
11		1		(56) ^d

^a All reactions were carried out at r. t. for 2 h by using **7** (1.0 mmol), **1** (1.5 mmol), $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (0.015 mmol), $\text{P}(o\text{-tol})_3$ (0.06 mmol), Pr_2NEt (3 mmol), and NMP (4 mL). ^b GLC yields are based on **7**. Yields in parentheses are isolated yields. ^c At 50 °C. ^d At 80 °C

transmetalation with the hydride.¹⁴

Reaction Mechanism.

Bearing in mind the previously described result,¹⁵ a hydrosilane as well as an aryl halide can add oxidatively to palladium(0) complexes. Chatgililoglu presented that the organic halides were the first to be added oxidatively to the palladium(0) complexes, forming a $\text{R-Pd}^{\text{II}}\text{-X}$ intermediate in preference to the hydrosilane.¹² Benkeser proposed that a silyl anion species was generated by the Et_3N -hydrosilane system.⁹ It is believed that transmetalation between an $\text{R-Pd}^{\text{II}}\text{-X}$ and a silyl anion analog provides the formation of an Si-C bond.⁸ However, the present treatment of isolated $\text{Ar-Pd}^{\text{II}}\text{-X}$ with $(\text{EtO})_3\text{SiH}$ **1** and Et_3N gave neither arylsilane nor reduced by-product. To a solution of $(4\text{-MeO-C}_6\text{H}_4)\text{PdI}(\text{PPh}_3)_2$ (0.050 mmol) in DMF (1 mL) was added Et_3N (0.30 mmol) and $(\text{EtO})_3\text{SiH}$ (0.098 mmol). After being stirred at 50 °C for 6 h, the GLC analysis indicated neither the formation of the corresponding **3** nor that of **4**. Consequently, a mechanism involving oxidative addition of aryl halides can effectively be ruled out in the present reaction.

On the other hand, Kunai and Ishikawa proposed a mechanism for the Si-H / C-I exchange involving oxidative addition of the hydrosilane followed by σ -bond metathesis between an Si-Pd bond and a C-I bond.¹¹ In analogy with this mechanism, the oxidative addition

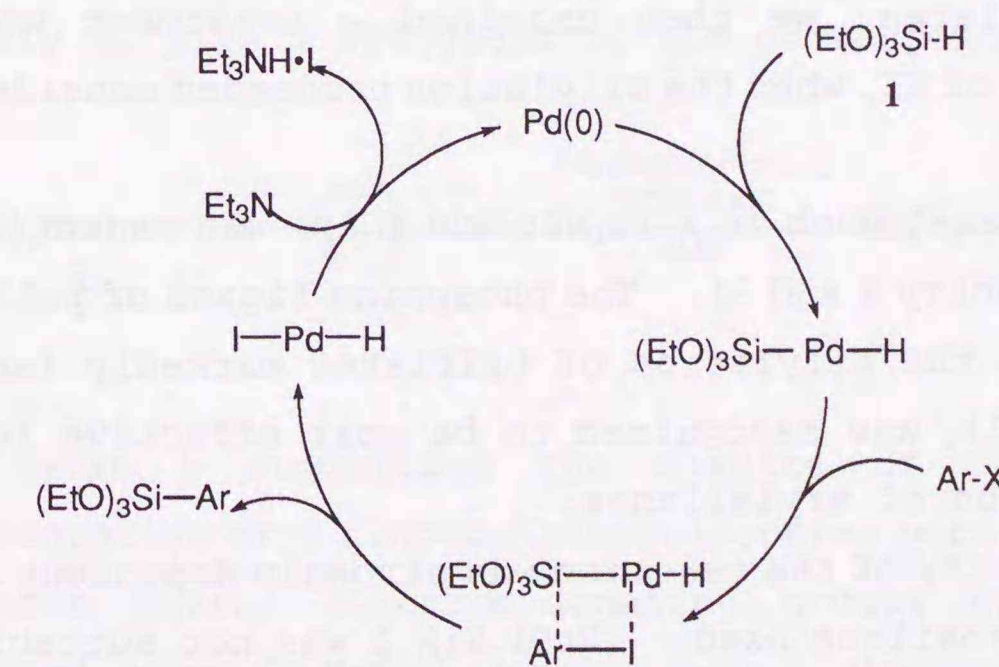


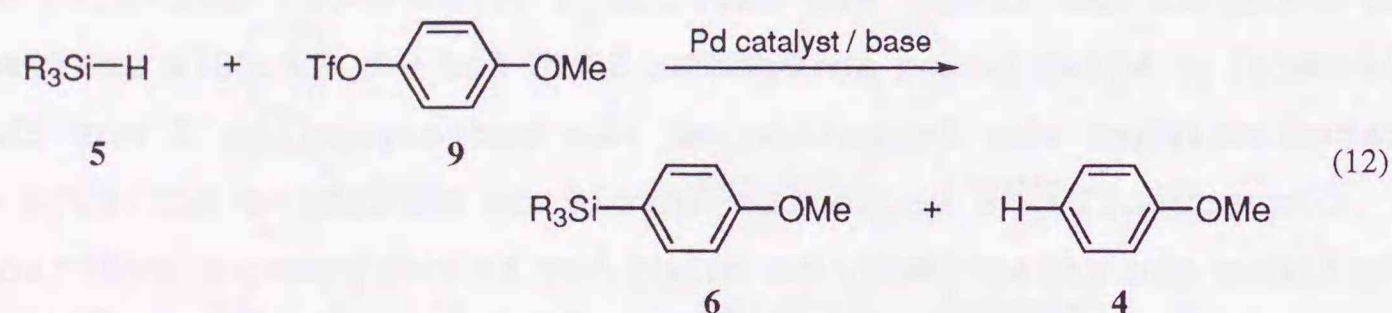
Figure 1. Catalytic Cycle

of $(\text{EtO})_3\text{SiH}$ 1 must be a key step in the present silylation.

As shown by Figure 1, it may be possible that the borane first adds to the palladium(0) and then the metathesis of the boryl-palladium complex with aryl halides takes place. The subsequent reductive elimination would furnish the $\text{Et}_3\text{NH}\cdot\text{X}$ along with the regeneration of the catalyst.

Silylation of aryl triflates.

In Table 4, the reaction of 4-methoxyphenyl trifluoromethanesulfonate ($X = \text{OSO}_2\text{CF}_3$) 9 with triethylsilane 5a under various conditions are summarized (eq.12). From the synthetic point of view, the use of aryl fluoroalkanesulfonates such as aryl triflates has some advantages, in part due to the easy access from phenols.¹⁶



However, the aryl triflate was not so reactive as the corresponding iodides (entry 1). Since the addition of metal halides have been used for palladium-catalyzed reaction of aryl and alkenyl triflates, we then examined a treatment with an additional 3 equiv of KI, when the silylation proceeded considerably (entry 2).

The use of base, such as *i*-Pr₂NEt and KOAc, was essential for this silylation (entry 2 and 3). The phosphine ligand of palladium catalyst affected the silylation of triflates markedly (entry 3 and 6-9). P(*o*-tol)₃ was recognized to be most effective for the selective formation of arylsilanes.

The selectivity of the reaction was strongly dependent on the nature of the hydrosilane used. $(\text{EtO})_3\text{SiH}$ 1 was not suitable for the silylation of aryl triflates, under which condition it merely

Table 4. Reaction condition for cross-coupling of **9** with **5**^a

entry	5	ligand	additive	base	solvent	yield (%) ^b	
						6	4
1	Et ₃ SiH (5a)	P(<i>o</i> -tol) ₃	none	^t Pr ₂ NEt	NMP	6	1
2		P(<i>o</i> -tol) ₃	KI	^t Pr ₂ NEt	NMP	46	31
3		P(<i>o</i> -tol) ₃	KI	KOAc	NMP	48	44
4		P(<i>o</i> -tol) ₃	LiI	KOAc	NMP	44	45
5		P(<i>o</i> -tol) ₃	Bu ₄ Nl	KOAc	NMP	43	51
6		dppf	KI	KOAc	NMP	0	0
7		PPh ₃	KI	KOAc	NMP	0	5
8		PCy ₃	KI	KOAc	NMP	0	1
9		none	KI	KOAc	NMP	1	24
10		P(<i>o</i> -tol) ₃	KI	KOAc	toluene	0	0
11		P(<i>o</i> -tol) ₃	KI	KOAc	dioxane	0	0
12	Me ₂ PhSiH (5b)	P(<i>o</i> -tol) ₃	KI	KOAc	NMP	36	52
13	MePh ₂ SiH (5c)	P(<i>o</i> -tol) ₃	KI	KOAc	NMP	(84)	16
14	Ph ₃ SiH (5d)	P(<i>o</i> -tol) ₃	KI	KOAc	NMP	(63)	23

^a All reactions were carried out at r. t. for 6 h by using 4-methoxyphenyl triflate **9** (1.0 mmol), R₃SiH **5** (1.5 mmol), Pd₂(dba)₃•CHCl₃ (0.015 mmol), phosphine ligand (0.12 mmol), base (3 mmol), and solvent (4 mL). ^b GLC yield based on **9**. Yields in parentheses are isolated yields.

afforded the reduction of 9. The phenyl group on the silicon atom affected the selectivity. The silylation of 4-methoxyphenyl triflate 9 with diphenylmethylsilane Ph_2MeSiH 5c resulted in high selectivity (entry 13).

The above reaction system was also effective for the silylation of aryl bromides (eq. 13). The silylation of 4-bromoanisole with 5c in the presence of KI (3 equiv) took place smoothly to give a 69% yield of the corresponding arylsilane.

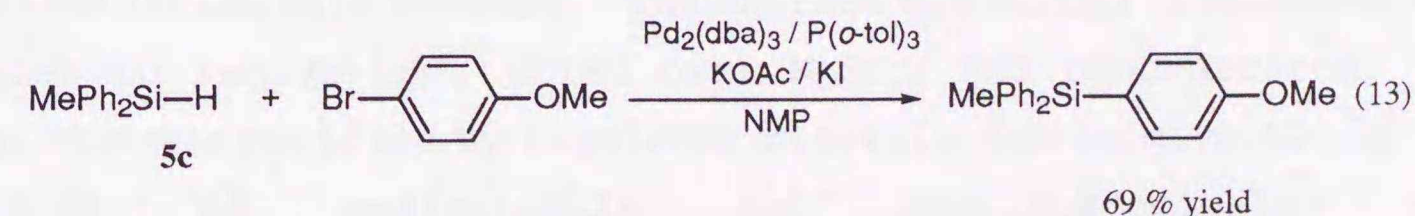
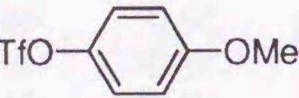
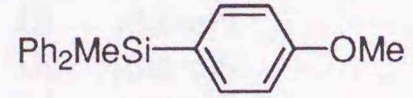
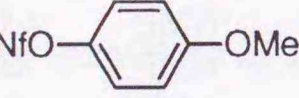
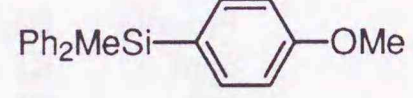
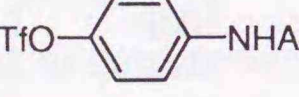
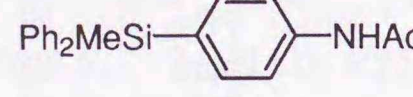
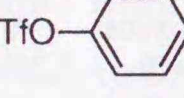
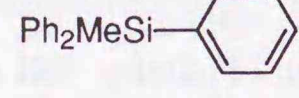
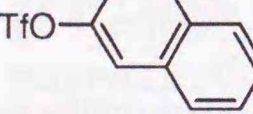
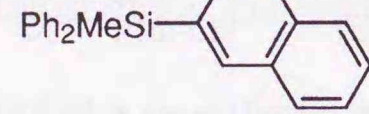


Table 5 summarizes the results of the silylation of representative aryl fluoroalkanesulfonates with Ph_2MeSiH 5c. Aryl triflates having electron-donating groups were very readily silylated with Ph_2MeSiH (entry 1-3). However, phenyl and 2-naphthyl triflates had a strong tendency to produce competitively

reduced arenes (entry 4 and 5).

Table 5. Reaction of Representative aryl triflates with 5c^a

entry	aryl triflate	time (h)	product	yield (%) ^b
1		6		84
2		6		83
3		6		72
4		6		55
5		6		53

^a All reactions were carried out at r.t. by using aryl triflates (1.0 mmol), 5c (1.5 mmol), Pd₂(dba)₃•CHCl₃ (0.015 mmol), P(*o*-tol)₃ (0.12 mmol), KI (3 mmol), KOAc (3 mmol), and NMP (4 mL). ^b Yields in parentheses are isolated yields.

Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. NMP was distilled from CaH₂ before use. Other solvents were purified as described in chapter 3. The salts from commercial sources were used without purification or drying. Pd₂(dba)₃•CHCl₃ was prepared by the established methods.¹⁷ Commercial hydrosilanes was used directly. All aryl iodides and bromides were purchased from Tokyo Kasei Kogyo Co. except for 4-iodobenzonitrile and 3-iodopyridine, which were prepared from the corresponding bromides by the known method.¹⁸ Aryl triflates were obtained from the corresponding phenols and trifluoromethanesulfonic anhydride.¹⁹

Synthesis of triethoxyphenylsilane²⁰ (Table 3, entry 1). **Typical procedure.** Triethoxyphenylsilane synthesis is used to illustrate the general procedure for synthesizing arylsilanes. To a solution of Pd₂(dba)₃•CHCl₃ (80 mg, 0.08 mmol) and P(*o*-tol)₃ (91 mg, 0.3 mmol) in NMP (20 mL) was added iodobenzene (1.00 g, 4.90 mmol), *i*-Pr₂NEt (2.6 mL, 15 mmol), and triethoxysilane (1.24 g, 7.5 mmol). After being stirred for 1 h at room temperature, the mixture was extracted with benzene. The extract was washed three times with water to remove NMP, dried over MgSO₄, and concentrated. The residue was purified by Kugelrohr distillation to give 846 mg (72% yield) of analytically and spectroscopically pure triethoxyphenylsilane: ¹H NMR (CDCl₃) δ 1.25 (t, *J* = 7.0 Hz, 9 H), 3.88 (q, *J* = 7.0 Hz, 6 H), 7.3-7.5 (m, 3 H), 7.6-7.8 (m, 2 H); ¹³C NMR (CDCl₃) δ 18.12, 58.68, 127.78, 130.22, 131.08, 134.74; MS (*m/z*) 240 (16), 195 (38), 181 (13), 162 (28), 147 (100), 139 (33), 135 (33); HRMS for C₁₂H₂₀O₃Si calcd 240.1182, found 240.1141.

The following compounds were prepared by the above procedure.

4-(Triethoxysilyl)anisole (eq. 9, Table 1):^{20c, d} IR (neat) 2975, 2360, 1598, 1567, 1506, 1459, 1390, 1282, 1250 cm⁻¹; ¹H NMR (CDCl₃) δ 1.24 (t, *J* = 7.0 Hz, 9 H), 3.86 (q, *J* = 7.0 Hz, 6 H), 6.92 (d, *J* = 8.6 Hz, 2 H), 7.61 (d, *J* = 8.6 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.12, 54.89, 58.55, 113.57, 122.00, 136.37, 161.37; MS (*m/z*) 270 (52), 255 (53), 225 (38), 211 (25), 181 (28), 169 (27), 149 (22), 147 (100), 135 (32); HRMS for C₁₃H₂₂O₄Si calcd 270.1287, found 270.1261.

4-(Triethylsilyl)anisole (Table 2, entry 1): ¹H NMR (CDCl₃) δ 0.76 (q, *J* = 8.0 Hz, 6 H), 0.95 (t, *J* = 8.0 Hz, 9 H), 3.81 (s, 3 H), 6.91 (d, *J* = 8.3 Hz, 2 H), 7.41 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 3.50, 7.40, 54.94, 113.44, 128.13, 135.55, 160.15; MS (*m/z*) 222 (10), 193 (58), 165 (53), 138 (13), 137 (100), 82 (12), 59 (36).

4-(Dimethylphenylsilyl)anisole (Table 2, entry 2): ¹H NMR (CDCl₃) δ 0.53 (s, 3 H), 3.81 (s, 3 H), 6.91 (d, *J* = 8.5 Hz, 2 H), 7.2-7.4 (m, 3H), 7.45 (d, *J* = 8.5 Hz, 2 H), 7.5-7.6 (m, 2 H); ¹³C NMR (CDCl₃) δ -2.20, 55.02, 113.60, 126.15, 127.77, 129.00, 133.06, 134.14, 135.65, 160.49; MS (*m/z*) 242 (19), 227 (100), 197 (2), 165 (6), 135 (5), 104 (11).

4-(Methyldiphenylsilyl)anisole (Table 2, entry 3): ¹H NMR (CDCl₃) δ 0.80 (s, 3 H), 3.81 (s, 3 H), 6.91 (d, *J* = 8.5 Hz, 2 H), 7.3-7.6 (m, 12 H); ¹³C NMR (CDCl₃) δ -3.21, 55.01, 113.63, 126.80, 127.79, 129.27, 135.21, 136.51, 136.75, 160.70; MS (*m/z*) 304 (24), 289 (100), 197 (5), 169 (5).

4-(Triphenylsilyl)anisole (Table 2, entry 4): ¹H NMR (CDCl₃) δ 3.82 (s, 3 H), 6.92 (d, *J* = 7.0 Hz, 2 H), 7.2-7.6 (m, 17 H); ¹³C NMR (CDCl₃) δ 55.02, 113.68, 127.83, 129.50, 134.98, 135.18, 136.35, 137.91, 160.85.

4-(Triethoxysilyl)-*N,N*-dimethylaniline (Table 3, entry 3):^{20c} IR (neat) 2973, 2884, 1600, 1517, 1389, 1360, 1167, 1077 cm⁻¹; ¹H NMR (CDCl₃) δ 1.23 (t, *J* = 7.0 Hz, 9 H), 2.97 (s, 3 H), 3.85 (q, *J* = 7.0 Hz, 6 H), 6.71 (d, *J* = 8.8 Hz, 2 H), 7.53 (d, *J* = 8.8 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.16, 39.90, 58.43, 111.57, 115.69, 135.96, 151.76; MS (*m/z*) 283 (100), 238 (12), 182 (8), 166 (13), 147 (29), 122 (12); HRMS for C₁₄H₂₅O₃NSi calcd 283.1604, found 283.1630.

4-(Triethoxysilyl)acetanilide (Table 3, entry 4): IR (neat) 3307, 2975, 1669, 1593, 1525, 1392, 1318, 1291 cm⁻¹; ¹H NMR (CDCl₃) δ 1.24 (t, *J* = 6.8 Hz, 9 H), 2.18 (s, 3 H), 3.85 (q, *J* = 6.8 Hz, 6 H), 7.52 (d, *J* = 8.3 Hz, 2 H), 7.64 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.18, 24.46, 58.71, 119.11, 128.64, 135.67, 140.10, 168.97; MS (*m/z*) 297 (10), 252 (68), 205 (100), 176 (31), 162 (15), 147 (48); HRMS for C₁₄H₂₃O₄NSi calcd 297.1396, found 297.1399.

4-Acetoxy(triethoxysilyl)benzene (Table 3, entry 5): IR (neat) 2976, 2887, 1767, 1593, 1499, 1392 cm⁻¹; ¹H NMR (CDCl₃) δ 1.22 (t, *J* = 6.8 Hz, 9 H), 2.28 (s, 3 H), 3.84 (q, *J* = 6.8 Hz, 6 H), 7.09 (d, *J* = 8.3 Hz, 2 H), 7.67 (d, *J* = 8.3 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.11, 20.98, 58.68, 120.98, 128.55, 136.06, 152.48, 169.00; MS (*m/z*) 298 (3), 256 (100), 210 (51), 183 (17), 155 (27), 147 (62); HRMS for C₁₄H₂₂O₅Si calcd 298.1237, found 298.1238.

4-(Triethoxysilyl)toluene (Table 3, entry 6):^{20c, d} IR (neat) 2975, 2926, 2360, 1604, 1443, 1390, 1295, 1167 cm⁻¹; ¹H NMR (CDCl₃) δ 1.24 (t, *J* = 7.0 Hz, 9 H), 2.36 (s, 3 H), 3.86 (q, *J* = 7.0 Hz, 6 H), 7.19 (d, *J* = 7.9 Hz, 2 H), 7.57 (d, *J* = 7.9 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.16, 21.50, 58.59, 127.41, 128.59, 134.82, 140.20; MS (*m/z*) 254 (23), 209 (38), 181 (5), 165 (16), 162 (30), 153 (19), 147 (100), 135 (17); HRMS for C₁₃H₂₂O₃Si calcd 254.1363, found 254.1338.

4-Chloro(triethoxysilyl)benzene (Table 3, entry 7):^{20d} IR (neat) 2975, 2888, 2360, 1699, 1583, 1557, 1485, 1443, 1389, 1296, 1261 cm⁻¹; ¹H NMR (CDCl₃) δ 1.17 (t, *J* = 7.0 Hz, 9 H), 3.79 (q, *J* = 7.0 Hz, 6 H), 7.28 (d, *J* = 8.5 Hz, 2 H), 7.54 (d, *J* = 8.5 Hz, 2 H); ¹³C NMR (CDCl₃) δ 18.12, 58.75, 128.06, 129.53, 136.13, 136.70; MS (*m/z*) 274 (3), 239 (27), 229 (44), 185 (15), 173 (25), 162 (31), 147 (100), 135 (9); HRMS for C₁₂H₁₉O₃ClSi calcd 274.0792, found 274.0792.

Ethyl 4-(Triethoxysilyl)benzoate (Table 3, entry 8): IR (neat) 2977, 2928, 2361, 1720, 1558, 1445, 1391, 1367, 1279, 1101 cm⁻¹; ¹H NMR (CDCl₃) δ 1.24 (t, *J* = 7.0 Hz, 9 H), 1.47 (t, *J* = 7.0 Hz, 3 H), 3.88 (q, *J* = 7.0 Hz, 6 H), 4.39 (q, *J* = 7.0 Hz, 2 H), 7.74 (d, *J* = 8.2 Hz, 2 H), 8.04 (d, *J* = 8.2 Hz, 2 H); ¹³C NMR (CDCl₃) δ

10.29, 14.16, 54.84, 56.96, 124.55, 128.05, 130.70, 132.94, 162.63; MS (m/z) 312 (5), 267 (100), 253 (15), 239 (61), 223 (16), 195 (22), 183 (17), 163 (25), 147 (20), 135 (8); HRMS for $C_{12}H_{20}O_3Si$ calcd 312.1393, found 312.1392.

4-(Triethoxysilyl)benzonitrile (Table 3, entry 9): IR (neat) 2977, 2231, 1444, 1390, 1296 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.25 (t, $J = 7.0$ Hz, 9 H), 3.88 (q, $J = 7.0$ Hz, 6 H), 7.65 (d, $J = 8.3$ Hz, 2 H), 7.78 (d, $J = 8.3$ Hz, 2 H); ^{13}C NMR ($CDCl_3$) δ 18.16, 59.04, 113.93, 131.12, 135.23, 137.88, 159.74; MS (m/z) 265 (43), 250 (17), 220 (100), 206 (46), 192 (20), 176 (34), 164 (62); HRMS for $C_{13}H_{19}O_3NSi$ calcd 265.1134, found 265.1144.

2-(Triethoxysilyl)thiophene (Table 3, entry 10):²¹ IR (neat) 2976, 2888, 1695, 1501, 1442, 1407, 1391, 1296, 1216, 1167 cm^{-1} ; 1H NMR ($CDCl_3$) δ 1.25 (t, $J = 7.0$ Hz, 9 H), 3.90 (q, $J = 7.0$ Hz, 6 H), 7.22 (dd, $J = 3.3, 4.5$ Hz, 1 H), 7.48 (d, $J = 3.3$ Hz, 1 H), 7.66 (d, $J = 4.5$ Hz, 1 H); ^{13}C NMR ($CDCl_3$) δ 19.42, 60.26, 129.37, 130.63, 133.15, 138.12; MS (m/z) 246 (52), 213 (6), 201 (34), 187 (7), 167 (7), 158 (13), 147 (100), 135 (34); HRMS for $C_{10}H_{18}O_3SiS$ calcd 246.0765, found 246.0746.

3-(Triethoxysilyl)pyridine (Table 3, entry 11):²² 1H NMR ($CDCl_3$) δ 1.26 (t, $J = 6.8$ Hz, 9 H), 3.90 (q, $J = 6.8$ Hz, 6 H), 7.2-7.3 (m, 1 H), 7.95 (d, $J = 5.9$ Hz, 1 H), 8.65 (d, $J = 4.9$ Hz, 1 H), 8.83 (s, 1 H); ^{13}C NMR ($CDCl_3$) δ 18.04, 58.80, 123.07, 126.55, 142.36, 151.05, 154.99; MS (m/z) 241 (54), 240 (100), 226 (18), 212 (27), 196 (88), 147 (29), 182 (25); HRMS for $C_{11}H_{19}O_3NSi$ calcd 241.1134, found 241.1112.

Silylation of aryl bromides and triflates (Table 4 and 5). A flask was charged with $Pd_2(dba)_3 \cdot CHCl_3$ (0.015 mmol), KOAc (3 mmol), KI (3 mmol), and NMP (4 mL) under an argon flow. Aryl bromides or triflates (1.0 mmol) and diphenylmethylsilane (1.5 mmol) were added successively, and the mixture was stirred at room temperature for 6 h. The reaction mixture was diluted with benzene, washed with water, and dried over $MgSO_4$. The solvent was evaporated and the product was isolated by column chromatography over silica gel.

4-(Methyldiphenylsilyl)acetanilide (Table 5, entry 3): 1H NMR ($CDCl_3$) δ 0.81 (s, 3 H), 2.17 (s, 3 H), 2.49 (s, 1H), 7.2-7.6 (m, 14 H); ^{13}C NMR ($CDCl_3$) δ -3.36, 24.67, 119.07, 127.83, 129.37, 135.21, 136.14.

Methyltriphenylsilane (Table 5, entry 4): 1H NMR ($CDCl_3$) δ 0.83 (s, 3 H), 7.2-7.8 (m, 15 H); ^{13}C NMR ($CDCl_3$) δ -3.40, 127.92, 129.37, 135.26, 136.09.

2-(Methyldiphenylsilyl)naphthalene (Table 5, entry 5): 1H NMR ($CDCl_3$) δ 0.83 (s, 3 H), 7.2-8.0 (m, 17 H).

References

- (1) Colvin, E. W. *Silicon Reagents in Organic Synthesis*; Academic: New York, 1988; pp 39. (b) Colvin, E. W. In *The Chemistry of the Metal-Carbon Bond*; Hartley, F. R., Patai, S., Eds.; Wiley: New York, 1987; Vol. 4, pp 562.
- (2) (a) Matsumoto, H.; Nagashima, S.; Yoshihiro, K.; Nagai, Y. *J. Organomet. Chem.* 1975, 85, C1. (b) Matsumoto, H.; Yoshihiro, K.; Nagashima, S.; Watanabe, H.; Nagai, Y. *J. Organomet. Chem.* 1977, 128, 409. (c) Matsumoto, H.; Shono, K.; Nagai, Y. *J. Organomet. Chem.* 1981, 208, 145. (d) Azarian, D.; Dua, S.; Eaborn, C.; Walton, D. R. M. *J. Organomet. Chem.* 1976, 117, C55.
- (3) Matsumoto, H.; Nagashima, S.; Kato, T.; Nagai, Y. *Angew. Chem., Int. Ed. Engl.* 1978, 17, 279.
- (4) (a) Matsumoto, H.; Yako, T.; Nagashima, S.; Motegi, T.; Nagai, Y. *J. Organomet. Chem.* 1978, 148, 97. (b) Lefort, M.; Simmonet, C.; Birot, M.; Dereris, G.; Dunogues, J.; Calas, R. *Tetrahedron Lett.* 1980, 21, 1857.
- (5) (a) Matsumoto, H.; Kasahara, M.; Matsubara, I.; Takahashi, M.; Nakano, T.; Nagai, Y. *Chem. Lett.* 1982, 399. (b) Nakano, T.; Takahashi, M.; Ashizawa, T.; Arai, T.; Seki, S.; Matsumoto, H.; Nagai, Y. *Chem. Lett.* 1982, 613. (c) Matsumoto, H.; Kasahara, M.; Matsubara, I.; Takahashi, M.; Arai, T.; Hasagawa, M.; Nakano, T.; Nagai, Y. *J. Organomet. Chem.* 1983, 250, 99. (d) Eaborn, C.; Griffiths, R. W.; Pidcock, A. *J. Organomet. Chem.* 1981, 225, 331.
- (6) Yamamoto, K.; Suzuki, S.; Tsuji, J. *Tetrahedron Lett.* 1980, 21, 1653.
- (7) (a) Hiyama, T.; Obayashi, M. *J. Org. Chem.* 1983, 48, 912. (b) Hiyama, T.; Obayashi, M. *Tetrahedron Lett.* 1983, 24, 4109. (c) Hiyama, T.; Obayashi, M.; Sawahara, M. *Tetrahedron Lett.* 1983, 24, 4113.
- (8) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* 1987, 28, 4715.
- (9) Benkeser, R. A.; Gaul, J. M.; Smith, W. E. *J. Am. Chem. Soc.* 1969, 91, 3666.
- (10) Furuya, N.; Sukawa, T. *J. Organomet. Chem.* 1975, 96, C1.
- (11) Boukherroub, R.; Chatgililoglu, C.; Manuel, G. *Organometallics* 1996, 15, 1508 and references cited therein.
- (12) Kunai, A.; Sakurai, T.; Toyoda, E.; Ishikawa, M.; Yamamoto, Y. *Organometallics* 1994, 13, 3233.
- (13) Farina, V.; Krishnan, B. *J. Am. Chem. Soc.* 1991, 113, 9585.
- (14) (a) Echavarrene, A. M.; Stille, J. K. *J. Am. Chem. Soc.* 1988, 110, 1557. (b) Baillargeon, V. P.; Stille, J. K. *J. Am. Chem. Soc.* 1986, 108, 452.
- (15) For a recent review of Pd-catalysed hydrosilylation, see: Horn, K. A. *Chem. Rev.* 1995, 95, 1317.
- (16) (a) Rottlander, M.; Knochel, P. *J. Org. Chem.* 1998, 63, 203. (b) For a recent review for synthetic transformation of aryl triflates, see: Ritter, K. *Synthesis* 1993, 735.
- (17) Ukai, T.; Kawazura, H.; Ishii, Y. *J. Organomet. Chem.* 1974, 65, 253.
- (18) Takagi, K.; Hayama, N.; Okamoto, T. *Chem. Lett.* 1978, 191.
- (19) Stang, P. J.; Hanack, M.; Subramanian, L. R. *Synthesis* 1982, 85.
- (20) Chappelow, C. C.; Elliott, R. L.; Goodwin, J. T., Jr. *J. Org. Chem.* 1960, 25, 435. (b) Sobolevskii, M. V.; Kleshchevnikova, S. I.; Rumyantseva, E. I.; Abramova, E. A.; Dubrovskaya, G. A. *Plast. Massy* 1971, 9. (c) Lutskaa, A. E.; Abukhova, E. M.; Voronkov, M. G.; Alksne, V. *Teor. Eksp. Khim.* 1973, 9, 123. (d) Ernst, C. R.; Spialter, L.; Buell, G. R.; Wilhite, D. L. *J. Am. Chem. Soc.* 1974, 96, 5375. (e) Chuy, N. D.; Chvalovsky, V.; Schraml, J.; Magi, M.; Lippmaa, E. *Collect. Czech. Chem. Commun.* 1974, 40, 875.
- (21) Voronkov, M. G.; Zelchan, G. I.; Savushkina, V. I.; Tabenko, B. M.; Chernyshev, E. A. *Khim. Geterotsikl. Soedin.* 1976, 772.
- (22) Rubinsztain, S.; Zeldin, M.; Fife, W. K. *Synth. React. Inorg. Met. -Org. Chem.* 1990, 20, 495.

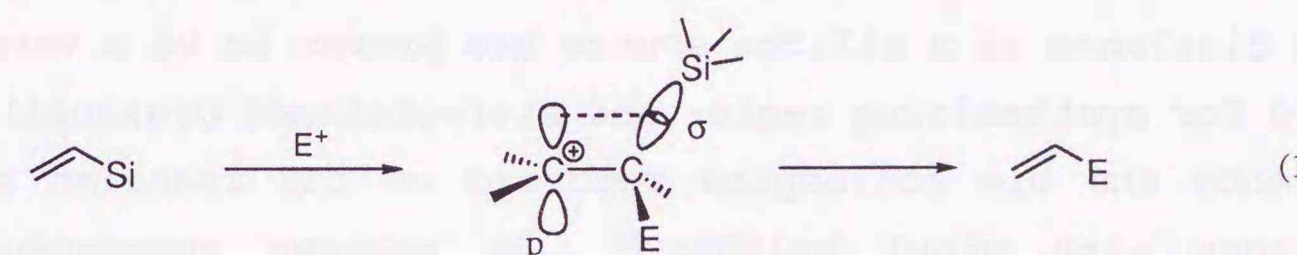
Chapter 7.

Synthesis of Alkenylsilanes via Palladium(0)-Catalyzed Silylation of Alkenyl Iodides with Hydrosilane

Various alkenyl iodides were silylated with hydrosilanes in the presence of KOAc and a catalytic amount of $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ to afford the corresponding regio- and stereodefined (*E*)-alkenylsilanes in high yields.

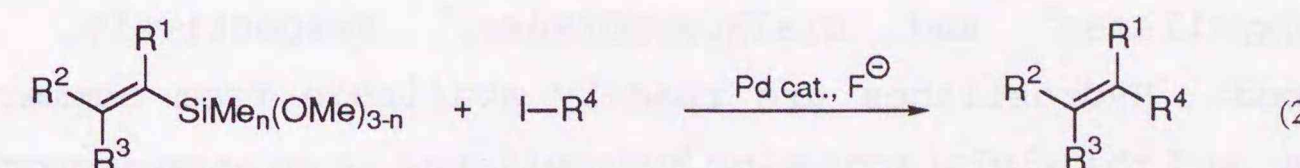
Introduction

Alkenylsilanes have been shown to be versatile intermediates in organic synthesis.¹ Since the organosilyl group is capable of stabilizing the carbocation β to silicon, the reaction of alkenylsilanes with electrophiles are facilitated with this stabilization of intermediate carbocations (eq. 1). This effect is believed to be attributable to the electron-donating property of the σ -bond between silicon and α -carbon atoms (σ -p conjugation).



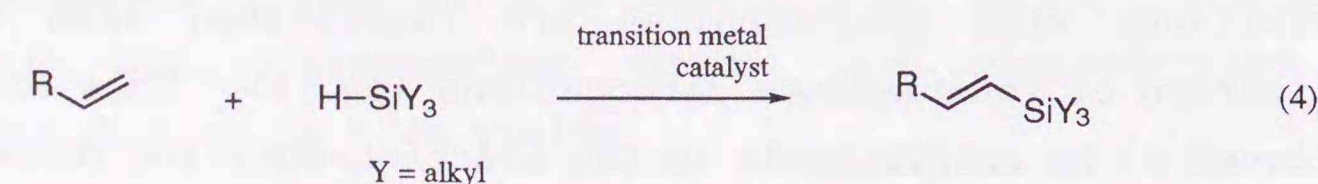
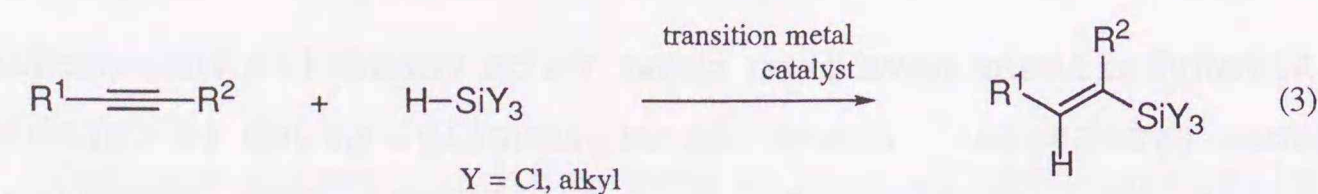
Alkenylsilicon compounds couple with organic halides in the presence of a fluoride ion promoter and a palladium catalyst. Electronegative groups, such as fluorine² and alkoxy group,³ on silicon atom is essential for the formation of a reactive pentacoordinated silicate.

This reaction is in general highly chemoselective and stereospecific (eq. 2). The alkenyl-alkenyl coupling proceeds with retention of configuration of both alkenylsilanes and alkenyl iodides to give (*E, E*)-, (*E, Z*)-, (*Z, E*)-, or (*Z, Z*)-dienes of high isomeric purity (>96%).

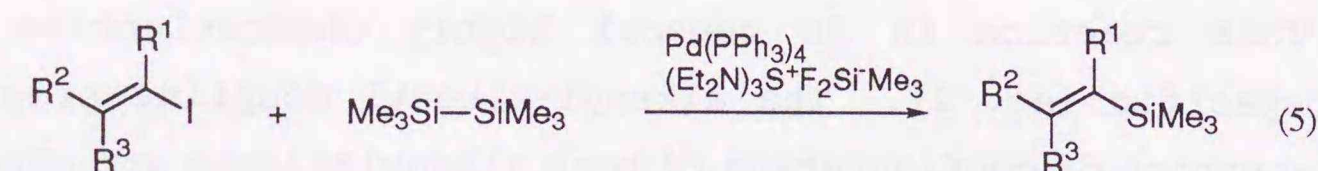


Various methods are available for their preparation.⁴ Most of these methods utilize alkynes (hydrosilylation of alkynes^{4a} or hydrogenation of silylacetylene), alkenes (dehydrogenative

silylation of alkenes^{4b}), or alkenyl halides (metalation followed by silylation) as starting materials. Among these methods, hydrosilylation of alkynes is the most popular.



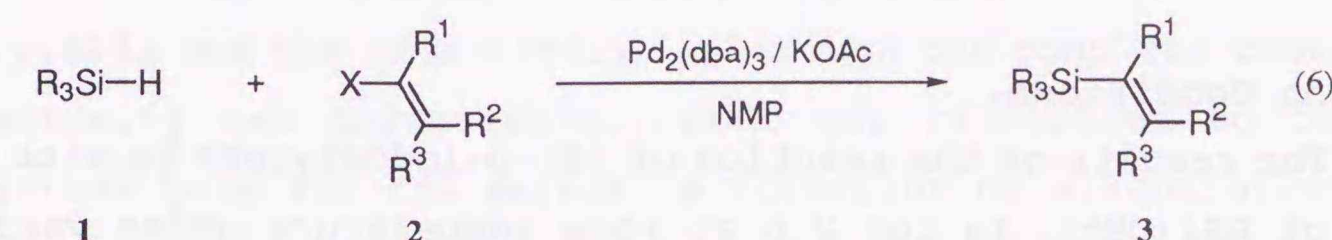
The catalytic cross-coupling reaction of organic halides using disilanes as a silicon source has proven to be a versatile method for synthesizing regio- and stereodefined organosilanes.⁵ Matsumoto and his colleagues reported on the reaction of the disilanes with vinyl halides.^{5a} To achieve successful the silylation, polychlorinated disilanes must be employed, as the electronegative substituent facilitates the transition-metal-catalyzed Si-Si bond cleavage. However, handling of the resulting chlorovinylsilanes is troublesome due to the moisture-sensitive character. Thus, Hiyama reported a useful variant (eq. 5).^{5b}



On the other hand, in previous chapters, palladium-catalyzed metalation reactions of organic halides utilizing trialkoxysilanes⁶ and dialkoxyboranes,⁷ respectively, were described. Hydrosilanes are readily available from commercial sources, and the silylation using hydrosilanes is an atom economical manner.

This chapter deals with a new and available synthetic route to alkenylsilanes. The author describes here a palladium(0)-catalyzed selective silylation of alkenyl iodides **2** with

hydrosilanes 1 to provide the corresponding alkenylsilanes 3 (eq 6).



Reaction Conditions.

$$\begin{array}{c}
 (\text{EtO})_3\text{Si}-\text{H} + \text{I}-\text{CH}=\text{CHPh} \longrightarrow \\
 \mathbf{1a} \qquad \qquad \mathbf{2a} \qquad \qquad \qquad (7) \\
 (\text{EtO})_3\text{Si}-\text{CH}=\text{CHPh} + (\text{EtO})_3\text{Si}-\text{CH}_2-\text{CH}_2\text{Ph} + \text{CH}=\text{CHPh} \\
 \mathbf{3a} \qquad \qquad \qquad \mathbf{4a} \qquad \qquad \mathbf{5a}
 \end{array}$$
Table 1. Reaction condition for silylation of **2a** with **1a**.^a

entry	base	solvent	yield (%) ^b		
			3a	4a	5a
1	KOAc	NMP	79	2	6
2 ^c	KOAc	NMP	40	1	5
3	K ₂ CO ₃	NMP	51	14	3
4	^t Pr ₂ NEt	NMP	22	30	8
5	Et ₃ N	NMP	6	9	14
6	KOAc	DMF	67	0	8
7	KOAc	toluene	0	0	2
8	KOAc	dioxane	0	0	1

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$$\text{Pd} + \text{N}(\text{CH}_2\text{CH}_3)_3 \longrightarrow \text{Pd}-\overset{\text{CH}_2\text{CH}_3}{\underset{\text{N}(\text{CH}_2\text{CH}_3)_2}{\text{N}}} \longrightarrow \text{Pd}-\text{H} \quad (8)$$
$$\text{R}_3\text{Si}-\text{H} + 2\text{a} \xrightarrow[\text{NMP}]{\text{Pd}_2(\text{dba})_3 / \text{KOAc}} \text{R}_3\text{Si}-\text{CH}=\text{CH}-\text{Ph} + \text{R}_3\text{Si}-\text{CH}_2\text{CH}_2-\text{Ph} + 5\text{a} \quad (9)$$
Table 2. Silylation of **2a** with various hydrosilanes **1**.^a

entry	hydrosilane 1	yield (%) ^b		
		3	4	5a
1	(EtO) ₃ Si-H (1a)	79	2	6
2	(MeO) ₂ MeSi-H (1b)	(60)	(5)	
3	Et ₃ Si-H (1c)	(61)	(9)	3
4	Ph ₂ MeSi-H (1d)	(72)	(11)	1
5	Ph ₃ Si-H (1e)	(69)	(8)	18

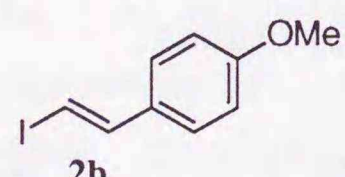
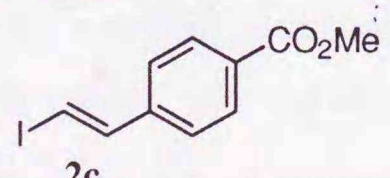
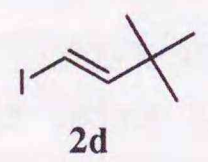
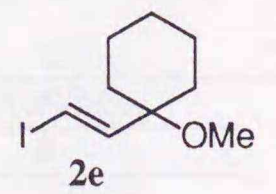
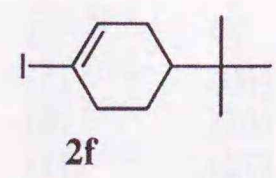
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hydrosilanes were not very significant in the present reaction (Table 2). It is interesting to note that the silylation with trialkylsilanes (1c-f) proceeded selectively in preventing the formation of 5, whereas commonly such hydrosilanes have been applied for the palladium-catalyzed reduction of organic halides (entries 3-5).^{7, 8} In the palladium-catalyzed silylation of aryl halides with hydrosilanes, Et₃SiH 1c was not suitable as a silylating reagent.

Silylation of representative alkenyl halides with (EtO)₃SiH.

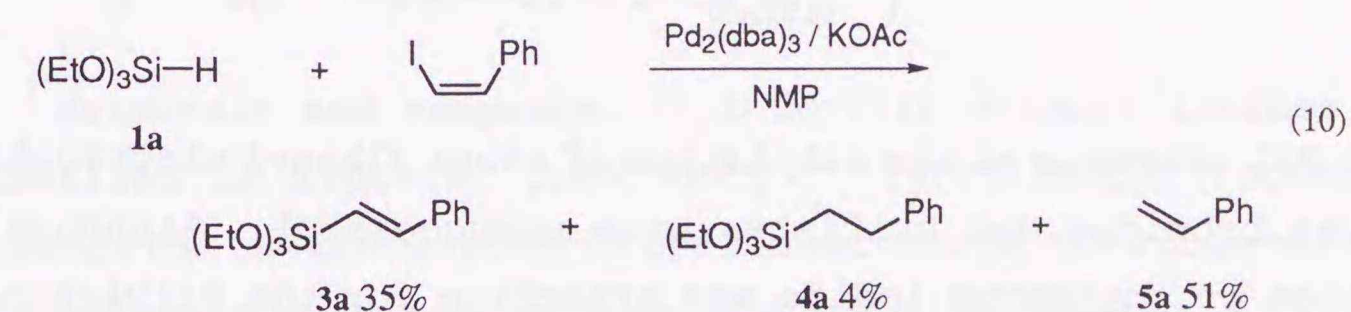
The representative results examined are listed in Table 3. Thus, a variety of (*E*)-alkenyl iodides 2 were silylated efficiently with HSi(OEt)₃ 1a to afford the desired (*E*)-alkenylsilanes 3 in high isolated yields in which 2, containing either electron-rich or

Table 3. Silylation of Representative 2 with 1a^a

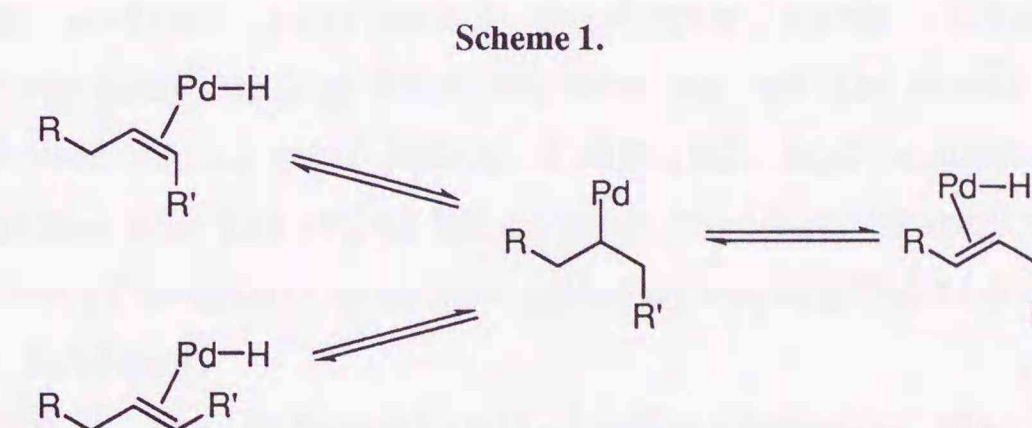
entry	alkenyl halide 2	yield (%) ^b	ratio (%) ^c	
			3	4
1		83	84	16
2		72	>99	
3		74	>99	
4		69	>99	
5		60	>99	

^a All reactions were conducted in NMP (4 mL) at room temperature for 2 h using 1a (1.5 mmol) and 2 (1.0 mmol) in the presence of Pd₂(dba)₃•CHCl₃ (0.015 mmol) and KOAc (3 mmol). ^b Isolated yields of a mixture of 3 and 4 were based on 2. ^c Determined by GLC and ¹H NMR analysis of isolated products.

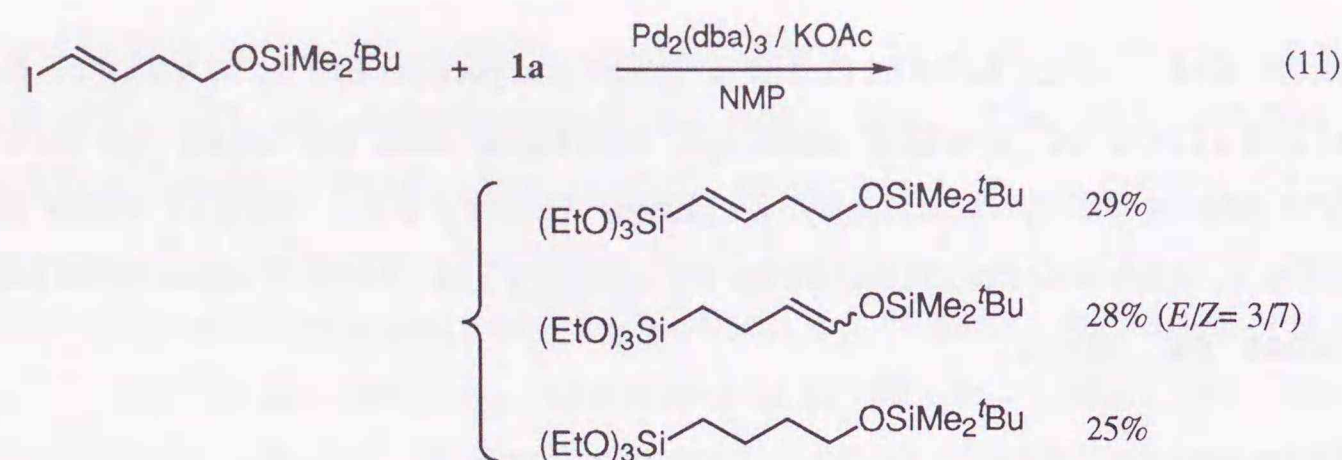
electron-deficient substituents, participated effectively. Also, the silylation of cyclic alkenyl halides can be used to achieve the synthesis of cycloalkenylsilanes (entry 5). In all runs shown in Table 3, the stereochemistry of alkenylsilanes 3 was consistent with that of (*E*)-2.



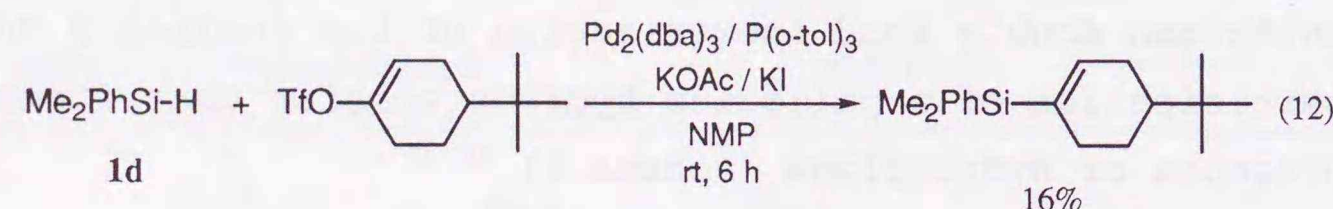
Unfortunately, in the case of using (*Z*)-β-iodostyrene, the inversion of starting geometry occurred to give (*E*)-3a along with 4a and 5a (eq. 10). Thus, the present silylation involved the carbon-carbon double bond isomerization of the desired 3 due to the participation of a palladium hydride species that formed in the presence of hydrosilane (Scheme 1).^{11, 12}



Also, the palladium-catalyzed silylation of alkenyl halides having hydrogen at allylic position with (EtO)₃SiH afforded several silylated products because of the carbon-carbon double bond isomerization. For example, the reaction of 1-iodo-4-siloxybutene gave a mixture of vinylsilane and silylated vinyl ether (eq. 11). Furthermore, in the case of eq. 10 and 11, the ratio of alkenylsilanes 3 to reduced by-products (alkylsilanes 4 and alkenes 5) decreased though a reason was not clear.



All attempts at the silylation of other alkenyl electrophiles such as bromides and triflates were unsuccessful. Although the addition of potassium iodide was effective for the silylation of aryl triflates, the reaction of 4-*t*-butyl-cyclohexenyl triflate with PhMe_2SiH 1d gave only a 16% yield of the corresponding alkenylsirane (eq. 12).



Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. All acyclic alkenyl iodides were synthesized as reported previously.¹³ Cycloalkenyl iodide was obtained from the corresponding cyclic ketones by the known method.¹⁴ Other reagents were prepared as described in chapter 6.

Silylation of 1-iodo-2-phenylethene (Table 1 and 2). To a suspension of KOAc (296 mg, 3.0 mmol) and $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (15 mg, 0.014 mmol) in NMP (4 mL) was added (*E*)-1-iodo-2-phenylethene (115 mg, 1.0 mmol) and hydrosilane (1.5 mmol). After being stirred for 2 h at room temperature, the reaction mixture was taken up in benzene, washed three times with water to remove the NMP. The yields of styrene and/or silylated products were determined by gas chromatography using tetradecane as an internal standard. The extract was dried over MgSO_4 , filtered, and concentrated *in vacuo*. The residue was purified by column chromatography on a silica gel.

The alkenylsilanes prepared by employing the above procedures are as follows.

(*E*)-1-(triethoxysilyl)-2-phenylethene (Table 1): IR (neat) 3025, 2886, 1574, 1495, 1448, 1390, 1293, 1167 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.26 (t, J = 7.0 Hz, 9 H), 3.89 (q, J = 7.0 Hz, 6 H), 6.16 (d, J = 19.3 Hz, 1 H), 7.1-7.5 (m, 6 H); ^{13}C NMR (CDCl_3) δ 18.24, 58.59, 117.92, 126.76, 128.51, 128.68, 137.76, 149.08; MS (m/z) 266 (11, M^+), 251 (24), 221 (24), 176 (62), 135 (14), 131 (27), 103 (26); HRMS for $\text{C}_{14}\text{H}_{20}\text{O}_3\text{Si}$ calcd 266.1338, found 266.1352.

1-(triethoxysilyl)-2-phenylethane (Table 1): ^1H NMR (CDCl_3) δ 1.00 (t, $J = 8.8$ Hz, 2 H), 1.25 (t, $J = 7.0$ Hz, 9 H), 2.74 (t, $J = 8.8$ Hz, 2 H), 3.83 (q, $J = 7.0$ Hz, 6 H), 7.1-7.4 (m, 5 H); ^{13}C NMR (CDCl_3) δ 12.46, 18.29, 28.85, 58.39, 125.60, 127.77, 128.29.

144.61; MS (m/z) 268 (26, M^+), 223 (8), 177 (18), 163 (100), 135 (34), 133 (6), 104 (14).

(*E*)-1-(dimethoxymethylsilyl)-2-phenylethene (Table 2, entry 2): ^1H NMR (CDCl_3) δ 0.28 (s, 3 H), 3.58 (s, 6 H), 6.28 (d, $J = 19.2$ Hz, 1 H), 7.12 (d, $J = 19.2$ Hz, 1 H), 7.2-7.6 (m, 5 H); ^{13}C NMR (CDCl_3) δ -5.11, 50.40, 121.24, 126.72, 128.58, 128.70, 147.90.

(*E*)-1-(triethylsilyl)-2-phenylethene (Table 2, entry 3): ^1H NMR (CDCl_3) δ 0.66 (q, $J = 7.9$ Hz, 6 H), 0.98 (t, $J = 7.9$ Hz, 9 H), 6.43 (d, $J = 19.2$ Hz, 1 H), 6.89 (d, $J = 19.2$ Hz, 1 H), 7.2-7.5 (m, 5 H); ^{13}C NMR (CDCl_3) δ 3.50, 7.39, 125.93, 126.29, 127.86, 128.48, 138.48, 144.78; MS (m/z) 218 (10, M^+), 190 (20), 189 (100), 161 (54), 159 (14), 133 (29), 105 (14); HRMS (m/z) for $\text{C}_{14}\text{H}_{22}\text{Si}$ calcd 218.1495, found 218.1493.

(*E*)-1-(diphenylmethylsilyl)-2-phenylethene (Table 2, entry 4): ^1H NMR (CDCl_3) δ 0.71 (s, 3 H), 6.76 (d, $J = 18.9$ Hz, 1 H), 6.96 (d, $J = 18.9$ Hz, 1 H), 7.2-7.6 (m, 15 H); MS (m/z) 300 (48, M^+), 285 (90), 222 (39), 207 (100), 197 (24), 183 (50); HRMS (m/z) for $\text{C}_{21}\text{H}_{20}\text{Si}$ calcd 300.1350, found 300.1342.

(*E*)-1-(triphenylsilyl)-2-phenylethene (Table 2, entry 5): ^1H NMR (CDCl_3) δ 6.98 (br. s, 2 H), 7.3-7.6 (m, 20 H); ^{13}C NMR (CDCl_3) δ 122.88, 126.73, 127.90, 128.49, 128.54, 129.58, 134.43, 135.63, 135.99, 148.84.

Synthesis of alkenylsilanes. Typical Procedure (Table 3). The following is a typical experimental procedure for the present silylation. To a suspension of KOAc (296 mg, 3.0 mmol) and $\text{Pd}_2(\text{dba})_3 \cdot \text{CHCl}_3$ (15 mg, 0.014 mmol) in NMP (4 mL) was added (*E*)-1-iodo-3,3-dimethylbut-1-ene (212 mg, 1.01 mmol) and triethoxysilane (249 mg, 1.5 mmol). After being stirred for 2 h at room temperature, the reaction mixture was taken up in benzene, washed three times with water to remove the NMP, dried over MgSO_4 , filtered, and concentrated in vacuo. The residue was purified by column chromatography on a silica gel (pentane/ether = 10/1) to give 183 mg (74% yield) of analytically and spectroscopically pure

(*E*)-3,3-dimethyl-1-(triethoxysilyl)-but-1-ene (Table 3, entry 3): IR (neat) 2971, 1609, 1443, 1390, 1168, 1080 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.02 (s, 9 H), 1.23 (t, $J = 7.0$ Hz, 9 H), 3.82 (q, $J = 7.0$ Hz, 6 H), 5.32 (d, $J = 19.5$ Hz, 1 H), 6.43 (d, $J = 19.5$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 18.20, 28.74, 35.70, 58.43, 112.26, 163.90; MS (m/z) 246 (1, M^+), 231 (1), 201 (4), 187 (3), 163 (100), 134 (10), 119 (42); HRMS for $\text{C}_{12}\text{H}_{26}\text{O}_3\text{Si}$ calcd 246.1641, found 246.1646.

The following compounds were prepared by the above procedure.

(*E*)-1-(triethoxysilyl)-2-(4-methoxyphenyl)ethene (Table 3, entry 1): IR (neat) 2973, 2837, 1607, 1509, 1442, 1390, 1253, 1170, 1078 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.26 (t, $J = 7.0$ Hz, 9 H), 3.82 (s, 3 H), 3.88 (q, $J = 7.0$ Hz, 6 H), 6.00 (d, $J = 19.2$ Hz, 1 H), 7.16 (d, $J = 19.2$ Hz, 1 H), 6.88 (d, $J = 8.9$ Hz, 2 H), 7.43 (d, $J = 8.9$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 18.26, 55.30, 58.55, 113.89, 114.66, 128.13, 130.58, 148.61, 160.13; MS (m/z) 296 (8, M^+), 281 (9), 252 (20), 179 (7), 162 (8), 147 (11), 134 (100); HRMS (m/z) for $\text{C}_{15}\text{H}_{24}\text{O}_4\text{Si}$ calcd 296.1512, found 296.1478.

(*E*)-1-(triethoxysilyl)-2-(4-methoxycarbonylphenyl)ethene (Table 3, entry 2): IR (neat) 2975, 1724, 1606, 1436, 1390, 1167, 1079 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.28 (t, $J = 7.0$ Hz, 9 H), 3.89 (q, $J = 7.0$ Hz, 6 H), 3.92 (s, 3 H), 6.30 (d, $J = 19.2$ Hz, 1 H), 7.24 (d, $J = 19.2$ Hz, 1 H), 7.53 (d, $J = 8.1$ Hz, 2 H), 8.04 (d, $J = 8.1$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 18.25, 52.11, 58.68, 121.25, 126.64, 129.87, 141.79, 147.76, 166.77; MS (m/z) 324 (9, M^+), 309 (24), 293 (7), 279 (100), 265 (12), 251 (10), 237 (5), 205 (10), 177 (12), 163 (11); HRMS (m/z) for $\text{C}_{16}\text{H}_{24}\text{O}_5\text{Si}$ calcd 324.1305, found 324.1349.

(*E*)-1-(triethoxysilyl)-2-(1-methoxycyclohexyl)ethene (Table 3, entry 4): IR (neat) 2928, 2822, 1615, 1447, 1389, 1294, 1253, 1167, 1079 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.8-1.8 (m, 10 H), 1.23 (t, $J = 7.0$ Hz, 9 H), 3.11 (s, 3 H), 3.83 (q, $J = 7.0$ Hz, 6 H), 5.56 (d, $J = 19.5$ Hz, 1 H), 6.26 (d, $J = 19.5$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 18.22, 21.72, 25.63, 29.69, 33.68, 49.63, 58.51, 118.73, 156.65; MS (m/z) 302 (0.4, M^+), 287 (39), 270 (2), 259 (2), 241 (13), 213 (1), 163 (63), 149 (14), 79 (100); HRMS (m/z) for $\text{C}_{15}\text{H}_{30}\text{O}_4\text{Si}$ calcd 302.1914, found 302.1942.

(*E*)-1-(triethoxysilyl)-4-*tert*-butyl-1-cyclohexene (Table 3, entry 5): ^1H NMR (CDCl_3) δ 0.85 (s, 9 H), 1.23 (t, $J = 7.0$ Hz, 9 H), 1.8-1.9 (m, 4 H), 2.0-2.2 (m, 2 H), 3.82 (q, $J = 7.0$ Hz, 6 H), 6.38 (s, 1 H); ^{13}C NMR (CDCl_3) δ 18.27, 23.97, 27.03, 28.30, 28.51, 32.24, 43.73, 58.39, 129.87, 142.48; MS (m/z) 300 (9, M^+), 285 (3), 255 (17), 243 (16), 199 (12), 163 (100), 135 (41); HRMS (m/z) for $\text{C}_{16}\text{H}_{32}\text{O}_3\text{Si}$ calcd 300.2155, found 300.2138.

References

1. For reviews, see: (a) Magnus, P. D.; Sarkar, T.; Djuric, S. *Comprehensive Organometallic Chemistry*; Wilkinson, G.; Stone, F. G. A.; Abel, E. W., Eds.; Pergamon: Oxford, 1982; Vol. 7, p 515. (b) Colvin, E. W. *Silicon Reagents in Organic Synthesis*; Academic: London, 1988. (c) Colvin, E. W. *Comprehensive Organometallic Chemistry II*; Abel, E. W.; Stone, F. G. A.; Wilkinson, G., Eds.; Pergamon: Oxford, 1995; Vol. 11, p 313.
2. For reviews, see: (a) Hiyama, T. *Metal-catalyzed Cross-coupling Reactions*; Diederich, F.; Stang, P. J., Eds.; Wiley: Weinheim, 1998; p 421. (b) Hatanaka, Y.; Hiyama, T. *Synlett* 1991, 845.
3. Tamao, K.; Kobayashi, K.; Ito, Y. *Tetrahedron Lett.* 1989, 30, 605.
4. For reviews, see: (a) Ojima, I. *The Chemistry of Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, 1989; p 1479. (b) Corey, J. Y. *Advances in Silicon Chemistry*; Larson, G. L., Ed.; JAI Press: Greenwich, 1991; p 327. (c) Takeda, T. *Synthesis of Organometallic Compounds*; Komiya, S., Ed.; Wiley: Chichester, 1997; p 391.
5. (a) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* 1987, 28, 4715. (b) Matsumoto, H.; Nagashima, S.; Kato, T.; Nagai, Y. *Angew. Chem., Int. Ed. Engl.* 1978, 17, 279.
6. Murata, M.; Suzuki, K.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 8569.
7. (a) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 2000, 65, 164. (c) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *Synthesis* in press.
8. (a) Murahashi, S.-I.; Watanabe, T. *J. Am. Chem. Soc.* 1979, 101, 7429. (b) Hagiwara, H.; Eda, Y.; Morohashi, K.; Suzuki,

- T.; Ando, M; Ito, N. *Tetrahedron Lett.* 1998, 39, 4055.
9. Kunai, A.; Sakurai, T.; Toyoda, E.; Ishikawa, M.; Yamamoto, Y. *Organometallics* 1994, 13, 3233.
 10. Boukherroub, R.; Chatgililoglu, C.; Manuel, G. *Organometallics* 1996, 15, 1508.
 11. For a recent review of Pd-catalysed hydrosilylation, see: Horn, K. A. *Chem. Rev.* 1995, 95, 1317.
 12. For a review of the palladium-catalyzed carbon-carbon double bond isomerization, see; Heck, R. F. *Palladium Reagents in Organic Synthesis*; Academic: New York, 1985; p. 19.
 13. Tucker, C. E.; Greve, B.; Klein, W.; Knochel, P. *Organometallics* 1994, 13, 94.
 14. Pross, A.; Sternhell, S. *Aust. J. Chem.* 1970, 23, 989.

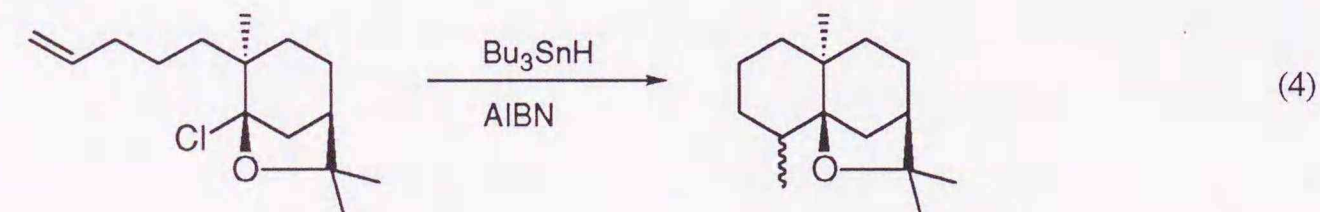
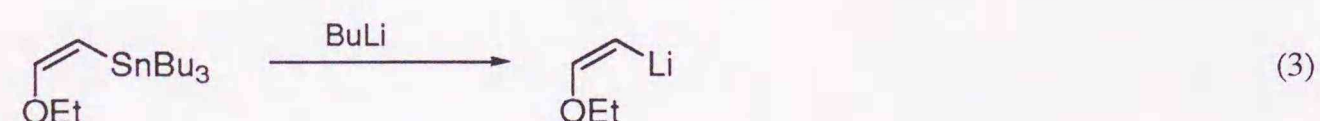
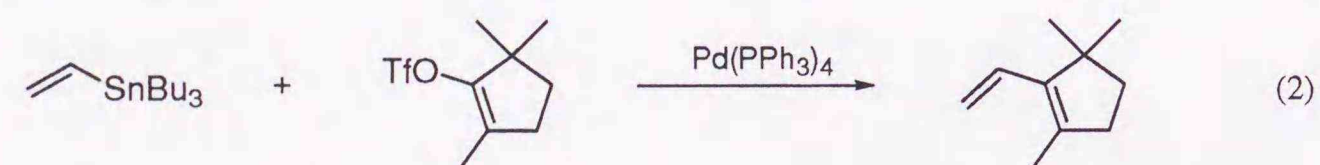
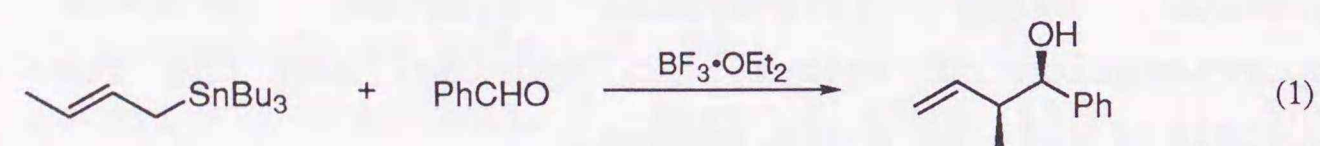
Chapter 8.

Palladium(0)-Catalyzed Stannylation of Aryl Halides with Tin Hydrides

Various aryl iodides were coupled with 2 equiv of tributyltin hydride (and/or 1.5 equiv of hexabutylditin) in the presence of potassium acetate and a catalytic amount of $\text{PdCl}_2(\text{PMePh}_2)_2$ to afford the corresponding arylstannanes under very mild conditions. The stannylation using tributyltin hydride involves the disproportionation of tributyltin hydride, and the resultant hexabutylditin acts as a tin source.

Introduction

Synthetically valuable organotin compounds are classified into the following categories; carbon nucleophiles in carbon-carbon bond forming reactions (eq. 1¹ and 2²), precursors of organolithiums in transmetallation reactions (eq. 3³), reagents for the generation of tin-centered or carbon radicals (eq. 4⁴), and reagents for functional group transformation.



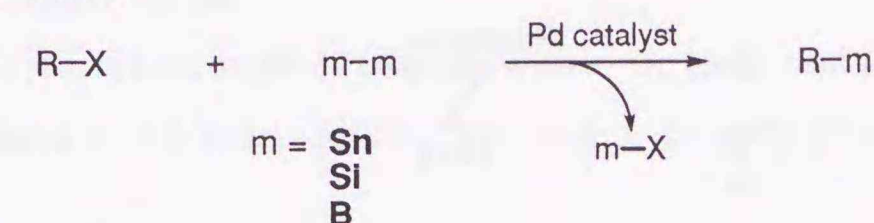
Several syntheses of unsymmetrical tetraorganotin compounds have been reported, but the most important methods are based on the reaction of haloorganostannanes with Grignard or lithium reagents (eq. 5).⁵ However, neither reagent tolerates a wide variety of functional groups.



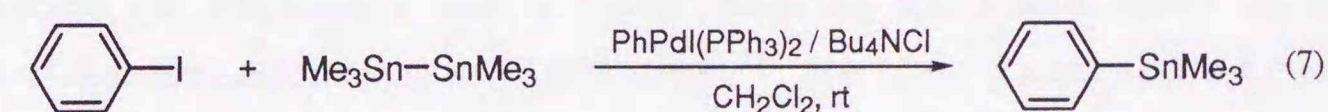
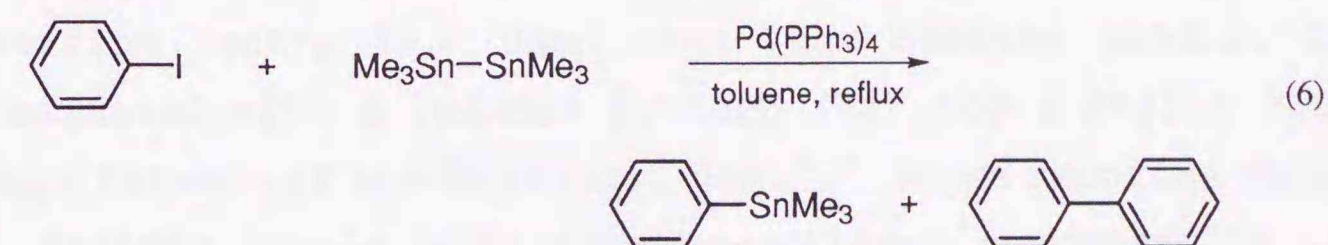
The palladium-catalyzed cross-coupling reactions of bimetallic reagents, such as ditins,⁶ disilanes,⁷ and diborons,⁸

have been shown to be versatile methods for carbon-metal bond formation from organic electrophiles, in which the organic group bears a reactive functional substituent (Scheme 1).

Scheme 1.



Eaborn and his colleagues reported on the reaction of the distannanes $\text{Me}_3\text{SnSnMe}_3$ with some organic halides (eq. 6).^{6a} However, it was only possible to obtain aryltrialkylstannanes containing electron-donating functional groups with satisfactory yields. Since in the case of aryl halides containing electron-withdrawing substituents only the biaryls were formed, Beletskaya reported a useful variant (eq. 7).^{6c}

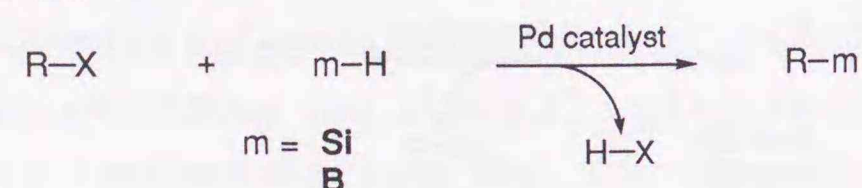


Generally, organotin compounds are more toxic than organosilicon compounds, and the toxicity is dependent of the structure of alkyl substituents. Since methyl and ethyl derivatives are highly toxic, the use of less toxic butyl derivatives is strongly recommended unless the experiment has a special purpose. However, $\text{Bu}_3\text{SnSnBu}_3$ is unreactive for the above palladium-catalyzed stannylation.

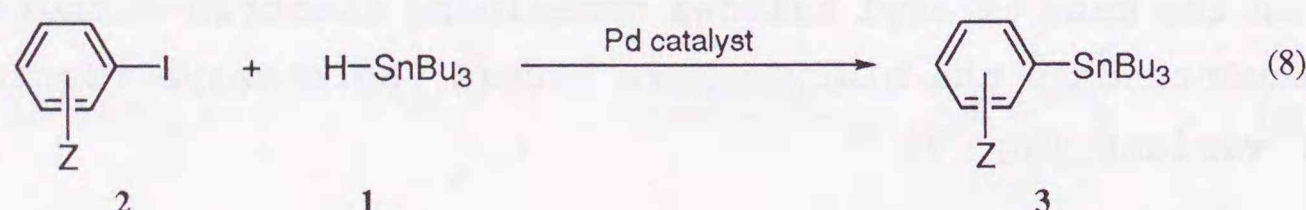
On the other hand, in previous chapters, palladium-catalyzed metalation reactions of organic halides utilizing dialkoxyboranes⁹ and trialkoxysilanes,¹⁰ respectively, were described. Although the mechanism for these metalations is unclear at the present stage,

such metal hydrides as well as bimetallic reagents are metalating reagents for the palladium-catalyzed metalations of organic electrophiles (Scheme 2).

Scheme 2.



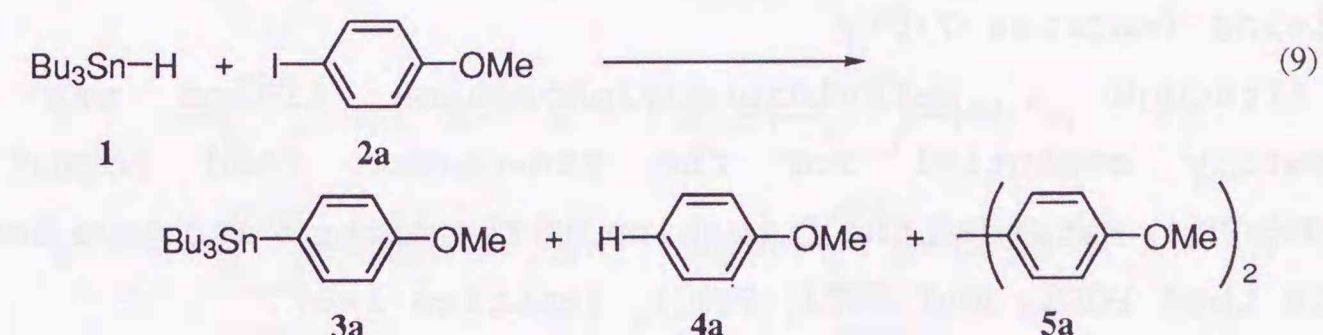
To extend the methods, this chapter is concerned with a tin-carbon bond formation. Herein, a useful palladium-catalyzed stannylation of aryl halides **2** with tributyltin hydride **1** as a tin source is described (eq. 8).



Results and Discussion

Reaction Conditions.

The reaction conditions were optimized using tributyltin hydride **1** and 4-iodoanisole (**2a**) as a substrate (eq. 9, Table 1).



At room temperature in *N*-methylpyrrolidinone (NMP), the reaction of **2a** with 2 equiv of tributyltin hydride **1** in the presence of $\text{PdCl}_2(\text{PMePh}_2)_2$ gave the corresponding arylstannane **3a** in medium conversion (entry 4). Upon this, the desired product **3a** was contaminated with a reduced product (**4a**) and a Stille coupling product between **3a** and **2a** (biaryl **5a**).^{2b, c} As we reported recently, aryl halides couple with triethoxysilanes successfully in the presence of $\text{Pd}_2(\text{dba})_3$ and a base such as Et_3N and KOAc in NMP to give the corresponding arylsilanes.¹⁰ We then examined a treatment with an additional 3 equiv of KOAc, where upon the stannylation proceeded efficiently and exclusively (entry 3), whereas use of

Table 1. Reaction of 4-Iodoanisole **2a** with **1** under Various Conditions^a

entry	catalyst	base	solvent	yield (%) ^b		
				3a	4a	5a
1	PdCl_2	KOAc	NMP	84	7	9
2	$\text{PdCl}_2(\text{PPh}_3)_2$	KOAc	NMP	90	4	3
3	$\text{PdCl}_2(\text{PMePh}_2)_2$	KOAc	NMP	94	3	0
4	$\text{PdCl}_2(\text{PMePh}_2)_2$	none	NMP	67	7	11
5	$\text{PdCl}_2(\text{PMePh}_2)_2$	K_2CO_3	NMP	85	2	0
6	$\text{PdCl}_2(\text{PMePh}_2)_2$	Et_3N	NMP	62	4	4
7	$\text{PdCl}_2(\text{PMePh}_2)_2$	KOAc	MeCN	5	16	4
8	$\text{PdCl}_2(\text{PMePh}_2)_2$	KOAc	dioxane	17	5	9
9	$\text{PdCl}_2(\text{PMePh}_2)_2$	KOAc	toluene	6	8	9

^a Reaction of **2a** (1.0 mmol) with **1** (2 mmol) were carried out at room temperature for 16 h in 4 mL of solvent by using 3 mol % of catalyst and base (3 mmol). ^b GLC yields based on **2a**.

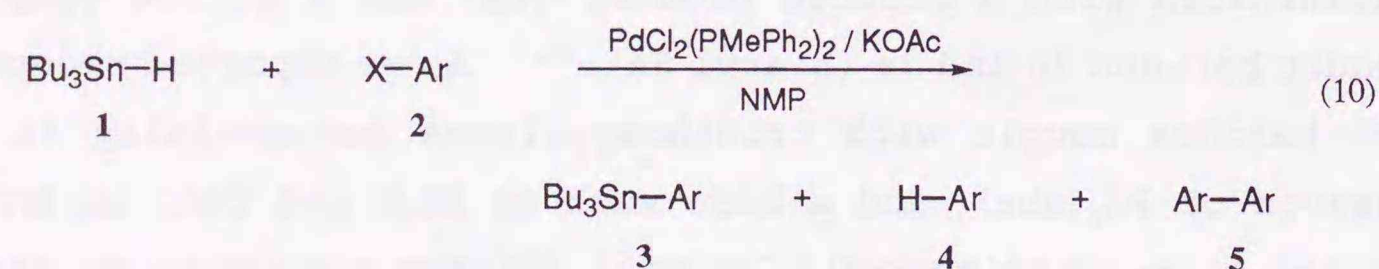
Et₃N was not effective (entry 6). In addition, the base played an important role in swaying the selectivity and, especially, the use of appropriate bases retarded the formation of the dimer 5 (entries 3 and 5). Thus, among bases, KOAc was recognized to be the most effective for the selective formation of arylstannane 3.

The use of a polar amide solvent such as NMP was also necessary for this stannylation (entry 3).^{6e} The reactions in other kinds of solvents, such as MeCN, dioxane, and toluene, resulted in quite low yields (entries 7-9).

Although a methyldiphenylphosphine ligand was not necessarily essential for the tin-carbon bond formation, PdCl₂(PMePh₂)₂ retarded the formation of the dimer 5 and gave better results than PdCl₂ and PdCl₂(PPh₃)₂ (entries 1-3).

Stannylation of representative aryl halides with Bu₃SnH.

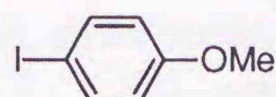
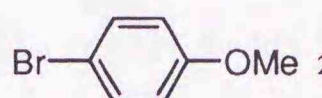
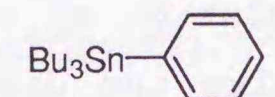
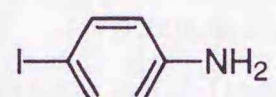
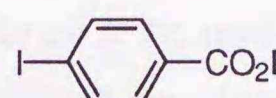
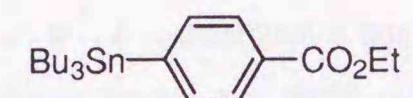
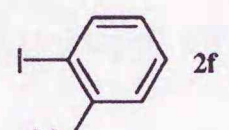
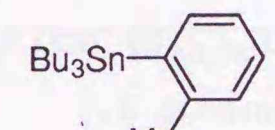
The results obtained with representative aryl halides 2, which gave product 3 in a manner similar to the above, are listed in Table 2 (eq. 10).



The rate of the stannylation was dependent to a considerable extent on the sort of aryl halide used; that is, the reactivity of aryl bromides was very inferior when compared with that of aryl iodides (entries 1 and 2).

The differences in the yields and the selectivity among aryl iodides having electron-donating or -withdrawing groups were not particularly large (entries 1 and 3-5), but the reaction of 2e having electron-withdrawing groups was sluggish at room temperature (3e, 46%), requiring a more elevated temperature. Also, the reactivity of aryl halides 2 was affected by their steric hindrance (entry 6).

Table 2. Reaction of Representative aryl iodides 2 with 1^a

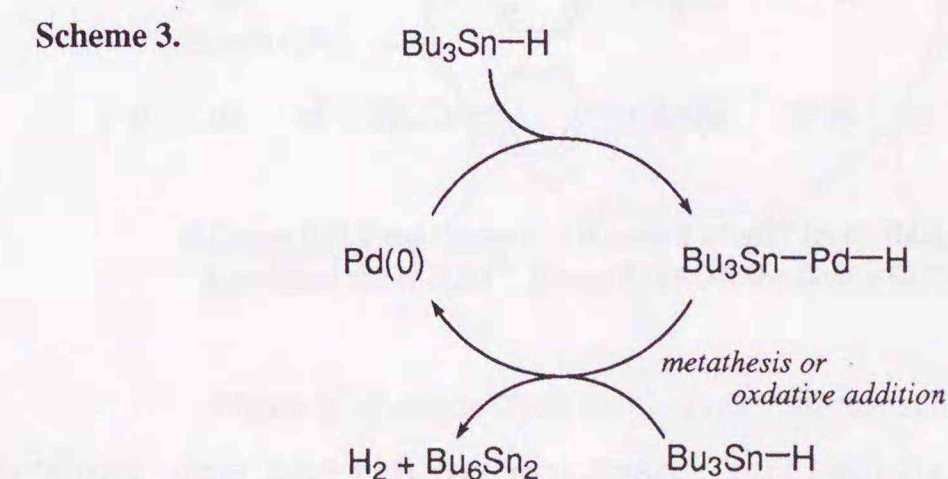
entry	aryl iodides 2	temp.	product 3	yield (%) ^b	
				3	4
1	 2a	rt	 3a	94	3
2	 2b	50 °C	3a	7	9
3	 2c	rt	 3c	91	
4	 2d	rt	 3d	(73)	
5	 2e	50 °C	 3e	86	8
6	 2f	80 °C	 3f	(70)	

^a All reactions were conducted in NMP (4 mL) for 16 h using 1 (2 mmol) and 2 (1.0 mmol) in the presence of PdCl₂(PMePh₂)₂ (0.03 mmol) and KOAc (3 mmol). ^b GLC yields based on 2. Isolated yields are shown in parentheses. 4c, d, and f were not determined.

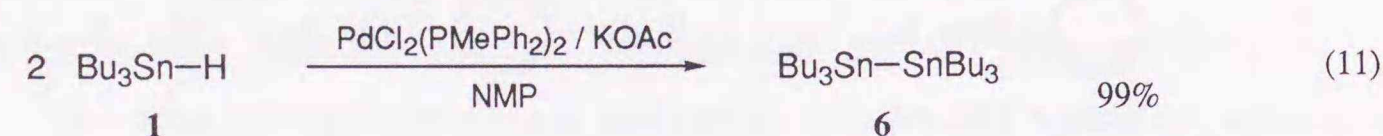
In all runs shown in Table 2, the reaction gave no detectable amount of dimer 5.

Stannylation of aryl halides with Bu₆Sn₂.

Bearing in mind the previously described result, the disproportionation of tributyltin hydride 1 would be catalyzed by palladium(0) complexes to give hexabutylditin 6 and hydrogen (Scheme 3).¹¹



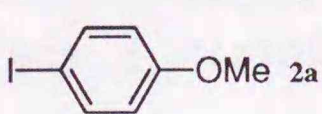
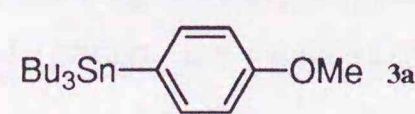
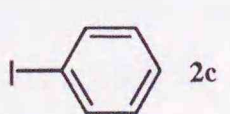
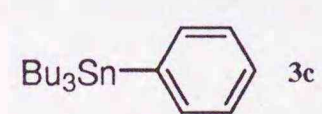
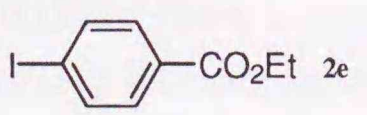
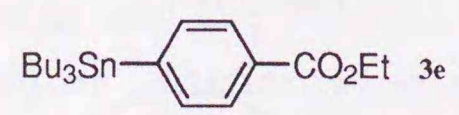
Actually, under the present conditions, the reaction of 1 in NMP at room temperature for 2 h in the presence of $\text{PdCl}_2(\text{PMePh}_2)_2$ and KOAc provided 6 quantitatively (eq. 11).



Thus, the stannylation of aryl halides 2 with tributyltin hydride 1 should involve the disproportionation of 1, and the resultant hexabutylditin 6 would act as a tin source. In the same system as used for 1, hexabutylditin 6 also could be used certainly as the stannylating reagent, *i. e.*, the reaction of 2 with 1.5 equiv of authentic 6, in NMP at appropriate temperature for 16 h in the presence of $\text{PdCl}_2(\text{PMePh}_2)_2$ (3 mol%) and KOAc (3 equiv), gave the corresponding arylstannane 3.

In all runs shown in Table 3, the reaction also gave no detectable amount of dimer 5. Furthermore, the reaction conditions are more mild than the previous stannylation of aryl halides with butyl derivatives.⁶ Thus, this catalytic system would be a useful variant of palladium-catalyzed cross-coupling reaction of ditins.

Table 3. Reaction of Representative aryl iodides 2 with 6^a

entry	aryl iodides 2	temp.	product 3	yield (%) ^b	
				3	4
1	 2a	rt	 3a	88	3
2	 2c	rt	 3c	86	
3	 2e	50 °C	 3e	80	0

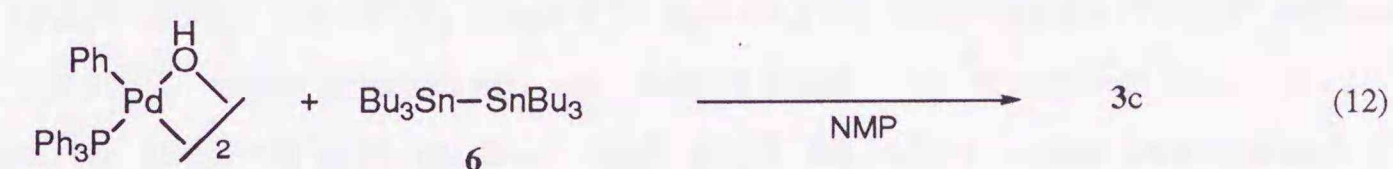
^a All reactions were conducted in NMP (4 mL) for 16 h using 6 (1.5 mmol) and 2 (1.0 mmol) in the presence of $\text{PdCl}_2(\text{PMePh}_2)_2$ (0.03 mmol) and KOAc (3 mmol). ^b GLC yields based on 2.

Reaction Mechanism.

The common cross-coupling reaction of ditins may involve a

sequence of oxidative addition of the electrophiles to Pd^0 giving an $\text{R-Pd}^{\text{II}}\text{-X}$ species, transmetalation with ditins $\text{R}'_3\text{Sn-SnR}'_3$ forming an $\text{R-Pd}^{\text{II}}\text{-SnR}'_3$, and reductive elimination of the $\text{R-SnR}'_3$.⁶ However, thereby the slow transmetalation with hexabutylditin 6 has been recognized. And then, the present treatment of isolated $\text{PhPdI}(\text{PPh}_3)_2$ with 6 in NMP gave no 3c.

On the other hand, in contrast to the case of palladium(II) halide, the authentic oxopalladium(II) complex, $[\text{PhPd}(\text{PPh}_3)(\mu\text{-OH})]_2$,¹² exhibited high reactivity toward hexabutylditin 6 giving a 73% yield of 3c (eq. 12).



Recently, Amatore and Jutand have found that the reaction of $\text{PhPdI}(\text{PPh}_3)_2$ with acetoxo anion afforded acetoxopalladium, $\text{PhPd}(\text{OAc})(\text{PPh}_3)_2$.^{13, 8a} Also, similar high reactivity of oxopalladium complexes toward transmetalation of bimetallic reagents such as disilanes^{7d} and diborons^{8a, c} has been reported.

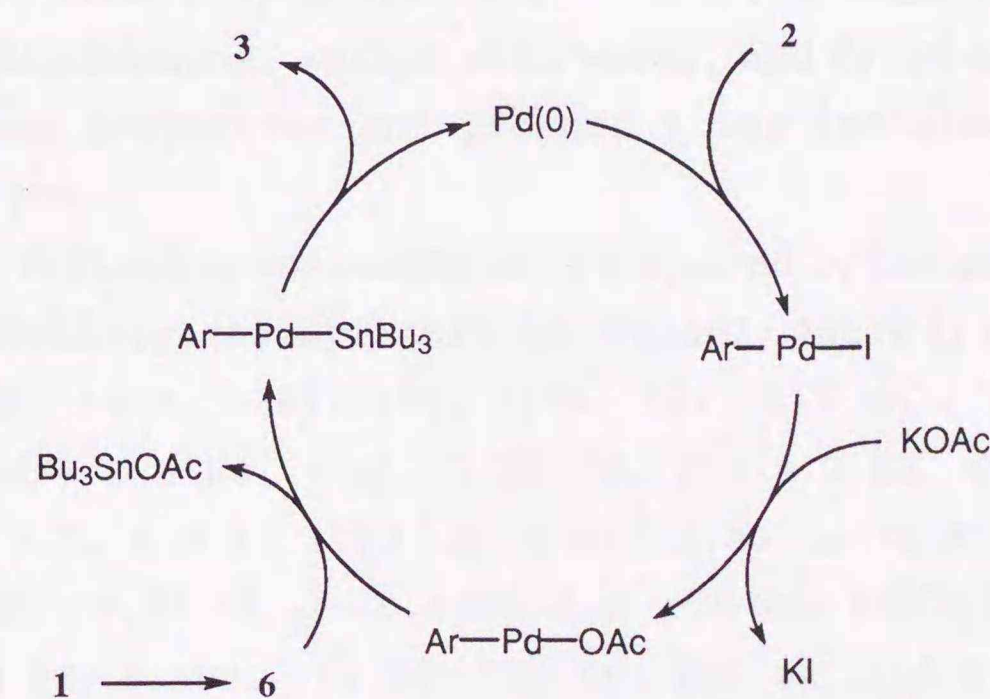


Figure 1. Catalytic Cycle for Coupling Reaction of 6 with 2

Thus, for the present stannylation, the base should displace X of $\text{Ar-Pd}^{\text{II}}\text{-X}$ to give a reactive oxopalladium(II) complex and play a significant role in accelerating the transmetalation step, as shown in Figure 1. Initially, aryl iodides 2 would add oxidatively to the palladium catalyst to give arylpalladium(II) species $\text{Ar-Pd}^{\text{II}}\text{-X}$. Then, the ligand exchange between X of $\text{Ar-Pd}^{\text{II}}\text{-X}$ and acetoxo anion would produce $\text{Ar-Pd}^{\text{II}}\text{-OAc}$ intermediate, and the subsequent reductive elimination would furnish arylstannanes 3 along with the regeneration of the catalyst.

Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. Solvents were distilled before use from either sodium benzophenone ketyl (toluene, dioxane) or CaH_2 (NMP). The bases and palladium(II) chloride from commercial sources were used without purification or drying. $\text{PdCl}_2(\text{PMePh}_2)_2$ ¹⁴ and $[\text{PhPd}(\text{PPh}_3)(\mu\text{-OH})]_2$ ¹² were prepared by the established methods. $\text{PdCl}_2(\text{PPh}_3)_2$ was prepared as described in chapter 2. All tin reagents (Bu_3SnH and Bu_4Sn) and aryl halides were purchased from Tokyo Kasei Kogyo Co.

Synthesis of arylstannanes. Typical Procedure. A flask was charged with $\text{PdCl}_2(\text{PMePh}_2)_2$ (0.03 mmol), KOAc (3 mmol), and NMP (4 mL) under an argon flow. Aryl iodide 2 (1.0 mmol) and tributyltin hydride 1 (2.0 mmol) were added successively, and the mixture was stirred at room temperature for 16 h. The reaction mixture was diluted with benzene, washed with water, and dried over MgSO_4 . The solvent was evaporated and product 3 was isolated by Kugelrohr distillation.

The following compounds were prepared by the above procedure.

4-(Tributylstannyl)anisole (Table 2, entry 1): IR (neat) 2926, 1588, 1495, 1458, 1243, 1180, 1074, 807, 517 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, J = 7.3 Hz, 9 H), 1.02 (t, J = 8.2 Hz, 6 H), 1.32 (tq, J = 7.3, 7.3, 6 H), 1.53 (m, 6 H), 3.80 (s, 3 H), 6.90 (d, J = 8.4 Hz, 2 H), 7.37 (d, J = 8.4 Hz, 2 H); ^{13}C NMR (CDCl_3) δ 9.58, 13.67, 27.38, 29.09, 54.92, 113.90, 132.00, 137.48, 159.67; MS (EI, m/z) 343 (100), 341 (68), 339 (41), 337 (2), 284 (11), 227 (30), 225 (12), 116 (5), 114 (4), 101 (2); HRMS (EI, m/z) calcd for $\text{C}_{15}\text{H}_{25}\text{O}^{120}\text{Sn}$ ($M - \text{C}_4\text{H}_9$) 341.0927, found 341.0898, calcd for $\text{C}_{15}\text{H}_{25}\text{O}^{118}\text{Sn}$ ($M - \text{C}_4\text{H}_9$) 339.0922, found 339.0908, calcd for $\text{C}_{15}\text{H}_{25}\text{O}^{116}\text{Sn}$ ($M - \text{C}_4\text{H}_9$) 337.0923, found

337.0918.

Tributylphenyltin (Table2, entry 3): IR(neat) 3063, 2926, 2853, 1464, 1428, 1376, 1074, 874, 700 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.3$ Hz, 9 H), 1.05 (t, $J = 8.2$ Hz, 6 H), 1.33 (tq, $J = 7.3$, 7.3, 6 H), 1.54 (m, 6 H), 3.61 (s, 2 H), 6.69 (d, $J = 8.2$ Hz, 2 H), 7.23 (d, $J = 8.2$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 9.53, 13.66, 27.38, 29.09, 127.93, 136.49, 142.04; MS (EI, m/z) 311(66), 309(37), 307(3), 254(15), 252(1), 250(2), 197(37), 195(11); HRMS (EI, m/z) calcd for $\text{C}_{14}\text{H}_{23}^{120}\text{Sn}$ (M - C_4H_9) 311.0822, found 311.0867, calcd for $\text{C}_{14}\text{H}_{23}^{118}\text{Sn}$ (M - C_4H_9) 309.0816, found 309.0842, calcd for $\text{C}_{14}\text{H}_{23}^{116}\text{Sn}$ (M - C_4H_9) 307.0817, found 307.0831.

4-(Tributylstannyl)aniline (Table2, entry 4): IR(neat) 3376, 2925, 1591, 1496, 1464, 1268, 1186, 1071, 811 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.3$ Hz, 9 H), 1.00 (t, $J = 8.2$ Hz, 6 H), 1.32 (tq, $J = 7.3$, 7.3, 6 H), 1.52 (m, 6 H), 3.61 (s, 2 H), 6.69 (d, $J = 8.2$ Hz, 2 H), 7.23 (d, $J = 8.2$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 9.52, 13.67, 27.38, 29.10, 115.19, 129.70, 137.38, 147.26; MS (EI, m/z) 326(22), 324(11), 322(2), 269(6), 267(5), 265(1), 212(7), 210(7), 83(100); HRMS (EI, m/z) calcd for $\text{C}_{14}\text{H}_{24}\text{N}^{120}\text{Sn}$ (M - C_4H_9) 326.0930, found 326.0965, calcd for $\text{C}_{14}\text{H}_{24}\text{N}^{118}\text{Sn}$ (M - C_4H_9) 324.0925, found 324.0958, calcd for $\text{C}_{14}\text{H}_{24}\text{N}^{116}\text{Sn}$ (M - C_4H_9) 322.0926, found 326.0972.

Ethyl 4-(Tributylstannyl)benzoate (Table2, entry 5): IR(neat) 2957, 2927, 1721, 1276, 1104, 1064, 752, 698 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.3$ Hz, 9 H), 1.07 (t, $J = 8.2$ Hz, 6 H), 1.33 (tq, $J = 7.3$, 7.3, 6 H), 1.52 (m, 6 H), 2.39 (s, 3 H), 7.1-7.4 (m, 4 H); ^{13}C NMR (CDCl_3) δ 13.64, 25.00, 27.39, 29.14, 124.83, 128.25, 128.83, 136.50, 141.90, 144.60; MS (EI, m/z) 383(43), 381(28), 379(2), 326(7), 324(1), 322(1), 269(38), 267(9), 265(1), 240(5), 238(3), 236(1), 196(6), 194(3), 149(3); HRMS (EI, m/z) calcd for $\text{C}_{17}\text{H}_{27}\text{O}_2^{120}\text{Sn}$ (M - C_4H_9) 383.1033, found 383.1054, calcd for $\text{C}_{17}\text{H}_{27}\text{O}_2^{118}\text{Sn}$ (M - C_4H_9) 381.1027, found 381.1042, calcd for $\text{C}_{17}\text{H}_{27}\text{O}_2^{116}\text{Sn}$ (M - C_4H_9) 379.1029, found 379.0995.

2-(Tributylstannyl)toluene (Table2, entry 6): IR(neat) 3053, 2957, 2871, 2854, 1523, 1464, 1376, 1073, 875, 741; ^1H NMR (CDCl_3) δ 0.88 (t, $J = 7.3$ Hz, 9 H), 1.00 (t, $J = 8.2$ Hz, 6 H), 1.32 (tq,

$J = 7.3$, 7.3, 6 H), 1.52 (m, 6 H), 3.61 (s, 2 H), 6.69 (d, $J = 8.2$ Hz, 2 H), 7.23 (d, $J = 8.2$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 9.52, 13.67, 27.38, 29.10, 115.19, 129.70, 137.38, 147.26; MS (EI, m/z) 325(100), 323(77), 321(45), 268(16), 266(16), 211(64), 209(45), 207(9); HRMS (EI, m/z) calcd for $\text{C}_{15}\text{H}_{25}^{120}\text{Sn}$ (M - C_4H_9) 325.0979, found 325.1005, calcd for $\text{C}_{15}\text{H}_{25}^{118}\text{Sn}$ (M - C_4H_9) 323.0972, found 323.1021, calcd for $\text{C}_{15}\text{H}_{25}^{116}\text{Sn}$ (M - C_4H_9) 321.0974, found 321.001.

Disproportionation of tributyltin hydride (eq. 11). A mixture of tributyltin hydride 1 (2.0 mmol), $\text{PdCl}_2(\text{PMePh}_2)_2$ (0.03 mmol), and KOAc (3 mmol) in NMP (4 mL) was stirred at room temperature for 2 h. The GLC analysis indicated the formation of hexabutylditin 6 in a 99% yield.

Stannylation of aryl iodides with hexabutylditin (Table 3). A flask was charged with $\text{PdCl}_2(\text{PMePh}_2)_2$ (0.03 mmol), KOAc (3 mmol), and NMP (4 mL) under an argon flow. Aryl iodide 2 (1.0 mmol) and hexabutylditin 6 (1.5 mmol) were added successively, and the mixture was stirred at room temperature for 16 h. The reaction mixture was diluted with benzene, washed with water. A GLC analysis of the reaction mixtures indicated formations of arylstannanes 3.

Reaction of $[\text{PhPd}(\text{PPh}_3)(\mu\text{-OH})_2]$ with hexabutylditin (eq. 12). A mixture of $[\text{PhPd}(\text{PPh}_3)(\mu\text{-OH})_2]$ (0.025 mmol) and hexabutylditin 6 (0.2 mmol) in NMP (1 mL) was stirred at room temperature for 16 h. The GLC analysis of the reaction mixture indicated the formation of the corresponding 3c (73% yield).

References

1. (a) Yamamoto, Y.; Yatagai, H.; Naruta, Y.; Maruyama, K. *J. Am. Chem. Soc.* **1980**, *102*, 7107. (b) Yamamoto, Y. *Acc. Chem. Res.* **1987**, *20*, 243.
2. (a) Scott, W.; Stille, J. K. *J. Am. Chem. Soc.* **1986**, *108*, 3033. For reviews, see: (b) Stille, J. K. *Angew. Chem., Int. Ed. Engl.* **1986**, *25*, 508. (c) Mitchell, T. N. *Synthesis* **1992**, 803.
3. Wollenberg, R. H.; Albizati, K. F.; Peries, R. *J. Am. Chem. Soc.* **1977**, *99*, 7365.
4. Büchi, G.; Wüest, H. *J. Org. Chem.* **1979**, *44*, 546.
5. Takeda, T. In *Synthesis of Organometallic Compounds*; Komiya, S., Ed.; Wiley: New York, 1997; p 392.
6. (a) Azarian, D.; Dua, S. S.; Eaborn, C.; Walton, D. R. M. *J. Organomet. Chem.* **1976**, *117*, C55. (b) Azizian, H.; Eaborn, C.; Pidcock, A. *J. Organomet. Chem.* **1981**, *215*, 49. (c) Kashin, A. N.; Bumagina, I. G.; Bumagin, N. A.; Bakunin, V. N.; Beletskaya, I. P. *J. Org. Chem. USSR* **1981**, *17*, 905. (d) Kosugi, M.; Shimizu, K.; Ohtani, A.; Migita, T. *Chem. Lett.* **1981**, 829. (e) Farina, V.; Hauk, S. I. *J. Org. Chem.* **1991**, *56*, 4317.
7. For examples, see: (a) Eaborn, C.; Griffiths, R. W.; Pidcock, A. *J. Organomet. Chem.* **1982**, *225*, 331. (b) Matsumoto, H.; Kasahara, M.; Matsubara, I.; Takahashi, M.; Arai, T.; Hasegawa, M.; Nakao, T.; Nagai, Y. *J. Organomet. Chem.* **1983**, *250*, 99. (c) Hatanaka, Y.; Hiyama, T. *Tetrahedron Lett.* **1987**, *28*, 4715. (d) Tsuji, Y.; Funato, M.; Ozawa, M.; Ogiyama, H.; Kajita, S.; Kawamura, T. *J. Org. Chem.* **1996**, *61*, 5779.
8. (a) Ishiyama, T.; Murata, M.; Miyaura, N. *J. Org. Chem.* **1995**, *60*, 7508. (b) Ishiyama, T.; Itoh, Y.; Kitano, T.; Miyaura, N. *Tetrahedron Lett.* **1997**, *38*, 3447. (c) Ishiyama, T.; Ahiko, T. -a.; Miyaura, N. *Tetrahedron Lett.* **1996**, *37*, 6889. (d) Ahiko, T. -a.; Ishiyama, T.; Miyaura, N. *Chem. Lett.* **1997**, 811.
9. (a) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **1997**, *62*, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **2000**, *65*, 164. (c) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *Synthesis* in press.
10. (a) Murata, M.; Suzuki, K.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* **1997**, *62*, 8569. (b) Murata, M.; Watanabe, S.; Masuda, Y. *Tetrahedron Lett.* **1999**, *40*, 9255.
11. Four, P.; Guibe, F. *J. Org. Chem.* **1981**, *46*, 4439.
12. Grushin, V. V.; Alper, H. *Organometallics* **1993**, *12*, 1890.
13. (a) Amatore, C.; Jutand, A.; M'Barki, M. A. *Organometallics* **1992**, *11*, 3009. (b) Amatore, C.; Carré, E.; Jutand, A.; M'Barki, M. A. *Organometallics* **1995**, *14*, 1818. (c) Amatore, C.; Carré, E.; Jutand, A.; M'Barki, M. A.; Meyer, G. *Organometallics* **1995**, *14*, 5605.
14. Jenkins, J. M.; Shaw, B. L. *J. Chem. Soc.* **1966A**, 770.

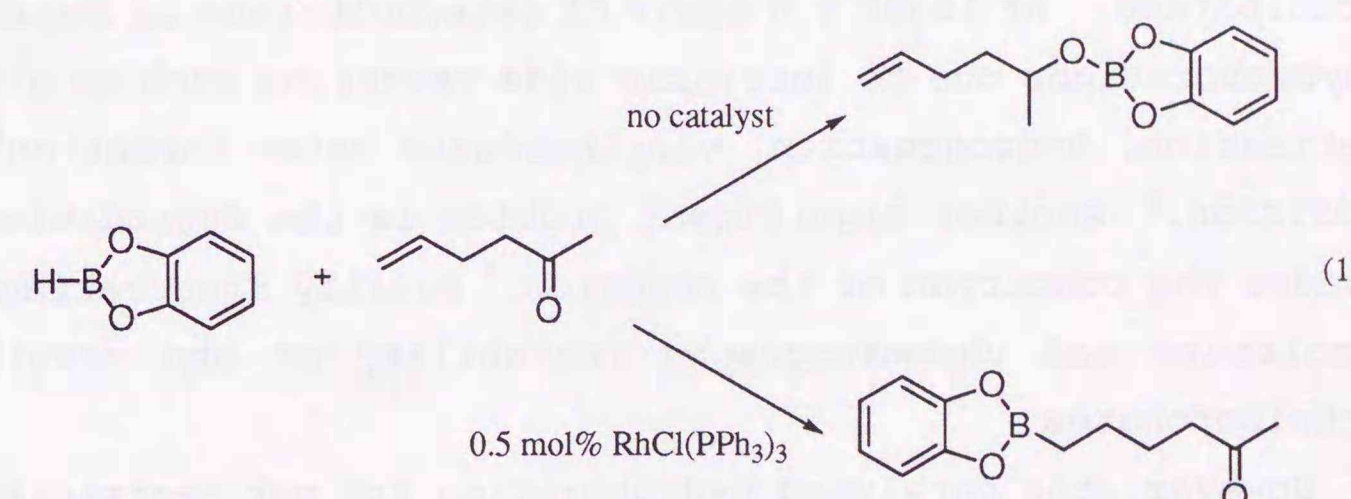
Chapter 9.

Synthesis of (Z)-Allylboronates via Ruthenium-Catalyzed Hydroboration of Propargyl Ethers with Pinacolborane

Hydroboration of alkynes with pinacolborane was catalyzed by $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ to provide stereodefined (*E*)-alkenylboronate. The reaction of propargyl ethers involved a carbon-carbon double bond isomerization to afford γ -alkoxyallylboronate with *Z* form in good yields.

Introduction

Additions of catecholborane to carbon-carbon multiple bonds are generally very slow at room temperature, but they can be greatly accelerated by small amounts of transition-metal complexes. There are several ways such "catalyzed hydroborations" may prove to be valuable in organic syntheses. Catalysis can alter the chemoselectivity of reactions of multifunctional substrates; for instance, without catalyst catecholborane adds to the carbonyl group of ketone, whereas hydroboration of the alkene takes place preferentially in the presence of less than 1 mol % of $\text{RhCl}(\text{PPh}_3)_3$ (eq. 1).¹ In addition to offering rate enhancements, the catalyzed reactions afford substantially modified chemo-, regio-, and stereoselectivities when compared to the uncatalyzed reaction.



A widely accepted mechanistic pathway for the catalyzed hydroboration of alkenes is that first proposed by Männig and Nöth (Figure 1). This mechanism very similar to the more thoroughly studied rhodium-catalyzed hydrometalation reaction, namely, hydroformylation, hydrogenation, and hydrosilylation.² The mechanism involves initial oxidative addition of the B-H bond to $\text{Rh}(\text{I})$, followed by alkene coordination and subsequent insertion into the Rh-H bond to afford a mixed alkyl, boryl complex. Reductive deborylation via B-C elimination then liberates the hydroborated

product and regenerates the catalyst. Computational studies have also supported this mechanism.³

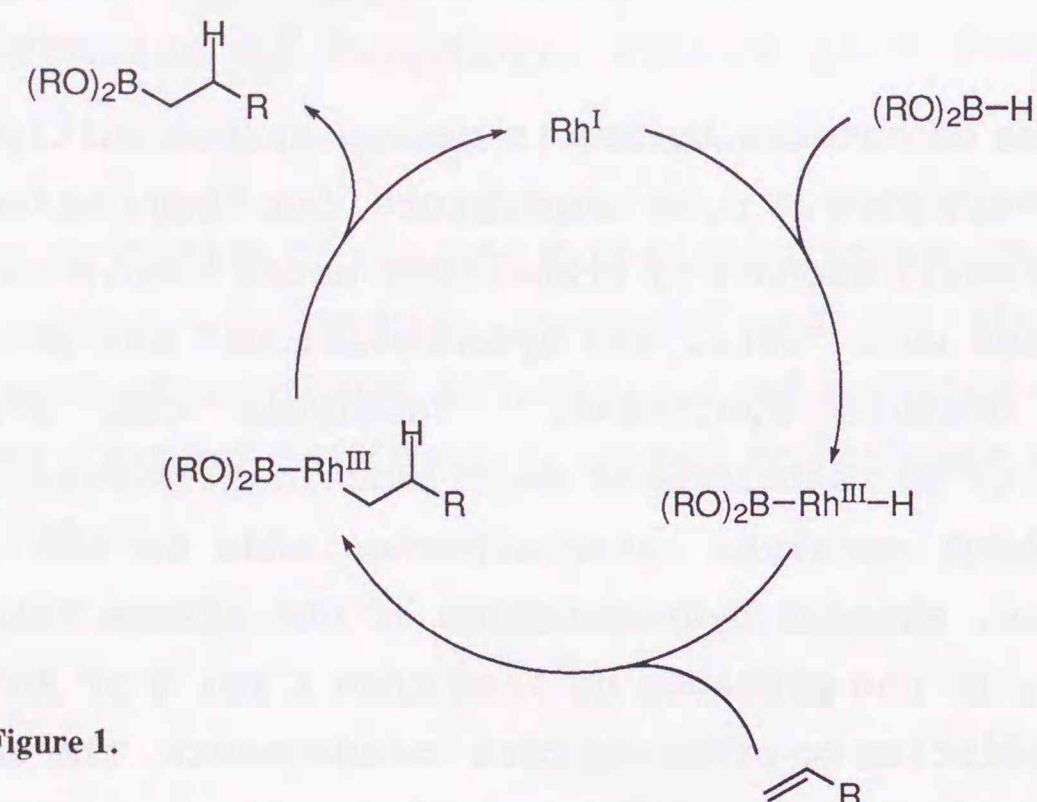
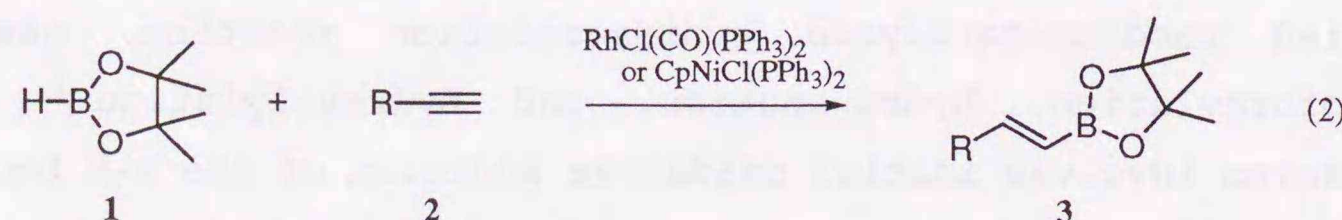


Figure 1.

Many unresolved problems are associated with the use of catecholborane. At least 1.5 equiv of catecholborane is required⁴ for hydroborations due to intrinsic side reactions such as alkene isomerization, hydrogenation, vinylboronate ester formation⁵ and BH_3 addition.⁶ Another significant problem is the degradation of CBH under the condition of the reaction.⁷ Equally frustrating are the moisture and chromatography instability of the resulting catecholboronates.

However, the catalyzed hydroboration are not restricted to catecholborane. Indeed, the catalytic hydroboration of alkynes 2 with pinacolborane 1 in the presence of several metals such as rhodium and nickel has been reported (eq. 2).⁸

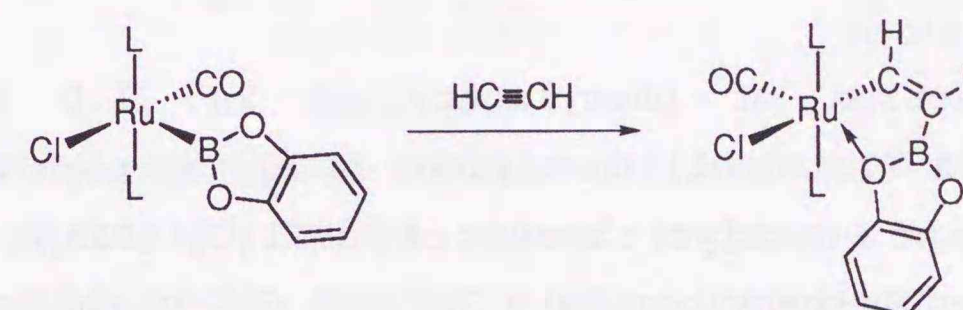


Considerable attention has recently been paid to pinacolborane 1 in view of its excellent chemoselectivity, and 1

is utilized in the synthesis of pinacol boronates via hydroboration of unsaturated compounds^{8, 9} or the palladium-catalyzed borylation of organic halides.¹⁰

In this chapter, a new catalytic system for hydroboration of alkynes 2 by using a ruthenium complex is described. Since insertion of ethyne into Ru-B bond of $\text{Ru}(\text{BO}_2\text{C}_6\text{H}_4)\text{Cl}(\text{CO})(\text{PPh}_3)_2$ has been reported (Scheme 1),¹¹ the author gave attention to the ruthenium complex in expectation of an alternative mechanistic pathway in which insertion into the metal-boron bond.

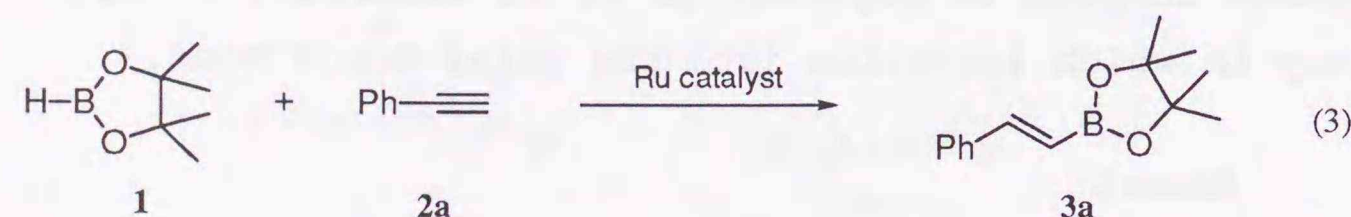
Scheme 1.



Results and Discussion

Ruthenium-catalyzed hydroboration of alkynes.

A simple hydroboration of phenylacetylene **2a** ($R = \text{Ph}$) was investigated (eq. 3, Table 1).



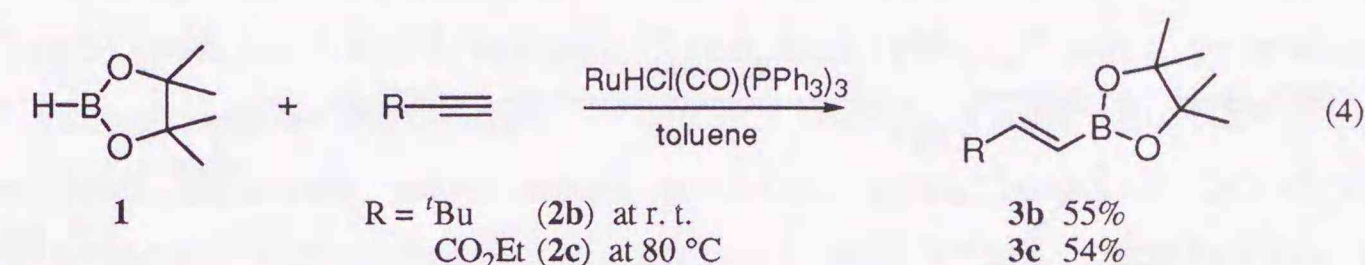
The reaction of phenylacetylene **2a** (1.0 mmol) with pinacolborane **1** (1.1 mmol) in toluene (4 ml) at room temperature in the presence of a catalytic amount of $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ (0.03 mmol) gave (*E*)-2-phenylethenylboronate **3a** (98% GLC yield based on **2a**, entry 1). The present reaction proceeded regio- and stereoselectively; i.e., neither 1-phenylethenylboronate nor the (*Z*)-isomer was produced. Among the catalysts we examined, $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ gave the best result, and other ruthenium complexes such as $\text{RuCl}_2(\text{PPh}_3)_3$, $\text{RuH}_2(\text{PPh}_3)_4$, $\text{RuCpCl}(\text{PPh}_3)_2$, and $\text{Ru}_3(\text{CO})_{12}$ were less effective (entries 2-4 and 7-8). Four solvents, including toluene, benzene, $\text{CH}_2\text{ClCH}_2\text{Cl}$, and dioxane, were tested, but it was observed that these did not play an important role (entries 5 and 6).

Table 1. Reaction of **2a** under various conditions^a

entry	catalyst	solvent	temp.	yield (%) ^b
1	$\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$	toluene	rt	98
2	$\text{RuCl}_2(\text{PPh}_3)_3$	toluene		22
3	$\text{Ru}_3(\text{CO})_{12}$	toluene		4
4	$\text{CpRuCl}(\text{PPh}_3)_3$	toluene		5
5	$\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$	$\text{CH}_2\text{ClCH}_2\text{Cl}$		98
6	$\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$	dioxane		81
7	$\text{RuCl}_2(\text{PPh}_3)_3$	toluene	80 °C	42
8	$\text{Ru}_3(\text{CO})_{12}$	toluene		34
9	$\text{CpRuCl}(\text{PPh}_3)_3$	toluene		74

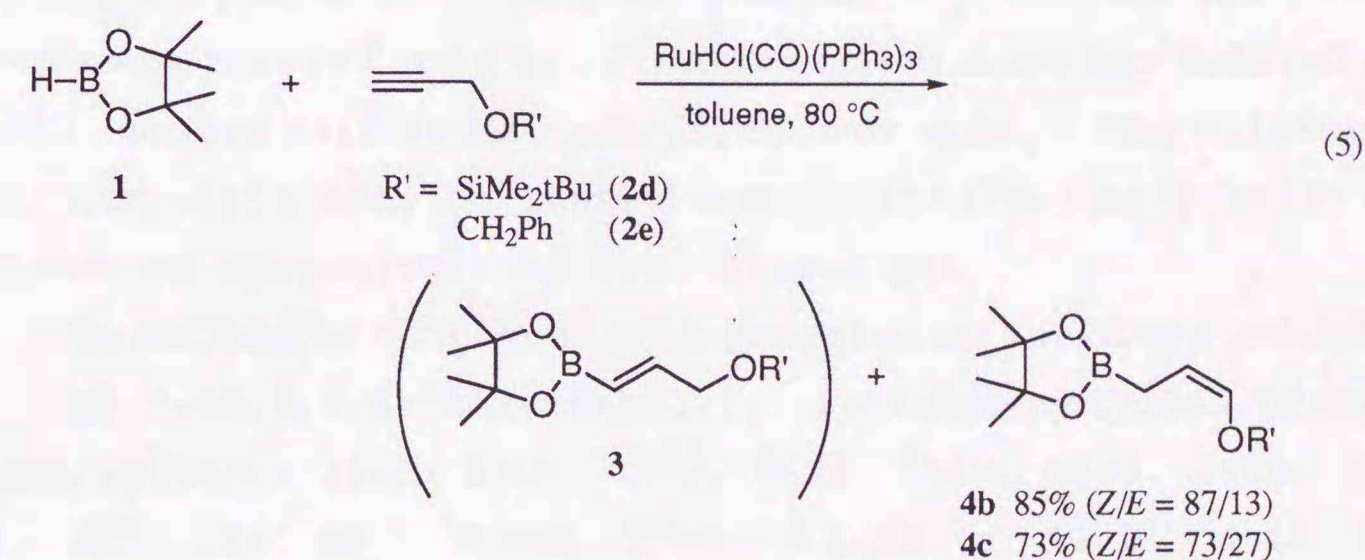
^a Reaction of **1** (1.1 mmol) with **2a** (1.0 mmol) were carried out for 16 h in 4 mL of solvent by using ruthenium catalyst (0.03 mmol). ^b GLC yields based on **2a**.

To examine the scope of the reaction, the ruthenium-catalyzed hydroboration of other alkynes **2** with pinacolborane **1** has been examined (eq. 4). The reaction of *tert*-butylacetylene **2b** afforded a 55% isolated yield of the corresponding (*E*)-**3b**. However, in the case of ethyl propiolate **2c**, the above reaction at room temperature gave no **3c**. At 80 °C, CO_2Et group tolerated the present reaction, a 54% yield of the adduct **3c** was obtained.



$\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ -catalyzed reaction of propargyl ethers.

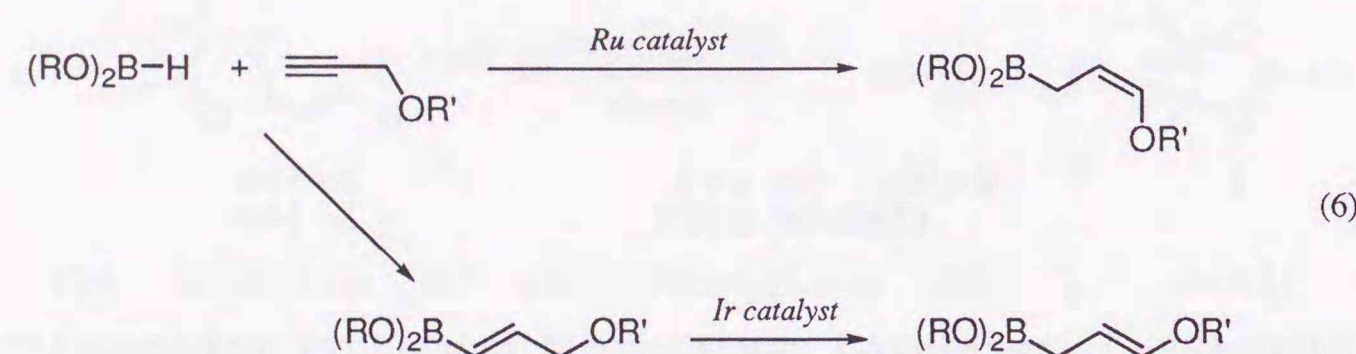
Interestingly, in the use of propargyl ethers **2d, e** as substrate, the above $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ -catalyzed hydroboration involved carbon-carbon double bond isomerization of the adduct **3** (eq. 5).



At room temperature, the reaction of **2d** with **1** gave a mixture of **3d** (6% yield) and **4d** (74% yield, *Z/E* = 87/13). Then, the reaction at 80 °C, bringing about complete isomerization to γ -alkoxyallylboronates **4**, took place smoothly. That of *t*-butyldimethylsilyl propargyl ether **2b** with **1** afforded an 85 % isolated yield of **4d**. At 80 °C, **3d, e** were obtained in trace amount. Stereochemically, ^1H NMR analysis of **4d** indicated a predominant

formation of its (Z)-isomer (Z/E = 87/13). The stereoselectivity was affected by the protective group of ethers used; i.e., the hydroboration of benzyl ether **2e** resulted in a 73 % yield of **4e** with lower isomeric ratio (Z/E = 73/27).

This (Z)-stereoselectivity in the present reaction is unique, because Miyaura has demonstrated the iridium-catalyzed isomerization of isolated 3-alkoxy-1-propenylboronate to (E)-allylboronate (eq. 6).¹²



Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. Solvents were distilled before use. $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$,¹³ $\text{RuCl}_2(\text{PPh}_3)_3$,¹⁴ and $\text{RuH}_2(\text{PPh}_3)_4$ ¹⁵ were prepared by the established methods. $\text{RuCpCl}(\text{PPh}_3)_2$ and $\text{Ru}_3(\text{CO})_{12}$ from commercial sources were used without purification or drying. Phenylethyne, 3,3-dimethyl-1-butyne, and ethyl propiolate were purchased from Tokyo Kasei Kogyo Co. Propargyl ethers were prepared from 2-propyn-1-ol by the known method.¹⁶

Hydroboration of alkynes with pinacolborane. A typical procedure. A flask was charged with $\text{RuHCl}(\text{CO})(\text{PPh}_3)_3$ (0.03 mmol) and toluene (4 ml) under an argon flow. After pinacolborane **1** (1.1 mmol) and alkynes **2** (1.0 mmol) were added, the mixture was stirred at room temperature for 16 h. The reaction mixture was diluted with toluene, washed with water, and dried over MgSO_4 . The solvent was evaporated, and alkenylboronate **3** was isolated by distillation with Kugelrohr or chromatography over silica gel.

The following compounds were prepared by the above procedure.

(E)-1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2-phenylethene: IR(neat) 2930, 2360, 1732, 1624, 1578, 1495, 1450, 1352, 1272, 1211, 1145 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.32 (s, 12 H), 6.16 (d, J = 18.5 Hz, 1 H), 7.3-7.6 (m, 6 H); ^{13}C NMR (CDCl_3) δ 24.84, 83.35, 127.09, 128.55, 128.88, 137.59, 149.52; MS (m/z) 230 (49, M^+), 215 (24), 187 (10), 172 (11), 157 (13), 144 (56), 130 (100); HRMS for $\text{C}_{14}\text{H}_{19}\text{O}_2\text{B}$ calcd 230.1478, found 230.1477.

(E)-1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-3,3-dimethyl-1-butene: IR (neat) 2978, 1147 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.02 (s, 9 H), 1.27 (s, 12 H), 5.35 (d, J = 18.5 Hz, 1 H), 6.64 (d, J = 18.5 Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.78, 28.77, 34.99, 82.98, 164.41;

MS (*m/z*) 210 (8, *M*⁺), 195 (16), 153 (36), 110 (25), 101 (100), 83 (61); HRMS (*m/z*) for C₁₂H₂₃O₂B calcd 210.1755, found 210.1751.

Ethyl (E)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-acrylate: IR (neat) 2981, 1726, 1629, 1348, 1167, 1144, 1035, 970 cm⁻¹; ¹H NMR (CDCl₃) δ 1.28 (s, 15 H), 4.21 (q, *J* = 7.0 Hz, 2 H), 6.63 (d, *J* = 18.3 Hz, 1 H), 6.77 (d, *J* = 18.3 Hz, 1 H); ¹³C NMR (CDCl₃) δ 14.11, 24.67, 60.49, 83.93, 138.68, 165.90; MS (*m/z*) 226 (1, *M*⁺), 211 (100), 199 (2), 184 (14), 181 (73), 169 (14), 157 (10), 153 (17), 142 (3), 126 (14), 110 (8), 99 (45), 86 (3), 73 (10); HRMS for C₁₁H₁₉O₄B calcd 226.1376, found 226.1414.

Reaction of propargyl ethers with pinacolborane. The above procedure by using propargyl ethers (1.0 mmol) as substrate was carried out at 80°C. The reaction mixture was diluted with toluene, washed with water, and dried over MgSO₄. The solvent was evaporated, and allylboronate was isolated by distillation with Kugelrohr. The isomer ratio was determined by ¹H NMR.

(Z)-1-tert-Butyldimethylsilyloxy-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-1-propene: IR (neat) 2931, 1655, 1323, 1146, 1101, 838, 677 cm⁻¹; ¹H NMR (CDCl₃) δ 0.12 (s, 6 H), 0.92 (s, 9 H), 1.24 (s, 12 H), 1.69 (d, *J* = 7.6 Hz, 2 H), 4.57 (dt, *J* = 5.8, 7.6 Hz, 1 H), 6.20 (d, *J* = 5.8 Hz, 1 H); ¹³C NMR (CDCl₃) δ -5.34, 24.57, 25.69, 83.06, 105.22, 138.47; MS (*m/z*) 298 (1, *M*⁺), 283 (3), 241 (22), 183 (5), 182 (1), 157 (2), 141 (100); HRMS for C₁₅H₃₁O₃SiB calcd 298.2136, found 298.2112.

1-Benzyloxy-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-1-propene. The spectral data were obtained from the mixture. ¹H NMR (CDCl₃) δ 1.24 (s, *Z*-isomer) and 1.27 (s, *E*-isomer) [total 12 H], 1.53 (d, *J* = 7.3 Hz, *E*-isomer) and 1.71 (d, *J* = 7.6 Hz, *Z*-isomer) [total 2H], 4.52 (dt, *J* = 6.1, 7.6 Hz, *Z*-isomer) and 4.93 (dt, *J* = 7.3, 12.5 Hz, *E*-isomer) [total 1H], 4.71 (s, *E*-isomer) and 4.80 (s, *Z*-isomer) [total 2 H], 6.04 (d, *J* = 6.1 Hz, *Z*-isomer) and 6.33 (d, *J* = 12.5 Hz, *E*-isomer) [total 1H]; ¹³C NMR (CDCl₃) δ 24.55, 24.75, 71.00, 73.29, 83.12, 99.85, 102.19, 127.15, 127.55, 127.60, 127.69, 128.33, 128.38, 144.57, 145.91.

References

1. (a) Männig, D.; Nöth, H. *Angew. Chem., Int. Ed. Engl.* 1985, 24, 878. (b) For a review, see: Burgess, K.; Ohlmeyer, M. *J. Chem. Rev.* 1991, 91, 1179.
2. Collman, J. P.; Finke, R. G.; Hegedus, L. S.; Norton, J. R. *Principles and Applications of Organotransition Metal Chemistry*; University Science: Mill Valley, 1987.
3. Dorigo, A. E.; Schleyer, P. v. R. *Angew. Chem., Int. Ed. Engl.* 1995, 34, 115.
4. Evans, D. A.; Fu, G. C.; Anderson, B. A. *J. Am. Chem. Soc.* 1992, 114, 6679.
5. Brown, J. M.; Lloyd-Jones, G. C. *J. Am. Chem. Soc.* 1994, 116, 866.
6. Burgess, K.; van der Donk, W. A.; Westcott, S. A.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. *J. Am. Chem. Soc.* 1992, 114, 9350.
7. Westcott, S. A.; Blom, H. P.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. *Inorg. Chem.* 1993, 32, 2175.
8. (a) Pereira, S.; Srebnik, M. *Organometallics* 1995, 14, 3127. (b) Pereira, S.; Srebnik, M. *J. Am. Chem. Soc.* 1996, 118, 909. (c) Pereira, S.; Srebnik, M. *Tetrahedron Lett.* 1996, 37, 3283. (d) Yamamoto, Y.; Fujikawa, R.; Yamada, A.; Miyaura, N. *Chem. Lett.* 1999, 1069.
9. Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* 1992, 57, 3482.
10. (a) Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 6458. (b) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 2000, 65, 164. (c) Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y. *Synthesis* in press.
11. Clark, G. R.; Irvine, G. J.; Roper, W. R.; Wright, L. J. *Organometallics* 1997, 16, 5499.
12. (a) Moriya, T.; Suzuki, A.; Miyaura, N. *Tetrahedron Lett.*

- 1995, 36, 1887. (b) Yamamoto, Y.; Miyairi, T.; Miyaura, N. *J. Org. Chem.* 1999, 64, 296.
13. Ahmad, N.; Levison, J. J.; Robinson, S. D.; Uttley, M. F. *Inorg. Synth.* 1974, 15, 45.
14. Hallman, P. S.; Stephenson, T. A.; Wilkinson, G. *Inorg. Synth.* 1970, 12, 237.
15. Young, R.; Wilkinson, G. *Inorg. Synth.* 1977, 17, 75.
16. Green, T. W.; Wuts, P. G. M. *Protective Groups in Organic Synthesis*; Wiley: New York, 1991.

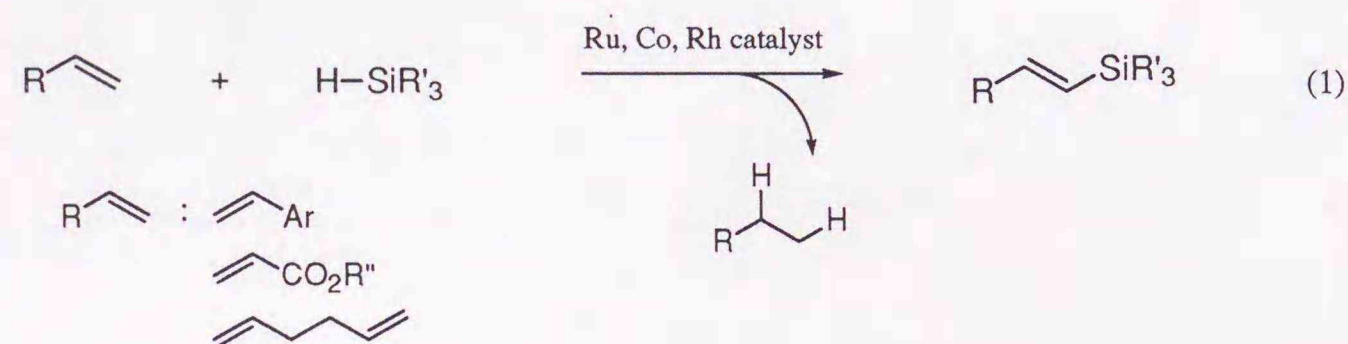
Chapter 10.

Rhodium-Catalyzed Dehydrogenative Coupling Reaction of Vinylarenes with Pinacolborane to Vinylboronates

The treatment of pinacolborane with vinylarenes in the presence of a catalytic amount of $[\text{RhCl}(\text{cod})]_2$, through a dehydrogenative borylation, provides pinacol esters of (*E*)-2-arylethenylboronates. In the presence of the phosphine-free rhodium complex, the reaction of pinacolborane involved boron, rather than hydride, migration to alkenes.

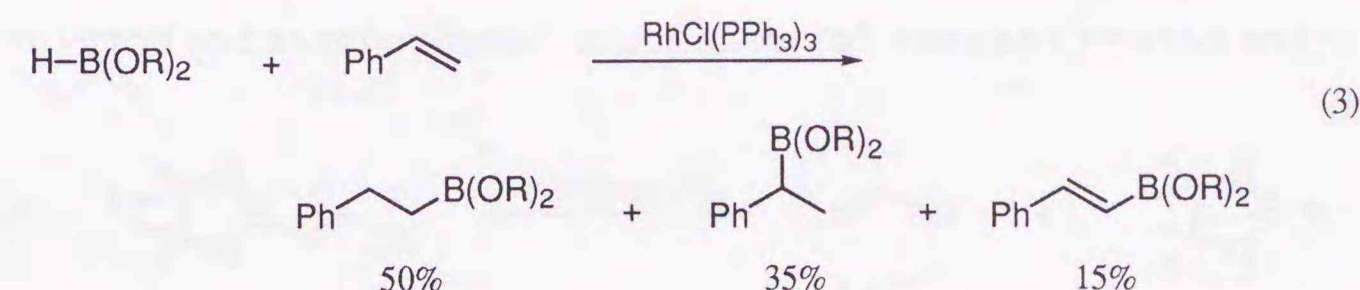
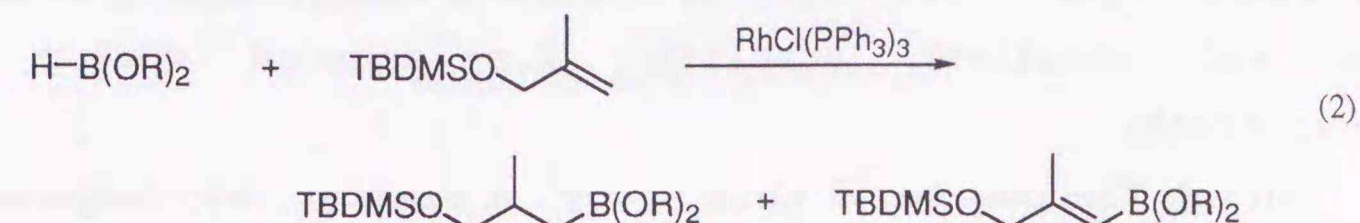
Introduction

Dehydrogenative silylation of organic compounds with hydrosilanes is useful method for the synthesis of organosilicon compounds.¹ The process is effectively catalyzed by transition metal complexes. Dehydrogenative silylation of alkenes is attractive as a useful alternative to hydrosilylation of alkynes,² a reaction in which there are regio- and stereochemical problems. Although the major drawback of dehydrogenative silylation of alkenes is that it is competitive with hydrosilylation of alkenes under the reaction conditions, Murai and co-workers have developed highly selective dehydrogenative silylation (eq. 1).³

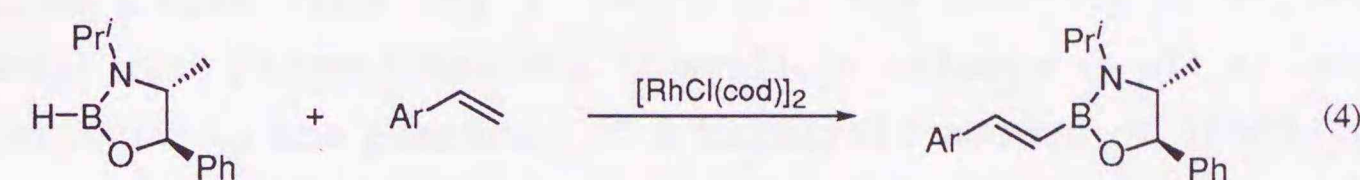


On the one hand, alkenylboronates are useful intermediates in organic synthesis, particularly with reactions involving carbon-carbon bond formation through a palladium-catalyzed Suzuki-Miyaura cross-coupling reaction.⁴ They can be prepared by several methods, notably by uncatalyzed⁵ or transition-metal-catalyzed⁶ hydroboration of alkynes with catecholborane.

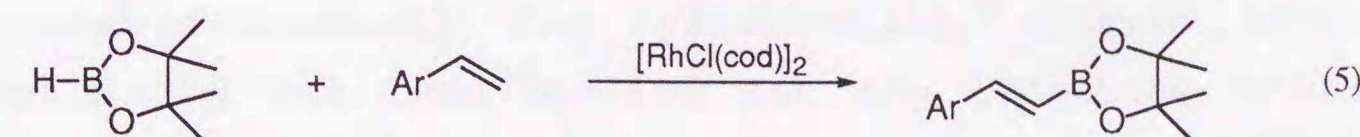
Several authors have observed the formation of dehydrogenated vinylboronates in the catalytic hydroboration of alkenes, suggesting the potential application of that process for preparing vinylboronates (eq. 2 and 3).^{7, 8} It is recognized that a mechanism involved regiospecific Rh-B addition to the double bond of the alkenes followed by Rh-H elimination.



Whereas dehydrogenative silylation is well studied, dehydrogenative borylation is relatively unexplored. Brown and Lloyd-Jones demonstrated a practical example of the rhodium-catalyzed dehydrogenative coupling reaction of vinylarenes with *N*-isopropyl oxazaborolidine (eq. 4).⁹



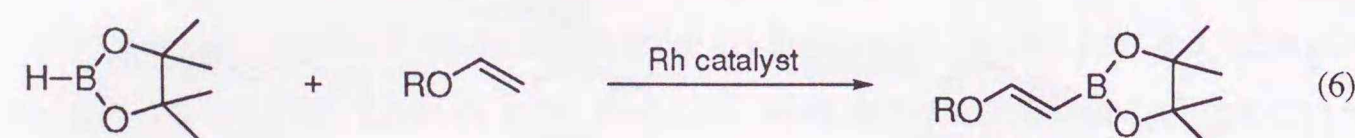
To our knowledge, however, there has been no report of dehydrogenative borylation using dialkoxyborane to provide a direct procedure for preparing vinylboronates from alkenes. In this chapter, the results of attempting the rhodium-catalyzed dehydrogenative borylation of vinylarenes by using pinacolborane is described (eq. 5).



Recently, pinacolborane has been widely recognized as a potent borane reagent,¹⁰ and utilized in the transition-metal-catalyzed hydroboration of alkynes or alkenes^{8, 11} and the borylation of aryl halides.¹² Further, the resulting pinacolboronates exhibit

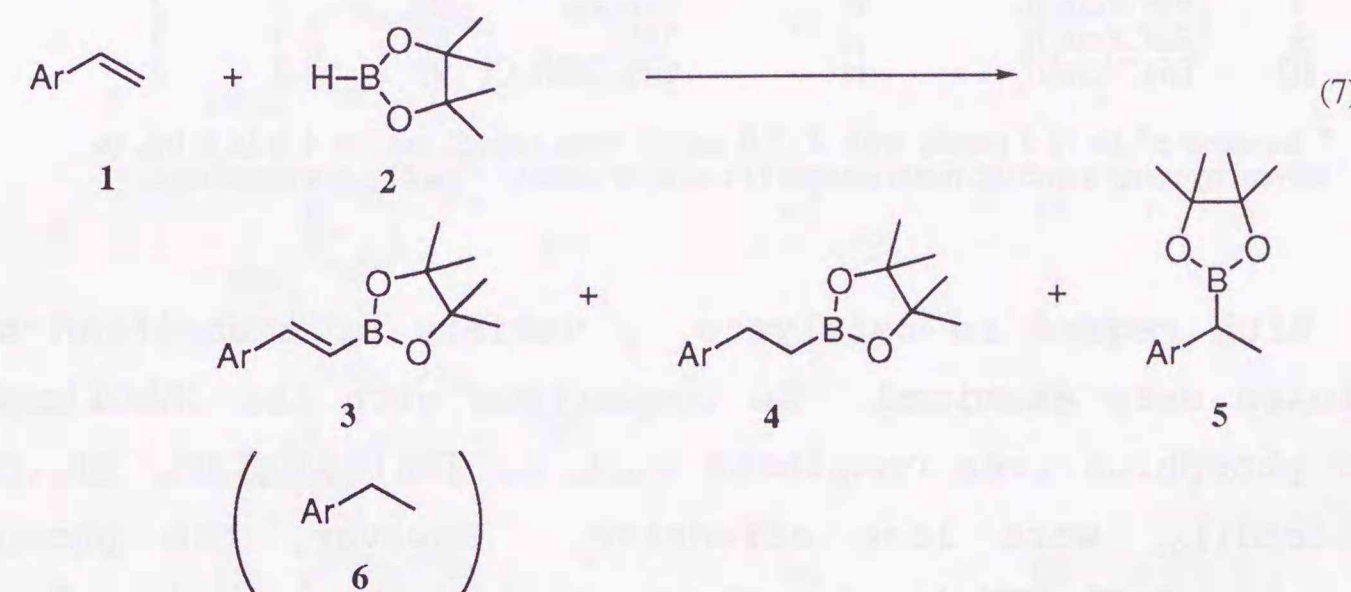
good reactivity for conversion of the boron functionality to other atoms and excellent stability for aqueous workup and chromatography.

During the course of this study, a similar dehydrogenative borylation of vinyl ethers with pinacolborane was reported by Westcott (eq. 6).¹³ Thus, pinacolborane has been recognized as an effective borane reagent for selective dehydrogenative borylation.



Results and Discussion

Reaction Conditions.



The reaction conditions were optimized using styrene 1a (Ar = Ph) as a substrate (eq. 7, Table 1). The reaction of styrene 1a (2 mmol) with pinacolborane 2 (1 mmol) in toluene (4 ml) at ambient temperature in the presence of a catalytic amount of $[\text{RhCl}(\text{cod})]_2$ (0.005 mmol) caused a dehydrogenative coupling to give (*E*)-2-phenylethenylboronate 3a (94% GLC yield based on 2) along with a small quantity of hydroboration products (2-phenylethylboronate 4a, 3%; 1-phenylethylboronate 5a, 3%). Concurrently, ethylbenzene 6a was generated in 46% yield based on 1a, exhibiting that styrene 1a acted as a hydrogen acceptor.³

It is interesting to note that dehydrogenative borylation by pinacolborane in the presence of a phosphine-free rhodium catalyst proceeded predominantly over hydroboration,⁹ whereas, commonly, pinacolborane has been applied for the phosphine-containing rhodium-catalyzed hydroboration of alkenes, including vinylarenes.⁸ It has hitherto been reported that other borane reagents usual for catalytic hydroboration, such as catecholborane or *N*-methyl oxazaborolidine, were not suitable for selective dehydrogenative borylation.⁹

Table 1. Reaction of Styrene under Various Conditions^a

entry	catalyst	temp.	solvent	yield (%) ^b		
				3a	4a	5a
1	[RhCl(cod)] ₂	rt	toluene	94	3	3
2	[RhCl(cod)] ₂ /4PPh ₃	rt	toluene	8	2	15
3	[Rh(cod)] ₂ BF ₄	rt	benzene	6	23	64
4	Rh ₄ (CO) ₁₂	rt	toluene	5	0	2
5	[IrCl(cod)] ₂	rt	toluene	3	12	44
6	[RuCl ₂ (cod)] _n /4PPh ₃	60°C	benzene	57	16	12
7	[RhCl(cod)] ₂	rt	benzene	90	5	3
8	[RhCl(cod)] ₂	rt	dioxane	95	2	3
9	[RhCl(cod)] ₂	rt	THF	85	7	3
10	[RhCl(cod)] ₂	rt	CH ₂ ClCH ₂ Cl	95	2	3

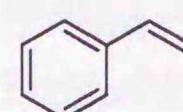
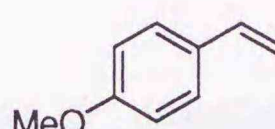
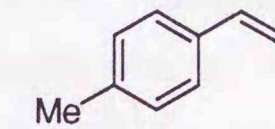
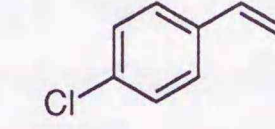
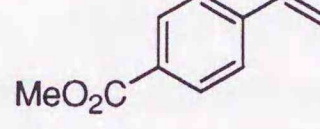
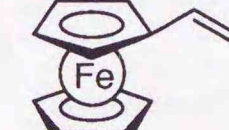
^a Reaction of **1a** (2.0 mmol) with **2** (1.0 mmol) were carried out for 4 h in 4 mL of solvent by using transition metal catalyst (1 mol% of metal). ^b GLC yields based on **2**.

With regard to catalysts, a variety of transition metal complexes were examined. In comparison with the [RhCl(cod)]₂, other phosphine-free complexes such as [Rh(cod)]₂BF₄, Rh₄(CO)₁₂, [IrCl(cod)]₂, were less effective. However, the phosphine containing RuCl₂(PPh₃)₃ showed some catalytic activity for the dehydrogenative borylation at 60 °C (**3a**, 57%; **4a**, 16%; **5a**, 12%). Five solvents, including toluene, benzene, CH₂ClCH₂Cl, THF, and dioxane, were tested, and it was observed that these did not play an important role.

Dehydrogenative borylation of representative alkenes.

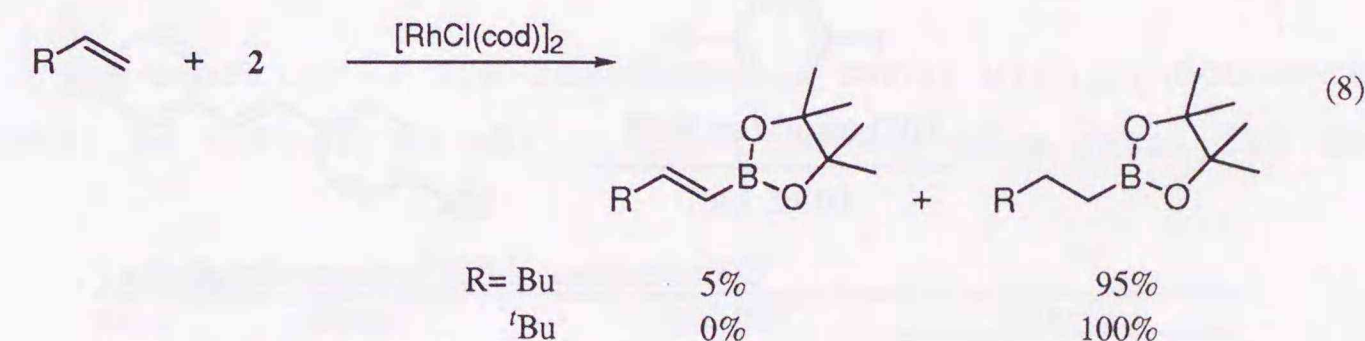
The results obtained with representative vinylarenes are summarized in Table 1. As shown, the present reaction proceeded regio- and stereoselectively; that is, neither 1-arylethenylboronate nor the (*Z*)-isomer was produced, although **3** was contaminated with a small amount of hydroboration products **4** and **5** in each case. The presence of functional groups such as MeCO₂ in the initial **1** did not interfere with the outcome of the present reaction (entry 5), corroborating that **2** was inert to many functional groups. In addition, the differences in yields and in selectivity among vinylarenes having electron-donating or electron-withdrawing groups were not significant (entries 2-5). Interestingly, the present application for vinylferrocene **1f**, which previously resulted in a low yield in the case of employment of

Table 2. Reaction of Representative **1**^a

entry	alkene 1	yield (%) of boronates ^b	ratio (%) ^c		
			3	4	5
1	 (1a)	84	96	3	1
2	 (1b)	90	95	4	1
3	 (1c)	93	95	3	2
4	 (1d)	87	95	3	2
5	 (1e)	86	93	4	3
6	 (1f)	85	85	15	0

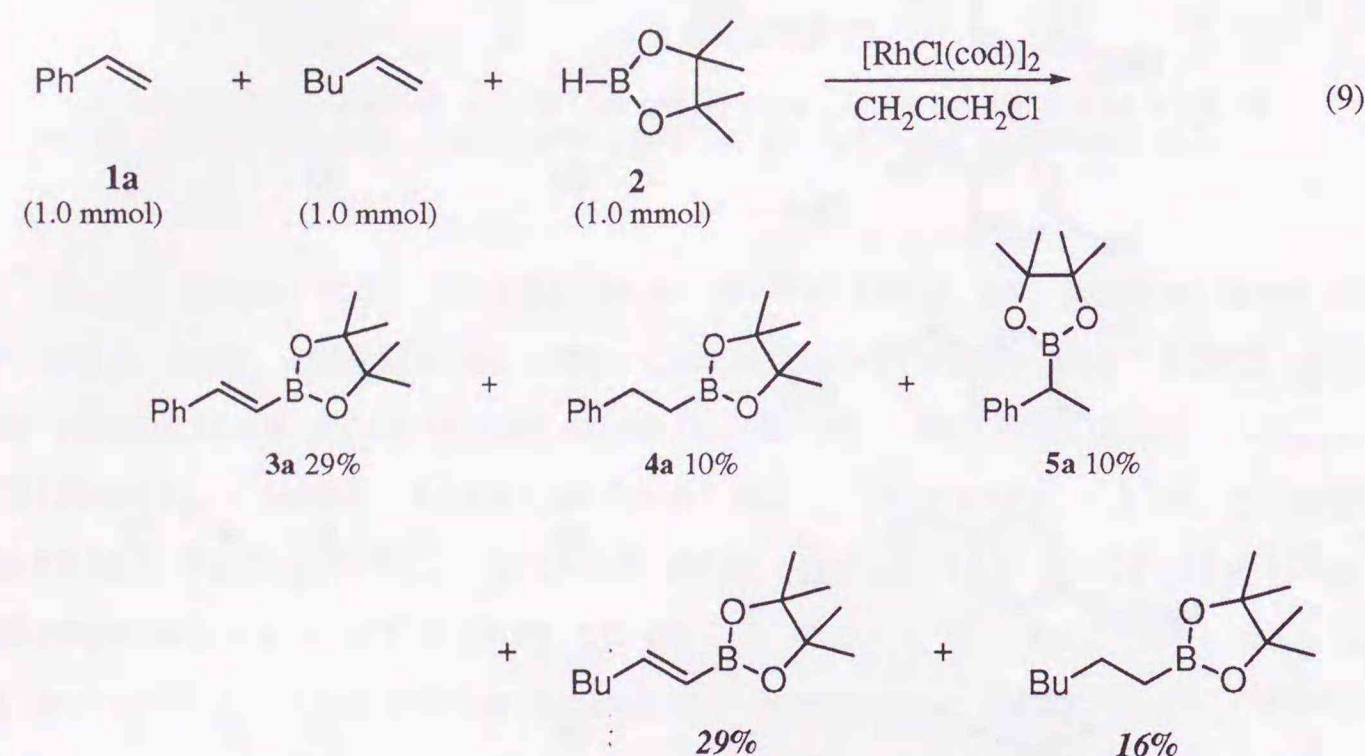
^a All reactions were conducted in toluene (4 ml) at room temperature for 4 h using **1** (2.0 mmol) and **2** (1.0 mmol) in the presence of [RhCl(cod)]₂ (0.005 mmol). ^b Isolated yields of a mixture of **3**, **4** and **5** by Kugelrohr distillation. ^c Determined by GLC analysis of isolated products.

N-isopropyl oxazaborolidine,⁹ also gave the corresponding **3** without significant difficulty (entry 6).



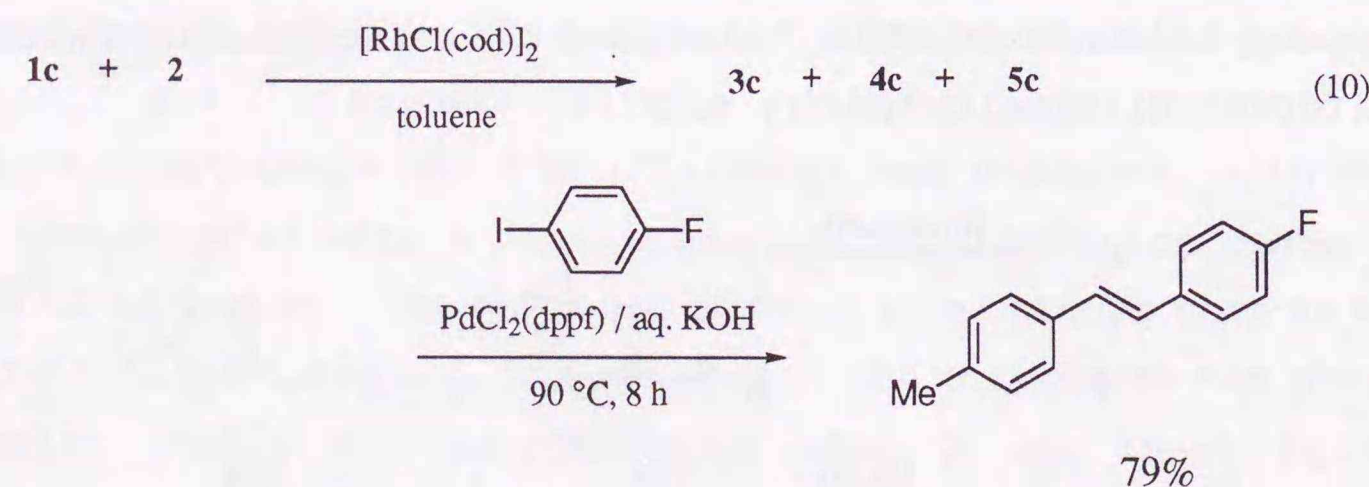
On the other hand, all attempts at the dehydrogenative borylation of other alkenes except for vinylarenes were unsuccessful. In the case of aliphatic alkenes such as 1-hexene and 3,3-dimethyl-1-butene, the usual hydroboration only proceeded

under the present condition, and trace amounts (less than 5%) of the vinylboronates could be detected by GLC (eq. 8). However, in the presence of additional styrene **1a**, the selectivity of dehydrogenative borylation of 1-hexene increased (eq. 9). Thus, vinylarene **1** appeared to play an important role as a ligand of phosphine-free rhodium catalyst.



One-pot synthesis of stilbenes.

The potential versatility of the present borylation was demonstrated by the one-pot synthesis of stilbenes (eq. 10).



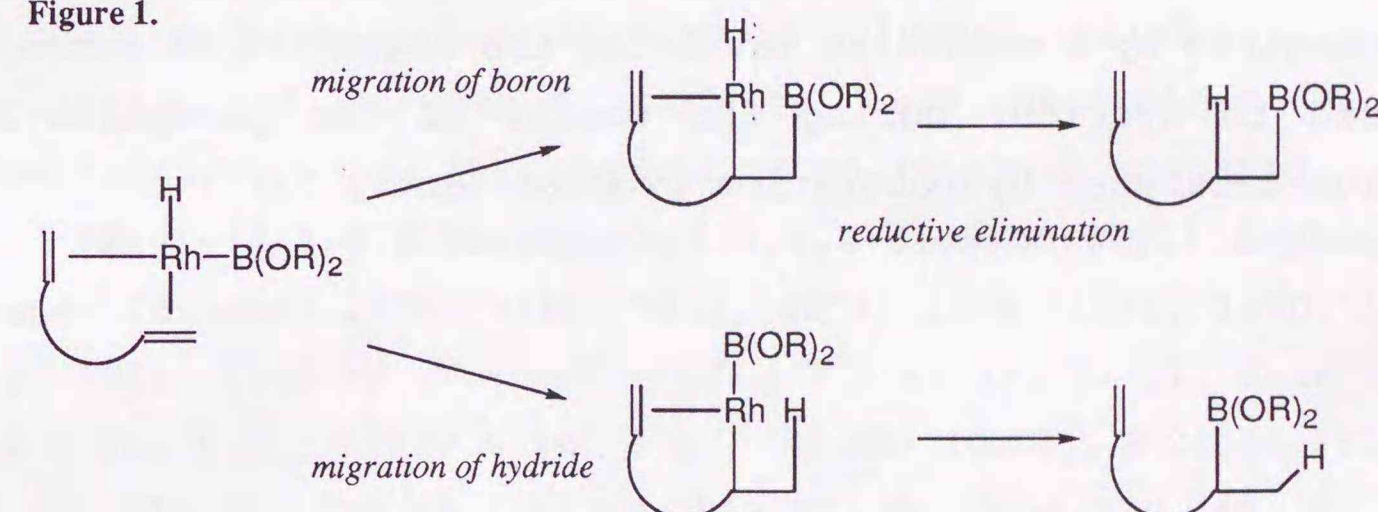
Although the dehydrogenative borylation of **1** provided a mixture of the major alkenylboronates and a small amount of alkylboronates, the resulting solution could be used directly for the next Suzuki-Miyaura reaction, since alkylboronates such as **4**

and **5** were not capable of palladium-catalyzed cross-coupling.¹⁴ Thus, the cross-coupling of **3c** prepared from **1c** (3 mmol) with 4-fluoriodobenzene (1.0 mmol) at 90 °C for 8 h in the presence of PdCl₂(dppf) (0.03 mmol) and 3M aq. KOH (1 ml) provided the corresponding stilbene in 79% isolated yield based on the iodoarene employed.

Hydroboration of 1,5-hexadiene with pinacolborane.

The above dehydrogenative borylation should involve migratory insertion of alkene into the Rh-B bond of borylrhodium complex generated by the oxidative addition of pinacolborane to phosphine-free [RhCl(cod)]₂. On the other hand, it is recognized that the catalytic hydroboration involves hydride, rather than boron, migration to alkenes.¹⁵ Thus, the effect of the phosphine ligand on the regioselectivity of the rhodium-catalyzed olefin-directed hydroboration was examined (Figure 1).

Figure 1.



The reaction of 1,5-hexadiene (4 mmol) with pinacolborane **2** (1 mmol) in toluene (4 ml) in the presence of a catalytic amount

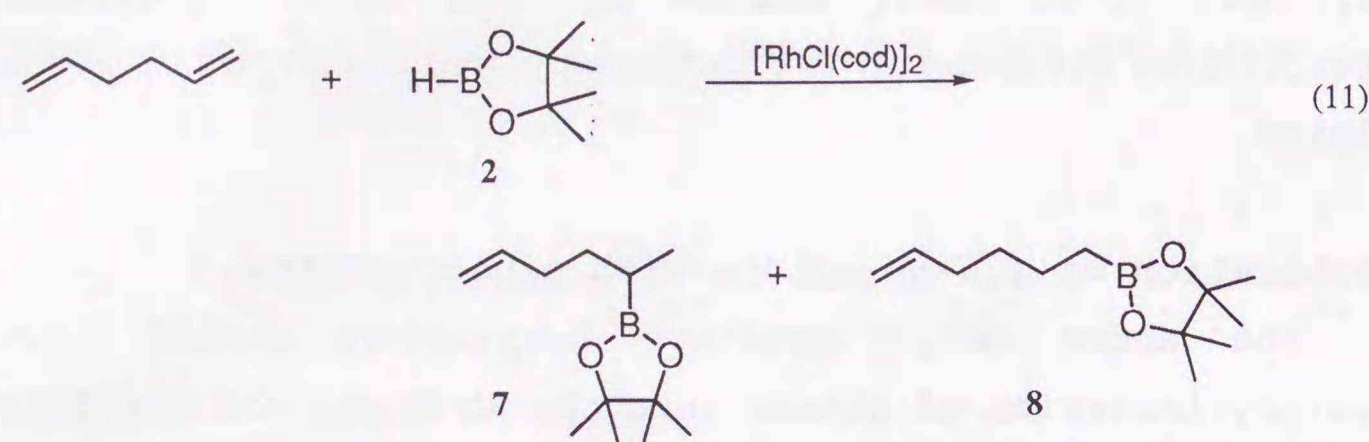
Table 3. Reaction of 1,5-hexadiene with **2**^a

entry	ligand	yield (%) ^b	ratio (%) ^b	
			7	8
1	dppf	64	83	17
2	PPh ₃	66	70	30
3	AsPh ₃	58	38	62

^a Reaction of 1,5-hexadiene (4.0 mmol) with **2** (1.0 mmol) were carried out for 4 h in 4 mL of toluene by using [RhCl(cod)]₂ (0.005 mmol) and ligand (0.04 mmol).

^b Determined by GLC.

of $[\text{RhCl}(\text{cod})]_2$ (0.005 mmol) caused hydroboration to give a mixture of Markovnikov- 7 and anti- Markovnikov-adduct 8 (eq. 11, Table 3).



In the presence of the phosphine ligand, such as dppf and PPh_3 , the reaction gave 7 predominantly (entries 1 and 2). Thus, the phosphine based rhodium catalysts induced hydride migration. The present regioselectivity was consistent with that of phosphinite- or amide-directed hydroboration.¹⁵

On the other hand, the regioselectivity was more economically accommodated by a mechanism involving the migration of boron, as opposed to hydride, during the course of the phosphine-free rhodium-catalyzed hydroboration process (entry 3).

Experimental Section

For general informations on instruments, see experimental section in chapter 3.

Materials and reagents. The catalysts from commercial sources were used without purification or drying. All alkenes were purchased from Tokyo Kasei Kogyo Co. except for methyl 4-vinylbenzoate, which were prepared from 4-chlorostyrene by the known method.¹⁶

Reaction of styrene with pinacolborane. Reaction conditions (Table 1). To a solution of rhodium (0.01 mmol) or ruthenium complex (0.03 mmol) in 4 mL of solvents was added pinacolborane 1 (115 mg, 1.0 mmol) and styrene 2a (1.5 mmol). After being stirred for 4 h, the reaction mixture was taken up in toluene, washed with water. The yields of borylated products were determined by gas chromatography using tetradecane as an internal standard.

(E)-1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2-phenyl-ethene: IR (neat) 2930, 2360, 1732, 1624, 1578, 1495, 1450, 1352, 1272, 1211, 1145 cm^{-1} ; ^1H NMR (CDCl_3) δ 1.32 (s, 12 H), 6.16 (d, J = 18.5 Hz, 1 H), 7.3-7.6 (m, 6 H); ^{13}C NMR (CDCl_3) δ 24.84, 83.35, 127.09, 128.55, 128.88, 137.59, 149.52; MS (m/z) 230 (49, M^+), 215 (24), 187 (10), 172 (11), 157 (13), 144 (56), 130 (100); HRMS for $\text{C}_{14}\text{H}_{19}\text{O}_2\text{B}$ calcd 230.1478, found 230.1477.

1-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2-phenyl-ethane: ^1H NMR (CDCl_3) δ 1.13 (t, J = 8.1 Hz, 2 H), 1.22 (s, 12 H), 2.75 (t, J = 8.1 Hz, 2 H), 7.2-7.3 (m, 5 H); ^{13}C NMR (CDCl_3) δ 24.72, 29.89, 82.99, 125.42, 127.94, 128.10, 144.35; MS (m/z) 232 (6, M^+), 217 (11), 175 (26), 146 (7), 132 (55), 105 (36), 84 (100).

2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-2-phenyl-ethane: MS (m/z) 232 (50, M^+), 217 (25), 174 (11), 146 (12), 132 (56), 105 (100).

Synthesis of alkenylboronates. Typical Procedure (Table 2).

A flask was charged with $[\text{RhCl}(\text{cod})]_2$ (0.005 mmol) and toluene (4 ml) under an argon flow. Pinacolborane 1 (1.0 mmol) and vinylarenes 2 (2.0 mmol) were added successively, and the mixture was stirred at room temperature for 4 h. The reaction mixture was diluted with toluene, washed with water, and dried over MgSO_4 . The solvent was evaporated, and alkenylboronate 3 was isolated by distillation with Kugelrohr or chromatography over silica gel.

The following compounds were prepared by the above procedure.

4-[(E)-2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-ethenyl]anisole (Table 2, entry 2): ^1H NMR (CDCl_3) δ 1.31 (s, 12 H), 3.81 (s, 3 H), 6.01 (d, $J = 18.6$ Hz, 1 H), 6.87 (d, $J = 8.5$ Hz, 2 H), 7.35 (d, $J = 18.6$ Hz, 1 H), 7.44 (d, $J = 8.5$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.81, 55.28, 83.23, 113.97, 128.48, 130.43, 149.07, 160.30; MS (m/z) 260 (100, M^+), 245 (15), 202 (6), 187 (8), 175 (20), 160 (74), 144 (83); HRMS for $\text{C}_{15}\text{H}_{21}\text{O}_3\text{B}$ calcd 260.1583, found 260.1584.

4-[(E)-2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-ethenyl]toluene (Table 2, entry 3): ^1H NMR (CDCl_3) δ 1.31 (s, 12 H), 2.34 (s, 3 H), 6.11 (d, $J = 18.6$ Hz, 1 H), 7.14 (d, $J = 7.9$ Hz, 2 H), 7.37 (d, $J = 18.6$ Hz, 1 H), 7.38 (d, $J = 7.9$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 21.33, 24.82, 83.28, 127.03, 129.29, 134.81, 138.96, 149.48; MS (m/z) 244 (70, M^+), 229 (22), 186 (11), 171 (11), 158 (47), 144 (100); HRMS for $\text{C}_{15}\text{H}_{21}\text{O}_2\text{B}$ calcd 244.1635, found 244.1638.

4-[(E)-2-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-ethenyl]chlorobenzene (Table 2, entry 4): ^1H NMR (CDCl_3) δ 1.31 (s, 12 H), 6.13 (d, $J = 18.6$ Hz, 1 H), 7.30 (d, $J = 8.2$ Hz, 2 H), 7.33 (d, $J = 18.6$ Hz, 1 H), 7.41 (d, $J = 8.5$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.82, 83.47, 128.24, 128.81, 134.63, 135.99, 148.03; MS (m/z) 266 (15), 264 (49, M^+), 249 (26), 206 (9), 178 (46), 164 (100); HRMS for $\text{C}_{14}\text{H}_{18}\text{O}_2^{35}\text{ClB}$ calcd 264.1088, found 264.1113.

Methyl 4-[(E)-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)-ethenyl]benzoate (Table 2, entry 5): ^1H NMR (CDCl_3) δ 1.32 (s, 12 H), 3.91 (s, 3 H), 6.28 (d, $J = 18.5$ Hz, 1 H), 7.41 (d, $J = 18.5$ Hz, 1 H), 7.53 (d, $J = 8.4$ Hz, 2 H), 8.01 (d, $J = 8.4$ Hz, 2 H); ^{13}C NMR (CDCl_3) δ 24.82, 52.13, 83.58, 126.91, 129.92, 130.15, 141.73,

148.14, 166.80; MS (m/z) 288 (41, M^+), 273 (31), 257 (18), 230 (9), 202 (61), 188 (42), 157 (100); HRMS for $\text{C}_{16}\text{H}_{21}\text{O}_4\text{B}$ calcd 288.1533, found 288.1513.

[(E)-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolyl)ethenyl]-ferrocene (Table 2, entry 6): ^1H NMR (CDCl_3) δ 1.30 (s, 12 H), 4.10 (s, 5 H), 4.27 (t, $J = 1.8$ Hz, 2 H), 4.42 (t, $J = 1.8$ Hz, 2 H), 7.53 (d, $J = 18.2$ Hz, 1 H), 8.01 (d, $J = 18.2$ Hz, 1 H); ^{13}C NMR (CDCl_3) δ 24.81, 67.58, 69.44, 69.60, 83.07, 149.44; MS (m/z) 338 (100, M^+), 280 (6), 256 (5), 238 (16), 173 (41); HRMS for $\text{C}_{18}\text{H}_{23}\text{O}_2\text{BFe}$ calcd 338.1141, found 338.1139.

Cross-coupling of alkenylboronate with iodoarene (eq. 8).

To the solution of 3c, prepared *in situ* from 2c (3 mmol), 4-fluoriodobenzene (218 mg, 0.98 mmol) was added. Aqueous 3M KOH (1 mL, 3 mmol) and $\text{PdCl}_2(\text{dppf})$ (22mg, 0.03 mmol) were added successively, and the mixture was stirred at 90 °C for 8 h. The mixture was diluted with ether, washed with water, and dried (MgSO_4). The coupling product, 1-(4-methylphenyl)-2-(4-fluorophenyl)-ethene, was isolated by column chromatography on a silica gel (hexane) to give a 79% yield (166 mg): ^1H NMR (CDCl_3) δ 2.36 (s, 3 H), 7.00 (d, $J = 4.0$ Hz, 2 H), 7.03 (t, $J = 8.7$ Hz, 2 H), 7.16 (d, $J = 7.8$ Hz, 2 H), 7.39 (d, $J = 7.8$ Hz, 2 H), 7.46 (dd, $J = 5.4$, 8.7 Hz, 2 H); ^{13}C NMR (CDCl_3) δ 21.23, 115.46, 115.63, 126.23, 127.79, 128.39, 129.41, 134.37, 137.56, 163.18.

Hydroboration of 1,5-hexadiene with pinacolborane (eq. 9).

To a mixture of $[\text{RhCl}(\text{cod})]_2$ (0.005 mmol) and AsPh_3 (0.04 mmol) in toluene (4 mL) was added pinacolborane 1 (1.0 mmol) and 1,5-hexadiene (2.0 mmol). After being stirred for 4 h at room temperature, the reaction mixture was taken up in benzene, washed with water, and dried over MgSO_4 . The products were isolated by column chromatography on a silica gel.

5-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-hexene: IR (neat) 3077, 2979, 2929, 1640, 1459, 1371, 1146 cm^{-1} ; ^1H NMR (CDCl_3) δ 0.97 (d, 3 H, $J = 6.7$ Hz), 1.04 (tq, 1 H, $J = 6.7$, 7.9 Hz), 1.24, (s

12 H), 1.38 (dt, 1 H, $J = 7.3, 7.9$ Hz), 1.55 (dt, 1 H, $J = 7.3, 7.9$ Hz), 2.07 (dt, 2 H, $J = 6.7, 7.3$ Hz), 4.92 (dd, 1 H, $J = 1.2, 10.4$ Hz), 5.00 (dd, 1 H, $J = 1.2, 17.1$ Hz), 5.82 (ddt, 1 H, $J = 6.7, 10.4, 17.1$ Hz); ^{13}C NMR (CDCl_3) δ 15.36, 23.55, 24.75, 32.43, 33.14, 82.82, 114.16, 139.27; MS (EI, m/z) 210 (4, M^+), 195 (16), 153 (25), 82 (100), 69 (79), 57 (65); HRMS (EI, m/z) for $\text{C}_{12}\text{H}_{23}\text{O}_2\text{B}$ calcd 210.1791, found 219.1804.

6-(4,4,5,5-Tetramethyl-1,3,2-dioxaborolyl)-1-hexene: ^1H NMR (CDCl_3) δ 0.78 (t, 2 H, $J = 7.3$ Hz), 1.24 (s, 12 H), 1.4-1.5 (m, 4 H), 2.04 (dt, 2 H, $J = 6.1, 7.3$ Hz), 4.92 (dd, 1 H, $J = 1.5, 9.8$ Hz), 4.99 (dd, 1 H, $J = 1.5, 17.1$ Hz), 5.81 (ddt, 1 H, $J = 6.1, 9.8, 17.1$ Hz); ^{13}C NMR (CDCl_3) δ 23.55, 24.80, 31.66, 33.57, 82.86, 114.03, 139.19; MS (EI, m/z) 210 (4, M^+), 195 (16), 153 (23), 125 (21), 101 (86), 82 (100), 57 (71); HRMS (EI, m/z) for $\text{C}_{12}\text{H}_{23}\text{O}_2\text{B}$ calcd 210.1792, found 210.1799.

References

1. For a recent review, see: Corey, J. Y. *Advances in Silicon Chemistry*; Larson, G. L., Ed.; JAI Press: Greenwich, 1991; p 327.
2. For a recent review, see: Ojima, I. *The Chemistry of Silicon Compounds*; Patai, S., Rappoport, Z., Eds.; Wiley: Chichester, 1989; p 1479.
3. (a) Kakiuchi, F.; Nogami, K.; Chatani, N.; Seki, Y.; Murai, S. *Organometallics* 1993, 12, 4748. (b) Kakiuchi, F.; Tanaka, Y.; Chatani, N.; Murai, S. *J. Organomet. Chem.* 1993, 456, 45. (c) Takeshita, K.; Seki, Y.; Kawamoto, K.; Murai, S.; Sonoda, N. *J. Org. Chem.* 1987, 52, 4846. (d) Seki, Y.; Takeshita, K.; Kawamoto, K.; Murai, S.; Sonoda, N. *J. Org. Chem.* 1986, 51, 3890.
4. For a recent review, see: Miyaura, N.; Suzuki, A. *Chem. Rev.* 1995, 95, 2457.
5. (a) Brown, H. C.; Gupta, S. K. *J. Am. Chem. Soc.* 1975, 97, 5249. (b) For a review, see: Lane, C. F.; Kabalka, G. W. *Tetrahedron* 1976, 32, 981.
6. (a) Gridnev, I. D.; Miyaura, N.; Suzuki, A. *Organometallics* 1993, 12, 590. (b) For a review, see: Burgess, K.; Ohlmeyer, M. J. *Chem. Rev.* 1991, 91, 1179.
7. Burgess, K.; van der Donk, W. A.; Westcott, S. A.; Marder, T. B.; Baker, R. T.; Calabrese, J. C. *J. Am. Chem. Soc.* 1992, 114, 9350.
8. Pereira, S.; Srebnik, M. *Tetrahedron Lett.* 1996, 37, 3283.
9. (a) Brown, J. M.; Lloyd-Jones, G. C. *Chem. Commun.* 1992, 710. (b) Brown, J. M.; Lloyd-Jones, G. C. *J. Am. Chem. Soc.* 1994, 116, 866.
10. Tucker, C. E.; Davidson, J.; Knochel, P. *J. Org. Chem.* 1992, 57, 3482.
11. a) Pereira, S.; Srebnik, M. *Organometallics* 1995, 14, 3127.

- (b) Pereira, S.; Srebnik, M. *J. Am. Chem. Soc.* 1996, 118, 909.
12. Murata, M.; Watanabe, S.; Masuda, Y. *J. Org. Chem.* 1997, 62, 6458.
 13. Vogels, C M.; Hayes, P. G.; Shaver, M. P.; Westcott, S. A. *Chem. Commun.* 2000, 51.
 14. Miyaura, N.; Ishiyama, T.; Sasaki, H.; Ishikawa, M.; Satoh, M.; Suzuki, A. *J. Am. Chem. Soc.* 1989, 111, 314.
 15. Evans, D. A.; Fu, G. C.; Anderson, B. A. *J. Am. Chem. Soc.* 1992, 114, 6679.
 16. Bowen, D. W. *Organic Syntheses*; Wiley: New York, 1955; Collect. Vol. III, p. 553.

List of Publications

1. "Palladium(0)-Catalyzed Cross-Coupling Reaction of Alkoxydiboron with Haloarenes: A Direct Procedure for Arylboronic Esters"
Ishiyama, T; Murata, M.; Miyaura, N.
J. Org. Chem., 1995, 60, 7508-7510.
2. "Novel Palladium(0)-Catalyzed Coupling Reaction of Dialkoxyborane with Aryl Halides: Convenient Synthetic Route to Arylboronates"
Murata, M.; Watanabe, S.; Masuda, Y.
J. Org. Chem. 1997, 62, 6458-6459.
3. "Synthesis of Arylsilanes via Palladium(0)-Catalyzed Silylation of Aryl Halides with Hydrosilane"
Murata, M.; Suzuki, K.; Watanabe, S.; Masuda, Y.
J. Org. Chem. 1997, 62, 8569-8571.
4. "Rhodium-Catalyzed Dehydrogenative Coupling Reaction of Vinylarenes with Pinacolborane to Vinylboronates"
Murata, M.; Watanabe, S.; Masuda, Y.
Tetrahedron Lett. 1999, 40, 2585-2588.
5. "Synthesis of Alkenylsilanes via Palladium(0)-Catalyzed Silylation of Alkenyl Iodides with Hydrosilane"
Murata, M.; Watanabe, S.; Masuda, Y.
Tetrahedron Lett. 1999, 40, 9255-9257.

6. "Palladium-Catalyzed Borylation of Aryl Halides or Triflates with Dialkoxyborane: A Novel and Facile Synthetic Route to Arylboronates"
Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y.
J. Org. Chem. 2000, 65, 164-168.
7. "Synthesis of Alkenylboronates via Palladium-Catalyzed Borylation of Alkenyl Triflates (or Iodides) with Pinacolborane"
Murata, M.; Oyama, T.; Watanabe, S.; Masuda, Y.
Synthesis 2000, 778-780.
8. "Palladium-Catalyzed Cross-Coupling Reaction of Tributyltin Hydride with Aryl Iodides: Formation of A Tin-Carbon Bond"
Murata, M.; Watanabe, S.; Masuda, Y.
Synlett 2000, 1043-1045.
9. "Regio- and Stereoselective Synthesis of Allylboranes via Platinum(0)-Catalyzed Borylation of Allyl Halides with Pinacolborane"
Murata, M.; Watanabe, S.; Masuda, Y.
Tetrahedron Lett. 2000, 41, 5877-5880.

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