



Title	Studies on the Nickel- and Platinum-Catalyzed Borylation of Aromatic Carbon-Hydrogen Bonds
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Doctoral Dissertation

**Studies on the Nickel- and Platinum-Catalyzed
Borylation of Aromatic Carbon–Hydrogen Bonds**

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January 2017

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Osaka University**

Preface and Acknowledgement

The research presented in this thesis was carried out under the direction of Professor Naoto Chatani of the Department of Applied Chemistry, Faculty of Engineering, Osaka University from April 2011 to March 2017. The thesis is concerned with the nickel- and platinum-catalyzed borylation of aromatic carbon-hydrogen bonds.

This thesis could not have been finished without the heartfelt help and support from numerous people. I wish to express my sincerest appreciation to all of those people who I spent the time with during the last 6 years in the Chatani group.

I express my utmost gratitude to Professor Naoto Chatani for his guidance and support throughout this work. He always gave me fruitful advice, support and encouragement for anything I attempted to do. He has a great enthusiasm for chemistry and deserves respect from his personality.

I would like to express my deepest gratitude to Professor Mamoru Tobisu for his valuable advice and continuous support. The advice derived from his logical and creative mind always encouraged me to work out issues and provided me new points of view to consider problems. Thanks to his respectable character and personality, there was always pleasant atmosphere to study in his group. It was a great delight for me to experience exciting chemistry and satisfying days under his supervision.

I deeply appreciate Professor Yoshiya Fukumoto for his instructive and expert advice based on his extensive and profound understanding in chemistry.

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January 2017

Takayuki Furukawa

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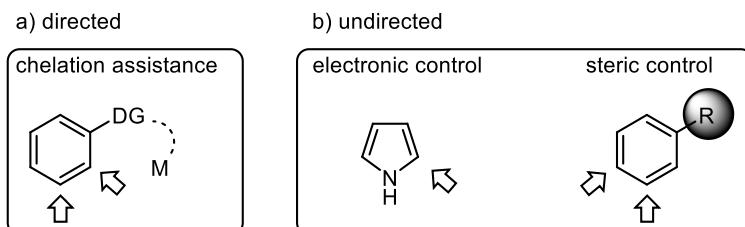
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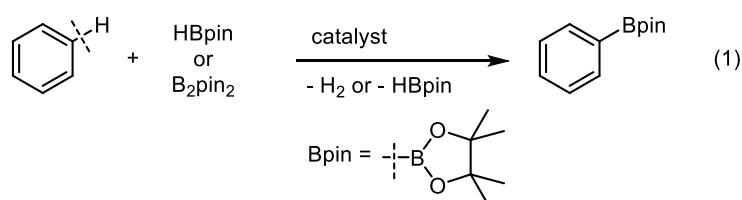
General Introduction

Catalytic C–H bond functionalization is one of the simplest and most straightforward methods for the synthesis of complex organic molecules from readily available hydrocarbons and their derivatives.¹ The catalytic transformation of C–H bonds omits the pre-activation steps prior to the introduction of the targeted functionality and therefore makes the process more efficient than traditional synthetic methods. One of the most reliable methods for C–H functionalization involves the use of a substrate containing a preinstalled coordinating group, which can direct a metal catalyst to react with a targeted C–H bond in a regioselective manner (Figure 1a, i.e., directed methodology). This method is very useful for the activation of C–H bonds that are located in close proximity to a directing group, which is normally the *ortho* position to the directing group in an aromatic system. C–H functionalization methods that do not rely on a directing group (i.e., undirected C–H functionalization) are highly desired from the view point that it could be used to achieve unique patterns of regioselectivity that would be otherwise unattainable using directed methods. The regioselectivity in undirected C–H functionalization is often determined by the electronic and steric properties of the substrate (Figure 1b).

Figure 1. Strategy for Regioselective C–H Functionalization

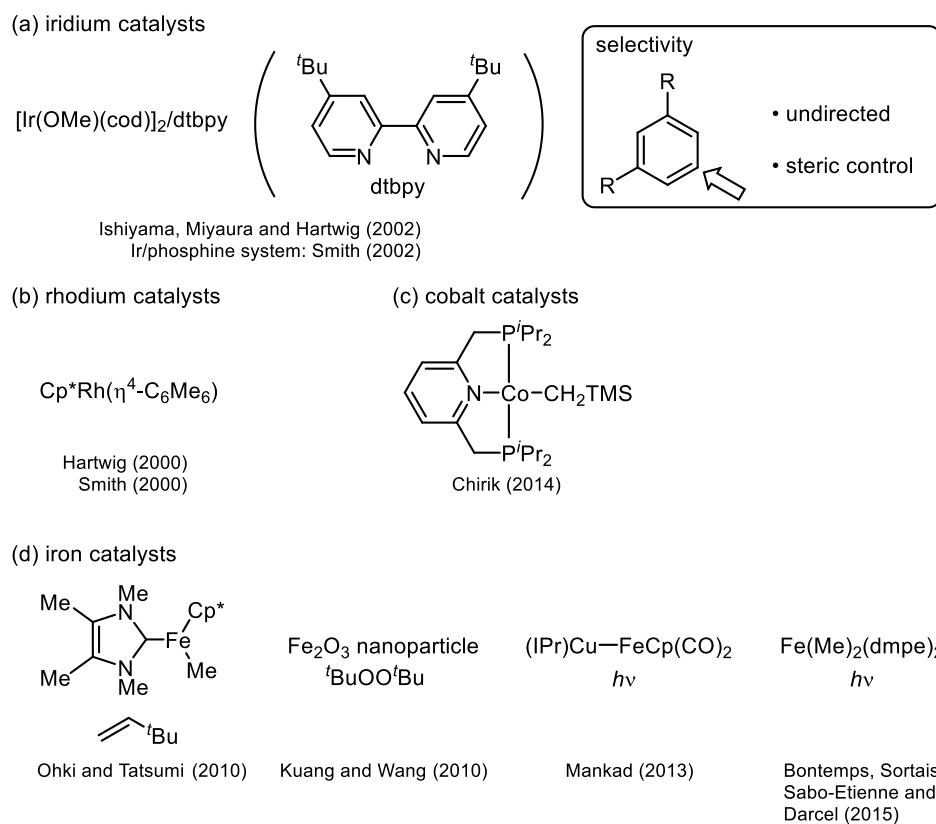


Among the undirected functionalization of C–H bonds, C–H borylation is currently recognized as one of the most powerful and reliable methods (eq. 1).^{2,3} The catalytic borylation of C–H bonds allows for the direct introduction of a synthetically useful boron functionality from readily available starting materials.³ Among the variety of catalysts that have been used in C–H borylation, the Ir/dtbpy-based complexes developed by Miyaura, Ishiyama and Hartwig are capable of catalyzing the borylation of aromatic C–H bonds with a high degree of efficiency and selectivity in an undirected manner (Figure 2a).² The regioselectivity of the C–H borylation reaction is normally controlled by the steric



environment surrounding the reacting C-H bonds. For example, the C-H borylation of 1,3-disubstituted benzene substrates occurs exclusively at the 5-position (Figure 2a, right). The outstanding catalytic activity and selectivity of iridium systems has resulted in their practical application in various areas in materials science and in the synthesis of fine chemicals. Since the first report on Ir/dtbpy catalysts, considerable progress has been made in the field of C-H borylation by modifying the properties of the ligands to the iridium complex. These attempts have resulted in considerable success in terms of improving catalytic efficiency⁴ and establishing novel levels of regioselectivity that go beyond simple steric control.⁵

Figure 2. Transition Metal Catalysts for the Borylation of Aromatic C-H Bonds.

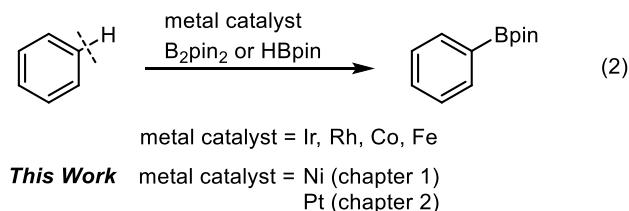


Another promising approach for the development of new C-H borylation catalysts involves the replacement of iridium with other metals. The catalytic activity of rhodium for C-H borylation reactions has long been established (Figure 2b).⁶ Cobalt-based catalysts have been studied extensively by Chirik, who demonstrated that well-defined pincer cobalt complexes could effectively promote C-H borylation reactions (Figure 2c).⁷ Iron complexes have also been shown to be suitable metal centers

for C–H borylation reactions when they are combined with oxidants or performed under photoirradiation conditions (Figure 2d).⁸

Compared to the development of catalytic reactions using group 9 metals such as Ir, Rh and Co for C–H borylation, the potential reactivity of group 10 metals for these reactions represents a less developed area. Except for the seminal work by Miyaura using a Pd/C catalyst for benzylic borylation,⁹ there were no other examples of group 10 metal-catalyzed C–H borylations when the author started the research.¹⁰ Varying the central metal could provide opportunities for the development of new types of catalysts for C–H borylation reactions with new reactivities and/or selectivity profiles.

The prime objective of this research was to investigate the catalytic activity of nickel and platinum metals in C–H borylation reactions and to explore their unique properties (eq. 2). This thesis consists of the following two chapters.



In chapter 1, nickel-catalyzed borylation of aromatic C–H bonds is discussed. This is the first demonstration of the catalytic activity of a nickel complex in the borylation of aromatic C–H bonds. This method can be applied to the borylation of indoles on a gram scale, which demonstrates that earth abundant nickel is a promising candidate as a substitute for a precious metal catalyst such as iridium and rhodium. The choice of *N*-heterocyclic carbene (NHC) as a ligand is important in achieving nickel catalysis, which represents a rare example of a nickel-catalyzed C–H bond activation process in the absence of a directing group.

In chapter 2, the platinum-catalyzed borylation of C–H bonds is discussed. NHC-ligated platinum catalysts have been found to be efficient catalysts for the borylation of aromatic $\text{C}(\text{sp}^2)\text{–H}$ bonds. This is the first example of a catalytic C–H borylation in which a platinum catalyst is used. The most remarkable feature of these Pt catalysts is their lack of sensitivity with respect to the degree of steric hindrance around the C–H bonds that participate in the borylation reaction. These Pt catalysts allow for the synthesis of sterically congested 2,6-disubstituted phenylboronic esters, which are otherwise difficult to synthesize using existing C–H borylation methods. Furthermore, platinum catalysis allows for the regioselective borylation of the C–H bonds *ortho* to fluorine substituents in fluoroarene systems. Preliminary mechanistic studies and work directed at synthetic applications of this platinum catalyzed C–H borylation process are described.

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Chapter 1

Nickel-Catalyzed Borylation of Aromatic C-H Bonds

1.1 Introduction

As described in the general introduction, the catalytic borylation of arenes is arguably the method of paramount importance, since it allows the introduction of a synthetically useful boron functionality directly at the C-H bond of an arene without the need for any directing groups. One remaining challenge in the catalytic C-H borylation methodology is the development of base metal catalysts, driven by recent concerns regarding the limited availability of precious metals. A pioneering work by Hartwig in 1995 demonstrated the potential activity of base metal complexes such as Fe and Mn in C-H borylation reactions.¹ Catalytic variants were achieved only recently, as already briefly mentioned in the general introduction. Ohki and Tatsumi reported on the iron-catalyzed borylation of furans and thiophenes in the presence of a hydrogen acceptor,² while Kuang and Wang demonstrated that Fe₂O₃ nanoparticles can also catalyze the borylation of arenes in the presence of more than a stoichiometric amount of *tert*-butyl peroxide.³ A mechanistically unique C-H borylation using a Cu/Fe bimetallic catalyst under photochemical conditions was developed by Mankad.⁴ The use of a bidentate phosphine-ligated iron complex in catalytic borylation reactions under photochemical conditions was reported by the group of Bontemps, Sortais, Sabo-Etienne and Darcel.⁵ As a base-metal variant of a group 9 metal, Chirik reported on a cobalt-catalyzed C-H borylation that is applicable to a broad range of arenes and heteroarenes and subsequent studies revealed that cobalt has promising catalytic activity for C-H borylations.⁶ Despite these advances, the full potential of base metals in promoting C-H borylation in a broader sense, to promote C-H activation, has still not yet been explored, especially in the case of metals other than iron⁷ and cobalt.⁸

The use of a nickel complex in C-H activation reactions has long been known since the pioneering work in 1963, in which the cyclometallation of stoichiometric cyclopentadienyl nickel with azobenzene was examined.⁹ Despite the early finding, the development of catalytic C-H functionalizations using nickel has only recently progressed. Chatani extensively studied the bidentate directing group strategy for effective nickel-catalyzed C-H functionalization.¹⁰ Concerning substrates that do not have directing groups, the nickel catalyst can function effectively only for substrates that contain acidic C-H bonds such as those located on the highly fluorinated arenes, azoles, and activated pyridine derivatives.¹¹ Although co-catalytic systems using nickel and aluminum Lewis acids have

recently broaden the scope of such reactions to aromatic rings bearing carbonyl functionalities,¹² the nickel-catalyzed C-H functionalization of the simple benzene, to the best of our knowledge, is limited to only one example, involving the oxidation of benzene to phenol.¹³ The author therefore investigated the C-H borylation of simple arenes using a nickel catalyst.

1.2 Results and Discussion

The author initially examined the nickel-catalyzed reaction of HBpin with benzene in the presence of a variety of ligands (Table 1). Phosphine ligand such as PCy₃ did not lead to the formation of the desired borylated product **1** (Entry 2). In contrast, the use of IMes, an *N*-heterocyclic carbene (NHC) bearing a mesityl group, was found to generate **1** in 51% yield (Entry 3). Replacing the mesityl group with either the larger 2,6-*i*Pr₂C₆H₃ group (i.e., IPr) or the smaller methyl group (i.e., IMe) decreased the yield of **1** (Entries 4 and 5).

Table 1. Nickel-Catalyzed Borylation of Benzene: Ligand Screening^a

Entry	Ligand	$\text{HBpin} + \text{benzene} \xrightarrow[\text{solvent}]{\text{Ni}(\text{cod})_2 \text{ (3 mol \%)} \atop \text{Ligand (3 mol \%)} \atop \text{NaO}^t\text{Bu (6 mol \%)} \atop 80^\circ\text{C, 20 h}} \text{Bpin}$			Yield (%) ^b
1	none				5
2 ^c	PCy ₃				0
3	IMes·HCl (R = 2,4,6-Me ₃ C ₆ H ₂)				51
4	IPr·HCl (2,6- <i>i</i> Pr ₂ C ₆ H ₃)				16
5	IMe·HCl (R = Me)				22
6	I ^t Pr·HBF ₄ (R = ^t Pr)				33
7	I ^t Bu·HCl (R = ^t Bu)				50
8	ICy·HCl (R = cyclohexyl)				75 (71) ^d
9	I(1-Ad)·HCl (R = 1-adamantyl)				36
10	I(2-Ad)·HCl (R = 2-adamantyl)				trace
11	SICy·HCl				2
12	BICy·HCl				69

Ligand:

SICy·HCl

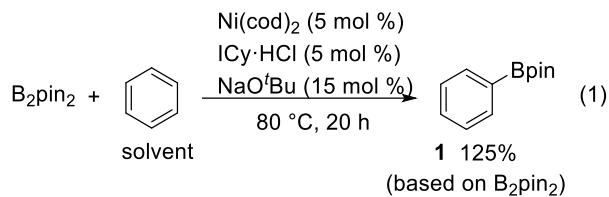
IPr·HCl

IMe·HCl

^a Reaction conditions: HBpin (1.2 mmol), Ni(cod)₂ (0.036 mmol), ligand (0.036 mmol), NaO^tBu (0.072 mmol) and benzene (1.0 mL) in a screw-capped vial under N₂ at 80 °C for 20 h. ^b GC yield based on HBpin. ^c NaO^tBu was not added ^d Isolated yield.

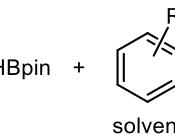
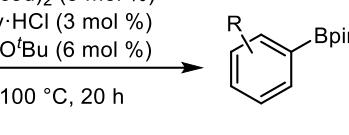
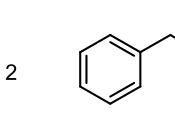
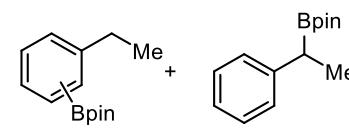
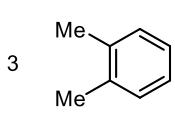
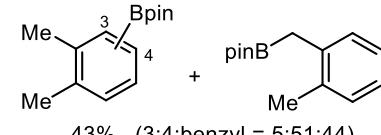
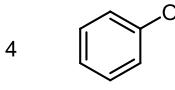
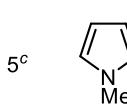
Further experimentation with the substituent on the nitrogen of the NHC ligand revealed that the cyclohexyl-substituted derivative (i.e., ICy) was the most effective ligand among those tested, with **1** being formed in 71% isolated yield (Entry 8). Whereas the use of a saturated analog of ICy (i.e., SICy) led to a complete loss of catalytic activity (Entry 11), the benzohomolog of ICy (i.e., BICy) promoted the borylation of benzene with comparable efficiency (Entry 12).

$B_2\text{pin}_2$ was also found to be a suitable boron source for this nickel-catalyzed borylation, forming **1** in a 125% yield based on $B_2\text{pin}_2$ (Eq 1).



The $\text{Ni}(\text{cod})_2/\text{ICy}$ -catalyzed borylation of substituted benzene derivatives was also investigated (Table 2). When toluene was used as the substrate, the borylation proceeded efficiently to give a mixture of regioisomers (Entry 1). The regioselectivity of the borylation was found to be primarily controlled by steric effects, forming the meta and para isomers as the major products, a result similar to those obtained using Ir^{14} , Fe^4 or Co^{6a} catalysts. The difference between the present work and these previously reported catalysts is that the borylation in the current study also occurred at the benzylic position. The observed product distribution was similar to that obtained using a rhodium-based catalyst¹⁵ although the rhodium system allows the benzylic isomer to be formed as the major product. The borylation of ethylbenzene under these nickel-catalyzed conditions also proceeded to deliver four isomers (Entry 2). Disubstituted benzenes were generally much less reactive than mono-substituted benzenes under the current reaction conditions (Entry 3). The use of anisole as the substrate resulted in borylation products, with the *ortho*-borylated isomer as the major product (Entry 4). This regioselectivity was in sharp contrast to that observed in homogeneous Ir^3 , Fe^4 and Co^{6a} systems, wherein the major products were the *meta* and *para* isomers. This result indicated that a methoxy group can serve as an *ortho*-directing group in the current nickel-catalyzed borylation reaction. Borylative cleavage of the C(aryl)-OMe bond¹⁶ in anisole was also observed, albeit in low yield (7%). Unlike the Hartwig's hydroarylation system,¹⁷ 1,3-bis(trifluoromethyl)benzene was not a good substrate in the present reaction (<10% yield). Halogen-substituted benzenes such as chloro, bromo and fluorobenzenes were found to be inapplicable since C-X bonds can react with the nickel species under these conditions.¹⁸

Table 2 Nickel-Catalyzed Borylation of Various Arenes^a

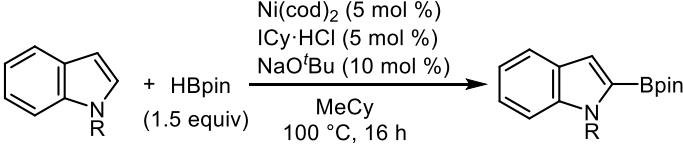
Entry	Arene	Product ^b	Reaction Conditions	
			Ni(cod) ₂ (3 mol %)	ICy·HCl (3 mol %)
1			NaO ^t Bu (6 mol %)	100 °C, 20 h
2				
3				
4				
5 ^c				68% (60%) ^d

^a Reaction conditions: HBpin (1.2 mmol), Ni(cod)₂ (0.035 mmol), ICy·HCl (0.035 mmol), NaO^tBu (0.070 mmol) and arene (1.0 mL) in a screw-capped vial under N₂ at 100 °C for 20 h. ^b Isolated yield based on HBpin. ^c At 80 °C. ^d N-Methylpyrrole (2.0 mmol) in methylcyclohexane (1.0 mL).

Heteroarenes were also examined as potential substrates for the nickel-catalyzed borylation reactions. Whereas furan, thiophene and pyridine could not be borylated under these conditions, pyrrole was found to be exceptionally reactive during this borylation, forming the 2-borylated product in a regioselective manner (Entry 5). Notably, the product was obtained in good yield even when the amount of pyrrole was reduced to 1.7 equivalents relative to HBpin.

The evident high reactivity of pyrrole prompted the author to examine indole derivatives in this nickel-catalyzed borylation reaction (Table 3). As expected, the borylation occurred efficiently using indole as the limiting agent and also took place regioselectively at the 2-position. In addition to *N*-methylindole (Entry 1), a bulkier *N*-butyl-substituted indole successfully underwent borylation without any decrease in the regioselectivity of the reaction (Entry 2). An *N,O*-acetal moiety remained intact,

Table 3 Nickel-Catalyzed Borylation of Indoles^a



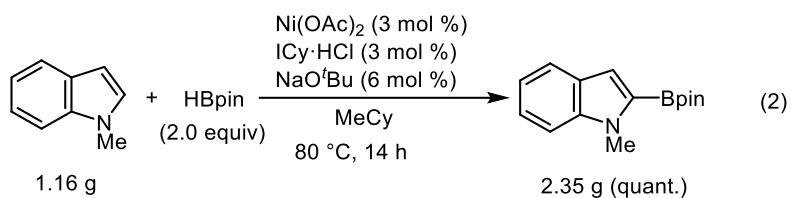
Entry	Indole	Product	Isolated yield (%)
1			78
2			68
3			68
4			82
5			76
6			87
7			76
8 ^b			82
9 ^c			53

^a Reaction conditions: indole (0.80 mmol), HBpin (1.2 mmol), Ni(cod)₂ (0.040 mmol), ICy-HCl (0.040 mmol), NaO'Bu (0.080 mmol), and methylcyclohexane (1.0 mL) in a screw-capped vial under N₂ at 80 °C for 16 h. ^b HBpin (1.2 equiv) was used. ^c Indole (0.72 mmol) and HBpin (0.98 mmol, 1.4 equiv) were used.

serving as a suitable protecting group in this reaction (Entry 3). In addition, *N*-benzyl groups were also tolerated, leaving the aryl group free from borylation (Entries 4 and 5). Installation of a boryl group at the sterically hindered 2-position of 3-substituted indoles was also possible (Entry 6). The reactivity and selectivity of this borylation was unaffected by the introduction of a methoxy group to the indole framework (Entry 7). Although a C(aryl)-F bond can be activated by a low valent nickel catalyst,¹⁸

fluoroiridole underwent borylation with its fluoride moiety remaining intact (Entry 8). Azaindole also served as a good substrate for this borylation, generating the corresponding 2-borylated product (Entry 9).

Although $\text{Ni}(\text{cod})_2$ was routinely used as the catalyst for this borylation during our exploratory studies, $\text{Ni}(\text{OAc})_2$ was found to serve as a more useful catalyst precursor. A protocol using $\text{Ni}(\text{OAc})_2$ allowed the successful implementation of this borylation on the gram-scale, highlighting the practical utility of the nickel-catalyzed system (eq. 2).



To obtain further insights into the mechanistic aspects of the nickel-catalyzed borylation, some preliminary mechanistic experiments were performed. Comparison of the initial rates of the borylation reactions of benzene and benzene- d_6 determined that k_H/k_D was 2.1 under these conditions, suggesting that cleavage of the C-H bond was involved in the turnover-limiting step. The nickel-catalyzed borylation of benzene or indole was also found to be completely inhibited when the reaction was attempted in the presence of an excess of mercury. In addition, filtration tests indicated that the liquid phase of the catalytic mixture did not contain catalytically active species (see experimental section for details). The currently available data indicate that the borylation examined here is likely mediated by a heterogeneous nickel species, although more detailed studies will be required for a definitive understanding of the nature of the catalysis.¹⁸ It is worth noting that the use of slight stoichiometric excess of $\text{NaO}'\text{Bu}$ relative to $\text{NHC}\cdot\text{HCl}$ was important for an efficient reaction, although the role of $\text{NaO}'\text{Bu}$ was initially thought to involve the generation of a free carbene ligand from the corresponding imidazolium salt. When the reaction was performed in the absence of the $\text{NaO}'\text{Bu}$ using free IMes, the yield dramatically decreased compared to the results when an IMes ligand generated from $\text{IMes}\cdot\text{HCl}$ and $\text{NaO}'\text{Bu}$ was used (see experimental section for details). Additionally, a seminal report on the $\text{KO}'\text{Bu}$ -catalyzed silylation of heteroarenes^{19,20} motivated the author to examine the borylation of indole in the presence of only $\text{NaO}'\text{Bu}$. No borylation product was detected under such conditions, indicating that the nickel species plays an essential role in this borylation reaction. It should also be noted that at the same time of our publication, Itami *et al.* independently reported nickel-catalyzed C-H borylation reaction using phosphine ligands and a catalytic amount of CsF .²¹

1.3 Conclusion

In summary, the findings reported here show, for the first time, that the direct borylation of arenes can be mediated by a nickel-based catalyst. Indoles are particularly reactive with this catalyst system, affording the corresponding 2-borylated products. The successful use of nickel is also noteworthy because nickel is rarely employed as a catalyst for the C-H bond activation process in the absence of a directing group.¹¹⁻¹³ The heterogeneous nature of the active species generated under the current conditions could be important in explaining the unprecedented reactivity of nickel,²² although further investigations will be required for a complete understanding of the mechanism of this borylation.

1.4 Experimental Section

1.4.1. General Information

¹H and ¹³C NMR spectra were recorded on a JEOL ECS-400 spectrometer (JEOL, Tokyo, Japan) or VARIAN UNITY INOVA-600 spectrometer in CDCl₃ with tetramethylsilane as an internal reference standard. Some NMR analysis were conducted using C₆D₆ solvent and a residual C₆H₆ peak was set as an internal reference standard (δ = 7.15 ppm). NMR data have been reported as follows: chemical shift (δ) in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), coupling constant (J) in Hz, and integration. NOE experiments were conducted with Delta noe_1d_dpgse pulse sequence and detail experimental parameter was listed in the spectroscopic data section for each compound. Infrared spectra (IR) were obtained on a JASCO FT/IR-4000 spectrometer, and the absorptions have been reported in reciprocal centimeters with the following relative intensities: s (strong), m (medium), or w (weak). Mass spectra were obtained on a Shimadzu GCMS-QP 5000 or GCMS-QP 2010 instrument with an ionization voltage of 70 eV. High resolution mass spectra (HRMS) were obtained on a JEOL JMS-DX303(EI) and a Bruker micrOTOF II (APCI). Analytical gas chromatography (GC) was carried out on Shimadzu GC-2014, equipped with a flame ionization detector. Melting points were determined using a Stanford Research Systems OptiMelt. Column chromatography was performed over SiO₂ (Silycycle Silica Flash F60 (230-400 mesh).

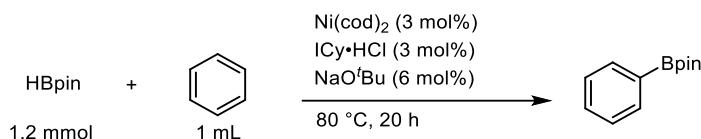
1.4.2. Materials

Ni(cod)₂ (Strem), Ni(OAc)₂•4H₂O (Wako), NaO'Bu (TCI), HBpin (TCI), B₂pin₂ (TCI), PCy₃ (Aldrich), IMes•HCl (TCI), IPr•HCl (TCI), IMe•HCl (TCI), I'Pr•HBF₄ (TCI), I(1-Ad)•HCl (TCI), BICy•HCl (Aldrich) were obtained from commercial suppliers and used as received. I'Bu•HCl,²³ ICy•HCl,²⁴ SICy•HCl²⁵ and I(2-Ad)•HCl²⁶ were synthesized according to the literature procedure. Methylcyclohexane (TCI), *N*-methylpyrrole (TCI), anisole (Nacalai), and *o*-xylene (TCI) were purified by distillation over CaH₂ prior use. 1,3-Bis(trifluoromethyl)benzene (Wako), *N*-methylindole (TCI), anhydrous benzene (Wako), benzene-*d*₆ (Wako), Hg (Wako) were obtained from commercial suppliers and used as received. 1-Butyl-1*H*-indole, 1-benzyl-1*H*-indole, 1-(4-methoxybenzyl)-1*H*-indole, 1,3-dimethyl-1*H*-indole, 1-(methoxymethyl)-1*H*-indole, 5-methoxy-1-methyl-1*H*-indole, 5-fluoro-1-

methyl-1*H*-indole, 1-methyl-7-azaindole, were synthesized by the reaction of the corresponding indole with alkyl halide according to literature procedures.²⁷

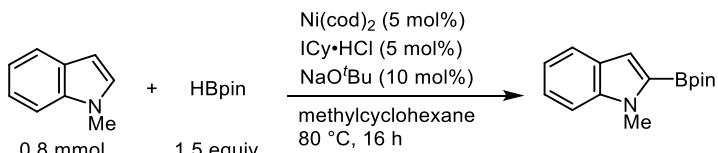
1.4.3. General Procedures for Nickel-Catalyzed Borylation of Arenes and Indoles

Method A: Procedure for the Nickel-Catalyzed Borylation of Benzene with Pinacolborane (Entry 8, Table 1)



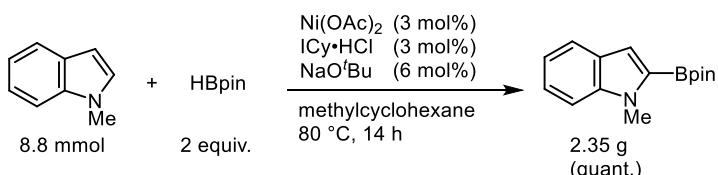
In a glovebox, Ni(cod)₂ (9.9 mg, 0.035 mmol), ICy•HCl (9.7 mg, 0.036 mmol), NaO'Bu (6.4 mg, 0.07 mmol) and HBpin (159 mg, 1.2 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. Benzene (1.0 mL) was then added, and the cap was applied to seal the vial. The vial was stirred at 80 °C over a hot plate for 20 h and the resulting mixture was filtered through silica gel (eluting with 10 mL of hexane/AcOEt = 5/1). The filtrate was analyzed by gas chromatography (GC) using dodecane as an internal standard (75% GC yield). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1) to give 4,4,5,5-tetramethyl-2-phenyl-1,3,2-dioxaborolane as a white solid (179 mg, 71% based on HBpin).

Method B: Procedure for the Nickel-Catalyzed Borylation of *N*-Methylindole with Pinacolborane (Entry 1, Table 3)



In a glovebox, Ni(cod)₂ (12.4 mg, 0.045 mmol), ICy•HCl (11.7 mg, 0.044 mmol), NaO'Bu (7.1 mg, 0.074 mmol), 1-methylindole (109 mg, 0.82 mmol) and HBpin (160 mg, 1.25 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. Methylcyclohexane (1.0 mL) was then added, and the cap was applied. The vial was stirred at 80 °C over a hot plate for 20 h. The resulting mixture was filtered through silica gel (eluting with 10 mL of hexane/AcOEt = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1) to give 1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole as a white solid (165 mg, 78% based on 1-methylindole).

A Procedure for the Gram Scale Synthesis of 2-Borylated Indole without a Glovebox (Scheme 2)



To a two-necked flask equipped with a rubber septum and a three-way stopcock connected to a vacuum line and a N₂ line, Ni(OAc)₂•4H₂O (76 mg, 0.31 mmol) was added. The flask was then heated by a

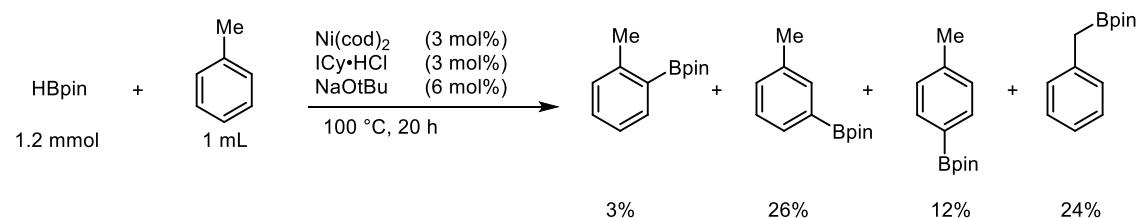
heat gun under vacuum until $\text{Ni(OAc)}_2 \cdot 4\text{H}_2\text{O}$ (initially light blue) completely changed color to a greenish yellow (ca. 1.5 min.). After the flask was cooled and refilled with N_2 , $\text{ICy} \cdot \text{HCl}$ (84.4 mg, 0.31 mmol) and $\text{NaO}'\text{Bu}$ (50.8 mg, 0.53 mmol) were added under a N_2 flow. Following the addition of these solid reagents, the vessel was again placed under vacuum and its volume subsequently purged with N_2 three times. Following this, *N*-methylindole (1.16 g, 8.8 mmol), HBpin (2.44 g, 19.1 mmol) and methylcyclohexane (25 mL) were added via syringe through the rubber septum. The reaction mixture was heated at 80 °C for 14 h in an oil bath, during which time the loss of the initial reagent *N*-methylindole was monitored by GC. The reaction mixture was then poured onto silica gel and eluted with 100 mL of a hexane/AcOEt (10/1) solution. The filtrate was concentrated in vacuo and analytically pure 1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole was obtained quantitatively as a white solid (2.35 g, quant.).

1.4.4. Spectroscopic Data for the Products

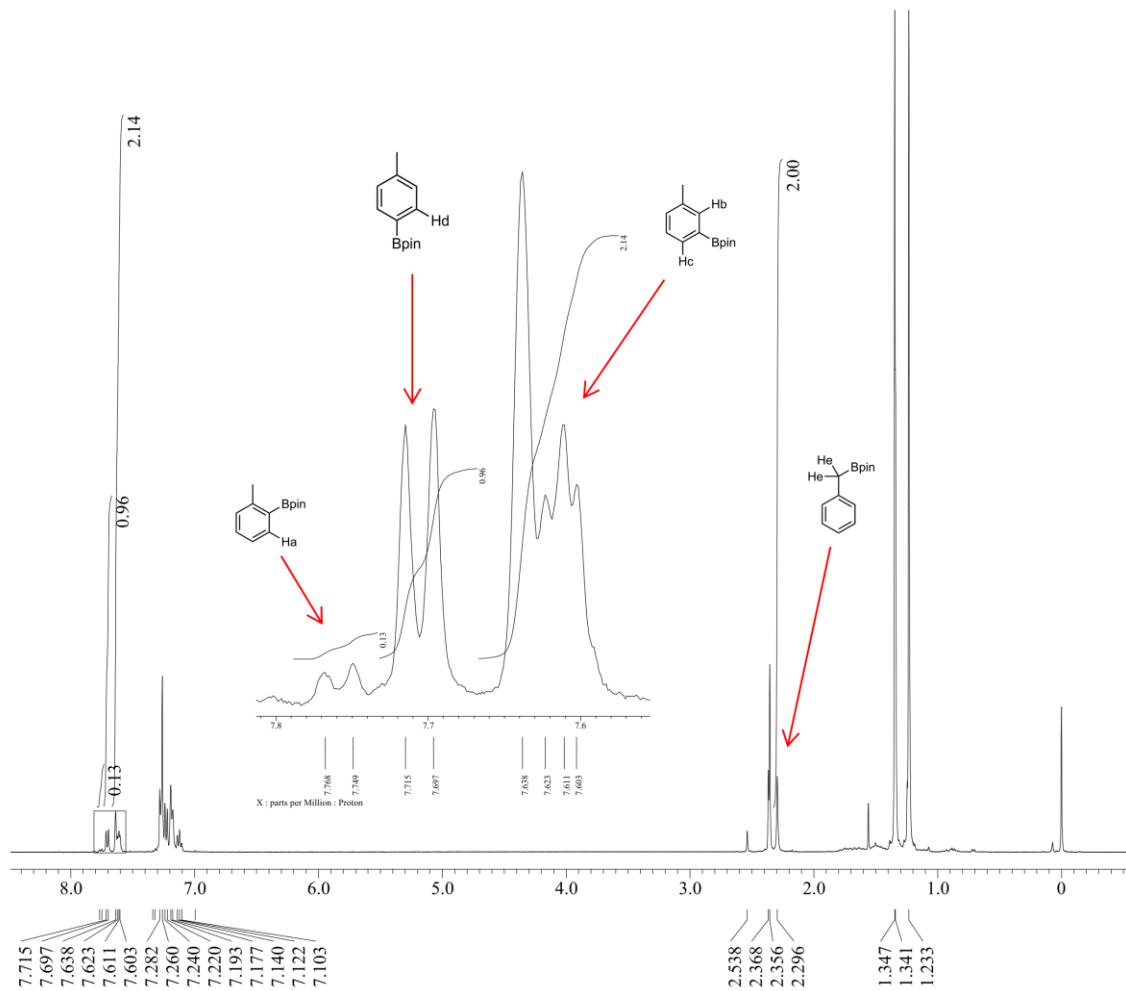
4,4,5,5-Tetramethyl-2-phenyl-1,3,2-dioxaborolane (entry 8, Table 1) [CAS: 24388-23-6].

 Rf 0.60 (hexane/EtOAc = 5/1). White solid (179mg, 71%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.34 (s, 12H), 7.37 (dt, J = 0.8, 7.2 Hz, 2H), 7.46 (tt, J = 1.6 Hz, 6.8 Hz, 1H). 7.81 (dd, J = 1.2 Hz, 7.2 Hz, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 83.7, 127.6, 131.2, 134.7. HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{17}\text{BO}_2$ 204.1322, Found 204.1321.

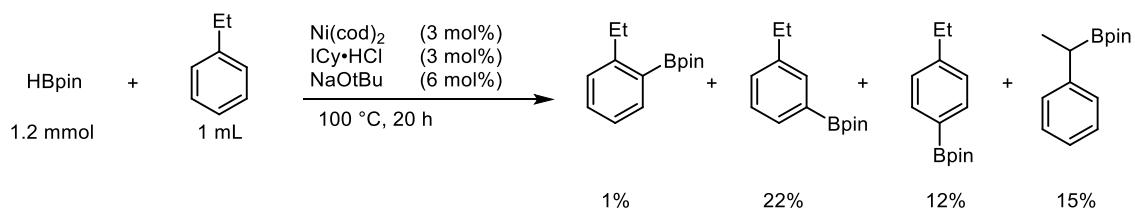
Borylation of toluene (Entry 1, Table 2).



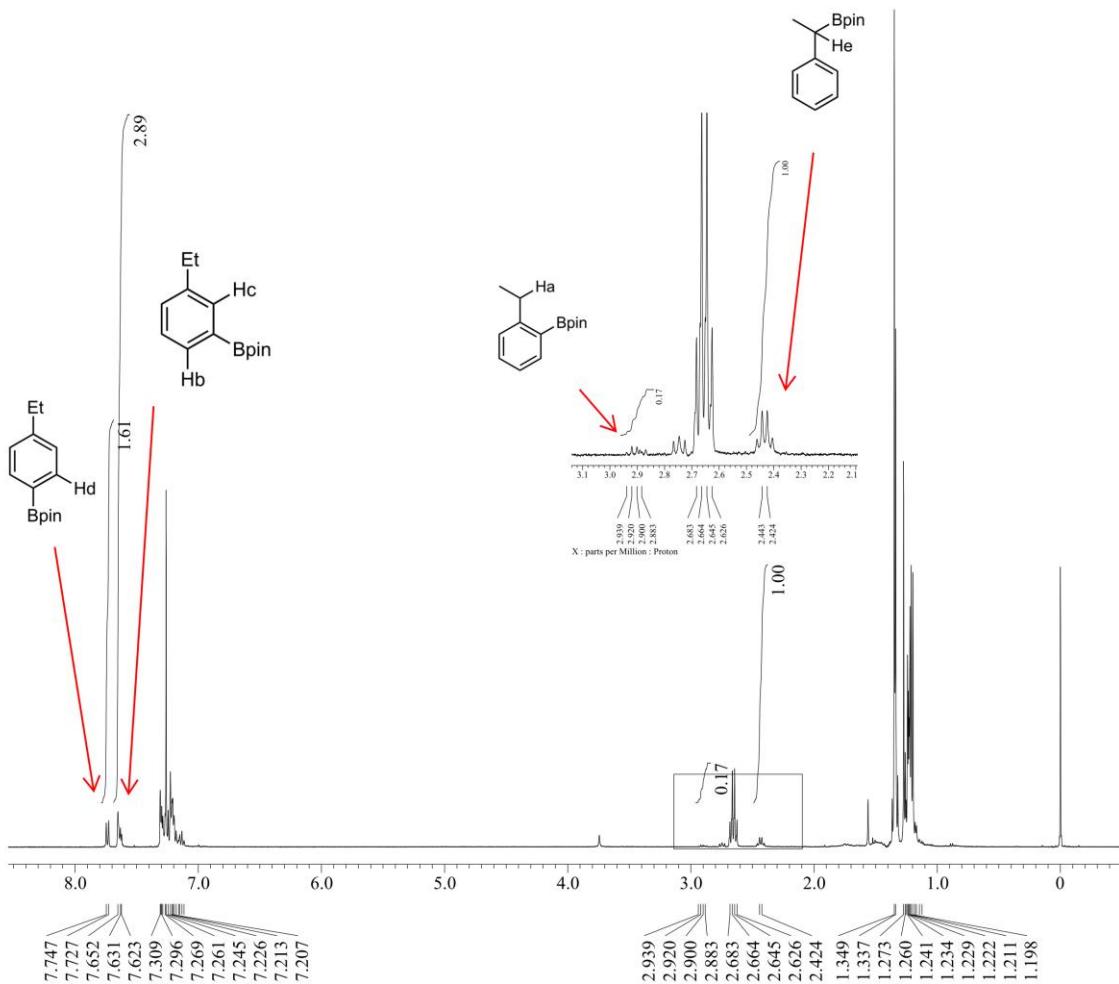
Method A was followed except that the reaction was conducted with HBpin (149 mg, 1.16 mmol) in toluene (1.0 mL) at 100 °C. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1), a mixture of four isomers was obtained (163 mg, 65%, >99% purity by GC). GC/MS analysis revealed the formation of four isomers of the borylated products, all of which had an m/z of 218 (M^+). The identity and ratio of each of the four isomers was determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.²⁸ The resonances specific to each isomer are as follows: 7.75 ppm (d, J = 7.6 Hz, 1H, ortho isomer, H_a); 7.60-7.64 ppm (m, 2H, meta isomer, H_b and H_c), 7.71 ppm (d, J = 6.0 Hz, 1H, para isomer, H_d); 2.29 ppm (s, 2H, benzylic isomer, H_e). (See below.)



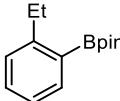
Borylation of ethylbenzene (Entry 2, Table 2).



Method A was followed except that the reaction was conducted with HBpin (160 mg, 1.25 mmol) in ethylbenzene (1.0 mL) at 100 °C. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1), a mixture of four isomers was obtained (145 mg, 50%, >99% purity by GC). GC/MS analysis revealed the formation of four isomers of the borylated products, all of which had an m/z of 232 (M⁺). The identities and proportions of the meta, para and benzylic isomers were determined by comparing the ¹H NMR spectrum of the product mixture with those reported in the literature.^{28b,29} Because the ortho isomer was a new compound, an authentic sample was synthesized by the reaction of 2-ethylphenylboronic acid with pinacol (see below). The identity and ratio of the ortho isomer was determined by comparing the ¹H NMR spectrum of the product mixture with that of the authentic sample. The resonances specific to each isomer are as follows: 2.91 ppm (q, *J* = 8.0 Hz, 2H ortho isomer, H_a); 7.62-7.65 ppm (m, 2H, meta isomer, H_b and H_c), 7.74 ppm (d, *J* = 8.0 Hz, 2H, para isomer, H_d); 2.43 ppm (q, *J* = 8.0 Hz 1H, benzylic isomer, H_e).

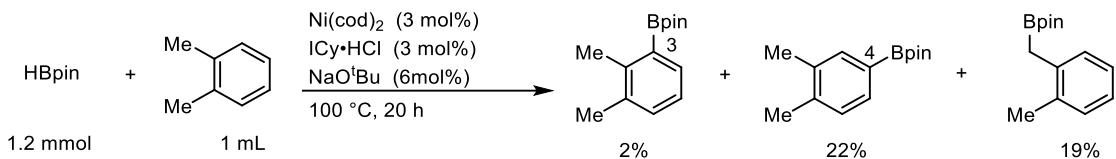


2-(2-Ethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane

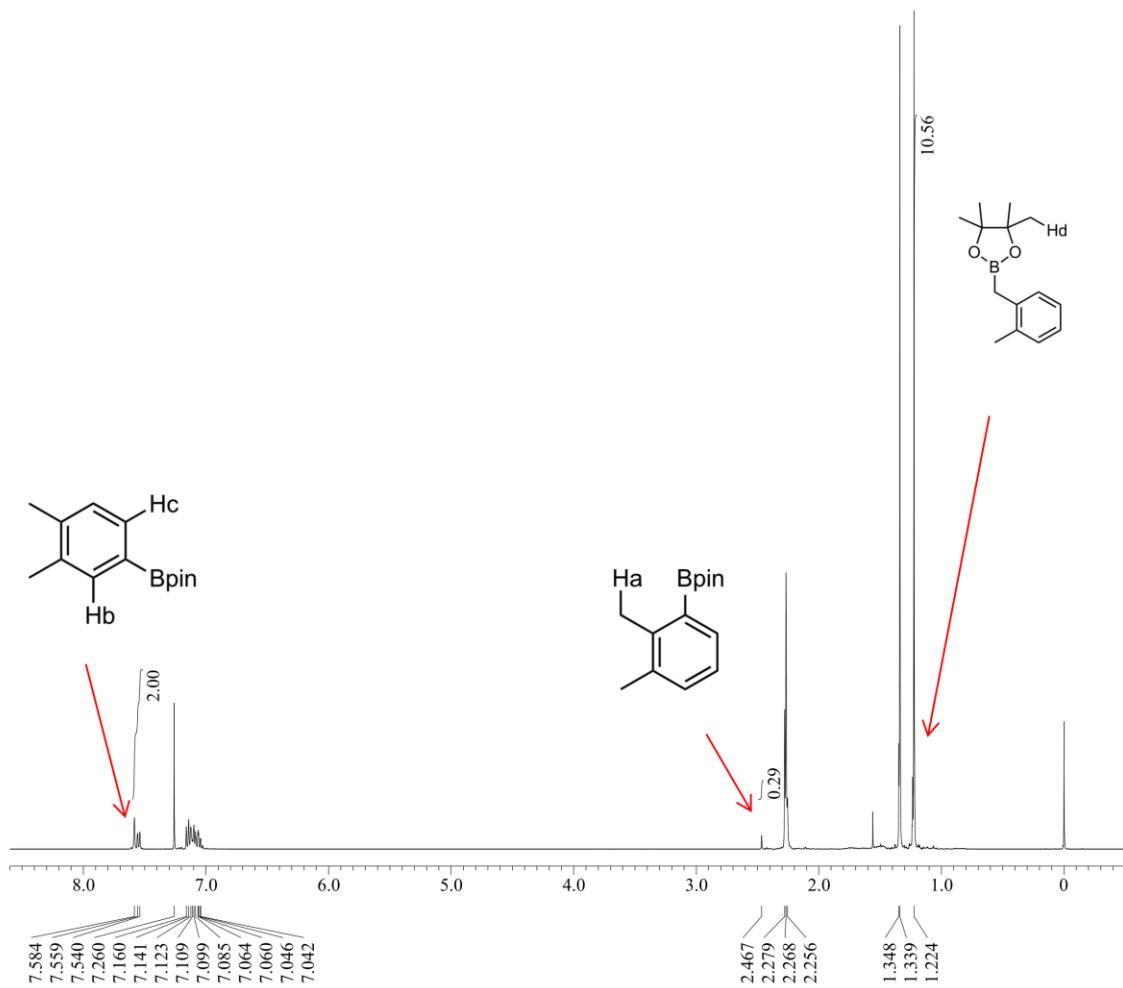

A combination of *o*-ethylphenylboronic acid (300 mg, 2.0 mmol), pinacol (260 mg, 2.2 mmol) and Et₂O (8 mL) were added to a round bottom flask, after which CaCl₂ (ca. 300 mg) was added and the reaction mixture was stirred overnight. The resulting suspension was filtered and the filtrate was concentrated in vacuo. The residue was purified by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1) to give the title compound as a colorless oil (24 mg, 5%).

Rf 0.60 (hexane/EtOAc = 5/1). Colorless oil. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.19 (t, *J* = 8.0 Hz, 3H), 1.34 (s, 12H), 2.91 (q, *J* = 8.0 Hz, 2H), 7.15-7.20 (m, 2H), 7.35 (t, *J* = 7.6 Hz, 1H), 7.76 (d, *J* = 7.2 Hz, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 17.3, 24.9, 28.9, 83.4, 124.9, 128.5, 131.0, 136.1, 151.5. IR (ATR): 2977 w, 2931 w, 2872 w, 1600 w, 1570 w, 1489 w, 1442 w, 1381 m, 1345 s, 1310 m, 1272 w, 1214 w, 1145 s, 1126 w, 1077 m, 1031 w, 962 w, 862 m, 830 w, 792 w, 755 m, 661 m. MS m/z (% relative intensity): 232 (M⁺, 11), 176 (11), 175 (100), 174 (33), 133 (59), 132 (87), 131 (45), 117 (36), 116 (11), 115 (27), 105 (32), 101 (63), 91 (19), 85 (23), 83 (28), 77 (11), 59 (15), 57 (17), 55 (13). HRMS (EI): Calcd for C₁₄H₂₁BO₂ 232.1635, Found 232.1630.

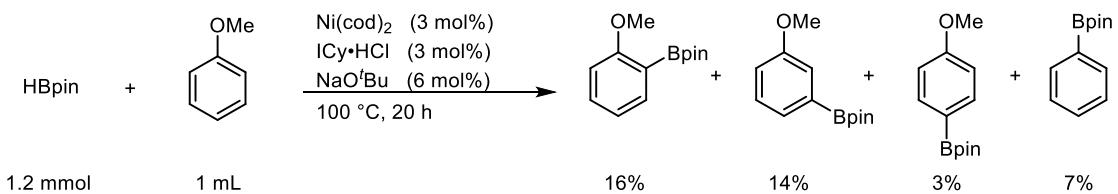
Borylation of *o*-xylene (Entry 3, Table 2).



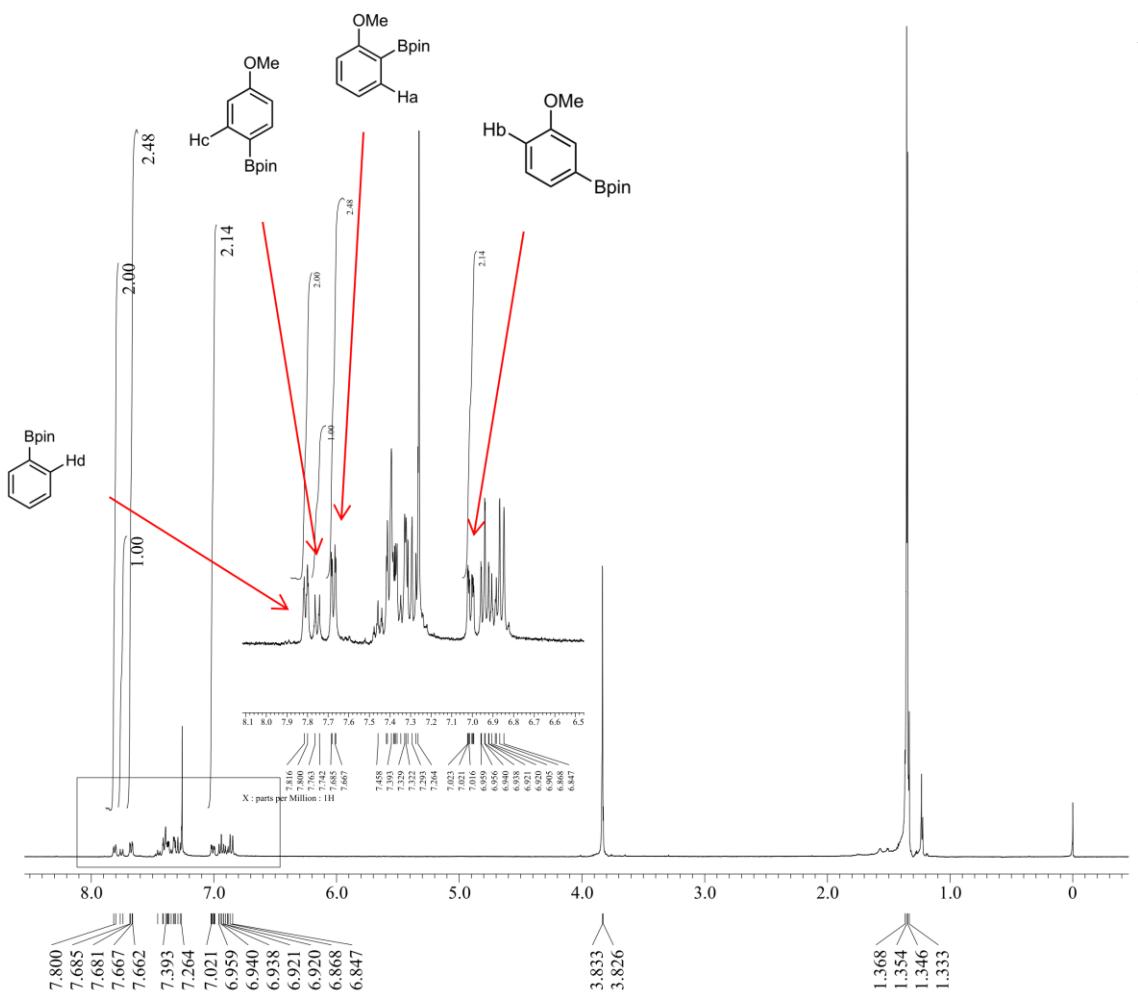
Method A was followed except that the reaction was conducted with HBpin (150 mg, 1.17 mmol) in *o*-xylene (1.0 mL) at 100 °C. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1), a mixture of three isomers was obtained (117 mg, 43%, >99% purity by GC). GC/MS analysis revealed the formation of three isomers of the borylated products, all of which had an *m/z* of 232 (M^+). The identity and ratio of each of the four isomers was determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.^{28a,30} The resonances specific to each isomer are as follows: 2.46 ppm (s, 3H, 3-isomer, H_a); 7.54-7.58 ppm (m, 2H, 4-isomer, H_b and H_c), 1.22 ppm (s, 12H, benzylic isomer, H_d). (See below.)



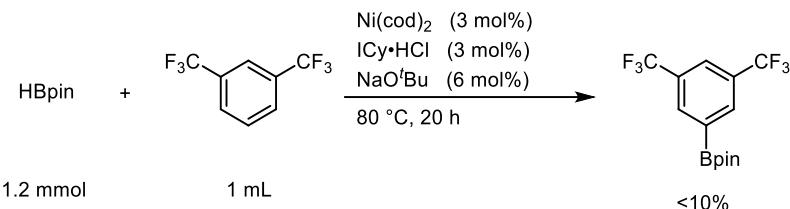
Borylation of anisole (Entry 4, Table 2).



Method A was followed except that the reaction was conducted with HBpin (160 mg, 1.25 mmol) in anisole (1.0 mL) at 100 °C. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1), a mixture of three isomers of the borylated products and PhBpin were obtained (108 mg; PhBpin 7% and borylated anisole 33%; >99% purity by GC). GC/MS analysis revealed the formation of three isomers of the borylated products, all of which had an m/z of 218 (M⁺) and PhBpin had an m/z of 204 (M⁺). The identity and ratio of each of the borylated products was determined by comparing the ¹H NMR spectrum of the product mixture with those reported in the literature.¹⁴ The resonances specific to each isomer are as follows: 7.67 ppm (dd, *J* = 1.6 Hz, 7.2 Hz, 1H ortho isomer, H_a); 7.01 ppm (ddd, *J* = 0.8 Hz, 2.8 Hz, 8.0 Hz, 1H, meta isomer, H_b), 7.75 ppm (d, *J* = 8.2 Hz, 2H, para isomer, H_c); 7.81 ppm (dd, *J* = 1.6 Hz, 6.4 Hz, 2H, PhBpin, H_d). (See below.)

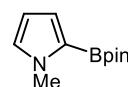


Borylation of 1,3-bis(trifluoromethyl)benzene.

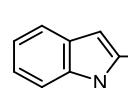


Method A was followed except that the reaction was conducted with HBpin (155 mg, 1.21 mmol) in 1,3-bis(trifluoromethyl)benzene (1.0 mL) at 80 °C. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 20/1), the product was obtained as a mixture with unidentifiable byproducts (44 mg, <10%, 84% purity by GC). HRMS analysis of this sample unambiguously determined the formation of the borylated product (Calcd for $\text{C}_{14}\text{H}_{15}\text{BF}_6\text{O}_2$ 340.1069, Found 340.1062). The identity of the borylated product was determined by comparing the ^1H NMR spectrum of the product mixture with that reported in the literature.³¹ The resonances specific to the compound are as follows: 7.94 ppm (s, 1H, H_a), 8.24 ppm (s, 2H, H_b).

1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-pyrrole (Entry 5, Table 2) [CAS: 850567-47-4].

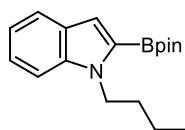
 Method A was followed except that the reaction was conducted with HBpin (160 mg, 1.25 mmol) in *N*-methylpyrrole (1.0 mL) at 80 °C. R_f 0.49 (hexane/EtOAc = 5/1). White solid (177 mg, 68%). ^1H and ^{13}C NMR data in CDCl_3 were in agreement with those reported for 2-borylated pyrrole.³² However, the title compound gradually decomposed in a CDCl_3 solution to form *N*-methylpyrrole. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.30 (s, 12H), 3.66 (s, *N*-methylpyrrole), 3.83 (s, 3H), 6.15-6.16 (m, 1H + *N*-methylpyrrole), 6.61 (s, *N*-methylpyrrole), 6.80-6.82 (m, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.5 (*N*-methylpyrrole), 24.7, 36.5, 83.0, 108.1 (*N*-methylpyrrole), 108.3, 121.6 (*N*-methylpyrrole), 121.8, 128.1. Pure spectra were obtained using C_6D_6 as the solvent. ^1H NMR (C_6D_6 , 399.78 MHz): δ 1.09 (s, 12H), 3.51 (s, 3H), 6.29-6.30 (m, 1H), 6.51-6.52 (m, 1H), 7.32-7.34 (m, 1H). ^{13}C NMR (C_6D_6 , 100.53 MHz): δ 24.8, 36.2, 82.9, 109.1, 123.3. One carbon peak is overlapped with the peak of residual solvent. HRMS (EI): Calcd for $\text{C}_{11}\text{H}_{18}\text{BNO}_2$ 207.1431, Found 207.1431.

1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (Entry 1, Table 3) [CAS: 596819-10-2].

 R_f 0.54 (hexane/EtOAc = 5/1). White solid (165 mg, 78%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 3.97 (s, 3H), 7.06 (t, J = 7.2 Hz, 1H), 7.13 (s, 1H), 7.23-7.27 (m, 1H), 7.34 (d, J = 8.4 Hz, 1H), 7.64 (d, J = 8.4 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 32.3, 83.8, 109.8, 114.3, 119.4, 121.7, 123.3, 127.9, 140.2. HRMS (EI): Calcd for $\text{C}_{15}\text{H}_{20}\text{BNO}_2$ 257.1587, Found 257.1584. All spectroscopic data were in agreement with the reported 2-borylated product.³³

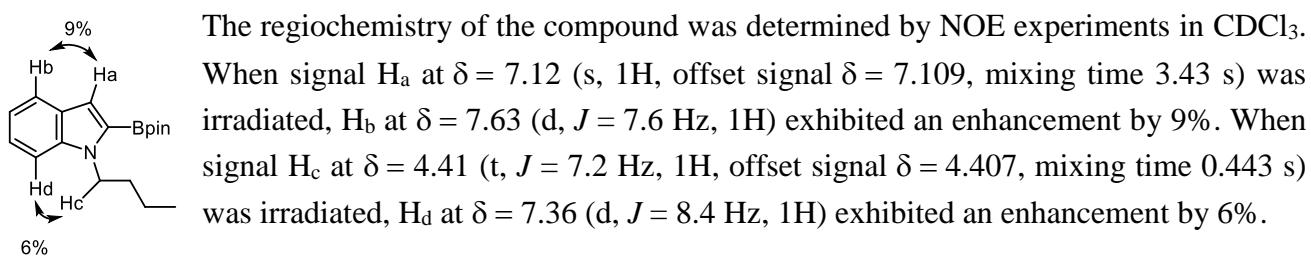
1-Butyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (Entry 2, Table 3).

Method B was followed using 1-butyl-1*H*-indole (146 mg, 0.84 mmol) instead of 1-methylindole.

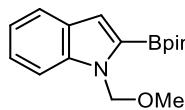


Rf 0.69 (hexane/EtOAc = 5/1). White solid (171 mg, 68%). Mp = 47-48 °C. ^1H NMR (CDCl₃, 399.78 MHz): δ 0.92 (t, J = 7.2 Hz, 3H), 1.29-1.34 (m, 2H), 1.36 (s, 12H), 1.74 (t, J = 7.2 Hz, 2H), 4.41 (t, J = 7.2 Hz, 2H), 7.06 (t, J = 7.6 Hz, 1H), 7.12 (s, 1H), 7.23 (t, J = 7.6 Hz, 1H), 7.36 (d, J = 8.4 Hz, 1H), 7.63 (d, J = 7.6 Hz, 1H). ^{13}C NMR (CDCl₃, 100.53 MHz): δ 14.0, 20.3, 24.9, 33.2, 45.3, 83.7, 110.6, 114.4, 119.2, 121.8, 123.0, 128.0, 139.4. IR (ATR): 3051 w, 2976 w, 2930 w, 2873 w, 1610 w, 1569 w, 1523 s, 1480 w, 1468 w, 1386 m, 1354 m, 1321 s, 1304 s, 1263 s, 1237 w, 1200 m, 1134 s, 1114 m, 1072 m, 1008 w, 964 w, 926 m, 858 m, 834 m, 803 m, 753 m, 732 s, 707 m, 690 s, 666m. MS m/z (% relative intensity): 299 (M+, 76), 257 (26), 256 (100), 156 (67), 130 (47). HRMS (EI): Calcd for C₁₈H₂₆BNO₂ 299.2057, Found 299.2053.

The regiochemistry of the compound was determined by NOE experiments in CDCl₃.

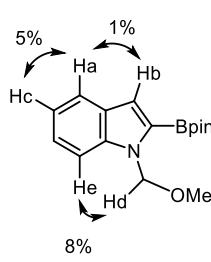


1-(Methoxymethyl)-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (Entry 3, Table 3).



Method B was followed using 1-(methoxymethyl)-1H-indole (127 mg, 0.79 mmol) instead of 1-methylindole.

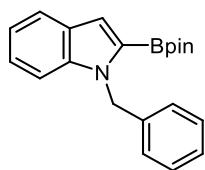
Rf 0.57 (hexane/EtOAc = 5/1). White solid (153 mg, 68%). Mp = 52-53 °C. ^1H NMR (C₆D₆, 399.78 MHz): δ 1.07 (s, 12H), 3.04 (s, 3H), 5.71 (s, 2H), 7.13 (m, 1H), 7.23 (dt, J = 1.2, 6.0 Hz, 1H), 7.53 (dd, J = 8.0 Hz, 1H), 7.55 (s, 1H), 7.63 (d, 8.0 Hz, 1H). ^1H NMR (CDCl₃, 399.78 MHz): δ 1.37 (s, 12H), 3.22 (s, 3H), 5.81 (s, 2H), 7.13 (t, J = 7.6 Hz, 1H), 7.18 (s, 1H), 7.28 (dt, J = 1.2, 7.4 Hz, 1H), 7.53 (d, J = 8.0 Hz, 1H), 7.65 (d, J = 7.8 Hz, 1H). ^{13}C NMR (C₆D₆, 100.53 MHz): δ 24.7, 55.0, 76.1, 83.7, 111.3, 117.0, 120.8, 122.1, 124.2, 129.3, 140.6. IR (ATR): 2979 w, 2933 w, 2363 w, 1723 w, 1612 w, 1573 w, 1528 s, 1482 w, 1369 m, 1346 m, 1322 s, 1305 s, 1263 s, 1224 m, 1191 w, 1164 m, 1137 s, 1101 m, 1081 s, 1050 m, 1010 w, 962 m, 913 w, 857 m, 833 m, 812 m, 738 s, 704 w, 688 s, 670 w. MS m/z (% relative intensity): 287 (M+, 100), 286 (27), 256 (77), 171 (27), 170 (20), 156 (68), 130 (39), 77 (20). HRMS (EI): Calcd for C₁₆H₂₂BNO₃ 287.1693, Found 287.1692.



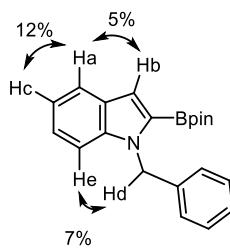
The regiochemistry of the compound was determined by NOE experiments in CDCl₃. When signal H_a at δ = 7.65 (d, J = 7.8 Hz, 1H, offset signal δ = 7.651, mixing time 0.8168 s) was irradiated, H_b at δ = 7.18 (s, 1H) was enhanced by 1% and H_c at δ = 7.13 (t, J = 7.6 Hz, 1H) by 5%. When signal H_d at δ = 5.81 (s, 2H, offset signal δ = 5.799, mixing time 0.8598 s) was irradiated, H_e at δ = 7.53 (d, J = 8.0 Hz, 1H) was enhanced by 8%.

1-Benzyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (Entry 4, Table 3).

Method B was followed using 1-benzyl-1H-indole (150 mg, 0.73 mmol) instead of 1-methylindole.

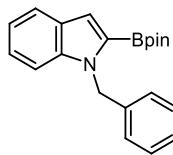


Rf 0.43 (hexane/EtOAc = 5/1). White solid (199 mg, 82%). Mp = 125-127 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.26 (s, 12H), 5.66 (s, 2H), 7.03-7.09 (m, 3H), 7.17-7.22 (m, 5H), 7.30 (d, *J* = 8.4 Hz, 1H), 7.66 (d, *J* = 8.0 Hz, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 24.8, 49.0, 83.8, 110.4, 115.1, 119.6, 121.8, 123.5, 126.6, 126.9, 128.3, 128.4, 139.4, 139.9. IR (ATR): 3030 w, 2979 w, 2925 w, 2852 w, 1609 w, 1523 m, 1494 w, 1480 w, 1452 w, 1387 m, 1360 m, 1324 s, 1300 s, 1267 s, 1192 m, 1136 s, 1114 m, 1087 m, 1031 w, 1005 w, 984 m, 960 w, 926 w, 855 m, 829 m, 799 m, 772 w, 726 s, 690 s, 672. MS m/z (% relative intensity): 333 (M+, 54), 332 (30), 91 (100). HRMS (EI): Calcd for C₂₁H₂₄BNO₂ 333.1900, Found 333.1899.



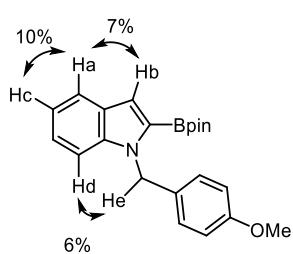
The regiochemistry of the compound was determined by NOE experiments in CDCl₃. When signal H_a at δ = 7.66 (d, *J* = 8.0 Hz, 1H, offset signal δ = 7.673, mixing time 2.601 s) was irradiated, H_b at δ = 7.20 (s, 1H) exhibited an enhancement by 5% and H_c at δ = 7.06 (t, *J* = 7 Hz, 1H) enhanced by 12%. When signal H_d at δ = 5.66 (s, 2H, offset signal δ = 5.659, mixing time 0.8 s) was irradiated, H_e at δ = 7.30 (d, *J* = 8.4 Hz, 1H) was enhanced by 7%.

1-(4-Methoxybenzyl)-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (Entry 5, Table 3).



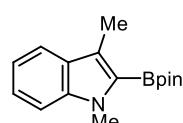
Method B was followed using 1-(4-methoxybenzyl)-1*H*-indole (174 mg, 0.73 mmol) instead of 1-methylindole.

Rf 0.54 (hexane/EtOAc = 5/1). White solid (201 mg, 76 %). Mp = 116 °C. ¹H NMR (C₆D₆, 399.78 MHz): δ 1.04 (s, 12H), 3.19 (s, 3H), 5.55 (s, 2H), 6.59 (d, *J* = 8.8 Hz, 2H), 6.92 (d, *J* = 8.8 Hz, 2H), 7.10 (t, *J* = 8.2 Hz, 1H), 7.19 (t, *J* = 7.2 Hz, 1H), 7.25 (d, *J* = 8.4 Hz, 1H), 7.65 (s, 1H), 7.70 (d, *J* = 8.0 Hz, 1H). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.30 (s, 12H), 3.74 (s, 3H), 5.59 (s, 2H), 6.76 (d, *J* = 8.7 Hz, 2H), 7.02 (d, *J* = 8.8 Hz, 2H), 7.07 (t, *J* = 8.0 Hz, 1H), 7.18 (s, 1H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.32 (d, *J* = 8.4 Hz, 1H), 7.65 (d, *J* = 7.8 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 24.6, 48.5, 54.5, 83.6, 110.8, 114.6, 116.1, 120.0, 122.2, 123.8, 127.8 (overlapped with the solvent peak), 129.0, 131.6, 140.4, 159.0. ¹³C NMR (CDCl₃, 100.53 MHz): δ 24.7, 48.3, 55.1, 83.7, 110.3, 113.6, 114.9, 119.4, 121.6, 123.2, 127.7, 128.1, 131.3, 139.6, 158.4. IR (ATR): 2977 w, 1613w, 1514 s, 1481 w, 1462 w, 1441 w, 1382 m, 1354 m, 1321 m, 1295 s, 1269 s, 1249 s, 1193 m, 1174 m, 1134 s, 1085 m, 1038 m, 985 w, 960 w, 856 m, 830 m, 805 737 s, 704 w, 688 s, 672 w. MS m/z (% relative intensity): 363 (M+, 17), 121 (100). HRMS (EI): Calcd for C₂₂H₂₆BNO₃ 363.2006, Found 363.2005.



The regiochemistry of the compound was determined by NOE experiments in CDCl₃. When signal H_a at δ = 7.65 (d, *J* = 7.8 Hz, 1H, offset signal δ = 7.647, mixing time 2.379 s) was irradiated, H_b at δ = 7.18 (s, 1H) was enhanced by 7% and H_c at δ = 7.07 (t, *J* = 8.0 Hz, 1H) had an enhancement of 10%. When signal H_d at δ = 7.32 (d, *J* = 8.4 Hz, 1H, offset signal δ = 7.317, mixing time 2.379 s) was irradiated, H_e at δ = 5.59 (s, 2H) had an NOE enhancement of 6%.

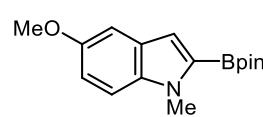
1,3-Dimethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (Entry 6, Table 3).



Method B was followed using 1,3-dimethyl-1*H*-indole (116 mg, 0.80 mmol) instead of 1-methylindole.

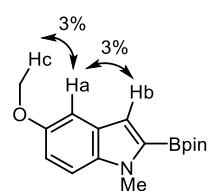
R_f 0.54 (hexane/EtOAc = 5/1). White solid (187 mg, 87%). Mp = 88-89 °C. ¹H NMR (C₆D₆, 399.78 MHz): δ 1.13 (s, 12H), 2.85 (s, 3H), 3.71 (s, 3H), 7.13 (d, *J* = 8.8 Hz, 1H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.31 (dt, *J* = 0.8, 8.0 Hz, 1H), 7.74 (d, *J* = 7.6 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 10.7, 24.7, 32.0, 83.0, 109.8, 119.0, 120.3, 123.8, 125.6, 129.3, 140.5. IR (ATR): 3051 w, 2979 w, 2932 w, 2863 w, 1711 w, 1610 w, 1530 m, 1438 m, 1410 m, 1370 m, 1334 m, 1294 s, 1264 s, 1242 m, 1213 m, 1166 m, 1144 s, 1088 m, 1045 m, 1007 w, 962 m, 859 m, 835 m, 739 s, 714 w, 697 s, 672 w. MS m/z (% relative intensity): 272 (16), 271 (M+, 100), 270 (36), 189 (22), 188 (41), 171 (20), 170 (32), 145 (10), 144 (44), 115 (12), 77 (14). HRMS (EI): Calcd for C₁₆H₂₂BNO₂ 271.1744, Found 271.1745.

5-Methoxy-1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (Entry 7, Table 3).



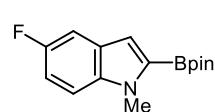
Method B was followed using 5-methoxy-1-methyl-1*H*-indole (127 mg, 0.79 mmol) instead of 1-methylindole.

R_f 0.46 (hexane/EtOAc = 5/1). White solid (172 mg, 76%). Mp = 100-101 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.35 (s, 12H), 3.84 (s, 3H), 3.93 (s, 3H), 6.93 (dd, *J* = 2.0 Hz, 9.2 Hz, 1H), 7.02 (s, 1H), 7.05 (d, *J* = 2.4 Hz, 1H), 7.23 (d, *J* = 9.2 Hz, 1H). ¹H NMR (C₆D₆, 399.78 MHz) δ 1.12 (s, 12H), 3.44 (s, 3H), 3.67 (s, 3H), 6.98 (d, *J* = 8.7 Hz, 1H), 7.06 (d, *J* = 2.3 Hz, 1H), 7.17 (dd, *J* = 2.4 Hz, 8.8 Hz, 1H), 7.56 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 24.9, 32.5, 55.9, 83.7, 102.1, 110.6, 113.5, 114.5, 128.1, 135.9, 154.0. IR (ATR): 2977 w, 1619 w, 1521 s, 1457 w, 1394 m, 1372 w, 1346 w, 1315 m, 1299 s, 1260 s, 1233 s, 1206 s, 1169 m, 1139 s, 1107 m, 1066 m, 1036 m, 963 m, 849 m, 832 s, 792 s, 706 w, 689 s, 677 w. MS m/z (% relative intensity): 287 (M+, 100), 286 (25), 272 (41), 190 (17). HRMS (EI): Calcd for C₁₆H₂₂BNO₃ 287.1693, Found 287.1695.



The regiochemistry of the compound was determined by NOE experiments in C₆D₆. When signal H_a at δ = 7.06 (d, *J* = 2.3 Hz, 1H, offset signal δ = 7.006, mixing time 1.52 s) was irradiated, H_b at δ = 7.56 (s, 1H) exhibited an enhancement by 9%, and H_c at δ = 3.44 (s, 3H) by 3 %.

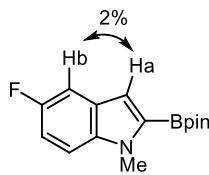
5-Fluoro-1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (Entry 8, Table 3).



Method B was followed using 5-fluoro-1-methyl-1*H*-indole (115 mg, 0.77 mmol) and 1.2 equivalent of HBpin (120 mg, 0.94 mmol).

R_f 0.49 (hexane/EtOAc = 5/1). White solid (173 mg, 82%). Mp = 116 °C. ¹H NMR (C₆D₆, 395.88 MHz) δ 1.09 (s, 12H), 3.56 (s, 3H), 6.77 (dd, *J* = 4.0 Hz, 8.8 Hz, 1H), 6.99 (dt, *J* = 2.4 Hz, 8.8 Hz, 1H), 7.26 (dd, *J* = 2.4 Hz, 9.2 Hz, 1H), 7.37 (d, *J* = 1.2 Hz, 1H). ¹³C NMR (C₆D₆, 99.54 MHz): δ 24.7, 32.1, 83.6, 106.3 (d, *J* = 23 Hz), 110.6 (d, *J* = 10 Hz), 112.2 (d, *J* = 27 Hz), 115.0 (d, *J* = 5 Hz), 128.6 (d, *J* = 10 Hz), 137.4, 158.4 (d, *J* = 235 Hz). IR (ATR): 2982 m, 1523 s, 1458 w, 1390

m, 1372 m, 1317 m, 1295 m, 1254 s, 1181 m, 1137 s, 1065 m, 962 m, 861 m, 846 s, 787 s, 707 w, 690 s, 678 m. MS m/z (% relative intensity): 276 (16), 275 (M+, 100), 274 (28), 202 (20), 193 (20), 190 (32), 176 (19), 175 (43), 174 (30). HRMS (APCI): Calcd for $[M+H]^+$ $C_{15}H_{20}BFNO_2$ 276.1568, Found 276.1569.

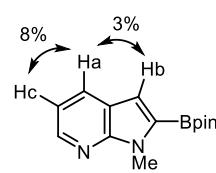


The regiochemistry of the compound was determined by NOE experiments in C_6D_6 . When signal H_a at $\delta = 7.37$ (d, $J = 1.2$ Hz, 1H, offset signal $\delta = 7.3116$, mixing time 1.5 s) was irradiated, H_b at $\delta = 7.26$ (dd, $J = 2.4, 9.2$ Hz, 1H) exhibited an enhancement of 2%.

1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-7-aza-1H-indole (Entry 9, Table 3).

Method B was followed using 1-methyl-7-aza-1H-indole (105 mg, 0.80 mmol) and 1.2 equivalent of HBpin (120 mg, 0.94 mmol).

Rf 0.14 (hexane/EtOAc = 5/1). White solid (116 mg, 56%). Mp = 66–68 °C. 1H NMR (C_6D_6 , 399.78 MHz): δ 1.07 (s, 12H), 4.09 (s, 3H), 6.74 (dd, $J = 4.6$ Hz, 7.8 Hz, 1H), 7.38 (s, 1H), 7.59 (dd, $J = 1.3$ Hz, 7.8 Hz, 1H), 8.48 (dd, $J = 1.3$ Hz, 4.4 Hz, 1H). ^{13}C NMR (C_6D_6 , 100.53 MHz): δ 24.7, 30.9, 83.7, 112.9, 115.9, 120.2, 129.3, 145.3, 151.1. IR (ATR): 2978 w, 1592 w, 1564 w, 1521 s, 1461 m, 1380 m, 1323 s, 1254 s, 1214 w, 1135 s, 1109 m, 1061 m, 961 w, 910 w, 855 m, 834 m, 816 m, 774 s, 724 w, 707 w, 690 s, 668 m. MS m/z (% relative intensity): 258 (M+, 100), 257 (31), 185 (20), 173 (30), 159 (27), 158 (27) 157 (32), 132 (24), 131 (72). HRMS (EI): Calcd for $C_{14}H_{19}BN_2O_2$ 258.1540, Found 258.1542.



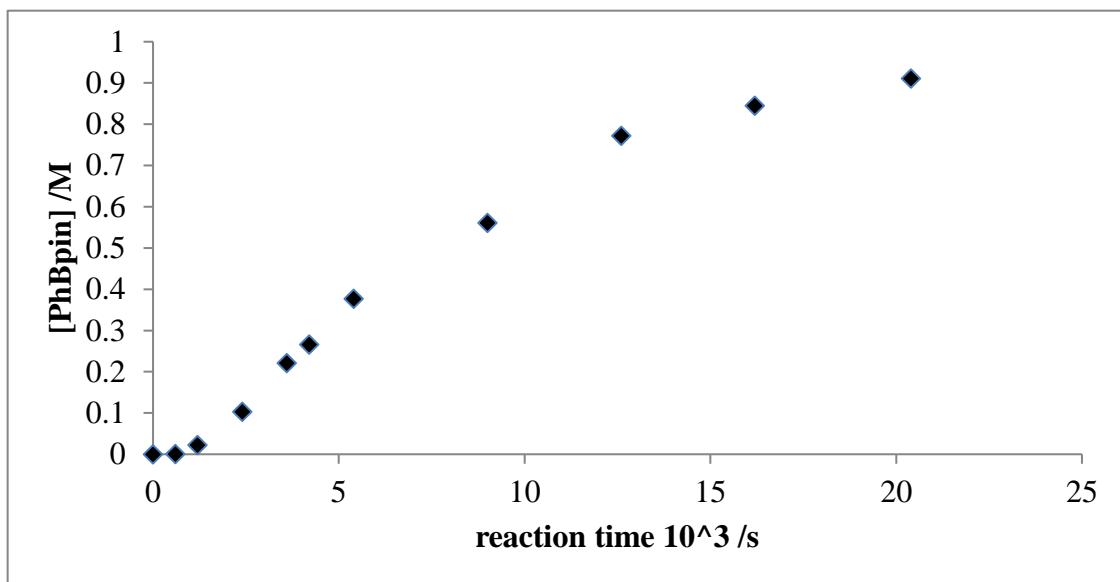
The regiochemistry of the compound was determined by NOE experiments in C_6D_6 . When signal H_a at $\delta = 7.59$ (dd, $J = 1.3, 7.8$ Hz, 1H, offset signal $\delta = 7.547$, mixing time 2.7 s) was irradiated, H_b at $\delta = 7.38$ (s, 1H) was enhanced by 3% and H_c at $\delta = 6.74$ (dd, $J = 4.6, 7.8$ Hz, 1H) by 8%.

1.4.5. Mechanistic Studies

5-1. Kinetic Isotope Effect

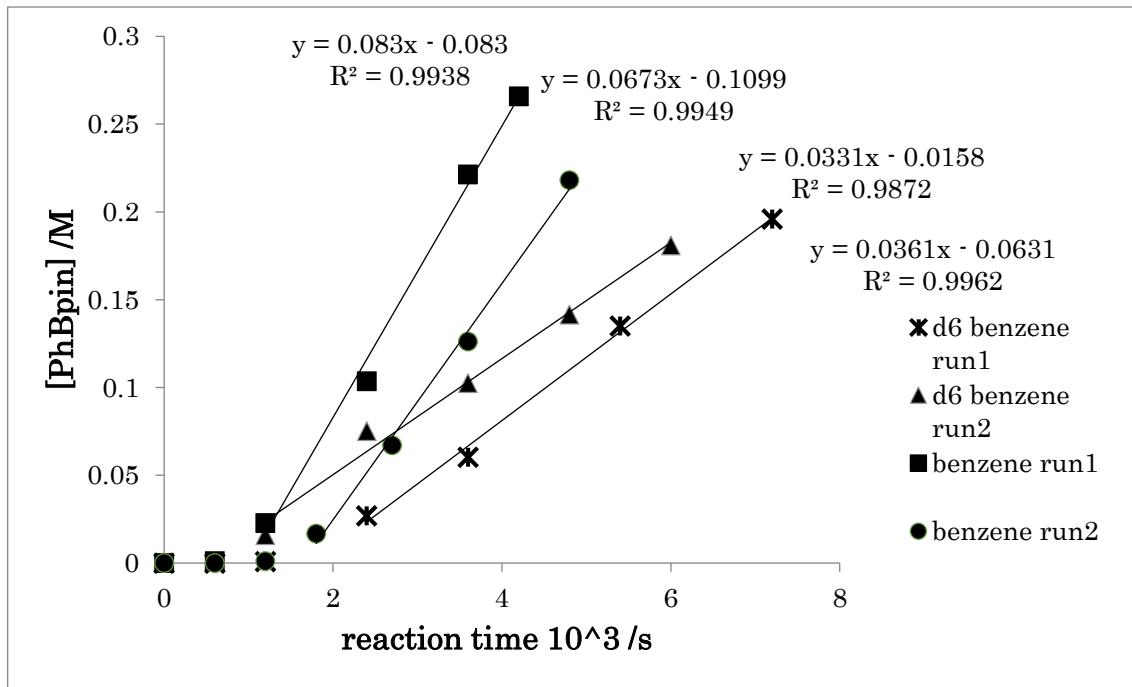
The reaction progress was monitored by GC. Dodecane was added as an internal standard.

A typical procedure for kinetic studies. In a glovebox, $Ni(cod)_2$ (9.6 mg, 0.035 mmol), ICy•HCl (9.2 mg, 0.034 mmol), $NaO^{\prime}Bu$ (6.4 mg, 0.067 mmol), HBpin (161 mg, 1.3 mmol) and dodecane (60 mg as internal standard) were added to a 10 mL-sample vial with a Teflon-sealed screw cap. Benzene (1.0 mL) was then added and the cap was applied. The vial was heated at 80 °C with stirring over a hot plate. At the indicated times, the vial was rapidly cooled with running water and an aliquot of the reaction mixture was taken from the vial in a glovebox. The aliquot was diluted with $AcOEt$ and analyzed by GC. After sampling, the reaction mixture was heated again until the next sampling. The amount of PhBpin in the reaction mixture was determined over time, and the results are shown below.



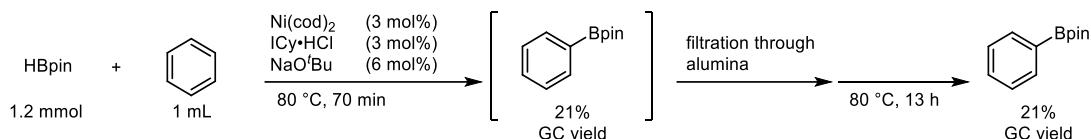
The total yield after 8 hours was 72%. These results showed that reaction monitoring by cooling did not deactivate the catalytic species. We observed that the reaction had an induction period of approximately 20 minutes at 80 °C.

Measurement of kinetic isotope effect. The initial rate up to 20% conversion was measured following the induction period, in which ca. 1 % of PhBpin was generated. The experiments were performed with benzene and benzene-*d*₆. Each experimental trial was performed in duplicate.



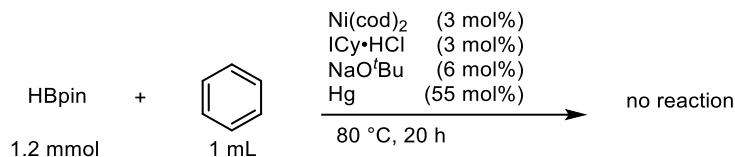
The average rate with benzene was determined to be 7.5×10^{-5} M/s, while the average rate with benzene-*d*₆ was determined to be 3.5×10^{-5} M/s. The KIE for this reaction was 2.1.

5-2. Test for Heterogeneous Catalyst



Filtration test. In a glovebox, $\text{Ni}(\text{cod})_2$ (9.1 mg, 0.033 mmol), $\text{ICy}\bullet\text{HCl}$ (9.4 mg, 0.035 mmol), $\text{NaO}'\text{Bu}$ (6.8 mg, 0.070 mmol), HBpin (163 mg, 1.3 mmol) and dodecane (59 mg as internal standard) were added to a 10 mL-sample vial with a Teflon-sealed screw cap. Benzene (1.0 mL) was then added and the cap was applied. The vial was heated at 80 °C with stirring over a hot plate. After 70 minutes, the vial was rapidly cooled under running water. An aliquot was taken from the mixture in a glovebox for GC analysis, which indicated that PhBpin was formed in 21% yield. The remainder of the reaction mixture was passed through alumina using 1 mL of benzene as the eluent. The filtrate was then transferred to a new 10 mL-sample vial and heated again for 13 h. The yield after 13 h was determined to be 21 %, thus demonstrating that the reaction did not proceed further following filtration.

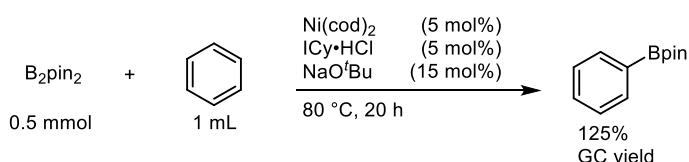
Note: When the reaction was performed under condition A with added alumina (40 mg), 63% GC yield was found following a 19 h reaction time span. This result indicated that alumina did not have a significant negative effect on this reaction.



Hg drop test. In a glovebox, $\text{Ni}(\text{cod})_2$ (10.5 mg, 0.038 mmol), $\text{ICy}\bullet\text{HCl}$ (10.2 mg, 0.038 mmol), $\text{NaO}'\text{Bu}$ (6.4 mg, 0.067 mmol), HBpin (164 mg, 1.3 mmol), dodecane (64 mg as internal standard) and Hg (145 mg, 0.72 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screw cap. Benzene (1.0 mL) was then added and the cap was applied. The vial was heated at 80 °C for 20 h with stirring over a hot plate. The resulting mixture was analyzed by GC and none of the target product was observed.

5-3. Diboron as a Borylating Reagent

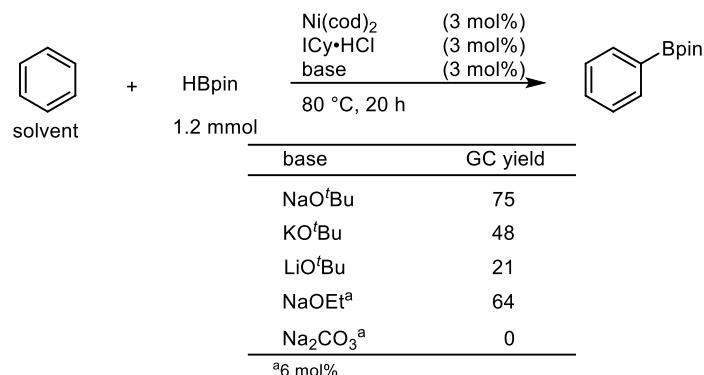
This reaction was conducted with B_2pin_2 as the boron source instead of HBpin.



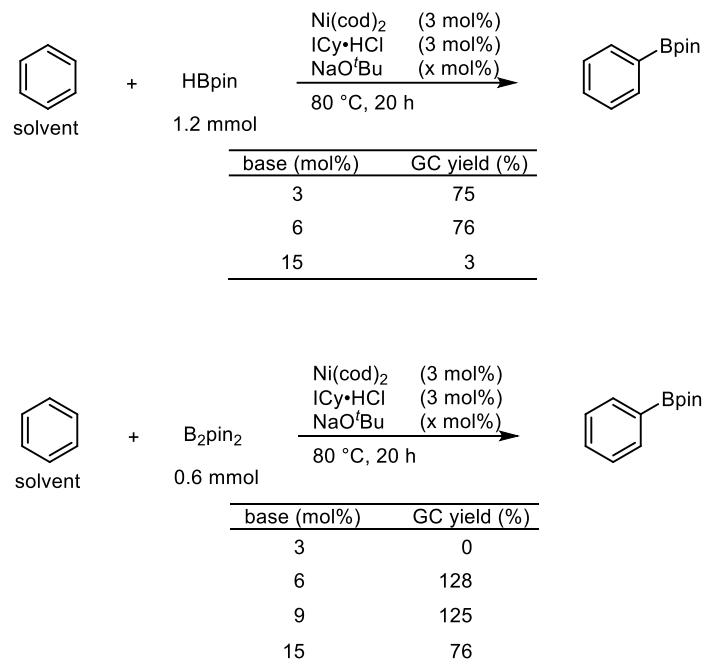
In a glovebox, $\text{Ni}(\text{cod})_2$ (7.5 mg, 0.027 mmol), $\text{ICy}\bullet\text{HCl}$ (7.4 mg, 0.028 mmol), $\text{NaO}'\text{Bu}$ (7.2 mg, 0.074 mmol) and B_2pin_2 (126 mg, 0.49 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screw cap. Benzene (1.0 mL) was then added and the cap was applied. The vial was heated at 80 °C for 20 h with stirring over a hot plate. The resulting mixture was filtered through a silica gel column (eluting with 10 mL of hexane/ $\text{AcOEt} = 5/1$). The filtrate was analyzed by GC with dodecane as the internal standard and the target product was found in a 125% GC yield based on the molar amount of B_2pin_2 .

5-4. Effect of Base

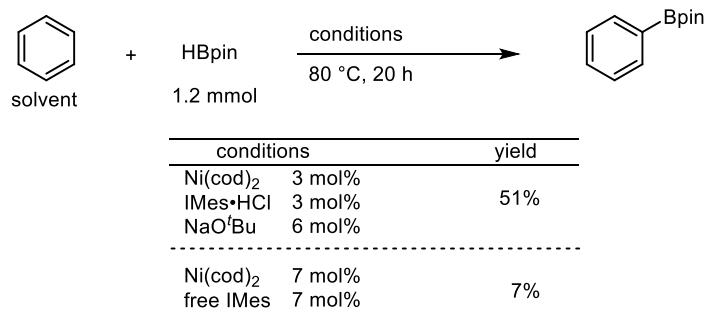
Method A was followed using 3 mol% of the bases listed in the table. NaO'Bu was chosen as the optimal base for nickel-catalyzed C-H borylation.



The equivalent of base dramatically influenced the reaction efficiency in both cases using HBpin and B₂pin₂.



When the reaction was performed in the absence of the NaO'Bu using free IMes, the yield dramatically decreased compared to the results when an IMes ligand generated from IMes•HCl and NaO'Bu was used.



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Chapter 2

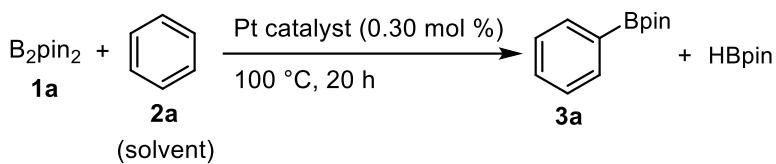
Platinum-Catalyzed Borylation of Aromatic C-H Bonds

2.1 Introduction

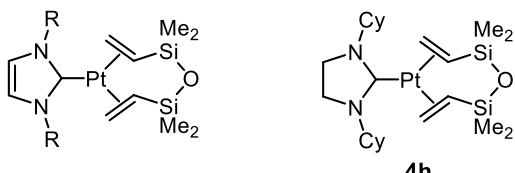
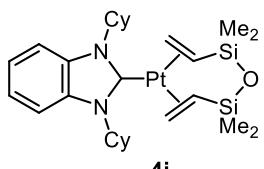
Based on the results for the nickel-catalyzed C-H borylation of arenes described in Chapter 1, the author became interested in the reactivity of its heavier congener platinum for the C-H borylation of arenes. When this study was initiated, there were no other reports in the literature describing the use of a platinum complex in a C-H borylation reaction. Additionally, catalytic C-H functionalization reactions of arenes using platinum catalysts have been much less studied¹ compared to reactions involving palladium and nickel catalysts, and only a few examples of C-H silylation,² intramolecular C-H amination,³ hydroarylation⁴ and arylation⁵ can be found in the literature. In contrast, it is well known that platinum complexes are efficient catalysts for hydroboration and diboration reactions,⁶ which have been postulated to be mediated by a platinum-boryl intermediate.⁷ The author hypothesized that a platinum-boryl species could also mediate C-H borylation reactions if it were used with an appropriate choice of ligand and/or additive. Herein, an efficient borylation reaction of aromatic C-H bonds catalyzed by N-heterocyclic carbene (NHC)-ligated platinum catalysts is described. It is noteworthy that Takaya and Iwasawa independently reported that platinum catalysts bearing a pincer ligand can effect the C-H borylation of polyfluorinated arenes.⁸

2.2 Results and Discussion

C-H Borylation with Pt/NHC Complexes. The author initially evaluated the performance of Karstedt's catalyst **4** [Pt₂(dvtms)₃, dvtms = 1,3-divinyltetramethyldisiloxane] for the reaction of benzene with bis(pinacolato)diboron (**1a**), and found that this system produced a small amount of the target borylated product **3a** (TON =5, Table1, Entry1). The effectiveness of NHCs as ligands in the nickel-catalyzed C-H borylation reaction described in Chapter 1 led the author to investigate the catalytic activity of Pt/NHC catalysts. Pt(NHC)(dvtms) complexes was chosen in this particular case because they are air stable and easy to handle platinum catalyst precursors, which can be prepared in two steps from H₂PtCl₆. The Pt(NHC)(dvtms) complexes have been reported to be effective catalysts for hydrosilylation.⁹ In the current study, the introduction of NHCs generally led to an improvement in the turnover number (TON) values of the catalysts. For example, the IMes-ligated platinum complex

Table 1. Platinum-Catalysts for the C-H Borylation of Benzene^a

Entry	Catalyst	NHC	TON ^b
1	$\text{Pt}_2(\text{dvtms})_3$ (4)	-	5
2	4a	IMes	40
3	4b	IPr	0
4	4c	IMe	6
5	4d	<i>i</i> Pr	69
6	4e	<i>t</i> Bu	16
7	4f	I(1-Ad)	58
8	4g	ICy	157
9	4h	SICy	106
10	4i	BICy	102
11	$\text{Pt}(\text{PPh}_3)_4$	-	0
12 ^c	4 + PCy_3	-	2
13 ^c	4 + 2,2'-bipyridine	-	13

**4a:** R = 2,4,6-Me₃C₆H₂**4b:** R = 2,6-*i*Pr₂C₆H₃**4c:** R = Me**4d:** R = *i*Pr**4e:** R = *t*Bu**4f:** R = 1-adamantyl**4g:** R = cyclohexyl

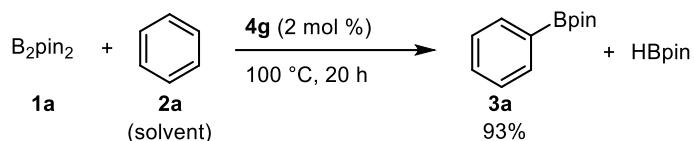
^aReaction conditions: **1a** (0.30 mmol), catalyst (0.90 μ mol) in benzene (1.0 mL) at 100 °C for 20 h.

^bTON: molar amount of **3a** formed per molar amount of catalyst. ^c**4** (6.0 μ mol) and PCy_3 or 2,2'-bipyridine (6.0 μ mol), if indicated, were used.

4a resulted in an 8-fold improvement in the TON to 40 (Entry 2), whereas the IPr complex **4b** gave none of the desired borylated product (Entry 3). Among the NHCs examined in this study, the ICy-ligated complex **4g** was determined to be optimal in terms of its TON for the borylation of benzene (Entry 8). In the presence of 2 mol% of **4g**, the borylated product **3a** was isolated in 93% yield (Scheme 1). In contrast, phosphine and bipyridine ligands were much less effective than **4g** (Entries 11-13). Diboron reagent **1a** was determined the most effective boron source for this platinum-catalyzed C-H borylation reaction. The use of other boron reagents such as pinacolborane (HBpin) or

bis(neopentylglycolato)diboron (B_2nep_2) gave insufficient results (1% and 6% yield, respectively, in the presence of 2 mol% **4g**).

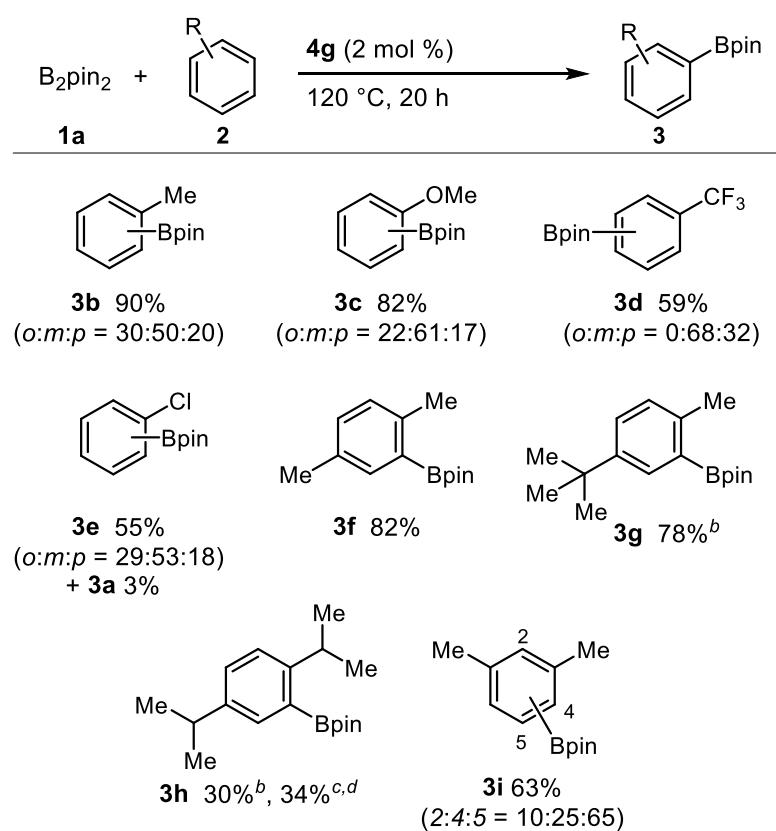
Scheme 1. Platinum-Catalyzed Borylation of Benzene



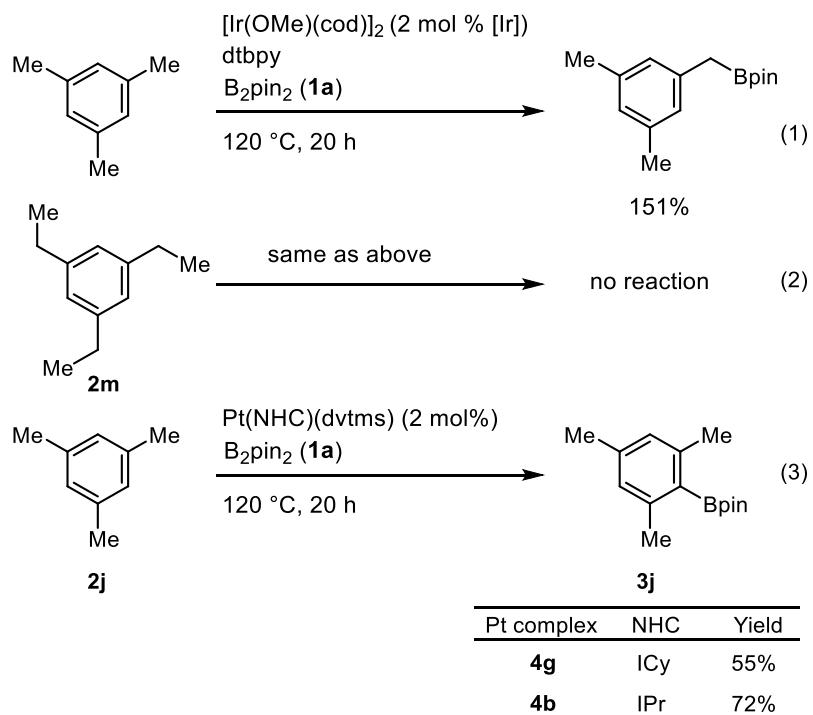
With the optimized conditions in hand, the author proceeded to investigate the borylation of a series of substituted arenes to examine the regioselectivity of this platinum-catalyzed borylation reaction (Figure 2). The borylation of toluene was conducted at 120 °C with 2 mol% of the ICy catalyst **4g**, leading to the formation of a mixture of *o*-, *m*- and *p*-borylated products **3b** without any of the benzylic borylation product. The formation of a significant amount of the *ortho*-borylated isomer indicated that the present platinum catalyst system was not particular sensitive to steric effects. Catalyst **4g** was also used to borylate anisole, trifluorobenzene and chlorobenzene, resulting in *o*- *m*- and *p*-borylated mixtures of the corresponding products **3c-3e**, respectively, indicating that this catalyst system was insensitive to the electronic properties of the arene substrate. The borylation of *p*-xylene proceeded efficiently to give the 2-borylated product **3f**, as a single product. In the case of 4-*tert*-butyltoluene (**2g**), the borylation proceeded at the least hindered 2-position to give **3g**. This platinum catalyst system was also used to borylate the C-H bond *ortho* to the isopropyl group in **2h**, albeit in a low yield. *m*-Xylene was also borylated under these platinum-catalyzed conditions to give a mixture of regioisomers. Surprisingly, some borylation was observed at the sterically congested 2-position of *m*-xylene, in addition to borylation at the 4- and 5-positions (2:4:5 = 10:25:65, **3i**). This reactivity contrasts sharply with the selectivity observed for iridium catalysts, where the least hindered 5-position is borylated exclusively.¹⁰

Borylation of Sterically Congested C-H Bonds. The high sensitivity of iridium catalysts to steric hindrance allows for the selective borylation of the least hindered C-H bond in an arene substrate. However, this sensitivity can become a problem for the borylation of sterically congested C-H bonds such as those of mesitylene. For instance, the borylation of mesitylene in the presence of an Ir(dtbbpy) catalyst occurs exclusively at the sterically more accessible benzylic C-H bond (eq 1). To the best of our knowledge, the only reported example of the C(sp²)-H borylation of mesitylene involved the use

Figure 2. Platinum-Catalyzed Borylation of Substituted Arenes^a



^aReaction conditions: arene (1.0 mL), **1a** (0.30 mmol), **4g** (2 mol%), 120 °C, 20 h. Yields are based on **1a**. The regioisomeric ratios were determined by ¹H NMR spectroscopy or GC analysis. ^b**4f** (2 mol%) was used instead of **4g**. ^cAt 140 °C. ^dIsolated yield determined by the conversion of the product to the corresponding phenol.



of a heterogeneous iron catalyst (41% GC yield after 4 days).¹¹ Furthermore, the more sterically hindered substrate 1,3,5-triethylbenzene (**2m**) failed to react under the iridium-catalyzed conditions (eq 2). The development of new methods for the C-H borylation of hindered arenes is therefore highly desired because these systems are common structural motifs in a variety of different fields, including pharmaceuticals,¹² photocatalyst,¹³ steric protection of reactive chemical species,¹⁴ chiral catalysts,¹⁵ and functional polymers¹⁶ (Figure 3). The low sensitivity exhibited by our platinum catalyst towards the steric hindrance exerted by neighboring substituents prompted the author to examine the borylation of mesitylene. Pleasingly, catalyst **4g** allowed for the successful borylation of the sterically hindered C(sp²)-H bond in mesitylene to give **3j** in 55% yield as the sole product (eq 3). In an attempt to improve the yield of this reaction, the author investigated the effect of the ligand (See experimental section for details about the effect of the ligand). In this regard, the IPr-bound platinum complex **4b** was found to be more effective than **4g**, leading to a considerable improvement in the yield of **3j** to 72%.

As shown in Entry 3 of Table 1, catalyst **4b** was totally ineffective for the borylation of benzene. NMR monitoring of the reaction using **4b** revealed that the dvtms ligand of **4b** does not decompose under the catalytic conditions at 100 °C, while the decomposition occurs at 120 °C. In contrast, the dvtms ligand of ICy-bound complex **4g** dissociates at 100 °C (see eq 6). Therefore, the nature of the ligand affects not only the catalytic activity for the borylation reaction, but also the efficiency of the generation of active catalytic species (i.e., the efficiency of the dissociation of dvtms), and both effects would lead to an improved yield of the borylated product.

Catalyst **4b** effectively borylated a series of 1,3,5-trisubstituted arenes to give the corresponding arylboronic ester bearing two *ortho* substituents (Figure 4). A *tert*-butyl group was sufficiently large to block borylation at its *ortho* position in **2k**, as evidenced by the exclusive formation of **3k**. Similarly, 1-isopropyl-3,5-dimethylbenzene (**2l**) was regioselectively borylated at its 4-position (the least hindered position) to give **3l**, although some borylation was also observed at the C-H bond *ortho* to the isopropyl group (positions 2:4 = 92:8), further highlighting that platinum is much less sensitive to steric hindrance than iridium. It is noteworthy that 1,3,5-triethylbenzene (**2m**) was successfully borylated through the activation of its C(sp²)-H bonds, which were shielded by two *ortho*-ethyl groups to give the corresponding borylated product **3m**. The iridium/dtbpy catalyst was completely inactive against **2m** (eq 2). This result therefore clearly highlights the unique properties of platinum catalyst systems for the borylation of sterically hindered C(sp²)-H bonds. Furthermore, several functional groups, including esters, amines, chlorides and fluorides were tolerated under these conditions, which allows access to a series of elaborate hindered arylboronic esters **3n-3q**.

Figure 3. Widespread Applications of Hindered Arenes

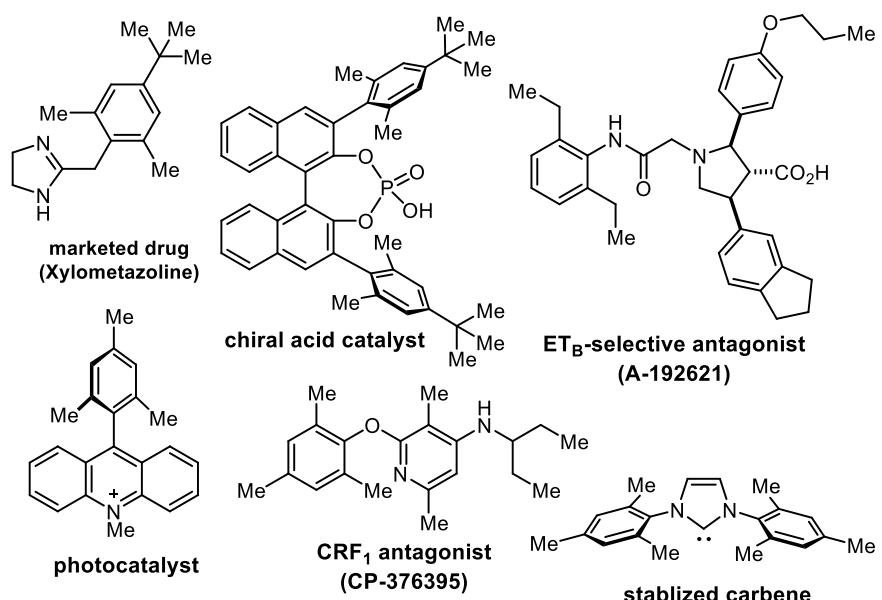
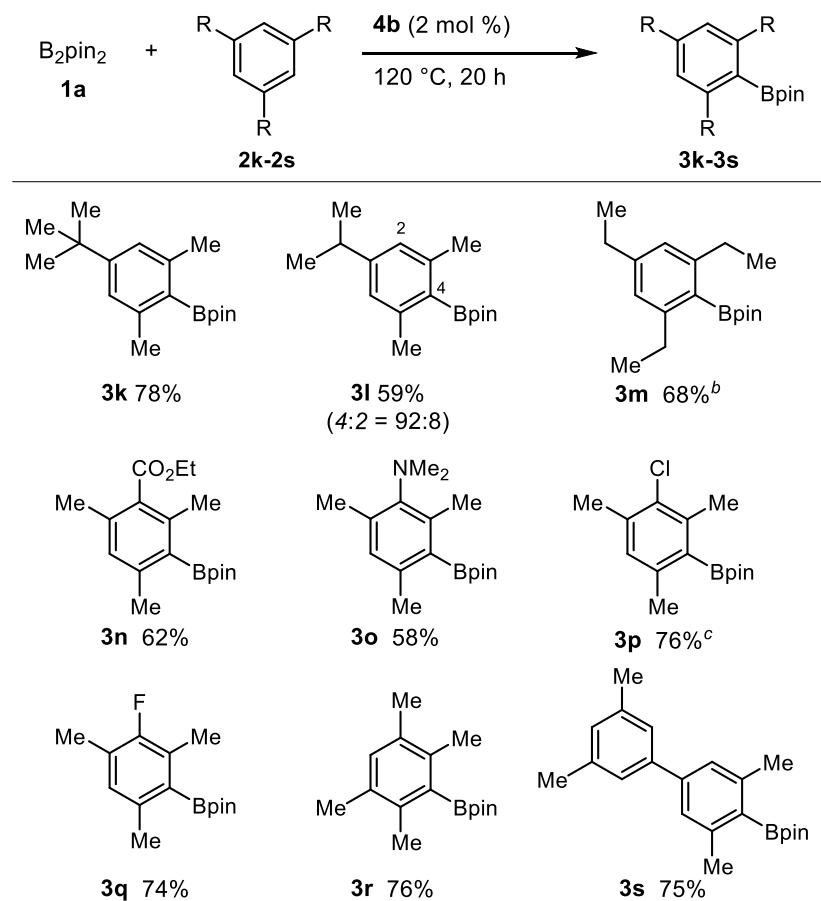


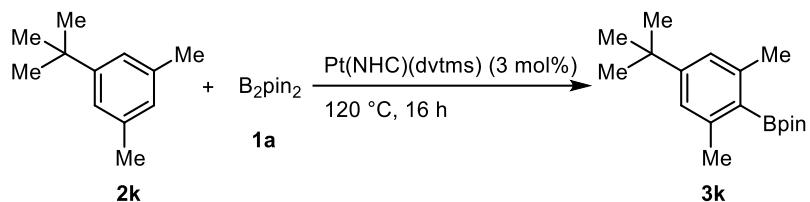
Figure 4. Platinum-Catalyzed Borylation of C-H Bonds in Sterically Congested Arenes^a



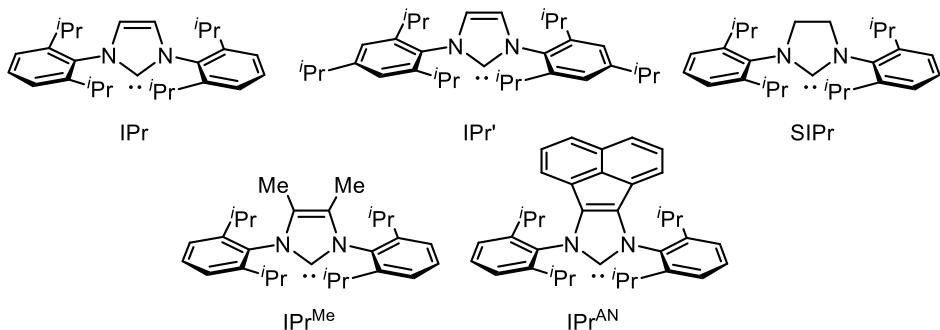
^aReaction conditions: arene (1.0 mL), **1a** (0.30 mmol), **4b** (2 mol%), 120°C , 20 h. Yields are based on **1a**. The regioisomeric ratios were determined by ^1H NMR spectroscopy. ^bAt 140°C , ^cThe dechlorinated product **3j** was also formed (4%).

Although this platinum-catalyzed borylation requires an excess (ca. 20-35 equiv) of the arene substrate to obtain satisfactory levels of conversion, the unreacted substrate can be recovered quantitatively and used for another borylation reaction. However, the need for such a large excess of substrate clearly limits the application of this method to more elaborate substrates. To address this issue, the author conducted a series of optimization to identify much more practical conditions. The effect of the ligand was investigated in much greater detail using hindered arene **2k** as a limiting agent in the presence of 1.0 equiv of **1a** under neat conditions (Table 2). The IPr-ligated catalyst **4b** was still active under these conditions and gave the borylated product **3k** in 51% yield (Entry 1). Although the yield of **3k** was moderate, **1a** was completely consumed, indicating that **1a** was also involved in some undesired pathways. There have been several reports pertaining to C-H borylation reactions, where the catalyst is deactivated through the C-H borylation of the ligand.¹⁷ These reports led the author to investigate the use of IPr derivatives with fewer C-H bonds capable of being borylated. Whilst the use of an NHC bearing 1,3,5-triisopropylphenyl groups (IPr', **4j**) was less effective than IPr (Entry 2), the use of IPr derivatives with modifications on the imidazole backbone, such as SIPr (**4k**), IPr^{Me} (**4l**) and IPr^{AN} (**4m**), all improved the yield of the borylated product **3k** (Entries 3-5). These results therefore suggested that the higher efficiency of catalysts **4k-4m** could be attributed to their larger size¹⁸ or limited rotation around their C(aryl)-N bonds,¹⁹ rather than suppressing the C-H borylation of the imidazole ring. To develop conditions applicable to various arene substrates, the author subsequently investigated the use of several solvents with platinum catalyst **4k** (Entries 6-10). The borylation was found to be highly sensitive to the concentration of the aromatic substrate. For example, concentration of 0.3 and 3.0 M resulted in yields of 18 and 58% for the borylation of **2k** in octane (Entries 6 and 7, respectively). Several other nonpolar solvents, such as cyclooctane, decane and triisopropylbenzene (TIPB) were also used without any discernible loss of catalytic activity, thereby expanding the scope of this borylation procedure to solid arene substrates. product **3q-di** was obtained as the major isomer when the borylation reaction was repeated (90% combined yield, **3q-mono:3q-di** = 28:72). The new protocol developed above allowed for the borylation of several relatively complicated arenes, such as those containing menthol (**3v**) and borneol (**3w**) substructures. The protocol was capable of regioselectively borylating a silyl-substituted substrate to form an arene bearing both boron and silicon functionalities (**3y**), which are amenable to orthogonal functionalization (*vide infra*). Trifluoromethyl (**3z**), alkyl chloride (**3aa**) and TBDMS ether (**3ab**) groups were also found to be compatible with these reaction conditions. Carbonyl functionalities such as benzamide (**3ac**), anilide (**3ad**) and alkyl ester (**3ae**) groups were also tolerated under these conditions.

Table 2. Optimization towards Practical C-H Borylation of Hindered Arenes^a



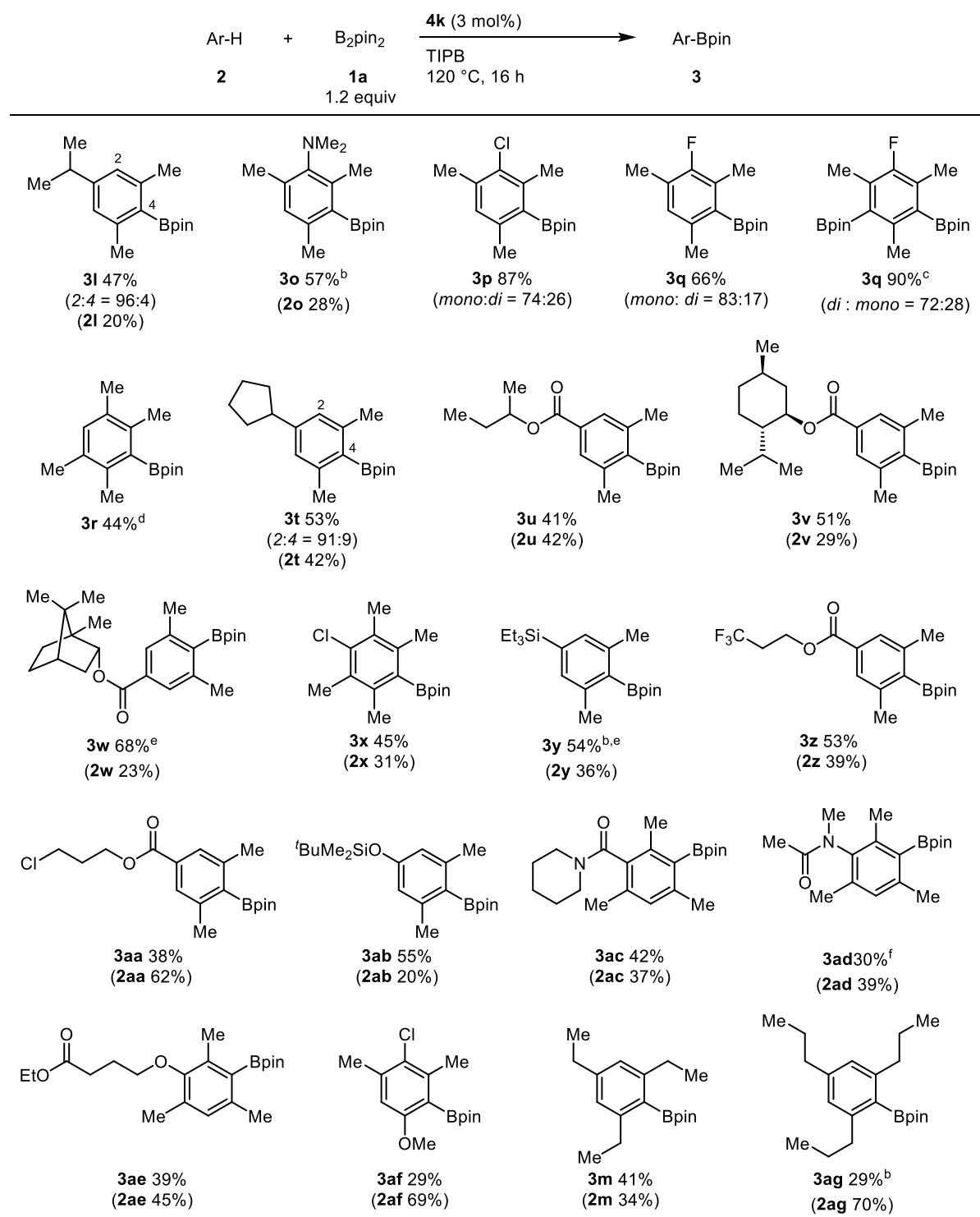
Entry	Catalyst	NHC	Solvent	Yields ^b
1	4b	IPr	neat	51
2	4j	IPr'	neat	39
3	4k	SIPr	neat	72 (65) ^c
4	4l	IPr ^{Me}	neat	76
5	4m	IPr ^{AN}	neat	72
6	4k	SIPr	octane (0.30 M)	18
7	4k	SIPr	octane (3.0 M)	58
8	4k	SIPr	cyclooctane (3.0 M)	57
9	4k	SIPr	decane (3.0 M)	58
10	4k	SIPr	TIPB (3.0 M)	53



^aReaction conditions: **2k** (0.30 mmol), **1a** (0.30 mmol for Entries 1-5; 0.36 mmol in Entries 6-10), Pt(NHC)(dvtms) (3 mol%), 120 °C, 16 h. ^bYields determined by GC based on **2k**. ^cIsolated yield. TIPB = 1,3,5-triisopropylbenzene.

It is noteworthy that this platinum-catalyzed methodology is not limited to the borylation of C-H bonds surrounded by two methyl groups. For example, C-H bonds between methyl and methoxy groups (**3af**), two ethyl groups (**3m**) and two *n*-propyl groups (**3ag**) were all successfully borylated under these modified conditions to form the corresponding products. Although the yields of these products were moderate, most of the unreacted substrates could be recovered in good yields. It was therefore possible to improve the yields of these borylated products by simply repeating the borylation reaction. For example, the elaborate boronic ester **3v** was successfully synthesized on a gram scale by simply repeating the borylation reaction (Scheme 2). Increasing the loading of the platinum catalyst did not generally lead to improvements in the yields of the borylated products. The origin of the unique

Figure 5. Substrate Scope for Sterically Congested Arenes under the Improved Conditions^a

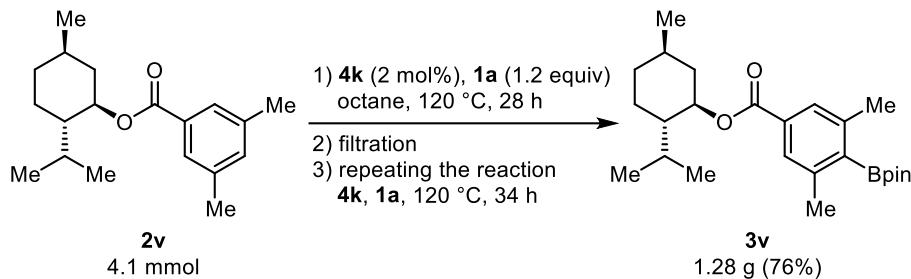


^aReaction conditions: **2** (0.30 mmol), **1a** (0.36 mmol) and **4k** (3 mol%) in TIPB (0.10 mL) at 120 °C for 16 h. Yields are the isolated yield based on **2**. Yields in parentheses refer to those of the recovered starting materials. ^b Octane (0.10 mL) was used instead of TIPB. ^c **2q** (0.15 mmol), **1a** (0.36 mmol), **4k** (6 mol%) were used and the reaction was repeated twice. ^d **2r** (0.60 mmol) and **1a** (0.30 mmol) were used; the yield is based on **1a**. See SI for details. ^eThe reaction was repeated twice. See SI for details.

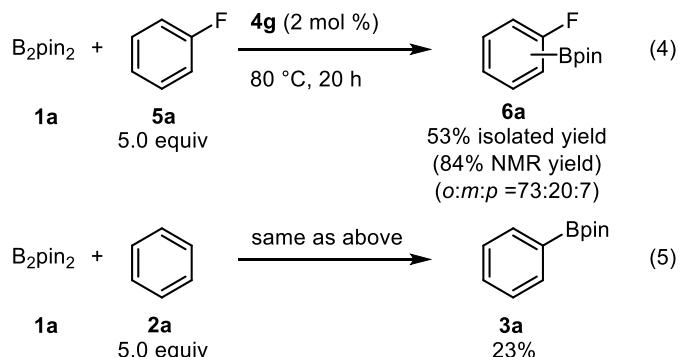
^f Isolated yield determined by the conversion of the product to the corresponding phenol.

regioselectivity by platinum catalysis currently remains elusive. Unlike iridium catalyst system, lack of the present platinum system in the activity toward C(sp³)–H bond activation should be the key to the successful borylation of mesitylene derivatives.

Scheme 2. Gram-Scale Borylation of **3v**



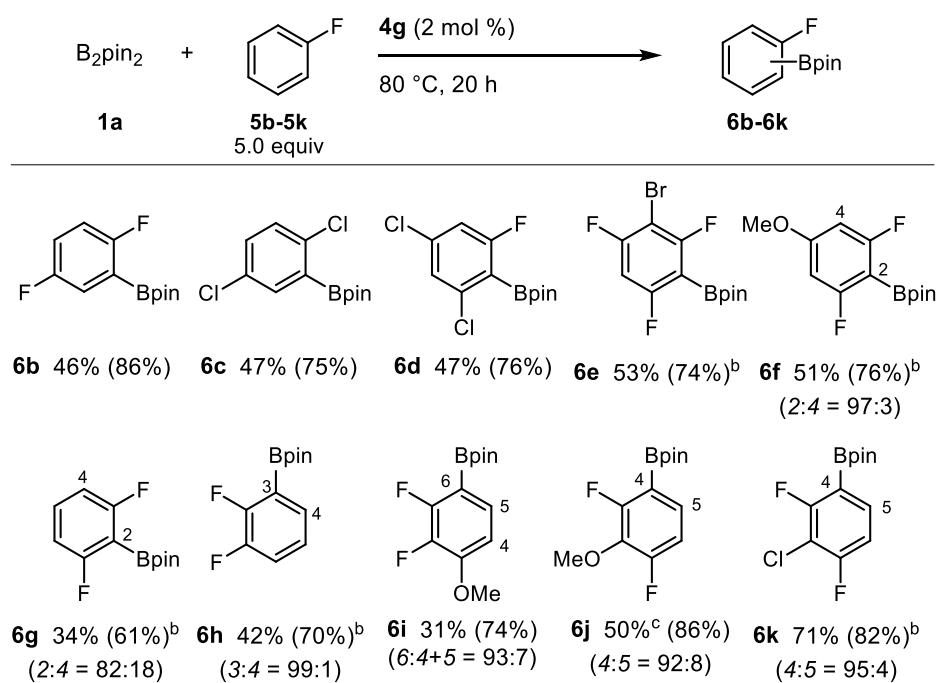
Borylation of Fluorinated Arenes. The introduction of a fluorine atom to the benzene ring had a profound effect on both the reactivity and selectivity of the platinum-catalyzed C–H borylation reaction. For example, the borylation of fluorobenzene (**5a**) proceeded efficiently even when the amount of the substrate was decreased to 5.0 equiv to give **6a** (eq 4). In contrast, the reaction of benzene under the same conditions resulted in insufficient yield of the borylated product (eq 5).



Notably, the C–H borylation of **5a** proceeded with a high level of *ortho* selectivity (73%), suggesting that fluorine atom exhibited an *ortho*-directing effect. When the borylation of fluorobenzene was performed with Ir/dtbipy catalyst, *meta*-borylated product was obtained as a major isomer (*o*/*m*/*p* ratio of 37:50:13). Fluorine has been reported to behave as a directing group in C–H borylation reactions involving rhodium²⁰ and cobalt²¹ catalyzed systems, although the scope of this directing effect has not been extensively investigated. Takaya and Iwasawa reported a similar *ortho*-directing effect for fluorine when they investigated the C–H borylation of polyfluorinated benzene substrates with

platinum catalysts bearing a pincer ligand.⁸ A similar activating effect was also observed for chloroarenes, as exemplified by the formation of **6c** and **6d** (Figure 6). Several 1,3-difluorobenzene derivatives were also borylated to give the 2-borylated products as the major isomers, although this position was the most congested among the C-H bonds available (**6e-6g**). Most notably, 1,2-difluorobenzene derivatives bearing a C-H bond *ortho* to a fluorine atom were selectively borylated at this position to form **6h** and **6i**, rather than being borylated at their much less hindered C-H bonds. The two difluorinated arenes **5j** and **5k** also showed high *ortho* selectivity to form the corresponding polysubstituted aryl boronic esters **6j** and **6k**. Although the isolated yields of these fluorinated phenylboronic esters were found to be modest because of their poor stability during chromatographic isolation, these borylated products could be used directly without isolation as useful building blocks for the synthesis of fluorinated aromatic compounds. For example, **6j** was directly converted to the corresponding phenol without isolation. The observed directing effect probably results from the increased acidity of a C-H bond that locates at the *ortho* position of fluorine,²² which facilitates the metalation process to occur at the *ortho* position of fluorine. The higher bond strength of carbon-metal bonds that are close to fluorine can also contribute to the observed *ortho* selectivity.²³

Figure 6. Substrate Scope of Fluorinated Arenes^a

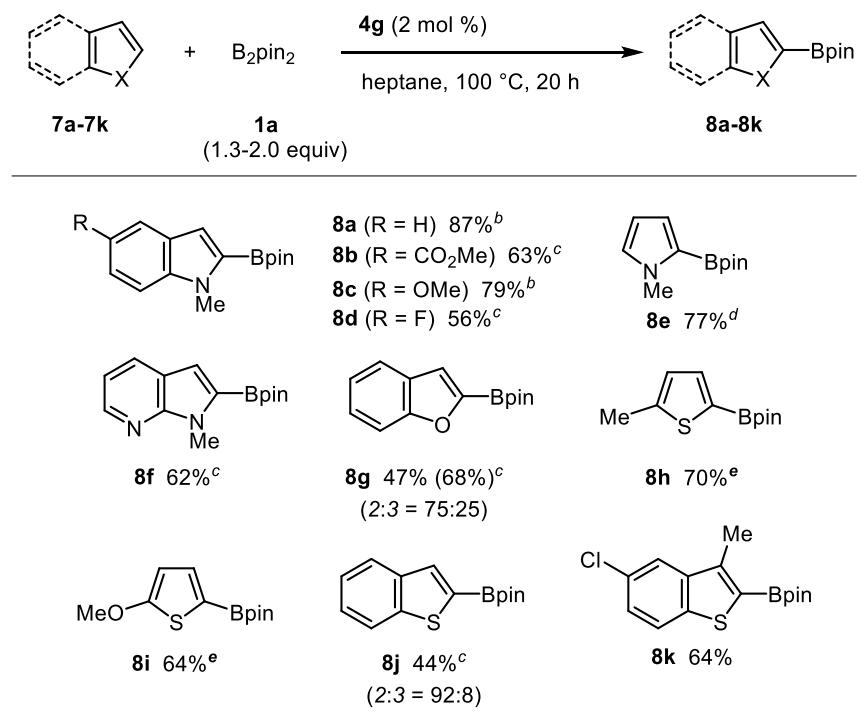


^aReaction conditions: **1a** (0.30 mmol), **5** (5 equiv), **4g** (2 mol%), 80 °C, 20 h. Yields are based on **1a**. The regioisomeric ratios were determined by ¹H NMR spectroscopy or GC analysis. Yields in

parentheses refer to the NMR yields. ^bAt 60 °C. ^cIsolated yield determined by the conversion of the product to the corresponding phenol.

Borylation of 5-Membered Heteroarenes. 5-Membered heteroarenes are generally considered to be highly reactive substrates for C-H borylation reactions.²⁴ A similar trend was also observed in the present platinum-catalyzed system. For example, *N*-methylindole **7a** was sufficiently reactive to undergo borylation in the presence of 2.0 equiv of **1a** and 2.0 mol% of platinum catalyst **4g** in heptane to afford the 2-borylated product **8a** in 87% isolated yield (Figure 7). Indoles bearing a variety of different substituents, including an ester (**7b**), ether (**7c**) and fluoride (**7d**) were also successfully borylated to give the corresponding 2-borylated indoles **8b-8d**, respectively. The exclusive formation of **8d** suggested that an indole C-H bond is more susceptible to borylation than a C-H bond *ortho* to a fluorine atom. Although pyrrole **7e** was also successfully borylated under our newly developed platinum-catalyzed conditions, the reaction needed to be conducted in the presence of a large excess of pyrrole to suppress the undesired diborylation reaction. Although 6-membered heteroarenes such as pyridine and quinoline were found to be unsuitable for this type of platinum catalysis, they were not detrimental to the C-H borylation of azoles, as evidenced by the successful formation of the borylated

Figure 7. Substrate Scope of 5-Membered Heteroarenes^a



^aReaction conditions: **7** (0.30 mmol), **1a** (1.2 equiv), **4g** (2 mol%), heptane (1.0 mL), 80 °C, 20 h. Yields are based on **7**. The regioisomeric ratios were determined by ¹H NMR spectroscopy or GC

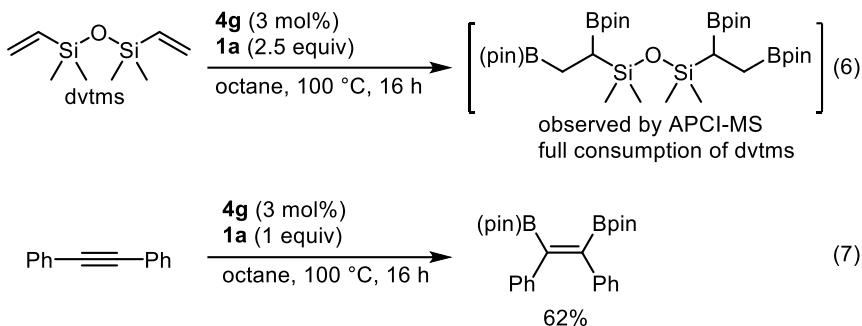
analysis. Yields in parentheses refer to the NMR yields. ^b**1a** (2.0 equiv) was used. ^c**4g** (4 mol%) was used. ^dN-Methylpyrrole **7e** (5.0 equiv to **1a**) was used. ^eHeteroarene was used as the solvent.

azaindole **8f**. Benzofuran **7g** was also borylated under these conditions, albeit with decreased reactivity and poor 2-/3-selectivity. Thiophenes and benzothiophenes served as good substrates for the platinum-catalyzed borylation and afforded the corresponding borylated products **8h-8k** in moderate to good yields.

Mechanistic Considerations. Several experiments were conducted to gain a deeper insight into the nature of the catalytically active platinum species involved in this C-H borylation reaction. It was previously proposed that the dvtms ligand in the platinum precursor decomposed prior to the formation of the catalytically active platinum species in hydrosilylation reactions involving Pt(NHC)(dvtms).^{9,25} With this in mind, the author investigated the reaction of dvtms with **1a** in the presence of Pt(ICy)(dvtms) **4g** to examine the reactivity of dvtms under the catalytic conditions used in the current C-H borylation reaction. APCI-MS analysis revealed that the dvtms was completely consumed under the reaction conditions to give the corresponding tetraborylated product (eq 6). This observation clearly demonstrated that the dvtms ligand could dissociate from the platinum center via the diboration of its alkene moieties to generate a coordinatively unsaturated platinum species, which could subsequently react with **1a**. It has been reported that several platinum(0) complexes can react with diboron reagents to afford platinum(II) diboryl species. For example, platinum diboryl complexes bearing phosphine ligands have been isolated and characterized, and their catalytic activity towards the diboration of alkenes and alkynes have been reported in detail.⁷

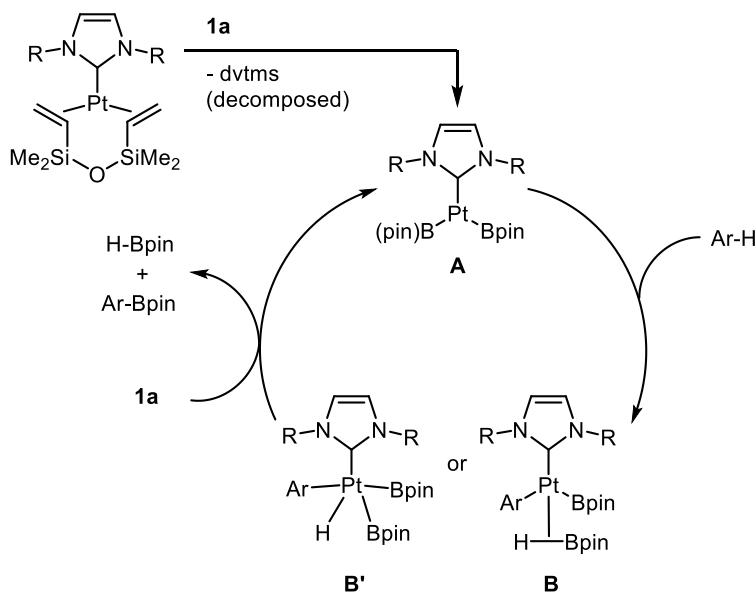
It has also been reported that the Pt(NHC)(dvtms) complex, where NHC is I^nBu or a triazole-based carbene, can catalyze the diboration of alkynes and alkenes, most likely through the formation of a Pt(NHC)(Bpin)₂ species.^{6d,e} It was also confirmed in our own hands that Pt(ICy)(dvtms) **4g** catalyzed the diboration of diphenylacetylene (eq 7). This observation suggested that **4g** could also generate a platinum diboryl species via its reaction with **1a**.

Scheme 2. Diboration of an Alkene and an Alkyne with Pt(ICy)(dvtms) Complex



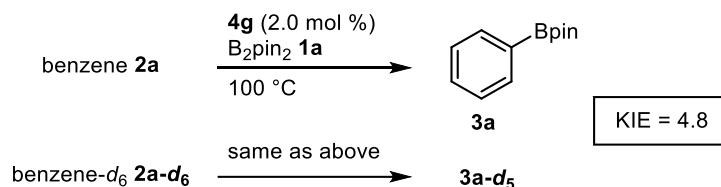
Based on these experiments, the author proposed a possible reaction mechanism for the Pt(NHC)-catalyzed borylation of arenes, which is shown in Scheme 3. The Pt(NHC)(dvtms) complex would be activated by its reaction with **1a** to give the platinum diboryl species **A** via the decomposition of the dvtms ligand. Complex **A** would then function as an active species to activate the C-H bond in the arenes. With regard to the subsequent C-H bond cleavage step, we considered two different mechanisms. The first of these mechanisms involve a σ -bond metathesis reaction between **A** and one of the Ar-H bonds of the substrate to form the Ar-Pt(II)-Bpin species **B**. The other mechanism would involve the oxidative addition of one of the C-H bonds to **A**, leading to the formation of the platinum(IV) species **B'**. It is noteworthy that σ -bond metathesis pathways have been proposed for rhodium- and iron-catalyzed C-H borylation reactions, based on DFT calculations,²⁶ whereas oxidative addition pathways have been proposed for iridium-catalyzed C-H borylation reactions.²⁷ However, there is currently no evidence to discriminate these two pathways. The subsequent reaction of **B** or **B'** with **1a** would result in the release of HBpin and ArBpin with the regeneration of **A**.²⁸

Scheme 3. Proposed Mechanism for the Pt-Catalyzed Borylation Reaction



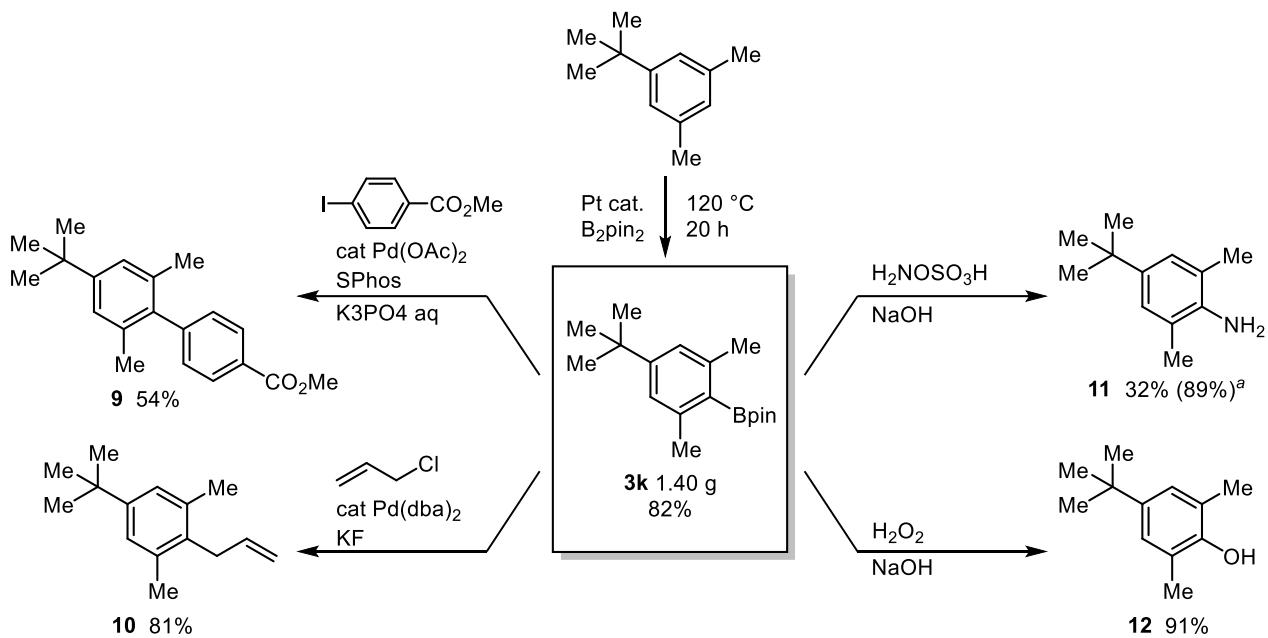
The platinum-catalyzed borylation of benzene was monitored by GC and $^1\text{H-NMR}$ spectrometry and the results revealed that there was an induction period before the borylation started to occur. The decomposition of the dvtms ligand most likely occurred during the induction period to generate the catalytically active platinum species. Other experiments revealed that HBpin was generated during the borylation of benzene, and that this material remained unreacted (see experimental section for details). Initial rate experiments for the borylation of benzene revealed a large KIE value (4.8), which indicated that the cleavage of the C-H bond was most likely the turnover-limiting step of the catalytic cycle (Scheme 4). A similarly large KIE value (2.7) was also observed for the platinum-catalyzed borylation of *N*-methylindole under dilute conditions.

Scheme 4. KIE Experiments



Synthetic Applications. The current platinum-catalyzed borylation was found to be amenable to scale up, as exemplified by the gram-scale synthesis of **3k**, which could be used as a versatile building block for the introduction of different groups (Scheme 5). For example, the steric demand around the boron moiety in **3k** did not hamper its reactivity towards a standard palladium-catalyzed Suzuki-Miyaura cross-coupling reactions for the introduction of aryl (**9**) and alkyl (**10**) groups. Compound **3k** also afforded a hindered aniline **11** and a hindered phenol **12** via known amination²⁹ and oxidation methods, respectively.

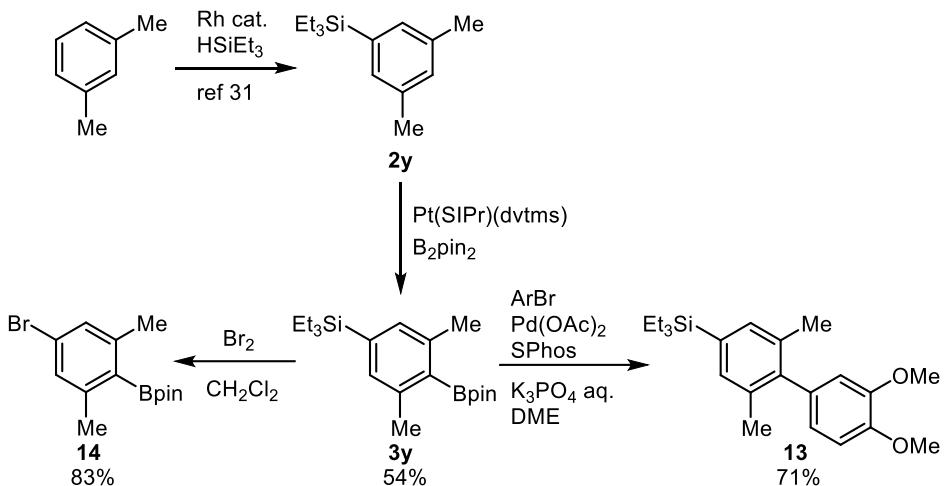
Scheme 5. Gram-Scale Synthesis of **3k** and Its Transformations



^aYield based on the recovered starting material.

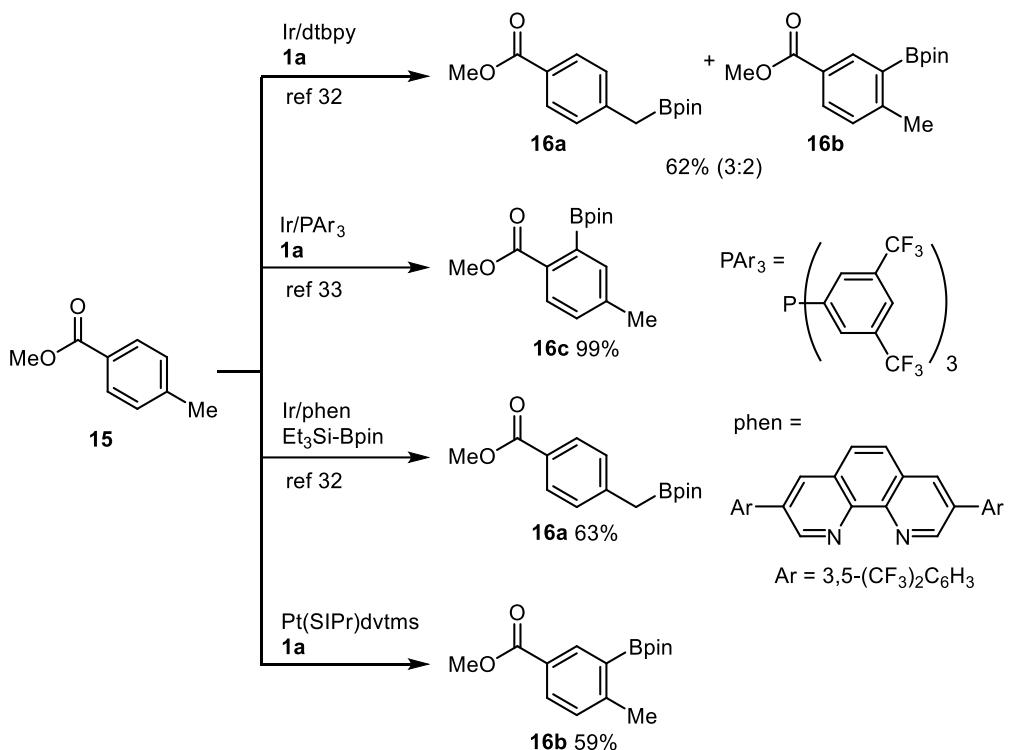
Sequential C-H functionalization reactions were also evaluated in this study (Scheme 6). The rhodium-catalyzed silylation of *m*-xylene is known to occur at the least hindered 5-position to form **2y**.^{30,31} the subsequent borylation of **2y** under our platinum-catalyzed conditions led to the activation of the C-H bond surrounded by two methyl groups to form **3y**. The silyl and boryl groups in **3y** could be converted to other functionalities in an orthogonal manner.³⁰ For example, the selective transformation of the boryl functionality in **3y** to an aryl group was successfully accomplished under standard Suzuki-Miyaura reaction conditions whilst leaving the silyl group unchanged to form **13**. Conversely, the silyl group in **3y** was brominated without the loss of the Bpin group to generate **14**. These examples further demonstrated the tolerance of our platinum catalyst towards steric demand, as well highlighting how it can be used in combination with existing methods to generate new synthetic strategy for the regioselective functionalization of hindered arenes.

Scheme 6. Sequential C-H Functionalization of *m*-Xylene and Divergent Functionalization of **3y**



As demonstrated in Figure 4-7, the platinum catalysts developed in the current study afforded unique levels of regioselectivity that are different to those observed with other catalysts. The complementary regioselectivities of these different systems is best exemplified by the borylation of *p*-methylbenzoate **15** (Scheme 7). The use of the standard Ir/dtbpy catalyst led to a mixture of products, including the benzylic borylation product **16a** and the 3-borylated product **16b**.³² Selective borylation at the 2-position was only achieved with an Ir/P(3,5-(CF₃)₂C₆H₃)₃ system, where the ester group of the substrate acted as an *ortho*-directing group to form **16c**.³³ Selective borylation at the benzylic position was possible with an iridium/phenanthroline system when silylborane was used as the borylating agent to deliver **16a**.³² In contrast, the robust Pt catalyst developed in the current study was found to be insensitive to the steric hindrance suffered by the other systems to allow for the exclusive C-H borylation of **15** at its 3-position to provide **16b**.

Scheme 7. Comparison of Regioselectivity for the C-H Borylation of Methyl *p*-Methylbenzoate Using Different Catalysts



2.3 Conclusion

The author have developed a Pt/NHC complex-catalyzed C-H borylation of aromatic substrates. The use of a platinum complex in conjunction with NHC ligands, such as ICy and IPr, resulted in effective catalysts for the C-H borylation of a wide range of arenes and heteroarenes. Notably, this platinum system was found to be largely insensitive to steric hindrance, allowing for the borylation of the sterically hindered aromatic C-H bond in a series of mesitylene derivatives to give the corresponding phenylboronic ester derivatives bearing two *ortho* substituents. Further ligand screening determined that SIPr was as a suitable ligand for the borylation of sterically hindered arenes, whilst avoiding the need for a large excess of the substrate, thereby broadening the scope of this reaction. Another feature of this platinum catalyst system is that it exhibited a pronounced *ortho*-directing effect in the presence of fluorine substituents, providing facile access to a wide range of *ortho*-fluorophenylboronic esters directly from fluoroarenes. It is noteworthy that iridium catalyst system cannot be used in this way to achieve regioselective borylation of both types of substrates. It is therefore envisaged that the unique features of our platinum catalyst system for C-H borylation will allow for the development of new synthetic strategies for the regioselective functionalization of arenes, especially those with steric demand.

2.4 Experimental Section

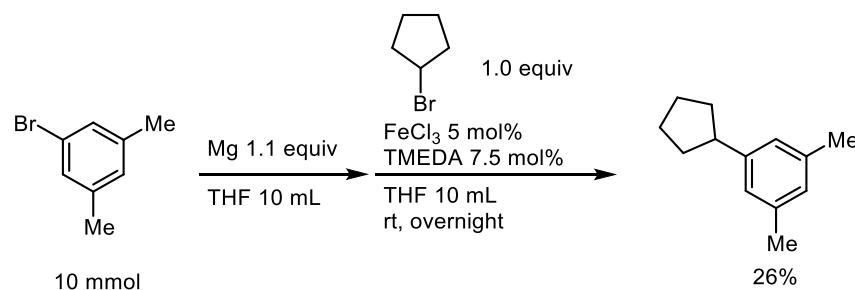
2.4.1 General Information

¹H and ¹³C NMR spectra were recorded on a JEOL ECS-400 spectrometer (JEOL, Tokyo, Japan) or VARIAN UNITY INOVA-600 spectrometer in either CDCl₃ with tetramethylsilane as an internal reference standard (δ = 0.00 ppm) or C₆D₆ with a residual C₆H₆ peak as an internal reference standard (δ = 7.15 ppm). NMR data have been reported as follows: chemical shift (δ) in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet), coupling constant (J) in Hz, and integration. NOE experiments were conducted with Delta noe_1d_dpgse pulse sequence and Delta noesy pulse sequence and detail experimental parameter was listed in the spectroscopic data section for each compound. Infrared spectra (IR) were obtained on a JASCO FT/IR-4000 spectrometer, and the absorptions have been reported in reciprocal centimeters with the following relative intensities: s (strong), m (medium), or w (weak). Mass spectra were obtained on a Shimadzu GCMS-QP 5000 or GCMS-QP 2010 instrument with an ionization voltage of 70 eV. High resolution mass spectra (HRMS) were obtained on a JEOL JMS-DX303 (EI) and a Bruker micrOTOF II (APCI). Analytical gas chromatography (GC) was carried out on Shimadzu GC-2014, equipped with a flame ionization detector. Melting points were determined using a Stanford Research Systems OptiMelt. Column chromatography was performed over SiO₂ (Silycycle Silica Flash F60 (230-400 mesh).

2.4.2 Materials

Pt₂(dvtms)₃ (0.1 M, Aldrich), Pt(PPh₃)₄ (TCI), H₂PtCl₆•nH₂O (Furuya Metal), PCy₃ (Aldrich), dtbpy (Aldrich), [Ir(OMe)(cod)]₂ (TCI), HBpin (TCI) and B₂pin₂ (TCI) were used as received. All arenes were obtained from commercial suppliers and used as received. *N*-Methylindole (TCI), *N*-methylpyrrole (Aldrich), 2-methoxythiophene (TCI), 2-methylthiophene (TCI), benzofuran (TCI), benzothiophene (TCI), and 5-chloro-3-methylbenzo[b]thiophene (TCI) were used as received. Other *N*-methylindoles used in this study were synthesized by the reaction of the corresponding indole with MeI according to the literature procedure.³⁴ (3,5-Dimethylphenyl)triethylsilane **2y** was synthesized according to the literature procedure³⁵ and all spectroscopic data were in agreement with the reported values.³⁶ 2-Chloro-5-methoxy-1,3-dimethylbenzene **2af** was synthesized according to the literature procedure.³⁷ 1,3,5-Tripropylbenzene **2ag** was synthesized according to the literature procedure.³⁸

1-Cyclopentyl-3,5-dimethylbenzene (**2t**, Figure 5).

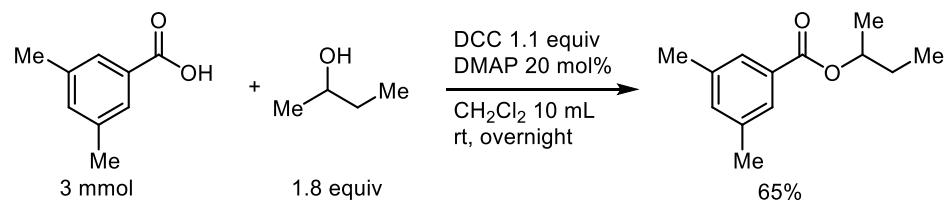


To a dried two-necked flask equipped with a reflux condenser, Mg (264 mg, 11 mmol) and THF (10 mL) were added. I₂ chip was added to activate Mg. 3,5-Dimethylphenyl bromide (1.85 g, 10 mmol)

was added slowly, and the mixture was refluxed for 1 h. In another round-bottom flask, cyclopentyl bromide (1.49 g, 10 mmol), FeCl_3 (81 mg, 0.5 mmol), TMEDA (87 mg, 0.75 mmol) and THF (10 mL) were added. The Grignard solution was transferred to a THF solution of cyclopentyl bromide at 0 °C by cannulation. After the addition of Grignard reagent, the mixture was warmed to ambient temperature and the resulting mixture was stirred overnight. To the resulting mixture, H_2O was added and extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over MgSO_4 . Concentrated mixture was filtered through a pad of silica gel (hexane as eluent). To remove homo-coupled biaryl byproduct, the material was further purified by GPC to give the title product in pure form (colorless oil, 460 mg, 26%).

Rf 0.86 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.54-1.88 (m, 6H), 1.92-2.12 (m, 2H), 2.29 (s, 6H), 2.81-3.00 (m, 1H), 6.82 (s, 1H), 6.86 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 21.3, 25.6, 34.6, 45.8, 124.9, 127.3, 137.6, 146.5. IR (ATR): 2950 s, 2915 m, 2866 m, 1604 m, 1452 m, 1375 w, 1036 w, 936 w, 888 w, 841 s, 702 s. MS m/z (% relative intensity): 174 (M^+ , 100), 159 (93), 145 (75), 133 (68), 132 (41), 131 (44), 119 (50), 117 (37), 115 (30), 106 (32), 105 (64), 91 (43). HRMS (EI): Calcd for $\text{C}_{13}\text{H}_{18}$ 174.1409, Found 174.1408.

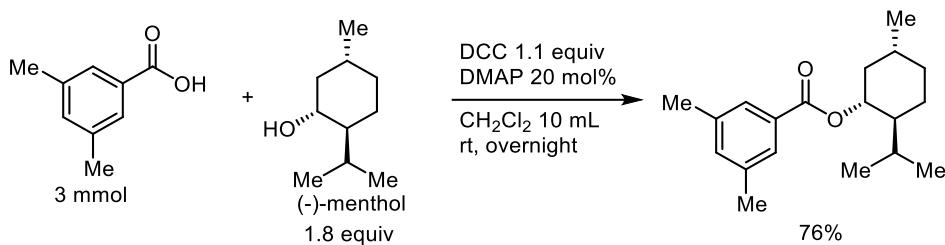
sec-Butyl 3,5-dimethylbenzoate (2u, Figure 5).



To a dried round-bottom flask, 3,5-dimethylbenzoic acid (450 mg, 3.0 mmol), DCC (680 mg, 3.3 mmol), DMAP (73 mg, 0.6 mmol), 2-propanol (490 μL , 5.4 mmol) and CH_2Cl_2 (10 mL) were added. The mixture was stirred at ambient temperature overnight. To the resulting reaction mixture, H_2O was added and extracted with CH_2Cl_2 three times. Combined organic extracts were washed with brine and dried over MgSO_4 . Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 10/1) to give the title compound (clear oil, 404 mg, 65%).

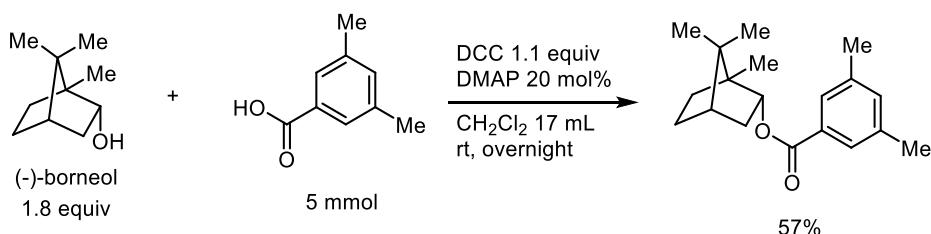
Rf 0.71 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.97 (t, J = 7.6 Hz, 3H), 1.33 (d, J = 6.4 Hz, 3H), 1.60-1.82 (m, 2H), 2.36 (s, 6H), 5.08 (sextet, J = 6.4 Hz, 1H), 7.17 (s, 1H), 7.65 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 9.9, 19.6, 21.2, 29.0, 72.6, 127.2, 130.8, 134.3, 137.9, 166.6. IR (ATR): 2972 w, 2934 w, 1712 s, 1608 w, 1455 w, 1379 w, 1354 w, 1307 m, 1215 s, 1111 m, 1095 w, 1000 w, 929 w, 867 w, 767 m, 679 w. MS m/z (% relative intensity): 206 (M^+ , 20), 151(25), 150 (50), 134 (13), 133 (100), 107 (6), 106 (6), 105 (41), 103 (8), 91 (12), 79 (10), 77 (10). HRMS (EI): Calcd for $\text{C}_{13}\text{H}_{18}\text{O}_2$ 206.1307, Found 206.1305.

(1*R*,2*S*,5*R*)-2-Isopropyl-5-methylcyclohexyl 3,5-dimethylbenzoate (2v, Figure 5).



To a dried round-bottom flask, 3,5-dimethylbenzoic acid (450 mg, 3.0 mmol), DCC (680 mg, 3.3 mmol), DMAP (73 mg, 0.6 mmol), (-)-menthol (843 mg, 5.4 mmol) and CH_2Cl_2 (10 mL) were added. The mixture was stirred at ambient temperature overnight. To the resulting reaction mixture, H_2O was added and extracted with CH_2Cl_2 twice. Combined organic extracts were washed with water and brine and then dried over MgSO_4 . Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 100/1 to 12/1) to give the title compound (colorless viscous oil, 658 mg, 76%).
 Rf 0.73 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.79 (d, J = 6.9 Hz, 3H), 0.87- 0.97 (m, 1H), 0.92 (dd, J = 6.4, 2.8 Hz, 6H), 1.02-1.22 (m, 2H), 1.45-1.64 (m, 2H), 1.67-1.80 (m, 2H), 1.96 (quintet-d, J = 6.9, 2.7 Hz, 1H), 2.03-2.16 (m, 1H), 2.36 (s, 6H), 4.93 (td, J = 10.9, 4.4 Hz, 1H), 7.17 (s, 1H), 7.65 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 16.4, 20.8, 21.2, 22.0, 23.5, 26.4, 31.4, 34.3, 41.0, 47.2, 74.5, 127.2, 130.7, 134.3, 137.9, 166.4. IR (ATR): 2953 w, 2923 w, 2868 w, 1712 s, 1608 w, 1454 w, 1382 w, 1305 m, 1214 s, 1116 m, 1010 w, 982 w, 965 w, 865 w, 766 m, 678 w. MS m/z (% relative intensity): 151 (11), 139 (9), 138 (82), 134 (10), 133 (100), 105 (34), 96 (19), 95 (75), 94 (11), 82 (20), 81 (41), 79 (12). HRMS (EI): Calcd for $\text{C}_{19}\text{H}_{28}\text{O}_2$ 288.2089, Found 288.2091.

(1*S*,2*R*,4*S*)-1,7,7-Trimethylbicyclo[2.2.1]heptan-2-yl 3,5-dimethylbenzoate (2w, Figure 5).

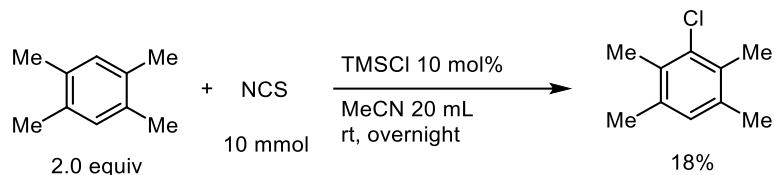


To a dried round-bottom flask, 3,5-dimethylbenzoic acid (750 mg, 5.0 mmol), DCC (1.1 g, 5.5 mmol), DMAP (122 mg, 1.0 mmol), (-)-borneol (1.4 g, 9.0 mmol) and CH_2Cl_2 (17 mL) were added. The mixture was stirred at ambient temperature overnight. To the resulting reaction mixture, H_2O was added and extracted with CH_2Cl_2 twice. Combined organic extracts were washed with brine and then dried over MgSO_4 . Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 100/1 to 20/1) to give the title compound (colorless oil, 816 mg, 57%).

Rf 0.63 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.91 (s, 6H), 0.97 (s, 3H), 1.11 (dd, J = 14.0, 3.4 Hz, 1H), 1.28-1.48 (m, 2H), 1.73 (t, J = 4.6 Hz, 1H), 1.75-1.87 (m, 1H), 2.06-2.20 (m, 1H), 2.37 (s, 6H), 2.41-2.56 (m, 1H), 5.10 (ddd, J = 9.8, 3.4, 2.3 Hz, 1H), 7.18 (s, 1H), 7.66 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 13.6, 18.9, 19.7, 21.2, 27.4, 28.1, 36.9, 45.0, 47.8, 49.0, 80.3, 127.2, 130.8, 134.4, 137.9, 167.1. IR (ATR): 2952 w, 2878 w, 1714 s, 1608 w, 1453 w,

1380 w, 1313 s, 1215 s, 1116 m, 1022 m, 979 w, 865 w, 766 m, 678 w. MS m/z (% relative intensity): 286 (M⁺, 9), 136 (17), 133 (100), 121 (5), 105 (17), 93 (9), 79 (6). HRMS (EI): Calcd for C₁₉H₂₆O₂ 286.1933, Found 286.1934.

3-Chloro-1,2,4,5-tetramethylbenzene (2x, Figure 5).

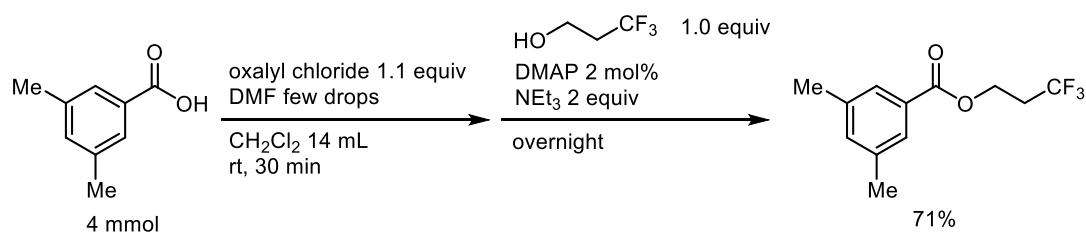


The title compound was synthesized according to the literature procedure.³⁹

In a round-bottom flask, 1,2,4,5-tetramethylbenzene (2.68 g, 20 mmol) and NCS (1.34 g, 10 mmol) was dissolved in MeCN (20 mL) to give a heterogeneous mixture. TMSCl (130 μ L, 1.0 mmol) was added dropwise, and the heterogeneous mixture changed to homogeneous with heat generation. The mixture was stirred at ambient temperature overnight. To the resulting mixture, H₂O was added and extracted with Et₂O three times. Combined organic extracts were washed with 1M NaOH aq. and brine, and dried over MgSO₄. Concentrated mixture was filtered through a pad of silica gel (hexane as eluent) to remove benzyl chlorides as byproducts. To remove unreacted starting material, the mixture was further purified by GPC to give the title product in pure form (white solid, 300 mg, 18%).

Rf 0.86 (hexane/EtOAc = 5/1). White solid. Mp = 49 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 2.24 (s, 6H), 2.30 (s, 6H), 6.85 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 16.8, 20.5, 129.4, 131.9, 134.6, 135.1. IR (ATR): 3007 w, 2969 w, 2923 w, 2862 w, 1554 w, 1473 m, 1455 m, 1391 m, 1273 w, 1188 m, 1000 s, 865 m, 822 s. MS m/z (% relative intensity): 170 (12), 168 (M⁺, 35), 153 (17), 133 (100), 117 (12), 115 (15), 105 (10), 91 (14). HRMS (EI): Calcd for C₁₀H₁₃Cl 168.0706, Found 168.0704.

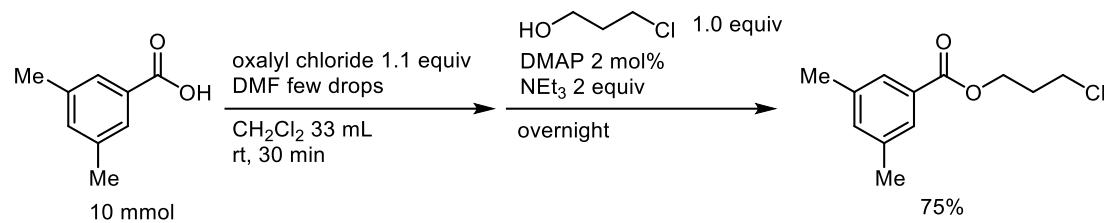
3,3,3-Trifluoropropyl 3,5-dimethylbenzoate (2z, Figure 5).



To a dried round-bottom flask, 3,5-dimethylbenzoic acid (600 mg, 4.0 mmol) was dissolved in CH₂Cl₂ (14 mL) and a few drops of DMF was added. Oxalyl chloride (370 μ L, 4.4 mmol) was added dropwise resulting in gas evolution. The mixture was stirred for 30 min. 3,3,3-Trifluoropropan-1-ol (460 mg, 4.0 mmol), DMAP (10 mg, 0.080 mmol) and NEt₃ (1.1 mL, 8.0 mmol) were dissolved in CH₂Cl₂ (2.0 mL) and the CH₂Cl₂ solution was added to the reaction mixture. The mixture was stirred at ambient temperature overnight. To the resulting mixture, H₂O was added and extracted with Et₂O three times. Combined organic extracts were washed with 1M NaOH aq., 1M HCl aq. and brine and dried over MgSO₄. Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 100/1 to 20/1) to give the title compound (colorless oil, 703 mg, 71%).

Rf 0.71 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 2.36 (s, 6H), 2.53-2.67 (qt, J = 10.5, 6.4 Hz, 2H), 4.52 (t, J = 6.4 Hz, 2H), 7.20 (s, 1H), 7.65 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 21.1, 33.47 (q, J = 29 Hz), 57.5 (q, J = 3.8 Hz), 125.8 (q, J = 277 Hz), 127.3, 129.4, 134.9, 138.1, 166.5. IR (ATR): 1721 s, 1609 w, 1387 w, 1347 w, 1311 m, 1256 m, 1209 s, 1154 s, 1134 s, 1117 s, 1067 m, 1008 m, 867 w, 844 w, 765 m. MS m/z (% relative intensity): 246 (M^+ , 100), 134 (12), 133 (100), 105 (43), 79 (12), 77 (14). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{13}\text{F}_3\text{O}_2$ 246.0868, Found 246.0865.

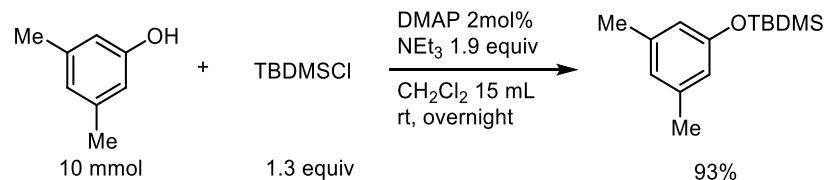
3-Chloropropyl 3,5-dimethylbenzoate (2aa, Figure 5).



The title compound was synthesized using the same procedure for **2z** except that 3-chloropropanol was used instead of 3,3,3-trifluoropropan-1-ol on a 10 mmol scale.

Rf 0.57 (hexane/EtOAc = 5/1). Colorless oil (1.69 g, 75%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 2.36 (quintet, J = 6.2 Hz, 2H), 2.36 (s, 6H), 3.70 (t, J = 6.4 Hz, 2H), 4.46 (t, J = 6.2 Hz, 2H), 7.19 (s, 1H), 7.64 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 21.1, 31.7, 41.3, 61.5, 127.2, 129.8, 134.7, 138.0, 166.7. IR (ATR): 2965 w, 2919 w, 1716 s, 1608 w, 1450 w, 1384 w, 1308 s, 1209 s, 1166 w, 1152 w, 1116 m, 1061 w, 1020 m, 945 w, 866 s, 765 s, 678 w, 656 w. MS m/z (% relative intensity): 228 (6), 226 (M^+ , 19), 151 (8), 150 (74), 133 (100), 105 (54), 91 (9), 79 (13), 77 (14). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{15}\text{ClO}_2$ 226.0761, Found 226.0759.

tert-Butyl(3,5-dimethylphenoxy)dimethylsilane (2ab, Figure 5).

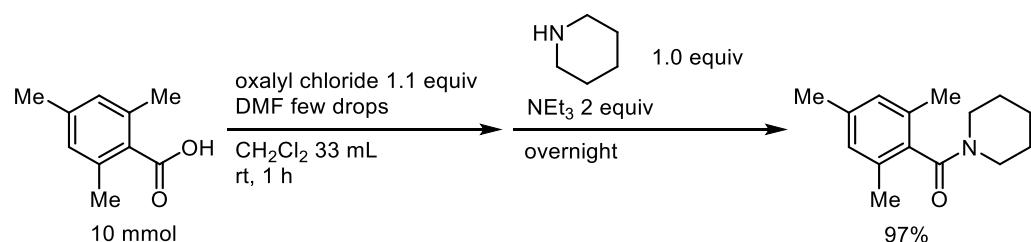


In a dried round-bottom flask, 3,5-dimethylphenol (1.2 g, 10 mmol) was dissolved in CH_2Cl_2 (15 mL). TBDMSCl (1.9 g, 12.5 mmol), DMAP (24 mg, 0.2 mmol) and NEt_3 (2.6 mL, 19 mmol) were then added. The mixture was stirred at ambient temperature overnight. To the resulting mixture, H_2O was added and extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over MgSO_4 . Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 200/1) to give the title compound (clear oil, 2.2 g, 93%).

Rf 0.78 (hexane/EtOAc = 5/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.18 (s, 6H), 0.98 (s, 9H), 2.25 (s, 6H), 6.46 (s, 2H), 6.59 (s, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ -4.42, 18.2, 21.3, 25.7, 117.8, 123.0, 139.0, 155.5. IR (ATR): 2955 w, 2929 w, 2857 w, 1592 w, 1468 w, 1316 m, 1253 w, 1159 m, 1038 w, 961 w, 835 s, 778 s. MS m/z (% relative intensity): 237 (5), 236 (M^+ , 20), 180 (20),

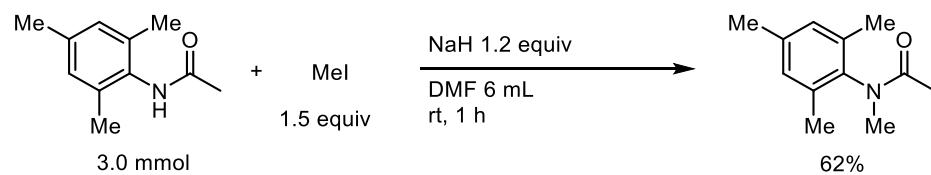
179 (100), 163 (5), 149 (9), 105 (33), 75 (8). HRMS (EI): Calcd for $C_{14}H_{24}OSi$ 236.1596, Found 236.1593.

Mesityl(piperidin-1-yl)methanone (2ac, Figure 5).



To a dried round-bottom flask, 2,4,6-tetramethylbenzoic acid (1.64 g, 10 mmol) was dissolved in CH_2Cl_2 (14 mL) and a few drops of DMF was added. Oxalyl chloride (930 μ L, 11 mmol) was added dropwise resulting in gas evolution. The mixture was stirred for 1 h. The mixture was cooled to 0 °C and then piperidine (990 μ L, 10 mmol) and NEt_3 (1.1 mL, 8.0 mmol) were added. The mixture was warmed to ambient temperature and stirred overnight. To the resulting mixture, H_2O was added and extracted with Et_2O three times. Combined organic extracts were washed with 1M NaOH aq., 1M HCl aq. and brine and then dried over $MgSO_4$. Concentrated mixture was treated with activated charcoal and removal of the charcoal by filtration gave the pure title compound. (pale-yellow oil, 2.24 g, 97%). R_f 0.16 (hexane/EtOAc = 5/1). Pale-yellow oil. 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.38-1.55 (m, 2H), 1.57-1.75 (m, 4H), 2.22 (s, 6H), 2.27 (s, 3H), 3.08-3.22 (m, 2H), 3.69-3.85 (m, 2H), 6.84 (s, 2H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 18.9, 21.0, 24.5, 25.7, 26.6, 41.9, 47.0, 128.1, 133.4, 133.7, 137.7, 169.6. IR (ATR): 2933 w, 2854 w, 1628 s, 1438 s, 1375 w, 1271 s, 1240 m, 1184 w, 1098 m, 1027 w, 998 m, 879 w, 851 m, 750 w. MS m/z (% relative intensity): 231 (M^+ , 25), 216 (31), 148 (11), 147 (100), 146 (32), 119 (19), 91 (12). HRMS (EI): Calcd for $C_{15}H_{21}NO$ 231.1623, Found 231.1619.

N-Mesityl-N-methylacetamide (3ad, Figure 5).

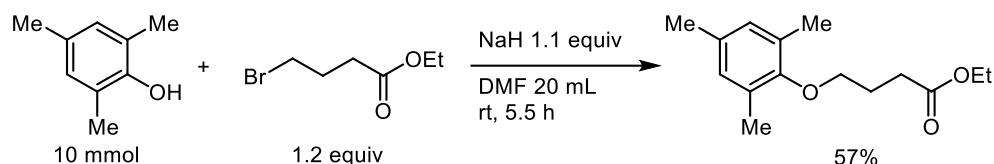


In a dried round-bottom flask, *N*-mesitylacetamide (530 mg, 3.0 mmol) was dissolved in DMF (6.0 mL). NaH (60% in mineral oil, 150 mg, 3.6 mmol) was added portionwise. The mixture was stirred overnight. To the resulting mixture, H_2O was added and extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over $MgSO_4$. Concentrated mixture was purified by flash column chromatography (hexane/EtOAc = 10/1 to 5/1) to give the title compound (colorless oil, 354 mg, 62%).

R_f 0.45 (hexane/EtOAc = 1/1). Colorless oil. 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.73 (s, 3H), 2.16 (s, 6H), 2.30 (s, 3H), 3.11 (s, 3H), 6.93 (s, 2H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 17.5, 20.9, 21.2, 34.3, 129.5, 135.1, 137.8, 139.2, 171.0. IR (ATR): 2921 w, 1658 s, 1483 m, 1424 m, 1374 s, 1348 m, 1308 w, 1282 w, 1133 w, 1078 w, 1033 w, 972 w, 854 w. MS m/z (% relative intensity): 191 (M^+ , 26), 176

(11), 148 (16), 134 (19), 91 (11), 56 (100). HRMS (EI): Calcd for $C_{12}H_{17}NO$ 191.1310, Found 191.1309.

Ethyl 4-(mesityloxy)butanoate (2ae, Figure 5).

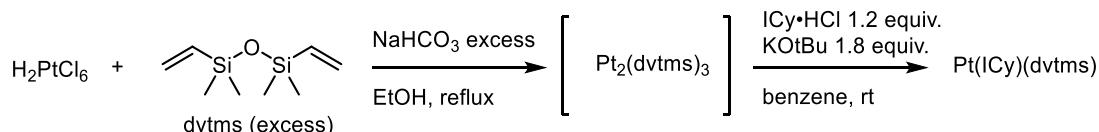


In a dried round-bottom flask, NaH (60% in mineral oil, 440 mg, 11 mmol) was dispersed in DMF (20 mL). 2,4,6-Trimethylphenol (1.36 g, 10 mmol) was added slowly, and the mixture was stirred at ambient temperature for 1 h. Ethyl 4-bromobutanoate (2.34 g, 12 mmol) was slowly added and stirred for another 5.5 h. To the resulting mixture, H_2O was added and extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over $MgSO_4$. Concentrated mixture was dried in vacuo at 160 °C to remove unreacted alkyl bromide and further purified by flash column chromatography (hexane/EtOAc = 100/1 to 25/1) to give the title compound (colorless oil, 1.42 g, 57%).

R_f 0.67 (hexane/EtOAc = 5/1). Colorless oil. 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.27 (t, J = 7.1 Hz, 3H), 2.11 (quintet, J = 7.1 Hz, 2H), 2.22 (s, 6H), 2.23 (s, 3H), 2.59 (t, J = 7.3 Hz, 2H), 3.76 (t, J = 6.2 Hz, 2H), 4.15 (q, J = 7.2 Hz, 2H), 6.81 (s, 2H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 14.2, 16.1, 20.6, 25.7, 30.9, 60.4, 70.7, 129.3, 130.4, 133.0, 153.4, 173.4. IR (ATR): 2923 w, 1733 s, 1482 m, 1443 w, 1373 m, 1308 w, 1214 s, 1173 s, 1147 s, 1096 w, 1029 m, 922 w, 853 m. MS m/z (% relative intensity): 205 (16), 136 (13), 121 (18), 115 (79), 91 (16), 87 (100). HRMS (EI): Calcd for $C_{15}H_{22}O_3$ 250.1569, Found 250.1565.

2.4.3 Synthesis of Pt(NHC)(dvtms) Complexes

Pt(NHC)(dvtms) complexes were synthesized by using slightly modified versions of the reported procedures,^{25a,40} as follows.



Pt(ICy)(dvtms) (4g). $H_2PtCl_6 \cdot nH_2O$ (1.8 g, 3.4 mmol, estimated as hexahydrate), $NaHCO_3$ (3.5 g, 42 mmol), dvtms (3.5 g, 19 mmol) and degassed $EtOH$ (10 mL) were added to an oven-dried round bottom flask. The mixture was heated at 80 °C for 1 h; the color of the solution changed from red to yellow. The mixture was stirred at room temperature (rt) for another 3 h. The resulting mixture was filtered through a Celite pad, and the pad was quickly washed with $EtOH$. The filtrate was concentrated in vacuo, and degassed benzene (3 mL) was added. The solution was again filtered through a Celite pad, and the pad was washed with benzene. The filtrate was then concentrated to give crude $Pt_2(dvtms)_3$ as a yellow oil. $ICy \cdot HCl$ (1.1 g, 4.1 mmol, 1.2 equiv), tBuOK (0.68 g, 1.8 equiv) and degassed benzene

(10 mL) were added to the crude mixture, and the mixture was stirred for 3 h at rt. The resulting mixture was filtered through a pad of silicagel/Celite (1:1), and the pad was washed with hexane/Et₂O (8:2, 100 mL). The filtrate was concentrated in vacuo to yield a pale-yellow solid, which was recrystallized from ⁱPrOH/Et₂O to give Pt(ICy)(dvtms) as a white solid (1.64 g, 79% based on H₂PtCl₆).

¹H NMR (CDCl₃, 399.78 MHz): δ -0.25 (s, 6H), 0.33 (s, 6H), 1.09-1.33 (m, 6H), 1.47 (q, J = 12.3 Hz, 4H), 1.66 (d, J = 12.4 Hz, 2H), 1.73-1.98 (m, 12H), 2.17 (d, J = 10.5 Hz, $^2J_{\text{Pt-H}}$ = 54 Hz, 2H), 4.21 (tt, J = 3.9 Hz, 12.4 Hz, 1H), 4.32 (tt, J = 3.9 Hz, 12.4 Hz, 1H), 7.01 (d, J = 1.3 Hz, $^4J_{\text{Pt-H}}$ = 11.5 Hz, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ -1.89, 1.44, 25.3, 25.4, 33.4 ($^1J_{\text{Pt-C}}$ = 119 Hz), 33.9, 40.3 ($^1J_{\text{Pt-C}}$ = 158 Hz), 58.2 ($^3J_{\text{Pt-C}}$ = 44 Hz), 58.4 ($^3J_{\text{Pt-C}}$ = 42 Hz), 117.16 ($^3J_{\text{Pt-C}}$ = 37 Hz), 117.21 ($^3J_{\text{Pt-C}}$ = 37 Hz), 179.8 ($^1J_{\text{Pt-C}}$ = 1390 Hz). HRMS (FAB): Calcd for C₂₃H₄₂N₂OPtSi₂ 613.2483, Found 613.2501.

The spectroscopic data were in agreement with the reported values.^{25a}

Other Pt(NHC)(dvtms) complexes were synthesized by the same procedure using the corresponding NHC•HCl [IMes•HCl (TCI), IPr•HCl (TCI), IⁱBu•HCl⁴¹, SICy•HCl⁴², BICy•HCl (Aldrich), IMe•HCl (TCI)] or NHC•HBF₄ [I(ⁱPr)•HBF₄ (TCI), I(Ad)•HBF₄⁴³]. The spectroscopic date for **4a**, **4b**, **4c**, **4e**, **4f** and **4k** were in agreement with the reported values.(40-2)

Pt(IⁱPr)(dvtms) (4d). Synthesis of the title compound was conducted on a 1.5 mmol scale based on H₂PtCl₆•nH₂O to give 548 mg of Pt(IⁱPr)(dvtms) as white solid (69%)

¹H NMR (CDCl₃, 399.78 MHz): δ -0.29 (s, 6H), 0.33 (s, 6H), 1.30 (t, J = 6.9 Hz, 12H), 1.72-1.98 (m, 4H), 2.20 (d, J = 10 Hz, $^2J_{\text{Pt-H}}$ = 54 Hz, 2H), 4.60-4.74 (m, 2H), 7.05 (s, $^4J_{\text{Pt-H}}$ = 12 Hz, 2H).

¹³C NMR (CDCl₃, 100.53 MHz): δ -2.21, 1.45, 23.1, 23.2, 33.6 ($^1J_{\text{Pt-C}}$ = 119 Hz), 40.4 ($^1J_{\text{Pt-C}}$ = 157 Hz), 50.9 ($^3J_{\text{Pt-C}}$ = 46 Hz), 51.1 ($^3J_{\text{Pt-C}}$ = 44 Hz), 116.8 ($^3J_{\text{Pt-C}}$ = 37 Hz), 179.7, ($^1J_{\text{Pt-C}}$ = 1370 Hz).

IR (ATR): 295w, 1424 w, 1368 w, 1297 w, 1246 m, 1213 m, 1171 m, 1131 w, 1002 w, 968 s, 901 w, 836 s, 781 s, 721 m, 707 m, 684 m. HRMS (FAB): Calcd for C₁₇H₃₄N₂OPtSi₂ 533.1857, Found 533.1851.

Pt(SICy)(dvtms) (4h). Synthesis of the title compound was conducted on a 1.4 mmol scale based on H₂PtCl₆•nH₂O to give 583 mg of Pt(SICy)(dvtms) as a white solid (66%).

¹H NMR (CDCl₃, 399.78 MHz): δ -0.28 (s, 6H), 0.32 (s, 6H), 0.94-1.05 (m, 2H), 1.11-1.23 (m, 4H), 1.30-1.43 (m, 4H), 1.54-1.74 (m, 12H), 1.83 (d, J = 13 Hz, $^2J_{\text{Pt-H}}$ = 54 Hz, 2H), 2.17 (d, J = 11 Hz, $^2J_{\text{Pt-H}}$ = 54 Hz, 2H), 3.56 (s, 4H), 3.88 (tt, J = 12, 3.2 Hz, 1H), 3.99 (tt, J = 12, 3.2 Hz, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ -2.03, 1.41, 25.25, 25.33, 25.4, 30.8, 30.9, 33.0 ($^1J_{\text{Pt-C}}$ = 113 Hz), 39.9 ($^1J_{\text{Pt-C}}$ = 160 Hz), 42.9 ($^3J_{\text{Pt-C}}$ = 43 Hz), 43.0 ($^3J_{\text{Pt-C}}$ = 43 Hz), 56.9 ($^3J_{\text{Pt-C}}$ = 46 Hz), 57.2 ($^3J_{\text{Pt-C}}$ = 44 Hz), 209.9 ($^3J_{\text{Pt-C}}$ = 1330 Hz). IR (ATR): 2934 m, 2855, w, 1482 m, 1440 m, 1290 m, 1271 m, 1237 s, 1168 m, 990 s, 893 w, 857 m, 829 s, 771 s, 703 m, 673 m. HRMS (FAB): Calcd for C₂₃H₄₄N₂OPtSi₂ 615.2640, Found 615.2647.

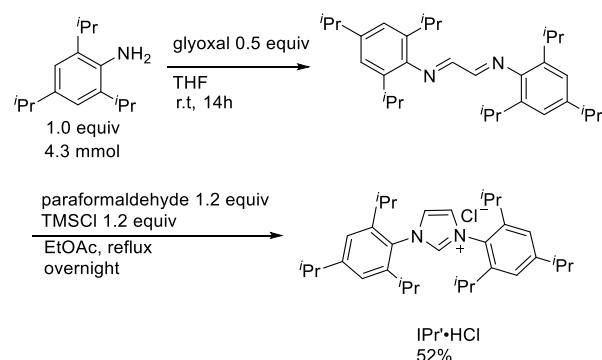
Pt(BICy)(dvtms) (4i). Synthesis of the title compound was conducted on a 1.3 mmol scale based on H₂PtCl₆•nH₂O to give 224 mg of Pt(BICy)(dvtms) as white solid (26%). The compound was further

purified by flash column chromatography over silica gel (eluting with hexane/AcOEt = 100/1) after the recrystallization from *i*PrOH.

¹H NMR (CDCl₃, 399.78 MHz): δ -0.21 (s, 6H), 0.36 (s, 6H), 1.20-1.38 (m, 7H), 1.65-2.03 (m, 13H), 2.09-2.34 (m, 6H), 4.79 (tt, J = 13, 3.4 Hz, 1H), 4.88 (tt, J = 13, 3.8 Hz, 1H), 7.15-7.19 (m, 2H), 7.56-7.62 (m, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ -1.86, 1.40, 25.40, 25.43, 25.5, 25.8, 30.6, 30.7, 34.4 (¹J_{Pt-C} = 115 Hz), 40.7 (¹J_{Pt-C} = 157 Hz), 59.7 (³J_{Pt-C} = 46 Hz), 60.0 (³J_{Pt-C} = 46 Hz), 111.8, 111.9, 120.9, 121.0, 134.3, 134.5, 196.3 (¹J_{Pt-C} = 1410 Hz). IR (ATR): 2929 w, 2857 w, 1476 w, 1450 w, 1409 w, 1374 m, 1341 w, 1293 m, 1239 m, 1168 w, 1054 w, 997 s, 909 w, 858 w, 834 s, 774 s, 736 s, 701 w. HRMS (FAB): Calcd for C₂₇H₄₄N₂OPtSi₂ 663.2640, Found 663.2624.

Pt(IPr')(dvtms) (4j)

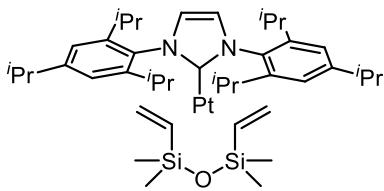
IPr' \bullet HCl was synthesized described below.



2,4,6-triisopropylaniine⁴⁴ (950 mg, 4.33 mmol), and aqueous solution of glyoxal (8.8 M, 0.25 mL, 2.2 mmol) were dissolved in THF (10 mL) and stirred for 14 h at room temperature. To the resulting mixture, EtOAc and water were added. The organic layer was separated and washed with brine and water, and dried over MgSO₄. The organic layer was concentrated *in vacuo* to give a diimine as a yellow solid (936 mg, ca. 94%). The diimine was used for the subsequent reaction without further purification.

Paraformaldehyde (137 mg, 2.36 mmol), diimine (920 mg, 2.00 mmol) and EtOAc (50 mL) were added to a 100 mL three-necked flask with a reflux condenser under N₂. The mixture was refluxed for 1 h. TMSCl (0.30 mL, 260 mg, 2.39 mmol) was added to the reaction flask and the mixture was refluxed overnight. To the resulting mixture, EtOAc and water were added. The organic layer was separated and washed with brine and water and dried over MgSO₄. The organic layer was concentrated *in vacuo* to give IPr'•HCl as a white solid (531 mg, 52%).

Mp = 237 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.19 (d, J = 6.9 Hz, 12H), 1.26 (d, J = 6.9 Hz, 12H), 1.28 (d, J = 6.9 Hz, 12H), 2.40 (septet, J = 6.9 Hz, 4H), 2.96 (d, J = 6.9 Hz, 2H), 7.14 (s, 4H), 8.16 (s, 2H), 9.43 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 23.7, 23.8, 24.7, 29.1, 34.4, 122.6, 127.2, 127.5, 137.7, 144.6, 153.0. IR (ATR): 2962 s, 2869 m, 2734 w, 1603 w, 1527 s, 1466 s, 1385 w, 1365 m, 1321 m, 1220 m, 1185 w, 1129 w, 1105 w, 1051 m, 957 m, 878 s, 767 s, 689 m. HRMS (FAB): Calcd for [M-HCl]⁺ C₃₃H₄₈N₂ 472.3817, Found 472.3818.

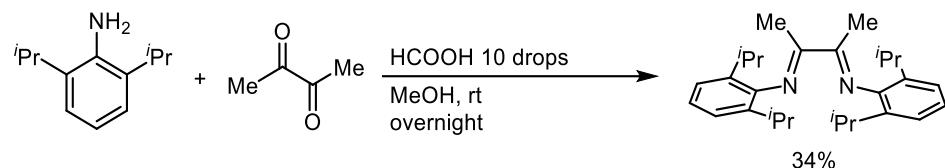


Synthesis of the title Pt complex was conducted with the same procedure for **4g** except that $\text{IPr}'\text{-HCl}$ was used instead of $\text{IPr}^{\text{Me}}\text{-HCl}$ on 0.12 mmol scale based on $\text{H}_2\text{PtCl}_6\text{-nH}_2\text{O}$ to give 58 mg of $\text{Pt}(\text{IPr}')(\text{dvtms})$ as a white solid (59%).

$\text{Mp} > 210$ $^{\circ}\text{C}$ (decomp.). ^1H NMR (CDCl_3 , 399.78 MHz): δ -0.76 (s, 6H), 0.13 (s, 6H), 1.12 (d, J = 6.9 Hz, 12H), 1.23 (d, J = 6.9 Hz, 12H), 1.24 (d, J = 6.9 Hz, 12H), 1.28-1.59 (m, 4H), 1.69 (d, J = 11.5 Hz, $^3J_{\text{Pt-C}} = 27$ Hz, 2H), 2.88 (septet, J = 6.9 Hz, 2H), 2.95 (septet, J = 6.9 Hz, 4H), 6.99 (s, 4H), 7.18 (s, $^5J_{\text{Pt-C}} = 4.6$ Hz, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ -2.17, 1.60, 22.5, 24.0, 25.9, 28.3, 34.3, 35.1 ($^1J_{\text{Pt-C}} = 59$ Hz), 41.6 ($^1J_{\text{Pt-C}} = 83$ Hz), 121.3, 123.9 ($^3J_{\text{Pt-C}} = 21$ Hz), 134.4, 145.2, 149.6, 186.0. IR (ATR): 2960 m, 1471 w, 1401 w, 1383 w, 1364 w, 1317 m, 1243 m, 1179 w, 1130 w, 1052 w, 990 m, 949 w, 909 w, 860 m, 836 s, 781 s, 731 m, 699 m. HRMS (FAB): Calcd for $\text{C}_{41}\text{H}_{66}\text{N}_2\text{OPtSi}_2$ 853.4361, Found 853.4359.

Pt(IPr^{Me})(dvtms) (4l).

$\text{IPr}^{\text{Me}}\text{-HCl}$ was synthesized according to the literature procedure⁴⁵ with a slight modification.

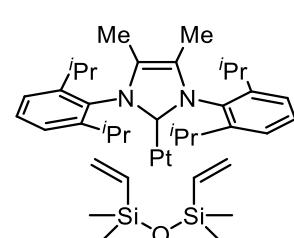


To a dried round bottom flask, 2,6-diisopropylaniline (6.0 mL, 32 mmol) and diacetyl (1.4 mL, 16 mmol) and HCOOH (10 drops) were added. The yellow homogeneous mixture was sonicated for 10 min then the yellow solution turned into cloudy yellow mixture. MeOH (20 mL) were added to give homogeneous solution again and the solution was left for 1 h without stirring. Additional MeOH (10 mL) was added and the mixture was stirred vigorously. Soon yellow precipitate appeared and the mixture was stirred overnight. Filtration of the precipitate and washing with cold methanol gave the pure target diimine (2.2 g, 34%).

All spectroscopic data were in agreement with the reported values in the literature.⁴⁵

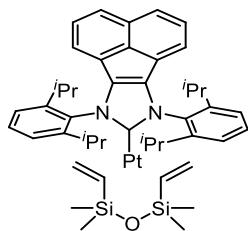
The formation of the imidazolium ring was conducted according to the literature method.⁴⁵

Synthesis of the title Pt complex was conducted on a 0.22 mmol scale based on $\text{H}_2\text{PtCl}_6\text{-nH}_2\text{O}$ to give 113 mg of $\text{Pt}(\text{IPr}^{\text{Me}})(\text{dvtms})$ as white solid (64%)



$\text{Mp} > 205$ $^{\circ}\text{C}$ (decomp.). ^1H NMR (CDCl_3 , 399.78 MHz): δ -0.77 (s, 6H), 0.11 (s, 6H), 1.12 (d, J = 6.9 Hz, 12H), 1.23 (d, J = 6.9 Hz, 12H), 1.25-1.65 (m, 6H), 2.01 (s, 6H), 2.92 (septet, J = 6.9 Hz, 4H), 7.17 (d, J = 7.8 Hz, 4H), 7.34 (t, J = 7.8 Hz, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ -2.39, 1.64, 11.0, 23.5, 24.9, 28.1, 35.4 ($^1J_{\text{Pt-C}} = 59$ Hz), 42.6 ($^1J_{\text{Pt-C}} = 84$ Hz), 123.9, 126.7, 129.1, 135.2, 146.2, 182.9 ($^1J_{\text{Pt-C}} = 721$ Hz). HRMS (FAB): Calcd for $\text{C}_{37}\text{H}_{58}\text{N}_2\text{OPtSi}_2$ 797.3735, Found 797.3733.

Pt(IPr^{AN})(dvtms) (**4m**).



IPr^{AN}•HCl was synthesized according to the literature procedure.⁴⁶

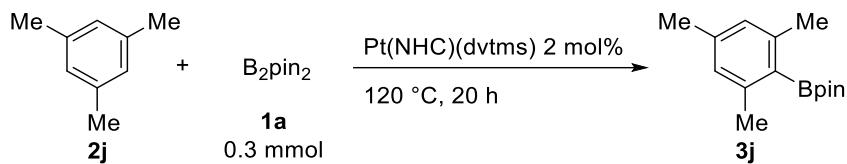
Synthesis of the title Pt complex was conducted with the same procedure for **4g** except that IPr^{AN}•HCl was used instead of IPr^{Me}•HCl on 0.47 mmol scale based on H₂PtCl₆•nH₂O to give 153 mg of Pt(IPr^{AN})(dvtms) as an orange solid (36%). Mp > 215 °C (decomp.). ¹H NMR (CDCl₃, 399.78 MHz): δ -0.72 (s, 6H), 0.16 (s, 6H), 0.98 (d, *J* = 6.4 Hz, 12H), 1.26 (d, *J* = 6.8 Hz, 12H), 1.50 (dd, *J* = 13.5, 11.7 Hz, ³J_{Pt-C} = 25 Hz, 2H), 1.71 (d, *J* = 13.3 Hz, ³J_{Pt-C} = 27 Hz, 2H), 1.84 (d, *J* = 11.5 Hz, ³J_{Pt-C} = 28 Hz, 2H), 3.19 (septet, *J* = 6.9 Hz, 4H), 6.84 (d, *J* = 6.9 Hz, 2H), 7.28 (d, *J* = 7.8 Hz, 4H), 7.33 (dd, *J* = 8.2, 6.9 Hz, 2H), 7.46 (t, *J* = 7.8 Hz, 2H), 7.68 (d, *J* = 7.8 Hz, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ -2.17, 1.61, 23.1, 25.4, 28.6, 36.4, 42.6 (¹J_{Pt-C} = 84 Hz), 121.3, 124.1, 126.9, 127.2, 127.4, 129.55, 129.60, 129.64, 135.4, 140.1, 145.9, 194.9.

IR (ATR): 2960 w, 2869 w, 1477 w, 1382 w, 1330 w, 1303 w, 1245 m, 1182 w, 1062 w, 988 m, 915 w, 859 w, 836 s, 820 s, 799 m, 781 s, 694 m. HRMS (FAB): Calcd for C₄₅H₅₈N₂OPtSi₂ 893.3735, Found 893.3731.

2.4.4 Optimization Studies

Effect of the ligand for Pt-catalyzed borylation of benzene. Pt(NHC)(dvtms) (0.90 μmol) was dissolved into 10 mL of benzene to prepare Pt(NHC)(dvtms) solution (9.0 × 10⁻⁴ M). B₂pin₂ (76 mg, 0.30 mmol) and Pt(NHC)(dvtms) benzene solution (1.0 mL, 0.9 μmol, 0.3 mol%) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N₂. The vial was stirred at 100 °C for 20 h, and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/EtOAc = 5/1). The filtrate was analyzed by gas chromatography (GC) using dodecane as an internal standard. As a result, ICy-ligated complex **4g** exhibited the highest TON among the complexes tested. The results are summarized in table 1.

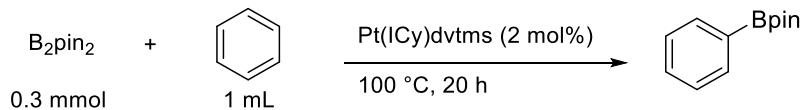
Optimization of the reaction of mesitylene. Pt(NHC)(dvtms) (6.0 μmol), B₂pin₂ (76 mg, 0.30 mmol) and mesitylene (1.0 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N₂. The vial was stirred at 120 °C for 20 h, and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/EtOAc = 5/1). The filtrate was analyzed by gas chromatography (GC) using dodecane as an internal standard. As a result, IPr-bound complex **4b** exhibited the highest activity.



Entry	Pt complex	NHC	GC yield (%)	
			product	recovered B ₂ pin ₂
1	4a	IMes	46	0
2	4b	IPr	72	0
3	4c	IMe	0	55
4	4d	I'Pr	17	41
5	4e	I' ^t Bu	37	0
6	4f	IAd	66	0
7	4g	ICy	55	5
8	4h	SICy	18	31
9	4i	BICy	31	28

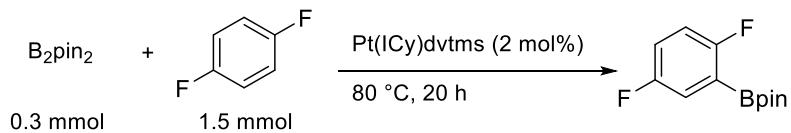
2.4.5 General Procedures for Platinum-Catalyzed Borylation of Arenes

Method A: Procedure for the Platinum-Catalyzed Borylation of Benzene with Bis(pinacolato)diboron (3a, Scheme 1)



Pt(ICy)(dvtms) (3.6 mg, 5.9 μ mol), B₂pin₂ (76 mg, 0.30 mmol) and benzene (1.0 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N₂. The vial was stirred at 100 °C for 20 h, and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was analyzed by gas chromatography (GC) using dodecane as an internal standard (94% GC yield). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ EtOAc = 25/1) to give 4,4,5,5-tetramethyl-2-phenyl-1,3,2-dioxaborolane as a white solid (57 mg, 93% based on B₂pin₂).

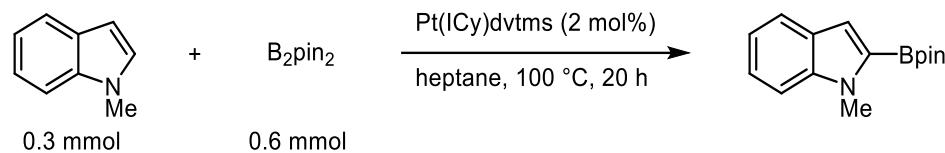
Method B: Procedure for the Platinum-Catalyzed Borylation of 1,4-Difluorobenzene with Bis(pinacolato)diboron (6b, Figure 6)



Pt(ICy)(dvtms) (3.6 mg, 5.9 μ mol), B₂pin₂ (76 mg, 0.30 mmol) and 1,4-difluorobenzene (154 μ L, 1.5 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N₂. The vial was stirred at 80 °C for 20 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was analyzed by NMR using 1,1,2,2-tetrachloroethane as an internal standard (86% NMR yield). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with

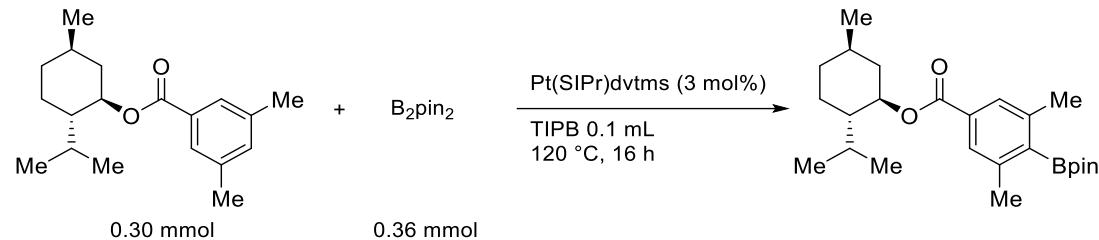
hexane/ EtOAc = 25/1) to give 2-(2,5-difluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane as a colorless oil (33 mg, 46% based on B_2pin_2).

Method C: Procedure for the Platinum-Catalyzed Borylation of *N*-Methylindole with Bis(pinacolato)diboron (8a, Figure 7)



$\text{Pt}(\text{ICy})\text{dvtms}$ (3.6 mg, 5.9 μmol), B_2pin_2 (152 mg, 0.60 mmol), *N*-methylindole (40 mg, 0.30 mmol) and heptane (1.0 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N_2 . The vial was stirred at 100 °C for 20 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ EtOAc = 25/1) to give 1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole as a white solid (69 mg, 87% based on *N*-methylindole).

Method D: Procedure for the Platinum-Catalyzed Borylation of 2v with Bis(pinacolato)diboron (3v, Figure 5)



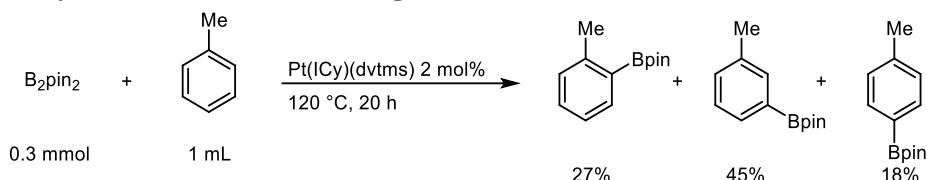
$\text{Pt}(\text{SIPr})\text{dvtms}$ (6.9 mg, 9.0 μmol), B_2pin_2 (91 mg, 0.36 mmol), **2v** (86 mg, 0.30 mmol) and 1,3,5-triisopropylbenzen (0.1 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 120 °C for 16 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ EtOAc = 100/1 to 50/1) to give the target borylated product as a white solid (63 mg, 51% based on **2v**) and 25 mg of unreacted starting **2v** was recovered (29%).

2.4.6 Spectroscopic Data of the Products

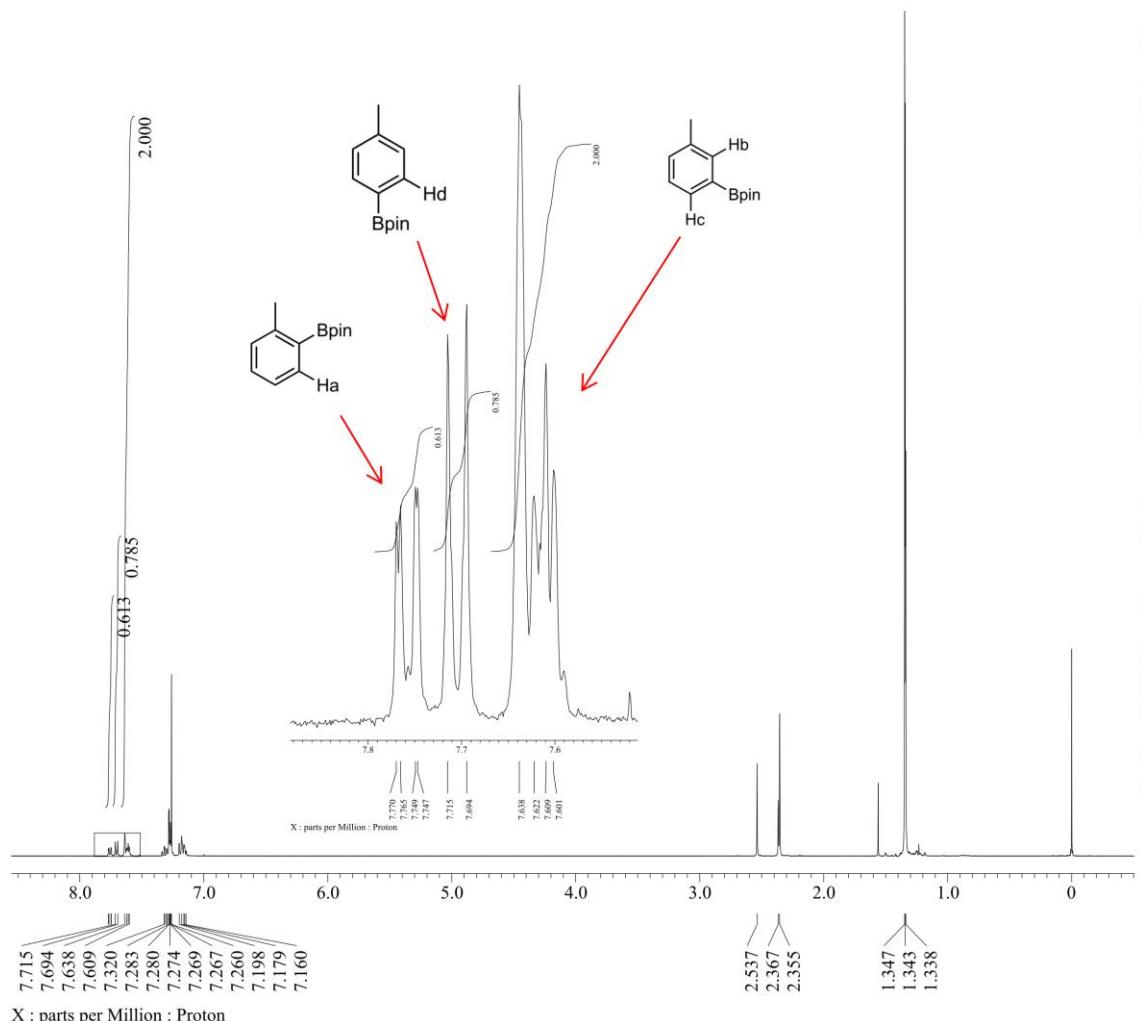
4,4,5,5-Tetramethyl-2-phenyl-1,3,2-dioxaborolane (3a) [CAS: 24388-23-6].

Rf 0.51 (hexane/EtOAc = 5/1). White solid (57 mg, 93%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.35 (s, 12H), 7.37 (t, J = 7.6 Hz, 2H), 7.46 (t, J = 7.3 Hz, 1H), 7.81 (d, J = 7.1 Hz, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 83.7, 127.6, 131.2, 134.7. HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{17}\text{BO}_2$ 204.1322, Found 204.1321.

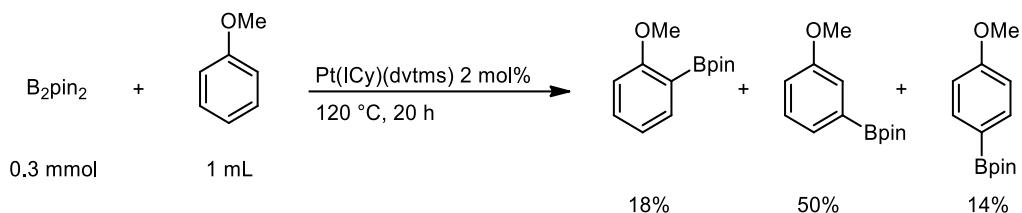
Borylation of toluene (3b, Figure 2).



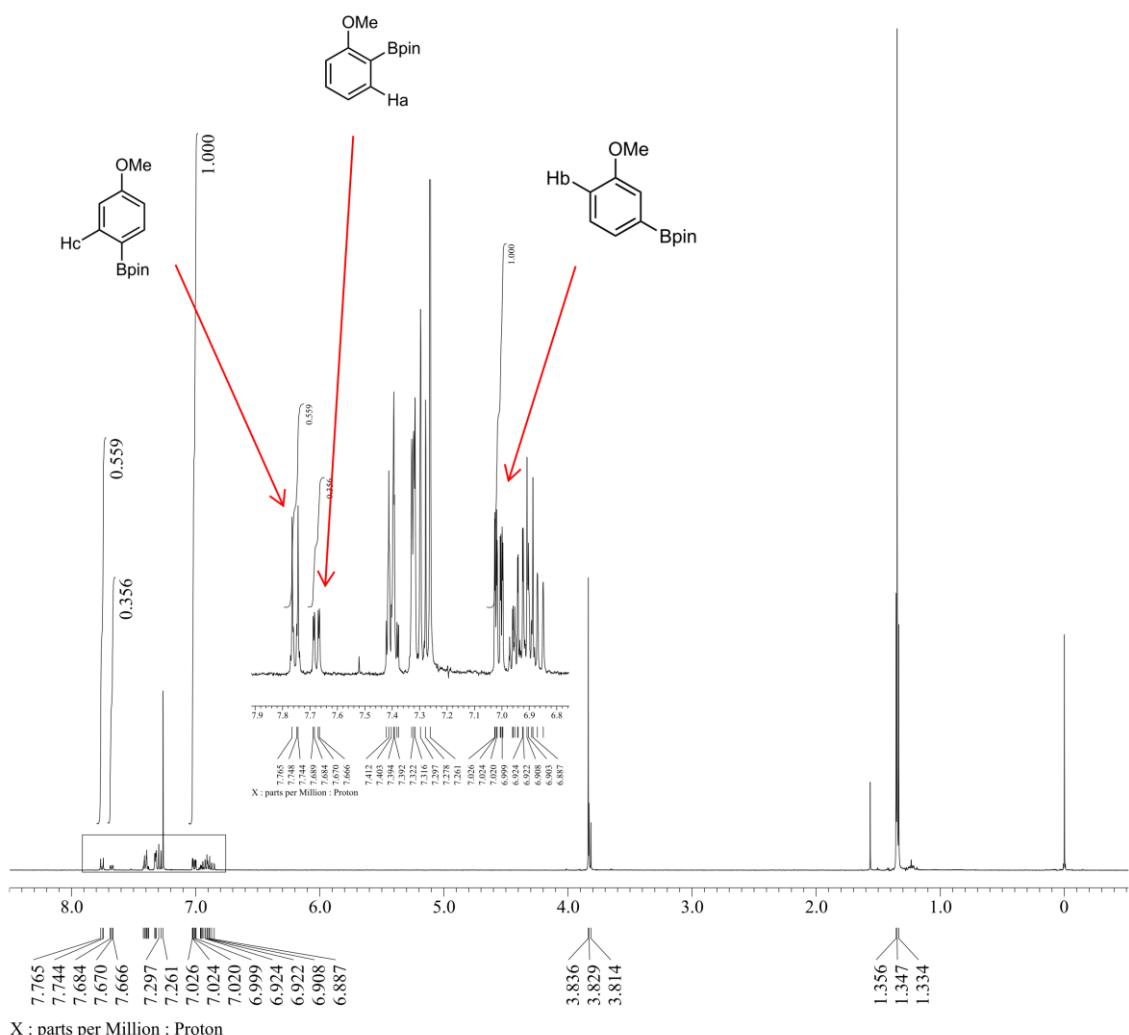
Method A was used, except that the reaction was conducted in toluene (1.0 mL) at 120 °C. After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of three isomers was obtained (59 mg, 90%, >99% purity by GC). GC/MS analysis showed the formation of three isomers of the borylated product, all of which had an m/z of 218 (M^+). The identity and ratio of each of the three isomers were determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.^{10a,11} The resonances specific to each isomer are as follows: 7.76 ppm (dd, $J = 7.6, 1.4$ Hz, 1H, ortho isomer, H_a); 7.60-7.64 ppm (m, 2H, meta isomer, H_b and H_c), 7.71 ppm (d, $J = 8.2$ Hz, 1H, para isomer, H_d). (see below.)



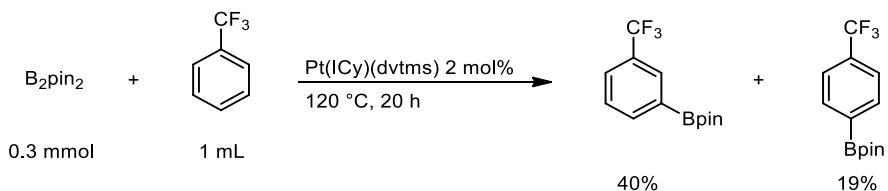
Borylation of anisole (3c, Figure 2).



Method A was used, except that the reaction was conducted in anisole (1.0 mL) at 120 °C. After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of three isomers of the borylated product were obtained (57 mg, 82%, >99% purity by GC). GC/MS analysis showed the formation of three isomers of the borylated product, all of which had an m/z of 234 (M⁺). The identity and ratio of each of the borylated products were determined by comparing the ¹H NMR spectrum of the product mixture with those reported in the literature.^{10a} The resonances specific to each isomer are as follows: 7.67 ppm (dd, *J* = 1.8 Hz, 7.3 Hz, 1H ortho isomer, H_a); 7.01 ppm (ddd, *J* = 0.9 Hz, 2.7 Hz, 8.2 Hz, 1H, meta isomer, H_b), 7.75 ppm (d, *J* = 8.7 Hz, 2H, para isomer, H_c). (See below.)

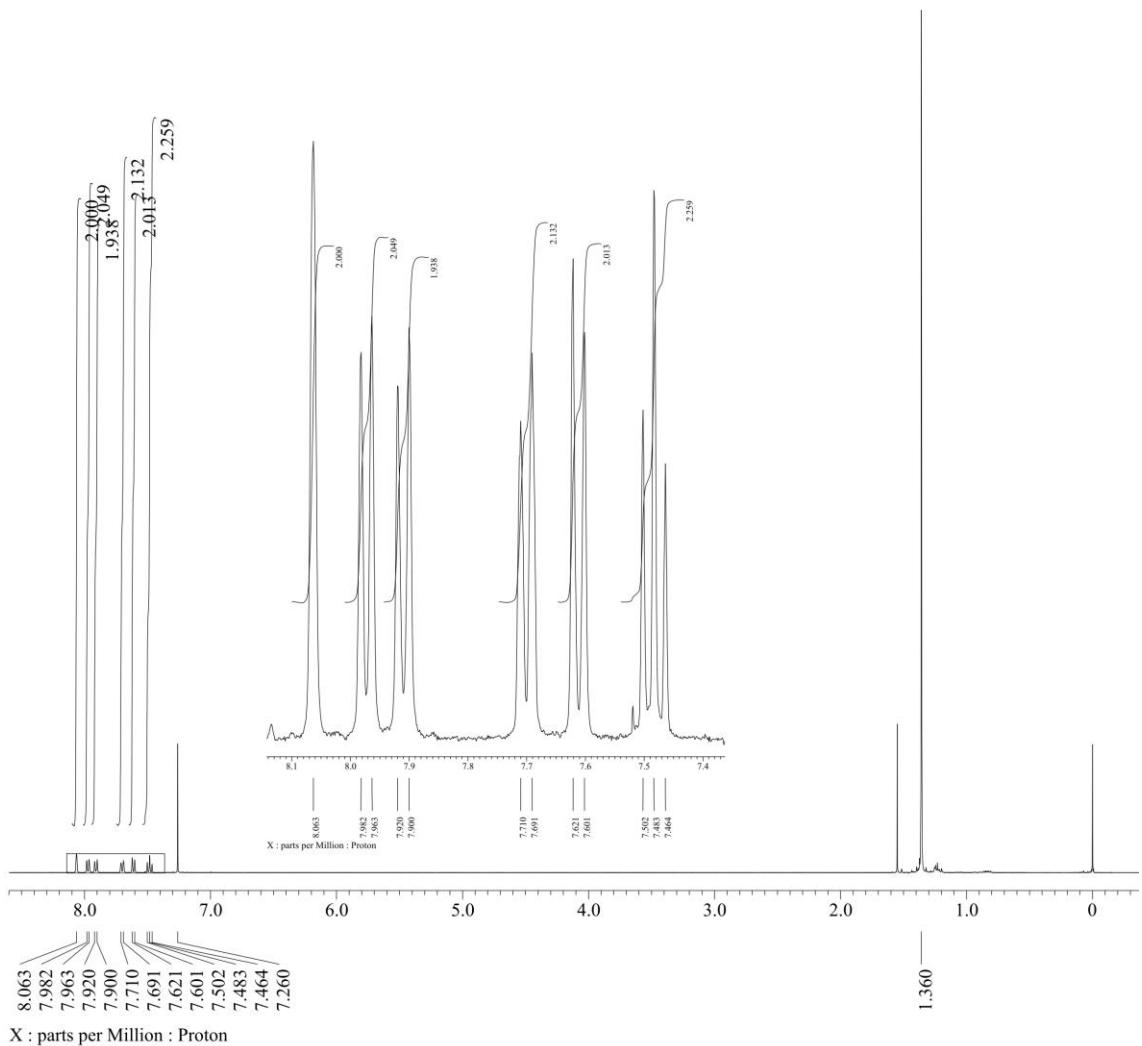


Borylation of (trifluoromethyl)benzene (3d, Figure 2).

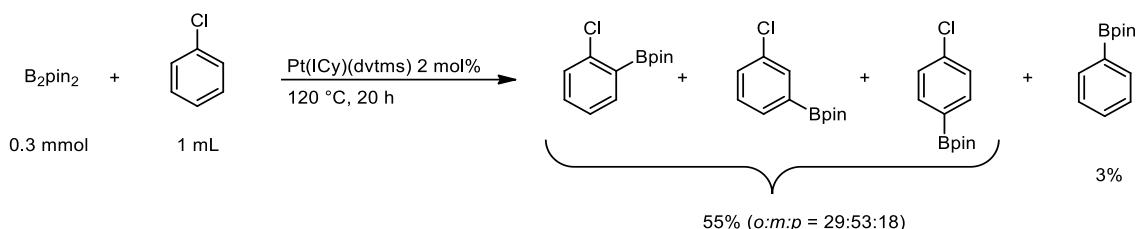


Method A was used, except that the reaction was conducted in (trifluoromethyl)benzene (1.0 mL) at 120 °C. After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of two isomers of the borylated product were obtained (46 mg, 59%, >99% purity by GC). GC/MS analysis showed the formation of two isomers of the borylated product, all of which had an *m/z* of 272 (M^+). The identity and ratio of each of the borylated products were determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.^{10a} The resonances specific to each isomer are as follows:

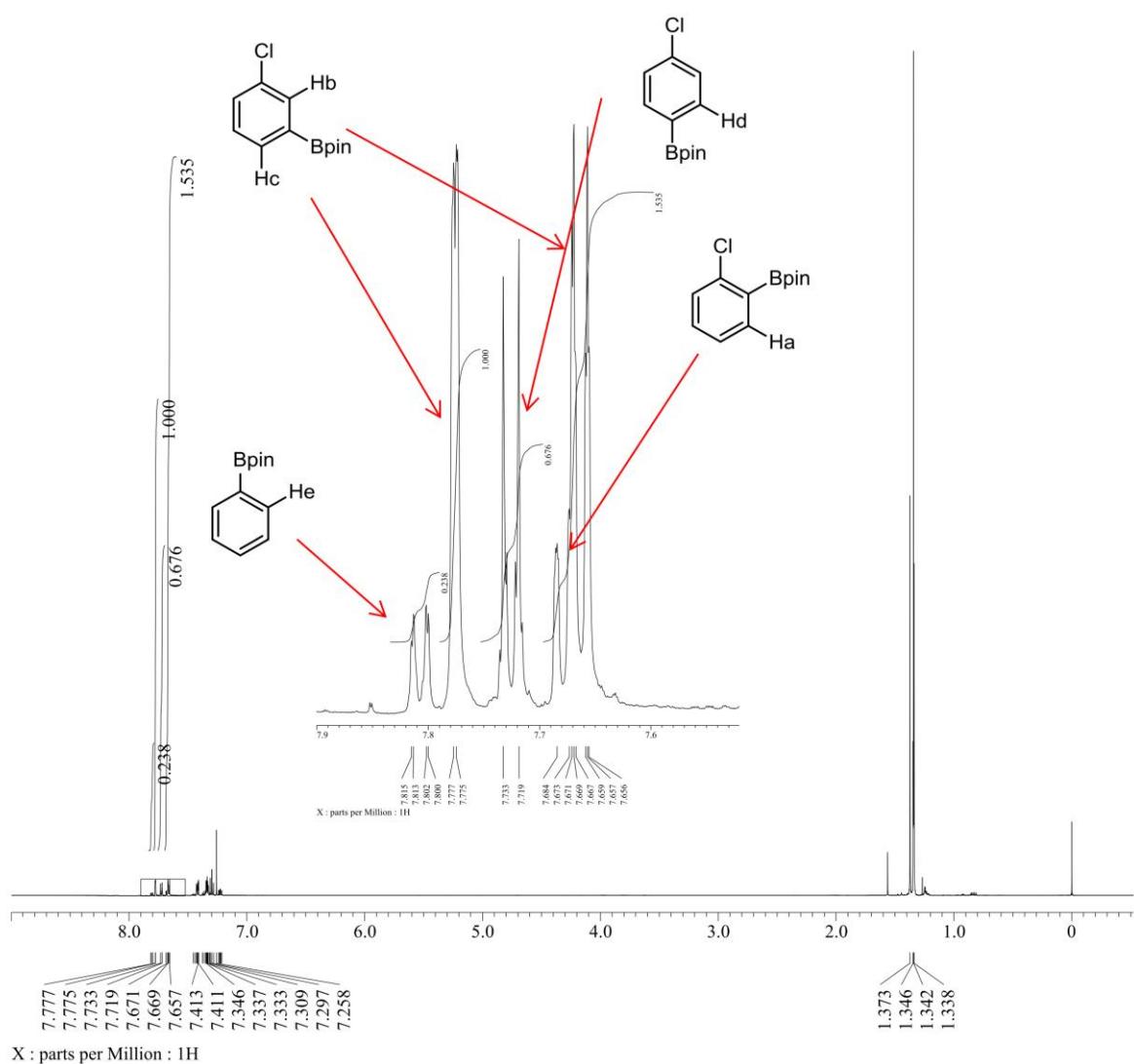
meta-isomer; δ 7.48 (t, $J = 7.4$ Hz, 1H), 7.70 (d, $J = 7.8$ Hz, 1H), 7.97 (d, $J = 7.3$ Hz, 1H), 8.06 (s, 1H). para-isomer; δ 7.61 (d, $J = 7.8$ Hz, 2H), 7.91 (d, $J = 7.8$ Hz, 1H). (See below.)



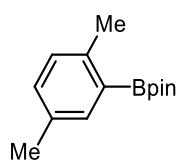
Borylation of chlorobenzene (3e, Figure 2).



Method A was used, except that the reaction was conducted in chlorobenzene (1.0 mL) at 120 °C. After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of three isomers of the borylated product and PhBpin was obtained (41 mg). GC/MS analysis showed the formation of three isomers of $\text{ClC}_6\text{H}_4\text{Bpin}$ ($m/z = 238$) and PhBpin ($m/z = 204$). The identity and ratio of each of the borylated products were determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.⁴⁷ The resonances specific to each isomer are as follows: ortho-isomer, δ 7.68 (d, partially overlapped in the H_c peak of meta-isomer, 1H, H_a). meta-isomer, δ 7.66 (dt, $J = 7.3, 1.1$ Hz, 1H, H_c), 7.78 (d, $J = 1.4$ Hz, 1H, H_b). para-isomer, δ 7.73 (d, $J = 8.4$ Hz, 2H, H_d). PhBpin , δ 7.81 (dd, $J = 8.0, 1.1$ Hz, 2H, H_e). ^1H NMR spectroscopic analysis showed that the yields of $\text{ClC}_6\text{H}_4\text{Bpin}$ and $\text{ClC}_6\text{H}_4\text{Bpin}$ were 55% and 3 %, respectively.

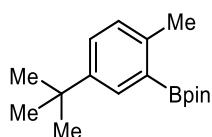


2-(2,5-Dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3f, Figure 2) [CAS: 356570-53-1].



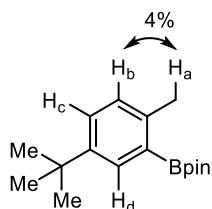
Method A was used, except that the reaction was conducted in *p*-xylene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μ mol) instead of Pt(ICy)(dvtms). Rf 0.63 (hexane/EtOAc = 5/1). White solid (57 mg, 82%). 1 H NMR (CDCl₃, 399.78 MHz): δ 1.34 (s, 12H), 2.30 (s, 3H), 2.49 (s, 3H), 7.06 (d, *J* = 7.8 Hz, 1H), 7.13 (dd, *J* = 7.8, 1.8 Hz, 1H), 7.57 (d, *J* = 1.4 Hz, 1H). 13 C NMR (CDCl₃, 100.53 MHz): δ 20.8, 21.7, 24.9, 83.3, 129.8, 131.5, 133.9, 136.3, 141.7. HRMS (EI): Calcd for C₁₄H₂₁BO₂ 232.1635, Found 232.1628.

2-(5-(tert-Butyl)-2-methylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6g, Figure 2).



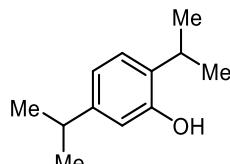
Method A was used, except that the reaction was conducted in 1-(tert-butyl)-4-methylbenzene (1.0 mL) at 120 °C with Pt(IAd)(dvtms) (4.3 mg, 6.0 μ mol) instead of Pt(ICy)(dvtms).

Rf 0.68 (hexane/EtOAc = 5/1). White solid (64 mg, 78%). Mp = 46-48 °C. 1 H NMR (CDCl₃, 399.78 MHz): δ 1.32 (s, 9H), 1.34 (s, 12H), 2.50 (s, 3H, H_a), 7.10 (d, *J* = 8.0 Hz, 1H, H_b), 7.35 (dd, *J* = 8.0, 2.3 Hz, 1H, H_c), 7.77 (d, *J* = 2.3 Hz, 1H, H_d). 13 C NMR (CDCl₃, 100.53 MHz): δ 21.7, 24.9, 31.4, 34.3, 83.3, 127.9, 129.6, 132.4, 141.9, 147.1. IR (ATR): 2969 w, 1461 w, 1398 m, 1368 s, 1337 s, 1307 s, 1269 m, 1255 m, 1211 w, 1165 w, 1141 s, 1116 m, 1067 m, 995 s, 963 m, 926 w, 889 w, 853 m, 829 m, 781 w, 737 m, 685 m, 575 m. MS m/z (% relative intensity): 274 (M+, 13), 260 (17), 259 (100), 258 (24), 159 (22), 131 (14), 101 (14), 83 (13), 57 (18). HRMS (EI): Calcd for C₁₇H₂₇BO₂ 274.2104, Found 204.2101.



The regiochemistry of the compound was determined by NOE experiments in CDCl₃. When the signal for H_a at δ = 2.50 (s, 3H, offset signal δ = 2.4937, mixing time 1 s) was irradiated, H_b at δ = 7.10 (d, *J* = 7.8 Hz, 1H) was enhanced by 4%.

2,5-Diisopropylphenol (3h, Figure 2) [CAS: 35946-91-9].

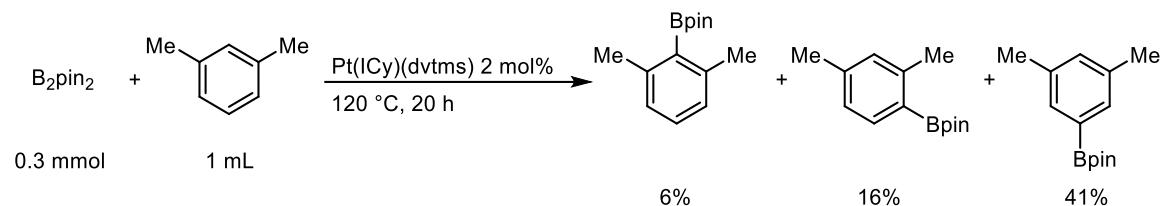


The borylated product contained inseparable unidentified impurities in this specific case, therefore product was isolated in the form of the corresponding phenol after oxidative work-up.

Method A was followed, except that the reaction was conducted in 1,4-diisopropylbenzene (1.0 mL) at 140 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μ mol) instead of Pt(ICy)(dvtms). After filtration of the mixture through a pad of Celite, an aqueous solution of NaOH (1.0 M, 1.0 mL) and an aqueous solution of H₂O₂ (30%, 0.5 mL) were added to the filtrate and the mixture was stirred for 30 min at ambient temperature. A small amount of KI was added to quench the residual H₂O₂ and the mixture was extracted three times with AcOEt. The combined organic extracts were concentrated in vacuo and purified by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1) to give 2,5-diisopropylphenol as a colorless oil (18 mg, 34% based on B₂pin₂).

Rf 0.40 (hexane/EtOAc = 5/1). Colorless oil (18 mg, 34%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.22 (d, J = 6.9 Hz, 6H), 1.25 (d, J = 6.9 Hz, 6H), 2.82 (septet, J = 6.9 Hz, 1H), 3.15 (septet, J = 6.9 Hz, 1H), 4.62 (br, 1H), 6.62 (d, J = 1.4 Hz, 1H), 6.78 (dd, J = 7.8, 1.4 Hz, 1H), 7.11 (d, J = 8.2 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 22.6, 23.9, 26.8, 33.5, 113.3, 119.0, 126.2, 131.5, 147.8, 152.5. HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{18}\text{O}$ 178.1358, Found 178.1355.

Borylation of *m*-xylene (3i, Figure 2).

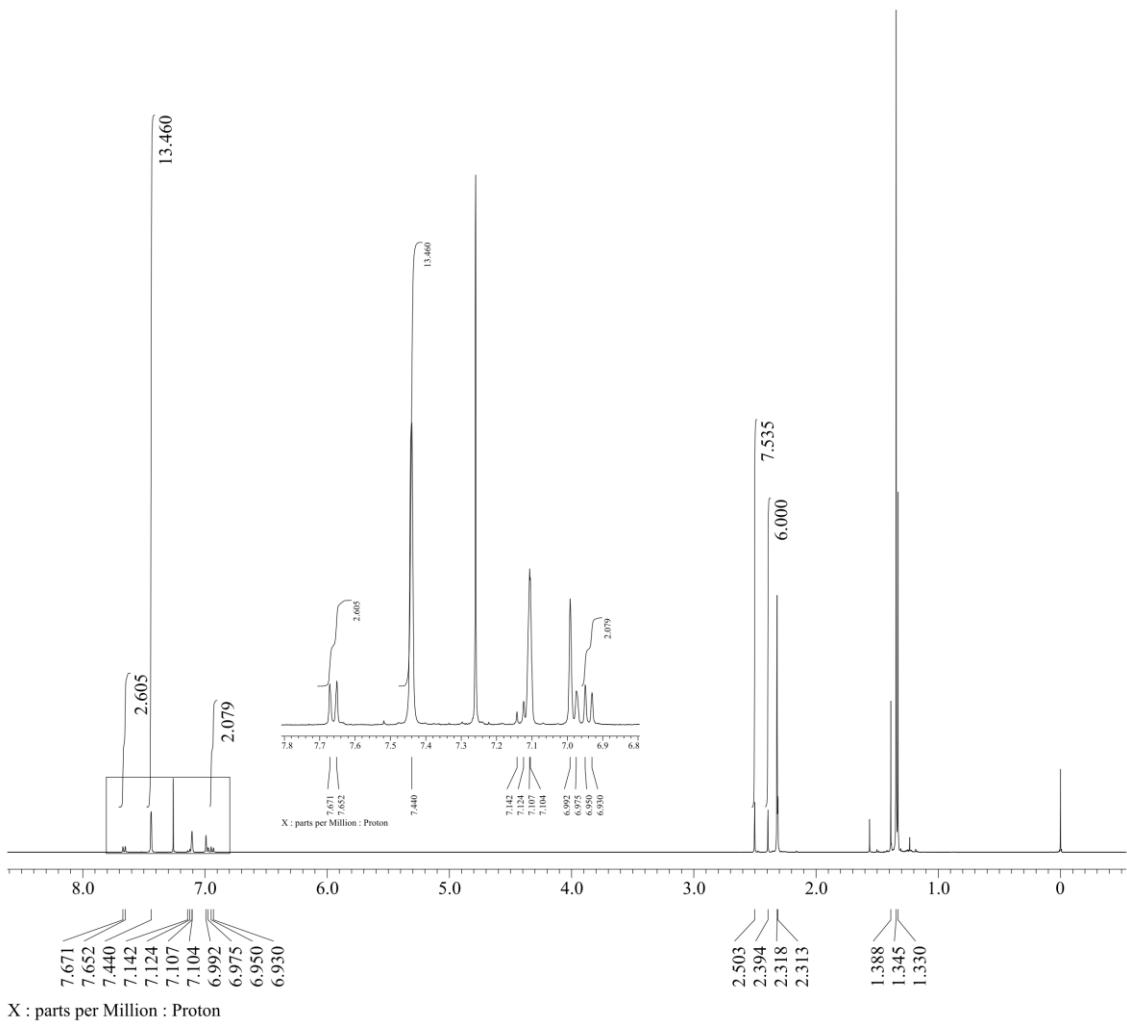


Method A was used, except that the reaction was conducted in *m*-xylene (1.0 mL) at 120°C . After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of three isomers of the borylated product were obtained (44 mg, 63%, >99% purity by GC). GC/MS analysis showed the formation of three isomers of the borylated product, all of which had an *m/z* of 232 (M^+). The identity and ratio of each of the borylated products were determined by comparing the ^1H NMR spectrum of the product mixture with those reported in the literature.^{10a,11,48} The resonances specific to each isomer are as follows.

2-Borylated isomer: δ 2.39 (s, 6H), 6.94 (d, J = 7.8 Hz, 1H), 7.12 (t, J = 7.3 Hz, 2H).

4-Borylated isomer: δ 2.31 (s, 3H), 2.50 (s, 3H), 6.97-7.00 (m, 2H), 7.66 (d, J = 7.8 Hz, 1H).

5-Borylated isomer: δ 2.32 (s, 6H), 7.10 (d, J = 0.9 Hz, 1H), 7.44 (s, 2H).



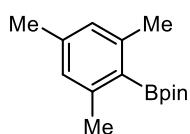
2-(3,5-Dimethylbenzyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (eq 1) [CAS: 356570-54-2].

Me
Me
Bpin

[Ir(OMe)(cod)]₂ (2.0 mg, 3.0 μmol), 4,4'-di-tert-butyl-2,2'-bipyridine (1.7 mg, 6.0 μmol), B₂pin₂ (76 mg, 0.30 mmol), and m-xylene (1.0 mL) were added to a 10 mL sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N₂. The mixture was stirred at 120 °C for 20 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/AcOEt = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1) to give 2-(3,5-dimethylbenzyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane as colorless oil (110 mg, 151% based on B₂pin₂).

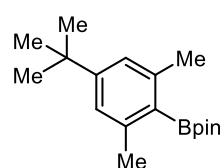
Rf 0.51 (hexane/EtOAc = 5/1). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.24 (s, 12H), 2.22 (s, 2H), 2.26 (s, 6H), 6.76 (s, 1H), 6.80 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 21.3, 24.7, 83.3, 126.5, 126.8, 137.6, 138.3. HRMS (EI): Calcd for C₁₅H₂₃BO₂ 246.1791, Found 246.1788.

2-Mesityl-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3j, eq 3) [CAS: 171364-84-4].



Method A was used except that the reaction was conducted in mesitylene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms). Rf 0.46 (hexane/EtOAc = 5/1). Colorless oil (53 mg, 72%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.37 (s, 12H), 2.24 (s, 3H), 2.37 (s, 6H), 6.77 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 21.2, 22.2, 24.9, 83.4, 127.4, 138.9, 142.1. HRMS (EI): Calcd for C₁₅H₂₃BO₂ 246.1791, Found 246.1792.

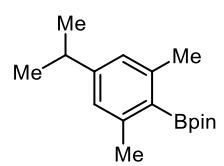
2-(4-(tert-Butyl)-2,6-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3k, Figure 4) [CAS: 1701449-62-8].



Method A was used, except that the reaction was conducted in 1-(tert-butyl)-3,5-dimethyl-benzene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms).

Rf 0.63 (hexane/EtOAc = 5/1). White solid (68 mg, 78%). Mp = 169 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.27 (s, 9H), 1.36 (s, 12H), 2.41 (s, 6H), 6.97 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 22.6, 24.9, 31.2, 34.3, 83.4, 123.6, 141.9, 152.2. IR (ATR): 2961 w, 2866 w, 1604 w, 1546 w, 1436 w, 1406 w, 1368 s, 1332 s, 1300 s, 1275 m, 1213 w, 1138 s, 1109 w, 1060 m, 963 w, 859 m, 781 w, 739 w, 680 m. MS m/z (% relative intensity): 288 (M+, 25), 274 (18), 273 (100), 272 (26), 231 (16), 189 (16), 173 (34), 101 (16), 83 (20), 57 (50), 55 (15). HRMS (EI): Calcd for C₁₈H₂₉BO₂ 288.2261, Found 288.2265.

2-(4-Isopropyl-2,6-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3l, Figure 4).



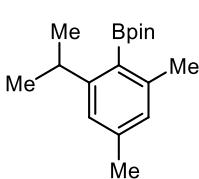
Method A was used, except that the reaction was conducted in 1-isopropyl-3,5-dimethylbenzene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms). The isomer ratio was determined to be 92:8 based on ¹H NMR.

The spectroscopic data for major isomer 3l are as follows.

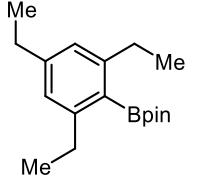
Rf 0.69 (hexane/EtOAc = 5/1). White solid (48 mg, 59%). Mp = 59-61 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.19 (d, J = 6.9 Hz, 6H), 1.37 (s, 12H), 2.39 (s, 6H), 2.78 (septet, J = 6.9 Hz, 1H), 6.81 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 22.4, 23.8, 24.9, 34.0, 83.4, 124.8, 142.2, 150.0. IR (ATR): 2960 m, 2926 w, 2867 w, 1606 w, 1559 w, 1433 m, 1370 m, 1328 s, 1301 s, 1273 m, 1213 w, 1140 s, 1106 w, 1085 m, 1059 m, 1006 w, 962 w, 853 m, 834 w, 796 w, 739 w, 679 m, 579 w. MS m/z (% relative intensity): 274 (M+, 51), 259 (33), 217 (64), 216 (26), 175 (100), 174 (70), 173 (18), 159 (44), 131 (27), 105 (14), 101 (22), 91 (16), 83 (24), 55 (17). HRMS (EI): Calcd for C₁₇H₂₇BO₂ 274.2104, Found 274.2106.

Method D was followed except that the reaction was conducted with 1-isopropyl-3,5-dimethylbenzene (42 mg, 0.28 mmol) as a substrate. The unreacted starting material (8.3 mg, 20%) was recovered and the borylated product (47 mg, 47%) was obtained. The isomer ratio was determined to be 96:4 based on ¹H NMR.

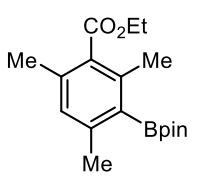
Resonances assignable to minor isomer are as follows


¹H NMR (CDCl₃, 399.78 MHz): δ 1.23 (d, *J* = 6.9 Hz, 6H), 1.37 (s, 12H), 2.67 (s, 3H), 2.34 (s, 3H), 3.03 (quintet, *J* = 6.9 Hz, 1H), 6.78 (s, 1H), 6.88 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 21.5, 24.4, 24.9, 30.9, 33.6, 83.6, 122.0, 127.6. Three peaks were overlapped with those for major isomer. MS m/z (% relative intensity): 274 (M+, 51), 259 (33), 217 (33), 175 (43), 174 (51), 173 (63), 159 (96), 158 (27), 157 (25), 145 (20), 131 (45), 101 (29), 84 (100), 83 (29). HRMS (EI): Calcd for C₁₇H₂₇BO₂ 274.2104, Found 274.2102.

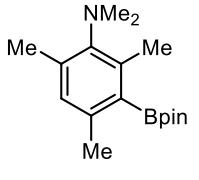
4,4,5,5-Tetramethyl-2-(2,4,6-triethylphenyl)-1,3,2-dioxaborolane (3m, Figure 4) [CAS: 1334181-19-9].


 Method A was used, except that the reaction was conducted in 1,3,5-triethylbenzene (1.0 mL) at 140 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μmol) instead of Pt(ICy)(dvtms). Rf 0.60 (hexane/EtOAc = 5/1). Colorless oil (60 mg, 68%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.17-1.25 (m, 9H), 1.37 (s, 12H), 2.57 (q, *J* = 7.5 Hz, 2H), 2.67 (q, *J* = 7.6 Hz, 4H), 6.83 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 15.5, 16.9, 24.9, 28.9, 29.4, 83.5, 124.8, 145.4, 148.3. IR (ATR): 2965 w, 2932 w, 2871 w, 1607 w, 1557 w, 1459 w, 1422 w, 1371 m, 1337 s, 1296 s, 1247 w, 1213 w, 1142 s, 1109 w, 1068 s, 961 w, 857 s, 781 w, 733 w, 681 m, 577 w. MS m/z (% relative intensity): 288 (M+, 31), 232 (15), 231 (100), 230 (30), 203 (17), 189 (18), 188 (35), 187 (23), 173 (15), 159 (26), 131 (14), 117 (17), 101 (39), 84 (20), 83 (22). HRMS (EI): Calcd for C₁₈H₂₉BO₂ 288.2961, Found 288.2263.

Ethyl 2,4,6-trimethyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (3n, Figure 4).

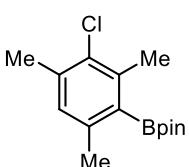

 Method A was used, except that the reaction was conducted in ethyl 2,4,6-trimethylbenzoate (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μmol) instead of Pt(ICy)(dvtms). Rf 0.27 (hexane/EtOAc = 10/1). Colorless oil (59 mg, 62%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.35 (t, *J* = 7.1 Hz, 3H), 1.37 (s, 12H), 2.24 (s, 3H), 2.34 (s, 3H), 2.35 (s, 3H), 4.35 (q, *J* = 7.1 Hz, 2H), 6.81 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 14.4, 19.7, 19.8, 22.2, 25.1, 60.8, 83.9, 128.5, 131.9, 135.6, 138.3, 143.0, 170.7. IR (ATR): 2978 w, 2930 w, 2868 w, 1724 s, 1599 w, 1443 w, 1372 w, 1333 m, 1300 m, 1257 s, 1201 s, 1142 s, 1098 s, 1023 m, 857 m. MS m/z (% relative intensity): 319 (M+1, 11), 318 (M+, 54), 273 (66), 272 (54), 261 (55), 215 (100), 189 (35), 173 (36), 172 (61), 83 (40). HRMS (EI): Calcd for C₁₈H₂₇BO₄ 318.2002, Found 318.2002.

N,N,2,4,6-Pentamethyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)aniline (3o, Figure 4).


 Method A was used, except that the reaction was conducted in *N,N*,2,4,6-pentamethylaniline (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μmol) instead of Pt(ICy)(dvtms). Rf 0.46 (hexane/EtOAc = 10/1). White solid (50 mg, 58%). Mp = 90-91 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.38 (s, 12H), 2.21 (s, 3H), 2.29 (s, 3H), 2.31 (s, 3H), 2.75 (s, 6H), 6.75 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 18.6, 19.2, 21.7, 25.1, 42.6, 83.7, 130.2, 138.0, 138.4, 140.9,

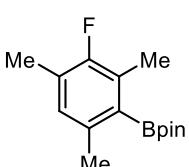
146.9. IR (ATR): 2976 w, 2919 w, 2783 w, 1439 w, 1392 m, 1372 m, 1334 s, 1298 s, 1211 w, 1136 s, 1023 s, 858 s. MS m/z (% relative intensity): 290 (M+1, 17), 289 (M+, 100), 274 (36), 83 (38). HRMS (EI): Calcd for $C_{17}H_{28}BNO_2$ 289.2213, Found 289.2215.

2-(3-Chloro-2,4,6-trimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3p, Figure 4).

 Method A was used, except that the reaction was conducted in 2-chloro-1,3,5-trimethylbenzene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms). Isolation by column chromatography gave the title compound as a colorless oil (67 mg). NMR analysis revealed that the sample contained 4% of a dechlorinated product **3j**. Thus, the yield of the borylated product was determined to be 76%.

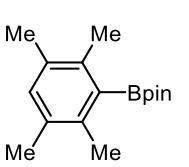
Rf 0.43 (hexane/EtOAc = 10/1). 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.38 (s, 12H), 2.31 (s, 3H), 2.32 (s, 3H), 2.42 (s, 3H), 6.86 (s, 1H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 205, 21.0, 21.7, 25.1, 84.0, 129.8, 132.2, 137.1, 139.1, 139.4. IR (ATR): 2978 w, 2926 w, 2866 w, 1436 w, 1375 m, 1323 s, 1299 s, 1211 w, 1143 s, 984 m, 857 m. MS m/z (% relative intensity): 282 (M+2, 14), 280 (M+, 39), 225 (33), 223 (100), 222 (36), 181 (48), 180 (81), 145 (34), 115 (30), 101 (31), 85 (30), 83 (30). HRMS (EI): Calcd for $C_{15}H_{22}BClO_2$ 280.1401, Found 280.1403.

2-(3-Fluoro-2,4,6-trimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3q, Figure 4).

 Method A was used, except that the reaction was conducted in 2-fluoro-1,3,5-trimethylbenzene (1.0 mL) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms).

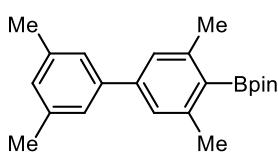
Rf 0.51 (hexane/EtOAc = 10/1). Colorless oil (59 mg, 74%). 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.38 (s, 12H), 2.19 (d, J = 2.3 Hz, 3H), 2.29 (d, J = 2.7 Hz, 3H), 2.31 (s, 3H), 6.76 (d, J = 6.9 Hz, 1H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 14.2 (d, J = 5.8 Hz), 14.8 (d, J = 3.8 Hz), 21.6, 25.1, 83.9, 125.3 (d, J = 18.2 Hz), 127.9 (d, J = 15.3 Hz), 130.0 (d, J = 4.8 Hz), 136.8 (d, J = 3.8 Hz), 158.1 (d, J = 242 Hz). IR (ATR): 2979 w, 2929 w, 1442 w, 1412 m, 1372 m, 1329 s, 1301 s, 1273 m, 1217 w, 1166 m, 1142 s, 1021 m, 858 m. MS m/z (% relative intensity): 264 (M+, 47), 207 (100), 206 (37), 165 (48), 164 (92), 163 (34). HRMS (EI): Calcd for $C_{15}H_{22}BFO_2$ 264.1697, Found 264.1698.

4,4,5,5-Tetramethyl-2-(2,3,5,6-tetramethylphenyl)-1,3,2-dioxaborolane (3r, Figure 4).

 Method A was used, except that the reaction was conducted in melted 1,2,4,5-tetramethylbenzene (805 mg, 20 equiv) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 µmol) instead of Pt(ICy)(dvtms).

Rf 0.34 (hexane/EtOAc = 10/1). White solid (59 mg, 76%). 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.39 (s, 12H), 2.16 (s, 6H), 2.23 (s, 6H), 6.88 (s, 1H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 19.0, 19.7, 25.2, 83.8, 132.4, 133.1, 136.7. IR (ATR): 2977 m, 2931 w, 1463 w, 1410 m, 1376 m, 1338 s, 1295 s, 1251 m, 1195 w, 1142 s, 1018 w, 962 w. MS m/z (% relative intensity): 260 (M+, 60), 259 (15), 204 (14), 203 (100), 202 (36), 188 (12), 161 (40), 160 (80), 159 (42), 145 (34), 119 (26), 117 (19), 115 (15), 105 (14), 101 (17), 91 (17), 85 (13), 83 (17), 55 (12). HRMS (EI): Calcd for $C_{16}H_{25}BO_2$ 261.1948, Found 260.1949.

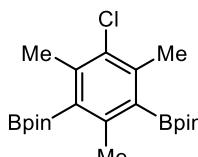
4,4,5,5-Tetramethyl-2-(3,3',5,5'-tetramethyl-[1,1'-biphenyl]-4-yl)-1,3,2-dioxaborolane (3s, Figure 4).



Method A was used, except that the reaction was conducted in melted 3,3',5,5'-tetramethyl-1,1'-biphenyl (1.19 g, 19 equiv) at 120 °C with Pt(IPr)(dvtms) (4.6 mg, 6.0 μ mol) instead of Pt(ICy)(dvtms).

Rf 0.34 (hexane/EtOAc = 10/1). White solid (76 mg, 75%). 1 H NMR (CDCl₃, 399.78 MHz): δ 1.39 (s, 12H), 2.36 (s, 6H), 2.46 (s, 6H), 6.96 (s, 1H), 7.17 (s, 2H), 7.19 (s, 2H). 13 C NMR (CDCl₃, 100.53 MHz): δ 21.4, 22.4, 25.0, 83.6, 125.0, 125.4, 128.8, 138.0, 141.3, 142.1, 142.4. IR (ATR): 2977 w, 2921 w, 1602 m, 1552 w, 1438 w, 1370 m, 1329 s, 1302 s, 1274 w, 1145 s, 1110 w, 1061 m, 962 w. MS m/z (% relative intensity): 338 (M+2, 18), 337 (M+1, 66), 336 (M+, 18), 279 (22), 237 (49), 236 (100), 235 (77). HRMS (EI): Calcd for C₂₂H₂₉BO₂ 336.2261, Found 336.2261.

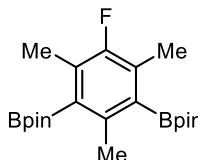
2,2'-(5-Chloro-2,4,6-trimethyl-1,3-phenylene)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (3p-di, Figure 5).



Method D was followed except that the reaction was conducted with 2-chloro-1,3,5-trimethylbenzene (46 mg, 0.30 mmol) as a substrate. Monoborylated product **3p-mono** (54 mg, 64%) and the title compound **3p-di** (27 mg, 23%) were obtained.

Rf 0.53 (hexane/EtOAc = 5/1). White solid (27 mg, 23%). Mp = 160-163 °C. 1 H NMR (CDCl₃, 399.78 MHz): δ 1.37 (s, 24H), 2.38 (s, 3H), 2.39 (s, 6H). 13 C NMR (CDCl₃, 100.53 MHz): δ 20.8, 22.0, 25.0, 83.8, 132.3, 139.6, 142.2. IR (ATR): 2978 m, 1425 w, 1373 m, 1337 m, 1300 s, 1267 m, 1141 s, 987 w, 857 w, 671 w. MS m/z (% relative intensity): 408 (9), 407 (9), 406 (M+, 26), 405 (12), 349 (12), 246 (24), 248 (16), 101 (100), 83 (35). HRMS (EI): Calcd for C₂₁H₃₃B₂ClO₄ 406.2253, Found 406.2257.

2,2'-(5-Fluoro-2,4,6-trimethyl-1,3-phenylene)bis(4,4,5,5-tetramethyl-1,3,2-dioxaborolane) (3q-di, Figure 5).



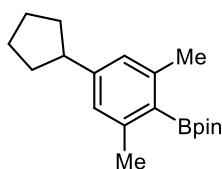
Method D was followed except that the reaction was conducted with 2-fluoro-1,3,5-trimethylbenzene (42 mg, 0.30 mmol) as a substrate. Monoborylated product **3q-mono** (44 mg, 55%) and the title compound **3q-di** (13 mg, 11%) were obtained.

Rf 0.51 (hexane/EtOAc = 5/1). White solid (13 mg, 11%). Mp = 144-145 °C. 1 H NMR (CDCl₃, 399.78 MHz): δ 1.40 (s, 24H), 2.26 (d, J = 2.3 Hz, 6H), 2.39 (s, 3H). 13 C NMR (CDCl₃, 100.53 MHz): δ 14.2 (d, J = 4.8 Hz), 21.9, 24.9, 83.7, 128.4 (d, J = 17 Hz), 139.9 (d, J = 4.8 Hz), 157.6 (d, J = 240 Hz). IR (ATR): 2977 w, 1444 w, 1370 m, 1306 s, 1267 m, 1213 w, 1138 s, 1109 w, 1031 w, 1007 w, 990 w, 857 m, 831 w, 758 w, 711 w, 672 m. MS m/z (% relative intensity): 390 (M+, 38), 389 (18), 333 (16), 289 (14), 233 (34), 232 (25), 101 (100), 83 (36). HRMS (EI): Calcd for C₂₁H₃₃B₂FO₄ 390.2549, Found 390.2548.

To obtain the title compound as a major product, the borylation was repeated twice as described below:

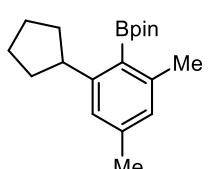
Pt(SIPr)(dvtms) (6.9 mg, 9.0 μ mol), B₂pin₂ (91 mg, 0.36 mmol), fluoromesitylene (21 mg, 0.15 mmol) and octane (0.10 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N₂. The mixture was stirred at 120 °C for 16 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and again filtered through a pad of silica gel (eluting with 7 mL of hexane/ EtOAc = 20/1) to give colorless filtrate. The filtrate was concentrated in vacuo and transferred to another vial for 2nd borylation. To the reaction mixture, Pt(SIPr)(dvtms) (6.9 mg, 9.0 μ mol), B₂pin₂ (91 mg, 0.36 mmol) and octane (0.10 mL) were added, and the mixture was stirred at 120 °C for 16 h. The resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ EtOAc = 100/1 to 50/1) to give the target diborylated product **3q-di** as a white solid (38 mg, 65%). The monoborylated product was formed in 25% yield based on ¹H-NMR analysis.

2-(4-Cyclopentyl-2,6-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3t, Figure 5).



Method D was followed except that the reaction was conducted with 1-cyclopentyl-3,5-dimethylbenzene (50 mg, 0.29 mmol) as a substrate. 42% of the starting material remained unreacted based on ¹H NMR analysis.

R_f 0.72 (hexane/EtOAc = 5/1). Colorless oil (45 mg, 53%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.36 (s, 12H), 1.45-1.60 (m, 2H), 1.60-1.71 (m, 2H), 1.71-1.89 (m, 2H), 1.89-2.08 (m, 2H), 2.38 (s, 6H), 2.87 (quintet, *J* = 8.6 Hz, 1H), 6.83 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 22.4, 24.9, 25.6, 34.4, 45.8, 83.4, 125.5, 142.1, 147.7. IR (ATR): 2952 w, 2867 w, 1607 w, 1436 m, 1370 m, 1330 s, 1299 s, 1274 m, 1213 w, 1142 s, 1108 w, 1066 s, 962 w, 858 m, 733 w, 677 w. MS m/z (% relative intensity): 301 (20), 300 (M+, 94), 299 (23), 285 (18), 244 (16), 243 (100), 242 (39), 201 (68), 200 (79), 199 (22), 175 (88), 158 (17), 157 (17), 131 (21), 101 (21), 83 (20), 69 (17). HRMS (EI): Calcd for C₁₉H₂₉BO₂ 300.2261, Found 300.2260.



Small amount of a regioisomer was also formed in 5% (¹H-NMR).

Resonances assignable to this isomer are as follows:

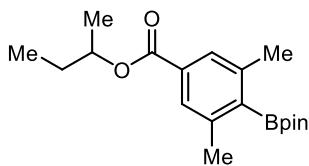
¹H NMR (CDCl₃, 399.78 MHz): δ 1.37 (s, 12H), 2.26 (s, 3H), 2.34 (s, 3H), 3.01 (quintet, *J* = 8.0 Hz, 1H), 6.77 (s, 1H), 6.88 (s, 1H). Other peaks were overlapped with those of the major isomer.

¹³C NMR (CDCl₃, 100.53 MHz): δ 21.5, 22.0, 24.9, 25.7, 35.2, 46.1, 83.6, 122.6, 127.6, 138.8, 140.9, 150.0.

MS m/z (% relative intensity): 301 (19), 300 (M+, 89), 299 (22), 259 (18), 217 (33), 216 (84), 215 (48), 200 (58), 199 (100), 198 (41), 185 (23), 173 (22), 172 (43), 171 (39), 159 (30), 158 (15), 157 (40), 146 (22), 145 (43), 133 (23), 131 (23), 129 (22), 101 (34), 85 (43), 84 (98), 83 (26), 69 (22).

HRMS (EI): Calcd for C₁₉H₂₉BO₂ 300.2261, Found 300.2255.

sec-Butyl 3,5-dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (3u, Figure 5).

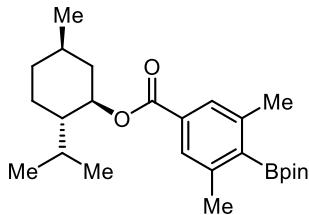


Method D was followed except that the reaction was conducted with sec-butyl 3,5-dimethylbenzoate (67 mg, 0.32 mmol) as a substrate. The unreacted starting material was recovered (28 mg, 42%).

R_f 0.63 (hexane/EtOAc = 5/1). White solid (44 mg, 41%). Mp = 62-63 °C.

¹H NMR (CDCl₃, 399.78 MHz): δ 0.96 (t, *J* = 7.6 Hz, 3H), 1.32 (d, *J* = 6.0 Hz, 3H), 1.42 (d, *J* = 14.7 Hz, 12H), 1.60-1.82 (m, 2H), 2.43 (s, 6H), 5.07 (sextet, *J* = 6.3 Hz, 1H), 7.60 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 9.8, 19.6, 22.1, 24.9, 28.9, 72.6, 84.0, 127.1, 131.2, 141.8, 166.7. IR (ATR): 2974 m, 2931 m, 1708 s, 1560 w, 1445 w, 1370 m, 1335 s, 1295 s, 1207 s, 1147 m, 1107 s, 1061 m, 1026 m, 997 m, 963 w, 943 w, 895 w, 882 w, 854 m, 807 w, 769 m, 732 w, 698 w, 679 m. MS m/z (% relative intensity): 332 (M⁺, 28), 317 (12), 276 (48), 275 (90), 274 (31), 260 (21), 259 (100), 258 (24), 233 (44), 232 (21), 219 (97), 218 (54), 201 (93), 200 (23), 177 (51), 176 (32), 159 (26), 131 (23), 105 (22), 101 (33), 83 (33), 57 (21), 56 (34). HRMS (EI): Calcd for C₁₉H₂₉BO₄ 332.2159, Found 332.2161.

(1*R*,2*S*,5*R*)-2-Isopropyl-5-methylcyclohexyl dioxaborolan-2-yl)benzoate (3v, Figure 5).

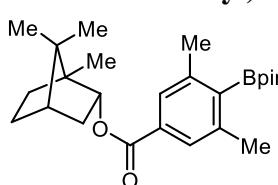


Method D was followed except that the reaction was conducted with (1*R*,2*S*,5*R*)-2-isopropyl-5-methylcyclohexyl 3,5-dimethylbenzoate (86 mg, 0.30 mmol) as a substrate. The unreacted starting material was recovered (25 mg, 29%).

R_f 0.60 (hexane/EtOAc = 5/1). White solid (63 mg, 51%). Mp = 88-89 °C.

¹H NMR (CDCl₃, 399.78 MHz): δ 0.78 (d, *J* = 6.9 Hz, 3H), 0.88-0.96 (m, 1H), 0.92 (t, *J* = 6.4 Hz, 6H), 1.02-1.20 (m, 2H), 1.39 (s, 12H), 1.46-1.59 (m, 2H), 1.72 (d, *J* = 11.4 Hz, 2H), 1.93 (quintet, *J* = 6.9, 2.8 Hz, 1H), 2.10 (d, *J* = 11.9 Hz, 1H), 2.43 (s, 6H), 4.92 (td, *J* = 10.9, 4.3 Hz, 1H), 7.60 (s, 2H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 16.5, 20.8, 22.1, 23.6, 24.9, 26.4, 31.4, 34.3, 41.0, 47.2, 74.6, 84.0, 127.1, 131.2, 141.9, 166.5. IR (ATR): 2959 w, 2866 w, 1708 s, 1443 w, 1407 w, 1370 m, 1331 m, 1296 s, 1210 s, 1182 w, 1141 m, 1123 s, 1062 m, 1037 w, 1010 w, 984 w, 962 m, 915 w, 851 m, 813 w, 771 m, 679 w. MS m/z (% relative intensity): 399 ([M-Me]⁺, 4), 277 (27), 276 (10), 260 (10), 259 (56), 258 (14), 219 (34), 218 (16), 177 (10), 138 (100), 133 (20), 123 (24), 96 (14), 95 (58), 83 (21), 82 (16), 81 (33), 55 (12). HRMS (EI): Calcd for C₂₅H₃₉BO₄ 414.2941, Found 414.2940.

(1*S*,2*R*,4*S*)-1,7,7-Trimethylbicyclo[2.2.1]heptan-2-yl 3,5-dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (3w, Figure 5).



Method D was followed except that the reaction was conducted with (1*S*,2*R*,4*S*)-1,7,7-trimethylbicyclo[2.2.1]heptan-2-yl 3,5-dimethylbenzoate (86 mg, 0.30 mmol) as a substrate. 46 mg of unreacted starting material was recovered (54%).

R_f 0.45 (hexane/EtOAc = 5/1). White solid (43 mg, 35%). Mp = 146-147 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 0.905 (s, 3H), 0.912 (s, 3H), 0.96 (s, 3H), 1.11 (dd, *J* = 13.7, 3.2 Hz, 1H), 1.29-1.41 (m, 2H), 1.39 (s, 12H), 1.73 (t, *J* = 4.3 Hz, 1H), 1.74-1.86 (m, 1H), 2.05-2.22 (m, 1H), 2.40-2.51 (m, 1H), 2.44

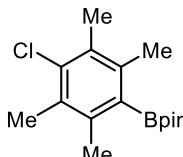
(s, 6H), 5.09 (d, $J = 10.1$ Hz, 1H), 7.61 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 13.6, 18.9, 19.7, 22.1, 24.9, 27.4, 28.1, 36.8, 45.0, 47.9, 49.1, 80.3, 84.0, 127.1, 131.2, 141.9, 167.2. IR (ATR): 2958 w, 1708 s, 1440 w, 1374 w, 1340 w, 1304 s, 1213 s, 1144 m, 1122 s, 1064 m, 1024 m, 963 w, 857 m, 768 m, 673 w. MS m/z (% relative intensity): 412 (M+, 6), 260 (16), 259 (100), 258 (25), 136 (11), 83 (6). HRMS (EI): Calcd for $\text{C}_{25}\text{H}_{37}\text{BO}_4$ 412.2785, Found 412.2789.

To improve the conversion, the reaction was repeated twice as described below:

Pt(SIPr)(dvtms) (6.9 mg, 9.0 μmol), B_2pin_2 (91 mg, 0.36 mmol), **2w** (95 mg, 0.33 mmol) and TIPB (0.10 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 120 $^{\circ}\text{C}$ for 16 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and again filtered through a pad of silica gel (eluting with 7 mL of hexane/ EtOAc = 10/1) to give colorless filtrate. The filtrate was concentrated in vacuo and transferred to another vial for 2nd borylation. To the reaction mixture, Pt(SIPr)(dvtms) (6.9 mg, 9.0 μmol), B_2pin_2 (91 mg, 0.36 mmol) and TIPB (0.10 mL) were added, and the mixture was stirred at 120 $^{\circ}\text{C}$ for 16 h. The resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ EtOAc = 100/1 to 50/1) to give the target borylated product as a white solid (93 mg, 68%). The unreacted starting material was recovered (22 mg, 23%).

2-(4-Chloro-2,3,5,6-tetramethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3x, Figure 5).

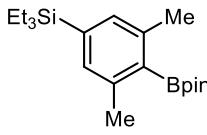
Method D was followed except that the reaction was conducted with 3-chloro-1,2,4,5-tetramethylbenzene (51mg, 0.30 mmol) as a substrate. 31% of the starting material remained unreacted based on ^1H -NMR analysis.



Rf 0.74 (hexane/EtOAc = 5/1). White solid (39 mg, 45%). Mp = 130-131 $^{\circ}\text{C}$. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.40 (s, 12H), 2.289 (s, 6H), 2.292 (s, 6H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 17.1, 20.5, 25.2, 84.0, 131.5, 136.5, 137.7. IR (ATR): 2977 m, 1555 w, 1453 w, 1408 m, 1372 m, 1337 s, 1296 s, 1256 m, 1185 m, 1140 s, 1020 s, 963 m, 853 s, 684 m. MS m/z (% relative intensity): 296 (19), 295 (15), 294 (M+, 57), 293 (14), 239 (33), 238 (24), 237 (100), 236 (34), 196 (29), 195 (45), 194 (83), 193 (24), 175 (39), 159 (27), 101 (19), 83 (15). HRMS (EI): Calcd for $\text{C}_{16}\text{H}_{24}\text{BClO}_2$ 294.1558, Found 294.1560.

(3,5-Dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)triethylsilane (3y, Figure 5).

Method D was followed except that the reaction was conducted with (3,5-dimethylphenyl)triethylsilane (66 mg, 0.30 mmol) as a substrate. The unreacted starting material was recovered (46 mg, 69%).



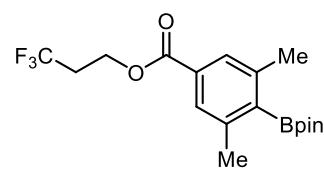
Rf 0.63 (hexane/EtOAc = 5/1). White solid (27 mg, 26%). Mp = 81-82 $^{\circ}\text{C}$. ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.74 (q, $J = 7.9$ Hz, 6H), 0.93 (t, $J = 7.8$ Hz, 9H), 1.38 (s, 12H), 2.39 (s, 6H), 7.05 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 3.23, 7.38, 22.3, 25.0, 83.6, 132.2, 138.4, 140.6. IR (ATR): 2955

m, 2875 w, 1435 m, 1369 s, 1333 s, 1305 s, 1259 w, 1213 w, 1142 s, 1109 w, 1058 s, 1014 m, 962 w, 884 m, 857 m, 790 w, 719 s, 700 m, 677 w. MS m/z (% relative intensity): 346 (M+, 10), 318 (23), 317 (90), 316 (22), 290 (20), 289 (87), 288 (21), 262 (21), 261 (100), 260 (24), 189 (12), 161 (17). HRMS (EI): Calcd for $C_{20}H_{35}BO_2Si$ 346.2499, Found 346.2499.

To improve the conversion, the reaction was repeated twice as described below:

Pt(SIPr)(dvtms) (6.9 mg, 9.0 μ mol), B_2pin_2 (91 mg, 0.36 mmol), (3,5-dimethylphenyl)triethylsilane (86 mg, 0.30 mmol) and octane (0.10 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 120 °C for 20 h and the resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/EtOAc = 5/1). The filtrate was concentrated in vacuo and again filtered through a pad of silica gel (eluting with 7 mL of hexane/EtOAc = 10/1) to give colorless filtrate. The filtrate was concentrated in vacuo and transferred to another vial for 2nd borylation. To the reaction mixture, Pt(SIPr)(dvtms) (6.9 mg, 9.0 μ mol), B_2pin_2 (91 mg, 0.36 mmol) and octane (0.10 mL) were added, and the mixture was stirred at 120 °C for 20 h. The resulting mixture was filtered through silica gel (eluting with 7 mL of hexane/EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/EtOAc = 100/1 to 50/1) to give the target borylated product as a white solid (56 mg, 54%). The unreacted starting material was recovered (24 mg, 36%).

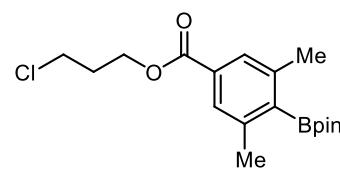
3,3,3-Trifluoropropyl 3,5-dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (3z, Figure 5).



Method D was followed except that the reaction was conducted with 3,3,3-trifluoropropyl 3,5-dimethylbenzoate (70 mg, 0.28 mmol) as a substrate. The unreacted starting material was recovered (27 mg, 39%).

Rf 0.51 (hexane/EtOAc = 5/1). Colorless oil (56 mg, 53%). ¹H NMR ($CDCl_3$, 399.78 MHz): δ 1.40 (s, 12H), 2.43 (s, 6H), 2.59 (qt, J = 10.5, 6.4 Hz, 2H), 4.51 (t, J = 6.4 Hz, 2H), 7.60 (s, 2H). ¹³C NMR ($CDCl_3$, 100.53 MHz): δ 22.1, 25.0, 33.5 (q, J = 30 Hz), 57.6 (q, J = 3.8 Hz), 84.2, 125.9 (q, J = 278 Hz), 127.31, 129.9, 142.0, 166.6. IR (ATR): 2978 w, 1722 m, 1436 w, 1373 m, 1339 m, 1300 s, 1256 m, 1206 s, 1123 s, 1060 m, 1009 w, 962 w, 898 w, 855 m, 813 w, 768 w, 668 w. MS m/z (% relative intensity): 372 (M+, 21), 316 (15), 315 (100), 314 (46), 273 (54), 272 (38), 201 (42), 159 (26), 131 (15), 101 (17), 83 (16). HRMS (EI): Calcd for $C_{18}H_{24}BF_3O_4$ 372.1720, Found 372.1722.

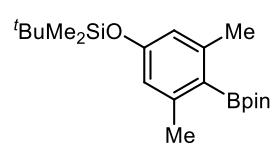
3-Chloropropyl 3,5-dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (3aa, Figure 5).



Method D was followed except that the reaction was conducted with 3-chloropropyl 3,5-dimethylbenzoate (65 mg, 0.29 mmol) as a substrate. The starting material was recovered (41 mg, 62%).

Rf 0.49 (hexane/EtOAc = 5/1). Colorless oil (39 mg, 55%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.40 (s, 12H), 2.23 (quintet, J = 6.4 Hz, 2H), 2.43 (s, 6H), 3.70 (t, J = 6.4 Hz, 2H), 4.45 (t, J = 6.0 Hz, 2H), 7.59 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 22.1, 25.0, 31.8, 41.4, 61.5, 84.1, 127.1, 130.3, 142.0, 166.8. IR (ATR): 2976 w, 1718 m, 1439 w, 1371 w, 1337 m, 1298 s, 1207 s, 1143 m, 1123 s, 1063 m, 1024 w, 961 w, 897 w, 855 m, 809 w, 768 m, 663 w. MS m/z (% relative intensity): 354 (8), 353 (6), 352 (M+, 21), 351 (5), 297 (32), 296 (28), 295 (100), 294 (41), 259 (23), 255 (10), 253 (32), 252 (17), 201 (53), 200 (13), 176 (40), 175 (16), 159 (15), 131 (19), 105 (15), 101 (20), 85 (12), 83 (18). HRMS (EI): Calcd for $\text{C}_{18}\text{H}_{26}\text{BClO}_4$ 352.1613, Found 352.1612.

tert-Butyl(3,5-dimethyl-4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenoxy)dimethylsilane (3ab, Figure 5).

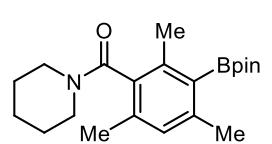


Method D was followed except that the reaction was conducted with *tert*-butyl(3,5-dimethylphenoxy)dimethylsilane (71 mg, 0.30 mmol) as a substrate. The starting material was recovered (14 mg, 20%).

Rf 0.79 (hexane/EtOAc = 5/1). White solid (59 mg, 55%). Mp = 103-104 °C.

^1H NMR (CDCl_3 , 399.78 MHz): δ 0.16 (s, 6H), 0.96 (s, 9H), 1.37 (s, 12H), 2.35 (s, 6H), 6.44 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ -4.4, 18.2, 22.4, 24.9, 25.7, 83.4, 118.6, 144.1, 156.5. IR (ATR): 2957 w, 2930 w, 2858 w, 1596 m, 1469 w, 1441 w, 1369 m, 1330 s, 1306 s, 1254 m, 1161 s, 1144 s, 1039 m, 961 w, 861 s, 844 s, 804 w, 781 m, 673 w. MS m/z (% relative intensity): 362 (M+, 32), 306 (16), 305 (48), 206 (18), 205 (100), 204 (24), 163 (17), 83 (59). HRMS (EI): Calcd for $\text{C}_{20}\text{H}_{35}\text{BO}_3\text{Si}$ 362.2449, Found 362.2447.

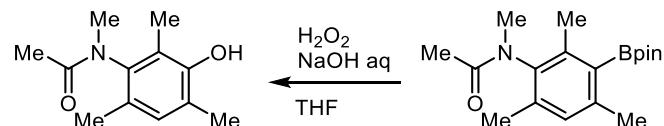
Piperidin-1-yl(2,4,6-trimethyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenyl)methanone (3ac, Figure 5).



Method D was followed except that the reaction was conducted with mesityl(piperidin-1-yl)methanone (69 mg, 0.30 mmol) as a substrate. The starting material was recovered (25 mg, 37%).

Rf 0.23 (hexane/EtOAc = 1/1). Colorless oil (45 mg, 42%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.34 (s, 12H), 1.40-1.54 (m, 2H), 1.56-1.73 (m, 4H), 2.18 (s, 3H), 2.29 (s, 3H), 2.35 (s, 3H), 3.11 (dd, J = 6.6, 4.4 Hz, 2H), 3.62-3.91 (m, 2H), 6.81 (s, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 19.1, 22.0, 24.6, 24.9, 24.9, 25.7, 26.6, 41.8, 47.0, 83.7, 128.4, 133.8, 134.5, 137.1, 141.7, 169.9. IR (ATR): 2977 w, 2934 w, 2856 w, 1627 s, 1440 s, 1394 m, 1372 m, 1329 s, 1298 s, 1268 s, 1210 m, 1141 s, 1107 m, 1026 m, 988 m, 958 w, 920 w, 856 m, 831 w, 730 m, 671 w. MS m/z (% relative intensity): 357 (M+, 18), 342 (35), 274 (17), 273 (100), 272 (61), 145 (11). HRMS (EI): Calcd for $\text{C}_{21}\text{H}_{32}\text{BNO}_3$ 357.2475, Found 357.2477.

N-(3-Hydroxy-2,4,6-trimethylphenyl)-N-methylacetamide (3ad, Figure 5).

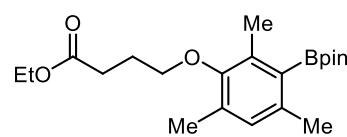


Because the target borylated product was inseparable from the starting material by chromatography, the borylated product was isolated after oxidation to the corresponding phenol.

After the borylation of N-mesityl-N-methylacetamide (57 mg, 0.3 mmol) according to Method D, the reaction mixture was treated with NaOH aq. (1 M, 0.5 mL) and H₂O₂ (30%, 0.60 g) in THF (1.0 mL) for 30 min. The mixture was then quenched with Na₂S₂O₃ aq, and the mixture was extracted with Et₂O three times. The combined organic extracts were washed with brine and dried over MgSO₄. Concentrated reaction mixture was purified by flash column chromatography (eluting with hexane/EtOAc = 5/1 to 1/1) to give the title compound as a white solid (19 mg, 30 %). 39% of the starting material remained unreacted based on ¹H NMR analysis.

Rf 0.09 (hexane/EtOAc = 5/1). White solid (19 mg, 30%). Mp = 149-150 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.73 (s, 3H), 2.11 (s, 6H), 2.25 (s, 3H), 3.11 (s, 3H), 6.90 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 10.7, 15.9, 16.9, 21.3, 34.6, 121.1, 123.1, 126.6, 130.1, 140.2, 151.1, 171.2. IR (ATR): 3285 w, 2922 w, 1632 s, 1482 m, 1442 m, 1383 m, 1307 m, 1247 m, 1220 w, 1180 m, 1129 w, 1051 m, 974 w, 941 w, 915 w, 869 w, 810 w, 743 w. MS m/z (% relative intensity): 207 (M⁺, 33), 192 (8), 164 (15), 150 (13), 91 (8), 56 (100). HRMS (EI): Calcd for C₁₂H₁₇NO₂ 207.1259, Found 207.1257.

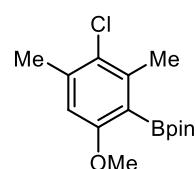
Ethyl 4-(2,4,6-trimethyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)phenoxy)butanoate (3ae, Figure 5).



Method D was followed except that the reaction was conducted with ethyl 4-(mesityloxy)butanoate (73 mg, 0.29 mmol) as a substrate. The unreacted starting material was recovered (32 mg, 45%).

Rf 0.45 (hexane/EtOAc = 5/1). Colorless oil (42 mg, 39%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.26 (t, *J* = 7.1 Hz, 3H), 1.38 (s, 12H), 2.09 (quintet, *J* = 6.9 Hz, 2H), 2.19 (s, 3H), 2.29 (s, 3H), 2.30 (s, 3H), 2.57 (t, *J* = 7.3 Hz, 2H), 3.69 (t, *J* = 6.2 Hz, 2H), 4.15 (q, *J* = 7.2 Hz, 2H), 6.77 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 14.2, 15.6, 16.2, 21.7, 25.0, 25.7, 31.0, 60.4, 70.7, 83.6, 130.0, 131.7, 134.2, 137.0, 153.2, 173.4. IR (ATR): 2977 w, 2930 w, 1734 s, 1441 w, 1409 m, 1372 m, 1327 s, 1296 s, 1272 m, 1226 m, 1167 s, 1142 s, 1107 w, 1024 s, 959 w, 922 w, 858 m, 698 w, 672 w. MS m/z (% relative intensity): 376 (M⁺, 1), 331 (6), 116 (7), 115 (100), 87 (57). HRMS (EI): Calcd for C₂₁H₃₃BO₅ 376.2421, Found 376.2419.

2-(3-Chloro-6-methoxy-2,4-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (3af, Figure 5).

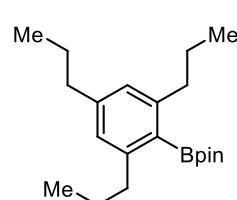


Method D was followed except that the reaction was conducted with 2-chloro-5-methoxy-1,3-dimethylbenzene (51 mg, 0.30 mmol) as a substrate. The starting material was recovered (35 mg, 69%).

Rf 0.51 (hexane/EtOAc = 5/1). White solid (26 mg, 29%). Mp = 102-103 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.38 (s, 12H), 2.35 (s, 3H), 2.36 (s, 3H), 3.73 (s, 3H), 6.55 (s, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 20.4, 21.5, 24.74, 55.8, 83.9, 110.4, 126.7, 138.1, 139.8, 160.5. IR (ATR): 2979 w, 1597 w, 1454 w, 1373 m, 1326 s, 1303 s, 1272 w, 1205 m, 1143 s, 1098 m, 1080 m, 1007 w, 982 w, 960 w, 855 m, 832 m, 674 w. MS m/z (% relative intensity): 298 (34), 297 (23), 296 (M⁺, 100),

295 (23), 241 (28), 240 (19), 239 (84), 238 (32), 225 (17), 224 (17), 223 (50), 222 (14), 180 (18), 167 (21), 155 (16), 153 (28), 85 (16). HRMS (EI): Calcd for $C_{15}H_{22}BClO_3$ 296.1351, Found 296.1354.

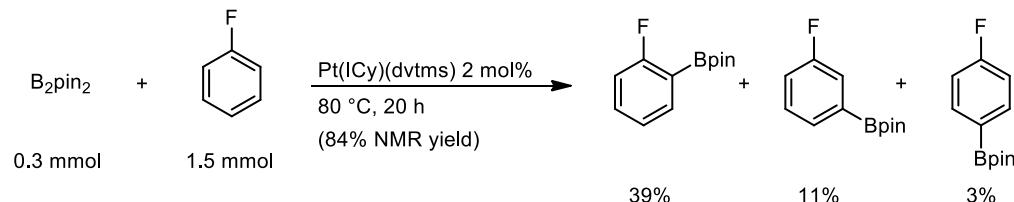
4,4,5,5-Tetramethyl-2-(2,4,6-tripropylphenyl)-1,3,2-dioxaborolane (3ag, Figure 5).



Method D was followed except that the reaction was conducted with 1,3,5-tripropylbenzene (61 mg, 0.30 mmol) as a substrate and in octane (0.10 mL) instead of TIPB. The unreacted starting material was recovered (43mg, 70%). R_f 0.63 (hexane/EtOAc = 5/1). Colorless oil (29 mg, 29%).

1H NMR ($CDCl_3$, 399.78 MHz): δ 0.89 (t, J = 7.8 Hz, 3H), 0.93 (t, J = 7.3 Hz, 6H), 1.37 (s, 12H), 1.52-1.64 (m, 6H), 2.49 (t, J = 7.8 Hz, 2H), 2.59 (t, J = 7.8 Hz, 4H), 6.77 (s, 2H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 13.8, 14.1, 24.5, 25.0, 26.0, 38.0, 38.7, 83.4, 126.3, 143.3, 146.6. IR (ATR): 2958 m, 2929 m, 2869 w, 1607 w, 1465 w, 1420 w, 1372 m, 1335 s, 1297 m, 1213 w, 1143 s, 1111 w, 1084 w, 1063 m, 962 w, 857 m, 680 w. MS m/z (% relative intensity): 331 (10), 330 (M $^+$, 46), 329 (11), 302 (15), 288 (15), 274 (19), 273 (100), 272 (30), 231 (37), 230 (30), 229 (24), 216 (20), 201 (44), 187 (22), 173 (15), 159 (14), 131 (12), 117 (14), 101 (36), 83 (27). HRMS (EI): Calcd for $C_{21}H_{35}BO_2$ 330.2730, Found 330.2732.

Borylation of fluorobenzene (6a, eq 4).



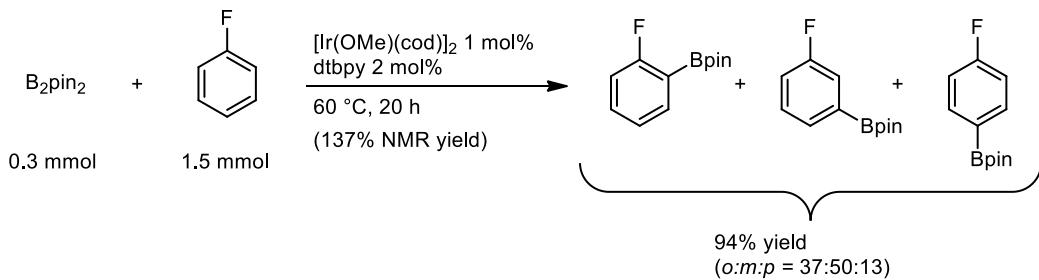
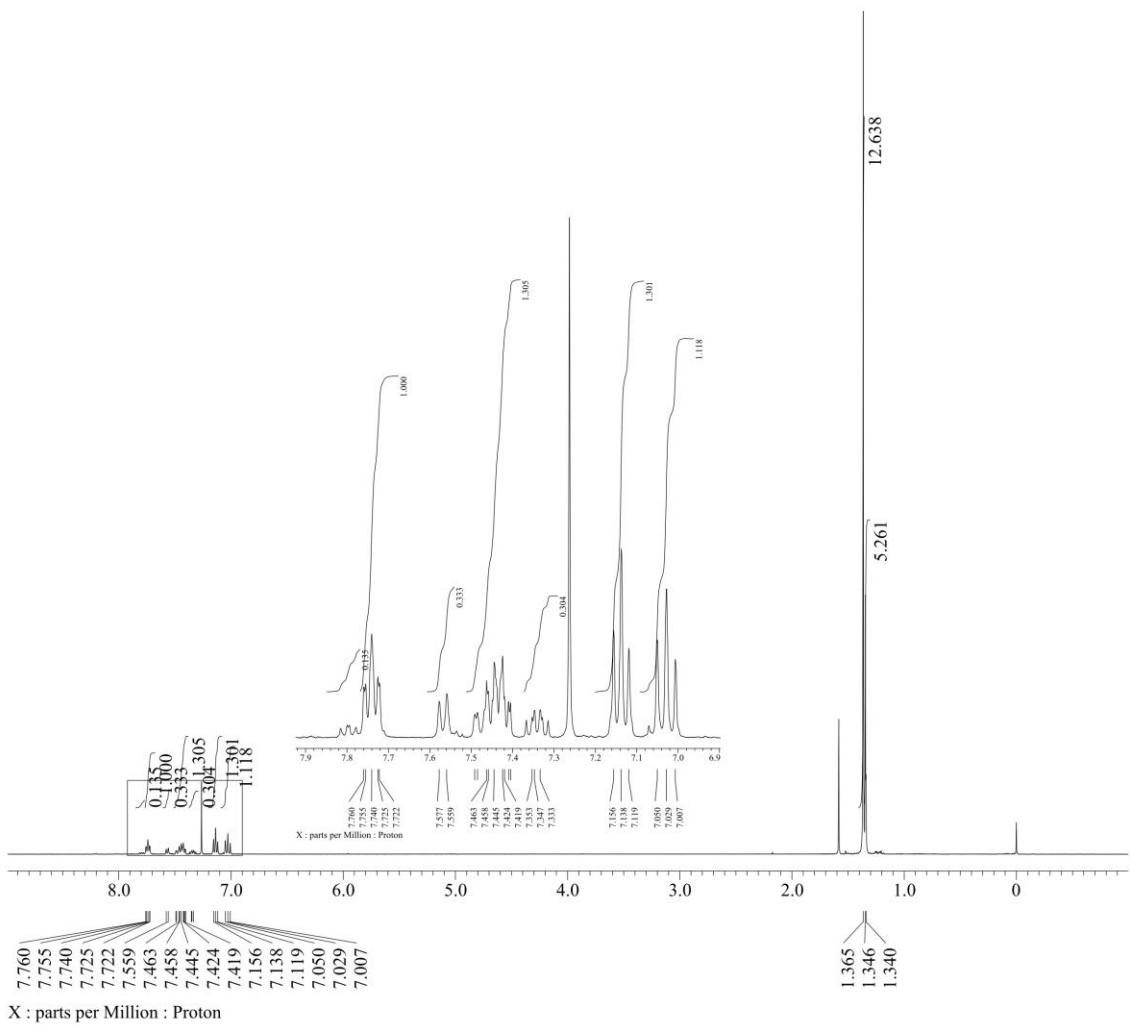
Method B was followed except that the reaction was conducted in fluorobenzene (141 μ L, 1.5 mmol). NMR analysis before the purification by column chromatography showed that the borylated products were produced in 84% ($o:m:p$ = 73:20:7).

After purification by flash column chromatography over silica gel (eluted with hexane/AcOEt = 25/1), a mixture of three isomers of the borylated products were obtained (35 mg, 53%, $o:m:p$ = 74:21:5, >99% purity by GC). GC/MS analysis revealed the formation of three isomers of the borylated product, all of which had an m/z of 222 (M^+). The identity and ratio of each of the borylated products were determined by comparing the 1H NMR spectrum of the product mixture with those reported in the literature.⁴⁹ The resonances specific to each isomer are as follows:

ortho-isomer, δ 7.03 (t, J = 8.7 Hz, 1H + 2H of *p*-isomer), 7.13 (t, J = 7.3 Hz, 1H + 1H of *m*-isomer), 7.4-7.5 (m, 1H + 1H of *m*-isomer), 7.74 (m, 1H).

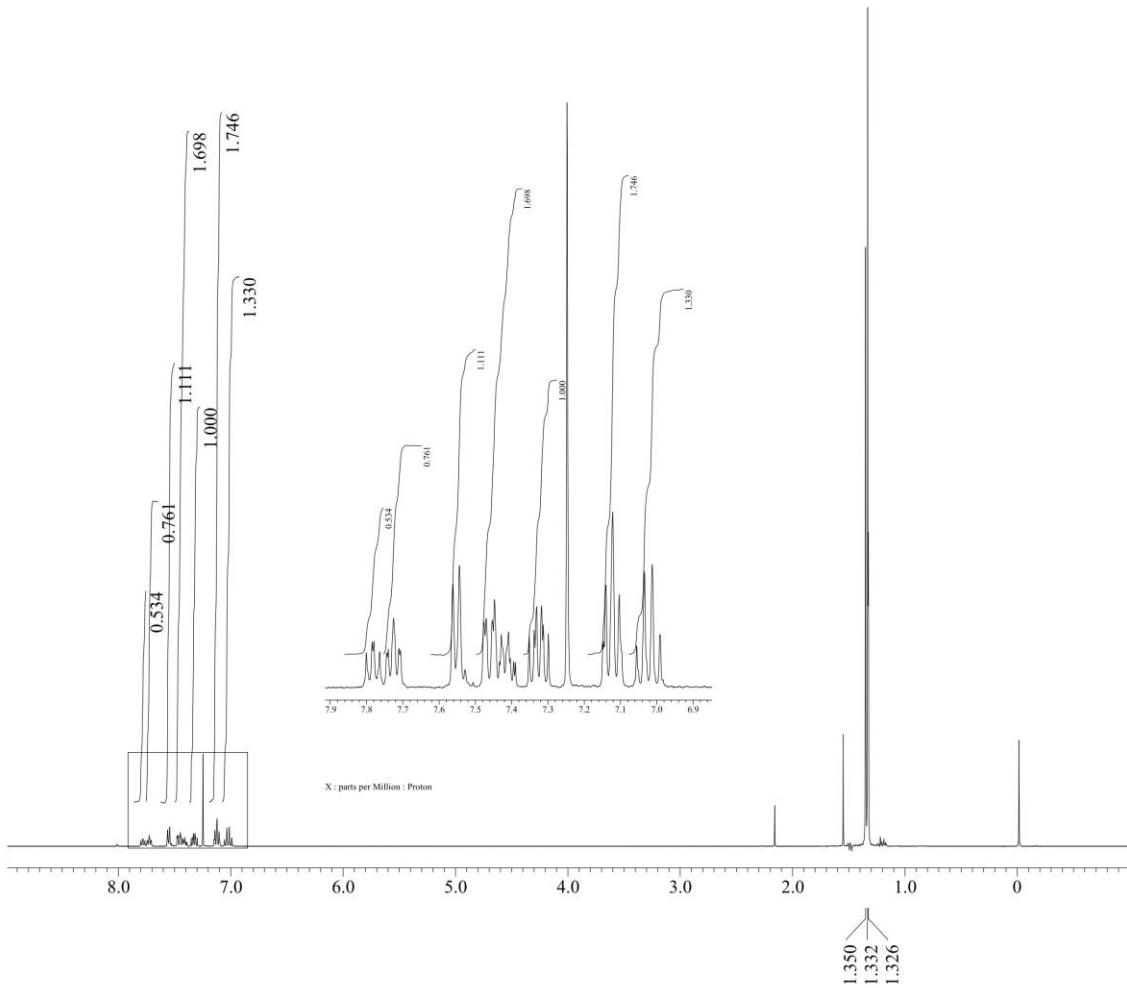
meta-isomer, δ 7.11-7.16 (m, overlapped, 1H), 7.31-7.37 (m, 1H), 7.41-7.47 (m, overlapped, 1H), 7.57 (d, J = 7.3 Hz, 1H).

para-isomer, 7.00-7.09 (m, overlapped, 1H), 7.80 (dd, J = 7.6, 2.3, 1H). (see below.)



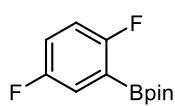
For comparison, the iridium-catalyzed borylation of fluorobenzene was investigated. $[\text{Ir}(\text{OMe})(\text{cod})]_2$ (2.0 mg, 3.0 μmol), 4,4'-di-tert-butyl-2,2'-bipyridine (1.7 mg, 6.0 μmol), B_2pin_2 (76 mg, 0.30 mmol) and fluorobenzene (141 μL , 1.5 mmol) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N_2 . The mixture was stirred at 60 $^\circ\text{C}$ for 20 h and the resulting mixture was filtered through silica gel (eluted with 7 mL of hexane/ AcOEt = 5/1). The filtrate was analyzed by NMR spectroscopy using 1,1,2,2-tetrachloroethane as an internal standard (137% NMR yield, $o:m:p$ = 41:48:11). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluted with hexane/ AcOEt = 25/1) to give a mixture

of three isomers of the borylated products (63 mg, 94% based on B_2pin_2 , $o:m:p = 37:50:13$, >99% purity by GC).



2-(2,5-Difluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6b, Figure 6) [CAS: 408492-25-1]

1j. Rf 0.57 (hexane/EtOAc = 5/1). Colorless oil (33 mg, 46%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 6.98 (td, J = 8.5 Hz, 4.1 Hz, 1H), 7.06-7.13 (m, 1H), 7.32-7.45 (quintet, J = 3.9, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 84.2, 116.5 (dd, J = 7.8, 27.8 Hz), 119.7 (dd, J = 9.6, 24.0 Hz), 122.2 (dd, J = 8.6, 22.0 Hz), 158.4 (d, J = 239 Hz), 162.9 (d, J = 245 Hz). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{15}\text{BF}_2\text{O}_2$ 240.1133. Found 240.1132.

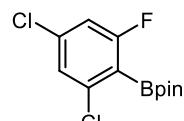


2-(2,5-Dichlorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6c, Figure 6) [CAS: 479411-91-1].

Method B was used, except that the reaction was conducted using *p*-dichlorobenzene (221 mg, 1.5 mmol) instead of 1,4-difluorobenzene (154 μ L, 1.5 mmol). NMR analysis before the purification by column chromatography showed that a 75% yield of the borylated product was formed.

Rf 0.54 (hexane/EtOAc = 5/1). White solid (38 mg, 47%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.37 (s, 12H), 7.23-7.34 (m, 2H), 7.65 (d, J = 2.3 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 84.5, 130.7, 131.7, 132.1, 136.0, 137.7. HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{15}\text{BCl}_2\text{O}_2$ 272.0542, Found 272.0536.

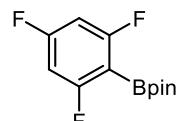
2-(2,4-Dichloro-6-fluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6d, Figure 6) [CAS: 1192002-89-3].



Method B was used, except that the reaction was conducted using 1,3-dichloro-5-fluorobenzene (247 mg, 1.5 mmol) instead of 1,4-difluorobenzene. NMR analysis before purification by column chromatography showed that a 76% yield of the borylated product was formed.

Rf 0.51 (hexane/EtOAc = 5/1). colorless oil (42 mg, 47%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.39 (s, 12H), 6.97 (dd, J = 8.2, 1.4 Hz, 1H), 7.17 (t, J = 0.9 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.7, 85.0, 114.4 (d, J = 28 Hz), 125.1 (d, J = 2.9 Hz), 136.9 (d, J = 12 Hz), 139.2 (d, J = 12 Hz), 165.3 (d, J = 251 Hz). IR (ATR): 2980 w, 1598 m, 1563 w, 1538 w, 1471 w, 1420 w, 1390 m, 1370 m, 1330 s, 1271 w, 1213 w, 1166 w, 1141 s, 1101 s, 1061 w, 1042 w, 962 w, 931 m, 850 m, 837 s, 785 w, 670 w. MS m/z (% relative intensity): 294 (1), 292 (5), 290 (M+, 9), 277 (28), 276 (11), 275 (42), 257 (28), 255 (83), 254 (22), 233 (10), 231 (14), 215 (13), 213 (38), 212 (11), 194 (12), 192 (47), 191 (21), 190 (77), 189 (24), 155 (10), 131 (10), 115 (14), 111 (17), 109 (50), 85 (100), 75 (10), 74 (12), 69 (16), 59 (65), 58 (80), 57 (40), 55 (13). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{14}\text{BCl}_2\text{FO}_2$ 290.0448, Found 290.0438.

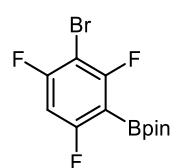
4,4,5,5-Tetramethyl-2-(2,4,6-trifluorophenyl)-1,3,2-dioxaborolane (supplementary data) [CAS: 325143-04-2].



Method B was used, except that the reaction was conducted in using 1,3,5-trifluorobenzene (156 μL , 1.5 mmol) instead of 1,4-difluorobenzene at 60 °C. NMR analysis before purification by column chromatography showed that a 88% yield of the borylated product was formed.

Rf 0.54 (hexane/EtOAc = 5/1). White solid (35 mg, 44%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.37 (s, 12H), 6.61 (t, J = 8.5 Hz, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.7, 84.2, 100.1, (ddd, J = 33, 24, 3.3 Hz), 165.0 (dd, J = 252, 16 Hz), 167.3 (dt, J = 252 Hz, 15 Hz). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{14}\text{BF}_3\text{O}_2$ 258.1039, Found 258.1038.

2-(3-Bromo-2,4,6-trifluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6e, Figure 6).

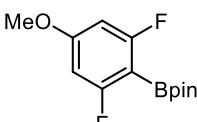


Method B was used, except that the reaction was conducted using in 2-bromo-1,3,5-trifluorobenzene (176 μL , 1.5 mmol) instead of 1,4-difluorobenzene at 60 °C. NMR analysis before purification by column chromatography showed that a 74% yield of the borylated product was formed.

Rf 0.49 (hexane/EtOAc = 5/1). Colorless oil (53 mg, 53%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.38 (s, 12H), 6.73 (td, J = 8.6 Hz, 2.0 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 84.6, 93.6 (ddd, J = 38 Hz, 22 Hz, 7.2 Hz), 101.1 (ddd, J = 33 Hz, 26 Hz, 4.3 Hz), 161.9 (ddd, J = 253 Hz, 15 Hz, 6.7 Hz), 163.7 (ddd, J = 253 Hz, 16 Hz, 7.3 Hz), 165.9 (dt, J = 252 Hz, 15 Hz). IR (ATR): 2981 w, 1610 m,

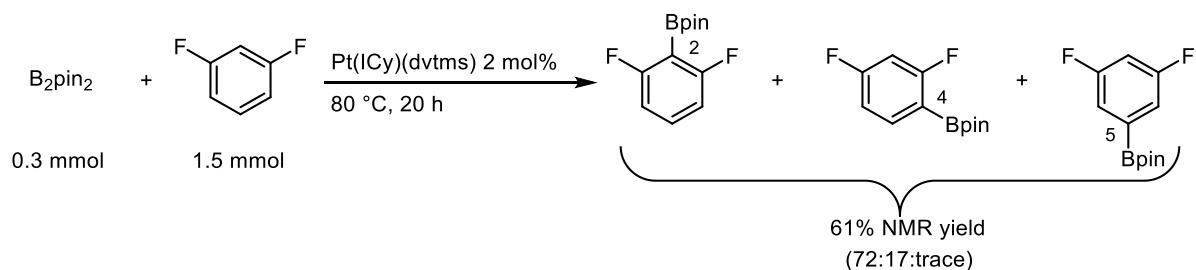
1582 w, 1468 w, 1419 m, 1371 w, 1331 s, 1272 m, 1213 w, 1140 s, 1101 m, 1040 s, 962 w, 854 m, 836 m, 781 w, 743 w, 694 w, 673 w, 620 w. MS m/z (% relative intensity): 338 (M+2, 10), 336 (M+, 9), 323 (36), 322 (12), 321 (37), 279 (33), 278 (12), 277 (35), 276 (24), 274 (16), 239 (13), 236 (16), 234 (15), 232 (16), 85 (79), 69 (18), 59 (78), 58 (100), 57 (47). HRMS (EI): Calcd for $C_{12}H_{13}BBrF_3O_2$ 336.0144, Found 336.0145.

2-(2,6-Difluoro-4-methoxyphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6f, Figure 6) [CAS: 1111096-19-5].

 Method B was used, except that the reaction was conducted using 1,3-difluoro-5-methoxybenzene (176 μ L, 1.5 mmol) instead of 1,4-difluorobenzene at 60 $^{\circ}$ C. NMR analysis before purification by column chromatography showed that a 76% yield of the borylated products were formed. GC-MS analysis showed that a small amount of 4-borylated isomer ($m/z = 270$) was also produced (GC area ratio 2:4 = 97:3).

Rf 0.43 (hexane/EtOAc = 5/1). Colorless oil (42 mg, 51%). 1H NMR ($CDCl_3$, 399.78 MHz): δ 1.36 (s, 12H), 3.80 (s, 3H), 6.36-6.46 (m, 2H). ^{13}C NMR ($CDCl_3$, 100.53 MHz): δ 24.7, 55.7, 83.7, 97.7 (d, $J = 32$ Hz), 163.9 (t, $J = 14$ Hz), 168.0 (dd, $J = 250$ Hz, 16 Hz). IR (ATR): 2978 w, 1629 m, 1572 m, 1461 w, 1431 m, 1377 m, 1349 m, 1333 s, 1272 m, 1198 m, 1138 s, 1090 m, 1033 m, 1020 m, 962 w, 856 m, 835 m, 738 w, 669 m, 613 w. MS m/z (% relative intensity): 270 (M+, 60), 269 (16), 255 (70), 254 (18), 212 (21), 211 (57), 210 (31), 197 (26), 185 (43), 181 (18), 171 (66), 170 (100), 169 (24), 156 (35), 141 (19), 140 (24), 105 (33), 85 (79), 77 (18), 75 (25), 69 (28), 59 (40), 58 (31), 57 (33). HRMS (EI): Calcd for $C_{13}H_{17}BF_2O_3$ 270.1239, Found 270.1237.

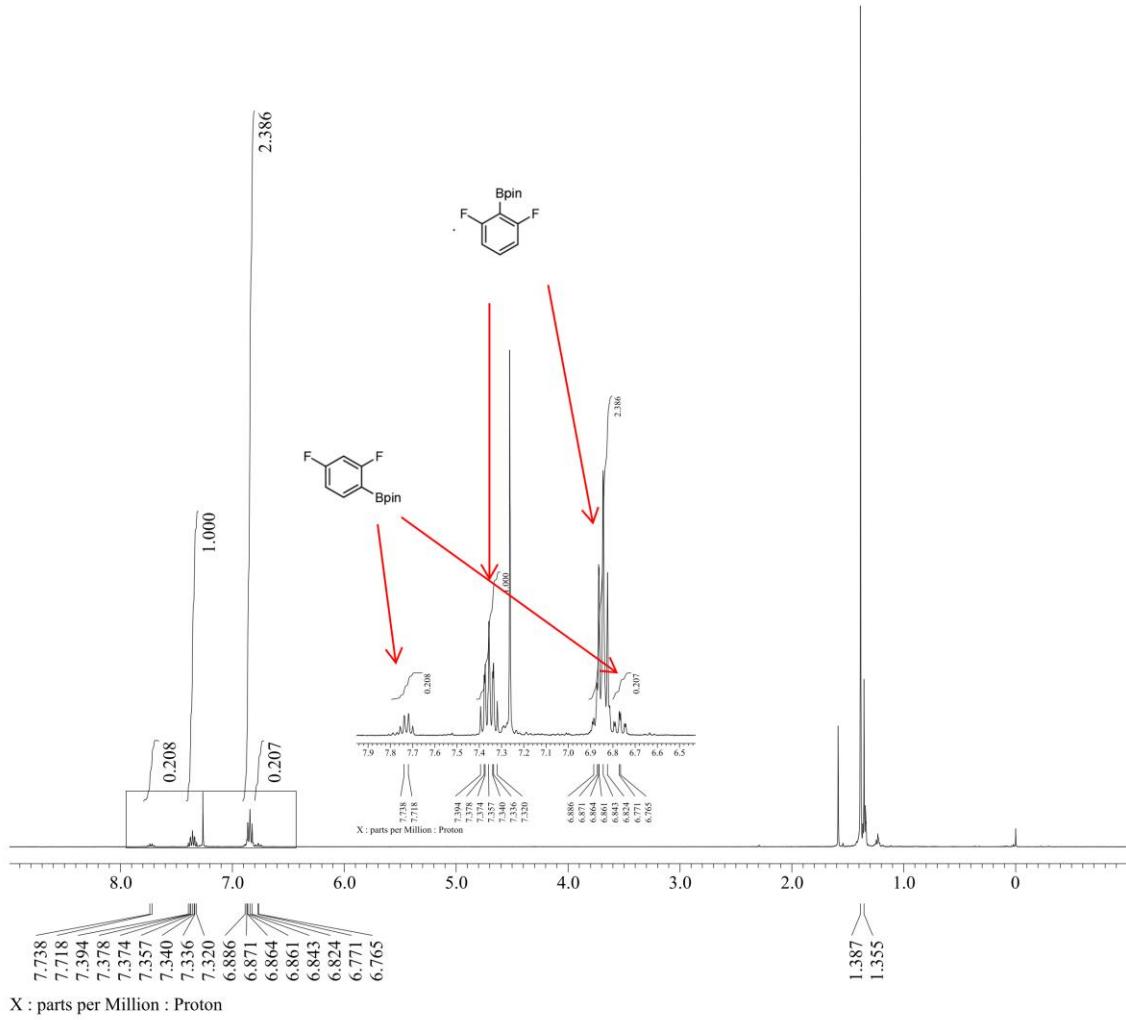
Borylation of *m*-difluorobenzene (6g, Figure 6).



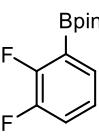
Method B was used, except that the reaction was conducted using *m*-difluorobenzene (118 μ L, 1.5 mmol) instead of 1,4-difluorobenzene at 60 $^{\circ}$ C. NMR analysis before purification by column chromatography showed that a 61% yield (2:4:5 = 72:17:trace) of the borylated products was formed. After purification by flash column chromatography over silica gel (eluting with hexane/AcOEt = 25/1), a mixture of two isomers of the borylated products was obtained (24 mg, 34%, 2:4 = 83:17, >99% purity by GC). GC/MS analysis revealed the formation of three isomers of the borylated products, all of which had an m/z of 240 (M^+). The identity and ratio of each of the borylated products was determined by comparing the 1H NMR spectrum of the product mixture with those reported in the literature.⁵⁰ The resonances specific to each isomer are as follows:

2-borylated isomer, δ 6.84 (t, $J = 7.8$ Hz, 2H), 7.35 (m, 1H).

4-borylated isomer, δ 6.84, (td, $J = 9.2$ Hz, 2.3 Hz, 1H), 7.73 (q, $J = 7.6$ Hz, 1H).

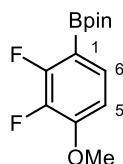


2-(2,3-Difluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6h, Figure 6) [CAS: 1073339-17-9].


 Method B was used, except that the reaction was conducted at 60 °C using 1,2-difluorobenzene (133 µL, 1.5 mmol) instead of 1,4-difluorobenzene. NMR analysis before purification by column chromatography showed that a 70% yield of the borylated product was formed. A trace amount of 4-borylated product was observed by GCMS (GC area ratio 3-isomer:4-isomer = 99:1)

Rf 0.51 (hexane/EtOAc = 5/1). Colorless oil (30 mg, 42%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.37 (s, 12H), 7.04-7.10 (m, 1H), 7.19-7.28 (m, 1H), 7.44-7.49 (m, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 84.3, 120.2 (d, J = 17 Hz), 124.0 (dd, J = 4.7 Hz, 5.7 Hz), 131.1 (dd, J = 6.7 Hz, 3.8 Hz), 150.5 (dd, J = 249 Hz, 15 Hz), 154.6 (dd, J = 252 Hz, 12 Hz). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{15}\text{BF}_2\text{O}_2$ 240.1133, Found 240.1141.

2-(2,3-Difluoro-4-methoxyphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6i, Figure 6).

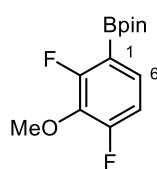


Method B was used, except that the reaction was conducted at 80 °C using 1,2-difluoro-3-methoxybenzene (216 mg, 1.5 mmol) instead of 1,4-difluorobenzene. NMR analysis before purification by column chromatography showed that a 74% yield of the borylated product was formed. GC analysis of the crude reaction mixture revealed that three isomers were formed in a ratio of 93/6/1 (The identity of the minor isomers was confirmed by GCMS). Spectroscopic data of the major isomer is shown below.

Rf 0.26 (hexane/EtOAc = 10/1). Colorless oil (25 mg, 31%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.35 (s, 12H), 3.92 (s, 3H), 6.73 (ddd, J = 8.2, 6.9, 1.4 Hz, 1H), 7.41 (ddd, J = 8.2, 6.0, 2.3 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 56.7, 84.0, 108.2 (d, J = 2.9 Hz), 130.7 (dd, J = 9.1, 5.3 Hz), 141.0 (dd, J = 248, 16 Hz), 151.9, 155.6 (dd, J = 252 9.6 Hz). IR (ATR): 2979 w, 2938 w, 1628 m, 1466 m, 1358 s, 1328 w, 1292 m, 1218 m, 1144 m, 1092 s, 972 m, 911 m. MS m/z (% relative intensity): 270 (M+, 54), 255 (39), 185 (50), 171 (43), 170 (100), 156 (34), 85 (56), 75 (37), 59 (37).

HRMS (EI): Calcd for $\text{C}_{13}\text{H}_{17}\text{BF}_2\text{O}_3$ 270.1239, Found 270.1242. The structure of the major isomer was unambiguously determined by NOE experiments, in which the following correlations were observed.

2-(2,4-Difluoro-3-methoxyphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6j, Figure 6).

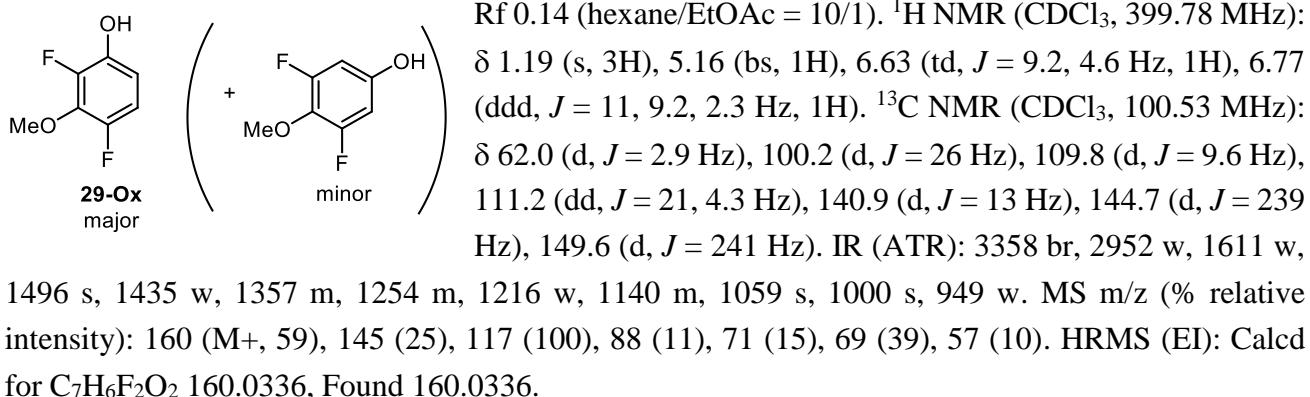


Method B was used, except that the reaction was conducted at 80 °C using 1,3-difluoro-2-methoxybenzene (216 mg, 1.5 mmol) instead of 1,4-difluorobenzene. NMR analysis before purification by column chromatography showed that an 86% yield of the borylated product was formed. GC analysis of the crude reaction mixture revealed that two isomers were formed in a ratio of 92/8. Because of the unstable nature of the title compound, it was unable to isolate **29** in pure form by column chromatography [Rf 0.29 (hexane/EtOAc = 10/1)]. The identity of **29** was unambiguously confirmed by the following spectroscopic data:

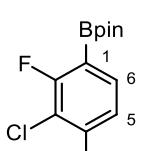
^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 3.97 (s, 3H), 6.88 (ddd, J = 10, 8.7, 1.4 Hz, 1H), 7.41 (dt, J = 8.3, 6.4 Hz, 1H).

HRMS (EI): Calcd for $\text{C}_{13}\text{H}_{17}\text{BF}_2\text{O}_3$ 270.1239, Found 270.1241.

Isolated yield was determined by directly converting the crude mixture to the corresponding phenol derivative after oxidative work-up. Thus, an aqueous solution of NaOH (1.0 M, 0.30 mL) and an aqueous solution of H_2O_2 (30%, 0.30 mL) were added to the crude reaction mixture at 0 °C and the mixture was stirred for 30 min at ambient temperature. A small amount of KI was added to quench the residual H_2O_2 and the mixture was extracted three times with AcOEt. The combined organic extracts were concentrated in vacuo and purified by flash column chromatography over silica gel (eluted with hexane → hexane/AcOEt = 4/1) to give 2,4-difluoro-3-methoxyphenol (**29-Ox**) as a colorless oil (24 mg, 50% yield based on B_2pin_2).

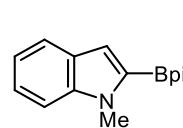


2-(3-Chloro-2,4-difluorophenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (6k, Figure 6).

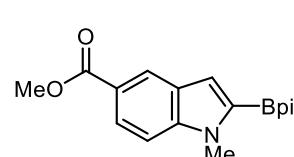

 Method B was used, except that the reaction was conducted at 60 °C using 2-chloro-1,3-difluorobenzene (223 mg, 1.5 mmol) instead of 1,4-difluorobenzene. NMR analysis before purification by column chromatography showed that a 82% yield of the borylated product was formed. GC analysis of the crude reaction mixture revealed that two isomers were formed in a ratio of 95/4 (The identity of the minor isomers was confirmed by GCMS). Spectroscopic data of the major isomer is shown below.

Rf 0.40 (hexane/EtOAc = 10/1). Colorless oil (49 mg, 60%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 6.94-6.99 (m, 1H), 7.59-7.64 (m, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 84.4, 112.0 (dd, J = 20, 3.8 Hz), 117.5 (d, J = 22 Hz), 134.9 (t, J = 9.6 Hz), 161.1 (d, J = 213 Hz), 163.6 (d, J = 207 Hz). IR (ATR): 2980 w, 2932 w, 1610 m, 1584 w, 1427 m, 1384 m, 1355 s, 1264 m, 1225 w, 1143 s, 1110 m, 1015 m, 963 m, 863 m. MS m/z (% relative intensity): 274 (M+, 20), 259 (82), 215 (63), 212 (30), 177 (31), 175 (84), 174 (36), 170 (52), 109 (34), 93 (39), 85 (92), 59 (87), 58 (100), 57 (64). HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{14}\text{BClF}_2\text{O}_2$ 274.0743, Found 274.0742.

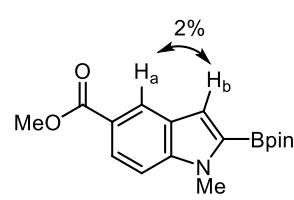
1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole (8a, Figure 7) [CAS: 596819-10-2].


 Rf 0.63 (hexane/EtOAc = 5/1). White solid (69 mg, 87%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 3.97 (s, 3H), 7.08 (td, J = 6.9 Hz, 0.9 Hz, 1H), 7.13 (d, J = 0.9 Hz, 1H), 7.25 (td, J = 8.2 Hz, 0.9 Hz, 1H), 7.34 (dd, J = 8.2 Hz, 0.9 Hz, 1H), 7.64 (dd, J = 8.2 Hz, 0.9 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 32.2, 83.7, 109.7, 114.2, 119.2, 121.5, 123.4, 127.8, 140.1. HRMS (EI): Calcd for $\text{C}_{15}\text{H}_{20}\text{BNO}_2$ 257.1587, Found 257.1584.

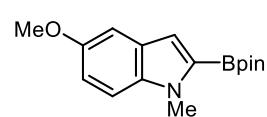
Methyl 1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-indole-5-carboxylate (8b, Figure 7).


 Method C was used, except that the reaction was conducted using methyl 1-methyl-1*H*-indole-5-carboxylate (56 mg, 0.30 mmol), 4 mol % of Pt(ICy)(dvtms) (7.2 mg, 1.2 μmol) and B_2pin_2 (92 mg, 0.36 mmol).

Rf 0.34 (hexane/EtOAc = 5/1). White solid (59 mg, 63%). Mp = 145-146 °C. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.37 (s, 12H), 3.93 (s, 3H), 3.98 (s, 3H), 7.21 (s, 1H), 7.34 (d, J = 8.7 Hz, 1H), 7.95 (dd, J = 8.7 Hz, 1.6 Hz, 1H), 8.40 (d, J = 0.9 Hz, 1H). ^1H NMR (C_6D_6 , 399.78 MHz): δ 1.09 (s, 12H), 3.51 (s, 3H), 3.61 (s, 3H), 6.95 (d, J = 8.7 Hz, 1H), 7.50 (d, J = 0.9 Hz, 1H), 8.31 (dd, J = 8.9, 1.6 Hz, 1H), 8.71 (d, J = 0.9 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 32.6, 51.9, 84.0, 109.4, 115.9, 121.5, 124.4, 124.9, 127.4, 142.4, 168.3. IR (ATR): 2977 w, 2952 w, 1709 m, 1610 w, 1533 m, 1452 m, 1438 m, 1389 m, 1371 m, 1348 m, 1305 s, 1266 m, 1248 s, 1213 s, 1194 m, 1155 m, 1137 s, 1109 m, 1086 m, 1064 m, 973 w, 963 m, 904 w, 862 w, 846 w, 830 w, 806 w, 768 w, 734 m, 705 w, 688 m, 669 m, 625 w, 607 w. MS m/z (% relative intensity): 316 (18), 315 (M+, 100), 314 (26), 284 (21), 230 (29), 215 (11), 202 (18), 184 (22), 156 (12), 77 (13). HRMS (CI): Calcd for $[\text{C}_{17}\text{H}_{22}\text{BNO}_4 + \text{H}]$ 316.1720, Found 316.1728. The regiochemistry of the compound was determined by NOE experiments in C_6D_6 . When the signal for H_a at δ = 8.71 (d, J = 0.9 Hz, 1H, offset signal δ = 8.655, mixing time 1 s) was irradiated, H_b at δ = 7.50 (d, J = 0.9 Hz, 1H) was enhanced by 2%.



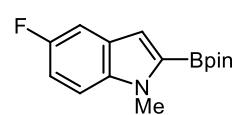
5-Methoxy-1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (8c, Figure 7) [CAS: 1256360-41-4].



Method C was used, except that the reaction was conducted with 5-methoxy-1-methyl-1H-indole (48 mg, 0.30 mmol).

Rf 0.51 (hexane/EtOAc = 5/1). White solid (67 mg, 79%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.36 (s, 12H), 3.84 (s, 3H), 3.94 (s, 3H), 6.93 (dd, J = 9.2 Hz, 2.3 Hz, 1H), 7.03 (s, 1H), 7.05 (d, J = 2.8 Hz, 1H), 7.22 (d, J = 9.2 Hz, 1H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.8, 32.3, 55.8, 83.6, 102.1, 110.4, 113.4, 114.3, 127.9, 135.8, 153.9. HRMS (CI): Calcd for $[\text{C}_{16}\text{H}_{22}\text{BNO}_3 + \text{H}]$ 288.1771, Found 288.1782.

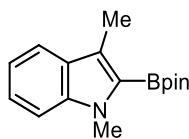
5-Fluoro-1-methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (8d, Fig. 2D) [CAS: 1683582-67-3].



Method C was used, except that the reaction was conducted with 5-fluoro-1-methyl-1H-indole (42 mg, 0.28 mmol), 4 mol% of Pt(ICy)(dvtms) (7.2 mg, 0.012 mmol) and B_2pin_2 (92 mg, 0.36 mmol).

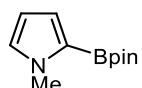
Rf 0.51 (hexane/EtOAc = 5/1). White solid (44 mg, 56%). ^1H NMR (C_6D_6 , 395.88 MHz) δ 1.09 (s, 12H), 3.56 (s, 3H), 6.78 (dd, J = 8.7 Hz, 4.1 Hz, 1H), 6.99 (td, J = 9.0 Hz, 2.4 Hz, 1H), 7.27 (dd, J = 9.6 Hz, 2.3 Hz, 1H), 7.36 (s, 1H). ^{13}C NMR (C_6D_6 , 100.53 MHz): δ 24.8, 32.1, 83.7, 106.3 (d, J = 22 Hz), 110.7 (d, J = 9.6 Hz), 112.2 (d, J = 27 Hz), 115.0 (d, J = 4.8 Hz), 128.6 (d, J = 11 Hz), 137.4, 158.4 (d, J = 233 Hz). HRMS (EI): Calcd for $\text{C}_{15}\text{H}_{19}\text{BFNO}_2$ 275.1493, Found 275.1493.

1,3-Dimethyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1H-indole (supplementary data) [CAS: 1683582-66-2].



Method C was used using 1,3-dimethyl-1*H*-indole (45 mg, 0.31 mmol). Rf 0.49 (hexane/EtOAc = 5/1). White solid (73 mg, 87%). ¹H NMR (C₆D₆, 399.78 MHz): δ 1.10 (s, 12H), 2.84 (s, 3H), 3.72 (s, 3H), 7.13 (d, *J* = 8.7 Hz, 1H), 7.19 (t, *J* = 7.6 Hz, 1H), 7.31 (dt, *J* = 8.2 Hz, 0.9 Hz, 1H), 7.73 (dd, *J* = 7.8, 0.9 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 10.6, 24.7, 31.9, 82.9, 109.7, 118.9, 120.2, 123.7, 125.5, 129.2, 140.5. HRMS (EI): Calcd for C₁₆H₂₂BNO₂ 271.1744, Found 271.1742.

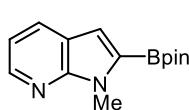
1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-1*H*-pyrrole (8e, Figure 7) [CAS: 850567-47-4].



Method C was used, except that the reaction was conducted with 1-methylpyrrole (133 μL, 1.5 mmol, 5 equiv.) and B₂pin₂ (76 mg, 0.30 mmol).

Rf 0.14 (hexane/EtOAc = 5/1). White solid (47 mg, 77% based on B₂pin₂). ¹H NMR (C₆D₆, 399.78 MHz): δ 1.01 (s, 12H), 3.51 (s, 3H), 6.30 (dd, *J* = 3.7 Hz, 2.7 Hz, 1H), 6.51-6.52 (m, 1H), 7.33 (dd, *J* = 1.3 Hz, 3.7 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 24.8, 36.2, 82.9, 109.1, 123.3, one carbon peak is overlapped with residual solvent peaks. ¹³C NMR(CDCl₃, 100.53 MHZ) δ 24.8, 36.6, 83.0, 108.3, 121.9, 128.2. HRMS (EI): Calcd for C₁₁H₁₈BNO₂ 207.1431, Found 207.1431. A trace amount of a diborylated product was detected by GC-MS analysis of the crude reaction mixture (m/z = 333).

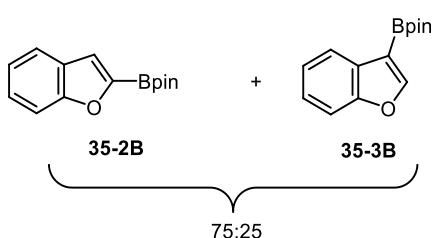
1-Methyl-2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-7-aza-1*H*-indole (8f, Figure 7) [CAS: 912331-71-6].



Method C was used, except that the reaction was conducted with 1-methyl-7-aza-1*H*-indole (39 mg, 0.29 mmol), 4 mol % of Pt(ICy)(dvtms) (7.2 mg, 0.012 mmol) and B₂pin₂ (92 mg, 0.36 mmol).

Rf 0.14 (hexane/EtOAc = 5/1). White solid (47 mg, 62%). ¹H NMR (C₆D₆, 399.78 MHz): δ 1.08 (s, 12H), 4.09 (s, 3H), 6.75 (dd, *J* = 4.6 Hz, 7.8 Hz, 1H), 7.37 (s, 1H), 7.60 (dd, *J* = 7.8 Hz, 1.8 Hz, 1H), 8.48 (dd, *J* = 4.6 Hz, 1.4 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 24.5, 30.6, 83.5, 112.7, 115.6, 120.0, 129.1, 145.1, 150.9. HRMS (EI): Calcd for C₁₄H₁₉BN₂O₂ 258.1540, Found 258.1537.

2-(Benzofuran-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (8g, Figure 7) [CAS: 402503-13-3].



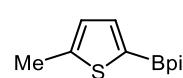
Method C was used, except that the reaction was conducted with benzofuran (35 mg, 0.30 mmol), 4 mol% of Pt(ICy)(dvtms) (7.2 mg, 0.012 mmol) and B₂pin₂ (91 mg, 0.36 mmol).

The product was obtained as a mixture of 2- and 3- borylated isomers (**35-2B**: **35-3B** = 75:25). The ratio of the isomers was determined by comparing the ¹H NMR spectrum of the product mixture with those reported in the literature.⁵¹

Rf 0.51 (hexane/EtOAc = 5/1). White solid (34 mg, 47%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.37 (s, 12H of **35-3B**), 1.39 (s, 12H of **35-2B**), 7.23 (t, *J* = 7.3 Hz, 1H of **35-2B**), 7.25-7.30 (m, 2H of **35-3B**), 7.34 (td, *J* = 7.8, 0.9 Hz, 1H of **35-2B**), 7.40 (s, 1H of **35-2B**), 7.50 (dd, *J* = 8.2, 1.8 Hz, 1H of **35-2B**), 7.57 (d, *J* = 8.2 Hz, 1H of **35-2B**), 7.63 (d, *J* = 7.3 Hz, 1H of **35-3B**), 7.91-7.93 (m, 1H of **35-3B**), 7.95 (s, 1H of **35-3B**). ¹³C NMR (CDCl₃, 100.53 MHz): δ 24.8 (**35-2B**), 24.9 (**35-3B**), 83.5 (**35-3B**), 84.7 (**35-2B**), 111.0 (**35-3B**), 112.0 (**35-2B**), 119.5 (**35-2B**), 121.9 (**35-2B**), 122.7 (**35-2B**), 122.87 (**35-3B**), 122.94 (**35-3B**), 124.2 (**35-3B**), 125.9 (**35-2B**), 127.5 (**35-2B**), 153.7 (**35-3B**), 157.5 (**35-2B**). HRMS (EI): Calcd for C₁₄H₁₇BO₃ 244.1271, Found 244.1276.

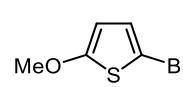
4,4,5,5-Tetramethyl-2-(5-methylthiophen-2-yl)-1,3,2-dioxaborolane (8h, Figure 7) [CAS: 476004-80-5].

Method A was used, except that the reaction was conducted in 2-methylthiophene (1 mL).

 Rf 0.49 (hexane/EtOAc = 5/1). Colorless oil (47 mg, 70%). ¹H NMR (C₆D₆, 399.78 MHz): δ 1.08 (s, 12H), 2.09 (s, 3H), 6.61 (dd, *J* = 0.9 Hz, 3.3 Hz, 1H), 7.77 (d, *J* = 3.2 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 14.8, 24.5, 83.5, 127.1, 138.0, 147.5. HRMS (EI): Calcd for C₁₁H₁₇BO₂S 224.1042, Found 224.1045.

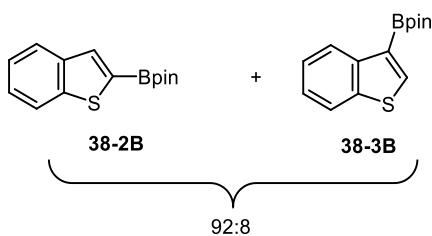
2-(5-Methoxythiophen-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (8i, Figure 7) [CAS: 596819-12-4].

Method A was used, except that the reaction was conducted in 2-methoxythiophene (1 mL).

 Rf 0.49 (hexane/EtOAc = 5/1). colorless oil (45 mg, 64%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.32 (s, 12H), 3.92 (s, 3H), 6.30 (d, *J* = 4.1 Hz, 1H), 7.33 (d, *J* = 3.7 Hz, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 24.7, 60.3, 83.8, 106.1, 136.5, 172.8. IR (ATR): 2977 w, 2933 w, 1546 w, 1479 s, 1422 s, 1389 m, 1362 s, 1333 m, 1298 m, 1271 w, 1239 m, 1208 m, 1140 s, 1111 w, 1060 s, 987 m, 955 w, 853 m, 830 w, 778 m, 724 w, 682 w, 660 s, 574 m. MS m/z (% relative intensity): 241 (15), 240 (M+, 100), 239 (31), 225 (20), 197 (34), 181 (16), 180 (75), 179 (20), 167 (19), 155 (41), 141 (63), 140 (95), 139 (35), 125 (32), 124 (15), 115 (15), 98 (16), 97 (28), 85 (20), 83 (52), 59 (25), 57 (18), 55 (31). HRMS (EI): Calcd for C₁₁H₁₇BO₃S 240.0991, Found 240.0998.

The regiochemistry of the compound was determined by NOE experiments in CDCl₃. When the signal for H_a at δ = 7.33 (d, *J* = 3.7 Hz, 1H, offset signal δ = 7.3093, mixing time 1 s) was irradiated, H_b at δ = 6.30 (d, *J* = 4.1 Hz, 1H) was enhanced by 2%. When the signal for H_b at δ = 6.30 (d, *J* = 4.1 Hz, 1H, offset signal δ = 6.2818, mixing time 1 s) was irradiated, H_c δ = 3.92 (s, 3H) was enhanced by 1%.

2-(Benzo[b]thiophen-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (8j, Figure 7) [CAS: 376584-76-8].

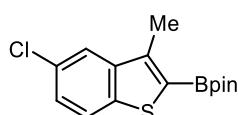


Method C was used, except that the reaction was conducted with benzo[b]thiophene (40 mg, 0.30 mmol), 4 mol% of Pt(ICy)(dvtms) (7.2 mg, 0.012 mmol) and B₂pin₂ (91 mg, 0.36 mmol).

The product was obtained as a mixture of 2- and 3-borylated isomers (**38-2B**: **38-3B** = 92:8). The ratio of the isomers was determined by comparing the ¹H NMR spectrum of the product mixture with those reported in the literature.⁵²

R_f 0.49 (hexane/EtOAc = 5/1). white solid (34 mg, 44%). ¹H NMR (CDCl₃, 399.78 MHz): δ 1.38 (s, 12H of **38-2B**, 12H of **38-3B**), 7.33-7.39 (m, 2H of **38-2B**, 2H of **38-3B**), 7.84-7.92 (m, 3H of **38-2B**, 1H of **38-3B**), 8.07 (s, 1H of **38-3B**), 8.37 (d, *J* = 7.8 Hz, 1H of **38-3B**). ¹³C NMR (CDCl₃, 100.53 MHz): **38-2B**; δ 24.8, 84.4, 122.5, 124.1, 124.4, 125.3, 134.5, 140.4, 143.7. HRMS (EI): Calcd for C₁₄H₁₇BO₂S 260.1042, Found 260.1042.

2-(5-Chloro-3-methylbenzo[b]thiophen-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (8k, Figure 7).

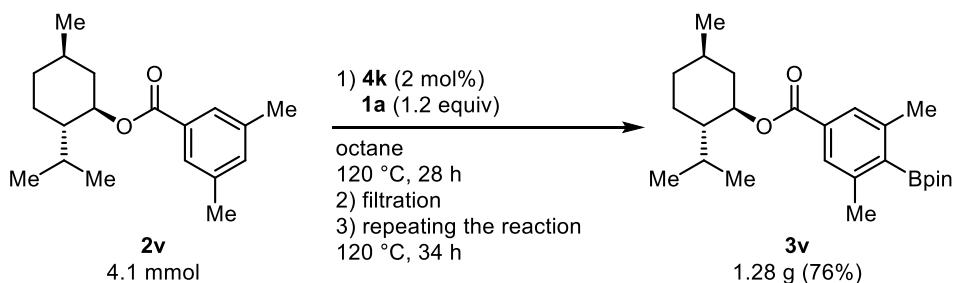


Method C was used, except that the reaction was conducted with 5-chloro-3-methylbenzo[b]thiophene (55 mg, 0.30 mmol) and B₂pin₂ (92 mg, 0.36 mmol).

R_f 0.49 (hexane/EtOAc = 5/1). White solid (59 mg, 64%). Mp = 141-142 °C. ¹H NMR (C₆D₆, 399.78 MHz): δ 1.06 (s, 12H), 2.50 (s, 3H), 7.03 (dd, *J* = 8.5, 2.1 Hz, 1H), 7.17 (d, *J* = 8.7 Hz, 1H), 7.62 (d, *J* = 1.8 Hz, 1H). ¹³C NMR (C₆D₆, 100.53 MHz): δ 13.6, 24.5, 83.8, 122.4, 123.7, 125.8, 130.2, 141.6, 142.5, 143.1. IR (ATR): 2975 w, 1557 w, 1526 m, 1437 w, 1361 s, 1306 s, 1263 m, 1248 m, 1207 w, 1166 w, 1136 s, 1105 s, 1077 m, 1029 m, 975 m, 947 w, 867 m, 848 s, 806 s, 780 w, 692 w, 671 s, 608 m, 586 w, 557 w, 544 w, 534 w. MS m/z (% relative intensity): 310 (34), 309 (23), 308 (M+, 100), 307 (23), 253 (25), 252 (19), 251 (71), 250 (36), 222 (42), 216 (19), 210 (38), 209 (44), 208 (100), 207 (39), 181 (17), 173 (27), 149 (18), 85 (27), 59 (26), 57 (15). HRMS (CI): Calcd for [C₁₅H₁₈BClO₂S + H] 309.0887, Found 309.0876.

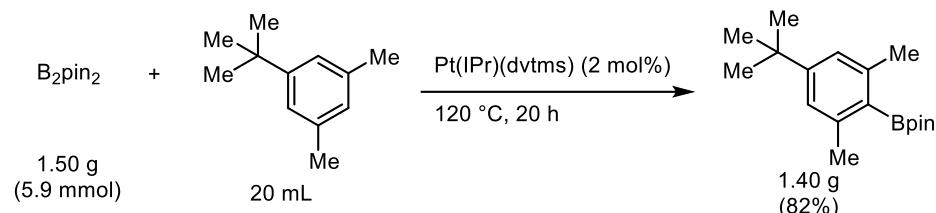
7. Synthetic Applications

7-1. Scale-up Experiment (Scheme 2)



To a dried two-necked flask equipped with a reflux condenser, $B_2\text{pin}_2$ (1.25 g, 4.9 mmol), $\text{Pt}(\text{SIPr})(\text{dvtms})$ (63 mg, 0.082 mmol), **2v** (1.17 g, 4.1 mmol) and octane (1.4 mL) were added. The mixture was heated at 120 °C for 28 h. The resulting mixture was filtered through a column of silica gel (eluting with 7 mL of hexane/EtOAc = 5/1) to give the target borylated product (104 mg) and a mixture of the target product and unreacted starting material. The mixture was again transferred to another dried two-necked flask, $B_2\text{pin}_2$ (1.25 g, 4.9 mmol), $\text{Pt}(\text{SIPr})(\text{dvtms})$ (63 mg, 0.082 mmol) and octane (1.4 mL) were added. The reaction mixture was heated at 120 °C for 34 h. The resulting mixture was purified by column chromatography to give the target borylated product (1.17 g) and unreacted starting material (129 mg, 11%). As a result of two borylation, 1.28 g of the target product was obtained as a white solid (1.28 g, 76%).

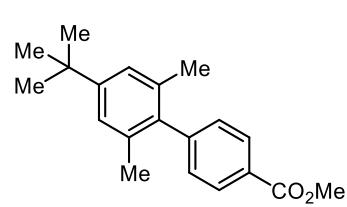
7.2.1 Gram-Scale Synthesis of **3k** and Its Transformations (**3k**, Scheme 5)



$\text{Pt}(\text{IPr})(\text{dvtms})$ (91 mg, 0.12 mmol), $B_2\text{pin}_2$ (1.50 g, 5.9 mmol) and 1-(tert-butyl)-3,5-dimethylbenzene (20 mL) were added to a 100 mL three-necked flask with a condenser under a N_2 atmosphere. The mixture was stirred at 120 °C for 20 h, and the resulting mixture was purified by flash column chromatography over silica gel (eluted with hexane to hexane/AcOEt = 95/5) to give 2-(4-(tert-butyl)-2,6-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane as a white solid (1.40 g, 82% based on $B_2\text{pin}_2$).

7.2.2 Synthetic Elaboration of the Borylated Product

Methyl 4'-(tert-butyl)-2',6'-dimethyl-[1,1'-biphenyl]-4-carboxylate (**9**, Scheme 5).

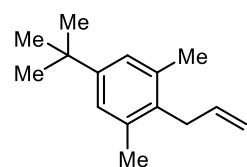


To a 10 mL sample vial with a Teflon-sealed screwcap, **3k** (86 mg, 0.30 mmol), methyl 4-iodobenzoate (87 mg, 0.33 mmol), $\text{Pd}(\text{OAc})_2$ (3.3 mg, 0.015 mmol), SPhos (12 mg, 0.030 mmol), toluene (1.0 mL), and an aqueous solution (0.50 mL) of K_3PO_4 (160 mg, 0.75 mmol) was added under an atmosphere of nitrogen. The resulting mixture was stirred at 120 °C for 12 h under an atmosphere of nitrogen. The mixture was then partitioned between Et_2O and H_2O , and the organic layer was separated. The extract was washed with brine, dried (MgSO_4) and concentrated. The residue was purified by column chromatography (SiO_2 , hexane/EtOAc = 95/5 to 85/15), followed by GPC, to give the title compound as a colorless oil (48 mg, 54%).

Rf 0.43 (hexane/EtOAc = 10/1). Colorless oil. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.35 (s, 9H), 2.02 (s, 6H), 3.94 (s, 3H), 7.13 (s, 2H), 7.25 (d, J = 8.7 Hz, 2H), 8.09 (d, J = 8.7 Hz, 2H). ^{13}C NMR (CDCl_3 100.53 MHz): δ 21.2, 31.5, 34.5, 52.2, 124.6, 128.6, 129.6, 129.8, 135.2, 138.1, 146.6, 150.4, 167.3.

IR (ATR): 2954 w, 1724 s, 1610 w, 1435 m, 1272 s, 1175 w, 1112 m, 1100 m, 1005 w. MS m/z (% relative intensity): 296 (M⁺, 26), 282 (21), 281 (100), 111 (24). HRMS (EI): Calcd for C₂₀H₂₄O₂ 296.1776, Found 296.1770.

2-Allyl-5-(tert-butyl)-1,3-dimethylbenzene (10, Scheme 5).

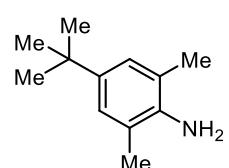


To a 10 mL sample vial with a Teflon-sealed screwcap, **3k** (86 mg, 0.30 mmol), allyl chloride (69 mg, 0.90 mmol), Pd(dba)₂ (8.6 mg, 0.015 mmol), and MeOH (1.0 mL) was added, and the mixture was stirred at room temperature for 10 min.

KF (52 mg, 0.90 mmol) was then added, and the resulting mixture was stirred at room temperature for 18 h under an atmosphere of nitrogen. The mixture was then partitioned between Et₂O and H₂O, and the organic layer was separated. The extract was washed with brine, dried (MgSO₄) and concentrated. The residue was purified by column chromatography (SiO₂, hexane to hexane/EtOAc = 95/5) to give the title compound as a colorless oil (49 mg, 81%).

Rf 0.80 (hexane/EtOAc = 10/1). Colorless oil. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.29 (s, 9H), 2.29 (s, 6H), 3.36 (dt, *J* = 5.5, 1.8 Hz, 2H), 4.90 (dq, *J* = 17.4 Hz, 1.8 Hz, 1H), 4.98 (dq, *J* = 10.1, 1.8 Hz, 1H), 5.88 (ddt, *J* = 17.4, 10.1, 5.5 Hz, 1H), 7.03 (s, 2H). ¹³C NMR (CDCl₃ 100.53 MHz): δ 20.1, 31.4, 33.5, 34.1, 114.8, 125.0, 133.1, 135.5, 136.1, 148.6. IR (ATR): 2961 s, 2867 m, 1729 m, 1637 w, 1609 w, 1575 w, 1485 m, 1455 m, 1361 m, 1274 s, 1233 w, 1191 w, 1113 m, 1100 m, 995 m, 910 s, 868 s. MS m/z (% relative intensity): 202 (M⁺, 29), 188 (16), 187 (100), 145 (18), 133 (19), 131 (11), 129 (11), 128 (11). HRMS (EI): Calcd for C₁₅H₂₂ 202.1722, Found 202.1720.

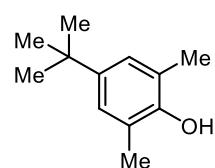
4-(tert-Butyl)-2,6-dimethylaniline (11, Scheme 5) [CAS: 42014-60-8].



To a mixture of **3k** (86 mg, 0.30 mmol) and H₂NOSO₃H (85 mg, 0.75 mmol) in CH₃CN (2.5 mL), an aqueous solution of NaOH (1 M, 2.5 mL) was added. The resulting mixture was stirred at room temperature under an atmosphere of nitrogen for 12 h. The mixture was then partitioned between Et₂O and H₂O, and the organic layer was separated. The extract was washed with brine, dried (MgSO₄) and concentrated. The residue was purified by column chromatography (SiO₂, hexane/EtOAc = 95/5 to 85/15) to give the title compound as a colorless oil (17 mg, 34%). The starting **3k** was also recovered as a colorless solid (55 mg, 64%).

Rf 0.26 (hexane/EtOAc = 10/1). Colorless oil. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.28 (s, 9H), 2.19 (s, 6H), 2.50-4.55 (br, 2H), 6.97 (s, 2H). ¹³C NMR (CDCl₃ 100.53 MHz): δ 17.9, 31.6, 33.7, 121.4, 125.1, 140.2, 140.8. HRMS (EI): Calcd for C₁₂H₁₉N 177.1517, Found 177.1518.

4-(tert-Butyl)-2,6-dimethylphenol (12, Scheme 5) [CAS: 879-97-0].



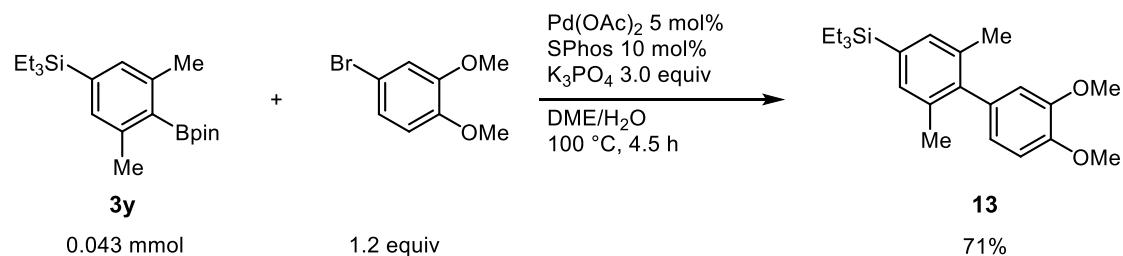
To a solution of **3k** (60 mg, 0.21 mmol) in EtOH (3.0 mL), an aqueous solution of H₂O₂ (30%, 1.0 mL) and an aqueous solution of NaOH (1M, 1.0 mL) were added sequentially. After being stirred at room temperature for 2 h, the mixture was concentrated in vacuo, and the residue was partitioned between EtOAc and an aqueous solution of HCl (1 M). The separated organic layer was washed with brine, dried (MgSO₄)

and concentrated. The residue was purified by column chromatography (SiO_2 , hexane/EtOAc = 95/5 to 85/15) to give the title compound as a colorless solid (35 mg, 93%).

Rf 0.31 (hexane/EtOAc = 10/1). White solid. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.28 (s, 9H), 2.24 (s, 6H), 4.48 (br, 1H), 6.99 (s, 2H). ^{13}C NMR (CDCl_3 100.53 MHz): δ 16.2, 31.6, 33.9, 122.3, 125.5, 142.9, 149.9. HRMS (EI): Calcd for $\text{C}_{12}\text{H}_{18}\text{O}$ 178.1358, Found 309.1358.

7.3. Orthogonal Functionalization of **3y**

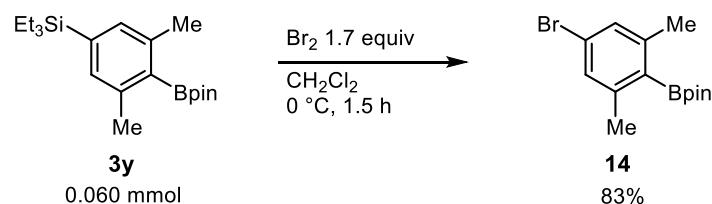
(3',4'-Dimethoxy-2,6-dimethyl-[1,1'-biphenyl]-4-yl)triethylsilane (**13**, Scheme 7).



To a 10 mL-sample vial with a Teflon-sealed screwcap, **3y** (15 mg, 0.043 mmol), $\text{Pd}(\text{OAc})_2$ (0.5 mg, 0.0022 mmol), SPhos (1.8 mg, 0.0043 mmol), K_3PO_4 (27 mg, 0.13 mmol) and 4-bromo-1,2-dimethoxybenzene (11 mg, 0.052 mmol) were added. After adding H_2O (0.3 mL) and 1,2-dimethoxyethane (0.3 mL), the cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 100°C until GC and TLC analysis showed full conversion of starting **3y** (4.5 h). To the resulting reaction mixture, H_2O was added and the aqueous phase was extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over MgSO_4 . The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/EtOAc = 100/1 to 50/1) to give the title compound as a colorless oil (11 mg, 71%).

Rf 0.46 (hexane/EtOAc = 5/1). Colorless oil (11 mg, 71%). ^1H NMR (CDCl_3 , 399.78 MHz): δ 0.81 (q, J = 7.9 Hz, 6H), 1.01 (t, J = 7.8 Hz, 9H), 2.07 (s, 6H), 3.85 (s, 3H), 3.93 (s, 3H), 6.65-6.74 (m, 2H), 6.93 (d, J = 8.2 Hz, 1H), 7.21 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 3.42, 7.53, 20.9, 55.8, 55.9, 111.0, 112.2, 121.0, 133.1, 133.7, 135.4, 135.9, 142.1, 147.5, 148.7. IR (ATR): 2952 m, 2909 m, 2874 m, 1512 s, 1461 m, 1403 w, 1320 w, 1294 w, 1242 s, 1214 m, 1172 m, 1136 s, 1028 m, 970 w, 861 w, 841 w, 808 w, 767 w, 733 s, 719 s, 700 m. MS m/z (% relative intensity): 357 (13), 356 (M^+ , 45), 327 (52), 299 (71), 272 (23), 271 (100), 135 (44), 114 (12). HRMS (EI): Calcd for $\text{C}_{22}\text{H}_{32}\text{O}_2\text{Si}$ 356.2172, Found 356.2172.

2-(4-Bromo-2,6-dimethylphenyl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane (**14**, Scheme 7).



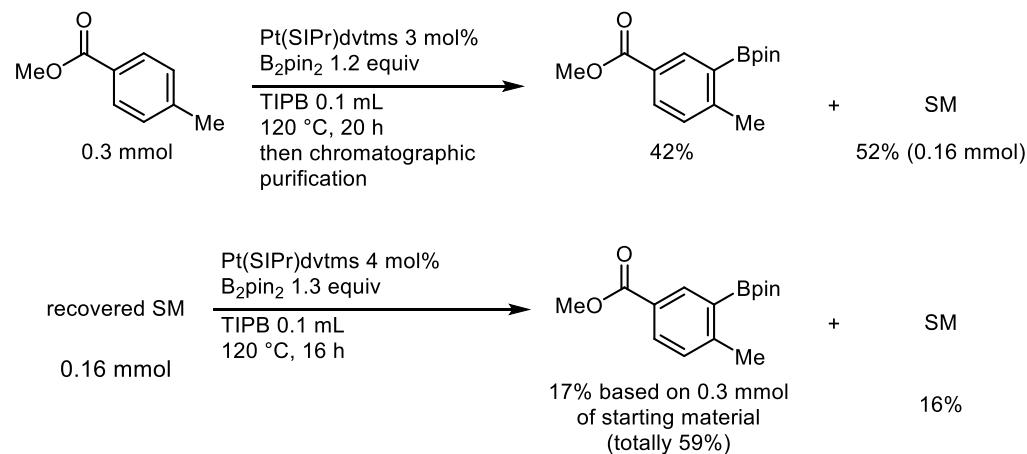
In a 10 mL-sample vial, **3y** (21 mg, 0.060 mmol) was dissolved in CH_2Cl_2 (0.3 mL) under N_2 atmosphere. The solution was cooled to 0°C in an ice bath. To the cooled solution, Br_2 solution (11

mg, 0.069 mmol, dissolved in 0.3 mL of CH_2Cl_2) was added dropwise. The resulting mixture was stirred at 0 °C for 1 h. Since TLC showed that starting **3y** remained, additional Br_2 solution (5.0 mg, 0.031 mmol, dissolved in 0.3 mL of CH_2Cl_2) were added and the mixture was stirred for another 30 min. To the resulting mixture, $\text{Na}_2\text{S}_2\text{O}_3$ aq was added and the mixture was extracted with Et_2O three times. Combined organic extracts were washed with brine and dried over MgSO_4 . The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ AcOEt = 200/1 to 100/1) to give the title compound as a white solid (16 mg, 83%).

Rf 0.60 (hexane/ EtOAc = 5/1). White solid (16 mg, 83%). $\text{Mp} = 101\text{--}103$ °C. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.38 (s, 12H), 2.36 (s, 6H), 7.11 (s, 2H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 22.0, 24.9, 83.9, 123.5, 129.3, 144.0. IR (ATR): 2977 m, 1575 m, 1443 w, 1401 w, 1369 s, 1334 s, 1301 s, 1272 w, 1211 w, 1164 w, 1145 m, 1111 m, 1063 m, 851 m, 677 m. MS m/z (% relative intensity): 312 (44), 310 (M^+ , 43), 255 (94), 254 (50), 253 (100), 252 (43), 213 (57), 212 (99), 211 (77), 210 (98), 209 (24), 174 (69), 131 (38), 105 (26), 101 (27), 83 (23). HRMS (EI): Calcd for $\text{C}_{14}\text{H}_{20}\text{BBrO}_2$ 310.0740, Found 310.0737.

7.4. Borylation of Methyl *p*-Methylbenzoate **15**

Methyl 4-methyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)benzoate (**16b**, Scheme 7).

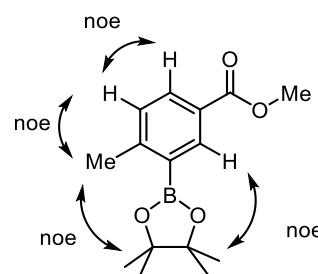


$\text{Pt}(\text{SIPr})(\text{dvtms})$ (6.9 mg, 9.0 μmol), B_2pin_2 (91 mg, 0.36 mmol), methyl 4-methylbenzoate (49 mg, 0.30 mmol) and 1,3,5-triisopropylbenzene (0.10 mL) were added to a 10 mL-sample vial with a Teflon-sealed screwcap. The cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 120 °C for 20 h and the resulting mixture was filtered through a pad of silica gel (eluting with 7 mL of hexane/ EtOAc = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography over silica gel (eluting with hexane/ AcOEt = 100/1 to 50/1) to give the target borylated product as a white solid (35 mg, 42%) and 26 mg of unreacted starting material was recovered (52%). The recovered starting material was transferred to another vial for repeating the borylation. $\text{Pt}(\text{SIPr})(\text{dvtms})$ (4.9 mg, 6.4 μmol), B_2pin_2 (51 mg, 0.20 mmol) and 1,3,5-triisopropylbenzen (0.1 mL) were added. The mixture was stirred at 120 °C for 16 h and the resulting mixture was filtered through a pad of silica gel (eluting with 7 mL of hexane/ AcOEt = 5/1). The filtrate was concentrated in vacuo and purified by flash column chromatography to give the target borylated product (14 mg, 17% based on starting arene) and 7.9 mg of unreacted starting material was recovered.

As a result of two borylation, 59% of the target product was obtained and 16% of unreacted starting was recovered.

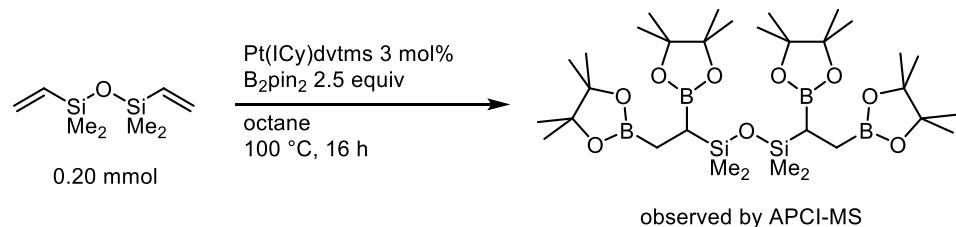
Rf 0.49 (hexane/EtOAc = 5/1). White solid (49 mg, 59%). Mp = 158-159 °C. ¹H NMR (CDCl₃, 399.78 MHz): δ 1.34 (s, 12H), 2.56 (s, 3H), 3.88 (s, 3H), 7.21 (d, *J* = 7.8 Hz, 1H), 7.95 (dd, *J* = 8.2, 1.8 Hz, 1H), 8.39 (d, *J* = 1.4 Hz, 1H). ¹³C NMR (CDCl₃, 100.53 MHz): δ 22.4, 24.9, 51.9, 83.7, 126.7, 129.9, 131.8, 137.0, 150.4, 167.3. IR (ATR): 2976 w, 1713 s, 1602 w, 1403 m, 1368 m, 1343 s, 1316 w, 1280 s, 1255 s, 1134 s, 1116 s, 1068 m, 1005 w, 969 m, 934 w, 855 m, 759 m, 733 w, 680 w, 654 m. MS m/z (% relative intensity): 276 (M+, 10), 261 (33), 245 (21), 233 (35), 219 (100), 218 (55), 201 (14), 177 (87), 176 (56), 145 (55), 144 (15), 117 (43), 85 (25), 59 (20). HRMS (EI): Calcd for C₁₅H₂₁BO₄ 276.1533, Found 276.1530.

The regiochemistry of the compound was determined by NOESY experiments.



8. Mechanistic Studies

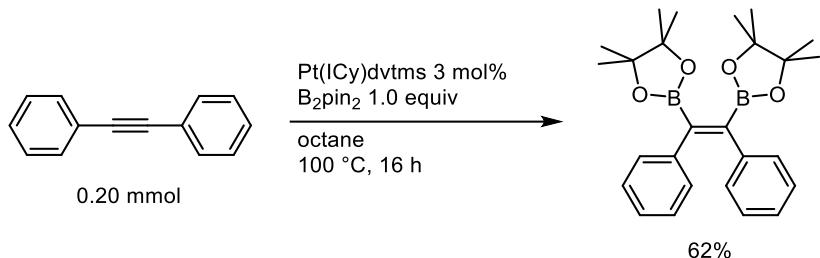
8-1. Diborylation of dvtms with Pt(ICy)dvtms catalyst.



To a 10 mL-sample vial with a Teflon-sealed screwcap, B₂pin₂ (127 mg, 0.50 mmol), Pt(ICy)dvtms (3.7 mg, 0.0060 mmol), dvtms (37 mg, 0.20 mmol) and octane (0.5 mL) were added. The cap was applied to seal the vial under the flow of N₂. The mixture was stirred at 100 °C for 16 h. The resulting mixture was analyzed by TLC and GC to show full conversion of starting dvtms. An aliquot of the reaction mixture was taken and diluted with 0.5 mL of EtOAc for APCI-MS analysis. APCI-MS analysis showed the target tetraborylated product exists in the reaction mixture.

HRMS(APCI): Calcd for [C₃₂H₆₆B₄O₉Si₂+H] 695.4713, Found 695.4717.

8-2. Diborylation of diphenylacetylene with Pt(ICy)dvtms catalyst.

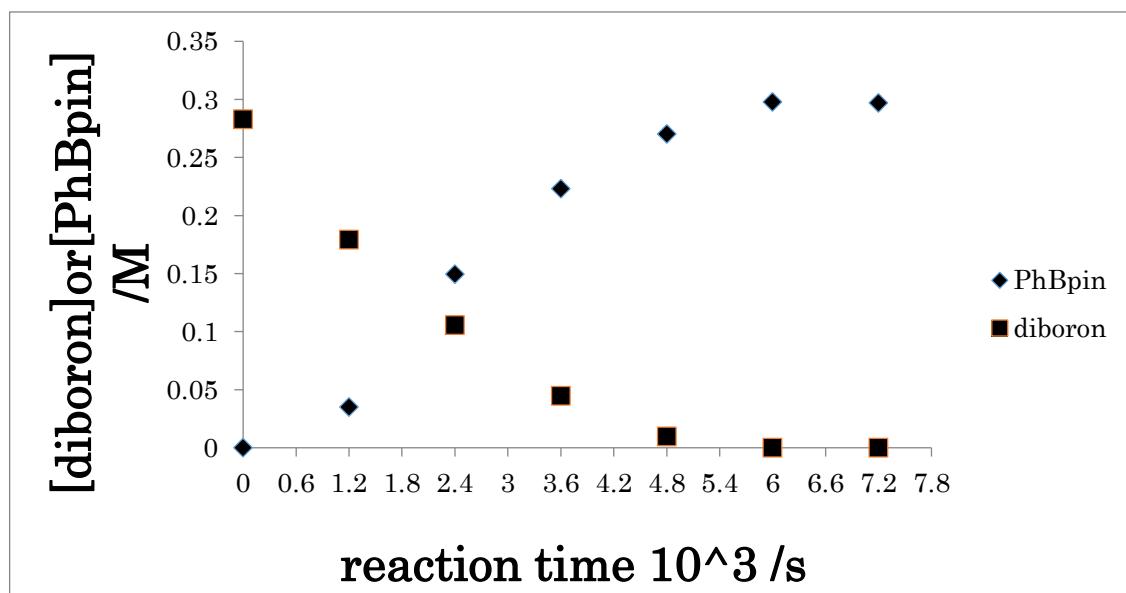


To a 10 mL-sample vial with a Teflon-sealed screwcap, diphenylacetylene (36 mg, 0.20 mmol), Pt(PhCy)dvtms (3.7 mg, 0.0060 mmol), B_2pin_2 (51 mg, 0.20 mmol) and octane (0.5 mL) were added. The cap was applied to seal the vial under the flow of N_2 . The mixture was stirred at 100 °C for 16 h. The resulting mixture was filtered through a pad of silica gel (eluting with 20 mL of hexane/EtOAc = 5/1). The filtrate was concentrated in vacuo to give a white solid. The solid was washed with minimal amount of hexane to give the pure target product as a white solid (54 mg, 62%).
 $\text{Rf} = 0.46$ (hexane/EtOAc = 5/1). White solid (54 mg, 62%). $\text{Mp} = 178 \text{ }^\circ\text{C}$. ^1H NMR (CDCl_3 , 399.78 MHz): δ 1.32 (s, 24H), 6.83-6.98 (m, 4H), 6.98-7.16 (m, 6H). ^{13}C NMR (CDCl_3 , 100.53 MHz): δ 24.9, 84.0, 125.6, 127.4, 129.3, 141.3. HRMS (EI): Calcd for $\text{C}_{26}\text{H}_{34}\text{B}_2\text{O}_4$ 432.2643, Found 432.2643. All spectroscopic data were in agreement with the reported *cis*-adduct.⁵³

8-3. Kinetic Isotope Effect

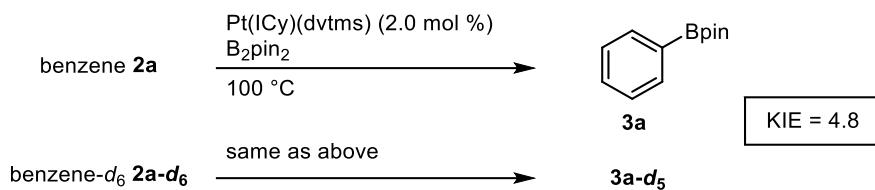
The reaction progress was monitored by GC. Dodecane was added as an internal standard.

Typical procedure for kinetic studies. Pt(PhCy)dvtms (3.6 mg, 5.9 μmol), B_2pin_2 (76 mg, 0.30 mmol), dodecane (30 mg, internal standard) and benzene (1.0 mL) were added to a 10 mL sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N_2 . The mixture was stirred at 100 °C. At specified times, the vial was rapidly cooled with running water and an aliquot of the reaction mixture was taken. The aliquot was diluted with EtOAc and analyzed by GC. After sampling, the reaction mixture was heated again until the next sampling. The amounts of PhBpin and B_2pin_2 in the reaction mixture were determined over time; the results are shown below.

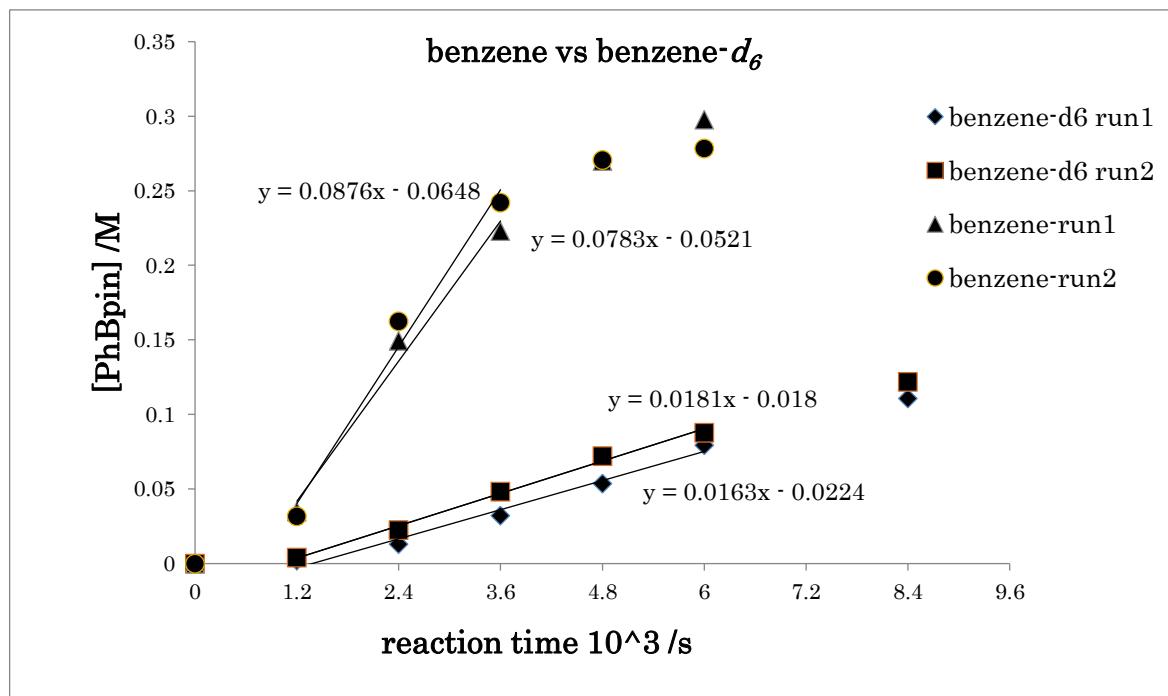


The total yield after 8 h was 99 %. These results show that reaction monitoring by cooling did not deactivate the catalytic species.

Measurement of KIE.



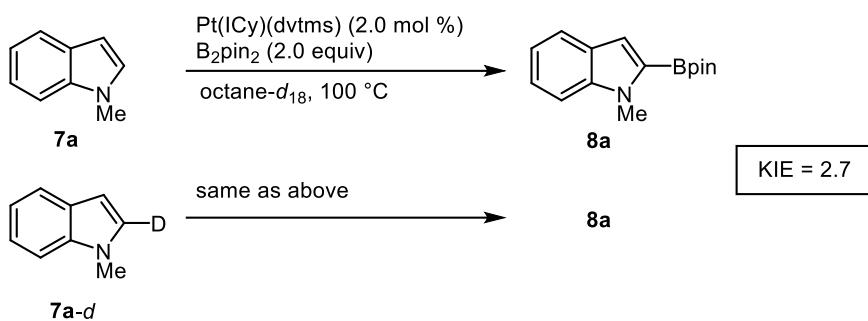
The reaction monitoring was also performed in benzene-*d*₆. The initial rate after 20 min in benzene and benzene-*d*₆ were compared. Each experimental trial was performed in duplicate.



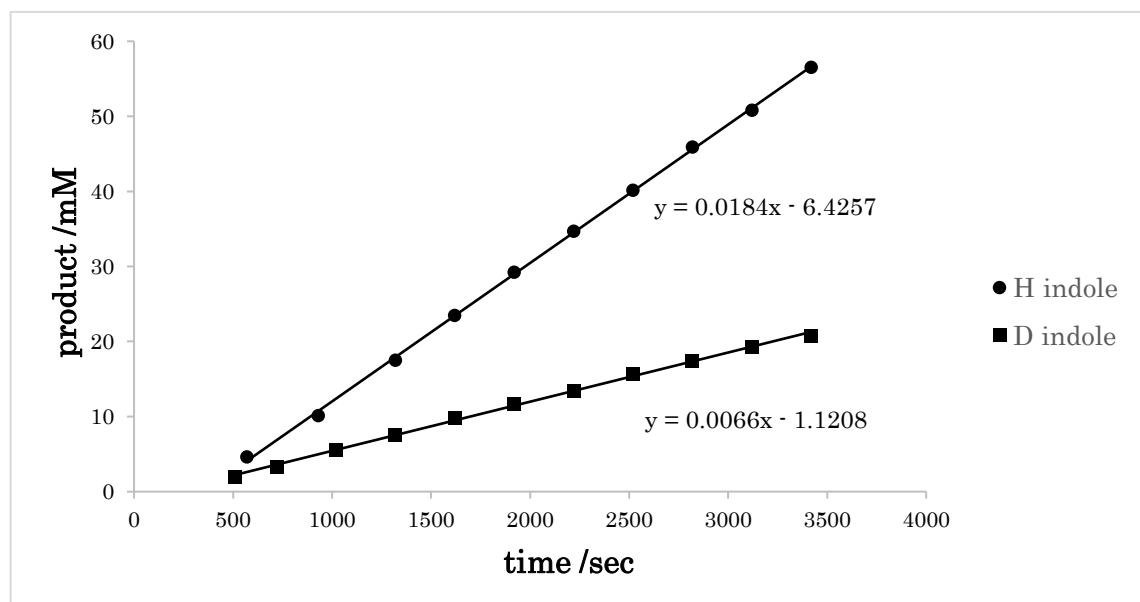
The average rate in benzene was 8.3×10^{-5} M/s, and that in benzene-*d*₆ was 1.7×10^{-5} M/s. The KIE for this reaction was 4.8.

Typical procedure for kinetic studies for *N*-methylindole.

N-Methylindole-*d* **7a-d** was synthesized according to the literature procedure⁵⁴ and the deuterium content was determined to be 95% by ¹H NMR.



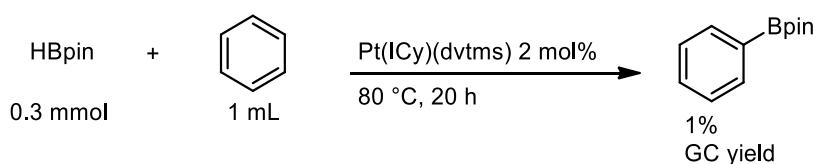
To an NMR tube with a Teflon-sealed screwcap, Pt(ICy)(dvtms) (1.2 mg, 2.0 μmol), B_2pin_2 (51 mg, 0.20 mmol), *N*-methylindole (13 mg, 0.10 mmol), 1,2,4,5-tetramethylbenzene (5.0 mg, as internal standard) and octane- d_{18} (0.50 mL) were added. The cap was used to seal the vial under a flow of N_2 . The mixture was heated at 100 $^\circ\text{C}$ by heat air in a NMR spectrometer and the reaction progress was monitored by $^1\text{H-NMR}$ each 5 min. The amounts of borylated products **8a** in the reaction mixture were determined over time. The same experiment was performed with *N*-methylindole-*d* **7a-d** and each initial rates after 10 min were compared.



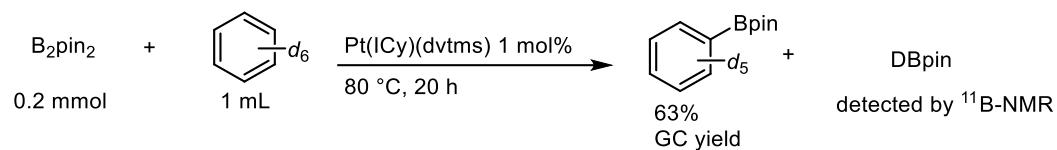
The rate with *N*-methylindole was $1.8 \times 10^{-5} \text{ M/s}$, and that with *N*-methylindole-*d* was $6.6 \times 10^{-6} \text{ M/s}$. The KIE for this reaction was 2.7.

8-3. Reactivity of HBpin

When the reaction was conducted with HBpin instead of B_2pin_2 , 1% PhBpin was formed.

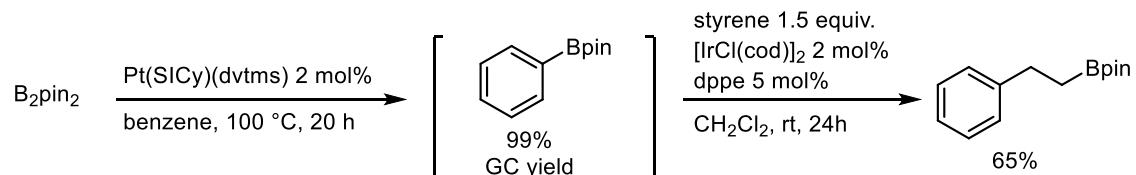


Moreover, HBpin was detected by ^{11}B -NMR analysis of the crude reaction mixture of the Pt-catalyzed borylation of benzene- d_6 using B_2pin_2 .



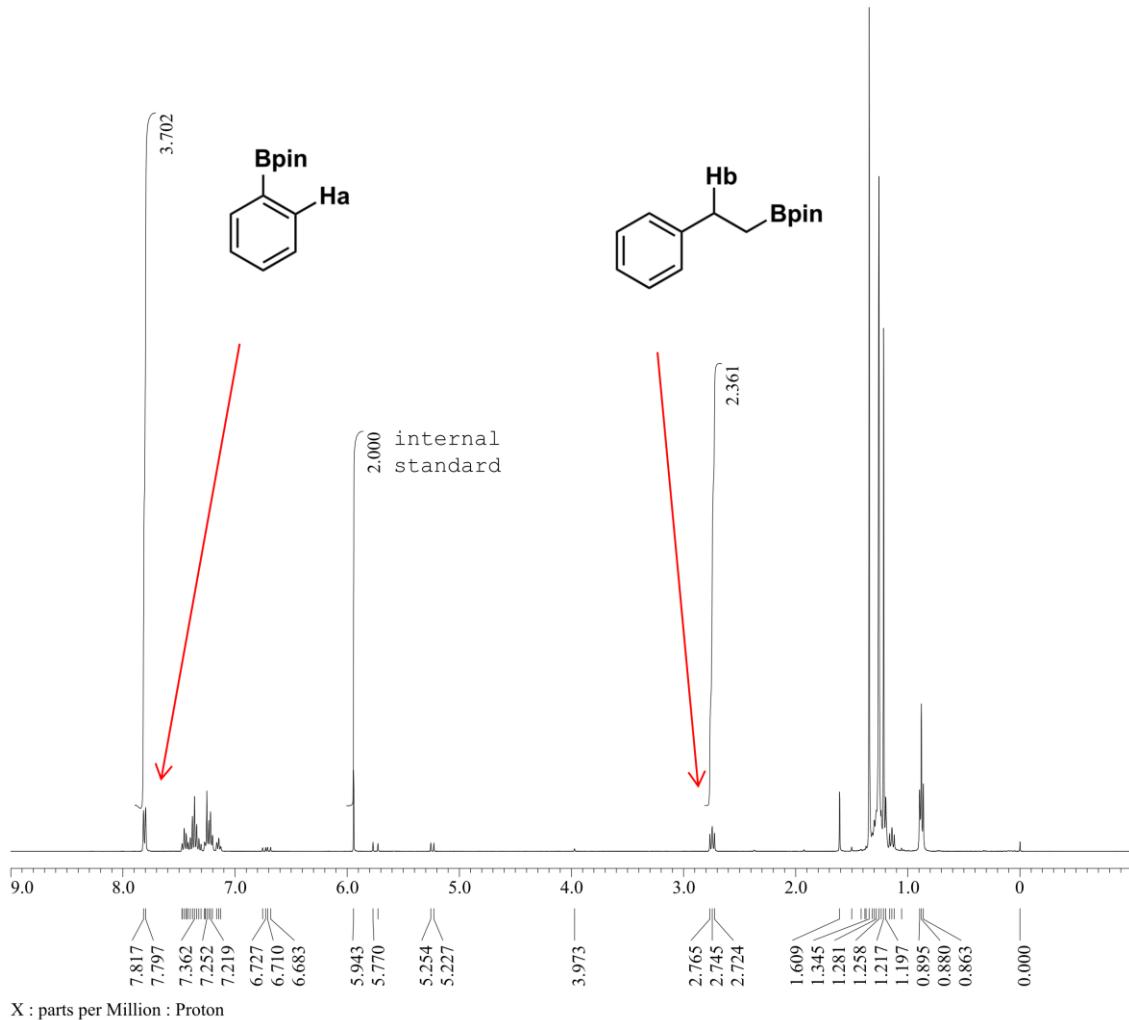
Experimental procedure. $\text{Pt}(\text{ICY})(\text{dvtms})$ (1.2 mg, 0.0020 mmol), B_2pin_2 (51 mg, 0.20 mmol) and benzene- d_6 (1.0 mL) were added to a 10 mL sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N_2 . The vial was stirred at 100°C over a hot plate for 20 h. The resulting reaction mixture was directly transferred to an NMR test tube and ^{11}B -NMR spectra were recorded. The ^{11}B -NMR spectra showed three peaks, at $\delta = 31.2$ (PhBpin), 28.4 (DBpin), and 21.7 ppm (HOBpin),⁵⁵ which could be generated by the reaction of HBpin with residual H_2O (external reference: 15% $\text{BF}_3\bullet\text{EtO}_2$ in CDCl_3). After the NMR analysis, GC analysis was conducted, and showed that 63 % PhBpin was produced and B_2pin_2 was consumed completely.

The amount of unreacted HBpin was quantified by conducting hydroborylation⁵⁶ with styrene after the Pt-catalyzed borylation of benzene with B_2pin_2 .



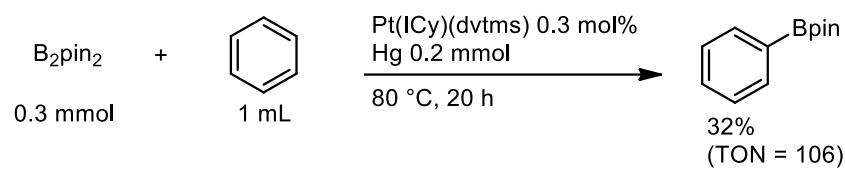
$\text{Pt}(\text{SICy})(\text{dvtms})$ (4.0 mg, 0.0065 mmol, 2 mol%), B_2pin_2 (76 mg, 0.30 mmol), dodecane (45 mg, as internal standard) and benzene (1.0 mL) were added to a 10 mL sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N_2 . The mixture was stirred at 100°C for 20 h. An aliquot of the reaction mixture was taken under a flow of N_2 . The aliquot was diluted with AcOEt and analyzed by GC (PhBpin 99%, full conversion of B_2pin_2). To the reaction mixture, $[\text{IrCl}(\text{cod})]_2$ (4.0 mg, 0.0060 mmol, 2 mol%), dppe (6.2 mg, 0.015 mmol, 5 mol %), styrene (50 μL , 0.44 mmol, 1.5 equiv) and CH_2Cl_2 (1 mL) were added.

The vial was capped again and the reaction mixture was stirred for 24h at ambient temperature. The resulting mixture was filtered through silica gel (eluted with 7 mL of hexane/ AcOEt = 5/1). The filtrate was analyzed by NMR using 1,1,2,2-tetrachloroethane as an internal standard, and showed that 4,4,5,5-tetramethyl-2-phenethyl-1,3,2-dioxaborolane was produced in 65% NMR yield, based on B_2pin_2 . The resonances specific to the compounds are as follows: $\delta = 2.75$ ppm (t, $J = 8.2$ Hz, 2H, hydroborylated product H_b); 7.81 (d, $J = 8.0$ Hz, 2H, PhBpin H_a).



8-4. Mercury Poisoning Test

The reaction was performed in the presence of excess mercury. The reaction was not inhibited by mercury, indicating that a homogeneous platinum species is involved as an active catalyst.



$\text{Pt}(\text{ICy})(\text{dvtms})$ (5.5 mg, 0.90 μmol) was dissolved in benzene (10 mL) to prepare 9.0×10^{-4} M $\text{Pt}(\text{NHC})(\text{dvtms})$ solution. B_2pin_2 (76 mg, 0.30 mmol), mercury (42 mg, 0.21 mmol, 233 equiv to catalyst) and 1.0 mL of 9.0×10^{-4} M $\text{Pt}(\text{ICy})(\text{dvtms})$ benzene solution (0.9 μmol , 0.3 mol %) were added to a 10 mL sample vial with a Teflon-sealed screwcap. The cap was used to seal the vial under a flow of N_2 . The vial was stirred at 100 $^\circ\text{C}$ for 20 h, and the resulting mixture was filtered through silica gel (eluted with 7 mL of hexane/ AcOEt = 5/1). The filtrate was analyzed by GC using dodecane as an internal standard; 32% PhBpin was produced (TON = 106).

2.5 References and Notes

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Conclusion

The research reported in this thesis was directed at the nickel- and platinum-catalyzed borylation of aromatic C-H bonds. The present study revealed that nickel and platinum complexes have promising catalytic activities for the C-H borylation of arenes. Their reactivity and selectivity were investigated for the purpose of comparison with the well-established iridium systems.

In chapter 1, the nickel-catalyzed borylation reaction of aromatic C-H bonds is described. The use of an NHC ligand is essential for an efficient reaction and a variety of indole derivatives could be selectively borylated at the 2-position. The protocol can be applied to the gram-scale borylation of indoles using the low cost, readily available $\text{Ni}(\text{OAc})_2$. This study demonstrated that an earth abundant base metal can mediate cutting-edge C-H functionalization reactions and will help to address recent concerns regarding the limited availability of precious metals.

In chapter 2, the platinum-catalyzed borylation of aromatic C-H bonds is described. A platinum/ICy complex effectively borylated C-H bonds in aromatic substrates. One unique feature of the platinum systems is their robustness to steric hindrance, enabling the borylation of C-H bonds that are located at sterically congested positions. Further ligand screening determined that the SIPr ligand as an optimal ligand for the borylation of sterically hindered arenes under practical conditions without the need for a large excess of the substrates. Another feature of the platinum catalyst is that a fluorine functionality exhibited an *ortho*-directing effect, providing facile access to a wide range of *ortho*-fluorinated phenylboronic ester from fluoroarenes. These unique selectivities are not attainable when the established iridium catalyst system is used. Some synthetic applications that were made possible by the characteristic features of the current platinum system were demonstrated in this study.

Catalytic borylation of C-H bonds is now undoubtedly recognized as one of the most powerful methods for introducing a synthetically versatile boron functionality, therefore the development of catalysts with new reactivities and/or selectivities are highly desired for further progress in C-H borylation and the next breakthrough in undirected C-H functionalization. The knowledge and findings obtained through this study indicates the possibility of nickel and platinum as promising candidates to be investigated for use as C-H borylation catalysts in the future and will contribute to the advancement of C-H functionalization chemistry.

List of Publications

(1) Nickel-Catalyzed Borylation of Arenes and Indoles via C-H Bond Cleavage

Takayuki Furukawa, Mamoru Tobisu, Naoto Chatani

Chem. Commun. **2015**, *51*, 6508.

(2) C-H Functionalization at Sterically Congested Positions by the Platinum-Catalyzed Borylation of Arenes

Takayuki Furukawa, Mamoru Tobisu, Naoto Chatani

J. Am. Chem. Soc. **2015**, *137*, 12211.

(3) C-H Borylation by Platinum Catalysis

Takayuki Furukawa, Mamoru Tobisu, Naoto Chatani

Bull. Chem. Soc. Jpn. **2017**, *in press*.

Supplementary List of Publications

(1) Modular Synthesis of Phenanthridine Derivatives by Oxidative Cyclization of 2-Isocyanobiphenyls with Organoboron Reagents
Mamoru Tobisu, Keika Koh, Takayuki Furukawa, Naoto Chatani
Angew. Chem. Int. Ed. **2012**, *51*, 11363.

(2) Visible Light-Mediated Direct Arylation of Arenes and Heteroarenes Using Diaryliodonium Salts in the Presence and Absence of a Photocatalyst
Mamoru Tobisu, Takayuki Furukawa, and Naoto Chatani
Chem. Lett. **2013**, *42*, 1203.

(3) Nickel-Catalyzed Borylation of Aryl and Benzyl 2-Pyridyl Ethers: A Method for Converting a Robust *ortho*-Directing Group
Mamoru Tobisu, Jiangning Zhao, Hirotaka Kinuta, Takayuki Furukawa, Takuya Igarashi and Naoto Chatani
Adv. Synth. Catal. **2016**, *358*, 2417.

(4) Nickel/*N*-Heterocyclic Carbene-Catalyzed Suzuki-Miyaura Type Cross-Coupling of Aryl Carbamates
Akimichi Ohtsuki, Kousuke Yanagisawa, Takayuki Furukawa, Mamoru Tobisu and Naoto Chatani
J. Org. Chem. **2016**, *81*, 9409.

(5) A Conia-Ene-Type Cyclization Under Basic Conditions Enables an Efficient Synthesis of (−)-Lycoposerramine R
Felix Hartrampf, Takayuki Furukawa, Dirk Trauner
Angew. Chem. Int. Ed. **2017**, *56*, 893.

(6) Nickel-Mediated Decarbonylation of Simple Unstrained Ketones through the Cleavage of Carbon–Carbon Bonds
Toshifumi Morioka, Akihiro Nishizawa, Takayuki Furukawa, Mamoru Tobisu and Naoto Chatani
J. Am. Chem. Soc. **2017**, *in press*.