Highly Efficient Catalytic Transformations of Unsaturated Compounds via Ligand-Induced Selective Addition of Copper Species

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Contents

Abbreviations

Ac	acetyl
AIBN	2,2'-azodiisobutyronitrile
9-BBN	9-borabicyclo[3.3.1]nonane
BINAP	2,2’-bis(diphenylphosphino)-1,1’-binaphthyl
Bn	benzyl
$B_2(pin)_2$	bis(pinacolato)diboron
Cy	cyclohexyl
COD	1,5-cyclooctadiene
Cp	η^5-cyclopentadienyl
CSA	5-chlorosalicylic acid
DFT	density functional theory
DHP	3,4-dihydropyran
DIT	dithranol
DMAP	4-dimethylaminopyridine
dppbz	1,2-bis(diphenylphosphino)benzene
dppb	1,2-bis(diphenylphosphino)butane
dppe	1,2-bis(diphenylphosphino)ethane
dppm	1,1’-bis(diphenylphosphino)methane
dppp	1,3-bis(diphenylphosphino)propane
DTBM	3,5-di-*tert*-butyl-4-methoxyphenyl
HB(pin)	pinacolborane
ICy	1,3-dicyclohexylimidazol-2-ylidene
IMes	1,3-dimesitylimidazol-2-ylidene
IPr	1,3-bis(2,6-diisopropylphenyl)imidazol-2-ylidene
LG	leaving group
Ms	mesyl
NHC	*N*-heterocyclic carbene
PMHS	polymethylhydrosiloxane
SEGPHOS	5,5'-Bis(diphenylphosphino)-4,4'-bi-1,3-benzodioxole
sia	1,2-dimehtylpropyl
TBS	*tert*-butyldimethylsilyl
Ts	tosyl
Tf	trifluoromethanesulfonyl
THF	tetrahydrofuran
THP	tetrahydropyran
Xantphos	4,5-bis(diphenylphosphino)-9,9-dimethylxanthene

General Introduction

Fine Organic Synthesis. For organic synthesis, controlling chemo-, regio- and stereoselectivity is one of the most important and challenging tasks because isomers have often different chemical properties. For examples, (*E*)-diniconazole have antiseptic property, while (*Z*)-diniconazole do not show such property (Figure 1). Traditionally, as for Wittig reaction, which is one of the most important reactions constructing an alkene moiety, the stereoselevtivity was controlled by stabilities of ylides.[1] Due to its high stereoselectivity, Wittig reaction has been applied to a number of total syntheses.[2]

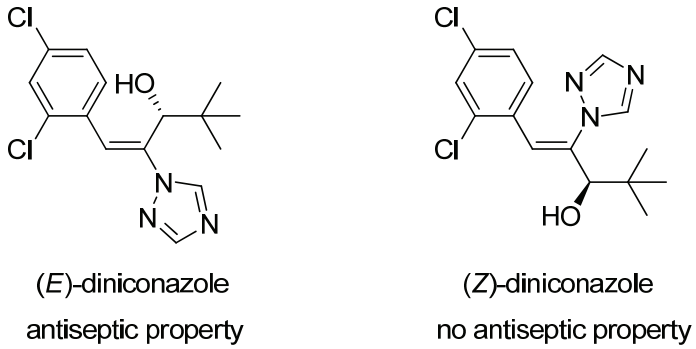


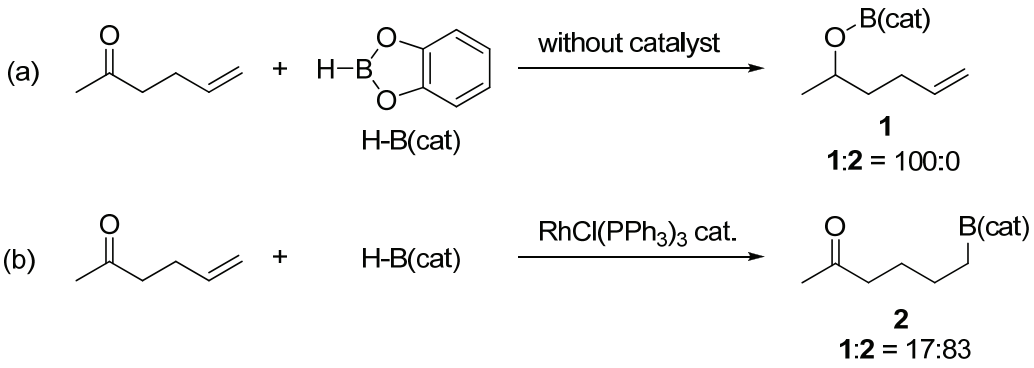
Figure 1. Importance of controlling stereochemistry

To control the selectivity, transition-metal catalysts are powerful tools. For examples, hydroboration of 5-hexen-2-one employing catecolborane proceed at carbonyl moiety without catalyst (Scheme 1a).[3] In contrast, the alkene moiety was hydroborated in the presence of $[RhCl(PPh_3)_3]$ as a catalyst (Scheme 1b). As for hydroboration of terminal alkynes, without catalyst (*E*)-β-borylalkenes were obtained through *syn*-addition (Scheme 2a).[4] Employing Rh catalysts, (*Z*)-β-borylalkenes were obtained selectively (Scheme 2b).[5] In this case, a vinylidene metal species was a key intermediates to control the stereoselectivity. Furthermore, in the presence of a copper catalyst, α-borylalkenes were obtained in high selectivities (Scheme 2c).[6]

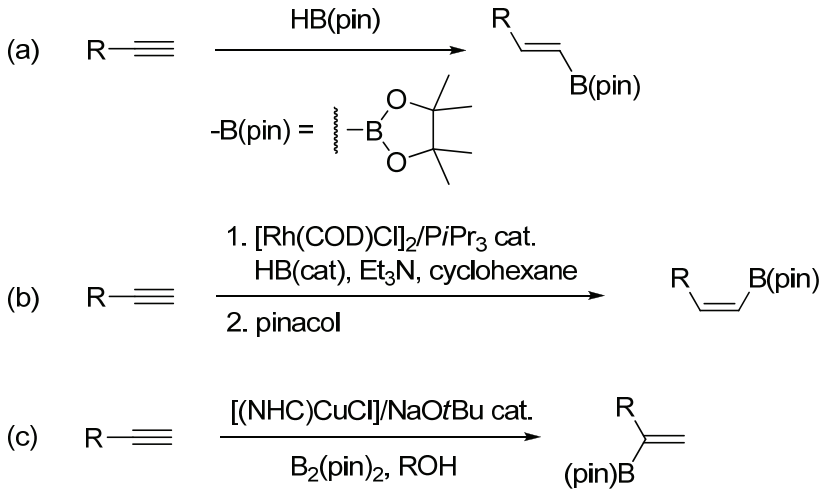
In this thesis, the author aimed at developing highly chemo-, regio- and stereoselevtive transformations using copper catalyst since the copper species are known to show mild and selective reactivity in various reactions. Copper is one of the oldest transition metals to be used in synthetic organic chemistry. After the Gilman's discovery about organocuprates in the 1950s,[7] organocuprates became one of the most versatile synthetic tools in the total synthesis of natural product due to their chemo-,

regio- and stereoselectivities such as the 1,4-addition reactions to α,β-unsaturated acceptors[8] and the clean S_N2 and S_N2' substitution.[9] Among them, the author has focued on copper hydride and borylcopper as active species.

Scheme 1. Hydroboration of 5-hexen-2-one without or with transition metal catalyst

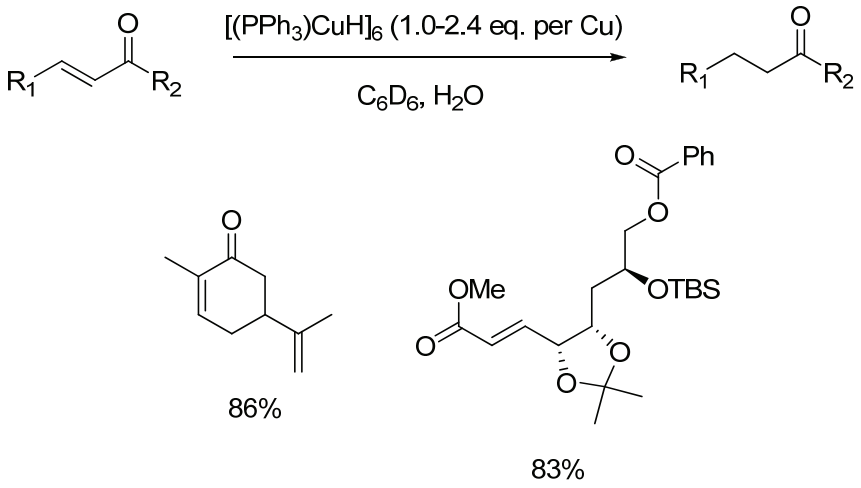


Scheme 2. Hydroboration of terminal alkynes with or without catalysts



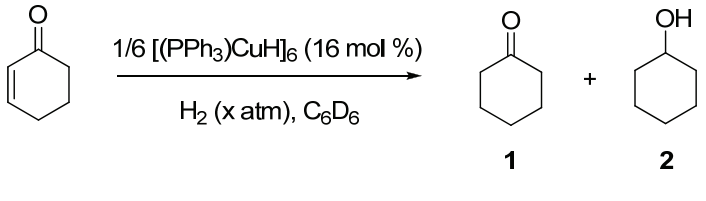
Copper Hydride in Organic Synthesis. Copper hydride, which is one of the oldest metal hydride, is useful reagents for C-H bond formation. However, its potential as a reagent in organic synthesis has been limited for a long time. Osborn and co-workers isolated copper hydride species as the hexameric form, $[(PPh_3)CuH]_6$ in 1971.[10] In 1988, Stryker and co-workers demonstrated that the complex was very useful reducing agent for the regioselective conjugate reductions of a number of α,β-unsaturated carbonyl compounds (Scheme 3).[11]

Scheme 3. 1,4-Reduction of α,β-unsaturated carbonyl compounds using stoichiometric $[(PPh_3)CuH]_6$

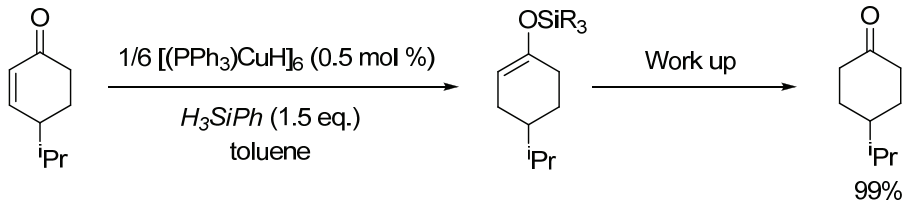


Stryker and co-workers also reported that catalytic reduction of α,β-unsaturated carbonyl compounds employing $[(PPh_3)CuH]_6$ under hydrogen atmosphere. However, careful monitoring was required to avoid the over reduction.[12] In 1998, Lipshutz and co-workers reported that $[(PPh_3)CuH]_6$ worked as catalyst in the reduction of α,β-unsaturated carbonyl compounds using hydrosilanes as reducing agents.[13] In this case, over reductions were completely suppressed because of the formation of corresponding silyl ethers (Scheme 4).

Scheme 4. Catalytic 1,4-reductions employing $[(PPh_3)CuH]_6$ and H_2 or H_3SiPh



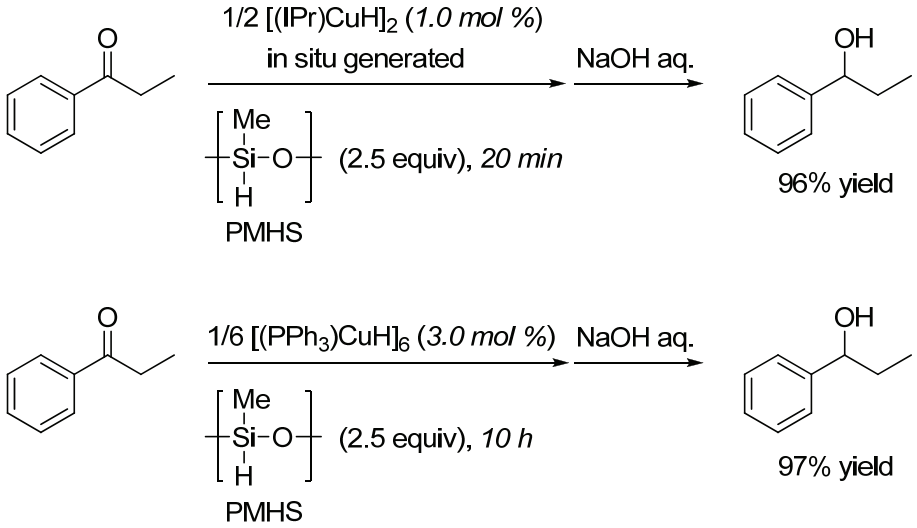
H_2	Ratio of **1/2**
69 atm	34/66
117 atm	0/100



This fine piece of work encouraged other researchers to develop copper hydride catalyzed reduction of various unsaturated compounds employing hydrosilanes as

reducing reagents. Asymmetric reductions were also accomplished employing copper catalysts with chiral ligands.[14] To date, a number of copper-catalyzed reduction of polar unsaturated bonds such as aldehydes, ketones, α,β-unsaturated carbonyl compounds, and Michael acceptors have been developed using copper hydride.[14] However, the catalytic reductive transformations of non-polar unsaturated bonds such as alkynes and alkenes are quite limited. It is surprising that one of the simplest reactions, semihydrogenation of alkynes, cannot be achieved using catalytic amount of copper complexes. To achieve that reaction, excess amounts of copper species must be used.[15] Another problem with copper hydride species as a catalyst is the deactivation by aggregation. As mentioned above, copper hydride with PPh_3 as an ancillary ligand was obtained as a hexameric form, $[(PPh_3)CuH]_6$, in the solid state.[10] In contrast, copper hydride with a bulky IPr as the ligand was obtained as a dimeric form, $[(IPr)CuH]_2$, in the solid state.[16] As for catalytic activity in 1,4-reduction of α,β-unsaturated compounds and 1,2-reduction of carbonyl compounds, $[(IPr)CuH]_2$ was more active than $[(PPh_3)CuH]_6$ (Scheme 5).[17] Therefore, to obtain highly active copper hydride, suppressing aggregation is one of the most important points.

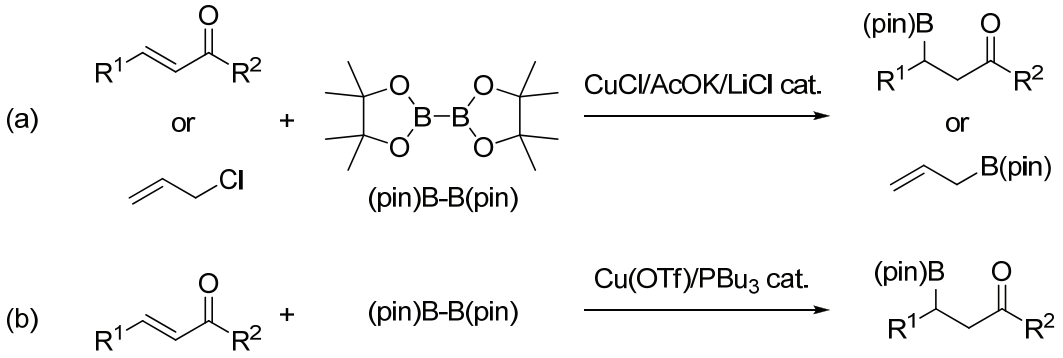
Scheme 5. Hydrosilylation of 1-phenyl-1-propanone employing $[(IPr)CuH]_2$ or $[(PPh_3)CuH]_6$



Borylcopper in Organic Synthesis. Much attention has been paid to the development of synthetic methods to produce organoboranes, which can be utilized in various transformations.[18] In spite of their stability toward oxygen and moisture, they still exhibit reasonable reactivities under certain reaction conditions such as those using

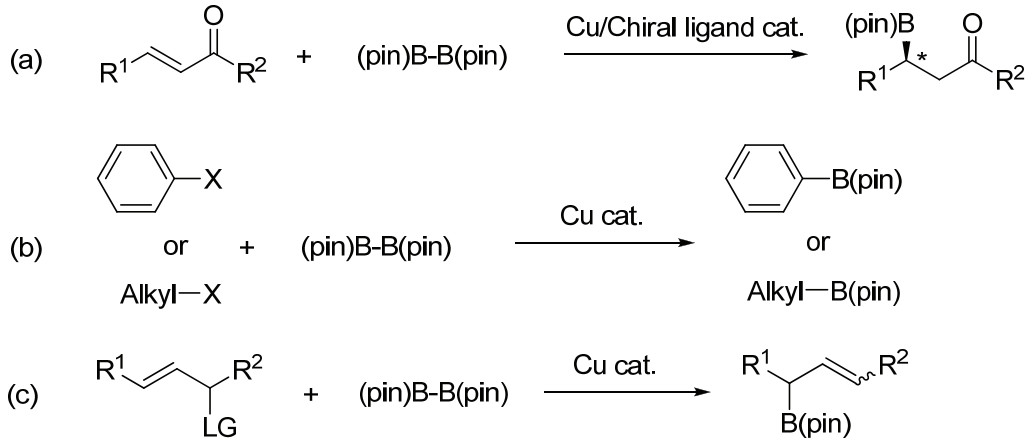
transition-metal catalysts. This remarkable point makes them versatile reagents in organic synthesis. To synthesize organoboranes, transition-metal catalyst was a powerful tool since chemo-, regio- and stereoselectivity of the reactions can be controlled by a choice of metal and ligands. Borylcopper is one of the useful borylation reagents. Borylcopper was first reported by Miyaura et al. and Hosomi et al., independently and used for allylic substitution reaction and 1,4-addition reaction to α,β-conjugated ketones (Scheme 6).[19] Borylcopper was typically synthesized from the reaction between copper alkoxide and diboron reagents.[20] Boryl moiety on borylcopper formally behaves as a boryl anion, which is difficult to be synthesized.[21]

Scheme 6. First examples of borylcopper-catalyzed borylation reactions



Until now, employing borylcopper as an active species, various borylation reactions such as asymmetrical 1,4-addition reactions to α,β-unsaturated carbonyl compounds or Michael acceptors,[22] as well as S_N2 [23]and S_N2' [24]substitution reactions have been reported (Scheme 7).

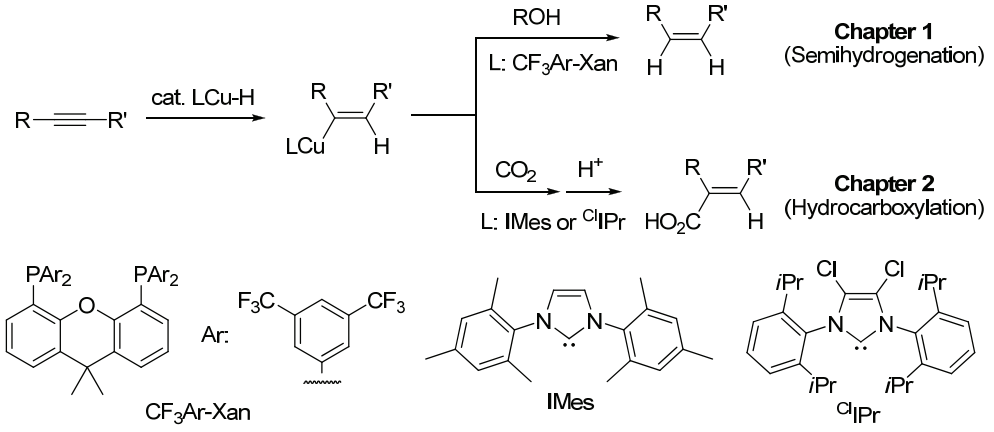
Scheme 7. Borylcopper-catalyzed borylation reactions



Overview of the present thesis

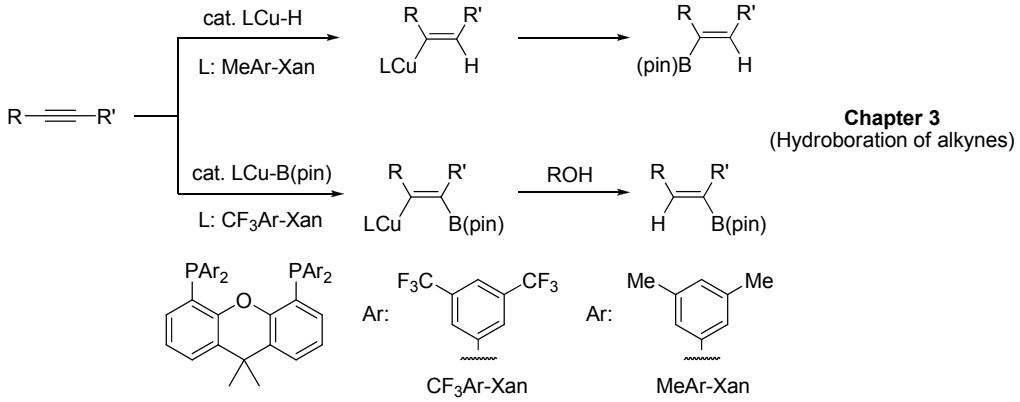
In this thesis, first of all, the author researched the reactivity of copper hydride to non-polar unsaturated bonds such as alkynes. As the results, the author successfully controlled the reactivity of copper hydride by ancillary ligands. The key of success is the smooth insertion of copper hydride to an alkyne, generating a vinyl copper intermediate. In Chapter 1, the author developed copper-catalyzed highly selective semihydrogenation of alkynes employing hydrosilanes and an alcohol. The eletrophilic trap of a vinyl copper species with an alcohol realized the catalytic semihydrogenation (Scheme 8).[25] Furthermore, this catalytic system was also applicable for semihydrogenation of other carbon-carbon unsaturated bonds such as 1,3-diynes, 1,3-dienes and allenes. In Chapter 2, the author developed copper-catalyzed hydrocarboxylation of alkynes with carbon dioxide (CO_2) with hydrosilanes. A catalytically generated vinyl copper species successfully reacted with CO_2, giving α,β-unsaturated carboxylic acids.[26] This transformation is highly valuable in terms of the use of hydrosilanes as reducing agents because previous transition-metal-catalyzed hydrocarboxylation required highly basic and air sensitive reducing reagents such as $AlEt_3$ and $ZnEt_2$.[27]

Scheme 8. Copper-hydride-catalyzed semihydrogenation or hydrocarboxylation of alkynes



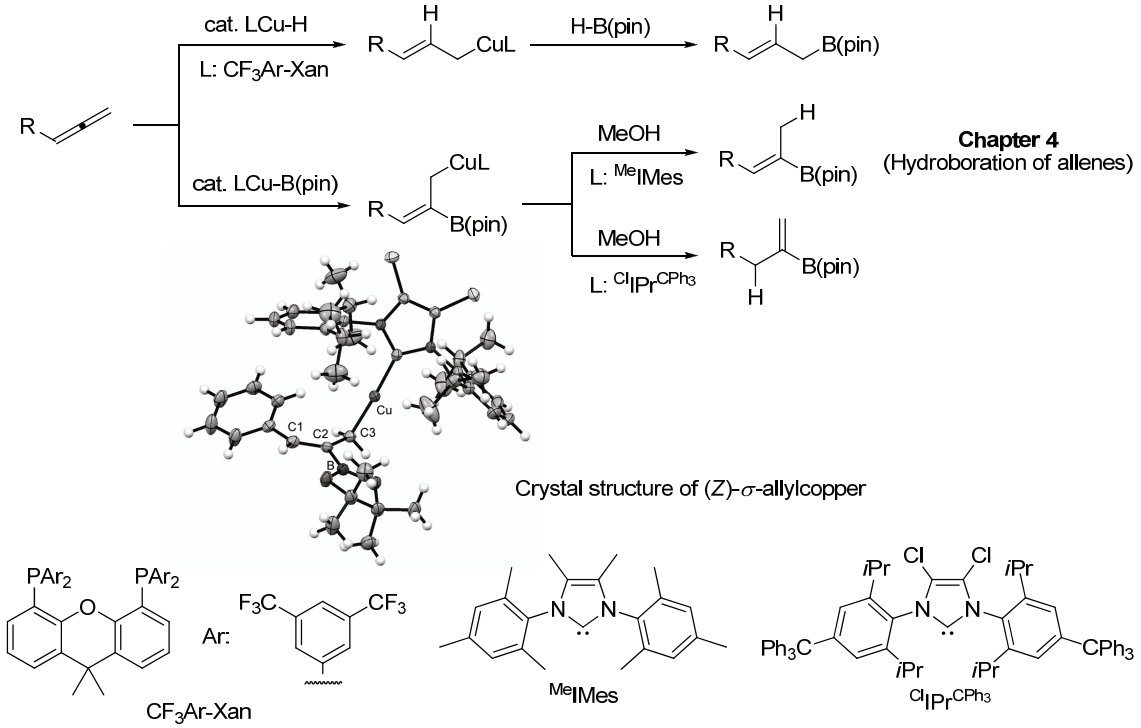
In Chapters 3, 4, 5 and 6, the author describes borylation reaction of carbon-carbon unsaturated bonds employing copper hydride or borylcopper as an active species. In Chapter 3, the author successfully developed copper-catalyzed highly regioselective hydroboration of unsymmetrical internal alkynes (Scheme 9).[28] Previously, it contained some difficulty to control the regioselectivity. In this study, the regioselectivity was successfully controlled by choice of catalytic species (copper hydride and borylcopper).

Scheme 9. Copper-catalyzed regioselective hydroboration of unsymmetrical alkynes



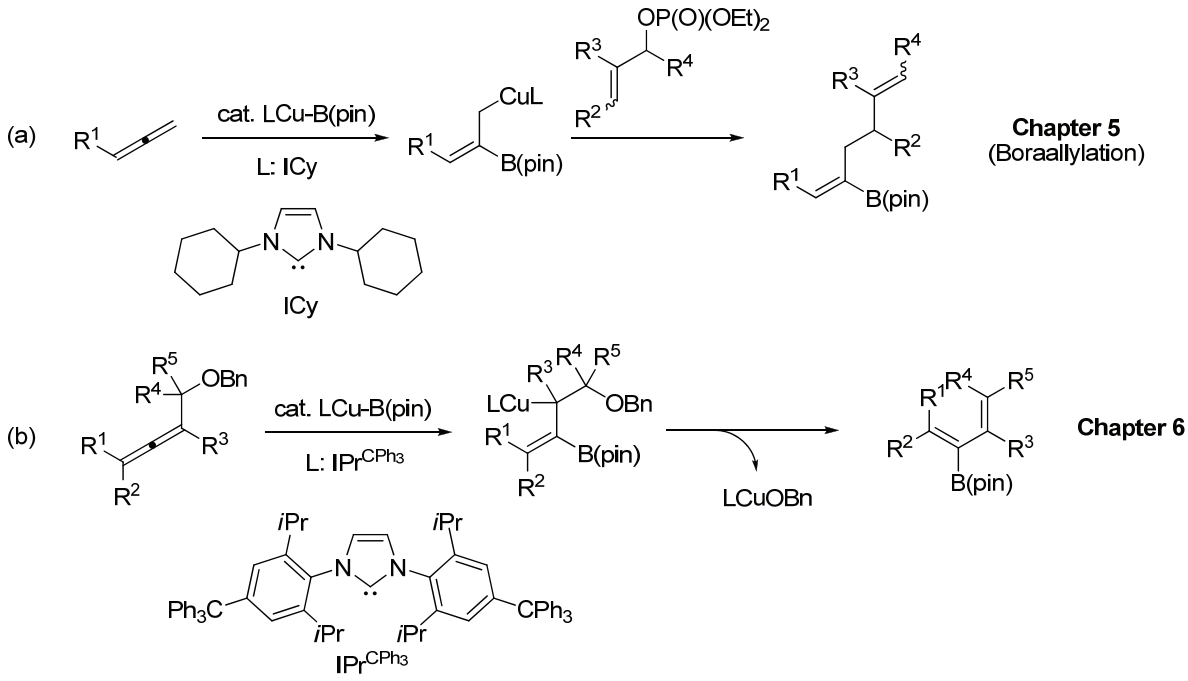
In Chapter 4, the author adapted the concept in Chapter 3 to regioselective hydroboration of other unsaturated compounds such as allenes and 1,3-dienes. As the result, highly regioselective copper-catalyzed hydroboration of allenes affording allylboranes and vinylboranes was developed (Scheme 10).[29] In the case of borylcopper-catalyzed hydroboration, two types of vinylboranes could be synthesized by choice of appropriate ligands. The mechanistic studies clarified that the protonation of (*Z*)-σ-allylcopper species, which was isolated and structurally characterized by the single crystal X-ray analysis, was a key step for the present reactions. Furthermore, the regioselective hydroboration of 1,3-dienes was also achieved employing similar catalytic system.

Scheme 10. Copper-catalyzed regioselective hydroboration of allenes



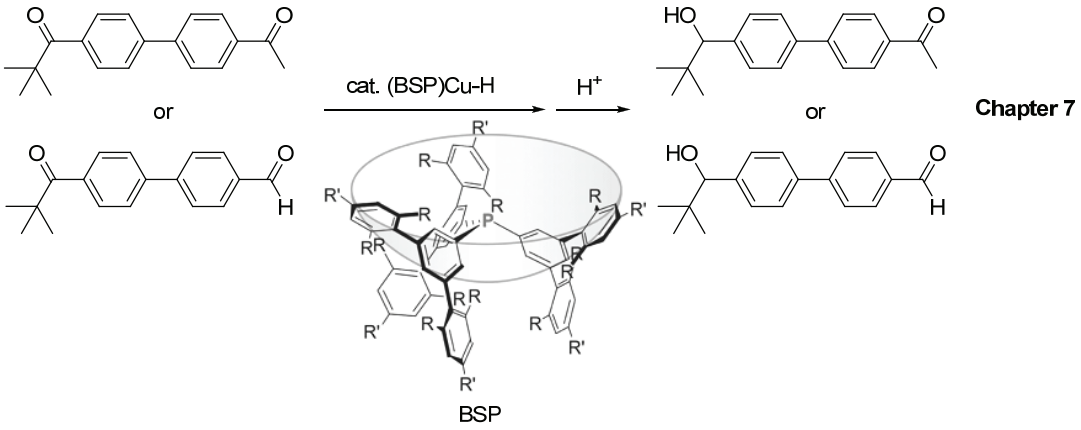
In Chapters 5 and 6, the author tried to develop more advanced transformation employing (*Z*)-β-boryl-σ-allylcopper, which is generated by the reaction between a borylcopper and an allene, as a key intermediate. As the result, in Chapter 5, copper-catalyzed allylboration of allenes was developed employing allyl phosphates as electrophiles (Scheme 11a).[30] In Chapter 6, the author found that 2-boryl-1,3-butadiene derivatives, which are difficult to be synthesized by previous methods, were obtained from the reaction between borylcopper and α-benzyloxyallenes (Scheme 11b).[31]

Scheme 11. Copper-catalyzed boraallylation of allenes and synthesis of 2-boryl-1,3-butadiene derivatives



In Chapter 7, the author developed the highly active copper catalyst bearing bowl-shaped phosphane as a ligand for the hydrosilylation of bulky ketones (Scheme 12).[32] One of the remarkable points of this catalyst is an unique chemoselectivity, which is preferential reduction of bulkier ketones in the presence of an less bulky ketones and even an aldehydes.

Scheme 12. BSP-Cu catalyzed hydrosilylation of bulky ketones



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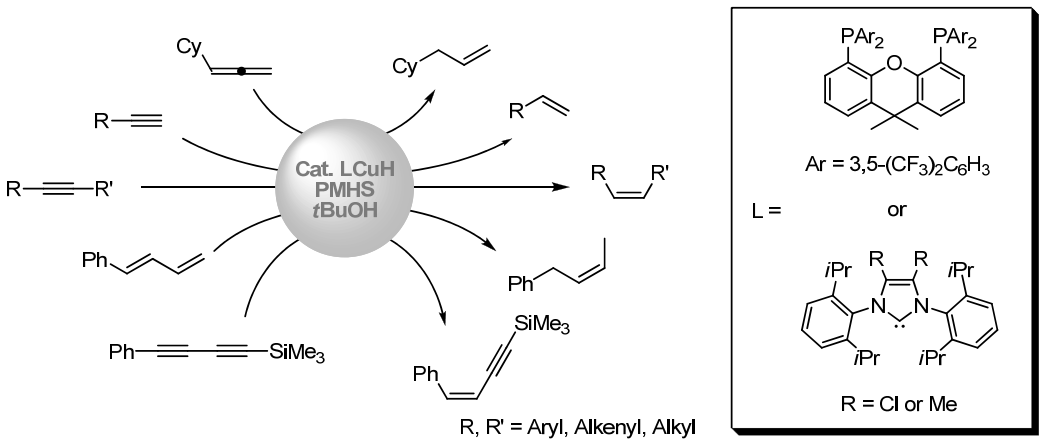
Chapter 1

Copper-Catalyzed Highly Selective Semihydrogenation of Non-Polar Carbon-Carbon Multiple Bonds using a Silane and an Alcohol

A copper catalyst bearing a suitable Xantphos derivative or NHC ligand was found to be highly efficient for selective semihydrogenation of non-polar unsaturated compounds using a mixture of a silane and an alcohol as a reducing agent. The catalytic system was useful for selective semihydrogenation of internal alkynes to (*Z*)-alkenes with suppressing overreduction to the corresponding alkanes. Furthermore, semihydrogenations of terminal alkynes, 1,2-diene, 1,3-diene, 1,3-enynes and 1,3-diyne were also achieved selectively.



1-1. Introduction

Copper compounds are highly valuable reagents in organic synthesis.[1] Among them, copper hydrides, typically $[CuH(PPh_3)]_6$,[2a,b] are powerful reducing reagents for 1,4-reduction of α,β-unsaturated carbonyl compounds.[2b,c] These reductions also can be carried out catalytically using various reducing reagents.[2d,e,3] Especially, hydrosilanes are widely applied in the catalytic reduction of *polar* unsaturated bonds such as C=O, C=N, and C=C conjugated with polar functionalities (viz., Michael acceptors).[3] However, it is quite surprising and frustrating that reduction of *non-polar* carbon-carbon multiple bonds such as simple alkynes cannot be carried out *catalytically* with copper complexes. To date, there have been six precedents[4] using an *excess* amount of copper reagents in reduction of alkynes. However, such an important class of transformations[5] should be performed catalytically.

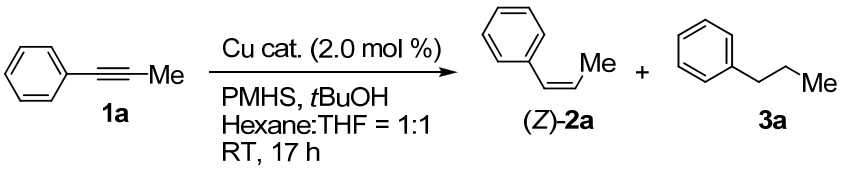
Semihydrogenation of internal alkynes is a crucial methodology to provide (*Z*)-alkenes which are often found in many biologically active compounds.[6] Various heterogeneous catalysts are effective in this transformation.[7] Especially, the Lindlar catalyst[8] is best known and most efficient, but it often suffers from *Z*/*E* isomerization, low chemoselectivity, and poor reproducibility. In the catalytic reactions, hydrogen uptake may be strictly monitored to prevent the overreduction to undesired alkanes. On the other hand, several homogeneous catalysts showed good selectivity in the semihydrogenation of alkynes.[9,10,11] Recently, homogeneous palladium catalysts were intensively developed.[9] In this chapter, the author found that *non-polar* carbon-carbon multiple bonds were efficiently semihydrogenated by a homogeneous copper catalyst. As reported herein, a copper complex bearing a suitable bidentate phosphane or *N*-heterocyclic carbene (NHC) ligand shows high catalytic activity and excellent selectivity by using a mixture of a silane and an alcohol as a reducing agent.

1-2. Results and Discussion

The semihydrogenation of 1-phenyl-1-propyne (**1a**) was carried out at room temperature (Table 1-1). As a reducing reagent, a mixture of polymethylhydrosiloxane (PMHS) and *t*BuOH was employed. Using $Cu(OAc)_2 \cdot H_2O$ as a catalyst precursor without any added ligands resulted in very low conversion of **1a** (entry 1). With added monodentate phosphanes (P/Cu = 4.0) such as PPh_3 and PCy_3, the conversions were also low and the corresponding (*Z*)-alkene ((*Z*)-**2a**) was afforded only in 6% and 9%

yields, respectively (entries 2 and 3). Bidentate phosphanes such as dppe, dppp, *rac*-BINAP and dppbz were not effective in the reaction (entries 4–7). In contrast, Xantphos (Xan) as a ligand afforded the product in 34% yield (entry 8). When the reaction temperature was raised to 65 ºC with Xan, the yield of (*Z*)-**2a** increased to 75%, but the undesired alkane (**3a**) via the overreduction was formed in considerable amount (9% yield, entry 9). Gratifyingly, a Xantphos derivative bearing 3,5-bis(trifluoromethyl)phenyl moieties on the phosphorus atoms (CF_3Ar-Xan[12], Figure 1-1) was found to be much more effective, giving (*Z*)-**2a** in 99% yield without the formation of (*E*)-**2a** (entry 10). This excellent (*Z*)-selectivity is noteworthy because such selective semihydrogenation of aromatic alkynes was often difficult owing to *Z*/*E* isomerization and overreduction to alkanes.[13] With a Xantphos derivative bearing 3,5-xylyl moieties (MeAr-Xan[14]), (*Z*)-**2a** was obtained in 80% yield with considerable formation of **3a** in 10% yield (entry 11). A Xantphos derivative bearing *t*Bu on the phosphorus atoms (*t*Bu-Xan) was not effective at all (entry 12). Thus, the electron-deficient aryl moieties on the phosphorus atoms would be preferable. Both PMHS and *t*BuOH are indispensable components in the reducing agent. When PMHS was removed from the reaction mixture, no hydrogenation occurred (entry 13). Removing *t*BuOH from the system decreased yield of (*Z*)-**2a** to 10% (entry 14). PMHS is a by-product of the silicon industry, and a cheap, easy-to-handle, and environmentally friendly reducing agent.[15] In place of PMHS in entry 10, other silanes such as $(EtO)_3SiH$, Ph_2SiH_2, $(EtO)_2MeSiH$, $PhMe_2SiH$, and Et_3SiH afforded (*Z*)-**2a** in 93%, 82%, 61%, 55%, and 0% yields, respectively. *t*BuOH can be replaced with *i*PrOH and MeOH in entry 10, and (*Z*)-**2a** was obtained in 99% and 94% yields, respectively. As for catalyst precursors, CuCl/*t*BuONa and $[(PPh_3)_3CuF]$ were not so effective (entries 15 and 16).

Table 1-1. Semihydrogenation of 1-phenyl-1-propyne (**1a**) with various catalysts[a]



Entry	Cu cat.	Ligand (P/Cu = 4.0)	Yield [%][b]	
			(*Z*)-**2a**	**3a**
1	$Cu(OAc)_2·H_2O$	None	2	0
2	$Cu(OAc)_2·H_2O$	PPh_3	6	0
3	$Cu(OAc)_2·H_2O$	PCy_3	9	0
4	$Cu(OAc)_2·H_2O$	dppe	2	0
5	$Cu(OAc)_2·H_2O$	dppp	3	0
6	$Cu(OAc)_2·H_2O$	*rac*-BINAP	8	0
7	$Cu(OAc)_2·H_2O$	dppbz	4	0
8	$Cu(OAc)_2·H_2O$	Xan	34	1
9[c]	$Cu(OAc)_2·H_2O$	Xan	75	9
10	$Cu(OAc)_2·H_2O$	CF_3Ar-Xan	99	<1
11	$Cu(OAc)_2·H_2O$	MeAr-Xan	80	10
12	$Cu(OAc)_2·H_2O$	*t*Bu-Xan	2	0
13[d]	$Cu(OAc)_2·H_2O$	CF_3Ar-Xan	0	0
14[e]	$Cu(OAc)_2·H_2O$	CF_3Ar-Xan	10	0
15	CuCl/*t*BuONa[f]	CF_3Ar-Xan	43	0
16	$[(PPh_3)_3CuF]$	CF_3Ar-Xan	54	0

[a] 1-Phenyl-1-propyne (**1a**, 0.50 mmol), Cu cat. (0.010 mmol, 2.0 mol %), ligand (P/Cu = 4.0), PMHS (2.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (1.0 mmol, 2.0 equiv), THF (0.50 mL), hexane (0.50 mL), at room temperature, for 17 h. [b] GC yields by the internal standard method. [c] At 65 ºC. [d] Without PMHS. [e] Without *t*BuOH. [f] CuCl (0.010 mmol) and *t*BuONa (0.060 mmol).

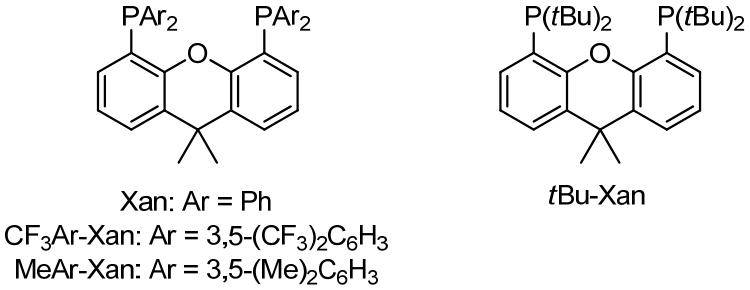
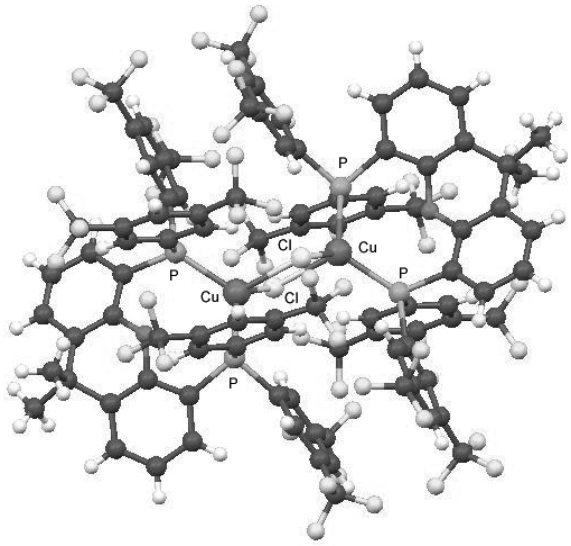


Figure 1-1. The structures of Xantphos derivatives

To confirm the coordination ability of CF_3-ArXan to copper, the author successfully isolated the chlorocopper (I) complex with CF_3-ArXan as a ligand and the structure of copper(I) chloride complexes with Xan and CF_3-ArXan was determined by X-ray crystallography. The complex bearing a CF_3-ArXan was obtained as a dimeric form (Figure 1-2a). The copper atom has a distorted tetrahedral geometry with two phosphorus atoms and two chlorine atom. Two copper atoms were bridged by two chlorine atoms. In contrast, the complex bearing Xan was obtained as a monomeric form (Figure 1-2b). The copper atom has a trigonal-planar coordination geometry with two phosphorus atoms and chlorine atom. Generally, a bulkier ligand supress the formation of muti-nuclear complexes.[16] However, the present result is interesting since a bulkier CF_3-ArXan gives dinuclear complex.[16] Electron-deficiency of the ligand would favor to form dimeric structure.

(a)



(b)

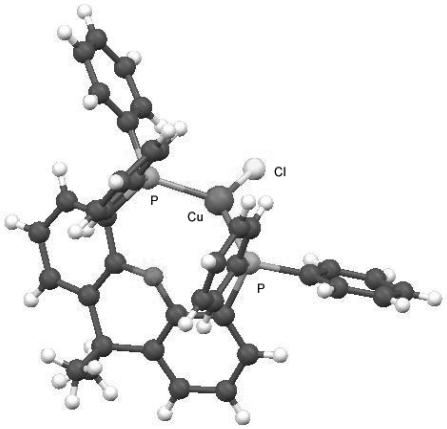
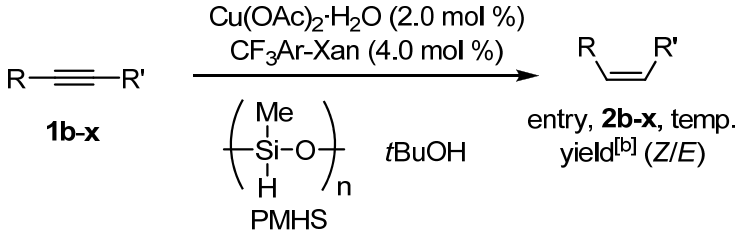


Figure 1-2. The crystal structures of (a) $[(CF_3\text{-ArXan})CuCl]_2$ and (b) [(Xan)CuCl]

The scope of the catalytic reaction was examined using various internal alkynes (**1b**–**x**), and the corresponding (*Z*)-alkenes ((*Z*)-**2b–x**) were isolated in high yields (Table 1-2). In the reaction of 1-phenyl-1-hexyne (**1b**), the (*Z*)-alkene ((*Z*)-**2b**) was isolated in 92% yield with concomitant overreduction to hexylbenzene in 2% yield (entry 1). Fortunately, however, in all the other reactions in Table 1-2 (entries 2–24), the overreduction to undesired alkanes (**3**) did not occur at all. Various functionalities such as hydroxy (entry 2), siloxy (entry 3), phthalimido (entry 4), chloro (entry 5), cyano (entry 6) and vinyl silane (entry 7) were tolerated in the reactions. An alkyne bearing a thienyl moiety also afforded the corresponding (*Z*)-alkene ((*Z*)-**2i**) exclusively (entry 8). Diaromatic internal alkynes also afforded the corresponding (*Z*)-alkenes stereoselectively without the formation of alkanes. Diphenylacetylene (**1j**) was reduced to stilbene (**2j**, *Z*/*E* = 98/2) in 93% isolated yield without formation of bibenzyl (entry 9), while the conventional Lindlar catalyst afforded a considerable amount of the alkane: selectivity of (*Z*)-**2j**/(*E*)-**2j**/bibenzyl = 93/2/5.[7d] It is noteworthy that even 0.10 mol % catalyst loading afforded satisfactory result at 50 ºC after 79 h (entry 10). Both electron-rich (entries 12 and 13) and electron-poor (entries 14–19) diaromatic alkynes afforded the (*Z*)-alkenes selectively. Functionalities on the phenyl rings such as ester (entry 14) and amide (entry 15) were intact in the reaction, while acetyl moiety of $4\text{-}CH_3CO\text{-}C_6H_4C{\equiv}CC_6H_5$ (**1p**) was reduced to the corresponding hydroxyl moiety (**2p'**, entry 16). Bromo and iodo moieties on the aromatic ring were intact (**2t** and **2u**, entries 20 and 21), which must undergo the oxidative addition reaction with most low-valent

transition metal catalyst centers such as Pd(0).[9] 6-Dodecyne (**1v**) was smoothly converted to the corresponding (*Z*)-alkene ((*Z*)-**2v**) in good yield with perfect selectivity (entry 22). However, other internal aliphatic alkynes such as **1w** and **1x** were not converted completely with the $Cu(OAc)_2 \cdot H_2O/CF_3Ar$-Xan catalyst system which was highly efficient in most entries in Table 1-2. In these cases, [(^{Cl}IPr)CuCl]/*t*BuONa catalyst system (for ^{Cl}IPr, see Figure 1-3) was much more effective, and (*Z*)-**2w** and (*Z*)-**2x** were isolated in high yields with perfect selectivities (entries 23 and 24).

Table 1-2. Semihydrogenation of various internal alkynes[a]



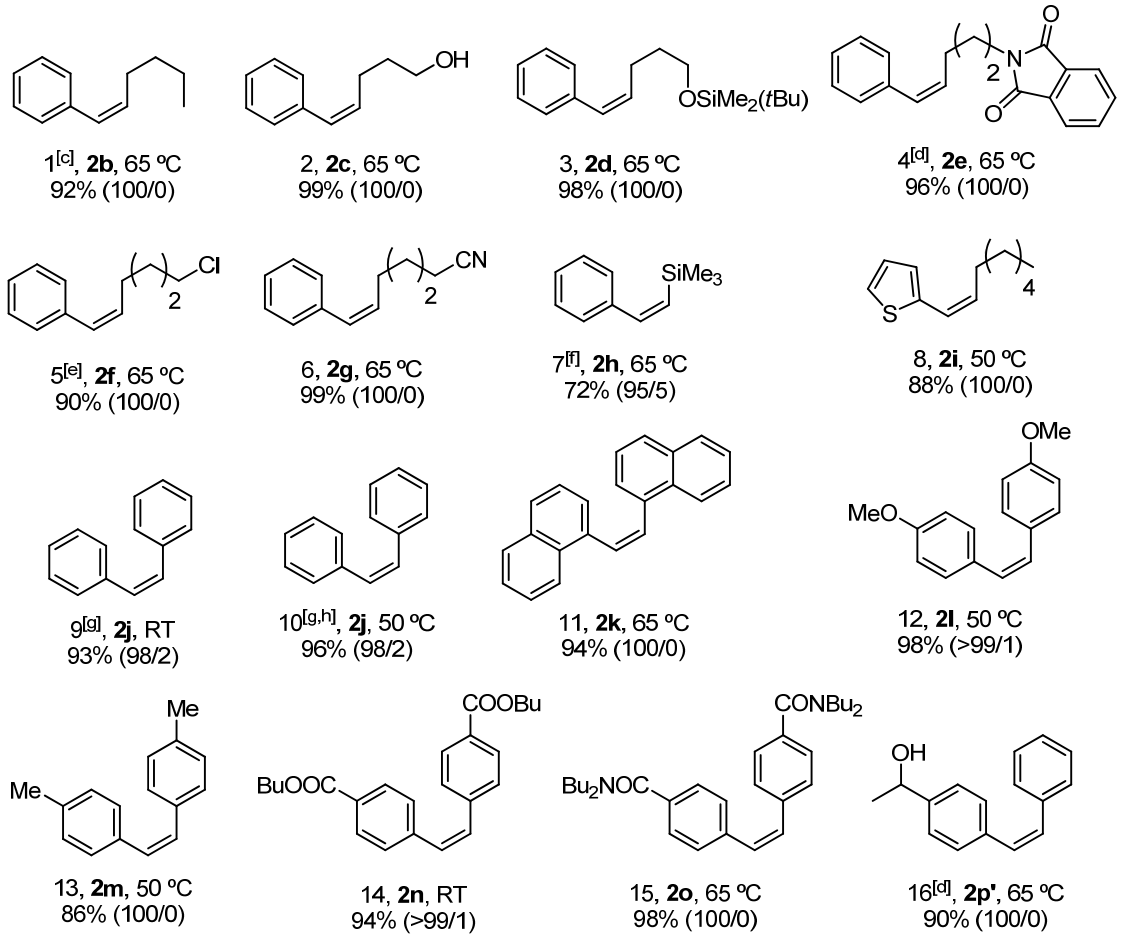
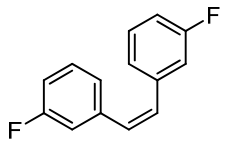
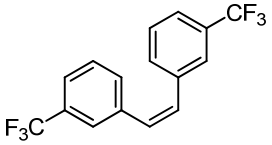


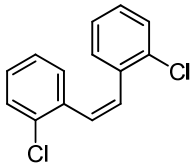
Table 1-2. (Continued)



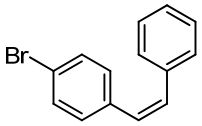
17, **2q**, RT
86% (100/0)



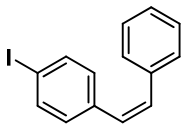
18, **2r**, RT
97% (100/0)



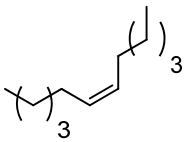
19[i], **2s**, 65 ºC
86% (100/0)



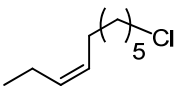
20, **2t**, 65 ºC
98% (100/0)



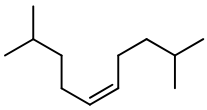
21, **2u**, 65 ºC
98% (100/0)



22[e,j], **2v**, 65 ºC
78% (100/0)



23[k], **2w**, 65 ºC
87% (100/0)

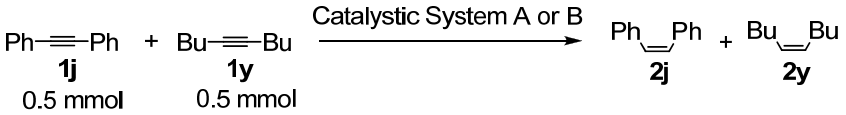


23[l], **2x**, 65 ºC
83% (100/0)

[a] Internal alkyne (0.50 mmol), $Cu(OAc)_2 \cdot H_2O$ (0.010 mmol, 2.0 mol %), CF_3Ar-Xan (0.020 mmol, 4.0 mol %), PMHS (2.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (1.0 mmol, 2.0 equiv), solvent (1.0 mL, hexane:THF = 1:1 (v/v)), for 20 h. [b] Isolated yields. In the case of **1c** and **1p**, **2c** and **2p´** were isolated after hydrolysis by adding 1.0 M HCl/MeOH. [c] Hexylbenzene was afforded in 2% yield. [d] Hexane:THF = 1:2 (v/v). [e] Hexane:THF = 10:1 (v/v). [f] Hexane (1.0 mL). [g] THF (1.0 mL). [h] $Cu(OAc)_2 \cdot H_2O$ (0.50 μmol, 0.10 mol %), CF_3Ar-Xan (1.0 μmol, 0.20 mol %), for 79 h. [i] Hexane:THF = 3:1 (v/v). [j] $Cu(OAc)_2 \cdot H_2O$ (0.020 mmol, 4.0 mol %), CF_3Ar-Xan (0.040 mmol, 8.0 mol %). [k] **2w** (1.0 mmol), [(^{Cl}IPr)CuCl] (0.040 mmol, 4.0 mol %), *t*BuONa (0.12 mmol, 12 mol %), PMHS (4.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (2.0 mmol, 2.0 equiv), hexane (2.0 mL). [l] **2x** (1.0 mmol), [(^{Cl}IPr)CuCl] (0.060 mmol, 6.0 mol %) and *t*BuONa (0.18 mmol, 18 mol %), PMHS (4.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (2.0 mmol, 2.0 equiv), hexane (2.0 mL).

One of the remarkable features of the present copper-catalyzed semihydrogenation is that diaromatic alkynes can be more easily reduced than dialkylalkynes (entries 9 vs 22 in Table 1-2). Such preferential reduction was confirmed in a competitive reaction with an equimolar mixture of diphenylacetylene (**1j**) and 5-decyne (**1y**) (Scheme 1-1). Notabely, **1j** was selectively reduced to **2j** in the presence of **1y**. In sharp contrast, employing the Lindlar catalyst, nonselective reduction was observed.

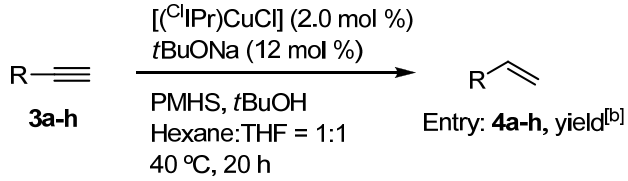
Scheme 1-1. Competitive reaction of diphenylacetylene (**1j**) and 5-decyne (**1y**) employing copper catalysts or Lindlar catalyst

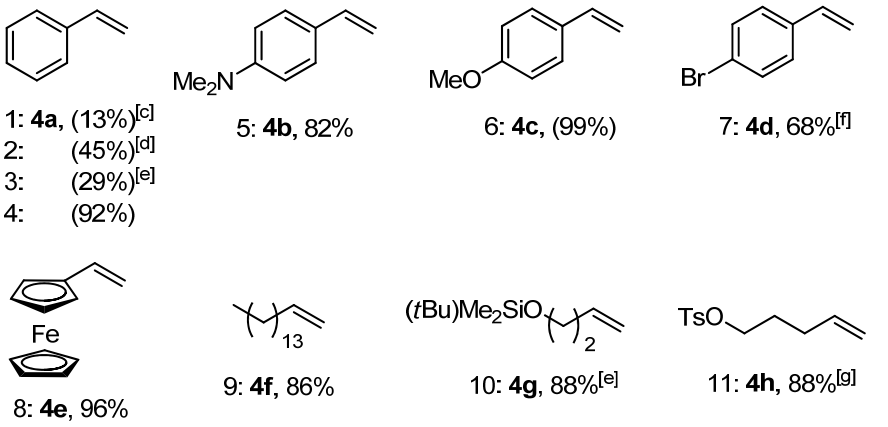


Catalytic System	Yield of **2j**	Yield of **2y**
A: $Cu(OAc)_2 \cdot H_2O$ (2 mol %), Xan (4 mol %) PMHS (4.0 equiv), *t*BuOH (2.0 equiv), THF, 28 °C, 20 h	99%	0%
B: Lindlar cat. (5 mol %) H_2 (balloon), CH_2Cl_2, 28 °C, 6 h	37%	62%

Selective semihydrogenation of terminal alkynes is known to be difficult due to the overreduction to the corresponding alkanes.[7b,9e] $Cu(OAc)_2 \cdot H_2O/CF_3$Ar-Xan catalyst system, which was efficient for internal alkynes (Table 1-2), was not active enough to realize complete conversion of terminal alkynes. Actually, phenylacetylene (**3a**) afforded styrene (**4a**) only in 13% yield with the $Cu(OAc)_2 \cdot H_2O/CF_3$Ar-Xan catalyst system (entry 1, Table 1-3), even overreduction to ethylbenzene did not occur at all. For terminal alkynes, NHC ligands such as IPr, ^{Me}IPr, and ^{Cl}IPr (Figure 1-3) were more effective than the Xan derivatives (entries 2–4). Especially, [(^{Cl}IPr)CuCl]/*t*BuONa catalyst system was highly effective to afford **4a** in 92% yield without the formation of ethylbenzene (entry 4). With the conventional Lindlar catalyst, considerable overreduction occurred (selectivity: **4a**/ethylbenzene = 89/11).[8a] Other aromatic and aliphatic terminal alkynes were also selectively semihydrogenated using [(^{Cl}IPr)CuCl]/*t*BuONa (entries 5–9) or [(^{Me}IPr)CuCl]/*t*BuONa (entries 10 and 11) catalyst system without the overreduction to the corresponding alkanes.

Table 1-3. Semihydrogenation of various terminal alkynes[a]





[a] Terminal alkyne (0.50 mmol), [(^{Cl}IPr)CuCl] (0.010 mmol, 2.0 mol %), *t*BuONa (0.060 mmol, 12 mol %), PMHS (2.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (1.0 mmol, 2.0 equiv), THF (0.50 mL), hexane (0.50 mL), at 40 ºC, for 20 h. [b] Isolated yields. The numbers in the parentheses show GC yields determined by the internal standard method. [c] $Cu(OAc)_2 \cdot H_2O$ (0.010 mmol, 2.0 mol %) and CF_3Ar-Xan (0.020 mmol, 4.0 mol %) as a catalyst. [d] [(IPr)CuCl] in place of [(^{Cl}IPr)CuCl]. [e] [(^{Me}IPr)CuCl] in place of [(^{Cl}IPr)CuCl]. [f] At 50 ºC. [g] [(^{Me}IPr)CuCl] (0.020 mmol, 4.0 mol %), *t*BuONa (0.12 mmol, 24 mol %), THF (1.0 mL), hexane (1.0 mL).

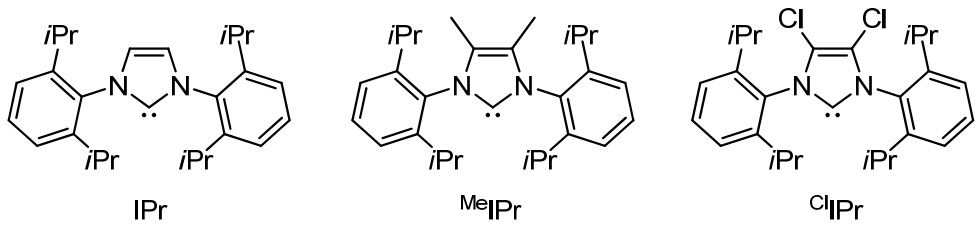


Figure 1-3. The structures of IPr derivatives

Besides simple alkynes, conjugated non-polar carbon-carbon unsaturated compounds such as 1,2-diene, 1,3-diene, 1,3-enyne and 1,3-diyne were selectively semihydrogenated to products (**6a**–**e**) in high yields (Table 1-4). No overreductions occurred in all the cases in Table 1-4. From a 1,2-diene (**5a**), the terminal alkene (**6a**) was selectively afforded in 81% yield (entry 1). 1-Phenyl-1,3-butadiene (**5b**) provided the corresponding (*Z*)-alkene ((*Z*)-**6b**) exclusively (entry 2).[17] Often semihydrogenation of 1,3-enynes was not so selective. As for **5c**, overreduction occurred considerably by the Lindlar catalyst (selectivity: **5c**/**6c**/ethylcyclohexene = 6/86/8)[8c] or a complex mixture of various isomers was obtained in transfer semihydrogenation with a NHC Pd(0) catalyst.[9d] In the present reaction, **5c** and **5d** were semihydrogenated to the corresponding 1,3-dienes (**6c** and **6d**) in high selectivities (entries 3 and 4). 1,3-Diynes are also known to be difficult substrates in selective semihydrogenation.[9d] However, with the $Cu(OAc)_2/CF_3Ar$-Xan catalyst system, a 1,3-diyne (**5e**) was reduced to the corresponding 1,3-enyne ((*Z*)-**6e**) exclusively (entry 5).

Table 1-4. Semihydrogenation of Conjugated Carbon-Carbon Unsaturated Compounds[a]

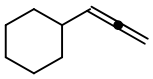
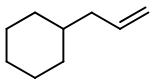
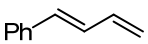
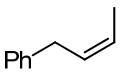
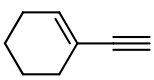
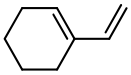
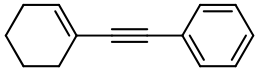
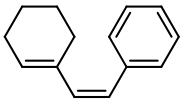
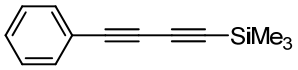
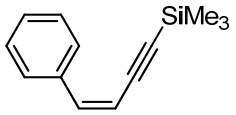
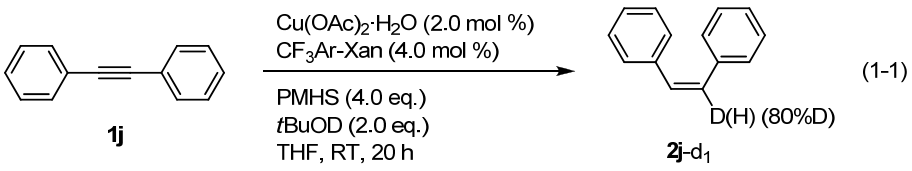
Entry	Substrate	Cat.[b] Temp.	Product (Yield [%][c])
1	 **5a**	A 65 ºC	 **6a** (81%)
2	 **5b**	B 50 ºC	 **6b** 75% (*Z*/*E* = 100/0)
3	 **5c**	B 40 ºC	 **6c** (75%)

Table 1-4. (Continued)

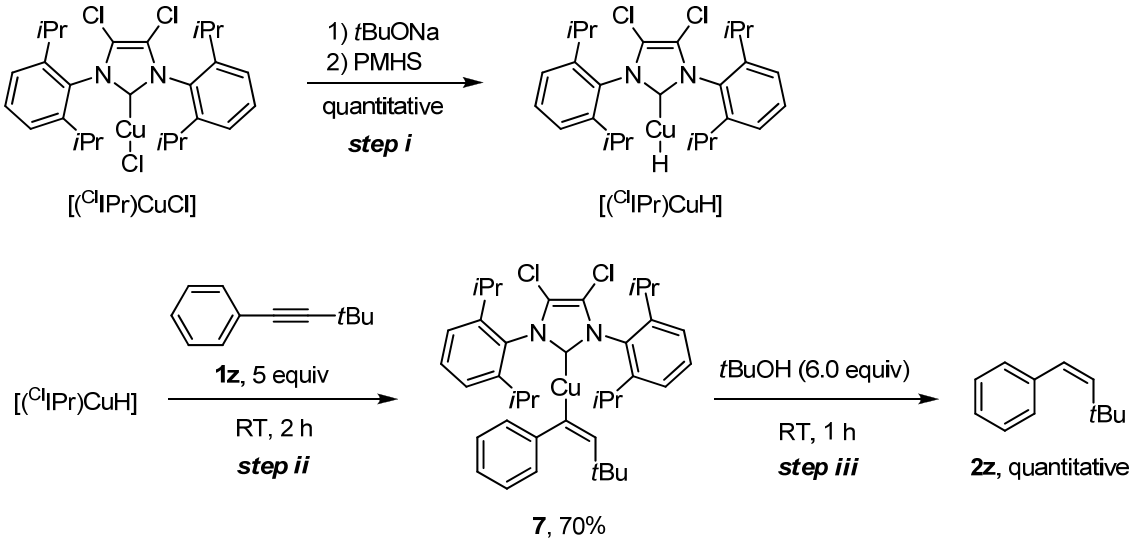
4	 **5d**	B 40 ºC	 **6d** 97% (*Z*/*E* = 98/2)
5[d]	 **5e**	A RT	 **6e** 90% (*Z*/*E* = 100/0)

[a] Substrate (0.50 mmol), Cat. A or B, PMHS (2.0 mmol as the Si-H unit, 4.0 equiv), *t*BuOH (1.0 mmol, 2.0 equiv), THF (0.50 mL), hexane (0.50 mL) for 20 h. [b] Cat. A: $Cu(OAc)_2 \cdot H_2O$ (0.010 mmol, 2.0 mol %), CF_3Ar-Xan (0.020 mmol, 4.0 mol %). Cat. B: [(^{Cl}IPr)CuCl] (0.010 mmol, 2.0 mol %), *t*BuONa (0.060 mmol, 12 mol %). [c] Isolated yields. The numbers in the parentheses show GC yields determined by the internal standard method. [d] PMHS (1.0 mmol as the Si-H unit, 2.0 equiv), for 18 h.

To gain insights into the reaction mechanism, a deuterium labeling experiment was carried out (eq 1-1). Employing nondeuterated PMHS and *t*BuOD (98 atom % D) in the semihydrogenation of diphenylacetylene (**1j**), a monodeuterated stilbene (**2j**-d_1, *Z*/*E* = 98/2) was selectively formed, and dideuterated stilbene (**2j**-d_2) was not detected at all, which was confirmed by ^{1}H NMR and GC-MS. Furthermore, several stoichiometric reactions relevant to each step in the catalytic cycle were carried out (Scheme 1-2). In the reactions of [(^{Cl}IPr)CuCl] with *t*BuONa[18] and successively with PMHS,[19] ^{1}H resonances of the reaction mixtures indicated that the reactions were very clean and the corresponding copper hydride, [(^{Cl}IPr)CuH], was afforded quantitatively as shown by the diagnostic ^{1}H resonance of Cu-H at 2.4 ppm[20] (step i in Scheme 1-2). The resulting [(^{Cl}IPr)CuH] easily underwent *syn*-addition[21] to $C_6H_5C{\equiv}C(t\text{Bu})$ (**1z**) at room temperature to afford the corresponding alkenyl copper complex (**7**), which was isolated in pure form in 70% yield[20] (step ii). The isolated **7** smoothly and cleanly reacted with *t*BuOH at room temperature for 1 h and the corresponding (*Z*)-alkene (**2z**) was quantitatively afforded (step iii) as judged by ^{1}H NMR and GC-MS analysis.

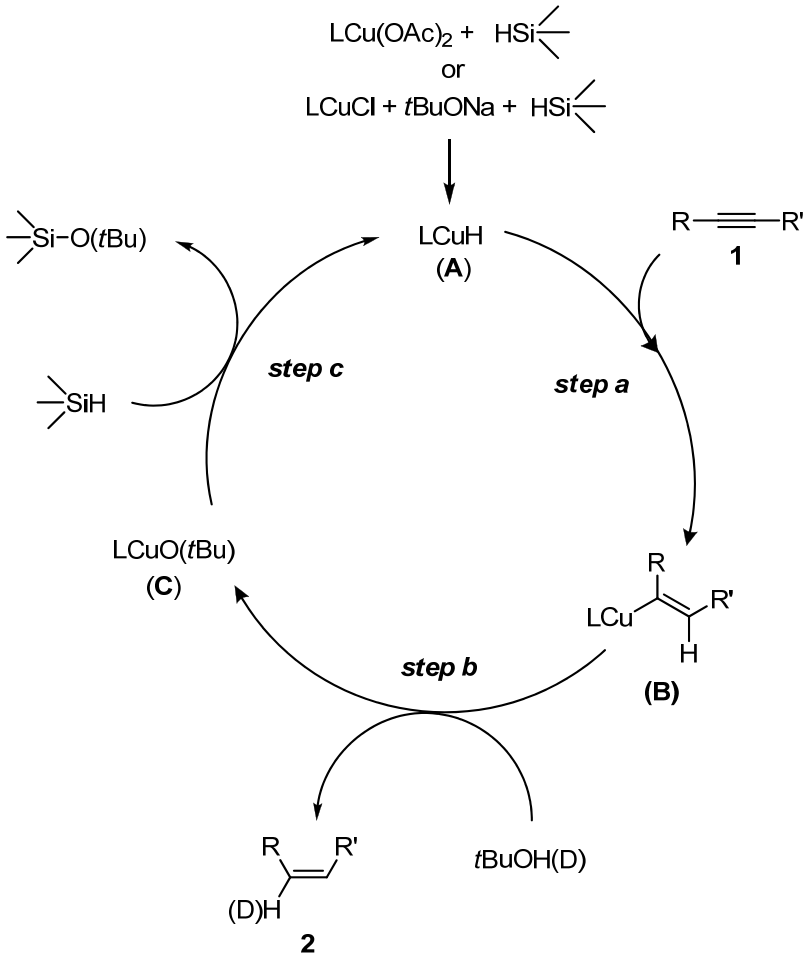


Scheme 1-2. Stoichiometric reactions relevant to reaction mechanism



With these results obtained in eq 1-1 and Scheme 1-2, a possible catalytic cycle for the present copper-catalyzed semihydrogenation of alkynes is shown in Scheme 1-3. A copper(I) hydride species (**A**) is generated by the reaction of the catalyst precursors with a silane. Addition of **A** to alkynes (**1**) must be much faster than to alkenes, and affords a copper alkenyl intermediate (**B**) stereoselectively via *syn*-addition[21] (step a). Successively, protonation of **B** with *t*BuOH provides (*Z*)-alkenes (**2**) selectively with the concomitant formation of [LCuO(*t*Bu)] (**C**) (step b). Finally, σ-bond metathesis between **C** and a silane regenerates **A** and the catalytic cycle is closed (step c).[19]

Scheme 1-3. A possible reaction mechanism



1-3. Conclusion

Non-polar unsaturated compounds such as internal alkyne, terminal alkyne, 1,2-diene, 1,3-diene, 1,3-enyne, and 1,3-diyne were semihydrogenated selectively. A copper catalyst bearing a suitable Xantphos derivative or NHC ligand was highly efficient in the semihydrogenation. Especially, the present catalytic system was useful for semihydrogenation of internal alkynes to the corresponding (*Z*)-alkenes with suppressing both *Z*/*E* isomerization and overreduction to alkanes.

1-4. Experimental Section

General procedures and synthesis of materials.

General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[22] ^{1}H NMR and

$^{13}C\{^{1}H\}$ NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). $^{31}P\{^{1}H\}$ NMR spectra were also recorded at a JEOL ECX-400 spectrometer using 85% H_3PO_4 as an external standard. EI-MS were recorded on a Shimadzu GCMS-QP5050A with a direct inlet. MALDI-TOF-MS spectra were recorded on a Bruker Autoflex. High-resolution mass spectra (EI-HRMS) were obtained with a JEOL SX-102A spectrometer. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-17A equipped with an integrator (C-R8A) with a capillary column (CBP-20, 0.25 mm i.d. × 25 m).

Materials: Unless otherwise noted, commercially available chemicals were used as received. Anhydrous THF was purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[23] Hexane was distilled from benzophenone ketyl. CuCl was purified according to a literature.[22] *t*BuOH was distilled over CaH_2. PMHS was degassed by freeze-pump-thaw cycling

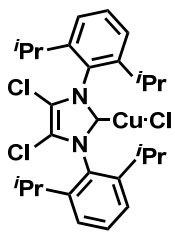
Synthesis of CF_3Ar-Xan. A literature method[12] was modified as follows. A solution of *n*BuLi (5.6 mL of 1.6 M solution in hexane, 9.1 mmol) was added to a solution of 9,9-dimethylxanthene (760 mg, 3.6 mmol) and *N*,*N*,*N'*,*N'*-tetramethylethylenediamine (1.4 mL, 9.3 mmol) in Et_2O (12 mL) at 0 ºC, and the mixture was stirred overnight at 0 ºC. The resulting orange suspension was cooled to –90 ºC, and a solution of bis[3,5-di(trifluoromethyl)phenyl]chlorophosphane (5.0 g, 10 mmol) in Et_2O (15 mL) was slowly added over 10 min to the solution at –90 ºC. The reaction mixture was allowed to warm to room temperature and further stirred overnight. After removal of the volatiles, CH_2Cl_2 (20 mL) and H_2O (20 mL) were added under air. After vigorous stirring, the aqueous layer was removed. The organic layer was washed twice with H_2O (20 mL) and dried over $MgSO_4$. After filtration, the solvent was removed and the

product was purified by silica gel column chromatography using eluent (Hexane/CH_2Cl_2 = 40/1 to 20/1) degassed by Ar bubbling. CF_3Ar-Xan was obtained in 46% yield (1.9 g, 1.7 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.88 (s, 4H), 7.61 (s, 8H), 7.57 (d, J = 8 Hz, 2H), 7.13 (t, J = 8 Hz, 2H), 6.40 (d, J = 8 Hz, 2H), 1.67 (s, J = 8 Hz, 6H). ^{31}P NMR (160 MHz, $CDCl_3$): δ –13.9. All the resonances in ^{1}H and ^{31}P NMR spectra were consistent with reported values.[12]

Synthesis of MeAr-Xan. A solution of *n*BuLi (3.9 mL of a 1.7 M solution in hexane, 6.5 mmol) was added to a solution of 9,9-dimethylxanthene (540 mg, 2.6 mmol) and *N*,*N*,*N'*,*N'*-tetramethylethylenediamine (990 μL, 6.6 mmol) in Et_2O (10 mL) at 0 ºC, and the mixture was stirred overnight at 0 ºC. The resulting orange suspension was cooled to –90 ºC, and a solution of bis(3,5-dimethylphenyl)chlorophosphane (2.0 g, 7.2 mmol) in Et_2O (8.0 mL) was slowly added over 10 min to the solution at –90 ºC. The reaction mixture was allowed to warm to room temperature and further stirred overnight. After removal of volatiles, degassed CH_2Cl_2 (15 mL) and H_2O (15 mL) were added under argon atmosphere. After vigorous stirring, the aqueous layer was removed. The organic layer was washed twice with degassed H_2O (10 mL) and dried over $MgSO_4$. After filtration, the solvent was removed and the product was purified by silica gel column chromatography using an eluent (Hexane/CH_2Cl_2 = 10/1) degassed by Ar bubbling. MeAr-Xan was obtained in 45% yield (800 mg, 1.2 mmol). All the ^{1}H and ^{31}P resonances of the product were consistent with reported values.[14]

Synthesis of [(^{Cl}IPr)CuCl]

[(^{Cl}IPr)CuCl] was synthesized according to the method of the previous report.[20]



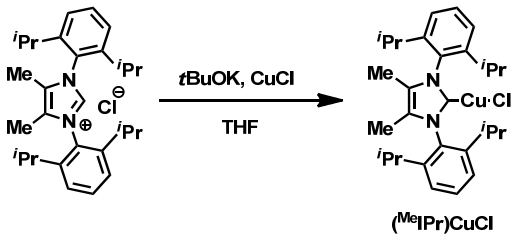
(^{Cl}IPr)CuCl

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.55 (t, J = 7.9 Hz, 2H), 7.33 (d, J = 7.9 Hz, 4H), 2.50-2.43 (m, 4H), 1.30 (d, J = 7.1 Hz, 12H), 1.27 (d, J = 6.7 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 179.6, 146.0, 131.5, 131.3, 124.5, 118.8, 29.0, 24.9, 23.3. MALDI-TOF-MS (CSA): *m/z* 519 (91%), 521 (100%) ([M-Cl]$^+$). Anal. Calcd. for $C_{13}H_{16}O_3$: C, 58.28; H, 6.16. Found: C, 58.18; H, 6.07.

Synthesis of (^{Me}IPr)·HCl

(^{Me}IPr)·HCl was prepared according to the literature.[24]

Synthesis of [(^{Me}IPr)CuCl]



(^{Me}IPr)·HCl (450 mg, 1.0 mmol), *t*BuOK (130 mg, 1.2 mmol), CuCl (99 mg, 1.0 mmol) and THF (20 mL) were added to a 50 mL schlenk flask, and the resulting mixture was stirred at room temperature for 24 h. After filtration through celite, the solvent was removed in vacuo. The crude product was washed with hexane. [(^{Me}IPr)CuCl] was obtained in 72% yield (370 mg, 0.72 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48 (t, J = 7.9 Hz, 2H), 7.29 (d, J = 7.5 Hz, 4H), 2.49–2.41 (m, 4H), 1.92 (s, 6H), 1.28 (d, J = 6.7 Hz, 12H), 1.23 (d, J = 7.1 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 176.8, 145.8, 132.8, 130.4, 126.0, 124.3, 28.6, 25.4, 23.3, 9.5. MALDI-TOF-MS (CSA): *m/z* 479 (100%), 480 (31%), 481 (45%) ([M-Cl]$^{+}$). Anal. Calcd. for $C_{13}H_{16}O_3$: C, 67.55; H, 7.82. Found: C, 67.26; H, 7.82.

Synthesis of [(Xan)CuCl]

CuCl (99 mg, 1.0 mmol) and Xan (610 mg, 1.1 mmol) were added to a 50 mL schlenk flask. The flask was evacuated and backfilled with argon three times. CH_2Cl_2 (20 mL) and toluene (20 mL) were added, and the mixture was stirred overnight at room temperature under an argon atmosphere. After filtration through a pad of celite, the solvents were removed in vacuo. The residue was washed by toluene. [(Xan)CuCl] was obtained in 87% yield (590 mg, 0.87 mmol) as a pinkish white solid. The single crystal of [(Xan)CuCl] was obtained by the diffusion of pentanes into concentrated CH_2Cl_2 solution. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 (d, J = 7.7 Hz, 2H), 7.43–7.39 (m, 8H), 7.29 (t, J = 7.7 Hz, 4H), 7.21 (t, J = 7.2 Hz, 8H), 7.09 (t, J = 7.7 Hz, 2H), 6.57–6.55 (m, 2H), 1.67 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 154.6 (t, J = 6.2 Hz), 133.8 (t, J = 8.1 Hz), 133.2, 131.4 (t, J = 18 Hz), 129.8, 128.5 (t, J = 4.8 Hz), 126.7, 124.7, 119.9 (t, J =

14 Hz), 35.7, 28.3. An Ar-C cannot be identified because of overlapping. ^{31}P NMR (160 MHz, $CDCl_3$): δ –17.1. ESI-HRMS: Calcd. for $C_{39}H_{32}ClCuOP_2$ ($[M+Na]^+$), 699.0805. Found, 699.0772.

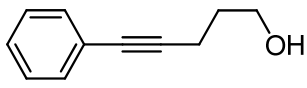
Synthesis of [(CF_3Ar-Xan)CuCl]$_2$

In a N_2 filled glovebox, CuCl (22 mg, 0.22 mmol), CF_3Ar-Xan (230 mg, 0.20 mmol) and CH_2Cl_2 (3.0 mL) were added to a 20 mL schlenk flask. The resulting mixture was stirred at room temperature for 3 h under an N_2 atmosphere. After filtration through a pad of celite, the solvents were removed in vacuo. The product was recrystalized by the diffusion of pentanes into concentrated CH_2Cl_2 solution. [(CF_3-ArXan)CuCl]$_2$ was obtained in 43% yield (110 mg, 0.043 mmol) as a white solid. The single crystal of [(CF_3-ArXan)CuCl]$_2$ was obtained by the diffusion of pentanes into concentrated CH_2Cl_2 solution. ^{1}H NMR (400 MHz, CD_2Cl_2): δ 7.97–7.95 (m, 24H), 7.78 (dd, J = 7.7 Hz, 1.4 Hz, 4H), 7.31 (t, J = 7.7 Hz, 4H), 6.59–6.55 (m, 4H), 1.77 (s, 12H). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 155.0 (t, J = 6.7 Hz), 135.2 (brs), 133.9 (q, J = 16.2 Hz), 132.8 (tq, J = 4.8 Hz, 34.0 Hz), 131.3, 129.3, 126.9 (t, J = 2.4 Hz), 125.4 (brs), 123.0 (q, J = 273.4 Hz), 115.7, 36.6, 27.5. ^{31}P NMR (160 MHz, $CDCl_3$): δ –16.5. ESI-HRMS: Calcd. for $C_{94}H_{48}Cl_2F_{48}Cu_2O_2P_4$ ($[M-Cl]^+$), 2405.0113. Found, 2405.0076.

Syntheses of Substrates.

Preparation of **1k**[25], **1l**[25], **1m**[25], **1n**[20], **1q**[25], **1r**[20], **1s**[25], **3h**[26] and **5b**[27] were according to literature methods.

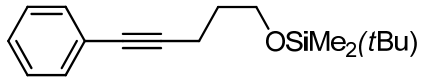
Preparation of 1c.

1c: 

[$Pd(PPh_3)_4$] (690 mg, 0.60 mmol) and CuI (230 mg, 1.2 mmol) were added to a mixture of iodobenzene (6.7 mL, 60 mmol), 4-pentyn-1-ol (2.8 mL, 30 mmol), triethylamine (42 mL, 300 mmol) and THF (15 mL) under Ar. The reaction mixture was stirred overnight at room temperature. After removal of volatiles, the mixture was dissolved in CH_2Cl_2 (100 mL) and washed with H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **1c** was obtained by silica gel column chromatography (eluent:

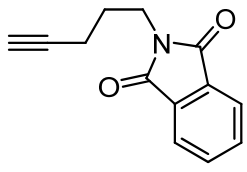
Hexane/EtOAc = 3/1) in 83% yield (4.0 g, 25 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.38 (m, 2H), 7.27–7.26 (m, 3H), 3.80 (t, J = 6.1 Hz, 2H), 2.53 (t, J = 6.7 Hz, 2H), 1.96 (s, 1H), 1.85 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.5, 128.2, 127.6, 123.7, 89.3, 81.1, 61.6, 31.3, 15.9. All the resonances in ^{1}H spectrum were consistent with reported values.[28]

Preparation of 1d.

1d: 

tert-Butyldimethylsilyl chloride (920 mg, 6.1 mmol) was added to a mixture of **1c** (810 mg, 5.0 mmol), imidazole (890 mg, 13 mmol) and DMF (2.0 mL) at 0 ºC, and the mixture was stirred overnight at room temperature. The resulting solution was poured into Et_2O (100 mL) and washed with H_2O, 1N HCl aq. and brine. The organic layer was dried over Na_2SO_4. After filtration, the solvent was removed and **1d** was obtained by silica gel column chromatography (eluent: Hexane/EtOAc = 50/1) in 64% yield (880 mg, 3.2 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.37 (m, 2H), 7.29–7.26 (m, 3H), 3.76 (t, J = 6.1 Hz, 2H), 2.50 (t, J = 7.1 Hz, 2H), 1.81 (m, 2H), 0.91 (s, 9H), 0.08 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.5, 128.2, 127.5, 124.0, 89.9, 80.7, 61.6, 31.7, 26.0, 18.4, 15.8, –5.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[29]

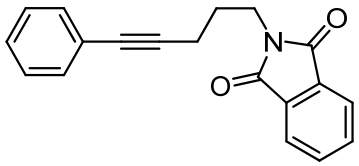
Preparation of 1-(4-pentynyl)-phthalimido.



5-Chloro-1-pentyne (5.3 mL, 50 mmol) was added to a suspension of phthalimide (8.8 g, 60 mmol), K_2CO_3 (5.1 g, 50 mmol), KI (100 mg) and DMF (50 mL). After the mixture was stirred at 70 ºC for 16 h, the resulting solution was cooled to room temperature and poured into H_2O (50 mL). The mixture was extracted with Et_2O (200 mL × 4), and the organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and the product was obtained by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 1/1) in 87% yield (9.3 g, 44 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.86–7.84 (m, 2H), 7.74–7.71 (m, 2H), 3.80 (t, J = 6.9 Hz ,2H), 2.28 (td, J = 6.9, 2.4 Hz, 2H), 1.97–1.90 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.3, 133.9, 132.0, 123.1, 82.9, 69.0, 37.0, 27.2,

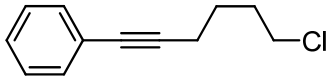
16.2. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[30]

Preparation of 1e.

1e: 

A flask was charged with benzene (25 mL) and triethylamine (7.5 mL). Oxygen in the system was removed by two freeze-pump-thaw cycles. Iodobenzene (1.4 mL, 12 mmol), 1-phthalimido-4-pentyne (2.1 g, 10 mmol), [$Pd(PPh_3)_4$] (230 mg, 0.20 mmol) and CuI (95 mg, 0.50 mmol) were added in this order to the flask, and the resulting mixture was stirred overnight at 50 ºC. The mixture was cooled to room temperature and quenched by MeOH (5 mL). All volatiles were removed in vacuo, and Et_2O (200 mL) was added. After filtration, the filtrate was washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **1e** was obtained by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 2/1) in 37% yield (1.1 g, 3.7 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83–7.81 (m, 2H), 7.68–7.65 (m, 2H), 7.29–7.26 (m, 2H), 7.23–7.21 (m, 3H), 3.87 (t, J = 6.9 Hz, 2H), 2.50 (t, J = 6.7 Hz, 2H), 2.02 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.4, 133.8, 132.1, 131.5, 128.1, 127.5, 123.6, 123.2, 88.7, 81.2, 37.4, 27.3, 17.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[31]

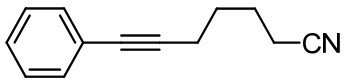
Preparation of 1f.

1f: 

A flask was charged with [$PdCl_2(PPh_3)_2$] (70 mg, 0.10 mmol), CuI (38 mg, 0.2 mmol), THF (60 mL), TBAF (20 mL of a 1.0 M solution in THF, 20 mmol), 6-chloro-1-hexyne (1.5 mL, 12 mmol) and iodobenzene (1.1 mL, 10 mmol) in this order. The mixture was stirred at room temperature for 6 h. After removal of all volatiles, the residue was dissolved in Et_2O (100 mL) and washed with H_2O. The organic layer was dried over Na_2SO_4. After filtration, the solvent was removed and **1f** was obtained by silica gel column chromatography (eluent: Hexane) in 57% yield (1.1 g, 5.7 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.38 (m, 2H), 7.28–7.25 (m, 3H), 3.60 (t, J = 6.5 Hz, 2H), 2.46 (t, J =

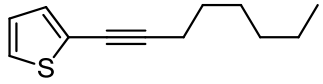
6.9 Hz, 2H), 2.00–1.93 (m, 2H), 1.80–1.72 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.5, 128.2, 127.6, 123.7, 89.2, 81.2, 44.5, 31.6, 25.8, 18.7. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[32]

Preparation of 1g.

1g: 

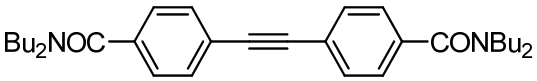
A flask was charged with benzene (25 mL) and triethylamine (7.5 mL). Oxygen in the system was removed by two freeze-pump-thaw cycles. Iodobenzene (1.4 mL, 12 mmol), 6-heptynenitrile (1.2 g, 10 mmol), [$Pd(PPh_3)_4$] (230 mg, 0.20 mmol) and CuI (95 mg, 0.50 mmol) were added in this order to the flask, and the resulting mixture was stirred overnight at 50 ºC. The mixture was cooled to room temperature and quenched by MeOH (5.0 mL). All volatiles were removed in vacuo, and Et_2O (100 mL) was added. After filtration, the filtrate was washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **1g** was obtained by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 2/1) in 39% yield (720 mg, 3.9 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39–7.38 (m, 2H), 7.29–7.26 (m, 3H), 2.48 (t, J = 6.7 Hz, 2H), 2.42 (t, J = 7.1 Hz, 2H), 1.90–1.82 (m, 2H), 1.79–1.73 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.5, 128.2, 127.7, 123.5, 119.5, 88.5, 81.5, 27.4, 24.4, 18.6, 16.8. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values. [33]

Preparation of 1i.

1i: 

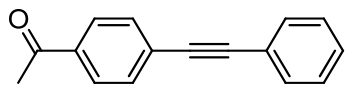
A flask was charged with [$PdCl_2(PPh_3)_2$] (140 mg, 0.20 mmol), CuI (76 mg, 0.40 mmol), 2-iodothiophene (1.3 mL, 12 mmol), 1-octyne (1.5 mL, 10 mmol), TBAF (20 mL of a 1.0 M solution in THF, 20 mmol) and THF (60 mL), and the mixture was stirred at room temperature for 16 h. After removal of all volatiles, **1i** was obtained by silica gel column chromatography (eluent: Hexane) in 74% yield (1.4 g, 7.4 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.16 (dd, J = 0.8 Hz, 4.8 Hz, 1H), 7.11 (dd, J = 1.0 Hz, 4.0Hz, 1H), 6.93 (dd, J = 3.8 Hz, 5.3 Hz, 1H), 2.41 (t, J = 7.1 Hz, 2H), 1.63–1.30 (m, 8H), 0.90 (t, J = 6.7 Hz, 3H). All the resonances in ^{1}H NMR spectrum were consistent with reported values.[34]

Preparation of 1o.

1o: 

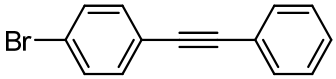
1o was synthesized with the same method of a reported procedure.[25] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56 (d, J = 7.9 Hz, 4H), 7.35 (d, J = 7.9 Hz, 4H), 3.49 (brd, 4H), 3.19 (brd, 4H), 1.64 (brd, 4H), 1.49 (brd, 4H), 1.41 (brd, 4H), 1.14 (brd, 4H), 0.98 (brd, 6H), 0.80 (brd, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.9, 137.2, 131.6, 126.6, 123.7, 89.8, 48.8, 44.5, 30.8, 29.6, 20.3, 19.7, 13.9, 13.6. MALDI-TOF-MS (DIT): *m/z* 489 (100%), 490 (35%), 491 (6%) ($[M+H]^+$). Anal. Calcd. for $C_{13}H_{16}O_3$: C, 78.65; H, 9.07. Found: C, 78.65; H, 9.26.

Preparation of 1p.

1p: 

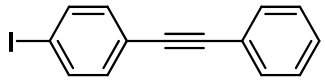
A flask was charged with benzene (50 mL) and triethylamine (15 mL). Oxygen in the system was removed by two freeze-pump-thaw cycles. To the mixture, phenylacetylene (2.8 mL, 25 mmol), 4-iodoacetophenone (4.9 g, 20 mmol), $[Pd(PPh_3)_4]$ (460 mg, 0.40 mmol) and CuI (190 mg, 1.0 mmol) were added to the flask in this order, and the resulting mixture was stirred overnight at 40 ºC. The mixture was cooled to room temperature and quenched by MeOH (10 mL). After removal of all volatiles, the product was dissolved in CH_2Cl_2 (200 mL) and washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and the product was purified by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 2/1). The product was further purified by recrystallization from hexane. **1p** was obtained in 57% yield (2.5 g, 11 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (d, J = 8.7 Hz, 2H), 7.60 (d, J = 7.9 Hz, 2H), 7.56–7.54 (m, 2H), 7.37–7.35 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.3, 136.2, 131.7, 131.7, 128.8, 128.4, 128.3, 128.2, 122.6, 92.7, 88.6, 26.6. . All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[35]

Preparation of 1t.

1t: 

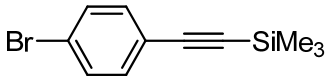
A flask was charged with $[PdCl_2(PPh_3)_2]$ (50 mg, 0.07 mmol), CuI (14 mg, 0.07 mmol), 4-bromoiodobenzene (4.0 g, 14 mmol), triethylamine (10 mL) and THF (20 mL). Phenylacetylene (1.5 mL, 14 mmol) was slowly added to the mixture, and the resulting mixture was stirred at room temperature for 24 h. After removal of all volatiles, the product was dissolved in CH_2Cl_2 (200 mL) and washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **1t** was obtained by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 10/1) in 86% yield (3.0 g, 12 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.53–7.50 (m, 2H), 7.46 (d, J = 8.7 Hz, 2H), 7.37 (d, J = 8.3 Hz, 2H), 7.34–7.32 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 133.0, 131.6, 131.6, 128.5, 128.4, 122.9, 122.4, 122.2, 90.5, 88.3. . All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[36]

Preparation of 1u.

1u: 

A flask was charged with $[Pd(PPh_3)_4]$ (120 mg, 0.10 mmol), CuI (40 mg, 0.21 mmol), 1,4-diiodobenzene (5.0 g, 15 mmol), phenylacetylene (550 μL, 5 mmol) and triethylamine (100 mL), and the mixture was stirred at room temperature for 1.5 h. After filtration through celite, the solvent was removed in vacuo. The product was absorbed on silica gel and purified by silica gel column chromatography (eluent: Hexane/CH_2Cl_2 = 50/1). **1u** was obtained in 65% yield (980 mg, 3.2 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.67 (d, J = 8.3 Hz, 2H), 7.53–7.50 (m, 2H), 7.35–7.33 (m, 3H), 7.24 (d, J = 8.3 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.5, 133.1, 131.6, 128.5, 128.4, 122.9, 122.8, 94.1, 90.8, 88.4. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[37]

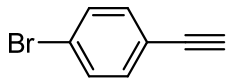
Preparation of 1-bromo-4-(trimethylsilylethynyl)benzene.



A flask was charged with THF (35 mL) and triethylamine (8 mL). Oxygen in the system was removed by two freeze-pump-thaw cycles. To the mixture, 4-bromoiodobenzene (4.1 g, 14 mmol),

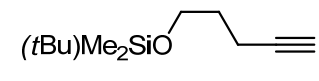
(trimethylsilyl)acetylene (2.0 mL, 14 mmol), [$PdCl_2(PPh_3)_2$] (200 mg, 0.28 mmol) and CuI (140 mg, 0.74 mmol) were added to the flask in this order, and the resulting mixture was stirred overnight at room temperature. After removal of all volatiles, Et_2O (200 mL) was added to the mixture. After the filtration, the mixture was washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and the product was obtained by silica gel column chromatography (eluent: Hexane) in 91% yield (3.3 g, 13 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.43 (d, J = 8.7 Hz, 2H), 7.32 (d, J = 8.7 Hz, 2H), 0.25 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 133.4, 131.4, 122.7, 122.1, 103.8, 95.6, –0.13. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[38]

Preparation of 3d.

3d: 

A flask was charged with 1-bromo-4-(trimethylsilylethynyl)benzene (1.9 g, 7.5 mmol), K_2CO_3 (3.7 g, 27 mmol), Ar bubbled MeOH (13 mL) and CH_2Cl_2 (10 mL). The mixture was stirred overnight at room temperature. The resulting mixture was washed with H_2O and the organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **3d** was obtained by silica gel column chromatography (eluent: Hexane) in 84% yield (1.1 g, 6.3 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, J = 8.3 Hz, 2H), 7.34 (d, J = 8.3 Hz, 2H), 3.12 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 133.5, 131.6, 123.1, 121.0, 82.6, 78.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[39]

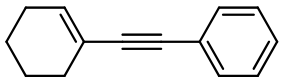
Preparation of 3g.

3g: 

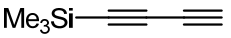
A flask was charged with 4-pentyne-1-ol (930 μL, 10 mmol), imidazole (1.7 g, 25 mmol) and DMF (17 mL). The resulting solution was cooled to 0 ºC, and a solution of *tert*-butyldimethylsilyl chloride (1.6 g, 11 mmol) in DMF (13 mL) was slowly added. The resulting mixture was stirred overnight at room temperature. The mixture was poured into H_2O and extracted with Et_2O (100 mL × 3). The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and **3g** was obtained by silica gel column

chromatography (eluent: Hexane/EtOAc = 40/1) in 79% yield (1.6 g, 7.9 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.70 (t, J = 6.1 Hz, 2H), 2.28 (td, J = 7.3, 2.8 Hz, 2H), 1.93 (t, J = 2.6 Hz, 1H), 1.76–1.69 (m, 2H), 0.90 (s, 9H), 0.057 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 84.3, 68.2, 61.4, 31.5, 25.9, 18.3, 14.8, –5.4. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[40]

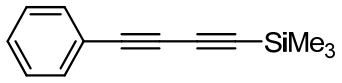
Preparation of 5d.

5d:  A flask was charged with $[PdCl_2(PPh_3)_2]$ (140 mg, 0.20 mmol), CuI (76 mg, 0.40 mmol), phenylacetylene (1.4 mL, 12 mmol), ethynylcyclohexene (1.2 mL, 10 mmol), TBAF (20 mL of a 1.0 M solution in THF, 20 mmol) and THF (60 mL), and the mixture was stirred at room temperature for 16 h. After removal of all volatiles, **5d** was obtained by silica gel column chromatography (eluent: Hexane) in 93% yield (1.7 g, 9.3 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44–7.41 (m, 2H), 7.32–7.25 (m, 3H), 6.23–6.20 (m, 1H), 2.25–2.21 (m, 2H), 2.17–2.12 (m, 2H), 1.71–1.59 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 135.2, 131.4, 128.2, 127.7, 123.7, 120.7, 91.2, 86.7, 29.2, 25.7, 22.3, 21.5. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[41]

Preparation of 1-trimethylsilyl-1,3-butadiyne.

 A flask was charged with 1,4-trimethylsilyl-1,3-butadiyne (2.5 g, 13 mmol),[42] LiBr (1.1 g, 13 mmol) and Et_2O (20 mL). To the mixture was added MeLi (18 mL of a 1.07 M solution in Et_2O, 19 mmol) at 0 ºC, and the resulting mixture was stirred for 4 h at room temperature. The mixture was poured into NH_4Cl aq. and extracted with Et_2O (100 mL × 3). The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and the product was obtained by distillation in 45% yield (720 mg, 5.9 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.10 (s, 1H), 0.20 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 87.4, 84.7, 68.3, 66.6, –0.58. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[43]

Preparation of 5e.

5e:  The similar procedure for the synthesis of **1t** was employed. 1-trimethylsilyl-1,3-butadiyne (710 mg, 5.9 mmol), iodobenzene (650 mL, 5.9 mmol), [$PdCl_2(PPh_3)_2$] (84 mg, 0.12 mmol), CuI (61 mg, 0.32 mmol), NEt_3 (3.3 mL) and THF (10 mL) were used. **5e** was obtained in 82% yield (960 mg, 4.8 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49 (d, J = 6.7 Hz, 2H), 7.36–7.29 (m, 3H), 0.23 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 132.6, 129.3, 128.4, 121.4, 90.6, , 87.8, 76.7, 68.3, –0.40. All the resonances in ^{13}C NMR spectrum were consistent with reported values.[44]

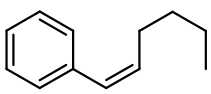
General Procedure for Copper-Catalyzed Semihydrogenation of 1a (Table 1-1). $Cu(OAc)_2·H_2O$ (2.0 mg, 0.010 mmol, 2.0 mol %) and a ligand (P/Cu = 4.0) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF (0.50 mL) and hexane (0.50 mL) were added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, **1a** (63 μL, 0.50 mmol), PMHS (130 μL, 2.0 mmol as the Si-H unit, 4.0 equiv) and *t*BuOH (96 μL, 1.0 mmol, 2.0 equiv) were added and the mixture was stirred at room temperature for 17 h. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard (tridecane).

General Procedure for Copper-Catalyzed Semihydrogenation of Internal Alkynes (Table 1-2). $Cu(OAc)_2·H_2O/CF_3$Ar-Xan as a catalyst: $Cu(OAc)_2·H_2O$ (2.0 mg, 0.010 mmol, 2.0 mol %) and CF_3Ar-Xan (22 mg, 0.040 mmol, 4.0 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF and hexane were added, and the mixture was stirred for 15 min at room temperature under an argon atmosphere. Alkyne (0.50 mmol), PMHS (130 μL, 2.0 mmol as the Si-H unit, 4.0 equiv) and *t*BuOH (96 μL, 1.0 mmol, 2.0 equiv) were added, and the mixture was stirred at indicated temperature for 20 h. After the reaction, isolated yields were determined after purification by silica gel column chromatography

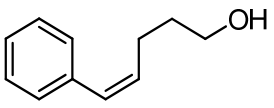
typically with a mixture of pentane and CH_2Cl_2 as an eluent. In the cases of **1c** and **1p**, hydrolysis was performed by adding 1M HCl/MeOH (1.0 mL) before the purification process.

[(^{Cl}IPr)CuCl]/*t*BuONa as a catalyst (entry 23, Table 1-2): [(^{Cl}IPr)CuCl] (22 mg, 0.040 mmol, 4.0 mol %) and *t*BuONa (12 mg, 0.12 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Hexane (2.0 mL) was added and the mixture was stirred for 15 min at room temperature under an argon atmosphere. The alkyne (**1w**, 190 μL, 1.0 mmol), PMHS (260 μL, 4.0 mmol as the Si-H unit, 4.0 equiv) and *t*BuOH (190 μL, 2.0 mmol, 2.0 equiv) were added, and the resulting mixture was stirred at 65 ºC for 20 h. After the reaction, (*Z*)-**2w** was isolated in 87% yield (150 mg, 0.87 mmol) by silica gel column chromatography with pentane as an eluent.

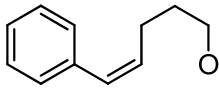
Characterization of the products in Table 1-2.

2b: 

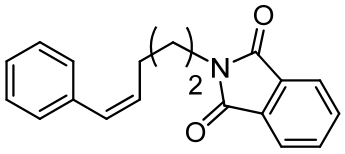
Yield 92% (73.0 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.18 (m, 5H), 6.40 (d, J = 11 Hz, 1H), 5.66 (td, J = 7.1 Hz, 12 Hz, 1H), 2.35–2.30 (m, 2H), 1.47–1.30 (m, 4H), 0.89 (t, J = 7.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.8, 133.2, 128.73, 128.68, 128.1, 126.4, 32.2, 28.3, 22.4, 14.0. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[45]

2c: 

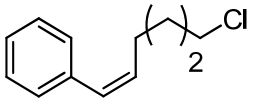
Yield 99% (80.3 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.20 (m, 5H), 6.45 (d, J = 11.5 Hz, 1H), 5.66 (td, J = 7.3 Hz, 11.5 Hz, 1H), 3.65 (t, J = 6.5 Hz, 2H), 2.44–2.38 (m, 2H), 1.75–1.67 (m, 2H), 1.45 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.5, 132.0, 129.4, 128.7, 128.1, 126.6, 62.4, 32.8, 24.8. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[46]

2d: 

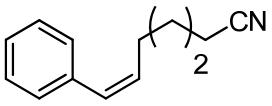
Yield 98% (134 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.16 (m, 5H), 6.39 (d, J = 11.5 Hz, 1H), 5.64 (td, J = 7.1 Hz, 10.7 Hz, 1H), 3.61 (t, J = 6.1 Hz, 2H), 2.45–2.35 (m, 2H), 1.69–1.61 (m, 2H), 0.85 (s, 9H), 0.00 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.6, 132.5, 129.1, 128.7, 128.1, 126.4, 62.6, 33.0, 25.9, 25.0, 18.3, –5.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[29]

2e: 

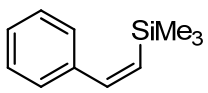
Yield 96% (139 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85–7.80 (m, 2H), 7.72–7.68 (m, 2H), 7.31–7.27 (m, 2H), 7.24–7.17 (m, 3H), 6.44 (d, J = 11.9 Hz, 1H), 5.67 (td, J = 7.3 Hz, 11.9 Hz, 1H), 3.70 (t, J = 7.3 Hz, 2H), 2.43–2.37 (m, 2H), 1.88–1.80 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.3, 137.3, 133.8, 132.1, 131.1, 129.8, 128.6, 128.1, 126.6, 123.2, 37.6, 28.7, 25.9. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[47]

2f: 

Yield 90% (87.7 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.31 (m, 2H), 7.27–7.20 (m, 3H), 6.44 (d, J = 11.9 Hz, 1H), 5.64 (td, J = 7.3 Hz, 11.5 Hz, 1H), 3.51 (t, J = 6.5 Hz, 2H), 2.39–2.33 (m, 2H), 1.83–1.76 (m, 2H), 1.64–1.56 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.5, 132.1, 129.4, 128.7, 128.1, 126.6, 44.8, 32.1, 27.7, 27.1. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[32]

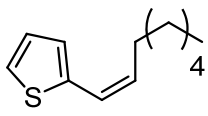
2g: 

Yield 99% (92.4 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36–7.32 (m, 2H), 7.26–7.21 (m, 3H), 6.47 (d, J = 11.5 Hz, 1H), 5.62 (td, J = 7.3 Hz, 11.5 Hz, 1H), 2.40–2.35 (m, 2H), 2.30 (t, J = 7.1 Hz, 2H), 1.70–1.58 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.3, 131.4, 129.8, 128.6, 128.2, 126.7, 119.6, 28.7, 27.5, 24.8, 16.9. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[48]

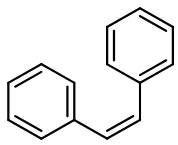
2h: 

Yield 72% (63.4 mg) (*Z*/*E* = 95/5). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, J = 15.0 Hz, 1H), 7.33–7.23 (m, 5H), 5.84 (d, J = 15.0 Hz, 1H), 0.05 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.6, 140.1, 132.8,

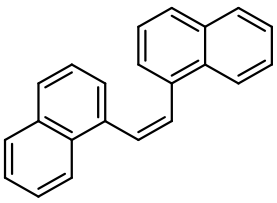
128.1, 127.9, 127.3, 30.9, 0.2. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[49]

2i: 

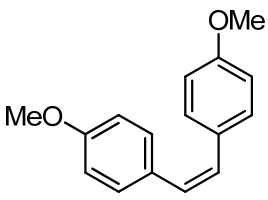
Yield 88% (86.0 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.24 (d, J = 5.5 Hz, 1H), 7.00 (dd, J = 3.4 Hz, 7.9 Hz, 1H), 6.96 (d, J = 3.2 Hz, 1H), 6.52 (d, J = 11.5 Hz, 1H), 5.58 (td, J = 7.1 Hz and 11.9 Hz, 1H), 2.43–2.37 (m, 2H), 1.52–1.46 (m, 2H), 1.41–1.28 (m, 6H), 0.89 (t, J = 7.1 Hz, 3H), 1.70–1.58 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.8, 131.3, 127.0, 126.7, 124.9, 121.6, 31.7, 29.4, 29.3, 29.1, 22.6, 14.1. EI-MS: *m/z* 196 (5%, $[M+2]^+$), 195 (13%, $[M+1]^+$), 194 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{12}H_{18}S$ ($[M]^+$), 194.1130. Found, 194.1132.

2j: 

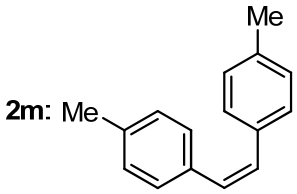
Yield 93% (83.8 mg) (*Z*/*E* = 98/2). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26–7.15 (m, 10H), 6.59 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.2, 130.2, 128.8, 128.2, 127.1. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[50]

2k: 

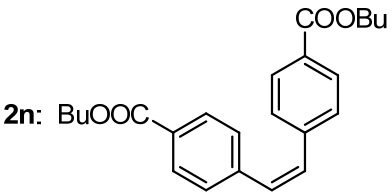
Yield 94% (132 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.18 (d, J = 7.1 Hz, 2H), 7.82 (d, J = 7.1 Hz, 2H), 7.64 (d, J = 6.7 Hz, 2H), 7.52–7.46 (m, 4H), 7.39 (s, 2H), 7.10–7.06 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 134.4, 133.5, 131.9, 130.2, 128.5, 127.3, 127.0, 126.0, 125.7, 125.4, 124.5. EI-MS: *m/z* 282 (3%, $[M+2]^+$), 281 (24%, $[M+1]^+$), 280 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{22}H_{16}$ ($[M]^+$), 280.1252. Found, 280.1262. The configuration of **2k** was determined by comparing the spectrum of **2k** to the spectrum of (*E*)-1,2-di(1-naphthyl)ethylene.[51]

2l: 

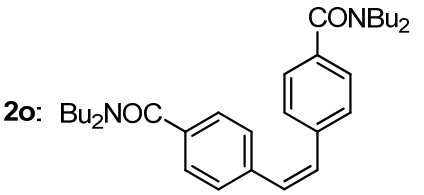
Yield 98% (118 mg) (*Z*/*E* = >99/1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.19 (d, J = 9.1 Hz, 4H), 6.76 (d, J = 9.1 Hz, 4H), 6.43 (s, 2H), 3.77 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.5, 130.0, 129.9, 128.3, 113.5, 55.1. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[52]



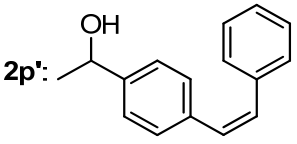
Yield 86% (90.0 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.21 (d, J = 7.9 Hz, 4H), 7.07 (d, J = 7.9 Hz, 4H), 6.56 (s, 2H), 2.35 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.7, 134.5, 129.5, 128.9, 128.7, 21.2. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[50]



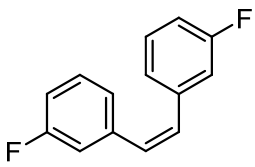
Yield 94% (179 mg) (*Z*/*E* = >99/1). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.90 (d, J = 8.3 Hz, 4H), 7.27 (d, J = 8.7 Hz, 4H), 6.71 (s, 2H), 4.31 (t, J = 6.7 Hz, 4H), 1.76–1.70 (m, 4H), 1.50–1.44 (m, 4H), 0.97 (t, J = 7.3 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.3, 141.3, 131.1, 129.6, 129.3, 128.8, 64.8, 30.7, 19.2, 13.7. EI-MS: *m/z* 382 (3%, $[M+2]^+$), 381 (26%, $[M+1]^+$), 380 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{24}H_{28}O_4$ ($[M]^+$), 380.1988. Found, 380.1978. The configuration of **2n** was determined by the derivatization of **2n** to (*Z*)-4,4'-benzyloxy stilbene.[53]

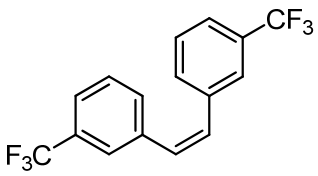


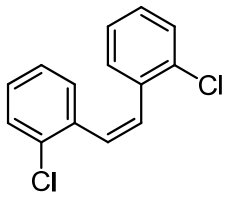
Yield 98% (242 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26 (d, J = 8.7 Hz, 4H), 7.21 (d, J = 7.9 Hz, 4H), 6.62 (s, 2H), 3.47 (brd, 4H), 3.19 (brd, 4H), 1.63 (brd, 4H), 1.47 (brd, 4H), 1.39 (brd, 4H), 1.14 (brd, 4H), 0.97 (brd, 6H), 0.79 (brd, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.3, 137.6, 136.1, 130.2, 128.8, 126.5, 48.7, 44.5, 30.8, 29.6, 20.2, 19.7, 13.9, 13.6. MALDI-TOF-MS (DIT): *m/z* 491 (100%), 492 (35%), 493 (6%) ($[M+H]^+$). EI-HRMS: Calcd. for $C_{32}H_{46}N_2O_2$ ($[M]^+$), 490.3559. Found, 490.3549. The configuration of **2o** was determined by the chemical shift of the proton at vinyl position.

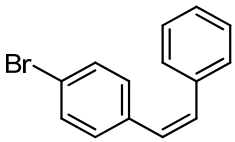


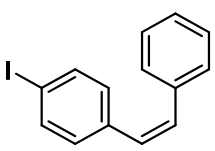
Yield 90% (101 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27–7.18 (m, 9H), 6.60 (d, J = 11.9 Hz, 1H), 6.56 (d, J = 11.9 Hz, 1H), 4.84 (q, J = 4.0 Hz, 1H), 1.91 (s, 1H), 1.47 (d, J = 4.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 144.5, 137.2, 136.4, 130.0, 129.8, 129.0, 128.8, 128.2, 127.1, 125.2, 70.1, 25.0. EI-MS: *m/z* 226 (1%, $[M+2]^+$), 225 (17%, $[M+1]^+$), 224 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{16}H_{16}O$ ($[M]^+$), 224.1201. Found, 224.1207.

2q:  Yield 86% (92.9 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22–7.16 (m, 2H), 6.98 (d, J = 7.5 Hz, 2H), 6.92–6.88 (m, 4H), 6.59 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 163 (J_{CF} = 245 Hz), 139 (J_{CF} = 8.9 Hz), 130.1 (J_{CF} = 1.9 Hz), 129.8 (J_{CF} = 8.6 Hz), 125 (J_{CF} = 2.9 Hz), 116 (J_{CF} = 22.0 Hz), 114 (J_{CF} = 21.0 Hz). All the resonances in ^{13}C NMR spectrum were consistent with reported values.[54]

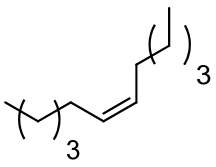
2r:  Yield 97% (153 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49–7.47 (m, 4H), 7.39–7.33 (m, 4H), 6.71 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.2, 132.0, 131 (J_{CF} = 32.5 Hz), 130.3, 128.9, 126 (J_{CF} = 3.8 Hz), 124.2 (J_{CF} = 3.8 Hz), 123.9 (J_{CF} = 273 Hz). All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[55]

2s:  Yield 86% (107 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (d, J = 7.9 Hz, 2H), 7.12 (t, J = 6.9 Hz, 2H), 7.02–6.95 (m, 4H), 6.85 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 135.2, 133.8, 130.7, 129.4, 128.9, 128.6, 126.3. All the resonances in ^{13}C NMR spectrum were consistent with reported values.[56]

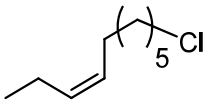
2t:  Yield 98% (126 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33 (d, J = 8.7 Hz, 2H), 7.24–7.19 (m, 5H), 7.09 (d, J = 8.3 Hz, 2H), 6.62 (d, J = 12.3 Hz, 1H), 6.49 (d, J = 12.3 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.8, 136.1, 131.3, 131.0, 130.5, 128.9, 128.8, 128.3, 127.3, 120.9. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[57]

2u:  Yield 98% (150 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.52 (d, J = 8.7 Hz, 2H), 7.22–7.18 (m, 5H), 6.96 (d, J = 7.9 Hz, 2H), 6.61 (d, J = 12.3 Hz, 1H), 6.46 (d, J = 12.3 Hz,

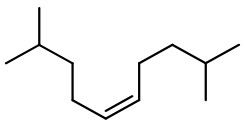
1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.3, 136.8, 136.6, 131.1, 130.7, 129.0, 128.7, 128.3, 127.3, 92.5. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[58]

2v: 

Yield 78% (65.9 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.35 (t, J = 4.8 Hz, 2H), 2.04–1.99 (m, 4H), 1.36–1.26 (m, 12H), 0.89 (t, J = 6.7 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 129.9, 31.5, 29.5, 27.2, 22.6, 14.1. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[59]

2w: 

Yield 87% (152 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.34 (dt, J = 11.4 and 6.1 Hz, 2H), 3.53 (t, J = 6.9 Hz, 2H), 2.07–2.00 (m, 4H), 1.81–1.74 (m, 2H), 1.47–1.31 (m, 6H), 0.96 (t, J = 7.5 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.8, 129.0, 45.1, 32.6, 29.5, 28.5, 26.9, 26.8, 20.5, 14.4. EI-MS: *m/z* 177 (4%, $[M+3]^+$), 176 (32%, $[M+2]^+$), 175 (11%, $[M+1]^+$) , 174 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{10}H_{19}Cl$ ($[M]^+$), 174.1175. Found, 174.1182.

2x: 
Yield 83% (139 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.33 (t, J = 5.0 Hz, 2H), 2.06–2.00 (m, 4H), 1.59–1.53 (m, 2H), 1.25–1.20 (m, 4H), 0.89 (d, J = 6.3 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 129.8, 39.0, 27.6, 25.1, 22.5. EI-MS: *m/z* 169 (13%, $[M+1]^+$), 168 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{12}H_{24}$ ($[M]^+$), 168.1878. Found, 168.1884.

The procedure for Scheme 1-1.

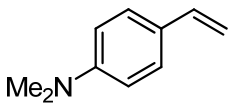
Catalyst System A: $Cu(OAc)_2 \cdot H_2O$ (2.0 mg, 0.010 mmol, 2.0 mol %) and Xan (P/Cu = 4.0) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, **1j** (89 mg, 0.50 mmol), **1y** (90 μL, 0.50 mmol), PMHS (130 μL, 2.0 mmol as the Si-H unit, 4.0 equiv) and *t*BuOH (96 μL, 1.0 mmol, 2.0 equiv) were added and the mixture was

stirred at room temperature for 20 h. After the reaction, the yields of the products were determined by GC analysis relative to an internal standard (tridecane).

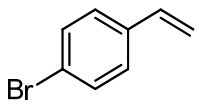
Catalyst System B: Lindlar cat. (2.7 mg, 5 mol %) and **1j** (89 mg, 0.50 mmol) were placed in an oven dried 20 mL Schlenk flask. The flask evacuated and backfilled with argon three times. CH_2Cl_2 (1.0 mL) and **1y** (90 μL, 0.50 mmol) were added, and the Schlenk flask was connected to H_2 balloon. The resulting mixture was stirred at room temperature for 6 h. After the reaction, the yields of the products were determined by GC analysis relative to an internal standard (tridecane).

General Procedure for Copper-Catalyzed Semihydrogenation of Terminal Alkynes (Table 1-3). [(^{Cl}IPr)CuCl] (5.6 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.8 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF (0.50 mL) and hexane (0.50 mL) were added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. Alkyne (0.50 mmol), PMHS (130 μL, 2.0 mmol as the Si-H unit, 4.0 equiv) and *t*BuOH (96 μL, 1.0 mmol, 2.0 equiv) were added, and the resulting mixture was stirred at indicated temperature for 20 h. After the reaction, isolated yields were determined after the purification by silica gel column chromatography with a mixture of pentane and CH_2Cl_2 as an eluent or Kugelrohr distillation.

Characterization of the products in Table 1-3.

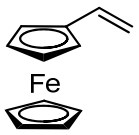
4b: 

Yield 82% (60.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31 (d, J = 11.9 Hz, 2H), 6.69–6.60 (m, 3H), 5.54 (d, J = 17.8 Hz, 1H), 5.02 (d, J = 10.7 Hz, 1H), 2.95 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.3, 136.6, 127.1, 126.2, 112.3, 109.3, 40.5. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[60]

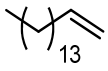
4d: 

Yield 68% (62.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.44 (d, J = 7.9 Hz, 2H), 7.26 (d, J = 7.9 Hz, 2H), 6.64 (dd, J = 10.7 Hz, 17.4 Hz, 1H), 5.73 (d, J = 17.8 Hz, 1H), 5.27 (d, J = 11.1 Hz,

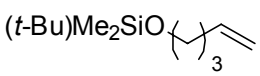
1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.4, 135.7, 131.6, 127.7, 121.6, 114.6. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[61]

4e: 

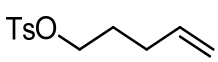
Yield 96% (101 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.45 (dd, J = 11.1 Hz, 17.4 Hz, 1H), 5.33 (d, J = 17.0 Hz, 1H), 5.02 (d, J = 10.7 Hz, 1H), 4.35 (brd, 2H), 4.20 (brd, 2H), 4.10 (s, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 134.6, 111.0, 83.5, 69.2, 68.6, 66.6. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[62]

4f: 

Yield 86% (95.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.86–5.76 (m, 1H), 5.49 (d, J = 17.0 Hz, 1H), 4.93 (d, J = 9.9 Hz, 1H), 2.07–2.01 (m, 2H), 1.26 (brd, 24H), 0.88 (t, J = 6.7 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.3, 114.1, 33.8, 31.9, 29.70, 29.68, 29.64, 29.5, 29.4, 29.2, 29.0, 22.7, 14.1. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[63]

4g: 

Yield 88% (87.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.87–5.77 (m, 1H), 5.02 (d, J = 17.4 Hz, 1H), 4.95 (d, J = 11.5 Hz, 1H), 3.62 (t, J = 6.7 Hz, 2H), 2.13–2.08 (m, 2H), 1.65–1.58 (m, 2H), 0.90 (s, 9H), 0.05 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.6, 114.5, 62.5, 32.0, 30.0, 26.0, 18.3, –5.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[64]

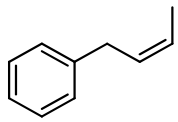
4h: 

Yield 88% (98.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.79 (d, J = 8.7 Hz, 2H), 7.35 (d, J = 8.3 Hz, 2H), 5.74–5.64 (m, 1H), 4.98–4.97 (m, 1H), 4.94–4.93 (m, 1H), 4.04 (t, J = 6.3 Hz, 2H), 2.45 (s, 3H), 2.11–2.06 (m, 2H), 1.78–1.71 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 144.7, 136.6, 133.1, 129.8, 127.9, 115.8, 69.8, 29.3, 27.9, 21.6. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[65]

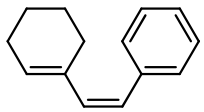
General Procedure for Copper-Catalyzed Semihydrogenation of Conjugated Carbon-Carbon Unsaturated Compounds (Table 1-4). The similar procedures for Table 1-2 and 1-3 were employed.

Characterization of the products in Table 1-4.

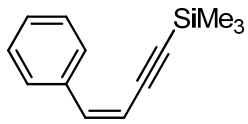
Yield of **6a** and **6c** were determined by GC analysis relative to an internal standard.

6b: 

Yield 75% (49.3 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30–7.26 (m, 2H), 7.20–7.16 (m, 3H), 5.61–5.58 (m, 2H), 3.41 (d, J = 5.1 Hz, 2H), 1.73 (d, J = 4.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.2, 129.0, 128.4, 128.3, 125.8, 124.8, 33.1, 12.8. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[66]

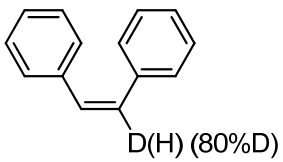
6d: 

Yield 97% (89.2 mg) [(*Z*,*E*)/(*E*,*E*) = 98/2]. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.23 (m, 4H), 7.19–7.16 (m, 1H), 6.31 (d, J = 12.3 Hz, 1H), 6.08 (d, J = 12.3 Hz, 1H), 5.76 (brd, 1H), 2.07 (brd, 2H), 1.89 (brd, 2H), 1.56–1.51 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.6, 135.6, 133.7, 129.1, 128.8, 127.7, 127.2, 126.4, 28.1, 25.7, 22.8, 22.1. EI-MS: *m/z* 186 (1%, $[M+2]^+$), 185 (15%, $[M+1]^+$), 184 (100%, $[M]^+$). EI-HRMS: Calcd. for $C_{14}H_{16}$ ($[M]^+$), 184.1252. Found, 184.1256.

6e: 

Yield 90% (90.4 mg) (*Z*/*E* = 100/0). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91 (d, J = 8.3 Hz, 2H), 7.37–7.29 (m, 3H), 6.65 (d, J = 12 Hz, 1H), 5.71 (dd, J = 12, 1.6 Hz, 1H), 0.25 (d, J = 1.6 Hz, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.8, 136.3, 128.8, 128.6, 128.1, 107.3, 103.7, 102.2, –0.27. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[67]

Characterization of the product in Eq 1-1.



2j-d$_1$

2j-d$_1$ was obtained by silica gel column chromatography in 98% yield (87.9 mg) (*Z*/*E* = 98/2). ^{1}H NMR (Figure S1, 400 MHz, $CDCl_3$): δ 7.26–7.15 (m, 10H), 6.59 (s, 1H). EI-MS: *m/z* 181 ($[M]^+$). All the resonances in ^{1}H NMR spectrum were consistent with reported values.[50]

[1]H NMR spectra of stoichiometric reactions in Scheme 1-2.

[1]H NMR spectrum after *step i* was shown in Figure 1-4.

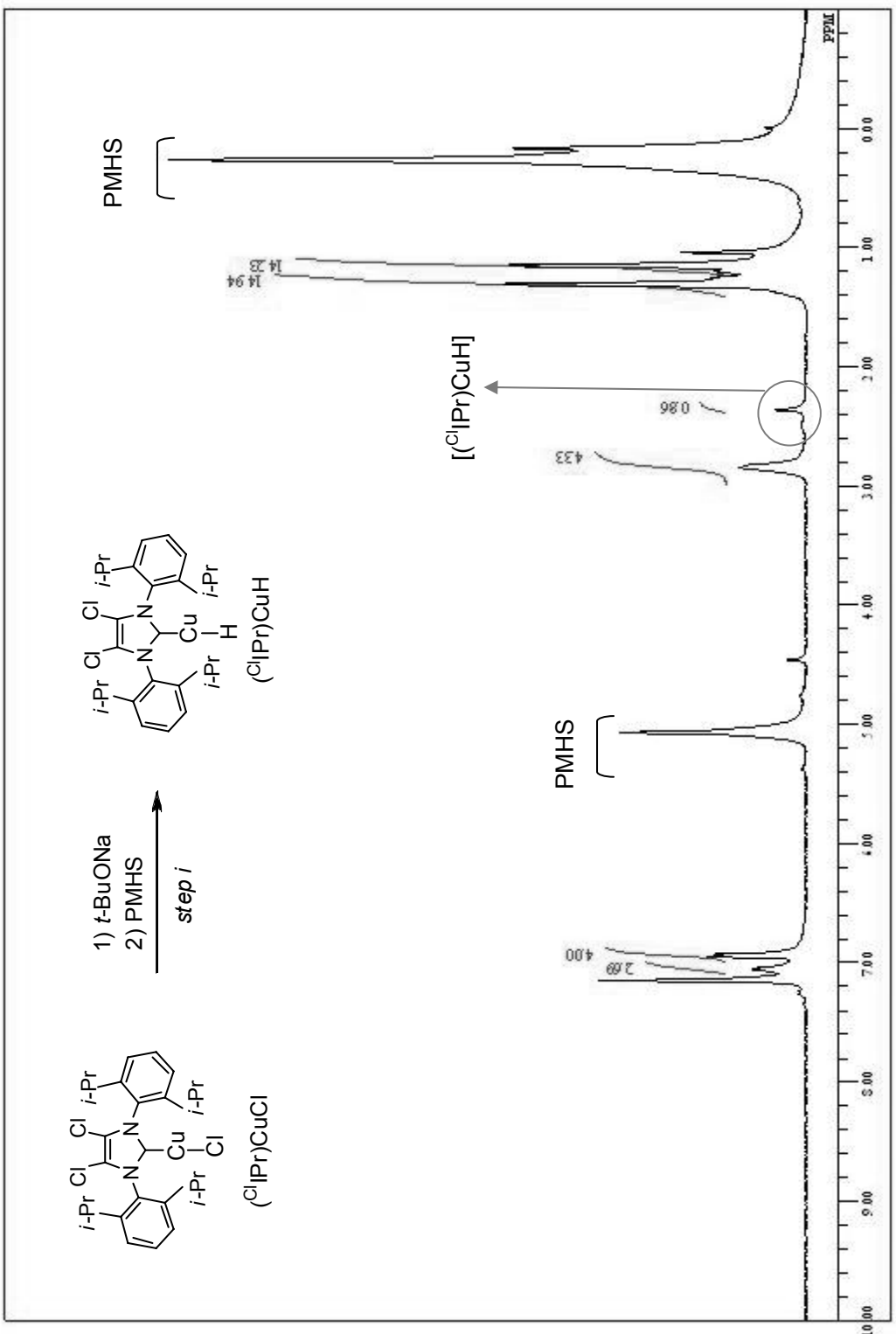


Figure 1-4. [1]H NMR spectrum of *step i*

^{1}H NMR spectrum after *step iii* was shown in Figure 1-5.

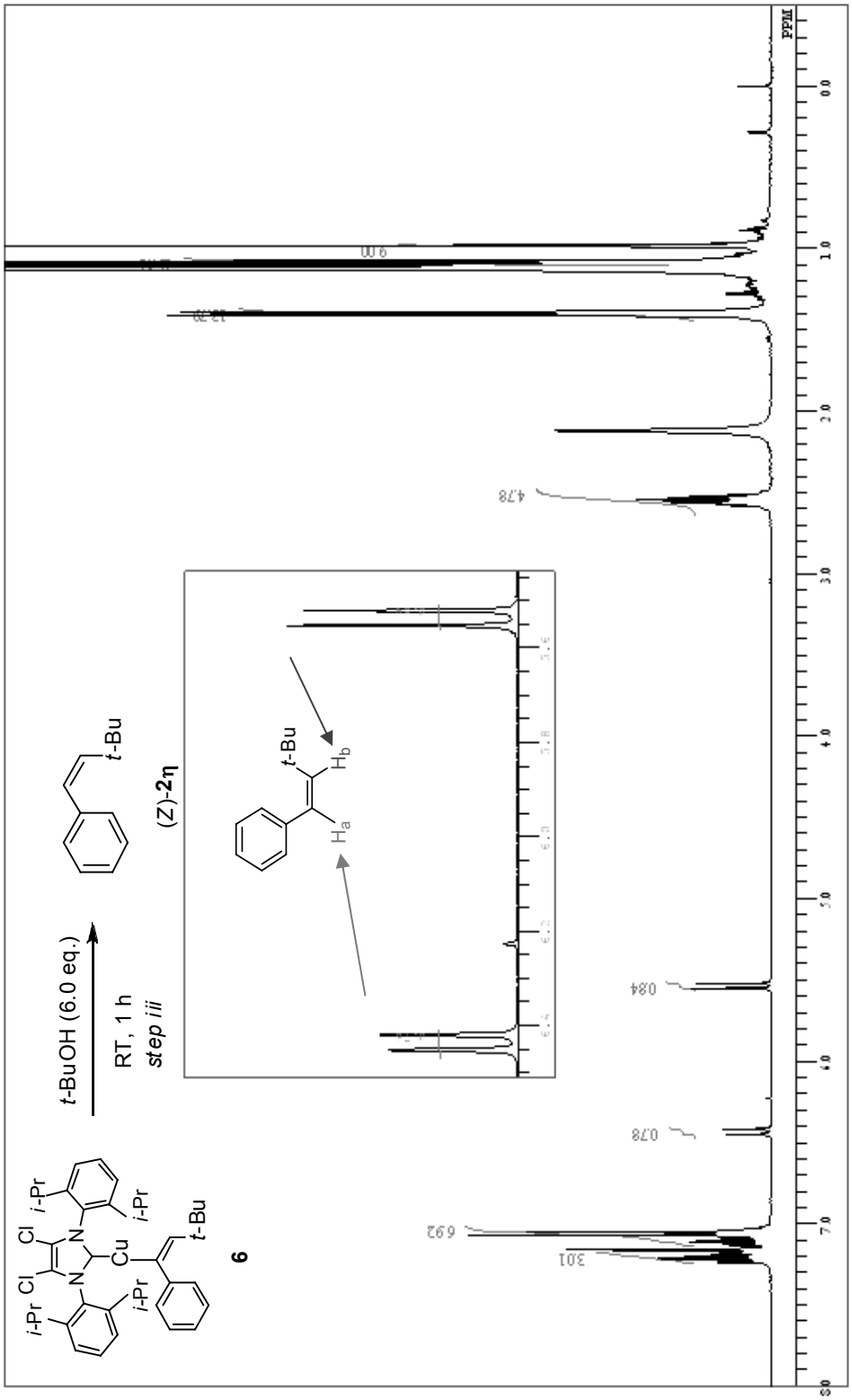


Figure 1-5. ^{1}H NMR spectrum of *step iii*

X-ray Crystallographic Analysis.

Crystallographic data of $[(CF_3Ar\text{-}Xan)CuCl]_2$ and [(Xan)CuCl] were summarized in Tables 1-5. All data of $[(CF_3Ar\text{-}Xan)CuCl]_2$ and [(Xan)CuCl] were collected on a Rigaku/Saturn70 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) at 153 K, and processed using CrystalClear (Rigaku).[68] The structures were solved by a direct method and refined by full-matrix least-square refinement on F2. The non-hydrogen atoms were refined anisotropically. All hydrogen atoms were located on the calculated positions and not refined. All calculations were performed using the CrystalStructure software package.[69] CCDC 870012 and 870011 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Table 1-5. Crystallographic data of $[(CF_3Ar\text{-}Xan)CuCl\cdot(CH_2Cl_2)]$ and [(Xan)CuCl].

compound	$[(CF_3Ar\text{-}Xan)CuCl\cdot(CH_2Cl_2)]$	[(Xan)CuCl]
empirical formula	$C_{48}H_{26}OCl_3P_2F_{24}Cu$	$H_{32}OCuC_{39}ClP_2$
formula weight	1306.55	677.63
temp / K	153	153
crystal system	monoclinic	monoclinic
space group	$P2_1/n$ (#14)	$P2_1/c$ (#14)
a / Å	15.377(2)	9.055(3)
b / Å	16.493(2)	18.263(5)
c / Å	22.132(3)	20.203(6)
α / deg	90	90
β / deg	96.0360(16)	94.104(4)
γ / deg	90	90
V / Å^3	5581.9(12)	3332.6(16)
Z	4	4
d_{cacd}/g cm^{-3}	1.555	1.350
observed reflections	12300	7560
unique reflections	12300 (all data)	7560 (all data)

Table 1-5. (Continued)

GOF	1.078	0.988
$R1$ ($I > 2\sigma(I)$), $wR2$[a]	0.0722, 0.1840[b]	0.0480, 0.1092[c]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma(w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] $w = 1/[0.0010F_o^2+3.0000s(F_o^2)]/(4 F_o^2)$. [c] $w = 1/[0.0001 F_o^2+1.0000s(F_o^2)]/(4 F_o^2)$.

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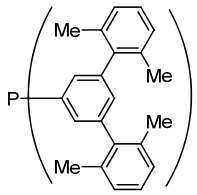

BSP

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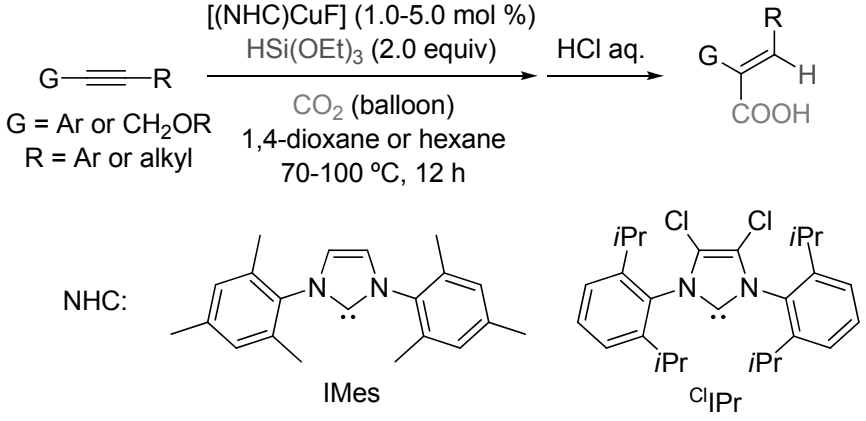
Chapter 2

Copper-Catalyzed Hydrocarboxylation of Alkynes Using Carbon Dioxide and Hydrosilanes

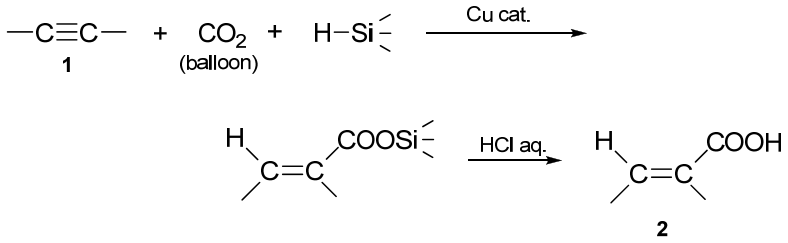
The copper-catalyzed hydrocarboxylation of alkynes under carbon dioxide (balloon) in the presence of hydrosilanes as a reducing agent has been developed. Copper fluorides bearing *N*-heterocyclic carbene (NHC) ligands such as IMes and ^{Cl}IPr show high catalytic activities.



2-1. Introduction

Carbon dioxide (CO_2) is a readily available and renewable chemical feedstock, although thermodynamic considerations limit its widespread use in chemical reactions.[1] For effective utilization of CO_2, transition-metal catalysts are requisite.[2] Useful transformations of CO_2 such as 1) cycloaddition via metallacycle[3] and 2) carboxylation of organozinc and organoboron compounds[4] have been reported to date. Besides these reactions, the hydrocarboxylation[5] of C-C multiple bonds using CO_2 is also very promising. The first example of the hydrocarboxylation using CO_2 was achieved as Ni-catalyzed *electrochemical* reaction with alkynes,[5a] 1,3-diynes,[5b] and 1,3-enynes[5c] as substrates. Later, in *supercritical* CO_2, Pd-catalyzed hydrocarboxylation of terminal alkenes was reported.[5d,e] As for more efficient hydrocarboxylations, recently Ni-catalyzed reaction of styrenes[5f] and Pd-catalyzed reaction of allenes[5g] were reported with $ZnEt_2$[5f,g] or $AlEt_3$[5g] as *reducing agents*. These reactions are very useful, but such strong and extremely air-sensitive reducing agents were indispensable in the reactions. In this chapter, the author reports Cu-catalyzed hydrocarboxylation of alkynes using CO_2 (balloon).[6,7] The use of mild and easy-to-handle hydrosilane[8] as a reducing agent realizes highly efficient hydrocarboxylation of alkynes to afford α,β-unsaturated carboxylic acids (**2**) (Scheme 2-1).

Scheme 2-1. Hydrocarboxylation of alkynes using CO_2 and hydrosilanes

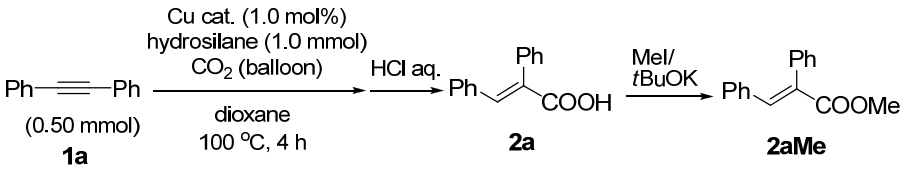


2-2. Results and Discussion

The hydrocarboxylation of diphenylacetylene (**1a**) with CO_2 (balloon) was carried out using $HSi(OEt)_3$ as a reducing agent in dioxane (Table 2-1). The yield of (*E*)-2,3-diphenyl-2-propenoic acid (**2a**) was determined by GC after derivatization[9] to the corresponding methyl ester (**2aMe**). Employing [(IPr)CuCl] + *t*BuONa (entry 1) or [(IMes)CuCl] + *t*BuONa (entry 2) as a catalyst, **2aMe** was obtained in only trace or

49% yield, respectively (Figure 2-1 shows structures of IPr and IMes). In the latter case (entry 2), a considerable amount (19% yield) of *cis*-stilbene (**3a**) was afforded as a byproduct. When [(IPr)CuF][10] was used as a catalyst, **2aMe** was obtained in 41% yield with suppressing the formation of **3a** to 3% (entry 3). Then, a new complex [(IMes)CuF] was synthesized from [(IMes)CuCl] similarly to [(IPr)CuF] and its structure was confirmed by X-ray crystallography (Scheme 2-2).[9] As a result, [(IMes)CuF] was much more effective catalyst providing **2aMe** in 86% yield with a small amount (3% yield) of **3a** (entry 4). The reaction is perfectly stereoselective to afford only the (*E*) isomer as confirmed by X-ray crystal structure of **2a**.[9] The reaction proceeds smoothly at 100 ºC (entry 4), but yields decreased to 42% at 70 ^{o}C and 27% at 50 ^{o}C, respectively. Polymethylhydrosiloxane (PMHS), a byproduct of the silicone industry, is a cheap, easy-to-handle, and environmentally friendly reducing agent. When $HSi(OEt)_3$ was replaced with PMHS, **2aMe** was obtained comparably in 80% yield (entry 5). Other hydrosilanes such as $HSi(OiPr)_3$ and H_2SiPh_2 afforded **2aMe** in 52% and 32% yields, respectively (entries 6 and 7), while $HSiEt_3$ did not provide **2aMe** at all (entry 8). In toluene as a solvent, **2aMe** was obtained in 81% yield under the same reaction conditions as entry 4, while **2a** was not obtained in DMF (entries 9 and 10).

Table 2-1. Hydrocarboxylation of diphenylacetylene (**1a**) using a hydrosilane under carbon dioxide[a]



Entry	Catalyst	Silane	Yield [%][b]	
			2aMe	**3a**[c]
1	[(IPr)CuCl]/*t*BuONa[d]	$HSi(OEt)_3$	trace	4
2	[(IMes)CuCl]/*t*BuONa[d]	$HSi(OEt)_3$	49	19
3	[(IPr)CuF]	$HSi(OEt)_3$	41	3
4	[(IMes)CuF]	$HSi(OEt)_3$	86 (72)[e]	3
5	[(IMes)CuF]	PMHS[f]	80	6
6	[(IMes)CuF]	$HSi(OiPr)_3$	52	12

Table 2-2. (Continued)

7	[(IMes)CuF]	H_2SiPh_2	32	10
8	[(IMes)CuF]	$HSiEt_3$	0	0
9[g]	[(IMes)CuF]	$HSi(OEt)_3$	81	4
10[h]	[(IMes)CuF]	$HSi(OEt)_3$	0	8

[a] Diphenylacetylene (**1a**, 0.50 mmol), hydrosilane (1.0 mmol), Cu catalyst (0.0050 mmol, 1.0 mol %), dioxane (2.0 mL), CO_2 (balloon), 100 °C, 4 h. [b] GC yield. [c] *cis*-Stilbene. [d] A mixture of [LCuCl] (L = IPr or IMes, 0.0050 mmol) and *t*BuONa (0.025 mmol). [e] Isolated yield of **2a**. [f] Polymethylhydrosiloxane. [g] Toluene was used as the solvent. [h] DMF was used as the solvent.

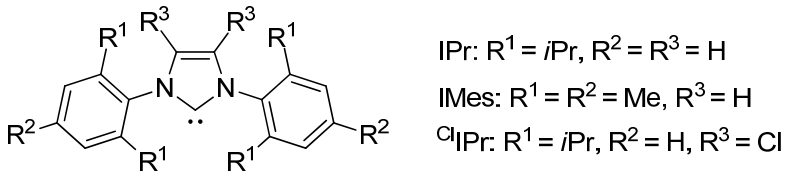
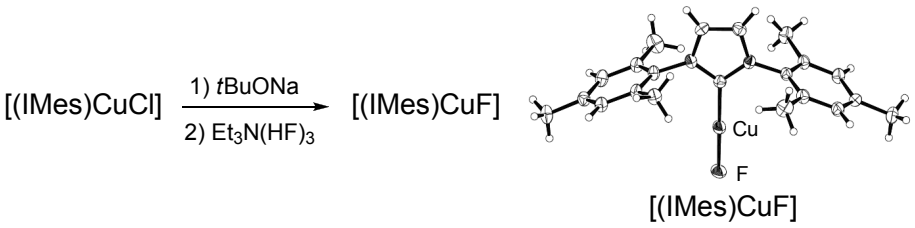


Figure 2-1. Structure of IPr, IMes, and ^{Cl}IPr.

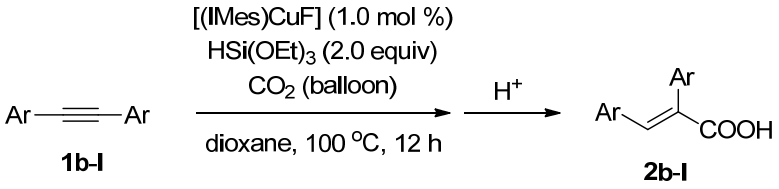
Scheme 2-2. Synthesis and X-ray structure of [(IMes)CuF][a]



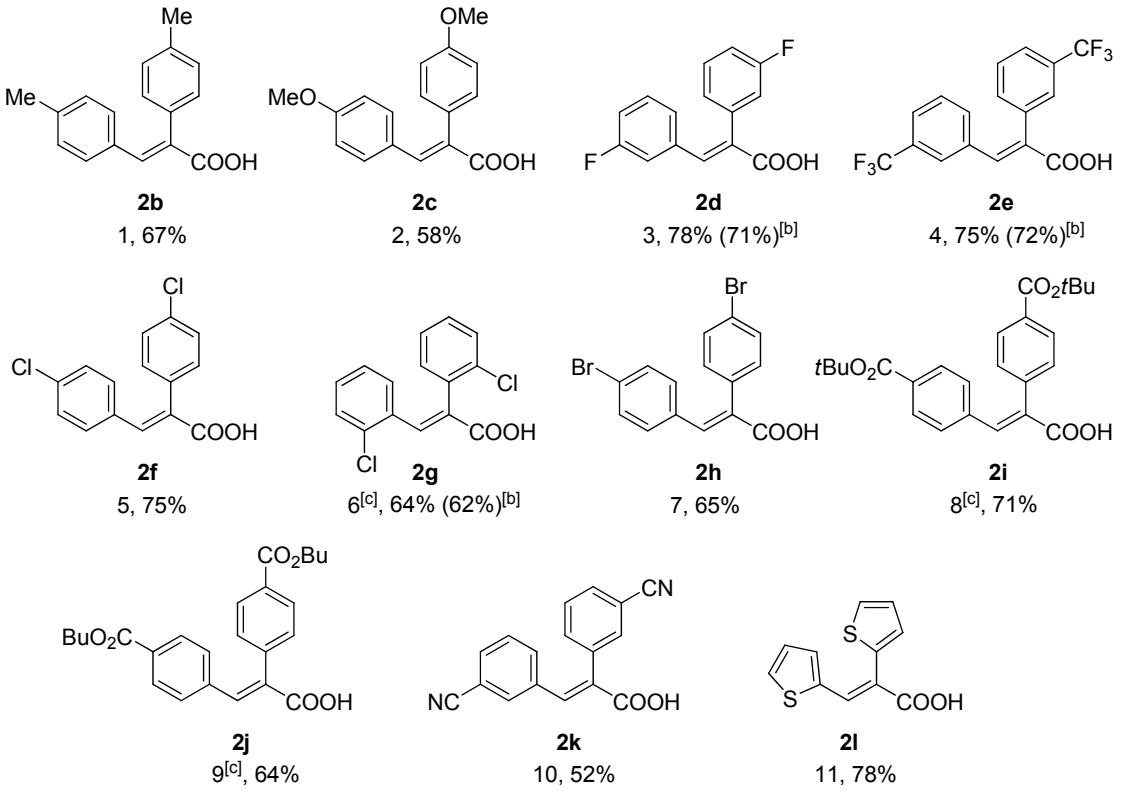
The hydrocarboxylation of a variety of symmetrical aromatic alkynes (**1b**–**l**) was carried out in the presence of [(IMes)CuF] as a catalyst (Table 2-2). From all the alkynes listed in Table 2-2, the corresponding α,β-unsaturated carboxylic acids (**2b**–**l**) were obtained in good isolated yields with the perfect (*E*) stereochemistry. The stereochemistry was confirmed by NOESY measurement after converting **2b**–**l** to the corresponding allylic alcohols (**4b**–**l**).[9] Alkynes bearing both electron-rich (entries 1 and 2) and electron-poor (entries 3–10) aryl moieties gave the corresponding products (**2b**–**k**) in good yields. Importantly, chloro (entries 5 and 6), bromo (entry 7),

alkoxycarbonyl (entries 8 and 9), and cyano (entry 10) functionalities were tolerated in the reaction to provide the corresponding products in good yields. An alkyne bearing thiophene rings (**1l**) also afforded the corresponding product (**2l**) in 78% yield

Table 2-2. Hydrocarboxylation of symmetrical aromatic alkynes[a]



1b: Ar = 4-MeC_6H_4 **1h**: Ar = 4-BrC_6H_4
1c: Ar = 4-$OMeC_6H_4$ **1i**: Ar = 4-C(O)O*t*BuC_6H_4
1d: Ar = 3-FC_6H_4 **1j**: Ar = 4-C(O)OBuC_6H_4
1e: Ar = 3-$CF_3C_6H_4$ **1k**: Ar = 3-CNC_6H_4
1f: Ar = 4-ClC_6H_4 **1l**: Ar = thienyl
1g: Ar = 2-ClC_6H_4



[a] Alkyne (0.50 mmol), $HSi(OEt)_3$ (1.0 mmol), [(IMes)CuF] (0.0050 mmol, 1.0 mol %), dioxane (2.0 mL), CO_2 (balloon), 100 ºC, 12 h. [b] PMHS (2.0 mmol) was used in place of $HSi(OEt)_3$. [c] [(IMes)CuF] (0.010 mmol, 2.0 mol %) was used.

stereoselectively (entry 11). PMHS could be used in place of $HSi(OEt)_3$ as an effective reducing reagent and the products was obtained in comparable yields (entries 3, 4 and 6).

The hydrocarboxylation of other various alkynes were carried out as shown in Table 2-3. The best catalyst in Table 2-1 and Table 2-2, [(IMes)CuF], provided only a trace amount of the product in the hydrocarboxylation of 1-phenyl-1-propyne (**1m**) in dioxane at 100 ºC (entry 1), while [(IPr)CuF] as the catalyst under the same reaction conditions afforded a mixture of regioisomers (**2m** and **2m'**) in low yield with poor regioselectivity (entry 2). Thus, [(^{Cl}IPr)CuF] was synthesized[9] in a similar way to [(IPr)CuF][10] using a known NHC ligand ^{Cl}IPr.[11] The reaction of **1m** in the presence of [(^{Cl}IPr)CuF] (2.5 mol %) in hexane as a solvent afforded **2m** and **2m'** in much higher yield (88%) even at 70 ºC with moderate regioselectivity (entry 3). The regioselectivity was considerably improved by replacing the methyl group of **1m** with butyl (**1n**) or secondary alkyl groups (**1o**). In these cases, the major regioisomers (**2n** and **2o**) were readily isolated in analytically pure form by a column chromatography. Gratifyingly, alkynes with cyclohexyl (**1p**) and *tert*-butyl groups (**1q**–**s**) afforded single regioisomers in good to high yields (entries 6–9). Here, bromo (entry 8) and alkoxycarbony (entry 9) functionalities on the phenyl ring were tolerated in the reaction. In the present reaction, simple internal aliphatic alkynes such as 5-decyne were much less reactive (conv. <5%) and did not give the corresponding carboxylic acid under the present reaction conditions. However, it was found that 1-methoxy-2-decyne (**1t**) gave a product in good yield with high regioselectivity (entry 10). Similar effect of the *β*-methoxy (**1u** and **1v**) and benzyloxy groups (**1w**) were evident (entries 11–13), suggesting coordination of the ether moieties to a copper center would be important in the reaction. 1,4-Dimethoxy-2-butyne (**1x**) and 2,5-dimethoxy-3-hexyne (**1y**) bearing the two *β*-ether functionalities also afforded the corresponding products (**2x** and **2y**) in good yields (entries 14 and 15). As for terminal alkynes, phenylacetylene (**1z**) afforded cinnamic acid (**2z**) in 44% yield using [(IPr)CuF] as the catalyst at 100 ºC in dioxane (entry 16). The yield was modest owing to considerable formation of the styrene in 28% yield.

Table 2-3. Hydrocarboxylation of various alkynes[a]

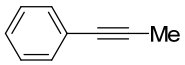
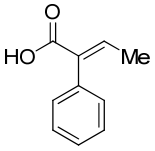
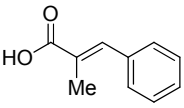
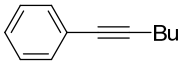
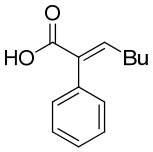
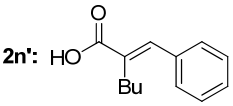
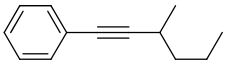
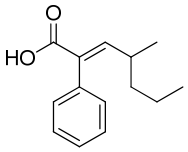
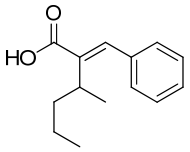
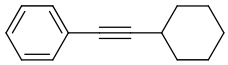
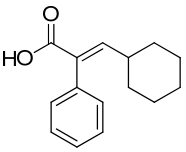
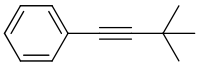
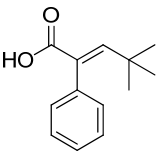
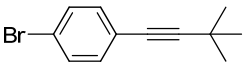
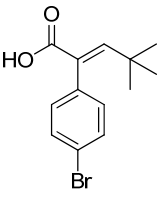
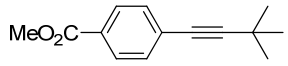
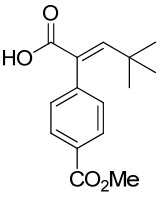
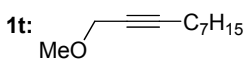
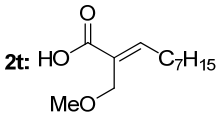
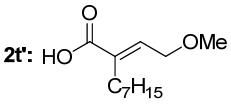
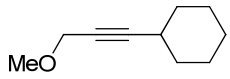
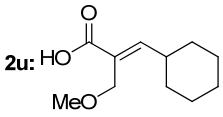
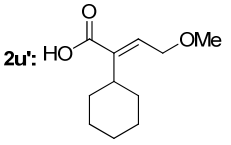
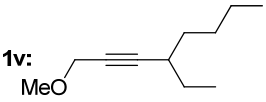
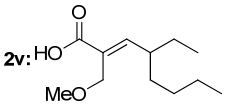
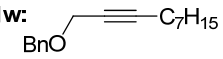
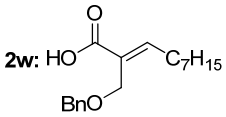
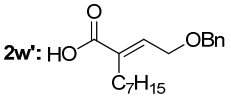
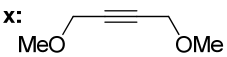
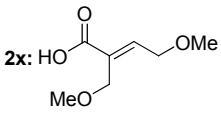
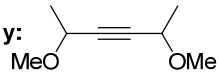
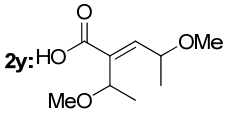
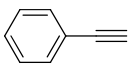
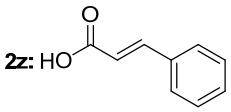
Entry	Substrate	Product	Yield [%][b]
1[c]	**1m:** 	**2m:**  **2m':** 	trace
2[d]			18 (66/34)[e]
3			86 (75/25) [e]
4	**1n:** 	**2n:**  **2n':** 	91 (88/12) [e] 75[f]
5	**1o:** 	**2o:**  **2o':** 	85 (93/7) [e]
6	**1p:** 	**2p:** 	88
7[g]	**1q:** 	**2q:** 	71
8[g]	**1r:** 	**2r:** 	68
9[g]	**1s:** 	**2s:** 	63

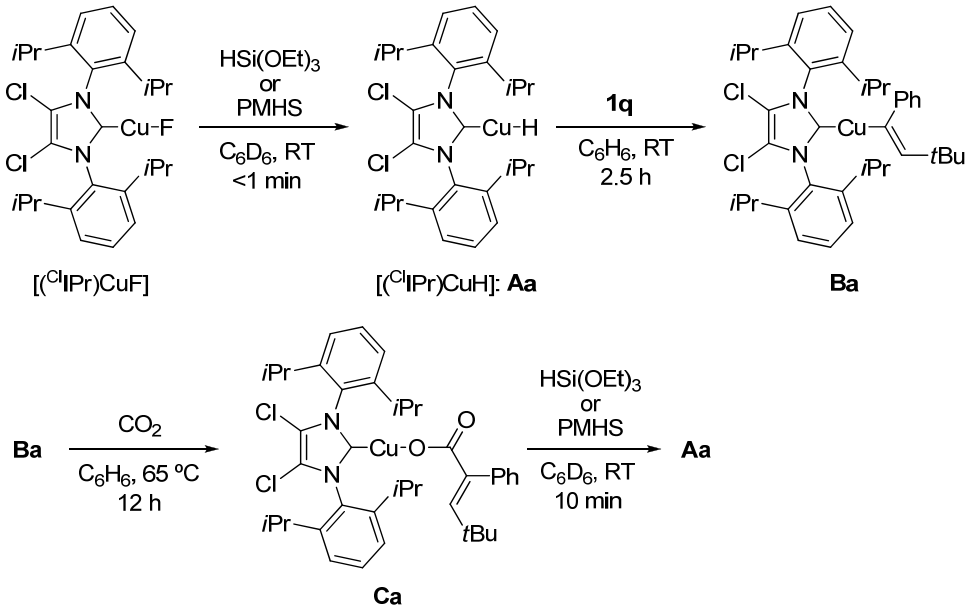
Table 2-3. (Continued)

10	**1t:** 	**2t:** 	**2t':** 	63 (93/7) [e]
11	**1u:** 	**2u:** 	**2u':** 	70 (90/10) [e]
12	**1v:** 	**2v:** 		74
13	**1w:** 	**2w:** 	**2w':** 	75 (85/15) [e] 48[h]
14[d]	**1x:** 	**2x:** 		66
15[d]	**1y:** 	**2y:** 		61
16[d]	**1z:** 	**2z:** 		44

[a] Alkyne (1.0 mmol), $HSi(OEt)_3$ (2.0 mmol), [(^{Cl}IPr)CuF] (0.025 mmol, 2.5 mol %), hexane (2.0 mL), CO_2 (balloon), 70 ºC, 14 h. [b] Isolated yield. [c] [(IMes)CuF] (0.025 mmol) in dioxane at 100 ºC. [d] [(IPr)CuF] (0.025 mmol) in dioxane at 100 ºC. [e] A ratio of **2** and **2**‘ was determined by ^{1}H NMR spectra. [f] Isolated yield of **2n** or **2o**. [g] [(^{Cl}IPr)CuF] (0.050 mmol). [h] Isolated yield of **2w** as the corresponding methyl ester.

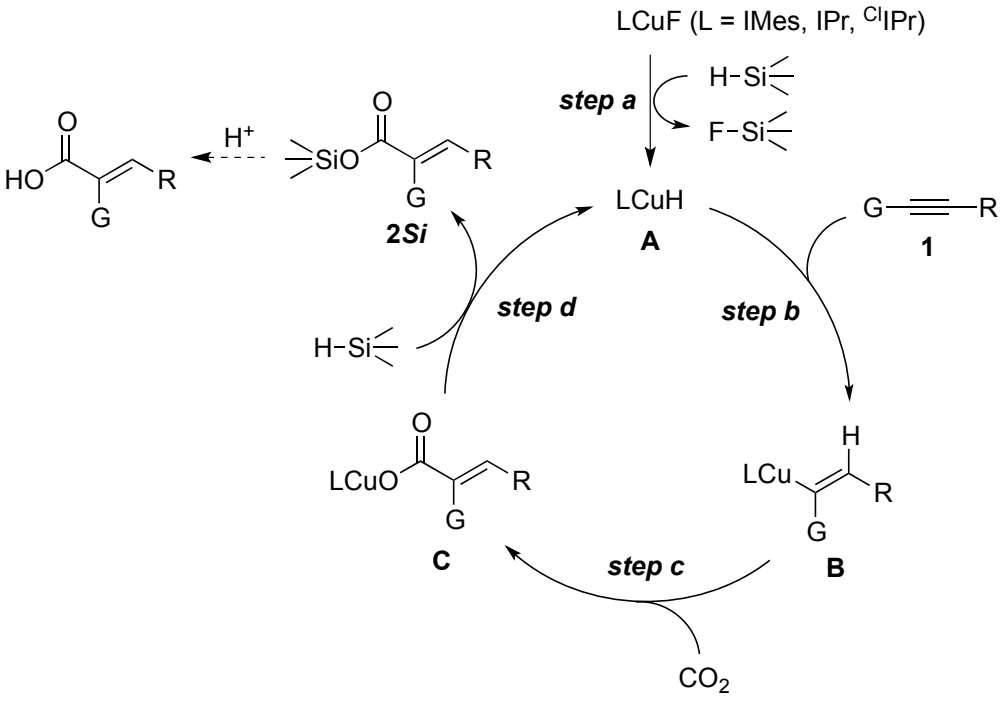
In order to gain insights into reaction mechanism, fundamental catalytic steps in the present hydrocarboxylation were examined by stoichiometric reactions (Scheme 2-3). When [(^{Cl}IPr)CuF], the catalyst precursor in Table 2-3, was treated with an excess (4.0 equiv) of silanes such as PMHS or $HSi(OEt)_3$ in C_6D_6, an immediate color change from colorless to bright orange was observed. The ^{1}H NMR spectrum indicated clean formation of [(^{Cl}IPr)CuH] (**Aa**) with a diagnostic proton resonance of Cu-H at 2.39 ppm, which is consistent with a reported value of [(IPr)CuH] at 2.63 ppm.[12] An aromatic alkyne such as **1q** reacted with **Aa** smoothly in 2.5 h at room temperature to afford the corresponding copper alkenyl complex (**Ba**). In contrast, an aliphatic alkyne such as 5-decyne did not react with **Aa**, which was decomposed rapidly under the reaction conditions. This low reactivity of the internal aliphatic alkyne is very reminiscent of the catalytic reaction. The copper alkenyl complex (**Ba**) was isolated in 70% yield and fully characterized by ^{1}H and ^{13}C NMR spectra. The reaction of **Ba** with CO_2 (balloon) was very slow at room temperature, but took place smoothly at a higher reaction temperature (65 ºC) in 12 h: the copper carboxylate complex (**Ca**) was also isolated in 84% yield and fully characterized by ^{1}H and ^{13}C NMR spectra. Finally, **Ca** reacted with an excess (4.0 equiv) of $HSi(OEt)_3$ at room temperature and the copper hydride complex (**Aa**) was afforded cleanly. The isolated **Ba** and **Ca** were active catalysts to afford **2q** in 80% and 74% yields, respectively, under the same reaction condition as entry 7 in Table 2-3.

Scheme 2-3. Stoichiometric reactions relevant to the reaction mechanism



Based on the stoichiometric reactions in Scheme 2-3, a possible catalytic cycle is shown in Scheme 2-4. A copper(I) hydride species (**A**)[13] is generated in situ from [LCuF] (L = IMes, IPr, or ^{Cl}IPr) and a hydrosilane by the aid of the strong silicon–fluorine interaction[10] (step a). *Syn*-addition of **A** to an alkyne (**1**) initiates the catalytic cycle and affords a copper alkenyl intermediate (**B**) stereoselectively (step b).[12] Then, insertion of CO_2 takes place to provide the corresponding copper carboxylate intermediate (**C**) [4c,14] (step c). Finally, σ-bond metathesis of **C** with a hydrosilane provides the corresponding silyl ester (**2si**) and regenerates **A** (step d). All the catalytic steps a-d were confirmed by the stoichiometric reactions in Scheme 2-4, in which only the insertion of CO_2 requires the higher reaction temperature (65 ºC), while other stoichiometric reactions proceeded at room temperature. Thus, step c in Scheme 5 must be a rate determining step.

Scheme 2-4. A plausible catalytic cycle



2-3. Conclusion

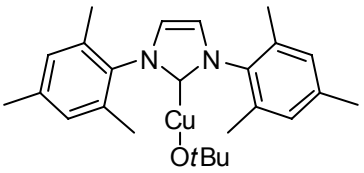
In conclusion, Cu-catalyzed hydrocarboxylation of alkynes (**1**) under carbon dioxide (balloon) has been developed. [(IMes)CuF] and [(^{Cl}IPr)CuF] complexs show high catalytic activity using a hydrosilane as a reducing agent.

2-4. Experimental Section

General Procedures: IR spectra were obtained on a Shimadzu FTIR-8300 spectrometer. ^{1}H, ^{13}C and ^{19}F NMR spectra were measured with a JEOL ECX-400P spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm). The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). High-resolution mass spectrum (FAB-HRMS) was obtained with a JEOL JMX-SX 102A spectrometer. Elemental analysis was carried out at the Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. GC analysis was carried out using a Shimadzu GC-17A equipped with an integrator (C-R8A) with a capillary column (CBP-5, 0.25 mm i.d. × 25 m). Melting points were measured on a Yanako MP-J3 apparatus. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). TLC analyses were performed on commercial glass plates bearing a 0.25 mm layer of Merck Silica gel $60F_{254}$.

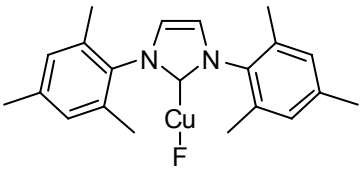
Materials: Unless otherwise noted, all manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. THF, 1,4-dioxane, hexane, pentane, toluene, and benzene were distilled from sodium benzophenone ketyl under Ar. DMF was distilled from calcium hydride under Ar. CCl_4 was purified by simple distillation. NMR solvents were dried and degassed as follows: C_6D_6 over sodium/benzophenone and CD_2Cl_2 over P_2O_5, and degassed with three freeze-pump-thaw cycles and vacuum-transferred prior to use. Hydrosilanes (except PMHS which was evacuated and refilled with argon three times) were distilled under reduced pressure. Phenylacetylene was purified by distillation. Unless otherwise noted, materials obtained from commercial suppliers were used without further purification.

Preparation of Catalysts: IPr·HCl,[15] IMes·HCl,[15] [(IMes)CuCl],[16] [(IPr)CuCl],[17] [(IPr)Cu(O*t*Bu)],[12] and [(IPr)CuF][10] were prepared by literature methods. A new complex [(IMes)CuF] and [(^{Cl}IPr)CuF] were prepared by a slightly modified method for [(IPr)CuF].[10]



[(IMes)Cu(O*t*Bu)]

In a glovebox, a 30-mL flat-bottom bottle equipped with a Teflon-coated stirbar was charged with [(IMes)CuCl] (1.32 g, 3.26 mmol) and sodium *tert*-butoxide (0.313 g, 3.26 mmol). Anhydrous THF (20.0 mL) was added; the resulting opaque brown solution was stirred for 2.0 h, filtered through Celite, and concentrated *in vacuo*, affording [(IMes)Cu(O*t*Bu)] as an off-white powder, 1.25 g (87%). ^{1}H NMR (400 MHz, C_6D_6): δ 1.34 (s, 9H), 1.99 (s, 12H), 2.11 (s, 6H), 6.11 (s, 2H), 6.72 (s, 4H). ^{13}C NMR (100 MHz, C_6D_6): δ 17.81, 21.07, 36.90, 68.80, 121.21, 129.41, 134.96, 136.20, 138.85, 182.43 (N<u>C</u>Cu).



[(IMes)CuF]

In a glovebox, [(IMes)Cu(O*t*Bu)] (0.50 g, 1.13 mmol) and benzene (10.0 mL) were added to a 30 mL round-bottom flask equipped with a Teflon-coated stirbar. The flask was sealed with a rubber septum and took out from the glovebox. Triethylamine tris(hydrofluoride) (56.0 μL, 0.34 mmol) was added via a syringe. The resulting white suspension was stirred for 6 h and the solvent was removed on a vacuum line. The resulting solid was then brought back into a glovebox. A white solid was suspended in pentane (10.0 mL), filtered, and washed with pentane (20.0 mL) to afford [(IMes)CuF] as a white powder (0.35 g; 88%). This complex is highly air-sensitive in solution. ^{1}H NMR (400 MHz, CD_2Cl_2): δ 2.12 (s, 12H), 2.38 (s, 6H), 7.06 (s, 4H), 7.10 (s, 2H). ^{19}F NMR (372 MHz, CD_2Cl_2): δ –240.90. ^{13}C NMR (100 MHz, CD_2Cl_2): δ 17.88, 21.22, 122.81, 129.63, 135.23, 135.75, 139.94, 179.07 (N<u>C</u>Cu). Anal. Calcd. for $C_{21}H_{24}CuFN_2$: C, 65.18; H, 6.25. Found: C, 64.55; H 6.14.

Single crystals of the complex were obtained by recrystallization from CH_2Cl_2/pentane in a glovebox. The structure was also confirmed by X-ray crystallography (Figure 2-2).

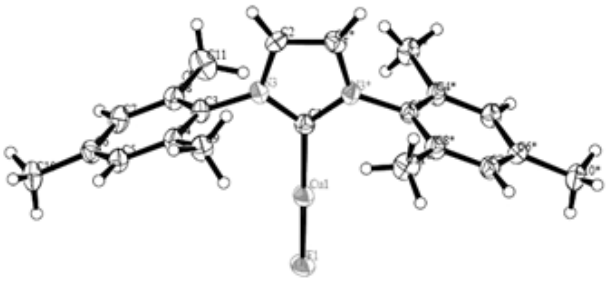
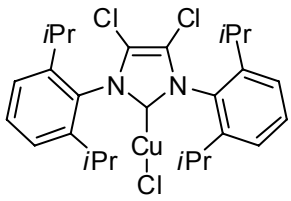
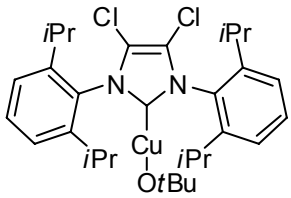


Figure 2-2. Crystal structure of [(IMes)CuF]



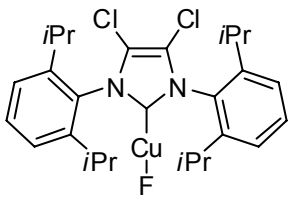
[(ClIPr)CuCl]

A 100 mL one-necked flask containing IPr·HCl (3.5 g, 8.23 mmol) and potassium *tert*-butoxide (1.15 g, 8.71 mmol) was evacuated/refilled with argon three times. Anhydrous THF (40.0 mL) was added; the resulting suspension was stirred for 1.0 h. Then, it was sent into a glovebox and filtered through Celite. The filtrate was took out of the golvebox and CCl_4 (1.59 mL, 16.46 mmol) was added. The reaction mixture was stirred for an additional 5 h, and CuCl (1.79 g, 18.1 mmol) was added with the argon flowing. The reaction mixture was stirred at room temperature for 3 h. The solvent was removed under vacuum. The resulting crude mixture was purified by silica gel chromatography using CH_2Cl_2 as an eluent. A white solid (3.80 g, 83%) was obtained. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.27 (d, J = 6.8 Hz, 12H), 1.30 (d, J = 6.8 Hz, 12H), 2.43–2.5.0 (m, 4H), 7.33 (d, J = 7.6 Hz, 4H), 7.55 (t, J = 7.6 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.32, 24.96, 29.10, 118.88, 124.55, 131.36, 131.54, 146.05, 179.73 (N<u>C</u>Cu).



[(ClIPr)Cu(O*t*Bu)]

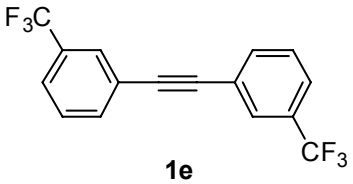
In a glovebox, a 30-mL flat-bottom bottle equipped with a Teflon-coated stirbar was charged with [(ClIPr)CuCl] (1.23 g, 2.21 mmol) and sodium *tert*-butoxide (212.0 mg, 2.21 mmol). Anhydrous THF (15.0 mL) was added; the resulting opaque brown solution was stirred for 1.5 h, filtered through Celite, and concentrated *in vacuo*, affording [(ClIPr)Cu(O*t*Bu)] as an off-white powder, 1.2 g (92%). ^{1}H NMR (400 MHz, C_6D_6): δ 1.09 (d, J = 6.8 Hz, 12H), 1.29 (s, 9H), 1.40 (d, J = 6.8 Hz, 12H), 2.53-2.63 (m, 4H), 7.06 (d, J = 8.0 Hz, 4H), 7.22 (t, J = 8.0 Hz, 2H). ^{13}C NMR (100 MHz, C_6D_6): δ 23.38, 24.92, 29.38, 37.21, 67.84, 118.12, 124.61, 131.41, 132.33, 146.25, 183.61 (N<u>C</u>Cu).



[(^{Cl}IPr)CuF]

In a glovebox, [(^{Cl}IPr)Cu(O*t*Bu)] (1.25 g, 2.10 mmol) and benzene (20.0 mL) were added to a 30 mL round-bottom flask equipped with a Teflon-coated stir bar. The flask was sealed with a rubber septum and took out from the glovebox. Triethylamine tris(hydrofluoride) (115.0 μL, 0.70 mmol) was added via a syringe. The resulting white suspension was stirred for 6 h and the solvent was removed on a vacuum line. The resulting solid was then brought back into a glovebox. A white solid was suspended in pentane (10.0 mL), filtered, and washed with pentane (20.0 mL) to afford [(^{Cl}IPr)CuF] as a white powder (1.02 g; 89%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.27 (d, J = 6.8 Hz, 12H), 1.31 (d, J = 6.8 Hz, 12H), 2.41–2.51 (m, 4H), 7.33 (d, J = 8.0 Hz, 4H), 7.54 (t, J = 8.0 Hz, 2H). ^{19}F NMR (372 MHz, $CDCl_3$): δ -246.61. ^{13}C NMR (100 MHz, $CDCl_3$): δ 23.36, 24.88, 29.10, 118.86, 124.55, 131.42, 131.55, 146.03, 179.88 (N<u>C</u>Cu). Anal. Calcd. for $C_{27}H_{34}Cl_2CuFN_2$: C, 60.05; H, 6.35. Found: C, 59.95; H 6.33.

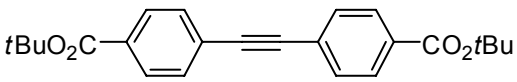
Preparation of the Substrates: 1,2-Diaromatic acetylenes (**1b–d**, **1f–h** and **1k–l**) were prepared according to literature methods.[18] **1p**,[19] **1q**,[20] **1r**,[21] **1s**,[22] **1u**,[23] **1x**,[24] and **1y**[25] were also prepared by literature methods.



1e

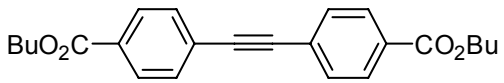
A 200 mL two-necked flask containing [$PdCl_2(PPh_3)_2$] (274.0 mg, 0.39 mmol), CuI (248.0 mg, 1.3 mmol) and 3-iodobenzotrifluoride (1.9 mL, 13.2 mmol) was evacuated/refilled with argon three times. To the flask was added benzene (65.0 mL) via syringe, which was dried over MS 4A and purged with dry argon. Then, the flask was covered with aluminium foil. Subsequently, degassed DBU (11.7 mL, 78.2 mmol) and distilled water (56.0 μL, 3.1 mmol) were added by syringes. Immediately, ice-chilled trimethylsilylacetylene (0.92 mL, 6.5 mmol) was added by a syringe. The reaction mixture was allowed to stir at room temperature for 36 h. At room temperature, CH_2Cl_2 (100 mL) was added to the flask, and the resulting mixture was washed with 10% HCl (3 × 100 mL). The collected organic layer was dried over anhydrous Na_2SO_4. After filtration, the crude products were absorbed onto silica gel (20 g). The product was purified by silica gel chromatography using hexane as an

eluent. A white solid (1.75 g, 5.6 mmol, 86%) was obtained. M.p. 89–90 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.49 (t, J = 8.0 Hz, 2H), 7.61 (d, J = 8.0 Hz, 2H), 7.71 (d, J = 8.0 Hz, 2H), 7.81 (s, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 89.19, 123.56, 123.65 (q, J_{C-F} = 274 Hz), 125.26 (q, J_{C-F} = 4 Hz), 128.50 (q, J_{C-F} = 4 Hz), 128.99, 131.11 (q, J_{C-F} = 33 Hz), 134.72. Anal. Calcd. for $C_{16}H_8F_6$: C, 61.16; H, 2.57. Found: C, 61.02; H 2.50.



1i

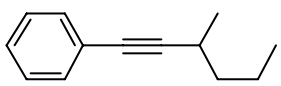
A 200 mL two-necked flask containing $[PdCl_2(PPh_3)_2]$ (160.0 mg, 0.23 mmol), CuI (144.0 mg, 0.76 mmol) and *tert*-butyl 4-iodobenzoate (2.3 g, 7.6 mmol) was evacuated/refilled with argon three times. To the flask was added benzene (40.0 mL) via a syringe, which was dried over MS 4A and purged with dry argon. Then, the flask was covered with aluminium foil. Subsequently, degassed DBU (6.8 mL, 45.5 mmol) and distilled water (32.0 μL, 1.8 mmol) were added by syringes. Immediately, ice-chilled trimethylsilylacetylene (0.53 mL, 3.8 mmol) was added by a syringe. The reaction mixture was allowed to stir at room temperature for 36 h. At room temperature, CH_2Cl_2 (100 mL) was added to the flask, and the resulting mixture was washed with 10% HCl (3 × 100 mL). The collected organic layer was dried over anhydrous Na_2SO_4. After filtration, the crude products were absorbed onto silica gel (20 g). The product was purified by silica gel chromatography using hexane/AcOEt (8:1, v/v) as an eluent. A white solid (0.85 g, 2.2 mmol, 62%) was obtained. M.p. 161-162 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.61 (s, 18H), 7.58 (d, J = 8.0 Hz, 4H), 7.98 (d, J = 8.0 Hz, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 28.18, 81.39, 91.24, 126.87, 129.39, 131.45, 131.79, 165.11. Anal. Calcd. for $C_{24}H_{26}O_4$: C, 76.17; H, 6.92. Found: C, 75.92; H 6.99.



1j

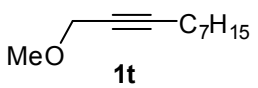
A 200 mL two-necked flask containing $[PdCl_2(PPh_3)_2]$ (274.0 mg, 0.39 mmol), CuI (248.0 mg, 1.3 mmol) and *n*-butyl 4-bromobenzoate (4.4 g, 17.1 mmol) was evacuated/refilled with argon three times. To the flask was added benzene (65.0 mL) via syringe, which was dried over MS 4A and purged with dry argon. Then, the flask was covered with aluminium foil. Subsequently, degassed DBU (11.7 mL, 78.2 mmol) and distilled water (56.0 μL, 3.1 mmol) were added by syringes. Immediately, ice-chilled trimethylsilylacetylene (0.92 mL, 6.5

mmol) was added by a syringe. The flask was submerged in an 80 ºC oil bath and left stirring for 36 h. After cooling to room temperature, CH_2Cl_2 (100 mL) was added to the flask. The resulting mixture was washed with 10% HCl (3 × 100 mL). The collected organic layer was dried over anhydrous Na_2SO_4. After filtration, the crude products were absorbed onto silica gel (20 g). The product was purified by silica gel chromatography using hexane/AcOEt (5:1, v/v) as an eluent followed by recrystallization from hexane. A white solid (1.3 g, 3.4 mmol, 53%) was obtained. M.p. 80–81 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.99 (t, J = 7.2 Hz, 6H), 1.46-1.52 (m, 4H), 1.73-1.80 (m, 4H), 4.34 (t, J = 6.4 Hz, 4H), 7.60 (d, J = 4.0 Hz, 2H), 8.04 (t, J = 4.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 68.08, 125.96, 128.30, 129.16, 130.09, 130.41, 132.76, 133.69, 134.59, 136.54, 140.88. Anal. Calcd. for $C_{24}H_{26}O_4$: C, 76.17; H, 6.92. Found: C, 76.19; H 7.08.



1o

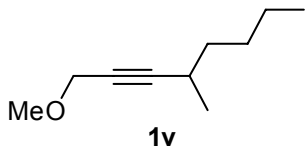
A 200 mL two-necked flask containing [$PdCl_2(PPh_3)_2$] (140.4.0 mg, 0.2 mmol) and CuI (76.2 mg, 0.4 mmol) were evacuated/refilled with argon three times. To the flask were added THF (60.0 mL), iodobenzene (1.35 mL, 12.0 mmol), 3-methyl-1-hexyne (1.35 mL, 10.0 mmol) and TBAF (20.0 mL, 1.0 mol/L in THF) via syringe. The reaction mixture was allowed to stir at room temperature for 16 h. Then, silica gel (20 g) was added into the falsk, and the solvent was removed with an evaporator. The product was purified by silica gel chromatography using hexane as an eluent. A light-yellow liquid (1.6 g, 89%) was obtained. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.95 (t, J = 7.2 Hz, 3H), 1.24 (d, J = 6.8 Hz, 3H), 1.44-1.59 (m, 4H), 2.63-2.66 (m, 1H), 7.24-7.29 (m, 3H), 7.38-7.40 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.96, 20.62, 21.10, 26.26, 39.20, 80.63, 94.84, 124.11, 127.40, 128.14, 131.56.



1t

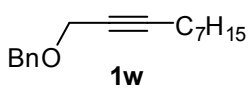
KOH (1.3 g, 23.2 mmol, powder), DMSO (10.0 mL) and 2-decyn-1-ol (2.0 mL, 11.3 mmol) were added to a 50 mL one-necked flask equipped with a Teflon-coated stir bar. The mixture was allowed to stir at room temperature for 30 min. The flask was put into a water bath. Then, MeI (2.0 mL, 32.1 mmol) was added slowly. The resulting mixture was stirred at room temperature overnight. Water (30 mL) was added to the flask. The mixture was extracted by Et_2O (3 × 30 mL). The collected organic layer was dried over anhydrous

Na_2SO_4. The product was purified by silica gel chromatography using hexane/AcOEt (20:1, v/v) as an eluent. A colorless liquid (1.80 g, 95%) was obtained. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.89 (t, J = 7.2 Hz, 3H), 1.27-1.40 (m, 8H), 1.48-1.54 (m, 2H), 2.20-2.24 (m, 2H), 3.37 (s, 3H), 4.08 (t, J = 2.4 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.03, 18.69, 22.58, 28.60, 28.76, 28.79, 31.70, 57.33, 60.19, 75.62, 87.19.



1v

A 100 mL one-necked flask containing 1,1-dibromo-2-(1-ethylpentyl)-ethene[26] (2.64 g, 9.29 mmol) was evacuated/refilled with argon three times. To the flask was added THF (50.0 mL) via syringe. The solution was cooled to –78 ºC. Then, *n*BuLi (12.3 ml, 1.67 mol/L in hexane) was added over 10 min. The mixture was allowed to reach room temperature over a period of 2 h. Subsequently, CH_3OCH_2Cl (0.8 mL, 10.22 mmol) was added dropwise at –78 ºC. The resulting mixture was warmed to room temperature slowly, and stirred at room temperature overnight. Water (30 mL) was added to the flask. The mixture was extracted with Et_2O (3 × 50 mL). The collected organic layer was dried over anhydrous Na_2SO_4. The product was purified by silica gel chromatography using hexane-AcOEt (25:1, v/v) as an eluent. A colorless liquid (1.22 g, 78%) was obtained. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.90 (t, J = 7.2 Hz, 3H), 1.00 (t, J = 7.6 Hz, 3H), 1.26-1.54 (m, 8H), 2.28-2.30 (m, 1H), 3.38 (s, 3H), 4.11 (d, J = 2.4 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 11.79, 14.03, 22.56, 28.00, 29.60, 33.43, 34.37, 57.22, 60.21, 76.73, 90.46.



1w

A 100 mL one-necked flask containing NaH (0.60 g, 15.0 mmol, 60%wt) was evacuated/refilled with argon three times. To the flask was added THF (30.0 mL) via syringe. The solution was cooled to 0 ºC. Then, 2-decyn-1-ol (2.0 mL, 11.3 mmol) was added. The mixture was allowed to stir at 0 ºC for 30 min. Subsequently, BnBr (1.75 mL, 14.71 mmol) was added dropwise at 0 ºC. The resulting mixture was stirred at room temperature overnight. Water (30 mL) was added to the flask. The mixture was extracted with Et_2O (3 × 30 mL). The collected organic layer was dried over anhydrous Na_2SO_4. The product was purified by silica gel chromatography using hexane-AcOEt (20:1, v/v) as an eluent. A colorless liquid (2.3 g, 94%) was obtained. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, J = 7.2 Hz, 3H), 1.27-1.40 (m, 8H), 1.50-1.56 (m, 2H), 2.21-2.25 (m, 2H), 4.16 (t, J = 2.0 Hz, 2H), 4.59 (s, 2H),

7.25-7.36 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.10, 18.81, 22.65, 28.66, 28.83, 28.87, 31.76, 57.75, 71.33, 75.81, 87.37, 127.75, 128.10, 128.40, 137.71.

Experimental Procedures in Tables 2-1, 2-2 and 2-3

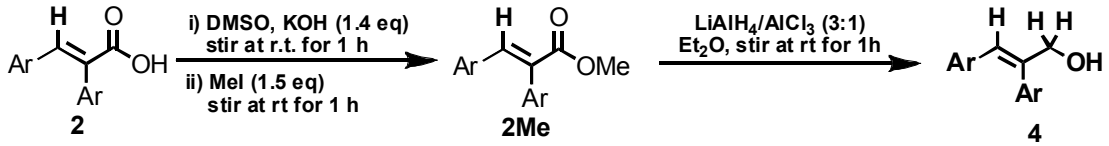
A) Procedure for the hydrocarboxylation of 1a (entry 4 in Table 2-1): A 20 mL schlenk tube dried with a heating-gun under vacuum was fitted with a balloon filled with CO_2, a rubber septum, and a teflon-coated magnetic stir bar. The schlenk tube was charged with **1a** (89.1 mg, 0.5 mmol) and [(IMes)CuF] (2.0 mg, 0.005 mmol). The schlenk tube was evacuated and refilled with CO_2 three times. Then, the schlenk tube was covered with aluminium foil. Subsequently, dioxane (2.0 mL) and $HSi(OEt)_3$ (185 μL, 1.0 mmol) was added via air-tight syringes, and the resulting mixture was stirred at room temperature for 1 min. Then the reaction tube was submerged in a pre-heated oil bath at 100 ºC and the reaction was carried out for 4 h with stirring. After cooling to room temperature, DMSO (2.0 mL) and *t*BuOK (0.2 g, 1.8 mmol) were added into the schlenk tube, and the resulting mixture was stirred at room temperature for 15 min. MeI (0.1 mL, 1.6 mmol) was then added, and the reaction mixture was allowed to stir for another 15 min at room temperature. Finally, the resulting mixture was diluted with THF (10.0 mL). The solution was analyzed with GC using tridecane (61.0 μL, 0.25 mmol) as an internal standard.

B) Procedure for the hydrocarboxylation of 1b–l (Table 2-2): The reaction was carried out similarly as entry 4 in Table 1. After the reaction, 36% HCl aq. (1.0 mL) and CH_2Cl_2 (4.0 mL) was added, and the mixture was stirred at room temperature for 15 min. The reaction mixture was roughly purified through a short silica gel column chromatography using EtOAc as an eluent. The collected organic solvents were evaporated, and the resulting crude products were further purified with silica gel chromatography using CH_2Cl_2 and then EtOAc as eluent.

C) Procedure for the hydrocarboxylation of internal alkynes 1m–z (Table 2-3): A 20 mL schlenk tube dried with a heating-gun under vacuum was fitted with a balloon filled with CO_2, a rubber septum, and a teflon-coated magnetic stir bar. The schlenk tube was charged with [(^{Cl}IPr)CuF] (13.5 mg, 0.025 mmol, 2.5 mol %) (for **1m–w**) or [(IPr)CuF] (11.8 mg, 0.025 mmol, 2.5 mol %) (for **1x–z**). The schlenk tube was

evacuated and refilled with CO_2 three times. Then, hexane (2.0 mL), **1m**–**z** (1.0 mmol, liquid alkynes should be freshly purified before use) and $HSi(OEt)_3$ (370 μL, 2.0 mmol) were added via air-tight syringes, and the resulting mixture was stirred at room temperature for 1 min. Then the reaction tube was submerged in a pre-heated oil bath at 70 ºC and the reaction was carried out for 12 h with stirring. After the reaction, 36% HCl aq. (2.0 mL) and CH_2Cl_2 (4.0 mL) was added, and the mixture was stirred at room temperature for 15 min. The reaction mixture was roughly purified through a short silica gel column chromatography using EtOAc as an eluent. The collected organic solvents were evaporated, and the resulting crude products were further purified with silica gel chromatography using Hexane/EtOAc (5/1, v/v) as an eluent.

D) Determination of the stereochemistry of the product 2:



Esterification of 2 to 2Me:[27] The carboxylic acid product **2** (1.0 mmol) and powdered KOH (78.4 mg, 1.4 mmol) were dissolved in DMSO (3.0 mL), and the mixture was stirred for 1 h. Then, MeI (94.0 μL, 1.5 mmol) was added to the solution and stirring was continued for 1 h. After the reaction, water (10 mL) was added and the resulting mixture was extracted with CH_2Cl_2 (3×10 mL). The combined organic solvent was evaporated to afford the crude product, which was purified by silica gel chromatography using CH_2Cl_2 as an eluent to afford **2Me**. The yields of **2Mea**–**o** were as follows. **2aMe**: 86%, **2bMe**: 97%, **2cMe**: 84%, **2dMe:** 73%, **2eMe**: 92%, **2fMe**: 72%, **2gMe**: 47%, **2hMe**: 83%, and **2lMe:** 90%.

Reduction of 2Me to the corresponding allylic alcohol (4):[28] Glassware was thoroughly dried prior to use. $AlCl_3$ (44.5 mg, 0.33 mmol) was carefully added in small portions to a stirred suspension of $LiAlH_4$ (38.0 mg, 1.0 mmol) in dry ether (3.0 mL) at 0 ºC. The resulting mixture was further stirred for 15 min at the same temperature, then for another 15 min at room temperature. An ethereal solution of **2Me** (1.0 mmol) was added dropwise to the solution over a period of 10 min at room temperature and the reaction was carried out (2 h) until TLC (silica gel, CH_2Cl_2) showed full conversion of

the ester. Water was carefully added to the cooled solution and stirred for 30 min. The reaction mixture was then extracted with ether (3×10 mL). The combined organic solvent was evaporated to afford the crude product, which was purified by silica gel chromatography using CH_2Cl_2 as an eluent to provide the corresponding allylic alcohol (**4**). The yields of **4a**–**o** were as follows. **4a**: 74%, **4b**: 88%, **4c**: 81%, **4d:** 56%, **4e**: 68%, **4f**: 65%, **4g**: 71%, **4h**: 70%, and **4l:** 74%.

Stoichiometric Reactions

Generation of [(^{Cl}IPr)CuH] (Aa) from [(^{Cl}IPr)CuF] and a Hydrosilane: In a glovebox under dry nitrogen, PMHS (7 μL, 0.1 mmol) was added dropwise via syringe to a NMR tube containing a solution of [(^{Cl}IPr)CuF] (13.5 mg, 0.025 mmol) in C_6D_6 (0.5 mL) at ambient temperature. The solution immediately became bright orange in color. Then, the solution was cooled in an ice-bath. ^{1}H NMR spectrum was recorded within 10 min (Figure 2-3). ^{1}H NMR (400 MHz, C_6D_6): δ 1.16 (d, J = 6.8 Hz, 12H, CH(C*H*$_3$)$_2$), 1.32 (d, J = 6.8 Hz, 12H, CH(C*H*$_3$)$_2$), 2.37 (s, 1H, Cu-*H*), 2.37 (sept, J = 7.0 Hz, 4H, C*H*(CH$_3$)$_2$), 5.56 (s, 1H, C*H*=C) 6.72 (d, J = 7.2 Hz, Ar), 6.95 (d, J = 7.7 Hz, 4H, Ar), 7.09–7.05 (m, 2H, Ar). The similar spectra were also obtained by the reaction of [(^{Cl}IPr)CuF] with other silanes such as HSi(OEt)$_3$ and H_2SiPh_2.

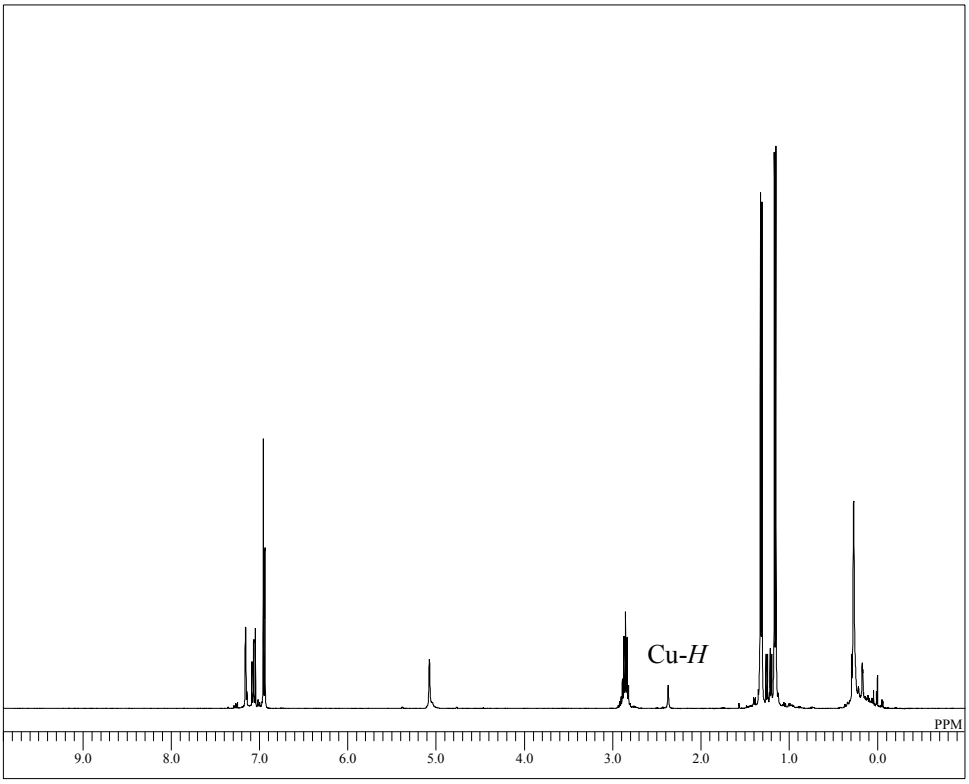


Figure 2-3. ^{1}H NMR spectrum of [(^{Cl}IPr)CuH] (**Aa**) generated by the reaction of [(^{Cl}IPr)CuF] with PMHS in C_6D_6

Reaction of Aa with an alkyne (1q) to provide a copper alkenyl complex (Ba): In a glovebox, [(^{Cl}IPr)CuF] (270.0 mg, 0.5 mmol), **1q** (440.0 μL, 2.5 mmol) and benzene (10.0 mL) were added to a 30 mL round-bottom flask equipped with a Teflon-coated stir bar. Triethoxysilane (185.0 μL, 1.0 mmol) was added dropwise via a syringe. The resulting bright orange solution faded in color to light-brown over 30 min. After stirring for 2 h, the solution was concentrated *in vacuo*, and hexane (5.0 mL) was added. Then, the mixture was cooled at –20 ºC for 20 min in a refrigerator. The resulting suspension was filtered and **Ba** was obtained as an off-white powder (237.0 mg, 70%).

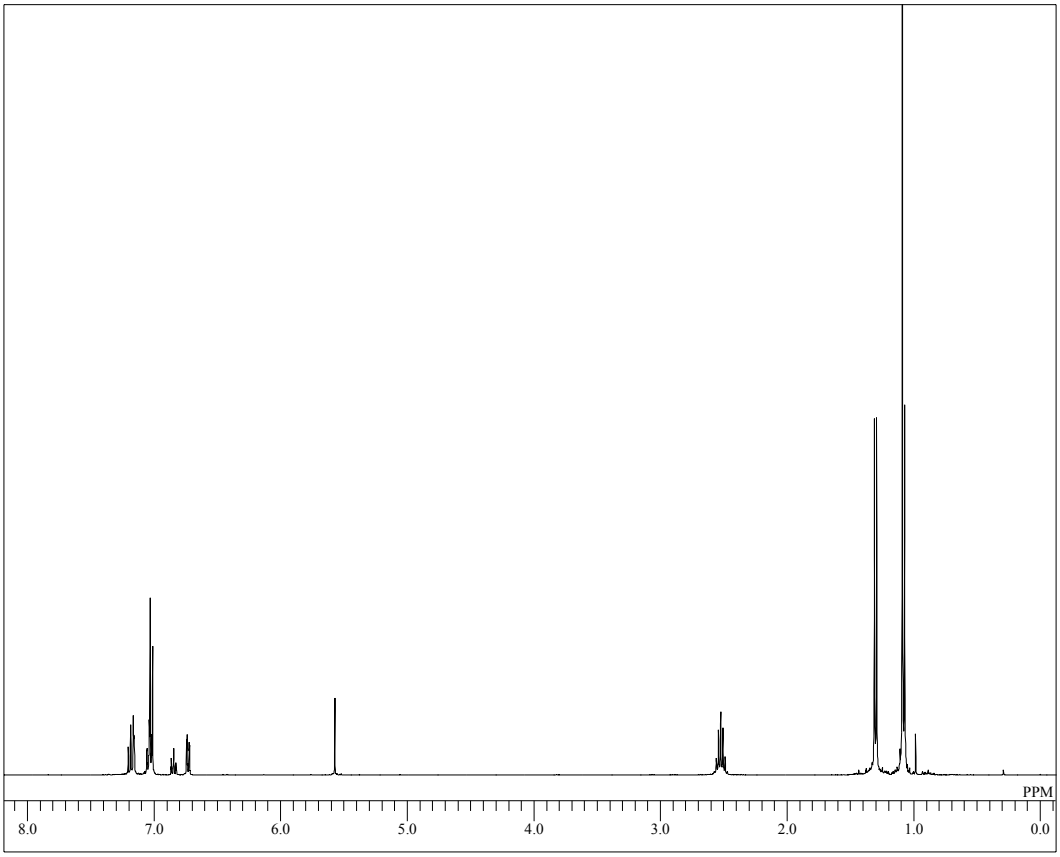


Figure 2-4. ^{1}H NMR spectrum of **Ba** in C_6D_6

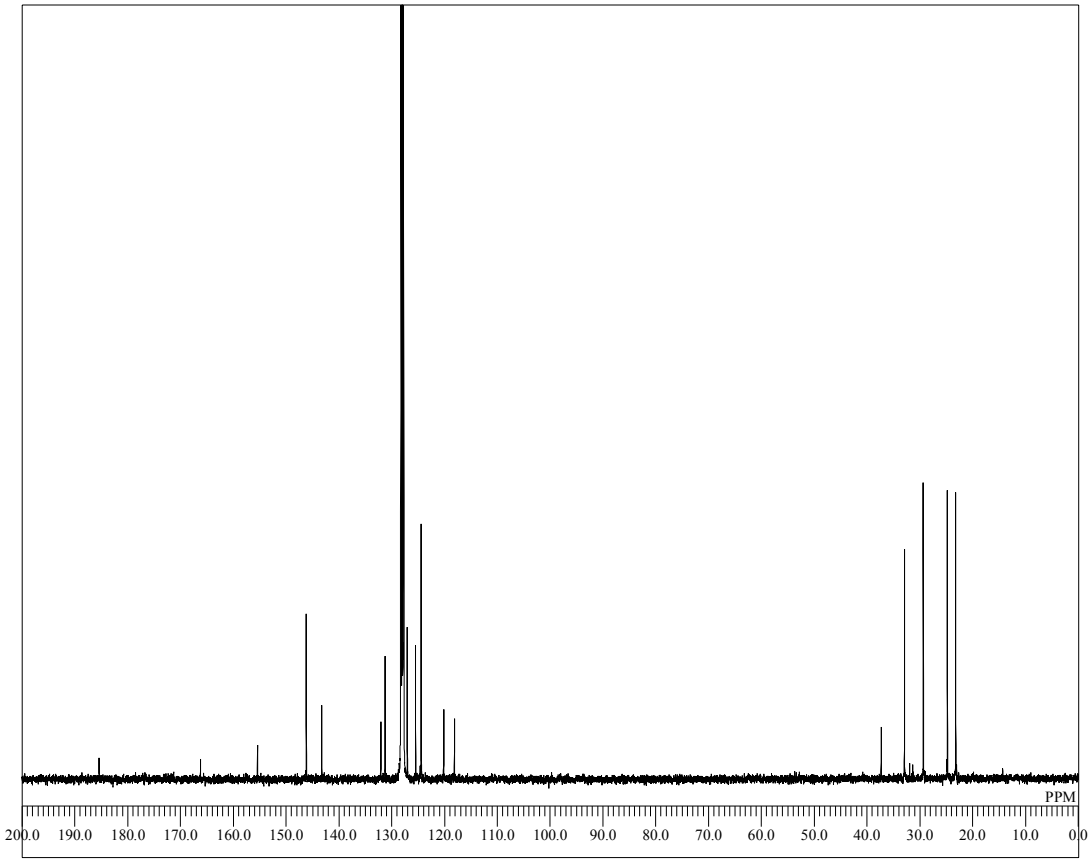
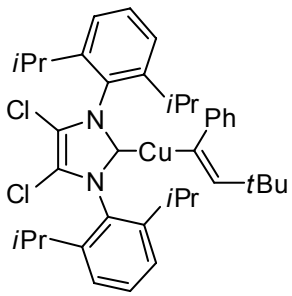


Figure 2-5. ^{13}C NMR spectrum of **Ba** in C_6D_6



Ba

^1H NMR (400 MHz, C_6D_6): δ 1.06 (d, J = 6.8 Hz, 12H, CH(CH_3)$_2$), 1.08 (s, 9H, C(CH_3)$_3$), 1.29 (d, J = 6.8 Hz, 12H, CH(CH_3)$_2$), 2.51 (sept, J = 6.8 Hz, 4H, CH(CH$_3$)$_2$), 5.56 (s, 1H, CH=C) 6.72 (d, J = 7.2 Hz, 2H, Ar), 6.83 (t, J = 7.2 Hz, 1H, Ar), 7.00-7.04 (m, 6H, Ar), 7.17 (t, J = 8.0 Hz, 2H, Ar). ^{13}C NMR (100 MHz, C_6D_6): 23.21, 24.76, 29.34, 32.91, 37.32, 118.14, 120.17, 124.45, 125.49, 127.06, 131.28, 132.07, 143.26 (*C*H=C), 146.19, 155.44, 166.30, 185.44. Further treatment of the obtained copper alkenyl complex (**Ba**) with *t*BuOH afforded (*Z*)-3,3-dimethyl-1-phenyl-1-butene, (*E*)-configuration of the compelx (**Ba**).

Insertion of CO_2 into the copper alkenyl complex (Ba) to afford a copper carboxylato compex (Ca): In a glovebox, a 20 mL Schlenk tube was charged with **3** (67.0 mg, 0.098 mmol) and benzene (2.0 mL). The resulting clear, colorless solution

was frozen at –78 °C, and the flask was evacuated and backfilled with CO_2 (balloon). After stirring for 12 h at 65 ºC, the solution was concentrated *in vacuo*, and hexane (4 mL) was added. Then, the mixture was cooled at –30 ºC for 20 min in the refrigerator. The resulting suspension was filtered to afford a copper carboxylato complex (**Ca**) as a white powder (60.0 mg, 84%).

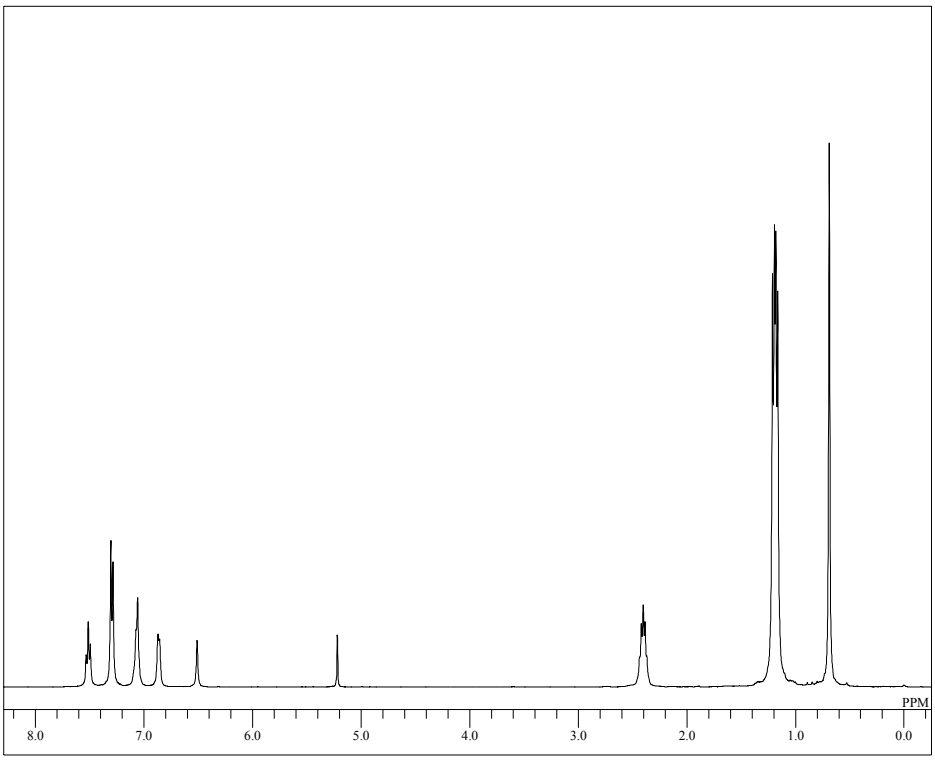


Figure 2-6. ^{1}H NMR spectrum of **Ca** in CD_2Cl_2

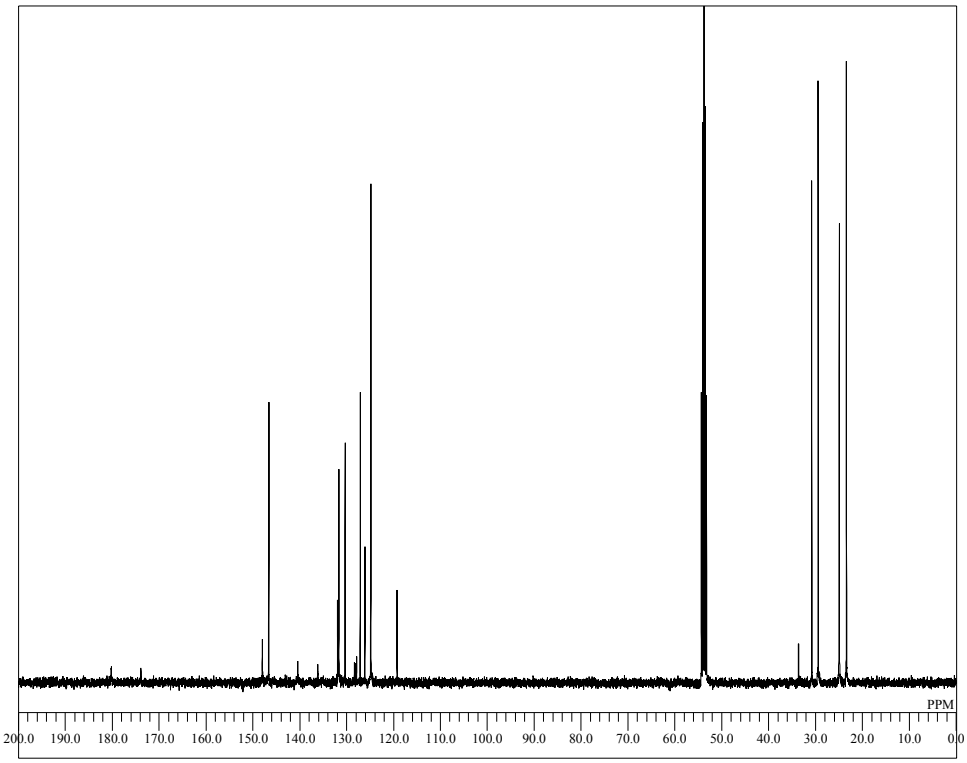
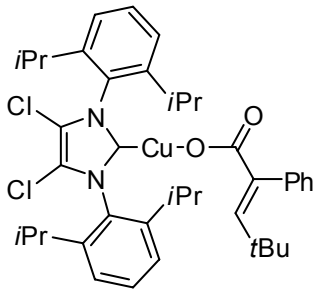


Figure 2-7. ^{13}C NMR spectrum of **Ca** in CD_2Cl_2



Ca

^{1}H NMR (400 MHz, CD_2Cl_2): δ 0.69 (s, 9H, C(CH_3)$_3$), 1.17 (d, J = 6.8 Hz, 12H, CH(CH_3)$_2$), 1.20 (d, J = 6.8 Hz, 12H, CH(CH_3)$_2$), 2.37-2.44 (m, 4H, CH(CH$_3$)$_2$), 6.51 (s, 1H, CH=C), 6.86 (d, J = 6.0 Hz, 2H, Ar), 7.07 (d, J = 5.2 Hz, 3H, Ar), 7.30 (d, J = 8.0 Hz, 2H, Ar), 7.51 (t, J = 7.2 Hz, 2H, Ar). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 23.40, 24.93, 29.43, 30.81, 33.62, 119.26, 124.86, 126.13, 127.11, 130.35, 131.68, 131.94, 136.16, 140.40, 146.63, 147.98, 173.95 (*C*OO), 180.25. IR (KBr): 2964.4, 2927.7, 2869.9, 1583.4, 1544.9, 1458.1, 1365.5, 1323.1, 1274.9, 1060.8, 804.3, 763.8, 711.7 cm^{-1}.

Reaction of Ca with HSi(OEt)$_3$ to afford [(^{Cl}IPr)CuH] (Aa): In a glovebox under dry nitrogen, HSi(OEt)$_3$ (9.3 μL, 0.05 mmol) was added dropwise via a syringe to a NMR tube containing a solution of **Ca** (9.1 mg, 0.0125 mmol) in C_6D_6 (0.5 mL) at ambient temperature. The colorless solution slowly within 5 min became bright yellow in color.

Then, the solution was cooled in an ice-bath and ^{1}H NMR spectrum was recorded within 10 min. A new singlet peak at 2.37 ppm appeared, which is most diagnostic of [(^{Cl}IPr)CuH] (**Aa**).

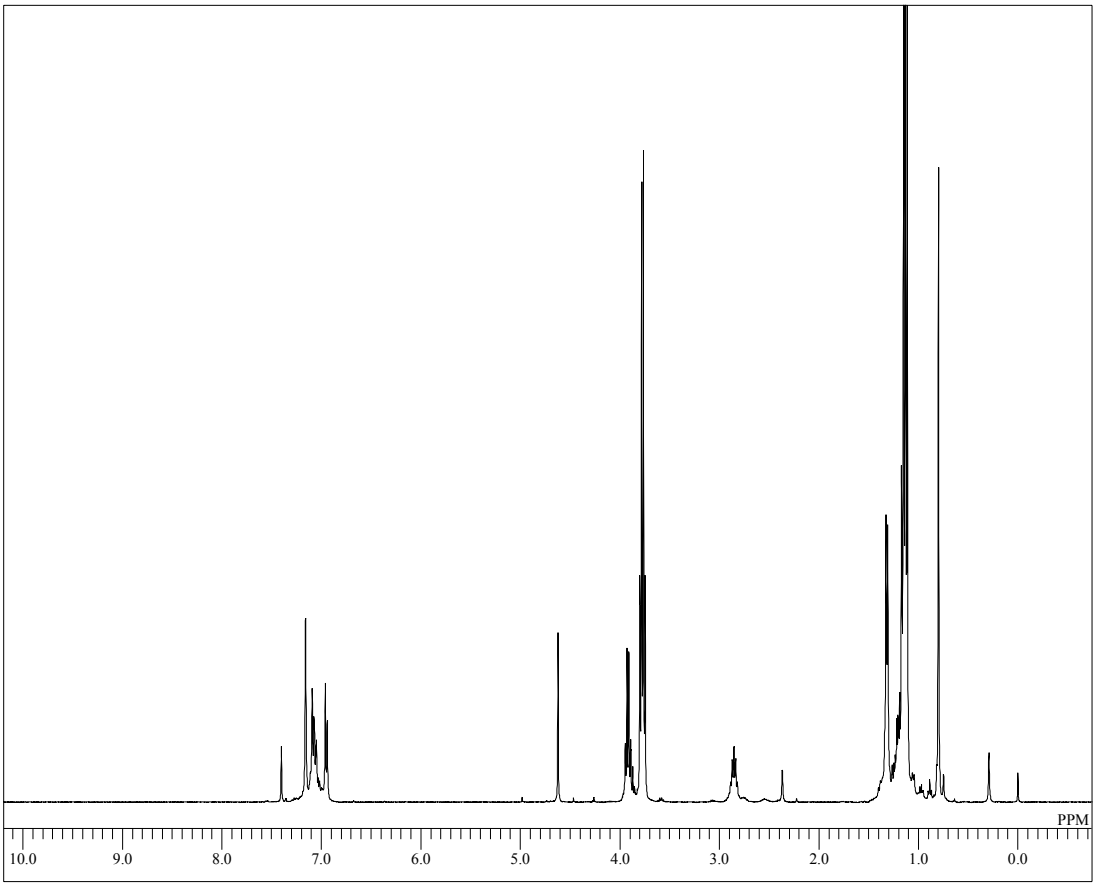


Figure 2-8. ^{1}H NMR spectrum of [(^{Cl}IPr)CuH] (**Aa**) regenerated by the reaction of **Ca** with $HSi(OEt)_3$ in C_6D_6

X-ray Crystallographic Analysis: Crystallographic data of [(IMes)CuF] and **2a** were summarized in Tables 2-4. All the data were collected on a Rigaku/Saturn70 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) at 153 K, and processed using CrystalClear (Rigaku).[29] The structures were solved by a direct method (SIR92) and refined by full-matrix least-square refinement on F^2. The non-hydrogen atoms, except disordered atom and solvated molecules, were refined anisotropically. All hydrogen atoms were located on the calculated positions and not refined. All calculations were performed using the CrystalStructure software package.[30] CCDC 780917 and 780918 contains the supplementary crystallographic

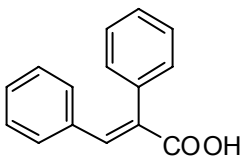
data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Table 2-4. Crystallographic data

compound	[(IMes)CuF]	**2a**
empirical formula	$C_{21}H_{24}N_2FCu$	$C_{15}H_{12}O_2$
formula weight	386.98	224.26
temp / K	153	153
crystal system	orthorhombic	monoclinic
space group	*F*dd2 (#43)	$P2_1/c$ (#14)
a / Å	14.554(5)	5.801(5)
b / Å	29.482(12)	24.979(19)
c / Å	8.800(4)	24.46(2)
α / deg	90	90
β / deg	90	93.294(11)
γ / deg	90	90
V / Å^3	3776(3)	3538(5)
Z	2	4
d_{cacd}/g cm^{-3}	1.247	1.263
observed reflections	1872	8002
unique reflections	1872 (all data)	8002 (all data)
GOF	1.361	1.017
*R*1 ($I > 2\sigma(I)$), *wR*2[a]	0.060, 0.157[b]	0.090, 0.195[c]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma (w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] $w = 1/[0.0009Fo^2 + 1.0\sigma(F_o^2)]/(4F_o^2)$. [c] $w = 1/[0.65\sigma(F_o^2)]/(4F_o^2)$.

Characterization of the Products



2a

2a:[6a] A white solid (81.0 mg, 72%): m.p. 174-176 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.07 (d, J = 8.0 Hz, 2H), 7.15-7.25 (m, 5H), 7.34-7.41 (m, 3H), 7.96 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 128.02, 128.24, 128.65, 129.45, 129.81, 130.81, 131.64, 134.34,

135.39, 142.73, 173.27. IR (KBr): 3100-2500 (br), 1674.1, 1618.2, 1419.5, 1269.1, 788.8, 704.0, 690.5 cm^{-1}.

Single crystals of the complex were obtained by recrystallization from CH_2Cl_2/hexane. The structure was also confirmed by X-ray crystallography (Figure 2-9).

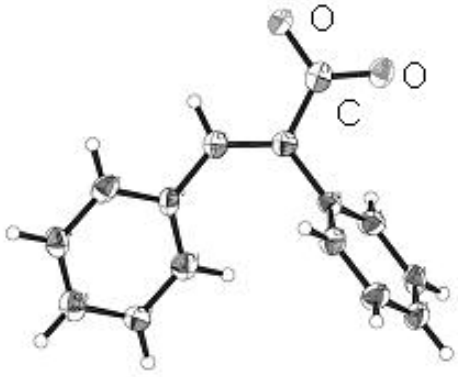
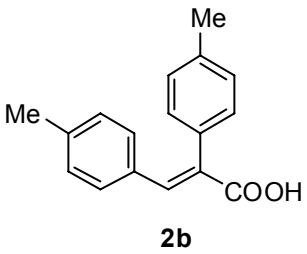
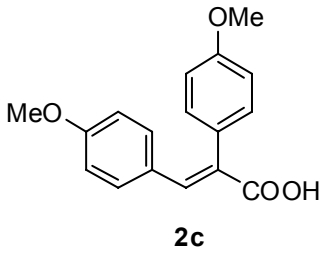


Figure 2-9. Crystal structure of **2a**



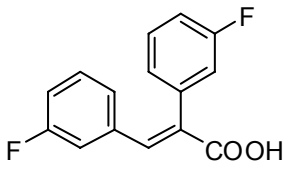
2b

2b: A white solid (84.0 mg, 67%): m.p. 183-184 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.28 (s, 3H), 2.39 (s, 3H), 6.99 (s, 4H), 7.12 (d, J = 8.0 Hz, 2H), 7.19 (d, J = 8.0 Hz, 2H), 7.89 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.37, 129.00, 129.47, 129.59, 130.54, 130.87, 131.63, 132.47, 137.68, 139.81, 142.22, 173.44. IR (KBr): 3100-2500 (br), 1674.1, 1604.7, 1508.2, 1423.4, 1265.2, 1182.3, 813.9, 734.8 cm^{-1}. Anal. Calcd. for $C_{17}H_{16}O_2$: C, 80.93; H, 6.39%. Found: C, 80.80; H 6.52%.



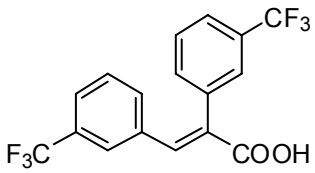
2c

2c:[31] A light-yellow solid, (82.0 mg, 58%): m.p. 218-219 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.77 (s, 3H), 3.85 (s, 3H), 6.71 (d, J = 8.0 Hz, 2H), 6.93 (d, J = 8.0 Hz, 2H), 7.05 (d, J = 8.0 Hz, 2H), 7.17 (d, J = 8.0 Hz, 2H), 7.87 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 55.22, 113.75, 114.29, 127.12, 127.81, 128.62, 131.03, 132.64, 141.95, 159.22, 160.52, 173.00. IR (KBr): 3100-2500 (br), 1664.5, 1600.8, 1508.2, 1425.3, 1276.8, 1249.8, 1170.7, 1024.1, 840.9, 829.3 cm^{-1}.



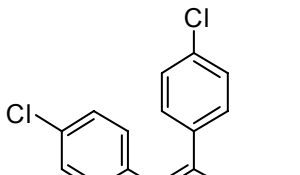
2d

2d: A white solid (101.2 mg, 78%): m.p. 160-161 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.70-6.73 (m, 1H), 6.90 (d, J = 8.0 Hz, 1H), 6.94-7.02 (m, 3H), 7.06-7.12 (m, 1H), 7.16-7.21 (m, 1H), 7.34-7.39 (m, 1H), 7.92 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 115.44 (d, J_{C-F} = 21 Hz), 116.89 (t, J_{C-F} = 22 Hz), 125.46 (d, J_{C-F} = 2.8 Hz), 126.72 (d, J_{C-F} = 2.8 Hz), 129.92 (d, J_{C-F} = 8.6 Hz), 130.44 (d, J_{C-F} = 7.6 Hz), 131.55, 135.92 (d, J_{C-F} = 7.6 Hz), 136.72 (d, J_{C-F} = 7.6 Hz), 141.72, 161.12, 161.67, 163.61, 164.16, 172.08. IR (KBr): 3100-2500 (br), 1676.0, 1608.5, 1581.5, 1477.4, 1419.5, 1282.6, 1236.3, 956.6, 893.0, 725.2 cm^{-1}. Anal. Calcd. for $C_{15}H_{10}F_2O_2$: C, 69.23; H, 3.87%. Found: C, 69.29; H 3.79%.



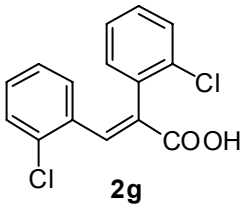
2e

2e: A white solid, (135.0 mg, 75%): m.p. 87-88 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.14 (d, J = 8.0 Hz, 1H), 7.18 (s, 1H), 7.25 (t, J = 8.0 Hz, 1H), 7.36 (d, J = 8.0 Hz, 1H), 7.43-7.48 (m, 3H), 7.59 (d, J = 8.0 Hz, 1H), 7.96 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 122.24 (d, J_{C-F} = 31.6 Hz), 124.98 (d, J_{C-F} = 30.7 Hz), 125.26 (d, J_{C-F} = 3.8 Hz), 126.30 (d, J_{C-F} = 3.8 Hz), 126.70 (d, J_{C-F} = 3.8 Hz), 127.23 (d, J_{C-F} = 3.9 Hz), 129.01, 129.41, 131.01 (d, J_{C-F} = 33.6 Hz), 131.40 (d, J_{C-F} = 32.6 Hz), 132.04, 133.22, 133.51, 134.38, 134.19, 141.81, 171.84. IR (KBr): 3100-2500 (br), 1678.0, 1610.5, 1419.5, 1330.8, 1292.2, 1265.2, 1170.7, 1124.4, 1074.3, 914.2, 808.1, 729.0 cm^{-1}. Anal. Calcd. for $C_{17}H_{10}F_6O_2$: C, 56.68; H, 2.80%. Found: C, 56.68; H 2.77%.



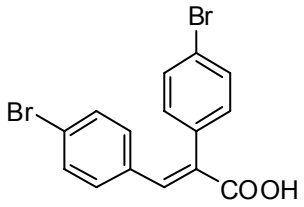
2f

2f: A White solid (110.0 mg, 75%): m.p. 180-182 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.00 (d, J = 8.0 Hz, 2H), 7.14-7.19 (m, 4H), 7.36 (d, J = 8.0 Hz, 2H), 7.90 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 128.74, 129.13, 130.87, 131.21, 131.90, 132.36, 133.18, 134.36, 135.78, 141.68, 172.54. IR (KBr): 3100-2500 (br), 1678.0, 1618.2, 1595.0, 1421.4, 1282.6, 1259.4, 1091.6, 1014.5, 997.1, 829.3, 738.7 cm^{-1}. Anal. Calcd. for $C_{15}H_{10}Cl_2O_2$: C, 61.46; H, 3.44%. Found: C, 61.73; H, 3.42%.



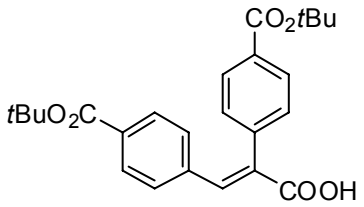
2g

2g: A white solid (94.0 mg, 64%): m.p. 188-190 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.77 (d, J = 8.0 Hz, 1H), 6.92 (t, J = 8.0 Hz, 1H), 7.07 (d, J = 8.0 Hz, 1H), 7.14-19 (m, 2H), 7.25-7.29 (m, 1H), 7.38 (d, J = 8.0 Hz, 1H), 7.43 (d, J = 8.0 Hz, 1H), 8.30 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 126.36, 126.99, 129.51, 129.54, 129.65, 130.30, 130.33, 131.44, 131.86, 132.76, 134.06, 134.43, 135.11, 140.32, 171.63. IR (KBr): 3100-2500 (br), 1672.2, 1612.4, 1591.2, 1463.9, 1438.8, 1296.1, 1269.1, 1211.2, 1055.0, 1041.5, 927.7, 740.6 cm^{-1}. Anal. Calcd. for $C_{15}H_{10}Cl_2O_2$: C, 61.46; H, 3.44%. Found: C, 61.31; H, 3.44%.



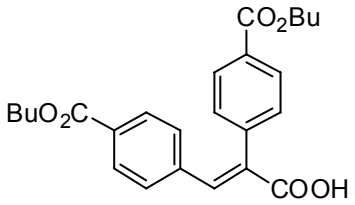
2h

2h: A light-yellow solid (125.0 mg, 65%): m.p. 188-190 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.86 (d, J = 8.0 Hz, 2H), 7.03 (d, J = 8.0 Hz, 4H), 7.27 (d, J = 8.0 Hz, 2H), 7.44 (d, J = 8.0 Hz, 2H), 7.81 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 122.60, 124.22, 131.01, 131.47, 131.73, 132.08, 132.79, 133.66, 141.67, 172.12. IR (KBr): 3100-2500 (br), 1678.0, 1618.2, 1583.4.0, 1485.1, 1421.4, 1307.6, 1259.4, 1211.2, 1184.2, 1072.3, 1008.7, 995.2, 827.4, 734.8 cm^{-1}. Anal. Calcd. for $C_{15}H_{10}Br_2O_2$: C, 47.16; H, 2.64%. Found: C, 47.35; H, 2.73%.



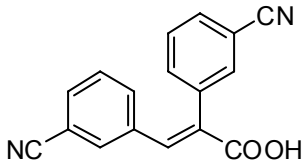
2i

2i: A white solid (150.0 mg, 71%): m.p. 198-200 ºC. ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.55 (s, 9H), 1.60 (s, 9H), 7.10 (d, J = 8.0 Hz, 2H), 7.28 (d, J = 8.0 Hz, 2H), 7.77 (d, J = 8.0 Hz, 2H), 7.98 (d, J = 8.0 Hz, 2H), 8.02 (s, 1H). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 27.48, 27.56, 80.77, 80.88, 128.83, 129.28, 129.52, 130.03, 131.58, 132.32, 132.59, 137.57, 138.97, 141.53, 164.44, 164.81, 171.73. IR (KBr): 3100-2500 (br), 1712.7, 1678.0, 1606.6, 1560.3, 1458.1, 1392.5, 1369.4, 1299.9, 1257.5, 1163.0, 1105.1, 1016.3, 997.1, 846.7, 767.6, 721.3 cm^{-1}. EI-HRMS: Calcd. for $C_{25}H_{28}O_6$ ($[M]^+$), 424.1886. Found, 424.1887.



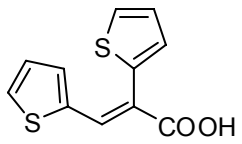
2j

2j: A white solid (135.0 mg, 64%): m.p. 137-139 ºC. ^{1}H NMR (400 MHz, CD_2Cl_2): δ 0.95-1.02 (m, 6H), 1.43-1.54 (m, 4H), 1.69-2.03 (m, 4H), 4.26-4.36 (m, *4*H), 7.16 (d, J = 8.0 Hz, 2H), 7.35 (d, J = 6.4 Hz, 2H), 7.84 (d, J = 8.4 Hz, 2H), 8.05 (d, J = 6.4 Hz, 2H), 8.07 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.86, 13.90, 19.60, 19.65, 31.06, 31.13, 65.34, 65.36, 129.66, 130.13, 130.39, 130.86, 131.56, 133.15, 138.58, 139.96, 142.26, 166.09, 166.44, 171.77. IR (KBr): 3100-2500 (br), 1716.5, 1676.0.0, 1606.6, 1431.1, 1272.9, 1176.5, 1103.2, 1018.3, 754.1, 725.2 cm^{-1}. EI-HRMS: Calcd. for $C_{25}H_{28}O_6$ ($[M]^+$), 424.1886. Found, 424.1885.



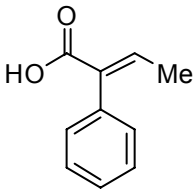
2k

2k: A white solid (71.0 mg, 52%): m.p. 181-183 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22 (d, J = 8.0 Hz, 1H), 7.32-7.36 (m, 2H), 7.47 (d, J = 8.0 Hz, 1H), 7.51-7.58 (m, 3H), 7.70 (d, J = 7.2 Hz, 1H), 8.00 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 113.12, 113.24, 117.73, 118.05, 129.49, 129.80, 132.00, 132.22, 133.03, 133.36, 133.78, 134.09, 134.31, 134.72, 135.38, 141.18, 171.26. IR (KBr): 3100-2500 (br), 2231.5, 1674.1, 1475.4, 1425.3, 1274.9, 1236.3, 927.7, 812.0, 723.3, 682.8 cm^{-1}. EI-HRMS: Calcd. for $C_{17}H_{10}N_2O_2$ ($[M]^+$), 274.0742. Found, 274.0742.

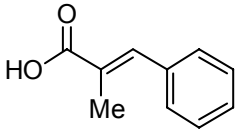


2l

2l: A light-yellow solid (92.0 mg, 78%): m.p. 241-243 ºC. ^{1}H NMR (400 MHz, Acetone-D_6): δ 7.15 (dd, J = 1.6 Hz, J = 1.2 Hz, 1H), 7.18 (dd, J = 3.6 Hz, J = 3.6 Hz, 1H), 7.28 (dd, J = 3.6 Hz, J = 3.2 Hz, 1H), 7.57 (d, J = 3.6 Hz, 1H), 7.68 (dd, J = 1.6 Hz, J = 1.2 Hz, 1H), 7.79 (dd, J = 1.6 Hz, J = 0.8 Hz, 1H), 8.32 (s, 1H). ^{13}C NMR (100 MHz, Acetone-D_6): δ 122.78, 127.58, 128.28, 128.77, 129.71, 132.82, 135.58, 136.35, 137.62, 139.04, 167.73. IR (KBr): 3100-2400 (br), 1670.2, 1604.7, 1637.5, 1560.3, 1529.4, 1438.8, 1411.8, 1278.7, 1240.1, 1215.1, 1055.0, 925.8, 852.5, 723.3, 700.1 cm^{-1}. Anal. Calcd. for $C_{11}H_8S_2O_2$: C, 55.91; H, 3.41%. Found: C, 55.76; H, 3.54%.

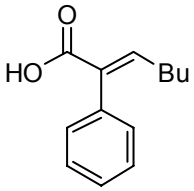


2m (major)



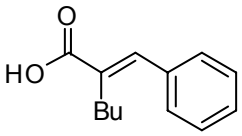
2m' (minor)

2m:[6a] A white solid (140.0 mg, 86%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.79 (d, J = 7.2 Hz, 3H), 7.21 (s, 1H), 7.32-7.42 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 15.77, 127.61, 128.05, 129.81, 134.12, 134.40, 142.82, 172.66. **2m':**[6a] This product was not isolated, diagnostic resonances observed in NMR spectra of its mixtures with the major product are listed. ^{1}H NMR (400 MHz, $CDCl_3$): δ 2.13 (s, CH_3), 7.82 (s, vinyl-H). ^{13}C NMR (100 MHz, $CDCl_3$): 13.68 (CH_3).



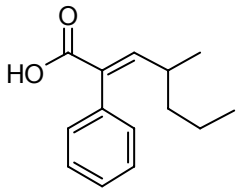
2n

2n:[32] A semi-solid (156.0 mg, 76%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.83 (t, J = 7.2 Hz, 3H), 1.24-1.32 (m, 2H), 1.37-1.44 (m, 2H), 2.08-2.14 (m, 2H), 7.16-7.22 (m, 3H), 7.29-7.39 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.81, 22.34, 29.46, 30.82, 127.57, 128.01, 129.75, 133.08, 134.77, 148.14, 172.41. IR (KBr): 3100-2500 (br), 1685.7, 1654.8, 1629.7, 1600.8, 1496.7, 1419.5, 1369.4, 1274.9, 1213.1, 1193.9, 914.2, 781.1cm^{-1}.



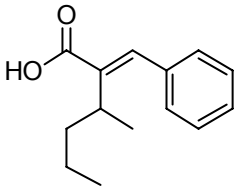
2n'

2n':[33] A white solid (20.0 mg, 9%): m.p. 84-85 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.94 (t, J = 7.2 Hz, 3H), 1.36-1.46 (m, 2H), 1.55-1.63 (m, 2H), 2.55 (t, J = 8.0 Hz, 2H), 7.33-7.43 (m, 5H), 7.81 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.86, 22.89, 27.06, 31.35, 128.53, 128.68, 129.42, 132.86, 135.54, 140.94, 174.14. IR (KBr): 3100-2500 (br), 1676.0, 1637.5, 1618.2, 1448.4, 1419.5, 1319.2, 1299.9, 1274.9, 1222.8, 927.7, 769.5, 686.6 cm^{-1}.



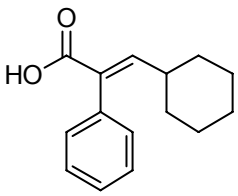
2o

2o: A white solid (164.0 mg, 75%): m.p. 88-90 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.77 (t, J = 7.2 Hz, 3H), 0.98 (d, J = 6.4 Hz, 3H), 1.13-1.33 (m, 4H), 2.27-2.32 (m, 1H), 6.95 (d, J = 10.8 Hz, 1H), 7.15 (d, J = 6.8 Hz, 2H), 7.29-7.38 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.05, 20.21, 20.57, 33.74, 38.88, 127.50, 128.02, 129.63, 131.88, 135.05, 153.54, 172.50. IR (KBr): 3100-2500 (br), 1685.7, 1629.7, 1458.1, 1419.5, 1274.9, 1228.6, 702.0, 686.6 cm^{-1}. Anal. Calcd. for $C_{14}H_{18}O_2$: C, 77.03; H, 8.31%. Found: C, 76.81; H, 8.36%.



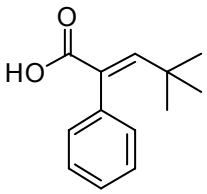
2o'

2o': A white solid (13.0 mg, 6%): m.p. 73-75 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.79 (t, J = 7.2 Hz, 3H), 1.17-1.26 (m, 2H), 1.29 (d, J = 7.2 Hz, 3H), 1.50-1.77 (m, 2H), 2.98-3.04 (m, 1H), 7.30-7.42 (m, 5H), 7.80 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.07, 19.43, 21.18, 32.50, 36.99, 128.17, 128.38, 128.87, 135.85, 137.24, 141.32, 173.26. IR (KBr): 3100-2500 (br), 1676.0, 1637.5, 1610.5, 1448.4, 1413.7, 1261.4, 1232.4, 923.8, 786.9, 696.3 cm^{-1}. EI-HRMS: Calcd. for $C_{14}H_{18}O_2$ ($[M+H]^+$), 219.1385. Found, 219.1376.



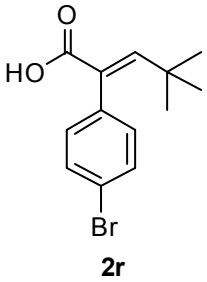
2p

2p: A white solid (202.0 mg, 88%): m.p. 97-99 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.07-1.28 (m, 5H), 1.59-1.68 (m, 5H), 2.09-2.17 (m, 1H), 7.00 (d, J = 10.4 Hz, 1H), 7.17 (d, J = 4.0 Hz, 2H), 7.29-7.39 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.06, 25.66, 31.92, 38.35, 127.53, 128.02, 129.59, 131.35, 135.01, 152.57, 172.76. IR (KBr): 3100-2500 (br), 1679.9, 1637.5, 1618.2, 1448.4, 1419.5, 1278.7, 1228.6, 966.3, 931.6, 786.9, 705.9 cm^{-1}. Anal. Calcd. for $C_{15}H_{18}O_2$: C, 78.23; H, 7.88%. Found: C, 77.99; H, 8.06%.



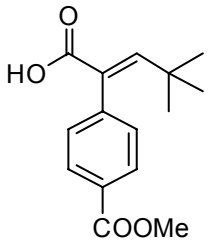
2q

2q:[34] A white solid (145.0 mg, 71%): m.p. 131-132 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (s, 9H), 7.11-7.15 (m, 2H), 7.16 (s, 1H), 7.28-7.32 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 30.23, 34.41, 127.48, 127.59, 130.08, 130.86, 135.63, 155.75, 173.73. IR (KBr): 3100-2500 (br), 1672.2, 1629.7, 1596.9, 1498.6, 1460.0, 1421.4, 1365.5, 1267.1, 1207.4, 921.9, 785.0, 702.0, 605.6 cm^{-1}.



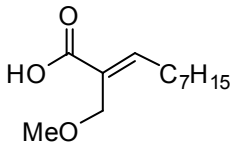
2r

2r: A white solid (193.1 mg, 68%): m.p. 232-234 ºC. ^{1}H NMR (400 MHz, CD_3OD): δ 0.93 (s, 9H), 7.06 (d, J = 8.4 Hz, 2H), 7.08 (s, 1H), 7.47 (d, J = 8.4 Hz, 2H). ^{13}C NMR (100 MHz, CD_3OD): δ 30.78, 35.19, 122.29, 131.74, 133.28, 137.40, 155.02, 164.74, 170.60. IR (KBr): 3100-2500 (br), 1670.2, 1624.0, 1488.9, 1460.0, 1425.3, 1365.5, 1265.2, 1207.4, 1070.4, 1014.5, 918.1, 827.4, 788.8, 734.8 cm^{-1}. Anal. Calcd. for $C_{13}H_{15}BrO_2$: C, 55.14; H, 5.34%. Found: C, 54.97; H, 5.26%.



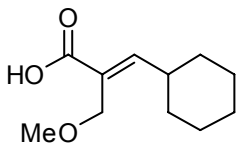
2s

2s: A white solid (166.0 mg, 63%): m.p. 227-229 ºC. ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (s, 9H), 3.92 (s, 3H), 7.20 (s, 1H), 7.23 (d, J = 8.0 Hz, 2H), 8.00 (d, J = 8.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 30.20, 34.51, 52.13, 128.90, 129.32, 129.76, 130.25, 140.78, 156.50, 166.86, 172.92. IR (KBr): 3100-2500 (br), 1724.2, 1674.1, 1629.7, 1604.7, 1436.9, 1425.3, 1272.9, 1174.6, 1114.8, 1105.1, 721.3 cm^{-1}. Anal. Calcd. for $C_{15}H_{18}O_4$: C, 68.68; H, 6.92%. Found: C, 68.39; H, 6.90%.



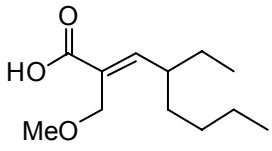
2t

2t: A colorless liquid (135.0 mg, 63%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, J = 7.2 Hz, 3H), 1.24-1.34 (m, 8H), 1.44-1.51 (m, 2H), 2.30-2.36 (m, *2*H), 3.36 (s, 3H), 4.19 (s, 2H), 7.17 (t, J = 8.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.09, 22.64, 28.62, 28.96, 29.07, 29.32, 31.74, 58.12, 65.41, 128.09, 151.31, 172.41. IR (KBr): 3100-2500 (br), 1689.5, 1637.5, 1419.5, 1379.0, 1244.0, 1191.9, 1105.1, 956.6, 912.3, 813.9, 669.3 cm^{-1}. Anal. Calcd. for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35%. Found: C, 67.38; H, 10.35%.



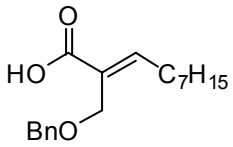
2u

2u: A colorless liquid (115.4 mg, 58%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.15-1.37 (m, 5H), 1.65-1.78 (m, 5H), 2.45-2.53 (m, 1H), 3.36 (s, 3H), 4.19 (s, 2H), 6.96 (d, J = 10.4 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.31, 25.69, 32.06, 38.00, 58.16, 65.69, 126.13, 155.48, 172.32. IR (KBr): 3100-2500 (br), 1685.7, 1637.5, 1448.4, 1419.5, 1191.9, 1155.3, 1099.3, 958.6, 908.4, 765.7, 617.2 cm^{-1}. Anal. Calcd. for $C_{11}H_{18}O_3$: C, 66.64; H, 9.15%. Found: C, 66.58; H, 9.13%.



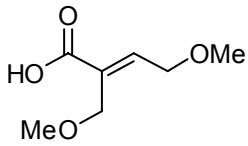
2v

2v: A colorless liquid (158.0 mg, 74%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.83-0.89 (m, 6H), 1.18-1.36 (m, 6H), 1.46-1.57 (m, 2H), 2.43-2.48 (m, 1H), 3.36 (s, 3H), 4.17 (s, 2H), 6.88 (d, J = 10.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 11.80, 13.99, 22.83, 27.81, 29.54, 34.40, 40.73, 58.16, 65.86, 128.11, 155.54, 172.24. IR (KBr): 3100-2500 (br), 1685.7, 1637.5, 1458.1, 1419.5, 1380.9, 1245.9, 1193.9, 1105.1, 958.6, 912.3 cm^{-1}. Anal. Calcd. for $C_{12}H_{22}O_3$: C, 67.26; H, 10.35%. Found: C, 67.28; H, 10.31%.



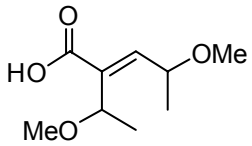
2w

2w: A colorless liquid (146.0 mg, 48%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.88 (t, J = 6.8 Hz, 3H), 1.26-1.33 (m, 8H), 1.39-1.60 (m, 2H), 2.21-2.27 (m, 2H), 3.76 (s, 3H), 4.25 (s, 2H), 4.53 (s, 2H), 7.02 (d, J = 8.0 Hz, 1H), 7.26-7.35 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 14.09, 22.63, 28.73, 28.80, 29.07, 29.33, 31.74, 51.84, 63.41, 72.47, 127.62, 127.84, 128.33, 128.75, 138.32, 148.90, 167.70. IR (KBr): 2927.7, 2856.4, 1718.5, 1685.7, 1647.1, 1496.7, 1436.9, 1236.3, 1193.9, 1070.4, 1028.0, 947.0, 906.5, 817.8, 736.8, 698.2 cm^{-1}. Anal. Calcd. for $C_{19}H_{28}O_3$: C, 74.96; H, 9.27%. Found: C, 75.11; H, 9.42%.



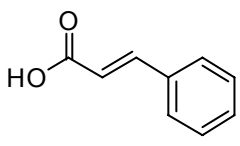
2x

2x: A colorless liquid (110.0 mg, 66%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.28 (s, 3H), 3.32 (s, 3H), 4.13 (s, 2H), 4.20 (d, J = 6.0 Hz, 2H), 7.11 (t, J = 5.6 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 58.25, 58.65, 66.03, 68.99, 129.05, 146.31, 171.19. IR (KBr): 3100-2500 (br), 1701.1, 1654.8, 1637.5, 1629.7, 1379.0, 1193.9, 1097.4, 1062.7, 954.7, 910.3, 819.7, 748.3 cm^{-1}. EI-HRMS: Calcd. for $C_7H_{12}O_4$ ($[M+H]^+$), 161.0814. Found, 161.0811.



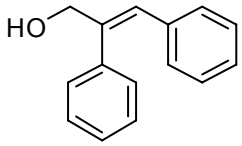
2y

2y: A colorless liquid (a mixture of diastereomer; 115.0 mg, 61%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.25-1.31 (m, 3H), 1.39-1.45 (m, 3H), 3.31-3.34 (m, 6H), 4.41-4.65 (m, 2H), 6.84-6.88 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 20.02, 20.62, 20.86, 21.45, 56.68, 56.71, 56.87, 57.01, 72.19, 72.71, 74.15, 74.41, 133.29, 133.57, 145.36, 148.44, 170.79, 171.02. IR (KBr): 3100-2500 (br), 1685.7, 1637.5, 1560.3, 1541.0, 1448.4, 1375.2, 1203.5, 1089.7, 1026.1, 846.7, 769.5, 690.5 cm^{-1}. EI-HRMS: Calcd. for $C_9H_{16}O_4$ ($[M+H]^+$), 189.1127. Found, 189.1132.



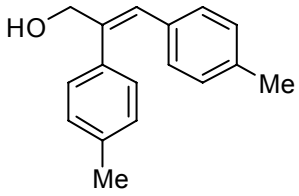
2z

2z: A light-yellow solid (65.0 mg, 44%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.47 (d, J = 16.0 Hz, 1H), 7.40-7.43 (m, 3H), 7.54-7.58 (m, 2H), 7.81 (d, J = 16.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 117.27, 128.37, 128.95, 130.76, 134.00, 147.13, 172.49. IR (KBr): 3100-2500 (br), 1685.7, 1629.7, 1494.7, 1448.4, 1419.5, 1286.4, 1205.4, 979.8, 769.5, 682.8 cm^{-1}.



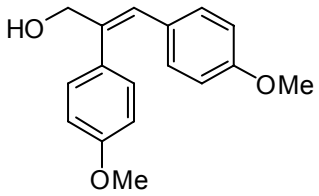
4a

4a: (320.0 mg, 1.34 mmol) of **2aMe** was used. A white solid, (210.0 mg, 74%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.79 (br, 1H), 4.44 (s, 2H), 6.68 (s, 1H), 6.98-7.00 (m, 2H), 7.09-7.11 (m, 3H), 7.21-7.23 (m, 2H), 7.28-7.34 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 68.49, 126.44, 126.78, 127.53, 127.93, 128.72, 128.77, 129.18, 136.41, 138.50, 141.46.



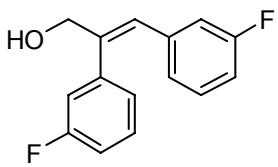
4b

4b: (240.0 mg, 0.90 mmol) of **2bMe** was used. A white solid (190.0 mg, 88%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.68 (br, 1H), 2.25 (s, 3H), 2.35 (s, 3H), 4.42 (d, J = 1.2 Hz, 2H), 6.62 (s, 1H), 6.89-6.94 (m, 4H), 7.10-7.15 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 21.10, 21.23, 68.73, 126.23, 128.59, 128.66, 129.07, 129.50, 133.65, 135.54, 136.49, 137.16, 140.48.



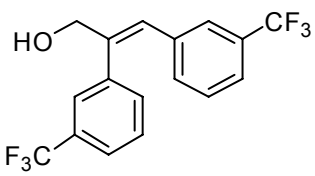
4c

4c: (150.0 mg, 0.50 mmol) of **2cMe** was used. A light-yellow solid (110.0 mg, 88%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.70 (br, 1H), 3.73 (s, 3H), 3.81 (s, 3H), 4.41 (d, J = 0.8 Hz, 2H), 6.58 (s, 1H), 6.65-6.68 (m, 2H), 6.85-6.89 (m, 2H), 6.93-6.97 (m, 2H), 7.14-7.18 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 55.10, 55.19, 68.81, 113.40, 114.26, 125.94, 129.19, 129.95, 130.36, 130.77, 139.03, 158.34, 158.90.



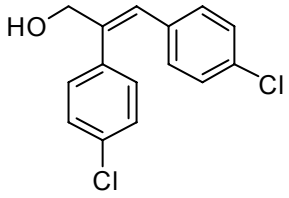
4d

4d: (200.0 mg, 0.73 mmol) of **2dMe** was used. Colorless oil, (101.0 mg, 56%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.89 (br, 1H), 4.42 (d, J = 1.6 Hz, 2H), 6.64-6.68 (m, 2H), 6.77-6.84 (m, 2H), 6.90-6.94 (m, 1H), 6.96-7.03 (m, 2H), 7.06-7.12 (m, 1H), 7.25-7.32 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 67.93, 113.95 (d, J_{C-F} = 21.1 Hz), 114.77 (d, J_{C-F} = 21.1 Hz), 115.48 (d, J_{C-F} = 7.6 Hz), 115.71 (d, J_{C-F} = 8.6 Hz), 124.40 (d, J_{C-F} = 2.9 Hz), 124.98 (d, J_{C-F} = 2.8 Hz), 125.90 (d, J_{C-F} = 2.9 Hz), 127.46 (d, J_{C-F} = 8.6 Hz), 130.48 (d, J_{C-F} = 7.7 Hz), 138.23 (d, J_{C-F} = 8.7 Hz), 140.29 (d, J_{C-F} = 7.7 Hz), 141.49 (d, J_{C-F} = 1.9 Hz), 161.48 (d, J_{C-F} = 55.6 Hz), 163.95 (d, J_{C-F} = 57.4 Hz).



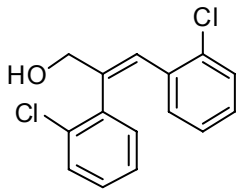
4e

4e: (240.0 mg, 0.64 mmol) of **2fMe** was used. Colorless oil, (150.0 mg, 68%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.83 (br, 1H), 4.49 (s, 2H), 6.79 (s, 1H), 7.09 (d, J = 8.0 Hz, 1H), 7.17 (s, 1H), 7.22 (t, J = 8.0 Hz, 1H), 7.34-7.37 (m, 2H), 7.44 (t, J = 8.0 Hz, 2H), 7.56 (d, J = 8.0 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 67.69, 122.45, 123.74 (d, J_{C-F} = 3.9 Hz), 124.65 (t, J_{C-F} = 3.8 Hz), 125.18, 125.45 (t, J_{C-F} = 3.9 Hz), 125.86 (t, J_{C-F} = 3.8 Hz), 126.23, 128.01 (d, J_{C-F} = 4 Hz), 128.55, 129.43, 130.53 (d, J_{C-F} = 33.6 Hz), 131.35 (d, J_{C-F} = 33.6 Hz), 132.14 (d, J_{C-F} = 3.8 Hz), 136.58, 138.72, 141.91.



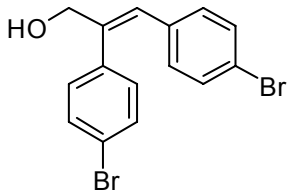
4f

4f: (170.0 mg, 0.55 mmol) of **2gMe** was used. A white solid (100.0 mg, 65%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.70 (br, 1H), 4.43 (s, 2H), 6.67 (s, 1H), 6.91-6.93 (m, 2H), 7.10-7.16 (m, 4H), 7.29-7.33 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 68.08, 125.96, 128.30, 129.16, 130.09, 130.41, 132.76, 133.69, 134.59, 136.54, 140.88.



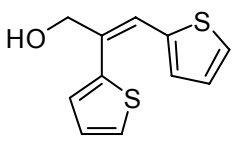
4g

4g: (70.0 mg, 0.23 mmol) of **2iMe** was used. A white solid (45.0 mg, 71%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.81 (br, 1H), 4.51 (s, 2H), 6.77-6.80 (m, 1H), 6.85-6.89 (m, 1H), 7.02-7.06 (m, 2H), 7.09-7.11 (m, 1H), 7.14-7.23 (m, 2H), 7.29-7.32 (m, 1H), 7.36-7.38 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 66.80, 125.22, 126.11, 127.02, 128.21, 129.01, 129.14, 129.67, 129.79, 131.18, 133.25, 133.87, 134.63, 136.83, 141.60.



4h

4h: (220.0 mg, 0.56 mmol) of **2jMe** was used. A white solid (145.0 mg, 70%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.75 (br, 1H), 4.41 (s, 2H), 6.64 (s, 1H), 6.84-6.86 (m, 2H), 7.06-7.09 (m, 2H), 7.24-7.28 (m, 2H), 7.44-7.47 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 67.97, 120.95, 121.85, 125.94, 130.36, 130.70, 131.24, 132.09, 134.99, 136.98, 140.98.



4l

4l: (115.0 mg, 0.46 mmol) of **2oMe** was used. Light-yellow oil (75.0 mg, 74%): ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.89 (br, 1H), 4.37 (s, 2H), 6.88-6.90 (m, 1H), 6.95 (s, 2H), 7.02-7.04 (m, 1H), 7.09-7.11 (m, 2H), 7.42-7.44 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 68.56, 123.34, 126.21, 126.58, 127.01, 127.57, 127.74, 129.01, 132.17, 138.03, 139.29.

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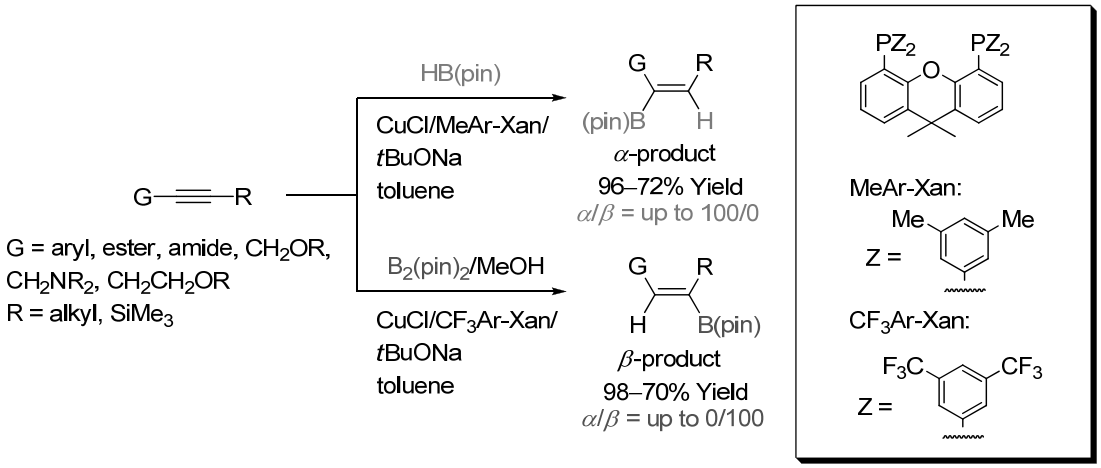
Chapter 3

Copper-Catalyzed Highly Regio- and Stereoselective Directed Hydroboration of Unsymmetrical Internal Alkynes: Controlling Regioselectivity by Choice of Catalytic Species

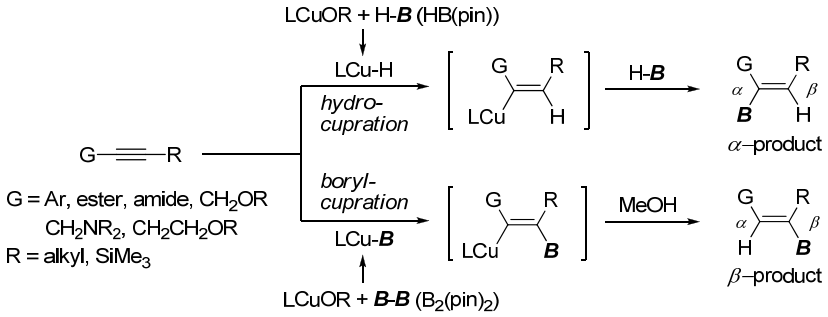
Copper-catalyzed highly regio- and stereoselective hydroboration of unsymmetrical internal alkynes has been developed. The regioselectivity was successfully controlled by choice of catalytic species (copper hydride and borylcopper).



3-1. Introduction

Hydroboration is a robust and practical synthetic method for organoboranes.[1] In particular, hydroboration of alkynes is of interest, since the products (vinylboranes) are potent intermediates in the Suzuki-Miyaura cross-coupling reaction[2] and other useful transformations.[3,4] It is well-known that the hydroboration of terminal alkynes proceeds regio- and stereoselectively.[5] However, the reaction of unsymmetrical internal alkynes often suffers from low regioselectivity even in the presence of a catalyst.[6] Generally, bulky boryl moieties tend to be added at a less bulky site in both uncatalyzed and catalyzed hydroboration. For example, hydroboration of alkylphenylacetylenes tends to produce β-boryl styrene derivatives (β-product).[7] Bis(pinacolato)diboron ($B_2(pin)_2$) also can be used as a borane source to afford the same β-products;[8] However, a general method for synthesizing the α-products (regioisomers of the β-products) has not been reported. To date, only acetylenic esters have led to the α-products.[9]

Scheme 3-1.



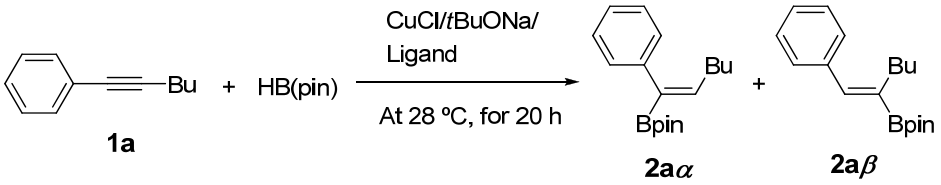
Herein, the author describes highly selective syntheses of the α-products and β-products by copper-catalyzed hydroboration utilizing two different catalytic copper species (Cu-H[9] and Cu-B[10]) generated from pinacolborane (HB(pin)) and $B_2(pin)_2$, respectively (Scheme 3-1). Regioselectivity was successfully controlled via hydrocupration and borylcupration through the directing effect of group G.[11,12]

3-2. Results and Discussion

First, the hydroboration of 1-phenyl-1-hexyne (**1a**) was carried out using HB(pin) at 28 ºC with a copper catalyst system (CuCl/*t*BuONa). Without catalyst, no reaction occurred (Table 3-1, entry 1). Employing monodentate phosphanes such as PPh_3 and

PCy_3 (entries 2 and 3) or bidentate phosphanes such as dppe, dppp, *rac*-BINAP, and dppbz (entries 4–7), led to almost no reactions. On the other hand, Xantphos (Xan; Figure 3-1) afforded the product in 13% yield with high regioselectivity: **2a**α/**2a**β = 95/5 (entry 8). With the use of the Xantphos derivative bearing 3,5-bis(trifluoromethyl)phenyl moieties (CF_3Ar-Xan;[13] Figure 3-1), the yield was dramatically improved to 89%, with somewhat lower regioselectivity (**2a**α/**2a**β = 88/12, entry 9). Gratifyingly, MeAr-Xan[14] bearing 3,5-xylyl moieties was highly effective as a ligand, giving the products in 92% total yield with high regioselectivity (**2a**α/**2a**β = 94/6, entry 10). Lowering the temperature to 20 ºC improved both the yield and the regioselectivity (entry 11). As ligands, *N*-heterocyclic carbenes (NHCs)[15] such as IPr and ^{Cl}IPr (Figure 3-1) could be used, albeit with slightly lower efficiencies (entries 12 and 13). Employing the $[(PPh_3)CuH]_6/PPh_3$ or CuCl/dppbz/*t*BuOK systems,[9] which are effective catalytic systems for the hydroboration of acetylenic esters, yielded the products with 0% and 4% yields, respectively (entries 14 and 15). Other transition metal catalysts such as $RhCl(PPh_3)_3$[16] and $[IrCl(COD)]_2$/dppm[7b] were used in the hydroboration of terminal alkynes, but for **1a** these catalysts showed only low catalytic activities and poor regioselectivities (entries 16 and 17).[17]

Table 3-1. Copper-catalyzed hydroboration of **1a** with pinacolborane (HB(pin)) using various catalysts[a]



1a **2a**α **2a**β

Entry	Ligand	Yield [%][b]	**2a**α/**2a**β
1	none[c]	0	-
2	PPh_3	0	-
3	PCy_3	5	-
4	dppe	trace	-
5	dppp	1	-
6	*rac*-BINAP	trace	-
7	dppbz	1	-

Table 3-1. (Continued)

8	Xan	13	95/5
9	CF_3Ar-Xan	89	88/12
10	MeAr-Xan	92	94/6
11[d]	MeAr-Xan	97 (97)[e]	95/5
12	IPr	89	90/10
13	^{Cl}IPr	88	90/10
14	$[(PPh_3)CuH]_6/PPh_3$[f]	0	-
15	CuCl/dppbz/*t*BuOK[g]	4	-
16	$RhCl(PPh_3)_3$[h]	9	21/79
17	$[IrCl(COD)]_2$/dppm[i]	65	54/46

[a] **1a** (0.50 mmol), HB(pin) (0.60 mmol), CuCl (0.010 mmol, 2.0 mol %), a ligand (0.010 mmol, 2.0 mol %), *t*BuONa (0.060 mmol, 12 mol %), toluene (1.0 mL), at 28 ºC, for 20 h. [b] Total Yield of **2a**α and **2a**β based on the GC internal standard technique. [c] The reaction was performed without CuCl, ligand and *t*BuONa. [d] At 20 ºC and HB(pin) (0.75 mmol) was used. [e] Isolated yield. [f] $[(PPh_3)CuH]_6$ (0.011 mmol, 2.1 mol %), PPh_3 (0.010 mmol, 2.0 mol %), HB(pin) (0.55 mmol), THF (0.50 mL). [g] CuCl (0.010 mmol, 2.0 mol %), dppbz (0.0050 mmol, 1.0 mol %), *t*BuOK (0.030 mmol, 6.0 mol %), HB(pin) (0.55 mmol), THF (0.50 mL). [h] $RhCl(PPh_3)_3$ (0.010 mmol, 2.0 mol %) was used as a catalyst. [i] $[IrCl(COD)]_2$ (0.0050 mmol, 2.0 mol %) and dppm (P/Ir = 2) were used as a catalyst.

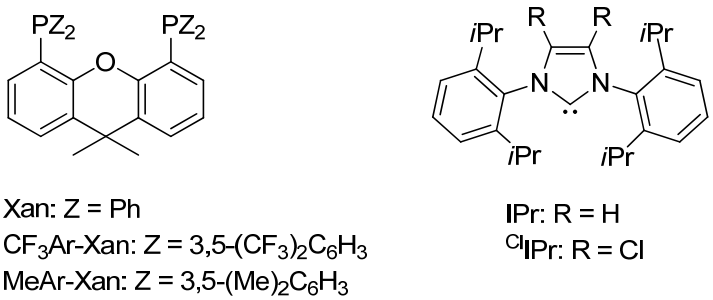
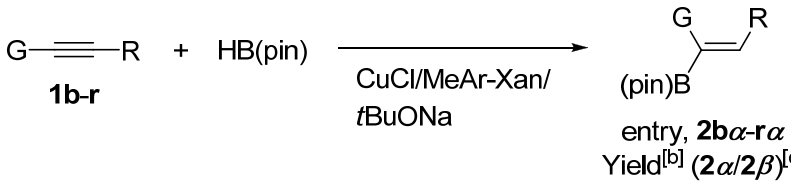


Figure 3-1. Structures of ligands

The hydroboration of various internal alkynes (**1b**–**r**) to afford the α-products was carried out using HB(pin) with MeAr-Xan as a ligand (Table 3-2). Regioselectivity in

the crude reaction mixtures (**2α**/**2β**) was high, and the corresponding α-products (**2α**) were isolated in good yields. The reaction of **1b** gave a **2bα**/**2bβ** ratio of 93/7 and **2bα** was isolated in 78% yield (entry 1). In non-catalytic[5b] and Ti-catalyzed[6c] hydroborations of **1b**, the selectivities of **2α**/**2β** were 15/85 (with HB(pin)) and 67/33 (with catecholborane), respectively. Electron donating and withdrawing groups on the aryl ring were tolerated while maintaining high yields and regioselectivities (entries 2–7). Alkynes bearing pyridine and thiophene rings on the acetylenic carbons (**1i** and **1j**) reacted with high regioselectivities and the α-products (**2iα** and **2jα**) were isolated in high yields (entries 8 and 9). An alkyne bearing a trimethylsilyl group was converted to the boryl, silyl bifunctional product (**2kα**) regioselectively in high yield (entry 10). In the case of an alkyne having an alkenyl moiety (**1l**), the regioselectivity decreased to **2lα**/**2lβ** = 72/28 (entry 11). On the other hand, alkynes having ester[9] (**1m**) and amide (**1n**) functionalities instead of aromatic substituents afforded the corresponding α-products (**2mα** and **2nα**) in high yields with perfect regioselectivities (entries 12 and 13). Furthermore, alkynes bearing O and N atoms at the propargylic position (entries 14–16) provided the corresponding α-products (**2oα**–**qα**) in good yields with high regioselectivities when employing CF_3Ar-Xan instead of MeAr-Xan as a ligand.[18] Unfortunately, an alkyne bearing a homopropargyl ether functionality afforded the α-product with low selectivity (entry 17).

Table 3-2. Copper-catalyzed hydroboration of various alkynes to the α-products with HB(pin)[a]



entry, **2bα-rα**
Yield[b] (**2α**/**2β**)[c]

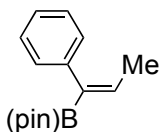
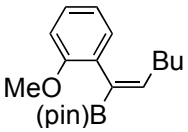
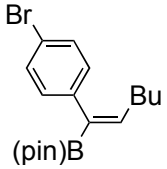
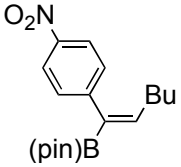
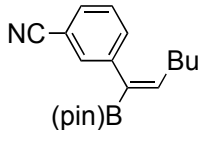
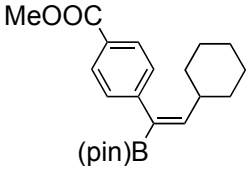
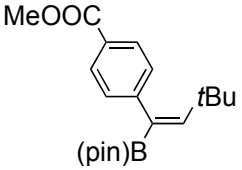
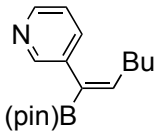
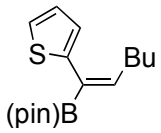
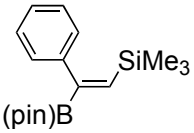
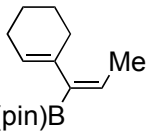
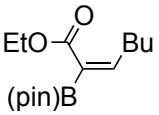
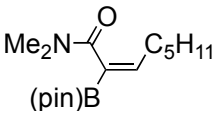
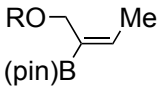
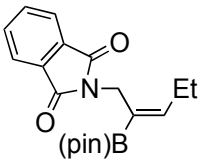
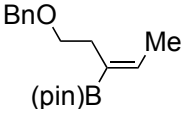
			
1, **2bα**	2, **2cα**	3, **2dα**	4, **2eα**
78% (93/7)[d]	74% (>99/1)	94% (98/2)	78% (100/0)

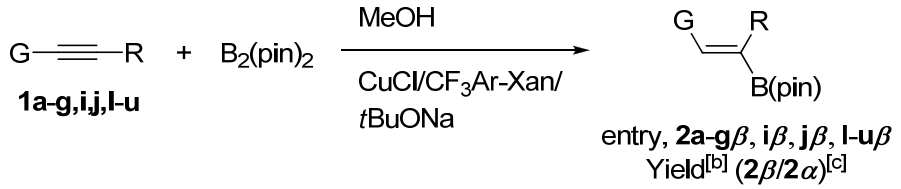
Table 3-2. (Continued)

			
5, **2f**α	6[e], **2g**α	7[f,g], **2h**α	8, **2i**α
72% (>99/1)	90% (100/0)	94% (100/0)	88% (97/3)
			
9[h], **2j**α	10[f,i], **2k**α	11[j], **2l**α	12[l], **2m**α
86% (97/3)	92% (100/0)	62%[k] (72/28)	82% (100/0)
	(Z/E = 98/2)		
			
	14[m,n] (R = Bn), **2o**α		
13[h], **2n**α	73%[k] (92/8)	16[m,o], **2q**α	17[m,p], **2r**α
96% (100/0)	15[m,n] (R = THP), **2p**α	76% (>99/1)	68%[k] (63/37)
	64%[k] (93/7)		

[a] Alkyne (0.50 mmol), HB(pin) (0.75 mmol), CuCl (0.010 mmol, 2.0 mol %), MeAr-Xan (0.010 mmol, 2.0 mol %), *t*BuONa (0.060 mmol, 12 mol %), toluene (1.0 mL), at 20 ºC, for 20 h. [b] Isolated yield. [c] Ratio of **2**α/**2**β in crude reaction mixture was determined by GC. [d] After purification α/β = 98/2. [e] HB(pin) (0.60 mmol), at 28 ºC. [f] CuCl (0.020 mmol, 4.0 mol %), MeAr-Xan (0.020 mmol, 4.0 mol %). [g] HB(pin) (1.0 mmol), at 60 ºC. [h] HB(pin) (0.60 mmol). [i] HB(pin) (1.0 mmol), at 50 ºC. [j] CuCl (0.020 mmol, 4.0 mol %), MeAr-Xan (0.020 mmol, 4.0 mol %), *t*BuONa (0.12 mmol, 24 mol %), toluene (0.50 mL), at 50 ºC. [k] Yield of the α- and β-products mixture. [l] HB(pin) (0.60 mmol), at 0 ºC, for 1 h. [m] CF_3Ar-Xan was used instead of MeAr-Xan. [n] Toluene (0.50 mL), at 28 ºC. [o] 28 ºC. [p] Toluene (0.25 mL), at 80 ºC.

In contrast, when HB(pin) was replaced with $B_2(pin)_2$/MeOH using CF_3Ar-Xan as a ligand, the regioselectivity was reversed to afford mostly the *β*-products and *β*-products were obtained in high yields and regioselectivities (Table 3-3). Electron donating and withdrawing groups on benzene rings almost did not affect on yields and regioselectivities (entries 1-6). Alkynes bearing pyridine and thiophene rings on the acetylenic carbons (**1i** and **1j**) reacted with high regioselectivities and the *β*-products (**2i*β*** and **2j*β***) were isolated in high yields (entries 7 and 8). It is noteworthy that even when secondary alkyl moieties were attached to the acetylenic carbon, regioselectivities of the *β*-products (**2g*β***, **2s*β***, and **2t*β***) were high (entries 9-11).[19] An alkyne bearing an alkenyl moiety[20] also afforded the product regioselectively in high yield (entry 12). Furthermore, alkynes bearing conjugated ester[21] and amide functionalities also afforded the respective *β*-products in high yields with high regioselectivities (entries 13 and 14). Remarkably, alkynes bearing O and N atoms at the propargylic (entries 15–18) and even homopropargylic positions (entry 19) provided the corresponding *β*-products (**2o*β***–**r*β*** and **2u*β***) selectively in good to high yields.[18,22] Such high regioselectivities have never been observed in the hydroboration of this class of substrates (**1o**–**r** and **1u**).

Table 3-3. Copper-catalyzed hydroboration of various alkynes to the *β*-products with $B_2(pin)_2$/MeOH[a]



1a-g,i,j,l-u

entry, **2a-g*β***, **i*β***, **j*β***, **l-u*β***
Yield[b] (**2*β***/**2*α***)[c]

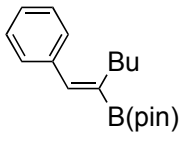
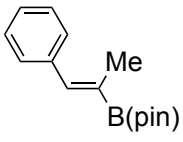
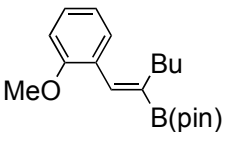
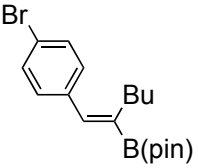
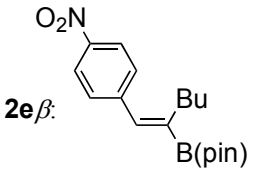
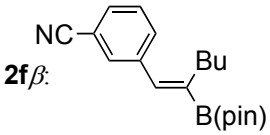
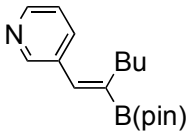
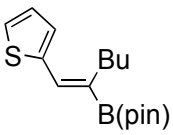
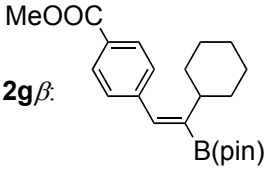
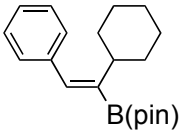
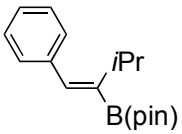
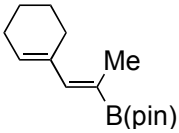
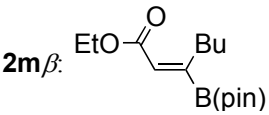
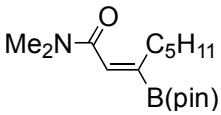
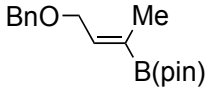
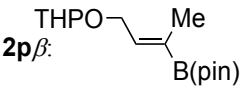
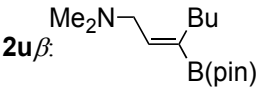
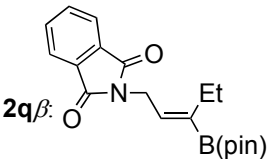
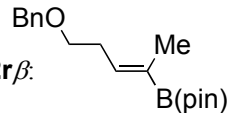
2a*β*: 	**2b*β***: 	**2c*β***: 	**2d*β***: 
1, **2a*β***	2, **2b*β***	3, **2c*β***	4, **2d*β***
98% (99/1)	74% (>99/1)	96% (100/0)	90% (99/1)

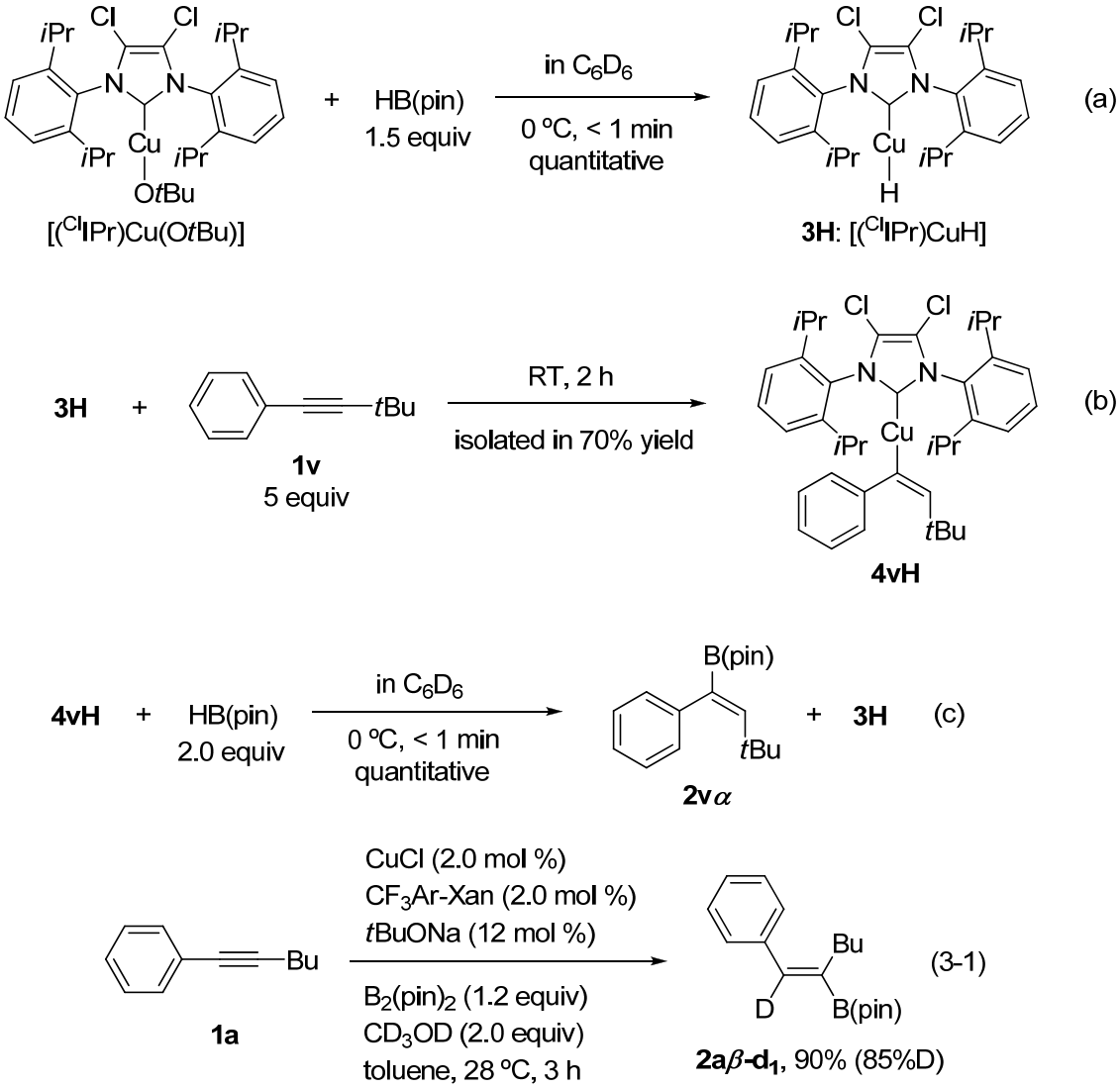
Table 3-3. (Continued)

2eβ: 	**2f**β: 	**2i**β: 	**2j**β: 
5, **2e**β	6, **2f**β	7, **2i**β	8, **2j**β
72% (>99/1)	96% (96/4)	82% (98/2)	98% (>99/1)
2gβ: 	**2s**β: 	**2t**β: 	**2l**β: 
9[d], **2g**β	10[e], **2s**β	11[e], **2t**β	12, **2l**β
88% (>99/1)	70% (92/8)[f]	76% (91/9)[f]	94% (99/1)
(*Z*/*E* = 95/5)			
2mβ: 	**2n**β: 	**2o**β: 	**2p**β: 
13[g], **2m**β	14[h], **2n**β	15, **2o**β	16, **2p**β
90% (100/0)	78% (97/3)	74% (98/2)	88% (99/1)
2uβ: 	**2q**β: 	**2r**β: 	
17[i], **2u**β	18, **2q**β	19[i], **2r**β	
74% (95/5)	92% (100/0)	86% (91/9)[j]	
	(*Z*/*E* = 96/4)		

[a] Alkyne (0.50 mmol), $B_2(pin)_2$ (0.60 mmol), MeOH (1.0 mmol), CuCl (0.010 mmol, 2.0 mol %), CF_3Ar-Xan (0.010 mmol, 2.0 mol %), *t*BuONa (0.060 mmol, 12 mol %), toluene (1.0 mL), at 28 ºC, for 3 h. [b] Isolated yield. [c] Ratio of **2**β/**2**α in crude reaction mixture was determined by GC. [d] At 50 ºC, for 20 h. [e] For 20 h. [f] After purification β/α = >99/1. [g] $B_2(pin)_2$ (0.53 mmol), for 1 h. [h] $B_2(pin)_2$ (0.53 mmol). [i] $B_2(pin)_2$ (0.75 mmol). [j] After purification β/α = 90/10.

To gain insight into the mechanism of the α-directed hydroboration using HB(pin), stoichiometric reactions were performed with the ^{Cl}IPrCu complex (Scheme 3-2), since ^{Cl}IPr is an efficient ligand in the reaction (entry 13 in Table 3-1) and copper complexes bearing ^{Cl}IPr are rather stable. [(^{Cl}IPr)Cu(O*t*Bu)] obtained from [(^{Cl}IPr)CuCl] and *t*BuONa[23] reacted with HB(pin) almost instantaneously at 0 ºC. A ^{1}H NMR spectrum of the resulting reaction mixture indicated that the reaction was clean and the corresponding copper hydride, [(^{Cl}IPr)CuH] (**3H**), was furnished quantitatively judging by the diagnostic ^{1}H resonance of the Cu-H at 2.4 ppm as well as other ^{1}H resonances of [(^{Cl}IPr)CuH][24] (Scheme 3-2a).[25] Next, **3H** was reacted with an alkyne (**1v**) (Scheme 3-2b). Here, **3H** was prepared from [(^{Cl}IPr)CuF] and $(EtO)_3SiH$[24] to avoid the further reaction of excess HB(pin) with the resulting product **4vH** (see Scheme 3-2c). As reported previously,[24,26] [(^{Cl}IPr)CuH] reacted with the alkyne (**1v**) and the corresponding alkenyl copper complex (**4vH**) was isolated in 70% yield (Scheme 3-2b). The complex **4vH** instantaneously reacted with HB(pin) at 0 ºC to provide the corresponding hydroboration product (**2v**α) quantitatively while regenerating **3H** cleanly, as confirmed by ^{1}H NMR (Scheme 3-2c).[25] This is the first example of the stoichiometric reaction of a borane with an alkenyl copper species. As for the β-directed hydroboration, **1a** was allowed to react with $B_2(pin)_2$ in the presence of CD_3OD under otherwise identical conditions to entry 1 in Table 3-3. The resultant deuterated product (**2a**β-$\mathbf{d_1}$) bearing D at the α-position was obtained in 90% yield with 85% deuterium-content [Eq.(3-1)].

Scheme 3-2. Stoichiometric reactions relevant to the mechanism



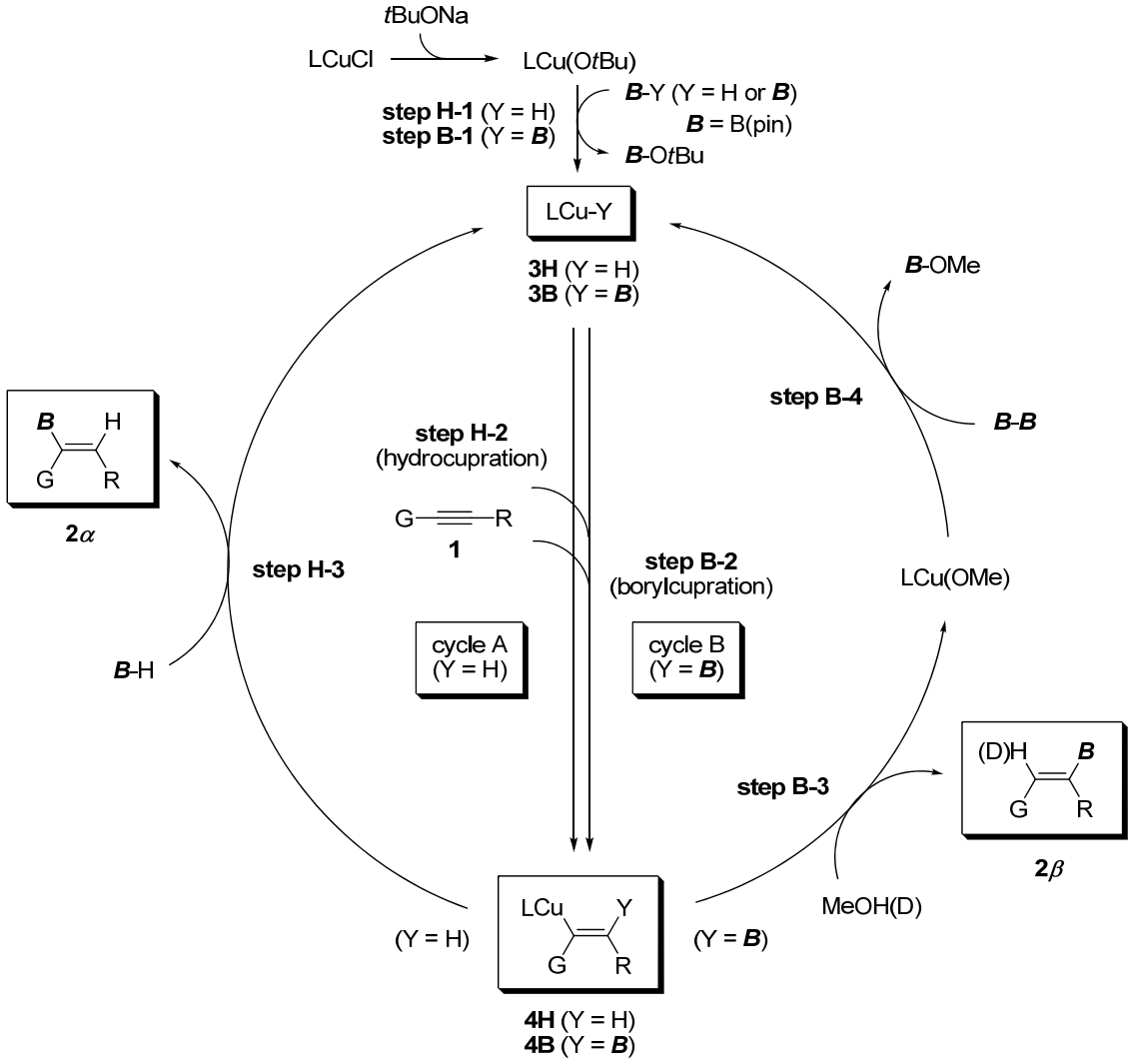
Based on these experimental results, possible catalytic cycles for the Cu-catalyzed hydroboration using HB(pin) (cycle A) and $B_2(pin)_2$ (cycle B), respectively, are shown in Scheme 3-3. First, [LCu(O*t*Bu)] is generated from LCuCl and *t*BuONa.[23] As indicated by the clean stoichiometric reaction of [(^{Cl}IPr)Cu(O*t*Bu)] with HB(pin) (Scheme 3-2a), the active catalytic species in the hydroboration using HB(pin) must be a copper hydride (LCu-H: **3H**, Y = H, step H-1, Scheme 3-3). *Syn*-addition of **3H** to alkynes[24,26] (hydrocupration: step H-2) affords alkenyl copper species (**4H**) with high regioselectivity owing to directing effect of the substituent G. Finally, reaction of **4H** with HB(pin) affords the corresponding α-product (**2**α) and closes the catalytic cycle by regenerating the active catalytic species LCu-H (**3H**) (step H-3). Step H-2 was

supported by the stoichiometric reaction in Scheme 3-2b and step H-3 was confirmed by the reaction in Scheme 3-2c.

In addition, Xan derivatives were so effective as ligands for the α-borylation reactions. This is because bulky Xan derivatives would suppress the aggregation of the Cu-H species. It is well-known that the Cu-H species prefer to aggregate and the reactivity is considerably decreased by the aggregation.[27] Furthermore, the bulky Xan ligand derivatives may accelerate the insertion of Cu-H to an alkyne: the recent paper reports that the bulky bidentate phosphane ligand accelerates the insertion of Cu-H to a styrene.[28]

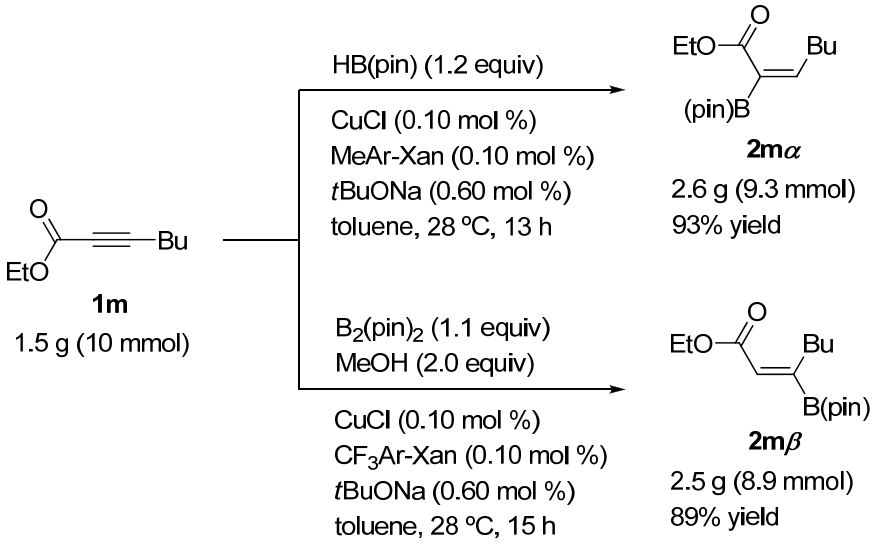
In contrast, for the hydroboration using $B_2(pin)_2$, a borylcopper species (LCu-B: **3B**) must be generated as a catalytic species in step B-1 (Y=B, Scheme 3-3). Indeed, Sadighi et al. reported that [(IPr)Cu(O*t*Bu)] reacted readily with $B_2(pin)_2$ at room temperature, forming [(IPr)CuB(pin)], whose X-ray structure has been determined.[29] Addition of the LCu-B species (**3B)** to alkynes (borylcupration:[30] step B-2) affords a (β-boryl)(alkenyl)copper intermediate (**4B**) with high regioselectivity owing to the same directing effect of the substituent G as that observed in step H-2. Next, protonation of **4B** with MeOH provides the β-products (**2**β) efficiently (step B-3). With CD_3OD, an α-deuterated product (**2a**β-$\mathbf{d_1}$) was obtained as shown in eq 3-1. Finally, the reaction between the resulting [LCuOMe] and $B_2(pin)_2$ regenerates LCu-B (**3B**), and the catalytic cycle is closed (step B-4). Through these mechanisms, the regioselectivity can be successfully controlled in the hydrocupration (step H-2) or borylcupration (step B-2) stage with the different catalytic species (LCu-H **3H** or LCu-B **3B**) in their respective catalytic cycles. In hydroboration catalyzed by other transition metals (such as Rh and Ir), selecting between hydro-metalation (Scheme 3-3, cycle A) and boryl-metalation (Scheme 3-3, cycle B) is difficult, because the oxidative addition of H-B to a metal center provides H-M-B species having both H-M and B-M bonds.[1b,c,31,32]

Scheme 3-3. A possible catalytic cycle

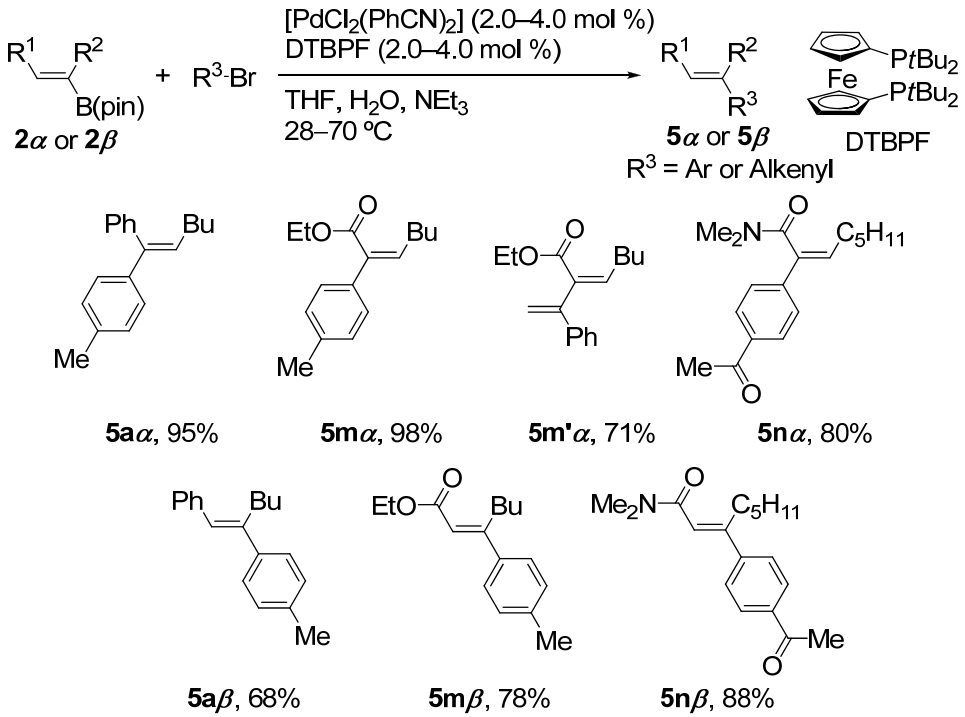


The usefulness of the present transformations is shown in Schemes 3-4 and 3-5. The copper-catalyzed hydroborations are amenable to gram-scale procedures with much lower catalyst loadings. For example, with only 0.10 mol % of either catalyst, 1.5 g of **1m** was readily converted to the corresponding hydroboration products **2m**α and **2m**β selectively in high yields depending on which reagent was used (HB(pin) and $B_2(pin)_2$) (Scheme 3-4). The α- and β-products (**2**α and **2**β) are valuable intermediates used in the Suzuki-Miyaura cross-coupling reactions[2] to prepare various types of trisubstituted alkenes; **5**α and **5**β regioselectively (Scheme 3-5).[33]

Scheme 3-4.



Scheme 3-5.



3-3. Conclusion

In conclusion, the author has developed a copper-catalyzed highly regio- and stereoselective hydroboration of unsymmetrical internal alkynes. The regioselectivity is controllable by using one of two different catalytic species (LCu-H and LCu-B)

generated from borylation reagents HB(pin) and $B_2(pin)_2$, respectively. This reactivity is expected to have wide applicability to other regioselective catalytic reactions.

3-4. Experimental Section

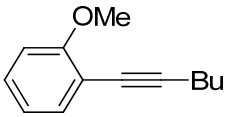
General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[34] ^{1}H NMR and $^{13}C\{^1H\}$ NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). $^{31}P\{^1H\}$ NMR spectra were also recorded at a JEOL ECX-400 spectrometer using 85% H_3PO_4 as an external standard. EI-MS were recorded on a Shimadzu GCMS-QP5050A with a direct inlet. High-resolution mass spectra (EI-HRMS and ESI-HRMS) were obtained with JEOL JMX-SX102A and Thermo SCIENTIFIC Exactive LC-MS spectrometers. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-2014 with a capillary column (GL Sciences InertCap 5, 0.25 mm × 30 m).

Materials: Unless otherwise noted, commercially available chemicals were used as received. Anhydrous toluene was purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[35] Hexane was distilled from benzophenone ketyl. CuCl was purified according to a literature.[34] MeOH was distilled over CaH_2. Pinacolborane (HB(pin)) and alkynes (**1a**, **1b** and **1m**) were distilled before use. [(IPr)CuCl] was prepared according to the literature.[36]

Syntheses of Substrates: **1c–g**, **1i–j** and **1s** was prepared according to the general method A shown below. **1h,**[24] **1l,**[37] **1r,**[38] **1u,**[39] **1v**[24] were prepared according to the literatures. **1t** was prepared by a similar method of the literature.[40]

General Method A: A flask was charged with THF (20 mL) and triethylamine (10 mL). Oxygen in the system was removed by two freeze-pump-thaw cycles. An aryl iodide, an alkyne, $[PdCl_2(PPh_3)_2]$ and CuI were added in this order to the flask, and the resulting mixture was stirred overnight at indicated temperature. Then, the mixture was cooled to room temperature and quenched by MeOH (10.0 mL). All volatiles were removed in vacuo, and Et_2O (100 mL) was added. After filtration, the filtrate was washed with 1N HCl aq. and H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed and an alkyne was obtained by silica gel column chromatography.

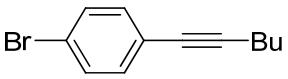
Preparation of 1c.



1c

Toluene (20 mL) was used instead of THF. $[PdCl_2(PPh_3)_2]$ (125 mg, 0.175 mmol), CuI (27.0 mg, 0.140 mmol), 2-iodoanisole (1.80 mL, 14.0 mmol), 1-hexyne (2.7 mL, 27.1 mmol), at 60 ºC, for 48 h. Yield 76% (1.99 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37 (dd, J = 7.5 Hz, 1.6 Hz, 1H), 7.25–7.21 (m, 1H), 6.89–6.84 (m, 2H), 3.87 (s, 3H), 2.47 (t, J = 7.0 Hz, 2H), 1.65–1.58 (m, 2H), 1.54–1.45 (m, 2H), 0.95 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 159.8, 133.6, 128.8, 120.4, 113.1, 110.5, 94.7, 76.5, 55.8, 30.9, 22.0, 19.5, 13.7. All the resonances in ^{13}C spectrum were consistent with reported values.[41]

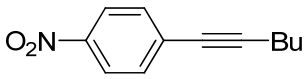
Preparation of 1d.



1d

$[PdCl_2(PPh_3)_2]$ (50.0 mg, 0.070 mmol), CuI (13.5 mg, 0.070 mmol), 4-bromoiodobenzene (4.0 g, 14.0 mmol), 1-hexyne (1.8 mL, 15.4 mmol), at RT, for 48 h. Yield 42% (1.40 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40 (d, J = 8.6 Hz, 2H), 7.24 (d, J = 8.2 Hz, 2H), 2.39 (t, J = 7.0 Hz, 2H), 1.62–1.54 (m, 2H), 1.51–1.42 (m, 2H), 0.94 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 133.0, 131.4, 123.0, 121.5, 91.7, 79.5, 30.7, 22.0, 19.1, 13.6. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[42]

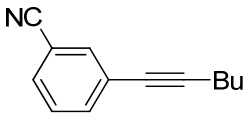
Preparation of 1e.



1e

$[PdCl_2(PPh_3)_2]$ (50.0 mg, 0.070 mmol), CuI (13.5 mg, 0.070 mmol), 4-nitroiodobenzene (3.5 g, 14.0 mmol), 1-hexyne (1.8 mL, 15.4 mmol), at 40 ºC, for 24 h. Yield 69% (1.98 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.15 (d, J = 9.1 Hz, 2H), 7.51 (d, J = 8.6 Hz, 2H), 2.45 (t, J = 7.0 Hz, 2H), 1.65–1.58 (m, 2H), 1.53–1.46 (m, 2H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.5, 132.2, 131.2, 123.5, 96.7, 79.3, 30.4, 22.0, 19.2, 13.6. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[43]

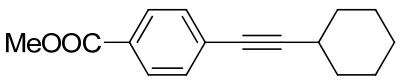
Preparation of 1f.



1f

$[PdCl_2(PPh_3)_2]$ (50.0 mg, 0.070 mmol), CuI (13.5 mg, 0.070 mmol), 4-nitroiodobenzene (3.2 g, 14.0 mmol), 1-hexyne (1.8 mL, 15.4 mmol), at 50 ºC, for 24 h. Yield 47% (1.21 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.66 (s, 1H), 7.59 (d, J = 7.7 Hz, 1H), 7.53 (d, J = 7.7 Hz, 1H), 7.38 (t, J = 7.9 Hz, 1H), 2.42 (t, J = 7.0 Hz, 2H), 1.63–1.56 (m, 2H), 1.52–1.45 (m, 2H), 0.95 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 135.6, 134.9, 130.6, 129.0, 125.7, 118.2, 112.5, 93.3, 78.5, 30.5, 22.0, 19.0, 13.6. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[43]

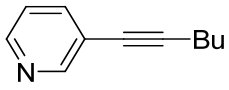
Preparation of 1g.[44]



1g

$[PdCl_2(PPh_3)_2]$ (50.0 mg, 0.070 mmol), CuI (13.5 mg, 0.070 mmol), 4-iodo methylbenzoate (3.67 g, 14.0 mmol), cyclohexylacetylene (2.20 mL, 16.8 mmol), at 50 ºC, for 24 h. Yield 67% (2.28 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.94 (d, J = 8.2 Hz, 2H), 7.44 (d, J = 8.6 Hz, 2H), 3.90 (s, 3H), 2.64–2.57 (m, 1H), 1.90–1.86 (m, 2H), 1.77–1.74 (m, 2H), 1.58–1.49 (m, 3H), 1.41–1.33 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.7, 131.5, 129.3, 129.0, 128.7, 97.9, 80.0, 52.1, 32.5, 29.7, 25.8, 24.8.

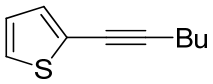
Preparation of 1i.



1i

$[PdCl_2(PPh_3)_2]$ (50.0 mg, 0.070 mmol), CuI (13.5 mg, 0.070 mmol), 3-iodopyridine (2.87 g, 14.0 mmol), 1-hexyne (1.93 mL, 16.8 mmol), at 50 ºC, for 24 h. Yield 88% (1.96 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.63 (d, J = 1.8 Hz, 1H), 8.48 (dd, J = 4.8 Hz, 1.6 Hz, 1H), 7.68–7.65 (m, 1H), 7.20 (dd, J = 7.7 Hz, 5.0 Hz, 1H), 2.43 (t, J = 7.0 Hz, 2H), 1.64–1.57 (m, 2H), 1.53–1.44 (m, 2H), 0.96 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.3, 147.9, 138.4, 122.8, 121.1, 94.0, 30.6, 22.0, 19.1, 13.6. One resonance was not confirmed due to overlapping with those of $CDCl_3$. All the resonances in ^{1}H spectrum were consistent with reported values.[45]

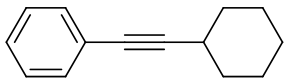
Preparation of 1j.



1j

$[PdCl_2(PPh_3)_2]$ (75.0 mg, 0.105 mmol), CuI (13.5 mg, 0.070 mmol), 2-iodothiphene (1.55 mL, 14.0 mmol), 1-hexyne (1.80 mL, 15.4 mmol), at 50 ºC, for 24 h. Yield 80% (1.84 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.16 (dd, J = 5.2 Hz, 1.1 Hz, 1H), 7.11 (d, J = 3.6 Hz, 1H), 6.93 (dd, J = 5.4 Hz, 3.6 Hz, 1H), 2.42 (t, J = 7.0 Hz, 2H), 1.62–1.54 (m, 2H), 1.51–1.42 (m, 2H), 0.94 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 130.8, 126.7, 125.8, 124.2, 94.5, 73.6, 30.6, 22.0, 19.3, 13.6. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[46]

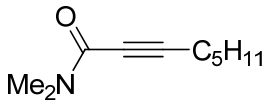
Preparation of 1s.



1s

$[PdCl_2(PPh_3)_2]$ (150 mg, 0.210 mmol), CuI (40.5 mg, 0.210 mmol), iodobenzene (1.57 mL, 14.0 mmol), cyclohexylacetylene (1.92 mL, 14.7 mmol), at 65 ºC, for 48 h. Yield 65% (1.67 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40–7.38 (m, 2H), 7.29–7.24 (m, 3H), 2.61–2.55 (m, 1H), 1.89–1.86 (m, 2H), 1.77–1.74 (m, 2H), 1.58–1.49 (m, 3H), 1.40–1.28 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.6, 128.1, 127.4, 124.1, 94.4, 80.5, 32.7, 29.6, 25.9, 24.9. All the resonances in ^{13}C spectrum were consistent with reported values.[40]

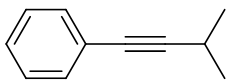
Preparation of 1n.[47]



1n

A flask was charged with *n*BuLi (14.6 mL of 1.65 M solution in hexane, 24.0 mmol) and THF (30 mL). 1-heptyne (1.92 g, 20.0 mmol) in THF (10 mL) was added over 10 min at −78 ºC and stirred for 30 min at −78 ºC. To the resulting mixture, dimethyl carbamoyl chloride (3.23 g, 30 mmol) in THF (10 mL) was added over 20 min at −78 ºC. The mixture was slowly warm up to 0 ºC and stirred for 2 h at 0 ºC. NH_4Cl aq. was added at 0 ºC and the mixture was extracted with $CHCl_3$. After removal of the volatiles, **1n** was obtained by silica gel column chromatography (eluent: hexane/EtOAc = 1/1) in 97% yield (3.24 g, 19.4 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 3.20 (s, 3H), 2.97 (s, 3H), 2.36 (t, J = 7.2 Hz, 2H), 1.62−1.55 (m, 2H), 1.43−1.30 (m, 4H), 0.90 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 154.8, 93.1, 74.0, 38.3, 34.0, 31.0, 27.5, 22.0, 18.8, 13.8.

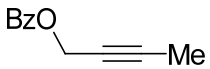
Preparation of 1t.



1t

A flask was charged with $CuCl_2$ (60.5 mg, 0.45 mmol), THF (15 mL) and 1-chloro-2-phenylethyne[40] (1.85 mL, 15 mmol). *i*PrMgCl (9.0 mL of 2.0 M solution in THF, 18 mmol) was added over 15 min at 0 ºC and the resulting mixture was stirred for 1 h at 0 ºC. 1N HCl aq. was added and the mixture was extracted with Et_2O. The organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo and **1t** was obtained by silica gel column chromatography (eluent: hexane) in 55 % yield (1.20 g, 8.3 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.40−7.38 (m, 2H), 7.29−7.25 (m, 3H), 2.77 (septet, J = 6.7 Hz, 1H), 1.26 (d, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 131.5, 128.1, 127.4, 124.0, 95.7, 79.7, 23.0, 21.1. All the resonances in ^{1}H spectrum were consistent with reported values.[48]

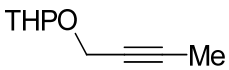
Preparation of 1o.



1o

A flask was charged with NaH (60%, dispersion in Paraffin Liquid) (1.2 g, 30 mmol) and THF (70 mL). 2-Butyn-1-ol (2.0 mL, 26.7 mmol) was added to the suspension at 0 ºC and the resulting mixture was stirred for 30 min at 0 ºC. To the mixture, benzyl bromide (3.6 mL, 30 mmol) was added dropwise at 0 ºC. The reaction mixture was allowed to warm to room temperature and further stirred overnight at room temperature. The mixture was carefully quenched by adding H_2O carefully and THF was removed in vacuo. The crude product was extracted with Et_2O and the organic layer was dried over $MgSO_4$. After filtration, all volatiles were removed in vacuo and **1o** was obtained by silica gel column chromatography (eluent: hexane/EtOAc = 10/1) in 62% yield (2.9 g, 16.6 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36–7.29 (m, 5H), 4.58 (s, 2H), 4.13 (q, J = 2.3 Hz, 2H), 1.88 (t, J = 2.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.6, 128.4, 128.0, 127.7, 82.7, 75.0, 71.4, 57.7, 3.6. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[49]

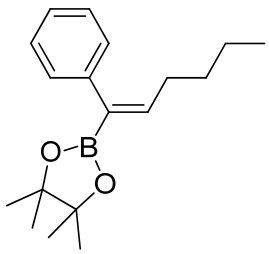
Preparation of 1p.



1p

A flask was charged with 2-butyn-1-ol (1.0 mL, 13.4 mmol), dihydropyran (1.8 mL, 20 mmol) and Et_2O (20 mL). $TsOH{\cdot}H_2O$ (190 mg, 1.0 mmol) was added to the mixture at 0 ºC and the reaction mixture was allowed to warm to room temperature and further stirred for 4 h at room temperature. The mixture was quenched by adding H_2O and extracted with Et_2O. The organic layer was dried over $MgSO_4$. After filtration, all volatiles were removed in vacuo and **1p** was obtained by silica gel column chromatography (eluent: hexane/EtOAc = 15/1) in 71% yield (1.47 g, 9.53 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 4.80 (t, J = 3.4 Hz, 1H), 4.28 (dq, J = 15.2 Hz, 2.4 Hz, 1H), 4.17 (dq, J = 15.4 Hz, 2.3 Hz, 1H), 3.87–3.81 (m, 1H), 3.56–3.50 (m, 1H), 1.86 (t, J = 2.3 Hz, 3H), 1.83–1.54 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 96.7, 82.1, 74.9, 61.9, 54.6, 30.2, 25.3, 19.1, 3.7. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[50]

General Procedure for Table 3-1. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), a ligand (0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, pinacolborane (HB(pin)) (87 μL, 0.60 mmol) was added at 0 ºC and the mixture was stirred at 0 ºC for 5 min. To the mixture, **1a** (88 μL, 0.50 mmol) was added at 0 ºC and the mixture was stirred at 28 ºC for 20 h. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard (tridecane). In entry 10, the mixture was filtrated through a pad of silica gel and all of the volatiles were removed in vacuo. **2a**α was obtained by silica gel column chromatography (eluent: hexane/Et_2O = 20/1).

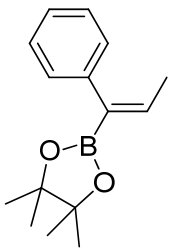


2aα

2aα[51]: Yield 97% (138.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32–7.28 (m, 2H), 7.21–7.13 (m, 3H), 6.58 (t, J = 7.2 Hz, 1H), 2.17–2.11 (m, 2H), 1.42–1.35 (m, 2H), 1.31–1.27 (m, 14H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.5, 140.3, 128.9, 127.7, 125.8, 83.4, 31.5, 29.6, 24.7, 22.5, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation.

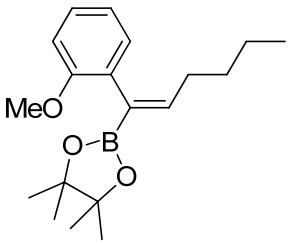
General Procedure for Table 3-2. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), MeAr-Xan (6.91 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, pinacolborane (HB(pin)) (109 μL, 0.75 mmol) was added at 0 ºC and the mixture was stirred at 0 ºC for 5 min. To the mixture, an alkyne (0.50 mmol) was added at 0 ºC and the mixture was stirred at 20 ºC for 20 h. After the reaction, the mixture was filtrated through a pad of silica gel and all of the volatiles were removed in vacuo. (In the cases of **2m**α and **2n**α, the filtration through a pad of silica gel must not be performed because these products were decomposed on silica gel.) The products were obtained by silica gel column chromatography (eluent: hexane/Et_2O) or preparative GPC in the cases of **2b**α, **2f**α, **2g**α, **2m**α and **2n**α. The regio- and stereochemistry of

the products (**2bα**–**2kα**) were determined by ^{1}H NMR and 2D NMR. In the cases of **2mα** and **2nα**, the stereochemistry were determined after derivatization in Scheme 3-5. The *Z* configuration of **2dα** was further confirmed by a single-crystal X-ray diffraction study.



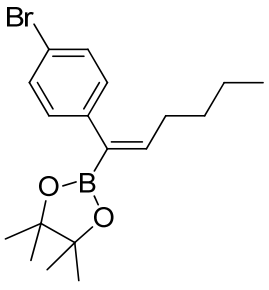
2bα

2bα: Yield 78% (94.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32 (t, J = 7.2 Hz, 2H), 7.22–7.15 (m, 3H), 6.72 (q, J = 6.6 Hz, 1H), 1.77 (d, J = 6.8 Hz, 3H), 1.27 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.7, 139.7, 129.1, 127.7, 125.8, 83.4, 24.7, 16.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{21}BO_2$ ($[M+NH_4]^+$), 262.1973. Found, 262.1969.



2cα

2cα: Yield 74% (116.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22–7.18 (m, 1H), 7.04 (dd, J = 7.2 Hz, 1.4 Hz, 1H), 6.92–6.85 (m, 2H), 6.52 (t, J = 7.2 Hz, 1H), 3.76 (s, 3H), 2.13–2.07 (m, 3H), 1.43–1.35 (m, 2H), 1.31–1.25 (m, 14H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 156.7, 147.1, 130.1, 129.4, 127.4, 120.1, 110.3, 83.1, 55.2, 31.4, 29.7, 24.7, 22.5, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{29}BO_3$ ($[M+NH_4]^+$), 334.2548. Found, 334.2542. Anal. Calcd. for $C_{19}H_{29}BO_3$: C, 72.16; H, 9.24. Found: C, 72.23; H, 9.37.



2dα

2dα: Yield 94% (171.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.42 (d, J = 7.7 Hz, 2H), 7.00 (d, J = 8.2 Hz, 2H), 6.59 (t, J = 7.0 Hz, 1H), 2.14–2.08 (m, 2H), 1.39–1.19 (m, 16H), 0.83 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.2, 139.2, 130.8, 130.7, 119.8, 83.5, 31.4, 29.6, 24.7, 22.4, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{26}BBrO_2$ ($[M+NH_4]^+$), 382.1548. Found, 382.1542. Anal. Calcd. for $C_{18}H_{26}BBrO_2$: C, 59.12; H, 7.18. Found: C, 59.22; H, 7.14.

Single crystals of **2dα** were obtained by slow evaporation of hexane solution. The structure of **2dα** was also confirmed by X-ray crystallography.

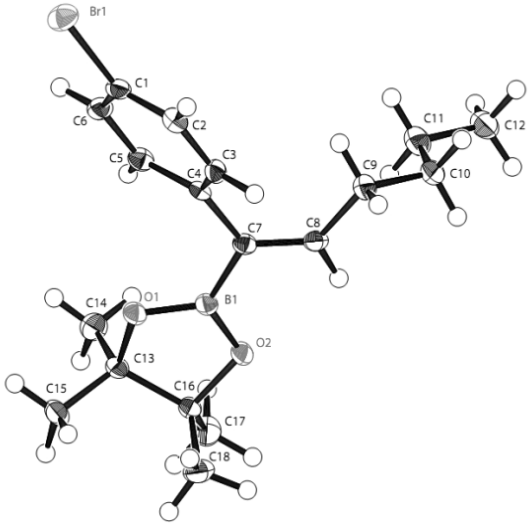
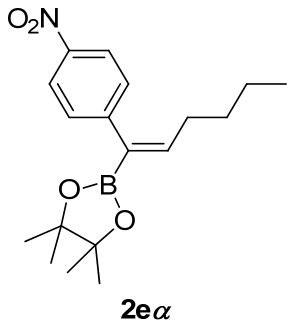
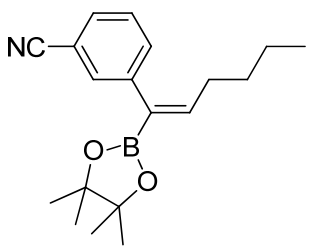


Figure 3-2. Crystal structure of **2dα**



2eα

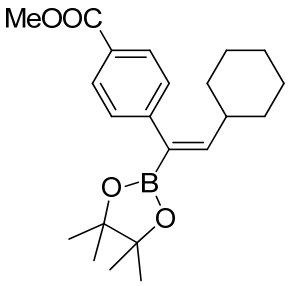
2eα: Yield 78% (130.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.17 (d, J = 9.1 Hz, 2H), 7.28 (d, J = 9.1 Hz, 2H), 6.70 (t, J = 7.2 Hz, 1H), 2.14–2.09 (m, 2H), 1.43–1.36 (m, 2H), 1.31–1.24 (m, 14H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.6, 147.8, 146.1, 129.8, 123.1, 83.8, 31.2, 29.8, 24.7, 22.4, 13.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{26}BNO_4$ ($[M+NH_4]^+$), 349.2293. Found, 349.2288. Anal. Calcd. for $C_{18}H_{26}BNO_4$: C, 65.27; H, 7.91; N, 4.23. Found: C, 65.02; H, 8.20; N, 4.23.



2fα

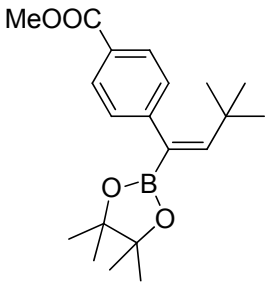
2fα: Yield 72% (110.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50–7.48 (m, 1H), 7.42–7.36 (m, 3H), 6.66 (t, J = 7.5 Hz, 1H), 2.12–2.06 (m, 2H), 1.42–1.34 (m, 2H), 1.31–1.21 (m, 14H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.3, 141.5, 133.6, 132.5, 129.5, 128.5, 119.4, 111.8, 83.7,

31.2, 29.6, 24.7, 22.4, 13.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{26}BNO_2$ ($[M+NH_4]^+$), 329.2395. Found, 329.2388. Anal. Calcd. for $C_{19}H_{26}BNO_2$: C, 73.32; H, 8.42; N, 4.50. Found: C, 73.07; H, 8.63; N, 4.24.



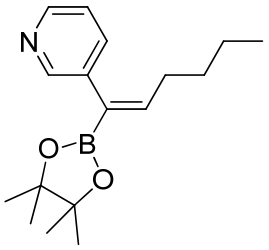
2gα

2gα: Yield 90% (166.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.98 (d, J = 8.6 Hz, 2H), 7.18 (d, J = 8.2 Hz, 2H), 6.41 (d, J = 10.4 Hz, 1H), 3.91 (s, 3H), 2.25–2.16 (m, 1H), 1.66–1.57 (m, 5H), 1.26 (s, 12H), 1.19–1.10 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.3, 154.4, 146.0, 129.1, 128.8, 127.5, 83.5, 51.9, 38.4, 32.5, 25.8, 25.4, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{22}H_{31}BO_4$ ($[M+H]^+$), 371.2388. Found, 371.2381.



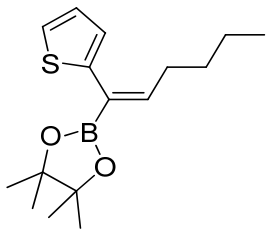
2hα

2hα: Yield 94% (161.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93 (d, J = 5.0 Hz, 2H), 7.14 (d, J = 5.0 Hz, 2H), 6.51 (s, 1H), 3.90 (s, 3H), 1.22 (s, 12H), 0.90 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.3, 156.5, 147.4, 128.8, 128.7, 127.4, 83.6, 51.9, 35.7, 30.9, 24.6. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{20}H_{29}BO_4$ ($[M+H]^+$), 345.2232. Found, 345.2224.



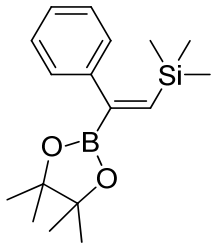
2iα

2iα: Yield 88% (126.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.44 (td, J = 3.2 Hz, 1.4 Hz, 2H), 8.40 (brs, 1H), 7.48–7.45 (m, 1H), 7.25–7.22 (m, 1H), 6.69 (t, J = 7.5 Hz, 1H), 2.17–2.11 (m, 2H), 1.43–1.36 (m, 2H), 1.30–1.25 (m, 14H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.4, 149.9, 147.0, 136.3, 135.8, 122.8, 83.6, 31.3, 29.6, 24.7, 22.4, 13.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{26}BNO_2$ ($[M+H]^+$), 288.2129. Found, 288.2116.



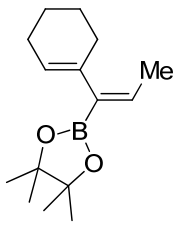
2jα

2jα: Yield 86% (125.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25–7.22 (m, 1H), 7.12 (t, J = 2.9 Hz, 1H), 7.02–6.99 (m, 1H), 6.55 (t, J = 7.0 Hz, 1H), 2.45–2.39 (m, 2H), 1.52–1.44 (m, 2H), 1.41–1.30 (m, 14H), 0.90 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.3, 141.7, 126.9, 126.5, 124.3, 83.6, 31.5, 30.4, 24.7, 22.6, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{16}H_{25}BO_2S$ ($[M+H]^+$), 293.1741. Found, 293.1729.



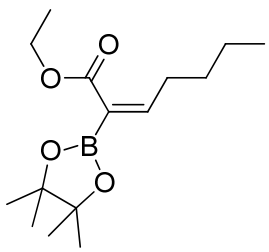
2kα

2kα: Yield 92% (137.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92 (s, 1H), 7.19–7.14 (m, 5H), 1.21 (s, 12H), –0.09 (s, 9H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.0, 141.4, 128.2, 127.7, 127.4, 83.2, 24.8, 0.875. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{27}BO_2Si$ ($[M+NH_4]^+$), 320.2212. Found, 320.2206.



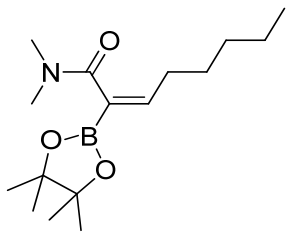
2lα

2lα: Yield 62% (76.4 mg, mixture of α- and β-products). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.38 (q, J = 6.6 Hz, 1H), 5.30–5.28 (m, 1H), 2.11–2.06 (m, 2H), 2.01–1.97 (m, 2H), 1.75 (d, J = 6.8 Hz, 3H), 1.69–1.57 (m, 4H), 1.25 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.0, 136.7, 123.1, 83.0, 29.0, 25.2, 24.7, 23.0, 22.3, 15.6. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{26}BO_2$ ($[M+H]^+$), 249.2020. Found, 249.2016.



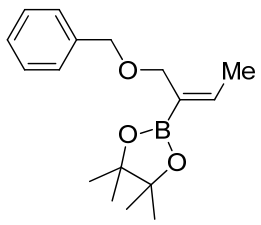
2mα

2mα: Yield 82% (114.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.69 (t, J = 7.2 Hz, 1H), 4.22 (q, J = 7.1 Hz, 2H), 2.40–2.35 (m, 2H), 1.47–1.38 (m, 2H), 1.34–1.27 (m, 17H), 0.89 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 169.3, 156.5, 83.7, 60.1, 30.9, 30.7, 24.6, 22.4, 14.2, 13.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{27}BO_4$ ($[M+H]^+$), 283.2075. Found, 283.2070. Anal. Calcd. for $C_{15}H_{27}BO_4$: C, 63.85; H, 9.64. Found: C, 63.88; H, 9.74.



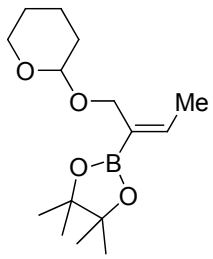
2nα

2nα: Yield 96% (142.9 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.50 (t, J = 7.2 Hz, 1H), 3.03 (s, 3H), 2.91 (s, 3H), 2.16–2.10 (m, 2H), 1.46–1.39 (m, 2H), 1.30–1.26 (m, 16H), 0.87 (t, J = 6.3 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.3, 150.4, 83.7, 37.8, 34.3, 31.6, 31.2, 28.1, 24.7, 22.4, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{16}H_{30}BNO_3$ ($[M+H]^+$), 296.2392. Found, 296.2386.



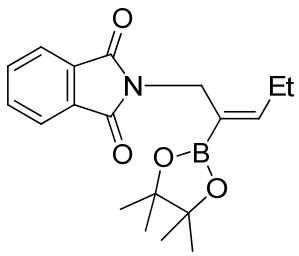
2oα

2oα: Yield 73% (105.1 mg, mixture of α- and β-products). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.23 (m, 5H), 6.67 (q, J = 6.8 Hz, 1H), 4.50 (s, 2H), 4.15 (s, 2H), 1.80 (d, J = 6.8 Hz, 3H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.0, 139.0, 128.1, 127.7, 127.3, 83.2, 71.9, 65.8, 24.8, 15.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{26}BO_3$ ($[M+H]^+$), 289.1970. Found, 289.1957.



2pα

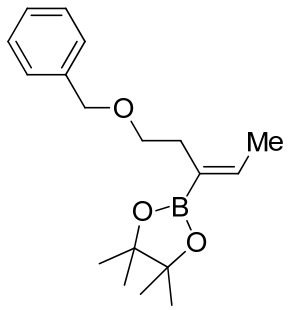
2pα: Yield 64% (90.9 mg, mixture of α- and β-products). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.61 (q, J = 6.8 Hz, 1H), 4.66 (t, J = 3.4 Hz, 1H), 4.34 (d, J = 10.9 Hz, 1H), 4.13 (d, J = 10.9 Hz, 1H), 3.98–3.93 (m, 1H), 3.53–3.48 (m, 1H), 1.82 (d, J = 6.8 Hz, 3H), 1.72–1.46 (m, 6H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 144.8, 97.7, 83.1, 63.0, 61.8, 30.7, 25.6, 24.8, 24.7, 19.3, 14.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{28}BO_4$ ($[M+H]^+$), 283.2075. Found, 283.2064.



2qα

2qα: Yield 76% (130.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.83 (dd, J = 5.4 Hz, 2.7 Hz, 2H), 7.68 (dd, J = 5.4 Hz, 3.2 Hz, 2H), 6.44 (t, J = 7.0 Hz, 1H), 4.43 (s, 2H), 2.31–2.23 (m, 2H), 1.08–1.05 (m, 15H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.5, 150.8, 133.4, 132.7, 122.8, 83.1, 36.5, 24.5, 22.3, 13.2. The carbon directly attached to the boron atom was not detected

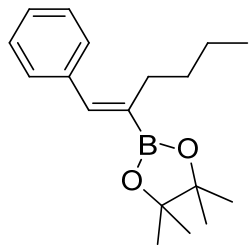
due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{25}BNO_4$ ($[M+H]^+$), 342.1871. Found, 342.1866.



2rα

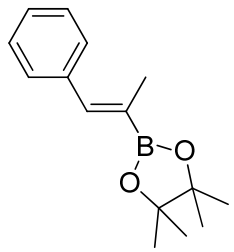
2rα: Yield 68% (102.0 mg, mixture of α- and β-products). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.23 (m, 5H), 6.50 (q, J = 6.8 Hz, 1H), 4.51 (s, 2H), 3.46 (t, J = 7.5 Hz, 2H), 2.51 (t, J = 7.5 Hz, 2H), 1.74 (d, J = 6.8 Hz, 3H), 1.22 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.4, 138.8, 128.2, 127.5, 127.3, 83.0, 72.6, 69.9, 28.6, 24.7, 14.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{28}BO_3$ ($[M+H]^+$), 303.2126. Found, 303.2118.

General Procedure in Table 3-3. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), CF_3Ar-Xan (11.2 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, bis(pinacolato)diboron ($B_2(pin)_2$) (152 mg, 0.60 mmol) was added and the mixture was stirred at room temperature for 5 min. To the mixture, an alkyne (0.50 mmol) and MeOH (42 μL, 1.0 mmol) was added and the mixture was stirred at 28 ºC for 3 h. After the reaction, the mixture was filtrated through a pad of silica gel and all of the volatiles were removed in vacuo. The products were obtained by silica gel column chromatography (eluent: hexane/Et_2O) or preparative GPC in the cases of **2g**β and **2n**β. The regio- and stereochemistry of the products (**2a**β, **2c**β–**2g**β, **2i**β, **2j**β, **2o**β–**2r**β, **2u**β) were determined by ^{1}H NMR and 2D NMR. In the cases of **2m**β and **2n**β, the stereochemistry were determined after derivatization in Scheme 5. The *Z* configuration of **2g**β was further confirmed by a single-crystal X-ray diffraction study.



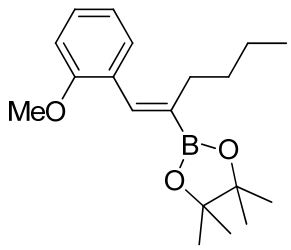
2aβ

2aβ: Yield 98% (141.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32 (m, 4H), 7.23–7.21 (m, 2H), 2.37 (t, J = 7.2 Hz, 2H), 1.50–1.42 (m, 2H), 1.36–1.30 (m, 14H), 0.88 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.6, 138.0, 129.0, 128.0, 126.9, 83.3, 32.2, 29.2, 24.7, 22.8, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{27}BO_2$ ($[M+NH_4]^+$), 304.2442. Found, 304.2438. Anal. Calcd. for $C_{18}H_{27}BO_2$: C, 75.53; H, 9.51. Found: C, 75.56; H, 9.78.



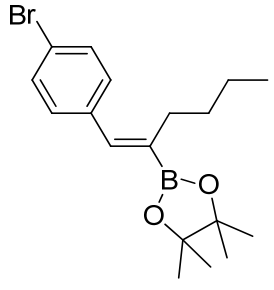
2bβ

2bβ: Yield 74% (89.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39–7.34 (m, 4H), 7.25–7.24 (m, 2H), 1.99 (s, 3H), 1.31 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.4, 137.9, 129.4, 128.0, 127.1, 83.5, 24.8, 15.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[8a]



2cβ

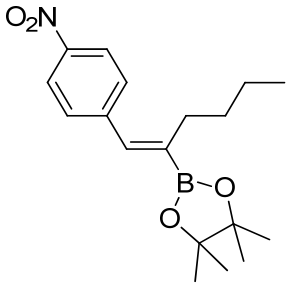
2cβ: Yield 96% (153.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29 (s, 1H), 7.23–7.21 (m, 2H), 6.91–6.85 (m, 2H), 3.82 (s, 3H), 2.29 (t, J = 7.7 Hz, 2H), 1.48–1.41 (m, 2H), 1.33–1.28 (m, 14H), 0.86 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.2, 137.4, 130.0, 128.4, 126.9, 119.8, 110.3, 83.2, 55.3, 32.4, 29.7, 24.8, 22.8, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{29}BO_3$ ($[M+NH_4]^+$), 334.2548. Found, 334.2543. Anal. Calcd. for $C_{19}H_{29}BO_3$: C, 72.16; H, 9.24. Found: C, 72.30; H, 9.33.



2dβ

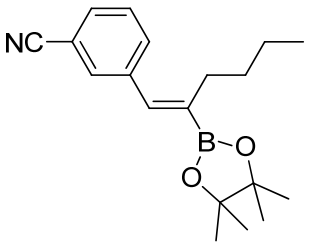
2dβ: Yield 94% (173.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.45 (d, J = 7.2 Hz, 2H), 7.17 (d, J = 6.8 Hz, 2H), 7.11 (s, 1H), 2.33 (t, J = 6.6 Hz, 2H), 1.45–1.21 (m, 16H), 0.88 (t, J = 6.1 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.2, 136.8, 131.2, 130.6, 120.9, 83.5, 32.0, 29.2, 24.7, 22.8, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation.

ESI-HRMS: Calcd. for $C_{18}H_{26}BBrO_2$ ($[M+NH_4]^+$), 382.1548. Found, 382.1541. Anal. Calcd. for $C_{18}H_{26}BBrO_2$: C, 59.21; H, 7.18. Found: C, 59.21; H, 7.07.



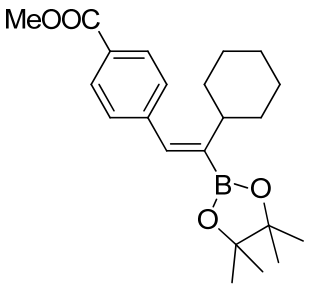
2e*β*

2e*β*: Yield 72% (120.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.20 (d, J = 8.6 Hz, 2H), 7.44 (d, J = 8.6 Hz, 2H), 7.21 (s, 1H), 2.35 (t, J = 7.7 Hz, 2H), 1.49–1.42 (m, 2H), 1.35–1.27 (m, 14H), 0.88 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.4, 144.7, 139.0, 129.5, 123.5, 83.7, 31.9, 29.4, 24.7, 22.7, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{26}BNO_4$ ($[M+NH_4]^+$), 349.2293. Found, 349.2288. Anal. Calcd. for $C_{18}H_{26}BNO_4$: C, 65.27; H, 7.91; N, 4.23. Found: C, 65.25; H, 8.06; N, 4.22.



2f*β*

2f*β*: Yield 96% (150.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.57 (s, 1H), 7.53–7.50 (m, 2H), 7.43 (t, J = 7.7 Hz, 1H), 7.14 (s, 1H), 2.32 (t, J = 7.7 Hz, 2H), 1.46–1.27 (m, 16H), 0.88 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.1, 138.8, 133.1, 132.3, 130.3, 128.9, 118.9, 112.3, 83.6, 31.9, 29.1, 24.7, 22.7, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{26}BNO_2$ ($[M+NH_4]^+$), 329.2395. Found, 329.2389. Anal. Calcd. for $C_{19}H_{26}BNO_2$: C, 73.32; H, 8.42; N, 4.50. Found: C, 73.13; H, 8.63; N, 4.42.



2g*β*

2g*β*: Yield 88% (162.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (d, J = 8.2 Hz, 2H), 7.31 (d, J = 8.2 Hz, 2H), 7.13 (s, 1H), 3.91 (s, 3H), 2.62–2.56 (m, 1H), 1.72–1.60 (m, 5H), 1.53–1.46 (m, 2H), 1.30 (s, 12H), 1.22–1.19 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.0, 143.0, 139.0, 129.3, 128.8, 128.3, 83.2, 52.0, 39.7, 31.8, 26.2, 25.9, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{22}H_{31}BO_4$ ($[M+H]^+$), 371.2388. Found, 371.2382.

Single crystals of **2g*β*** were obtained by slow evaporation of pentane solution. The structure of **2g*β*** was also confirmed by X-ray crystallography.

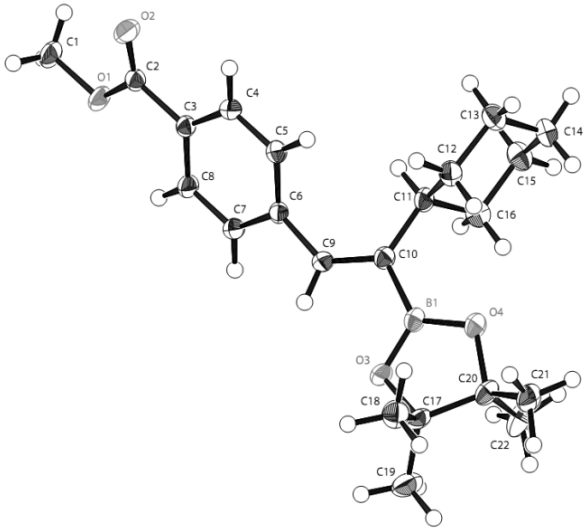
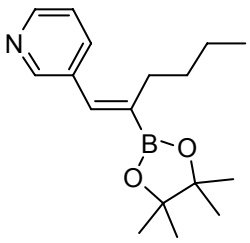
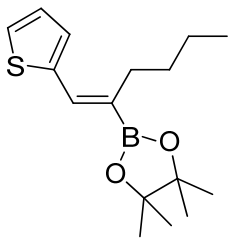


Figure 3-3. Crystal structure of **2g*β***



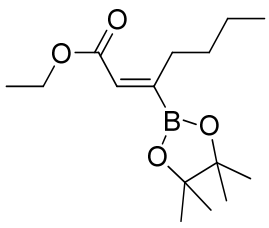
2i*β*

2i*β*: Yield 82% (118.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.57 (s, 1H), 8.47 (d, J = 2.7 Hz, 1H), 7.61 (d, J = 7.7 Hz, 1H), 7.27 (t, J = 3.9 Hz, 1H), 7.13 (s, 1H), 2.35 (t, J = 7.7 Hz, 2H), 1.49–1.41 (m, 2H), 1.37–1.30 (m, 14H), 0.88 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 150.1, 147.9, 137.6, 135.9, 133.6, 123.1, 83.6, 32.1, 29.3, 24.7, 22.7, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{26}BNO_2$ ($[M+H]^+$), 288.2129. Found, 288.2112.



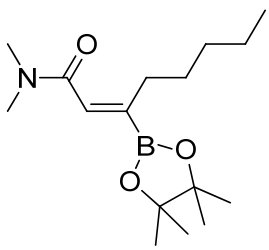
2j*β*

2j*β*: Yield 99% (145.4 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32–7.31 (m, 2H), 7.11 (d, J = 3.6 Hz, 1H), 7.01 (dd, J = 5.0 Hz, 3.6 Hz, 1H), 2.52 (t, J = 7.5 Hz, 2H), 1.51–1.37 (m, 4H), 1.29 (s, 12H), 0.94 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.8, 133.9, 129.6, 126.7, 126.6, 83.4, 31.4, 30.0, 24.7, 23.1, 14.1. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{16}H_{25}BO_2S$ ($[M]^+$), 292.1668. Found, 292.1669.



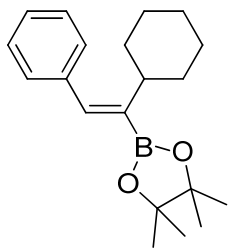
2mβ

2mβ: Yield 90% (127.4 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.40 (s, 1H), 4.17 (q, J = 7.1 Hz, 2H), 2.66 (t, J = 6.3 Hz, 2H), 1.42–1.27 (m, 19H), 0.90 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.0, 129.7, 84.0, 59.7, 31.8, 29.8, 24.7, 22.8, 14.2, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{27}BO_4$ ($[M+H]^+$), 283.2075. Found, 283.2070. Anal. Calcd. for $C_{15}H_{27}BO_4$: C, 63.85; H, 9.64. Found: C, 63.58; H, 9.94.



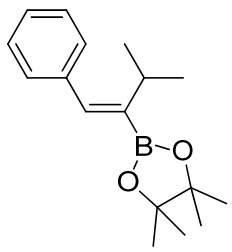
2nβ

2nβ: Yield 78% (116.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.63 (s, 1H), 3.00 (s, 3H), 2.98 (s, 3H), 2.25 (t, J = 7.7 Hz, 2H), 1.45–1.38 (m, 2H), 1.29–1.22 (m, 16H), 0.87 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.8, 135.0, 83.6, 37.8, 34.2, 31.8, 30.8, 29.0, 24.7, 22.5, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{16}H_{30}BNO_3$ ($[M+H]^+$), 296.2392. Found, 296.2385.



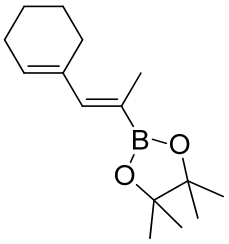
2sβ

2sβ: Yield 70% (110.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.31 (m, 2H), 7.27–7.21 (m, 3H), 7.13 (s, 1H), 2.69–2.63 (m, 1H), 1.71–1.62 (m, 5H), 1.55–1.51 (m, 2H), 1.30 (s, 12H), 1.26–1.19 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.1, 138.2, 128.9, 128.0, 126.7, 83.0, 39.4, 32.0, 26.4, 26.0, 24.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{13}C spectrum were consistent with reported values.[8b]



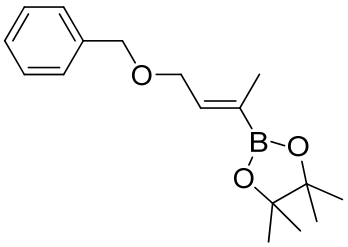
2tβ

2tβ: Yield 76% (104.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.21 (m, 5H), 7.14 (s, 1H), 3.01 (sept, J = 6.7 Hz, 1H), 1.30 (s, 12H), 1.13 (d, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.9, 138.2, 128.8, 127.9, 126.7, 83.0, 28.6, 24.7, 22.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[8b]



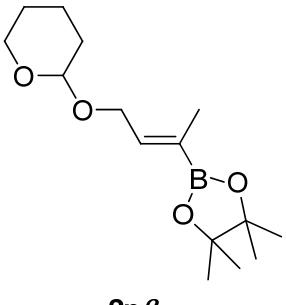
2lβ

2lβ: Yield 94% (115.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.58 (s, 1H), 5.80 (s, 1H), 2.22–2.20 (m, 2H), 2.14–2.13 (m, 2H), 1.88 (d, J = 1.4 Hz, 3H), 1.66–1.54 (m, 4H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 145.5, 136.3, 130.4, 83.2, 28.9, 25.8, 24.8, 22.9, 22.0, 16.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values.[20]



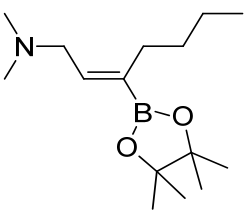
2oβ

2oβ: Yield 74% (105.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.27 (m, 5H), 6.48 (t, J = 5.7 Hz, 1H), 4.53 (s, 2H), 4.17 (d, J = 5.9 Hz, 2H), 1.69 (s, 3H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.8, 138.3, 128.3, 127.7, 127.5, 83.4, 72.5, 70.0, 24.8, 14.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{25}BO_3$ ($[M+H]^+$), 289.1970. Found, 289.1961.



2pβ

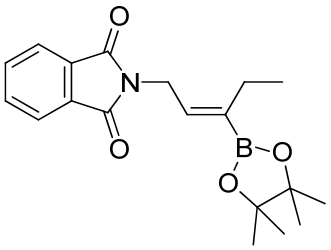
2pβ: Yield 88% (123.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.44 (t, J = 5.7 Hz, 1H), 4.66 (t, J = 3.4 Hz, 1H), 4.37 (dd, J = 13.6 Hz, 5.4 Hz, 1H), 4.14 (dd, J = 13.6 Hz, 6.3 Hz, 1H), 3.87 (t, J = 10.0 Hz, 1H), 3.53–3.49 (m, 1H), 1.87–1.51 (m, 9H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.7, 98.0, 83.3, 64.0, 61.8, 30.5, 25.4, 24.8, 19.2, 14.2. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{27}BO_4$ ($[M+NH_4]^+$), 300.2341. Found, 300.2334. Anal. Calcd. for $C_{15}H_{27}BO_4$: C, 63.85; H, 9.64. Found: C, 63.59; H, 9.89.



2uβ

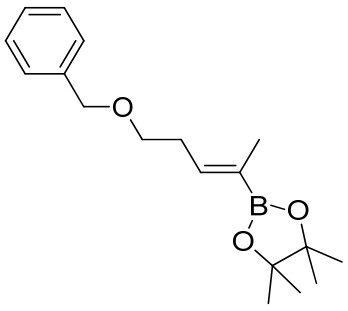
2uβ: Yield 74% (98.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.34 (t, J = 6.3 Hz, 1H), 3.01 (d, J = 6.3 Hz, 2H), 2.24 (t, J = 1.8 Hz, 6H), 2.14 (t, J = 6.6 Hz, 2H), 1.33–1.28 (m, 4H), 1.25 (s, 12H), 0.91–0.87 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.9, 83.1, 57.1, 45.6, 32.2, 28.5, 24.7, 22.6, 14.1. The carbon directly

attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{30}BO_2$ ([M+H]$^+$), 268.2442. Found, 268.2437.



2q*β*

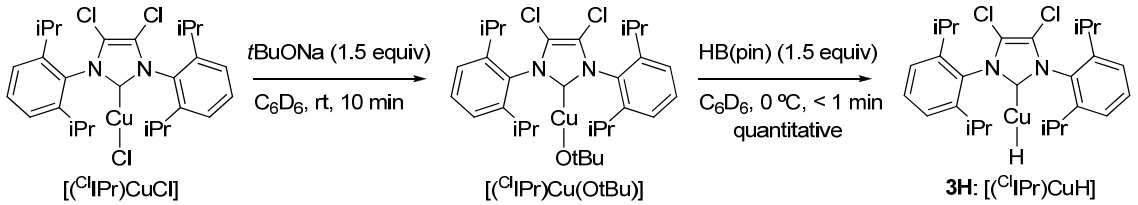
2q*β*: Yield 92% (157.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.84 (dd, J = 5.4 Hz, 3.2 Hz, 2H), 7.70 (dd, J = 5.4 Hz, 3.2 Hz, 2H), 6.15 (t, J = 6.3 Hz, 1H), 4.42 (d, J = 6.3 Hz, 2H), 2.34 (q, J = 7.4 Hz, 2H), 1.23 (s, 12H), 1.06 (t, J = 7.5 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.9, 136.8, 133.8, 132.2, 123.1, 83.3, 35.5, 24.7, 22.1, 14.4. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{19}H_{24}BNO_4$ ([M+H]$^+$), 342.1871. Found, 342.1864. Anal. Calcd. for $C_{19}H_{24}BNO_4$: C, 66.88; H, 7.09; N, 4.11. Found: C, 66.75; H, 6.96; N, 4.09.



2r*β*

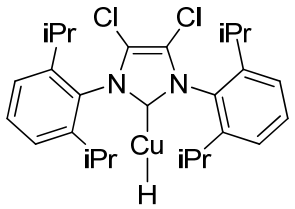
2r*β*: Yield 74% (105.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34–7.27 (m, 5H), 6.31 (brs, 1H), 4.52 (brs, 2H), 3.54–3.52 (brm, 2H), 2.49–2.47 (brm, 2H), 1.71 (s, 3H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.7, 138.5, 128.3, 127.7, 127.5, 83.2, 72.9, 69.2, 29.4, 24.8, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{27}BO_3$ ([M+H]$^+$), 303.2126. Found, 303.2116.

The Procedures for Scheme 3-2.



Scheme 3-2a. In a glove box filled with N_2, a flask was charged with [(^{Cl}IPr)CuCl] (22.2 mg, 0.040 mmol), *t*BuONa (5.77 mg, 0.060 mmol) and C_6D_6 (0.75 mL) and stirred for 10 min at room temperature. The reaction mixture was filtered through a pad of celite. To the resulting solution, HB(pin) (8.7 μL, 0.06 mmol) was added at 0 ºC. The

color was changed to bright orange immediately and [(^{Cl}IPr)CuH] (**3H**)[24] was formed quantitatively. It was judged by ^{1}H NMR.



3H: [(^{Cl}IPr)CuH]

^{1}H NMR (400 MHz, C_6D_6): δ 7.06 (t, J = 7.7 Hz, 2H), 6.94 (d, J = 7.7 Hz, 4H), 2.85 (sept, J = 6.7 Hz, 4H), 2.36 (s, 1H), 1.31 (d, J = 6.8 Hz, 12H), 1.15 (d, J = 6.8 Hz, 12H).

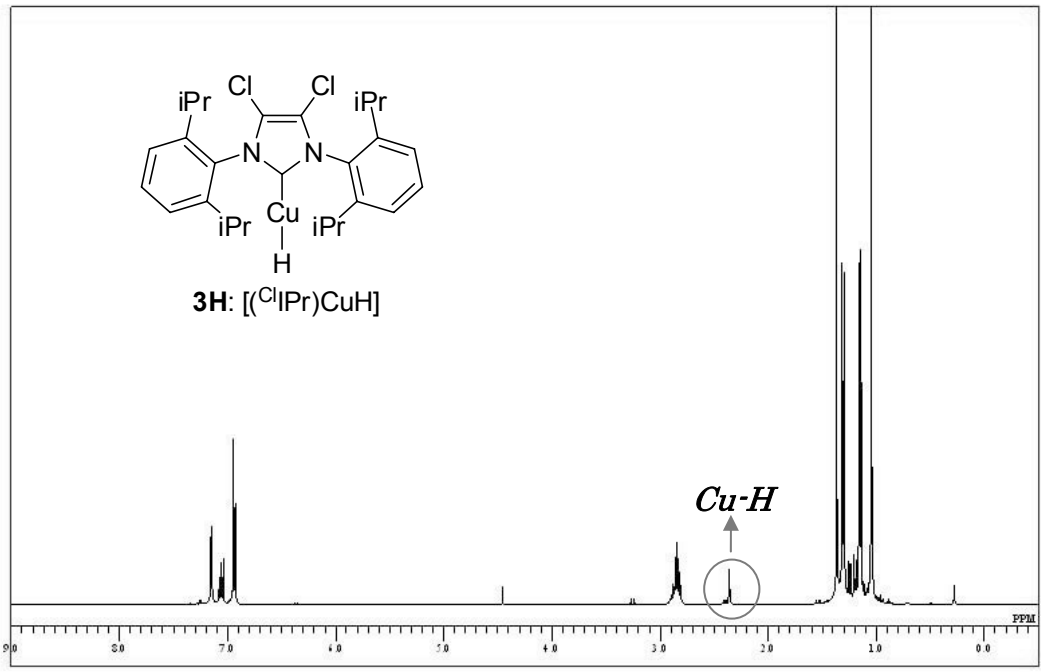
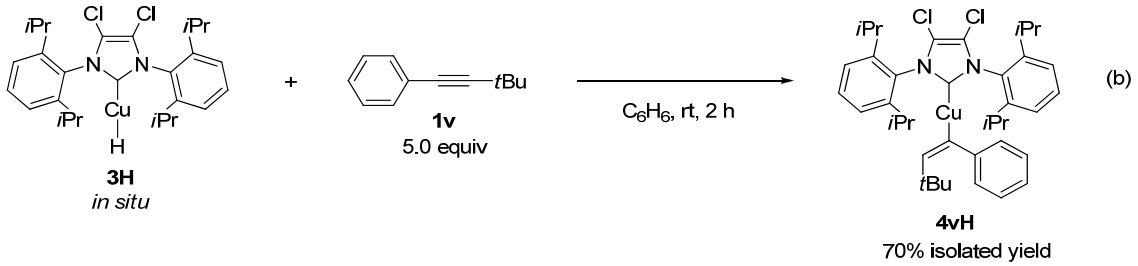


Figure 3-4. ^{1}H NMR spectrum of **3H** (Scheme 3-2a)



Scheme 3-2b. Scheme 3-2b was performed according to the previous report.[24]

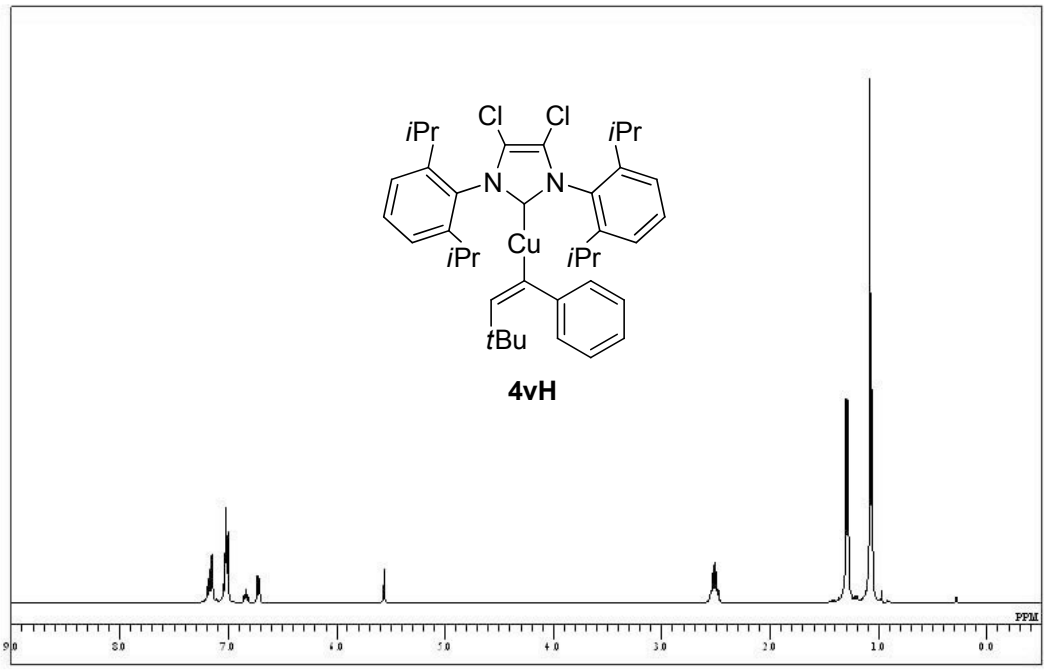
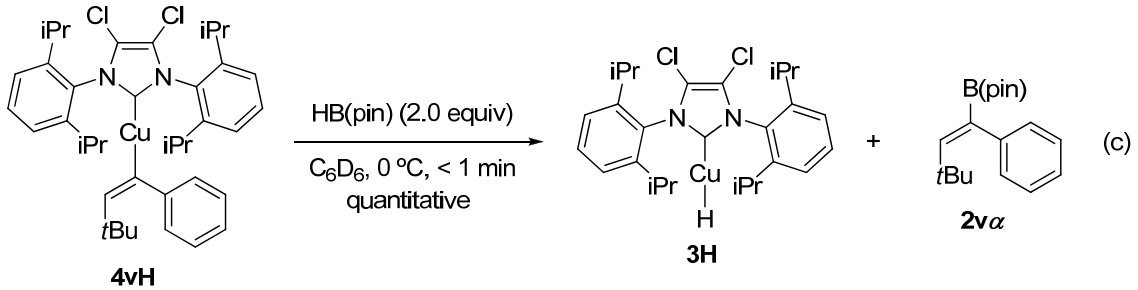
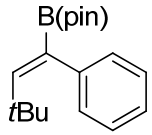


Figure 3-5. ^{1}H NMR spectrum of **4vH** (Scheme 3-2b)



Scheme 3-2c. In a glove box filled with N_2, NMR tube was charged with **4vH** (15 mg, 0.022 mmol) and C_6D_6 (0.75 mL). To the resulting solution, HB(pin) (6.4 mL, 0.044 mmol) was added at 0 ºC. The color was changed to bright orange immediately.

[(^{Cl}IPr)CuH] and **2vα** were formed quatitatively. It was judged by ^{1}H NMR and GC-MS analysis.



2vα

^{1}H NMR (400 MHz, C_6D_6): δ 7.28 (t, J = 7.2 Hz, 2H), 1.02 (s, 12H), 0.95 (s, 9H). Other resonances were not confirmed due to overlapping with **3H**. EI-MS: *m/z* 286 ([M]$^+$).

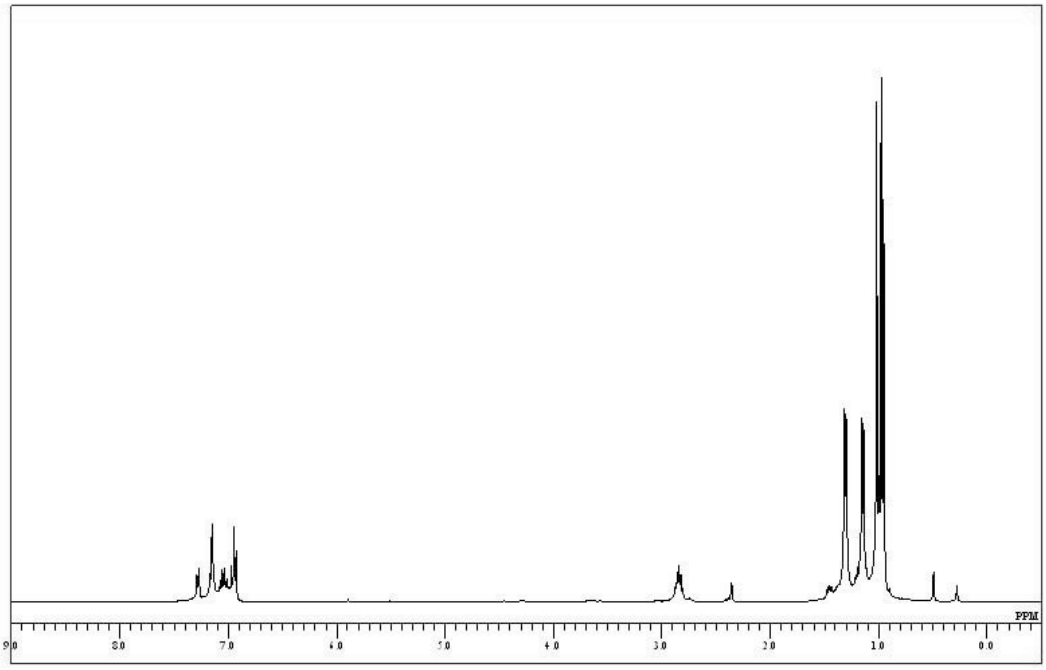
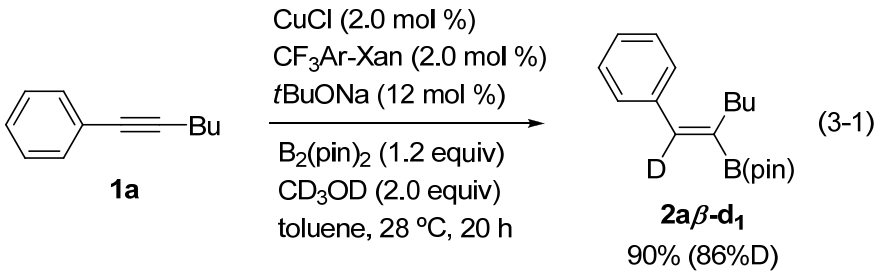
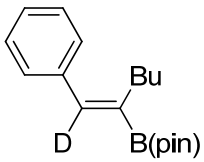


Figure 3-6. ^{1}H NMR spectrum of the reaction mixture which was obtained the reaction in Scheme 3-2c

The Procedure for Eq. 3-1.



A similar procedure of Table 3-3 was employed. CD_3OD (99.8% D) was used instead of MeOH.



2aβ-d$_1$

Yield 94% (133.9 mg). ^{1}H NMR (400 MHz, CD_2Cl_2): δ 7.27–7.22 (m, 4H), 7.18–7.13 (m, 1H), 2.26 (t, J = 7.7 Hz, 2H), 1.41–1.34 (m, 2H), 1.27–1.17 (m, 14H), 0.81 (t, J = 7.2 Hz, 3H).

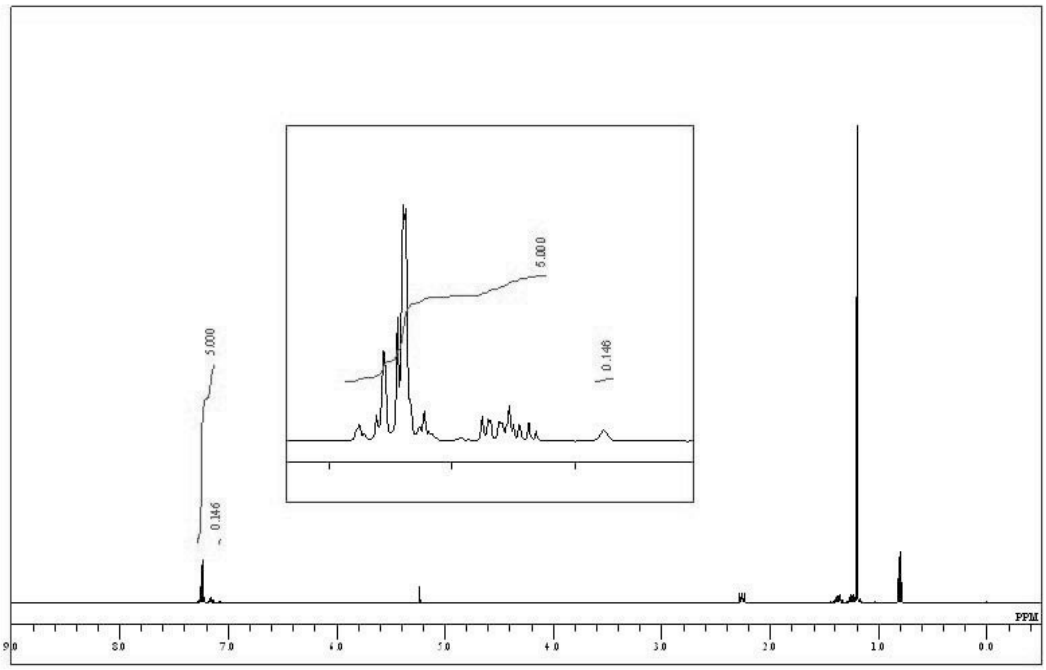


Figure 3-7. ^{1}H NMR spectrum of **2aβ-d$_1$**

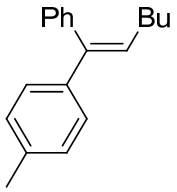
The Procedures for Scheme 3-4.

Synthesis of 2mα. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), MeAr-Xan (6.91 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, pinacolborane (HB(pin)) (1.74 mL, 12.0 mmol) was added at 0 ºC and the mixture was stirred at 0 ºC for 5 min. To the mixture, **2m** (1.68 mL, 10.0 mmol) was added at 0 ºC and the mixture was stirred at 28 ºC for 13 h. After the reaction, **2mα** was obtained by preparative GPC in 93% yield (9.25 mmol).

Synthesis of 2mβ. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), CF_3Ar-Xan (11.2 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (2.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, B_2pin_2 (2.66 g, 10.5 mmol) was added and the mixture was stirred at room temperature for 5 min. To the mixture, **2m** (10.0 mmol) and MeOH (840 μL, 20.0 mmol) was added and the mixture was stirred at 28 ºC for 15 h. After the reaction, the mixture was filtrated through a pad of silica gel and all volatiles were removed in vacuo. **2mβ** was obtained by silica gel column chromatography (eluent: hexane/Et_2O = 10/1) in 89% yield (8.86 mmol).

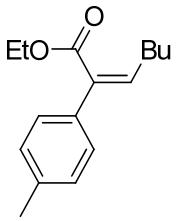
The Procedures for Scheme 3-5. [$PdCl_2(PhCN)_2$] (2 mol %) and DTBPF (2 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, an aryl or alkenyl bromide (1.0 equiv), NEt_3 (3 equiv), H_2O (11 equiv) and an alkenyl boronates (1.05 equiv) were added in this order and the mixture was stirred at indicated temperature for indicated time. After the reaction, the mixture was filtrated through a pad of celite and all volatiles were removed in vacuo. The product**s** were obtained by

silica gel column chromatography (eluent: hexane/Et_2O). The regio- and stereochemistry of all products were determined by ^1H NMR and 2D NMR.



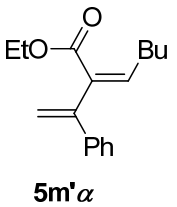
5aα

4-bromotoluene (53 μL, 0.43 mmol), **2a**α (129 mg, 0.45 mmol), at 60 ºC, for 20 h. Yield 95% (103.3 mg). ^1H NMR (400 MHz, $CDCl_3$): δ 7.35 (t, J = 7.0 Hz, 2H), 7.30–7.26 (m, 1H), 7.17 (d, J = 8.6 Hz, 2H), 7.11 (d, J = 8.2 Hz, 2H), 7.06 (d, J = 8.2 Hz, 2H), 6.04 (t, J = 7.5 Hz, 1H), 2.31 (s, 3H), 2.12–2.06 (m, 2H), 1.45–1.26 (m, 4H), 0.85 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.2, 140.5, 140.1, 136.4, 129.9, 129.4, 128.7, 128.0, 127.1, 126.7, 32.2, 29.4, 22.4, 21.0, 14.0. EI-HRMS: Calcd. for $C_{19}H_{22}$ ($[M]^+$), 250.1722. Found, 250.1720.



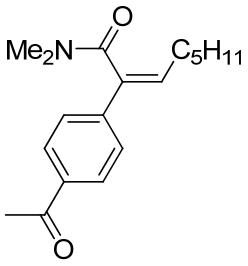
5mα

4-bromotoluene (62 μL, 0.50 mmol), **2m**α (129 mg, 0.53 mmol), at 28 ºC, for 3 h. Yield 98% (121.4 mg). ^1H NMR (400 MHz, $CDCl_3$): δ 7.21 (d, J = 7.7 Hz, 2H), 7.12 (d, J = 7.7 Hz, 2H), 6.13 (t, J = 7.5 Hz, 1H), 4.29 (q, J = 6.9 Hz, 2H), 2.43–2.38 (m, 2H), 2.34 (s, 3H), 1.50–1.35 (m, 4H), 1.31 (t, J = 7.2 Hz, 3H), 0.92 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 168.5, 128.6, 137.2, 135.0, 134.5, 128.9, 126.9, 60.6, 31.5, 29.7, 22.4, 21.1, 14.3, 13.9. ESI-HRMS: Calcd. for $C_{16}H_{22}O_2$ ($[M+H]^+$), 247.1693. Found, 247.1686.



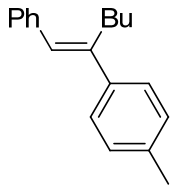
5m'α

α-bromostyrene (90% purity, 53 μL, 0.45 mmol), **2m**α (153 μL, 0.53 mmol), at 60 ºC, for 22 h. Yield 71% (82.5 mg). ^1H NMR (400 MHz, $CDCl_3$): δ 7.34–7.27 (m, 5H), 6.04 (t, J = 7.7 Hz, 1H), 5.31 (d, J = 1.4 Hz, 1H), 5.25 (d, J = 1.4 Hz, 1H), 4.11 (q, J = 7.1 Hz, 2H), 2.46–2.40 (m, 2H), 1.48–1.34 (m, 4H), 1.07 (t, J = 7.2 Hz, 3H), 0.92 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 167.7, 147.5, 142.3, 140.2, 135.1, 128.1, 127.6, 127.3, 114.7, 60.3, 31.3, 29.5, 22.4, 13.9. ESI-HRMS: Calcd. for $C_{17}H_{22}O_2$ ($[M+H]^+$), 259.1693. Found, 259.1686.



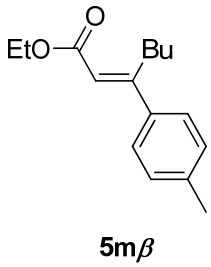
5nα

[$PdCl_2(PhCN)_2$] (4 mol %) and DTBPF (4 mol %) were used. 4-bromoacetophenone (50 mg, 0.25 mmol), **2nα** (76 μL, 0.26 mmol), at 60 ºC, for 18 h. Yield 80% (57.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.92 (d, J = 8.6 Hz, 2H), 7.45 (d, J = 8.2 Hz, 2H), 6.21 (t, J = 7.7 Hz, 1H), 3.11 (s, 3H), 2.90 (s, 3H), 2.59 (s, 3H), 2.23–2.17 (m, 2H), 1.55–1.48 (m, 2H), 1.36–1.31 (m, 4H), 0.90 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.5, 169.5, 140.7, 136.5, 136.0, 132.5, 128.8, 125.4, 37.7, 34.3, 31.6, 30.1, 28.6, 26.6, 22.4, 13.9. ESI-HRMS: Calcd. for $C_{18}H_{25}NO_2$ ($[M+H]^+$), 288.1958. Found, 288.1949.



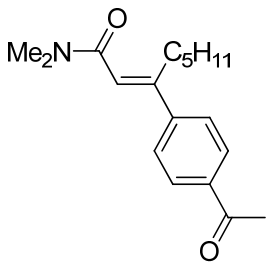
5aβ

4-bromotoluene (62 μL, 0.50 mmol), **2aβ** (148 mg, 0.52 mmol), at 60 ºC, for 18 h. Yield 68% (83.9 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.30 (m, 6H), 7.24–7.20 (m, 1H), 7.16 (d, J = 7.7 Hz, 2H), 6.67 (s, 1H), 2.68 (t, J = 7.9 Hz, 2H), 2.36 (s, 3H), 1.45–1.26 (m, 4H), 0.84 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.2, 140.2, 138.4, 136.8, 129.0, 128.7, 128.2, 127.4, 126.4, 126.3, 31.0, 29.9, 22.8, 21.1, 13.9. EI-HRMS: Calcd. for $C_{19}H_{22}$ ($[M]^+$), 250.1722. Found, 250.1717.



5mβ

4-bromotoluene (62 μL, 0.50 mmol), **2mβ** (155 μL, 0.53 mmol), at 60 ºC, for 18 h. Yield 78% (96.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34 (d, J = 8.2 Hz, 2H), 7.17 (d, J = 7.7 Hz, 2H), 6.01 (s, 1H), 4.20 (q, J = 7.1 Hz, 2H), 3.08 (t, J = 7.7 Hz, 2H), 2.37 (s, 3H), 1.45–1.35 (m, 4H), 1.31 (t, J = 7.0 Hz, 3H), 0.88 (t, J = 7.0 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 166.6, 160.8, 138.9, 138.4, 129.2, 126.6, 116.4, 59.7, 31.2, 30.6, 22.9, 21.2, 14.3, 13.9. ESI-HRMS: Calcd. for $C_{16}H_{22}O_2$ ($[M+H]^+$), 247.1693. Found, 247.1686.



5nβ

[$PdCl_2(PhCN)_2$] (4 mol %) and DTBPF (4 mol %) were used. 4-bromoacetophenone (50 mg, 0.25 mmol), **2nβ** (83 μL, 0.26 mmol), at 70 ºC, for 12 h. Yield 88% (62.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.96 (d, J = 8.6 Hz, 2H), 7.49 (d, J = 8.6 Hz, 2H), 6.22 (s, 1H), 3.08 (s, 3H), 3.04 (s, 3H), 2.75 (t, J = 7.5 Hz,

2H), 2.62 (s, 3H), 1.38–1.23 (m, 6H), 0.82 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 197.5, 167.7, 149.5, 145.9, 136.4, 128.5, 126.7, 122.0, 37.8, 34.7, 31.6, 31.0, 28.0, 26.6, 22.3, 13.9. ESI-HRMS: Calcd. for $C_{18}H_{25}NO_2$ ($[M+H]^+$), 288.1958. Found, 288.1948.

X-ray Crystallographic Analysis.

Crystallographic data of **2d**α and **2g**β were summarized in Tables 3-4. All Data were collected on a Rigaku/Saturn70 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) at 153 K, and processed using CrystalClear (Rigaku).[52] The structures were solved by a direct method and refined by full-matrix least-square refinement on F2. The non-hydrogen atoms, except disordered atom and solvated molecules, were refined anisotropically. All hydrogen atoms were located on the calculated positions and not refined. All calculations were performed using the CrystalStructure software package.[53]

Table 3-4. Crystallographic data of **2d**α and **2g**β.

compound	**2d**α	**2g**β
empirical formula	$C_{18}H_{26}O_2BrB$	$C_{22}H_{31}O_4B$
formula weight	365.12	370.29
temp / K	153	153
crystal system	monoclinic	triclinic
space group	$P2_1/c$ (#14)	P-1 (#2)
a / Å	15.898(3)	5.9537
b / Å	6.0720(11)	13.3515(2)
c / Å	18.603(4)	14.0345(2)
α / deg	90	73.417(9)
β / deg	95.421(2)	78.332(9)
γ / deg	90	79.833(10)
V / Å^3	1787.8(6)	1038.70(2)
Z	4	2
d_{cacd}/g cm^{-3}	1.356	1.184
observed reflections	3995	4461
unique reflections	3995 (all data)	3232 ($I > 2\sigma(I)$)
GOF	1.029	0.981
$R1$ ($I > 2\sigma(I)$), $wR2$[a]	0.0295, 0.0381[b]	0.0450,[c] 0.1107[c,d]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma(w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] $w = 1/[1.0000s(F_o^2)]/(4 F_o^2)$. [c] [b] R ($I > 3\sigma(I)$) and Rw ($I > 2\sigma(I)$) values, respectively. [d] $w = 1/[0.0009 F_o^2+1.0000s(F_o^2)]/(4 F_o^2)$.

References

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[2] a) N. Miyaura, A. Suzuki, *Chem. Rev.* **1995**, *95*, 2457–2483; b) In *Metal-Catalyzed Cross-Coupling Reaction*, *Vol. 1* (Eds.: A. de Meijere, F. Diederich), Wiley-VCH, Weinheim, **2004**, pp 41–123; c) A. Suzuki, H. C. Brown, *Organic Syntheses Via Boranes*, *Vol. 3*, Suzuki Coupling, Aldrich, Milwaukee, **2003**.

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[23] [(IPr)CuCl] reacted with *t*BuONa to afford [(IPr)Cu(O*t*Bu)]. See: a) N. P. Mankad, D. S. Laitar, J. P. Sadighi, *Organometallics* **2004**, *23*, 3369–3371; b) T. Ohishi, M. Nishiura, Z. Hou, *Angew. Chem. Int. Ed.* **2008**, *47*, 5792–5795.

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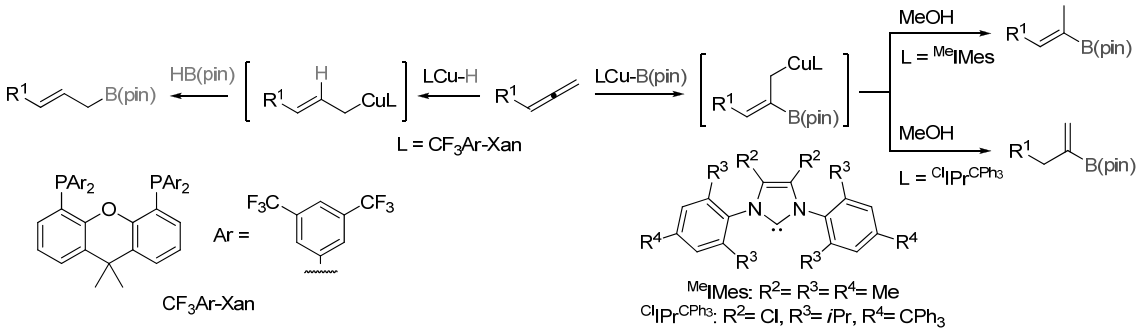
Chapter 4

Copper-Catalyzed Highly Selective Hydroboration of Allenes and 1,3-Dienes

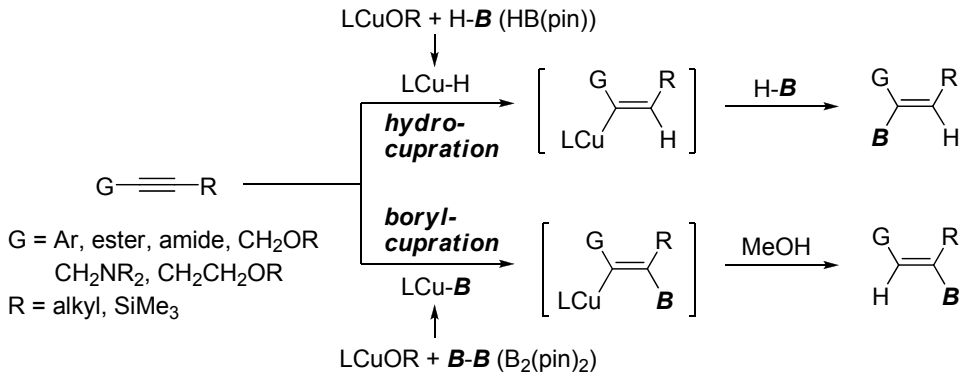
Copper-catalyzed highly selective hydroboration of allenes was developed. Allylboranes and vinylboranes were prepared selectively by choice of catalytic species (copper hydride and borylcopper). Furthermore, two types of vinylboranes could be synthesized selectively by choice of appropriate ligand. The mechanistic studies clarified that the protonation of (*Z*)-σ-allylcopper species, which was isolated and structurally characterized by the single crystal X-ray analysis, was a key step for the present reactions. Besides allenes, the methodology can be applicable to selective hydroboration of 1,3-diene derivatives to afford allylboranes and homoallylboranes.



4-1. Introduction

Pinacolborane (HB(pin))[1] and bis(pinacolato)diboron ($B_2(pin)_2$)[2] are stable and easy-to-handle borylation reagents in the presence of transition metal-catalysts. Especially, in the presence of a copper catalyst, HB(pin) generates copper hydride (Cu-H)[3] and $B_2(pin)_2$ affords borylcopper (Cu-B)[4] as catalytic species. In Chaper 3, the author described the copper-catalyzed regioselective hydroboration of unsymmetrical internal alkynes by choice of one of these two catalytic species (Cu-H or Cu-B) (Scheme 4-1).[5] The authour anticipates that the same idea will realize selective hydroboration of allenes (see, Scheme 4-3).

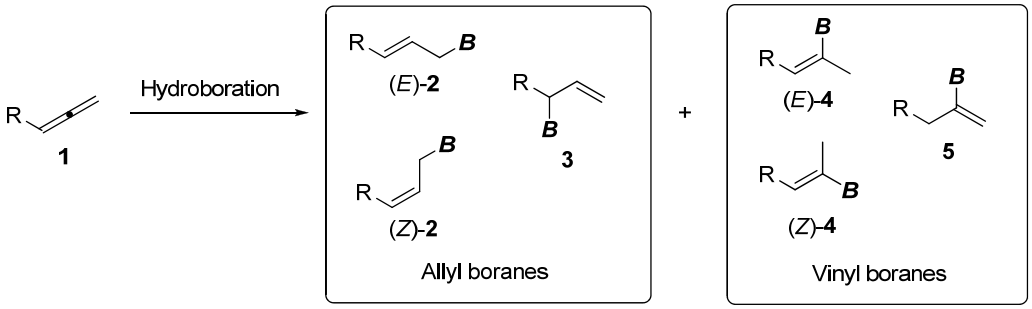
Scheme 4-1. Copper-catalyzed regioselective hydroboration of unsymmetrical internal alkynes



With even mono-substituted allene as a substrate, hydroboration may provide up to six regio- and stereoisomers (Scheme 4-2). As for uncatalyzed reaction, hydroboration of mono-substituted allenes employing reactive di(*alkyl*)boranes such as 9-BBN (9-borabicyclo[3.3.1]nonane),[6a] $HBCy_2$ (Cy = cyclohexyl),[6a] $HB(sia)_2$ (sia = 1,2-dimehtylpropyl),[6b] and 10-TMS-9-BBD-H (10-TMS-9-borabicyclo[3.3.2]decane)[6c] afforded allylboranes (**2**) as major products. However, the drawback of the methods using these di(*alkyl*)boranes is instability both of the borane reagents and the resulting hydroboration products. Furthermore, these reactions were often suffering from low regioselectivity and/or di-hydroboration by-products. On the other hand, di(*alkoxy*)boranes are stable and easy-to-use reagents, and the resulting allyl or vinylborane products can be isolated and stored for further reactions. However, as shown by the reaction of 4,4,6-trimethyl-1,3,2-dioxaborinane

(HBR_2: R_2 = -$OCMe_2CH_2CHMeO$-) with allenes,[6d] the uncatalyzed hydroboration with di(*alkoxy*)boranes required harsh reaction conditions (at 130 ºC) and selectivity between allylboranes and vinylboranes was not high.

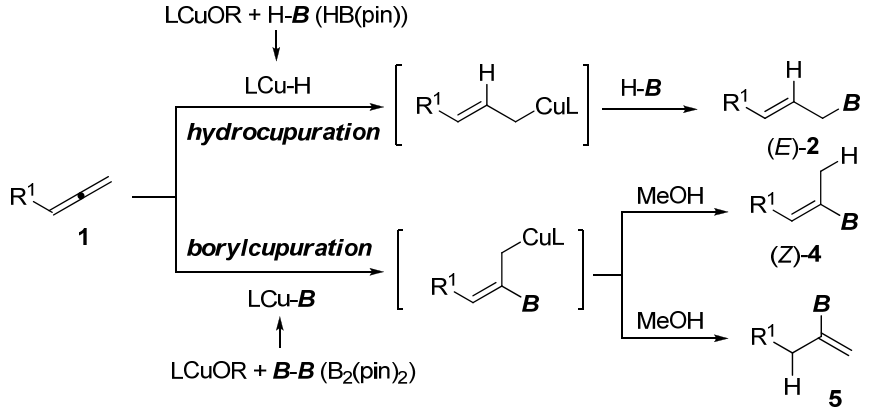
Scheme 4-2. Plausible products for the hydroboration of 1-substituted allenes



To utilize di(*alkoxy*)boranes, transition metal-catalyzed reaction must be beneficial. However, surprisingly, there are only two precedents for transition metal-catalyzed hydroboration of allenes.[7a,b] Miyaura and co-workers reported the first transition metal-catalyzed hydroboration of terminal allenes employing HB(pin) in the presence of a platinum catalyst.[7a] Selectivities of (*Z*)-**4** and **5** depend on the nature of added phosphane ligands. In the case of alkoxyallenes, (*Z*)-**2** was obtained. Very recently, during the preparation of this thesis, Ma and co-workers reported the second example of the transition metal-catalyzed hydroboration of allenes: copper-catalyzed hydroboration of terminal allenes using $B_2(pin)_2$ as a hydroboration reagents to afford (*Z*)-**4** and **5**.[7b]

In this Chapter 4, the author describes the copper-catalyzed hydroboration of allenes employing HB(pin) or $B_2(pin)_2$ as a borylation reagent (Scheme 4-3).[8] The selective synthesis of allyboranes ((*E*)-**2**) and vinylboranes ((*Z*)-**4** and **5**) was successfully controlled by a choice of catalytic species (Cu-H or Cu-B). Notably, two types of vinylboranes ((*Z*)-**4** and **5**) were selectively obtained by choice of suitable ligands. Thus, the present methodology can afford three different hydroboration products selectively from a single substrate. Furthermore, this catalytic procedure also can be applicable to selective hydroboration of 1,3-dienes.

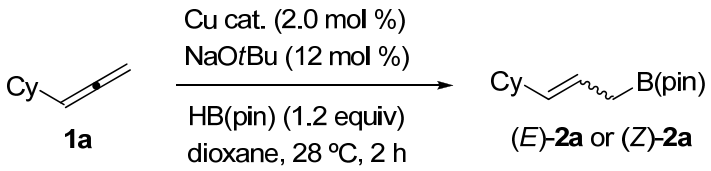
Scheme 4-3. Copper-catalyzed hydroboration of allenes.



4-2. Results and Discussion

Hydroboration of Allenes with HB(pin) to Allylboranes ((*E*)-2). First, copper-catalyzed hydroboration of cyclohexylallene (R^1 = Cy: **1a**) was carried out employing HB(pin) as a hydroboration reagent in the presence of various ligands (Table 4-1). Monodentate phosphane ligands such as PPh_3 and PCy_3 were not effective and almost no allyborane **2a** was obtained (entries 1 and 2). On employing bidentate phosphane ligands such as 1,2-diphenylphosphinobenzene (dppbz), Xantphos (Xan), Me-ArXan, and CF_3-ArXan (for structures of the ligands used in this study, see Figure 4-1), yields were dramatically improved and **2a** was obtained in good to high yield with high (*E*)-selectivity. (entries 4–6). Among them, CF_3Ar-Xan, which was the most effective ligand for the regioselective hydroboration of unsymmetrical internal alkynes,[5] was also a most effective ligand, giving **2a** in 99% yield with high selevtivity (*E*/*Z* = 95/5, entry 6). It is noteworthy that (*E*)-**2a** could be isolated by silica gel column chromatography under air in 78% isolated yield as a pure form. When *N*-heterocyclic carbene (NHC) ligands such as IPr and IMes (Figure 4-1) were used, both yields and regioselectivities decreased considerably (entries 7 and 8). In all these cases, other isomers such as allylborane (**3a**) and vinylboranes (**4a** and **5a**) were not afforded at all.

Table 4-1. Hydroboration of cyclohexylallene (**1a**) with HB(pin) using various copper catalysts[a]



Entry	Cu cat.	Yield [%][b]	*E*/*Z*[c]
1	CuCl/PPh_3	<1	-
2	CuCl/PCy_3	<1	-
3	CuCl/dppbz	78	88/12
4	CuCl/Xan	85	>99/1
5	CuCl/MeAr-Xan	99	93/7
6	CuCl/CF_3Ar-Xan	99 (78)[d]	95/5
7	[(IPr)CuCl]	68	65/35
8	[(IMes)CuCl]	12	49/51

[a] Cyclohexylallene (0.50 mmol), HB(pin) (0.60 mmol), CuCl (0.010 mmol, 2.0 mol %)/ligand (0.010 mmol, 2.0 mol %) or [(NHC)CuCl] (0.010 mmol, 2.0 mol %), NaO*t*Bu (0.060 mmol, 12 mol %), dioxane (4.0 mL), 28 ºC, 2 h. [b] Yield of products based on the GC internal standard technique. [c] A ratio of *E*/*Z* in the crude reaction mixture was determined by GC. [d] Isolated yield with silica gel column chromatography.

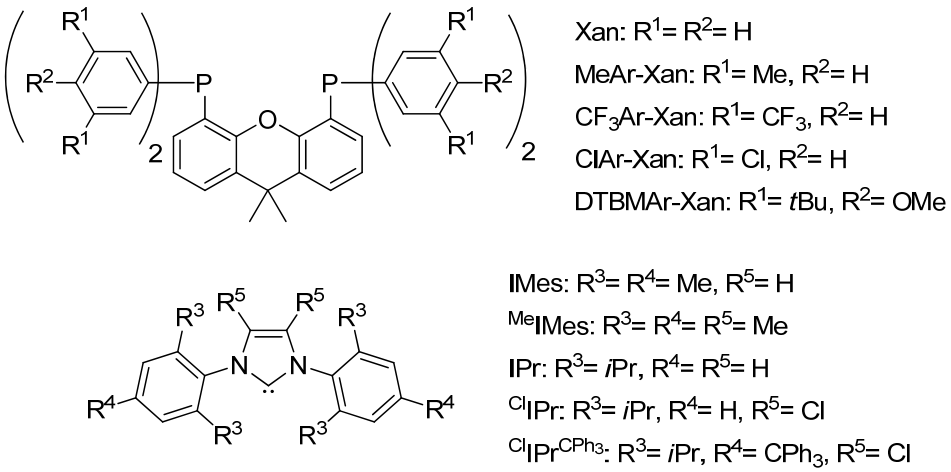
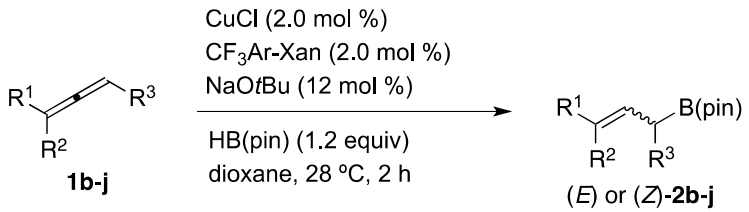


Figure 4-1. Ligands used in this study

The hydroboration of various allenes was carried out employing HB(pin) in the presence of a catalytic amount of CuCl with CF_3Ar-Xan as a ligand (Table 4-2). Allenes bearing a primary alkyl group (**1b** and **1c**) afforded the corresponding allylboranes (**2b** and **2c**) in good isolated yields, albeit with slightly low *E*/*Z* ratio (entries 1 and 2). In contrast, allenes bearing a secondary or a tertiary alkyl substituent (**1d** and **1e**) afforded allylboranes (**2d** and **2e**) in good isolated yields with high *E*/*Z* ratio (entries 3 and 4). In the case of allenes conjugated with an aromatic ring, the products (**2f-h**) were obtained with perfect stereoselectivity (entries 5–7). A 1,1-disubstituted allene (**1i**) also provided the corresponding allylborane (**2i**) (entry 8). It should be noted that an unsymmetrical 1,3-disubstituted allene (**1j**) successfully underwent the hydroboration and gave a single isomer (**2j**) (entry 9). This is the first example of transition metal-catalyzed hydroboration of 1,3-disubstituted allenes.

Table 4-2. Copper-catalyzed hydroboration of various allenes to allylboranes[a]



1b-j → (*E*) or (*Z*)-**2b-j**

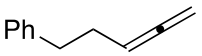
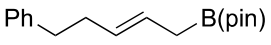
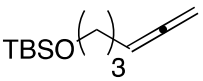
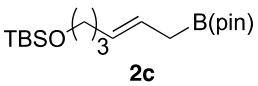
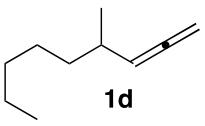
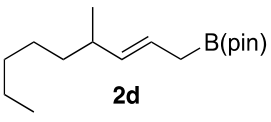
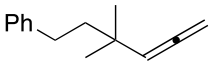
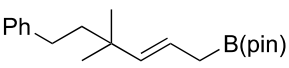
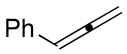
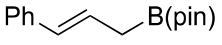
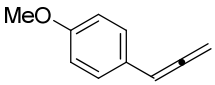
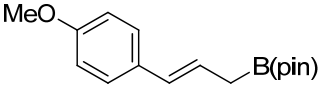
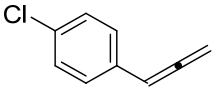
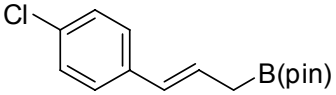
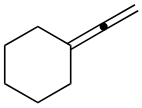
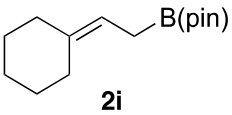
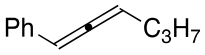
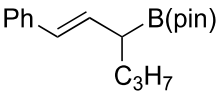
Entry	Substrate	Product	Yield [%][b] (*E*/*Z*)[c]
1	 **1b**	 **2b**	74 (91/9)
2	 **1c**	 **2c**	71 (89/11)
3	 **1d**	 **2d**	70 (98/2)
4	 **1e**	 **2e**	78 (100/0)

Table 4-2. (Continued)

5	 **1f**	 **2f**	60 (100/0)
6	 **1g**	 (*E*)-**2g**	68 (100/0)
7	 **1h**	 (*E*)-**2h**	58 (100/0)
8	 **1i**	 **2i**	66
9	 **1j**	 **2j**	52 (100/0)

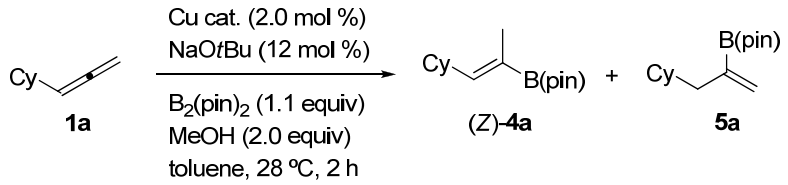
[a] An allene (0.50 mmol), HB(pin) (0.60 mmol), CuCl (0.010 mmol, 2.0 mol %), CF_3Ar-Xan (0.010 mmol, 2.0 mol %), NaO*t*Bu (0.060 mmol, 12 mol %), dioxane (4.0 mL), 28 ºC, 2 h. [b] Yield of isolated products. [c] A ratio of *E*/*Z* in the crude reaction mixture was determined by GC.

Hydroboration of Allene with $B_2(pin)_2$ to Vinylboranes ((*Z*)-4 or 5). Hydroboration of **1a** was carried out employing $B_2(pin)_2$ in place of HB(pin) in the presence of a catalytic amount of CuCl with various ligands (Table 4-3). Remarkably, as compared with the hydroboration employing HB(pin), the regioselectivity was completely changed to afford vinylboranes ((*Z*)-**4a** and **5a**), and no other isomers such as **2a**, **3a**, and (*E*)-**4a** were provided at all (Table 4-3). The use of monodentate phosphanes such as PPh_3 and PCy_3 led to a mixture of (*Z*)-**4a** and **5** with low selectivities (entries 1 and 2). The NHC ligand, IMes, tended to produce (*Z*)-**4a** preferentially (84% yield, (*Z*)-**4a**/**5a** = 77/23, entry 3). ^{Me}IMes ligand bearing methyl substituents on the *N*-heterocyclic ring was the most effective ligand, giving (*Z*)-**4a** in higher yield and selectivity (92% yield, (*Z*)-**4a**/**5a** = 86/14, entry 4). Gratifyingly, by lowering the reaction temperature to –20 ºC, (*Z*)-**4a** was obtained almost exclusively and in

quantitative yield (99% yield, (*Z*)-**4a**/**5a** = 99/1, entry 5). From the reaction mixture, (*Z*)-**4a** was isolated in 90% yield. Thus, the catalyst system in entry 5 (with ^{Me}IMes as the ligand) is regarded as the best for the preparation of (*Z*)-**4**.

As for selective preparation of **5**, **5a** was afforded as a major product with Xan as a ligand ((*Z*)-**4a**/**5a** = 28/72), but yield and selectivity were not satisfactory (entry 6). Employing CF_3Ar-Xan as a ligand, **5a** was selectively obtained ((*Z*)-**4a**/**5a** = 2/98), but the yield was not satisfactory. When IPr was used as the ligand, yield of the products increased to 92% yield, but with low selectivity ((*Z*)-**4a**/**5a** = 35/65, entry 3). In the case of ^{Cl}IPr bearing Cl substituents on the *N*-heterocyclic ring, both yield and selectivity were dramatically improved (99% yield, (*Z*)-**4a**/**5a** = 9/91, entry 9). Finally, ^{Cl}IPr^{CPh3} (Figure 4-1) bearing Cl substituents on the *N*-heterocycle ring and CPh_3 substituents on the phenyl rings[9] was the most effective ligand, giving **5a** in 99% yield with high selectivity ((*Z*)-**4a**/**5a** = 2/98, entry 10). The selectivity was further improved by using THF as a solvent (entry 11), from which **5a** was isolated in 94% yield with a silica gel column chromatography. Thus, the catalyst system in entry 11 (with ^{Cl}IPr^{CPh3} as the ligand) is determined to be the best for preparation of **5**.

Table 4-3. Hydroboration of **1a** with bis(pinacolato)diboron ($B_2(pin)_2$) using various copper catalysts[a]



Entry	Cu cat.	Yield [%][b]	(*Z*)-**4a**/**5a** [c]
1	CuCl/PPh_3	40	84/16
2	CuCl/PCy_3	56	47/53
3	[(IMes)CuCl]	84	77/23
4	[(^{Me}IMes)CuCl]	92	86/14
5[d]	[(^{Me}IMes)CuCl]	99 (90)[e]	99/1
6	CuCl/Xan	66	28/72
7	CuCl/CF_3Ar-Xan	73	2/98
8	[(IPr)CuCl]	92	35/65

Table 4-3. (Contined)

9	[(^{Cl}IPr)CuCl]	99	9/91
10	[(^{Cl}IPr^{CPh_3})CuCl]	99	2/98
11[f]	[(^{Cl}IPr^{CPh_3})CuCl]	99 (94)[e]	1/99

[a] **1a** (0.50 mmol), $B_2(pin)_2$ (0.53 mmol), MeOH (1.0 mmol), CuCl (0.010 mmol, 2.0 mol %)/ligand (0.010 mmol, 2.0 mol %) or [(NHC)CuCl] (0.010 mmol, 2.0 mol %), NaO*t*Bu (0.060 mmol, 12 mol %), toluene (1.0 mL), 28 ºC, 2 h. [b] Yield of products based on the GC internal standard technique. [c] A ratio of (*Z*)-**4a**/**5a** in the crude reaction mixture was determined by GC. [d] MeOH (4.0 mmol), at –20 ºC. [e] Isolated yield after silica gel column chromatography. [f] $B_2(pin)_2$ (0.60 mmol) and THF (2.0 mL) were used.

Now the author established the best catalyst system for the two vinylborane derivatives, (*Z*)-**4** (entry 5) and **5** (entry 11), respectively. The structures of [(^{Me}IMes)CuCl] and [(^{Cl}IPr^{CPh_3})CuCl] were determined as monomeric forms by X-ray crystallography as shown in Figure 4-2, which are quite similar to those of other [(NHC)CuCl] complexes.[10]

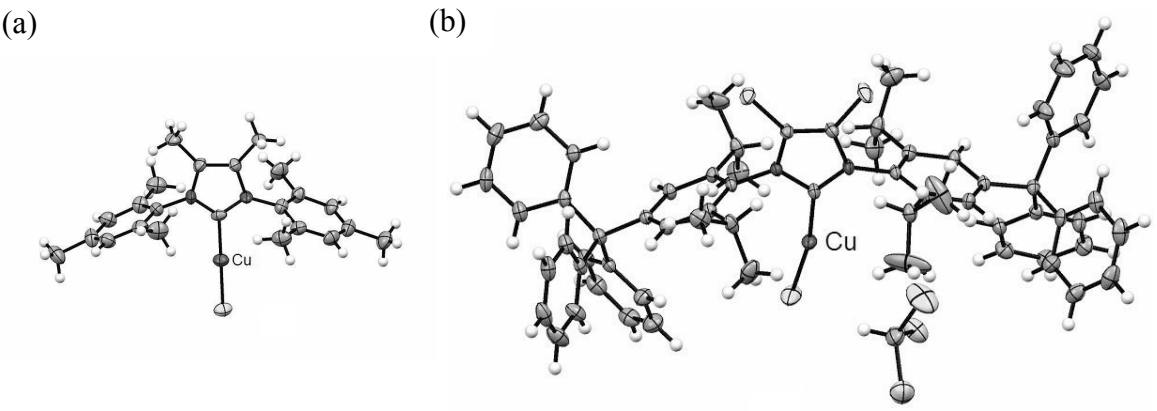
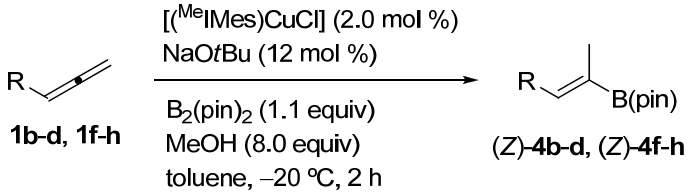


Figure 4-2. Crystal structure of (a) [(^{Me}IMes)CuCl] and (b) [(^{Cl}IPr^{CPh_3})CuCl·$CHCl_3$]

The hydroboration of various allenes to afford (*Z*)-**4** was carried out with $B_2(pin)_2$ in the presence of [(^{Me}IMes)CuCl] as a catalyst (Table 4-4). Very recently, Ma et al. reported that CuCl/P(*p*-$MeOC_6H_4)_3$ catalyst system afforded (*Z*)-**4** by the hydroboration

of mono-substituted allenes employing $B_2(pin)_2$.[7b] With Ma's catalyst system, only aryl-substituted allenes were applicable, but alkyl-substituted allenes could not be used due to their poor selectivities of the products. In sharp contrast, by use of [(^{Me}IMes)CuCl] as a catalyst, mono-substituted allenes having primary alkyl (entries 1 and 2) and secondary alkyl substituents (entry 3) as well as aromatic ones (entries 4–6) selectively afforded (*Z*)-**4b-h** in good to high yields. For the arylallenes (**1f**–**h**), the reactions proceeded smoothly with $CF_3CH(OH)CF_3$ (4.0 equiv) in place of MeOH (entries 4–6) as a proton source.

Table 4-4. Copper-catalyzed hydroboration of various allenes to vinylborane ((*Z*)-**4**)[a]



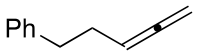
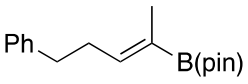
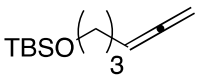
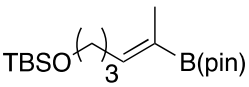
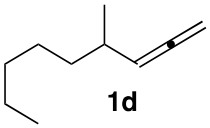
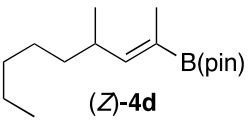
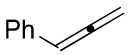
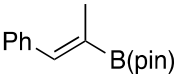
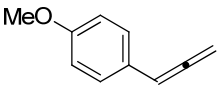
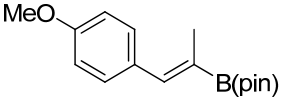
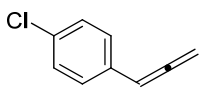
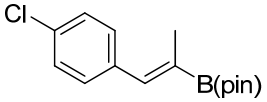
Entry	Substrate	Product	Yield [%][b] ((*Z*)-**4**/**5**)[c]
1	 **1b**	 (*Z*)-**4b**	90 (93/7)
2	 **1c**	 (*Z*)-**4c**	89 (91/9)
3	 **1d**	 (*Z*)-**4d**	90 (97/3)
4[d]	 **1f**	 (*Z*)-**4f**	83 (95/5)
5[e]	 **1g**	 (*Z*)-**4g**	56 (97/3)

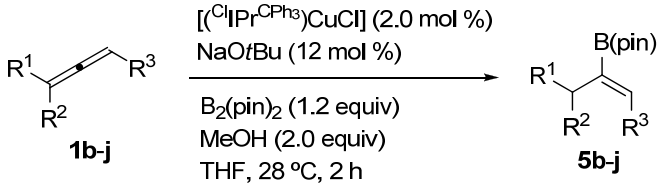
Table 4-4. (Continued)

6[f]	 **1h**	 (*Z*)-**4h**	81 (91/9)

[a] An allene (0.50 mmol), $B_2(pin)_2$ (0.53 mmol), [(^{Me}IMes)CuCl] (0.010 mmol, 2.0 mol %), NaO*t*Bu (0.060 mmol, 12 mol %), toluene (1.0 mL), –20 ºC, 2 h. [b] Yield of the isolated products. [c] A ratio of (*Z*)-**4**/**5** in the crude reaction mixture was determined by GC. [d] $B_2(pin)_2$ (0.75 mmol) and [(^{Me}IMes)CuCl] (0.038 mmol, 7.5 mol %) were used and $CF_3CH(OH)CF_3$ (2.0 mmol) was used instead of MeOH. [e] $B_2(pin)_2$ (0.75 mmol), [(^{Me}IMes)CuCl] (0.025 mmol, 5.0 mol %) were used and $CF_3CH(OH)CF_3$ (2.0 mmol) was used instead of MeOH. [f] $B_2(pin)_2$ (0.60 mmol) and [(^{Me}IMes)CuCl] (0.025 mmol, 5.0 mol %) were used and $CF_3CH(OH)CF_3$ (2.0 mmol) was used instead of MeOH.

On the other hand, with [(^{Cl}IPr^{CPh_3})CuCl] as a catalyst, vinylboranes **5** were selectively afforded (Table 4-5). Allenes bearing primary (entries 1 and 2), secondary (entry 3), and tertiary (entry 4) alkyl groups (**1a**–**e**) provided the corresponding products in good to high yields with high selectivities. The reactions of arylallenes (**1f**–**h**) also proceeded in high yields and selectivities (entries 5–7). Electron donating and withdrawing groups on the aryl ring did not affect both yields and selectivities. Not only 1-substituted allenes but also 1,1-disubstituted (**1i**) and 1,3-disubstituted allenes (**1j**) gave the corresponding products (**5i** and **5j**) with high selectivities (entries 8 and 9).

Table 4-5. Copper-catalyzed hydroboration of various allenes to vinylborane (**5**)[a]



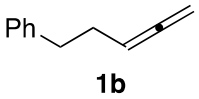
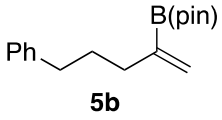
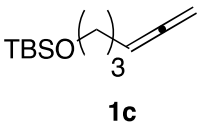
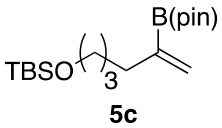
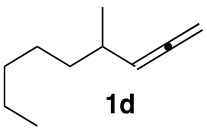
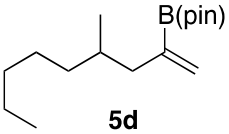
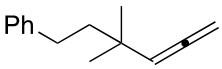
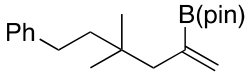
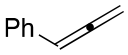
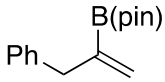
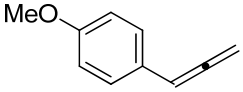
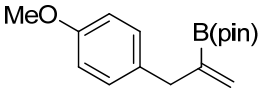
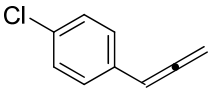
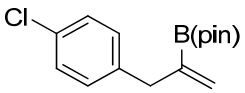
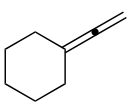
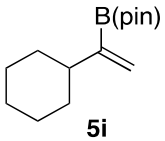
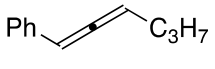
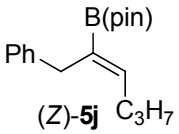
Entry	Substrate	Product	Yield [%][b] (**5**/(*Z*)-**4**)[c]
1	 **1b**	 **5b**	88 (97/3)
2	 **1c**	 **5c**	90 (98/2)
3	 **1d**	 **5d**	88 (98/2)
4	 **1e**	 **5e**	94 (100/0)
5	 **1f**	 **5f**	82 (98/2)
6	 **1g**	 **5g**	80 (99/1)
7	 **1h**	 **5h**	90 (97/3)
8	 **1i**	 **5i**	56 (100/0)[d]

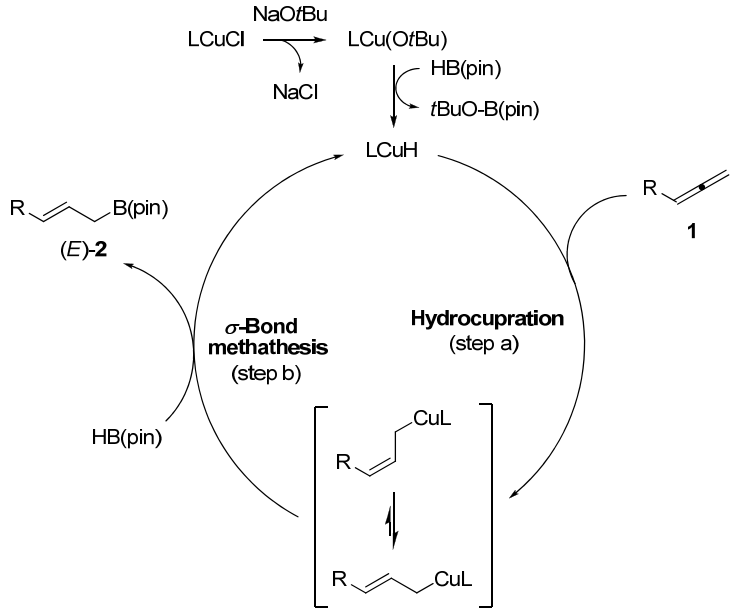
Table 4-5. (Continued)

9	 **1j**	 (*Z*)-**5j**	85 (100/0)[e]

[a] An allene (0.50 mmol), $B_2(pin)_2$ (0.60 mmol), [(^{Cl}IPr^{CPh_3})CuCl] (0.010 mmol, 2.0 mol %), NaO*t*Bu (0.060 mmol, 12 mol %), THF (2.0 mL), 28 ºC, 2 h. [b] Yield of the isolated products. [c] A ratio of **5**/(*Z*)-**4** in the crude reaction mixture was determined by GC. [d] **5i**/**2i** = 93/7. [e] *Z*/*E* = 83/17.

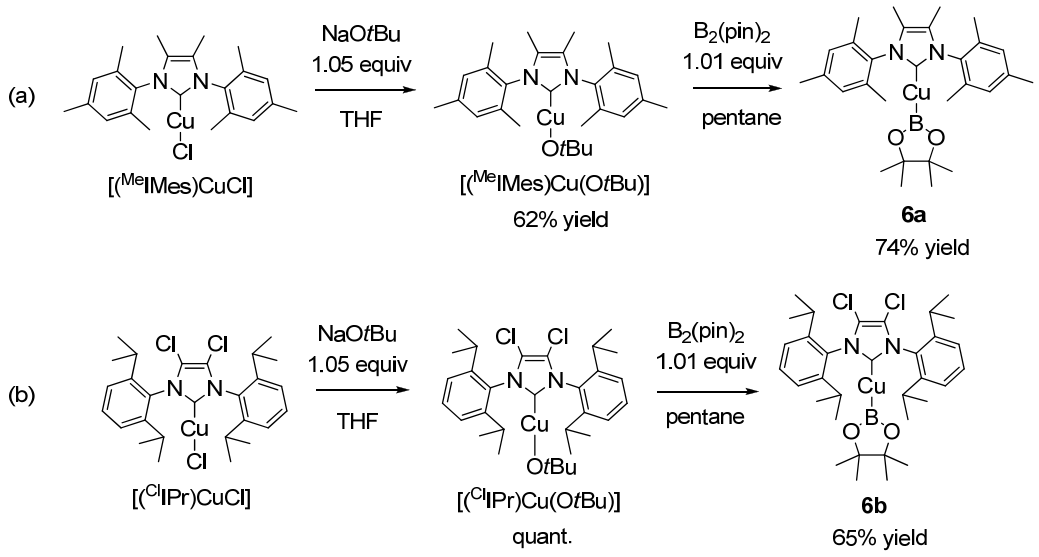
Reaction Mechanism about Hydroboration of Allenes. The hydroboration of allene with HB(pin) must be very similar to that of alkynes,[5] and a possible catalytic cycle is shown in Scheme 4-4. A copper hydride would be generated by the reaction between an copper alkoxide and HB(pin). The author already confirmed that [(^{Cl}IPr)CuH] was obtained quantitatively by a stoichiometric reaction of [(^{Cl}IPr)Cu(O*t*Bu)] with HB(pin).[5] The copper hydride inserts into an allene from the sterically less encumbered face of the allene to give (*Z*)-σ-allyl copper species as a kinetic product (step a in Scheme 4-4), which is isomerized to the corresponding thermodynamically stable (*E*)-σ-allyl copper species. σ-Bond metathesis between an (*E*)-σ-allyl copper and HB(pin) gives (*E*)-**2** and [LCuH] respectively[11] (step b in Scheme 4-4).

Scheme 4-4. A plausible reaction mechanism employing HB(pin)



As for mechanism of hydroboration employing $B_2(pin)_2$, some stoichiometric reactions were carried out employing ^{Me}IMes and ^{Cl}IPr as the ligands. In the catalytic reactions, ^{Me}IMes was an effective ligand for synthesizing (*Z*)-**4** (entry 5 in Table 4-3) and ^{Cl}IPr was a good ligand for synthesizing **5** (entry 9 in Table 4-3). First, two boylcopper complexes [(^{Me}IMes)CuB(pin)] (**6a**) and [(^{Cl}IPr)CuB(pin)] (**6b**) were prepared in good yields by the reaction of [(NHC)Cu(O*t*Bu)][12] with $B_2(pin)_2$ (Scheme 4-5a,b) according to a literature method for [(IPr)CuB(pin)].[13] The isolated complexes **6a** and **6b** were stable in the solid state under N_2 atmosphere. In toluene solution, **6a** was decomposed at room temperature, while **6b** was stable at room temperature for a few hours. The crystal structure of **6b** was determined by X-ray crystallography (Figure 4-3). The copper atom has a nearly linear geometry with a carbon atom on the NHC ligand and a boron atom. The bond angle of C-Cu-B is 165.51(15) º which is comparable to that of [(IPr)CuB(pin)] (168.07(10) º).

Scheme 4-5. Syntheses of borylcopper complexes **6a** and **6b**



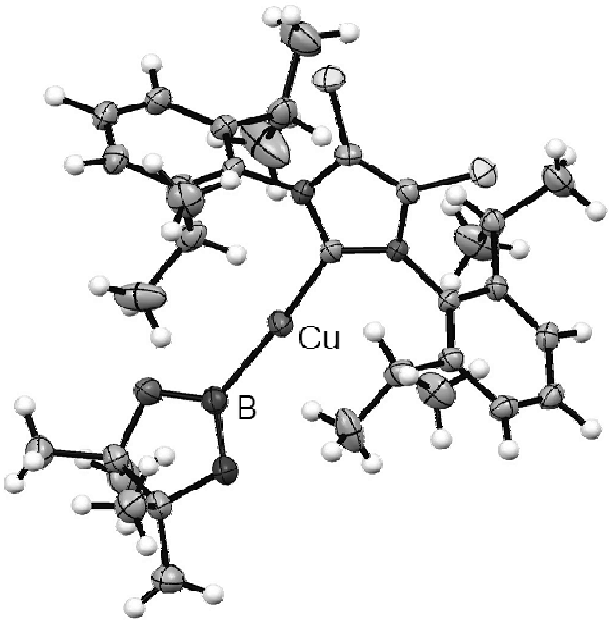


Figure 4-3. Crystal structure of **6b**

The borylcopper complexes **6a** and **6b** reacted with **1a** smoothly[14] and formation of similar (*Z*)-σ-allyl copper species **7a** and **7b** were confirmed by ^{1}H NMR and NOESY measurements (Scheme 4-6a,b). All attempts to grow single crystals of **7a** and **7b** suitable for X-ray crystallography analysis were failed. On the other hand, an allylcopper complex (**7c**) was prepared from **6b** and **1f** in 61% isolate yield (Scheme 4-6c), and afforded good single crystals. Noteworthy is that the (*Z*)-σ-allyl form suggested for **7a** and **7b** by NMR was successfully confirmed by X-ray crystallography analysis of **7c** (Figure 4-4). In the unit cell, there are two independent complexes. The one of them is depicted in Figure 4-4. The average bond length of C1-C2 (1.361(4) Å) is considerably shorter than that of C2-C3 (1.492(4) Å), which clearly indicates the σ-allyl structure of **7c**.

Scheme 4-6. Stoichiometric reaction between **1a** and [(^{Me}IMes)CuB(pin)] (**6a**) and [(^{Cl}IPr)CuB(pin)] (**6b**)

(a) **6a** + **1a** → **7a** (MeOH, 1.5 equiv, Temp.) → (*Z*)-**4a** + **5a**

Temp.	Yield ((*Z*)-**4a**/**5a**)
–20 ºC	71% (47/53)
–80 ºC	53% (99/1)

7a

Observed by ^{1}H NMR

H^a: 5.61 (d, *J* = 7.7 Hz, 1H)

H^b: 1.56 (s, 2H)

(b) **6b** + **1a** → **7b** (MeOH, 1.5 equiv, Temp.) → (*Z*)-**4a** + **5a**

Temp.	Yield ((*Z*)-**4a**/**5a**)
RT	75% (6/94)
–20 ºC	54% (6/94)

7b

Observed by ^{1}H NMR

H^a: 5.58 (d, *J* = 7.7 Hz, 1H)

H^b: 1.41 (s, 2H)

(c) **6b** + **1f** → **7c**, 61% islated yield

H^a: 6.78 (s, 1H)

H^b: 2.21 (s, 2H)

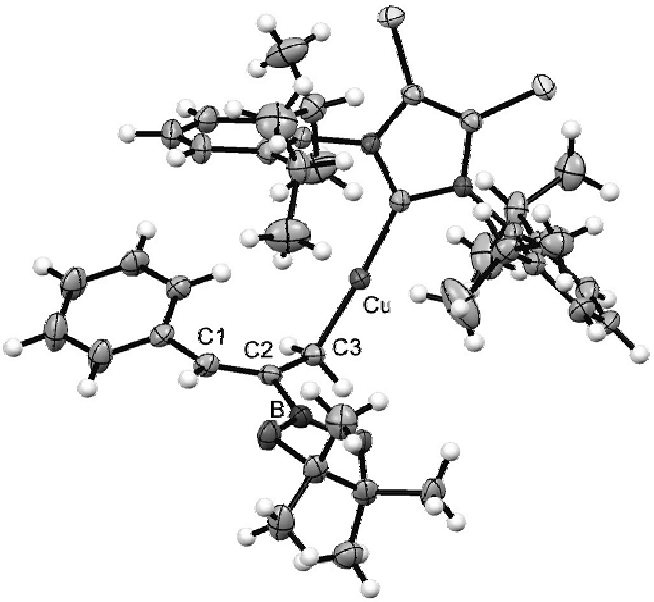
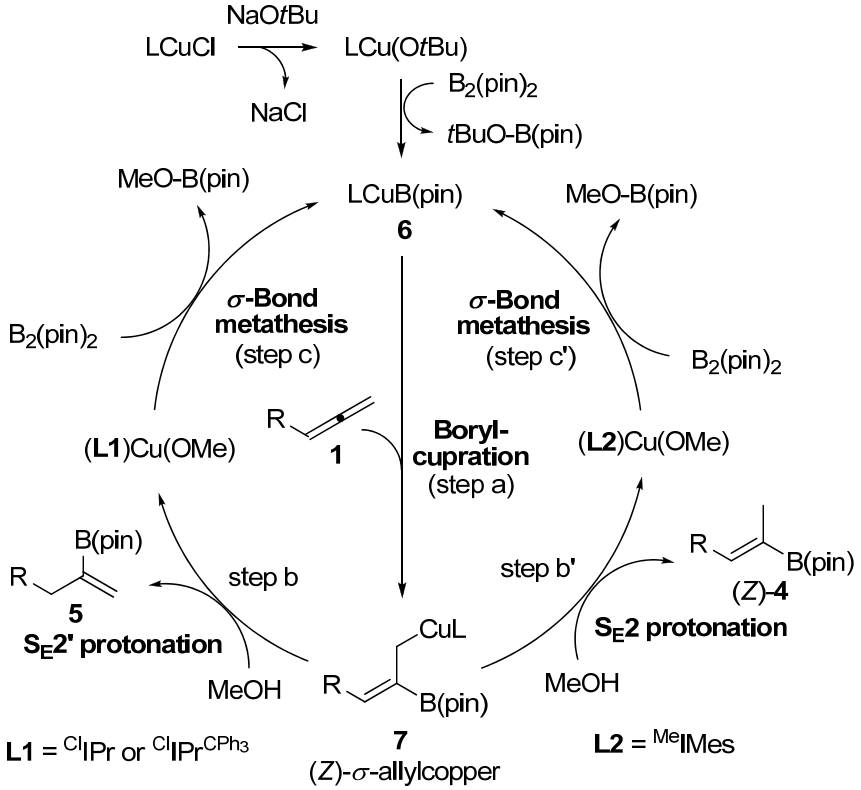


Figure 4-4. Crystal Structure of **7c**

When **7a** was protonated with MeOH at –20 ºC, a ratio of (*Z*)-**4a/5a** was 47/53 (Scheme 4-6a) and not very selective as compared with the catalytic reaction with [(^{Me}IMes)CuCl] as a catalyst (entry 5 in Table 4-3). The ^{1}H NMR spectra of **7a** measured at 20 ºC, –10 ºC, –30 ºC and –50 ºC almost did not change (see experimental section for detail). However, the protonation at –80 ºC provided the ratio of (*Z*)-**4a/5a** = 99/1 (Scheme 4-6a), which is comparable with the catalytic reaction. On the other hand, similar protonation of **7b** with MeOH provided **5a** selectively ((*Z*)-**4a/5a** = 6/94) in S_E2' fashion at both room temperature and –20 ºC (Scheme 4-6b). This selectivity is very reminiscent of the product selectivity in the hydroboration catalyzed by [(^{Cl}IPr)CuCl] (entry 9 in Table 4-3).

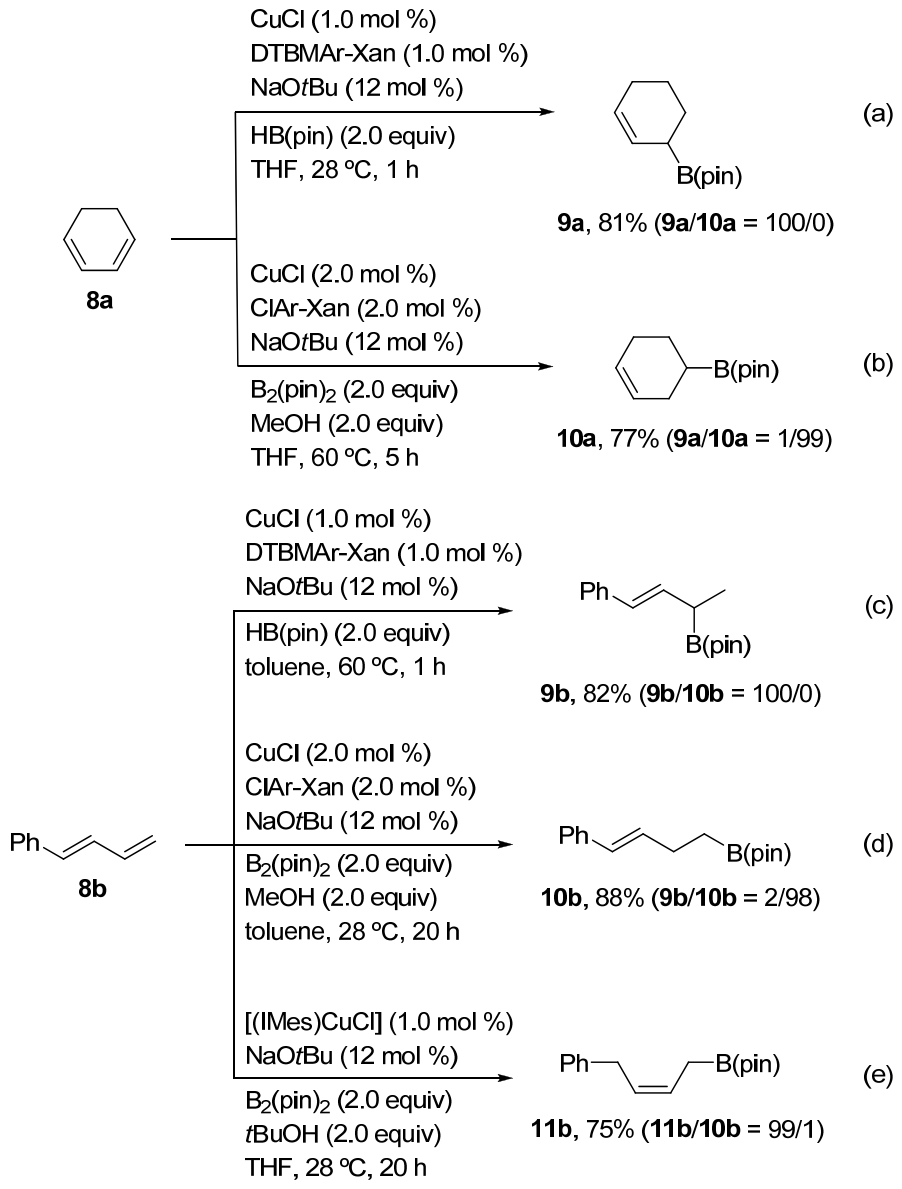
From these results in the stoichiometric reactions, a possible catalytic cycle for the hydroboration using $B_2(pin)_2$ was shown in Scheme 4-7. First, a borylcopper species is generated by the reaction between a copper alkoxide and $B_2(pin)_2$. The borylcopper (**6**) inserts into an allene (**1**) from the sterically less encumbered face of the allene affording (*Z*)-σ-allylcopper intermediate, exclusively (Scheme 4-7). In the case of bulky NHC ligands such as ^{Cl}IPr and ^{Cl}IPr^{CPh_3}, an (*Z*)-σ-allyl copper is protonated in S_E2' fashion preferentially to afford **5** (step b in Scheme 4-7). On the other hand, in the case of less bulky ^{Me}IMes as the ligand, an (*Z*)-σ-allylcopper is protonated in S_E2 fashion preferentially, giving (*Z*)-**4** (step b' in Scheme 4-7). As clearly indicated in Scheme 4-6, the author first shows that protonation of the σ-allylcopper species could be controlled by choice of ligands.[15]

Scheme 4-7. A plausible reaction mechanisms employing $B_2(pin)_2$



Hydroboration of 1,3-diene derivatives. Besides allenes, the methodology can be applicable to selective hydroboration of 1,3-diene derivatives (Scheme 4-8).[16] Hydroboration of 1,3-dienes is a useful reaction for synthesizing allylboranes and homoallylboranes, which are important intermediates in organic synthesis. However, to date, catalytic systems which provide both allylboranes and homoallylboranes from a single substrate are rare.[16b] Employing 1,3-cyclohexadiene (**8a**) as a substrate and HB(pin) as a hydroboration reagent, an allylborane (**9a**) was selectively obtained with DTBMAr-Xan (Figure 4-1) as a ligand (Scheme 4-8a). On switching the boron source from HB(pin) to $B_2(pin)_2$, a homoallylborane (**10a**) was selectively obtained with ClAr-Xan as a ligand in THF at 60 ºC (Scheme 4-8b). Notably, when 1-phenyl-1,3-butadiene (**8b**) was used as the substrate, an allylborane (**9b**) and a homoallyl borane (**10b**) were obtained selectively by employing HB(pin) and $B_2(pin)_2$ as the boron sources, respectively (Scheme 4-8c and 8d). Moreover, employing $B_2(pin)_2$ as the boron source and [(IMes)CuCl] as a catalyst, a 1,4-hydroborated allylborane (**11b**) was obtained quite selectively (Scheme 4-8e).

Scheme 4-8. Copper-catalyzed hydroboration of 1,3-dienes



4-3. Conclusion

In conclusion, the author has developed copper-catalyzed highly selective hydroboration of allenes, giving an allylborane and two vinylboranes. The present catalytic system was also useful for selective hydroboration of 1,3-dienes, giving allylboranes and homoallylboranes. The key to the success of the present reaction is the controlling both catalytic species (LCu-H and LCu-B) and the reactivity of allylcopper species. These perceptions will be valuable for allylcopper chemistry and the present

reaction system is expected to have wide applicability to other regioselective catalytic reactions.

4-4. Experimental Section

General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[17] ^{1}H NMR and ^{13}C{^{1}H} NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). ^{31}P{^{1}H} NMR spectra were also recorded at a JEOL ECX-400 spectrometer using 85% H_3PO_4 as an external standard. EI-MS were recorded on a Shimadzu GCMS-QP5050A with a direct inlet. High-resolution mass spectra (EI-HRMS and ESI-HRMS) were obtained with JEOL JMX-SX102A and Thermo SCIENTIFIC Exactive LC-MS spectrometers. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-2014 with a capillary column (GL Sciences InertCap 5, 0.25 mm × 30 m).

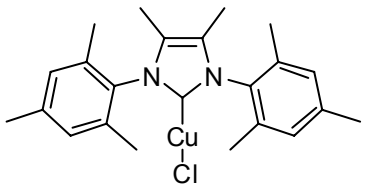
Materials: Unless otherwise noted, commercially available chemicals were used as received. Anhydrous toluene and THF were purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[18] 1,4-Dioxane was distilled from benzophenone ketyl. CuCl was purified according to a literature.[17] MeOH was distilled over CaH_2. Pinacolborane (HB(pin)) was distilled before use. CF_3Ar-Xan,[5] MeAr-Xan,[5] [(IPr)CuCl],[19] [(^{Cl}IPr)CuCl],[19] and [(IMes)CuCl][19] were prepared according to the literature.

Synthesis of [(^{Me}IMes)CuCl].

In a N_2 filled glove box, CuCl (432 mg, 4.36 mmol), NaO*t*Bu (400 mg, 4.16 mmol) and THF (30 ml) were added to a round bottom flask and the resulting mixture was stirred

for 2 h at room temperature. Then, ^{Me}IMes·HCl[20] (1.46 g, 3.96 mmol) was added to the flask and the mixture was stirred overnight at room temperature. The flask was removed from the glove box. The mixture was filtrated through a pad of Celite under air and the solvent was removed in vacuo. CH_2Cl_2 (20 mL) was added to the crude product and the resulting suspension was filtrated through a pad of Celite. The solvent was removed in vacuo. [(^{Me}IMes)CuCl] was obtained after recrystallization (CH_2Cl_2/hexane). Yield 43% (740 mg).

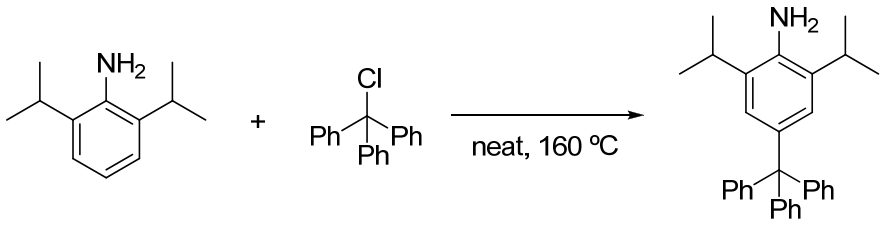
A single crystal of [(^{Me}IMes)CuCl] was obtained by slow diffusion of CH_2Cl_2 solution into pentane. The structure of [(^{Me}IMes)CuCl] was also confirmed by X-ray crystallography.



[(^{Me}IMes)CuCl]

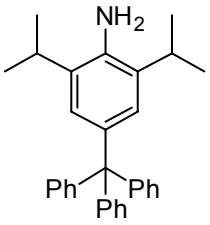
^{1}H NMR (400 MHz, $CDCl_3$): δ 6.99 (s, 4H), 2.34 (s, 6H), 2.03 (s, 12H), 1.88 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 175.2, 139.1, 134.9, 133.6, 129.4, 125.4, 21.1, 17.7, 9.0. ESI-HRMS: Calcd. for $C_{23}H_{28}ClCuN_2$ ([M+Na]$^+$), 453.1129. Found, 453.1112. Anal. Calcd. for $C_{23}H_{28}ClCuN_2$: C, 64.02; H, 6.54; N, 6.49. Found: C, 63.91; H, 6.48; N, 6.43.

Synthesis of [(^{Cl}IPr^{CPh_3})CuCl].



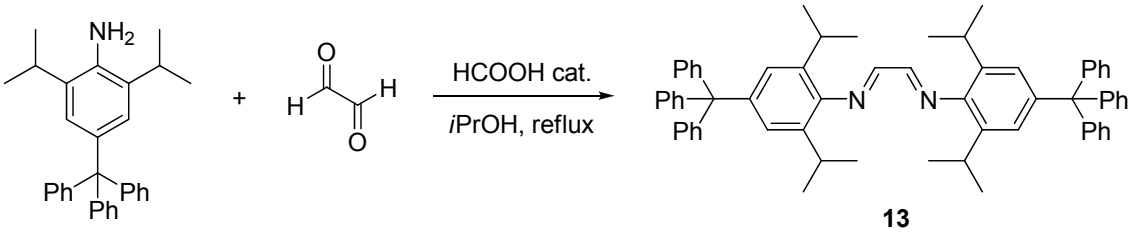
12

2,6-Diisopropylaniline (7.9 mL, 42 mmol) and trityl chloride (11 g, 40 mmol) were added to a round bottom flask and the mixture was stirred for 1 h at 160 ºC under Ar atmosphere. The mixture was cooled to room temperature. Then, $CHCl_3$ and H_2O were added to the mixture and the resulting solution was extracted with $CHCl_3$ and the organic layer was washed with $NaHCO_3$ aq. and dried over $MgSO_4$. After filtration, the solvent was removed and the desired product (**12**) was obtained in 84% yield (14 g, 33 mmol) after recrystallization from hot EtOH.



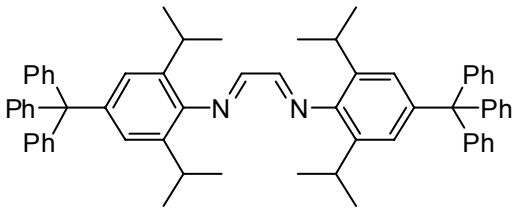
12

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22–7.13 (m, 15H), 6.83 (s, 2H), 2.86 (sept, J = 6.8 Hz, 2H), 1.09 (d, J = 6.8 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 147.5, 137.7, 136.4, 131.2, 127.1, 126.0, 125.5, 64.8, 28.0, 22.4. All the resonances in ^{1}H and ^{13}C spectra were consistent with reported values.[9]



13

Under argon atmosphere, **12** (8.4 g, 20 mmol), glyoxal (40% in water) (1.1 mL, 10 mmol), *i*PrOH (160 mL) and HCOOH (10 drops) were added to a round bottom flask and the mixture was stirred overnight under reflux. Then, the reaction mixture was filtered off without cooling. The product was washed with EtOH and dried in vacuo. Yellow solid (**13**) was obtained in 70% yield (6.0 g, 7.0 mmol).



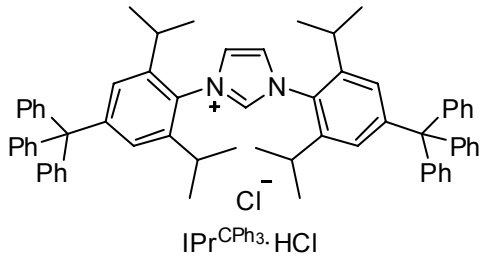
13

^{1}H NMR (400 MHz, $CDCl_3$): δ 8.10 (s, 2H), 7.25–7.16 (m, 30H), 6.99 (s, 4H), 2.88 (sept, J = 6.8 Hz, 4H), 1.02 (d, J = 6.8 Hz, 24H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 163.2, 147.1, 145.5, 143.2, 135.6, 131.1, 127.3, 126.4, 125.8, 65.0, 28.0, 23.4. All the resonances in ^{1}H spectrum were consistent with reported values. [9]

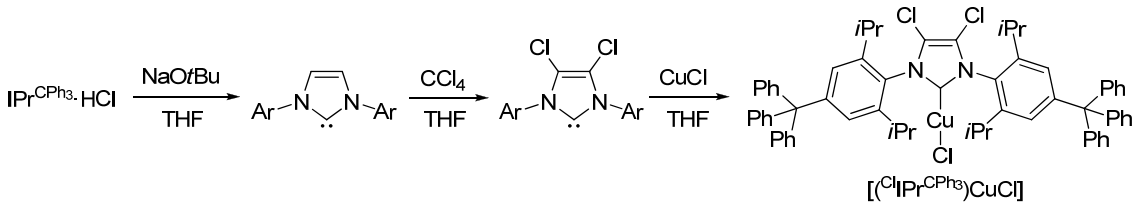
13 IPr^{CPh_3}·HCl

Under argon atmosphere, **13** (6.0 g, 7.0 mmol), paraformaldehyde (210 mg, 7.0 mmol) and EtOAc (140 mL) were added to a round bottom flask. The mixture was stirred at 70 ºC and TMSCl (970 μL, 7.7 mmol) was added dropwise at 70 ºC. Then, the resulting

mixture was stirred overnight at 70 ºC. After stirring, hot filtration was carried out and the product was washed with EtOAc and Et_2O and dried in vacuo. Pale yellow solid was obtained in 66% yield (4.2 g, 4.6 mmol).

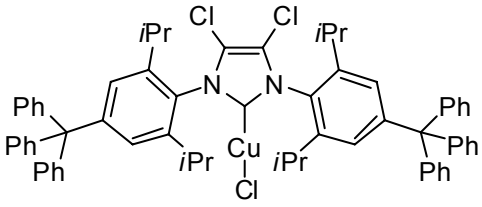


^{1}H NMR (400 MHz, $CDCl_3$): δ 9.03 (s, 1H), 8.29 (s, 2H), 7.31–7.19 (m, 34H), 2.37 (sept, J = 6.8 Hz, 4H), 1.09 (d, J = 6.8 Hz, 12H), 1.02 (d, J = 6.8 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.2, 145.8, 143.6, 136.6, 130.8, 127.7, 127.63, 127.56, 127.2, 126.2, 65.3, 29.0, 24.4, 23.5. All the resonances in ^{1}H and ^{13}C spectra were consistent with reported values. [9]



In a N_2 filled glove box, IPr^{CPh_3}·HCl (2.1 g, 2.3 mmol) and NaO*t*Bu (240 mg, 2.5 mmol) were stirred overnight in THF (10 mL) at room temperature. The resulting mixture was filtrated through a pad of Celite. To the filtrate, CCl_4 (450 μL, 4.6 mmol) was added and the resulting solution was stirred for 2 h at room temperature. To the solution, CuCl (200 mg, 2.0 mmol) was added and the mixture was stirred overnight at room temperature. After the reaction, under air, the mixture was filtrated through a pad of Celite and all volatiles were removed in vacuo. The crude product was purified by silica gel column chromatography (eluent: CH_2Cl_2). Furthermore, the product was purified by recrystallization (CH_2Cl_2/Hexane). White solid ([($^{Cl}IPr^{CPh_3}$)CuCl]) was obtained in 26% yield (629 mg, 0.60 mmol).

A single crystal of [($^{Cl}IPr^{CPh_3}$)CuCl] was obtained by slow diffusion of $CHCl_3$ solution into pentane. The structure of [($^{Cl}IPr^{CPh_3}$)CuCl] was also confirmed by X-ray crystallography.



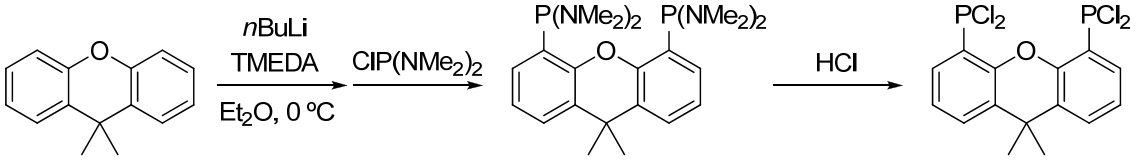
[(^{Cl}IPr^{CPh3})CuCl]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.19 (m, 30H), 7.15 (s, 4H), 2.38 (sept, J = 7.0 Hz, 4H), 1.12 (d, J = 6.8 Hz, 12H), 1.04 (d, J = 6.8 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 180.1, 150.1, 146.1, 144.6, 131.1, 129.1, 127.60, 127.56, 126.2, 118.7, 65.3, 29.0, 24.6, 23.1. MALDI-HRMS: Calcd. for $C_{65}H_{62}Cl_3CuN_2$ ([M-Cl]$^+$), 1003.3586. Found, 1003.3583. Anal. Calcd. for $C_{65}H_{62}Cl_3CuN_2$: C, 74.99; H, 6.00; N, 2.69. Found: C, 74.93; H, 6.00; N, 2.70.

Preparation of DTBMAr-Xan and ClAr-Xan.

Preparation of ClP(NMe$_2$)$_2$: ClP(NMe$_2$)$_2$ was synthesized according to the literature[21] and ClP(NMe$_2$)$_2$ was used without purification.

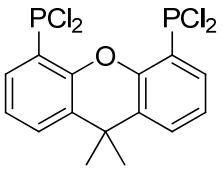
Preparation of Cl-Xan.



Cl-Xan

A flask was charged with 9.9-dimethylxanthene (10 g, 48 mmol), TMEDA (18 mL, 120 mmol) and Et_2O (72 mL). To the solution, *n*BuLi (72 mL of 1.65 M solution in hexane, 120 mmol) was added dropwise at 0 ºC and the resulting solution was stirred overnight at 0 ºC. To the solution, Et_2O (20 mL) solution of ClP(NMe$_2$)$_2$ (140 mmol) was added dropwise at –78 ºC, and the mixture was slowly warmed up to room temperature and stirred overnight. The reaction mixture was concentrated to a quarter in vacuo and dry hexane (150 mL) was added to the mixture. After filtration through a pad of Celite, dry HCl was passed through the solution at room temperature for 3 h and then the solvent was removed in vacuo. To the mixture, dry hexane (100 mL) was added and then 4N HCl (50 mL of 4.0 M solution in dioxane, 200 mmol) was added at 0 ºC. The resulting mixture was stirred at room temperature for 3 h. The mixture was filtrated with a pad of Celite and the solvent was removed in vacuo. The crude product was purified by

recrystallization from dry hexane at –30 ºC. The desired product Cl-Xan (7.7 g, 19 mmol) was obtained in 39% yield as a white solid.

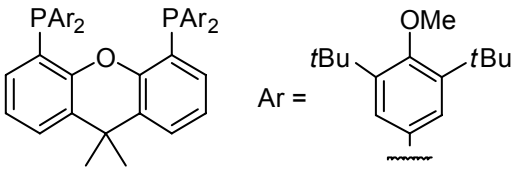


Cl-Xan

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.91 (d, J = 7.7 Hz, 2H), 7.60 (d, J = 7.7 Hz, 2H), 7.30 (d, J = 7.7 Hz, 2H), 1.66 (s, 6H). ^{31}P NMR (100 MHz, $CDCl_3$): δ 158.3.

Preparation of DTBMAr-Xan.

A flask was charged with 3,5-di-*tert*-butyl-4-methoxy bromobenzene (2.7 g, 9.0 mmol) and THF (20 mL). To the solution, *n*BuLi (5.4 mL of 1.65 M solution in THF, 9.0 mmol) was added dropwise at –78 ºC and the resulting solution was stirred at –78 ºC for 1 h. To the mixture, THF (6.0 mL) solution of Cl-Xan (810 mg, 2.0 mmol) was added dropwise and the mixture was stirred for 1.5 h at –78 ºC. The solution was slowly warmed up to room temperature and stirred overnight at room temperature. All volatiles were removed in vacuo. Under Ar atmosphere, the solid was dissolved in degassed CH_2Cl_2 (16 mL) and the solution was washed with degassed H_2O. The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed in vacuo. The desired product was purified by recrystallization from hot degassed EtOH. DTBMAr-Xan was obtained in 40% yield (910 mg, 0.79 mmol) as a white solid.

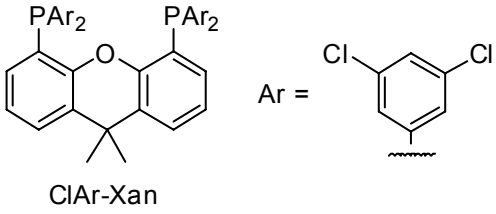


DTBMAr-Xan

^{1}H NMR (400MHz, $CDCl_3$): δ 7.32 (br d, J = 7.2 Hz, 2H), 7.11–7.09 (m, 8H), 6.92 (t, J = 7.7 Hz, 2H), 6.47 (d, $J_{P,C}$ = 7.2 Hz, 2H), 3.66 (s, 12H), 1.59 (s, 6H) , 1.29 (s, 72H). ^{31}P NMR (160MHz, $CDCl_3$): –16.2. All resonances in ^{1}H and ^{31}P NMR spectra were consistent with reported values.[22]

Preparation of ClAr-Xan.

A flask was charged with Cl-Xan (620 mg, 1.5 mmol) and THF (5.0 mL). To the solution, 3,5-dichlorophenyl magnesium bromide (13 mL of 0.75 M solution in THF, 9.8 mmol) was added dropwise at –78 ºC and the resulting solution was stirred at –78 ºC for 1 h. The solution was slowly warmed up to room temperature and stirred overnight. The solvent was removed in vacuo and CH_2Cl_2 was added. Under air, the solution was washed with H_2O and then dried over $MgSO_4$. After filtration, the solvent was removed in vacuo and the solid was washed with EtOH. The desired product was further purified by recrystallization (CH_2Cl_2/EtOH). ClAr-Xan was obtained in 31% yield (570 mg, 0.67 mmol) as a white solid.

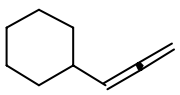


ClAr-Xan

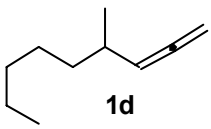
^{1}H NMR (400MHz, $CDCl_3$): δ 7.52 (d, $J_{P,C}$ = 7.7 Hz, 2H), 7.31 (t, J = 1.8 Hz, 4H), 7.09 (t, $J_{P,C}$ = 7.7 Hz, 2H), 7.00–6.98 (m, 8H), 6.50–6.47 (m, 2H), 1.69 (s, 6H). ^{31}P NMR (160MHz, $CDCl_3$): –13.1. ^{13}C NMR (100MHz, $CDCl_3$): δ 152.42, 139.94 (t, $J_{P,C}$ = 10.0 Hz), 135.37 (t, $J_{P,C}$ = 3.8 Hz), 133.58, 131.60, 131.42 (t, $J_{P,C}$ = 11.0 Hz), 130.77, 129.32, 127.52, 124.56, 34.71, 31.10. ESI-HRMS: Calcd. for $C_{39}H_{25}Cl_8O_1P_2$ ($[M+H]^+$), 850.8883. Found, 850.8868.

Syntheses of Substrates.

1a was prepared according to the literature.[23] **1d** was prepared with similar procedures of **1a**.


1a

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.09 (dt, J = 6.5 Hz, 6.5 Hz, 1H), 4.68 (dd, J = 6.8 Hz, 3.2 Hz, 2H), 2.02–1.93 (m, 1H), 1.77–1.69 (m, 4H), 1.64–1.61 (m, 1H), 1.33–1.05 (m, 5H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 207.4, 96.1, 75.4, 36.6, 33.0, 26.1, 26.0.

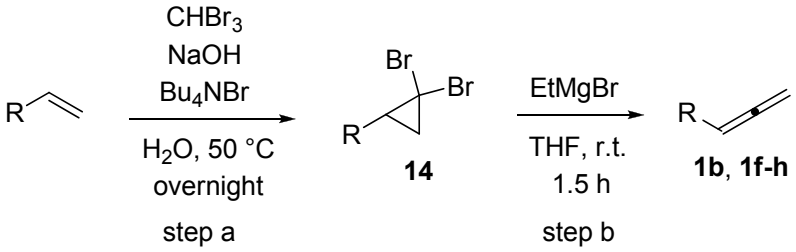

1d

1d: 39% yield. ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.05 (dt, J = 6.8 Hz, 6.8 Hz, 1H), 4.67 (dd, J = 6.3 Hz, 2.7 Hz, 2H), 2.17–2.09 (m, 1H), 1.33–1.27 (m, 8H), 1.00 (d, J = 6.8 Hz, 3H), 0.88 (t, J = 6.8 Hz, 3H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 207.5, 96.1, 75.2, 37.1, 32.9, 31.9, 26.9, 22.7, 20.4, 14.1. EI-HRMS: Calcd. for $C_{10}H_{18}$ ($[M]^+$), 138.1409. Found, 138.1409.

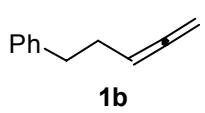
Allenes **1b**, **1f**, **1g** and **1h** were prepared according to General Procedure A according to literatue.[24]

General Procedure A.



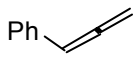
Step a: A mixture of an alkene (50 mmol), bromoform (8.7 mL, 100 mmol), and tetrabuthylammonium bromide (1.61g, 5.0 mmol) were stirred in a flask. A solution of sodium hydroxide (5.0 g, 130 mmol) in water (7.5 mL) was added in small potion and stired overnight at 50 °C. The reaction was quenched by adding NH_4Cl aq. and product was extracted with dichloromethane (3 ×50 mL). The combined organic fractions were washed with brine (50 mL), dried over $MgSO_4$ and evaporated in vacuo. Purified by distillation, the *gem*-dibromocyclopropane (**14**) was obtained.

Step b: To a stirred solution of **14** (42 mmol) in THF (80 mL), EtMgBr (56 mL, 55 mmol, 0.98 M solution of THF) was added and stirred at room temperature for 1.5 h. The reaction was quenched by adding NH_4Cl aq. and product was extracted with Et_2O, dried over $MgSO_4$, and evaporated in vacuo. The allene was purified by silica gel column chromatography.



1b

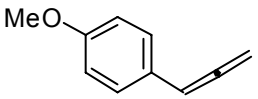
19% yield (2 step): ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33–7.29 (m, 2H), 7.24–7.19 (m, 3H), 5.21–5.15 (m, 1H), 4.73–4.69 (m, 2H), 2.73 (t, J = 7.7 Hz, 2H), 2.39–2.31 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 208.6, 141.7, 128.5, 128.3, 125.9, 89.4, 75.1, 35.4, 30.0. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[25]



1f

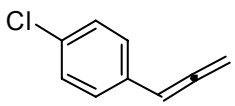
36% yield (2 step): ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.30 (m, 4H), 7.22–7.17 (m, 1H), 6.16 (t, J = 6.8 Hz, 1H), 2.39–2.31 (m, 2H). ^{13}C NMR

(100 MHz, $CDCl_3$): δ 209.8, 133.9, 128.6, 126.9, 126.7, 93.9, 78.8. All the resonances in ^1H NMR spectrum were consistent with reported values. [25]



1g

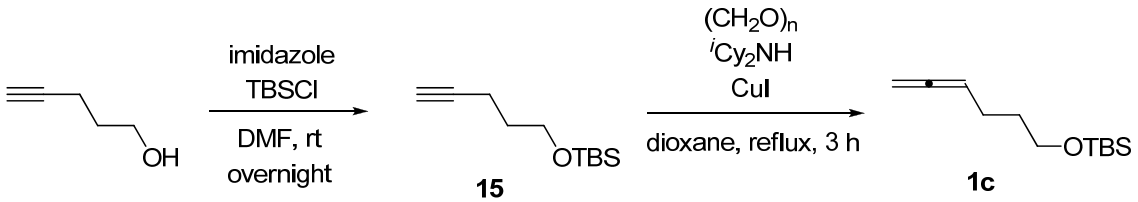
41% yield (2 step): ^1H NMR (400 MHz, $CDCl_3$): δ 7.22 (dt, J = 9.4, 2.5 Hz, 2H), 6.85 (dt, J = 9.4, 2.5 Hz, 2H), 6.12 (t, J = 6.8 Hz, 1H), 5.11 (d, J = 6.8 Hz, 2H), 3.79 (s, 3H). ^{13}C {^1H} NMR (100 MHz, $CDCl_3$): δ 209.4, 158.7, 127.7, 126.1, 114.1, 93.3, 78.7, 55.3. All the resonances in ^1H NMR spectrum were consistent with reported values. [25]



1h

45% yield (2 step): ^1H NMR (400 MHz, $CDCl_3$): δ 7.26 (d, J = 8.6 Hz, 2H), 7.20 (d, J = 8.2 Hz, 2H), 6.11 (t, J = 6.8 Hz, 1H), 5.15 (d, J = 6.8 Hz, 2H). ^{13}C {^1H} NMR (100 MHz, $CDCl_3$): δ 209.8, 132.5, 132.4, 128.7, 127.8, 93.1, 79.2. All the resonances in ^1H NMR spectrum were consistent with reported values.[26]

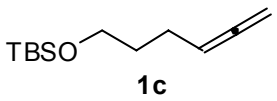
Preparation of 1c.



15 **1c**

A flask was charged with 4-pentyne-1-ol (930 μL, 10 mmol), imidazole (1.7 g, 25 mmol) and DMF (17 mL). The resulting solution was cooled to 0 ºC, and a solution of *tert*-butyldimethylsilyl chloride (1.6 g, 11 mmol) in DMF (13 mL) was slowly added. The resulting mixture was stirred overnight at room temperature. The mixture was poured into H_2O and extracted with Et_2O (100 mL × 3). The organic layer was dried over $MgSO_4$. After filtration, the solvent was removed in vacuo and **15** was obtained by silica gel column chromatography (eluent: Hexane/EtOAc = 40/1) in 79% yield (1.6 g, 7.9 mmol). ^1H NMR (400 MHz, $CDCl_3$): δ 3.70 (t, J = 6.1 Hz, 2H), 2.28 (td, J = 7.3, 2.8 Hz, 2H), 1.93 (t, J = 2.6 Hz, 1H), 1.79–1.69 (m, 2H), 0.90 (s, 9H), 0.057 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 84.3, 68.2, 61.4, 31.5, 25.9, 18.3, 14.8, –5.4. All the resonances in ^1H and ^{13}C NMR spectra were consistent with reported values.[27]

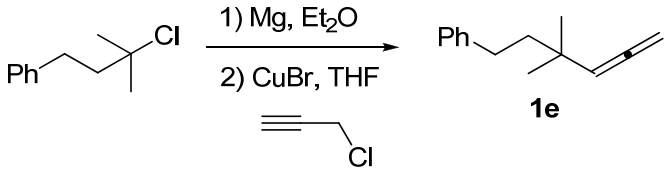
$(CH_2O)_n$ (1.8 g, 60 mmol), CuI (2.3g, 12 mmol) in dioxane (120 mL), alkyne **15** (4.8 g, 24 mmol) , and dicyclohexylamine (8.6 mL, 43 mmol) were added sequentially into an oven-dried reaction tube equipped with a reflux condenser under an argon atmosphere. The resulting mixture was stirred under reflux for 3 h. Water and Et_2O were added and then the mixture was filtrated by Celite. Then the organic layer was extracted with Et_2O, washed with 1N HCl aq. and H_2O and dried over $MgSO_4$. After filtration, the solvent was removed and **1c** was afforded by silica gel column chromatography (eluent: Hexane/EtOAc = 80/1) in 21 % yield (1.06 g, 5.0 mmol).



1c

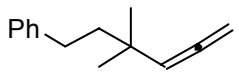
^{1}H NMR (400 MHz, $CDCl_3$): δ 5.15–5.08 (m, 1H), 4.68–4.65 (m, 2H), 3.64 (t, J = 6.3 Hz, 2H), 2.10–2.03 (m, 2H), 1.67-1.60 (m, 2H), 0.89 (s, 9H), 0.05 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 208.5, 89.7, 74.9, 62.4, 32.1, 26.0, 24.5, 18.4, –5.3. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[28]

Preparation of 1e.



1e

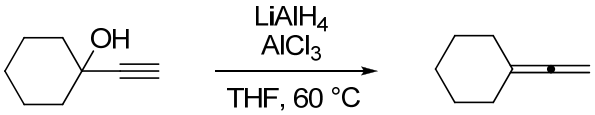
Mg turnings (1.46 g, 60 mmol) were activated by evacuation and heating with stirring in a flask. The flask was backfilled with argon. A small drop of 3-chloro-3-methyl-1-phenylbutane[29] (9.2 g, 51 mmol) in Et_2O (13 mL) was added. Then the remaining mixture of 3-chloro-3-methyl-1-phenylbutane in Et_2O was slowly added. Then the mixture was stirred under reflux for 1 h to afford Grignard-reagent solution. A solution of propargyl chloride (1.5 mL, 21 mL) and CuBr (83 mg, 5.7 mmol) in THF (10 mL) was cooled to –40 °C. Then the prepared Grignard-reagent solution was added dropwise, and resulting mixture was slowly warmed up to room temperature and stirred overnight at room temperature. The reaction mixture was poured into NH_4Cl aq. The product was extracted with Et_2O, dried over $MgSO_4$, and evaporated in vacuo. After distillation, **1e** was obtained in 62 % yield (2.4 g, 13 mmol).



1e

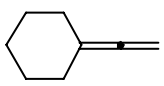
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28–7.23 (m, 2H), 7.18–7.14 (m, 3H), 5.10 (t, J = 6.8 Hz, 1H), 4.76 (d, J = 6.3 Hz, 2H), 2.61–2.57 (m, 2H), 1.64–1.60 (m, 2H), 1.08 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 206.8, 143.2, 128.31, 128.29, 125.6, 100.3, 76.4, 45.4, 34.3, 31.4, 27.9. EI-HRMS: Calcd. for $C_{14}H_{18}$ ($[M]^+$), 186.1409. Found, 186.1400.

Preparation of 1i.



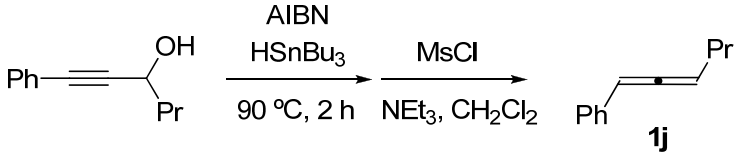
1i

A flask was charged with $AlCl_3$ (8.9 mg, 67 mmol) and $LiAlH_4$ (7.6 g, 200 mmol) under an argon atmosphere. The mixture was cooled to 0 °C, and THF (200 mL) was added. The solution was stirred at 0 °C for 15 minute, and the solution of 1-ethynyl-cyclohexan-1-ol (12.8 mL, 100 mmol) in THF (100 mL) was added dropwise. The resulting mixture was stirred at 60 °C for 1.5 h. After reaction, the mixture was cooled to 0 °C and water and 1N HCl aq. was added in this order. After filtration through a pad of Celite, the product was extracted with Et_2O, dried over $MgSO_4$, and evaporated in vacuo. After purification by silica gel column chromatography (eluent: pentane) and distillation, **1i** was obtained in 3% yield (324 mg, 3.0 mmol).



1i

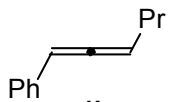
^{1}H NMR (400 MHz, $CDCl_3$): δ 4.53 (quin, J = 2.5 Hz, 2H), 2.14–2.10 (m, 4H), 1.61–1.55 (m, 4H), 1.53–1.48 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 203.4, 101.2, 72.5, 31.1, 27.1, 26.1. All the resonances in ^{1}H NMR spectrum were consistent with reported values.[25]



1j

A flask was charged with 1-phenyl-1-hexyn-3-ol[30] (2.74 g, 15.7 mmol), AIBN (129 mg, 0.785 mmol) and $HSnBu_3$ (6.24 mL, 23.6 mmol) and the mixture was stirred at 90 ºC for 2 h. The resulting mixture was cooled to room temperature and then CH_2Cl_2 (12

mL) was added. To the mixture, NEt_3 (4.37 mL, 31.4 mmol) was added at 0 ºC and then CH_2Cl_2 (10 mL) solution of MsCl (1.83 mL, 23.6 mmol) was added dropwise at 0 ºC. The resulting mixture was stirred at room temperature for 30 min. The reaction mixture was quenched by 1N HCl aq. The organic layer was extracted with CH_2Cl_2, washed with $NaHCO_3$ aq. and dried over $MgSO_4$. After filtration, all volatiles were removed in vacuo and the product was purified by silica gel column chromatography. Yellow oil was obtained in 50% yield (1.25 g, 7.90 mmol).

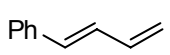


1j

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29–7.28 (m, 4H), 7.19–7.16 (m, 1H), 6.12 (dt, J = 6.3 Hz, 3.2 Hz, 1H), 5.56 (dt, J = 6.6 Hz, 6.6 Hz, 1H), 2.11 (dq, J = 3.2 Hz, 7.2 Hz, 2H), 1.56–1.47 (m, 2H), 0.97 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 205.2, 135.1, 128.5, 126.58, 126.55, 94.9, 94.5, 30.8, 22.4, 13.7. All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[31]

Preparation of 8b.

1-Phenyl-1,3-butadiene (**8b)** was synthesized according to the literature.[32]

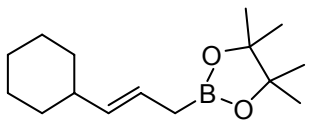


8b

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36–7.24 (m, 5H), 6.78 (dd, J = 15.4 Hz, 10.4 Hz, 1H), 6.54–6.48 (m, 2H), 5.32 (d, J = 16.3 Hz, 1H), 5.16 (d, J = 10.4 Hz, 1H). All the resonances in ^{1}H spectrum were consistent with reported values.[33]

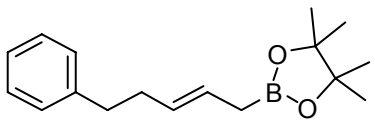
General Procedure for Table 4-1. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), a ligand (0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask (In the cases of entries 7 and 8, [(NHC)CuCl] (0.010 mmol, 2.0 mol %) was used instead of a mixture of CuCl and ligands). The flask was evacuated and backfilled with argon three times. 1,4-Dioxane (4.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, pinacolborane (HB(pin), 87 μL, 0.60 mmol) was added at 0 ºC and the mixture was stirred at 0 ºC for 5 min. To the mixture, **1a** (88 μL, 0.50 mmol) was added at 0 ºC and the mixture was stirred at 28 ºC for 2 h. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard

(tridecane). In entry 6, the mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. **2a** was isolated with silica gel column chromatography (eluent: hexane/Et_2O = 80/1).

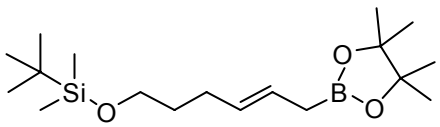

(*E*)-**2a**

(*E*)-**2a**: Yield 78% (97.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.41 (dt, J = 15.3 Hz, 6.5 Hz, 1H), 5.34 (dd, J = 15.6 Hz, 6.1 Hz, 1H), 1.93–1.85 (m, 1H), 1.69–1.61 (m, 7H), 1.28–0.99 (m, 17H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.1, 122.1, 83.1, 40.8, 33.3, 26.2, 26.1, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{15}H_{27}BO_2$ ($[M]^+$), 250.2104. Found, 250.2108.

General Procedure for Table 4-2. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), CF_3Ar-Xan (11.2 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. 1,4-Dioxane (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, HB(pin) (87 μL, 0.60 mmol) was added at 0 ºC and the mixture was stirred at 0 ºC for 5 min. To the mixture, an allene (0.50 mmol) was added at 0 ºC and the mixture was stirred at 28 ºC for 2 h. After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of silica gel and all of the volatiles were removed in vacuo. The products were obtained by silica gel column chromatography (eluent: hexane/Et_2O) or preparative GPC in the cases of (*E*)-**2g** and (*E*)-**2h** due to their unstability.

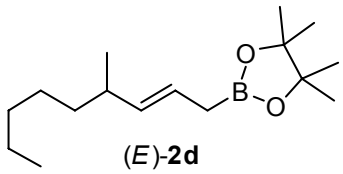

(*E*)-**2b**

(*E*)-**2b**: Yield 74% (100.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28–7.24 (m, 2H), 7.21–7.14 (m, 3H), 5.50 (dt, J = 15.1 Hz, 6.1 Hz, 1H), 5.44 (dt, J = 15.4 Hz, 5.6 Hz, 1H), 2.65 (t, J = 7.9 Hz, 2H), 2.30 (td, J = 7.6 Hz, 5.4 Hz, 2H), 1.64 (d, J = 6.3 Hz, 2H), 1.24 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.3, 130.0, 128.4, 128.2, 125.6, 125.5, 83.1, 36.2, 34.5, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values. [34]



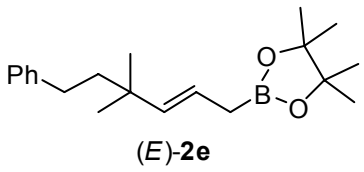
(*E*)-**2c**

(*E*)-**2c**: Yield 71% (121.4 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.46 (dt, J = 15.1 Hz, 6.9 Hz, 1H), 5.38 (dt, J = 15.4 Hz, 6.1 Hz, 1H), 3.59 (t, J = 6.3 Hz, 2H), 2.03 (dt, J = 7.2 Hz, 7.2 Hz, 2H), 1.64 (d, J = 7.2 Hz, 2H), 1.58–1.54 (m, 2H), 1.25 (s, 12H), 0.89 (s, 9H), 0.04 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 130.3, 125.0, 83.1, 62.7, 32.7, 28.9, 26.0, 24.7, 18.3, –5.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. FAB-HRMS: Calcd. for $C_{18}H_{37}BO_3Si$ ($[M+H]^+$), 341.2687. Found, 341.2678.



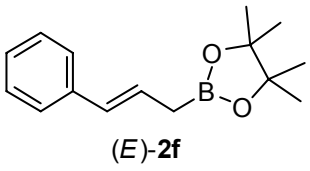
(*E*)-**2d**

(*E*)-**2d**: Yield 70% (93.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.39 (dt, J = 15.4 Hz, 7.2 Hz, 1H), 5.23 (dd, J = 15.6 Hz, 7.5 Hz, 1H), 2.09–1.99 (m, 1H), 1.62 (d, J = 7.2 Hz, 2H), 1.28–1.19 (m, 20H), 0.93 (d, J = 6.8 Hz, 3H), 0.87 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.0, 122.8, 83.1, 37.2, 36.8, 32.0, 27.0, 24.8, 24.7, 22.7, 21.0, 14.1. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{16}H_{31}BO_2$ ($[M]^+$), 266.2417. Found, 266.2416.



(*E*)-**2e**

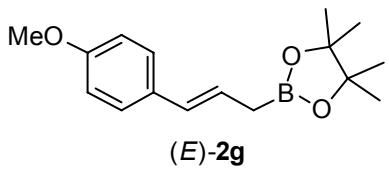
(*E*)-**2e**: Yield 77% (120.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27–7.23 (m, 2H), 7.17–7.13 (m, 3H), 5.46–5.37 (m, 2H), 2.53–2.49 (m, 2H), 1.67 (d, J = 5.4 Hz, 2H), 1.57–1.52 (m, 2H), 1.24 (s, 12H), 1.02 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.7, 140.0, 128.3, 128.2, 125.4, 121.3, 83.1, 45.4, 36.0, 31.3, 27.5, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{20}H_{31}BO_2$ ($[M]^+$), 314.2417. Found, 314.2411.



(*E*)-**2f**

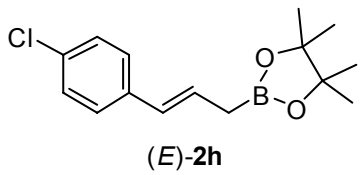
(*E*)-**2f**: Yield 60% (73.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33 (d, J = 7.2 Hz, 2H), 7.28–7.25 (m, 2H), 7.16 (t, J = 7.2 Hz, 1H), 6.37 (d, J = 15.9 Hz, 1H), 6.28 (dt, J = 15.4 Hz, 7.5 Hz, 1H), 1.87 (d, J = 6.8 Hz, 2H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.2, 130.2, 128.3, 126.5, 126.3, 125.8, 83.4, 24.8. The carbon

directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values. [35]



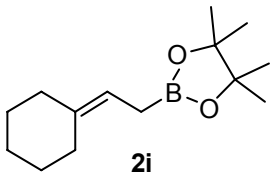
(*E*)-**2g**

(*E*)-**2g**: Yield 68% (93.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.26 (d, J = 8.6 Hz, 2H), 6.81 (d, J = 8.6 Hz, 2H), 6.13 (d, J = 15.4 Hz, 1H), 6.13 (dt, J = 15.9 Hz, 7.7 Hz, 1H), 3.79 (s, 3H), 1.84 (d, J = 7.2 Hz, 2H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.4, 131.1, 129.6, 126.9, 124.0, 113.8, 83.3, 55.3, 24.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{16}H_{23}BO_3$ ($[M]^+$), 274.1740. Found, 274.1737.



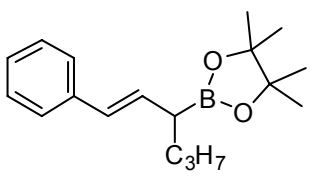
(*E*)-**2h**

(*E*)-**2h**: Yield 58% (81.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25 (d, J = 8.6 Hz, 2H), 7.22 (d, J = 9.1 Hz, 2H), 6.32 (d, J = 15.9 Hz, 1H), 6.25 (dt, J = 15.4 Hz, 6.6 Hz, 1H), 1.86 (d, J = 6.3 Hz, 2H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.7, 132.0, 129.1, 128.4, 127.1, 127.0, 83.4, 24.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{15}H_{20}BClO_2$ ($[M]^+$), 278.1245. Found, 278.1247.



2i

2i: Yield 66% (77.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.10 (t, J = 7.7 Hz, 1H), 2.04–1.99 (m, 4H), 1.53 (t, J = 7.7 Hz, 2H), 1.46–1.40 (m, 6H), 1.17 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.7, 114.9, 83.0, 37.0, 28.7, 28.5, 27.6, 27.0, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{14}H_{25}BO_2$ ($[M]^+$), 236.1948. Found, 236.1940.

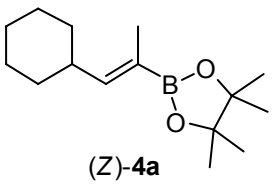


(*E*)-**2j**

(*E*)-**2j**: Yield 52% (73.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.33 (m, 2H), 7.29–7.25 (m, 2H), 7.16 (t, J = 7.2 Hz, 1H), 6.36 (d, J = 15.9 Hz, 1H), 6.20 (dd, J = 15.6 Hz, 8.8 Hz, 1H), 2.03–1.97 (m, 1H), 1.67–1.28 (m, 4H), 1.24 (s, 12H), 0.91 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.2, 132.0, 128.9, 128.4, 126.5, 125.8, 83.2, 33.0, 24.7, 22.2, 14.1. The carbon

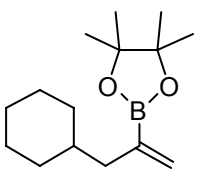
directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{18}H_{27}BO_2$ ([M]$^+$), 286.2104. Found, 286.2092.

General Procedure in Table 4-3. CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), a lignad (0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask (In the cases of entries 3-5 and 8-11, [(NHC)CuCl] (0.010 mmol, 2.0 mol %) was used instead of a mixture of CuCl and ligands). The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, bis(pinacolato)diboron ($B_2(pin)_2$, 133 mg, 0.53 mmol) was added and the mixture was stirred at room temperature for 5 min. To the mixture, MeOH (42 μL, 1.0 mmol) and **1a** (74 μL, 0.50 mmol) were added in this order and the mixture was stirred at 28 ºC for 2 h. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard (tridecane). In entry 5 and 11, the mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. (*Z*)**-4a** or **5a** was obtained by silica gel column chromatography (eluent: hexane/Et_2O = 60/1). The configuration of (*Z*)**-4a** was determined by NOESY spectrum.



(*Z*)-**4a**

(*Z*)**-4a**: Yield 90% (112.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.12 (dq, J = 9.1 Hz, 1.8 Hz, 1H), 2.40–2.31 (m, 1H), 1.73–1.59 (m, 5H), 1.69 (d, J = 1.8 Hz, 3H), 1.33–1.04 (m, 17H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.8, 83.0, 37.5, 32.2, 26.1, 25.9, 24.8, 13.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{27}BO_2$ ([M+H]$^+$), 251.2177. Found, 251.2170. Anal. Calcd. for $C_{15}H_{27}BO_2$: C, 72.01; H, 10.88. Found: C, 71.74; H, 11.08.

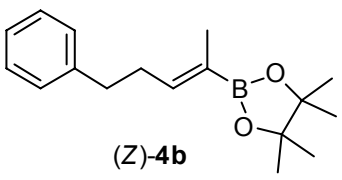


5a

5a: Yield 94% (117.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.78 (d, J = 3.6 Hz, 1H), 5.54 (d, J = 3.6 Hz, 1H), 2.04 (d, J = 6.8 Hz, 2H), 1.69–1.59 (m, 5H), 1.45–1.36 (m, 1H), 1.30–1.10 (m, 15H), 0.89–0.81 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$):

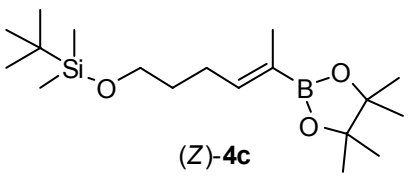
δ 129.9, 83.2, 43.3, 37.7, 33.2, 26.6, 26.4, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{15}H_{27}BO_2$ ($[M]^+$), 250.2104. Found, 250.2111. Anal. Calcd. for $C_{15}H_{27}BO_2$: C, 72.01; H, 10.88. Found: C, 71.99; H, 10.97.

General Procedure in Table 4-4. [(^{Me}IMes)CuCl] (4.31 mg, 0.010 mmol, 2.0 mol %), and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, $B_2(pin)_2$ (133 mg, 0.53 mmol) was added and the mixture was stirred at room temperature for 5 min. Then, MeOH (168 μL, 4.0 mmol) and an allene (0.50 mmol) were added in this order at –20 ºC and the mixture was stirred at –20 ºC for 2 h (In the cases of entries 4-6, $CF_3CH(OH)CF_3$ (208 μL, 2.0 mmol) was used instead of MeOH.). After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. The products were obtained by silica gel column chromatography (eluent: hexane/Et_2O) or preparative GPC in the cases of (*Z*)-**4f** and (*Z*)-**4h** due to their unstability. The configurations of (*Z*)-**4b**, (*Z*)-**4c**, (*Z*)-**4d** and (*Z*)-**4h** were determined by NOESY spectrum.



(*Z*)-**4b**

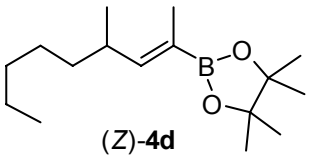
(*Z*)-**4b**: Yield 90% (123.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.29–7.25 (m, 2H), 7.20–7.16 (m, 3H), 6.39 (t, J = 6.8 Hz, 1H), 2.71 (t, J = 8.2 Hz, 2H), 2.47–2.41 (m, 2H), 1.66 (s, 3H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 145.2, 142.2, 128.3, 125.8, 83.1, 35.1, 30.7, 24.8, 13.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. An Ar-C cannot be identified because of overlapping. ESI-HRMS: Calcd. for $C_{17}H_{25}BO_2$ ($[M+H]^+$), 273.2020. Found, 273.2011. Anal. Calcd. for $C_{17}H_{25}BO_2$: C, 75.01; H, 9.26. Found: C, 74.97; H, 9.56.



(*Z*)-**4c**

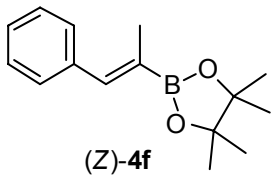
(*Z*)-**4c**: Yield 89% (151.4 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.32 (td, J = 7.0 Hz, 1.8 Hz, 1H), 3.61 (t, J

= 6.3 Hz, 2H), 2.18 (dt, J = 7.2 Hz, 7.0 Hz, 2H), 1.68 (br m, 3H), 1.66–1.59 (m, 2H), 1.26 (s, 12H), 0.89 (s, 2H), 0.04 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.0, 83.0, 62.8, 32.0, 25.9, 25.0, 24.8, 18.3, 13.8, –5.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{37}BO_3Si$ ($[M+H]^+$), 341.2678. Found, 341.2673. Anal. Calcd. for $C_{18}H_{37}BO_3Si$: C, 63.51; H, 10.96. Found: C, 63.61; H, 11.23.



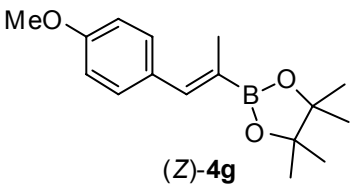
(*Z*)-**4d**

(*Z*)-**4d**: Yield 88% (117.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.07 (dq, J = 9.5 Hz, 1.7 Hz, 1H), 2.58–2.47 (m, 1H), 1.69 (d, J = 1.8 Hz, 3H), 1.31–1.22 (m, 21H), 0.94 (d, J = 6.8 Hz, 3H), 0.87 (t, J = 7.0 Hz, 3H), ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.6, 83.0, 36.9, 32.7, 32.0, 27.2, 24.84, 24.76, 22.6, 20.2, 14.1, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{16}H_{31}BO_2$ ($[M+Na]^+$), 289.2309. Found, 289.2308. ESI-HRMS: Calcd. for $C_{16}H_{31}BO_2$ ([M+Na]+), 289.2309. Found, 289.2308.



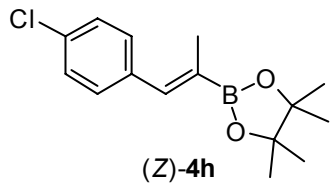
(*Z*)-**4f**

(*Z*)-**4f**: Yield 50% (60.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39–7.34 (m, 4H), 7.25–7.24 (m, 2H), 1.99 (s, 3H), 1.31 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.4, 137.9, 129.4, 128.0, 127.1, 83.5, 24.8, 15.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values. [36]



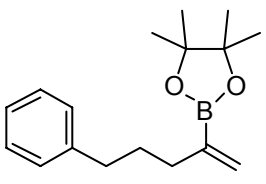
(*Z*)-**4g**

(*Z*)-**4g**: Yield 56% (77.9 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36 (d, J = 8.6 Hz, 2H), 7.18–7.17 (m, 1H), 6.88 (d, J = 8.6 Hz, 2H), 3.81 (s, 3H), 1.99 (d, J = 1.8 Hz, 3H), 1.30 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 158.6, 141.9, 130.9, 130.7, 113.5, 83.4, 55.2, 24.8, 15.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values. [36]

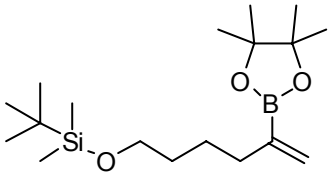

(*Z*)-**4h**

(*Z*)-**4h**: Yield 81% (113.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32–7.29 (br m, 4H), 7.17 (q, J = 1.8 Hz, 1H), 1.96 (d, J = 1.8 Hz, 3H), 1.31 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.0, 136.3, 132.8, 130.6, 128.2, 83.6, 24.8, 15.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{15}H_{20}BClO_2$ ($[M]^+$), 278.1245. Found, 278.1236. Anal. Calcd. for $C_{15}H_{20}BClO_2$: C, 64.67; H, 7.24. Found: C, 64.39; H, 7.09.

General Procedure in Table 4-5. [(^{Cl}IPr^{CPh_3})CuCl] (10.4 mg, 0.010 mmol, 2.0 mol %), and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF (2.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, $B_2(pin)_2$ (152 mg, 0.60 mmol) was added and the mixture was stirred at room temperature for 5 min. Then, MeOH (42 μL, 1.0 mmol) and an allene (0.50 mmol) were added in this order at 28 ºC and the mixture was stirred at 28 ºC for 2 h. After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. The products were obtained by silica gel column chromatography (eluent: hexane/Et_2O) or preparative GPC in the cases of **5j** due to its unstability.

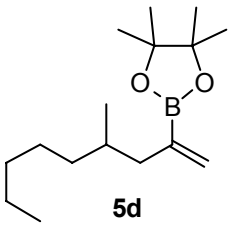

5b

5b: Yield 88% (120.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28–7.24 (m, 2H), 7.19–7.14 (m, 3H), 5.80 (d, J = 3.6 Hz, 1H), 5.61 (d, J = 3.6 Hz, 1H), 2.60 (t, J = 7.9 Hz, 2H), 2.21 (t, J = 7.5 Hz, 2H), 1.80–1.72 (m, 2H), 1.26 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 142.8, 129.3, 128.4, 128.2, 125.5, 83.3, 35.5, 35.1, 30.9, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{17}H_{25}BO_2$ ($[M]^+$), 272.1948. Found, 272.1948. Anal. Calcd. for $C_{17}H_{25}BO_2$: C, 75.01; H, 9.26. Found: C, 74.76; H, 9.51.



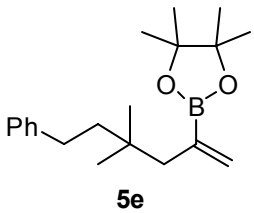
5c

5c: Yield 90% (153.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.76 (d, J = 3.6 Hz, 1H), 5.59 (d, J = 3.2 Hz, 1H), 3.61 (t, J = 6.3 Hz, 2H), 2.15 (t, J = 7.2 Hz, 2H), 1.56–1.41 (m, 4H), 1.26 (s, 12H), 0.89 (s, 9H), 0.04 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 128.9, 83.3, 63.2, 35.1, 32.5, 26.0, 25.4, 24.7, 18.3, –5.3. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. FAB-HRMS: Calcd. for $C_{18}H_{37}BO_3Si$ ($[M+H]^+$), 341.2683. Found, 341.2691. Anal. Calcd. for $C_{18}H_{37}BO_3Si$: C, 63.51; H, 10.96. Found: C, 63.63; H, 11.16.



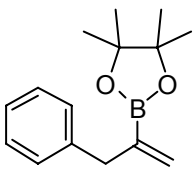
5d

5d: Yield 88% (117.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.78 (d, J = 3.6 Hz, 1H), 5.55 (d, J = 3.6 Hz, 1H), 2.17 (dd, J = 13.1 Hz, 6.3 Hz, 1H), 1.92 (dd, J = 13.1 Hz, 8.2 Hz, 1H), 1.63–1.52 (m, 1H), 1.32–1.23 (m, 19H), 1.11–1.02 (m, 1H), 0.88 (t, J = 7.0 Hz, 3H), 0.81 (d, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 129.9, 83.2, 43.2, 36.7, 32.7, 32.1, 26.7, 24.75, 24.66, 22.7, 19.5, 14.1. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{16}H_{31}BO_2$ ($[M]^+$), 266.2417. Found, 266.2416. Anal. Calcd. for $C_{16}H_{31}BO_2$: C, 72.18; H, 11.74. Found: C, 72.41; H, 11.80.



5e

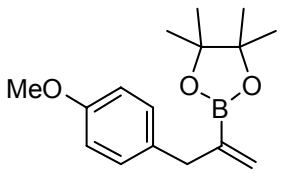
5e: Yield 93% (146.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.24 (d, J = 8.2 Hz, 2H), 7.17–7.12 (m, 3H), 5.88 (d, J = 3.6 Hz, 1H), 5.57 (d, J = 3.6 Hz, 1H), 2.60–2.56 (m, 2H), 2.16 (s, 2H), 1.52–1.48 (m, 2H), 1.21 (s, 12H), 0.91 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 143.6, 132.2, 128.4, 128.2, 125.4, 83.4, 47.3, 44.7, 34.1, 30.7, 26.5, 24.6. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{20}H_{31}BO_2$ ($[M]^+$), 314.2417. Found, 314.2413. Anal. Calcd. for $C_{20}H_{31}BO_2$: C, 76.44; H, 9.94. Found: C, 76.14; H, 10.07.



5f

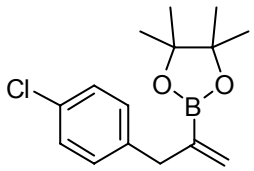
5f: Yield 82% (100.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.27–7.14 (m, 5H), 5.83 (d, J = 3.2 Hz, 1H), 5.53 (br s, 1H), 3.48 (s, 2H), 1.21 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$):

δ 140.7, 129.8, 129.1, 128.1, 125.7, 83.5, 41.4, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectrum were consistent with reported values. [37]



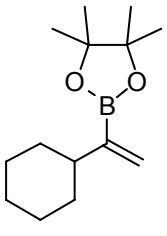
5g

5g: Yield 80% (109.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.10 (d, J = 8.6 Hz, 2H), 6.80 (d, J = 8.6 Hz, 2H), 5.80 (d, J = 3.2 Hz, 1H), 5.50 (br s, 1H), 3.77 (s, 3H), 3.41 (s, 2H), 1.21 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 157.7, 132.8, 130.0, 129.4, 113.5, 83.4, 55.2, 40.5, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. FAB-HRMS: Calcd. for $C_{16}H_{23}BO_3$ ($[M]^+$), 274.1740. Found, 274.1743. Anal. Calcd. for $C_{16}H_{23}BO_3$: C, 70.09; H, 8.46. Found: C, 69.83; H, 8.69.



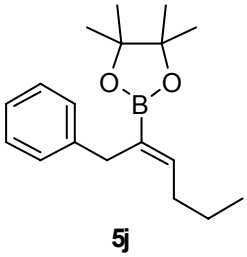
5h

5h: Yield 90% (124.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.22 (d, J = 8.6 Hz, 2H), 7.12 (d, J = 8.6 Hz, 2H), 5.84 (d, J = 3.2 Hz, 1H), 5.53 (br s, 1H), 3.43 (s, 2H), 1.20 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 139.2, 131.4, 130.4, 130.2, 128.1, 83.6, 40.8, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. EI-HRMS: Calcd. for $C_{15}H_{20}BClO_2$ ($[M]^+$), 278.1245. Found, 278.1245. Anal. Calcd. for $C_{15}H_{20}BClO_2$: C, 64.67; H, 7.24. Found: C, 64.46; H, 7.17.



5i

5i: Yield 56% (66.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.71 (d, J = 3.2 Hz, 1H), 5.55 (d, J = 2.7 Hz, 1H), 2.12–2.06 (m, 1H), 1.76–1.64 (m, 5H), 1.33–1.09 (m, 17H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 125.9, 83.1, 42.8, 32.5, 26.7, 26.3, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H spectrum were consistent with reported values. [37]

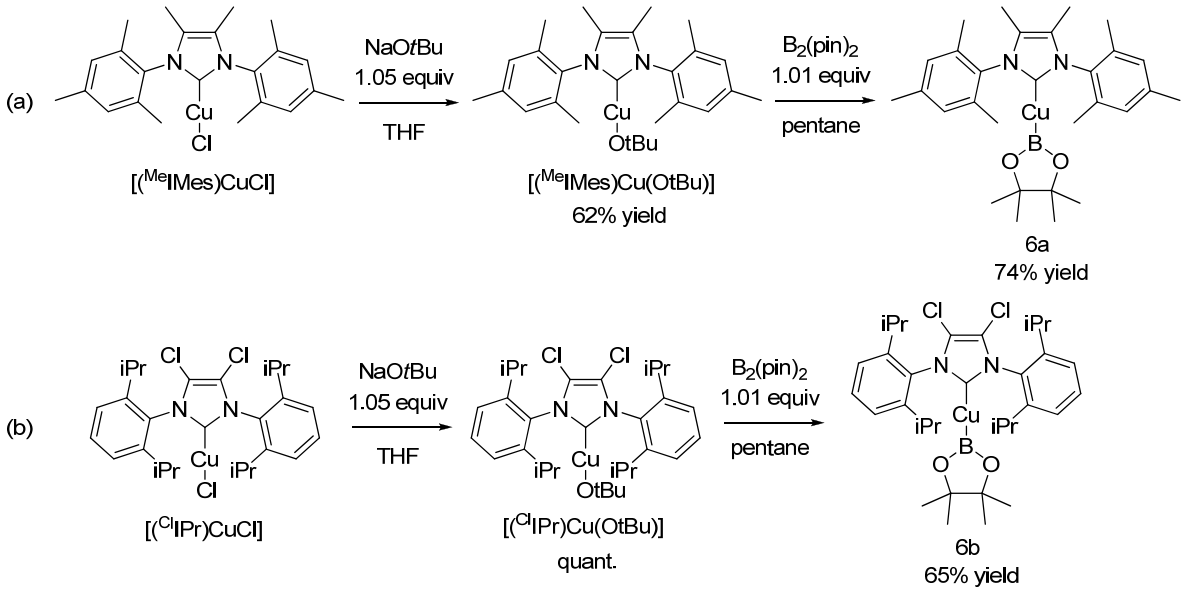


5j

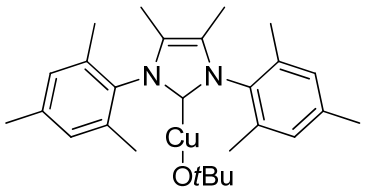
5j: Yield 85% (122.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.23–7.19 (m, 4H), 7.14–7.09 (m, 1H), 6.42 (t, J = 7.0 Hz, 1H), 3.50 (s, 2H), 2.19 (dt, J = 7.4 Hz, 7.4 Hz, 2H), 1.45–1.40 (m, 2H), 1.18 (s, 12H), 0.91 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz,

$CDCl_3$): δ 146.8, 142.0, 128.6, 128.0, 125.3, 83.1, 34.2, 31.0, 24.6, 22.2, 14.1. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{18}H_{27}BO_2$ ([M+H]$^+$), 287.2177. Found, 287.2175. Anal. Calcd. for $C_{18}H_{27}BO_2$: C, 75.53; H, 9.51. Found: C, 75.28; H, 9.81.

The Procedures for Scheme 4-5.



[(^Me^IMes)Cu(O*t*Bu)]: In a N_2 filled glove box, a flask was charged with [(^Me^IMes)CuCl] (431 mg, 1.00 mmol), *t*BuONa (101 mg, 1.05 mmol) and THF (10 mL) and the mixture was stirred for 1.5 h at room temperature. The mixture was filtrated through a pad of Celite and half of THF was removed in vacuo. To the resulting solution, pentane (30 mL) was added and then the suspension was filtrated. The desired product was obtained in 62% yield.



[(^Me^IMes)Cu(O*t*Bu)]

^{1}H NMR (400 MHz, C_6D_6): δ 6.75 (s, 4H), 2.12 (s, 6H), 1.94 (s, 12H), 1.40 (s, 9H), 1.36 (s, 6H). ^{13}C NMR (100 MHz, C_6D_6): δ 178.9, 138.9, 135.2, 134.6, 129.5, 124.4, 65.7, 21.1, 17.78, 17.77, 8.56.

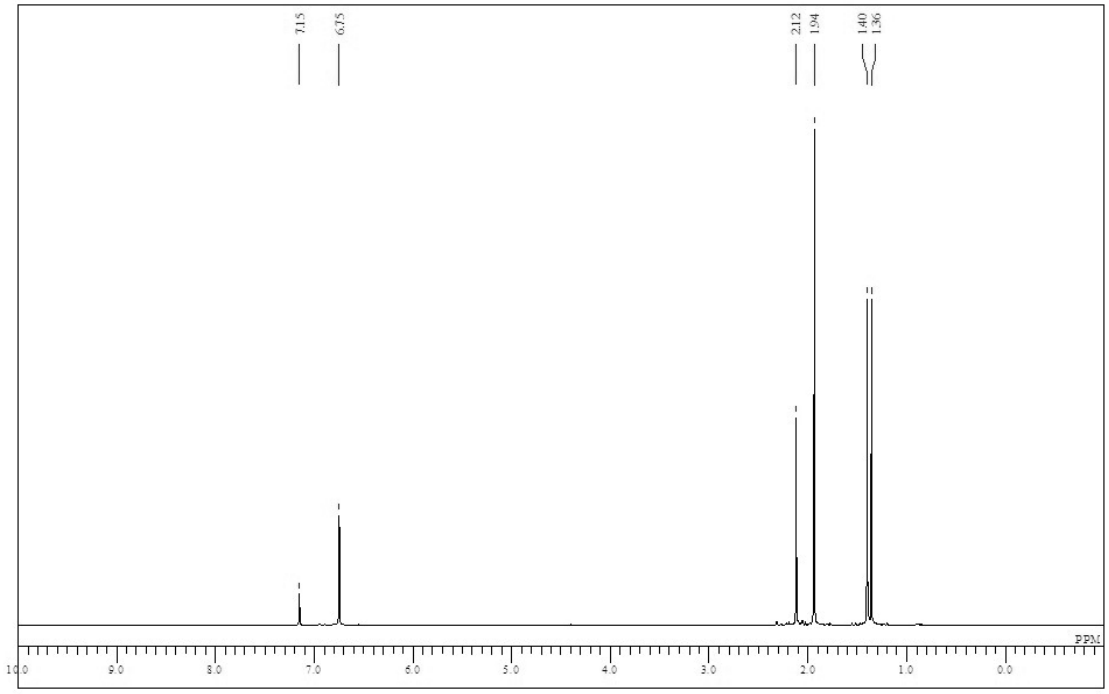


Figure 4-5. ^{1}H NMR spectrum of [(^{Me}IMes)Cu(O*t*Bu)]

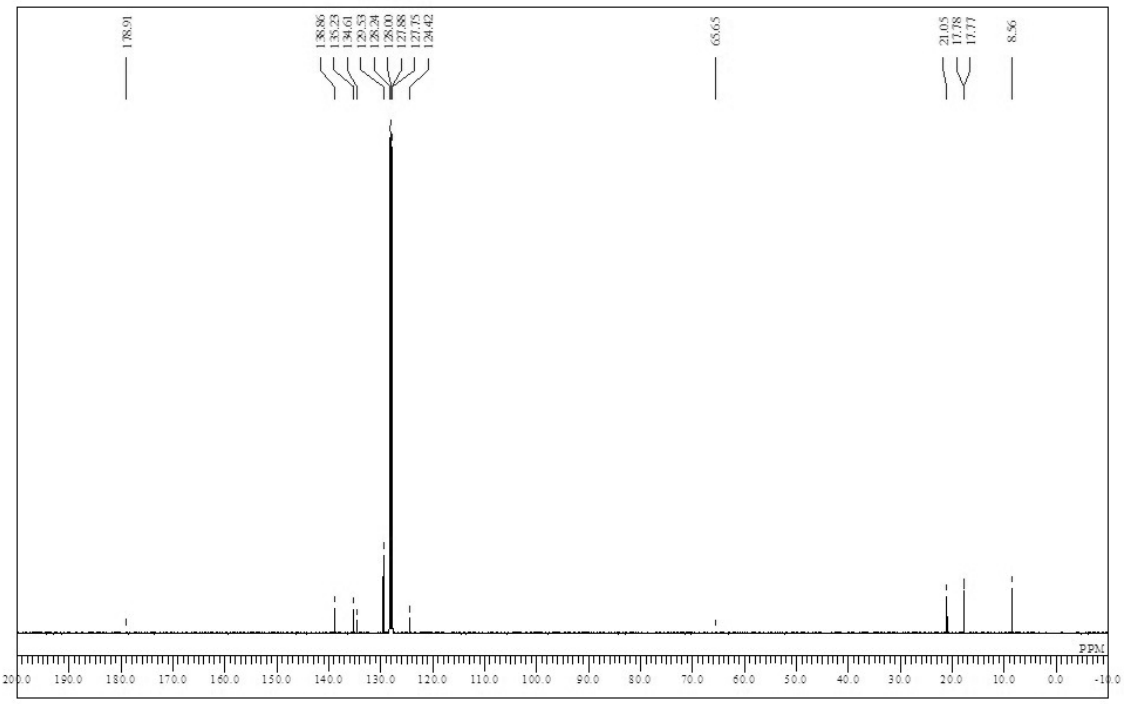
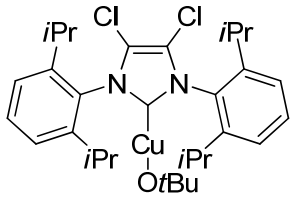


Figure 4-6. ^{13}C NMR spectrum of [(^{Me}IMes)Cu(O*t*Bu)]

[(^{Cl}IPr)Cu(O*t*Bu)]: In a N_2 filled glove box, a flask was charged with [(^{Cl}IPr)CuCl] (558 mg, 1.00 mmol), *t*BuONa (101 mg, 1.05 mmol) and THF (10 mL) and the mixture was stirred overnight at room temperature. The mixture was filtrated through a pad of Celite and the solvent was removed in vacuo. The desired product was obtained in quantitative yield.



[(^{Cl}IPr)Cu(O*t*Bu)]

^{1}H NMR (400 MHz, $C_6D_5CD_3$): δ 7.23 (t, J = 7.9 Hz, 2H), 7.07 (d, J = 8.2 Hz, 4H), 2.58 (sept, J = 6.9 Hz, 4H), 1.40 (d, J = 6.8 Hz, 12H), 1.20 (s, 9H), 1.13 (d, J = 6.8 Hz, 12H). ^{13}C NMR (100 MHz, $C_6D_5CD_3$): δ 184.4, 147.0, 133.1, 132.1, 125.3, 118.8, 69.7, 37.9, 30.1, 25.5, 24.1.

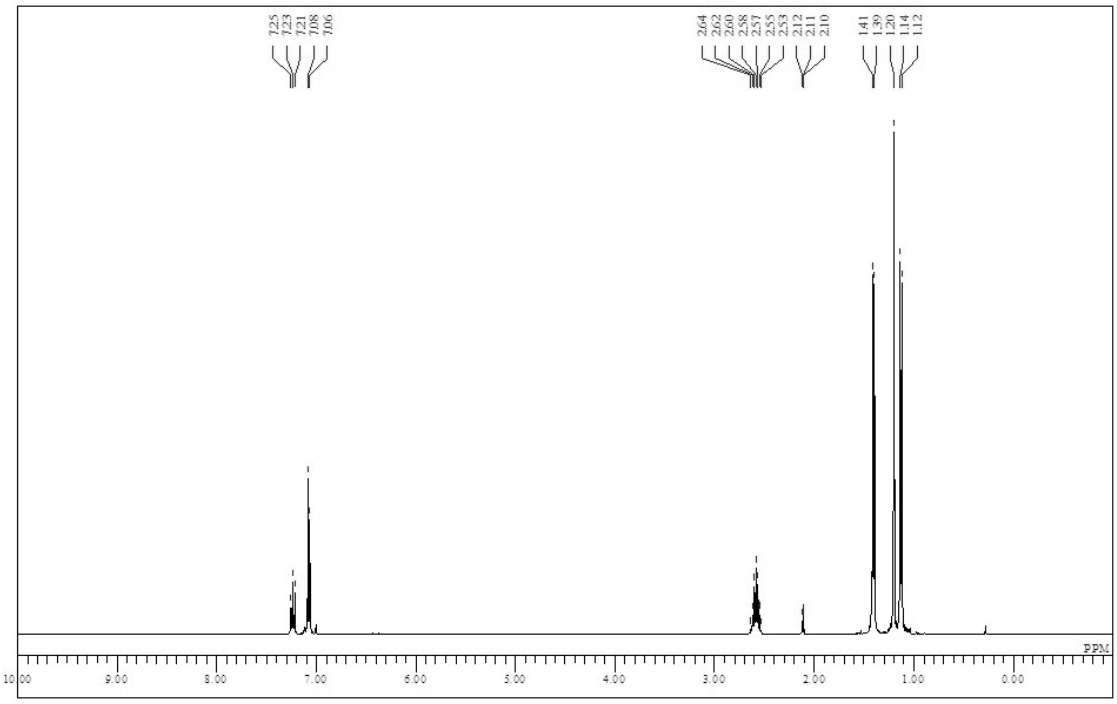


Figure 4-7. ^{1}H NMR spectrum of [(^{Cl}IPr)Cu(O*t*Bu)]

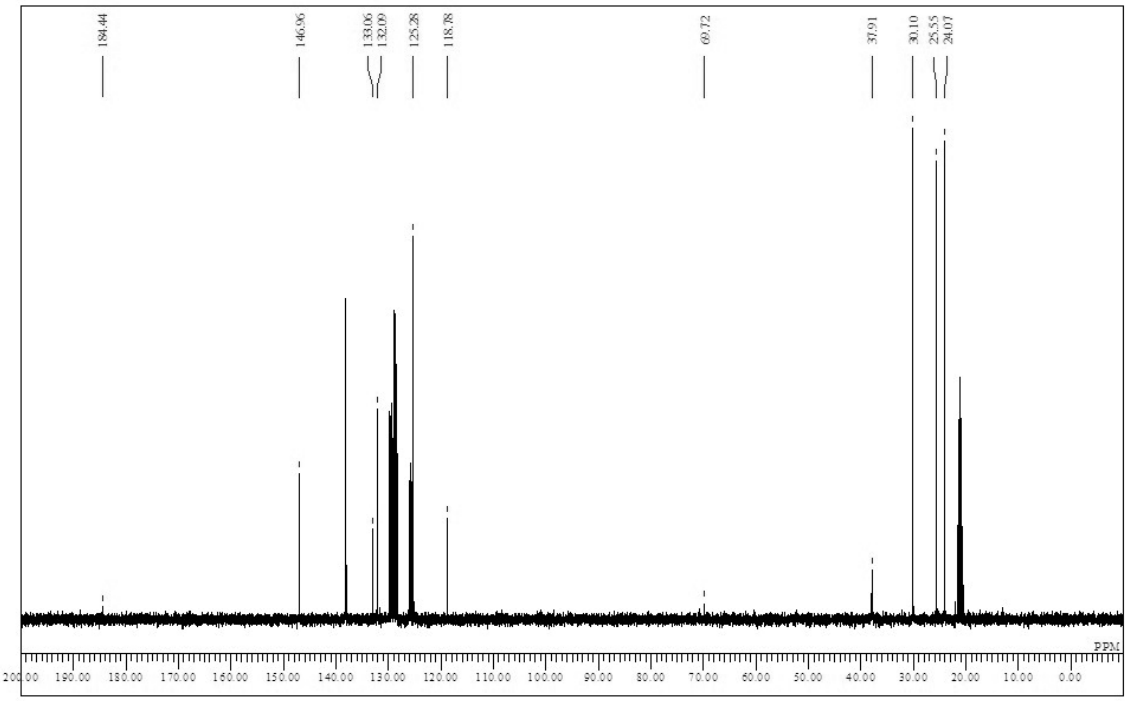
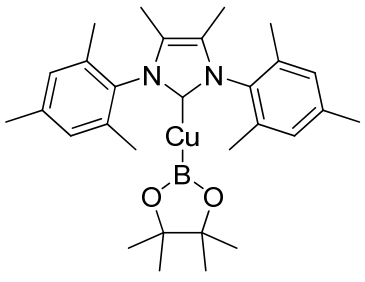


Figure 4-8. ^{13}C NMR spectrum of [(^{Cl}IPr)Cu(O*t*Bu)]

General Procedures for preparation of [(NHC)CuB(pin)].

In a N_2 filled glove box, a flask was charged with [(NHC)Cu(O*t*Bu)] (0.150 mmol), $B_2(pin)_2$ (38.6 mg, 0.152 mmol) and pentane (3.0 mL) and the reaction mixture was vigorously stirred for 20 min at room temperature. The desired product was obtained after filtration.



6a

6a: Yield 53% (43 mg). ^{1}H NMR (400 MHz, $C_6D_5CD_3$): δ 6.62 (s, 4H), 2.09 (s, 6H), 1.98 (s, 12H), 1.28 (s, 6H), 1.08 (s, 12H). ^{13}C NMR spectrum of **6a** could not measure due to rapid decomposition of **6a** in solution.

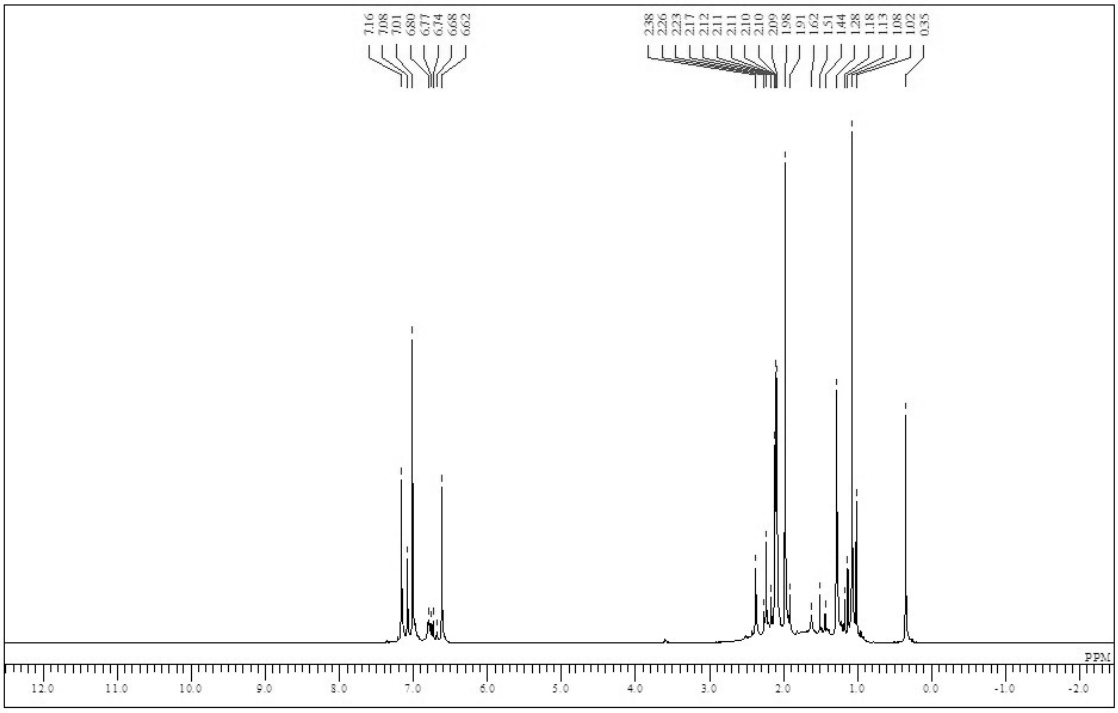
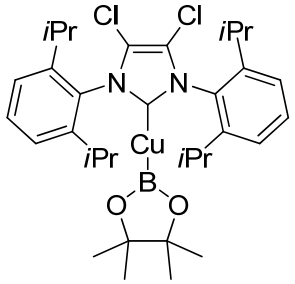


Figure 4-9. ^{1}H NMR spectrum of **6a**



6b

6b: Yield 65% (63 mg). ^{1}H NMR (400 MHz, $C_6D_5CD_3$): δ 7.15 (t, J = 7.7 Hz, 2H), 7.04 (d, J = 7.7 Hz, 4H), 2.62 (sept, J = 6.8 Hz, 4H), 1.45 (d, J = 6.8 Hz, 12H), 1.13 (d, J = 6.8 Hz, 12H), 1.02 (s, 12H). ^{13}C NMR (400 MHz, $C_6D_5CD_3$): δ 186.2, 147.0, 132.6, 131.9, 125.0, 118.7, 79.6, 30.2, 26.6, 25.8, 24.0.

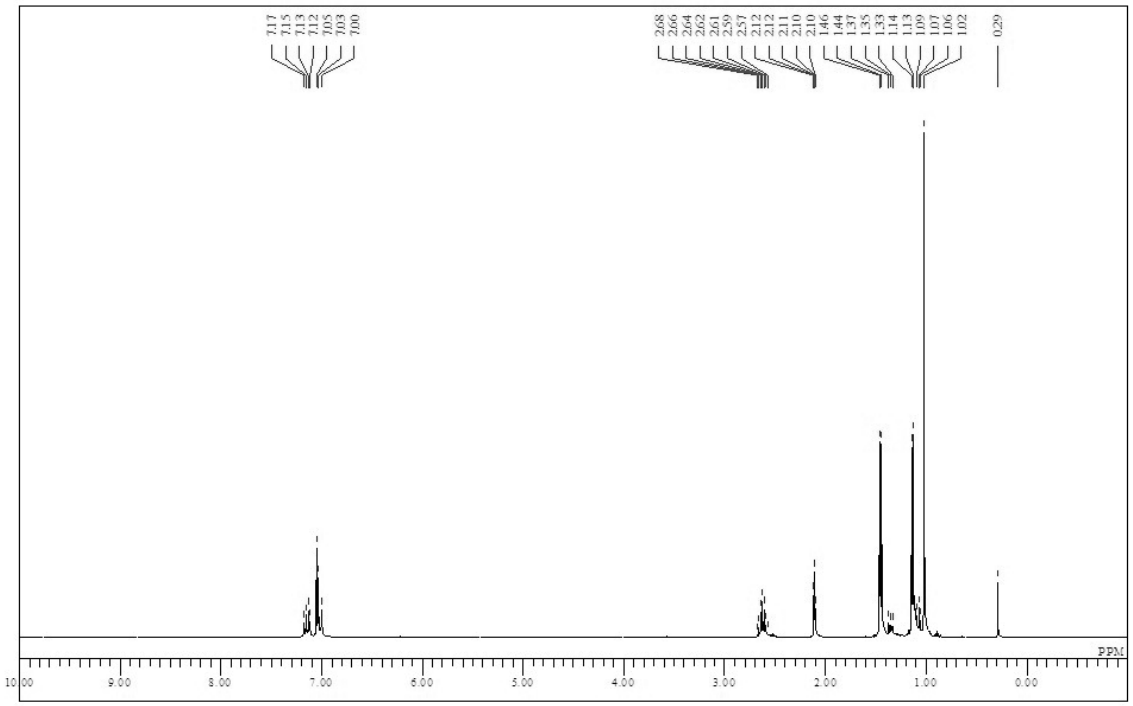


Figure 4-10. ^{1}H NMR spectrum of **6b**

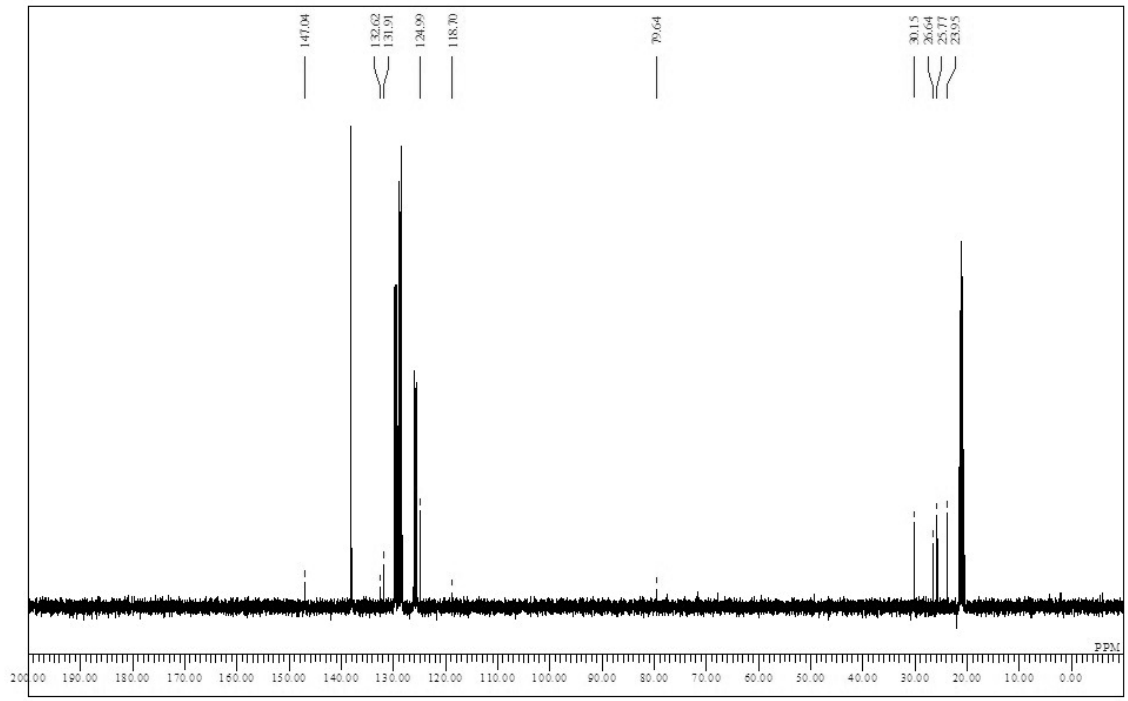
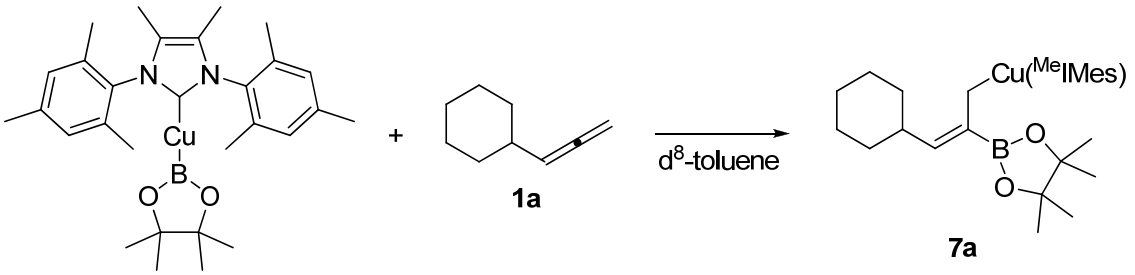


Figure 4-11. ^{13}C NMR spectrum of **6b**

A single crystal of **6b** was obtained by slow diffusion of toluene solution into hexane at –20 ºC under inert atmosphere. The structure of **6b** was also confirmed by X-ray crystallography.

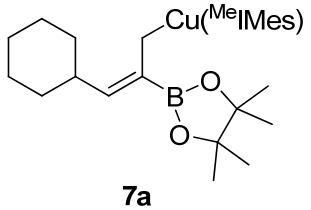
The Procedures for Scheme 4-6.

Preparation of 7a.



6a

In a N_2 filled glove box, **6a** (11 mg, 0.020 mmol) was dissolved in d^8-toluene (1 mL) and then to the solution, **1a** (3.0 μL, 0.020 mmol) was added. The ^{1}H NMR spectrum indicated that **7a** was formed (Figure 4-12) and the configuration of **7a** was confirmed by NOESY spectrum (Figure 4-13). ^{1}H NMR spectra of **7a** at 20 ºC, –10 ºC, –30 ºC and –50 ºC were shown in Figure 4-14.



7a

^{1}H NMR (400 MHz, $C_6D_5CD_3$): δ 6.81 (s, 4H), 5.61 (d, J = 7.7 Hz, 1H), 2.57-2.46 (m, 1H), 2.18 (s, 12H), 1.77-1.75 (m, 5H), 1.56 (s, 2H), 1.36-1.28 (m, 5H), 1.16 (s, 12H).

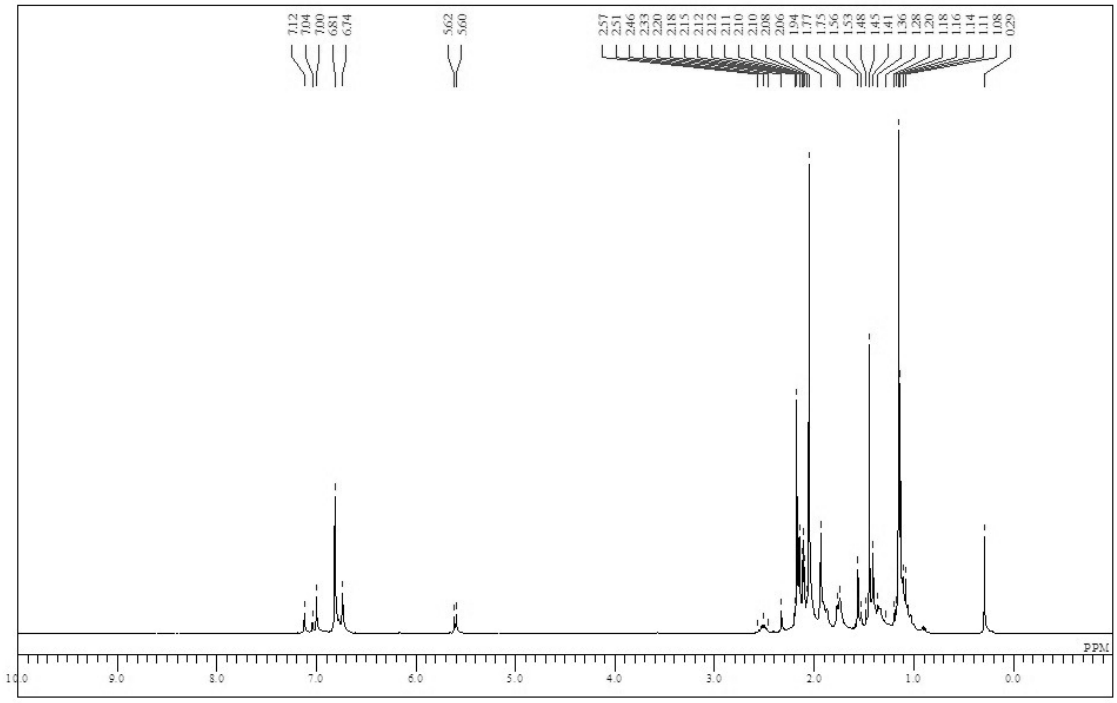


Figure 4-12. ^{1}H NMR spectrum of **7a**

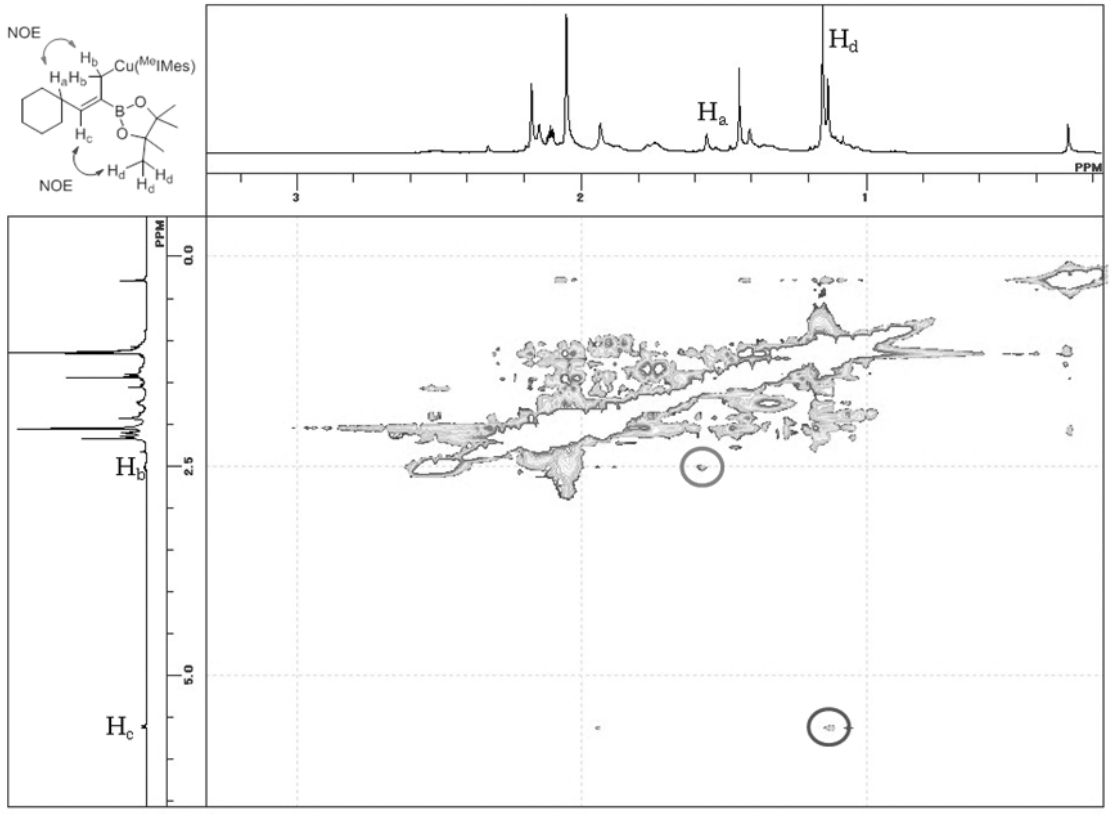


Figure 4-13. NOESY spectrum of **7a**

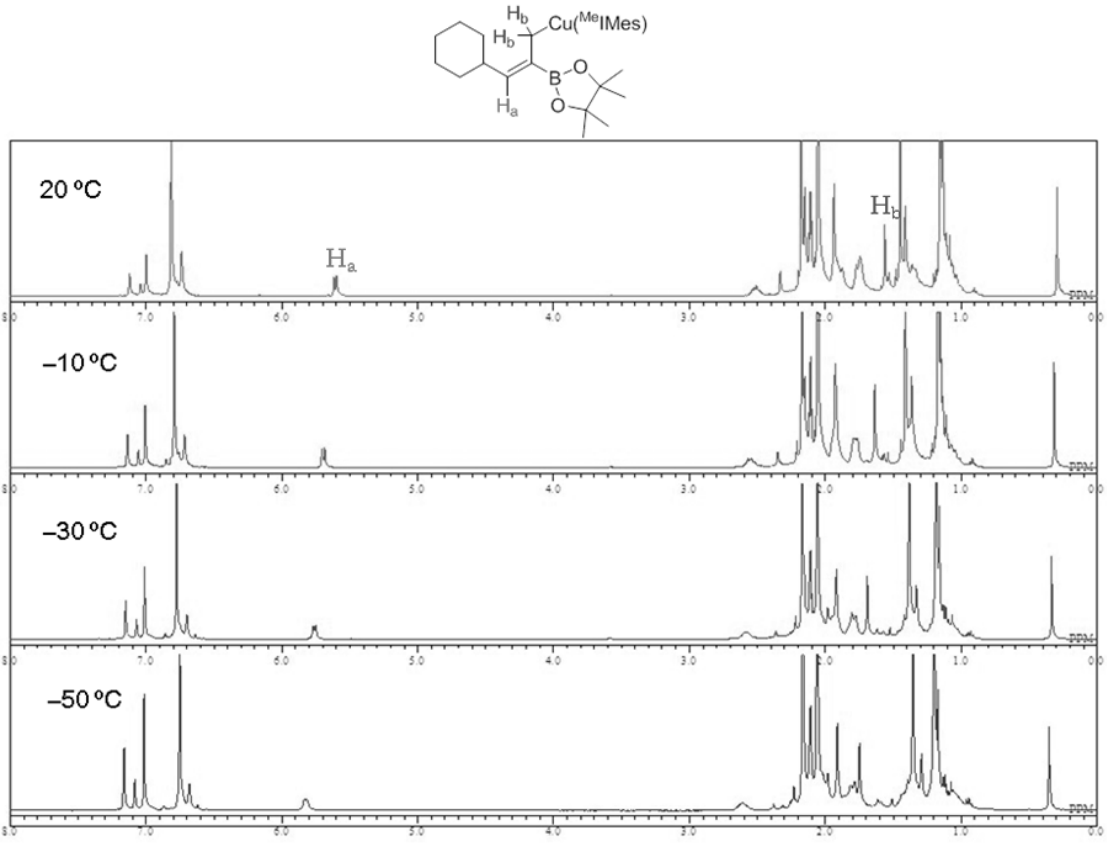
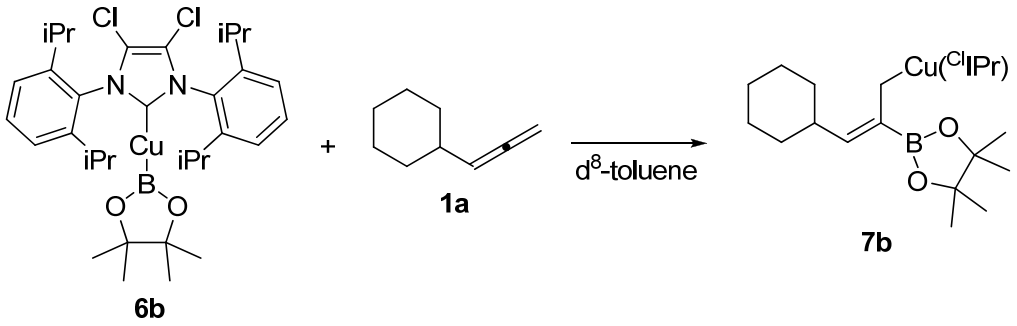
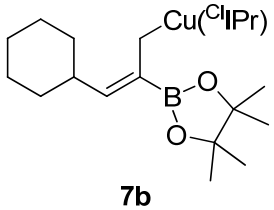


Figure 4-14. ^{1}H NMR spectra of **7a** at 20 ºC, –10 ºC, –30 ºC and –50 ºC

Preparation of 7b.



In a N_2 filled glove box, **6b** (13 mg, 0.020 mmol) was dissolved in d^8-toluene (1.0 mL) and then to the solution, **1a** (3.0 μL, 0.020 mmol) was added. The ^{1}H NMR spectrum indicated that **7b** was obtained quantitatively (Figure 4-15) and the configuration of **7b** was confirmed by NOESY spectra (Figure 4-16).



7b

^{1}H NMR (400 MHz, $C_6D_5CD_3$): δ 7.21 (t, J = 7.9 Hz, 2H), 7.08 (d, J = 7.7 Hz, 4H), 5.58 (d, J = 7.7 Hz, 1H), 2.64-2.57 (m, 4H), 2.32-2.23 (m, 1H), 1.73-1.62 (m, 5H), 1.46 (d, J = 6.8 Hz, 12H), 1.41 (s, 2H), 1.37-1.25 (m, 5H), 1.16 (d, J = 6.8 Hz, 12H), 1.09 (s, 12H).

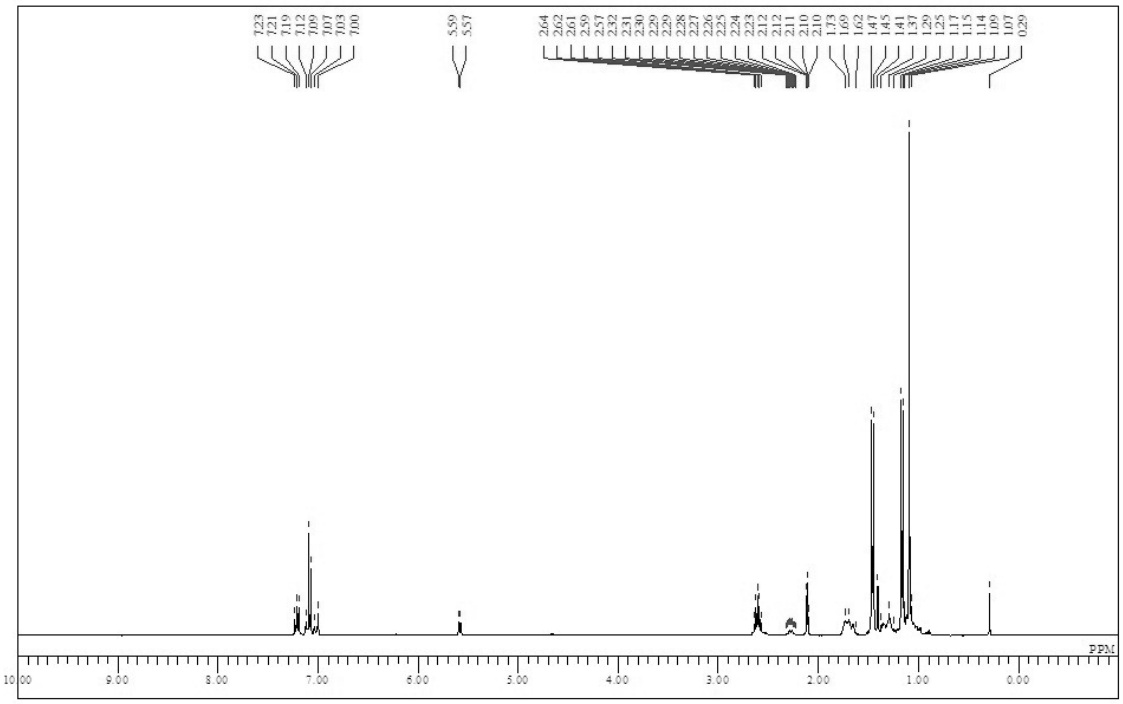


Figure 4-15. ^{1}H NMR spectrum of **7b**

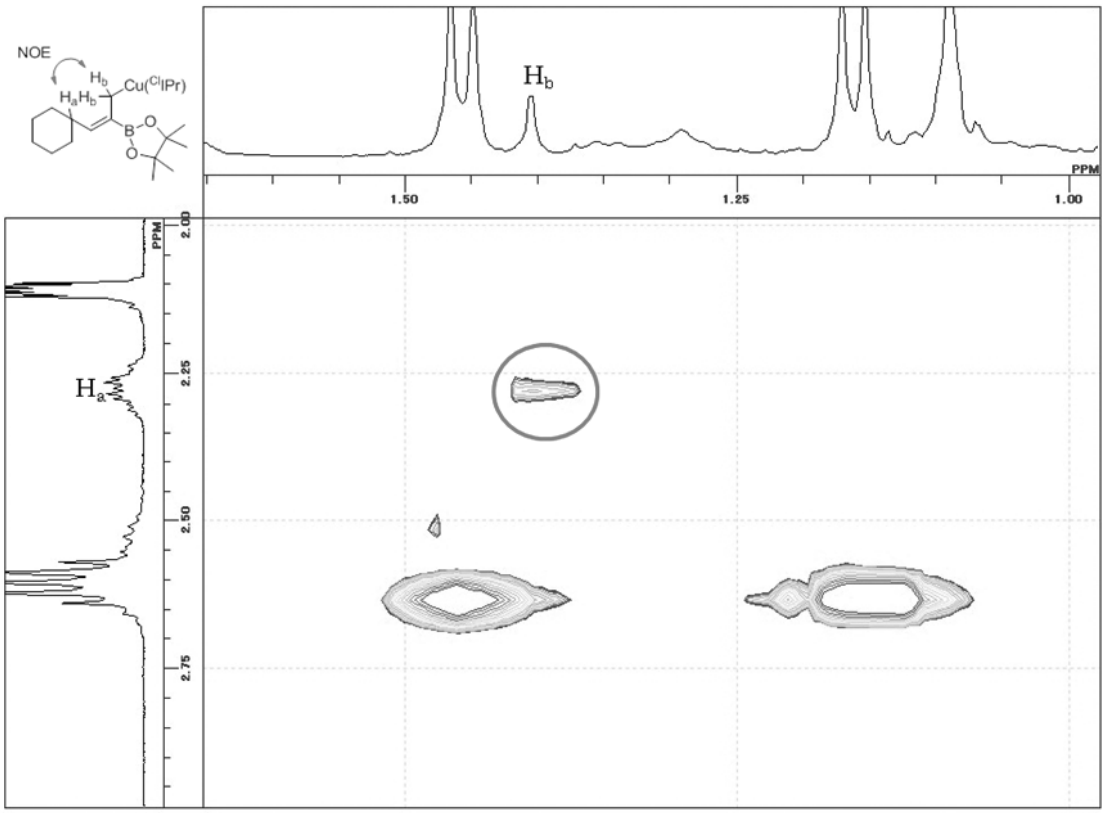
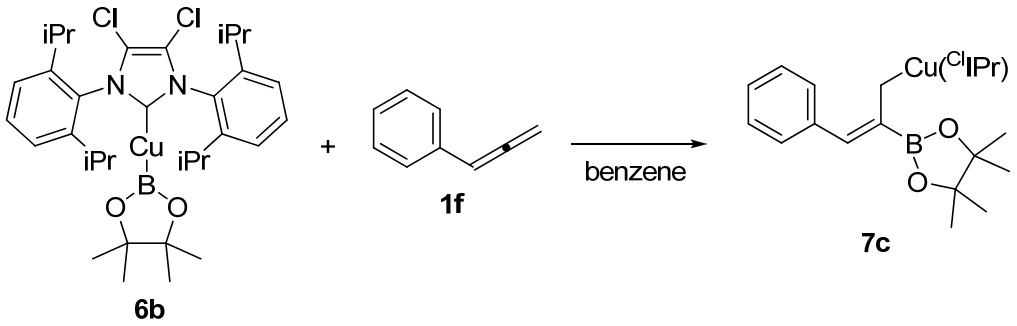


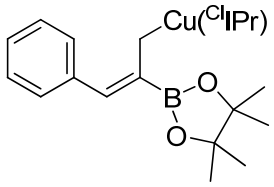
Figure 4-16. NOESY spectrum of **7b**

Preparation of 7c.



In a N_2 filled glove box, **6b** (160 mg, 0.25 mmol) was dissolved in benzene (3.0 mL). To the solution, **1f** (37 μL, 0.30 mmol) was added and the mixture was stirred for 10 min at room temperature. Half of benzene was removed in vacuo. To the resulting solution, pentane (30 mL) was added and the mixture was stored at –20 ºC under inert atmosphere. After filtration, the desired product was obtained in 61% yield (120 mg, 0.15 mmol).

A single crystal of **7c** was obtained by slow diffusion of toluene solution into hexane at –20 ºC under inert atmosphere. The structure of **7c** was also confirmed by X-ray crystallography.



7c

^{1}H NMR (400 MHz, C_6D_6): δ 7.56 (d, J = 6.8 Hz, 2H), 7.18–7.15 (m, 2H), 7.04–7.02 (m, 6H), 6.78 (s, 1H), 2.55 (sept, J = 6.8 Hz, 4H), 2.21 (s, 2H), 1.35 (d, J = 6.8 Hz, 12H), 1.10–1.08 (m, 24H).

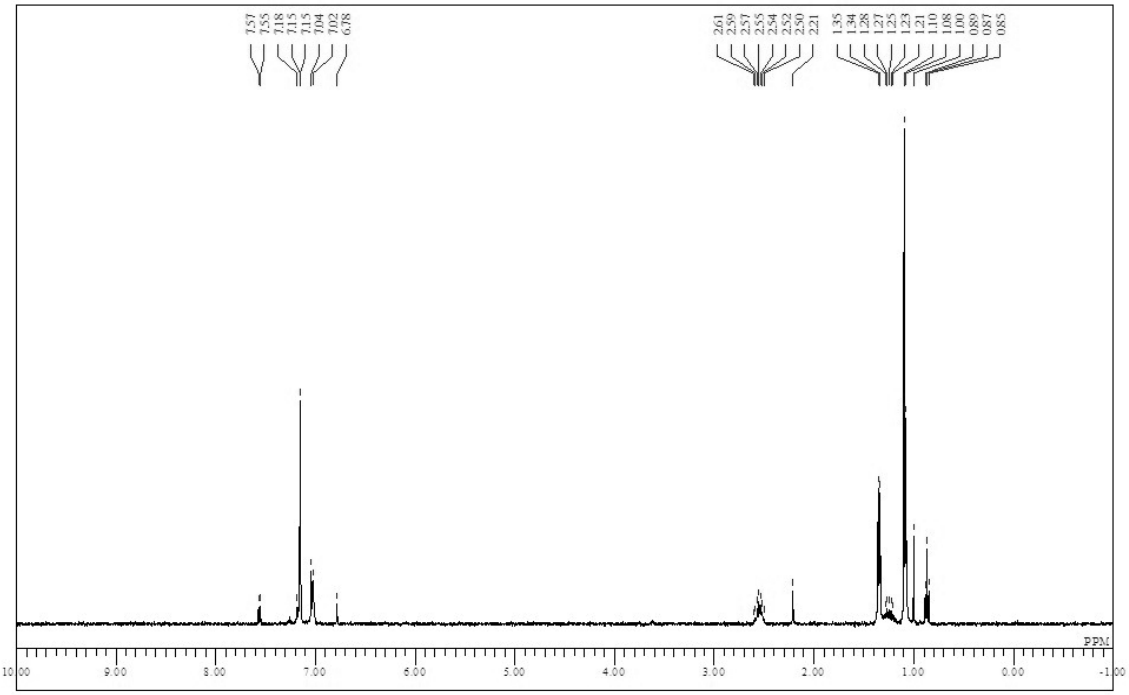


Figure 4-17. ^{1}H NMR spectrum of **7c**

Protonation of 7a or 7b by MeOH.

Scheme 4-6a at –20 ºC: A 20 mL Schlenk falsk was charged with [(^{Me}IMes)CuCl] (22mg, 0.050 mmol), NaO*t*Bu (7.2 mg, 0.075 mmol) and $B_2(pin)_2$ (14 mg, 0.055 mmol). To the flask, toluene (1.0 mL) was added and the resulting mixture was stirred at room temperature for 5 min. To the solution, **1a** (8 μL, 0.050 mmol) was added at room

temperature and the mixture was stirred at room temperature for 5 min. The mixture was cooled to –20 ºC and MeOH (3 μL, 0.075 mmol) was added at –20 ºC. The resulting mixture was stirred at –20 ºC for 30 min and then 1N HCl/MeOH (0.50 mL) was added. The yield and selectivity of the products were determined by GC.

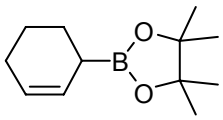
Scheme 4-6a at –80 ºC: A 20 mL Schlenk falsk was charged with [(^{Me}IMes)Cu(O*t*Bu)] (24 mg, 0.050 mmol) and $B_2(pin)_2$ (14 mg, 0.055 mmol). To the flask, toluene (1.0 mL) was added and then **1a** (8 μL, 0.050 mmol) was added at 0 ºC. The mixture was stirred at room temperature for 5 min and cooled to –80 ºC. To the mixture, MeOH (3 μL, 0.075 mmol) was added at –80 ºC. The resulting mixture was stirred at –80 ºC for 5 min and then to the resulting mixture, 1N HCl/MeOH (0.50 mL) was added. The yield and selectivity of the products were determined by GC.

Scheme 4-6b: A 20 mL Schlenk flask was charged with [(^{Cl}IPr)CuCl] (56 mg, 0.10 mmol), NaO*t*Bu (14 mg, 0.15 mmol) and $B_2(pin)_2$ (28 mg, 0.11 mmol). To the flask, toluene (1.0 mL) was added and the resulting mixture was stirred at room temperature for 5 min. To the solution, **1a** (15 μL, 0.10 mmol) was added at room temperature and the mixture was stirred at room temperature for 5 min. To the solution, MeOH (6 μL, 0.15 mmol) was added at room temperature or –20 ºC. The mixture was stirred at room temperature for 5 sec or at –20 ºC for 30 min and then 1N HCl/MeOH (0.50 mL) was added. The yield and selectivity of the products were determined by GC.

Procedures for Scheme 4-8.

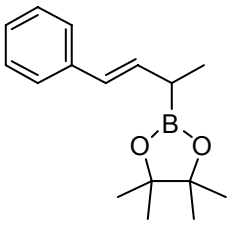
Scheme 4-8a and 8c: CuCl (0.50 mg, 0.0050 mmol, 1.0 mol %), DTBMAr-Xan (5.74 mg, 0.0050 mmol, 1.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. The solvent (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, HB(pin) (150 μL, 1.0 mmol) was added at 0 ºC and the mixture was stirred at room temperature for 5 min. To the mixture, a 1,3-diene (0.50 mmol) was added and the mixture was stirred at indicated temperature for 1 h. After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of Celite and

silica gel. All of the volatiles were removed in vacuo. The product was obtained by silica gel column chromatography (eluent: hexane/Et_2O).



9a

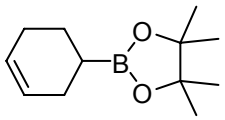
9a: Yield 81% (83.9 mg). ^{1}H NMR (400 MHz, $CHCl_3$): δ 5.74–5.65 (m, 2H), 2.01–1.98 (m, 2H), 1.79–1.60 (m, 5H), 1.25 (s, 12H). ^{13}C NMR (400 MHz, $CHCl_3$): δ 127.6, 126.0, 83.1, 25.0, 24.8, 24.6, 24.1, 22.5. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectra were consistent with reported values.[38]



9b

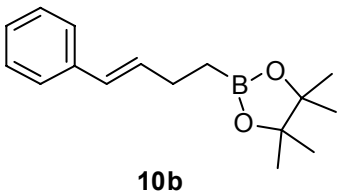
9b: Yield 82% (107 mg). ^{1}H NMR (400MHz, $CDCl_3$): δ 7.35 (d, J = 7.7 Hz, 2H), 7.27 (t, J = 6.8 Hz, 2H), 7.16 (t, J = 7.2 Hz, 1H), 6.35-6.34 (m, 2H), 2.11-2.01 (m, 1H), 1.24 (s, 12H), 1.19 (d, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.27, 133.29, 128.36, 127.57, 126.45, 125.87, 83.26, 24.71, 24.64, 14.81. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. APCI-HRMS: Calcd. for $C_{16}H_{24}B_1O_2$ ($[M+H]^+$), 259.1864. Found, 259.1859.

Scheme 4-8b and 8d: CuCl (0.99 mg, 0.010 mmol, 2.0 mol %), ClAr-Xan (8.54 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF or toluene (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, $B_2(pin)_2$ (255 mg, 1.0 mmol) was added and the mixture was stirred at room temperature for 5 min. To the mixture, a 1,3-diene (0.50 mmol) and MeOH (42 μL, 1.0 mmol) were added in this order and the mixture was stirred at indicated temperature for indicated time. After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. The product was obtained by silica gel column chromatography (eluent: hexane/Et_2O).



10a

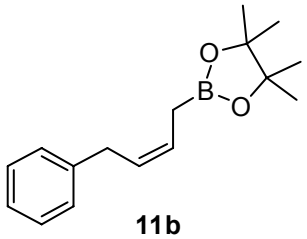
10a: Yield 77% (80.2 mg). ^{1}H NMR (400 MHz, $CHCl_3$): δ 5.73–5.64 (m, 2H), 2.12–1.93 (m, 4H), 1.82–1.76 (m, 1H), 1.59–1.49 (m, 1H), 1.24–1.19 (m, 13H). ^{13}C NMR (400 MHz, $CHCl_3$): δ 127.6, 127.0, 82.9, 26.3, 25.2, 24.73, 24.70, 23.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. All the resonances in ^{1}H and ^{13}C spectra were consistent with reported values.[16b]



10b

10b: Yield 88% (114 mg). ^{1}H NMR (400MHz, $CDCl_3$): δ 7.33 (d, J = 7.2 Hz, 2H), 7.27 (t, J = 7.0 Hz, 2H), 7.17 (t, J = 7.0 Hz, 1H), 6.38 (d, J = 15.9 Hz, 1H), 6.28 (dt, J = 15.9, 6.1 Hz, 1H), 2.33 (q, J = 7.2 Hz, 2H), 1.24 (s, 12H), 0.98 (t, J = 7.9 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.96, 132.74, 128.78, 128.40, 126.65, 125.90, 83.05, 27.31, 24.83. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. APCI-HRMS: Calcd. for $C_{16}H_{24}B_1O_2$ ($[M+H]^+$), 259.1864. Found, 259.1860.

Scheme 4-8e: [(IMes)CuCl] (4.03 mg, 0.010 mmol, 2.0 mol %) and *t*BuONa (5.77 mg, 0.060 mmol, 12 mol %) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated and backfilled with argon three times. THF (1.0 mL) was added, and the mixture was stirred for 15 min at room temperature under argon atmosphere. To the resulting solution, $B_2(pin)_2$ (255 mg, 1.0 mmol) was added and the mixture was stirred at room temperature for 5 min. To the mixture, **8b** (71 μL, 0.50 mmol) and *t*BuOH (96 μL, 1.0 mmol) were added in this order and the mixture was stirred at room temperature for 20 h. After the reaction, the selectivity of the product was determined by GC analysis. The mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed in vacuo. The product was obtained by silica gel column chromatography (eluent: hexane/Et_2O = 10/1).



11b

11b: Yield 75% (97.2 mg). ^{1}H NMR (400MHz, $CDCl_3$): δ 7.28-7.15 (m, 5H), 5.64 (dt, J = 10.4 Hz, 7.7 Hz, 1H), 5.57 (dt, J = 10.4 Hz, 7.0 Hz, 1H), 3.39 (d, J = 6.8 Hz, 2H), 1.80 (d, J = 7.7 Hz, 2H), 1.25 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.27, 128.43, 128.28, 128.08, 125.71, 125.26, 83.29, 33.29, 24.77. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. APCI-HRMS: Calcd. for $C_{16}H_{24}B_1O_2$ ($[M+H]^+$), 259.1864. Found, 259.1860.

X-ray Crystallographic Analysis.

Crystallographic data of [(^{Me}IMes)CuCl], [(^{Cl}IPr^{CPh_3})CuCl·$CHCl_3$], **6b** and **7c** were summarized in Table 4-6 and 4-7. Data of [(^{Me}IMes)CuCl], [(^{Cl}IPr^{CPh_3})CuCl·$CHCl_3$], **6b** and **7c** were collected on a Rigaku/Saturn70 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) at 153 K, and processed using CrystalClear (Rigaku).[39] The structures were solved by a direct method and refined by full-matrix least-square refinement on *F*2. The non-hydrogen atoms, except disordered atom and solvated molecules, were refined anisotropically. All hydrogen atoms were located on the calculated positions and not refined. All calculations were performed using the CrystalStructure software package.[40]

Table 4-6. Crystallographic data of [(^{Me}IMes)CuCl] and [(^{Cl}IPr^{CPh_3})CuCl·$CHCl_3$]

compound	[(^{Me}IMes)CuCl]	[(^{Cl}IPr^{CPh_3})CuCl·$CHCl_3$]
empirical formula	$C_{23}H_{28}N_2ClCu$	$H_{63}N_2Cl_6CuC_{66}$
formula weight	431.49	1160.50
temp / K	153	153
crystal system	monoclinic	triclinic
space group	Cc (#9)	P-1 (#2)
a / Å	14.551(18)	12.044(3)
b / Å	29.03(3)	14.910(3)
c / Å	9.033(11)	16.933(4)
α / deg	90	95.207(4)
β / deg	143.593(16)	101.056(2)
γ / deg	90	93.634(3)
V / Å^3	2265(4)	2961.9(11)
Z	4	2
d_{cacd}/g cm^{-3}	1.265	1.301
observed reflections	3980	12689
unique reflections	3980 (all data)	12689 (all data)
GOF	1.282	1.008
$R1$ ($I > 2\sigma(I)$), $wR2$[a]	0.0832, 0.1814[b]	0.0483, 0.1388[c]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma (w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] $w = 1/[0.0002F_o^2 + 1.0000\sigma(F_o^2)]/(4F_o^2)$. [c] $w = 1/[0.0016F_o^2+1.0000\sigma(F_o^2)]/(4F_o^2)$.

Table 4-7. Crystallographic data of **6b** and **7c**

compound	**6b**	**7c**
empirical formula	$H_{46}N_2O_2CuBCl_2C_{33}$	$C_{91}H_{116}N_4O_4Cu_2B_2Cl_4$
formula weight	648.00	1620.47
temp / K	153	153
crystal system	triclinic	triclinic
space group	P-1 (#2)	P-1 (#2)
a / Å	10.434(2)	15.1961(12)
b / Å	11.060(2)	15.7208(12)
c / Å	15.334(4)	20.6434(15)
α / deg	84.454(5)	68.273(3)
β / deg	89.070(6)	73.460(3)
γ / deg	76.254(5)	81.548(4)
V / Å^3	1710.7(7)	4386.9(6)
Z	2	2
d_{cacd}/g cm^{-3}	1.258	1.227
observed reflections	7361	18837
unique reflections	7361 (all data)	18837 (all data)
GOF	1.121	0.999
$R1$ ($I > 2\sigma(I)$), $wR2$[a]	0.0596, 0.1769[b]	0.0526, 0.1398[c]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma (w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] $1/[0.0020F_o^2+1.0000\sigma(F_o^2)]/(4F_o^2)$. [c] $w = 1/[0.0010F_o^2+3.0000\sigma(F_o^2)+0.5000]/(4F_o^2))$.

References

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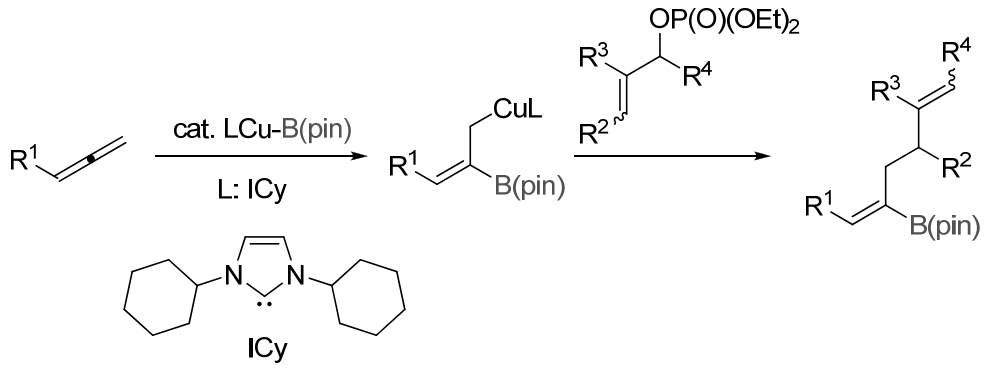
Chapter 5

Copper-Catalyzed Allylboration of Allenes Employing Bis(pinacolato)diboron and Allyl Phosphates

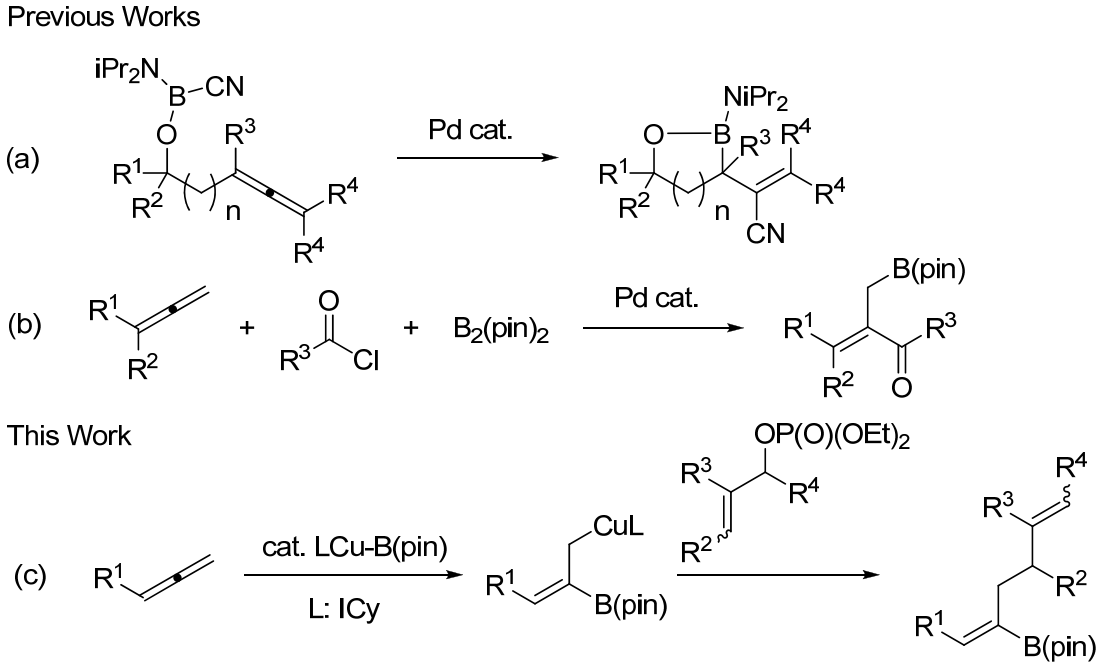
Copper-catalyzed allylboration of allenes employing bis(pinacolato)diboron ($B_2(pin)_2$) and allyl phosphates was developed. Generation of (*Z*)-β-boryl-σ-allylcopper by the reaction of a borylcopper species with an allene was a key step for this reaction and the species reacted with allyl phosphates, realizing allylboration of allenes. Noteworthy is that this reaction proceeds in high regio- and stereoselectivities.



5-1. Introduction

Organoboronic acids and their derivatives are highly useful in organic synthesis since these compounds show reasonable reactivity and stability.[1] Therefore, much attention has been paid to development of synthetic methods for organoboronic acids and their derivatives such as hydroboration,[2] C-H[3] or C-X[4] borylation, diboration[5] and silaboration[6] and so on. Among them, *carboboration*, which allows simultaneous introduction of both *carbon* and *boron* substituents onto unsaturated bonds, is a powerful tool to provide more complicated organoboranes.[7] Suginome and co-workers have intensively studied in this field and reported Pd or Ni-catalyzed cyanoboration,[8] alkynylboration,[9] arylboration[10] and alkenylboration[10] of alkynes. Very recently, copper-catalyzed carboboration of alkynes was reported.[11] However, carboboration of other unsaturated bonds are rare. To date, intramolecular cyanoboration of allenes[12] and acylboration of allenes[13] have been only reported (Scheme 5-1a and b).

Scheme 5-1.



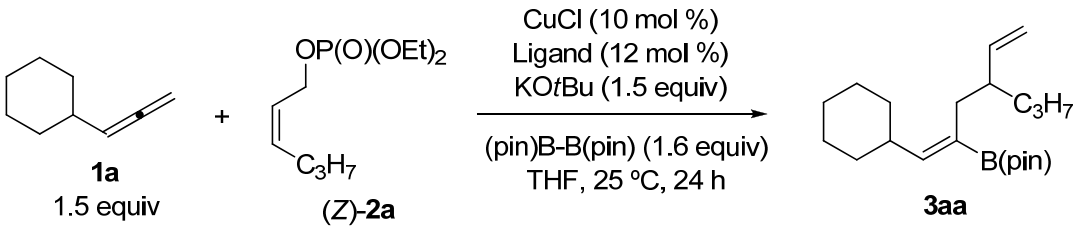
In Chapters 4 and 5, the author described the copper-catalyzed regioselective hydroboration of unsymmetrical internal alkynes, allenes and 1,3-dienes by choice of catalytic species (Cu-H and Cu-B). In the study of hydroboration of allenes, the author found that a borylcopper smoothly inserted to an allene, giving the corresponding

(*Z*)-β-boryl-σ-allylcopper species selectively. The result engaged the author to develop carboboration by the reaction of the allylcopper with carbon-based electrophiles. In this Chapter, the author describes copper-catalyzed allylboration of allenes employing a borylcopper[14] and an allyl phosphate as an electrophile[15] (Scheme 5-1c).

5-2. Result and Discussion

First, the reaction conditions were optimized employing **1a,** (*Z*)-**2a** and $B_2(pin)_2$ as substrates in the presence of a catalytic amount of copper complex in THF at 25 °C (Table 5-1). Employing CuCl without any ligands, the reaction did not proceed at all (entry 1). When PPh_3 was used as a ligand, a mixture of the desired allylborated products was obtained in 27% yield, but the selectivity was low (**3aa**/other isomers = 61/39, entry 2). PCy_3 was an effective ligand and afforded **3aa** in high yield and selectivity (entry 3, 84% yield, **3aa**/other isomers = 91/9). Bidentate phosphane ligands such as dppe, dppp, dppb, dppbz and Xantphos were not effective (entries 4–8). Next, the author tested *N*-heterocyclic carbenes (NHCs) as ligands (entries 9–12). A bulky IPr was not effective (entry 9). Employing less hindered NHCs such as IMes, ^{Me}IMes and ICy, the yields and selectivities were dramatically improved (entries 10–12). Among them, ICy was found to be the most effective ligand and afforded the product in 84% yield with high selectivity (**3aa**/other isomers = 95/5) (entry 12). When the amount of KO*t*Bu was reduced to 30 mol %, the yield decreased to 17% (entry 13). Employing (*E*)-**2a** as a substrate, the yield and selectivity slightly decreased (entry 14).

Table 5-1. Allylboration of **1a** employing various catalysts[a]



1a 1.5 equiv + (*Z*)-**2a** → **3aa**

Entry	Ligand	Yield (%)[b]	Ratio of **3aa**/other isomers[c]
1	none	2	-
2	PPh_3	27	61/39

Table 5-1. (Continued)

3	PCy_3	84	91/9
4	dppe	40	53/47
5	dppp	41	36/64
6	dppb	71	90/10
7	dppbz	42	76/24
8	Xantphos	48	72/28
9	IPr·HCl	8	78/22
10	IMes·HCl	88	91/9
11	^{Me}IMes·HCl	85	94/6
12	ICy·HBF_4	84	95/5
13[d]	ICy·HBF_4	17	97/3
14[e]	ICy·HBF_4	58	91/9

[a] **1a** (0.38 mmol, 1.5 equiv), $B_2(pin)_2$ (0.40 mmol, 1.6 equiv), (*Z*)-**2a** (0.25 mmol), CuCl (0.025 mmol, 10 mol %), a ligand (0.030 mmol, 12 mol %), KO*t*Bu (1.0 M solution of KO*t*Bu in THF, 380 μL, 1.5 equiv), THF (2.0 mL), 25 ºC, 24 h. [b] Yield of products based on the GC internal standard technique. [c] A ratio of **3aa**/other isomers in the crude reaction mixture was determined by GC. [d] KO*t*Bu (1.0 M solution of KO*t*Bu in THF, 75 μL, 30 mol %) was used. [e] (*E*)-**2a** was used instead of (*Z*)-**2a**.

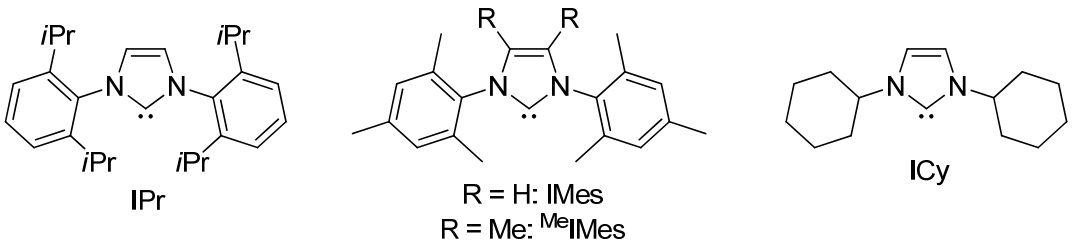
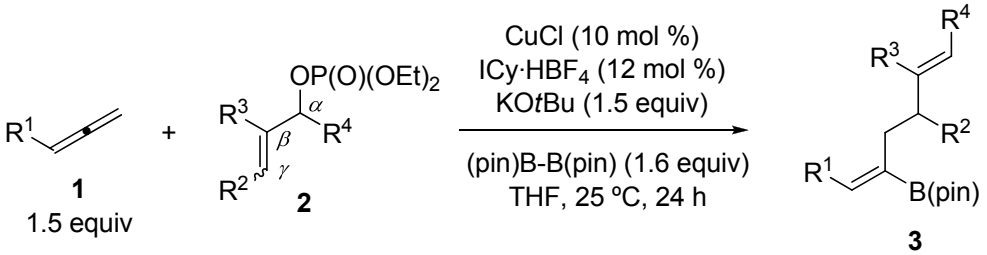


Figure 5-1. The structures of ligands

Allylboration of various allenes (**1a**-**e**) were examined employing various allyl phosphates (**2a**-**d**) and $B_2(pin)_2$ (Table 5-2). Under the optimized reaction conditions (Table 5-1, entry 12), **3aa** was isolated in 77% yield (**3aa**/other isomers = 98/2) with silica gel column chromatography. The reactions of allenes bearing secondary alkyl groups such as **1b** and **1c** with (*Z*)-**2a** proceeded smoothly and the corresponding

products (**3ba** and **3ca**) were obtained in good to high yields and high selectivities (entries 2 and 3). Employing **1d**, which has a primary alkyl moiety, the product was also obtained in good yield and high selectivity (entry 4). Gratifyingly, a silyl ether functionality on an allene did not affect the yield and selectivity (entry 5). Next, the scope of allyl phosphates (**2b-d**) was examined. In the case of a β-substituted allyl phosphate, the corresponding product (**3ab**) was obtained in 76% with high selectivity (**3ab**/other isomers = 95/5) (entry 6). The reactions of γ-substituted allyl phosphates (**2c** and **2d**) proceeded smoothly and the corresponding products (**3ac** and **3ad**) were obtained in good yields, but the selectivities were relatively low. Major by-products in entries 7 and 8 were the corresponding (*Z*)-isomer derived from an allyl phosphate.

Table 5-2. Allylboration of various allenes (**1**) employing various allyl phosphate (**2**)[a]



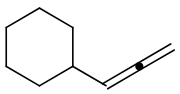
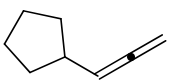
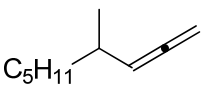
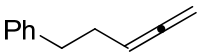
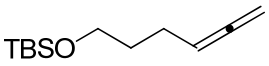
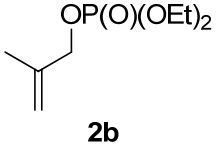
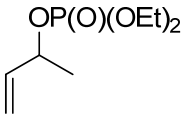
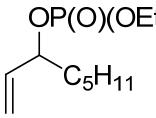
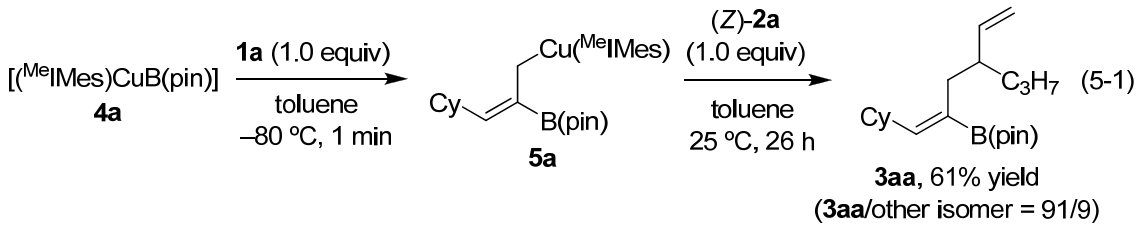
Entry	Allene	Allyl phosphate	Yield (%)[b]	Ratio of **3**/other isomers[c]
1	 **1a**	(*Z*)-**2a**	77	98/2
2	 **1b**	(*Z*)-**2a**	75	97/3
3	 **1c**	(*Z*)-**2a**	82	95/5
4	 **1d**	(*Z*)-**2a**	76	96/4
5	 **1e**	(*Z*)-**2a**	57	98/2

Table 5-2. (Continued)

6	**1a**	 **2b**	76	95/5
7	**1a**	 **2c**	65	80/20
8	**1a**	 **2d**	57	97/3 (82/18)[d]

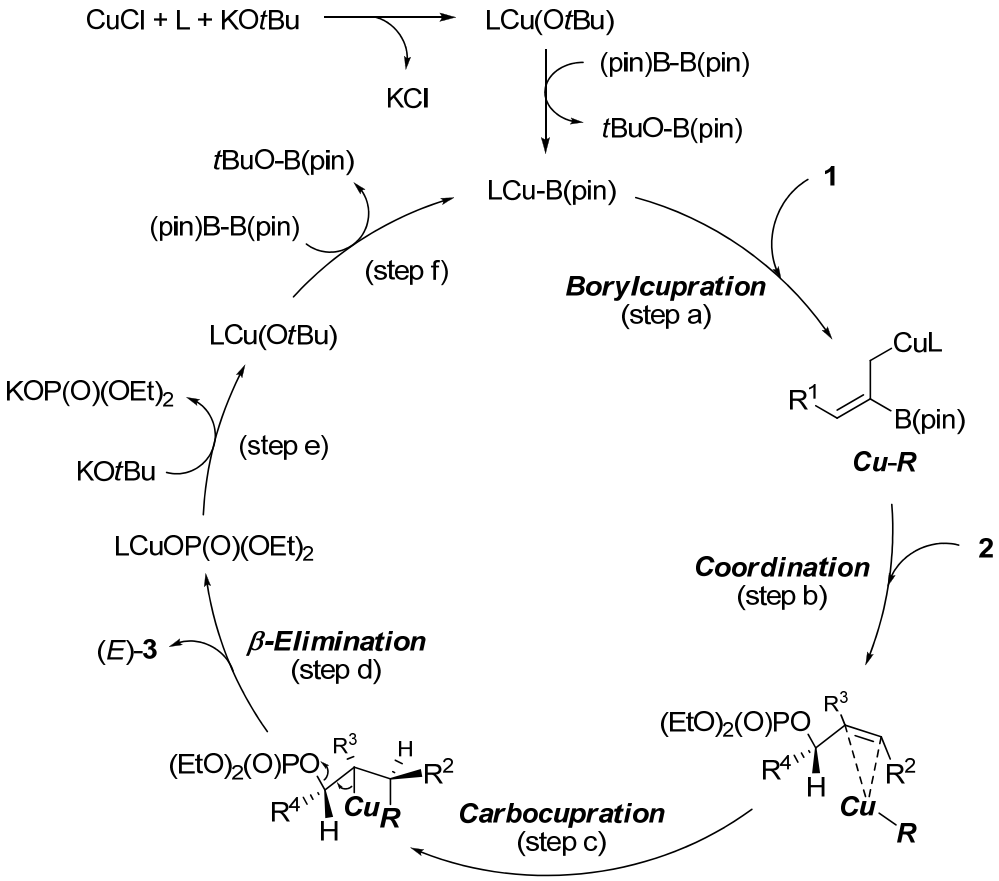
[a] An allene (0.75 mmol, 1.5 equiv), $B_2(pin)_2$ (0.80 mmol, 1.6 equiv), an allyl phosphate (0.50 mmol), CuCl (0.050 mmol, 10 mol %), ICy·HBF_4 (0.060 mmol, 12 mol %), KO*t*Bu (1.0 M solution of KO*t*Bu in THF, 750 μL, 1.5 equiv), THF (4.0 mL), 25 ºC, 24 h. [b] Yield of the isolated product. [c] A ratio of **3a**/other isomers was determined by GC after isolation. [d] The ratio of **3ad**/other isomers in the crude mixture.

To gain insights into the reaction mechanism, a stoichiometric reaction was carried out employing ^{Me}IMes, which is an effective ligand for allylboration of **1a** (Table 5-1, entry 11), as a ligand (Eq. 5-1). As described in Chapter 4, [(^{Me}IMes)CuB(pin)] (**4a**) smoothly inserted to **1a**, giving (*Z*)-*β*-boryl-*σ*-allylcopper (**5a**) selectively. The reaction between **5a** and (*Z*)-**2a** afforded **3aa** in 61% yield with high selectivity. This result clearly shows that the allylcopper (**5a**) is a real intermediate for the present reaction.



According to the result in Eq. 5-1 and the previous reports for the reaction of copper-catalyzed γ-selective allyl-alkyl coupling,[15a,g] a possible reaction mechanism was depicted in Scheme 5-2. First, a borylcopper was generated by the reaction between in situ generated copper alkoxide and $B_2(pin)_2$. As describing in Chapter 4, the borylcopper inserts into an allene smoothly and (*Z*)-σ-allylcopper is generated selectively (step a). The allylcopper species would coordinate to **2**, giving a π-complex (step b). The *syn*-addition of R-Cu across the C-C double bond of **2** occurs with *anti*-stereochemistry to form an alkylcopper intermediate. The alkylcopper complex undergoes *anti*-β-elimination to afford **3** and $LCuOP(O)(OEt)_2$ (step d). $LCuOP(O)(OEt)_2$ reacts with KO*t*Bu and LCu(O*t*Bu) is regenerated (step e). Finally, σ-bond metathesis between LCu(O*t*Bu) and $B_2(pin)_2$ affords the borylcopper species and the catalytic cycle is closed (step f).

Scheme 5-2. A possible reaction mechanism



5-3. Conclusion

In conclusion, the author has developed a copper-catalyzed highly regio- and stereoselective allylboration of terminal allenes. This methodology will be useful for developments of other carboborations.

5-4. Experimental Section

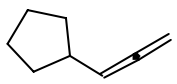
General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[16] ^{1}H NMR and $^{13}C\{^{1}H\}$ NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). EI-MS were recorded on a Shimadzu GCMS-QP5050A with a direct inlet. High-resolution mass spectra (EI-HRMS and ESI-HRMS) were obtained with JEOL JMX-SX102A and Thermo SCIENTIFIC Exactive LC-MS spectrometers. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-2014 with a capillary column (GL Sciences InertCap 5, 0.25 mm × 30 m).

Materials: Unless otherwise noted, commercially available chemicals were used as received. Anhydrous THF was purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[17] CuCl was purified according to a literature.[16]

Syntheses of Substrates: **1a** and **1c-e** were prepared according to the procedures in Chapter 4. **2a-d** were prepared according to the general method A as shown below.

Preparation of 1b: A flask was charged with THF (160 mL) and cyclopentylmagnesium bromide (2.0 M solution of cyclopentylmagnesium bromide in Et_2O, 100 mL, 200 mmol). To the solution, THF (16 mL) suspension of LiBr (4.0 g, 46

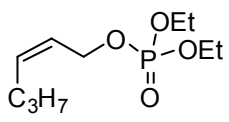
mmol) and CuBr (2.0 g, 14 mmol) was added at –78 ºC and the resulting solution was stirred for 20 min at –78 ºC. To the mixture, THF (20 mL) solution of propargyl bromide was added dropwise over 30 min at –78 ºC and the resulting mixture was stirred for 30 min –78 ºC. The mixture was slowly warmed up to room temperature and stirred overnight at room temperature. The reaction was quenched with NH_4Cl aq. and the mixture was filtrated through a pad of Celite. The mixture was extracted with Et_2O and the organic layer was dried over $MgSO_4$. After filtration, the solvents were removed in vacuo and then the product was purified by silica gel column chromatography (eluent: pentane). The product was further purified by vacuum distillation (b.p. 65 ºC (50 Torr)). **1b** was obtained in 30 % yield (6.4 g, 59 mmol) as colorless oil.



1b

^{1}H NMR (400 MHz, $CDCl_3$): δ 5.14 (dt, J = 6.8 Hz, 6.6 Hz, 1H), 4.67 (dd, J = 6.8 Hz, 2.7 Hz, 2H), 2.51–2.40 (m, 1H), 1.83–1.75 (m, 2H), 1.68–1.50 (m, 4H), 1.41–1.32 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): 207.4, 95.0, 75.3, 38.7, 32.7, 24.9. EI-HRMS: Calcd. for C_8H_{12} ($[M]^+$), 108.0934. Found, 108.0939.

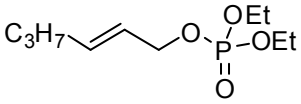
General method A for the preparation of allyl phosphates: A 100 mL round-bottom flask charged with DMAP (*N*,*N*-dimethyl-4-aminopyridine, 370 mg, 10 mol %) was evacuated and backfilled with argon. Anhydrous CH_2Cl_2 (30 mL), a corresponding allylalcohol (30 mmol) and pyridine (2.7 mL, 1.1 equiv) were added and the mixture was cooled at 0 ºC. To the solution, diethyl chlorophosphate (4.5 mL, 1.1 equiv) was added dropwise and the mixture was stirred at 0 ºC for 5 minutes. The mixture was allowed to warm up to room temperature and stirred overnight at room temperature. The resulting mixture was diluted with ether (50 mL) and washed successively with 1N HCl solution (15 mL x 3), saturated $NaHCO_3$ (15 mL x 3), and H_2O. The organic layer was dried over $MgSO_4$. After filtration and removal of the solvents *in vacuo*, distillation or silicagel column chromatography gave **2** as colorless oils.



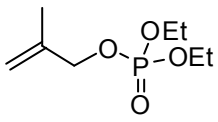
(*Z*)-**2a**

(*Z*)-**2a**: Yield 68% (4.8 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.66 (dt, J = 11.3, 6.8 Hz, 1H), 5.60 (dt, J = 11.3, 6.1 Hz, 1H), 4.60 (dd, J = 8.2 Hz, 6.3 Hz, 2H), 4.11 (dq, J = 7.4 Hz, 7.2 Hz, 4H), 2.08 (dt, J =

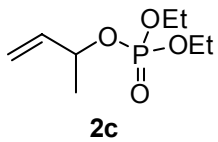
6.3 Hz, 7.2 Hz, 2H), 1.43-1.38 (m, 2H), 1.34 (td, J = 7.0 Hz, 0.9 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 135.1, 124.2 (d, J = 6.7 Hz), 63.66 (d, J = 5.7 Hz), 63.04 (d, J = 5.7 Hz), 29.44, 22.50, 16.10 (d, J = 6.7 Hz), 13.61. ESI-HRMS: Calcd. for $C_{10}H_{21}O_4P$ ($[M+H]^+$), 237.1250. Found, 237.1247.


(*E*)-**2a**

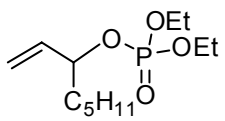
(*E*)-**2a**: Yield 69% (4.9 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.80 (dt, J = 15.4 Hz, 6.8 Hz, 1H), 5.60 (dtt, J = 15.4 Hz, 6.3 Hz, 1.4 Hz, 1H), 4.50–4.46 (m, 2H), 4.11 (dq, J = 7.7 Hz, 6.9 Hz, 4H), 2.04 (td, J = 7.2 Hz, 6.8 Hz, 2H), 1.41 (qt, J = 7.2 Hz, 7.2 Hz, 2H), 1.34 (td, J = 7.0 Hz, 0.9 Hz, 6H), 0.91 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 136.4, 124.5 (d, J = 6.7 Hz), 68.16 (d, J = 5.7 Hz), 63.64 (d, J = 5.7 Hz), 34.20, 21.98, 16.12 (d, J = 6.7 Hz), 13.61. All the resonances in ^{1}H NMR spectrum was consistent with reported values.[18]


2b

2b: Yield 70% (4.4 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.05 (br m, 1H), 4.95 (br m, 1H), 4.43 (d, J = 7.2 Hz, 2H), 4.14 (dq, J = 8.2 Hz, 7.1 Hz, 4H), 1.78 (br m, 3H), 1.35 (td, J = 7.0 Hz, 0.9 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 140.1 (d, J = 7.6 Hz), 113.1, 70.6 (d, J = 5.7 Hz), 63.8 (d, J = 5.7 Hz), 19.0, 16.1 (d, J = 6.7 Hz). All the resonances in ^{1}H and ^{13}C NMR spectra were consistent with reported values.[19]


2c

2c: Yield 50% (3.1 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.94–5.85 (m, 1H), 5.33–5.28 (m, 1H), 5.18–5.14 (m, 1H), 4.96–4.88 (m, 1H), 4.15–4.06 (m, 4H), 1.42 (d, J =6.3 Hz, 3H), 1.36–1.31 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 138.1 (d, J = 5.7 Hz), 115.8, 75.49 (d, J = 5.7 Hz), 63.45 (d, J = 4.8 Hz), 63.39 (d, J = 4.8 Hz), 21.78 (d, J = 4.8 Hz), 15.95 (d, J =6.7 Hz). All the resonances in ^{1}H NMR spectrum was consistent with reported values.[19]

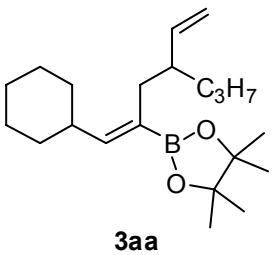

2d

2d: Yield 71% (5.6 g). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.88–5.79 (m, 1H), 5.36–5.28 (m, 1H), 5.25–5.19 (m, 1H), 4.74 (dt, J = 13.6 Hz, 6.8 Hz, 1H), 4.15–4.04 (m, 4H), 1.78–1.57 (m, 2H), 1.35–1.30 (m, 12H), 0.90–0.87 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 137.08 (d, J = 3.8 Hz), 117.1, 79.84 (d, J = 5.7 Hz), 63.53 (d, J = 2.9 Hz), 63.47 (d, J = 1.9 Hz),

35.78 (d, J = 5.7 Hz), 31.48, 24.36, 22.50, 16.13 (d, J = 2.9 Hz), 16.06 (d, J = 1.9 Hz), 13.96. ESI-HRMS: Calcd. for $C_{12}H_{25}O_4P$ ($[M+NH_4]^+$), 282.1829. Found, 282.1824.

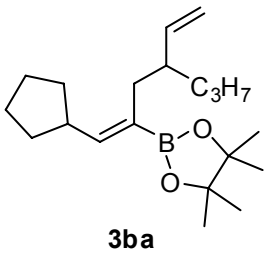
General Procedures for Table 5-1: CuCl (2.5 mg, 0.025 mmol, 10 mol %), a ligand (0.030 mmol, 12.0 mol %) and $B_2(pin)_2$ (100 mg, 0.40 mmol) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated for 1 h and backfilled with argon. THF (2.0 mL), **1a** (55 μL, 0.38 mmol) and (*Z*)**-2a** (59 μL, 0.25 mmol) were added in this order at room temperature under argon atmosphere. Then, KO*t*Bu (1.0 M solution of KO*t*Bu in THF, 380 μL, 0.38 mmol) was added at room temperature and the mixture was stirred at 25 ºC for 24 h. After the reaction, yield and isomer ratio of the product were determined by GC analysis relative to an internal standard (tridecane).

General Procedures for Table 5-2: CuCl (5.0 mg, 0.050 mmol, 10 mol %), ICy·BF_4 (19 mg, 0.060 mmol, 12.0 mol %) and $B_2(pin)_2$ (200 mg, 0.80 mmol) were placed in an oven dried 20 mL Schlenk flask. The flask was evacuated for 1 h and backfilled with argon. THF (4.0 mL), an allene (0.75 mmol) and an allyl phosphate (0.50 mmol) were added in this order at room temperature under argon atmosphere. Then, KO*t*Bu (1.0 M solution of KO*t*Bu in THF, 750 μL, 0.75 mmol) was added at room temperature and the mixture was stirred at 25 ºC for 24 h. After the reaction, the mixture was filtrated through a pad of Celite and silica gel. All of the volatiles were removed *in vacuo*. The products were obtained by silica gel column chromatography (eluent: hexane) or preparative GPC in the cases of **3da**, **3ea**, **3ab**, **3ac** and **3ad**. The configurations of **3ba**, **3ca** and **3da** were determined by NOESY spectrum.



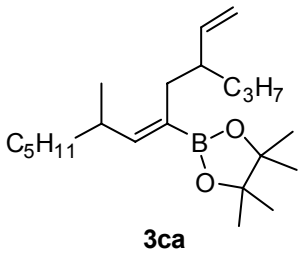
3aa

3aa: Yield 77% (129 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.10 (d, J = 9.5 Hz, 1H), 5.55 (ddd, J = 16.8 Hz, 10.4 Hz, 8.6 Hz, 1H), 4.88 (dd, J = 10.4 Hz, 2.3 Hz, 1H), 4.86 (dd, J = 16.8 Hz, 2.3 Hz, 1H), 2.30 (tdt, J = 11.1 Hz, 9.5 Hz, 3.6 Hz, 1H), 2.22–2.16 (m, 1H), 2.11–2.01 (m, 2H), 1.72–1.56 (m, 5H), 1.40–1.03 (m, 21H), 0.87 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.8, 143.4, 113.7, 82.91, 45.10, 37.64, 36.86, 34.23, 32.58, 26.07, 25.90, 24.72, 24.68, 20.39, 14.07. ESI-HRMS: Calcd. for $C_{21}H_{37}BO_2$ ($[M+H]^+$), 333.2959. Found, 333.2956.



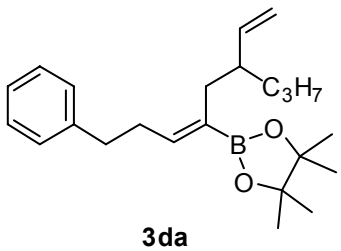
3ba

3ba: Yield 75% (119 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.21 (d, J = 9.5 Hz, 1H), 5.55 (ddd, J = 17.9 Hz, 9.3 Hz, 7.5 Hz, 1H), 4.88 (dd, J = 10.4 Hz, 2.3 Hz, 1H), 4.86 (dd, J = 16.8 Hz, 2.3 Hz, 1H), 2.80–2.69 (m, 1H), 2.23–2.19 (m, 2H), 2.14-2.01 (m, 2H), 1.79–1.71 (m, 2H), 1.69–1.62 (m, 2H), 1.61–1.50 (m, 2H), 1.40-1.18 (m, 18H), 0.86 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.6, 143.4, 113.7, 82.91, 45.11, 39.22, 36.83, 34.31, 33.44, 33.36, 25.68, 25.66, 24.73, 24.68, 20.41, 14.09. ESI-HRMS: Calcd. for $C_{20}H_{35}BO_2$ ($[M+NH_4]^+$),336.3068. Found, 336.3064.



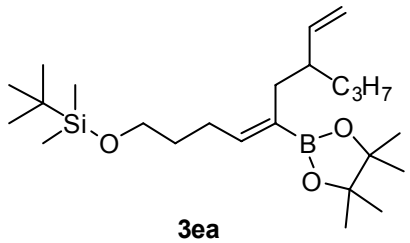
3ca

3ca: Yield 82% (143 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.05 (d , J = 10.0 Hz, 0.5H), 6.04 (d, J = 10.0 Hz, 0.5H), 5.60–5.49 (m, 1H), 4.89–4.83 (m, 2H), 2.52–2.43 (m, 1H), 2.22–2.14 (m, 1H), 2.11–2.06 (m, 2H), 1.37–1.17 (m, 24H), 0.93 (t, J = 6.6 Hz, 3H), 0.88–0.84 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 152.60, 152.57, 113.73, 113.71, 82.88, 45.12, 45.05, 37.03, 37.00, 36.83, 34.28, 32.78, 32.76, 32.10, 29.69, 27.32, 27.20, 24.80, 24.74, 24.65, 24.61, 22.64, 22.62, 20.59, 20.50, 20.43, 20.40, 14.09. ESI-APCI: Calcd. for $C_{22}H_{41}BO_2$ ($[M+H]^+$),349.3272. Found, 349.3275.



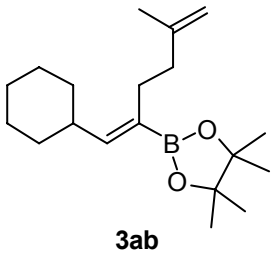
3da

3da: Yield 76% (135 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30–7.24 (m, 2H), 7.20–7.16 (m, 3H), 6.39 (t, J = 7.1 Hz, 1H), 5.53 (ddd, J = 16.6, 10.2, 8.8 Hz, 1H), 4.88 (dd, J =10.2, 2.0 Hz, 1H), 4.85 (dd, J = 16.6, 2.0 Hz, 1H), 2.71–2.67 (m, 2H), 2.45–2.39 (m, 2H), 2.20–2.15 (m, 1H), 2.12–2.02 (m, 2H), 1.35–1.16 (m, 16H), 0.85 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 145.2, 143.3, 142.2, 128.3, 125.8, 113.9, 83.04, 44.78, 36.92, 35.51, 34.21, 31.04, 24.73, 24.69, 20.40, 14.11. One peak could not be confirmed due to overwrapping. ESI-HRMS: Calcd. for $C_{23}H_{35}BO_2$ ($[M+H]^+$), 355.2803. Found, 355.2801.



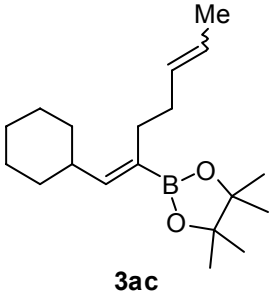
3ea

3ea: Yield 57% (120 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.31 (t, J = 7.2 Hz, 1H), 5.54 (ddd, J = 10.9 Hz, 8.6 Hz, 5.9 Hz, 1H), 4.87 (dd, J = 10.9 Hz, 2.3 Hz, 1H), 4.86 (dd, J = 16.8 Hz, 2.3 Hz, 1H), 3.61 (t, J = 6.6 Hz, 2H), 2.22–2.04 (m, 5H), 1.64–1.57 (m, 2H), 1.37–1.30 (m, 2H), 1.28–1.18 (m, 15H), 0.89 (s, 9H), 0.87–0.84 (m, 3H), 0.04 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.0, 143.4, 113.8, 82.98, 62.86, 44.84, 36.93, 34.14, 32.30, 25.96, 25.26, 24.74, 24.69, 20.42, 18.33, 14.12, –5.26. ESI-HRMS: Calcd. for $C_{24}H_{47}BO_3Si$ ($[M+NH_4]^+$), 440.3726. Found, 440.3729.



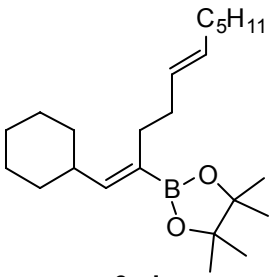
3ab

3ab: Yield 76% (116 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.09 (d, J = 9.5 Hz, 1H), 4.69–4.67 (m, 2H), 2.34 (tdt, J = 11.1 Hz, 9.5 Hz, 3.6 Hz, 1H), 2.28–2.24 (m, 2H), 2.05–2.01 (m, 2H), 1.75 (s, 3H), 1.73–1.60 (m, 4H), 1.34–1.19 (m, 15H), 1.18–1.06 (m, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.5, 146.3, 109.7, 82.95, 38.91, 37.47, 32.80, 27.21, 26.06, 25.92, 24.75, 22.60. ESI-HRMS: Calcd. for $C_{19}H_{33}BO_2$ ($[M+H]^+$), 305.2646. Found, 305.2642.



3ac

3ac: Yield 65% (99.8 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.09 (d, J = 9.5 Hz, 1H), 5.49–5.36 (m, 2H), 2.34 (tdt, J = 11.1 Hz, 10.0 Hz, 3.7 Hz, 1H), 2.18 (t, J = 7.5 Hz, 2H), 2.04–1.99 (m, 2H), 1.73–1.60 (m, 7H), 1.29–1.05 (m, 18H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.6, 131.6, 124.5, 82.91, 37.46, 33.65, 32.67, 28.80, 26.05, 25.90, 24.74, 17.93. ESI-HRMS: Calcd. for $C_{19}H_{33}BO_2$ ($[M+H]^+$), 305.2646. Found, 305.2642.



3ad

3ad: Yield 57% (102 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.09 (d, J = 9.5 Hz, 1H), 5.42 (dt, J = 15.4 Hz, 5.4 Hz, 1H), 5.39 (dt, J = 15.4 Hz, 5.4 Hz, 1H), 2.39–2.29 (m, 1H), 2.20–2.16 (m, 2H), 2.05-2.00 (m, 2H), 1.98–1.93 (m, 2H), 1.73–1.60 (m, 4H), 1.38–1.19 (m, 20H), 1.17–1.05 (m, 3H), 0.88 (t, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 151.6, 130.3, 130.2, 82.90,

37.44, 33.62, 32.68, 32.61, 31.49, 29.30, 28.95, 26.06, 25.90, 24.74, 22.57, 14.07. ESI-HRMS: Calcd. for $C_{23}H_{41}BO_2$ ($[M+NH_4]^+$), 378.3538. Found, 378.3536.

The procedures for Eq. 5-1: In a N_2 filled glove box, a 10 mL schlenk tube was charged with [(^{Me}IMes)CuB(pin)] (51 mg, 0.098 mmol). Out of the glove box, the precooled mixture of **1a** (15 μL, 0.098 mmol) and toluene (0.50 mL) was slowly added at –80 ºC and the resulting mixture was stirred at –80 ºC for 1 min. To the mixture, **2a** (23 μL, 0.098 mmol) was added at –80 ºC and the resulting mixture was stirred at 25 ºC for 26 h. The yield and selectivity of the products were determined by GC.

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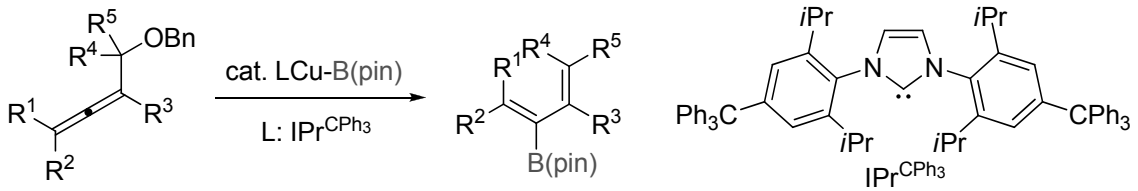
Chapter 6

Synthesis of 2-Boryl-1,3-butadiene Derivatives via Copper-Catalyzed Borylation of α-Benzyloxyallenes

Copper-catalyzed highly selective synthesis of 2-boryl-1,3-butadiene derivatives, which is difficult to be synthesize by previous methods, was developed. This reaction can supply various multi substituted 1,3-dienes selectively.



6-1. Introduction

1,3-Dienes are highly valuable synthetic intermediates in many organic syntheses including Diels-Alder reaction.[1] In addition, they are often observed in biologically active compounds[2] (Figure 6-1). Therefore, significant efforts have been paid to the selective synthesis of functionalized 1,3-dienes.[3,4,5] However, even now, their selective synthesis remains a difficult task. Among them, boryl substituted 1,3-diene derivatives are thought to be particularly valuable for the synthesis of highly substituted and functionalized 1,3-dienes since boryl moieties are known to be converted to carbon-carbon bonds and carbon-heteroatom bonds using well established reactions such as palladium-catalyzed Suzuki-Miyaura cross coupling,[6] rhodium-catalyzed conjugate addition,[7] copper-catalyzed C-N and C-O couplings[8] and copper or rhodium-catalyzed carboxylation.[9] Furthermore, boryl substituted 1,3-dienes are also useful intermediates for Diels-Alder reaction to afford cyclic allyl- and vinylboranes which are difficult to be synthesized by hydroboration.[10] Among boryl substituted 1,3-butadiene derivatives, 1-boryl-1,3-butadiene derivatives can be synthesized by hydroboration of 1,3-enynes.[11] In contrast, the synthetic methods for 2-boryl-1,3-butadiene derivatives are quite limited (Scheme 6-1). As stoichiometric reactions, Srebnik et al. reported zirconocene mediated homo or cross dimerization of alkynyl borane (Scheme 6-1a).[12] Suzuki and Miyaura et al. also reported the synthesis of 1-pincolboryl-1,3-butadiene by hydroboration of 1,4-dichloro-2-butyne followed by reduction with zinc (Scheme 6-1b).[13] Regarding catalytic reactions, Renaud et al. found that Ru-catalyzed enyne metathesis of alkynyl boranes afforded 2-boryl-1,3-butadiene derivatives (Scheme 6-1c).[14] However, these methods have narrow substrate scope and low selectivities.

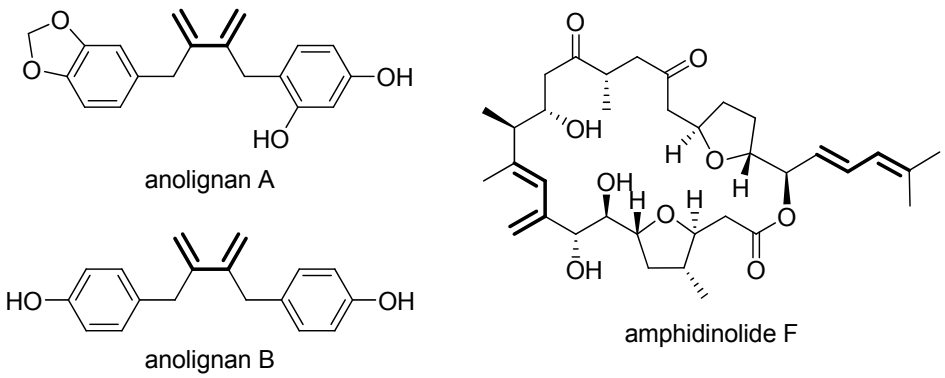
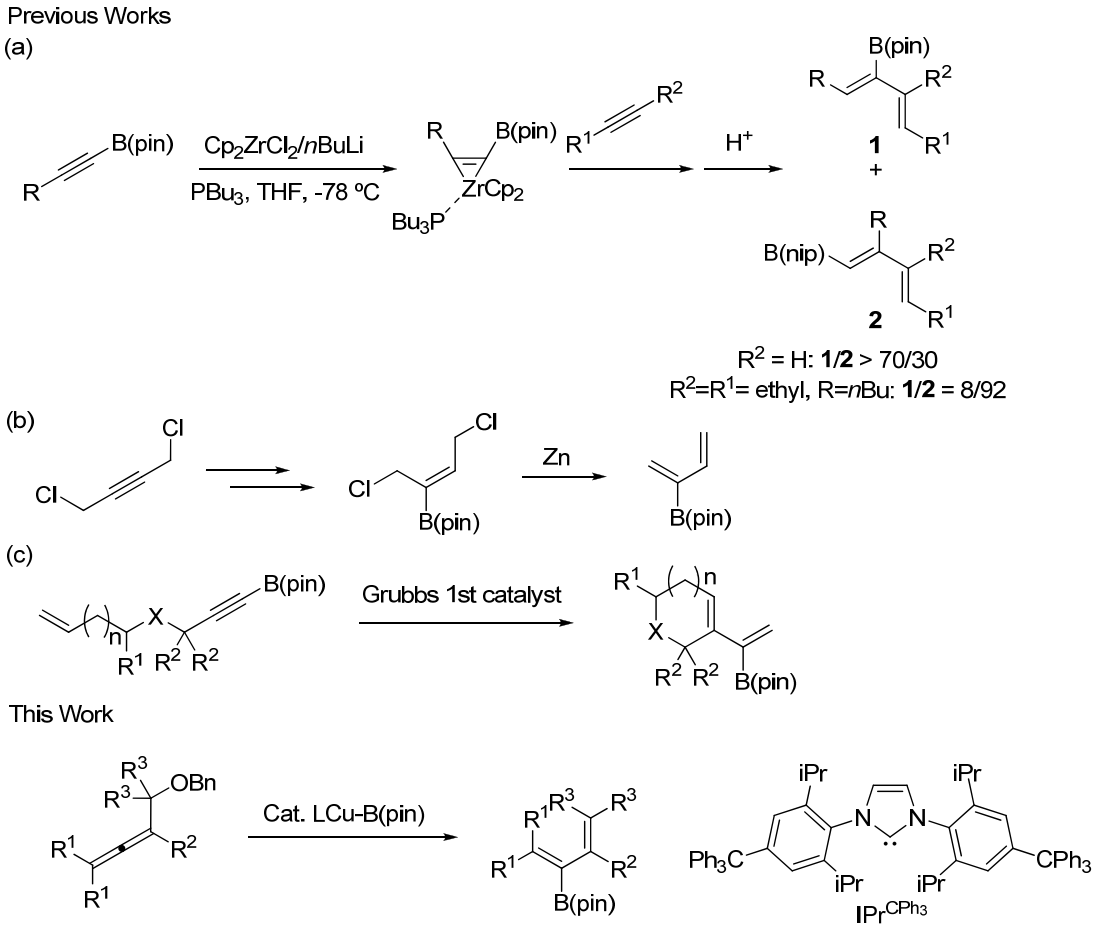


Figure 6-1. Biologically Active Compounds Containing 1,3-Diene Moieties

Scheme 6-1.



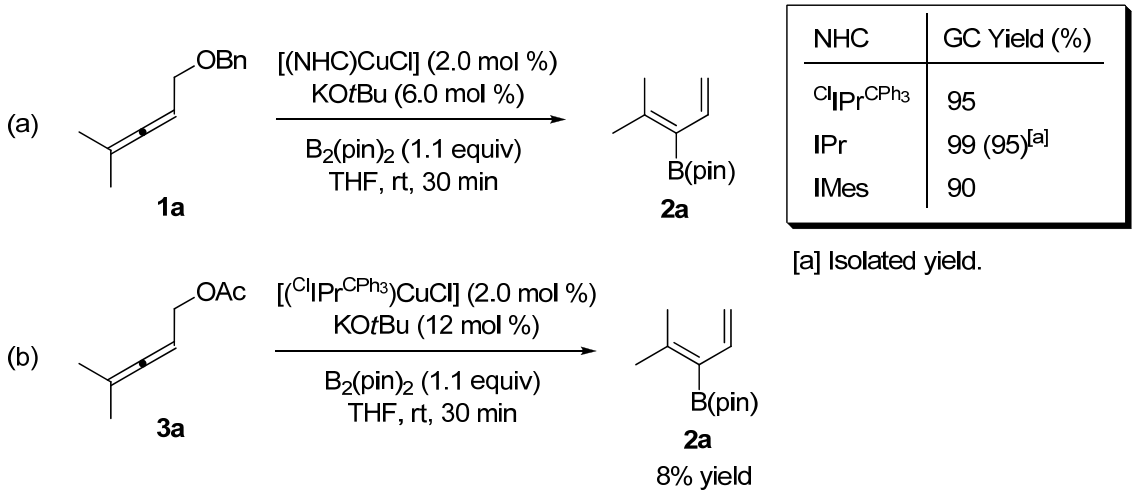
In Chapter 4 and 5, the author has described copper-catalyzed regioselective hydroboration of unsymmetrical internal alkynes, allenes and 1,3-dienes.[15] During the course of the study on copper-catalyzed hydroboration, the author found that 2-boryl-1,3-butadiene derivatives could be obtained from the reaction between borylcopper and allenes bearing a leaving group at alpha position. This reaction is a highly valuable method because various substituted 2-boryl-1,3-butadiene derivatives, which were difficult to be synthesized by previous methods, were obtained selectively from the corresponding substituted allenes with an ether moiety as a leaving group.

6-2. Result and Discussion

First, the reaction was carried out employing **1a** as a substrate in the presence of $B_2(pin)_2$ in THF at room temperature (Scheme 6-2a). Employing [(^{Cl}IPr^{CPh_3})CuCl][15b] (see Figure 6-2), which was an effective catalyst for hydroboration of allenes, a boryl

substituted diene (**2a**) was obtained in 95% GC yield after 30 min. Other complexes such as [(IPr)CuCl] and [(IMes)CuCl] also afforded **2a** in high yields. With [(IPr)CuCl] as a catalyst, **2a** was isolated in 95% yield. In this reaction, the benzyloxy group is highly effective as a leaving group. When the benzyloxy group was replaced with acetoxy group, which is a good leaving group for various transformations, the desired product was obtained in only 8% GC yield (Scheme 6-2b).

Scheme 6-2. Optimization of the reaction conditions



NHC	GC Yield (%)
^{Cl}IPr^{CPh_3}	95
IPr	99 (95)[a]
IMes	90

[a] Isolated yield.

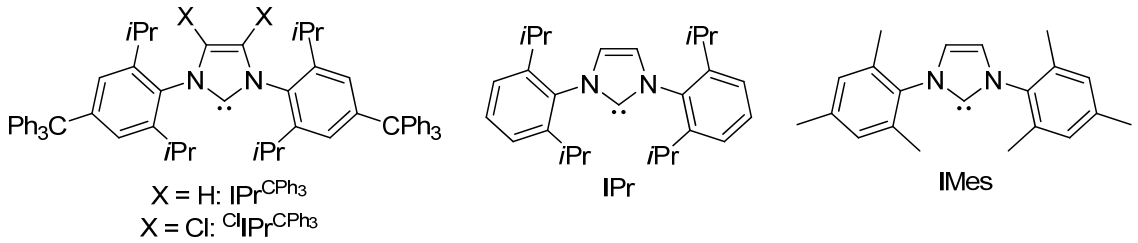
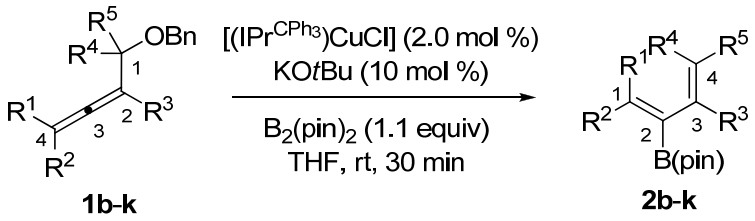


Figure 6-2. Structures of ligands

Next, the reaction was carried out employing various allenes using [(IPr^{CPh_3})CuCl] as a catalyst (Table 6-1). Employing a 4,4-disubstituted allene (**1b**), the 1,1-disubstituted 2-borylbutadiene (**2b**) was obtained in 85% yield (entry 1). Noteworthy is that in the case of **1c**, (*Z*)-**2c** was obtained in high yield with high stereoselectivity using [(Xantphos)CuCl] as a catalyst (entry 2). 2-Substituted allenes such as **1d** and **1e** were also good substrates for this reaction and the corresponding 3-substituted 2-borylbutadienes (**2d** and **2e**) were obtained in high yields with high

selectivities (entries 3 and 4). In the cases of symmetrical 1,1-disubstituted allenes such as **1f** and **1g**, 4,4-disubstituted 2-borylbutadienes (**2f** and **2g**) were obtained selectively in good to high yields (entries 5 and 6). In the case of **1f** and **1g**, a more convenient catalyst, which is [(IPr)CuCl], was also a good catalyst (entries 5 and 6 in parentheses). It is surprising that employing unsymmetrical 1,1-disubstituted allenes such as **1h** and **1i**, (*E*)-**2h** and (*E*)-**2i** were obtained with high stereoseletivities (entries 7 and 8). Finally, to obtain highly substituted 2-borylbutadienes, **1j** and **1k** were employed for this reaction (entries 9 and 10). As the results, multi-substituted 2-borylbutadienes (**2j** and **2k**) were successfully obtained (entries 9 and 10). Noteworthy is that all of the products in Table 6-1 are new compounds. This means that this transformation is very unique and gives a new opportunity for organic syntheses.

Table 6-1. Synthesis of various 2-boryl-1,3-butadiene derivatives[a]



1b-k **2b-k**

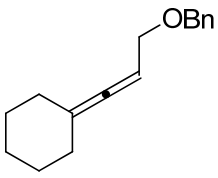
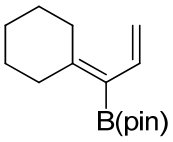
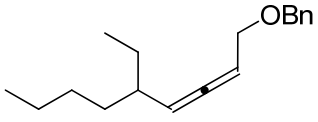
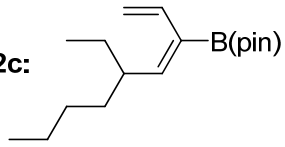
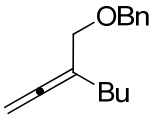
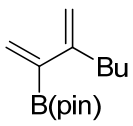
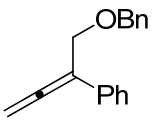
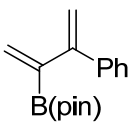
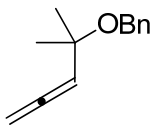
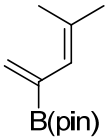
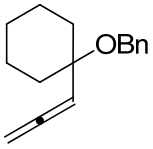
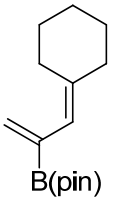
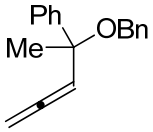
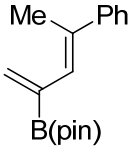
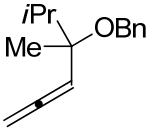
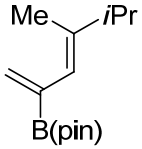
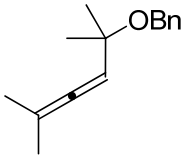
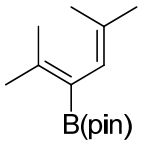
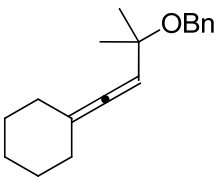
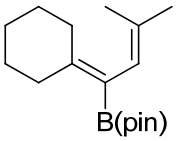
Entry	Substrate	Product	Yield (%)[b]
1	**1b:** 	**2b:** 	85
2[c]	**1c:** 	(*Z*)-**2c:** 	76 (*E*/*Z* = 6/94)
3	**1d:** 	**2d:** 	71
4	**1e:** 	**2e:** 	90

Table 6-1. (Continued)

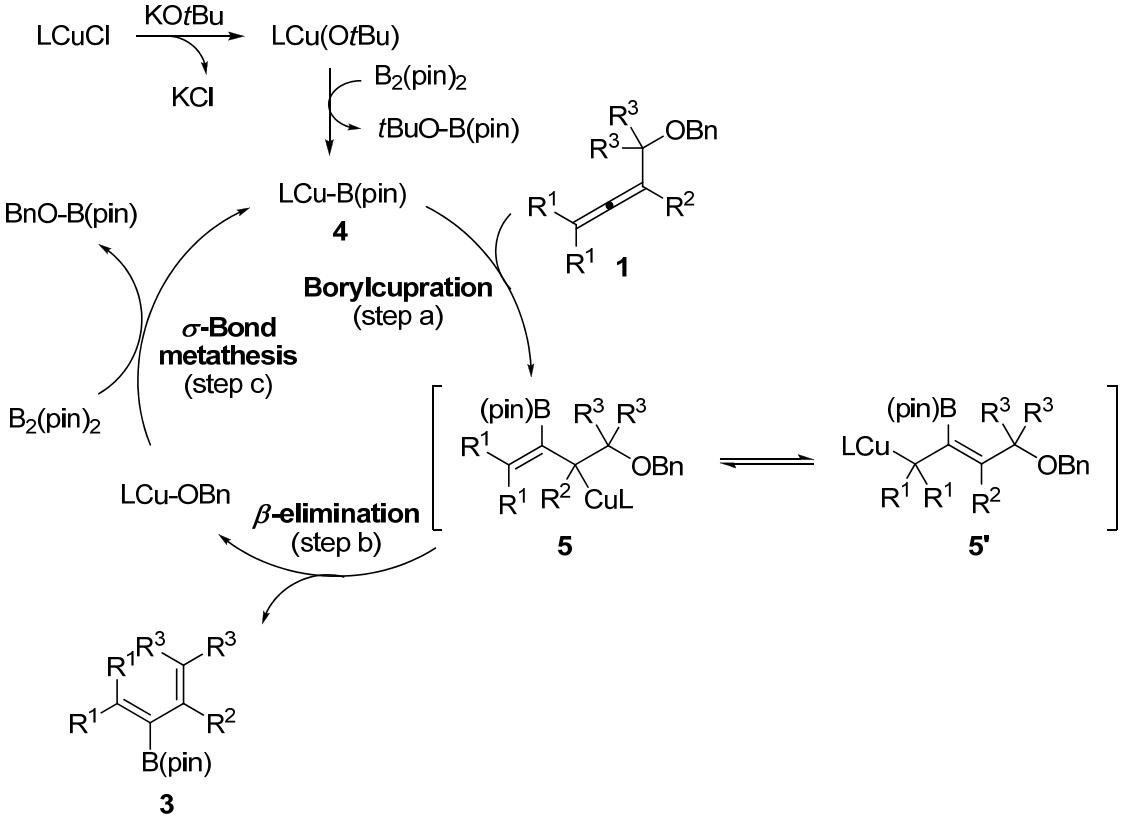
5	**1f:** 	**2f:** 	59 (67)[d]
6	**1g:** 	**2g:** 	62 (78)[d,e]
7[f]	**1h:** 	(*E*)-**2h:** 	63 (*E*/*Z* = 96/4)
8[g]	**1i:** 	(*E*)-**2i:** 	96 (*E*/*Z* = 90/10)
9	**1j:** 	**2j:** 	87
10[h]	**1k:** 	**2k:** 	99

[a] [(IPr^{CPh_3})CuCl] (0.0050 mmol, 2.0 mol %), KO*t*Bu (25 μL of 1.0 M solution in THF, 10 mol %), $B_2(pin)_2$ (0.28 mmol), an allene (0.25 mmol), THF (0.50 mL), at room temperature, for 30 min. [b] Isolated yield. [c] [(Xantphos)CuCl] (0.0050 mmol, 2.0 mol %) was used. [d] [(IPr)CuCl] (0.0050 mmol, 2.0 mol %) was used. [e] At 10 ºC. [f] At 0 ºC, for 11 h. [g] At –40 ºC, for 17 h. [h] At 60 ºC, for 14 h.

A plausible reaction mechanism was depicted in Scheme 6-3. First, a borylcopper species (**4**) is generated by the reaction between a copper alkoxide and $B_2(pin)_2$. The borylcopper inserts into an allene affording allylcopper intermediates **5** or **5'** (step a). *β*-Elimination of a benzyloxy moiety from **5** affords a product (**3**) and a copper alkoxide

(LCuOBn) (step b). Finally, σ-bond metathesis between LCuOBn and $B_2(pin)_2$ gives a borylcopper.

Scheme 6-3. A plausible reaction mechanism



6-3. Conclusion

In conclusion, the author has developed highly selective synthesis of 2-boryl-1,3-butadiene derivatives employing allenes with an benzyloxy group as a leaving group and $B_2(pin)_2$ in the presence of a copper catalyst. This method can supply a new kind of boronic esters and that boronic esters are expected to be used as new building blocks for various transformation.

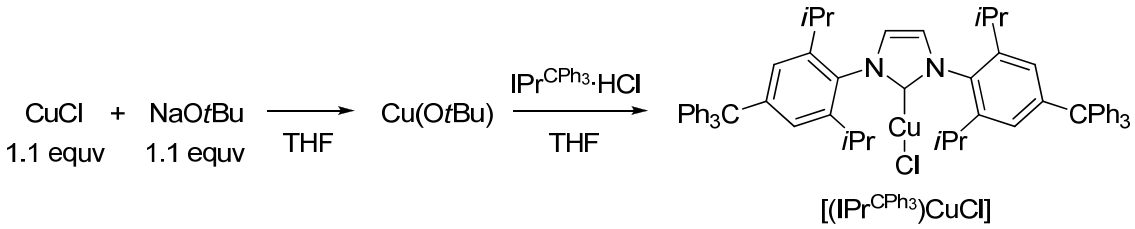
6-4. Experimental Section

General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[16] ^1H NMR and $^{13}C\{^1H\}$ NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^1H

NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). EI-MS were recorded on a Shimadzu GCMS-QP5050A with a direct inlet. High-resolution mass spectra (EI-HRMS and ESI-HRMS) were obtained with JEOL JMX-SX102A and Thermo SCIENTIFIC Exactive LC-MS spectrometers. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-2014 with a capillary column (GL Sciences InertCap 5, 0.25 mm × 30 m).

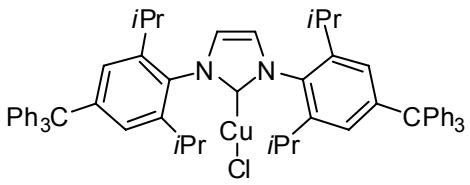
Materials: Unless otherwise noted, commercially available chemicals were used as received. Anhydrous THF was purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[17] [(^{Cl}IPr^{CPh_3})CuCl],[18] [(IPr)CuCl][19] and [(IMes)CuCl][19] were prepared according to the literature.

Preparation of [(IPr^{CPh_3})CuCl]



In a N_2 filled glove box, a flask was charged with CuCl (240 mg, 2.5 mmol), NaO*t*Bu (240 mg, 2.5 mmol) and THF (15 mL), and the mixture was stirred at room temperature for 1 h. To the resulting mixture, IPr^{CPh_3}·HCl (2.0 g, 2.2 mmol) was added and the mixture was stirred overnight at room temperature. Out of the glove box, the mixture was filtrated through a pad of Celite under air. All of the volatiles were removed in vacuo. To the mixture, CH_2Cl_2 was added and the mixture was filtrated through a pad of Celite. The solvent was removed in vacuo. and then the product was purified by silica gel column chromatography (eluent: hexane/CH_2Cl_2 = 1/1). The desired product was

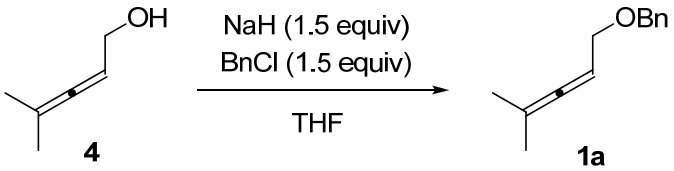
further purified by recrystallization from CH_2Cl_2/hexane. [(IPr^{CPh_3})CuCl] was obtained as a white solid in 48% yield (1.1 g, 1.1 mmol).



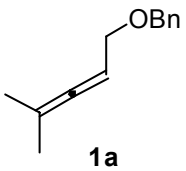
[(IPr^{CPh_3})CuCl]

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.31–7.26 (m, 24H), 7.22–7.18 (m, 6H), 7.14 (s, 4H), 7.13 (s, 2H), 2.48 (sept, J = 6.8 Hz, 4H), 1.14 (d, J = 6.8 Hz, 12H), 1.00 (d, J = 6.8 Hz, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 181.0, 149.0, 146.4, 144.2, 132.1, 131.1, 127.6, 127.2, 126.0, 123.0, 65.3, 28.7, 24.6, 23.7. ESI-HRMS: Calcd. for $C_{65}H_{64}N_2CuCl$ ($[M+NH_4]^+$), 988.4392. Found, 988.4380.

Preparation of 1a.

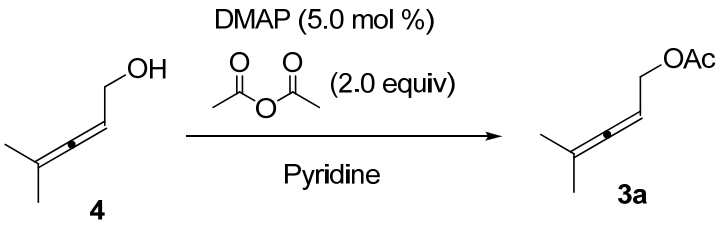


A flask was charged with NaH (60% oil dispersion, 350 mg, 7.5 mmol) and THF (3.0 mL). To the mixture, THF (3.0 mL) solution of **4**[20] (670 μL, 6.0 mmol) was added dropwise at room temperature. To the mixture, BnCl (1.0 mL, 9.0 mmol) was added and the resulting mixture was stirred overnight at 50 ºC. The reaction was quenched withH_2O and the mixture was extracted with Et_2O. The organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by silica gel column chromatography (eluent: hexane/Et_2O = 80/1 to 40/1). **1a** was obtained in 56% yield (630 mg, 3.3 mmol).

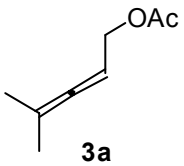


^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.27 (m, 5H), 5.13–5.07 (m, 1H), 4.53 (s, 2H), 4.01 (d, J = 6.8 Hz, 2H), 1.71 (d, J = 3.2 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 203.0, 138.4, 128.3, 127.9, 127.5, 95.9, 86.2, 71.4, 68.9, 20.4. ESI-HRMS: Calcd. for $C_{13}H_{16}O$ ($[M+H]^+$), 189.1274. Found, 189.1274.

Preparation of 3a.

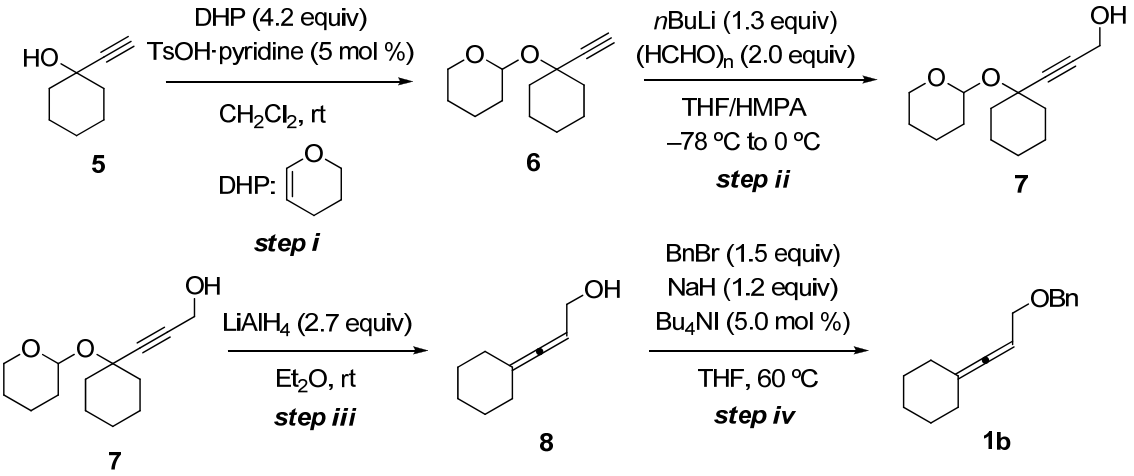


A flask was charged with DMAP (37 mg, 0.30 mmol), pyridine (12 mL), **4** (670 μL, 6.0 mmol) and Ac_2O (1.1 mL, 12 mmol) and the mixture was stirred overnight at room temperature. The reaction was quenched with$NaHCO_3$ aq. and the mixture was extracted with Et_2O. The organic layer was washed with 1N HCl aq. and then dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by silica gel column chromatography (eluent: hexane/CH_2Cl_2 = 5/1). **3a** was obtained in 70% yield (580 mg, 4.2 mmol).



^{1}H NMR (400 MHz, $CDCl_3$): δ 5.13–5.07 (m, 1H), 4.51 (d, J = 6.3 Hz, 2H), 2.06 (s, 3H), 1.71 (d, J = 2.7 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 203.3, 170.8, 97.2, 84.7, 63.4, 21.0, 20.2. ESI-HRMS: Calcd. for $C_8H_{12}O_2$ ($[M+NH_4]^+$), 158.1176. Found, 158.1177.

Preparation of 1b.



step i: A flask was charged with TsOH·pyridine (1.9 g, 7.5 mmol), CH_2Cl_2 (60 mL), 5 (19 mL, 150 mmol) and dihydropyrane (58 mL, 630 mmol) and the resulting mixture was stirred overnight at room temperature. All of the volatiles were removed in vacuo.

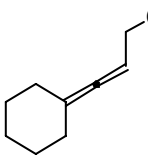
To the mixture, H_2O was added and the resulting mixture was extracted with Et_2O. The organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by vacuum distillation. **6** was obtained in 91% yield (29 g, 140 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.13 (dd, J = 5.2 Hz, 3.4 Hz, 1H), 3.99–3.94 (m, 1H), 3.54–3.48 (m, 1H), 2.49 (s, 1H), 2.07–2.01 (m, 1H), 1.91–1.80 (m, 2H), 1.75–1.48 (m, 12H), 1.29–1.21 (m, 1H).

step ii: A flask was charged with **6** (10 g, 50 mmol) and THF (40 mL). To the mixture, *n*BuLi (40 mL of 1.65 M solution in hexane, 65 mmol) was added dropwise at –78 ºC. The mixture was warmed up to 0 ºC, and HMPA (11 mL) and $(HCHO)_n$ (3.0 g, 100 mmol) were added. The mixture was slowly warmed up to room temperature and stirred overnight at room temperature. The reaction mixture was quenched withNH_4Cl aq. and the solvents were removed in vacuo. The mixture was extracted with Et_2O and the organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by silica gel column chromatography (eluent: hexane/EtOAc = 10/1 to 5/1). **7** was obtained in 80% yield (9.6 g, 40 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.14–5.12 (m, 1H), 4.32 (d, J = 6.3 Hz, 2H), 3.99–3.94 (m, 1H), 3.54–3.48 (m, 1H), 2.03–1.98 (m, 2H), 1.88–1.83 (m, 2H), 1.72–1.49 (m, 12H), 1.30–1.21 (m, 1H).

step iii: A flask was charged with $LiAlH_4$ (4.1 g, 110 mmol) and dry Et_2O (40 mL). To the suspension, Et_2O (40 mL) solution of **7** was added dropwise at room temperature and the mixture was stirred overnight at room temperature. The reaction was quenched with H_2O and 1N HCl aq. and then the mixture was filtrated through a pad of Celite. The mixture was extracted with Et_2O and the organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by silica gel column chromatography (eluent: hexane/EtOAc = 10/1). **8** was obtained in 62% yield (3.5 g, 25 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.24–5.19 (m, 1H), 4.07 (dd, J = 5.8 Hz, 5.8 Hz, 2H), 2.16–2.12 (m, 4H), 1.64–1.45 (m, 7H).

step iv: A flask was charged with NaH (60% oil dispersion, 1.2 g, 30 mmol) and THF (30 mL). To the suspension, THF (20 mL) solution of **8** was added dropwise at room temperature and the resulting suspension was stirred at room temperature for 1 h. To the mixture, Bu_4NI (470 mg, 1.3 mmol) and BnBr (4.5 mL, 38 mmol) were added in this order and then the mixture was stirred overnight at 60 ºC. The mixture was cooled to room temperature. To the mixture, H_2O and 1N HCl aq. were added and the mixture

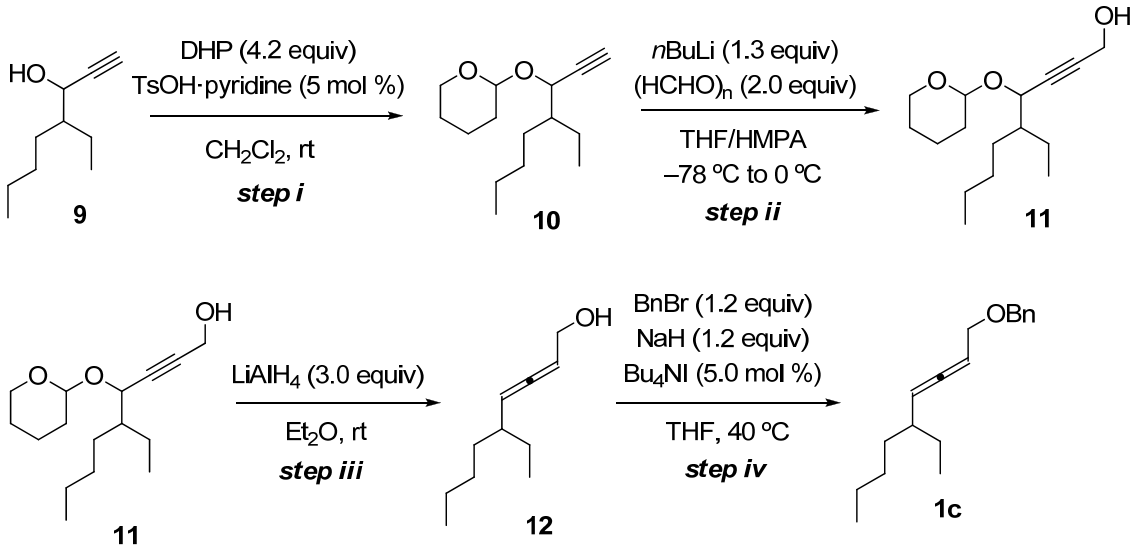
was extracted with Et_2O. The organic layer was dried over $MgSO_4$. After filtration, all of the volatiles were removed in vacuo. The product was purified by silica gel column chromatography (eluent: hexane/Et_2O = 100/1 to 50/1). **1b** was obtained in 94% yield (5.4 g, 24 mmol).



1b

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.26 (m, 5H), 5.13–5.08 (m, 1H), 4.53 (s, 2H), 4.01 (d, J = 6.8 Hz, 2H), 2.15–2.12 (m, 4H), 1.62–1.49 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 199.9, 138.4, 128.3, 127.9, 127.5, 103.1, 86.0, 71.2, 69.2, 31.4, 27.3, 26.0. All the resonances in ^{1}H spectrum were consistent with reported values.[21]

Preparation of 1c.

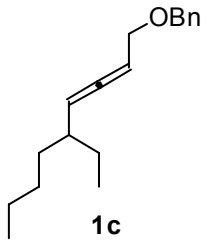


step i: Similar procedures for the synthesis of **6** were employed and **9** (25 mL, 140 mmol) was used. A mixture of diastereomixtures of **10** was obtained in 97% yield (32 g, 140 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.00–4.98 (m, 1H), 4.71–4.70 (m, 1H), 4.46–4.43 (m, 1H), 4.29–4.28 (m, 1H), 4.07–4.01 (m, 1H), 3.82–3.77 (m, 1H), 3.56–3.51 (m, 2H), 2.40 (d, J = 2.3 Hz, 1H), 2.35 (d, J = 2.3 Hz, 1H), 1.87–1.29 (m, 28H), 0.96–0.88 (m, 12H).

step ii: Similar procedures for the synthesis of **7** were employed and **10** (12 g, 50 mmol) was used. **11** was roughly purified by silica gel column chromatography and then used for step iii.

step iii: Similar procedures for the synthesis of **8** were employed and **11** (11 g, 39 mmol) was used. A mixture of diastereomixtures of **12** was obtained in 56% yield (3.7 g, 22 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.35–5.30 (m, 1H), 5.13–5.08 (m, 1H), 4.12 (dd, J = 6.1 Hz, 2.9 Hz, 1H), 1.98–1.90 (m, 1H), 1.49–1.26 (m, 10H), 0.92–0.88 (m, 6H).

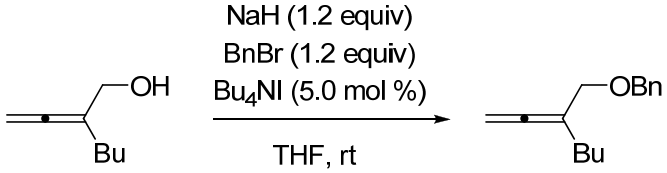
step iv: Similar procedures for the synthesis of **1b** were employed and **12** (3.7 g, 22 mmol) was used. A mixture of diastereomixtures of **1c** was obtained in 85% yield (4.8 g, 19 mmol).



1c

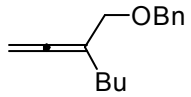
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.26 (m, 5H), 5.27–5.22 (m, 1H), 5.04–4.99 (m, 1H), 4.53 (s, 2H), 4.05 (dt, J = 7.1 Hz, 1.9 Hz, 2H), 1.99–1.90 (m, 1H), 1.49–1.23 (m, 8H), 0.91–0.86 (m, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 204.87, 204.85, 138.3, 128.3, 127.8, 127.6, 95.9, 88.2, 71.6, 68.93, 68.90, 41.12, 41.05, 34.64, 34.45, 29.42, 29.38, 28.07, 27.96, 22.79, 22.74, 14.1, 11.65, 11.56. ESI-HRMS: Calcd. for $C_{18}H_{26}O$ ($[M+NH_4]^+$), 276.2322. Found, 276.2322.

Preparation of 1d.



13 **1d**

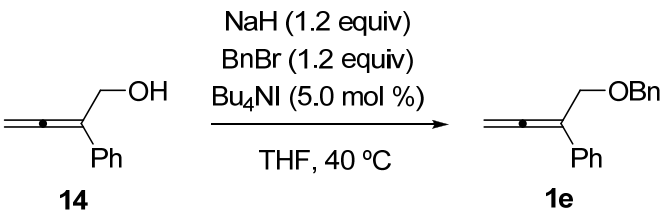
Similar procedures for the synthesis of **1b** were employed and **13**[22] (630 mg, 5.0 mmol) was used. **1d** was obtained in 24% yield (260 mg, 1.2 mmol).



1d

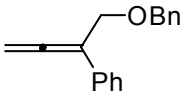
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.26 (m, 5H), 4.75 (br s, 2H), 4.50 (s, 2H), 4.02 (br s, 2H), 2.07–2.01 (m, 2H), 1.48–1.31 (m, 4H), 0.91 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 206.8, 138.3, 128.3, 127.8, 127.6, 100.6, 75.6, 71.5, 71.1, 29.6, 28.7, 22.4, 13.9. ESI-HRMS: Calcd. for $C_{15}H_{20}O$ ($[M+NH_4]^+$), 234.1852. Found, 234.1851.

Preparation of 1e.



14 **1e**

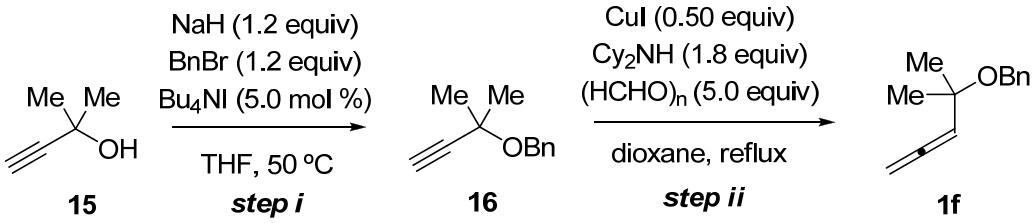
Similar procedures for the synthesis of **1b** were employed and **14**[22] (1.0 g, 7.1 mmol) was used. **1e** was obtained in 22% yield (370 mg, 1.6 mmol).



1e

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.50 (d, J = 7.2 Hz, 2H), 7.35–7.26 (m, 7H), 7.22 (d, J = 7.5 Hz, 1H), 5.17 (t, J = 2.0 Hz, 2H), 4.57 (s, 2H), 4.50 (t, J = 2.0 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): 209.7, 138.1, 134.3, 128.4, 128.3, 128.0, 127.6, 126.9, 126.4, 102.0, 78.1, 71.5, 69.4. ESI-HRMS: Calcd. for $C_{17}H_{16}O$ ($[M+NH_4]^+$), 254.1539. Found, 254.1538.

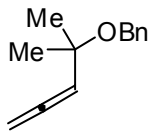
Preparation of 1f.



15 **16** **1f**

step i: Similar procedures for the synthesis of **1b** were employed and **15** (4.0 mL, 42 mmol) was used. **16** was obtained in 81% yield (5.8 g, 34 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.41–7.24 (m, 5H), 4.64 (s, 2H), 2.47 (s, 1H), 1.56 (s, 6H).

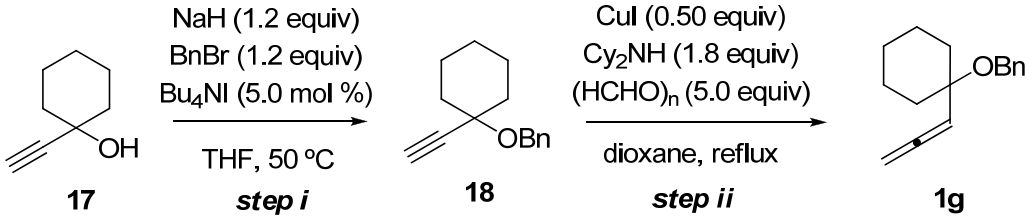
step ii: A flask was charged with $(CH_2O)_n$ (750 mg, 25 mmol), CuI (960 mg, 5.0 mmol) and dioxane (15 mL). To the suspension, **16** (1.7 g, 10 mmol) and Cy_2NH (3.6 mL, 18 mmol) were added sequentially. The resulting mixture was stirred overnight under reflux. Water and Et_2O were added and then the mixture was filtrated by Celite. The organic layer was extracted with Et_2O, washed with 1N HCl aq. and H_2O and dried over $MgSO_4$. After filtration, the solvent was removed and **1f** was afforded by silica gel column chromatography (eluent: hexane/Et_2O = 80/1) in 49 % yield (920 mg, 4.9 mmol).



1f

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.22 (m, 5H), 5.24 (t, J = 6.8 Hz, 1H), 4.85 (d, J = 6.8 Hz, 2H), 4.44 (s, 2H), 1.39 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 207.5, 139.5, 128.3, 127.5, 127.2, 97.0, 77.0, 74.5, 65.1, 26.9. ESI-HRMS: Calcd. for $C_{13}H_{16}O$ ($[M+NH_4]^+$), 206.1539. Found, 206.1541.

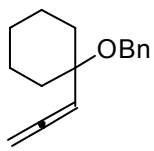
Preparation of 1g.



17 ***step i*** **18** ***step ii*** **1g**

step i: Similar procedures for the synthesis of **1b** were employed and **17** (5.2 g, 42 mmol) was used. **18** was obtained in 76% yield (6.8 g, 32 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.39–7.24 (m, 5H), 4.65 (s, 2H), 2.51 (s, 1H), 2.00–1.94 (m, 2H), 1.75–1.66 (m, 4H), 1.62–1.49 (m, 3H), 1.38–1.27 (m, 1H).

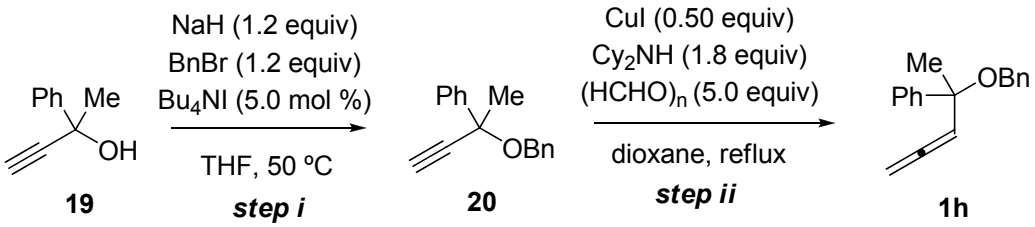
step ii: Similar procedures for the synthesis of **1f** were employed and **18** (3.2 g, 15 mmol) was used. **1g** was obtained in 17% yield (585 mg, 2.6 mmol).



1g

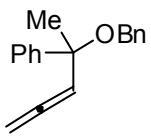
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.30 (m, 4H), 7.26–7.22 (m, 1H), 5.13 (t, J = 6.8 Hz, 1H), 4.84 (d, J = 6.8 Hz, 2H), 4.41 (s, 2H), 1.85–1.80 (m, 2H), 1.68–1.58 (m, 4H), 1.52–1.44 (m, 3H), 1.39–1.30 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): 208.3, 139.7, 128.2, 127.5, 127.1, 96.1, 76.7, 75.6, 63.8, 35.3, 25.7, 22.3. ESI-HRMS: Calcd. for $C_{16}H_{20}O$ ($[M+NH_4]^+$), 246.1852. Found, 246.1853.

Preparation of 1h.



step i: Similar procedures for the synthesis of **1b** were employed and **19** (6.1 g, 42 mmol) was used. **20** was obtained in 61% yield (6.1 g, 26 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.70–7.68 (m, 2H), 7.41–7.23 (m, 8H), 4.65 (d, J = 10.9 Hz, 1H), 4.17 (d, J = 10.9 Hz, 1H), 2.78 (s, 1H), 1.82 (s, 3H).

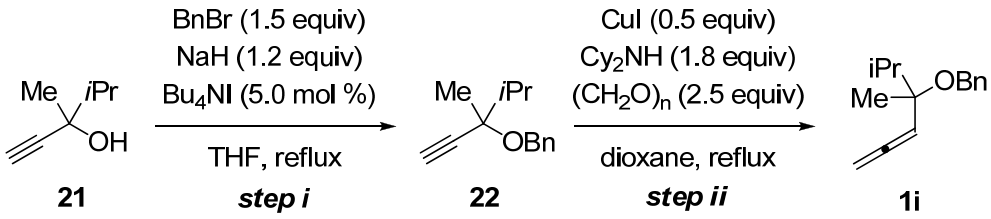
step ii: Similar procedures for the synthesis of **1f** were employed and **20** (3.5 g, 15 mmol) was used. **1h** was obtained in 33% yield (1.2 g, 4.9 mmol).



1h

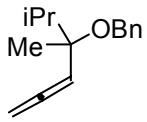
^{1}H NMR (400 MHz, $CDCl_3$): δ 7.56–7.53 (m, 2H), 7.40–7.32 (m, 6H), 7.28–7.24 (m, 2H), 5.52 (t, J = 6.8 Hz, 1H), 4.95 (d, J = 6.8 Hz, 2H), 4.51 (d, J = 11.3 Hz, 1H), 4.48 (d, J = 11.3 Hz, 1H), 1.67 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 208.1, 145.9, 139.3, 128.3, 128.2, 127.3, 127.2, 127.1, 125.9, 95.5, 78.6, 77.7, 65.2, 26.7. ESI-HRMS: Calcd. for $C_{18}H_{18}O$ ($[M+H]^+$), 251.1430. Found, 251.1430.

Preparation of 1i.



step i: Similar procedures for the synthesis of **1b** were employed and **21** (6.4 mL, 50 mmol) was used. **22** was obtained in 51% yield (5.2 g, 26 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.37–7.30 (m, 4H), 7.27–7.23 (m, 1H), 4.70 (d, J = 11.3 Hz, 1H), 4.58 (d, J = 11.3 Hz, 1H), 2.47 (s, 1H), 2.00 (sept, J = 6.8 Hz, 1H), 1.44 (s, 3H), 1.08 (d, J = 6.8 Hz, 1H), 1.03 (d, J = 6.8 Hz, 1H).

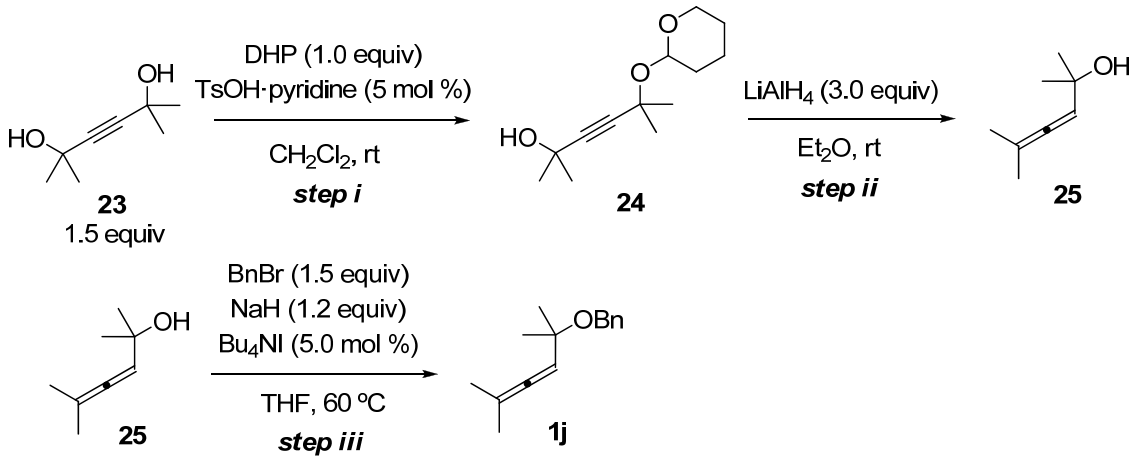
step ii: Similar procedures for the synthesis of **1f** were employed and **22** (3.0 g, 15 mmol) was used. **1i** was obtained in 37% yield (1.2 g, 5.5 mmol).



1i

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.29 (m, 4H), 7.25–7.22 (m, 1H), 5.14 (t, J = 6.6 Hz, 1H), 4.82 (d, J = 6.8 Hz, 2H), 4.48 (d, J = 11.8 Hz, 1H), 4.43 (d, J = 11.8 Hz, 1H), 1.92 (sept, J = 6.8 Hz, 1H), 1.25 (s, 3H), 0.97 (t, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 208.9, 140.4, 128.5, 127.4, 127.3, 95.0, 80.0, 76.7, 64.7, 37.9, 18.6, 18.1, 17.6. ESI-HRMS: Calcd. for $C_{15}H_{20}O$ ($[M+H]^+$), 217.1587. Found, 217.1588.

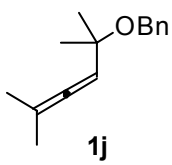
Preparation of 1j.



step i: Similar procedures for the synthesis of **6** were employed and **23** (14 g, 100 mmol) was used. **24** was afforded by silica gel column chromatography (eluent: hexane/EtOAc = 10/1 to 3/1) in 27% yield (4.1 g, 18 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.03 (dd, J = 5.2 Hz, 3.4 Hz, 1H), 3.98–3.93 (m, 1H), 3.53–3.47 (m, 1H), 2.33 (s, 1H), 1.89–1.80 (m, 1H), 1.73–1.66 (m, 1H), 1.57–1.51 (m, 13H), 1.46 (s, 3H).

step ii: Similar procedures for the synthesis of **8** were employed and **24** (4.1 g, 18 mmol) was used. **25** was obtained in 19% yield (440 mg, 3.5 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.17 (t, J = 2.7 Hz, 1H), 1.73 (d, J = 2.7 Hz, 6H), 1.67–1.66 (br m, 1H), 1.32 (s, 6H).

step iii: Similar procedures for the synthesis of **1b** were employed and **25** (630 mg, 5.0 mmol) was used. **1j** was obtained in 72% yield (780 mg, 3.6 mmol).

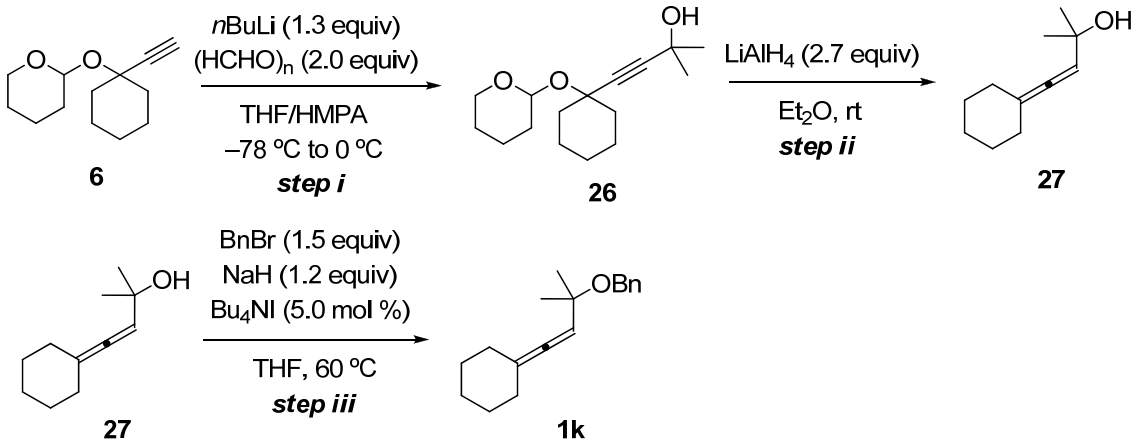


1j

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.36–7.29 (m, 4H), 7.26–7.21 (m, 1H), 5.03 (sept, J = 2.7 Hz, 1H), 4.44 (s, 2H), 1.73 (d, J = 2.7 Hz, 6H), 1.34 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 201.1, 139.8, 128.2, 127.5, 127.1,

97.3, 95.5, 75.4, 64.9, 27.0, 20.5. All the resonances in ^{1}H and ^{13}C spectra were consistent with reported values.[23]

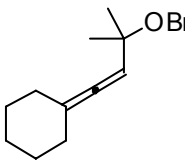
Preparation of 1k.



step i: Similar procedures for the synthesis of **7** were employed and **6** (10 g, 50 mmol) was used. **26** was obtained in 59% yield (7.8 g, 29 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.10–5.08 (m, 1H), 3.99–3.94 (m, 1H), 3.53–3.47 (m, 1H), 2.26 (s, 1H), 2.02–1.96 (m, 1H), 1.90–1.81 (m, 2H), 1.70–1.47 (m, 18H), 1.29–1.19 (m, 1H).

step ii: Similar procedures for the synthesis of **8** were employed and **26** (7.8 g, 29 mmol) was used. **27** was obtained in 35% yield (1.7 g, 10 mmol). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.20–5.18 (m, 1H), 2.20–2.07 (m, 4H), 1.68–1.48 (m, 7H), 1.33 (s, 6H).

step iii: Similar procedures for the synthesis of **1b** were employed and **27** (1.7 g, 10 mmol) was used. **1k** was obtained in 75% yield (2.0 g, 7.8 mmol).

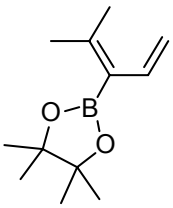


1k

^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35–7.29 (m, 4H), 7.25–7.21 (m, 1H), 5.06–5.04 (m, 1H), 4.44 (s, 2H), 2.21–2.09 (m, 4H), 1.69–1.46 (m, 6H), 1.35 (s, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 197.8, 139.9, 128.2, 127.5, 127.1, 104.6, 95.4, 75.3, 64.9, 31.6, 27.5, 27.0, 26.1. ESI-HRMS: Calcd. for $C_{18}H_{24}O$ ($[M+H]^+$), 257.1900. Found, 257.1899.

General Procedure for Scheme 6-2a. [(NHC)CuCl] (0.0050 mmol, 2.0 mol %) and $B_2(pin)_2$ (71 mg, 0.28 mmol) were placed in an oven dried 20 mL Schlenk flask, and the flask was evacuated for 30 min. The flask was evacuated and backfilled with argon three times. THF (0.50 mL) and KO*t*Bu (15 μL of 1.0 M solution in THF, 10 mol %)

were added, and the resulting mixture was stirred at room temperature for 5 min. To the mixture, **1a** (50 μL, 0.25 mmol) was added and the mixture was stirred at room temperature for 30 min. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard (tetradecane). In the case of [(IPr)CuCl], the mixture was filtrated through a pad of silica gel and all of the volatiles were removed in vacuo. **2a** was obtained by silica gel column chromatography (eluent: hexane/Et_2O = 80/1).



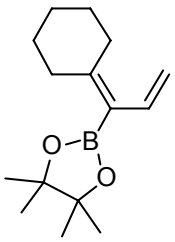
2a

2a: Yield 95% (49.5 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.70 (dd, J = 17.7 Hz, 10.9 Hz, 1H), 5.19 (dd, J = 17.7 Hz, 1.8 Hz, 1H), 5.02 (dd, J = 10.9 Hz, 1.8 Hz, 1H), 1.93 (s, 3H), 1.82 (s, 3H), 1.33 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 146.3, 136.4, 114.4, 83.3, 25.4, 24.9, 20.5. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{12}H_{21}BO_2$ ($[M+H]^+$), 209.1710. Found, 209.1706.

General Procedure for Scheme 6-2b. [(^{Cl}IPr^{CPh_3})CuCl] (10.4 mg, 0.010 mmol, 4.0 mol %) and $B_2(pin)_2$ (71 mg, 0.28 mmol) were placed in an oven dried 20 mL Schlenk flask, and the flask was evacuated for 30 min. The flask was evacuated and backfilled with argon three times. THF (0.50 mL) and KO*t*Bu (30 μL of 1.0 M solution in THF, 12 mol %) were added, and the resulting mixture was stirred at room temperature for 5 min. To the mixture, **3a** (39 μL, 0.25 mmol) was added and the mixture was stirred at room temperature for 30 min. After the reaction, the yield of the product was determined by GC analysis relative to an internal standard (tetradecane).

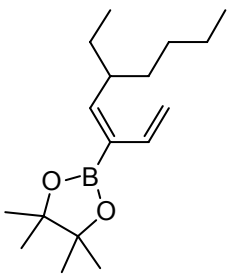
General Procedure for Table 6-1. [(IPr^{CPh_3})CuCl] (4.9 mg, 0.0050 mmol, 2.0 mol %) and $B_2(pin)_2$ (71 mg, 0.28 mmol) were placed in an oven dried 20 mL Schlenk flask, and the flask was evacuated for 30 min. The flask was evacuated and backfilled with argon three times. THF (0.50 mL) and KO*t*Bu (25 μL of 1.0 M solution in THF, 10 mol %) were added, and the resulting mixture was stirred at room temperature for 5 min. To the mixture, an allene was added at the indicated reaction temperature and the mixture was stirred at indicated temperature for indicated time. After the reaction, the mixture was filtrated through a pad of Celite and silica gel and all of the volatiles were

removed in vacuo. The product was obtained by silica gel column chromatography (eluent: hexane/Et_2O). In the cases of entries 3 and 4, the product was purified with preperative GPC due to their instability for silica gel.



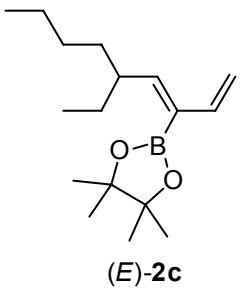
2b

2b: Yield 85% (52.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.77 (dd, J = 17.7 Hz, 10.9 Hz, 1H), 5.17 (dd, J = 17.7 Hz, 1.8 Hz, 1H), 5.02 (dd, J = 10.9 Hz, 1.8 Hz, 1H), 2.35–2.28 (m, 4H), 1.63–1.55 (m, 6H), 1.33 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 153.5, 135.6, 114.6, 83.4, 36.3, 30.4, 28.6, 27.9, 26.8, 24.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{25}BO_2$ ([M+H]$^+$), 249.2023. Found, 249.2017.



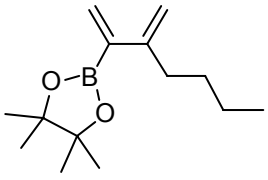
(*Z*)-**2c**

(*Z*)-**2c**: Yield 76% (53.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.69 (dd, J = 17.2 Hz, 10.9 Hz, 1H), 6.02 (d, J = 10.4 Hz, 1H), 5.67 (ddd, J = 17.2 Hz, 2.4 Hz, 0.8 Hz, 1H), 5.13 (ddd, J = 10.9 Hz, 2.5 Hz, 1.4 Hz, 1H), 2.56–2.47 (m, 1H), 1.49–1.37 (m, 2H), 1.29 (s, 12H), 1.27–1.13 (m, 6H), 0.86 (t, J = 6.8 Hz, 3H), 0.83 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 153.2, 134.5, 117.2, 83.1, 39.9, 34.8, 29.6, 28.1, 24.8, 22.9, 14.1, 12.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{31}BO_2$ ([M+H]$^+$), 279.2493. Found, 279.2485. The stereochemistry of (*Z*)-**2c** was confirmed by a NOESY spectrum.



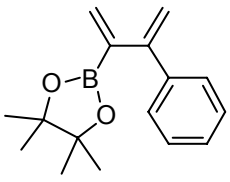
(*E*)-**2c**

(*E*)-**2c**: ^{1}H NMR (400 MHz, $CDCl_3$): δ 6.39 (dd, J = 17.4 Hz, 10.6 Hz, 1H), 5.83 (d, J = 10.4 Hz, 1H), 5.29 (dd, J = 17.7 Hz, 0.9 Hz, 1H), 4.95 (dd, J = 10.6 Hz, 1.1 Hz, 1H), 2.44–2.34 (m, 1H). Other peaks could not be identified due to overlapping. ^{13}C NMR (100 MHz, $CDCl_3$): 153.4, 141.8, 113.7, 83.2, 42.9, 35.1, 29.5, 28.5, 24.9, 22.8, 14.1, 11.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation.



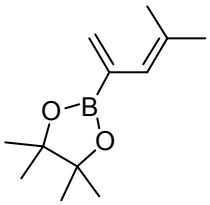
2d

2d: Yield 71% (41.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.79 (d, J = 3.2 Hz, 1H), 5.78 (d, J = 3.2 Hz, 1H), 5.27 (d, J = 1.8 Hz, 1H), 4.96 (br s, 1H), 2.26 (t, J = 7.7 Hz, 2H), 1.45–1.29 (m, 16H), 0.90 (t, J = 7.2 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 149.2, 127.7, 113.9, 83.5, 33.8, 30.4, 24.7, 22.6, 14.0. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{14}H_{25}BO_2$ ($[M+H]^+$), 237.2023. Found, 237.2017.



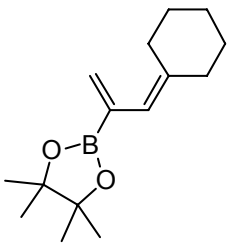
2e

2e: Yield 90% (57.3 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.32–7.23 (m, 5H), 5.95 (d, J = 3.2 Hz, 1H), 5.72 (d, J = 3.2 Hz, 1H), 5.50 (d, J = 1.8 Hz, 1H), 5.28 (d, J = 1.8 Hz, 1H), 1.24 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 150.4, 141.3, 131.7, 127.92, 127.86, 127.1, 115.2, 83.6, 24.6. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{16}H_{21}BO_2$ ($[M+H]^+$), 257.1710. Found, 257.1702.



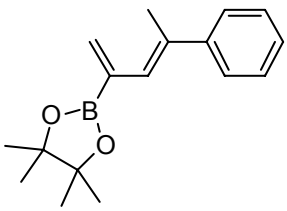
2f

2f: Yield 59% (30.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.91 (br s, 1H), 5.82 (d, J = 3.6 Hz, 1H), 5.60 (d, J = 3.6 Hz, 1H), 1.79 (br s, 3H), 1.73 (br s, 3H), 1.29 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 135.1, 129.9, 126.0, 83.5, 26.5, 24.7, 19.8. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{12}H_{21}BO_2$ ($[M+H]^+$), 209.1710. Found, 209.1705.



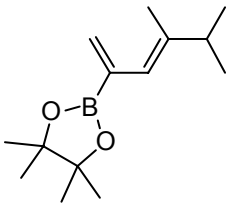
2g

2g: Yield 62% (38.1 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.86 (s, 1H), 5.77 (d, J = 3.6 Hz, 1H), 5.59 (d, J = 3.6 Hz, 1H), 2.21–2.14 (m, 4H), 1.61–1.51 (m, 6H), 1.29 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 143.0, 129.7, 122.9, 83.5, 37.3, 30.6, 28.4, 27.8, 26.6, 24.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{15}H_{25}BO_2$ ($[M+H]^+$), 249.2023. Found, 249.2017.



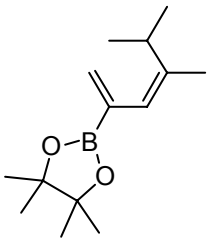
(*E*)-**2h**

(*E*)-**2h**: Yield 63% (42.2 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.47–7.44 (m, 2H), 7.34–7.29 (m, 2H), 7.24–7.20 (m, 1H), 6.52 (br s, 1H), 5.98 (d, J = 3.2 Hz, 1H), 5.79 (d, J = 3.2 Hz, 1H), 2.15 (d, J = 1.4 Hz, 3H), 1.31 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 143.7, 136.5, 131.5, 128.7, 128.1, 126.8, 125.9, 83.7, 24.8, 17.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{23}BO_2$ ($[M+H]^+$), 271.1867. Found, 271.1859. The stereochemistry of (*E*)-**2h** was confirmed by a NOESY spectrum.



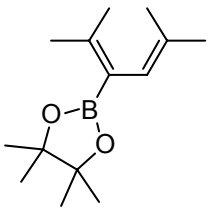
(*E*)-**2i**

(*E*)-**2i**: Yield 96% (56.7 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.92 (br s, 1H), 5.80 (d, J = 3.6 Hz, 1H), 5.61 (d, J = 3.6 Hz, 1H), 2.32 (sept, J = 6.8 Hz, 1H), 1.69 (d, J = 1.4 Hz, 3H), 1.29 (s, 12H), 1.03 (d, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 144.1, 129.6, 123.6, 83.5, 37.2, 24.7, 21.4, 15.4. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{14}H_{25}BO_2$ ($[M+H]^+$), 237.2023. Found, 237.2017. The stereochemistry of (*E*)-**2i** was confirmed by a NOESY spectrum.



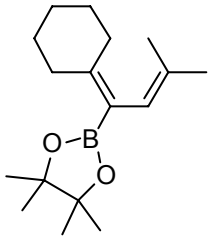
(*Z*)-**2i**

(*Z*)-**2i**: ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.83 (br s, 1H), 5.76 (d, J = 3.6 Hz, 1H), 5.57 (d, J = 3.6 Hz, 1H), 2.83 (sept, J = 6.8 Hz, 1H), 1.68 (d, J = 0.9 Hz, 3H), 1.29 (s, 12H), 0.98 (d, J = 6.8 Hz, 6H). ^{13}C NMR (100 MHz, $CDCl_3$): 143.9, 129.4, 125.1, 83.5, 30.1, 24.7, 20.9, 17.9. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation.



2j

2j: Yield 87% (51.6 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.83 (br s, 1H), 1.97 (d, J = 1.4 Hz, 3H), 1.77 (d, J = 1.4 Hz, 3H), 1.69 (br s, 3H), 1.56 (d, J = 0.9 Hz, 3H), 1.28 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 147.8, 132.4, 125.3, 82.9, 25.7, 24.9, 24.0, 22.1, 19.7. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{14}H_{25}BO_2$ ($[M+H]^+$), 237.2023. Found, 237.2017.



2k

2k: Yield 99% (69.0 mg). ^{1}H NMR (400 MHz, $CDCl_3$): δ 5.84 (br s, 1H), 2.45–2.42 (m, 2H), 2.17–2.14 (m, 2H), 1.76 (d, J = 0.9 Hz, 3H), 1.61–1.50 (m, 9H), 1.27 (s, 12H). ^{13}C NMR (100 MHz, $CDCl_3$): 154.8, 132.6, 124.5, 82.8, 34.6, 31.9, 28.9, 27.8, 26.8, 25.7, 24.9, 19.6. The carbon directly attached to the boron atom was not detected due to quadrupolar relaxation. ESI-HRMS: Calcd. for $C_{17}H_{29}BO_2$ ($[M+H]^+$), 277.2337. Found, 277.2329.

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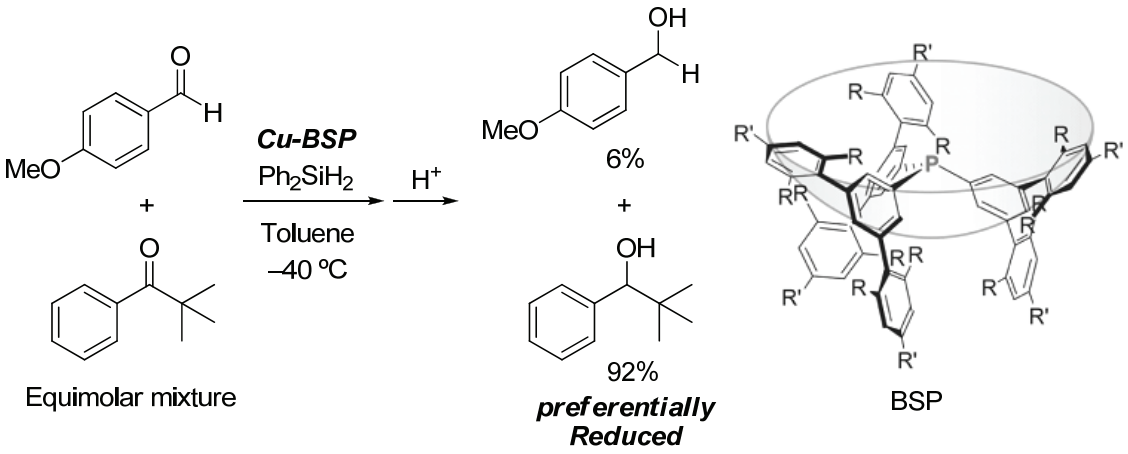
Chapter 7

Copper-Catalyzed Hydrosilylation with a Bowl-Shaped Phosphane Ligand: Preferential Reduction of a Bulky Ketone in the Presence of an Aldehyde

A highly active Cu catalyst with bowl-shaped phosphane (BSP) as a ligand in the hydrosilylation has been developed. The reactions are faster with more bulky ketones as substrates. Noteworthy is that the present catalysts realize unprecedented preferential reduction of a bulky ketone in the presence of an aldehyde without any protections.



7-1. Introduction

In homogeneous catalysis, ligands play a crucial role to determine efficiency and selectivity of catalysts.[1] Therefore, much effort has been paid to develop efficient ligands. Tris(*m*-terphenyl)phosphanes (**1**–**3** in Figure 7-1A)[2] are bowl-shaped (Figure 7-1B) and have very unique structural feature: bulkiness occurs at the periphery (at the rim of the bowl having diameters of 2.0–2.6 nm) with substantial empty space around the phosphorus atom. Our group has recently reported that **2** and **3** were particularly effective ligands in Rh-catalyzed hydrosilylation of ketones[2a,b] and Pd-catalyzed Suzuki-Miyaura coupling reaction of aryl chlorides.[2c] In this Chapter, the author describes extremely active Cu catalysts[3] with the bowl-shaped phosphane (BSP: **2** and **3**) in hydrosilylation reaction. Noteworthy is that the present catalysts realize unprecedented preferential reduction of a bulky ketone in the presence of an aldehyde without any protections.

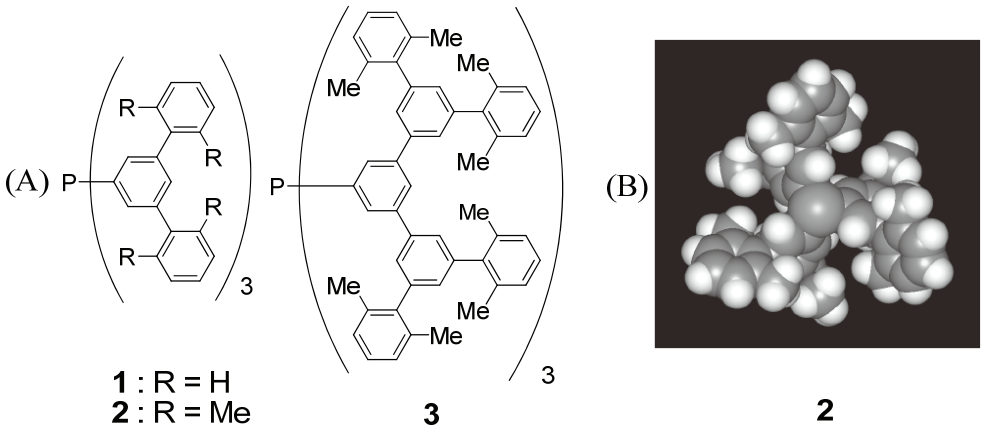


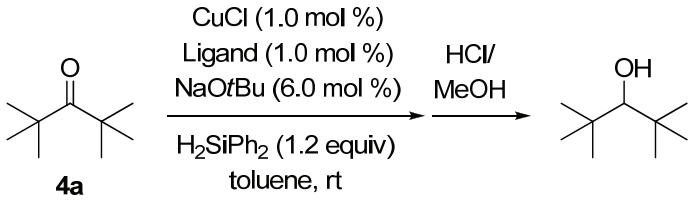
Figure 7-1. (A) Bowl-shaped phosphanes (**1**-**3**) and (B) optimized structure of **2** calculated by HF/6-31G(d)-CONFLEX/MM3 method[2]

7-2. Results and Discussion

At first, hydrosilylation of 2,2,4,4-tetramethyl-3-pentanone (**4a**), one of the least reactive ketones in the reaction,[4] was carried out with Ph_2SiH_2 at room temperature (Table 7-1). Employing a CuCl/*t*BuONa catalyst system with the conventional phosphane ligands such as PPh_3, P(*o*-tol)$_3$, P(Mes)$_3$, and P(*t*Bu)$_3$, the corresponding alcohol after the hydrolysis was afforded only in 2%, <1%, 2%, and 11% yields, respectively, after 5 h (entries 1–4). In contrast, **2** was remarkably effective to afford the

product in 92% after 5 h (entry 6). Furthermore, **3** was more efficient ligand and provided the alcohol in quantitative yield even after 20 min (entry 7). Bidentate phosphanes such as Dppbz and (*S*)-DTBM-SEGPHOS, which are known as very effective ligands in the Cu-catalyzed hydrosilylation,[5] were not beneficial (entries 8 and 9). Under the same reaction conditions as in entry 6 (5 h), other silanes such as Et_3SiH, $MePh_2SiH$, and $Me(OEt)_2SiH$ afforded the product in trace, 2% and 51% yields, respectively. Here, even excess (5 equiv) silanes hardly improved the yields: trace with Ei_3SiH and 8% with $MePh_2SiH$. Nolan et al. reported that NHC ligands such as ICy, IMes, and IPr were highly efficient in Cu-catalyzed hydrosilylation of bulky ketones.[4b,6] In the hydrosilylation of **4a** using these NHC ligands under the same

Table 7-1. Effect of the ligand on the copper-catalyzed hydrosilylation of **4a**[a]



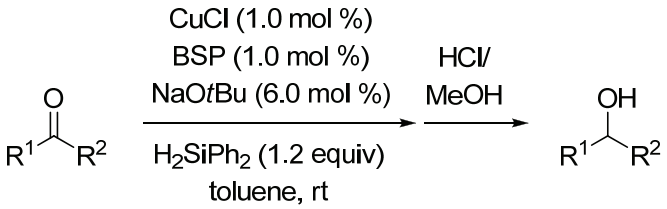
Entry	Ligand	Yield after 20 min[b]	Yield after 5 h[b]
1	PPh_3	<1	2
2	P(*o*-tol)$_3$	<1	<1
3	P(Mes)$_3$	<1	2
4	P(*t*Bu)$_3$	9	11
5	**1**	7	25
6	**2**	43	92
7	**3**	99	--
8	Dppbz	<1	4
9	DTBM-SEGPHOS[c]	<1	1
10[d]	**2**	<1	5

[a] **4a** (2.0 mmol), Ph_2SiH_2 (2.4 mmol), CuCl (0.020 mmol, 1.0 mol %), phosphane (0.020 mmol, 1.0 mol %), *t*BuONa (0.12 mmol, 6.0 mol %), toluene (2.0 mL), RT. [b] Yield of the alcohol based on the GC internal standard technique. [c] (*S*)-DTBM-SEGPHOS. [d] $[RhCl(C_2H_4)_2]_2$ (0.010 mmol, 1.0 mol %) and **2** (0.020 mmol, 1.0 mol %) were used as the catalyst.

reaction conditions as in entry 7 (20 min), ICy was not an efficient ligand (6% yield of the product), while IMes and IPr afforded the alcohol in high yields (84% and 94%, respectively). On the other hand, a reported Rh catalyst with BSP ($[RhCl(C_2H_4)_2]_2$ with **2**; 1 mol % as Rh and P/Rh = 1)[2a,b] was not effective for the bulky ketone (entry 10).

The efficacy of the BSPs as the ligand was further confirmed using various ketones (Table 7-2). The results with PPh_3 were also listed for comparison, since PPh_3 is corresponding to the core part of all the BSPs (**1**-**3**). Less bulky cyclohexanone (**4b**) was easily reduced to cyclohexanol in 10 min in 98% and 68% yields with **1** or **3** as a ligand, respectively (entries 1 and 2), while yield was only 23% yield with PPh_3 (entry 3). More bulky 2-*tert*-butylcyclohexanone (**4c**) afforded the corresponding alcohol in 98% yield with **3** (entry 5). The highly congested 2,2,6,6-tetramethylcyclohexanone (**4d**) afforded the corresponding alcohol easily in almost quantitative yields in 20 min with **2** or **3** as the ligand (entries 7 and 8). Dicyclohexyl ketone (**4e**) and 1-adamantyl methyl ketone (**4f**) were also readily reduced to the corresponding alcohols by the Cu-BSP catalyst systems (entries 10, 11, and 14). Aromatic ketones such as cyclohexyl phenyl ketone (**4g**), *tert*-butyl phenyl ketone (**4h**), and 2-acetylthiophene (**4i**) were smoothly reduced in high yields (entries 17, 19, 20, and 22), while methyl 2,4,6-trimethylphenyl ketone was not converted in the reaction with **1**–**3** as the ligand.

Table 7-2. Hydrosilylation of various ketones[a]



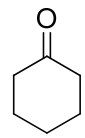
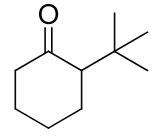
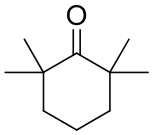
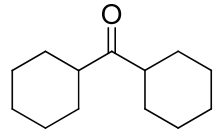
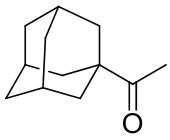
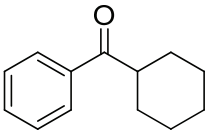
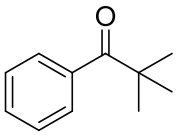
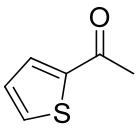
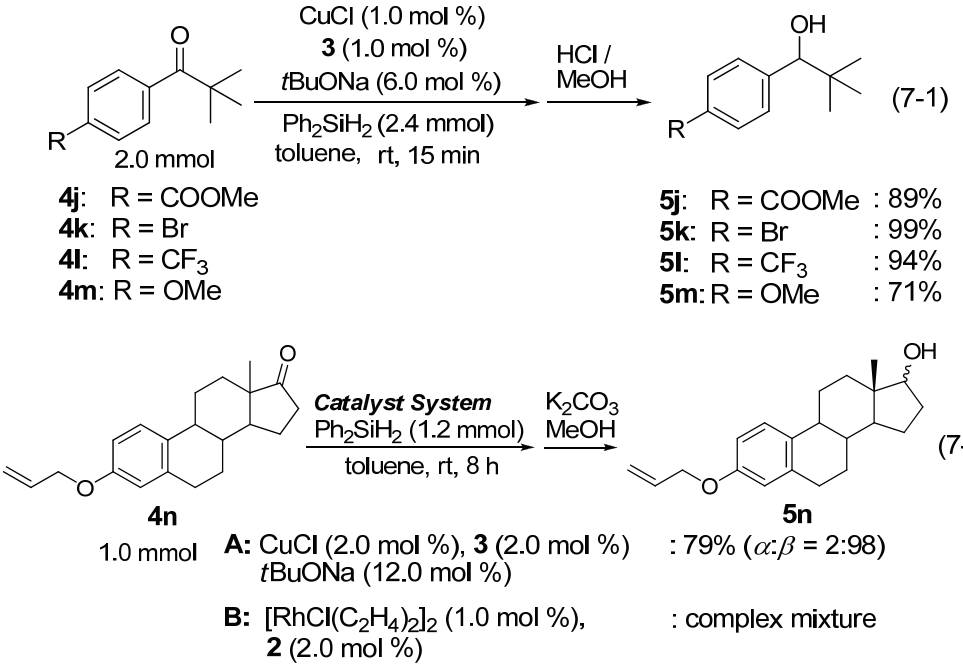
Entry	Ketone	Time	Ligand	Yield [%][b]
1		10 min	**1**	98
2	**4b:**		**3**	68
3			PPh_3	23
4		360 min	**2**	28[c]
5	**4c:**		**3**	98[d]
6			PPh_3	<1

Table 7-2. (Continued)

7		20 min	**2**	99
8	**4d:**		**3**	99 (83)[e]
9			PPh_3	8
10		40 min	**2**	79
11	**4e:**		**3**	95 (89)[e]
12			PPh_3	3
13		90 min	**2**	53
14	**4f:**		**3**	83 (75)[e]
15			PPh_3	4
16		60 min	**2**	77
17	**4g:**		**3**	(93)[e]
18			PPh_3	2
19		10 min	**2**	95
20	**4h:**		**3**	99 (87)[e]
21			PPh_3	9
22		20 min	**1**	84 (69)[e]
23	**4i:**		**3**	24
24			PPh_3	5

[a] Ketone (**4**: 2.0 mmol), Ph_2SiH_2 (2.4 mmol), CuCl (0.020 mmol, 1.0 mol %), phosphane (0.020 mmol, 1.0 mol %), *t*BuONa (0.12 mmol, 6.0 mol %), toluene (2.0 mL), rt. [b] Yield of an alcohol after hydrolysis based on the GC internal standard technique. [c] *cis*/*trans* = 44/56. [d] *cis*/*trans* = 58/42. [e] Yield of the isolated product.

Bulky ketones with several functionalities (**4j–4m**) were converted to the corresponding alcohols in 15 min at room temperature with retaining the functionalities in excellent to good isolated yields [Eq. (7-1)]. In addition, in the hydrosilylation of the estrone derivative (**4n**) containing the allyl ether functionality, the Cu-BSP catalyst realized chemoselective hydrosilylation of carbonyl moiety and the product bearing the intact allyloxy group was isolated as a pure form in 79% yield [Eq. (7-2)]. In contrast, the Rh catalyst system[2a,b] with BSP provided an intractable mixture via hydrosilylation of both the allyl and the carbonyl functionalities.



Initial rates of hydrosilylation of **4h**, isopropyl phenyl ketone (**4o**), and acetophenone (**4p**) with Ph_2SiH_2 were found to be 1.1, 4.9×10^{-1}, and 8.5×10^{-2} mol L^{-1} h^{-1}, respectively,[7] indicating the reaction is much faster with a more bulky substrate (Figure 7-2). Such an intriguing rate difference was also confirmed in a competitive reaction with an equimolar mixture of the two ketones of different bulkiness (**A**: more bulky and **B**: less bulky) in the presence of the same molar amount of Ph_2SiH_2 at room temperature (Table 7-3). With **4h** and **4p**, the more bulky **4h** was preferentially reduced by employing **3** or **2** as the ligand (entries 1 and 2). Similarly, more bulky **4d** was reduced in preference to **4b** with **3** (entry 3). However, with PPh_3 as the ligand, the less bulky **4b** was preferentially reduced normally (entry 4). Higher reactivity of a more bulky **4a** than less bulky 5-nonanone (**4q**) was also evident (entry 5). With **4o** and **4p** (isopropyl ketone vs. methyl ketone), the alcohol from the isopropyl ketone was obtained as a major product (entry 6). Even with aldehydes, more bulky substrates (**6a** and **6c**) were predominantly reduced as compared with heptanal (**6b**) (entries 7 and 8).

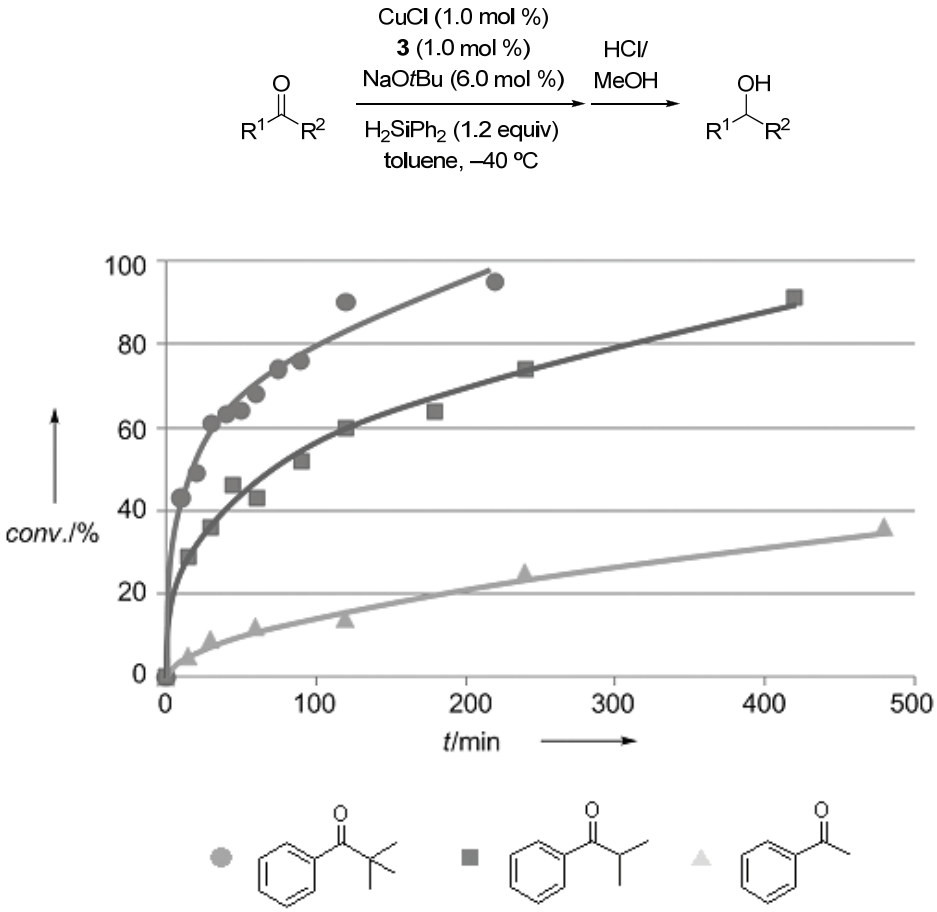


Figure 7-2. Time-dependent changes of **4h (●)**, **4o (■)** and **4p (▲)**.

Table 7-3. Competitive hydrosilylation between two substrates (A and B) of different bulkiness.[a]

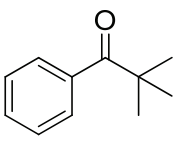
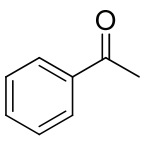
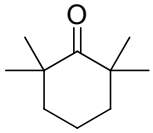
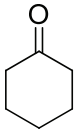
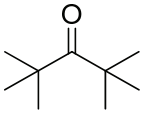
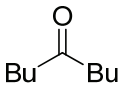
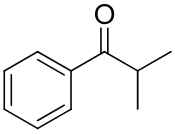
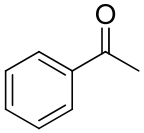
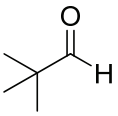
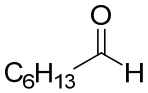
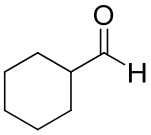
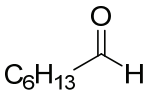
Entry	Substrates		Temp. [°C]	Time [h]	Yield [%][b] from	
	A	B			A	B
1	**4h:** 	**4p:** 	25	0.2	88	2
2[c]					87	3

Table 7-3. (Continued)

3	**4d:** 	**4b:** 	25	0.3	89	11
4[d]					21	79
5	**4a:** 	**4q:** 	25	0.5	71	17
6	**4o:** 	**4p:** 	25	0.2	99	11
7	**6a:** 	**6b:** 	-40	3	87	13
8	**6c:** 	**6b:** 	-40	1	78	25

[a] Bulky substrate (A: 2.0 mmol), less bulky substrate (B: 2.0 mmol), Ph_2SiH_2 (2.0 mmol), CuCl (0.020 mmol), **3** (0.020 mmol), *t*BuONa (0.12 mmol), toluene (2.0 mL). [b] Yield of the corresponding alcohol after hydrolysis based on the GC internal standard technique. [c] **2** was used instead of **3**. [d] PPh_3 was used instead of **3**. [e] Toluene (4.0 mL).

The most remarkable feature of the present catalyst system is preferential reduction of a ketone (**4**) in the presence of an aldehyde (**6**). The hydrosilylation of an equimolar mixture of **4h**, 2,4,6-trimethylbenzaldehyde (**6d**), and Ph_2SiH_2 with **3** as the ligand afforded the corresponding alcohol from the ketone in 90% yield and the alcohol from the aldehyde only in 5% yield (Table 7-4, entry 1). When PPh_3 was used instead of **3**, the alcohol from the aldehyde was predominantly obtained (entry 2). NHC ligands such as ICy, IMes, and IPr were reported to be highly efficient in Cu-catalyzed hydrosilylation of bulky ketones.[4b,6] However, with all these ligands no selectivity between ketones and aldehydes appeared (entries 3–5). In the reactions of **4h** with

4-methoxybenzaldehyde (**6e**), benzaldehyde (**6f**), and an even **6b**, the alcohol from **4h** was obtained preferentially in 92%, 81%, and 87% yields, respectively (entries 6–8). Surprisingly, even highly congested ketones such as **4d** and **4a** were preferentially reduced in the presence of aldehydes (**6b** or **6d**) to the corresponding alcohols in 92%, 72%, and 62% yields, respectively (entries 9–11). To date, there have been only six precedents for preferential reduction of a ketone in the presence of an aldehyde.[8] However, all these previous reactions necessitated in situ prior protection of more reactive aldehyde, followed by reduction of an unprotected ketone and successive deprotection to the aldehyde during a work up procedure. Unfortunately, in these reactions, the in situ protections were significantly affected by subtle changes in reaction conditions, thus making these methods unreliable.

Table 7-4. Hydrosilylation of bulky ketones in the presence of aldehydes.[a]

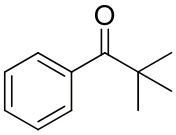
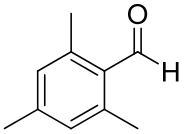
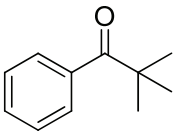
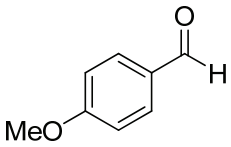
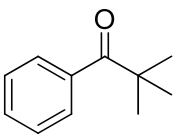
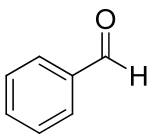
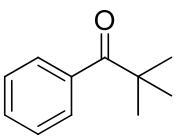
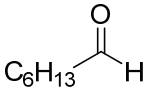
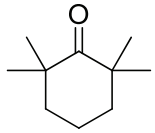
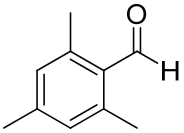
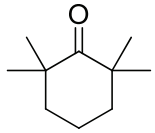
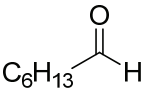
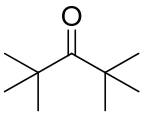
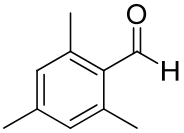
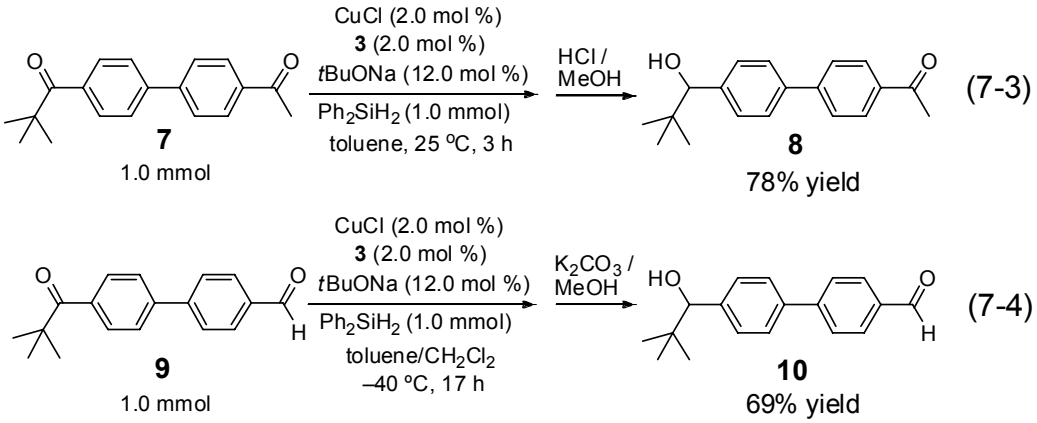
Entry	Substrates		Time [h]	Yield [%][b] from	
	A	B		A	B
1	**4h:** 	**6d:** 	3	90	5
2[c]				8	86
3[d]				41	46
4[e]				56	41
5[f]				55	43
6	**4h:** 	**6e:** 	2.5	92	6
7	**4h:** 	**6f:** 	12	81	12
8	**4h:** 	**6b:** 	3	87	12

Table 7-4. (Continued)

9	**4d:** 	**6d:** 	2	92	9
10	**4d:** 	**6b:** 	3	72	21
11	**4a:** 	**6d:** 	1	62	28

[a] Bulky ketone (A: 2.0 mmol), aldehyde (C: 2.0 mmol), Ph_2SiH_2 (2.0 mmol), CuCl (0.020 mmol), **3** (0.020 mmol), *t*BuONa (0.12 mmol), toluene (4.0 mL) at –40 °C. [b] Yield of the corresponding alcohol after hydrolysis based on the GC internal standard technique. [c] PPh_3 was used instead of **3**. [d] ICy was used instead of **3**. [e] IMes was used instead of **3**. [f] IPr was used instead of **3**.

The hydrosilylation of the substrate with two ketone groups (**7**) was carried out as shown in Eq. (7-3). After almost all **7** was converted in 3 h, the reaction mixture was found to contain **8** as a major product with a small amount of the corresponding diol by the reduction of the both keto groups (5% yield). From the mixture, **8** was isolated in 78% yield in pure form. Thus, the more bulky ketone functionality of **7** was preferentially reduced in the reaction. In the hydrosilylation of **9** bearing the ketone and the formyl functionalities [Eq. (7-4)], **9** was fully converted in 17 h and a resulting reaction mixture contained **10** as a major product with a small amount of the corresponding diol via the reduction of both the keto and the formyl moieties (3% yield) and the mono-ol bearing the keto functionality via the reduction of the formyl moiety (3% yield). The pure **10** was isolated in 69% yield from the mixture, indicating the keto functionality was preferentially reduced.



It is well-known that Cu complexes are easy to aggregate.[9] Actually, it was reported that the Cu *tetramer* $[CuCl(PPh_3)]_4$ of cubane structure was obtained in the reaction of an equimolar mixture of CuCl and PPh_3.[10] In contrast, when the similar reaction of an equimolar mixture of CuCl and **2** was carried out,[7] a lower-nuclearity complex, the Cu-*dimer* $[CuCl(\mathbf{2})]_2$, was obtained in 54% yield as confirmed by X-ray crystallography (Figure 7-3). These results suggest that unique bulkiness of **2** (vide supra) could suppress the aggregation of a Cu center.

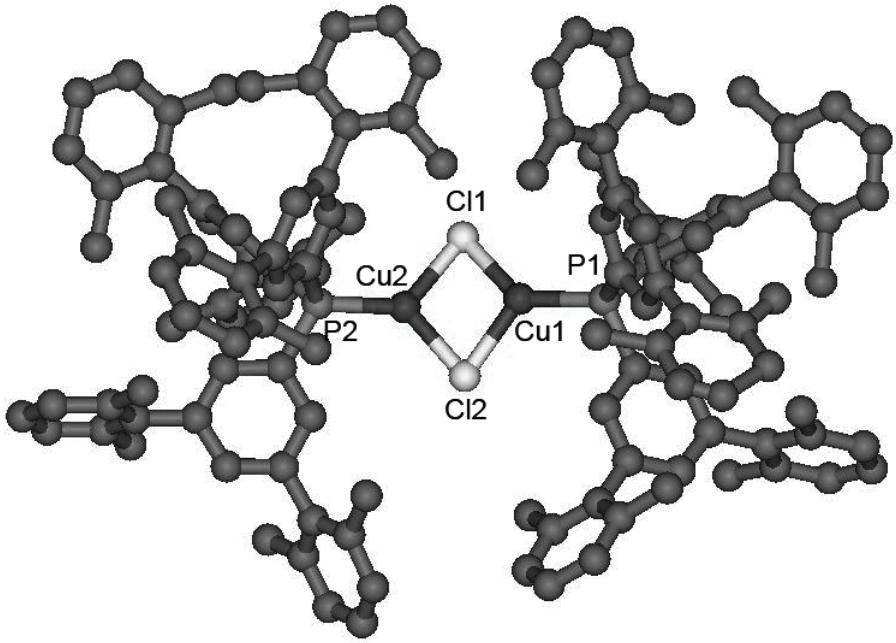
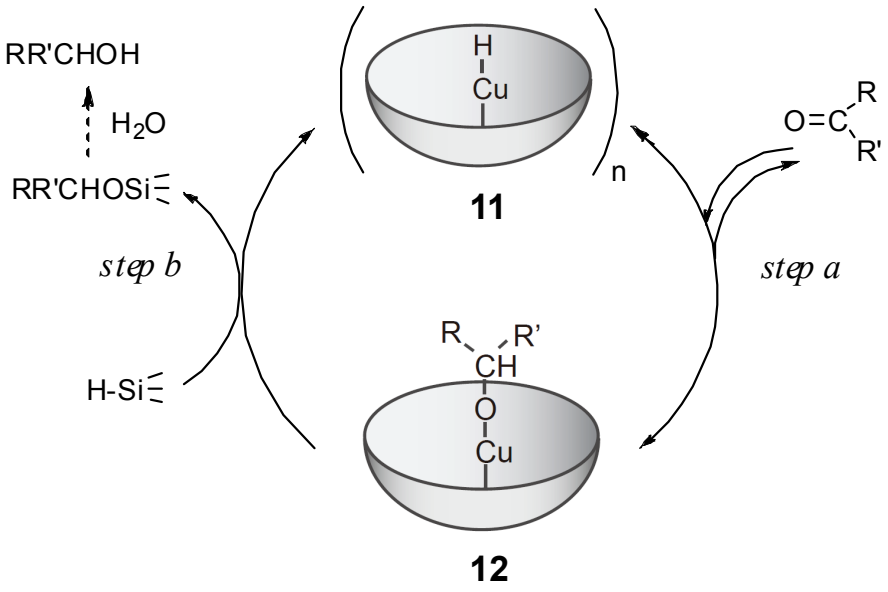


Figure 7-3. Crystal structure of $[CuCl(\mathbf{2})]_2$

Possible catalytic cycle of the present reaction was shown in Scheme 7-1. Key intermediates in the cycle are Cu-hydride (**11**) and Cu-alkoxide (**12**) bearing BSP. Usually, Cu-hydrides prefer to aggregate. Indeed, the Cu-hydride with PPh_3 was isolated as a hexamer $[(Ph_3P)CuH]_6$.[11] In the cycle, **11** with kentones or aldehydes would afford **12** reversibly (step a). Here, **12** from bulky ketones could be of much lower-nuclearity (possibly, mono) owing to the bulkiness of BSP and bulky alkoxide moieties. Such highly unsaturated **12** must be extremely reactive in the σ-bond metathesis[12] with a silane to afford the product and regenerate **11** (step b). On the other hand, with less bulky ketones or aldehydes, **12** might be susceptible to aggregate due to smaller alkoxide moieties, thus their reactivity in step b would be low.

Scheme 7-1. Plausible reaction mechanism



7-3. Conclusion

In conclusion, the author has developed a highly active Cu catalyst with BSP as a ligand in the hydrosilylation. The reactions are faster with more bulky ketones as substrates. Noteworthy is that the present catalysts realize unprecedented preferential reduction of a bulky ketone in the presence of an aldehyde without any protections.

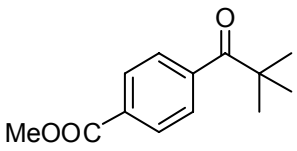
7-4. Experimental Section

General Procedures: All manipulations were performed under an argon atmosphere using standard Schlenk-type glasswares on a dual-manifold Schlenk line. Reagents and solvents were dried and purified before use by usual procedures.[13] ^{1}H NMR and $^{13}C\{^{1}H\}$ NMR spectra were measured with a JEOL ECX-400 spectrometer. The ^{1}H NMR chemical shifts are reported relative to tetramethylsilane (TMS, 0.00 ppm) or residual protonated solvent (7.26 ppm) in $CDCl_3$. The ^{13}C NMR chemical shifts are reported relative to $CDCl_3$ (77.0 ppm). $^{31}P\{^{1}H\}$ NMR spectra were also recorded at a JEOL ECX-400 spectrometer using 85% H_3PO_4 as an external standard. Elemental analysis was carried out at Center for Organic Elemental Microanalysis, Graduate School of Pharmaceutical Science, Kyoto University. Column chromatography was carried out on silica gel (Kanto N60, spherical, neutral, 63-210 μm). Preparative recycling gel permeation chromatography (GPC) was performed with a JAI LC9104. GC analysis was carried out using Shimadzu GC-17A equipped with an integrator (C-R8A) with a capillary column (CBP-20, 0.25 mm i.d. × 25 m).

Materials: Unless otherwise noted, commercially available chemicals were distilled and degassed before use. Anhydrous toluene and CH_2Cl_2 were purchased from Kanto Chemical and further purified by passage through activated alumina under positive argon pressure as described by Grubbs et al.[14] Ligands (**1**,[2a] **2**[2b,15] and **3**[2c]) were prepared according to literatures. CuCl was purified according to literature.[13] Substrates (**4j**, **4k**, **4l**, **4m**, **4n**, **7** and **9**) were prepared according to the following procedures.

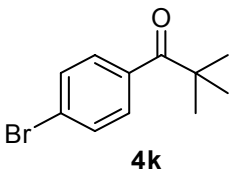
Preparation of ketones (4j, 4k, 4l and 4m): The ketones were synthesized with a modified method of a previous report:[16] CuI (4.4 g, 23 mmol), *t*BuOLi (1.9 g, 23 mmol) and THF (50 mL) were added to a frame dried flask and the mixture was stirred for 15 min under an argon atmosphere. The suspension was cooled to –78 ºC. *t*BuLi in pentane (1.77 M, 22 mmol) and the corresponding acid chloride (20 mmol) in THF (20 mL) were added in this order. Then the solution was stirred for 30 min at –78 ºC. The reaction was quenched with MeOH (10 mL). After warming to room temperature, the mixture was poured into NH_4Cl aq. (50 mL) and extracted with Et_2O. The organic layer

was dried over $MgSO_4$. After removal of the solvent, the product was isolated by silicagel column chromatography or distillation.



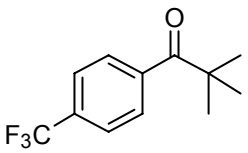
4j

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.33 (s, 9H), 3.94 (s, 3H), 7.66 (d, J = 8 Hz, 2H), 8.07 (d, J = 8 Hz, 2H) ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.6, 44.3, 52.3, 127.3, 129.3, 131.6, 166.3, 209.4. EI-MS: *m/z* 220 ($[M]^+$). Anal. Calcd. for $C_{13}H_{16}O_3$: C, 70.89; H, 7.32. Found: C, 70.59; H, 7.30. Yield 62 %.



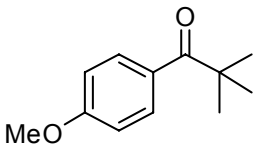
4k

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.34 (s, 9H), 7.54 (d, J = 8 Hz, 2H), 7.59 (d, J = 8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.9, 44.2, 125.6, 129.6, 131.3, 137.0, 207.8. EI-MS: *m/z* 242 ($[M+1]^+$), 240 ($[M-1]^+$). Anal. Calcd. for $C_{11}H_{13}BrO$: C, 54.79; H, 5.43. Found: C, 54.55; H, 5.37. Yield 85 %.



4l

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.34 (s, 9H), 7.67 (d, J = 8 Hz, 2H), 7.73 (d, J = 8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 27.6, 44.3, 77.3, 122.3, 125.1 (q, J = 4 Hz), 127.8, 132.2 (q, J = 33 Hz), 142.1, 208.8. EI-MS: *m/z* 230 ($[M]^+$). Anal. Calcd. for $C_{12}H_{13}F_3O$: C, 62.60; H, 5.69. Found: C, 62.30; H, 5.60. Yield 80 %.



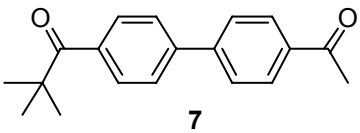
4m

^{1}H NMR (400 MHz, $CDCl_3$): δ 1.37 (s, 9H), 3.84 (s, 3H), 6.90 (d, J = 12 Hz, 2H), 7.86 (d, J = 12 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 28.3, 43.8, 55.3, 113.2, 130.0, 130.9, 161.9, 206.2. EI-MS: *m/z* 192 ($[M]^+$). Anal. Calcd. for $C_{12}H_{16}O_2$: C, 74.97; H, 8.39. Found: C, 74.83; H, 8.28. Yield 80 %.

Preparation of alloxy estrone (4n): This compound was synthesized with a modified method of a previous report:[17] Estrone (2.8 g, 10 mmol), 3-bromopropene (1.7 mL, 20 mmol), K_2CO_3 (9.7 g, 70 mmol) and acetone (150 mL) were added to a frame dried flask, and a solution was stirred at 50 ºC for 48 h. After removal of the solvent, the residue was extracted with CH_2Cl_2. The organic layer was dried over $MgSO_4$. After removal of the solvent, **4n** was isolated by silicagel column chromatography (eluent:

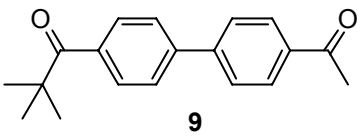
CH_2Cl_2). White solids, 2.7 g (86%). ^{1}H NMR (400 MHz, $CDCl_3$): δ 0.91 (s, 3H), 1.41-2.53 (m, 13H), 2.87-2.91 (m, 2H), 4.51 (d, J = 5.2 Hz, 2H), 5.27 (d, J = 10.4 Hz, 1H), 5.40 (d, J = 17.6 Hz, 1H), 6.00-6.10 (m, 1H), 6.66 (d, J = 2.8 Hz, 1H), 6.73 (dd, J = 8.8 Hz and 2.8 Hz, 1H), 7.19 (d, J = 8.8 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 13.8, 21.5, 25.9, 26.5, 29.6, 31.5, 35.8, 38.3, 43.9, 48.0, 50.3, 68.7, 112.3, 114.7, 117.4, 126.3, 132.1, 133.5, 137.7, 156.6, 220.9.

General procedure for preparation of 7 and 9: $Pd(dba)_2$ (144 mg, 0.25 mmol), PCy_3 (84.1 mg, 0.30 mmol), **4k** (1.21 g, 5 mmol), the corresponding boronic acid ($CH_3COC_6H_4B(OH)_2$ or $HCOC_6H_4B(OH)_2$, 5.5 mmol), KF (960 mg, 16.5 mmol) and THF (10 mL) were added to a frame dried flask. The resulting suspension was stirred overnight at 50 ºC. The mixture was cooled to room temperature and diluted with Et_2O. After filtration through celite, the solvent was removed. The products were isolated by silicagel column chromatography.



7

Yield 69%. ^{1}H NMR (400 MHz, $CDCl_3$): δ 1.39 (s, 9H), 2.65 (s, 3H), 7.66 (d, J = 8.0 Hz, 2H), 7.71 (d, J = 8.0 Hz, 2H), 7.83 (d, J = 8.0 Hz, 2H), 8.06 (d, J = 8.0 Hz, 2H). ^{13}C NMR (100MHz, $CDCl_3$): δ 26.6, 28.0, 44.2, 126.8, 127.2, 128.7, 128.9, 136.2, 137.8, 142.1, 144.4, 197.6, 208.4. EI-MS: *m/z* 280 ($[M]^+$). Anal. Calcd. for $C_{19}H_{20}O_2$: C, 81.40; H, 7.19. Found: C, 81.10; H, 7.16.



9

Yield 71%. ^{1}H NMR (400 MHz, $CDCl_3$):δ1.39 (s, 9H), 7.68 (d, J = 12 Hz), 7.78 (d, J = 8 Hz, 2H), 7.83 (d, J = 8 Hz, 2H), 7.98 (d, J = 8 Hz, 2H), 10.1 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 28.0, 44.3, 127.0, 127.8, 128.7, 130.3, 135.6, 138.2, 142.0, 146.0, 191.8, 208.5. EI-MS: *m/z* 266 ($[M]^+$). Anal. Calcd. for $C_{18}H_{18}O_2$: C, 81.17; H, 6.81. Found: C, 80.92; H, 6.70.

General procedures in Table 7-1.

Entries 1-9: CuCl (1.98 mg, 0.02 mmol), a ligand (0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (2.0 mL) was added and the mixture was

stirred for 30 min at room temperature under an argon atmosphere. Ph_2SiH_2 (2.4 mmol) was added and the mixture was stirred for 30 min under an argon atmosphere. 2,2,4,4-Tetramethyl-3-pentanone (**4a**, 2.0 mmol) was added and the mixture was stirred for 20 min or 5 h at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1 N, 1.0 mL) and the yield of the product was determined by GC analysis relative to an internal standard.

Entry 10: $[RhCl(C_2H_4)_2]_2$ (3.89 mg, 0.01 mmol) and **2** (17.7 mg, 0.02 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (2.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. **4a** (2.0 mmol) and Ph_2SiH_2 (2.4 mmol) were added in this order and the mixture was stirred for 20 min or 5 h at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1N, 1.0 mL) and the yield of the product was determined by GC analysis relative to an internal standard.

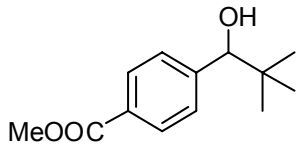
General procedures in Table 7-2.

CuCl (1.98 mg, 0.02 mmol), a ligand (0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (2.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Ph_2SiH_2 (2.4 mmol) was added and the mixture was stirred for 30 min under an argon atmosphere. A ketone (2.0 mmol) was added and the mixture was stirred at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1N, 1.0 mL). Yields were determined by GC analysis relative to an internal standard. Isolated yields were determined after the purification by silica gel column chromatography.

General procedures in Eq. 7-1.

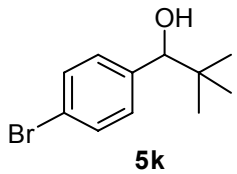
CuCl (1.98 mg, 0.02 mmol), **3** (0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (2.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Ph_2SiH_2 (2.4 mmol) was added and the mixture was stirred for 30 min under an argon atmosphere. The ketone (2.0

mmol) was added and the mixture was stirred for 15 min at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1N, 1.0 mL). Isolated yields were determined after the purification by silica gel column chromatography.



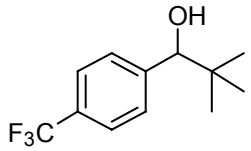
5j

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.91 (s, 9H), 2.16 (d, J = 3.2 Hz, 1H), 3.06 (s, 3H), 4.44 (d, J = 3.2 Hz, 1H), 7.37 (d, J = 8 Hz, 2H), 7.96 (d, J = 8 Hz, 2H) ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.8, 35.7, 52.0, 81.9, 127.6, 128.8, 129.0, 147.4, 167.1. EI-MS: *m/z* 223 ($[M+1]^+$). Anal. Calcd. for $C_{13}H_{18}O_3$: C, 70.24; H, 8.16. Found: C, 70.06; H, 8.13. Yield 89% (396 mg).



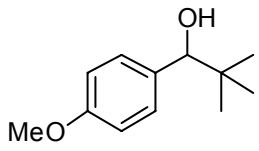
5k

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.89 (s, 9H), 1.94 (d, J = 4 Hz, 1H), 4.34 (d, J = 3 Hz, 1H), 7.17 (d, J = 8 Hz), 7.43 (d, J = 8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.7, 35.5, 81.6, 121.0, 129.2, 130.5, 141.0. EI-MS: *m/z* 244 ($[M+1]^+$), 242 ($[M-1]^+$). Anal. Calcd. for $C_{11}H_{15}BrO$: C, 54.34; H, 6.22. Found: C, 54.27; H, 6.24. Yield 91% (497 mg).



5l

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.92 (s, 9H), 1.99 (d, J = 8 Hz, 1H), 4.44 (d, J = 2.4 Hz, 1H), 7.42 (d, J = 8 Hz, 2H), 7.57 (d, J = 8 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.8, 35.7, 81.8, 124.2 (q, $^3J_{C\text{-}F}$ = 274 Hz), 124.4 (q, $^1J_{C\text{-}F}$ = 4 Hz), 127.9, 129.5 (q, $^2J_{C\text{-}F}$ = 33 Hz), 146.0. EI-MS: *m/z* 232 ($[M]^+$). Anal. Calcd. for $C_{12}H_{15}F_3O$: C, 62.06; H, 6.51. Found: C, 62.28; H, 6.64. Yield 94% (435 mg).



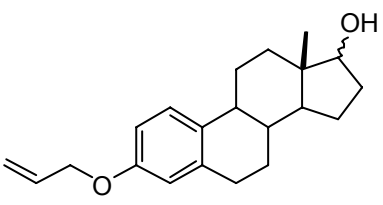
5m

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.91 (s, 9H), 1.83 (m, 1H), 3.80 (s, 3H), 4.35 (d, J = 2 Hz, 1H), 6.85 (d, J = 9 Hz, 2H), 7.23 (d, J = 9 Hz, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.9, 35.7, 55.2, 82.0, 112.9, 128.6, 134.4, 158.8. EI-MS: *m/z* 194 ($[M]^+$). Anal. Calcd. for $C_{12}H_{18}O_2$: C, 74.19; H, 9.34. Found: C, 74.22; H, 9.57. Yield 71% (276 mg).

Procedures in Eq. 7-2.

A: CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Ph_2SiH_2 (1.2 mmol) was added and the mixture was stirred for 30 min under an argon atmosphere. The estrone derivative (**4n**, 1.0 mmol) dissolved in a mixture of toluene (1.0 mL) and CH_2Cl_2 (0.50 mL) was added, and the resulting mixture was stirred for 8 h at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding a mixture of K_2CO_3 (20 mg) and MeOH (1.0 mL). The mixture was concentrated and the product was isolated by silica gel column chromatography (eluent: CH_2Cl_2) to afford the product (**5n**) in 79% yield (248 mg).

B: $[RhCl(C_2H_4)_2]_2$ (3.89 mg, 0.01 mmol) and **2** (17.7 mg, 0.02 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (1.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. To the resulting solution, **4n** (1.0 mmol) dissolved in a mixture of toluene (1.0 mL) and CH_2Cl_2 (0.50 mL), then Ph_2SiH_2 (1.2 mmol) were added in this order. The mixture was stirred for 8 h at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding a mixture of K_2CO_3 (20 mg) and MeOH (1.0 mL). The mixture was concentrated and the products were obtained by silica gel column chromatography (eluent: CH_2Cl_2).



5n

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.77 (s, 3H), 1.14-2.31 (m, 14H), 2.82-2.86 (m, 2H), 3.71 (t, J = 8.3 Hz, 1H), 4.50 (d, J = 5.54 Hz, 2H), 5.26 (d, J = 10.3 Hz, 1H), 5.39 (d, J = 17.0 Hz, 1H), 6.00-6.09 (m, 1H), 6.64 (d, J = 2.4 Hz, 1H), 6.71 (dd, J = 8.7 Hz and 2.4 Hz, 1H), 7.19 (d, J = 8.7 Hz, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 11.0, 23.1, 26.2, 27.2, 29.7, 30.5, 36.6, 38.8, 43.2, 43.9, 50.0, 68.7, 81.8, 112.1, 114.7, 117.4, 126.2, 132.8, 133.5, 137.9, 156.4. Anal. Calcd. for $C_{21}H_{28}O_2$: C, 80.73; H, 9.03. Found: C, 80.44; H, 9.09.

Time-course dependency of the reaction with 4h, 4o and 4p.

CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.020 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (4.0 mL) and tridecane (as an internal standard, 50 μL, 0.21 mmol) were added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. The ketone (2.0 mmol) was added and the mixture was cooled to –40 ºC. Then, Ph_2SiH_2 (2.4 mmol) was added and the mixture was stirred at –40 ºC under an argon atmosphere. The conversion of the ketone at each reaction time was determined by GC analysis relative to the internal standard.

Table 7-5. Time-dependent changes of **4h**

Time (min)	10	20	30	40	50	60	75	90	120
Conv. (%)	43	49	61	63	64	68	74	76	90
Time (min)	220	900							
Conv. (%)	95	99							

Table 7-6. Time-dependent changes of **4o**

Time (min)	15	30	45	60	90	60	120	180	240
Conv. (%)	29	36	46	43	52	68	60	64	74
Time (min)	420	1260							
Conv. (%)	91	99							

Table 7-7. Time-dependent changes of **4p**

Time (min)	15	30	60	120	240	480	630	720	1300
Conv. (%)	5	9	12	14	25	36	40	46	63
Time (min)	1450	1680	1920	2820	3360	4440			
Conv. (%)	66	71	77	89	92	98			

General procedures in Table 7-3.

CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (2.0 mL or 4.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Ph_2SiH_2 (2.0 mmol) was added and the mixture was stirred for 30 min under an argon atmosphere. A bulky substrate (**A**, 2.0 mmol) and a less bulky substrate (**B**, 2.0 mmol) were added simultaneously and the mixture was stirred at room temperature or –40 ^oC under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1N, 1.0 mL) and yields of the products were determined by GC analysis relative to an internal standard.

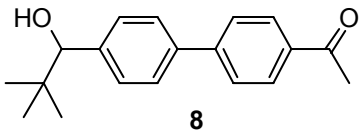
General procedures in Table 7-4.

CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (4.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. With stirring at at –40 ºC, a bulky ketone (**A**, 2.0 mmol), an aldehyde (**C**, 2.0 mmol) and Ph_2SiH_2 (2.0 mmol) were added under an argon atmosphere in this order. After the reaction, hydrolysis was performed by adding HCl/MeOH (1N, 1.0 mL) and yields of the products were determined by GC analysis relative to an internal standard.

Procedure for the reaction in Eqs. 7-3 and 7-4.

Eq. 7-3: CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (4.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Then, **7** (1.0 mmol) and Ph_2SiH_2 (1.0 mmol) were added in this order and the mixture was stirred for 3 h at room temperature under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1 N, 1.0 mL). The mixture was concentrated and **8** was isolated by silica gel column chromatography (eluent: CH_2Cl_2) to give **8** in 78% yield (219 mg).

Eq. 7-4: CuCl (1.98 mg, 0.02 mmol), **3** (39.4 mg, 0.02 mmol) and *t*BuONa (11.5 mg, 0.12 mmol) were placed in an oven dried 20 mL Schlenk tube. The tube was evacuated and backfilled with argon three times. Toluene (4.0 mL) was added and the mixture was stirred for 30 min at room temperature under an argon atmosphere. Toluene (6 mL), CH_2Cl_2 (0.5 mL) and **9** (1.0 mmol) were added in this order and the mixture was cooled to –40 ºC. Then, Ph_2SiH_2 (1.0 mmol) was added and the mixture was stirred for desired time at –40 ºC under an argon atmosphere. After the reaction, hydrolysis was performed by adding HCl/MeOH (1 N, 1.0 mL). The mixture was evaporated and purified by silica gel column chromatography (eluent: CH_2Cl_2) to give **10** in 63% yield (169 mg).



8

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.96 (s, 9H), 1.95 (d, J = 4 Hz, 1H), 2.64 (s, 3H), 4.47 (d, J = 4 Hz, 1H), 7.41 (d, J = 8 Hz, 2H), 7.59 (d, J = 8 Hz, 2H), 7.69 (d, J = 8 Hz, 2H), 8.03 (d, J = 8 Hz, 2H). ^{13}C NMR (100MHz, $CDCl_3$): δ 25.9, 26.7, 35.8, 82.1, 126.4, 127.1, 128.2, 128.9, 135.8, 138.7, 142.4, 145.4, 197.8. EI-MS: *m/z* 282 ($[M]^+$). Anal. Calcd. for $C_{19}H_{22}O_2$: C, 80.82; H, 7.85. Found: C, 80.87; H, 7.69.

Single crystals of **8** were obtained by recrystallization from CH_2Cl_2/pentane. The structure of **8** was also confirmed by X-ray crystallography (Figure 7-4).

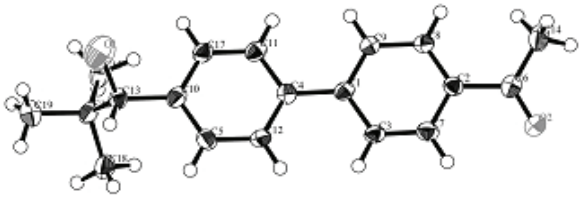
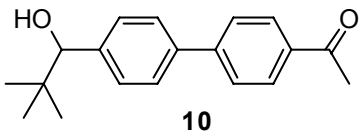


Figure 7-4. Crystal structure of **8**.



10

^{1}H NMR (400 MHz, $CDCl_3$): δ 0.96 (s, 9H), 2.11 (brd, 1H), 4.46 (brd, 1H), 7.42 (d, J = 8 Hz, 2H), 7.58 (d, J = 8 Hz, 2H), 7.75 (d, J = 8 Hz, 2H), 7.93 (d, J = 8 Hz, 2H), 10.0 (s, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 25.9, 35.7, 82.0, 126.4, 127.5, 128.3, 130.2, 135.0, 138.4, 142.7, 146.8, 191.9. EI-MS: *m/z* 268 ($[M]^+$). Anal. Calcd. for $C_{18}H_{20}O_2$: C, 80.56; H, 7.51. Found: C, 80.52; H, 7.44.

Single crystals of **10** were obtained by recrystallization from CH_2Cl_2/pentane. The structure of **10** was also confirmed by X-ray crystallography (Figure 7-5).

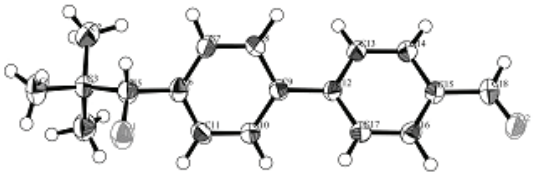


Figure 7-5. Crystal structure of **10**.

Synthesis of [CuCl(2)]$_2$.

A suspension of CuCl (14.8 mg, 0.15 mmol) and **2** (0.133 g, 0.15 mmol) in CH_2Cl_2 (2.0 mL) was stirred at room temperature for 2 h under Ar. After removal of the solvent under vacuum, the residue was dissolved in CH_2Cl_2 and crystallized by adding diethyl ether. White crystals thus obtained was filtered off and dried under vacuum. Yield 80 mg (54%). Single crystals of the complex were obtained from the recrystalization from CH_2Cl_2/Et_2O (Figure 7-3). ^{1}H NMR (400 MHz, CD_2Cl_2): δ 1.82 (s, 36H), 6.96 (m, 3H), 7.00 (m, 12H), 7.09 (m, 6H), 7.24 (dd, J = 11.6 Hz, 1.4 Hz, 6H). ^{13}C NMR (100 MHz, CD_2Cl_2): δ 20.2, 126.9, 127.0, 131.3 (d, J = 36.4 Hz), 132.0, 132.4 (d, J = 14.3 Hz), 135.3, 140.2, 141.9 (d, J = 10.5 Hz). ^{31}P NMR (160 MHz ,CD_2Cl_2, −80 ºC): δ −1.23. MALDI-TOF-MS (CSA): *m/z* 1971 ([M]$^+$). Anal. Calcd. for $C_{132}H_{126}Cl_2Cu_2P_2$: C, 80.38; H, 6.44. Found: C, 80.31; H, 6.45.

X-ray Crystallographic Analysis.

Crystallographic data of [CuCl(**2**)]$_2$·1.5($C_4H_{10}O$)·0.5(CH_2Cl_2), **8** and **10** were summarized in Tables 7-8. All the data were collected on a Rigaku/Saturn70 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.71070 Å) at 153 K, and processed using CrystalClear (Rigaku).[21] The structures were solved by a direct method and refined by full-matrix least-square refinement on F^2. The non-hydrogen atoms, except disordered atom and solvated molecules, were refined anisotropically. All hydrogen atoms were located on the calculated positions and not refined. All calculations were performed using the CrystalStructure software package.[22] CCDC 753994, 753995, and 753996 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge from the Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.

Table 7-8. Crystallographic data.

compound	$[CuCl(\mathbf{2})]_2 \cdot 1.5(C_4H_{10}O) \cdot 0.5(CH_2Cl_2)$	**8**	**10**
empirical formula	$C_{110}H_{102}Cl_6O_8P_2$	$C_{90}H_{88}N_2O_{10}P_2$	$C_{118}H_{146}O_{10}P_2$
formula weight	1826.68	1419.64	1881.30
temp / K	153	153	153
crystal system	triclinic	monoclinic	monoclinic
space group	*P*-1 (#2)	*P*2 (#4)	$P2_1/c$ (#14)
a / Å	16.588(9)	6.035(4)	10.163(5)
b / Å	17.581(10)	7.667(5)	6.184(3)
c / Å	23.634(14)	16.316(10)	23.417(13)
α / deg	99.964(8)	90	90
β / deg	107.783(7)	94.948(7)	100.314(7)
γ / deg	103.209(4)	90	90
V / Å^3	6166(6)	3668(2)	1448(1)
Z	2	2	4
d_{cacd}/g cm^{-3}	1.145	1.247	2.268
observed reflections	27321	2536	3184
unique reflections	15809 ($I > 3\sigma(I)$)	2536 (all data)	3184 (all data)
GOF	1.124	1.579	1.002
*R*1 ($I > 2\sigma(I)$), *wR*2[a]	0.0682,[b] 0.1549[b,c]	0.0937, 0.2511[d]	0.0818, 0.2469[e]

[a] $R1 = \Sigma[|F_o| - |F_c|]/\Sigma|F_o|$, $wR2 = [\Sigma(w(F_o^2 - F_c^2)^2) / \Sigma w(F_o^2)^2]^{1/2}$. [b] *R* ($I > 3\sigma(I)$) and *Rw* ($I > 3\sigma(I)$) values, respectively. [c] $w = 1/[0.001Fo^2 + 3.0\sigma(F_o^2) + 0.5]/(4F_o^2)$. [d] $w = 1/[0.001Fo^2 + \sigma(F_o^2)]/(4F_o^2)$. [e] $w = 1/[\sigma(F_o^2)]/(4F_o^2)$.

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List of Publications

I. The present Thesis is composed of the following papers.

Chapter 1

(1) Copper-Catalyzed Highly Selective Semihydrogenation of Non-Polar Carbon-Carbon Multiple Bonds using a Silane and an Alcohol
Kazuhiko Semba, Tetsuaki Fujihara, Tinghua Xu, Jun Terao, Yasushi Tsuji
Adv. Synth. Catal. **2012**, *354*, 1542–1550.

Chapter 2

(2) Copper-Catalyzed Hydrocarboxylation of Alkynes Using Carbon Dioxide and Hydrosilanes
Tetsuaki Fujihara, Tinghua Xu, Kazuhiko Semba, Jun Terao, Yasushi Tsuji
Angew. Chem. Int. Ed. **2011**, *50*, 523–527.

Chapter 3

(3) Copper-Catalyzed Highly Regio- and Stereoselective Directed Hydroboration of Unsymmetrical Internal Alkynes: Controlling Regioselectivity by Choice of Catalytic Species
Kazuhiko Semba, Tetsuaki Fujihara, Jun Terao, Yasushi Tsuji
Chem. Eur. J. **2012**, *18*, 4179–4184.

Chapter 4

(4) Copper-Catalyzed Highly Selective Hydroboration of Allenes and 1,3-Dienes
Kazuhiko Semba, Masataka Shinomiya, Tetsuaki Fujihara, Jun Terao, Yasushi Tsuji
Chem. Eur. J. **2013**, *19*, in press. DOI:10.1002/chem.201300443

Chapter 5

(5) Copper-Catalyzed Allylboration of Allenes Employing Bis(pinacolato)diboron and Allyl Phosphates
Kazuhiko Semba, Naoto Bessho, Tetsuaki Fujihara, Jun Terao, Yasushi Tsuji
In preparation.

Chapter 6

(6) Synthesis of 2-Boryl-1,3-butadiene Derivatives via Copper-Catalyzed Borylation of α-Benzyloxyallenes
Kazuhiko Semba, Tetsuaki Fujihara, Jun Terao, Yasushi Tsuji
In preparation.

Chapter 7

(7) Copper-Catalyzed Hydrosilylation with a Bowl-Shaped Phosphane Ligand: Preferential Reduction of a Bulky Ketone in the Presence of an Aldehyde
Tetsuaki Fujihara, Kazuhiko Semba, Jun Terao, Yasushi Tsuji
Angew. Chem. Int. Ed. **2010**, *49*, 1472–1476.

II. Following publications are not included in this Thesis.

(8) Copper-Catalyzed Silacarboxylation of Internal Alkynes by Employing Carbon Dioxide and Silylboranes
Tetsuaki Fujihara, Yosuke Tani, Kazuhiko Semba, Jun Terao, Yasushi Tsuji
Angew. Chem. Int. Ed. **2012**, *51*, 11487–11490.

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