Asymmetric Copper Catalyzed Addition to Activated Alkenes

Hershel Lackey
ASYMMETRIC COPPER CATALYZED ADDITION TO ACTIVATED ALKENES

By

HERSHEL LACKEY

A Thesis submitted to the
Department of Chemistry and Biochemistry
in partial fulfillment of the
requirements for the degree of
Master of Science

Degree Awarded
Spring Semester, 2011
The members of the committee approve the dissertation of Hershel Lackey defended December 3, 2010.

_________________________________
Tyler D. McQuade
Professor Directing Thesis

_________________________________
Greg B. Dudley
Committee Member

_________________________________
Michael Shatruk
Committee Member

_________________________________
Lei Zhu
Committee Member

The Graduate School has verified and approved the above-named committee members.
The views expressed in this article are those of the author and do not reflect the official policy or position of the United States Air Force, Department of Defense, or the U.S. Government
ACKNOWLEDGEMENTS

I would like to acknowledge Dr. Tyler McQuade and the McQuade Research lab for allowing me to join the group and providing me with an excellent learning environment. I would like to particularly thank Dr. Jin Kyoon Park for his contributions and support. His knowledge, patience, and teaching skills are amazing and I'll miss working with him. I also greatly appreciate the contributions provided by Brian Ondrusek and Matt Rexford, without their help the projects discussed within would not be where they are today. Special thanks also to Suzie Opalka, Tyler McQuade and Jin Kyoon Park for editing this manuscript.

I’m also wish to acknowledge the Air Force Institute of Technology and Air Force ROTC detachment at FSU for their funding and support they have provided.
TABLE OF CONTENTS

LIST OF TABLES .................................................................................................................................................. VI
LIST OF FIGURES ................................................................................................................................................ VII
ABSTRACT ............................................................................................................................................................ VIII

PART I THE β-BORYLATION REACTION ........................................................................................................... 1
  1.1 Overview and History of the β-Borylation Reaction .................................................................................. 1
  1.2 Applications of Chiral Boronate Esters .................................................................................................. 5
  1.3 Strategy and Synthesis of a Chiral 6 Membered NHC Copper Catalyst .................................................. 7
  1.4 Application of 1 to the β-Borylation Reaction and Optimization of Conditions .............................. 10
  1.5 Exploring the Substrate Scope of the Reaction .................................................................................... 11
  1.6 Determining the Activity of the Catalyst .............................................................................................. 14
  1.7 Conclusions ............................................................................................................................................ 14

PART II THE ALLYLIC SUBSTITUTION REACTION .............................................................................. 16
  2.1 Discovery of a Unique Allylic Substitution Reaction ............................................................................ 16
  2.2 Previously Reported Allylic Substitutions with Nucleophillic Boron .................................................. 18
  2.3 Optimization of Conditions and Discovery of Stereoconvergence .................................................. 19
  2.4 Reaction Scope .................................................................................................................................... 25
  2.5 Conclusions ............................................................................................................................................ 30

APPENDIX A PART I SUPPORTING INFORMATION ............................................................................ 31

APPENDIX B PART II SUPPORTING INFORMATION ........................................................................... 64

BIBLIOGRAPHY .................................................................................................................................................. 97

BIOGRAPHICAL SKETCH ................................................................................................................................. 102
LIST OF TABLES

Table 1. Overview of Copper Catalyzed Asymmetric β-Borylations ........................................... 4
Table 2. Optimization of Conditions for the β-Borylation Reaction .......................................... 11
Table 3. Application of Optimized β-borylation Conditions to Aliphatic Substrates............... 12
Table 4. Application of Optimized β-Borylation Conditions to Aromatic Substrates.............. 13
Table 5. Determining the Activity of the Catalyst. ................................................................. 14
Table 6. Screening Optimal Aryl Leaving Groups ................................................................. 19
Table 7. Substrate Screen with Geometric Isomers in High Purity. ......................................... 26
Table 8. Substrate Screen to Mixtures of Geometric Isomer ................................................... 27
Table 9. Function Group Compatibility Under Reaction Conditions ..................................... 28
# LIST OF FIGURES

**Figure 1.** General Donors and Acceptors in the Michael Addition Reaction ........................................... 1  
**Figure 2.** 1,4 Addition Versus 1,2 Addition .................................................................................................. 1  
**Figure 3.** Copper’s Proposed Role in Directing Nucleophilic Attack ..................................................... 2  
**Figure 4.** The β-Borylation Reaction ........................................................................................................ 3  
**Figure 5.** Marder’s Proposed Catalytic Cycle for the β-Borylation Reaction ........................................ 3  
**Figure 6.** Oxidation of Chiral Boronate Esters and 1,2 Homologations .................................................. 6  
**Figure 7.** The Suzuki-Miyaura Cross Coupling and Amination of Boronate Esters ............................... 6  
**Figure 8.** The Addition of Allyl Boronates to Aldehydes ......................................................................... 7  
**Figure 9.** Average N-C-N Bond Angle For NHC Carbenes Complexes ................................................ 7  
**Figure 10.** Design of a Chiral 6 membered NHC Copper Complex ......................................................... 8  
**Figure 11.** Synthesis of a Chiral 6 Membered NHC Copper Complex ....................................................... 9  
**Figure 12.** X-ray Crystal Structure of the Monorhodium NHC Complex ............................................... 9  
**Figure 13.** Comparison between NHC Complexes .................................................................................. 10  
**Figure 14.** Borylation of Substrate 5 with the 6-Membered NHC Copper Complex ............................... 15  
**Figure 15.** Borylation of Substrate 5 with the 5-membered NHC Copper Complex ............................... 15  
**Figure 16.** Chemoselectivity Differences Between Copper Complexes ............................................... 16  
**Figure 17.** Reactivity of Various Copper Complexes to Form Allylated Products ................................. 17  
**Figure 18.** Proposed Catalytic Cycle for Copper Catalyzed Diboron Addition to Allylic Carbonates .......................................................................................................................... 18  
**Figure 19.** Screening Steric Environments for the Optimal Catalyst ....................................................... 19  
**Figure 20.** Hoveyda’s Diboron Addition is Stereodivergent; E Alkenes Give Opposite Configuration than Z Alkenes ................................................................................................................... 21  
**Figure 21.** Palladium Catalyzed Allylation Reaction Going Through a Palladium-π-allyl Intermediate .......................................................................................................................................... 22  
**Figure 22.** Plausible Catalyst and Substrate Spatial Arrangement to Give Stereoconvergence. ........... 23  
**Figure 23.** Rate Comparison of the Consumption of the E isomer Compared to the Z Isomer. ............. 24  
**Figure 24.** Methods Used to Access Aryl Allylic Ethers ....................................................................... 25  
**Figure 25.** Catalyst’s Chemoselectivity for Disubstituted Alkenes vs. Trisubstituted ............................ 29
ABSTRACT

This thesis presents the synthesis of a chiral 6-membered NHC catalyst copper catalyst and its use in the β-borylation and allylic substitution reactions. The application of the catalyst in the known β-borylation reaction demonstrates that the catalyst can provide high yields, enatoselectivities, and activity comparable if not improved to traditional 5-membered NHCs and phosphine copper complexes. The 6-membered NHC copper complex was then used in a nucleophilic diboron addition to allylic aryl ethers where the catalyst demonstrated different chemoselectivity compared to 5-membered NHC and phosphine catalyst. Further investigation of this phenomenon led to development of a stereoconvergent, asymmetric reaction which could convert mixtures of $E$ and $Z$ isomers into a single enantiomer in high yield.
Part 1

The β-Borylation Reaction

1.1 Overview and History of the β-Borylation Reaction

Conjugate addition of a nucleophile to an electron deficient alkene or alkyne is one of the most fundamental concepts in organic chemistry. The conjugate addition reaction, sometimes known as a Michael addition, encompasses a large number of nucleophiles and a large scope of electron deficient alkenes or alkynes to which nucleophiles add (Figure 1).\(^1\,2\,3\)

\[
\begin{align*}
R' \rightarrow X & \quad \text{Michael Donor Nucleophile} \\
\text{R} \equiv \equiv \text{EWG} & \quad \text{Michael Acceptor Electron Deficient Alkene} \\
X = C, O, N, S, Si, \text{ etc} & \quad \text{EWG} = \quad \text{NO}_2, \text{SO}_2R, \text{ etc}
\end{align*}
\]

**Figure 1.** General Donors and Acceptors in the Michael Addition Reaction.

The ability of the conjugate addition to form carbon-carbon bonds and carbon-heteroatom bonds with useful substrates has allowed the reaction to be used in numerous synthetic applications. The Michael Addition’s main drawback, however, is that other reactions such as 1,2 addition compete with the desired 1,4 addition (Figure 2).

**Figure 2.** 1,4 Addition Versus 1,2 Addition.

One strategy often employed to control addition to the desired 1,4 product is the use of additives. In particular, addition of copper salts promotes formation of the 1,4 product. Copper, as an
additive, was first used as a stoichiometric agent, where it was added to alkyl lithium or Grignard reagents to form a cuprate or mixed cuprate\(^4,5\), which could then associate with electron deficient alkenes to direct conjugate addition(Figure 3).\(^6\) Later refinements include the use of copper in catalytic amounts. The mechanism of copper catalyzed additions to alkenes is debated, but it is postulated the mechanism might be similar to the use of a stoichiometric amount of copper (Figure 3).\(^7\)

![Figure 3. Copper’s Proposed Role in Directing Nucleophilic Attack.](image)

Over the last few decades chiral copper complexes have been used to affect asymmetric Michael additions. A variety of chiral ligands, such as phosphine, carbene, amine, etc, have been demonstrated to associate with copper and provide a steric environment around copper that produces Michael addition products in high yield and enantioselectivity. Copper’s selectivity and relative abundance have allowed the asymmetric copper catalyzed addition reaction to become one of the most important methods for the synthesis of pharmaceutical agents and materials.\(^7,8,9\)

The scope of asymmetric copper catalyzed nucleophilic additions is growing, and there are a number of Michael acceptors, and donors that can be used in this process. Only recently, however, has nucleophilic boron been used to realize asymmetric Michael additions. Named, the \(\beta\)-borylation reaction, it was first demonstrated, racemically, in 2000, by Hosmi’s group. They demonstrated that a phosphine copper complex could catalyze the 1,4 nucleophilic boron addition to unsaturated carbonyls.\(^10\) They postulated this reaction occurred by copper inserting into a boron-boron bond and then the copper-boron bond reacting with the activated alkene (Figure 1).
This reaction led to a surge of research in the field of 1,4 nucleophilic addition of boron to unsaturated carbonyls. Subsequent papers illustrated that the reaction could be catalyzed by a number of transition metals including Ni$^{11}$, Pt$^{12,13}$, and Rh$^{14}$. However, because of the harsh conditions used in these reactions asymmetric catalysis was not possible.

Then in 2006, very mild/low temperature β-borylation conditions were discovered by Yun’s Group. In particular, they found that the use of one equivalent of methanol greatly increases the reaction rate.$^{15}$ Methanol allowed for presumably easier formation of the copper oxygen bond and protonation of the enolate formed (Figure 5).

The use of methanol allowed for the subsequent use of milder conditions and the use of chiral phosphine ligands which were demonstrated to induce high enantioselectivity on a wide variety of substrates to include unsaturated esters, nitriles$^{16}$, amides$^{17}$ and acyclic and cyclic enones (Table 1).$^{18,19}$

---

**Figure 4.** The β-Borylation Reaction

**Figure 5.** Marder’s Proposed Catalytic Cycle for the β-Borylation Reaction.
The field of asymmetric copper catalyzed β-borylations reactions has steadily expanded, and table 1 illustrates the optimal catalyst structures, resulting enantioselectivities and yields, and substrate scope of some these reactions.

<table>
<thead>
<tr>
<th>Group</th>
<th>Optimal Ligand</th>
<th>Ligand Type(s)</th>
<th>Substrates</th>
<th>General Yields/ee</th>
<th>Papers</th>
</tr>
</thead>
</table>

Chiral NHC copper complexes were demonstrated to perform β-borylations effectively, but with lower enantioselectivity than the phosphine ligand, josiphos, and mandyphos catalyzed versions. Axially chiral phosphine ligands such as quinap and quinazoline were also shown to be effective at catalyzing the reaction, but with modest enantioselectivity. The substrate scope of the asymmetric β-borylation reaction has been expanded to cyclic enones using a chiral phosphine complexes, and to β,β disubstituted linear enones using a diamine ligand. Hoyevda has demonstrated an asymmetric version of the β-borylation to β,β disubstituted linear activated alkenes using a 5 membered chiral NHC ligand.

Studies on the role of copper in these systems have been performed by a number of laboratories. Sadighi’s group isolated and obtained crystal structures of the copper pinacolboron complex. In some cases, free ligand has been shown to catalyze the β-borylation but with lower ee and rates.
For instance, Hoveyda group has demonstrated a transition metal free racemic borylation of enones using only a 5 membered NHC, and Fernadez’s group has demonstrated that chiral phosphines, without transition metals, catalyze the borylation reaction with mixed enatioselectivity. DFT studies performed on the reaction have also helped elucidate the mechanism. Since the asymmetric copper catalyzed reaction several other metal and ligand combinations have been used asymmetrically as well.

The β-borylation reaction is particularly useful because it enables the rapid synthesis of boronate esters and alkyl boronates that tended to be very difficult to prepare otherwise. Before the demonstration of the asymmetric addition of nucleophilic boron, routes to organic boronates were limited to such reactions as hydroboration, diboration, and dehydrogentive boration which have limited substrate scopes and/or produce racemic products.

1.2 Applications of Chiral Boronate Esters

Organic boranes have been directly targeted for applications as serine protease inhibitors, in certain supramolecular sensors, and in precursors to boron carbides. Moreover, boronate esters and alkyl boronates are important to the organic community because they can be used as versatile intermediates to make complex molecules. For instance, the carbon-boron bond can be oxidized with retention of stereochemistry, to form chiral alcohols (Figure 6). Chiral boronates also undergo 1,2 homologations with carbon nucleophiles to give chiral carbon-carbon bonds (Figure 6).
Figure 6. Oxidation of Chiral Boronate Esters and 1,2 Homologations.

The Suzuki Miyaura Cross Coupling reaction has also been demonstrated to transform carbon-boron bonds to a carbon-carbon process, and has recently been demonstrated with the retention of stereochemistry. Amination of the carbon-boron bond has also demonstrated with retention of stereochemistry.

Figure 7. The Suzuki-Miyaura Cross Coupling and Amination of Boronate Esters.
Chiral allyl boronates, similarly to allyl silanes in the Sakurai allylation, have been demonstrated to add to ketones and aldehydes in the presence of a Lewis acid to give chiral alcohols (Figure 8). 44,45

Figure 8. The Addition of Allyl Boronates to Aldehydes.

Chiral boronate esters are particularly useful in synthetic organic chemistry. The expansion of these reactions and easier access to chiral boronates, through reactions as the $\beta$-borylation, gives high potential that even more methods to use chiral boronates will be developed.

1.3 Strategy and Synthesis of a Chiral 6 Member NHC Copper Catalyst

NHC transition metal complexes are excellent catalysts for organic reactions. 46 5-membered NHC complexes are the most commonly NHC metal complexes reported, but there are several examples of enhanced reaction rates and yields, seen with 6-membered NHC rings. 47,48,49 These advantages associated with the use of a 6–membered ring NHC stem from the change in both steric and electronic properties associated with the increase in ring size. It has been demonstrated these properties are often correlated to the N-C-N bond angle of the NHC ligand (Figure 9).

Generally, the size of the N-C-N bond angle increases with an increasing ring size with 5-membered NHC rings having an average N-C-N angle of 102-105°, 6 membered rings 112-114°, and 7 membered rings 113-116° respectively. 50

Figure 9. Average N-C-N Bond Angle For NHC Carbenes Complexes.
The increase in the N-C-N bond size leads to a change in the steric environment around the carbene metal bond, providing a more restrictive chiral pocket as the angle increases. Size increase in the N-C-N angle generally correlates with well the NHC ligand electron donating ability. Electron donating ability directly correlates to a NHC’s nucleophilicity, and standards for measurement of nucleophilicity of NHC ligands have been developed by measuring changes in IR stretching.\textsuperscript{51,52} Nucleophilicity of the NHC ligand is important because the NHC ligand will affect the electronic properties of transition metal the NHC ligand is associated with. The transition metal’s electronic state will in turn many times influences the chemoselectivity and activity of the catalyst.

No 6-membered NHC rings reported to date have the necessary steric environment to perform asymmetric catalysis. It was hypothesized that the more flexible 6 membered ring could not provide the necessary rigid chiral environment to induce enatioselectivity, compared to commonly used 5 membered ring. To circumvent this problem, we envision a 6 membered NHC ring with two aromatic rings annulated to the central core. These aromatic rings would stabilize the 6 membered ring and provide a rigid core. A chiral pocket around the carbene could then be created with a blocking group on one side and two chiral phenyl groups on the other (Figure 10).

**Figure 10.** Design of a Chiral 6 membered NHC Copper Complex

From a known intermediate, 2, nucleophilic aromatic substitution followed by annulation with triethoxy orthoformate gave 4 as a shelf stable salt in 95% yield. The salt can be treated with
potassium \( t \)-butoxide and copper(I) chloride as illustrated to give the NHC copper complex, 1, in high yield.

Figure 11. Synthesis of a Chiral 6 Membered NHC Copper Complex

Unfortunately, crystals of the copper NHC complex suitable for X-ray analysis have not yet been obtained. However, reacting the NHC salt with LHMDS and rhodium(I) chloride 1,5 cyclooctadiene complex dimer gives a mixture of rhodium NHC complexes. Treatment with pyridine leads to isolation of a pure 1:1 NHC rhodium complex that could be crystallized from X and whose crystals x-ray analysis was performed (Figure 12).

Figure 12. X-ray Crystal Structure of the Monorhodium NHC Complex.

X-ray analysis indicates the metal complex has a flat core and blocking mesityl group on one side and chiral phenyl groups on the other. The complex has a N-C-N bond angle of 115°.
ruthenium complex has an CO IR average stretching band of 2036 cm\(^{-1}\) indicating it falls
between 7 membered NHC rings and 5 membered NHC with respect to donor ability. Figure 13
compares our catalyst’s N-C-N bond angle and IR stretching frequency with several known NHC
rhodium complexes.

![Figure 13. Comparison between NHC Complexes](attachment:image.png)

**1.4 Application of the 1 to the β-Borylation Reaction and Optimization of Conditions**

The field of β-borylation was rapidly progressing; we had noted that no NHC ligand had
produced high enantioselectivity in catalyzing disubstituted alkenes (mono-substituted in the β-
position) in the β-borylation reaction. We envisioned the β-borylation reaction as a known
medium where we could test the chiral environment of our ligand, its activity, and compare it
against known NHC and phosphine ligands. We also envisioned that we could add to the
knowledge of the field of β-borylation, by synthesizing a NHC catalyst that could be used to β-
borylate disubstituted alkenes with high enatioslectivity. Lastly, we realized chiral boronate
esters produced by the reaction could be used in the synthesis of complex products in our labs or
with collaborators.

With the copper complex in hand, we investigated its ability to catalyze the β-borylation
reaction. Initial screening, as seen in entry 1 Error! Reference source not found., illustrated
that our copper complex was effective at catalyzing the β-borylation reaction with high
enantioselectivity using slight modifications to Yun’s conditions (See Supporting Information for details).

Table 2. Optimization of Conditions for the β-Borylation Reaction

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Temp (°C)</th>
<th>Time</th>
<th>Yield (%)b</th>
<th>ee (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Et₂O</td>
<td>0</td>
<td>&lt;1min</td>
<td>&gt;98</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>Et₂O</td>
<td>-30</td>
<td>3h</td>
<td>&gt;98</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>Et₂O</td>
<td>-55</td>
<td>6h</td>
<td>&gt;98</td>
<td>86</td>
</tr>
<tr>
<td>4</td>
<td>Toluene</td>
<td>0</td>
<td>&lt;1min</td>
<td>&gt;98</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>THF</td>
<td>0</td>
<td>&lt;1min</td>
<td>&gt;98</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>CH₃CN</td>
<td>0</td>
<td>&lt;1min</td>
<td>&gt;98</td>
<td>63</td>
</tr>
<tr>
<td>7</td>
<td>CH₂Cl₂</td>
<td>0</td>
<td>&lt;1min</td>
<td>&gt;98</td>
<td>64</td>
</tr>
</tbody>
</table>

We screened the reaction to determine optimized conditions for the reaction. We found that decreasing the temperature to -55°C gave the highest selectivity (Error! Reference source not found. entries 1-3). Screening the reaction in diethyl ether, toluene, tetrahydrofuran, acetonitrile, and dichloromethane at 0°C, (Error! Reference source not found. entries 1, 4-7), indicated that both diethyl ether and toluene were optimal solvents for high yield and enantioselectivity.
1.5 Exploring the Substrate Scope of the Reaction

The optimized reaction conditions were then applied to a variety of unsaturated esters to illustrate the scope of the unsaturated esters that could be borylated using 1 (Table 3 & Table 4).

**Table 3.** Application of Optimized β-borylation Conditions to Aliphatic Substrates.

<table>
<thead>
<tr>
<th>entry</th>
<th>substrate</th>
<th>Product</th>
<th>yield (%)</th>
<th>ee(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>93</td>
<td>90 (R)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>92</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>90</td>
<td>91</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>91</td>
<td>96 (S)</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td>95</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td></td>
<td>92</td>
<td>91</td>
</tr>
</tbody>
</table>
Complex 1 effectively borylates a wide variety of linear aliphatic substrate entries (Table 3, entries 1-3) with high enatioselectivity. The complex tolerates $\gamma$-branching well (Table 3, entries 4-6).
Table 4. Application of Optimized \( \beta \)-Borylation Conditions to Aromatic Substrates.

\[
\begin{align*}
\text{R}_1\text{C}=&\text{O} \quad \rightarrow \quad \text{Bpin} \quad \text{O} \\
\text{R}_1\text{C}=&\text{O} \quad \rightarrow \quad \text{Bpin} \quad \text{O} \\
\text{R}_1\text{C}=&\text{O} \quad \rightarrow \quad \text{Bpin} \quad \text{O} \\
\text{R}_1\text{C}=&\text{O} \quad \rightarrow \quad \text{Bpin} \quad \text{O}
\end{align*}
\]

<table>
<thead>
<tr>
<th>entry</th>
<th>substrate</th>
<th>Product</th>
<th>yield (%)</th>
<th>ee(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td>88</td>
<td>87</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td>91</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>95</td>
<td>96</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td>90</td>
<td>92</td>
</tr>
</tbody>
</table>

The application of complex 1 to aromatic substrates (Table 4 entries 1-4) illustrates the ability of the complex to \( \beta \)-borylate aromatic unsaturated esters with high yield and selectivity.

1.6 Determining the Activity of the Catalyst

Convinced that complex 1 could competently borylate a range of unsaturated esters with high enantioselectivity and yield we investigated the activity of the catalyst (Table 5).
Choosing a substrate that exhibited high enantioselectivity under our conditions previously (Table 4 Entry 9) we demonstrated the reaction went to full completion with 10 mol % of the catalyst with 92 % ee. Gradually decreasing the catalyst loading to 0.01 mol % (Table 5 Entries 2-5) we found that at even relatively low loadings the reaction goes to completion, in a less than 2 hours, and enantioselectivty is not significantly decreased. This experiment indicates that 1 is a relatively stable complex under reaction conditions and illustrates high reactivity towards the \( \beta \)-borylation reaction.

### 1.7 Conclusions

In summary, we developed a new chiral 6-membered NHC catalyst that catalyzes the \( \beta \)-borylation reaction on a wide range of disubstituted unsaturated aliphatic and aryl esters with high yield and enantioselectivity. These results indicate that the 6-membered NHC copper complex provides the necessary steric environment for the addition of diboron, and its performance is comparable if not improved compared to 5-membered NHC ring or phosphine catalysts. We also demonstrate that the copper complex is relatively stable under reaction conditions performing the \( \beta \)-Borylation reaction with catalyst loading of 0.01 mol % without significant decay in enantioselectivity or yield.
Part 2
The Allylic Substitution Reaction

2.1 Discovery of a Unique Allylic Substitution Reaction

In the process of screening substrates for the β-borylation reaction we ran substrate 5 under standard β-borylation conditions with the 6-membered NHC copper complex, 1, and received unexpected results. The catalyst did not provide the expected β-borylated product, but gave a deallylation product (Figure 14).

![Figure 14](image1.png)

Figure 14. Borylation of Substrate 5 with the 6-Membered NHC Copper Complex

Even more surprising, using the same reaction conditions, but with the 5-membered NHC, the reaction yielded only the β-borylated product (Figure 15).

![Figure 15](image2.png)

Figure 15. Borylation of Substrate 5 with the 5-membered NHC Copper Complex
Further investigation into the observation revealed that the result was not just a neighboring group effect. As illustrated in Figure , even a substrate with an allyl group in the para position exhibited a preference for the electron rich alkene over the electron poor alkene. Further experimentation also revealed that the 5-membered ring still displayed a preference for the electron poor alkene, providing the \( \beta \)-borylation product over reaction with the electron rich alkene to provide the allylic substituted product. Experimentation with Xantphos, a phosphine copper complex, which has been reported to catalyze addition of diboron to alkenes, provided a mixture of \( \beta \)-borylated and allylic substitution products.\(^5\)

![Figure 16. Chemoselectivity Differences Between Copper Complexes.](image_url)

Further investigation revealed that the 6-membered NHC catalyst showed much higher activity and yield compared to the 5-membered NHC and phosphine catalysts to a non terminal alkene (Figure 14).
Figure 14. Reactivity of Various Copper Complexes to Form Allylated Products.

These results intrigued us. It was clear that the conjugate addition of boron to allylic ethers was not induced by a neighboring group effect. It was also clear that the ligands associated with copper affected the chemoselectivity of nucleophilic addition. The results also indicated that the 6-membered ring was optimal in the addition of nucleophilic boron to aryl allylic ethers.

2.2 Previously Reported Allylic Substitutions with Nucleophilic Boron

Copper(I) catalyzed nucleophilic boron addition to allylic carbonates and allyl ethers has been reported in literature recently. Sawamura’s group first demonstrated the reaction using the achiral xantphos copper(I) complex as the catalyst and proposed the following catalytic cycle (Figure).\textsuperscript{52}
Sawamura’s group has since demonstrated the reaction could be performed on *cis* allylic carbonates using chiral phosphine copper complexes with excellent enantioselectivity.\(^{53}\) They have since extended this protocol to cyclic allylic alkyl ethers in an enantio-convergent addition of boron.\(^ {54}\) Hoveyda’s group recently broadened the protocol, using a 5-membered NHC copper complex and carbonates as leaving groups, to a wider scope of substrates to include both *E* and *Z* alkenes as well as trisubstituted alkenes with high enantioselectivity.\(^ {55}\)

**2.3 Optimization of Conditions and Discovery of Stereoconvergence**

To begin work on an asymmetric reaction we first investigated the optimal catalyst for enantioselectivity. Initial experimentation revealed that the catalyst 1, gave full conversion of substrate 6 at 0°C, but only modest ee 47%. Modification of the steric environment from the mesitylene blocking group to a more bulky, symmetric *tert*-butyl *m*-xylene substituent, (Figure) led higher enantioselectivity under the same reaction conditions (84% ee).
Using catalyst 7 we screened for the best leaving group (Table 6). While screening leaving groups we noticed the best ee was obtained either using the \textit{m}-nitro phenol, \textit{p}-nitro phenol or the 3,5-dimethyl phenol (Table 6 Entries 3, 5, and 6). However, the more interesting result obtained in the screen was that both \textit{cis} and \textit{trans} isomers gave the same enantiomer and the reaction appeared to be stereoconvergent (Table 6 entry 8 and 9).

\textbf{Table 6. Screening Optimal Aryl Leaving Groups}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Yield</th>
<th>ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>91</td>
<td>84 (S)</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>91</td>
<td>80 (S)</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>86</td>
<td>88 (S)</td>
</tr>
</tbody>
</table>
These results intrigued us. Conversion of both $E$ and $Z$ isomers to the same enantiomer through a transition metal catalyzed reaction is uncommon. For instance, in most cases allylic substitutions are stereodivergent, where cis gives an opposite enantiomer than trans, as illustrated in Hoveyda’s work where the addition of diboron to a $Z$ alkene gives the opposite enantiomer configuration than addition to the $E$ alkene (Figure).

Table 6. Continued.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Yield</th>
<th>ee</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td><img src="image" alt="Substrate 4" /></td>
<td>95</td>
<td>65 (S)</td>
</tr>
<tr>
<td>5</td>
<td><img src="image" alt="Substrate 5" /></td>
<td>94</td>
<td>87 (S)</td>
</tr>
<tr>
<td>6</td>
<td><img src="image" alt="Substrate 6" /></td>
<td>74</td>
<td>84 (S)</td>
</tr>
<tr>
<td>7</td>
<td><img src="image" alt="Substrate 7" /></td>
<td>92</td>
<td>62 (S)</td>
</tr>
<tr>
<td>8</td>
<td><img src="image" alt="Substrate 8" /></td>
<td>79</td>
<td>89 (S)</td>
</tr>
<tr>
<td>9</td>
<td><img src="image" alt="Substrate 9" /></td>
<td>47</td>
<td>91 (S)</td>
</tr>
</tbody>
</table>
We hypothesized two different scenarios that could explain the stereoconvergence observed in our system. One explanation could be a dynamic kinetic asymmetric transform (DYKAT). In this system, starting material could racemize to a common intermediate which could then undergo a directed nucleophilic attack to give one enantiomer in excess. Stereoconvergent Pd-π-allyl systems, a type of DYKAT, are well known.\textsuperscript{56,57} These systems convert mixtures of enantiomers into optically pure materials, and it could be possible to extrapolate this type of mechanism to our method (Figure ).
Figure 21. Palladium Catalyzed Allylation Reaction Going Through a Palladium-π-allyl Intermediate

A second possibility that could occur is direct conversion of the substrate into the enantiomer through a preferred spatial arrangement by the catalyst and the substrate. One explanation of this would be if the β-substituent on the alkene would control the preferred transition state between itself and the catalyst (Figure ).
In this scenario, the leaving group would have relatively ample space to be placed on top of the catalyst backbone and the leaving group’s orientation would not affect the final products stereochemistry. However, the $\beta$-substituent on the alkene might be hindered and only be able to be positioned to one side. We hypothesized that either a spatial arrangement as described above or a DYKAT was responsible for the stereoconvergence observed.

To investigate our hypothesis, we wanted to measure rate of the consumption of trans isomer versus the consumption of cis isomer during the reaction. To setup the experiment, we used 1 equivalent of $\text{B}_2\text{Pin}_2$ (the limiting reagent), one equivalent of the trans isomer and one equivalent of the cis isomer, and standard reaction conditions (Figure ). We then monitored the reaction progress by GC and HNMR.
Figure 23. Rate Comparison of the Consumption of the E isomer Compared to the Z Isomer.

Interestingly, the trans isomer reacted faster than the cis isomer during the reaction, but we did not see any definite signs of the racemization of starting material. Based on this information, it led us to believe that the stereoconvergence observed in the reaction might not be from dynamic kinetic resolution, but from the substrate’s spatial arrangement with the NHC catalyst.

2.4 Reaction Scope

Stereoconvergence of E and Z isomers is intriguing from a strictly scientific point of view; however, we thought we could apply this methodology in a practical manner as well. There has been considerable effort dedicated to developing stereoconvergent methods to convert racemic starting material to chiral products.\textsuperscript{58,59} The potential for this application is high. The use of both isomers increases the efficiency of the overall process, and allows a greater range of methods to access the starting material.
In the allylic substitution reaction, for instance, pure $E$ or $Z$ alkenes have to be used as substrates to obtain products of high optical purity. To make these substrates, reactions that provide only one isomer in high purity must be used, or the isomers must be separated, a typically difficult and inefficient process. We realized that our method could alleviate those restrictions. By enabling the conversion of a scope of aryl allylic ethers in low geometric purity to optically pure materials, our method allows the use of a broader range of olefination methods to access alkenes without needing to separate the mixture of isomers.

Wanting to illustrate the utility of our method, we examined yields and selectivities of our reaction with mixtures of both high and low geometric purity substrates, with varying steric hindrance, and substrates with different functional groups. We could use a range of methods to access those substrates as illustrated in Figure 24.

**Figure 24.** Methods Used to Access Aryl Allylic Ethers.

In cases where we wanted to demonstrate the methodology against a substrate with high geometric purity, olefination methods such as Horner-Wadsworth-Emmons reaction were used. This was followed by reduction of the ester, and conversion to the aryl ether either through nucleophilic aromatic substitution or Buchwald’s conditions. Allylic aryl ethers with low geometric purity were accessed as well. These substrates could be synthesized in one step using Grubbs metathesis, a method that is simple and powerful in the construction of alkenes, but one
not commonly used in applications that need a resulting high geometric purity because it creates mixtures of $E$ and $Z$ isomers.

With substrates in both high and low geometric purity in hand, we began to investigate our ability to convert these materials into chiral allyl boronates. Substrates with high geometric purity gave excellent yields and enantioselectivity (Table 7). 7 converts both pure cis and trans isomers to allyl boronates in high yield and enantioselectivity. The reaction also tolerates $\gamma$-branching well (entry 3).

**Table 7.** Substrate Screen with Geometric Isomers in High Purity.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Trans/Cis Ratio</th>
<th>Yield</th>
<th>ee%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1" alt="Substrate" /></td>
<td>&gt;30/1</td>
<td>90</td>
<td>93 (S)</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2" alt="Substrate" /></td>
<td>&lt;1/30</td>
<td>80</td>
<td>96 (S)</td>
</tr>
<tr>
<td>3</td>
<td><img src="image3" alt="Substrate" /></td>
<td>30/1</td>
<td>84</td>
<td>99</td>
</tr>
</tbody>
</table>

Exploring reaction scope further, we found that mixtures of different isomers of alkenes were readily consumed to give a single enantiomer with high yield (Table 8).
Table 8. Substrate Screen to Mixtures of Geometric Isomer

The reaction also tolerates a wide variety of functional groups, halogens, ketones, esters, and silicon protecting groups (Table 8).
**Table 9. Function Group Compatibility Under Reaction Conditions**

![Catalyst Structure](image)

\[ \text{R} = \text{CuPh} \quad \text{Cl} \quad (1 \text{ mol } \%) \]

\[ \text{Et}_2\text{O}, -55^\circ \text{C} \]

\[ \text{B}_2\text{Pin}_2 \text{ (1.2 equiv.), NaO} \text{tBu (30 mol %), MeOH (2 equiv.)} \]

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Trans/Cis Ratio</th>
<th>Yield</th>
<th>ee%</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>3.2/1</td>
<td>50</td>
<td>94</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>12/1</td>
<td>83</td>
<td>93</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>&lt;1/30</td>
<td>91</td>
<td>93</td>
</tr>
<tr>
<td>4</td>
<td></td>
<td>12/1</td>
<td>83</td>
<td>93</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>&gt;30/1</td>
<td>92</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>3.3/1</td>
<td>92</td>
<td>93</td>
</tr>
</tbody>
</table>
Finally we tested substrate 8 which contained both a trisubstituted alkene and a disubstituted alkene within the same structure. Boron added only to the disubstituted alkene using this method, giving only the monosubstituted product in 80% yield.

![Figure 25. Catalyst’s Chemoselectivity for Disubstituted Alkenes vs. Trisubstituted](image)

This result differs from Hoveyda’s case where the 5-membered NHC copper complex reacts with both di and trisubstituted alkenes.\textsuperscript{55} This result further illustrates the difference in reactivity between our 6-membered ring NHC catalyst and 5-membered NHC catalyst.

### 2.5 Conclusions

In conclusion we presented that our copper complex 1 shows unique chemoselectivity to traditional 5-membered NHCs and phosphine ligands. 1 performs the allylic aromatic ether substitution in much higher yields than either phosphine or 5-membered NHC ligand. Furthermore, we’ve demonstrated that the allylic substitution reaction using aromatic ethers as a leaving group is practical and can be optimized to give high ee. The reaction displays stereoconvergence between $E$ and $Z$ isomers, a rare phenomenon that allows for the reaction to be performed on a diverse group of substrates and still give high yield and selectivity. Lastly, we demonstrated that the reaction will tolerate a large scope of substrates.
Appendix A

Part I Supporting Information

Table of Content

1. General information
   1.1 General procedures
   1.2 Instrumentation

2. Experimental Section
   2.1 Synthesis of 6-NHC copper chloride
   2.2 Synthesis of substrates
   2.3 Typical reaction conditions for β-borylation reactions
   2.4 Solvent and Temperature Screening for β-borylated ester synthesis
   2.5 Reaction results and data for β-borylated ester synthesis
   2.6 Conversion determination in catalyst loading experiments
   2.7 X-Ray Crystallography
   2.8 Preparation of Rhodium Complex

3. Supporting Information References

4. Spectral data of 1 and its intermediates
   4.1 N-(2-((4S,5S)-4,5-diphenyl-4,5-dihydro-1H-imidazol-2-yl)phenyl)-2,4,6-trimethylaniline
   4.2 (2S,3S)-6-mesityl-2,3-diphenyl-2,3-dihydroimidazo[1,2-c]quinazolin-6-ium tetrafluoroborate
   4.3 ((2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c]quinazolin-5-yl)copper(I) chloride
   4.4 Chloro(η-1,5-cyclooctadiene)((2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c]quinazolin-5-yl)rhodium
1. **General Information**

1.1 General Procedure

All commercially available reagents were used without purification unless otherwise noted. Some substrates were synthesized according to the literature. Column chromatography was performed using silica gel from Merck (230-400 mesh). Visualization of the compounds was accomplished with UV light (254 nm), alkaline KMnO$_4$ and anisaldehyde solution followed by heating.

1.2 Instrumentation

$^1$H NMR and $^{13}$C NMR spectra were recorded in CDCl$_3$ operating at 300.070 MHz and 75.452 MHz, respectively, 400 MHz spectrometer operating at 400.172 and 100.623 MHz, respectively, and 600 MHz spectrometer operating at 600.133 and 150.914 MHz, respectively. Proton chemical shifts are reported relative to the residual proton signals of the deuterated solvent CDCl$_3$ (7.26 ppm) or CD$_2$Cl$_2$ (5.32 ppm) or TMS. Carbon chemical shifts were internally referenced to the deuterated solvent signals in CDCl$_3$ (77.00 ppm) or CD$_2$Cl$_2$ (53.8 ppm). Data are represented as follows: chemical shift, multiplicity (bs = broad singlet, s = singlet, d = doublet, t = triplet, q = quartet, h = heptet, m = multiplet), coupling constant in Hertz (Hz), and integration. Products were identified by comparison to spectral data reported in the literature. High performance liquid chromatography (HPLC) was performed using a chromatograph equipped with a Daicel CHIRALPAK IA (250 mm x 4.6 mm) and a CHIRALPAK IA guard column (1 cm x 0.4 cm) with hexane/iPrOH as the eluent. Gas chromatographic (GC) analyses were performed using a GC equipped with an autosampler, a flame ionization detector (FID), and a column (Astec CHIRALDEX$^\text{TM}$ B-DM : 30 m x 0.25 mm x 0.12 µm, Beta DEX$^\text{TM}$ : 30 m x 0.25 mm x 0.12 µm and Varian CP-Sil 5 CB : 15 m x 0.25 mm x 0.25 µm). Elemental analyses were performed by Atlantic Microlabs, Inc.

2. **Experimental Section**
2.1 Synthesis of 6-NHC copper chloride, 4

Fluoroimidate, 5 and Fluoroimidazoline, 6 were synthesized according to the literature.¹

N-(2-((4S,5S)-4,5-diphenyl-4,5-dihydro-1H-imidazol-2-yl)phenyl)-2,4,6-trimethylaniline, 7

Fluoroimidazoline, 6 (1.13 g, 3.57 mmol) and 2,4,6-trimethylaniline (552 µl, 3.93 mmol) were dissolved in THF (20 mL). After the addition of LiNH₂ (205 mg, 8.93 mmol), the mixture was heated to 80 °C. The color of the reaction mixture changed to brown and ammonia gas evolved. The reaction mixture was stirred overnight. The reaction mixture was cooled to rt and quenched with sat. NH₄Cl solution and extracted with EtOAc and the combined organic layer was dried with Na₂SO₄. The crude product was purified by short path column chromatography (Hexane : EtOAc = 20 : 1) to give the desired product (1.53 g, 3.54 mmol) as a brownish foam in 99% yield. Rᵣ = 0.29 (Hexane : EtOAc = 20 : 1)

¹H NMR (CDCl₃, 300 MHz) : δ 10.49 (s, 1H), 7.51 (d, J=8.3 Hz, 1H), 7.43-7.26 (m, 10H)  7.15 (m, 1H), 6.95 (s, 2H) 6.67 (t, J=8.0 Hz, 1H) 6.32 (d, J=9.3 Hz, 1H), 5.39 (br s, 1H), 5.20 (d, J=8.7 Hz, 1H), 4.64 (d, J=7.3 Hz, 1H) 2.32 (s, 3H) 2.21 (s, 6H) ¹³C NMR (CDCl₃, 75 MHz) : δ 164.4, 148.7, 144.0, 143.5, 137.0, 136.6, 135.8, 135.7, 132.0, 129.2, 129.0, 128.8, 128.1, 127.9, 127.4, 126.9, 115.1, 112.6, 110.2, 80.8, 68.9, 21.1, 18.6 IR (neat) 3062, 3026, 2914, 1618, 1589,
Aminoimidazoline, 7 (810 mg, 1.88 mmol) and NH$_4$BF$_4$ (237 mg, 2.26 mmol) were added to the triethyl orthoformate (10 mL) and the mixture was heated to 120 °C. After 1 h, white solid formed. The reaction mixture was stirred for an additional 4 h. After cooling to rt, Et$_2$O was added. The slurry was filtered yielding 815 mg of solid was obtained. 180 mg of solid was obtained after the filtrate was reflux to remove Et$_2$O and stirred at 50 °C overnight. The combined solid was stirred in the presence of H$_2$O and EtOAc. After phase separation, water layer was extracted again with EtOAc. The combined organic layers were dried with Na$_2$SO$_4$ and evaporated under reduced pressure. Pure product (942 mg, 1.78 mmol) was obtained by recrystallization under EtOAc as a white solid in 95% yield.

$^1$H NMR (CDCl$_3$, 300 MHz) : \( \delta \) 8.44 (m, 1H), 8.32 (s, 1H), 7.67 (m, 2H), 7.51-7.35 (m, 10H), 7.10 (s, 1H), 6.96 (s, 1H), 6.78 (m, 1H), 6.12 (d, J=8.0 Hz, 1H), 5.55 (d, J=8.0 Hz, 1H), 2.33 (s, 3H), 2.30 (s, 3H), 1.86 (s, 3H)$^{13}$C NMR (CDCl$_3$, 75 MHz) : \( \delta \) 149.0, 146.8, 142.1, 138.8, 137.5, 136.9, 135.9, 135.6, 134.3, 131.2, 130.9, 130.8, 130.3, 130.1, 130.0, 129.1, 128.6, 128.0, 127.8, 127.3, 118.0, 116.3, 80.8, 71.5, 21.2, 17.3 IR (neat) 3036, 1674, 1625, 1474, 1354, 1059, 753, 701 $[^{\alpha}]_D^{25}$ = -178° (c=1.0, CHCl$_3$) HRMS (ESI+) [M-BF$_4$]$^+$ calcd for C$_{31}$H$_{28}$N$_3$: 442.2283; found, 442.2342

((2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c]quinazolin-5-yl)copper(I) chloride, 4

Imidazoquinazolium salt, 1 (100 mg, 0.189 mmol) and CuCl (21.0 mg, 0.212 mmol) were charged into a schlenk flask and placed under high vacuum for 1 h. Anhydrous THF was added to the mixture at 0 °C. KOTBu solution in THF (212 \( \mu \)L, 0.212 mmol, 1 M solution in THF) was added to the mixture dropwise. During the addition of KOTBu, a blue color appeared and immediately disappeared. After complete addition of KOTBu solution, the blue color maintained for ten seconds and then changed to light brown. After 10 min, THF was carefully removed
under vacuum and CH$_2$Cl$_2$ was added to the reaction mixture. The reaction mixture was stirred for 18 h. The reaction mixture was filtered through Celite and washed with CH$_2$Cl$_2$. The filtrate was reduced under high vacuum. The crude product was used for asymmetric reactions without further purification. For analytically pure samples, the crude product was purified by flash column chromatography on silica gel (CH$_2$Cl$_2$ to CH$_2$Cl$_2$ : EtOAc = 100 : 1) to give the desired copper chloride complex (100 mg, 0.185 mmol) as a yellow solid in 98% yield. R$_f$ = 0.20 (CH$_2$Cl$_2$ : EtOAc = 100 : 1)

$^1$H NMR (400 MHz, CD$_2$Cl$_2$): δ 8.92 (d, J=7.8 Hz, 1H) 7.69 (t, J=7.7 Hz, 1H) 7.63 (t, J=7.4 Hz, 1H) 7.50-7.43 (m, 6H) 7.38-7.36 (m, 4H) 7.11 (s, 1H) 7.06 (s, 1H) 6.71 (d, J=8.1 Hz, 1H) 5.52 (d, J=6.5 Hz, 1H) 5.40 (d, J=6.5 Hz, 1H) 2.38 (s, 3H) 2.10 (s, 3H) 1.92 (s, 3H)

$^{13}$C NMR (CD$_2$Cl$_2$, 100 MHz) : δ 140.9, 140.2, 137.5, 136.6, 136.3, 135.4, 135.2, 130.6, 130.2, 129.9, 129.7, 129.2, 128.5, 128.1, 127.9, 127.1, 127.0, 126.1, 117.8, 114.7, 77.7, 75.3, 21.4, 17.8, 17.9

IR (neat) 2922, 2852, 1623, 1471, 1456, 1380, 1274, 756, 698 [α]$_D^{25}$ = -119° (c=1.0, CHCl$_3$)

Anal. Calcd for C$_{31}$H$_{28}$ClCuN$_3$: C, 77.62; H, 5.88; Cl, 7.40. N, 8.76 Found: C, 78.19; H, 6.09; Cl, 7.21; N, 8.43

2.2 Synthesis of substrates

(E)-isobutyl 3-(p-tolyl)acrylate

Representative Procedure: 4-methyl cinnamic acid (0.500 g, 3.08 mmol) was added to a round bottom flask followed by the addition of isobutyl alcohol (2.11 g, 28.52 mmol) and a catalytic amount of concentrated sulfuric acid (77 μL). The solution then was refluxed for 5 h. The reaction was then quenched with ca 15 mL of cold water and the aqueous solution was extracted with diethyl ether. The organic layer was then washed with a solution of sodium bicarbonate and dried with magnesium sulfate. The solution was concentrated in vacuo to give the corresponding ester as a yellow oil in 78% yield. $^1$H NMR (600 MHz, CDCl$_3$) δ 7.67 (d, J=16.0 Hz, 1H) 7.42 (d, J=8.1 Hz, 2H) 7.18 (d, J=7.9 Hz, 2H) 6.41 (d, J=16.0 Hz, 1H) 3.98 (d, J=6.6 Hz, 3 H) 2.37 (s, 3H) 2.04-1.98 (m, 1H) 0.98 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$) δ 167.3, 144.6, 140.6, 131.8, 129.6, 128.1, 117.2, 70.6, 27.9, 21.5, 19.2
(E)-isobutyl 3-(2-methoxyphenyl)acrylate Following the representative procedure 2-methoxy cinnamic acid (1.00 g, 5.61 mmol), isobutyl alcohol (3.85 g, 51.91 mmol) and concentrated sulfuric acid (140 μL) were reacted to give the corresponding ester as a yellow oil with 82% yield. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 8.00 (d, J=16.1 Hz, 1H) 7.51 (dd, J=1.6 Hz, J=7.7 Hz, 1H) 7.35 (td, J=1.6 Hz, J=8.5 Hz, 1H) 6.96 (t, J=7.0 Hz, 1H) 6.91 (d, J=8.3 Hz, 1H) 6.54 (d, J=16.2 Hz, 1H) 3.98 (d, J=6.7 Hz, 2H) 3.89 (s, 3H) 2.05-1.98 (m, 1H) 0.98 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 167.6, 158.3, 140.0, 131.3, 128.9, 123.5, 120.7, 118.8, 111.2, 70.5, 55.5, 27.9, 19.2

(E)-ethyl 3-(o-tolyl)acrylate Following the representative procedure 4-methyl cinnamic acid (0.500 g, 3.08 mmol) ethyl alcohol (1.71 g, 28.5 mmol) and concentrated sulfuric acid (80 μL) were reacted to give the corresponding ester as a colorless oil with 86% yield. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 7.66 (d, J=16.0 Hz, 1H) 7.42 (d, J=8.1 Hz, 2H) 7.19 (d, J=7.9 Hz, 2H) 6.39 (d, J=16.0 Hz, 1H) 4.26 (q, J=7.1 Hz, 2H) 2.37 (s, 3H) 1.34 (t, J=7.1 Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 167.2, 144.6, 140.6, 131.8, 129.6, 128.0, 117.2, 60.4, 21.4, 14.3

(E)-isobutyl 3-(o-tolyl)acrylate Following the representative procedure 2-methyl cinnamic acid (5.00 g, 30.8 mmol) isobutyl alcohol (21.1 g, 285 mmol) and concentrated sulfuric acid (720 μL) were reacted to give the corresponding ester as a yellow oil with 89% yield. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 7.99 (d, J=15.9 Hz, 1H) 7.56 (d, J=7.7 Hz, 1H) 7.27 (t, J=7.4 Hz, 1H) 7.21 (t, J=7.6 Hz, 2H) 6.34 (d, J=15.8 Hz, 1H) 4.00 (d, J=6.7 Hz, 2H) 2.02 (q, 1H) 2.44 (s, 3H) 0.99 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 167.1, 142.3, 137.6, 133.5, 130.8, 129.9, 126.4, 119.3, 70.6, 27.9, 19.8, 19.2

Typical procedure for preparation of aliphatic $\alpha,\beta$-unsaturated esters

In a flame dried Schlenk tube, LiCl (17.9 mmol, 1.1 eq.) was dried under vacuum, then taken into dry THF (100 mL) and cooled to 0 °C. Triethyl phosphonoacetate (17.9 mmol, 1.1 eq) and aldehyde (16.3 mmol, 1.0 eq) were sequentially added in a dropwise fashion. After 5 min, diazabicyclo[5.4.0]undec-7-ene (16.3 mmol, 1.0 eq.) was added. Reaction mixture was allowed to warm to ambient temperature and stir overnight. The organic layer was sequentially washed.
with a saturated solution of ammonium chloride, and brine. Organic layer was dried over MgSO$_4$ and reduced in vacuo. Crude product was purified by column chromatography (5% ethyl acetate in hexanes) to give the corresponding unsaturated ester in good yield.

**(E)-ethyl 4-methylpent-2-enoate** Isolated as a colorless oil in 92% yield. $^1$H NMR (600 MHz, CDCl$_3$): δ 6.94 (dd, J=15.7 Hz, 6.7 Hz, 1H) 5.76 (d, J=15.7 Hz, 1H) 4.19 (q, J=7.1 Hz, 2H) 2.49-2.43 (m, 1H) 1.29 (t, J=7.1 Hz, 3H) 1.07 (d, J=6.9 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 167.0, 155.4, 118.7, 60.1, 31.0, 21.3, 14.3

**(E)-ethyl 3-cyclohexylprop-2-enoate** Isolated as a colorless oil in 93% yield. $^1$H NMR (600 MHz, CDCl$_3$): δ 6.91 (dd, J=15.8 Hz, 6.8 Hz, 1H) 5.77-5.75 (m, 1H) 4.20-4.16 (m, 2H) 2.15-2.11 (m, 1H) 1.76-1.66 (m, 5H) 1.32-1.27 (m, 5H) 1.21-1.12 (m, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 167.1, 154.2, 119.0, 60.1, 40.4, 31.8, 26.0, 25.8, 14.3

**(E)-ethyl 4-ethylhex-2-enoate** Isolated as a colorless oil in 91% yield. $^1$H NMR (600 MHz, CDCl$_3$): δ 6.40 (dd, J=15.7 Hz, 9.2 Hz, 1H) 5.78 (d, J=14.7 Hz, 1H) 4.19 (q, J=7.1 Hz, 2H) 1.99-1.96 (m, 1H) 1.52-1.46 (m, 2H) 1.39-1.27 (m, 5H) 0.86 (t, J=7.5 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 166.7, 153.3, 121.4, 60.1, 46.0, 26.8, 14.3, 11.7

### 2.3 Typical reaction condition for β-borylation reactions

$\alpha,\beta$-unsaturated ester (0.20 mmol) and bis(pinacolato) diboron (56 mg, 0.22 mmol) were dissolved in Et$_2$O or toluene (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled to resulting temperature and MeOH (18 μL, 0.4 mmol) was added. After 5 min, 6-NHC copper catalyst, 4 (1.1 mg, 0.0020 mmol or 3.3 mg, 0.0060 mmol) was added. After complete consumption of $\alpha,\beta$-unsaturated ester, the reaction mixture was filtered through silica gel and washed with Et$_2$O. The filtrate was concentrated under rotary evaporator. The resulting residue was purified by column chromatography (Hexane : EtOAc = 20 : 1) to afford the desired products. Note : we found that the order of addition was critical to achieve high yields and ee’s reproducibly.
For the determination of enantioselectivity, the resulting boronate was dissolved in EtOAc (2 mL) and oxidized by treatment of H₂O₂ (5 eq.) and 1 M NaOH solution (5 eq.) for 30 min. After phase separation, the organic layer was evaporated under high vacuum. The crude alcohol product was purified by column chromatography.

2.4 Solvent and Temperature Screening for β-borylated Ester Synthesis

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>Temp.(°C)</th>
<th>Time</th>
<th>Yield (%)&lt;sup&gt;b&lt;/sup&gt;</th>
<th>ee (%)&lt;sup&gt;c,d&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Et₂O</td>
<td>0</td>
<td>&lt;1 min</td>
<td>&gt;98</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>Et₂O</td>
<td>-30</td>
<td>3 h</td>
<td>&gt;98</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>Et₂O</td>
<td>-55</td>
<td>6 h</td>
<td>&gt;98</td>
<td>86</td>
</tr>
<tr>
<td>4</td>
<td>Toluene</td>
<td>0</td>
<td>&lt;1 min</td>
<td>&gt;98</td>
<td>78</td>
</tr>
<tr>
<td>5</td>
<td>THF</td>
<td>0</td>
<td>&lt;1 min</td>
<td>&gt;98</td>
<td>69</td>
</tr>
<tr>
<td>6</td>
<td>CH₃CN</td>
<td>0</td>
<td>&lt;1 min</td>
<td>&gt;98</td>
<td>63</td>
</tr>
<tr>
<td>7</td>
<td>CH₂Cl₂</td>
<td>0</td>
<td>&lt;1 min</td>
<td>&gt;98</td>
<td>64</td>
</tr>
</tbody>
</table>

<sup>a</sup>Reactions run in N₂ atm. <sup>b</sup>Determined by <sup>1</sup>H NMR of the crude material. <sup>c</sup>Determined by GC after oxidizing the boronate to alcohol by the treatment with H₂O₂/NaOH. <sup>d</sup>Configuration was assigned by comparison to the alcohol. B₂Pin₂: Bis(pinacolato)diboron.

Exploratory studies on the model reaction were performed to assess optimal solvent and temperature conditions for complex 4 to yield β-borylated products in high yield and enantioselectivity. These results revealed that 1 is a highly active catalyst providing complete consumption of starting materials within 1 min at 0 °C with 1 mol% catalyst in diethyl ether to give 78% ee of the desired product (entry 1). Further temperature screenings revealed that 86% ee could be realized at -55 °C with maintenance of useful reaction rate (entries 2, 3). Non-polar solvents such as diethyl ether and toluene were identified as optimal solvents for the β-borylation reaction. Diethyl ether was selected for further experiments because of easy removal.
2.5 Reaction results and data for β-borylated ester synthesis

**Ethyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)butanoate**

Prepared according to the general procedure using ethyl crotonate (-55 °C, 6 h, 1 mol% of catalyst) in Et\(_2\)O to afford the desired compound as a colorless oil. (92% yield, 86% ee) \(^1\)H NMR (600 MHz, CDCl\(_3\)): \(\delta\) 4.11 (q, \(J=7.2\) Hz, 2H) 2.42 (dd, \(J=16.3\) Hz, 7.7 Hz, 1H) 2.35 (dd, \(J=16.3\) Hz, 6.6 Hz, 1H) 1.39-1.34 (m, 1H) 1.25-1.23 (m, 15H) 1.00 (d, \(J=7.5\) Hz) \(^1\)C NMR (150 MHz, CDCl\(_3\)): \(\delta\) 173.9, 83.1, 60.1, 37.7, 24.72, 24.66, 15.0, 14.3. MS(Cl) [M+H] 243.2 Optical Rotation [\(\alpha\)]\(_D\)\(^{25}\) = -2.9° (c=1.00, CHCl\(_3\))

The enantiomeric ratio was determined by GC using β-DM column after oxidation (80 °C, 4 mL/min) \(^1\)H NMR (600 MHz, CDCl\(_3\)): \(\delta\) 4.20-4.14 (m, 3H) 3.04 (s, 1H) 2.51 (dd, \(J=16.5\) Hz, 3.3 Hz, 1H) 2.43 (dd, \(J=16.5\) Hz, 8.7 Hz, 1H) 1.31-1.24 (m, 6H) \(^1\)C NMR (150 MHz, CDCl\(_3\)): \(\delta\) 173.0, 64.2, 60.7, 42.7, 22.4, 14.2

**tert-Butyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)butanoate**

Prepared according to the general procedure using tbutyl crotonate (-55 °C, 6 h, 1 mol% of catalyst) in Et\(_2\)O to afford the desired compound as a colorless oil. (91% yield, 90% ee) \(^1\)H NMR (600 MHz, CDCl\(_3\)): \(\delta\) 2.34 (dd, \(J=16.5\) Hz, 7.8 Hz, 1H) 2.26 (dd, \(J=16.5\) Hz, 7.0 Hz, 1H) 1.43 (s, 9H) 1.36-1.32 (m, 1H) 1.23 (s, 6H) 1.23 (s, 6H) 0.98 (d, \(J=7.5\) Hz, 3H) \(^1\)C NMR (150 MHz, CDCl\(_3\)): \(\delta\) 173.3, 83.0, 79.8, 38.8, 28.1, 24.74, 24.66,
14.9. MS(Cl) [M+H] 271.2 Optical Rotation [$\alpha$]$_{D}^{25}$ = -3.8° (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using $\beta$-DM column after oxidation. (80 °C, 4 mL/min) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 4.16-4.13 (m, 1H) 3.14 (d, J=3.5 Hz, 1H) 4.41 (dd, J=16.5 Hz, 3.1 Hz, 1H) 2.33 (dd, J=16.5 Hz, 9.0 Hz, 1H) 1.47 (s, 9H) 1.21 (d, J=6.3 Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 172.4, 81.2, 64.4, 43.8, 28.1, 22.3 Optical Rotation [$\alpha$]$_{D}^{25}$ = -32.7° (c=0.2, CHCl$_3$)

iso-Butyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)butanoate$^4$

Prepared according to the general procedure using $i$-butyl crotonate (-55 °C, 6 h, 1 mol% of catalyst) in Et$_2$O to afford the desired compound as a colorless oil(93% yield, 88% ee) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 3.88-3.81 (m, 2H) 2.45 (dd, J=16.4, 7.6 Hz, 1H) 2.36 (dd, J=16.4 Hz, 6.9 Hz, 1H) 1.94-1.88 (m, 1H) 1.41-1.37 (m, 1H) 1.24-1.23 (m, 12H) 1.01 (d, J=7.5 Hz, 3H) 0.92 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 174.0, 83.2, 70.4, 37.6, 27.8, 24.74, 24.68, 19.1, 15.1. MS(Cl) [M+H] 271.3 Optical Rotation [$\alpha$]$_{D}^{25}$ = -2.7° (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using $\beta$-DM column after oxidation. (80 °C, 4 mL/min) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 4.15-4.11 (m, 1H) 3.86-3.81 (m, 2H) 2.91 (d, J=3.6 Hz, 1H) 2.46 (dd, J=16.5 Hz, 3.2 Hz, 1H) 2.37 (dd, J=16.6 Hz, 8.9 Hz, 1H) 1.91 (m, 1H) 1.17 (d, J=6.4 Hz, 3H) 0.87 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 173.0, 70.8, 64.3, 42.7, 27.7, 22.4, 19.1

40
Ethyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hexanoate

Prepared according to the general procedure using (E)-ethyl hex-2-enoate (-55 °C, 6 h, 1 mol% of catalyst) in Et₂O to afford the desired compound as a colorless oil (92% yield, 90% ee).

\[ \text{\^{1}}H \text{ NMR (600 MHz, CDCl}_3\text{): } \delta 4.14-4.06 \text{ (m, 2H)}, 2.43-2.35 \text{ (m, 2H)}, 1.45-1.41 \text{ (m, 1H)}, 1.36-1.29 \text{ (m, 4H)}, 1.25-1.22 \text{ (m, 15H)}, 0.88 \text{ (t, J=6.8 Hz, 3H)} \]

\[ \text{\^{13}}C \text{ NMR (150 MHz, CDCl}_3\text{): } \delta 174.0, 83.1, 60.1, 35.8, 32.8, 24.8, 24.7, 21.9, 14.3, 14.2 \]

HRMS (EI) calcd for C₁₄H₂₇BO₂ 270.20025 found: 270.20031 Optical Rotation [\( \alpha \) ]\text{D}{^25} = -6.5°

(c=1.00, CHCl₃) The enantiomeric ratio was determined by GC using β-DM column after oxidation. (80 °C, 4 mL/min) \[ \text{\^{1}}H \text{ NMR (600 MHz, CDCl}_3\text{): } \delta 4.18 \text{ (q, J=7.2 Hz, 2H)}, 4.03-4.0 (m, 1H) 2.91 \text{ (d, J=4.0 Hz, 1H)}, 2.50 \text{ (dd, J=16.5 Hz, 2.9 Hz, 1H)}, 2.40 \text{ (dd, J=16.5 Hz, 9.1 Hz, 1H)}, 1.51-1.34 \text{ (m, 4H)}, 1.28 \text{ (t, J=7.1 Hz, 3H)}, 0.94 \text{ (t, J=7.1 Hz, 3H)} \]

\[ \text{\^{13}}C \text{ NMR (150 MHz, CDCl}_3\text{): } \delta 173.1, 67.8, 60.7, 41.3, 38.7, 31.6, 18.7, 14.2, 14.0 \]
Ethyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)octanoate

Prepared according to the general procedure using (E)-ethyl oct-2-enoate (-55 °C, 6 h, 1 mol% of catalyst) in Et₂O to afford the desired compound as a colorless oil (90% yield, 91% ee). ¹H NMR (600 MHz, CDCl₃): δ 4.14-4.06 (m, 2H) 2.44-2.35 (m, 2H) 1.46-1.42 (m, 1H) 1.34-1.22 (m, 23H) 0.86 (t, J=7.0 Hz, 3H) ¹³C NMR (150 MHz, CDCl₃): δ 174.0, 83.1, 60.1, 35.8, 32.0, 30.5, 28.4, 24.8, 24.7, 22.5, 14.3, 14.0 HRMS(EI) calcd for C₁₆H₃₁BO₄ 298.23067 found: 298.23155 Optical Rotation [α]D²⁵ = -4.1° (c=1.00, CHCl₃) The enantiomeric ratio was determined by GC using β-DM column after oxidation. (80 °C, 4 mL/min) ¹H NMR (600 MHz, CDCl₃): δ 4.17 (q, J=7.2 Hz, 2H) 4.02-3.98 (m, 1H) 2.95 (s, br 1H) 2.50 (dd, J=16.4 Hz, 3.0 Hz, 1H) 2.40 (dd, J=16.5 Hz, 9.3 Hz, 1H) 1.55-1.27 (m, 11H) 0.89 (t, J=6.8 Hz, 3H) ¹³C NMR (150 MHz, CDCl₃): δ 173.1, 68.1, 60.6, 41.3, 36.5, 31.7, 25.1, 22.6, 14.2, 14.0
Ethyl 4-methyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)pentanoate

Prepared according to the general procedure using (E)-ethyl 4-methylpent-2-enate (-55 °C, 6 h, 1 mol% of catalyst) in Et₂O to afford the desired compound as a colorless oil. (91% yield, 96% ee) ¹H NMR (600 MHz, CDCl₃): δ 4.11-4.07 (m, 2H) 2.46 (dd, J=16.4 Hz, 10.8 Hz, 1H) 2.36 (dd, J=16.4 Hz, 5.5 Hz, 1H) 1.77-1.72 (m, 1H) 1.25-1.23 (m, 13H) 0.95-0.93 (m, 6H) ¹³C NMR (600 MHz, CDCl₃): δ 174.4, 83.1, 60.1, 33.8, 29.1, 25.0, 24.7, 22.0, 14.3 MS(CI) [M+H] 271.2 Optical Rotation [α]D²⁵ = -11.8° (c=1.00, CHCl₃) The 43nantioeric ratio was determined by GC using β-DM column after oxidation. (70 °C, 4 mL/min) ¹H NMR (600 MHz, CDCl₃): δ 4.18 (q, J=7.2 Hz, 2H) 3.80-3.76 (m, 1H) 2.89 (d, J=3.8 Hz, 1H) 2.50 (dd, J=16.3 Hz, 2.7 Hz, 1H) 2.40 (dd, J=16.3 Hz, 9.7 Hz, 1H) 1.74-1.69 (m, 1H) 1.28 (t, J=7.1 Hz, 3H) 0.96 (d, J=6.8 Hz, 3H) 0.93 (d, J=6.5 Hz, 3H) ¹³C NMR (150 MHz, CDCl₃): δ 173.5, 72.8, 60.7, 38.5, 33.2, 18.4, 17.8, 14.2 Optical Rotation [α]D²⁵ = -38.4° (c=0.50, CHCl₃)
Ethyl 3-cyclohexyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate

Prepared according to the general procedure using (E)-ethyl 3-cyclohexylacrylate (-55 °C, 6 h, 1 mol% of catalyst) in Et₂O to afford the desired compound as a colorless oil. (95% yield, 90% ee) ¹H NMR (600 MHz, CDCl₃): δ 4.14-4.05 (m, 2H) 2.45 (dd, J=16.5 Hz, 10.9 Hz, 1H) 2.36 (dd, J=16.4 Hz, 5.5 Hz, 1H) 1.70-1.68 (m, 2H) 1.63-1.61 (m, 1H) 1.40-1.34 (m, 1H) 1.30-0.97 (m, 21H) ¹³C NMR (600 MHz, CDCl₃): δ 174.4, 83.1, 60.1, 39.2, 33.6, 32.5, 32.1, 26.73, 26.67, 25.0, 24.7, 14.3 HRMS(EI) calcd for C₁₇H₃₁BO₄ 310.23155 found : 310.23150 Optical Rotation [α]D²⁵ = -4.4° (c=1.00, CHCl₃) The enantiomeric ratio was determined by GC using β-DM column after oxidation. (120 °C, 4 mL/min) ¹H NMR (600 MHz, CDCl₃): δ 4.17 (q, J=7.2, 2H) 3.79-3.76 (m, 1H) 2.86 (d, J=4.0 Hz, 1H) 2.51 (dd, J=16.3 Hz, 2.8 Hz, 1H) 2.41 (dd, J=16.3 Hz, 9.7 Hz, 1H) 1.88-1.85 (m, 1H) 1.78-1.74 (m, 2H) 1.68-1.65 (m, 2H) 1.40-1.35 (m, 1H) 1.29-1.13 (m, 6H) 1.08-0.98 (m, 2H) ¹³C NMR (150 MHz, CDCl₃): δ 173.6, 72.2, 60.7, 43.1, 38.6 28.8, 28.3, 26.3, 26.2, 26.1, 14.2
Ethyl 4-ethyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hexanoate

Prepared according to the general procedure using (E)-ethyl 4-ethylhex-2-enoate (-55 °C, 6 h, 1 mol% of catalyst) in Et₂O to afford the desired compound as a colorless oil (92% yield, 91% ee). ¹H NMR (600 MHz, CDCl₃): δ 4.15-4.05 (m, 2H), 2.43 (dd, J= 16.4 Hz, 11.0 Hz, 1H), 2.28 (dd, J= 16.4 Hz, 5.34 Hz, 1H), 1.56 (m, 1H), 1.35-1.21 (m, 20H), 0.87 (t, J=7.0 Hz, 6H). ¹³C NMR (150 MHz, CDCl₃): δ 174.5, 83.1, 60.1, 42.5, 33.0, 25.0, 24.9, 24.6, 14.3, 12.1, 11.8 HRMS(EI) calcd for C₁₆H₃₁BO₄ 298.23155 found : 298.23191 Optical Rotation [α]D²⁵ = -4.0° (c=1.00, CHCl₃) The enantiomeric ratio was determined by HPLC using CHIRALPAK IA column after oxidation and acylation. (Hexane : iPrOH = 99 : 1, 0.5 mL/min, 210 nm) ¹H NMR (600 MHz, CDCl₃): δ 4.20-4.16 (m, 2H), 4.06-4.03 (m, 1H), 2.81 (d J=3.3 Hz) 2.49-2.41 (m, 2H), 1.51-1.45 (m, 1H), 1.43-1.38 (m, 2H), 1.29-1.21 (m, 5H), 0.92-0.90 (m, 6H). ¹³C NMR (150 MHz, CDCl₃): δ 173.6, 69.3, 60.7, 46.15, 38.5, 21.8, 21.4, 14.2, 11.6
Methyl 3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate

Prepared according to the general procedure using methyl cinnamate (-55 °C, 6 h) in toluene to afford the desired compound as a colorless solid (88% yield, 87% ee, 3 mol% of catalyst)

$^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.25-7.14 (m, 5H) 3.65 (s, 3H) 2.89 (dd, J=16.4 Hz, 10.2 Hz, 1H) 2.74 (m, 1H) 2.66 (dd, J=16.4 Hz, 6.0 Hz, 1H) 1.22 (s, 6H) 1.17 (s, 6H)

$^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 173.8, 141.3, 128.6, 128.5, 128.2, 125.70, 125.66, 83.6, 51.5, 43.2

Optical Rotation $[\alpha]_{D}^{25} = +16.3^\circ$ (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by HPLC using CHIRALPAK IA column after oxidation (Hexane : iPrOH = 97 : 3, 1 mL/min, 254 nm) $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 7.39-7.35 (m, 4H) 7.31-7.28 (m, 1H) 5.15-5.14 (m, 1H) 3.73 (s, 3H) 3.16 (d, J=3.4Hz, 1H) 2.80-2.71 (m, 2H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 172.8, 142.5, 128.6, 127.9, 125.6, 70.3, 51.9, 43.2
Ethyl 3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate

Prepared according to the general procedure using ethyl cinnamate (-55 °C, 6 h) in toluene to afford the desired compound as a colorless solid (88% yield, 85% ee, 3 mol% of catalyst).

$^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.77-7.13 (m, 5H); 4.15-4.06 (m, 2H); 2.87 (dd, J=16.2 Hz, 10.2 Hz, 1H); 2.75-2.72 (m, 1H); 2.65 (dd, J=16.4 Hz, 6.1 Hz, 1H); 1.27-1.21 (m, 15H)

$^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 174.4, 141.4, 128.4, 128.2, 125.6, 83.5, 60.3, 37.3, 24.6, 24.5, 14.2 MS(CI) [M+H] 305.3 Optical Rotation $[\alpha]_D^{25} = +19.8^\circ$ (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using $\beta$-DM column after oxidation. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 7.31-7.19 (m, 5H); 5.07 (ddd, J=5.6 Hz, 6.7 Hz, 12.3 Hz, 1H); 4.12 (q, J=10.7 Hz, 2H); 3.19 (d, J=5.1 Hz, 1H); 2.73-2.61 (m, 2H); 1.20 (t, J=10.7 Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 172.4, 142.6, 128.5, 127.8, 125.7, 70.3, 60.9, 43.4, 14.1 Optical Rotation $[\alpha]_D^{25} = -42.5^\circ$ (c=0.54, CHCl$_3$)
iso-Butyl 3-phenyl-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate

Prepared according to the general procedure using ibutyl cinnamate (-55°C, 6 h, 3 mol% of catalyst) in toluene to afford the desired compound as a colorless oil. (88% yield, 80% ee) $^1$H NMR (600 MHz, CDCl$_3$): δ 7.27-7.13 (m, 5H) 3.88-3.78 (m, 2H) 2.89 (dd, J=16.3 Hz, 9.8 Hz, 1H) 2.76-2.73 (m, 1H) 2.67 (dd, J=16.4 Hz, 6.4 Hz, 1H) 1.92-1.85 (m, 1H) 1.21 (s, 6H) 1.17 (s, 6H) 0.89 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 178.7, 141.7, 128.7, 128.4, 125.8, 83.8, 70.7, 37.4, 28.0, 24.8, 24.7, 19.31, 19.29 HRMS(EI) calcd for C$_{19}$H$_{29}$BO$_4$ 332.21672 found : 332.21590 Optical Rotation $[^{[a]}$D]$_{25}$ = +14.9° (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using β-DM column after oxidation. (140°C, 4 mL/min) $^1$H NMR (600 MHz, CDCl$_3$): δ 7.39-7.34 (m, 4H) 7.30-7.26 (m, 1H) 5.14-5.13 (m, 1H) 3.91-3.90 (m, 2H) 3.30 (s, 1H) 2.80-2.71 (m, 2H) 1.95-1.90 (m, 1H) 0.91 (d, J=6.2 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 172.5, 142.5, 128.5, 127.8, 125.7, 71.0, 70.3, 43.3, 27.7, 19.0
iso-Butyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-p-tolylpropanoate

Prepared according to the general procedure using (E)-isobutyl 3-p-tolylacrylate (-55 °C, 6 h, 3 mol% of catalyst) in toluene to afford the desired compound as a colorless oil. (92% yield, 82% ee) 

$^1$H NMR (600MHz, CDCl$_3$) $\delta$ 7.11 (d, J=8.1 Hz, 2H) 7.06 (d, J=7.9 Hz, 2H) 3.86 (dd, J=6.8 Hz, J=10.9 Hz, 1H) 3.81-3.78 (dd, J=6.7 Hz, J=10.6 Hz, 1H) 2.87 (dd, J=9.7 Hz, J=16.2 Hz, 1H) 2.70 (dd, J=6.4 Hz J=9.7 Hz, 1H) 2.64 (dd, J=6.4 Hz J=16.3 Hz, 1H) 2.29 (s, 3H) 1.92-1.85 (m, 1H), 1.21 (s, 6H) 1.17 (s, 6H) 0.9 (d, J=6.7 Hz, 1H) 13$^3$C NMR (150 MHz, CDCl$_3$) $\delta$ 173.6, 138.3, 135.0, 129.2, 128.1, 83.5, 70.5, 37.4, 27.7, 24.5, 24.1, 21.0, 19.1 HRMS(EI) calcd for C$_{20}$H$_{31}$BO$_4$ 346.23116 found : 346.23155

Optical Rotation $[\alpha]_D^{25} = +18.3^\circ$ (c=1.00, CHCl$_3$)

The enantiomeric ratio was determined by GC using Supelco Beta DEX™ 325 column after oxidation. (130 °C, 1.6 mL/min) 

$^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.27-7.26 (m, 2H) 7.17-7.15 (m, 2H) 5.12-5.09 (m, 1H) 3.91-3.90 (m, 2H) 3.18 (d, J=3.3 Hz, 1H) 2.77 (dd, J=16.3 Hz, 9.2 Hz, 1H) 2.71 (dd, J=16.3 Hz, 3.4 Hz, 1H) 2.34 (s, 3H) 1.96-1.89 (m, 1H) 0.92 (d, J=6.7 Hz, 6H)

$^1$C NMR (150 MHz, CDCl$_3$): $\delta$ 172.5, 139.6, 137.5, 129.2, 125.6, 70.9, 70.2, 43.3, 27.7, 21.1, 19.0
Ethyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-o-tolylpropanoate

Prepared according to the general procedure using (E)-ethyl 3-o-tolylacrylate (-30 °C, 6 h, 1 mol% of catalyst) in toluene to afford the desired compound as a colorless oil. (93% yield, 92% ee) $^1$H NMR (600 MHz, CDCl$_3$):

$\delta$ 7.19-7.04 (m, 4H) 4.15-4.06 (m, 2H) 2.96-2.93 (m, 1H) 2.86 (dd, $J=16.5$ Hz, 10.1 Hz, 1H) 2.60 (dd, $J=16.5$ Hz, 6.0 Hz, 1H) 2.36 (s, 3H) 2.36 (m, 2H) 2.36 (s, 3H) 1.23-1.17 (m, 15H)

$^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 173.8, 140.1, 136.4, 130.6, 127.9, 126.2, 125.7, 83.7, 60.5, 37.0, 24.8, 24.7, 20.2, 14.6 MS(CI) [M+H] 319.3 Optical Rotation $[\alpha]_D^{25} = +13.6^\circ$ (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using $\beta$-DM column after oxidation. (140 °C, 4 mL/min) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.51-7.50 (m, 1H) 7.25-7.14 (m, 3H) 5.37-5.35 (m, 1H) 4.23-4.20 (m, 2H) 3.17 (d, $J=2.9$ Hz, 1H) 2.72-2.64 (m, 2H) 2.36 (s, 3H) 1.29 (t, $J=7.1$ Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 172.6, 140.5, 134.3, 130.5, 127.6, 126.4, 125.3, 67.0, 60.9, 42.1, 19.0, 14.2 Optical Rotation $[\alpha]_D^{25} = -45.8^\circ$ (c=0.20, CHCl$_3$)
iso-Butyl 3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)-3-o-tolylpropanoate

Prepared according to the general procedure using (E)-isobutyl 3-o-tolylacrylate (-30 °C, 6 h, 1 mol% of catalyst) in toluene to afford the desired compound as a colorless oil. (85% yield, 96% ee) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.19-7.03 (m, 4H) 3.87-3.78 (m, 2H) 2.97-2.94 (m, 1H) 2.88 (dd, J=16.4 Hz, 10.0 Hz, 1H) 2.63 (dd, J=16.4 Hz, 6.1 Hz, 1H) 1.92-1.84 (m, 1H) 1.21 (s, 6H) 1.17 (s, 6H) 0.89 (d, J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 173.9, 140.1, 136.4, 130.6, 127.8, 126.2, 125.7, 83.7, 70.7, 36.9, 28.0, 24.84, 24.76, 20.2, 19.31, 19.28 HRMS(EI) calcd for C$_{20}$H$_{31}$BO$_4$ 346.23116 found : 362.22703 Optical Rotation $[\alpha]_D^{25} = +13.9^\circ$ (c=1.00, CHCl$_3$) The enantiomeric ratio was determined by GC using $\beta$-DM column after oxidation. (140 °C, 4 mL/min) $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.51-7.51 (m, 1H) 7.26-7.14 (m, 3H) 5.38-5.35 (m, 1H) 3.96-3.91 (m, 2H) 3.15 (d, J=3.2 Hz, 1H) 2.74-2.66 (m, 2H) 2.36 (s, 3H) 1.98-1.91 (m, 1H) 0.93 (d J=6.7 Hz, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 172.6, 140.4, 134.3, 130.3, 127.5, 126.4, 125.2, 71.0, 67.1, 42.1, 27.7, 19.04, 18.98
iso-Butyl 3-(2-methoxyphenyl)-3-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)propanoate

Prepared according to the general procedure using (E)-isobutyl 3-(2-methoxyphenyl)acrylate (-30 °C, 6 h, 1 mol% of catalyst) in toluene to afford the desired compound as a colorless oil (90% yield, 92% ee)

\[
\begin{align*}
\text{1H NMR} & \quad (600 \text{ MHz, CDCl}_3) \quad \delta \quad 7.19-7.12 \text{ (m, 2H)} \quad 6.86-6.79 \text{ (m, 2H)} \quad 3.82-3.73 \text{ (m, 5H)} \quad 2.87-2.81 \text{ (m, 2H)} \\
\text{13C NMR} & \quad (600 \text{ MHz, CDCl}_3) \quad \delta \quad 174.1, 157.2, 130.7, 127.2, 120.9, 110.3, 83.6, 70.5, 55.2, 36.1, 27.9, 25.0, 24.9, 19.9, 19.3 \text{ HRMS(EI) calcd for C}_{20}\text{H}_{31}\text{BO}_5 362.22646 found : 362.22703} \\
\text{Optical Rotation} & \quad [\alpha]_D^{25} = +59.4^\circ \text{ (c=1.00, CHCl}_3) \\
\end{align*}
\]

The enantiomeric ratio was determined by GC using β-DM column after oxidation. (140 °C, 4 mL/min) \textsuperscript{1}H NMR (600 MHz, CDCl\textsubscript{3}): δ 7.37-7.35 (m, 1H) 7.20-7.17 (m, 1H) 6.92-6.90 (m, 1H) 6.81-6.79 (m, 1H) 5.31-5.28 (m, 1H) 3.86-3.81 (m, 2H) 3.78 (s, 3H) 3.80 (d, J=5.4 Hz, 1H) 2.77 (dd, J=16.1 Hz, 3.6 Hz 1H) 2.66 (dd, J=16.1 Hz, 9.2 Hz, 1H) 1.89-1.82 (m, 1H) 0.85 (d, J=6.6 Hz, 6H) \textsuperscript{13}C NMR (150 MHz, CDCl\textsubscript{3}): δ 172.7, 156.1, 130.6, 128.6, 126.6, 120.8, 110.3, 70.8, 66.6, 55.3, 41.7, 27.7, 19.0
### 2.6 Conversion determination in catalyst loading experiments

Catalyst loading experiments were set up using standard reaction conditions except the concentration of the reaction mixture and the catalyst loading were varied as illustrated in the table above. Reaction progress was monitored by GC chromatography and complete consumption of the starting material in the times indicated in the table above. Representative GC chromatograms are shown below in Figure S-1 and S-2. We confirmed there was less than 1% of starting material by examining product $^{13}$C satellites in relationship to residual starting material peaks (note: no starting material peaks were observed) in the reaction mixture by $^1$H NMR.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ester</th>
<th>Mol%</th>
<th>Time</th>
<th>Conv. (%)$^d$</th>
<th>ee (%)</th>
<th>TON</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^a$</td>
<td>44 mg</td>
<td>10</td>
<td>&lt;1 min</td>
<td>&gt;99</td>
<td>92</td>
<td>10</td>
</tr>
<tr>
<td>2$^a$</td>
<td>44 mg</td>
<td>1</td>
<td>&lt;1 min</td>
<td>&gt;99</td>
<td>91</td>
<td>100</td>
</tr>
<tr>
<td>3$^b$</td>
<td>0.44 g</td>
<td>0.1</td>
<td>3 min</td>
<td>&gt;99</td>
<td>88</td>
<td>1,000</td>
</tr>
<tr>
<td>4$^b$</td>
<td>0.44 g</td>
<td>0.05</td>
<td>80 min</td>
<td>&gt;99</td>
<td>87</td>
<td>2,000</td>
</tr>
<tr>
<td>5$^c$</td>
<td>2.0 g</td>
<td>0.01</td>
<td>100 min</td>
<td>&gt;99 (93)$^e$</td>
<td>88</td>
<td>10,000</td>
</tr>
</tbody>
</table>

$^a$0.2 M conc. $^b$0.4 M conc. $^c$0.8 M conc. $^d$Conversion was determined by GC and $^1$H NMR. $^e$Isolated yield
NMR shown in Figure S-3. Based on this information, we concluded that the conversion is >99%.

GC condition: Varian CP-Sil 5 CB: 15 m × 0.25 mm × 0.25 μm, 140 °C (hold for 1 min) to 200 °C (20 °C/min), constant pressure (22 psi)

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.210</td>
<td>B₂Pin₂</td>
</tr>
<tr>
<td>3.787</td>
<td>Starting material</td>
</tr>
<tr>
<td>6.777</td>
<td>Product</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>12199</td>
</tr>
<tr>
<td>Area</td>
<td>0</td>
</tr>
<tr>
<td>86007</td>
<td></td>
</tr>
</tbody>
</table>
2.7 X-Ray Crystallography

Single-crystal X-ray data were collected on a Bruker AXS SMART diffractometer with an APEX-II CCD detector. The data sets were recorded as $\omega$ scans at a 0.3° stepwidth and integrated with the Bruker SAINT software package. An analytical absorption correction was applied using face-indexing of the crystal. Solution and refinement of the crystal structures was carried out using the SHELX suite of programs. Structure solution was carried out by direct methods that revealed all non-hydrogen atoms. Hydrogen atoms were placed at calculated positions. The final refinement was performed with anisotropic thermal parameters for all non-hydrogen atoms. A summary of pertinent information relating to unit cell parameters, data collection, and refinements is provided in Table 1.

Table 1. Crystal structural data and refinement parameters.

<p>| Formula | ( C_{37.6}H_{35.6}N_3O ) (4·( 1.1C_6H_6 )) | ( Rh_3Cl_3C_90H_{100}N_6O ) |</p>
<table>
<thead>
<tr>
<th><strong>Space group</strong></th>
<th>(P2_12_12_1)</th>
<th>(P2_12_12_1)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unit cell</strong></td>
<td>(a = 12.126(2) , \text{Å})</td>
<td>(a = 10.721(1) , \text{Å})</td>
</tr>
<tr>
<td></td>
<td>(b = 22.411(3) , \text{Å})</td>
<td>(b = 16.981(2) , \text{Å})</td>
</tr>
<tr>
<td></td>
<td>(c = 25.459(4) , \text{Å})</td>
<td>(c = 42.662(5) , \text{Å})</td>
</tr>
<tr>
<td><strong>Unit cell volume, (V)</strong></td>
<td>(6918(2) , \text{Å}^3)</td>
<td>(7767(2) , \text{Å}^3)</td>
</tr>
<tr>
<td><strong>Formula units, (Z)</strong></td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td><strong>Density, (\rho_{\text{calc}})</strong></td>
<td>1.047 g/cm(^3)</td>
<td>1.451 g/cm(^3)</td>
</tr>
<tr>
<td><strong>Absorption coefficient, (\mu)</strong></td>
<td>0.063 mm(^{-1})</td>
<td>0.785 mm(^{-1})</td>
</tr>
<tr>
<td><strong>Crystal color and habit</strong></td>
<td>light-yellow plate</td>
<td>light-yellow plate</td>
</tr>
<tr>
<td><strong>Crystal size</strong></td>
<td>(0.75 \times 0.51 \times 0.12 , \text{mm})</td>
<td>(0.58 \times 0.38 \times 0.09 , \text{mm})</td>
</tr>
<tr>
<td><strong>Temperature</strong></td>
<td>173 K</td>
<td>153 K</td>
</tr>
<tr>
<td><strong>Radiation, (\lambda)</strong></td>
<td>Mo-K(\alpha), 0.71073 Å</td>
<td>Mo-K(\alpha), 0.71073 Å</td>
</tr>
<tr>
<td><strong>Min. And max. (\theta)</strong></td>
<td>1.82 to 25.00°</td>
<td>1.87 to 28.00°</td>
</tr>
<tr>
<td><strong>Reflections collected</strong></td>
<td>64034 ([R_{\text{int}} = 0.0351])</td>
<td>87094 ([R_{\text{int}} = 0.0604])</td>
</tr>
<tr>
<td><strong>Independent reflections</strong></td>
<td>12192</td>
<td>17914</td>
</tr>
<tr>
<td><strong>Data/parameters/restraints</strong></td>
<td>12192/728/2</td>
<td>17914/936/0</td>
</tr>
<tr>
<td><strong>(R) ([F_o &gt; 4\sigma(F_o)])</strong></td>
<td>(R_1 = 0.068)</td>
<td>(R_1 = 0.035)</td>
</tr>
<tr>
<td></td>
<td>(wR_2 = 0.198)</td>
<td>(wR_2 = 0.068)</td>
</tr>
<tr>
<td><strong>G.o.f. on (F^2)</strong></td>
<td>1.077</td>
<td>1.024</td>
</tr>
<tr>
<td><strong>Max./min. Residual densities, e-Å(^3)</strong></td>
<td>0.95, -0.41</td>
<td>0.49, -0.46</td>
</tr>
</tbody>
</table>

2.8 Preparation of Rhodium Complex Chloro(\(\eta-1,5\)-cyclooctadiene){(2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c]quinazolin-5-yl}rhodium

The imidazoquinazolinium salt, \(1(100 \, \text{mg}, 0.19 \, \text{mmol})\) was mixed with benzene (10 mL). LiHMDS (0.38 mmol, 380 \(\mu\)L, 1 M in hexane) was added to the reaction mixture followed by
the addition of [Rh(COD)Cl]_2 (47 mg, 0.095 mmol) at 0 °C. The reaction mixture was stirred at room temperature overnight. After the reaction the reaction mixture was evaporated under reduced pressure. And crude product was dissolved in CHCl_3. Pyridine (8 eq.) was added and stirred for 30 min. The mixture was evaporated under reduced pressure and purified by column chromatography (CHCl_3) to give in 60% yield. In order to get single crystal, the crude product was dissolved in Et_2O and pentane was added and crystals suitable for X-ray crystallography emerged after 12 hours.
$^1$H NMR (CDCl$_3$, 300MHz) : δ 8.22 (d, 1H, J=8.6Hz) 7.54 (d, 2H, J=8.6Hz) 7.46-7.24 (m, 11H), 6.97 (s, 1H), 6.83 (d, 1H, J=6.0Hz), 6.43 (d, 1H, J=9.3Hz), 4.91 (d, 1H, J=6.0Hz), 4.72 (s, 2H), 2.64 (s, 3H), 2.64 (m, 1H), 2.51 (m, 1H), 2.42 (s, 3H), 1.91 (m, 1H), 1.82 (s, 3H), 1.73 (m, 1H), 1.54-1.13 (m, 6H)

$^{13}$C NMR (CDCl$_3$, 75MHz) : δ 215.5 (d, J=86Hz), 149.0, 145.3, 141.7, 139.6, 138.5, 138.3, 137.9, 136.2, 133.9, 130.9, 129.7, 129.1, 129.0, 128.3, 128.0, 127.3, 126.4, 126.0, 115.8, 115.5, 97.9 (d, J=13Hz), 97.4 (d, J=12Hz), 80.0, 74.6, 71.9 (d, J=9.7Hz), 71.7 (d, J=9.7Hz), 33.3, 31.3, 28.5, 27.3, 21.3, 20.0, 18.3

HRMS (ESI+) [M-Cl]$^+$ calcd for C$_{39}$H$_{39}$N$_3$Rh: 652.2199; found, 652.2192.

3. Reference


(7) SMART and SAINT; Siemens Analytical X-ray Instruments Inc.: Madison, WI, USA, 1996.

(8) G. M. Sheldrick, SHELXS-97 and SHELXL-97; University of Gottingen: Gottingen, Germany, 1997.
4. Spectral data of 1 and its intermediates

4.1 N-((4S,5S)-4,5-diphenyl-4,5-dihydro-1H-imidazol-2-yl)phenyl)-2,4,6-trimethylaniline
4.2 (2S,3S)-6-mesityl-2,3-diphenyl-2,3-dihydroimidazo[1,2-c]quinazolin-6-ium tetrafluoroborate
4.3 ((2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c] quinazolin-5-yl)copper(II) chloride
4.4 Chloro(η-1,5-cyclooctadiene){(2S,3S)-6-mesityl-2,3-diphenyl-2,3,5,6-tetrahydroimidazo[1,2-c]quinazolin-5-yl}rhodium
Appendix B

Part II Supporting Information

Table of Content

1. General information
   1.1 General procedures
   1.2 Instrumentation

2. Experimental Section
   2.1 Typical Reaction Conditions for Chemoselectivity Comparison
   2.2 Validation of reaction condition for Xantphos catalyzed reaction
   2.3 Reaction conditions for allylic substitution reactions
   2.4 Experimental details for ratio determination of branched and linear products
   2.5 Synthesis of Substrates for Leaving Group Screen
   2.6 Synthesis of Substrates for Substrate Scope Tables
   2.7 Typical reaction conditions for allylic substitution
   2.8 $E$ vs $Z$ Substrate Rate Consumption Determination
   2.9 Reaction results and data for allylic substitution

3. References

1. General Information

1.1 General Procedure

All commercially available reagents were used without purification unless otherwise noted. Some substrates were synthesized according to the literature. Column chromatography was performed using silica gel from Merck (230-400 mesh). Visualization of the compounds was accomplished with UV light (254 nm), alkaline KMnO4 and anisaldehyde solution followed by heating.

1.2 Instrumentation
1H NMR and 13C NMR spectra were recorded in CDCl3 operating at 300.070 MHz and 75.452 MHz, respectively, 400 MHz spectrometer operating at 400.172 and 100.623 MHz, respectively, and 600 MHz spectrometer operating at 600.133 and 150.914 MHz, respectively. Proton chemical shifts are reported relative to the residual proton signals of the deuterated solvent CDCl3 (7.26 ppm) or CD2Cl2 (5.32 ppm) or TMS. Carbon chemical shifts were internally referenced to the deuterated solvent signals in CDCl3 (77.00 ppm) or CD2Cl2 (53.8 ppm). Data are represented as follows: chemical shift, multiplicity (bs = broad singlet, s = singlet, d = doublet, t = triplet, q = quartet, h = heptet, m = multiplet), coupling constant in Hertz (Hz), and integration. Products were identified by comparison to spectral data reported in the literature.

High performance liquid chromatography (HPLC) was performed using a chromatograph equipped with a Daicel CHIRALPAK IA (250 mm x 4.6 mm) and a CHIRALPAK IA guard column (1 cm x 0.4 cm) with hexane/iPrOH as the eluent. Gas chromatographic (GC) analyses were performed using a GC equipped with an autosampler, a flame ionization detector (FID), and a column (Astec CHIRALDEX B-DM : 30 m x 0.25 mm x 0.12 μm, Beta DEX : 30 m x 0.25 mm x 0.12 μm and Varian CP-Sil 5 CB : 15 m x 0.25 mm x 0.25 μm). Elemental analyses were performed by Atlantic Microlabs, Inc.

2. Experimental Section

2.1 Typical reaction condition for chemoselectivity comparisons

Substrate (51 mg, 0.22 mmol) and bis(pinacolato) diboron (51 mg, 0.20 mmol) were dissolved in Et2O (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled down to -20 °C and MeOH (18 μL, 0.4 mmol) was added. After 5 min, 6-NHC copper catalyst, 1 (1.1 mg, 0.0020 mmol) was added. After complete consumption of bis(pinacolato) diboron, the reaction mixture was filtered through silica gel and washed with Et2O. The filtrate was concentrated under rotary evaporator. 1H NMR of crude product was taken for the determination of the ratio of deallylated product to borylated product (>25/1). The resulting residue was purified by column chromatography (Hexane : EtOAc = 6 : 1 to 4 : 1) to afford the shown products (27 mg, 70% yield). 1H NMR (600 MHz, CDCl3) 7.63 (d, J=15.3 Hz,
1H) 7.43 (d, J=8.9 Hz, 2H) 6.85 (d, J=8.6 Hz, 2H) 6.30 (d, J=16.0 Hz, 1H) 4.26 (q, J=7.1 Hz, 2H) 1.34 (t, J=7.1 Hz, 3H) 13C NMR (150 MHz, CDCl$_3$) $\delta$ 167.8, 157.9, 144.6, 130.2, 127.5, 116.1, 115.9, 60.7, 14.6 HRMS(EI) calcd for C$_{11}$H$_{12}$O$_3$ 192.07865 found : 192.07866

Substrate (51mg, 0.22 mmol) and bis(pinacolato) diboron (51 mg, 0.20 mmol) were dissolved in Et$_2$O (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled down to -20 °C and MeOH (18 µL, 0.4 mmol) was added. After 5 min, 5-NHC copper catalyst (0.8 mg, 0.0020 mmol) was added. After complete consumption of bis(pinacolato) diboron, the reaction mixture was filtered through silica gel and washed with Et$_2$O. The filtrate was concentrated under rotary evaporator. $^1$H NMR of crude product was taken for the determination of the ratio of deallylated product to borylated product (<1/24). The resulting residue was purified by column chromatography (Hexane : EtOAc = 50 : 1 to 20 : 1) to afford the illustrated products (51 mg, 71% yield). $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 7.13-7.11 (m, 2H) 6.83-6.80 (m, 2H) 6.08-6.02 (m, 1H) 5.40 (ddd, J=17.2 Hz, 3.1 Hz, 1.6 Hz, 1H) 5.26 (ddd, J=10.5 Hz, 2.8 Hz, 1.4 Hz, 1H) 4.49 (dt, J=5.3 Hz, 1.5 Hz, 2H) 4.11-4.06 (m, 2H) 2.82 (dd, J=16.2 Hz, 9.8 Hz, 1H) 2.67 (dd, J=9.8 Hz, 6.2 Hz, 1H) 2.61 (dd, J=16.2 Hz, 6.2 Hz, 1H) 1.22-1.20 (m, 9H) 1.17 (s, 6H) 13C NMR (150 MHz, CDCl$_3$): $\delta$ 173.7, 157.0, 133.81, 133.77, 129.4, 117.7, 115.0, 83.7, 69.1, 60.5, 37.8, 24.8, 24.7, 14.5 HRMS(EI) calcd for C$_{20}$H$_{29}$BO$_5$ 360.21081 found : 360.21141

Xantphos (8.7 mg, 0.015 mmol), CuCl (1.5 mg, 0.015 mmol) and NaOtBu (4.3 mg, 0.045 mmol) were dissolved in THF (0.4 mL) and the reaction mixture was stirred for 30 min.

Bis(pinacolato) diboron (127 mg, 0.50 mmol) were added to the reaction mixture. After 3 min, stirring, the substrate (128 mg, 0.55 mmol) in solution with THF (1.6 mL) was added to the reaction mixture, followed by the addition of MeOH (45 µL, 1.0 mmol) After complete consumption of bis(pinacolato) diboron, the reaction mixture was filtered through silica gel and
washed with Et$_2$O. The filtrate was concentrated under rotary evaporator. $^1$H NMR of crude product was taken for the determination of the ratio of deallylated product to borylated product (1/1.3). The resulting residue was purified by column chromatography (Hexane : EtOAc = 8 : 1 to 6 : 1) to afford the desired products, A (17 mg, 16% yield).

### 2.2 Validation of reaction condition for Xantphos catalyzed reaction

We tried to reproduce the β-borylation reaction of ethyl cinnamate using Yun’s reaction conditions. And we had same results as Yun’s group. However, when we tested ethyl 4-hydroxy cinnamate, we had a significant lower yield. We thought aromatic hydroxyl group could be deleterious effect on the active catalytic species, which could explain why we had a low yield in the reaction using Xantphos.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Temp.</th>
<th>Reaction time</th>
<th>Yield (%)$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image1.png" alt="Substrate" /></td>
<td>rt</td>
<td>2 h</td>
<td>99 %</td>
</tr>
<tr>
<td>2</td>
<td><img src="image2.png" alt="Substrate" /></td>
<td>rt</td>
<td>5 h</td>
<td>68 %</td>
</tr>
</tbody>
</table>

$^a$Yields were determined by $^1$H NMR.

### 2.3 Reaction conditions for allylic substitution reactions

(E)-(hex-2-enyloxy)benzene (35 mg, 0.20 mmol) and bis(pinacolato) diboron (57 mg, 0.22 mmol) were dissolved in Et$_2$O (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled down to 0 °C and MeOH (18 μL, 0.4 mmol) was added, followed by the addition of cyclooctane solution (100 μL, 1.0 M in Et$_2$O). After 5 min, 6-NHC copper catalyst, 1 (1.1 mg, 0.0020 mmol) were added. The reaction was monitored by GC according to the time and GC yield was determined by the calibration of area ratio between product peak and internal standard (cyclooctane) peak. After 20 min, the reaction mixture was filtered through silica gel and washed with Et$_2$O. The filtrate was concentrated.
under rotary evaporator. The resulting residue was purified by column chromatography (Hexane) to afford the desired products, (37 mg, 86% yield). $^1$H NMR (600 MHz, CDCl$_3$): $\delta$ 5.79 (ddd, J=17.1 Hz, 10.1 Hz, 8.8 Hz, 1H) 4.97 (ddd, J=17.1 Hz, 1.8 Hz, 1.2 Hz, 1H) 4.92 (ddd, J=10.1 Hz, 1.8 Hz, 0.7 Hz, 1H) 1.84 (q, J=7.8 Hz, 1H) 1.56-1.50 (m, 1H) 1.44-1.25 (m, 3H) 1.24 (s, 6H) 1.23 (s, 6H) 0.89 (t, J=7.3 Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$): $\delta$ 140.0, 113.6, 83.3, 32.7, 24.94, 24.85, 22.3, 14.3 HRMS(EI) calcd for C$_{12}$H$_{23}$BO$_2$ 210.17912 found : 210.18004

(E)-(hex-2-enyloxy)benzene (35mg, 0.20 mmol) and bis(pinacolato) diboron (57 mg, 0.22 mmol) were dissolved in Et$_2$O (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled down to 0 °C and MeOH (18 μL, 0.4 mmol) was added, followed by the addition of cyclooctane solution (100 μL, 1.0 M in Et$_2$O). After 5 min, 5-NHC copper catalyst(0.8 mg, 0.0020 mmol) were added. The reaction was monitored by GC according to the time and GC yield was determined by the calibration of area ratio between product peak and internal standard (cyclooctane) peak. The reaction was carried out until no conversion was detected.

Xantphos (8.7 mg, 0.015 mmol), CuCl (1.5 mg, 0.015 mmol) and NaOtBu (4.3 mg, 0.045 mmol) were dissolved in THF (0.4 mL) and the reaction mixture was stirred for 30min. Bis(pinacolato) diboron (127 mg, 0.50 mmol) were added to the reaction mixture. After 3 min, stirring, (E)-(hex-2-enyloxy)benzene (88 mg, 0.50 mmol) solution in THF (1.6 mL) was added to the reaction mixture, followed by the addition of cyclooctane solution (100 μL, 1.0 M in Et$_2$O) and MeOH (45 μL, 1.0 mmol). The reaction was monitored by GC according to the time and GC yield was determined by the calibration of area ratio between product peak and internal standard (cyclooctane) peak. The reaction was carried out until no conversion was detected.
2.4 Experimental details for ratio determination of branched product (6a) and linear product (6b)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst (mol%)</th>
<th>Time</th>
<th>6a/6b&lt;sup&gt;b&lt;/sup&gt;</th>
<th>Yield(%)&lt;sup&gt;c&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 (1 mol%)</td>
<td>20 min</td>
<td>&gt;99/1</td>
<td>91 % (86 %)&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td>2</td>
<td>2 (1 mol%)</td>
<td>3 h</td>
<td>&gt;99/1</td>
<td>17 %</td>
</tr>
<tr>
<td>3&lt;sup&gt;e&lt;/sup&gt;</td>
<td>3 (3 mol%)</td>
<td>22 h</td>
<td>14/1</td>
<td>11 %</td>
</tr>
</tbody>
</table>

<sup>a</sup>See footnote a in Table 1. <sup>b</sup>Ratio was determined by GC. <sup>c</sup>Yields were determined by GC using internal standard (cyclooctane). <sup>d</sup>Isolated yield. <sup>e</sup>Reaction was carried out in THF at rt.

Linear product (6b) was synthesized and confirmed by comparison with known data. We didn’t observe any peak of 6b in GC chromatogram for 1 or 2 catalyzed allylic substitution reaction (see below GC chromatogram).

Calibration curve between product, 6a (1.0 eq) and cyclooctane (0.5 eq)

![Calibration curve](image-url)
GC chromatogram for entry 1

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.497</td>
<td>12.2</td>
</tr>
<tr>
<td>3.205</td>
<td>31.6</td>
</tr>
<tr>
<td>4.735</td>
<td>1.25</td>
</tr>
<tr>
<td>4.899</td>
<td>2.39</td>
</tr>
</tbody>
</table>

1.497 min: cyclooctane
3.205 min: 6a
4.735 min: starting material
4.899 min: B_3P Ib

GC chromatogram for entry 2

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.497</td>
<td>12.2</td>
</tr>
<tr>
<td>3.206</td>
<td>31.6</td>
</tr>
<tr>
<td>4.734</td>
<td>1.25</td>
</tr>
<tr>
<td>4.901</td>
<td>2.39</td>
</tr>
</tbody>
</table>

1.497 min: cyclooctane
3.206 min: 6a
4.734 min: starting material
4.901 min: B_3Pin_2
### 2.5 Synthesis of Substrates for Leaving Group Screen

Representative Procedure A: A 7 mL screw-top vial was equipped with a stir bar and charged with aryl iodide (1 Eq), allylic alcohol (2 Eq), copper iodide (10 mol %), cesium carbonate (2
Eq), 1, 10-phenanthroline (20 mol %) and 1 mL toluene. The vial was sealed and heated to 110 °C with stirring for 48 hours, after which time it was cooled to room temperature and filtered through a pad of silica gel, using diethyl ether as an eluant. The solvent was removed under vacuum, and the crude product was purified by silica gel flash chromatography (9:1 Hexanes:EtOAc). Any remaining aryl iodide was removed by vacuum distillation to yield the pure desired compounds.

Representative Procedure B: Sodium hydride (1.3 Eq.) was carefully weighed out and placed in a 100 mL 3-necked round-bottom flask with fitted with a condenser and stir bar, then suspended in 10 mL dry DMF. A solution of the allylic alcohol (1.5 Eq.) in 10 mL dry DMF was added dropwise over 30 minutes, then the solution was stirred for an additional hour. A solution of the aryl fluoride (1 Eq.) in 2 mL DMF was added dropwise and the entire solution was stirred at room temperature for 1 hour, then stirred at 50 °C for 14 hours, after which time the solution became a bright yellow color. The reaction was quenched with 10 mL saturated ammonium chloride solution, and extracted with 4 x 20 mL diethyl ether. The combined organic layers were washed with 20 mL each of 1M HCl solution and brine, then dried over MgSO₄ and concentrated under vacuum. Flash chromatography of the crude product, and subsequent vacuum distillation yielded the pure desired compounds.

(E)-(hex-2-en-1-yloxy)benzene

Produced by procedure A. Isolated as a yellow oil in 78% yield. ¹H NMR (400 MHz, CDCl₃): δ 7.30-7.26 (m, 2H) 6.96-6.91 (m, 3H) 5.88-5.81 (m, 1H) 5.75-5.67 (m, 1H) 4.48 (dt, J=5.9 Hz, 1.0 Hz, 2H) 2.10-2.05 (m, 2H) 1.44 (hd, J=7.4 Hz, 1.0 Hz, 2H) 0.92 (td, J=7.4 Hz, 1.4 Hz, 3H) ¹³C NMR (100 MHz, CDCl₃): δ 159.0, 135.7, 129.6, 125.2, 120.9, 115.0, 69.0, 34.6, 22.3, 13.9 HRMS (El) calcd for C₁₂H₁₆O 176.12012 found : 176.11988

(E)-1-(hex-2-en-1-yloxy)-2-methylbenzene

Produced by procedure A. Isolated as a dark yellow oil in 62% yield. 

Rᵣ (9:1 Hexanes:EtOAc) = 0.68. ¹H NMR (CDCl₃, 600 MHz): δ = 0.92
(E)-1-(hex-2-en-1-yloxy)-3,5-bis(trifluoromethyl)benzene

Produced by procedure A. Isolated as a light yellow oil in 88% yield. Rf (9:1 Hexanes:EtOAc) = 0.79. 1H NMR (CDCl₃, 600 MHz) δ = 0.91 (t, J = 7.4 Hz, 3H, CH₃CH₂CH₂CHCH), 1.43 (sx, J = 7.4 Hz, 2H, CH₃CH₂CH₂CHCH), 2.08 (dq, J = 0.84, 7.4 Hz, 2H, CH₃CH₂CH₂CHCH), 4.57 (dd, J = 0.90, 6.1 Hz, 2H, CHCHCH₂OPh), 5.67 – 5.90 (m, 2H, CHCHCH₂OPh), 7.30 (s, 2H, CHCHCH₂OPh), 7.44 (s, 1H, CHCHCH₂OPh). 13C NMR (CDCl₃, 150 MHz) δ = 159.4, 137.0 (2), 133.0, 132.8, 123.7 (2), 115.4 (2), 114.3, 69.7, 34.5, 22.2, 13.7. IR (neat, cm⁻¹): 2963, 2932,
Produced by procedure B. Isolated as a dark yellow oil in 30% yield. Rf (7:3 Hexanes:EtOAc) = 0.58. ¹H NMR (CDCl₃, 600 MHz) δ = 0.91 (t, J = 7.3 Hz, 3H, CH₃CH₂CH₂CHCH), 1.44 (sx, J = 7.4 Hz, 2H, CH₃CH₂CH₂CHCH), 2.08 (dq, J = 1.0, 6.1 Hz, 2H, CHCHCH₂OPhNO₂), 4.56 (dd, J = 1.0, 6.1 Hz, 2H, CHCHCH₂OPhNO₂), 5.66 – 5.91 (m, 2H, CHCHCH₂OPhNO₂), 7.23 (dq, J = 0.72, 2.5, 8.3 Hz, 1H, CHCHCH₂OPhNO₂), 7.41 (t, J = 8.2 Hz, 1H, CHCHCH₂OPhNO₂), 7.74 (t, J = 2.3 Hz, 1H, CHCHCH₂OPhNO₂), 7.81 (dq, J = 0.72, 1.2, 7.3 Hz, 1H, CHCHCH₂OPhNO₂). ¹³C NMR (CDCl₃, 150 MHz) δ = 159.4, 149.4, 136.8, 129.9, 123.9, 122.2, 115.8, 109.2, 66.6, 34.5, 22.2, 13.8. IR (neat, cm⁻¹): 2960, 2922, 2884, 1619, 1579, 1510, 1482, 1461, 1349, 1320, 1284, 1243, 1092, 1011. LRMS (m/z, EI⁺): Calcd. 221.1, found 221.1
(E)-1-(hex-2-en-1-yloxy)-4-nitrobenzene

Prepared by procedure B. Isolated as a yellow oil in 47% yield. 

R_f (9:1 Hexanes:EtOAc) = 0.42. ^1H NMR (CDCl_3, 600 MHz) δ = 0.91 (t, J = 7.3 Hz, 3H, CH_2CH_3), 1.44 (sx, J = 7.4 Hz, 2H, CH_2CH_3), 2.08 (dq, J = 0.96, 6.8, 13.6 Hz, 2H, CHCHCH_2CH_2O), 4.57 (dd, J = 0.96, 6.1 Hz, 2H, CHCHCH_2CH_2O), 5.65 – 5.70 (m, 1H, CHCHCH_2CH_2O), 5.85 – 5.90 (m, 1H, CHCHCH_2CH_2O), 6.95 (dd, J = 3.4, 5.5 Hz, 2H, Ph), 8.19 (dd, J = 3.4, 5.5 Hz, 2H, Ph). ^13C NMR (CDCl_3, 150 MHz) δ = 16γ.8, 141.5, 136.8, 125.9, 125.9, 123.6, 114.7, 114.7, 69.6, 34.3, 22.0, 13.6. IR (neat, cm^{-1}): 2960, 1606, 1579, 1510, 1469, 1456, 1362, 1334, 1269, 1248, 1173, 1077, 1035. LRMS (m/z, EI+): Calcd. 221.1, found 221.0.

(E)-4-(hex-2-en-1-yloxy)-2-methyl-1-nitrobenzene

Prepared according to procedure B. Isolated as a dark yellow oil in 41% yield. R_f (7:3 Hexanes:EtOAc) = 0.66. ^1H NMR (CDCl_3, 600 MHz) δ = 0.91 (t, J = 7.3 Hz, 3H, CH_3CH_2CH_2CHCH), 1.43 (sx, J = 7.4 Hz, 2H, CH_3CH_2CH_2CHCH), 2.08 (dq, J = 1.0, 7.4, 14.8 Hz, 2H, CH_3CH_2CH_2CHCH), 2.62 (s, 3H, CHCHCH_2OPhMe), 4.54 (dd, J = 1.0, 6.1 Hz, 2H, CHCHCH_2OPhMe), 5.64 – 5.88 (m, 2H, CHCHCH_2OPhMe), 6.77 – 6.81 (m, 2H, CHCHCH_2OPhMe), 8.08 (d, J = 8.8 Hz, 1H, CHCHCH_2OPhMe). ^13C NMR (CDCl_3, 150 MHz) δ = 162.4, 142.3, 137.1, 136.7, 127.6, 123.9, 118.4, 112.6, 69.5, 34.5, 22.2, 21.8, 13.8. IR (neat, cm^{-1}): 2960, 2931, 2872, 1671, 1606, 1579, 1510, 1469, 1456, 1362, 1334, 1269, 1248, 1173, 1077, 1035. LRMS (m/z, EI+): Calcd. 235.1, found 235.0.

(E)-1-(hex-2-en-1-yloxy)-4-methoxybenzene

Prepared according to procedure A. Isolated as a light yellow liquid. ^1H NMR (CDCl_3, 600 MHz) δ = 0.90 (t, J = 7.3 Hz, 3H,
CH₃CH₂CH₂CHCH, 1.43 (sx, J = 7.4 Hz, 2H, CH₃CH₂CH₂CHCH), 2.06 (dq, J = 0.9, 7.7, 14.7 Hz, 2H, CH₃CH₂CH₂CHCH), 3.76 (s, 3H, CHCHCH₂OPhOMe), 4.42 (dd, J = 0.9, 6.1 Hz, 2H, CHCHCH₂OPhOMe), 5.67 – 5.83 (m, 2H, CHCHCH₂OPhOMe), 6.80 – 6.84 (m, 4H, CHCHCH₂OPhOMe). ¹³C NMR (CDCl₃, 150 MHz) δ = 154.0, 15γ.1, 1γ5.4, 1β5.4, 115.9 (β), 114.8 (2), 69.7, 55.9, 34.6, 22.3, 13.8.

2.6 Synthesis of Substrates for Substrate Scope Tables

1-(allyloxy)-3-nitrobenzene (1)⁴

A 250 mL round-bottom flask was charged with 3-nitrophenol (5 g, 35.9 mmol, 1 eq.), allyl bromide (4.67 mL, 53.9 mmol, 1.5 eq.), anhydrous K₂CO₃ (9.94 g, 71.9 mmol, 2 eq.) and 120 mL acetone (0.3 M) and stirred at room temperature for 14 hours. The reaction mixture was then filtered through Celite and concentrated by N₂ flow. The product was redissolved into hexanes, and filtered through Celite to remove KBr salt. Desired product was isolated as a bright yellow oil in 98 % yield. ¹H NMR (CDCl₃, 600 MHz) δ = 4.62 (m, 2H, CH₂CH₂CHCH₂OPhNO₂), 5.35 (dd, J = 1.2, 10.6 Hz, 1H, CH₂CHCH₂OPhNO₂), 5.45 (dd, J = 1.4, 17.3 Hz, 1H, CH₂CHCH₂OPhNO₂), 6.02 – 6.09 (m, 1H, CH₂CHCH₂OPhNO₂), 7.25 (ddd, J = 0.6, 2.5, 8.3 Hz, 1H, CH₂CHCH₂OPhNO₂), 7.42 (t, J = 8.2 Hz, 1H, CH₂CHCH₂OPhNO₂), 7.74 (t, J = 2.3 Hz, 1H, CH₂CHCH₂OPhNO₂), 7.83 (m, 1H, CH₂CHCH₂OPhNO₂). ¹³C NMR (CDCl₃, 150 MHz) δ = 159.1, 149.2, 132.1, 130.0, 121.9, 118.5, 115.9, 109.1, 69.4. IR (neat, cm⁻¹) = 3097, 2871, 1617, 1582, 1524, 1481, 1460, 1424, 1349, 1321, 1286, 1242, 1230, 1157, 1096, 1022. LRMS (m/z, EI+): Calcd. 179.1, found 179.1.

Representative Metathesis Procedure⁵,⁶:

A 50 mL round-bottom flask was flame-dried and kept under N₂ atmosphere. The flask was charged with 1 (4 eq.), terminal olefin (1 eq.) and methylene chloride (0.2 M) and stirred at room temperature for 10 minutes. Grubbs’ 1st generation catalyst was added (5 mol %) and the reaction was heated to reflux (45 °C) for 14 hours, then cooled to room temperature. The crude material was adsorbed onto silica and flash chromatography was used to isolate the product (10% Et₂O in Hexanes). Remaining 1 was then removed by Kügelrohr distillation (100 °C at 150 mTorr), and the dimer of 1 was precipitated out of solution by dissolving in methanol, yielding the desired product.
1-((3-Cyclohexylallyl)oxy)-3-nitrobenzene

Isolated as a brown oil in 37% yield. \( R_f = 0.49 \). \(^1\)H NMR

\((\text{CDCl}_3, 600 \text{ MHz, } E\text{-isomer only}) \delta = 1.07 – 1.35 (m, 5H, CyCHCH), 1.71 – 1.76 (m, 5H, CyCHCH), 2.00 – 2.05 (m, 1H, CyCHCH), 4.55 (d, \( J = 6.1 \text{ Hz} \), 2H, CHCH\(\text{CHCH}_2\text{OAr}\)), 5.60 – 5.85 (m, 2H, CHCH\(\text{CHCH}_2\text{OAr}\)), 7.23 (ddd, \( J = 0.72, 2.5, 8.9 \text{ Hz} \), 1H, CHCH\(\text{CHCH}_2\text{OAr}\)), 7.41 (t, \( J = 8.2 \text{ Hz} \), 1H, CHCH\(\text{CHCH}_2\text{OAr}\)), 7.73 (t, \( J = 2.3 \text{ Hz} \), 1H, CHCH\(\text{CHCH}_2\text{OAr}\)), 7.81 (ddd, \( J = 0.60, 1.8, 7.9 \text{ Hz} \), 1H, CHCH\(\text{CHCH}_2\text{OAr}\)). \(^{13}\)C NMR (CDCl\(_3\), 150 MHz): \( \delta = 159.4, 149.5, 134.8, 130.0, 128.72 (2), 128.67 (2), 126.5, 125.3, 122.1, 115.9, 109.3, 69.9, 40.6, 33.2, 32.7 (2), 26.2, 25.9 (2). IR (neat, cm\(^{-1}\)): 2924, 2851, 1620, 1579, 1523, 1481, 1448, 1348, 1285, 1244, 1075, 1012. LRMS (m/z, EI\(^+\)): Calcd. 261.1, found 261.0.

1-Nitro-3-((4-phenylbut-2-en-1-yl)oxy)benzene

Isolated as a dark brown oil in 31% yield. \( R_f = 0.33 \). \(^1\)H NMR

\((\text{CDCl}_3, 600 \text{ MHz, } E/Z = 4.6/1) \delta = 1.44 (d, \( J = 6.8 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 4.59 (dd, \( J = 1.0, 5.8 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 5.73 – 5.77 (m, 1H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 6.02 – 6.06 (m, 1H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 7.17 – 7.23 (m, 4H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 7.30 (t, \( J = 7.6 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 7.31 (t, \( J = 8.2 \text{ Hz} \), 1H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 7.73 (t, \( J = 2.3 \text{ Hz} \), 1H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)), 7.81 (ddd, \( J = 0.78, 2.1, 8.2 \text{ Hz} \), 1H, PhCH\(\text{CH}_2\text{CHCHCH}_2\text{OAr}\)). \(^{13}\)C NMR (CDCl\(_3\), 150 MHz): \( \delta = 159.3, 149.4, 139.5, 134.8, 130.0, 128.72 (2), 128.67 (2), 126.5, 125.3, 122.1, 115.9, 109.3, 69.2, 38.8. IR (neat, cm\(^{-1}\)): 3028, 1617, 1581, 1528, 1494, 1481, 1453, 1347, 1321, 1286, 1244, 1093, 1012. LRMS (m/z, EI\(^+\)): Calcd. 269.1, found 269.1.

1-Nitro-3-((5-phenylpent-2-en-1-yl)oxy)benzene

Isolated as a light yellow oil in 79% yield. \(^1\)H NMR

\((\text{CDCl}_3, 600 \text{ MHz, } E/Z = 3.3/1) \delta = 2.42 (q, \( J = 7.1 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CH}_2\text{CHCH}\)), 2.73 (t, \( J = 7.4 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CH}_2\text{CHCH}\)), 4.54 (dd, \( J = 0.84, 6.0 \text{ Hz} \), 2H, PhCH\(\text{CH}_2\text{CH}_2\text{CHCH}\)).
CHCH₂OAr), 5.69 – 5.94 (m, 2H, CHCH₂OAr), 7.17 (t, J = 7.0 Hz, 3H, PhCH₂CH₂CHCH), 7.21 (dd, J = 2.2, 7.7 Hz, 1H, CHCHCH₂OAr), 7.27 (t, J = 7.6 Hz, 2H, PhCH₂CH₂CHCH), 7.41 (t, J = 8.2 Hz, 1H, CHCHCH₂OAr), 7.72 (ddd, J = 0.72, 2.1, 8.2 Hz, 1H, CHCHCH₂OAr).

13C NMR (CDCl₃, 150 MHz): δ = 159.γ, 149.4, 141.5, 135.6, 130.0, 128.7, 128.6, 128.5, 128.5, 126.1, 124.5, 122.1, 115.9, 109.2, 69.4, 35.5, 34.1. IR (neat, cm⁻¹): 3027, 2920, 1618, 1580, 1526, 1495, 1481, 1454, 1383, 1348, 1321, 1285, 1076, 1010.

1-((6-Bromohex-2-en-1-yl)oxy)-3-nitrobenzene

Isolated as a bright orange oil in 47% yield. ¹H NMR (CDCl₃, 600 MHz, E/Z = 3.3/1): δ = 1.98 (p, J = 6.8 Hz, 2H, BrCH₂CH₂CH₂CHCH), 2.28 (q, J = 7.0 Hz, 2H, BrCH₂CH₂CH₂CHCH), 3.42 (t, J = 6.6 Hz, 2H, BrCH₂CH₂CH₂CHCH), 4.57 (d, J = 5.8 Hz, 2H, CHCH₂OAr), 5.74 – 5.88 (m, 2H, CHCH₂OAr), 7.23 (dd, J = 2.3, 8.2 Hz, 1H, CHCH₂OAr), 7.42 (t, J = 8.2 Hz, 1H, CHCH₂OAr), 7.73 (d, J = 1.7 Hz, 1H, CHCH₂OAr), 7.82 (d, J = 8.1 Hz, 1H, CHCH₂OAr).

13C NMR (CDCl₃, 150 MHz): δ = 159.3, 149.4, 134.1, 130.0, 125.5, 122.1, 116.0, 109.2, 69.2, 33.0, 31.8, 30.7. IR (neat, cm⁻¹): 2941, 1619, 1579, 1528, 1482, 1459, 1349, 1321, 1285, 1242, 1093, 1011.

7-(3-Nitrophenoxy)hept-5-en-2-one

Isolated as a dark brown oil in 51% yield. ¹H NMR (CDCl₃, 600 MHz, E/Z = 3.2/1): δ = 2.16 (s, 3H, CH₃COCH₂CH₂CHCH), 2.39 (q, J = 7.0 Hz, 2H, CH₃COCH₂CH₂CHCH), 2.57 (t, J = 7.0 Hz, 2H, CH₃COCH₂CH₂CHCH), 4.55 (d, J = 5.8, 2H, CHCH₂OAr), 5.66 – 5.91 (m, 2H, CHCH₂OAr), 7.22 (dd, J = 2.1, 8.3 Hz, 1H, CHCH₂OAr), 7.42 (t, J = 8.2 Hz, 1H, CHCH₂OAr), 7.72 (s, 1H, CHCH₂OAr).

¹³C NMR (CDCl₃, 150 MHz): δ = 207.5, 159.1, 149.2, 134.4, 129.9, 124.8, 121.9, 115.8, 109.1, 69.1, 42.6, 29.9, 26.3. IR (neat, cm⁻¹): 3097, 2918, 2871, 1619, 1579, 1524, 1482, 1410, 1349, 1322, 1286, 1243, 1163, 1012.

Methyl 6-(3-nitrophenoxy)hex-4-enoate
Isolated as a brown oil in 57% yield. $^1$H NMR (CDCl$_3$, 600 MHz, $E$/Z = 1.1/1) $\delta$ = 2.29 – 2.32 (m, 1.3H, Z-MeOOCCCH$_2$CH$_2$CHCH), 2.35 – 2.39 (m, 2.5H, E-MeOOCCCH$_2$CH$_2$CHCH), 2.44 (m, 4H, E-MeOOCCCH$_2$CH$_2$CHCH), 2.46 – 2.51 (m, 3.4H, Z - MeOOCCCH$_2$CH$_2$CHCH), 3.68 (s, 3H, Z - MeOOCCCH$_2$CH$_2$CHCH), 3.69 (s, 3H, E-MeOOCCCH$_2$CH$_2$CHCH), 4.56 (dd, $J$ = 0.6, 5.8 Hz, 2H, E-CHCHCH$_2$OAr), 4.70 (dd, $J$ = 0.6, 5.8 Hz, 1.8H, Z-CHCHCH$_2$OAr), 5.66 – 5.92 (m, 2H, E/Z-CHCHCH$_2$OAr), 7.23 (m, 1H, E/Z-CHCHCH$_2$OAr), 7.42 (m, 1H, E/Z-CHCHCH$_2$OAr), 7.73 (m, 1H, , E/Z-CHCHCH$_2$OAr), 7.82 (m, 1H, , E/Z-CHCHCH$_2$OAr). $^{13}$C NMR (CDCl$_3$, 150 MHz): $\delta$ = 173.3, 159.3, 149.4, 134.1, 130.1, 130.0, 129.6, 129.2, 122.0, 116.0, 109.2, 69.6, 64.7, 51.7, 34.1, 33.6, 27.6, 23.5. IR (neat, cm$^{-1}$): 3023, 2952, 2913, 1736, 1617, 1580, 1523, 1482, 1349, 1321, 1286, 1248, 1101, 1024. LRMS (\textit{m/z}, EI+): Calcd. 265.3, found 265.1.

**tert-Butyldimethyl((4-(3-nitrophenoxy)but-2-en-1-yl)oxy)silane**

Isolated as a dark brown oil in 47% yield. $R_f$ = 0.34. $^1$H NMR (CDCl$_3$, 600 MHz, $E$/Z = 12/1) $\delta$ = 0.08 (s, 6H, TBDMSOCH$_2$CHCH), 0.91 (s, 9H, TBDMSOCH$_2$CHCH), 4.23 (m, 2H, TBDMSOCH$_2$CHCH), 4.62 (m, 2H, CHCHCH$_2$OAr), 5.91 – 6.00 (m, 2H, CHCHCH$_2$OAr), 7.27 (ddd, $J$ = 0.72, 2.4, 8.3 Hz, 1H, CHCHCH$_2$OAr), 7.42 (t, $J$ = 8.2 Hz, 1H, CHCHCH$_2$OAr), 7.73 (t, 2.3 Hz, 1H, CHCHCH$_2$OAr), 7.82 (ddd, $J$ = 0.9, 2.1, 8.2 Hz, 1H, CHCHCH$_2$OAr). $^{13}$C NMR (CDCl$_3$, 150 MHz): $\delta$ = 159.3, 149.3, 134.2, 130.0, 123.5, 122.0, 115.9, 109.3, 68.8, 62.9, 26.0 (3), 18.5, -5.2 (2). IR (neat, cm$^{-1}$): 2950, 2930, 2884, 2857, 1616, 1581, 1530, 1472, 1463, 1349, 1321, 1286, 1248, 1101, 1024. LRMS (\textit{m/z}, CI+): Calcd. 323.1, found 324.2.

**Z-tert-Butyldimethyl((4-(3-nitrophenoxy)but-2-en-1-yl)oxy)silane**

cis-2-Butene-1,4-diol (2.18 mL, 26.5 mmol, 4 eq.), DMAP (81 mg, 0.66 mmol, 10 mole %) and triethylamine (1.2 mL, 8.6 mmol, 1.3 eq.) were charged to a 100 mL round-bottom flask and dissolved in 20 mL DCM (0.3M). A solution of $t$-Butylchlorodimethylsilane (1g, 6.6 mmol, 1 eq.) in 2 mL DCM was added dropwise at room temperature over 3 hours, then stirred at room
temperature for an additional hour before the reaction was quenched with a brine solution. The aqueous phase was extracted with 3 x 20 mL DCM, then the combined organic layers were washed with brine and dried over MgSO$_4$. The crude product was purified by flash chromatography (3/1 hexanes/ethyl acetate), yielding 815 mg (61 % yield) of (Z)-4-((tert-Butyldimethylsilyl)oxy)but-2-en-1-ol.

The above product (815 mg, 4 mmol, 1 eq.), 1-Iodo-3-nitrobenzene (1.5 g, 6 mmol, 1.5 eq.), copper iodide (76.8 mg, 0.4 mmol, 10 mol%), 1,10-phenanthroline (145 mg, 0.8 mmol, 20 mol%) and cesium carbonate (1.96 g, 6 mmol, 1.5 eq.) were charged to a 7 ml screw-top vial with 3 mL toluene. The vial was sealed tightly and stirred at 100 °C for 36 hours. After cooling to room temperature, the reaction mixture was filtered through a pad of silica gel with diethyl ether. The filtrate was concentrated and the resulting residue was purified by gradient flash chromatography, using two column-lengths of pentanes to flush and eluting with 7/3 hexanes/ethyl acetate. The reaction yielded 250 mg desired product as a dark yellow liquid (19.2% yield).

**1H NMR** (CDCl$_3$, 600 MHz): $\delta = 0.10$ (s, 6H, TBDMSOCH$_2$CHCH), 0.92 (s, 9H, TBDMSOCH$_2$CHCH), 4.32 – 4.34 (m, 2H, TBDMSOCH$_2$CHCH), 4.74 (dd, $J = 1.3$, 6.0 Hz, 2H, CHCH$_2$OAr), 5.69 – 5.82 (m, 2H, CHCH$_2$OAr), 7.23 (dd, $J = 0.78$, 2.6, 8.3 Hz, 1H, CHCH$_2$OAr), 7.42 (t, $J = 8.2$ Hz, 1H, CHCH$_2$OAr), 7.82 (ddd, $J = 0.96$, 2.2, 8.2 Hz, 1H, CHCH$_2$OAr). $^{13}$C NMR (CDCl$_3$, 150 MHz): $\delta = 159.3$, 149.4, 133.8, 130.1, 124.8, 122.0, 116.0, 109.1, 65.1, 60.2, 26.0 (3), 18.5, -5.1 (2). IR (neat, cm$^{-1}$): 2954, 2930, 2857, 1620, 1581, 1530, 1471, 1408, 1350, 1319, 1286, 1251, 1091, 1023. LRMS ($m/z$, CI+): Calcd. 323.1, found 324.1.

**1-(4-(4-Methoxyphenoxy)but-2-en-1-yl)-3-nitrobenzene**

Isolated as a dark brown oil in 49 % yield. $R_f = 0.27$. $^1$IH NMR (CDCl$_3$, 600 MHz, $E/Z = 5.5/1$): $\delta = 3.38$ (d, $J = 6.7$ Hz, 2H, CHCH$_2$PhOMe), 3.79 (s, 3H, CHCH$_2$PhOMe), 4.58 (dd, $J = 1.0$, 5.9 Hz, 2H, ArOCH$_2$CHCH), 6.04 – 5.70 (m, 2H, ArOCH$_2$CHCH), 6.84 (dt, $J = 3.8$, 6.8 Hz, 2H, CHCH$_2$PhOMe), 7.10 (dt, $J = 2.9$, 4.7 Hz, 2H, CHCH$_2$PhOMe), 7.22 (ddd, $J = 0.72$, 2.4, 8.3 Hz, 1H, ArOCH$_2$CHCH), 7.41 (t, $J = 8.3$ Hz, 2H, ArOCH$_2$CHCH), 7.73 (t, $J = 8.3$ Hz, 2H, ArOCH$_2$CHCH), 7.82 (ddd, $J = 0.96$, 2.2, 8.2 Hz, 1H, CHCH$_2$OAr). $^{13}$C NMR (CDCl$_3$, 150 MHz): $\delta = 159.3$, 149.4, 133.8, 130.1, 124.8, 122.0, 116.0, 109.1, 65.1, 60.2, 26.0 (3), 18.5, -5.1 (2). IR (neat, cm$^{-1}$): 2954, 2930, 2857, 1620, 1581, 1530, 1471, 1408, 1350, 1319, 1286, 1251, 1091, 1023. LRMS ($m/z$, CI+): Calcd. 323.1, found 324.1.
Hz, 1H, ArOCH2CHCH), 7.30 (t, J = 2.3 Hz, 1H, ArOCH2CHCH), 7.81 (ddd, J = 0.72, 2.0, 8.0 Hz, 1H, ArOCH2CHCH). 13C NMR (CDCl3, 150 MHz): δ = 159.3, 158.3, 149.3, 135.3, 134.1, 129.7, 129.4 (2), 125.0, 122.1, 115.9, 114.2 (2), 109.3, 69.2, 55.4, 37.9. IR (neat, cm⁻¹): 2918, 1611, 1581, 1523, 1511, 1482, 1463, 1349, 1321, 1291, 1286, 1244, 1177, 1094, 1034, 1012. LRMS (m/z, EI+): Calcd. 299.1, found 299.1.

tert-Butyl (4-(4-methoxyphenoxy)but-2-en-1-yl)carbamate

Isolated as a light yellow solid. 1H NMR (CDCl3, 600 MHz): δ = 1.45 (s, 9H, BocHNCH2CHCH), 3.82 (br s, 2H, BocHNCH2CHCH), 4.60 (dd, J = 1.1, 5.4 Hz, 2H, CHCHCH2OAr), 5.82 – 5.93 (m, 2H, CHCHCH2OAr), 7.23 (ddd, J = 0.78, 2.6, 8.3 Hz, 1H, CHCHCH2OAr), 7.43 (t, J = 8.2 Hz, 1H, CHCHCH2OAr), 7.73 (t, J = 2.3 Hz, 1H, CHCHCH2OAr), 7.83 (ddd, J = 0.72, 2.2, 8.2 Hz, 1H, CHCHCH2OAr). 13C NMR (CDCl3, 150 MHz): δ = 159.2, 155.8, 149.4, 131.9, 130.1, 125.4, 121.9, 116.0, 109.2, 79.7, 68.6, 42.0, 28.5 (3). IR (neat, cm⁻¹): 3432, 3337, 2978, 1700, 1619, 1524, 1483, 1391, 1365, 1350, 1243, 1168, 1074, 1014. LRMS (m/z, EI+): Calcd. 308.1, found 293.1.

2.8 E vs Z Substrate Rate Consumption Determination

(E)-1-(hex-2-en-1-yloxy)-4-nitrobenzene(44 mg, .2mol) and (Z)-1-(hex-2-en-1-yloxy)-4-nitrobenzene(44 mg, .2mol) and bis(pinacolato) diboron(51 mg, .2mol) and cyclooctane (12 μL), as an internal standard, were dissolved in diethyl ether(1.5mL). NaOtBu(6 mg, .06 mol) was added to the reaction mix. And then the reaction mixture was cooled to -55°C and MeOH (18 μL) was added. After 5 minutes the 6-NHC copper catalyst (1.2 mg .02 mol), 4, was added. Reaction was then monitored by taking aliquots of the reaction mixture at set times and analyzing the sample by GC removing the solvent and then analyzing by HNMR. All measurement taken were normalized by the internal standard. Internal standard calibration curve can be viewed in supporting information part II figure S-3.
### GC Analysis

<table>
<thead>
<tr>
<th>Time (min)</th>
<th>Internal Standard (IS)</th>
<th>Product (P)</th>
<th>P/IS</th>
<th>Yield*</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>37</td>
<td>0</td>
<td>0.00</td>
<td>0</td>
</tr>
<tr>
<td>3</td>
<td>37</td>
<td>12.8</td>
<td>0.35</td>
<td>12</td>
</tr>
<tr>
<td>10</td>
<td>35.8</td>
<td>27.4</td>
<td>0.77</td>
<td>26</td>
</tr>
<tr>
<td>20</td>
<td>32.1</td>
<td>33.3</td>
<td>1.04</td>
<td>35</td>
</tr>
<tr>
<td>30</td>
<td>29.8</td>
<td>39.6</td>
<td>1.33</td>
<td>44</td>
</tr>
<tr>
<td>50</td>
<td>30.7</td>
<td>53</td>
<td>1.73</td>
<td>58</td>
</tr>
<tr>
<td>60</td>
<td>29</td>
<td>54</td>
<td>1.86</td>
<td>62</td>
</tr>
<tr>
<td>80</td>
<td>27.2</td>
<td>57.2</td>
<td>2.10</td>
<td>70</td>
</tr>
<tr>
<td>100</td>
<td>23.2</td>
<td>53.1</td>
<td>2.29</td>
<td>76</td>
</tr>
<tr>
<td>120</td>
<td>25</td>
<td>61.3</td>
<td>2.45</td>
<td>82</td>
</tr>
<tr>
<td>150</td>
<td>23.2</td>
<td>61</td>
<td>2.63</td>
<td>88</td>
</tr>
<tr>
<td>180</td>
<td>37.8</td>
<td>105</td>
<td>2.78</td>
<td>93</td>
</tr>
<tr>
<td>240</td>
<td>23.9</td>
<td>68.4</td>
<td>2.86</td>
<td>95</td>
</tr>
</tbody>
</table>

*Yield is based on a maximum value of P/IS = 3 value based on calibration curve
### HNMR Analysis

<table>
<thead>
<tr>
<th>Time</th>
<th>Z*</th>
<th>E*</th>
<th>E (%)**</th>
<th>Z (%)**</th>
<th>E (%)***</th>
<th>Z (%)***</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>21.16</td>
<td>19.29</td>
<td>0.52</td>
<td>0.48</td>
<td>0.99</td>
<td>0.90</td>
</tr>
<tr>
<td>10</td>
<td>11.41</td>
<td>9.30</td>
<td>0.55</td>
<td>0.45</td>
<td>0.96</td>
<td>0.78</td>
</tr>
<tr>
<td>20</td>
<td>8.70</td>
<td>6.57</td>
<td>0.57</td>
<td>0.43</td>
<td>0.94</td>
<td>0.71</td>
</tr>
<tr>
<td>30</td>
<td>6.04</td>
<td>4.25</td>
<td>0.59</td>
<td>0.41</td>
<td>0.91</td>
<td>0.64</td>
</tr>
<tr>
<td>50</td>
<td>5.74</td>
<td>3.47</td>
<td>0.62</td>
<td>0.38</td>
<td>0.89</td>
<td>0.54</td>
</tr>
<tr>
<td>60</td>
<td>4.34</td>
<td>2.51</td>
<td>0.63</td>
<td>0.37</td>
<td>0.87</td>
<td>0.50</td>
</tr>
<tr>
<td>80</td>
<td>3.62</td>
<td>1.88</td>
<td>0.66</td>
<td>0.34</td>
<td>0.86</td>
<td>0.44</td>
</tr>
<tr>
<td>100</td>
<td>3.50</td>
<td>1.78</td>
<td>0.66</td>
<td>0.34</td>
<td>0.82</td>
<td>0.42</td>
</tr>
<tr>
<td>120</td>
<td>3.95</td>
<td>1.78</td>
<td>0.69</td>
<td>0.31</td>
<td>0.81</td>
<td>0.37</td>
</tr>
<tr>
<td>150</td>
<td>3.22</td>
<td>1.33</td>
<td>0.71</td>
<td>0.29</td>
<td>0.80</td>
<td>0.33</td>
</tr>
<tr>
<td>180</td>
<td>2.88</td>
<td>1.09</td>
<td>0.72</td>
<td>0.28</td>
<td>0.78</td>
<td>0.30</td>
</tr>
<tr>
<td>240</td>
<td>3.01</td>
<td>1.03</td>
<td>0.75</td>
<td>0.25</td>
<td>0.78</td>
<td>0.27</td>
</tr>
</tbody>
</table>

*Assuming a 1:1 Ratio at time 0  
** Ratio of specific isomer (E or Z) over total area (E+Z)  
***Based on Formation of Product

#### 2.7 Typical reaction condition for allylic substitution reactions

Allylic ether (0.20 mmol) and bis(pinacolato) diboron (56 mg, 0.22 mmol) were dissolved in Et₂O or toluene (1 mL). NaOtBu (6 mg, 0.060 mmol) was added to the reaction mixture. And then the reaction mixture was cooled to resulting temperature and MeOH (18 µL, 0.4 mmol) was added. After 5 min, 6-NHC copper catalyst, 4 (1.1 mg, 0.0020 mmol) was added. After complete consumption of allylic ether, the reaction mixture was filtered through silica gel and washed with Et₂O. The filtrate was concentrated under rotary evaporator. The resulting residue was purified by column chromatography (Hexane : EtOAc = 20 : 1) to afford the desired products.

#### 2.9 Reaction results and data for allylic substitutions

Boronate Ester was prepared according to the general procedure from E and Z isomer substrates. From the E isomer: isolated as clear oil (90 % yield 93 % ee). From the Z isomer: isolated as a
clear oil (80 % yield 96 % ee). Ee was determined by GC analysis after oxidation and acetylation of the alcohol. $^1$H NMR (600 MHz, CDCl$_3$): δ 5.79 (ddd, J=17.1 Hz, 10.1 Hz, 8.8 Hz, 1H) 4.97 (ddd, J=17.1 Hz, 1.8 Hz, 1.2 Hz, 1H) 4.92 (ddd, J=10.1 Hz, 1.8 Hz, 0.7 Hz, 1H) 1.84 (q, J=7.8 Hz, 1H) 1.56-1.50 (m, 1H) 1.44-1.25 (m, 3H) 1.24 (s, 6H) 1.23 (s, 6H) 0.89 (t, J=7.3 Hz, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$): δ 140.0, 113.6, 83.3, 32.7, 24.94, 24.85, 22.3, 14.3 $[\alpha]D^{25} = +11.1^\circ$ (c=1.5, CH$_2$Cl$_2$, 96% ee) HRMS(EI) calcd for C$_{12}$H$_{23}$BO$_2$ 210.17912 found : 210.18004
1-cyclohexylprop-2-en-1-ol

Boronate Ester was prepared according to the general procedure. The boronate ester was oxidized to the alcohol and purified by column chromatography.

Isolated as clear oil (84% yield 99% ee) Ee was determined by GC analysis after acetylation of the alcohol. $^1$H NMR (600 MHz, CDCl$_3$) δ 5.86 (ddd, J = 6.5 Hz, 10.4 Hz, 17.0 Hz, 1H) 5.21 (dt, J = 1.4 Hz, J = 17.2 Hz, 1H) 5.15 (dt, J = 1.3 Hz, J = 10.4 Hz, 1H) 3.85 (t, J = 6.1 Hz, 1H) 1.85 (d, J = 12.7 Hz, 1H) 1.80-1.72 (m, 2H), 1.71-1.64 (m, 2H) 1.48-1.44 (br, 1H), 1.44-1.37 (m, 1H), 1.28-0.95 (m, 5H) $^{13}$C NMR (150 MHz, CDCl$_3$) δ 139.8, 115.5, 43.5, 28.8, 28.3, 26.5, 26.2, 26.1. HRMS (Cl+) calcd for C$_{15}$H$_{28}$BO$_2$ 251.2182 found : 251.2183.
4,4,5,5-tetramethyl-2-(1-phenylbut-3-en-2-yl)-1,3,2-dioxaborolane

Prepared according to the general procedure. Isolated as a clear oil 95 % yield 93 % ee. Ee was determined after oxidation to the alcohol. (1H NMR (600 MHz, CDCl₃) δ 7.26-7.20 (m, 4H), 7.16-7.13 (m, 1H), 5.84 (ddd, J=8.3 Hz, J=9.36 Hz, J=17.5 Hz, 1H) 5.00 (dt, J=1.4 Hz, J=17.2 Hz, 1H) 4.95 (dt, J=1.02 Hz, J=10.3 Hz, 1H) 2.89 (dd, J=8.5 Hz, J=13.7 Hz, 1H) 2.78 (dd, J=7.6 Hz, J=13.7 Hz, 1H) 2.2 (q, J=8.1 Hz, 1H) 1.17 (s, 6H) 1.15 (s, 6H) 13C NMR (150 MHz, CDCl₃) δ 141.6, 138.8, 128.9, 128.0, 125.7, 114.1, 83.3, 36.4, 24.6. HRMS(CI+) calcd for C₁₆H₂₄BO₂ 259.1869 found : 259.1867
methyl 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-5-enoate

Prepared according to general procedure. Isolated as a clear oil 88 % yield, 93 % ee. Ee was determined after oxidation to the alcohol. \(^1\)H NMR (600 MHz, CDCl\(_3\)) \(\delta\) 7.28-7.15 (m, 5H) 5.82 (ddd, J=8.1 Hz, J=10.2 Hz, J=18.6 Hz, 1H) 5.04-4.98 (m, 2H) 2.68-2.54 (m, 2H) 1.92-1.89 (m, 2H) 1.79-1.70 (m, 1H) 1.24 (s, 12H) \(^13\)C NMR (150 MHz, CDCl\(_3\)) \(\delta\) 142.7, 139.2, 128.5, 128.2, 125.6, 114.0, 83.2, 35.2, 24.7, 24.6
2-(1-(3-methoxyphenyl)but-3-en-2-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane

Prepared according to the general procedure. Isolated as a clear oil 87% yield 92% ee. Ee was determined after oxidation to the alcohol. $^1$H NMR (600 MHz, CDCl$_3$) δ 7.13 (d, J=8.6 Hz, 2H), 6.79 (d, J=8.6 Hz, 2H), 5.82 (ddd, J=8.3 Hz, J=9.4 Hz, J=17.8 Hz, 1H) 5.02 (dt, J=1.4 Hz, J=17.2 Hz, 1H) 4.94 (d, J=10.2 Hz, 1H) 3.77 (s, 3H) 2.83 (dd, J=8.5 Hz, J=13.3 Hz, 1H) 2.72 (dd, J=7.6 Hz, J=13.9 Hz, 1H) 2.19 (q, J=8.2 Hz, 1H) 1.17 (s, 6H) 1.15 (s, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$) δ 157.7, 138.8, 133.8, 129.8, 114.1, 113.5, 83.3, 55.2, 35.5, 24.7, 24.6. HRMS(CI+) calcd for C$_{17}$H$_{26}$BO$_3$ 289.1975 found : 289.1971
5-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hept-6-en-2-one

Prepared according to the general procedure. Isolated as a clear oil 50 % yield, 94 % ee. Ee was determined by GC analysis after oxidation and acetylation of the alcohol. $^1$H NMR (600 MHz, CDCl$_3$) δ 5.74 (ddd, J=8.6 Hz, J=10.2 Hz, 17.2 Hz, 1H) 5.01-4.97 (m, 2H) 2.50-2.38 (m, 2H) 2.13 (s, 3H) 1.87-1.68 (m, 3H) 1.24 (s, 12H) $^{13}$C NMR (150 MHz, CDCl$_3$) δ 209.1, 138.7, 114.4, 83.3, 42.9, 29.9, 24.7, 24.6, 24.0. HRMS(CI+) calcd for C$_{13}$H$_{24}$BO$_3$ 239.18186 found : 239.18199.
methyl 4-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)hex-5-enoate

Prepared according to the general procedure. Isolated as a clear oil 83 % yield, 93 % ee. Ee was determined by GC analysis after oxidation and acetylation of the alcohol. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 5.78-5.72 (m, 1H) 5.02-4.98 (m, 2H) 3.66 (s, 3H) 2.39-2.34 (m, 1H) 2.33-2.28 (m, 1H) 1.93-1.87 (m, 1H) 1.83-1.73 (m, 2H) 1.24 (s, 12H). $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 174.1, 138.4, 114.6, 83.3, 51.4, 33.3, 25.2, 24.7, 24.6. HRMS(CI+) calcd for C$_{13}$H$_{24}$BO$_4$ 255.1768 found : 255.1772
tert-butyldimethyl(2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-3-en-1-yl)oxy)silane

Prepared according to the general procedure with both the $E$ and $Z$ alkene isomers. Isolated from the predominately cis isomer as a clear oil 91 % yield, 93 % ee. Isolated from the predominately trans isomer as a clear oil 83% yield, 93 % ee. Ee was determined by GC analysis after oxidation to the alcohol. $^1$H NMR (600 MHz, CDCl$_3$) δ 5.82 (ddd, $J=8.6$ Hz, $J=10.2$ Hz, 17.3 Hz, 1H) 5.04 (dt, $J=1.6$ Hz, $J=16.9$ Hz, 1H) 4.99 (dd, $J=1.56$ Hz, $J=10.4$ Hz, 1 H) 3.78-3.72 (m, 2H) 2.12 (q, $J=7.4$ Hz, 1H) 1.24 (s, 12H) .88 (s, 9H) .04 (s, 6H) $^{13}$C NMR (150 MHz, CDCl$_3$) δ 136.6, 115.0, 83.2, 64.3, 25.9, 24.7, 18.3, -5.4
tert-butyl (2-(4,4,5,5-tetramethyl-1,3,2-dioxaborolan-2-yl)but-3-en-1-yl)carbamate

Prepared according to the general procedure. The boronate ester was oxidized to the alcohol and purified by column chromatography. Isolated as a clear oil 92% yield 90% ee. Ee was determined by GC analysis after oxidation to the alcohol. $^1$H NMR (600 MHz, CDCl₃) δ 5.86 (ddd, J=5.5 Hz, J=10.5 Hz, J=17.1 Hz 1H) 5.34 (dt, J=1.4 Hz, J=17.2, 1H) 5.20 (d, J=10.6, 1H) 5.03-4.90 (br, 1H) 4.29-4.20 (br, 1H) 3.43-3.32 (br, 1H) 3.12-3.07 (m, 1H) 2.72-2.66 (br, 1H) 1.45 (s, 9H) $^{13}$C NMR (150 MHz, CDCl₃) δ 156.8, 138.0, 116.2, 79.7, 72.4, 46.3, 28.3
2-(6-bromohex-1-en-3-yl)-4,4,5,5-tetramethyl-1,3,2-dioxaborolane

Prepared according to the general procedure. Isolated as a clear oil 92 % yield. Ee was determined by GC analysis after oxidation and acetylation of the alcohol 92 % ee. $^1$H NMR (600 MHz, CDCl$_3$) $\delta$ 5.76 (ddd, J=8.7 Hz, J=10.1, J=17.1 Hz, 1H) 5.02-4.96 (m, 2H) 3.40 (td, J=2.6 Hz, J=8.0 Hz, 2H) 1.96-1.88 (m, 1H) 1.88-1.80 (m, 2H) 1.73-1.65 (m, 1H) 1.60-1.53 (m, 1H) 1.25 (s, 12H) $^13$C NMR (150 MHz, CDCl$_3$) $\delta$ 138.8, 114.2, 83.3, 33.7, 32.2, 28.7, 24.7, 24.6. HRMS(CI+) calcd for C$_{12}$H$_{23}$BO$_2$Br 289.0974 found : 289.0968.
Testing the Reactivity of the Tri-substituted Alkene versus the Di-substituted Alkene

3,3’-(((2E,6E)-3-methylocta-2,6-diene-1,8-diyl)bis(oxy))bis(nitrobenzene)

$^1$H NMR (600 MHz, CDCl$_3$) $\delta$: 7.81 (d, J=8.7 Hz, 2H), 7.72 (t, J=2.4 Hz, 2H), 7.41 (t, J=9.2 Hz, 2H), 7.22 (td, J=2.5 Hz, J=8.2 Hz, 2H), 5.90-5.82 (m, 1H), 5.74-5.67 (m, 1H), 4.61 (d, J=6.8 Hz, 2H), 4.53 (d, J=6.2, 2H), 2.28 (q, J=7.2 Hz, 2H) 2.20 (t, J=7.0 Hz, 2H), 1.78 (s, 3H) $^{13}$C NMR (150 MHz, CDCl$_3$) $\delta$ 159.3, 159.1, 149.2, 141.3, 135.3, 129.8, 124.4, 122.1, 122.0, 109.0, 108.9, 69.2, 65.4, 38.7, 30.3, 16.7
Allylic ether (19 mg, 0.048 mmol) and bis(pinacolato) diboron (12 mg, 0.053 mmol) was dissolved in Et₂O (1 mL). NaOtBu (1.5 mg, 0.015 mmol) was added to the reaction mixture. And then the reaction mixture was cooled to -55° C and MeOH (5 μL, 0.1 mmol) was added. After 5 min, 6-NHC copper catalyst, 4 (.3 mg, 0.000480 mmol) was added. The reaction was quenched after 18 hours. Solvent was evaporated in vacuo and ¹H NMR spectra was taken of the crude mixture.
Appendix B References:


Bibliography


13. Addition Reactions of Bis(pinacolato) diborance(4) to Carbonyl Enones and Synthesis of (pinacolato)₂BCH₂B and (pinacolato)₂BCH₂CH₂B by Insertation and Coupling. Ali, Hijazi Abu,


Biographical Sketch

Hershel Lackey was born and raised in central and western North Carolina. He attended Virginia Military Institute from 2003-2007 and graduated with a B.S. degree in chemistry. Upon graduation he commissioned into the United States Air Force where he was stationed at Tyndall AFB, Fl serving in the Air Force Research Labs. In 2008 he was selected by the Air Force Institute of Technology to obtain an advanced degree in chemistry. In 2009 he joined FSU chemistry department and has since been working toward obtaining his masters degree in organic chemistry. His next assignment, winter 2010, will be at the Air Force Technical Application Center at Patrick AFB, Fl.