JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Subscriber access provided by University of Newcastle, Australia

Communication

Benzyltriboronates: Building Blocks for Diastereoselective Carbon-Carbon Bond Formation

W. Neil Palmer, Cayetana Zarate, and Paul J. Chirik

J. Am. Chem. Soc., **Just Accepted Manuscript** • DOI: 10.1021/jacs.6b12896 • Publication Date (Web): 03 Feb 2017

Downloaded from http://pubs.acs.org on February 3, 2017

Just Accepted

"Just Accepted" manuscripts have been peer-reviewed and accepted for publication. They are posted online prior to technical editing, formatting for publication and author proofing. The American Chemical Society provides "Just Accepted" as a free service to the research community to expedite the dissemination of scientific material as soon as possible after acceptance. "Just Accepted" manuscripts appear in full in PDF format accompanied by an HTML abstract. "Just Accepted" manuscripts have been fully peer reviewed, but should not be considered the official version of record. They are accessible to all readers and citable by the Digital Object Identifier (DOI®). "Just Accepted" is an optional service offered to authors. Therefore, the "Just Accepted" Web site may not include all articles that will be published in the journal. After a manuscript is technically edited and formatted, it will be removed from the "Just Accepted" Web site and published as an ASAP article. Note that technical editing may introduce minor changes to the manuscript text and/or graphics which could affect content, and all legal disclaimers and ethical guidelines that apply to the journal pertain. ACS cannot be held responsible for errors or consequences arising from the use of information contained in these "Just Accepted" manuscripts.

ACS Publications

Journal of the American Chemical Society is published by the American Chemical Society. 1155 Sixteenth Street N.W., Washington, DC 20036

Published by American Chemical Society. Copyright © American Chemical Society. However, no copyright claim is made to original U.S. Government works, or works produced by employees of any Commonwealth realm Crown government in the course of their duties.

Benzyltriboronates: Building Blocks for Diastereoselective Carbon-Carbon Bond Formation

W. Neil Palmer, Cayetana Zarate, Paul J. Chirik*

Department of Chemistry, Princeton University, Princeton, New Jersey 08544, U. S. A

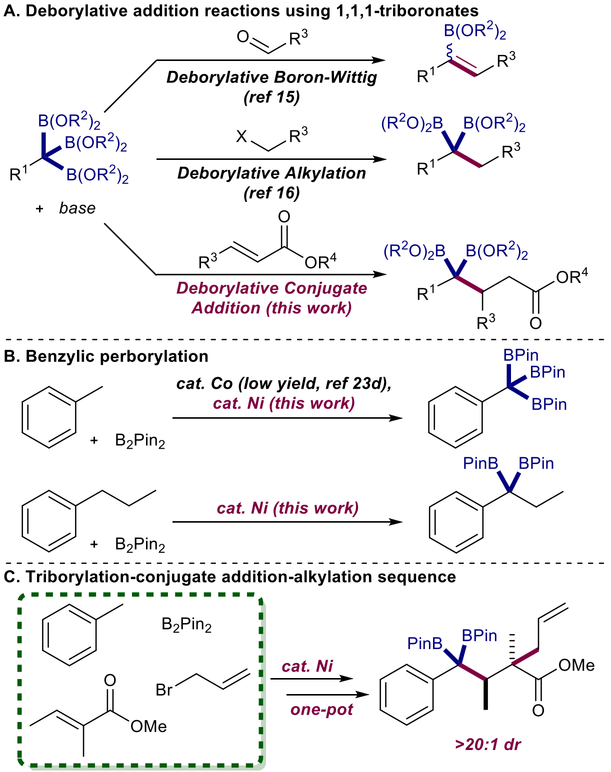
Supporting Information Placeholder

ABSTRACT: A highly diastereoselective carbon-carbon bond forming reaction involving the tandem coupling of benzyltriboronates, enoates and alkyl halides is described. This method was enabled by the discovery of α-diimine nickel catalysts that promote the chemoselective triborylation of benzylic C(sp^3)–H bonds using B_2Pin_2 (Pin = pinacolate). The C-H functionalization method is effective with methylarenes and for the diborylation of secondary benzylic C-H bonds, providing direct access to polyboron building blocks from readily available hydrocarbons. Combination of the benzylic perborylation and conjugate addition-alkylation methods enables a one-pot procedure in which multiple simple precursors are combined to generate diastereopure products containing quaternary stereocenters.

Organoboron compounds are versatile reagents for carbon-carbon and carbon-heteroatom bond formation.[1] Arylboronates are the most widely used nucleophilic partner in Suzuki-Miyaura cross couplings[2,3] and most commonly deployed in the pharamaceutical industry due to their ease of handling, synthetic accessibility and reliability.[4] Alkylboronates, typically synthesized by alkene hydroboration[5] or Miyaura-type borylation of alkyl halides,[6] are likewise valuable reagents for C-C bond formation whose utility will continue to grow as methods for C(sp^3)-C(sp^3) cross coupling mature.[7] Polyboron compounds such as *gem*-diboronates are beginning to emerge as useful reagents for C-C bond formation as well and have been applied to alkylation reactions,[8] boron-Wittig olefinations,[9] 1,2-additions to carbonyls[10] and imines,[11] addition to pyridine-*N*-oxides,[12] allylic substitution,[13] and enantioselective cross couplings.[14] The use of 1,1,1-alkyltriboronates for C–C bond formation offers similar, if not greater, potential but is less explored and limited to deborylative boron-Wittig olefination[15] or deborylative alkylation (Scheme 1A).[16]

The full synthetic potential of geminal alkylpolyboronates has yet to be realized principally due to the paucity of straightforward methods for their preparation. The direct, metal-catalyzed polyborylation of C(sp^3)–H bonds offers a potentially transformative route as readily available, minimally functionalized hydrocarbons may be used as starting materials. Although C-H borylation is one of the most widely used C-H functionalization methods, most precious[17] and base metal catalysts[18] favor C(sp^2)-H sites, a result of established kinetic preference for oxidative addition.[19] Metal-catalyzed methods for alkane borylation have been reported[17,20] including recent notable examples of iridium- and rhodium-catalyzed borylation of methane at high pressures,[21] but chemoselective C(sp^3)–H borylation *in the presence of* C(sp^2)–H bonds is far less common and more challenging. Strategies to overcome this selectivity bias rely primarily on the use of directing groups,[22] while a handful of non-directed methods selectively functionalize benzylic C–H bonds.[23] In most of these examples, only one C-H bond is converted to a C-B bond.[24] New catalytic methods that convert multiple C-H bonds on the same carbon to boron functional groups would be valuable and enable exploration of the full synthetic potential of alkyl polyboronates.

Scheme 1. Utility of alkyltriboronates in C–C bond-formation, synthesis of benzylpolyboronates by C–H borylation, and combination of these methods to provide a diastereoselective tandem coupling sequence.



Our laboratory previously reported α-diimine cobalt dialkyl and bis(carboxylate) compounds that are active for the catalytic borylation of C(sp^3)-H bonds of methylarenes with B_2Pin_2 as the boron source.[23d] The 1,1-diboronates were the major products but, with toluene as the substrate, a small amount (18% yield) of the 1,1,1-triboronate product was isolated when excess boron reagent and high cobalt loadings of 50 mol% were used. The forcing conditions, low yield and difficulty in isolation precluded reactivity studies of this interesting benzylpolyboronate and inspired development of a synthetically useful catalytic method. Here we describe α-diimine nickel dialkyl and bis(carboxylate) complexes that enable the selective preparation of benzyltriboronates via perborylation of benzylic C–H bonds (Scheme 1B). Combination of the Ni-catalyzed perborylation method with a new deborylative conjugate addition protocol (Scheme 1A) provides a convenient one-pot, tandem procedure for the diastereoselective synthesis of value-added products from simple, abundant precursors (Scheme 1C).

Inspired by the observation of benzylboronate products by Tobisu, Chatani and coworkers in Ni-catalysis[18f] and our own success with N-alkyl substituted α-diimine (^{R}ADI) cobalt dialkyl complexes,[23d] the analogous Ni(II) dialkyl complexes were targeted for evaluation in catalytic C–H borylation. $(^{Cy}ADI)Ni(CH_2SiMe_3)_2$ (**1**) was isolated as a teal, diamagnetic solid in 79% yield following pyridine displacement by addition of the free α-diimine to $(py)_2Ni(CH_2SiMe_3)_2$ (py = pyridine).[25] The solid-state structure of **1** established a distorted square planar geometry (See SI, Figure S2). Because both cobalt and nickel bis(carboxylate) compounds have proven to be readily synthesized, bench stable precursors for a host of catalytic reactions,[18e,23d,26] $(^{Cy}ADI)Ni(OPiv)_2$ (**2**) (Piv = pivaloyl) was also prepared by addition of the free α-diimine to a well-defined Ni(II) pivalate precursor, $[(NEt_3)Ni(OPiv)_2]_2$, a compound first reported by Eremenko and coworkers.[27]

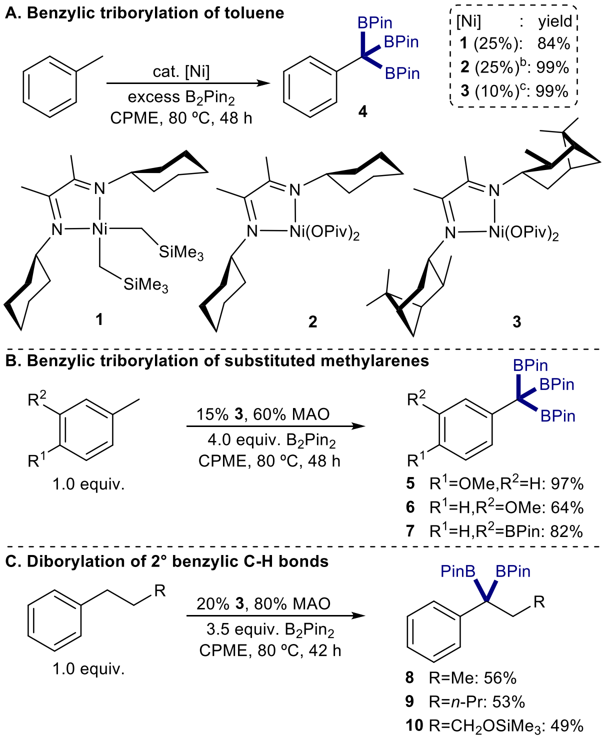
With excess (4.0 equiv) B_2Pin_2 and 25 mol% of **1**, the catalytic borylation of toluene in cyclopentylmethyl ether (CPME) at 80 °C resulted in isolation of the benzyltriboronate **4** in 84% yield (Scheme 2A). Repeating this procedure with 25 mol% of **2** in combination with 100 mol% of methylaluminoxane (MAO) activator provided a quantitative yield of **4**. Notably, the yields of **4** using **1** and **2** were significantly higher with lower pre-catalyst loadings and temperatures than with cobalt, highlighting the advantage of the nickel-catalyzed method.

Nickel sources, α-diimine ligands and catalytic conditions were evaluated to lower the amount of Ni required (See SI, Table S1). Because formation of bis(chelate) nickel complexes was believed to be a deactivation pathway (See SI, Scheme S1), the nickel bis(pivalate) complex bearing a bulkier diimine ligand was synthesized. Pale green $(^{ipc}ADI)Ni(OPiv)_2$ (**3**, Scheme 2A) was isolated in 89% yield and was active for the triborylation of toluene. With only 10 mol% of **3** in combination with 40 mol% MAO, quantitative formation of **4** was obtained. This reaction was also successfully scaled; starting with 2.17 mmol of toluene, 1.00 g (99% yield) of **4** was isolated.

With the improved performance of **3**, the generality of benzylic triborylation was examined with a series of methylarenes (Scheme 2B). High yields of the benzyltriboronate products derived from 3-methylanisole, 4-methylanisole, and *m*-tolylboronic acid pinacol ester were obtained. Although these products were isolated following acidic aqueous workup with no additional purification, the benzyltriboronates underwent protodeborylation to mono- or diboronates upon prolonged exposure to aqueous conditions or by attempted purification by column chromatography. Extended exposure to air also resulted in decomposition, likely by autoxidation.

The polyborylation of the benzylic positions of linear alkyl arenes was also explored with **3**. C(sp^3)-H borylation of this substrate class has only been achieved previously using silyl directing groups[22d] or vast excess of substrate and long reaction times.[23b,e] Using 20 mol% of **3** and excess (3.5 equiv) B_2Pin_2, the benzylic diborylation of *n*-propylbenzene, *n*-pentylbenzene, and trimethylsilyl-protected 3-phenylpropanol was accomplished to afford **8**, **9**, and **10**, respectively (Scheme 2C). Precatalyst **3** was also effective for the synthesis of benzyl *di*boronates from methylarenes (See SI, Scheme S2) at superior yields and lower catalyst loadings than previously reported with cobalt.[23d]

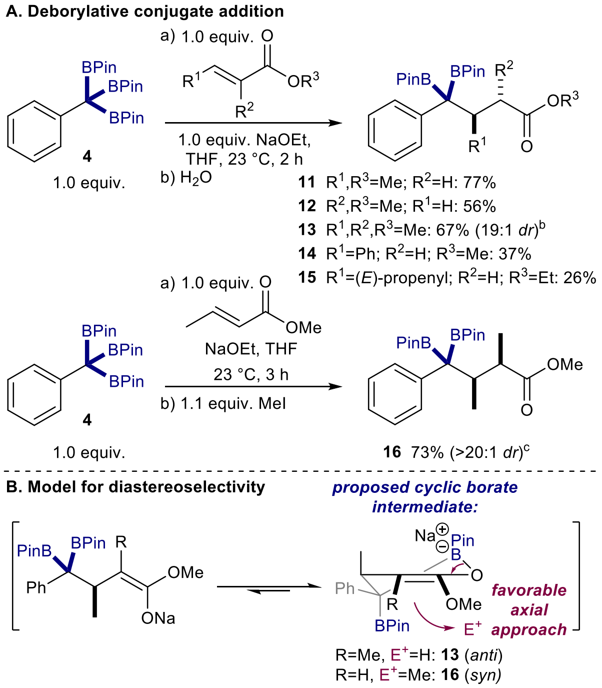
Scheme 2. Benzylic perborylation of substituted methylarenes and linear alkylarenes using α-diimine nickel dialkyl and bis(pivalate) precatalysts.[a]



[a] Isolated yields. Reactions conducted with 0.55 mmol methylarene or alkylarene in 0.55 mL of CPME at 80 ºC. See SI for experimental details. [b] 100 mol% MAO as catalyst activator. **4** was isolated with 13% impurity of remaining B_2Pin_2. [c] 40 mol% MAO activator used.

The development of a direct method for the preparation of 1,1,1-alkyltriboronates from C(sp^3)-H functionalization offers a new opportunity to explore the utility of these products in C–C bond forming reactions. Known deborylative boron-Wittig olefination[15] and deborylative alkylation[16] protocols were demonstrated (See SI, Scheme S3). Further efforts focused on development of new C-C bond forming transformations. Conjugate addition of α-boryl nucleophiles to unsaturated carbonyls has previously been reported for α-boryl radicals[28] and α-boryl-zirconocenes.[29] Benzylic α-diboryl anions were postulated to be sufficiently soft nucleophiles to exhibit similar reactivity. To test this, a THF solution of **4** and (*E*)-methylcrotonate was treated with NaOEt at room temperature, providing **11** (Scheme 3A) in 77% yield following aqueous workup. Repeating this procedure with methyl methacrylate and methyl tiglate provided **12** and **13**, respectively, in good yield and, in the case of **13**, excellent diastereoselectivity (19:1). Notably, products resulting from the deborylative conjugate addition to phenyl-substituted (*E*)-methyl cinnamate (**14**) and the α,β,γ,δ-unsaturated ethyl sorbate (**15**) were also obtained, albeit at reduced yields predominantly due to competing 1,2-addition to the more electron deficient enoates.

Scheme 3. Base-mediated deborylative conjugate addition using isolated benzyltriboronate 4.[a]



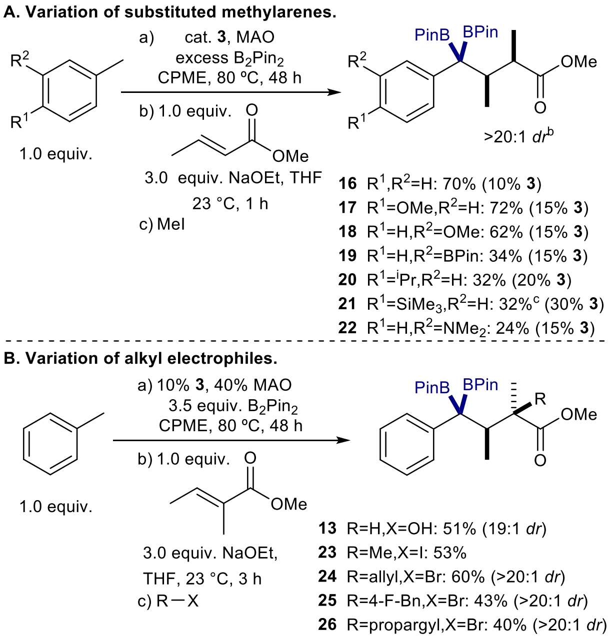
[a] Isolated yields. Reactions conducted with 0.28 mmol of benzyltriboronate in 5.6 mL THF. See SI for experimental details. Diastereomeric ratios determined by gas chromatography of crude reaction mixtures and confirmed by ^{1}H NMR spectroscopy of isolated products. [b] Major diastereomer **13** assigned as opposite of that assigned for **16** (minor diastereomer). [c] Diastereomer of **16** determined by X-ray crystallography (see SI, Figure S4).

Given that the intermediate in the deborylative conjugate addition of **4** to methyl tiglate proceeds through a sodium enolate, the stereocontrol at the α-position of the ester in **13** likely occurs during protonation when the reaction is quenched. Intramolecular coordination of the enolate to a boronate substituent and subsequent axial approach of an electrophile was hypothesized to explain this phenomenon (Scheme 3B).[30] To test this, the deborylative conjugate addition of **4** and (*E*)-methylcrotonate was carried out and the reaction was quenched with iodomethane (Scheme 3A). The resulting product, **16**, was isolated in >20:1 *dr* as the *syn* diastereomer opposite that of **13**, consistent with the stereochemical model. These results highlight the unique ability of the boronate groups to act not only as masking groups for soft nucleophilic anions but also elements for substrate-controlled diastereoselectivity.

The possibility of generating these benzyltriboronates *in-situ* and directly applying them toward further chemistry was also investigated. This would not only obviate the need for difficult isolation of these sensitive reagents, but it would provide a convenient one-pot method for rapidly building molecular complexity directly from toluene or other simple substituted methylarenes. The synthesis of **16** was conducted directly from toluene, B_2Pin_2, (*E*)-methylcrotonate, and iodomethane without isolating **4** (Scheme 4A). Following the Ni-catalyzed triborylation of toluene, the crude triboronate product was exposed to the conjugate addition-alkylation conditions to provide **16** in 70% yield and >20:1 *dr*. The method was then successfully extended to other substituted methylarenes. Generation of **5**, **6**, and **7** *in-situ* followed by conjugate-addition and alkylation yielded products **17**, **18**, and **19**, respectively, in good to modest yields with high diastereoselectivity (>20:1). The one-pot procedure was also applied using *p*-cymene, 4-tolyltrimethylsilane, and *N,N*-dimethyl-*m*-toluidine resulting in isolation of **20**, **21**, and **22**, respectively, following column chromatography without the need for purification of the 1,1,1-triboronate intermediates.

The scope of the alkyl electrophile was also explored. Using toluene, B_2Pin_2, methyltiglate, and quenching with water, **13** was isolated (19:1 *dr*) in 51% yield (Scheme 4B). Quenching the reaction with iodomethane provided the methylated product **23** in 53% yield. Further variation of the alkyl electrophile might provide access to diastereomerically enriched products with quaternary stereocenters. This was successfully demonstrated using allylbromide, 4-fluorobenzylbromide, and propargylbromide to give products **24**, **25**, and **26**, respectively, with high degrees (>20:1) of diastereoselectivity. The solid state structure of **25** was confirmed by X-ray crystallography (See SI, Figure S5), verifying the identity of the isolated diastereomer as that predicted by the stereochemical model in Scheme 3B and allowing for assignment of the diastereomers of **24** and **26** by analogy.

Scheme 4. Diastereoselective, one-pot tandem triborylation-conjugate addition-alkylation.[a]



[a] Isolated yields. See SI for experimental details. Diastereomeric ratios determined by gas chromatography of crude reaction mixtures and confirmed by ^{1}H NMR spectroscopy of isolated products. [b] Diastereomers assigned by analogy to that of **16**. [c] NMR yield; 22% isolated yield.

In summary, an α-diimine nickel catalyst has been developed that is effective for the perborylation of benzylic C(sp^3)–H bonds of methyl- and alkylarenes. The unique products are useful building blocks for a diastereoselective conjugate addition-alkylation sequence, highlighting the ability of the multiple boronate groups to act simultaneously as soft carbanion masking groups and intramolecular stereocontrol elements. Combination of the C(sp^3)–H polyborylation with deborylative C–C bond-formation into a one-pot procedure allowed an effective method for rapid elaboration of simple and abundant precursors to complex products poised for further elaboration with remaining C–B bond functionality.[31]

ASSOCIATED CONTENT

Supporting Information

Complete experimental details, pre-catalyst optimization studies, and characterization data of nickel complexes and of boronate products. This material is available free of charge via the Internet at http://pubs.acs.org.

AUTHOR INFORMATION

Corresponding Author

pchirik@princeton.edu

Notes

The authors declare no competing financial interests.

ACKNOWLEDGMENT

WNP acknowledges the National Science Foundation (CHE-1265988) and the 2016 Eli Lilly Graduate Research Fellowship Award for financial support. CZ acknowledges MINECO for a FPU fellowship. We thank M. J. Bezdek and I. Pappas for crystallographic studies, and we also thank Allychem for a generous gift of B_2Pin_2.

REFERENCES

(1) Hall, D. G. Boronic Acids; Wiley-VCH: Weinheim, 2005.

(2) Miyaura, N.; Suzuki, A. *Chem. Rev.* **1995**, *95*, 2457.

(3) Lennox, A. J. J.; Lloyd-Jones, G. *Chem. Soc. Rev.* **2014**, *43*, 412.

(4) Roughley, S. D.; Jordan, A. M. *J. Med. Chem.* **2011**, *54*, 3451.

(5) (a) Burgess, K.; Ohlmeyer, M. J. *Chem. Rev.* **1991**, *91*, 1179. (b) Beletskaya, I.; Pelter, A. *Tetrahedron* **1997**, *53*, 4957. (c) Crudden, C. M.; Edwards, D. *Eur. J. Org. Chem.* **2003**, *24*, 4695.

(6) (a) Yang, C.-T.; Zhang, Z.-Q.; Tajuddin, H.; Wu, C.-C.; Liang, J.; Liu, J.-H.; Fu, Y.; Czyzewska, M.; Steel, P. G.; Marder, T. B. Liu, L. *Angew. Chem. Int. Ed.* **2012**, *51*, 528. (b) Ito, H.; Kubota, K. *Org. Lett.* **2012**, *14*, 890.

(7) (a) Jana, R.; Pathak, T. P.; Sigman, M. S. *Chem. Rev.* **2011**, *111*, 1417. (b) Leonori, D.; Aggarwal, V. K. *Angew. Chem. Int. Ed.* **2014**, *54*, 1082.

(8) Hong, K.; Liu, X.; Morken, J. P. *J. Am. Chem. Soc.* **2014**, *136*, 10581.

(9) (a) Endo, K.; Hirokami, M.; Shibata, T. *J. Org. Chem.* **2010**, *75*, 3469. (b) Coombs, J. R.; Zhang, L.; Morken, J. P. *Org. Lett.* **2015**, *17*, 1708.

(10) (a) Joannou, M. V.; Moyer, B. S.; Meek, S. J. *J. Am. Chem. Soc.* **2015**, *137*, 6176. (b) Joannou, M. V.; Moyer, B. S.; Goldfogel, M. J.; Meek, S. J. *Angew. Chem. Int. Ed.* **2015**, *54*, 14141. (c) Murray, S. A.; Green, J. C.; Tailor, S. B.; Meek, S. J. *Angew. Chem. Int. Ed.* **2016**, *55*, 9065.

(11) Park, J.; Lee, Y.; Kim, J.; Cho, S. H. *Org. Lett.* **2016**, *18*, 1210.

(12) Jo, W.; Kim, J.; Choi, S.; Cho, S. H. *Angew. Chem. Int. Ed.* **2016**, *55*, 9690.

(13) (a) Zhan, M.; Li, R.-Z.; Mou, Z.-D.; Cao, C.-G.; Liu, J.; Chen, Y.-W.; Niu, D. *ACS Catal.* **2016**, *6*, 3381. (b) Kim, J.; Park, S.; Park, J.; Cho, S. H. *Angew. Chem. Int. Ed.* **2016**, *55*, 1498. (c) Shi, Y.; Hoveyda, A. H. *Angew. Chem. Int. Ed.* **2016**, *55*, 3455.

(14) (a) Sun, C.; Potter, B.; Morken, J. P. *J. Am. Chem. Soc.* **2014**, *136*, 6534. (b) Potter, B.; Szymaniak, A. A.; Edelstein, E. K.; Morken, J. P. *J. Am. Chem. Soc.* **2014**, *136*, 17918.

(15) (a) Matteson, D. S.; Moody, R. J.; Jesthi, P. K. *J. Am. Chem. Soc.* **1975**, *97*, 5608. (b) Matteson, D. S.; Moody, R. J. *J. Org. Chem.* **1980**, *45*, 1091.

(16) (a) Matteson, D. S.; Thomas, J. R. *J. Organomet. Chem.* **1970**, *24*, 263. (b) Zhang, L.; Huang, Z. *J. Am. Chem. Soc.* **2015**, *137*, 15600.

(17) Mkhalid, I. A. I.; Barnard, J. H.; Marder, T. B.; Murphy, J. M.; Hartwig, J. F. *Chem. Rev.* **2010**, *110*, 890.

(18) (a) Dombray, T.; Werncke, C. G.; Jiang, S.; Grellier, M.; Vendier, L.; Bontemps, S.; Sortais, J.-B.; Sabo-Etienne, S.; Darcel, C. *J. Am. Chem. Soc.* **2015**, *137*, 4062. (b) Obligacion, J. V.; Semproni, S.; Chirik, P. J. *J. Am. Chem. Soc.* **2014**, *136*, 4133. (c) Schaefer, B. A.; Margulieux, G. W.; Small, B. L.; Chirik, P. J. *Organometallics* **2015**, *34*, 1307. (d) Obligacion, J. C.; Semproni, S. P.; Pappas, I.; Chirik, P. J. *J. Am. Chem. Soc.* **2016**, *138*, 10645. (e) Léonard, N. G.; Bezdek, M. J.; Chirik, P. J. *Organometallics* **2017**, *36*, 142. (f) Furukawa, T.; Tobisu, M.; Chatani, N.; *Chem. Commun.* **2015**, *51*, 6508.

(19) Jones, W. D.; Feher, F. J. *Acc. Chem. Res.* **1989**, *22*, 91.

(20) Chen, H.; Schlecht, S.; Semple, T. C.; Hartwig, J. F. *Science* **2000**, *287*, 1995.

(21) (a) Cook, A. K.; Schimer, S. D.; Matzger, A. J.; Sanford, M. S. *Science* **2016**, *351*, 1421. (b) Smith, K. T.; Berritt, S.; González-Moreiras, M.; Ahn, S.; Smith, M. R.; Baik, M.H.; Mindiola, D. J. *Science* **2016**, *351*, 1424.

(22) (a) Kawamorita, S.; Miyazaki, T.; Iwai, T.; Ohmiya, H.; Sawamura, M. *J. Am. Chem. Soc.* **2012**, *134*, 12924. (b) Kawamorita, S.; Murakami, R.; Iwai, T.; Sawamura, M. *J. Am. Chem. Soc.* **2013**, *135*, 2947. (c) Mita, T.; Ikeda, Y.; Michigami, K.; Sato, Y. *Chem. Commun.* **2013**, *49*, 5601. (d) Cho, S. H.; Hartwig, J. F. *J. Am. Chem. Soc.* **2013**, *135*, 8157. (e) Cho, S. H.; Hartwig, J. F. *Chem. Sci.* **2014**, *5*, 694.

(23) (a) Shimada, S.; Batsanov, A. S.; Howard, J. A. K.; Marder, T. B. *Angew. Chem. Int. Ed.* **2001**, *40*, 2168. (b) Ishiyama, T.; Ishida, K.; Takagi, J.; Miyaura, N. *Chem. Lett.* **2001**, *30*, 1082. (c) Larsen, M. A.; Wilson, C. V.; Hartwig, J. F. *J. Am. Chem. Soc.* **2015**, *137*, 8633. (d) Palmer, W. N.; Obligacion, J. V.; Pappas, I.; Chirik, P. J. *J. Am. Chem. Soc.* **2016**, *138*, 766. (e) Manna, K.; Ji, P.; Lin, Z.; Greene, F. X.; Urban, A.; Thacker, N. C.; Lin, W. *Nat. Commun.* **2016**, *7*, 12610.

(24) For examples of general methods for C(sp^3)–H polyborylation, see references 22c and 22e (*directed*) or 23d (*non-directed*).

(25) Carmona, E.; González, F.; Poveda, M. L.; Atwood, J. L.; Rogers, R. D. *J. Chem. Soc., Dalton Trans.* **1981**, 777.

(26) (a) Scheuermann, M. L.; Johnson, E. J.; Chirik, P. J. *Org. Lett.* **2015**, *17*, 2716. (b) Noda, D.; Tahara, A.; Sunada, Y.; Nagashima, H. *J. Am. Chem. Soc.* **2016**, *138*, 2480. (c) Schuster, C. H.; Diao, T.; Pappas, I.; Chirik, P. J. *ACS Catal.* **2016**, *6*, 2632. (d) Pappas, I.; Treacy, S.; Chirik, P. J. *ACS Catal.* **2016**, *6*, 4105.

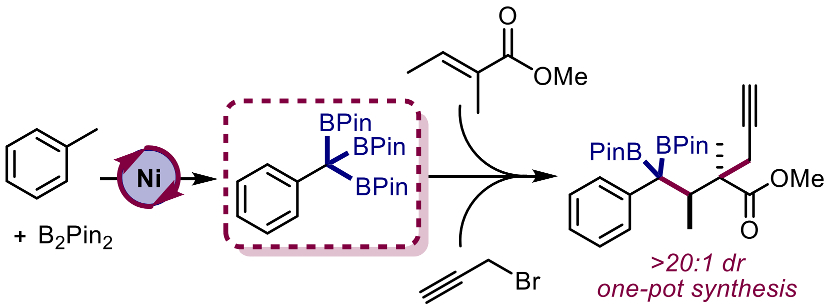
(27) Eremenko, I. L.; Nefedov, S. E.; Sidorov, A. A.; Golubnichaya, M. A.; Danilov, P. V.; Ikorskii, V. N.; Shvedendov, Y. G.; Novotortsev, V. M.; Moiseev, I. I. *Inorg. Chem.* **1999**, *38*, 3764.

(28) Batey, R. A.; Pedram, B.; Yong, K.; Baquer, G. *Tetrahedron Lett.* **1996**, *37*, 6847.

(29) Pereira, S.; Srebnik, M. *Tetrahedron Lett.* **1995**, *36*, 1805.

(30) (a) Molander, G. A.; Bobbitt, K. L.; Murray, C. K. *J. Am. Chem. Soc.* **1992**, *114*, 2759. (b) Curtis, A. D. M.; Mears, R. J.; Whiting, A. *Tetrahedron* **1993**, *49*, 187.

(31) The geminal diboronate functionality in the conjugate addition products in Schemes 3 and 4 can likely be further elaborated using the methods described in references 8-14.



Diastereoselective, tandem coupling using simple precursors