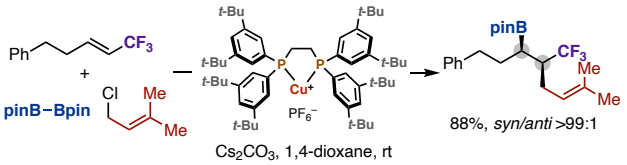
Ligand-Enabled Copper-Catalyzed Regio- and Stereoselective Allylboration of 1-Trifluoromethylalkenes

Yuki Kojima,† Yuji Nishii,† and Koji Hirano*,†,‡

†Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan

‡Innovative Catalysis Science Division, Institute for Open and Transdisciplinary Research Initiatives (ICS-OTRI), Osaka University, Suita, Osaka 565-0871, Japan

Supporting Information Placeholder

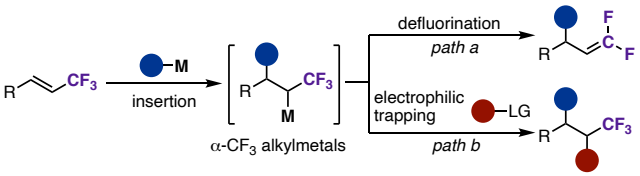


ABSTRACT: A copper-catalyzed regio- and stereoselective allylboration of 1-trifluoromethylalkenes with bis(pinacolato)diboron (pinB–Bpin) and allylic chlorides has been developed to form functionalized trifluoromethylated products with high diastereoselectivity. The key to success is the judicious choice of Cs_2CO_3 base and *t*-Bu-modified dppe-type ligand, which enables the otherwise challenging high catalyst turnover and suppression of the competing defluorination side reaction from an alkylcopper intermediate. The product derivatization of the resulting Bpin moiety can deliver diverse CF_3-containing molecules with high stereochemical fidelity.

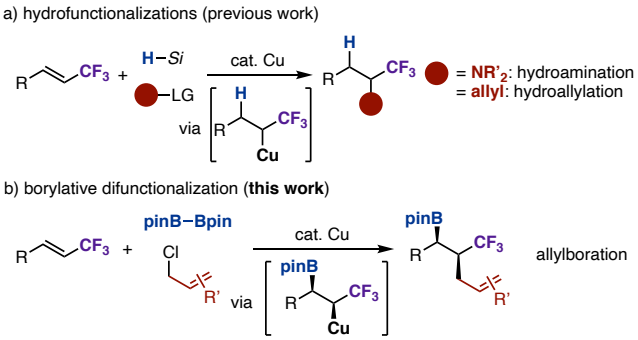
Since the introduction of the fluorine atom into parent organic molecules often increases the lipophilicity and metabolic stability to improve the biological activity, fluorinated compounds have received significant attention in the fields of pharmaceutical and medicinal chemistry.[1] In particular, the trifluoromethyl (CF_3) group is most frequently found in marketed drugs and agrochemicals.[2] Accordingly, numerous synthetic strategies for the preparation of CF_3-containing organic molecules have been developed.[3] Among them, the selective functionalization of CF_3-substituted substrates is a powerful way to synthesize structurally diverse fluorinated molecules.[3c,d] Recently, many synthetic chemists have focused on 1-trifluoromethylalkenes as CF_3-containing starting platforms and developed a variety of transition-metal-catalyzed coupling reactions with external nucleophilic components to afford the corresponding organofluorine compounds with increased molecular complexity (Scheme 1). However, almost all reported procedures involve the defluorination process from an α-CF_3 alkylmetal intermediate via β-F elimination, thus giving the corresponding gem-difluoroalkenes as main products (path a).[4] The CF_3-compatible catalytic functionalization through the electrophilic trapping of the intermediate is theoretically possible but still remains underdeveloped (path b),[5] except for specially designed substrates conjugated with additional activating groups such as vinyl, Ar, NO_2, and carbonyl.[6]

Our group recently succeeded in developing of copper-catalyzed hydrofunctionalizations of 1-trifluoromethylalkenes with hydrosilane nucleophiles and external electrophiles (Scheme 2a), in which the CF_3 group was successfully retained by the judicious choice of supporting ligands and basic additives.[5a,b] In our continuing interest in this chemistry, we envisioned that replacement of the hydrosilane with bis(pinacolato)diboron (pinB–Bpin) enabled the borylative difunctionalization of the 1-trifluoromethylalkene. Herein, we report a copper-catalyzed regio- and stereoselective allylboration with pinB–Bpin and allylic chlorides (Scheme 2b).[7] The combination of modified dppe-type ancillary ligands and Cs_2CO_3 base successfully promotes the otherwise challenging difunctionalization over the defluorination side reaction. The related deuterioboration using pinB–Bpin and D_2O was reported by Hoveyda,[5c] but the application of other electrophiles is not trivial, to the best of our knowledge.

Scheme 1. Defluorinative Functionalization vs Difunctionalization of 1-Trifluoromethylalkenes



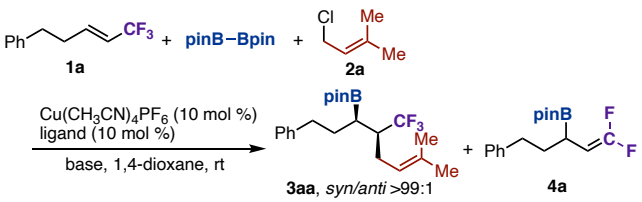
Scheme 2. CF_3-Compatible Catalytic Functionalizations of 1-Trifluoromethylalkenes



On the basis of our previous work on the hydroallylation reaction,[5b] our initial trial was performed with the 1-trifluoromethylalkene **1a**, pinB–Bpin (3.0 equiv), and prenyl chloride (**2a**; 2.0 equiv) in the presence of $Cu(CH_3CN)_4PF_6$/MeO-dppbz catalyst and Cs_2CO_3 base at room temperature (Table 1, entry 1). The desired allylborated product **3aa** was obtained in 40% ^{1}H NMR yield with high regioselectivity and >99:1 *syn/anti* ratio, but the conversion was moderate and the possible *gem*-difluoroalkene byproduct **4a** was also formed in 10 % yield. The parent dppbz and related substituted dppbz ligands such as *t*-Bu-dppbz and DTBM-dppbz were then tested, but no significant improvement was observed (entries 2–4). Thus, we moved attention to structurally relevant but more electron-donating ethylene-bridged analogues, dppe ligands.[8] While the MeO-dppe ligand showed performance and selectivity similar to MeO-dppbz (entry 5), *t*-Bu-dppe and DTBM-dppe dramatically increased the yield of **3aa** to 94 and 80% yields, respectively (entries 6 and 7). Several other para- and meta-substituted dppe derivatives as well as the parent dppe were also examined, but moderate conversion and chemoselectivity were observed regardless of their electronic nature of substituents (entries 8–14). The choice of base was also critical: less basic CsOPiv, K_2CO_3, and KOPiv resulted in lower conversion (entries 15–17), whereas NaO-*t*-Bu and LiO-*t*-Bu mainly afforded the *gem*-difluoroalkene **4a** (entries 18 and 19) by the β-F elimination from an α-CF_3 alkylcopper intermediate (Scheme 1), which is accelerated by strong interaction between F and Na or Li alkali metal.[5c,9] The suitable basicity of Cs_2CO_3 promotes regeneration of the catalytically active Cu-Bpin species (Scheme S3a) while its lower affinity to F and B atoms[5c] effectively suppresses the undesired β-F elimination. We also tested pinB-Bdan and neoB-Bneo instead of pinB-Bpin, but the targeted allylborated products **3aa-Bdan** and **3aa-Bneo** were not obtained at all (entries 20 and 21). Additional observations are noted: no conversion occurred in the absence of Cu, ligand, or base. Other Cu salts and solvents were also evaluated, but the combination of $Cu(CH_3CN)_4PF_6$ and 1,4-dioxane was optimal. The Cl leaving group was important for the successful three-component-coupling, and other common leaving groups such as Br and OAc gave only a negligible amount of **3aa**. Different from the previous hydroallylation,[5b] any positive effects of crown ethers were not detected (see the Supporting Information for more details).

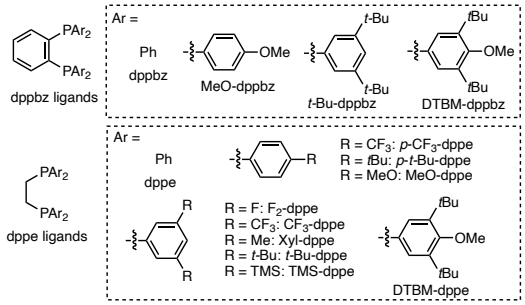
With optimal conditions in hand, we examined the generality of the reaction (Scheme 3). The copper catalysis accommodated primary and secondary alkyl substituents at

Table 1. Optimization Studies for Copper-Catalyzed Regio- and Stereoselective Allylboration of 1a with B_2pin_2 and Allyl Chloride 2a[a]

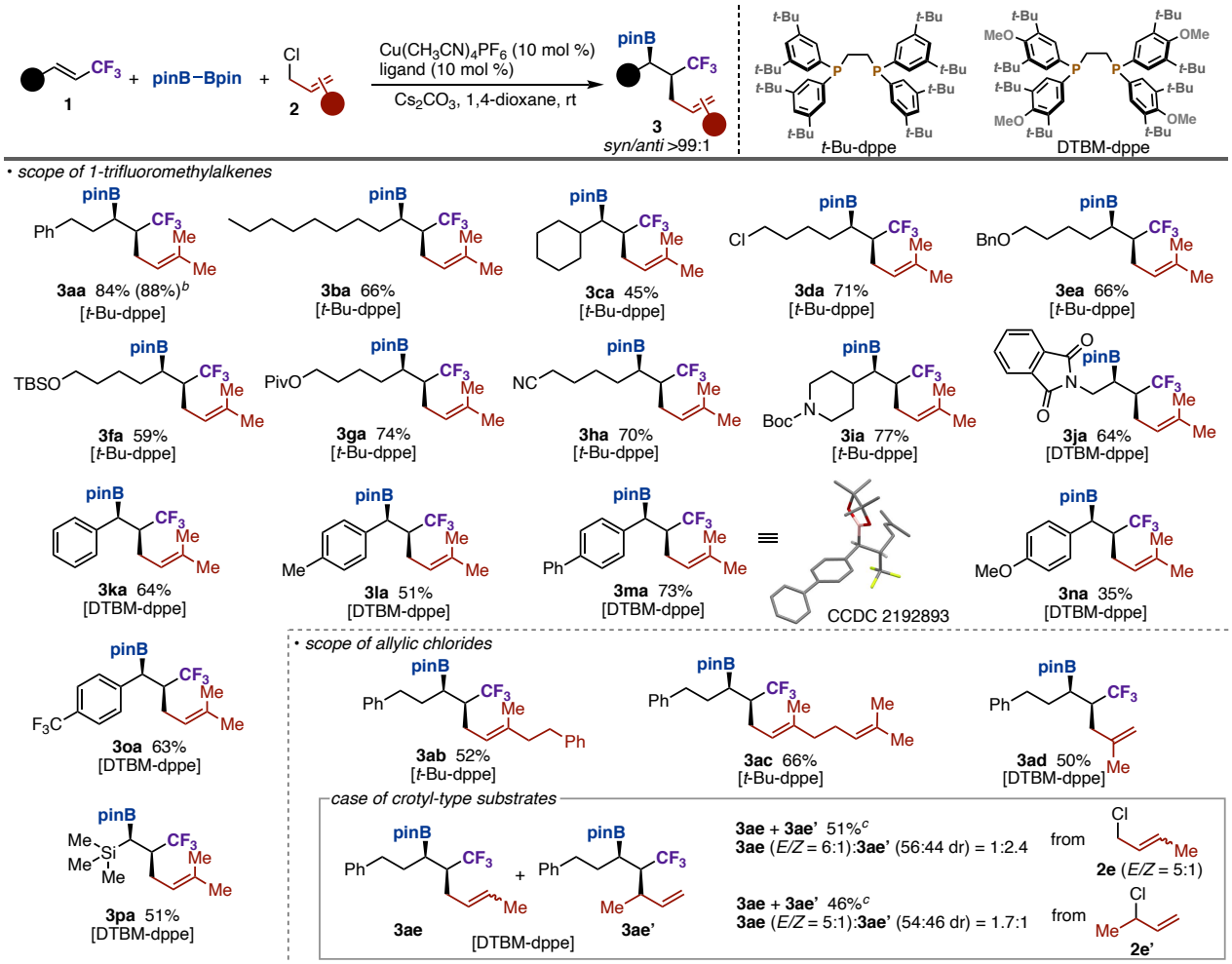


entry	ligand	base	yield (%)[b]	
			3aa	**4a**
1	MeO-dppbz	Cs_2CO_3	40	10
2	dppbz	Cs_2CO_3	23	7
3	*t*-Bu-dppbz	Cs_2CO_3	13	19
4	DTBM-dppbz	Cs_2CO_3	36	7
5	MeO-dppe	Cs_2CO_3	34	4
6	*t*-Bu-dppe	Cs_2CO_3	94 (84)	3
7	DTBM-dppe	Cs_2CO_3	80	3
8	dppe	Cs_2CO_3	30	5
9	*p*-CF_3-dppe	Cs_2CO_3	22	19
10	*p*-*t*-Bu-dppe	Cs_2CO_3	21	0
11	F_2-dppe	Cs_2CO_3	24	17
12	CF_3-dppe	Cs_2CO_3	9	17
13	Xyl-dppe	Cs_2CO_3	22	1
14	TMS-dppe	Cs_2CO_3	39	4
15	*t*-Bu-dppe	CsOPiv	19	4
16	*t*-Bu-dppe	K_2CO_3	31	0
17	*t*-Bu-dppe	KOPiv	17	4
18	*t*-Bu-dppe	NaO-*t*-Bu	6	51
19	*t*-Bu-dppe	LiO-*t*-Bu	0	34
20[c]	*t*-Bu-dppe	Cs_2CO_3	trace	15
21[d]	*t*-Bu-dppe	Cs_2CO_3	0	0

[a]Conditions: **1a** (0.20 mmol), pinB–Bpin (0.60 mmol), **2a** (0.40 mmol), $Cu(CH_3CN)_4PF_6$ (0.020 mmol), ligand (0.020 mmol), base (0.40 mmol), 1,4-dioxane (1.0 mL), rt, 18 h, N_2. [b] Estimated by ^{1}H NMR. Isolated yields are given in parentheses. [c] With pinB–Bdan instead of pinB–Bpin. The desired product and byproduct were Bdan-derived **3aa-Bdan** and **4a-Bdan**, respectively. [d] With neoB–Bneo instead of pinB–Bpin. The desired product and byproduct were Bneo-derived **3aa-Bneo** and **4a-Bneo**, respectively.



Scheme 3. Cu-Catalyzed Regio- and Diastereoselective Allylboration of 1-Trifluoromethylalkenes 1 with pinB–Bpin and Allylic Chlorides 2[a]



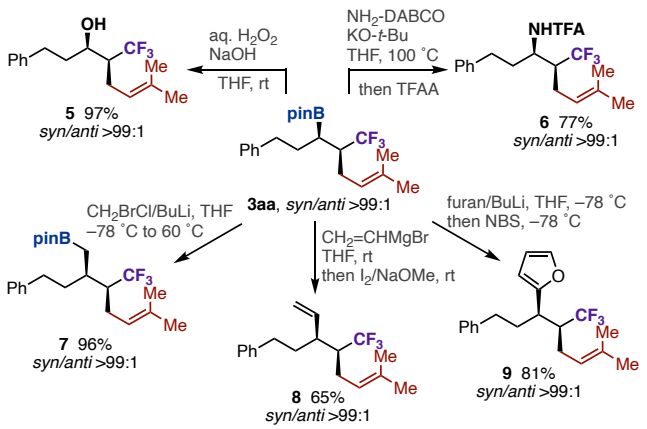
[a] Reaction Conditions: $Cu(CH_3CN)_4PF_6$ (0.020 mmol), ligand (0.020 mmol), **1** (0.20 mmol), pinB–Bpin (0.60 mmol), **2** (0.40 mmol), Cs_2CO_3 (0.40 mmol), 1,4-dioxane (1.0 mL), rt, 18–48 h. Isolated yields are shown. The ligand employed is shown in square bracket. [b] On a 1.0 mmol scale. [c] ^{1}H NMR yields.

the β-position of 1-trifluoromethylalkene (**3aa**–**3ca**). The reaction conditions were compatible with several functional groups, including the alkyl chloride (**3da**), benzyl ether (**3ea**), silyl ether (**3fa**), pivalate ester (**3ga**), and nitrile (**3ha**). The amine-based functions such asBoc-protected amine (**3ia**) and phthalimide (**3ja**) were also tolerated. Notably, aryl-conjugated 1-trifluoromethylalkenes also underwent the regioselective allylboration (**3ka**–**oa**): the boryl group and allyl group selectively introduced at the β- and α-position, respectively, to the CF_3 probably because the regioselectivity in the insertion step of 1-trifluoromethylalkene into the Cu–Bpin bond is predominantly controlled by strong electron-withdrawing nature of the CF_3 group over the aryl-vinyl conjugation.[10] Furthermore, the Me_3Si-substituted substrate was converted to the desired **3pa** with the *gem*-borylsilyl carbon center. Regardless of steric and electronic nature of the substituent, both regioselectivity and diastereoselectivity were uniformly high. The regioselectivity and relative stereochemistry were confirmed by the X-ray analysis of **3ma** (CCDC 2192893), and those of other compounds were assigned by analogy. As a general trend, in cases of aryl-conjugated substrates DTBM-dppe showed better performance than *t*-Bu-dppe. The scope and limitation of allylic chlorides **2** were also investigated. Other prenyl-type electrophiles **2b** and **2c** could be employed with maintenance of the starting (*E*)-geometry (**3ab** and **3ac**). The methally chloride (**2d**) also participated in the reaction (**3ad**). In the case of crotyl chloride (**2e**; *E/Z* = 5/1), a 1:2.4 mixture of **3ae** and **3ae'** was observed. On the other hand, the regioisomeric **2e'** also afforded a mixture of **3ae** and **3ae'** but with the opposite selectivity (**3ae**:**3ae'** = 1.7:1). These phenomena suggest that the electrophilic allylation step involves both the S_N2'-type addition-elimination-type mechanism and the formation of π-allyl- (or π-en-σ-yl) copper species and that the major pathway is dependent on the substitution pattern of allylic electrophile. We tested additional functionalized allylic chlorides, but low to moderate reaction efficiency was observed (see the Supporting Information for more details).

The resulting Bpin moiety in the allylborated product **3aa** could be readily transformed with high stereochemical fidelity (Scheme 4). The oxidation and amination were possible with aq. H_2O_2 and NH_2-DABCO,[11] respectively, and the corresponding CF_3-containing alcohol **5** and amine **6**

were obtained in good yields without any erosion of the diastereomeric ratio. One-carbon homologation was also feasible (**7**).[12] Moreover, the stereospecific oxidative cross-couplings[13] with the vinyl Grignard reagent and 2-furyllithium proceeded smoothly to form the corresponding C–C coupled products **8** and **9** in 65 and 81% yields, respectively.

Scheme 4. Stereospecific Transformations of Bpin Moiety in 3aa[a]



[a] See the Supporting Information for more detailed conditions.

Finally, to investigate the origin of higher catalytic performance of the *t*-Bu-dppe ligand than that of the parent dppe, several experiments were implemented. One possibility is the attractive London dispersion between the *t*-Bu substituents and 1-trifluoromethylalkene to accelerate the insertion step.[14] However, in our preliminary computational studies based on DFT calculations, the activation barrier was small enough to promote the insertion smoothly for both *t*-Bu-dppe- and parent dppe-ligated Cu-Bpin species (see the Supporting Information for details). Thus, the London dispersion cannot be a pivotal factor for the observed higher activity of *t*-Bu-dppe. Another possibility is the smooth generation of a catalytically competent monomeric Cu-Bpin species, which is generally unfavored with (bis)phosphine ligands and in equilibrium with the corresponding dimer and/or its higher aggregate.[15] Actually, in the stoichiometric reaction of $Cu(CH_3CN)_4PF_6$/*t*-Bu-dppe, pinB–Bpin, Cs_2CO_3, and **1a**, the conversion of **1a** started just upon mixing and completed within 35 min (Figure 1). In contrast, a ca. 1 h induction period was observed with the dppe ligand, and full conversion was achieved after 2.5 h. These distinct reaction profiles support the rapid generation of monomeric *t*-Bu-dppe-ligated Cu-Bpin, which is promoted by the bulky *t*-Bu groups at the remote meta-position of ligand to increase the overall reaction efficiency. However, we cannot completely exclude the possibility that the *t*-Bu substituent accelerates the allylation step with the allylic chloride electrophile (Scheme S3a).

In conclusion, we have developed a copper-catalyzed regio- and diastereoselective allylboration of 1-trifluoromethylalkenes with pinB–Bpin and allylic chlorides. The judicious choice of Cs-based base and ancillary bisphosphine ligands with the remote steric bulkiness enables suppression of the otherwise competitive defluorination process and high reaction efficiency. The boryl group in the obtained product is readily transformed to versatile functional groups with high stereochemical fidelity. Thus, the present Cu catalysis can provide stereoselective access to CF_3-containg molecules of potent interest in pharmaceutical chemistry. More detailed mechanistic studies and development of asymmetric catalysis are currently underway in our laboratory.

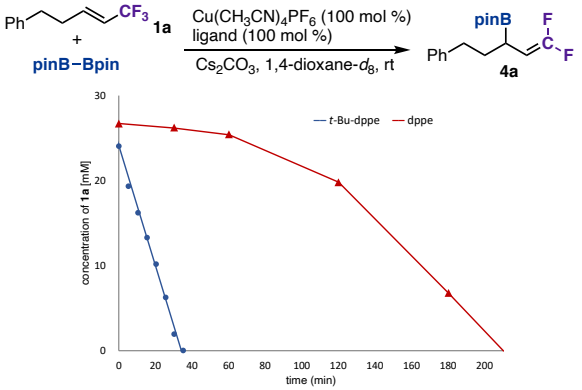


Figure 1. Reaction progresses of stoichiometric reactions of Cu/ligand, **1a**, and pinB–Bpin.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.orglett.xxxx.

^{1}H, ^{13}C{^{1}H}, ^{19}F{^{1}H}, ^{31}P{^{1}H}, and ^{11}B NMR spectra, ORTEP drawing, detailed optimization studies, control experiments, proposed reaction mechanisms, and DFT studies (PDF)

Accession Code

CCDC 2192893 contains the supplementary crystallographic data for this paper. These data can be obtained free of charge via www.ccdc.cam.ac.uk/data_request/cif, or by emailing data_request@ccdc.cam.ac.uk, or by contacting The Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; fax: +44 1223 336033.

AUTHOR INFORMATION

Corresponding Author

Koji Hirano – Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan; Innovative Catalysis Science Division, Institute for Open and Transdisciplinary Research Initiatives (ICS-OTRI), Osaka University, Suita, Osaka 565-0871, Japan; orcid.org/0000-0001-9752-1985; Email: k_hirano@chem.eng.osaka-u.ac.jp.

Authors

Yuki Kojima – *Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan*

Yuji Nishii – *Department of Applied Chemistry, Graduate School of Engineering, Osaka University, Suita, Osaka 565-0871, Japan;* orcid.org/ 0000-0002-6824-0639.

Complete contact information is available at: https://pubs.acs.org/10.1021/xxxx.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

This work was supported by JSPS KAKENHI Grant No. JP 22H02077 (Grant-in-Aid for Scientific Research(B) to K.H.) as well as by JST FOREST Program (Grant Number JPMJFR211X to K.H.).

REFERENCES

(1) (a) Swallow, S. In *Fluorine in Pharmaceutical and Medicinal Chemistry: From Biophysical Aspects to Clinical Applications*; Gouverneur, V. Müller, K., Eds.; Imperial College Press: London, 2012; p 141. (b) Müller, K.; Faeh, C.; Diederich, F. Fluorine in Pharmaceuticals: Looking Beyond Intuition. *Science* **2007**, *317*, 1881–1886. (c) Gillis, E. P.; Eastman, K. J.; Hill, M. D.; Donnelly, D. J.; Meanwell, N. A. Applications of Fluorine in Medicinal Chemistry. *J. Med. Chem.* **2015**, *58*, 8315–8359. (d) Ogawa, Y.; Tokunaga, E.; Kobayashi, O.; Hirai, K.; Shibata, N. Current Contributions of Organofluorine Compounds to the Agrochemical Industry. *iScience* **2020**, *23*, 101467. (e) Inoue, M.; Sumii, Y.; Shibata, N. Contribution of Organofluorine Compounds to Pharmaceuticals. *ACS Omega* **2020**, *5*, 10633–10640.

(2) (a) Wishart, D. S.; Feunang, Y. D.; Guo, A. C.; Lo, E. J.; Marcu, A.; Grant, J. R.; Sajed, T.; Johnson, D.; Li, C.; Sayeeda, Z.; Assempour, N.; Iynkkaran, I.; Liu, Y.; Maciejewski, A.; Gale, N.; Wilson, A.; Chin, L.; Cummings, R.; Le, D.; Pon, A.; Knox, C.; Wilson, M. DrugBank 5.0: A Major Update to The DrugBank Database for 2018. *Nucleic Acids Res.* **2018**, *46*, D1074–D1082. (b) Meanwell, N. A. Fluorine and Fluorinated Motifs in the Design and Application of Biosisosteres for Drug Design. *J. Med. Chem.* **2018**, *61*, 5822. (c) O'Hagan, D. Understanding organofluorine chemistry. An introduction to the C–F bond. *Chem. Soc. Rev.* **2008**, *37*, 308.

(3) (a) Yang, X.; Wu, T.; Phipps, R. J.; Toste, F. D. Advances in Catalytic Enantioselective Fluorination, Mono-, Di-, and Trifluoromethylation, and Trifluoromethylthiolation Reactions. *Chem. Rev.* **2015**, *115*, 826–870. (b) Alonso, C.; de Marigorta, E.; Rubiales, G.; Palacios, F. Carbon Trifluoromethylation Reactions of Hydrocarbon Derivatives and Heteroarenes. *Chem. Rev.* **2015**, *115*, 1847–1935. (c) Nie, J.; Guo, H.-C.; Cahard, D.; Ma, J.-A. Asymmetric Construction of Stereogenic Carbon Centers Featuring a Trifluoromethyl Group from Prochiral Trifluoromethylated Substrates. *Chem. Rev.* **2011**, *111*, 455–529. (d) Onyeagusi, C. I.; Malcolmson, S. J. Strategies for the Catalytic Enantioselective Synthesis of α-Trifluoromethyl Amines. *ACS Catal.* **2020**, *10*, 12507–12536. (e) Hirano, K. Catalytic Asymmetric Construction of CF3-Substituted Chiral sp3 Carbon Centers. *Synthesis*, **2022**, *54*, 3708–3718.

(4) For a recent review, see: Wang, M.; Shi, Z. Catalytic Enantioselective Allylic C–F Bond Functionalization. *Chem. Lett.* **2021**, *50*, 553–559. See the Supporting Information for selected recent examples.

(5) (a) Takata, T.; Hirano, K.; Miura, M. Synthesis of α-Trifluoromethylamines by Cu-Catalyzed Regio- and Enantioselective Hydroamination of 1-Trifluoromethylalkenes. *Org. Lett.* **2019**, *21*, 4284–4288. (b) Kojima, Y.; Miura, M.; Hirano, K. Copper-Catalyzed Regio- and Enantioselective Hydroallylation of 1-Trifluoromethylalkenes: Effect of Crown Ether. *ACS Catal.* **2021**, *11*, 11663–11670. (c) Paioti, P. H. S.; del Pozo, J.; Mikus, M. S.; Lee, J.; Koh, M. J.; Romiti, F.; Torker, S.; Hoveyda, A. H. Catalytic Enantioselective Boryl and Silyl Substitution with Trifluoromethyl Alkenes: Scope, Utility, and Mechanistic Nuances of Cu–F β-Elimination. *J. Am. Chem. Soc.* **2019**, *141*, 19917–19934.

(6) For examples, (a) Dong, K.; Li, Y.; Wang, Z.; Ding, K. Catalytic Asymmetric Hydrogenation of α-CF3- or β-CF3-Substituted Acrylic Acids using Rhodium(I) Complexes with a Combination of Chiral and Achiral Ligands. *Angew. Chem., Int. Ed.* **2013**, *52*, 14191–14195. (b) Wu, J.; Wu, H.; Li, X.; Liu, X.; Zhao, Q.; Huang, G.; Zhang, C. Copper-Catalyzed Highly Selective Protoboration of CF3-Containing 1,3-Dienes. *Angew. Chem., Int. Ed.* **2021**, *60*, 20376–20382. (c) Yamauchi, D.; Nakamura, I.; Nishimura, T. Iridium-catalyzed enantioselective addition of an N-methyl C–H bond to α-trifluoromethylstyrenes via C–H activation. *Chem. Commun.* **2021**, *57*, 11787–11790. (d) Zhu, C.; Zhang, H.; Liu, Q.; Chen, K.; Liu, Z.-Y.; Feng, C. Nickel-Catalyzed anti-Markovnikov Hydroalkylation of Trifluoromethylalkenes. *ACS Catal.* **2022**, *12*, 9410–9417.

(7) For related Cu-catalyzed allylboration of alkynes, alkenes, and diynes, see: (a) Alfaro, R.; Parra, A.; Alemán, J.; Ruano, J. L. G.; Tortosa, M. Copper(I)-Catalyzed Formal Carboboration of Alkynes: Synthesis of Tri- and Tetrasubstituted Vinylboronates. *J. Am. Chem. Soc.* **2012**, *134*, 15165–15168. (b) Yoshida, H.; Kageyuki, I.; Takaki, K. Copper-Catalyzed Three-Component Carboboration of Alkynes and Alkenes. *Org. Lett.* **2013**, *15*, 952–955. (c) Semba, K.; Bessho, N.; Fujihara, T.; Terao, J.; Tsuji, Y. Copper-Catalyzed Borylative Allyl–Allyl Coupling Reaction. *Angew. Chem., Int. Ed.* **2014**, *53*, 9007–9011. (d) Jia, T.; Cao, P.; Wang, B.; Lou, Y.; Yin, X.; Wang, M.; Liao, J. A Cu/Pd cooperative catalysis for enantioselective allylboration of alkenes. *J. Am. Chem. Soc.* **2015**, *137*, 13760–13763. (e) Lee, J.; Radomkit, S.; Torker, S.; del Pozo, J.; Hoveyda, A. H. Mechanism-based enhancement of scope and enantioselectivity for reactions involving a copper-substituted stereogenic carbon centre. *Nat. Chem.* **2018**, *10*, 99–108. (f) Rivera-Chao, E.; Mitxelena, M.; Varela, J. A.; Fañanás-Mastral, M. Copper-Catalyzed Enantioselective Allylboration of Alkynes: Synthesis of Highly Versatile Multifunctional Building Blocks. *Angew. Chem., Int. Ed.* **2019**, *58*, 18230–18234.

(8) For selected examples of modified dppe ligands in catalysis, see: Tran, G.; Hesp, K. D.; Mascitti, V.; Ellman, J. A. Base-Controlled Completely Selective Linear or Branched Rhodium(I)-Catalyzed C–H ortho-Alkylation of Azines without Preactivation. *Angew. Chem., Int. Ed.* **2017**, *56*, 5899–5903.

(9) Mikami, K.; Itoh, Y.; Yamanaka, M. Fluorinated Carbonyl and Olefinic Compounds: Basic Character and Asymmetric Catalytic Reactions. *Chem. Rev.* **2004**, *104*, 1–16.

(10) (a) Dang, L.; Zhao, H.; Lin, Z.; Marder, T. B. DFT Studies of Alkene Insertions into Cu–B Bonds in Copper(I) Boryl Complexes. *Organometallics* **2007**, *26*, 2824–2832. (b) Dang, L.; Lin, Z.; Marder, T. B. DFT Studies on the Borylation of α,β-Unsaturated Carbonyl Compounds Catalyzed by Phosphine Copper(I) Boryl Complexes and Observations on the Interconversions between O- and C-Bound Enolates of Cu, B, and Si. *Organometallics* **2008**, *27*, 4443–4454.

(11) Liu, X.; Zhu, Q.; Chen, D.; Wang, L.; Jin, L.; Liu, C. Aminoazanium of DABCO: An Amination Reagent for Alkyl and Aryl Pinacol Boronates. *Angew. Chem., Int. Ed.* **2020**, *59*, 2745–2749.

(12) Matteson, D. S. α-Halo boronic esters: intermediates for stereodirected synthesis. *Chem. Rev.* **1989**, *89*, 1535–1551.

(13) (a) Sonawane, R. P.; Jheengut, V.; Rabalakos, C.; Larouche-Gauthier, R.; Scott, H. K.; Aggarwal, V. K. Enantioselective Construction of Quaternary Stereogenic Centers from Tertiary Boronic Esters: Methodology and Applications. *Angew. Chem., Int. Ed.* **2011**, *50*, 3760–3763. (b) Bonet, A.; Odachowski, M.; Leonori, D.; Essafi, S.; Aggarwal, V. K. Enantiospecific sp2–sp3 coupling of secondary and tertiary boronic esters. *Nat. Chem.* **2014**, *6*, 584–589.

(14) (a) Liptrot, D. J.; Power, P. P. *Nat. Rev. Chem.* **2017**, *1*, 00004. (b) Lu, G.; Liu, R. Y.; Yang, Y.; Fang, C.; Lambrecht, D. S.; Buchwald, S. L.; Liu, P. Ligand–Substrate Dispersion Facilitates the Copper-Catalyzed Hydroamination of Unactivated Olefins. *J. Am. Chem. Soc.* **2017**, *139*, 16548–16555. (c) Xi, Y.; Su, B.; Qi, X.; Pedram, S.; Liu, P.; Hartwig, J. F. Application of Trimethylgermanyl-Substituted Bisphosphine Ligands with Enhanced Dispersion Interactions to Copper-Catalyzed Hydroboration of Disubstituted Alkenes. *J. Am. Chem. Soc.* **2020**, *142*, 18213–18222.

(15) Borner, C.; Anders, L.; Brandhorst, K.; Kleeberg, C. Elusive Phosphine Copper(I) Boryl Complexes: Synthesis, Structures, and Reactivity. *Organometallics* **2017**, *36*, 4687–4690.