N-Heterocyclic Carbene Ligand-Controlled Chemodivergent Suzuki-Miyaura Cross Coupling

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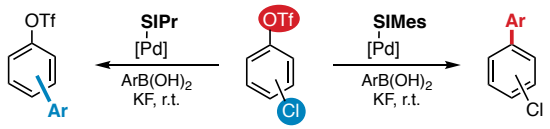


ABSTRACT

Two *N*-heterocyclic carbene (NHC) ligands provide orthogonal chemoselectivity during the Pd-catalyzed Suzuki-Miyaura (SM) cross coupling of chloroaryl triflates. The use of SIPr [SIPr = 1,3-bis(2,6-diisopropylphenyl)-4,5-dihydroimidazol-2-ylidene] leads to selective cross coupling at chloride, while the use of SIMes [SIMes = 1,3-bis(2,4,6-trimethylphenyl)-4,5-dihydroimidazol-2-ylidene] provides selective coupling at triflate. With most chloroaryl triflates and arylboronic acids, ligand-controlled selectivity is high (≥10:1). The scope of this methodology is significantly more general than previously reported methods for selective SM coupling of chloroaryl triflates using phosphine ligands. Density functional theory (DFT) studies suggest that palladium's ligation state during oxidative addition is different with SIMes compared to SIPr.

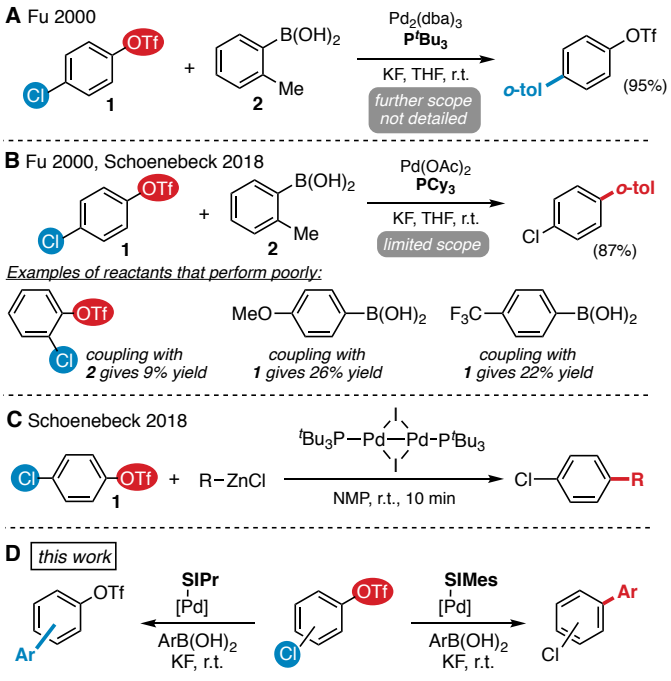
INTRODUCTION

Palladium-catalyzed cross couplings are among the most widely used strategies for C—C bond formation during the preparation of diverse classes of products.[1] The Suzuki-Miyaura (SM) reaction is particularly attractive due to its mild reaction conditions, its high functional group and moisture tolerance, and the low toxicity and good commercial availability of boronic acids and esters.[1] Sequential cross coupling reactions can be used to prepare polyfunctionalized arenes,[2] which are ubiquitous in pharmaceuticals, agrochemicals, materials, and natural products.

However, controlling the site selectivity of sequential cross coupling reactions can be challenging when multiple (pseudo)halides are present. A particularly attractive strategy for manipulating selectivity is through catalyst or ligand choice.[3]

For example, aryl chlorides and triflates are known to react with Pd(0) under similar conditions. The only previously known system for ligand-controlled divergent SM cross coupling of chloroaryl triflates was initially reported by Fu (Scheme 1A and B).[4,5,6] The SM coupling of **1** with **2** favors reaction at C—Cl over C—OTf with the bulky ligand P^{t}Bu$_3$. Conversely, the less hindered PCy$_3$ effects reaction at triflate. However, this methodology has limited synthetic utility. Selective cross coupling at C—OTf using PCy$_3$ under the reported conditions is specific to the reaction between **1** and **2**; the use of other chloroaryl triflates or boronic acids leads to poor yields and/or selectivity (Scheme 1B).[7] A detailed scope of the chloride-selective cross coupling with P^{t}Bu$_3$ under the original conditions has not been reported.[8] As such, alternative methods are needed for selective SM cross coupling of chloroaryl triflates.

Scheme 1. Chemodivergent Cross Coupling of Chloroaryl Triflates



An elegant procedure for triflate-selective coupling of chloroaryl triflates with organozinc reagents was recently described (Scheme 1C).[7] However, a general method to achieve the opposite selectivity—cross coupling of aryl chlorides in the presence of triflates—has not been detailed. Moreover, organozinc reagents have disadvantages compared to organoboron reagents related to functional group tolerance and commercial availability.[1]

Herein we demonstrate that the use of NHC ligands enables chemodivergent SM coupling of chloroaryl triflates. A Pd/SIPr precatalyst provides selective reaction at chloride, while a Pd/SIMes precatalyst favors reaction at triflate. In contrast to the limited scope reported for the prior phosphine ligand-controlled method,[4,7] this NHC ligand-controlled SM coupling is general to a variety of chloroaryl triflates and arylboronic acids.

RESULTS AND DISCUSSION

Initial Catalytic Results with NHC Ligands. Inspired by recent reports of the high reactivity of Pd(II) precatalysts bearing NHC ligands,[9,10] we investigated the selectivity of Pd/NHC complexes **3**–**7** (Figure 1) in SM reactions of chloroaryl triflates.

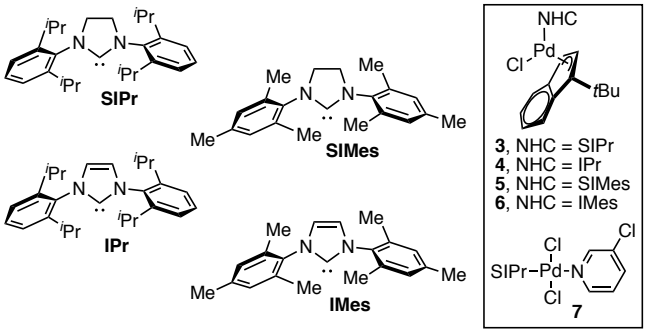
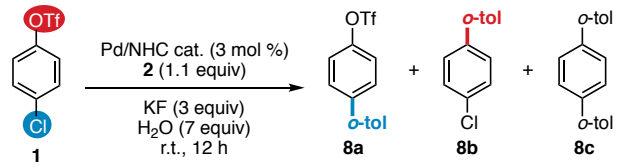


Figure 1. Pd/NHC catalysts used in this work.

Gratifyingly, the use of Hazari's[10] air-stable Pd/SIPr precatalyst **3** or PEPPSI™-SIPr[11] complex **7** provides high selectivity for coupling at C—Cl in the room-temperature SM reaction of **1** with **2** in THF (Table 1, entries 1-2). Precatalyst **4** bearing the related unsaturated ligand IPr gives comparable selectivity to **3**, albeit with reduced yield of the desired product (entry 3). In

stark contrast, however, however, catalysts containing the moderately smaller ligands SIMes and IMes provide the opposite selectivity under otherwise identical conditions (entries 4-5).[12,13,14] For example, the Pd/SIMes-catalyzed reaction of **1** with **2** yields **8b** in high yield, resulting from selective C—OTf activation (entry 4). Only small amounts of products from C—Cl activation (**8a** and **8c**) are detected with this catalyst.

Table 1. Evaluation of NHC ligands for selective Pd-catalyzed SM coupling.[a]



entry	cat.	NHC	solvent	**8a** (%)	**8b** (%)	**8c** (%)
1	**3**	SIPr	THF	85	5	13
2	**7**	SIPr	THF	55	7	9
3	**4**	IPr	THF	68	4	16
4	**5**	SIMes	THF	3	90	3
5	**6**	IMes	THF	2	79	13
6	**3**	SIPr	PhMe	92	5	2
7	**5**	SIMes	PhMe	8	13	2
8	**3**	SIPr	DMF	1	6	n.d.
9	**5**	SIMes	DMF	n.d.	57	n.d.
10	**3**	SIPr	1,4-dioxane	93	5	8
11	**5**	SIMes	1,4-dioxane	7	84	2
12[b]	**3**	SIPr	THF	trace	trace	n.d.
13[c]	**3**	SIPr	THF	trace	trace	n.d.
14[b]	**5**	SIMes	THF	n.d.	trace	n.d.
15[c]	**5**	SIMes	THF	trace	7	n.d.
16[d]	--	SIPr	THF	n.d.	n.d.	n.d.
17[d]	--	SIMes	THF	n.d.	n.d.	n.d.
18[e]	**9**	--	THF	1	2	0

[a]GC yields calibrated against undecane as internal standard. Estimated error in total mass balance ±6%. Entries 1–11 are the average of two runs. n.d. = not detected. [b]Without KF.

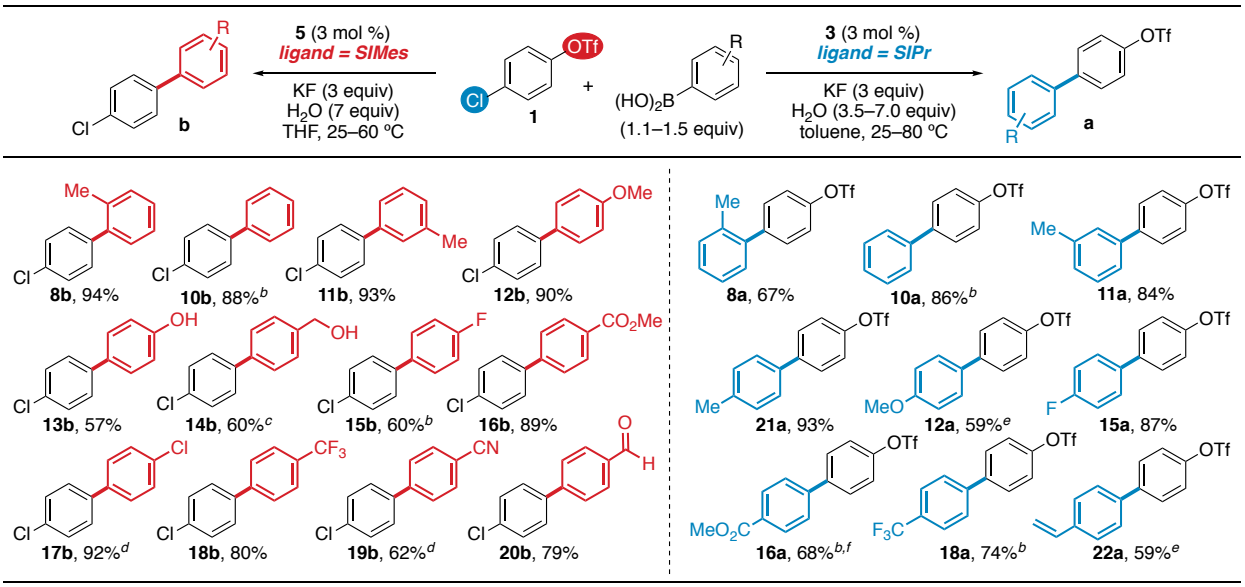
[c]Without H_2O. [d]No Pd catalyst; free SIPr or SIMes was added (3 mol %). [e]**9** = [(η^3-1-^{t}Bu-indenyl)Pd(Cl)]$_2$.

The use of toluene instead of THF minimizes unwanted diarylation (**8c**) with SIPr (entry 6), but poor conversion is observed with SIMes in toluene (entry 7). Dimethylformamide (DMF) is an effective solvent for the reaction with SIMes (entry 9) but not with SIPr (entry 8), while 1,4-dioxane is an effective solvent with both ligands (entries 10–11). Control reactions demonstrate that catalyst, KF, and water are each necessary for both the triflate- and the chloride-selective cross couplings using SIMes and SIPr, respectively (entries 8–13). Furthermore, only trace cross-coupling products are detected under ligand-free conditions using [(η^3-1-^{t}Bu-indenyl)Pd(Cl)]$_2$ (**9**, entry 14).

Scope of Arylboronic Acids. The divergent selectivities displayed by SIMes and SIPr are general to the cross coupling of **1** with diverse arylboronic acids (Scheme 2).[15,16] In most cases, ≤5% of the minor product and ≤5% of a diarylated product are observed. Pd/SIMes **5** catalyzes coupling at triflate using electron-rich (**8b**, **11b**–**14b**), -neutral (**10b**), and -deficient (**15b**–**20b**) arylboronic acids. An unprotected phenol (**13b**), benzylic alcohol (**14b**), aldehyde (**20b**), and a chloro substituent (**17b**) are tolerated on the boronic acid coupling partner. This scope is notable because the previously reported conditions for triflate-selective SM cross coupling using Pd/PCy_3 are ineffective with representative electron-rich and -deficient arylboronic acids (see Scheme 1B).[7]

Conversely, Pd/SIPr complex **3** catalyzes selective cross coupling of **1** at chloride using both electron-rich and -deficient arylboronic acids. The Pd/SIPr-catalyzed cross coupling of **1** with 4-vinylphenyl boronic acid to form **22a** is chemoselective for both the electrophile (preferential reaction at C—Cl) and the nucleophile (SM coupling is favored over Heck coupling).[17]

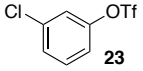
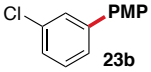
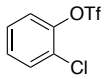
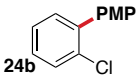
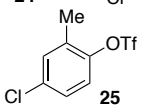
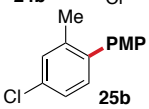
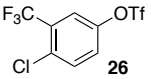
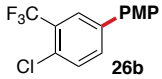
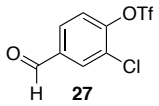
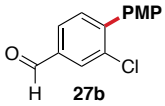
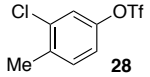
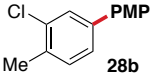
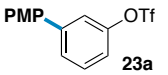
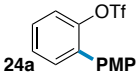
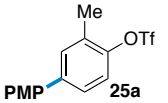
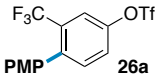
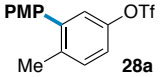
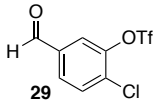
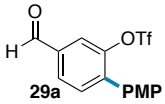
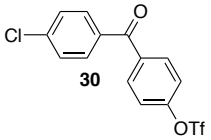
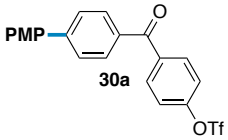
Scheme 2. Scope of arylboronic acids in the NHC ligand-controlled chemodivergent SM coupling.[a]



[a]Isolated yields. Unless noted, ≤5% of minor monoarylated products and ≤5% of diarylated products were detected by crude GC. [b]~10% of diarylated product by crude GC. [c]~6% of minor monoarylated product by crude GC. [d]Solvent = DMF. [e]Solvent = 1,4-dioxane. [f]Solvent = THF.

Scope of Chloroaryl Triflates.[15,16] In addition to *para*-chlorophenyl triflate **1**, the *meta* and *ortho* analogs undergo triflate- (Table 2, entries 1-2) or chloride-selective (entries 7-8) cross coupling with catalysts **5** and **3**, respectively. Even in the presence of steric bias (entries 3, 10, 11) or additional electron-withdrawing or -donating substituents (entries 3–6, 9–13), selectivity remains ligand-controlled. However, conversions and selectivities are poor for some electronically biased substrates that were evaluated (see Supporting Information).[15] The expected ligand-based selectivity is retained when chloride and triflate are connected to different aryl rings (entry 13).

Table 2. Scope of chloroaryl triflates in the NHC ligand-controlled chemodivergent SM coupling.[a]

entry	substrate	cat. (NHC)	major product[b]	isolated yield
1	 **23**	**5** (***SIMes***)	 **23b**	74%
2	 **24**		 **24b**	77%
3	 **25**		 **25b**	91%
4	 **26**		 **26b**	61%[c]
5	 **27**		 **27b**	69%[d]
6	 **28**		 **28b**	79%
7	**23**	**3** (***SIPr***)	 **23a**	76%
8	**24**		 **24a**	60%
9	**25**		 **25a**	58%
10	**26**		 **26a**	50%
11	**28**		 **28a**	71%[e]
12	 **29**		 **29a**	58%
13	 **30**		 **30a**	57%

[a]General procedure: chloroaryl triflate (1 equiv), *p*-methoxyphenylboronic acid (1.25–1.5 equiv), **3** or **5** (3 mol %), KF (3 equiv), H_2O (3.5–7.0 equiv), THF, DMF, toluene, 1,4-dioxane, or 1,4-dioxane/toluene (1:1), 4–12 h, 25–60 °C. PMP = *p*-methoxyphenyl. Isolated yields. [b]Unless noted, ≤5% of minor monoarylated products and ≤5% of diarylated products were detected by crude GC. [c]~28% of diarylated product by crude GC. [d]~6% of diarylated product by crude GC. [e]~19% of minor monoarylated product by crude GC.

DFT Studies. Having established that SIPr and SIMes ligand-controlled divergent selectivity is general to a variety of chloroaryl triflates and arylboronic acids, we next turned to DFT calculations to understand the origin of selectivity in this system. Calculations were performed at the CPCM(THF) M06/BS2//M06L/BS1 level of theory (see Computational Methods for details). Neutral transition structures were located using monoligated [Pd(SIPr)] for oxidative addition at both C—Cl and C—OTf of **1** (Figure 2A, top). Consistent with experiment, [Pd(SIPr)] is predicted to favor reaction at C—Cl by 4.6 kcal mol^{-1} (compare **TS31a** and **TS31b**). However, the same computational method predicts that [Pd(SIMes)] should also favor reaction at C—Cl, by 9.5 kcal mol^{-1} (compare **TS32a** and **TS32b**). The latter result strongly contradicts the observed experimental preference for cross coupling at C—OTf using SIMes. A variety of other DFT methods were evaluated (see SI), and nearly all provide the same prediction that reaction at C—OTf is disfavored with [Pd(SIMes)].

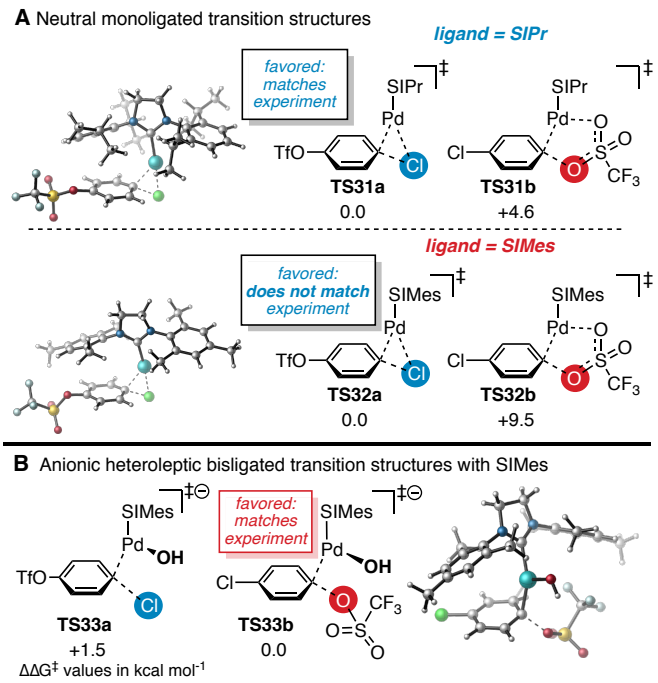


Figure 2. Calculated transition structures for oxidative addition involving SIPr and SIMes.

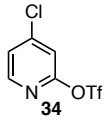
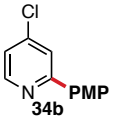
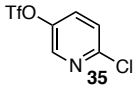
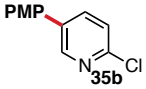
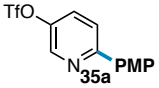
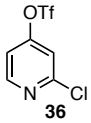
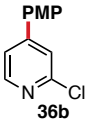
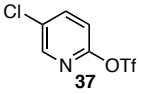
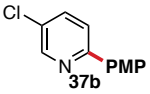
This disagreement between computational and experimental results strongly suggests that monoligated [Pd(SIMes)] is not responsible for oxidative addition of C—OTf. Instead, one

possibility is that oxidative addition at triflate takes place through a bisligated [Pd(SIMes)$_2$] transition structure. This possibility is analogous to the current mechanistic understanding of Fu's phosphine ligand-controlled SM coupling of chloroaryl triflates.[4] DFT calculations by Schoenebeck and Houk,[18] as well as studies by Sigman,[6] showed that selectivity in Fu's system relates to palladium's ligation state by phosphine during oxidative addition. PdL$_2$, favored with PCy$_3$, reacts at the C—OTf site of **1** while PdL, favored with P^{t}Bu$_3$, reacts at C—Cl (Scheme 1A and 1B). This relationship between ligation state and selectivity was explained by the distortion-interaction model.[18,19] PdL$_2$ is more electron-rich than PdL and thus has a stronger interaction with the more electrophilic C—O site compared to C—Cl. It may be possible that SIMes behaves analogously to PCy$_3$, and that [Pd(SIMes)$_2$] is responsible for the selectivity observed with this ligand. However, our attempted calculations to locate sterically congested transition structures involving [Pd(SIMes)$_2$] have all failed to converge.

An alternative explanation for the triflate selectivity observed with SIMes is that oxidative addition involves an anionic species [Pd(SIMes)X]$^-$ (X = small anionic ligand).[20] Indeed, DFT calculations predict that an anionic transition structure involving [Pd(SIMes)(OH)]$^-$ (**TS33a**) favors reaction at triflate by 1.5 kcal mol^{-1} (Figure 2B). Formation of a palladium hydroxide species is plausible under the catalytic conditions, which include both water and base (KF).[21] The preference for [Pd(SIMes)OH]$^-$ to react at OTf is consistent with previously reported calculations using phosphine ligands. Anionic [Pd(P^{t}Bu$_3$)X]$^-$ (X = F$^-$ or PhB(OH)O$^-$) has been shown computationally to favor oxidative addition at C—OTf over C—Cl.[18,22] Interestingly however, previous studies suggest that involvement of putative [Pd(P^{t}Bu$_3$)X]$^-$ is only favored in certain polar solvents like DMF and MeCN.[23] In THF or other nonpolar solvents, the active catalyst is [Pd(P^{t}Bu$_3$)] and preferential SM cross coupling at C—Cl is observed.[22] As such, if [Pd(SIMes)X]$^-$ is the active catalyst in THF, it suggests that SIMes is better than P^{t}Bu$_3$ at stabilizing anionic Pd. Further studies will be needed to distinguish between mechanisms involving [Pd(SIMes)$_2$], [Pd(SIMes)X]$^-$, or other active catalysts.[24]

Limitations to Selective Reaction at Chloride: Heteroaryl Substrates. To test the limits of the NHC ligand-controlled selectivity, chloropyridyl triflates were examined as substrates for the SM reaction (Table 3). All else being equal, the reactivity of pyridine C—X bonds toward Pd(0) generally follows the order C2 > C4 > C3/C5.[25] We were interested in whether the strong electronic biases of this substrate class would erode the NHC ligand-controlled selectivity. Furthermore, the mechanism of oxidative addition of chloropyridines at Pd(0) may be different from that of chloroarenes, which could affect selectivity.[26] The results of the reactions of **34** and **35** with Pd/SIMes indicate that selectivity for triflate using SIMes remains ligand-controlled (entries 1-2). Selective cross-coupling at triflate of substrate **35** occurs even though pyridine electronics should favor reaction at the C2—Cl bond. Interestingly, however, the selectivity with SIPr is less predictable. Selective Pd/SIPr-catalyzed cross coupling at chloride only occurs with **35**, the substrate that is most heavily electronically biased for reaction at C—Cl. With this substrate, cross coupling at C2—Cl takes place preferentially over reaction at C5—OTf to give **35a** (entry 3). However, with substrates **36**, **34**, and **37**, Pd/SIPr-catalyzed cross coupling takes place selectively at C—OTf (entries 4-6). The results with substrate **36** are particularly intriguing: reaction at chloride should be expected based on both the electronic bias of the pyridine ring and SIPr's usual preference for reaction at chloride. However, coupling takes place selectively at C4—OTf. Further study is needed to understand these incongruous results and their possible relationship to differences in the mechanism of oxidative addition of chloroarenes compared to chloropyridines.[26]

Table 3. Scope and limitations of the NHC ligand-controlled chemodivergent SM coupling of chloropyridyl triflates.[a]

entry	substrate	cat. (NHC)	major product[b]	isolated yield
1	 **34**	**5** (***SIMes***)	 **34b**	93%
2	 **35**		 **35b**	53%
3	**35**	**3** or **7** (***SIPr***)	 **35a**	77%
4	 **36**		 **36b**	79%
5	**34**		**34b**	(~27%)[c]
6	 **37**		 **37b**	75%

[a]General procedure: chloropyridyl triflate (1 equiv), *p*-methoxyphenylboronic acid (1.25–1.5 equiv), **3**, **5**, or **7** (3 mol %), KF (3 equiv), H_2O (3.5–14.0 equiv), THF (entries 1, 2, 5), toluene (entries 3, 4), or THF/toluene (2:1, entry 6), 12 h, r.t. PMP = *p*-methoxyphenyl. [b]≤5% of the minor monoarylated products and ≤5% of diarylated products were detected by crude GC. [c]Product not isolated; crude GC yield.

CONCLUSIONS

This work provides an improved method for chemodivergent Suzuki-Miyaura cross coupling of chloroaryl triflates. Although phosphine ligands (P^tBu_3 and PCy_3) have been previously shown to control selectivity in the cross coupling of **1** with **2**, the Pd/phosphine-catalyzed method is narrow in scope.[4,7] In contrast, the use of Pd/NHC catalysts enables selective coupling with diverse chloroaryl triflates and arylboronic acids. Pd/SIPr favors cross coupling at chloride, while Pd/SIMes favors reaction at triflate.

DFT studies suggest that, with SIPr, oxidative addition takes place preferentially at chloride through a neutral monoligated transition state. However, monoligated [Pd(SIMes)] is not responsible for oxidative addition of C—OTf. Instead, triflate selectivity with SIMes may be

attributed to oxidative addition at bisligated [Pd(SIMes)$_2$] or [Pd(SIMes)X]$^-$. Further study is needed to distinguish between these and other mechanistic possibilities for oxidative addition with Pd/SIMes.

The Pd/SIMes system remains selective for reaction of triflate even with electronically biased chloropyridyl triflate substrates. However, the Pd/SIPr-catalyzed cross coupling of chloropyridyl triflates does not clearly fit a pattern dictated by pyridine electronics or SIPr's typical preference for chloride. The incongruous results with chloropyridyl triflates and SIPr may relate to differences in the mechanism for oxidative addition of chloropyridines versus chloroarenes.[26] This possibility is the subject of ongoing study in our laboratory.

EXPERIMENTAL AND COMPUTATIONAL DETAILS

Computational Methods. Calculations were performed with Gaussian 09.[27] An ultrafine integration grid and the keyword 5d were used for all calculations. Unless otherwise specified in Section II-D of the Supporting Information, geometry optimizations of stationary points were carried out in the gas phase with the M06L[28] functional with BS1 (BS1 = the SDD[29] pseudopotential for Pd, the 6-31+G(d) basis set for O and Cl, and the the 6-31G(d) basis set for all other atoms). Frequency analyses were carried out at the same level to evaluate the zero-point vibrational energy and thermal corrections at 298 K. Gibbs free energy values are reported after applying Cramer and Truhlar's anharmonic correction to frequencies that are less than 100 cm^{-1}.[30] The nature of the stationary points was determined in each case according to the appropriate number of negative eigenvalues of the Hessian matrix. Forward and reverse intrinsic reaction coordinate (IRC) calculations were carried out on the optimized transition structures to ensure that the TSs indeed connect the appropriate reactants and products.[31] Multiple conformations were considered for all structures, and the lowest energy conformations are reported. Unless otherwise specified in Section 1D of the Supporting Information, single point energy calculations were performed on the gas-phase optimized geometries using the M06 functional with BS2 (BS2

= the SDD pseudopotential for Pd and the 6-311++G(2d,p) basis set for all other atoms). Bulk solvent effects in tetrahydrofuran were considered implicitly in the single point energy calculations through the CPCM continuum solvation model.[32] Images of optimized structures were generated with CYLview.[33]

General Materials and Methods. PEPPSI™-SIPr (**7**) and $Pd(OAc)_2$ were obtained from Sigma-Aldrich and used as received. $(\eta^3\text{-}1\text{-}^t\text{Bu-indenyl})_2(\mu\text{-Cl})_2Pd_2$, ($\eta^3$-1-^{t}Bu-indenyl)Pd(IMes)(Cl), and (η^3-1-^{t}Bu-indenyl)Pd(IPr)(Cl) were synthesized from a literature procedure.[10] NMR spectra were recorded at 298 K on a Bruker DRX 500 MHz (500.233 MHz for ^{1}H, 125.795 MHz for ^{13}C, 470.639 MHz for ^{19}F) or a Bruker DPX 300 MHz (300.172 MHz for ^{1}H) spectrometer. ^{1}H and ^{13}C NMR chemical shifts are reported in parts per million (ppm) relative to TMS, with the residual solvent peak used as an internal reference [^{1}H NMR: $CHCl_3$ (7.26 ppm) or C_6D_5H (7.16 ppm); ^{13}C NMR: $CDCl_3$ (77.16 ppm) or C_6D_6 (128.06 ppm)]. ^{19}F chemical shifts are reported in ppm relative to hexafluorobenzene (–164.9 ppm). Multiplicities are reported as follows: singlet (s), doublet (d), doublet of doublets (dd), doublet of doublets of doublets (ddd), triplet (t), triplet of doublets (td), triplet of triplets (tt), quartet (q), and multiplet (m). GC data were collected using a Shimadzu GC-2010 Plus with a flame ionization detector equipped with a SH-Rxi-5ms capillary column (15 m x 0.25 mm ID x 0.25 μm df). HRMS data were collected on an Agilent 6538 UHD-QTOF or a Bruker MicroTOF. LRMS (GC-MS) data were collected on an Agilent 7890A/5975C GC/MSD system equipped with an Agilent J&W VF-5ms column (30 m x 0.25 mm x 0.25 μm). Melting points were measured using a Thomas-Hoover "Uni-Melt" capillary melting point apparatus. Flash column chromatography was performed on SiliCycle silica gel 60 (40-63 μm particle size) and thin layer chromatography was performed on SiliCycle TLC plates pre-coated with extra hard silica gel 60 F_{254}.

General Procedure for Synthesis of Chloroaryl Triflates. Chloroaryl triflates were prepared according to a modified literature procedure.[34] To an oven-dried 250 mL round-bottom flask equipped with a stir bar was added the chlorophenol (1 equiv). The flask was then sealed

with a septum and subjected to 3 evacuation-refill cycles using N_2. Degassed pyridine (2 equiv) and CH_2Cl_2 were added by syringe. The solution was cooled to 0 °C and trifluoromethanesulfonate anhydride (1.2 equiv) was added dropwise over 15 minutes. The solution was allowed to warm to room temperature and stir for 16 hours under N_2. The reaction was quenched with 5% aqueous HCl (2/3 of the volume of CH_2Cl_2 used) and diluted with Et_2O (2/3 of the volume of CH_2Cl_2 used). The layers were separated, and the aqueous layer was extracted with Et_2O (3 x 2/3 of the volume of CH_2Cl_2 used). The combined organic layers were washed with 10% aqueous $NaHCO_3$ (1 x the volume of CH_2Cl_2 used) and brine (1 x 2/3 of the volume of CH_2Cl_2 used), dried over $MgSO_4$, filtered, and concentrated under reduced pressure. The crude residue was purified by flash column chromatography on silica gel or by taking up the residue in a nonpolar solvent and filtering through a silica plug.

4-Chlorophenyl trifluoromethanesulfonate (**1**): Chloroaryl triflate **1** was prepared according to the general procedure using 4-chlorophenol (2.57 g, 20 mmol, 1.0 equiv), pyridine (3.2 mL, 40 mmol, 2.0 equiv), CH_2Cl_2 (30 mL), and Tf_2O (4 mL, 24 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.45 in 100% hexanes) to yield **1** as a pale yellow oil (3.40 g, 65% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.43 (d, J = 9.1 Hz, 2H), 7.23 (d, J = 9.1 Hz, 2H); ^{13}C{^{1}H} NMR (126 MHz, $CDCl_3$, δ): 148.0, 134.5, 130.5, 122.9, 118.9 (q, $^1J_{CF}$ = 320.7 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −72.7. Spectral data are consistent with those previously reported.[35]

3-Chlorophenyl trifluoromethanesulfonate (**23**): Chloroaryl triflate **23** was prepared according to the general procedure using 3-chlorophenol (1.93 g, 15 mmol, 1 equiv), pyridine (2.4 mL, 30 mmol, 2.0 equiv), CH_2Cl_2 (20 mL), and Tf_2O (3 mL, 18 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.45 in 100% hexanes) to yield **23** as a colorless oil (3.15 g, 81% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.38-7.42 (multiple peaks, 2H), 7.30-7.32 (m, 1H), 7.18-7.23 (m, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 149.7, 135.9, 131.1,

129.0, 122.2, 119.9, 119.0 (q, $^1J_{CF}$ = 320.2 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.7. Spectral data are consistent with those previously reported.[35]

2-Chlorophenyl trifluoromethanesulfonate (**24**): Chloroaryl triflate **24** was prepared according to the general procedure using 2-chlorophenol (1.29 g, 10 mmol, 1 equiv), pyridine (1.6 mL, 20 mmol, 2.0 equiv), CH_2Cl_2 (15 mL), and Tf_2O (2 mL, 12 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.32 in 100% hexanes) to yield **24** as a colorless oil (1.75 g, 67% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.56-7.51 (m, 1H), 7.38-7.31 (multiple peaks, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 145.9, 131.5, 129.4, 128.5, 127.4, 123.2, 118.7 (q, $^1J_{C\text{-}F}$ = 320.7 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –73.5. Spectral data are consistent with those previously reported.[35]

4-Chloro-2-methylphenyl trifluoromethanesulfonate (**25**): Chloroaryl triflate **25** was prepared according to the general procedure using 4-chloro-2-methylphenol (0.5 g, 3.5 mmol, 1 equiv), pyridine (0.56 mL, 7 mmol, 2.0 equiv), CH_2Cl_2 (5 mL), and Tf_2O (0.71 mL, 4.2 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.43 in 100% hexanes) to yield **25** as a colorless oil (1.21 g, 41% yield). ^{1}H NMR (300 MHz, $CDCl_3$, δ): 7.31 (d, *J* = 2.1 Hz, 1H), 7.24 (m, 1H, overlaps with solvent), 7.18 (d, *J* = 7.2 Hz, 1H), 2.37 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 147.0, 134.0, 133.0, 132.2, 127.9, 122.7, 118.8 (q, $^1J_{CF}$ = 319.8 Hz), 16.5; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –73.7. HRMS (ESI/Q-TOF) *m*/*z*: [M - H]$^-$ Calcd for $C_8H_5ClF_3O_3S^-$ 272.9606; Found 272.9612.

4-Chloro-3-(trifluoromethyl)phenyl trifluoromethanesulfonate (**26**): Chloroaryl triflate **26** was prepared according to the general procedure using 4-chloro-3-(trifluoromethyl)phenol (487.4 mg, 2.5 mmol, 1 equiv), pyridine (0.4 mL, 5 mmol, 2 equiv), CH_2Cl_2 (5 mL), and Tf_2O (0.5 mL, 3 mmol, 1.2 equiv). The crude residue was purified by dissolving in pentane and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **26** as a colorless oil (676.4 mg, 83% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.62 (d, *J* = 8.8 Hz, 1H), 7.61 (d, *J* = 3.1 Hz, 1H), 7.43 (dd, *J* = 8.8, 3.1 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 147.5, 133.6, 132.8,

130.7 (q, $^{2}J_{CF}$ = 32.9 Hz), 126.0, 121.6 (q, $^{1}J_{CF}$ = 274.5 Hz), 121.3 (q, $^{3}J_{CF}$ = 5.6 Hz), 118.9 (q, $^{1}J_{CF}$ = 322.2 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.5, −63.4. Anal. Calcd for $C_8H_3ClF_6O_3S$: C, 29.24; H, 0.92. Found: C, 29.21; H, 0.92.

2-Chloro-4-formylphenyl trifluoromethanesulfonate (**27**): Chloroaryl triflate **27** was prepared according to the general procedure using 3-chloro-4-hydroxybenzaldehyde (187.9 mg, 1.2 mmol, 1 equiv), pyridine (0.3 mL, 3.6 mmol, 2 equiv), CH_2Cl_2 (2.9 mL), and Tf_2O (0.29 mL, 3.6 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.36 in 95% hexanes, 5% acetone) to yield **27** as a colorless oil (131.6 mg, 38% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 10.01 (s, 1H), 8.06 (d, *J* = 2.0 Hz, 2H), 7.88 (d, *J* = 8.5, 2.0 Hz, 2H), 7.56 (d, *J* = 8.5 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 188.9, 149.3, 136.5, 132.1, 129.4, 128.8, 123.9, 118.6 (q, $^{1}J_{CF}$ = 320 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.2. Spectral data are consistent with those previously reported.[36]

3-Chloro-4-methylphenyl trifluoromethanesulfonate (**28**): Chloroaryl triflate **28** was prepared according to the general procedure using 3-chloro-4-methylphenol (171.1 mg, 1.2 mmol, 1 equiv), pyridine (0.29 mL, 1.8 mmol, 2 equiv), CH_2Cl_2 (3 mL), and Tf_2O (0.3 mL, 1.8 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **28** as a colorless oil (198 mg, 60% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.30 (s, 1H), 7.24 (d, *J* = 8.6 Hz, 1H, overlaps with solvent), 7.18 (d, *J* = 8.6 Hz, 1H), 2.37 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 146.9, 134.0, 133.0, 132.1, 127.8, 122.7, 118.8 (q, $^{1}J_{CF}$ = 320.2 Hz), 16.4. ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.7. Anal. Calcd for $C_8H_6ClF_3O_3S$: C, 34.99; H, 2.20; Found: C, 35.19; H, 2.22.

2-Chloro-5-formylphenyl trifluoromethanesulfonate (**29**): Chloroaryl triflate **29** was prepared according to the general procedure using 4-chloro-3-hydroxybenzaldehyde (388.3 mg, 2.5 mmol, 1 equiv), pyridine (0.4 mL, 5 mmol, 2 equiv), CH_2Cl_2 (5 mL), and Tf_2O (0.5 mL, 3 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and Et_2O and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **29** as a yellow oil (243.4

mg, 34% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 10.09 (s, 1H), 7.86 (d, J = 8.4 Hz, 1H), 7.85 (s, 1H), 7.73 (d, J = 8.4 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 188.9, 146.5, 136.6, 134.0, 132.4, 130.1, 123.3, 118.7 (q, $^{1}J_{CF}$ = 322.7 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.2. HRMS (EI/Q-TOF) m/z: $[M]^+$ Calcd for $C_8H_4ClF_3O_4S^+$ 287.9471; Found 287.9475. The product gradually decomposes in ambient conditions.

4-(4-Chlorobenzoyl)phenyl trifluoromethanesulfonate (**30**): Chloroaryl triflate **30** was prepared according to the general procedure using 4-chloro-4'-hydroxybenzophenone (500 mg, 2.15 mmol, 1 equiv), pyridine (0.34 mL, 4.3 mmol, 2 equiv), CH_2Cl_2 (3 mL), and Tf_2O (0.43 mL, 2.58 mmol, 1.2 equiv). The crude residue was purified by flash column chromatography on silica gel (R_f = 0.48 in 90% hexanes, 10% acetone) to yield **30** as a colorless oil (203.9 mg, 26% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.88 (d, J = 8.8 Hz, 2H), 7.75 (d, J = 8.5 Hz, 2H), 7.49 (d, J = 8.6 Hz, 2H), 7.41 (d, J = 8.6 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 193.6, 152.2, 139.8, 137.4, 135.1, 132.1, 131.5, 129.1, 121.7, 118.9 (q, $^{1}J_{CF}$ = 321.4 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −72.7. Spectral data are consistent with those previously reported.[37] The product gradually decomposes in ambient conditions.

4-Chloropyridin-2-yl trifluoromethanesulfonate (**34**): Chloropyridyl triflate **34** was prepared according to the general procedure using 4-chloro-2-hydroxypyridine (321.3 mg, 2.5mmol, 1 equiv), pyridine (0.40 mL, 5 mmol, 2 equiv), CH_2Cl_2 (5 mL), and Tf_2O (0.50 mL, 3 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **34** as a yellow oil (418.6 mg, 64% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.32 (d, J = 5.4 Hz, 1H), 7.40 (dd, J = 5.4, 1.6 Hz, 1H), 7.21 (d, J = 1.6 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 156.3, 149.2, 148.1, 124.9, 118.7 (q, $^{1}J_{CF}$ = 320.7 Hz), 115.9; ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.0. HRMS (EI/Q-TOF) m/z: $[M]^+$ Calcd for $C_6H_3ClF_3NO_3S^+$ 260.9474; Found 260.9484.

6-Chloropyridin-3-yl trifluoromethanesulfonate (**35**): Chloroaryl triflate **35** was prepared according to the general procedure using 2-chloro-5-hydroxypyridine (155.4 mg, 1.2

mmol, 1 equiv), pyridine (0.29 mL, 3.6 mmol, 2 equiv), CH_2Cl_2 (3 mL), and Tf_2O (0.3 mL, 1.8 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **35** as a white solid (235.4 mg, 75% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.39 (d, J = 2.9 Hz, 1H), 7.61 (d, J = 8.8, 2.9 Hz, 1H), 7.45 (d, J = 8.8 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 151.1, 145.8, 142.8, 132.0, 125.8, 118.8 (q, $^1J_{CF}$ = 321.9 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): −72.3. Spectral data are consistent with those previously reported.[7]

2-Chloropyridin-4-yl trifluoromethanesulfonate (**36**): Chloroaryl triflate **36** was prepared according to the general procedure using 2-chloro-4-hydroxypyridine (453.4 mg, 3.5 mmol, 1 equiv), pyridine (0.56 mL, 7 mmol, 2 equiv), CH_2Cl_2 (3 mL), and Tf_2O (0.7 mL, 4.2 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **36** as a colorless oil (677.5 mg, 74% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.52 (d, J = 5.6 Hz, 1H), 7.31 (d, J = 1.9 Hz, 1H), 7.21 (dd, J = 5.6, 1.9 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 157.1, 153.6, 152.0, 118.6 (q, $^1J_{CF}$ = 322.4 Hz), 117.2, 115.3. ^{19}F NMR (470 MHz, $CDCl_3$, δ): −72.6. Anal. Calcd for $C_6H_3ClF_3NO_3S$: C, 27.55; H, 1.16; N, 5.35. Found: C, 27.27; H, 1.13; N, 5.26.

5-Chloropyridin-2-yl trifluoromethanesulfonate (**37**): Chloroaryl triflate **37** was prepared according to the general procedure using 5-chloro-2-hydroxypyridine (453.4 mg, 3.5 mmol, 1 equiv), pyridine (0.56 mL, 7 mmol, 2 equiv), CH_2Cl_2 (3 mL), and Tf_2O (0.7 mL, 4.2 mmol, 1.2 equiv). The crude residue was purified by dissolving in hexanes and filtering through a silica plug to remove solid impurities before drying *in vacuo* to yield **37** as a colorless oil (460.7 mg, 68% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.35 (d, J = 2.5 Hz, 1H), 7.86 (dd, J = 8.7, 2.5 Hz, 1H), 7.16 (d, J = 8.7 Hz, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 154.0, 147.6, 140.7, 132.6, 118.7 (q, $^1J_{CF}$ = 320.6 Hz), 116.4. ^{19}F NMR (470 MHz, $CDCl_3$, δ): −73.0. Spectral data are consistent with those previously reported.[38]

Synthesis of (η^3-1-^{t}Bu-indenyl)Pd(SIPr)Cl (3): In a nitrogen-atmosphere glovebox, (η^3-1-^{t}Bu-indenyl)$_2$(μ-Cl)$_2$Pd$_2$ (100 mg, 0.16 mmol, 1 equiv), SIPr (125 mg, 0.32 mmol, 2 equiv), and a 1:1 mixture of THF/Et$_2$O (5 mL) were combined in a 20 mL vial equipped with a magnetic stir bar. The vial was sealed with a PTFE-lined cap and the reaction was allowed to stir for 2 h at room temperature. The vial was removed from the glovebox, opened to air, and the contents filtered through celite to afford a deep red filtrate. The filtrate was concentrated under vacuum, triturated with hexanes, and the residue was purified by recrystallization from DCM/hexanes to yield **3** as orange-red needles (225 mg, 80% yield). ^{1}H NMR (500 MHz, C$_6$D$_6$, δ): 7.23 (dd, *J* = 15.3, 7.6 Hz, 2H), 7.15 (d, 3H, overlaps with solvent), 7.07 (dd, *J* = 7.7, 1.4 Hz, 2H), 6.80 (td, *J* = 7.6, 1.0 Hz, 1H), 6.39 (t, *J* = 7.4 Hz, 1H), 6.06 (d, *J* = 3.0 Hz, 1H), 5.83 (d, *J* = 7.4 Hz, 1H), 5.20 (d, *J* = 3.0 Hz, 1H), 3.72-3.38 (multiple peaks, 8H), 1.57 (d, *J* = 6.6 Hz, 6H), 1.42 (s, 9H), 1.18 (d, *J* = 6.6 Hz, 6H), 1.13 (d, *J* = 6.8 Hz, 6H), 1.06 (d, *J* = 6.8 Hz, 6H); ^{13}C{^{1}H} NMR (125 MHz, C$_6$D$_6$, δ): 204.6, 147.8, 147.5, 139.3, 139.0, 137.2, 129.2, 124.7, 124.5, 124.2, 119.4, 117.0, 116.0, 107.4, 64.0, 53.7, 35.0, 34.9, 34.2, 32.0, 30.0, 29.4, 28.9, 28.6, 26.7, 26.5, 25.7, 24.4, 23.5, 23.1, 20.9, 18.0, 14.3, 11.7; HRMS (ESI/Q-TOF) *m*/*z*: [M – Cl]$^+$ Calcd for [C$_{40}$H$_{53}$N$_2$Pd]$^+$ 667.3238; Found 667.3253.

Synthesis of (η^3-1-^{t}Bu-indenyl)Pd(SIMes)Cl (5): In a nitrogen-atmosphere glovebox, (η^3-1-^{t}Bu-indenyl)$_2$(μ-Cl)$_2$Pd$_2$ (100 mg, 0.16 mmol, 1 equiv), SIMes (98 mg, 0.32 mmol, 2 equiv), and a 1:1 mixture of THF/Et$_2$O (5 mL) were combined in a 20 mL vial equipped with a magnetic stir bar. The vial was sealed with a PTFE-lined cap and the reaction was allowed to stir for 2 h at room temperature. The vial was removed from the glovebox, opened to air, and the contents filtered through celite to afford a deep red filtrate. The filtrate was concentrated under vacuum, triturated with hexanes, and the residue was purified by recrystallization from DCM/hexanes to yield **5** as red crystals (198 mg, 87% yield). ^{1}H NMR (500 MHz, C$_6$D$_6$, δ): 7.09 (d, *J* = 7.8 Hz, 1H), 6.80 (s, 2H), 6.76 (td, *J* = 8.0, 1.1 Hz, 1H), 6.68 (s, 2H), 6.57 (td, *J* = 7.8, 0.8 Hz, 1H), 6.48 (d, *J* = 7.4 Hz, 1H), 5.88 (d, *J* = 2.8 Hz, 1H), 5.05 (d, *J* = 2.6 Hz, 1H), 3.13 (m, 4H),

2.39 (s, 6H), 2.27 (s, 6H), 2.15 (s, 6H), 1.42 (s, 9H); $^{13}C\{^{1}H\}$ NMR (125 MHz, C_6D_6, δ): 203.8, 139.2, 139.0, 137.8, 136.6, 129.6, 129.5, 125.2, 122.9, 119.6, 117.7, 115.5, 108.3, 64.2, 50.7, 34.2, 29.7, 21.0, 19.1, 18.7; HRMS (ESI/Q-TOF) *m/z*: $[M - Cl]^+$ Calcd for $[C_{34}H_{41}N_2Pd]^+$ 583.2299; Found 583.2287.

General Procedure for Chemoselective SM Coupling. Pd catalyst **3**, **5**, or **7** (3 mol %), KF (3 equiv), and boronic acid (1-1.5 equiv) were combined in a 4 mL vial. The vial was transferred into a nitrogen-atmosphere glovebox, and solvent and chloroaryl triflate substrate (1 equiv) were added. The vial was sealed with a cap equipped with a PTFE-lined septum and removed from the glovebox. Within 60 seconds, degassed water was added through the septum cap, and the puncture hole in the septum was sealed with grease. The reactions were stirred at room temperature for 12 h unless otherwise indicated. The reaction mixture was diluted with Et_2O and filtered through celite. The product was purified according to procedures A, B, or C as follows. Purification Procedure A: The crude filtrate was concentrated onto silica under vacuum and dry-loaded onto a silica column for purification by flash column chromatography. Purification Procedure B: The crude filtrate was concentrated under vacuum and purified by flash column chromatography or preparatory thin layer chromatography. Following isolation, the product was stored under nitrogen or in a desiccator to avoid hydrolysis. Purification Procedure C: The crude filtrate was concentrated under vacuum. The residue was dissolved in a minimal amount of acetonitrile or DMSO/acetone and purified by reverse-phase preparatory HPLC using H_2O/MeCN (note: no acidic additives were added to the mobile phase in order to avoid hydrolysis of the product). The aqueous fractions were extracted with pentane, dried over $MgSO_4$, filtered, concentrated to a small volume, and passed over a plug of silica pretreated with 1% triethylamine/99% hexanes. The silica plug was rinsed with pentane and the collected solution was concentrated under vacuum. Following isolation, the product was stored under nitrogen or in a desiccator to avoid hydrolysis.

General Procedure for Larger Scale Chemoselective SM Coupling. Pd catalyst **3** or **5** (1.5 mol %), KF (3 equiv), and boronic acid (1.1 equiv) were combined in a 20 mL vial. The vial was transferred into a nitrogen-atmosphere glovebox, and solvent and chloroaryl triflate substrate (1 equiv) were added. The vial was sealed with a rubber septum and removed from the glovebox. Within 60 seconds, degassed water was added through the septum, and the puncture hole in the septum was sealed with grease. The reactions were stirred vigorously at room temperature for 12 h. The reaction mixture was diluted with Et_2O and filtered through celite. The crude filtrate was dissolved in MeCN, then filtered to remove solid precipitates. The crude material was then purified by flash column chromatography.

4'-Chloro-2-methyl-1,1'-biphenyl (**8b**): Product **8b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 2-tolylboronic acid (68.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.62 in 100% hexanes) provided **8b** as a colorless oil (76.2 mg, 94% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.38 (d, *J* = 8.4 Hz, 2H), 7.28-7.21 (multiple peaks, 5H, overlaps with solvent), 7.19 (d, *J* = 6.9 Hz, 1H), 2.25 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 140.8, 140.5, 135.4, 133.0, 130.7, 130.6, 129.8, 128.4, 127.7, 126.0, 20.5. Spectral data are consistent with those previously reported.[4] *Larger scale reaction:* Product **8b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 437.5 μL, 2.5 mmol, 1 equiv), 2-tolylboronic acid (373.9 mg, 2.75 mmol, 1.1 equiv) KF (435.6 mg, 7.5 mmol, 3 equiv), **5** (18.6 mg, 0.03 mmol, 1.5 mol %), degassed H_2O (312.5 μL, 17.25 mmol, 7 equiv), and THF (5 mL). Purification by flash column chromatography (R_f = 0.62 in 100% hexanes) provided **8b** as a colorless oil (366.9 mg, 72% yield). Spectral data are identical to those reported above.

4-Chloro-1,1'-biphenyl (**10b**): Product **10b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv),

phenylboronic acid (61.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (1.6 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.69 in 100% hexanes) provided **10b** as a white solid (66.2 mg, 88% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.58-7.51 (multiple peaks, 4H), 7.48-7.40 (multiple peaks, 4H), 7.37 (tt, *J* = 7.5, 1.3 Hz, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 140.1, 139.8, 133.5, 129.05, 129.02, 128.5, 127.7, 127.1. Spectral data are consistent with those previously reported.[4]

4'-Chloro-3-methyl-1,1'-biphenyl **(11b)**: Product **11b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 3-tolylboronic acid (68.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.69 in 100% hexanes) provided **11b** as a white solid (75.7 mg, 93% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.52 (d, *J* = 8.6 Hz, 2H). 7.40 (d, *J* = 8.6 Hz, 2H), 7.38-7.31 (multiple peaks, 3H), 7.18 (d, *J* = 6.9 Hz, 1H), 2.43 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 140.1, 139.9, 138.7, 133.4, 129.0, 128.9, 128.54, 128.48, 127.9, 124.2, 21.7. Spectral data are consistent with those previously reported.[39]

4-Chloro-4'-methoxy-1,1'-biphenyl (**12b**): Product **12b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.41 in 3% EtOAc, 97% hexanes) provided **12b** as a white solid (78.7 mg, 90% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.49 (d, *J* = 8.8 Hz, 2H), 7.47 (d, *J* = 8.5 Hz, 2H), 7.38 (d, *J* = 8.5 Hz, 2H), 6.98 (d, *J* = 8.8 Hz, 2H), 3.85 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 159.5, 139.4, 132.8, 132.7, 129.0, 128.2, 128.1, 114.5, 55.5. Spectral data are consistent with those previously reported.[22]

4'-Chloro-[1,1'-biphenyl]-4-ol (**13b**): Product **13b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-hydroxyphenylboronic acid (82.8 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.48 in 20% EtOAc, 10% benzene, 70% hexanes) provided **13b** as an off-white solid (46.4 mg, 57% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.46 (d, *J* = 9.3 Hz, 2H), 7.44 (d, *J* = 9.3 Hz, 2H), 7.37 (d, *J* = 8.6 Hz, 2H), 6.90 (d, *J* = 8.6 Hz, 2H), 4.71 (s, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 155.4, 139.3, 133.0, 132.9, 129.0, 128.4, 128.1, 115.9. Spectral data are consistent with those previously reported.[40]

(4'-Chloro-[1,1'-biphenyl]-4-yl)methanol (**14b**): Product **14b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-(hydroxymethyl)phenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.3 in 20% EtOAc, 10% benzene, 70% hexanes) provided **14b** as a white solid (52.9 mg, 60% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.56 (d, *J* = 8.3, 2H). 7.52 (d, *J* = 8.6, 2H), 7.45 (d, *J* = 8.3, 2H), 7.41 (d, *J* = 8.6, 2H), 4.75 (d, *J* = 4.0 Hz, 2H), 1.66 (s, 1H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 140.3, 139.4, 139.3, 133.5, 129.0, 128.3, 127.5, 127.2, 65.1. Spectral data are consistent with those previously reported.[41]

4-Chloro-4'-fluoro-1,1'-biphenyl (**15b**): Product **15b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-fluorophenylboronic acid (78.4 mg, 0.56 mmol, 1.4 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (1.6 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.59 in

100% hexanes) provided **15b** as a white solid (49.6 mg, 60% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.51 (dd, *J* = 8.5, 5.8 Hz, 2H), 7.47 (d, 2H, *J* = 8.5 Hz), 7.40 (d, *J* = 8.5 Hz, 2H), 7.13 (t, *J* = 8.5 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 162.8 (d, $^{1}J_{CF}$ = 247.0 Hz), 138.9, 136.3 (d, $^{4}J_{CF}$ = 3.2 Hz), 133.6, 129.1, 128.7 (d, $^{3}J_{CF}$ = 8.2 Hz), 128.4, 115.92 (d, $^{2}J_{CF}$ = 21.76 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –115.17. Spectral data are consistent with those previously reported.[42]

Methyl 4'-chloro-[1,1'-biphenyl]-4-carboxylate (**16b**): Product **16b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-(methoxycarbonyl)phenyl)boronic acid (108.0 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.41 in 5% EtOAc, 95% hexanes) provided **16b** as a white solid (87.7 mg, 89% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.11 (d, *J* = 8.4 Hz, 2H), 7.62 (d, *J* = 8.4 Hz, 2H), 7.56 (d, *J* = 8.4 Hz, 2H), 7.44 (d, *J* = 8.4 Hz, 2H), 3.95 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 144.6, 138.6, 134.6, 130.4, 129.4, 129.3, 128.7, 127.1, 52.4. Spectral data are consistent with those previously reported.[43]

4,4'-Dichloro-1,1'-biphenyl (**17b**): Product **17b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-chlorophenylboronic acid (68.8 mg, 0.44 mmol, 1.1 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and DMF (0.8 mL), with a reaction time of 7 h at 60 °C, followed by purification procedure A. Purification by flash column chromatography (R_f = 0.62 in 100% hexanes) provided **17b** as a white solid (81.7 mg, 92% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.48 (d, *J* = 8.4 Hz, 4H), 7.40 (d, *J* = 8.4 Hz, 4H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 138.6, 133.9, 129.2, 128.4. Spectral data are consistent with those previously reported.[44]

4-Chloro-4'-(trifluoromethyl)-1,1'-biphenyl (**18b**): Product **18b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1

equiv), (4-(trifluoromethyl)phenyl)boronic acid (87.5 mg, 0.44 mmol, 1.1 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.67 in 100% hexanes) provided **18b** as a white solid (82.2 mg, 80% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.70 (d, *J* = 8.3 Hz, 2H), 7.65 (d, *J* = 8.3 Hz, 2H), 7.53 (d, *J* = 8.5 Hz, 2H), 7.45 (d, *J* = 8.5 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 143.5, 138.2, 134.5, 129.7 (q, $^2J_{CF}$ = 32.4 Hz), 129.2, 128.5, 127.3, 125.9 (q, $^3J_{CF}$ = 3.7 Hz), 124.2 (q, $^1J_{CF}$ = 272.5 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –62.5. Spectral data are consistent with those previously reported.[45]

4'-Chloro-[1,1'-biphenyl]-4-carbonitrile (**19b**): Product **19b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-cyanophenyl)boronic acid (70.7 mg, 0.48 mmol, 1.2 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and DMF (0.8 mL), with a reaction temperature of 60 °C, followed by purification procedure A. Purification by flash column chromatography (R_f = 0.33 in 5% EtOAc, 95% hexanes) provided **19b** as a white solid (52.9 mg, 62% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.73 (d, *J* = 8.6 Hz, 2H), 7.65 (d, *J* = 8.6 Hz, 2H), 7.52 (d, *J* = 8.6 Hz, 2H), 7.46 (d, *J* = 8.6 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz $CDCl_3$, δ): 144.6, 137.8, 135.2, 132.9, 129.5, 128.7, 127.8, 118.9, 111.5. Spectral data are consistent with those previously reported.[46]

4'-Chloro-[1,1'-biphenyl]-4-carbaldehyde (**20b**): Product **20b** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-formylphenyl)boronic acid (75.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.26 in 5% EtOAc, 95% hexanes) provided **20b** as a white solid (68.2 mg, 79% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 10.06 (s, 1H), 7.96 (d, *J* = 8.3 Hz, 2H), 7.72 (d, *J* = 8.3 Hz, 2H), 7.57 (d, *J* =

8.6 Hz, 2H) 7.46 (d, *J* = 8.6 Hz, 2H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, δ): 191.9, 146.1, 138.3, 135.6, 134.9, 130.5, 129.4, 128.8, 127.7. Spectral data are consistent with those previously reported.[47]

3-Chloro-4'-methoxy-1,1'-biphenyl (**23b**): Product **23b** was prepared according to the general procedure using 3-chlorophenyl trifluoromethanesulfonate (**23**, 70.5 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (1.6 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.52 in 5% EtOAc, 95% hexanes) provided **23b** as a white solid (64.8 mg, 74% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.53 (dd, *J* = 1.9, 1.9 Hz 1H), 7.50 (d, *J* = 8.8 Hz, 2H), 7.42 (ddd, *J* = 7.9, 1.9, 1.9 Hz, 1H), 7.34 (dd, *J* = 7.9, 7.9 Hz, 1H), 7.27 (ddd, *J* = 7.9, 1.9, 1.9 Hz, 1H, overlaps with solvent), 6.98 (d, *J* = 8.8 Hz, 2H), 3.86 (s, 3H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, δ): 159.6, 142.7, 134.6, 132.3, 129.9, 128.2, 126.8, 126.6, 124.8, 114.3, 55.4. Spectral data are consistent with those previously reported.[48]

2-Chloro-4'-methoxy-1,1'-biphenyl (**24b**): Product **24b** was prepared according to the general procedure using 2-chlorophenyltrifluoromethanesulfonate (**24**, 69.5 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and DMF (0.8 mL) with a reaction time of 4 h at 60 °C followed by purification procedure A. Purification by flash column chromatography (R_f = 0.51 in 5% EtOAc, 95% hexanes) provided **24b** as a pale yellow oil (67.8 mg, 77% yield). ^{1}H NMR (300 MHz, $CDCl_3$, δ): 7.48-7.18 (multiple peaks, 6H, overlaps with solvent), 6.96 (d, *J* = 8.3 Hz, 2H), 3.84 (s, 3H); $^{13}C\{^{1}H\}$ NMR (125 MHz, $CDCl_3$, δ): 159.3, 140.3, 132.8, 132.0, 131.6, 130.8, 130.1, 128.4, 127.0, 113.67, 55.5. Spectral data are consistent with those previously reported.[7]

4-Chloro-4'-methoxy-2-methyl-1,1'-biphenyl (**25b**): Product **25b** was prepared according to the general procedure using 4-chloro-2-methylphenyl trifluoromethanesulfonate (**25**, 74.5 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg,

1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and DMF (0.8 mL) with a reaction time of 4 h at 60 °C followed by purification procedure A. Purification by flash column chromatography (R_f = 0.64 in 10% CH_2Cl_2, 20% toluene, 70% hexanes) provided **25b** as a pale yellow oil (84.9 mg, 91% yield). ^{1}H NMR (300 MHz, $CDCl_3$, δ): 7.25-7.15 (multiple peaks, 4H), 7.11 (d, *J* = 8.1 Hz, 1H), 6.93 (dd, *J* = 9.0, 4.9 Hz, 2H), 3.84 (s, 3H), 2.23 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 158.9, 140.2, 137.6, 133.3, 132.7, 131.3, 130.4, 130.2, 126.0, 113.8, 55.5, 20.6. HRMS (ESI/Q-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{14}H_{14}ClO$ 233.0728; Found 233.0728.

4-Chloro-4'-methoxy-3-(trifluoromethyl)-1,1'-biphenyl (**26b**): Product **26b** was prepared according to the general procedure using 4-chloro-3-(trifluoromethyl)phenyl trifluoromethanesulfonate (**26**, 131.4 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.8 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.48 in 5% EtOAc, 95% hexanes) to yield **26b** as a white solid (70.0 mg, 61% yield); m.p. 47-48 °C [uncorrected, measured against benzoic acid (109–112 °C)]. ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.85 (d, *J* = 2.0 Hz, 1H), 7.63 (dd, *J* = 8.4, 2.0 Hz, 1H), 7.53 (d, *J* = 8.4 Hz, 1H), 7.50 (d, *J* = 8.7 Hz, 2H), 7.00 (d, *J* = 8.7 Hz, 2H), 3.86 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 160.1, 139.9, 131.9, 131.2, 130.9, 130.5, 128.8 (q, $^2J_{CF}$ = 31.9 Hz), 128.3, 125.8 (q, $^3J_{CF}$ = 5.5 Hz), 123.1 (q, $^1J_{CF}$ = 272.6 Hz), 114.7, 55.6; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –62.6. HRMS (EI/Q-TOF) *m*/*z*: $[M]^+$ Calcd for $C_{14}H_{10}ClF_3O$ 286.0372; Found 286.0373.

2-Chloro-4'-methoxy-[1,1'-biphenyl]-4-carbaldehyde (**27b**): Product **27b** was prepared according to the general procedure using 2-chloro-4-formylphenyl trifluoromethanesulfonate (**27**, 115.4 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.8 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure A. The crude residue was

purified by flash column chromatography (R_f = 0.3 in 5% EtOAc, 95% hexanes) to yield **27b** as a off-white solid (68.5 mg, 69% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 10.00 (s, 1H), 7.97 (d, J = 1.6 Hz, 1H), 7.80 (dd, J = 7.9, 1.6 Hz, 1H), 7.51 (d, *J* =7.9 Hz, 1H), 7.43 (d, *J* = 8.7 Hz, 2H), 7.00 (d, *J* = 8.7 Hz, 2H), 3.87 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 190.7, 160.0, 146.2, 136.3, 133.8, 132.2, 131.3, 130.7, 130.6, 128.0, 113.9, 55.5. Spectral data are consistent with those previously reported.[49]

3-Chloro-4'-methoxy-4-methyl-1,1'-biphenyl (**28b**): Product **28b** was prepared according to the general procedure using 3-chloro-4-methylphenyl trifluoromethanesulfonate (**28**, 109.9 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL, 0.5 M) followed by purification procedure A. Purification by flash column chromatography (R_f = 0.63 in 15% EtOAc, 85% hexanes) provided **28b** as a white solid (73.4 mg, 79% yield). ^{1}H NMR (500 MHz, $CDCl_3$), δ (ppm): 7.54 (d, *J* = 1.8 Hz, 1H), 7.49 (d, *J* = 8.7 Hz, 2H), 7.34 (dd, *J* = 7.8, 1.8 Hz, 1H), 7.25 (d, *J* = 7.8 Hz, 1H, overlaps with solvent), 6.97 (d, *J* = 8.7 Hz, 2H), 3.85 (s, 3H), 2.40 (s, 3 H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$), δ (ppm): 159.5, 140.2, 134.8, 134.3, 132.5, 131.3, 128.1, 127.3, 125.0, 114.4, 55.5, 19.8. Spectral data are consistent with those previously reported.[50]

4-Chloro-2-(4-methoxyphenyl)pyridine (**34b**): <u>*With SIMes:*</u> Product **34b** was prepared according to the general procedure using 4-chloropyridin-2-yl trifluoromethanesulfonate (**34**, 104.6 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.8 mmol, 6.9 equiv), and THF (0.8 mL, 0.5 M) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.32 in 8% EtOAc, 92% hexanes) to yield **34b** as a white solid (81.7 mg, 93% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.54 (d, *J* = 5.3 Hz, 1H); 7.94 (d, *J* = 8.8 Hz, 2H), 7.67 (d, *J* = 1.7 Hz, 1H), 7.18 (dd, *J* = 5.3, 1.7 Hz, 1H), 7.00 (d, *J* = 8.8 Hz, 2H), 3.87 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 161.1, 158.1, 150.5, 144.8, 130.9, 128.5, 121.7,

120.1, 114.4, 55.5. Spectral data are consistent with those previously reported.[51] *With SIPr:* Product **34b** was prepared according to the general procedure using using 4-chloropyridin-2-yl trifluoromethanesulfonate (**34**, 20.9 mg, 0.08 mmol, 1 equiv), 4-methoxyphenylboronic acid (15.2 mg, 0.1 mmol, 1.25 equiv), KF (13.9 mg, .24 mmol, 3 equiv), **3** (1.7 mg, 0.0024 mmol, 3 mol %), degassed H_2O (10 μL, 0.56 mmol, 7 equiv), and THF (0.32 mL). Undecane was added as an internal GC standard, and the reaction mixture was diluted with Et_2O, filtered through celite, and analyzed by GC, indicating 27% crude GC yield of **34b**. The retention time of the product prepared by this method matches that of the analogous reaction with SIMes.

2-Chloro-5-(4-methoxyphenyl)pyridine (**35b**): Product **35b** was prepared according to the general procedure using 2-chloropyridin-5-yl trifluoromethanesulfonate (**35**, 104.6 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **5** (7.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (100 μL, 5.6 mmol, 13.9 equiv), and THF (0.8 mL) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.35 in 10% EtOAc, 90% hexanes) to yield **35b** as a white solid (47.0 mg, 53% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.56 (d, *J* = 2.6 Hz, 1H), 7.79 (dd, *J* = 8.4, 2.6 Hz, 1H), 7.48 (d, *J* = 8.7 Hz, 2H), 7.36 (d, *J* = 8.4 Hz, 1H), 7.01 (d, *J* = 8.7 Hz, 2H), 3.86 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 160.2, 149.8, 147.7, 136.8, 135.4, 129.0, 128.3, 124.3, 114.8, 55.6. Spectral data are consistent with those previously reported.[52]

2-Chloro-4-(4-methoxyphenyl)pyridine (**36b**): Product **36b** was prepared according to a modified procedure using 2-chloropyridin-4-yl trifluoromethanesulfonate (**36**, 104.6 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **7** (8.2 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL). The reaction was run at 60 °C, followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.42 in 20% EtOAc, 80% hexanes) to yield **36b** as a white solid (105.5 mg, 79% yield); ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.38 (d, *J* = 5.2 Hz, 1H), 7.58 (d, *J* = 8.8 Hz, 2H), 7.50 (d, *J* = 1.2 Hz, 1H), 7.39 (dd, *J* = 5.2, 1.2 Hz, 1H), 7.01 (d, *J*

= 8.8 Hz, 2H), 3.87 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 161.2, 152.4, 151.2, 150.0, 129.2, 128.4, 121.5, 120.0, 114.8, 55.6. Spectral data are consistent with those previously reported.[53]

5-Chloro-2-(4-methoxyphenyl)pyridine (**37b**): Product **37b** was prepared according to the general procedure using 5-chloropyridin-2-yl trifluoromethanesulfonate (104.6 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.8 mmol, 6.9 equiv), and 2:1 THF/toluene (0.8 mL) purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.42 in 5% EtOAc, 95% hexanes) to yield **37b** as a white solid (100.0 mg, 75% yield); m.p. 90-93 °C [uncorrected, measured against benzoic acid (109–112 °C)]. ^1H NMR (500 MHz, $CDCl_3$, δ): 8.59 (d, *J* = 2.3 Hz, 1H), 7.92 (d, *J* = 8.7 Hz, 2H), 7.68 (dd, *J* = 8.8, 2.3 Hz, 1H), 7.61 (d, *J* = 8.8 Hz, 1H) 7.00 (d, *J* = 8.7 Hz, 2H), 3.87 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 160.8, 155.4, 148.5, 136.5, 131.0, 129.9, 128.3, 120.5, 114.4, 55.5. Spectral data are consistent with those previously reported.[51]

2'-Methyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**8a**): Product **8a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 2-tolylboronic acid (68.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL) followed by purification procedure C. Purification by HPLC provided **8a** as a colorless oil (85.1 mg, 67% yield). ^1H NMR (500 MHz, $CDCl_3$, δ): 7.39 (d, *J* = 8.6 Hz, 2H), 7.34-7.23 (multiple peaks, overlaps with solvent, 5H), 7.19 (d, *J* = 7.3 Hz, 1H), 2.25 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 148.7, 142.6, 140.1, 135.4, 131.2, 130.7, 129.8, 128.2, 126.2, 121.2, 118.9 (q, $^1J_{CF}$ = 320.8 Hz), 20.5; ^{19}F NMR (470 MHz, $CDCl_3$, δ): −72.8. Spectral data are consistent with those previously reported.[4] *Larger scale reaction:* Product **8a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 437.5 μL, 2.5 mmol, 1 equiv), 2-tolylboronic acid (373.9 mg, 2.75 mmol, 1.1 equiv) KF (435.6 mg, 7.5 mmol, 3 equiv), **3** (21.1 mg, 0.03 mmol, 1.5 mol %), degassed H_2O (125 μL, 8.75 mmol, 3.5 equiv), and toluene (5

mL). Purification by flash column chromatography (R_f = 0.70 in 1% Et_3N, 99% hexanes) provided **8a** as a colorless oil (572.1 mg, 72% yield). Spectral data are identical to those reported above.

[1,1'-Biphenyl]-4-yl trifluoromethanesulfonate (**10a**): Product **10a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 74.7 μL, 0.4 mmol, 1 equiv), phenylboronic acid (61.0 mg, 0.44 mmol, 1.1 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (1.6 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.59 in 100% pentane) to yield **10a** as a white solid (104.4 mg, 86% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.65 (d, J = 8.8 Hz, 2H), 7.56 (d, J = 7.7 Hz, 2H), 7.47 (m, 2H), 7.40 (tdd, J = 7.7, 1.4, 1.4 Hz, 1H), 7.35 (d, J = 8.8 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 149.1, 141.9, 139.5, 129.1, 129.0, 128.2, 127.3, 121.8, 118.9 (q, $^1J_{C\text{-}F}$ = 322.1 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8. Spectral data are consistent with those previously reported.[4]

3'-Methyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**11a**): Product **11a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 3-tolylboronic acid (68.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL) followed by purification procedure A. Purification by flash column chromatography (R_f = 100% hexanes) provided **11a** as a white solid (106.0 mg, 84% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.64 (d, J = 8.7 Hz, 2H); 7.38-7.31 (multiple peaks, 6H); 2.43 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 149.0, 142.0, 139.4, 138.8, 129.0, 128.9, 128.1, 127.6, 124.4, 121.7, 118.9 (q, $^1J_{C\text{-}F}$ = 322.0 Hz), 21.6; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8. HRMS (EI/Q-TOF) m/z: $[M]^+$ Calcd for $C_{14}H_{11}F_3O_3S$ 316.0381; Found 316.0351.

4'-Methoxy-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**12a**): Product **12a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7

mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and dioxane (0.8 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.41 in 1% Et_3N, 3% benzene, 5% EtOAc, 91% hexanes) to yield **12a** as a white solid (79.0 mg, 59% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.60 (d, *J* = 8.8 Hz, 2H), 7.49 (d, *J* = 8.8 Hz, 2H), 7.31 (d, *J* = 8.8 Hz, 2H), 6.99 (d, *J* = 8.8 Hz, 2H), 3.86 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 159.9, 148.6, 141.5, 131.9, 128.5, 128.4, 121.7, 119.0 (q, $^1J_{CF}$ = 321.2 Hz), 114.6, 55.5; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8. Spectral data are consistent with those previously reported.[22]

4'-Fluoro-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**15a**): Product **15a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-fluorophenylboronic acid (67.2 mg, 0.48 mmol, 1.2 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.37 in 1% Et_3N, 5% benzene, 94% hexanes) to yield **15a** as a colorless, low-melting solid (111.3 mg, 87% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.60 (d, *J* = 8.7 Hz, 2H), 7.52 (dd, $^3J_{HH}$ = 8.8 Hz, $^3J_{HF}$ = 5.3 Hz, 2H), 7.34 (d, *J* = 8.7 Hz, 2H), 7.16 (t, *J* = 8.8 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 164.1, 162.1, 149.10, 140.91, 135.62 (d, $^3J_{CF}$ = 3.5 Hz), 128.95, 121.91, 119.14 (q, $^1J_{CF}$ = 320.8 Hz, *C*F_3), 116.14 (d, $^2J_{CF}$ = 22.0 Hz); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8, –114.32; HRMS (EI/Q-TOF) *m/z*: $[M]^+$ Calcd for $C_{13}H_8F_4O_3S$ 320.0130; Found 320.0111.

4'-(((Trifluoromethyl)sulfonyl)oxy)-[1,1'-biphenyl]-4-yl acetate (**16a**): Product **16a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-(methoxycarbonyl)phenyl)boronic acid (108.0 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and THF (0.8 mL, 0.5 M) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.38 in 1% Et_3N, 10% EtOAc,

89% hexanes) to yield **16a** as a white solid (98.0 mg, 68% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 8.13 (d, *J* = 8.2 Hz, 2H), 7.69 (d, *J* = 8.8 Hz, 2H), 7.63 (d, *J* = 8.2 Hz, 2H), 7.38 (d, *J* = 8.8 Hz, 2H), 3.95 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 166.9, 149.6, 143.7, 140.7, 130.4, 129.9, 129.3, 127.3, 122.0, 119.0 (q, $^{1}J_{CF}$ = 322.0 Hz), 52.4; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.7; HRMS (ESI/Q-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{15}H_{12}F_3O_5S$ 361.0352; Found 361.0345.

4'-(Trifluoromethyl)-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**18a**): Product **18a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-(trifluoromethyl)phenyl)boronic acid (91.2 mg, 0.48 mmol, 1.2 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.37 in 1% Et_3N, 5% benzene, 94% hexanes) to yield **18a** as a white solid (109.8 mg, 74% yield); m.p. 56–59 °C [uncorrected, measured against benzoic acid (108–112 °C)]; ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.73 (d, *J* = 8.1 Hz, 2H), 7.68-7.65 (multiple peaks, 4H), 7.39 (d, *J* = 8.8 Hz, 2H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 149.70, 142.97, 140.42, 130.40 (q, $^{2}J_{CF}$ = 32.9 Hz), 129.33, 127.74, 126.17 (q, $^{3}J_{CF}$ = 3.7 Hz), 124.29 (q, $^{1}J_{CF}$ = 272.5 Hz, Ar*C*F_3), 122.14, 119.05 (q, $^{1}J_{CF}$ = 320.0 Hz, S*C*F_3); ^{19}F NMR (470 MHz, $CDCl_3$, δ): –62.6, –72.8; HRMS (EI/Q-TOF) *m*/*z*: $[M]^+$ Calcd for $C_{14}H_8F_6O_3S$ 370.0098; Found 370.0087.

4'-Methyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**21a**): Product **21a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), 4-tolylboronic acid (68.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (0.8 mL) followed by purification procedure B. The crude residue was purified by preparatory TLC (R_f = 0.47 in 100% pentane) to yield **21a** as a white solid (117.7 mg, 93% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.63 (d, *J* = 8.9 Hz, 2H), 7.46 (d, *J* = 8.1 Hz, 2H), 7.33 (d, *J* = 8.9 Hz, 2H), 7.27 (d, *J* = 8.1 Hz, 2H, overlaps with solvent), 2.41 (s, 3H, CH_3); ^{13}C{^{1}H} NMR (125 MHz,

$CDCl_3$, δ): 148.9, 141.8, 138.2, 136.6, 129.9, 128.8, 127.2, 121.8, 119.0 (q, $^1J_{CF}$ = 323.1 Hz), 21.3; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8. Spectral data are consistent with those previously reported.[54]

4'-Vinyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**22a**): Product **22a** was prepared according to the general procedure using 4-chlorophenyl trifluoromethanesulfonate (**1**, 70 μL, 0.4 mmol, 1 equiv), (4-vinylphenyl)boronic acid (74.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and dioxane (0.8 mL), with a reaction time of 4 h at 60 °C, followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.4 in 1% Et_3N, 5% benzene, 94% hexanes) to yield **22a** as a white solid (77.8 mg, 59% yield). BHT (1.0 mg) was added to the product following column chromatography in order to prevent polymerization during concentration and storage. The product mass reported above excludes the added mass of the BHT. ^1H NMR (500 MHz, $CDCl_3$, δ): 7.65 (d, *J* = 8.8 Hz, 2H), 7.53 (d, *J* = 8.6 Hz, 2H), 7.50 (d, *J* = 8.6 Hz, 2H), 7.34 (d, *J* = 8.8 Hz, 2H), 6.76 (dd, *J* = 17.8, 10.9 Hz, 1H), 5.82 (dd, *J* = 17.8, 0.6 Hz, 1H), 5.31 (dd, *J* = 10.9, 0.6 Hz, 1H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 149.1, 141.4, 138.7, 137.6, 136.3, 128.9, 127.5, 127.0, 121.9, 119.2 (q, $^1J_{CF}$ = 320.8 Hz), 114.8; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8; HRMS (ESI/Q-TOF) *m/z*: $[M + H]^+$ Calcd for $C_{15}H_{12}F_3O_3S$ 329.0454; Found 329.0450.

4'-Methoxy-[1,1'-biphenyl]-3-yl trifluoromethanesulfonate (**23a**): Product **23a** was prepared according to the general procedure using 3-chlorophenyl trifluoromethanesulfonate (**23**, 70.5 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (91.2 mg, 0.6 mmol, 1.5 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and toluene (1.6 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.52 in 1% Et_3N, 10% EtOAc, 89% hexanes) to yield **23a** as a white solid (100.9 mg, 76% yield). ^1H NMR (500 MHz, $CDCl_3$, δ): 7.56 (ddd, *J* = 7.9, 1.6, 1.6 Hz, 1H), 7.53-7.46 (multiple peaks, 3H), 7.46 (dd, *J* = 1.6, 1.6 Hz, 1H), 7.20 (m, 1H), 7.00 (d, *J* = 8.9 Hz, 2H), 3.87 (s, 3H); $^{13}C\{^1H\}$ NMR (125 MHz, $CDCl_3$, δ): 160.0, 150.2, 143.7,

131.6, 130.6, 128.4, 126.7, 119.6, 119.3, 119.0 (q, $^1J_{CF}$ = 320.9 Hz), 114.5, 55.41; ^{19}F NMR (470 MHz, $CDCl_3$, δ): –72.8. Spectral data are consistent with those previously reported.[55]

4'-Methoxy-[1,1'-biphenyl]-2-yl trifluoromethanesulfonate (**24a**): Product **24a** was prepared according to the general procedure using 2-chlorophenyl trifluoromethanesulfonate (**24**, 69.5 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.58 in 10% DCM, 20% benzene, 70% hexanes) to yield **24a** as a pale yellow oil (80.1 mg, 60% yield). ^{1}H NMR (300 MHz, $CDCl_3$, δ): 7.50-7.32 (multiple peaks, 6H), 6.99 (d, *J* = 8.7 Hz, 2H), 3.86 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 159.9, 147.1, 135.5, 132.1, 130.7, 128.7, 128.1, 122.2, 118.6 (q, $^1J_{CF}$ = 321.2 Hz), 114.2, 55.5 (two signals are coincidentally overlapping); ^{19}F NMR (282 MHz, $CDCl_3$, δ): –74.0; HRMS (EI/Q-TOF) *m/z*: $[M]^+$ Calcd for $C_{14}H_{11}F_3O_4S$ 332.0330; Found 332.0307.

4'-Methoxy-2-methyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**25a**): Product **25a** was prepared according to the general procedure using 4-chloro-2-methylphenyl trifluoromethanesulfonate (**25**, 74.7 μL, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL, 0.5 M) followed by purification procedure B. Purification by flash column chromatography (R_f = 0.57 in 10% DCM, 20% benzene, 70% hexanes) provided **25a** as a pale yellow oil (80.5 mg, 58% yield). ^{1}H NMR (500 MHz, $CDCl_3$), δ (ppm): 7.48 (d, *J* = 8.8 Hz, 2H), 7.46 (d, *J* = 2.1 Hz, 1H), 7.41 (dd, *J* = 8.6, 2.4 Hz, 1H), 7.27 (d, *J* = 8.7 Hz, 1H, overlaps with solvent), 6.98 (d, *J* = 8.6 Hz, 2H), 3.86 (s, 3H), 2.43 (s, 3H). ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$), δ (ppm): 159.8, 147.6, 141.2, 132.1, 131.1, 130.5, 128.4, 125.9, 121.6, 118.8 (q, $^1J_{C\text{-}F}$ = 320 Hz), 114.5, 55.5, 16.7. ^{19}F NMR (282 MHz, $CDCl_3$), δ (ppm): –73.8. HRMS (EI/Q-TOF) m/z: $[M]^+$ Calcd for $C_{15}H_{13}F_3O_4S$ 346.0487; Found 346.0461.

4'-Methoxy-2'-(trifluoromethyl)-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**26a**): Product **26a** was prepared according to the general procedure using 4-chloro-3-(trifluoromethyl) phenyl trifluoromethanesulfonate (**26**, 131.4 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and 1:1 dioxane/toluene (1.6 mL) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.41 in 3% EtOAc, 97% hexanes, 1% Et_3N) to yield **26a** as a cololrless oil (80.3 mg, 50% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.64 (d, *J* = 1.7 Hz, 1H), 7.49 (dd, *J* = 8.4, 1.7 Hz, 1H), 7.44 (d, *J* = 8.4 Hz, 1H, 7.24 (d, *J* = 8.2 Hz, 2H), 6.95 (d, *J* = 8.2 Hz, 2H), 3.86 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 159.9, 148.1, 142.0, 134.6, 130.9 (q, $^2J_{CF}$ = 31.3 Hz), 130.2, 124.3, 123.0 (q, $^1J_{CF}$ = 278.3 Hz), 119.7 (q, $^3J_{CF}$ = 5.5 Hz), 119.0 (q, $^1J_{CF}$ = 319.9 Hz), 113.7, 55.4 (two signals are coincidentally overlapping); ^{19}F NMR (282 MHz, $CDCl_3$, δ): −57.7, −72.7. HRMS (EI/Q-TOF) *m*/*z*: $[M]^+$ Calcd for $C_{15}H_{10}F_6O_4S$ 400.0204; Found 400.0178.

4'-Methoxy-2-methyl-[1,1'-biphenyl]-4-yl trifluoromethanesulfonate (**28a**): Product **28a** was prepared according to the general procedure using 3-chloro-4-methylphenyl trifluoromethanesulfonate (**28**, 109.9 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.0120 mmol, 3 mol %), degassed H_2O (50 μL, 2.76 mmol, 6.9 equiv), and THF (0.8 mL) followed by purification procedure B. The crude residue was purified by flash column chromatography (R_f = 0.50 in 1% NEt_3, 4% EtOAc, 10% benzene, 85% hexanes) to yield **28a** as a colorless oil (98.8 mg, 71% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.48 (d, *J* = 8.7 Hz, 2H), 7.46 (d, *J* = 2.3 Hz, 1H), 7.40 (dd, J = 8.7, 2.3 Hz, 1H), 7.27 (d, *J* = 8.7 Hz, 1H, overlaps with solvent), 6.98 (d, *J* = 8.7 Hz, 2H), 3.86 (s, 3H), 2.44 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 159.8, 147.6, 141.2, 132.1, 131.1, 130.5, 128.4, 125.9, 121.6, 118.8 (q, $^1J_{CF}$ = 320.1 Hz), 114.5, 55.5, 16.7; ^{19}F NMR (282 MHz, $CDCl_3$, δ): −73.8; HRMS (EI/Q-TOF) *m*/*z*: $[M]^+$ Calcd for $C_{15}H_{13}F_3O_4S$ 346.0487; Found 346.0467.

4-Formyl-4'-methoxy-[1,1'-biphenyl]-2-yl trifluoromethanesulfonate (**29a**): Product **29a** was prepared according to the general procedure using 2-chloro-5-formylphenyl trifluoromethanesulfonate (**29**, 115.4 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and dioxane (0.8 mL) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.36 in 15% EtOAc, 85% hexanes) to yield **29a** as a yellow oil (83.7 mg, 58% yield). ^{1}H NMR (500 MHz, $CDCl_3$, δ); 10.0 (s, 1H), 7.94 (dd, *J* = 7.9, 1.3 Hz, 1H), 7.86 (d, *J* = 1.3 Hz, 1H), 7.65 (d, *J* = 7.9 Hz, 1H), 7.45 (d, *J* = 8.5 Hz, 2H), 7.02 (d, *J* = 8.5 Hz, 2H), 3.87 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 189.9, 160.6, 147.4, 141.3, 136.6, 132.7, 130.8, 129.6, 126.9, 123.0, 118.5 (q, $^1J_{CF}$ = 320.9 Hz), 114.4, 55.5; ^{19}F NMR (282 MHz, $CDCl_3$, δ): −73.8. Anal. Calcd for $C_{15}H_{11}F_3O_5S$: C, 50.00; H, 3.08. Found: C, 49.99, H, 3.06.

4-[4'-Methoxy-(1,1'-biphenyl)-4-carbonyl]phenyl trifluoromethanesulfonate (**30a**): Product **30a** was prepared according to the general procedure using 4-(4-chlorobenzoyl)phenyl trifluoromethanesulfonate (**30**, 145.9 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (1.6 mL) followed by purification procedure A. The crude residue was purified by flash column chromatography (R_f = 0.38 in 10% EtOAc, 10% acetone, 80% hexanes) to yield **30a** as a white solid (124.4 mg, 57% yield); m.p. 124-128 °C [uncorrected, measured against benzoic acid (109–112 °C)].). ^{1}H NMR (500 MHz, $CDCl_3$, δ): 7.93 (d, *J* = 8.8 Hz, 2H), 7.86 (d, *J* = 8.4 Hz, 2H), 7.69 (d, *J* = 8.4 Hz, 2H), 7.61 (d, *J* = 8.8 Hz, 2H), 7.42 (d, *J* = 8.8 Hz, 2H), 7.02 (d, *J* = 8.8 Hz, 2H), 3.89 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 194.4, 160.2, 152.0, 145.7, 138.1, 134.5, 132.22, 132.19, 130.9, 128.6, 126.7, 121.5, 118.9 (q, $^1J_{CF}$ = 333.3 Hz), 114.7, 55.6; ^{19}F NMR (282 MHz, $CDCl_3$, δ): −72.7. HRMS (ESI/Q-TOF) *m*/*z*: $[M + H]^+$ Calcd for $C_{21}H_{15}F_3O_5S$ 437.0671; Found 437.0652.

6-(4-Methoxyphenyl)pyridin-3-yl trifluoromethanesulfonate (**35a**): Product **35a** was prepared according to the general procedure using 2-chloropyridin-5-yl trifluoromethanesulf onate (104.6 mg, 0.4 mmol, 1 equiv), 4-methoxyphenylboronic acid (76.0 mg, 0.5 mmol, 1.25 equiv), KF (69.7 mg, 1.2 mmol, 3 equiv), **3** (8.5 mg, 0.012 mmol, 3 mol %), degassed H_2O (25 μL, 1.4 mmol, 3.5 equiv), and toluene (1.6 mL, 0.25 M) followed by workup A. The crude residue was purified by flash column chromatography (R_f = 0.28 in 5% EtOAc, 95% hexanes) to yield **35a** as a white solid (103.1 mg, 77% yield); m.p. 63-64°C [uncorrected, measured against benzoic acid (109–112 °C)]. ^{1}H NMR (500 MHz, $CDCl_3$, δ); 8.60 (d, *J* = 2.8 Hz, 1H), 7.95 (d, *J* = 8.7 Hz, 2H), 7.75 (d, *J* = 8.9 Hz, 1H), 7.64 (dd, *J* = 8.9, 2.8 Hz, 1H), 7.01 (d, *J* = 8.7 Hz, 2H), 3.87 (s, 3H); ^{13}C{^{1}H} NMR (125 MHz, $CDCl_3$, δ): 161.3, 157.3, 145.4, 142.4, 130.3, 129.7, 128.6, 120.5, 119.0 (q, $^1J_{CF}$ = 321.5 Hz), 114.5, 55.5; ^{19}F NMR (282 MHz, $CDCl_3$, δ): –72.5. HRMS (EI/Q-TOF) *m*/*z*: $[M]^+$ Calcd for $C_{13}H_{10}F_3NO_4S$ 333.0283; Found 333.0263.

ASSOCIATED CONTENT

Supporting Information. The Supporting Information is available free of charge on the ACS Publications website.

NMR spectra, crystallographic details, computational details, energies and Cartesian coordinates of minimum energy calculated structures (PDF)

X-ray crystallographic data for **3** and **5** (CIF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

This work was supported by NSF CAREER (CHE-1848090) and Montana State University. The NSF REU program (CHE-1461218) is acknowledged for support for J.N.H. Calculations were performed on Comet at SDSC through XSEDE (CHE-170089), which is supported by NSF (ACI-1548562). NMR spectra were recorded on an instrument purchased with support from the NSF (NSF-MRI:DBI-1532078) and the Murdock Charitable Trust Foundation (2015066:MNL). X-ray crystallographic data were collected at the University of Montana X-ray diffraction core facility (NIH, CoBRE NIGMS P20GM103546) using an instrument principally supported by NSF (MRI CHE-1337908). We thank Daniel A. Decato for his assistance in solving crystal structures and the Cloninger lab at MSU for use of HPLC.

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13. For an example of an NHC ligand providing the opposite stereoselectivity as a phosphine ligand in a Ni-catalyzed cross coupling, see (a) Harris, M. R.; Hanna, L. E.; Greene, M. A.; Moore, C. E.; Jarvo, E. R. Retention or Inversion in Stereospecific Nickel-Catalyzed Cross-Coupling of Benzylic Carbamates with Arylboronic Esters: Control of Absolute Stereochemistry with an Achiral Catalyst. *J. Am. Chem. Soc.* **2013**, *135*, 3303–3306. (b) Zhang, S.-Q.; Taylor, B. L. H.; Ji, C.-L.; Gao, Y.; Harris, M. R.; Hanna, L. E.; Jarvo, E. R.; Houk, K. N.; Hong, X. Mechanism and Origins of Ligand-Controlled Stereoselectivity of Ni-Catalyzed Suzuki–Miyaura Coupling with Benzylic Esters: A Computational Study. *J. Am. Chem. Soc.* **2017**, *139*, 12994–13005.
14. For an example of an NHC ligand providing the opposite regioselectivity as a phosphine ligand in a Cu-catalyzed aminoboration see Sakae, R.; Hirano, K.; Miura, M. Ligand-Controlled Regiodivergent Cu-Catalyzed Aminoboration of Unactivated Terminal Alkenes. *J. Am. Chem. Soc.* **2015**, *137*, 6460–6463.
15. A few substrate/arylboronic acid combinations that were evaluated led to poor conversions or to products that were challenging to isolate due to decomposition. In most of these cases, selectivity (analyzed by GC) appeared as expected based on ligand. However, yield and selectivity are poor for some strongly electronically biased substrates (in particular, those containing —CHO substituents). See the Supporting Information for details.

16. With some substrate/arylboronic acid combinations, we found that better results could be obtained by modifying the reaction conditions (solvent, equivalents of H_2O, temperature) from the optimized conditions in Table 1. See the Supporting Information for details.
17. Suzuki-Miyaura couplings were recently shown to be favored over Heck couplings in the presence of water or another hydroxide source: Molloy, J. J.; Seath, C. P.; West, M. J.; McLaughlin, C.; Fazakerley, N. J.; Kennedy, A. R.; Nelson, D. J.; Watson, A. J. B. Interrogating Pd(II) Anion Metathesis Using a Bifunctional Chemical Probe: A Transmetalation Switch. *J. Am. Chem. Soc.* **2018**, *140*, 126–130.
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20. Anionic Pd species in cross coupling have been proposed. Selected examples: (a) Amatore, C.; Jutand, A., Anionic Pd(0) and Pd(II) Intermediates in Palladium-Catalyzed Heck and Cross-Coupling Reactions. *Acc. Chem. Res.* **2000**, *33*, 314—321; (b) Kozuch, S.; Shaik, S.; Jutand, A.; Amatore, C. Active Anionic Zero-Valent Palladium Catalysts: Characterization by Density Functional Calculations. *Chem. Eur. J.* **2004**, *10*, 3072–3080; (c) Roy, A. H.; Hartwig, J. F. Oxidative Addition of Aryl Sulfonates to Palladium(0) Complexes of Mono- and Bidentate Phosphines. Mild Addition of Aryl Tosylates and the Effects of Anions on Rate and Mechanism. *Organometallics* **2004**, *23*, 194—202. (d) Guest, D.; da Silva, V. H. M.; Batista, A. P. D.; Roe, S. M.; Braga, A. A. C.; Navarro, O. (N-Heterocyclic Carbene)-Palladate Complexes in Anionic Mizoroki-Heck Coupling Cycles: A Combined Experimental and Computational Study. *Organometallics* **2015**, *34*, 2463–2470.

21. Similar selectivity is expected with a Pd–fluoride rather than Pd–hydroxide species, but DFT calculations on transition structures for oxidative addition at C—Cl using [Pd(F)—SIMes]$^-$ fail to converge at the level of theory used for geometry optimizations.
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23. Oxidative addition of aryl triflates at anionic [PdLX]$^-$ (L = P(*o*-tol)$_3$, X = Br] has been proposed even in nonpolar solvents such as toluene; see reference 20c.
24. It is logical to assume that, like other anionic bisligated complexes, [Pd(SIPr)X]$^-$ would favor reaction at C—OTf over C—Cl. However, we are unable to evaluate this computationally, as all attempts to calculate a transition structure for oxidative addition of **1** at C—Cl with [Pd(SIPr)X]$^-$ (X = F or OH) failed to converge.
25. For a recent review, see Almond-Thynne, J.; Blakemore, D. C.; Pryde, D. C.; Spivey, A. C. Site-Selective Suzuki–Miyaura Coupling of Heteroaryl Halides – Understanding the Trends for Pharmaceutically Important Classes. *Chem. Sci.* **2017**, *8*, 40–62.
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