Phenyl Backbone-Derived P,O- and P,N-Ligands for Palladium/Ligand-Catalyzed Aminations of Aryl Bromides, Iodides, and Chlorides. Syntheses and Structures of $(P,O)_n$-Palladium(II)Aryl(Br) Complexes

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The phenyl backbone-derived P,O- and P,N-compounds **1**−**10** were investigated for their utility as ligands in palladium/ligand-catalyzed aryl aminations. The P,O-ligands 2-(2′-diphenylphosphinophenyl)-2-methyl-1,3-dioxolane (**1**) and 2-(2′-dicyclohexylphosphinophenyl)-2-methyl-1,3-dioxolane (**6**) in combination with $Pd(dba)_2$ afford active catalysts for general aminations of aryl bromides, iodides, and chlorides. The Pd/ligand **6** catalyst, in particular, is efficient for general aminations of aryl chlorides. But the structurally related ligand 2-(2′-diphenylphosphinophenyl)-1,3-dioxolane (**2**) and other P,O- or P,N-ligands were less effective. The reactions of $Pd(dba)_2$ with excess 4-^{t}Bu-C_6H_4Br and excess ligand (**1**, **6**, **2**) or the ligand displacement reactions of $\{Pd[P(o\text{-toluyl})_3](4\text{-}^t\text{Bu-}C_6H_4)(\mu\text{-Br})\}_2$ with ligands **1**, **6**, and **2** afford the potential catalytic intermediates of Pd/L-catalyzed (L = **1**, **6**, **2**) aryl aminations, viz., LPd(4-^{t}Bu-C_6H_4)(Br) (**11**, L = **1**; **12**, L = **6**) and L_2Pd(4-^{t}Bu-C_6H_4)(Br) (**13**, L = **2**), respectively. The X-ray crystallographic studies establish that ligands **1** and **6** function as P,O-chelating ligands in complexes **11** and **12**, respectively, while ligand **2** functions as a monodentate P-ligand in complex **13**. The NMR spectroscopic studies indicate that complexes **11**−**13** retain their solid-state structures in solution. The higher efficiency of ligands **1** and **6** in comparison with ligand **2** and other P,O- or P,N-ligands in Pd/L-catalyzed aryl aminations most likely results from the formation of the P,O-chelating Pd/L complexes, which appear to be most suitable for aryl aminations involving this class of ligands.

Introduction

The palladium-catalyzed aminations[1] of aryl bromides,[2] iodides,[3] triflates,[4] chlorides,[5] and tosylates[5b,6] with primary and secondary amines provide a general and efficient route to a wide variety of industrially significant arylamines[7] and represent a truly remarkable development in the important field of metal-catalyzed C−N bond formation.[8] After the original discovery of the utility of the tris(*o*-toluyl)phosphine ligand in assisting palladium-catalyzed aminations of aryl halides,[1a,b,d,2a,c] a variety of ligands exhibiting improved, but substrate-specific, efficiency were discovered.[2b,d−f,4,5] The bis-phosphines 2,2′-bis(diphenylphosphino)-1,1′-binaphthyl (BINAP) and diphenylphosphinoferrocene (DPPF) were found to exhibit improved ability in assisting palladium- and nickel-catalyzed aminations of aryl bromides, iodides, and triflates with primary alkylamines and secondary cyclic amines, but proved to be unsuitable in related aminations involving secondary acyclic alkylamines and diarylamines. Similarly, bis[2-(diphenylphosphino)phenyl]ether (DPEphos) was found to exhibit improved efficiency in specifically assisting palladium-catalyzed amination of aryl bromides with anilines.[2h] The ferrocenyl backbone-derived mono-phos-

(1) Palladium-catalyzed aminations of aryl halides with aminostannanes were first investigated and reported by Kosugi et al.: (a) Kosugi, M.; Kameyama, M, Migita, T. *Chem. Lett.* **1983**, 927−928. (b) Kosugi, M.; Kameyama, M.; Sano, H.; Migita, T. *Nippon Kagaku Kaishi* **1985**, *3*, 547−551. The aminostannane-based methodology was later significantly generalized by the employment of a transamination-Pd-catalysis protocol by Buchwald et al. (c) Guram, A. S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1994**, *116*, 7901−7902. The tin-free metal-catalyzed aryl aminations were subsequently developed; see refs 2−5 and: (d) Buchwald, S. L.; Guram, A. S. US Patent 5,576,460, 1996.

(2) For leading references to palladium-catalyzed aminations of aryl bromides, see: (a) Guram, A. S.; Rennels, R. A.; Buchwald, S. L. *Angew. Chem., Int. Ed. Engl.* **1995**, *34*, 1348−1350. (b) Wolfe, J. P.; Wagaw, S.; Buchwald, S. L. *J. Am. Chem. Soc.* **1996**, *118*, 7215−7216. (c) Louie, J.; Hartwig, J. F. *Tetrahedron Lett.* **1995**, *36*, 3609−3612. (d) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 7217−7218. (e) Marcoux, J.-F.; Wagaw, S.; Buchwald, S. L. *J. Org. Chem.* **1997**, *62*, 1568−1569. (f) Nishiyama, M.; Yamamoto, T.; Koie, Y. *Tetrahedron Lett.* **1998**, *39*, 617−620. (g) Wolfe, J. P.; Buchwald, S. L. *Tetrahedron Lett.* **1997**, *38*, 6359−6362. (h) Sadighi, J. P.; Harris, M. C.; Buchwald, S. L. *Tetrahedron Lett.* **1998**, *39*, 5327−5330. (i) Rossen, K.; Pye, P. J.; Maliakal, A.; Volante, R. P. *J. Org. Chem.* **1997**, *62*, 6462−6463. For palladium-catalyzed aminations of solid-supported aryl bromides, see: (j) Willoughby, C. A.; Chapman, K. T. *Tetrahedron Lett.* **1996**, *37*, 7181−7184. (k) Ward, Y. D.; Farina, V. *Tetrahedron Lett.* **1996**, *37*, 6993−6996. For palladium-catalyzed aryl aminations in water-containing solvent systems (biphase catalysis), see: (l) Wullner, G.; Jansch, H.; Kannenberg, S.; Schubert, F.; Boche, G. *Chem. Commun.* **1998**, 1509. For latest developments in Pd/L-catalyzed aryl aminations of aryl bromides, see also ref 5.

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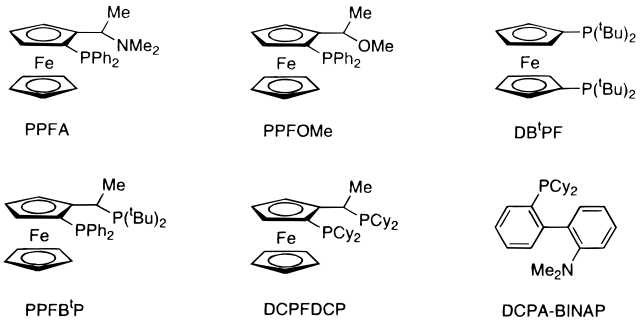
phines, 1-[2-(diphenylphosphino)ferrocenyl]ethyl dimethylamine (PPFA) and 1-[2-(diphenylphosphino)ferrocenyl]ethyl methyl ether (PPFOMe), containing a pendant nitrogen and oxygen functionality, respectively, were later identified as ligands of choice for palladium-catalyzed aminations of aryl bromides with acyclic secondary alkylamines.[2e] The palladium-catalyzed aryl aminations remained generally[9] limited to aryl bromides, idodides, and triflates until it was discovered that simple monophosphines, tricylcohexylphosphine and tri-*tert*-butylphosphine, exhibit promising ability in assisting palladium-catalyzed aminations of aryl halides including aryl chlorides,[2f,5c,g] although only cyclic secondary amines and biarylamines were demonstrated to be practically suitable substrates. Following these reports, it was more recently demonstrated that di-*tert*-butylphosphine and dicyclohexylphosphine containing bis-phosphines, 1,1′-bis(di-*tert*-butylphosphino)ferrocene (DB^{t}PF), 1-[2-(diphenylphosphino)ferrocenyl]ethyldi-*tert*-butylphosphine (PPFB^{t}P), and 1-[2-(dicyclohexylphosphino)ferrocenyl]ethyldicyclohexyl phosphine (DCPFDCP), and the dicylohexylphosphine containing mono-phosphine, 2-(dicylcohexylphosphino)-2′-(dimethylamino)-1,1′-binaphthyl (DCPA-BINAP), exhibit improved ability in assisting palladium-catalyzed aminations of aryl chlorides with a wider variety of arylamines (Scheme 1).[5a,b] The DB^{t}PF and PPFB^{t}P ligands were also found to assist similar aminations of aryl tosylates.[5b] While several ligands exhibiting improved abilities in assisting the palladium- and nickel-catalyzed aryl aminations are now available, a general solution to the metal-catalyzed aryl aminations of all substrates has not been completely achieved. Particularly, prior to this work,[10] the aminations of aryl chlorides with secondary acylic alkylamines were not generally achieved, and similar aminations of aryl bromides and general aryl aminations of aryl chlorides were limited to rather exotic, expensive, or relatively inaccessible ferrocenyl and binaphthyl backbone-derived ligands. It is anticipated that further commercial development of this important synthetic methodology will necessitate the discovery of simple, inexpensive, and readily accessible ligands which exhibit similar, if not better, ability in assisting metal-catalyzed aryl aminations compared to the present state of the art.

Scheme 1



Thus, as part of our ongoing efforts to identify, develop, and utilize high-throughput methods for the rapid discovery of useful materials,[11] we investigated the utility of a variety of simple and readily accessible ligands in assisting metal-catalyzed aryl aminations. This investigation led to the identification of a class of 1,2-phenyl backbone-substituted phosphines containing a pendant heteroatom functionality as promising lead ligand structures.[12] We then initiated a more detailed study of these and several related ligand structures, their palladium complexes, and their utility in assisting palladium-catalyzed aryl aminations. Herein, we describe the results of this study and demonstrate that these simple and readily accessible ligands efficiently assist the palladium-catalyzed aryl aminations of a wide variety of substrates, including secondary acyclic alkylamines and the commercially significant aryl chlorides. We also demonstrate that slight variations in ligand structures dramatically influence the structures of the palladium−ligand complexes and the catalytic efficiency.

Results

I. Synthesis of Ligands 1−10. The ligands **1**−**10** (Scheme 2) were prepared by utilizing standard synthetic organic methods.[13] The ligands **1**, **2**, **4**−**7**, and **10** were prepared by halogen metal exchange reaction of appropriate starting aryl bromo precursor with ^{n}BuLi

(3) Leading references for palladium-catalyzed aminations of aryl iodides, see refs 2b,d and: (a) Wolfe, J. P.; Buchwald, S. L. *J. Org. Chem*. **1996**, *61*, 1133−1135. For latest developments, see ref 5.

(4) For leading references for palladium-catalyzed aminations of aryl triflates, see: (a) Wolfe, J. P.; Buchwald, S. L. *J. Org. Chem*. **1997**, *62*, 1264−1267. (b) Louie, J.; Driver, M. S.; Hamann, B. C.; Hartwig, J. F. *J. Org. Chem*. **1997**, *62*, 1268−1273. (c) Ahman, J.; Buchwald, S. L. *Tetrahedron Lett.* **1997**, *38*, 6363−6366.

(5) For leading references for palladium-catalyzed aminations of aryl chlorides, see: (a) Old, D. W.; Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1998**, *120*, 9722−9723. (b) Hamann, B. C.; Hartwig, J. F. *J. Am. Chem. Soc.* **1998**, *120*, 7369−7370. (c) Reddy, N. P.; Tanaka, M. *Tetrahedron Lett.* **1997**, *38*, 4807−4810. (d) Beller, M.; Reirmeier, T. H.; Resinger, C.; Herrman, W. A. *Tetrahedron Lett.* **1997**, *38*, 2073−2074. (e) Brenner, E.; Fort, Y. *Tetrahedron Lett*. **1998**, *39*, 5359−5362. (f) Riermeier, T. H.; Zapf, A.; Beller, M. *Top. Catal*. **1997**, *4*, 301−309. (g) Yamamoto, T.; Nishiyama, M.; Koie, Y. *Tetrahedron Lett*. **1998**, *39*, 2367−2370. For related nickel-catalyzed aminations of aryl chlorides, see: (h) Wolfe, J. P.; Buchwald, S. L. *J. Am. Chem. Soc.* **1997**, *119*, 6054−6058. (i) Hong, Y. P.; Tanoury, G. J.; Wildinson, H. S.; Bakale, R. P.; Wald, S. A.; Senanyake, C. H. *Tetrahderon Lett*. **1997**, *38*, 56663−5666. Also see ref 2f.

(6) Hartwig, J. F.; Driver, M. S.; Louie, J.; Hamann, B. US patent 5,817,877, 1998.

(7) For a general recent review of palladium- and nickel-catalyzed aryl aminations, which provides an extensive list of references to the mechanistic studies and applications of this chemistry, see: (a) Wolfe, J. P.; Wagaw, S.; Marcoux, J.-F.; Buchwald, S. L. *Acc. Chem. Res*. **1998**, *31*, 805−818. (b) Hartwig, J. F. *Acc. Chem. Res*. **1998**, *31*, 852−860. (c) Hartwig, J. F. *Angew. Chem., Int. Ed. Engl.* **1998**, *37*, 2046−2067. More recently reported applications of Pd/L-catalyzed aryl aminations include: (d) Bolm, C.; Hildebrand, J. P. *Tetrahedron Lett*. **1998**, *39*, 5731−5734.

(8) For a general review of metal-initiated aminations, see: Muller, T. E.; Beller, M. *Chem. Rev.* **1998**, *675*, 5−703, and references therein.

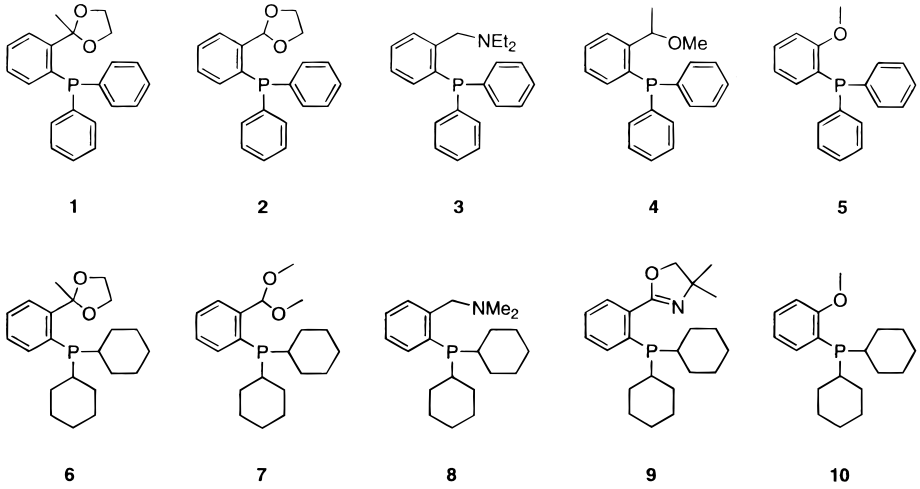
(9) Concurrently, DPPF-based nickel catalysts were demonstrated to be generally useful for the aminations of aryl chlorides; see ref 5h. Similarly, palladacylces were demonstrated to be effective for the aminations of aryl chlorides with cyclic secondary amines at higher temperatures; however, significant amounts of side-products presumably resulting from benzyne intermediates were also observed; see ref 5d.

(10) Our preliminary studies of palladium-catalyzed aminations of aryl chlorides were recently communicated; see: Bei, X.; Guram, A. S.; Turner, H. W.; Weinberg, W. H. *Tetrahedron Lett*. **1999**, *40*, 1237−1240.

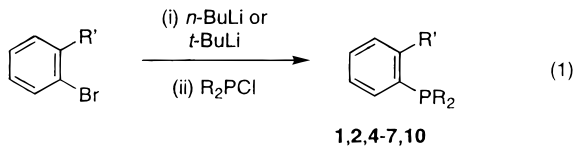
(11) (a) Danielson, E.; Golden, J. H.; McFarland, E. W.; Reaves, C. M.; Weinberg, W. H.; Wu, X. D. *Nature* **1997**, *389*, 944−948. (b) Weinberg, W. H.; McFarland, E.; Goldwasser, I.; Boussie, T.; Turner, H.; van Beek, J. A. M.; Murphy, V.; Powers, T. WO 98/03521, 1998. (c) Boussie, T. R.; Coutard, C.; Turner, H. W.; Murphy, V.; Powers, T. S. *Angew. Chem., Int. Ed. Engl*. **1998**, *37*, 3272−3274. (d) LaPointe, A. M. *J. Comb. Chem*. **1999**, *1*, 101−104.

(12) These lead ligand structures were identified in a high-throughput fashion by conducting reactions in parallel in a micro titer plate format (48−96 reactions) and screening for performance using parallel thin layer chromatography (TLC)-based detection methods (48−56 analyses per TLC plate).

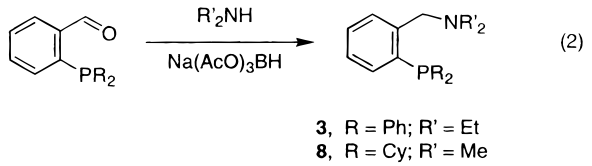
Scheme 2



or ^{t}BuLi, followed by quenching of the generated aryllithium intermediate with the desired Ph_2PCl or Cy_2PCl electrophile (eq 1), whereas ligands **3** and **8** were

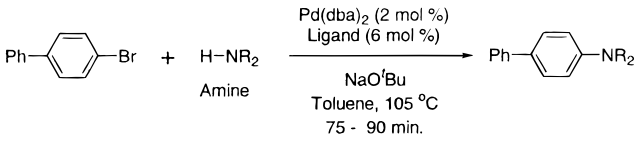


obtained by reductive amination of the 2-(diphenylphosphino)benzaldehyde and 2-(dicyclohexylphosphino)-benzaldehyde with $Et_2NH/NaB(AcO)_3H$ and $Me_2NH/NaB(AcO)_3H$, respectively (eq 2).[14]



Ligand **9**, on the other hand, was prepared by fluoride ion displacement of 2-(2-fluorophenyl)-4,4-dimethyl-4,5-dihydrooxazole with $LiPCy_2$.[15] Ligands **1**−**10** were purified either by recrystallization from deoxygenated alcohol solvents (EtOH or MeOH) or by rapid column chromatography on silica gel using deoxygenated solvents and were obtained as white solids or colorless oils and unambiguously characterized by ^{1}H, ^{13}C, and ^{31}P NMR spectroscopy and elemental analysis.

Table 1. Ligand Effects in the Pd/Ligand-Catalyzed Aminations of 4-Bromobiphenyl with Morpholine and Dibutylamine[a]



	amine = morpholine		amine = dibutylamine	
ligand	conversion (%)	selectivity[b] (%)	conversion (%)	selectivity[b] (%)
1	100	98	100	>99 (93)[c]
2	100	88−98	62	16
3	100	99	36−64	53−63
4	100	98	10−60	16−84
5	10		trace	

[a] Reaction time = 75 min for morpholine substrate; reaction time = 90 min for dibutylamine substrate; reaction temperature = 105 °C for all substrates. Conversion and selectivity are based on GC analysis and are average of 2−4 reactions. A range is given in cases where the results of two or more identical experiments were substantially different and irreproducible. [b] Selectivity = [product/(product + reduced S.M.)] × 100. [c] Isolated yield.

IIa. Pd/L (L = 1−5)-Catalyzed Aminations of Aryl Halides. The $Pd(dba)_2$/L-catalyzed aminations of 4-bromobiphenyl with two different amines, morpholine (a secondary cyclic amine) and dibutylamine (a secondary acyclic amine), were chosen as model reactions for investigating the efficiency of the ligands **1**−**5** (Table 1).[16] For $Pd(dba)_2$/L-catalyzed amination of 4-bromobiphenyl with morpholine, ligands **1**−**4** were all found to be generally efficient, affording the desired arylamine in high GC yields.[17] However, for the related $Pd(dba)_2$/L-catalyzed amination of 4-bromobiphenyl with dibutylamine, ligands **1**−**4** were found to exhibit different

(13) Ligands **1**−**5** have been synthesized previously. For ligand **1** and **2**, see: (a) Schiemenz, G. P.; Kaack, H. *Liebigs Ann. Chem.* **1973**, 1480−1493. (b) Rauchfuss, T. B.; Patino, F. T.; Roundhill, D. *Inorg. Chem.* **1975**, *14*, 652−656. For ligand **3**, see: (c) Tomcufcik, A. S.; Wright, W. B., Jr.; Meyer, W. E. US patent 4892885. For ligand **4**, see: (d) Terfort, A.; Brunner, H. *J. Chem. Soc., Perkin Trans. 1* **1996**, 1467−1479. Ligand **5** is commercially available.

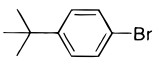
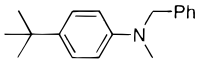
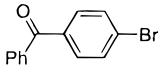
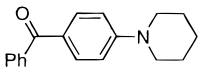
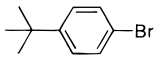
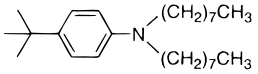
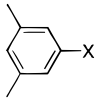
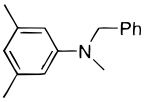
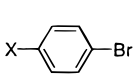
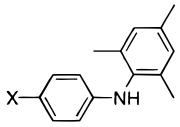
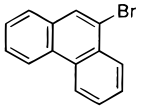
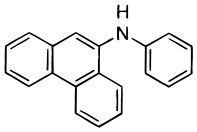
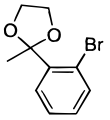
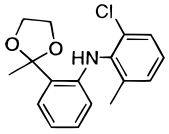
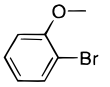
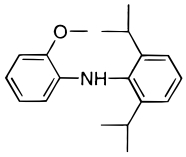
(14) 2-(Diphenylphosphino)benzaldehyde was purchased from Aldrich Chemical Co., Inc., while 2-(dicyclohexylphosphino)benzaldehyde was obtained in a quantitative yield from the hydrolysis reaction of ligand **7**; see Experimental Section for details.

(15) The synthesis of the diphenylphosphino analogue of ligand **9** via a similar fluoride ion displacement route has been described previously; see: Peer, M.; de Jong, J. C.; Kiefer, M.; Langer, T.; Rieck, H.; Schell, H.; Sennhenn, P.; Sprinz, J. Steinhagen, H.; Wiese, B.; Helmchen, G. *Tetrahedron* **1996**, *52*, 7547−7583.

(16) Our studies utilized $Pd(dba)_2$ as a source of Pd(0), but other suitable sources of Pd(0) and/or suitable Pd(II) salts from which Pd(0) species can be generated in situ could presumably be used. Different Pd(II) salts have been previously employed in Pd/L-catalyzed aryl aminations; see refs 1−7.

(17) The efficiency of ligands **1**−**4** in assisting palladium-catalyzed amination of 4-bromobiphenyl with morpholine is not shared by other structurally related phenyl backbone-derived PCCCX ligands (X = O, N, S); for example, 2-diphenylphosphinobenzaldehyde and its benzylimine derivative, 2-methyl-2-(2-diphenylphosphinoethyl)-1,3-dioxolane, 2-diphenylphosphinobenzophenone, and 1,3-dithiane analogue of **1** and **2** were found to be inefficient under similar reaction conditions.

Table 2. Pd(dba)$_2$/Ligand 1-Catalyzed Amination of Aryl Halides[a]

entry	starting materials		product	yield[b]
A			 14	83
B[c]			 15	98
C			 16	93
			 17	
D[c]	X = Br			91
E[d]	X = I			83
				
F[e]			18 X = CN	88
G			19 X = OEt	90
H			 20	92
I			 21	96
J[c]			 22	97

[a] Unless noted otherwise, all reactions were performed at 105 °C until complete using 1.0 equiv of aryl halide, 1.1−1.2 equiv of amine, 1.1−1.2 equiv of NaO^{t}Bu, 2 mol % Pd(dba)$_2$/6 mol % ligand **1** as catalyst, and toluene as the reaction solvent. [b] Yields reported correspond to isolated material of >95% purity as determined by GC−MS, NMR, and/or elemental analysis. [c] These reactions were also performed using 0.5 mol % Pd. [d] Dioxane was used as the reaction solvent. [e] Diarylated product was also observed.

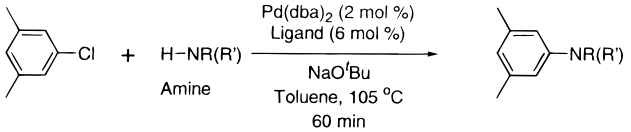
efficiency, with only ligand **1** consistently affording the desired arylamine in >99% GC yield. Ligand **5** was found to be inefficient in both reactions.

The utility of the Pd(dba)$_2$/ligand **1** catalyst for the general aminations of aryl halides was further investigated to determine its scope and limitations. In general, as illustrated in Table 2, the Pd(dba)$_2$/ligand **1** catalyst was found to exhibit a wide scope. The Pd/ligand **1** catalyst efficiently catalyzed the reaction of a wide variety of electron-deficient, electron-rich, and sterically demanding aryl bromides with a wide variety of secondary cyclic (entry B) and acyclic amines (entries A, C, D) and primary aromatic amines including anilines containing sterically demanding ortho substituents (entries F−J).[18] The Pd(dba)$_2$/ligand **1** catalyst was found also to be suitable for the efficient amination of an aryl iodide (entry E), although a slightly lower yield was obtained. However, similar aminations involving octylamine (a primary aliphatic amine) were found to be inefficient, resulting mostly in the formation of the undesired hydrodehalogenated aryl product. The Pd/ligand **1** catalyst was also not suitable for aminations of aryl chlorides under otherwise similar conditions; the starting aryl chloride substrate remained mostly unreacted in these cases. All the isolated arylamine products obtained from Pd/ligand **1**-catalyzed aryl aminations were unambiguously characterized by GC−MS, ^{1}H and ^{13}C NMR spectroscopy, and elemental analysis.

IIb. Pd/L (L = 6−10)-Catalyzed Aminations of Aryl Halides. The Pd(dba)$_2$/L-catalyzed aminations of 5-chloro-*m*-xylene with morpholine and *N*-heptylmeth-

(18) Although, the Pd/ligand **1** catalyst was found to be effective for the amination of a hindered aryl bromide with aniline (Table 1, entry H), in general it was found to be unsuitable for aminations of unhindered aryl bromides with aniline under the conditions investigated.

Table 3. Ligand Effects in the Pd/Ligand-Catalyzed Aminations of 5-Chloro-*m*-xylene with Morpholine and *N*-Heptylmethylamine[a]



	amine = morpholine		amine = *N*-heptylmethylamine	
ligand	conversion (%)	selectivity[b] (%)	conversion (%)	selectivity[b] (%)
6	100	100	100	100
7	48−65	98	30	98
8	30	98	23	98
9	15	99	5−23	86−98
10	35−44	99	35	98

[a] Reaction time = 60 min for all substrates; reaction temperature = 105 °C for all substrates. Conversion and selectivity are based on GC analysis and are average values of two or more experiments. A range is given in cases where the results of two or more identical experiments were substantially different and irreproducible. [b] Selectivity = [product/(product + reduced S.M.)] × 100.

ylamine (a secondary acyclic amine) were chosen as model reactions for investigation of the efficiency of ligands **6**−**10** (Table 3). The presence of a basic dicyclohexylphosphine moiety in ligands **6**−**10** was anticipated to increase the electron density at the palladium center, thereby facilitating the oxidative addition and thus the subsequent aminations of the usually unreactive aryl chloride substrates.[19,20] The Pd(dba)$_2$/L (L = **7**−**10**) catalysts were found to exhibit good selectivity but low to moderate activity in the aminations of 5-chloro-*m*-xylene with morpholine and *N*-methylheptylamine, while the Pd/ligand **6** catalyst was found to be extremely efficient for both reactions.

Further studies of Pd(dba)$_2$/ligand **6**-catalyzed aryl aminations revealed the Pd/ligand **6** catalyst to be generally efficient in catalyzing the amination of a wide variety of aryl chlorides (Table 4). Aryl chlorides containing both electron-withdrawing and electron-donating substituents reacted rapidly with a wide variety of secondary cyclic and acyclic alkylamines to afford the desired arylamines in very high selectivity and isolated yields (entries A−D and I, Table 4). These reactions were essentially complete in 1 h and formed undetectable to only trace (less than 1%) amounts of the undesired hydrodehalogenated product. Aryl chlorides containing ortho substituents also reacted efficiently with primary aromatic and aliphatic amines to afford the desired arylamines in high selectivity and isolated yields (entries E−H, Table 4). These reactions also proceeded rapidly and were complete in 3 h.[21] Products resulting from diarylation were not detected in these reactions. The Pd(dba)$_2$/ligand **6** catalyst system was also found to be equally efficient in catalyzing the aminations of aryl bromides and iodides with secondary amines in high selectivity and isolated yields (entries J,K, Table 4).[22] All the isolated arylamine products obtained from Pd/ligand **6**-catalyzed aryl aminations were unambiguously characterized by GC−MS, ^{1}H and ^{13}C NMR, and elemental analysis.

III. Isolation and Structural Characterization of Potential Catalytic Intermediates. The hemilabile ligands used in this work contain one P- and at least one O- or N-binding sites and therefore can function as P,O- or P,N-chelating ligands. The significantly improved efficiency exhibited by the potentially chelating ligands **1** and **6** compared to the parent monodentate nonchelating analogues, PPh_3 and $PPhCy_2$, suggests that the pendant oxygen functionality in ligands **1** and **6** plays a crucial role in the catalytic process.[23] The dramatic difference in efficiency between structurally very similar ligands **1**/**6** and **2** (and other closely related ligands including ligands **3**−**5**, **7**−**10**) is further suggestive of a potential difference in interaction between ligands **1**/**6** with the Pd-center compared to ligand−Pd interactions of other ligands. To gain further insights into this interesting ligand structure−catalytic performance relation, the isolation of potential catalytic intermediates of the Pd/ligand **1**, Pd/ligand **2**, and Pd/ligand **6** catalysts was undertaken.

a. Isolation of LPd(4-^{t}Bu-C$_6$H$_4$)Br (11, L = 1; 12, L = 6) and L$_2$Pd(4-^{t}Bu-C$_6$H$_4$)Br (13, L = 2) Complexes. The complexes **11**−**13** were formed on contacting Pd$_2$(dba)$_3$ or Pd(dba)$_2$, excess ligand (ligand = **1**, **6**, **2**), and excess 4-^{t}Bu-C$_6$H$_4$Br in toluene solution.[24] The same complexes **11**−**13** were also formed and more conveniently isolated from the ligand displacement reactions of complex [Pd{P(*o*-toluyl)$_3$}(4-^{t}Bu-C$_6$H$_4$)(μ-Br)]$_2$[25] with ligands **1**, **6**, and **2**, respectively (eqs 3 and 4).

(19) Palladium-catalyzed cross-coupling reactions of aryl chlorides are generally challenging. For notable contributions, see ref 5 and: (a) Ben-David, Y.; Portnoy, M.; Milstein, D. *J. Am. Chem. Soc.* **1989**, *111*, 8742−8744. (b) Ben-David, Y.; Portnoy, M.; Milstein, D. *J. Chem. Soc., Chem. Commun.* **1989**, 1816−1817. (c) Gouda, K.; Hagiwara, E.; Hatanaka, Y.; Hiyama, T. *J. Org. Chem.* **1996**, *61*, 7232−7233. For related nickel-catalyzed cross-coupling reactions, see: (d) Saito, S.; Ohtani, S.; Miyaura, N. *J. Org. Chem.* **1997**, *62*, 8024−8030. (e) Saito, S.; Sakai, M.; Miyaura, N. *Tetrahedron Lett.* **1996**, *37*, 2993−3996. (f) Perec, V.; Bae, J. Y.; Hill, D. H. *J. Org. Chem.* **1995**, *60*, 1060−1065. (g) Indolese, A. F. *Tetrahedron Lett.* **1997**, *38*, 3513. (h) Grushin, V. V.; Alper, H. *Chem. Rev.* **1994**, *94*, 1047−1062.

(20) This rationale was recently demonstrated to be useful in ligand design in Pd/L-catalyzed aminations of aryl chlorides; see ref 5.

(21) The Pd(dba)$_2$/ligand **6**-catalyzed aminations of aryl chlorides with primary aliphatic amines is not limited to ortho-substituted aryl chlorides. Thus, the reaction of 5-chloro-*meta*-xylene with octylamine under the conditions described proceeds to completion in 2 h and affords the desired arylamine. The formation of the undesired hydrodehalogenated product was undetectable. However, the diarylated product was detected (ca. 15−20% by GC−MS) particularly at higher temperatures.

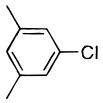
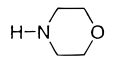
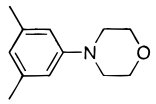
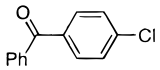
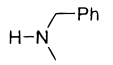
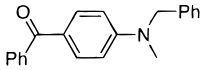
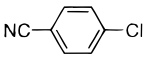
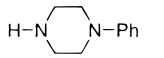
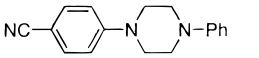
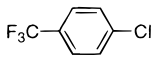
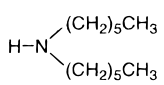
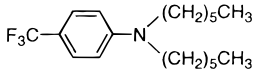
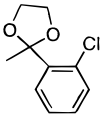
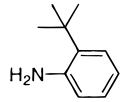
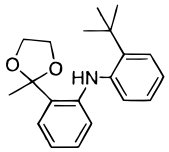
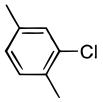
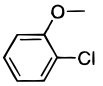
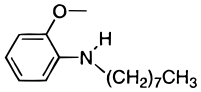
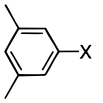
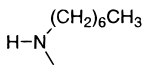
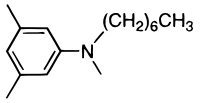
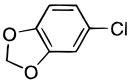
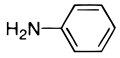
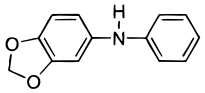
(22) However, the Pd(dba)$_2$/ligand **6**-catalyzed aminations of aryl bromides appear to be senstive to aryl bromide substrate, and the Pd(dba)$_2$/ligand **1** catalyst represents a more general catalyst for aryl aminations involving aryl bromides.

(23) Pd(dba)$_2$/PPh_3 and Pd(dba)$_2$/$PPhCy_2$ are not suitable catalysts for general aryl aminations of aryl halides. The $PdCl_2(PCy_3)_2$ catalyst, although a lead catalyst, was found to be of limited scope and efficiency, affording low yields of the desired arylamines; see ref 5c.

(24) The analogous complexes LPd(4-Ph-C$_6$H$_4$)Br (L = **1**) and L$_2$Pd(4-Ph-C$_6$H$_4$)Br (L = **2**) were obtained similarly from the reaction of 1 equiv of Pd(dba)$_2$, 1.7 equiv of ligand **1** (or ligand **2**), and 2.2 equiv of 4-Ph-C$_6$H$_4$Br at 80 °C in toluene. *LPd(4-Ph-C$_6$H$_4$)Br (L = 1)*, ^{31}P NMR ($CDCl_3$, 23 °C): δ 16.8. ^{1}H NMR ($CDCl_3$, 23 °C): δ 7.8−7.0 (m, 19H, ArH), 6.8 (br s, 4H, ArH), 4.73 (br s, 1H, −OCH$_2$CH$_2$O−), 4.15 (br s, 1H, OCH$_2$CH$_2$O), 3.82 (br s, 2H, −OCH$_2$CH$_2$O−), 2.10 (s, 3H, Me). ^{1}H NMR ($CDCl_3$, 55 °C): δ 7.75 (m, 1H, ArH), 7.7−7.0 (m, 18 H, ArH), 6.85 (m, 4H, ArH), 4.40 (br s, 2H, −OCH$_2$CH$_2$O−), 3.75 (m, 2H, −OCH$_2$CH$_2$O−), 2.11 (s, 3H, Me). Anal. Calcd for $C_{34}H_{30}BrO_2PPd$: C, 59.36; H, 4.40; P, 4.50; Pd, 15.47. Found: C, 58.96; H, 4.46; P, 4.62; Pd, 15.23. *L$_2$Pd(4-Ph-C$_6$H$_4$)Br (L = 2)*, ^{1}H NMR (C_6D_6, 23 °C): δ 8.0−6.5 (m, 39H, ArH + CH), 3.8−3.6 (br AB, 8H, OCH$_2$CH$_2$O). ^{31}P NMR C_6D_6, 23 °C): δ 19.8.

(25) The complex [Pd{P(*o*-tol)$_3$}(4-^{t}Bu-C$_6$H$_4$)(μ-Br)]$_2$ was prepared as described in: (a) Widenhoefer, R. A.; Zhong, H. A.; Buchwald, S. L. *Organometallics* **1996**, *15*, 2745−2754. This complex was prepared earlier using an alternate route; see: (b) Paul, F.; Patt, J.; Hartwig, J. F. *J. Am. Chem. Soc.* **1994**, *116*, 5969−5970. (c) Hartwig, J. F.; Paul, F. *J. Am. Chem. Soc.* **1995**, *117*, 3030−3039.

Table 4. Pd(dba)$_2$/Ligand 6-Catalyzed Amination of Aryl Chlorides[a]

entry	starting materials		product	yield[b]
A[c]			23 	92
B			24 	96
C[c]			25 	90
D[d]			26 	97
E[e]			27 	89
F		H_2N–R	28 R = 2,4,6-Me_3-C_6H_2	96
G[f]			29 R = octyl	92
H[f]		H_2N–$(CH_2)_7CH_3$	30 	83
			31 	
I[c]	X = Cl			95
J	X = Br			93
K[g]	X = I			91
L			32 	96

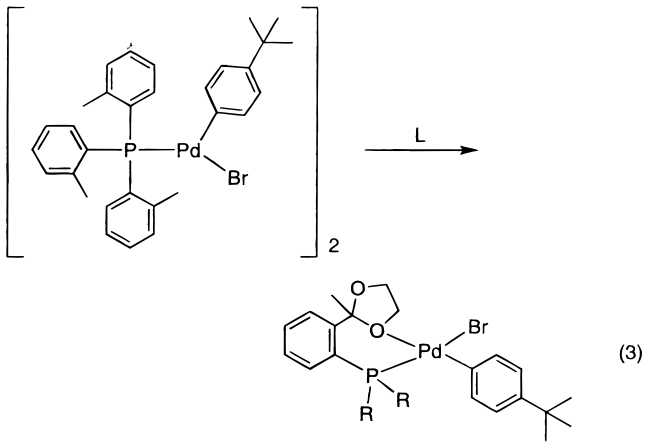
[a] Unless noted otherwise, all reactions were performed at 105 °C for 1 h using 1.0 equiv of aryl halide, 1.1−1.2 equiv of amine, 1.1−1.2 equiv of NaO^{t}Bu, 2 mol % Pd(dba)$_2$/6 mol % ligand **6** as catalyst, and toluene as the reaction solvent. [b] Yields reported correspond to isolated material of >95% purity as determined by GC−MS, NMR, and/or elemental analysis. [c] These reactions were also performed using 0.5 mol % Pd. [d] This reaction was also performed using 0.25 mol % Pd. [e] 2 h reaction time. [f] 3 h reaction time. [g] 15 min reaction time.

These ligand displacement reactions were performed at ambient temperature in CH_2Cl_2 solvent, and the complexes were isolated as solids from concentrated solutions by addition of a hydrocarbon solvent, e.g., pentane or heptane.

The complexes **11**−**13** in the solid state are fairly stable and can be conveniently handled in air. The complexes **11** and **12** in solution (solvents: toluene-d_8, C_6D_5Cl, $CDCl_3$) also exhibit good thermal stability. The complex **11** was observed to decompose at temperatures above 80 °C in neat toluene-d_8 or C_6D_5Cl, while complex **12** was found to be stable even at 105 °C in neat toluene-d_8. The complexes **11**−**13** catalyze aryl aminations and exhibit efficiency similar to that of the corresponding Pd(dba)$_2$/L (L = **1**, **6**, **2**) catalyst combinations, respectively.

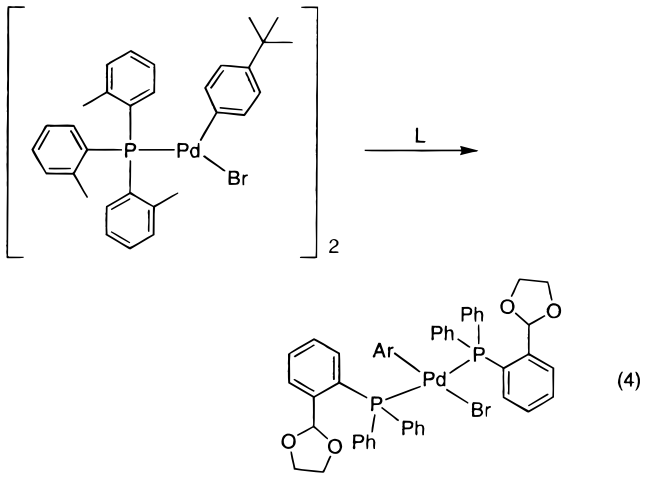
b. Solid-State Structures of Complexes 11−13. The X-ray quality crystals of complexes **11**−**13** were grown from a methylene chloride/heptane solvent system using the layering technique to induce slow crystallization, and the solid-state structures were determined by single-crystal X-ray diffraction. The molecular structures of complexes **11**−**13** are shown in Figures 1, 2, and 3, respectively, and the crystallographic details and key bond lengths and bond angles are listed in Tables 5−7.

The complexes **11** and **12** adopt square planar structures in which ligands **1** and **6** are bound to the Pd-center through both P and O atoms (Figures 1 and 2 and Table 6). The short Pd−O bond distances of 2.204(8) and 2.164(3) Å in complexes **11** and **12**, respectively, conclusively establish the coordination of the O atom to the Pd-center in these complexes.[2e,26] The Pd−P, Pd−O, Pd−C, and Pd−Br bond distances in complexes **11**



(3)

11, L = **1**, R = Ph
12, L = **6**, R = Cy



(4)

13, L = **2**, Ar = 4-^{t}Bu-C_6H_4

and **12** are generally similar to each other and are also similar to the corresponding bond distances observed in the previously reported ferrocenyl-based (P,O)-Pd complex, (PPFOMe)Pd(4-^{t}Bu-C_6H_4)Br.[2e] The P−Pd−O bite angle in complexes **11** and **12** is also similar (85.7(2)° and 84.95(9)°, respectively), but is smaller than the P−Pd−O angle observed in the (PPFOMe)Pd(4-^{t}Bu-C_6H_4)Br complex (90.5(2)°).[2e]

The complex **13** also adopts a square planar structure, but in this case the two molecules of ligand **2** occupy trans positions each coordinating to the Pd-center only through its P atom with no close Pd−O contacts (Figure 3 and Table 7). The Pd−P, Pd−C, and Pd−Br bond lengths are slightly longer than the corresponding bond lengths observed in complexes **11** and **12**, presumably due to the presence of two sterically demanding ligands.

c. Solution Structures of Complexes 11−13. The solution structures of complexes **11−13** were established by the solution NMR spectroscopic studies. The ^{31}P NMR spectra of complexes **11−13** in $CDCl_3$ solvent exhibit a single resonance at δ 16.3, 28.5, and 18.0 ppm, respectively. These resonances are significantly downfield shifted compared to the corresponding resonance in the ^{31}P NMR spectra of the free ligands **1**, **6**, and **2** in $CDCl_3$ solvent (δ −9.6, −8.2, and −16.2 ppm, respectively) and establish that the P atom is coordinated to the Pd-center in these complexes.

The ^{1}H NMR spectra of complexes **11** and **12** in $CDCl_3$ exhibit characteristic resonances for the $-OCH_2CH_2O-$ group. For complex **11**, the $-OCH_2CH_2O-$ protons appear as three broad resonances at δ 4.70, 4.21, and 3.85 in a 1:1:2 ratio,[27] whereas for complex **12**, the analogous $-OCH_2CH_2O-$ protons appear as four resonances at δ 4.71, 4.12, 3.81, 3.71 in a 1:1:1:1 ratio. For both complexes **11** and **12**, the $-OCH_2CH_2O-$ proton resonances are downfield shifted compared with the corresponding resonances of the free ligands (3.72 and 3.20 for ligand **1** and 4.02 and 3.73 for ligand **6**). This indicates that one O atom of the $-OCH_2CH_2O-$ group in both complexes **11** and **12** is coordinated to the Pd center.[28,29]

Unlike the ^{1}H NMR spectrum of complexes **11** and **12**, the ^{1}H NMR spectrum of complex **13** exhibits two sharper resonances at δ 4.11 and 3.95 in a 4:4 ratio for two $-OCH_2CH_2O-$ groups. These resonances are nearly identical to those observed for the free ligand **2** (δ 4.21 and 3.98 ppm), establishing a lack of coordination of any O atom to the Pd-center and the presence of two P-coordinated ligands **2** in complex **13**.[30] The presence of only a single sharp resonance in the ^{31}P NMR spectrum of complex **13** further indicates that the two phosphine ligands adopt a trans configuration which makes them equivalent.

Collectively, the solution NMR data for complexes **11−13** are consistent with the observed solid-state structures and indicate that complexes **11−13** maintain the observed solid-state structures in solution.

Discussion

The results illustrated above clearly establish that the simple and readily accessible[31] phenyl backbone-derived P,O-ligands **1** and **6** effectively assist general Pd/L-

(26) These bond distances compare favorably to the Pd−O covalent bond distances observed for square planar complexes of palladium; see: (a) Bryndza, H. E.; Tam, W. *Chem. Rev.* **1988**, *88*, 1163−1188. (b) Kiers, N. H.; Feringa, B. L.; Kooijman, H.; Spek, A. L.; van Leeuwen, P. W. N. M. *J. Chem. Soc., Chem. Commun.* **1992**, 1169−1170. (c) Kapteijn, G. M.; Grove, D. M.; Kooijman, H.; Smeets, W. J.; Spek, A. L.; van Koten, G. *Inorg. Chem.* **1996**, 35, 526−533.

(27) A similar ^{1}H NMR resonance pattern is also observed for the analogous complex LPd(4-Ph-C_6H_4)Br (L = **1**); see ref 24 for details.

(28) At higher temperatures, the resonances for the $-OCH_2CH_2O-$ group of both complexes **11** and **12** broaden and coalesce to afford only two resonances in 2:2 ratio (chemical shifts can be found in the Experimental Section), which presumably results from rapid exchange of the O−Pd coordination between the two O atoms. Such broadening and coalescence of the resonances of the $-OCH_2CH_2O-$ group appear to be facilitated in the presence of amines (*N*-methylbenzylamine, morpholine) and in C_6D_5Cl (for complex **11**).

(29) Although the data support coordination of the O atom of the $-OCH_2CH_2O-$ to the Pd-center in complex **11** and **12**, it does not preclude the dissociation of the O atom from the Pd-center under catalysis conditions. The rapid exchange of O−Pd coordination between the two O atoms at higher temperatures and in the presence of certain additives suggests that the O atoms remain in close proximity to the Pd-center at all times. Attempts to synthesize, isolate, and characterize $Pd^{(0)}L_n$, $Pd^{(II)}(L_n)ArX$ (X = O^{t}Bu, NR_2) and related complexes were unsuccessful, and thus it is not clear if such O−Pd coordination is also present in these subsequent catalytic intermediates.

(30) A similar ^{1}H NMR resonance pattern is also observed for the analogous complex L_2Pd(4-Ph-C_6H_4)Br (L = **2**); see ref 24 for details.

(31) As described in the results section, ligands **1** and **6** are readily available in two high-yield synthetic steps from inexpensive commercially available starting materials. Ligands **1** and **6** are isolated as stable colorless solids and can be conveniently handled in air.

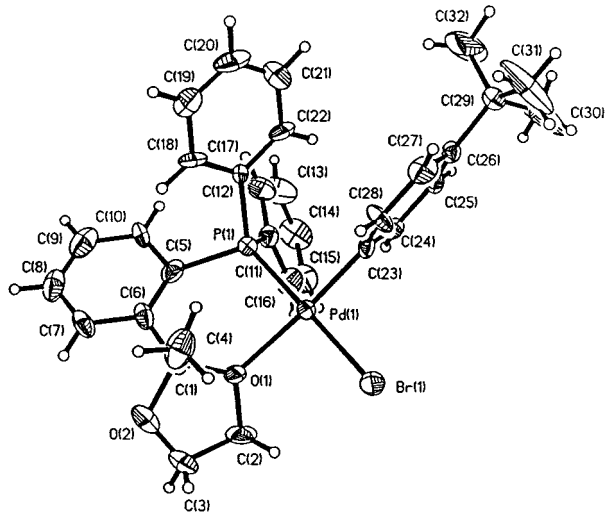


Figure 1. Molecular structure and atom-numbering scheme of complex **11** (molecule 1).

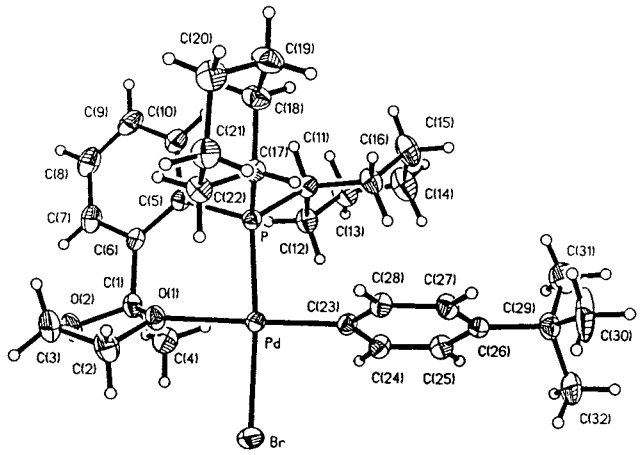


Figure 2. Molecular structure and atom-numbering scheme of complex **12**.

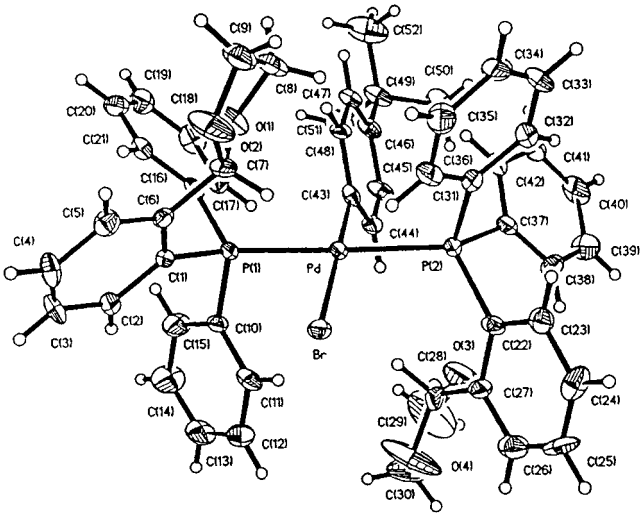


Figure 3. Molecular structure and atom-numbering scheme of complex **13**.

catalyzed aminations of aryl bromides, iodides, and chlorides.[32]

The Pd/ligand **1** catalyst efficiently catalyzes the aminations of a variety of aryl bromides and iodides with a variety of primary aromatic amines and secondary cyclic and acyclic alkylamines to afford the desired arylamines in high isolated yields. The efficiency of the Pd/ligand **1** catalyst for aminations of aryl bromides with secondary acyclic alkylamines is particularly notable because such aryl aminations are generally difficult to achieve. Overall, the Pd/ligand **1** catalyst exhibits catalytic performance similar to that of the structurally related, but ferrocenyl backbone-derived, Pd/PPFOMe and Pd/PPFA catalysts,[2e] which previously were the only catalysts suitable for aminations of aryl bromides with secondary acyclic alkylamines. Like the Pd/PPFOMe and Pd/PPFA catalysts, the Pd/ligand **1** catalyst does not appear to be suitable for the general aminations of aryl bromides and iodides with primary alkylamines, of aryl chlorides, and involving parent unsubstituted aniline under otherwise standard conditions.

The observed similarity in catalytic performance between the Pd/ligand **1** catalyst and the Pd/PPFOMe and Pd/PPFA catalysts may not be surprising given the similarity of structures of the ligands involved, i.e., the presence of a rigid PCCCX (X = O, N) unit. However, the observed difference in efficiency between the Pd/ligand L (L = **1**, PPFOMe and PPFA) catalysts and the Pd/ligand L (L = **2**, **3**, **4**, and other related ligands) catalysts is immensely surprising given the closer resemblance of ligands **3**/**4** to ligands PPFOMe/PPFA, respectively. The difference in efficiency between the Pd/ligand **1** catalyst and the Pd/ligand **2** catalyst is particularly remarkable given the nearly identical structures of ligands **1** and **2**. These differences in reactivity most likely result due to the generation and involvement of structurally different catalytic intermediates in each of the Pd/L catalyst systems. This is consistent with the isolation and characterization of structurally different complexes **11** and **13**. In complex **11**, one molecule of ligand **1** coordinates to the Pd-center via both P and O atoms and exhibits a structure similar to that of the Pd/PPFOMe complex; while in complex **13**, two molecules of ligand **2** coordinate to the Pd-center in a trans fashion each via only the P atom. Such trans P atom coordinated "Pd(P)$_2$" organometallic structures may also be generated in other Pd/ligand L (L = **3**−**5**) catalysts and may be responsible for the observed inefficiency of such catalysts in the aryl aminations involving certain substrates and conditions.

The Pd/ligand **6** catalyst, on the other hand, efficiently catalyzes the aminations of a variety of aryl chlorides with a variety of primary aromatic amines and secondary cyclic and acyclic alkylamines to afford the desired arylamines in high isolated yields. In general, the Pd/ligand **6**-catalyzed aryl aminations are characterized by high rates and selectivity, and the undesired reduced products are either undetectable or formed in only trace amounts. The Pd/ligand **6** catalyst is also efficient for the amination of ortho-substituted aryl chlorides with primary alkylamines, however lack of ortho substitution on the aryl halide substrate results in the formation of the diarylated primary alkylamine byproduct. The formation of diarylated byproduct is minimized at lower reaction temperatures and higher concentrations of the

(32) While ligands **1** and **6** exhibit the best efficiency, ligands **2**−**4**, **7**−**10** are also potentially suitable candidates and may exhibit equal or better aryl amination efficiency with other substrates and/or under other reaction conditions.

Table 5. Crystal Data and Structure Refinement Parameters for Complexes 11−13[a]

	11	**12**·CH_2Cl_2	**13**·C_7H_{16}
empirical formula	$C_{32}H_{34}BrO_2PPd$	$C_{32}H_{46}BrO_2PPd{\cdot}CH_2Cl_2$	$C_{59}H_{67}BrO_4P_2Pd$
MW	667.87	764.89	1088.38
temp	295(2) K	295(2) K	173(2) K
wavelength	0.717 073 Å	0.710 73 Å	0.710 73 Å
cryst syst	triclinic	triclinic	triclinic
space group	$P\bar{1}$	$P\bar{1}$	$P\bar{1}$
unit cell dimens	a = 11.055(2) Å α = 89.45(1)° b = 20.160(5) Å β = 81.95(2)° c = 20.521(3) Å γ = 80.80(2)°	a = 11.254(1) Å α = 105.46(1)° b = 11.565(2) Å β = 94.38(1)° c = 14.104(2) Å γ = 95.93(1)°	a = 12.909(1) Å α = 75.498(6)° b = 13.850(1) Å β = 74.335(5)° c = 17.241(1) Å γ = 69.703(6)°
volume	4469.8(1.4) Å^3	1749.5(4) Å^3	2741.5(4) Å^3
Z	6	2	2
density (calcd)	1.489 g/cm^3	1.452 g/cm^3	1.319 g/cm^3
abs coeff	20.44 cm^{-1}	18.98 cm^{-1}	11.7 cm^{-1}
F(000)	2028	784	1128
cryst size	0.3 × 0.07 × 0.4 mm	0.18 × 0.20 × 0.36 mm	0.24 × 0.34 × 0.36 mm
θ range for data collection	2.00−20.00°	2.03−25.00°	2.64−22.50°
index ranges	$0 \le h \le 10$, $-19 \le k \le 19$, $-19 \le l \le 19$	$-1 \le h \le 13$, $-13 \le k \le 13$, $-16 \le l \le 16$	$0 \le h \le 13$, $-13 \le k \le 14$, $-17 \le l \le 18$
no. of reflns collected	8837	7068	7395
no. of ind reflns	8263 (R_{int} = 0.0436)	6055 (R_{int} = 0.0262)	7026 (R_{int} = 0.043)
refinement method	full-matrix least-squares on F^2	full-matrix least-squares on F^2	full-matrix least-squares on F^2
no. of data/restraints/params	7291/0/1012	5482/42/397	6373/53/609
goodness-of-fit on F^2	1.039	1.019	1.048
final R indices (all data)	R1 = 0.0572, wR2 = 0.1172	R1 = 0.0428, wR2 = 0.0732	R1 = 0.0604, wR2 = 0.1521
R indices (all data)	R1 = 0.1178, wR2 = 0.1443	R1 = 0.0839, wR2 = 0.0853	R1 = 0.1022, wR2 = 0.1783
largest diff peak and hole	0.968 and −0.517 e Å^{-3}	0.490 and −0.394 e Å^{-3}	1.299 and −0.428 e Å^{-3}
extinction coeff		0.0006(2)	

[a] R1 = $||F_o| - |F_c||/|F_o|$, wR2 = $[(wi(F_o^2 - F_c^2)^2)/(wi(F_o^2)^2)]^{1/2}$, GOF = $[(wi(F_o^2 - F_c^2)^2)/(n - p)]^{1/2}$.

Table 6. Selected Bond Lengths and Bond Angles of Complexes 11 and 12

	bond lengths			bond angles	
	11	**12**		**11**	**12**
Pb−Br	2.475(2)	2.4678(12)	Br−Pd−O1	93.8(2)	90.16(9)
Pd−O1	2.204(8)	2.164(3)	O1−Pd−P	85.7(2)	84.95(9)
Pd−P	2.236(4)	2.273(2)	P−Pd−C23	89.0(4)	94.34(13)
Pd−C23	1.972(13)	1.979(4)	C23−Pd−Br	91.6(4)	90.64(13)
			C23−Pd−O1	174.3(5)	178.1(2)
			P−Pd−Br	177.67(11)	174.09(4)

Table 7. Selected Bond Lengths and Bond Angles of Complex 13

bond lengths		bond angles	
Pd−Br	2.5378(7)	P−Pd−C43	86.5(2)
Pd−P1	2.3478(14)	C43−Pd−P2	89.8(2)
Pd−P2	2.3514(14)	P2−Pd−Br	91.11(3)
Pd−C43	2.001(4)	Br−Pd−P1	92.53(4)
		C43−Pd−Br	178.15(12)
		P1−Pd−P2	176.29(5)

primary amine. Furthermore, unlike the Pd/ligand **1** catalyst, the Pd/ligand **6** catalyst is also suitable for the aryl aminations involving unhindered primary aromatic amines.

The effectiveness of the Pd/ligand **6** catalyst in the aminations of aryl chlorides is generally superior to that of the previously described Pd/PCy_3, palladacycle, Pd/P^tBu_3,[33] and Ni/DPPF catalysts and similar to that of the recently described naphthyl-derived Pd/P,N (P,N = DCPA-BINAP) and the ferrocenyl-derived Pd/P,P (P,P = DB^{t}PF, PPFB^{t}P, DCPFDCP) catalysts. However, the Pd/ligand **6** catalyst and the recent Pd/P,N (P,N = DCPA-BINAP) catalyst currently represent the only two suitable catalysts for efficient aminations of aryl chlorides with secondary acyclic alkylamines.

The aryl aminations catalyzed by Pd/ligand **6** catalyst most likely involve organometallic intermediates similar to those of Pd/ligand **1** catalyst. This is consistent with the isolation and characterization of complex **12**. Like complex **11**, complex **12** contains one molecule of ligand **6** coordinated to the Pd-center via both the P and O atoms.

The efficiency of the Pd/ligand **1** and Pd/ligand **6** catalysts for aryl aminations can be ascribed to the structures of ligands **1** and **6**, which presumably favor the generation and stability of the chelating "(P,O)-Pd" intermediates, consistent with the isolation of intermediates **11** and **12**. The unique efficiency of Pd/ligand L (L = **1**, **6**, PPFOMe,[2e] and PPFA[2e]) suggests that the chelating "(P,X)-Pd" (X = O, N) intermediates may play an important role in the catalytic process.[34] The potential role of structurally related P,O- and P,N-ligands in beneficially influencing the Pd/L-catalyzed aryl aminations of aryl bromides has been discussed previously by the Buchwald group.[2e] The higher efficiency of the Pd/ligand **6** catalyst, particularly for the aminations of aryl chlorides, can be attributed to the dicyclohexylphosphino group, which makes the Pd-center sufficiently electron rich to promote oxidative addition of the usually unreactive aryl chloride substrates.

(33) Pd/P^{t}Bu$_3$ is the most efficient catalyst to date for the aryl aminations of aryl bormides with biarylamines; see refs 2f and 5g.

(34) The Pd/L-catalyzed (e.g., L = P(*o*-toluyl)$_3$, DPPF, BINAP) aryl aminations proceed via oxidative addition of an aryl halide, formation of an "Pd(Ar)(amide)" intermediate, and reductive elimination of the arylamine. This mechanism has been postulated and studied extensively, independently by the groups of Buchwald and Hartwig; see refs 2a−d, 24, and: (a) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1995**, *117*, 4708−4709. (b) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1997**, *119*, 8232−8245. (c) Mann, G.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 13109−13110. (d) Driver, M. S.; Hartwig, J. F. *J. Am. Chem. Soc.* **1996**, *118*, 4206−4207. (e) Driver, M. S.; Hartwig, J. F. *Organometallics* **1997**, *16*, 5706. (f) Widenhoefer, R. A.; Buchwald, S. L. *Organometallics* **1996**, *15*, 2755−2763. (g) Widenhoefer, R. A.; Buchwald, S. L. *Organometallics* **1996**, *15*, 3534−3542. For general chelate effect of structure and activity and mechanistic studies of oxidative addition of aryl chlorides to $Pd^{(0)}L_n$ complexes, see: (h) Portnoy, M.; Milstein, D. *Organometallics* **1993**, *12*, 1655−1664. (i) Portnoy, M.; Milstein, D. *Organometallics* **1993**, *12*, 1665−1673.

Conclusions

The phenyl backbone-derived ligands **1** and **6** in combination with $Pd(dba)_2$ afford active catalysts for the efficient amination of aryl bromides, iodides, and chlorides. The efficiency of ligands **1** and **6** in Pd/L-catalyzed aryl aminations results from the presence of the R_2P (R = Ph, Cy) and ketal groups on a rigid phenyl backbone which presumably allow for the generation and stability of P,O-chelating palladium−ligand complexes. Such P,O-chelating palladium−ligand complexes appear to be most suitable for aryl aminations involving certain substrates. However, the mere presence of P and O atoms in the ligand framework does not necessarily provide efficient ligands for Pd/L-catalyzed aryl aminations. Minor differences in ligand structures can lead to major differences in catalytic efficiency due to the generation of quite different palladium−ligand complexes.

Overall, the efficiency of the Pd/ligand **1** and Pd/ligand **6** catalysts for aryl aminations involving primary aromatic amines and secondary cyclic and acyclic amines is generally superior to that of Pd/P(*o*-toluyl)$_3$, Pd/PCy_3, Pd/P(^{t}Bu)$_3$, and palladacycle catalysts. For aminations of aryl bromides with secondary acyclic amines, the Pd/ligand **1** catalyst efficiency is also superior to that of Pd/DPPF and Pd/BINAP and is equal to that of Pd/PPFOMe and Pd/PPFA catalysts. For aminations of aryl chlorides with secondary acyclic amines, the Pd/ligand **6** catalyst efficiency is superior to that of the ferrocenyl-derived Pd/L catalysts (L = DB^{t}PF, PPFB^{t}P, DCPFDCP) and is similar to that of the binaphthyl-derived Pd/L catalyst (L = DCPA-BINAP). Moreover, the ready accessibility and low cost of ligands **1** and **6** compared to the binaphthyl- and ferrocenyl-derived ligands make ligands **1** and **6** more attractive candidates for general Pd/L-catalyzed aryl aminations.[35]

Experimental Section

General Comments. All reactions were performed under an argon atmosphere in oven-dried glass Schlenk tubes using standard Schlenk techniques. All aryl halides, all amines, sodium *tert*-butoxide, bis(dibenzylideneacetone)palladium, benzene, ethanol, diethyl ether, methylene chloride, toluene, and 1,4-dioxane were purchased from commercial sources and used as such. {Pd[P(*o*-toluyl)$_3$](4-^{t}Bu-C_6H_4)(μ-Br)}$_2$ was prepared according to literature procedures.[25] All solvents were of the anhydrous, sure-seal grade. Column chromatography was performed using commercially available Silica Gel 60 (particle size: 0.063−0.100 mm), hexanes, and ethyl acetate. GC−MS analyses were conducted on a Hewlett-Packard 6890 instrument. ^{1}H, ^{13}C, and ^{31}P NMR spectra were obtained using a Bruker 300 MHz FT-NMR spectrometer. Chemical shifts in ^{1}H and ^{13}C NMR spectra were calibrated with reference to the chemical shift of residual protiated solvent. Chemcial shifts in ^{31}P NMR spectra were calibrated with reference to 85% H_3PO_4; a negative value of chemical shift denotes resonance upfield from H_3PO_4. Coupling constants are reported in hertz. Elemental analyses were performed by E & R Microanalytical Laboratory, Inc., NJ.

2-(2′-Diphenylphosphinophenyl)-2-methyl-1,3-dioxolane (Ligand 1).[13a,b] **Part I.** A solution of 2-bromoacetophenone (5.08 g, 25.5 mmol), ethylene glycol (6.64 g, 106 mmol), and *p*-toluenesulfonic acid monohydrate (0.1 g, 0.5 mmol) in benzene (60 mL) was heated at reflux for 24 h using a Dean Stark setup to remove water. The reaction mixture was taken up in methylene chloride (100 mL) and washed with water (3 × 25 mL) and brine (25 mL). The organic phase was dried over magnesium sulfate and concentrated under vacuum to afford 2-(2′-bromophenyl)-2-methyl-1,3-dioxalane (yield: 5.99 g, 97%) as a pale yellowish oil, which was found to be of >95% purity by ^{1}H and GC−MS analysis.

Part II. The 2-(2′-bromophenyl)-2-methyl-1,3-dioxalane (5.99 g, 24.6 mmol) was dissolved in anhydrous diethyl ether (60 mL), and the solution was cooled to −78 °C. *n*-Butyllithium (15.6 mL, 1.6 M solution in hexane, 25 mmol) was added dropwise with stirring. The reaction mixture was stirred for 2 h at −78 °C. Chlorodiphenylphosphine (6.60 g, 0.030 mol) was added dropwise via a syringe at −78 °C with stirring. The reaction mixture was allowed to warm to room temperature and stirred for an additional 18 h. The reaction mixture was taken up in methylene chloride (150 mL) and washed under inert atmosphere with 0.5 M degassed sodium hydroxide solution and water (50 mL). The organic phase was concentrated under vacuum to afford a yellowish solid. The yellowish solid was recrystallized from hot ethanol to afford ligand **1** (7.10 g, 83% yield) as a crystalline white solid. Alternatively, ligand **1** may be purified by rapid column chromatography on silica gel using 4:1 hexanes/ethyl acetate as eluent. ^{31}P{^{1}H} NMR ($CDCl_3$): δ −9.6. ^{1}H NMR ($CDCl_3$): δ 7.70 (m, 1H, ArH), 7.5−7.2 (m, 12H, ArH), 7.09 (m, 1H, ArH), 3.72 (m, 2H, $-OCH_2CH_2O-$), 3.20 (m, 2H, $-OCH_2CH_2O-$), 2.02 (s, 3H, $-CH_3$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 147.9 (d, J_{PC} = 23), 138.6 (d, J_{PC} = 12), 135.8, 134.6 (d, J_{PC} = 25), 133.8, 133.5, 128.6, 128.1 (m, 2C), 126.2 (d, J_{PC} = 6), 109.8 (−OCO−), 63.9 (OCH_2), 28.0 (CH_3). Anal. Calcd for $C_{22}H_{21}O_2P$: C, 75.85; H, 6.08; P, 8.89. Found: C, 75.83; H, 6.38; P, 8.73.

2-(2′-Diphenylphosphinophenyl)-1,3-dioxolane (Ligand 2).[13a,b] Ligand **2** (white crystalline solid) was prepared from 2-bromobenzaldehyde by the procedure described for the preparation of ligand **1**. ^{31}P{^{1}H} NMR ($CDCl_3$): δ −16.2. ^{1}H NMR ($CDCl_3$): δ 7.73 (d/d, J = 7.5/3.9, 1H, ArH), 7.43 (t, J = 7.5, 1H, ArH), 7.4−7.2 (m, 11H, ArH), 7.00 (d/d, J = 7.2/4.2, 1H, ArH), 6.47 (d, J_{PH} = 4.8, CH), 4.12 (m, 2H, $-OCH_2CH_2O-$), 3.98 (m, 2H, $-OCH_2CH_2O-$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 142.0 (d, J_{PC} = 21), 137.0 (d, J_{PC} = 10), 135.4 (d, J_{PC} = 19), 134.0, 133.8, 133.6, 129.2 (d, J_{PC} = 13), 128.5 (d, J_{PC} = 6), 128.4 (d, J_{PC} = 7), 126.4 (d, J_{PC} = 6), 101.7 (d, J_{PC} = 24, −OCO−), 65.4 ($-OCH_2-$). Anal. Calcd for $C_{21}H_{19}O_2P$: C, 75.44; H, 5.73; P, 9.26. Found: C, 75.64; H, 5.88; P, 9.15.

***o*-Diphenylphosphino-*N*,*N*-diethylbenzylamine (Ligand 3).**[13c] To a degassed mixture of 2-diphenylphosphinobenzaldehyde (310 mg, 1.07 mmol) and sodium triacetoxyborohydride (272 mg, 1.28 mmol) was added methylene chloride (10 mL). Diethylamine (1.0 mL, excess) was added via syringe to the reaction slurry at room temperature and the reaction mixture stirred for 30 min at room temperature and then 30 min at 40 °C. The reaction color changed from yellow to colorless. The reaction mixture was cooled to room temperature and concentrated under vacuum. The residue was filtered through a short column of silica gel using 4:1 hexanes/ethyl acetate as the eluent. Removal of solvents afforded ligand **3** (360 mg, 96% yield) as a colorless to pale yellow oil. ^{31}P{^{1}H} NMR ($CDCl_3$): δ −14.6. ^{1}H NMR ($CDCl_3$): δ 7.5 (m, 1H, ArH), 7.3−7.1 (m, 11H, ArH), 7.05 (t/d, J = 7.5/1.2, 1H, ArH), 6.79 (d/d/d, J = 7.5/4.2/1.5, 1H, ArH), 3.67 (d, J = 2.1, 2H, $-NCH_2-$), 2.32 (q, J = 7.2, 4H, $-NCH_2CH_3$), 0.75 (t, J = 7.2, 6H, 2 CH_3's).

3-(2′-Diphenylphosphinophenyl)-2-oxabutane (Ligand 4).[13d] Ligand **4** (off-white crystalline solid) was prepared from 3-(2′-bromophenyl)-2-oxabutane by the procedure described in part II for the preparation of ligand **1**. ^{31}P{^{1}H} NMR ($CDCl_3$): δ −16.1. ^{1}H NMR ($CDCl_3$): δ 7.59 (d/d, J = 7.8/4.2, 1H, ArH), 7.42 (t, J = 7.7, 1H, ArH), 7.41−7.25 (m, 10H, ArH), 7.20 (t/d,

(35) We have found these catalysts to be also useful for other metal-catalyzed reactions. For applications of such catalyst in Suzuki biaryl couplings involving aryl chlorides, see: Bei, X.; Crevier, T.; Guram, A. S.; Jandeleit, B.; Powers, T. S.; Turner, H. W.; Uno, T.; Weinberg, W. H. *Tetrahedron Lett.*, in press.

J = 7.5/1.2, 1H, ArH), 6.93 (d/d/d, J = 7.5/6/1, 1H, ArH), 5.18 (pentet, $^2J_{HH} = {}^3J_{PH}$ = 6.3, 1H, $-CHCH_3$), 3.11 (s, 3H, $-OCH_3$), 1.30 (d, J = 6.3, 3H, $-CHCH_3$). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 148.4 (d, J_{PC} = 26), 136.8 (d, J_{PC} = 10), 136.3 (d, J_{PC} = 10), 134.8 (d, J_{PC} = 14), 134.2 (d, J_{PC} = 20), 133.8 (d, J_{PC} = 20), 133.3, 129.5, 128.8, 128.7, 128.5 (d, J_{PC} = 6), 128.4 (d, J_{PC} = 5), 127.4, 125.5 (d, J_{PC} = 5), 76.1 (d, J_{PC} = 26, $-CHCH_3$), 56.3 ($-OCH_3$), 23.4 ($CHCH_3$). Anal. Calcd for $C_{21}H_{21}OP$: C, 78.73; H, 6.61; P, 9.67. Found: C, 78.70; H, 6.83; P, 9.57.

***o*-Diphenylphosphinoanisole (Ligand 5).** Ligand **5** (off-white crystalline solid) was prepared from the sequential reaction of *o*-bromoanisole, ^{t}BuLi, and Ph_2PCl by the procedure described for the preparation of ligand **7**. Ligand **5** is also commercially available. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −15.5. ^1H NMR ($CDCl_3$): δ 7.35−7.15 (m, 11H, ArH), 6.90−6.78 (m, 2H, ArH), 6.68−6.60 (m, 1H, ArH), 3.70 (s, 3H, $-OCH_3$).

2-(2′-Dicyclohexylphosphinophenyl)-2-methyl-1,3-dioxolane (Ligand 6). 2-(2′-Bromophenyl)-2-methyl-1,3-dioxalane (2.02 g, 8.31 mmol) was dissolved in anhydrous diethyl ether (30 mL), and the solution was cooled to −78 °C. *n*-Butyllithium (5.7 mL, 1.6 M solution in hexane, 9.13 mmol) was added dropwise with stirring. The reaction was stirred for 2 h. Chlorodicyclohexylphosphine (2.32 g, 9.96 mmol) was added dropwise via a syringe at −78 °C with stirring. The reaction mixture was allowed to warm to room temperature and stirred for an additional 18 h. To the reaction mixture was added argon-purged water (25 mL) slowly. The organic phase was separated under argon, and the aqueous phase was washed with diethyl ether (20 mL). The combined organic phase was concentrated under vacuum to afford a colorless oil, which was crystallized from methanol to afford ligand **6** as a white crystalline solid (yield: 2.13 g, 71% unoptimized yield). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −8.2. ^1H NMR ($CDCl_3$): δ 7.67 (br 1H, ArH), 7.59 (br, 1H, ArH), 7.29 (br, 2H, ArH), 4.02 (m, 2H, $-OCH_2CH_2O-$), 3.73 (m, 2H, $-OCH_2CH_2O-$), 1.97−1.15 (br m, 25H, CyH and CH_3). ^{13}C NMR ($CDCl_3$): δ 149.3 (d, J_{PC} = 23), 134.8 (d, J_{PC} = 28), 134.0, 128.0, 127.1, 125.4 (d, J_{PC} = 6), 109.6 ($-OCO-$), 64.0 ($-OCH_2-$), 36.3 (d, J_{PC} = 15), 30.8 (d, J_{PC} = 18), 30.0 (d, J_{PC} = 11), 29.4 (d, J_{PC} = 14), 27.4 (d, J_{PC} = 9), 27.2 (d, J_{PC} = 12), 26.4. Anal. Calcd for $C_{22}H_{33}O_2P$: C, 73.30; H, 9.23; P, 8.59. Found: C, 73.50; H, 9.46; P, 8.36.

1-(2′-Dicyclohexylphosphinophenyl)-1,1-dimethoxymethane (Ligand 7). *o*-Dimethoxymethylbromobenzene (4.13 g, 17.9 mmol) was dissolved in anhydrous diethyl ether (60 mL), and the solution was cooled to −78 °C. *tert*-Butyllithium (21.2 mL, 1.7 M solution in hexane, 36 mmol) was added dropwise with stirring. The reaction was stirred for 1 h. Chlorodicyclohexylphosphine (5.0 g, 21.5 mmol) was added dropwise via a syringe at −78 °C with stirring. The reaction mixture was allowed to warm to room temperature over an additional 18 h. To the mixture was added deoxygenated water (40 mL) slowly. The organic phase was separated under argon, and the aqueous phase was washed with diethyl ether (20 mL). The combined organic phase was dried under vacuum at 40 °C. The crude product was washed with methanol (3 × 10 mL) and dried under vacuum, affording ligand **7** as a white solid product (yield: 5.66 g, 90.7%). $^{31}P\{^1H\}$ ($CDCl_3$): δ −18.5. ^1H NMR ($CDCl_3$): δ 7.62 (br, 1H, ArH), 7.40 (br, 1H, ArH), 7.25 (m, 2H, ArH), 6.17 (d, J_{PH} = 6.5, 1H $CH(OCH_3)_2$), 3.35 (s, 6H, $-OCH_3$), 2.0−0.9 (m, 22H, CyH). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 144.8 (d, J_{PC} = 22), 134.3 (d, J_{PC} = 25), 132.3, 128.5, 127.5, 126.2 (d, J_{PC} = 5), 101.8 (d, J_{PC} = 29), 53.8, 34.2 (d, J_{PC} = 12), 30.3 (d, J_{PC} = 17), 29.3 (d, J_{PC} = 9), 27.0 (m, 2C), 26.2. Anal. Calcd for $C_{21}H_{33}O_2P$: C, 72.38; H, 9.55; P, 8.89. Found: C, 72.46; H, 9.90; P, 9.03.

***o*-Dicyclohexylphosphino-*N*,*N*-dimethylbenzylamine (Ligand 8). Part I.** A reaction mixture of ligand **7** (1.0 g, 2.9 mmol), deoxygenated water (5 mL), and *p*-toluenesulfonic acid monohydrate (55 mg, 0.29 mmol) in THF (10 mL) was stirred at 50−55 °C for 20 h. The reaction was cooled to ambient temperature and extracted with diethyl ether (2 × 5 mL). The organic phase was concentrated under vacuum, affording a yellow oil. The crude product was purified by column chromatography on silica gel using hexanes/ethyl acetate (8:1) as the eluent to afford *o*-dicyclohexylphosphinobenzaldehyde as a yellow oil (yield: 740 mg, 85%).

Part II. To an air-free slurry of sodium triacetoxyborohydride (523 mg, 2.47 mmol) in methylene chloride (10 mL) and *o*-dicyclohexylphosphinobenzaldehyde (370 mg, 1.23 mmol) was added a solution of NMe_2H (5 mL, 2.0 M in THF) at room temperature, and the mixture was stirred for 30 min. Deoxygenated H_2O (10 mL) was added slowly to the reaction mixture with stirring. The organic phase was separated and concentrated under vacuum, affording ligand **8** as a colorless oil in quantitative yield. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −16.7. ^1H NMR ($CDCl_3$): δ 7.52 (d/d, J = 7.5/3.6, 1H, ArH), 7.41 (d, J = 7.2, 1H, ArH), 7.29 (t/d, J = 7.2/0.9, 1H, ArH), 7.20 (t/d, J = 7.5/1.2, 1H, ArH), 3.82 (d, J_{PH} = 2.7, 2H, $-NCH_2$), 2.25 (s, 6H, NMe_2), 2.0−0.9 (m, 22H, CyH). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 146.0 (d, J_{PC} = 23), 134.3 (d, J_{PC} = 20), 132.2 (d, J_{PC} = 3), 129.4 (d, J_{PC} = 5), 128.5, 125.8, 61.3 (d, J_{PC} = 25), 45.1, 34.0 (d, J_{PC} = 13), 30.3 (d, J_{PC} = 17), 29.1 (d, J_{PC} = 12), 27.0 (m, 2C), 26.3. Anal. Calcd for $C_{21}H_{34}NP$: C, 76.09; H, 10.34; P, 9.34. Found: C, 76.39; H, 10.65; P, 9.72.

2-(2-Dicyclohexylphosphinophenyl)-4,4-dimethyl-4,5-dihydrooxazole (Ligand 9). A solution of dicyclohexylphosphine (2.74 g, 13.8 mmol) in tetrahydrofuran (20 mL) was cooled to −78 °C. A solution of *n*-butyllithium (9.08 mL. 1.6 M in hexanes) was added dropwise with stirring. The reaction mixture was stirred for 30 min at −78 °C and was allowed to warm to −20 °C over 2.5 h. A solution of 2-(2-fluorophenyl)-4,4-dimethyloxazole (1.86 g, 9.70 mmol) in tetrahydrofuran (10 mL) was added to the mixture, and the mixture was stirred and allowed to warm to room temperature. The mixture was concentrated under vacuum. The product was purified by rapid column chromatography on silica gel using 4:1 hexanes/ethyl acetate as eluent, yielding ligand **9** in a quantitative yield. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −5.8. ^1H NMR ($CDCl_3$): δ 7.55 (m, 2H, ArH), 7.38 (m, 2H, ArH), 4.14 (s, 2H, OCH_2), 2.2−0.9 (m, 28H, CyH and CMe_2). $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 164.1, 136.4 (d, J_{PC} = 28), 132.5, 130.3 (d, J_{PC} = 35), 129.4 (d, J_{PC} = 7), 129.0, 128.2, 79.1, 67.7, 34.3 (d, J_{PC} = 13), 30.2 (d, J_{PC} = 17), 29.6 (d, J_{PC} = 11), 28.2, 27.1 (m, 2C), 26.3. Anal. Calcd for $C_{23}H_{34}NOP$: C, 74.36; H, 9.22; P, 8.34. Found: C, 74.36; H, 9.14; P, 8.56.

2-(Dicyclohexylphosphino)anisole (Ligand 10). Ligand **10** was prepared from the sequential reaction of *o*-bromoanisole (1.00 gm, 5.35 mmol), ^{t}BuLi (6.3 mL of 1.7 M solution in hexane, 10.7 mmol), and dicylcohexylphosphinochloride (1.5 g, 6.2 mmol) (yield: 1.36 g, 84%) by the procedure described for the preparation of ligand **7**. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −9.6. $^{13}C\{^1H\}$ NMR ($CDCl_3$): δ 162.7 (d, J_{PC} = 11), 134.8 (d, J_{PC} = 10), 129.8, 122.7 (d, J_{PC} = 21), 120.0 (d, J_{PC} = 4), 110.3, 55.1, 32.6 (d, J_{PC} = 12), 30.4 (d, J_{PC} = 17), 29.1 (d, J_{PC} = 8), 27.0 (m, 2C), 26.3. Anal. Calcd for $C_{19}H_{29}OP$: C, 74.97; H, 9.60; P, 10.18. Found: C, 74.98; H, 9.94; P, 10.02.

Complex 11. Methylene chloride (4 mL) was added to a mixture of $\{Pd[P(o\text{-toluyl})_3](4\text{-}^tBu\text{-}C_6H_4)(\mu\text{-}Br)\}_2$ (250 mg, 0.20 mmol) and ligand **1** (140 mg, 0.40 mml) at room temperature under argon. The mixture was stirred for 4 h and concentrated to ca. 0.5 mL. Heptane (20 mL) was added to the solution, and the mixture was stirred for 30 min and filtered. The solid was washed with heptane (4 × 5 mL) and dried under vacuum, yielding compound **11** as a pale yellow solid (yield: 235 mg, 88%). Crystals of compound **11** suitable for X-ray crystallographic diffraction were obtained from the solution of CH_2Cl_2/heptane (volume ratio = 1:32) at room temperature. $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 16.3. ^1H NMR ($CDCl_3$): δ 7.8−7.0 (m, 12H, ArH), 6.65 (m, 6H, ArH), 4.70 (br, 1H, $-OCH_2$), 4.21 (br, 1H, $-OCH_2$), 3.85 (br s, 2H, $-OCH_2CH_2O-$), 2.15 (s, 3H, $-CH_3$), 1.14 (s, 9H, $-C(CH_3)_3$). ^1H NMR ($CDCl_3$, 55 °C): δ 7.81 (d/d, J = 8.7/5.1, 2H, ArH), 7.50 (t, J = 6.9, 2H, ArH), 7.46−

7.10 (br m, 10H, ArH), 6.76 (d/d, J = 8.4/3.6, 2H, ArH), 6.67 (d, J = 8.4, 2H, ArH), 4.48 (br, 2H, $-OCH_2CH_2O-$), 3.86 (m, 2H, $-OCH_2CH_2O-$), 2.20 (s, 3H, CH_3), 1.19 (s, 9H, $C(CH_3)$). ^{1}H NMR (C_6D_5Cl, 30 °C): δ 4.5 (br, 1H, $-OCH_2-$), 3.6 (br, 1H, $-OCH_2-$, partially overlapped), 3.31 (br, 2H, $-OCH_2-CH_2-$, partially overlapped). ^{1}H NMR (C_6D_5Cl, 70 °C): δ 4.01 (br s, 2H, $-OCH_2CH_2-$), 3.32 (br m, 2H, $-OCH_2CH_2-$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 147.1(d, J_{PC} = 13), 145.4, 136.6, 135.6, 134.7 (d, J_{PC} = 4.7), 133.6 (br, 2C), 131.4, 130.5 (br), 128.6 (br, 2C), 126.8, 126.3 (d, J_{PC} = 8), 124.4, 109.3 ($-OCO-$), 67.3 (br, $-OCH_2-$), 64.8 (br, $-OCH_2-$), 33.8, 31.5, 30.4. Anal. Calcd for $C_{32}H_{34}BrO_2PPd$: C, 57.54; H, 5.13; P, 4.64. Found: C, 58.25; H, 5.13; P, 4.45.

Complex 12. Methylene chloride (1.5 mL) was added to a mixture of {Pd[P(*o*-toluyl)$_3$](4-^{t}Bu-C_6H_4)(μ-Br)}$_2$ (150 mg, 0.12 mmol) and ligand **6** (120 mg, 0.33 mmol) at room temperature under argon. The mixture was stirred for 3 h and filtered. The filtrate was concentrated to ca. 1 mL under vacuum and layered with heptane (16 mL), and the mixture was kept at room temperature for 12 h. Crystals of **12** suitable for X-ray analysis were obtained. ^{31}P{^{1}H} NMR ($CDCl_3$): δ 28.5. ^{1}H NMR ($CDCl_3$): δ 7.70 (d/d/d, J = 7.8/4.2/1.5, 1H, ArH), 7.59 (t, J = 7.8, 1H, ArH), 7.47 (t, J = 7.7, 1H, ArH), 7.37 (t, J = 7.7, 1H, ArH), 7.18 (br d, 2H, ArH), 6.98 (d, J = 7.8, 2H, ArH), 4.71 (q, J = 7.1, 1H, $-OCH_2-$), 4.12 (m, 1H, $-OCH_2-$), 3.81 (m, 1H, $-OCH_2-$), 3.71 (m, 1H, $-OCH_2-$), 2.30 (s, 3H, CH_3), 1.23 (9H, $C(CH_3)_3$). The 22 hydrogens of the two Cy groups show broad multiple resonances in the range 1.9−0 ppm. ^{1}H NMR (toluene-d_8, 23 °C): δ 4.83 (q, J = 7.1, 1H, $-OCH_2-$), 3.54 (m, 1H, $-OCH_2-$), 3.42 (m, 1H, $-OCH_2-$), 3.15 (m, 1H, $-OCH_2-$). ^{1}H NMR (toluene-d_8, 105 °C): δ 4.7−3.8 (br, 2H, $-OCH_2CH_2O-$), 3.39 (br, 2H, $-OCH_2CH_2O-$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 148.7 (d, J_{PC} = 10), 145.8, 135.4, 134.0, 133.1, 130.8, 127.8 (d, J_{PC} = 5), 126.3 (d, J_{PC} = 7), 124.7 (d, J = 27), 124.3 (br), 109.5 (OCO), 67.2 ($-OCH_2-$), 64.5 ($-OCH_2-$), 37.3 (d, J_{PC} = 23), 35.5 (d, J_{PC} = 24), 33.9, 31.6, 31.5, 30.1 (d, J_{PC} = 4), 29.2, 27.5−26.7 (overlapping signals), 26.0, 25.5.

Complex 13. Methylene chloride (4 mL) was added to a mixture of {Pd[P(*o*-toluyl)$_3$](4-^{t}Bu-C_6H_4)(μ-Br)}$_2$ (187 mg, 0.150 mmol) and ligand **2** (201 mg, 0.600 mmol) at room temperature under argon. The mixture was stirred for 4 h and filtered, and the filtrate was concentrated to ca. 0.5 mL under vacuum. Pentane (20 mL) was added to the concentrated solution, and the mixture was stirred for 30 min and then filtered. The solid was washed with pentane (4 × 5 mL) and dried under vacuum, yielding compound **13** as a pale yellow solid (yield: 285 mg, 87%). Crystals of compound **13** suitable for X-ray crystallographic diffraction were obtained from the solution of CH_2Cl_2/heptane (volume ratio = 1:32) at room temperature. ^{31}P{^{1}H} NMR ($CDCl_3$): δ18.0. ^{1}H NMR ($CDCl_3$): δ 7.82 (d, J = 6.9, 2H, ArH), 7.44 (t, J = 7.5, 2H, ArH), 7.40−7.10 (m, 24H, ArH), 6.91 (m, 2H, ArH), 6.73 (d, J = 8.1, 2H, ArH), 6.52 (d, J = 7.8, 2H, CH), 4.08 (m, 4H, OCH_2CH_2O), 3.92 (m, 4H, OCH_2CH_2O), 1.16 (s, 9H, CMe_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 147.1, 145.5, 141.3, 136.2, 135.6 (2C), 133.3, 131.5, 130.2, 129.4, 128.5, 127.5 (2C), 125.1, 102.2, 65.4, 33.8, 31.7. Anal. Calcd for $C_{52}H_{51}BrO_4P_2Pd$: C, 63.20; H, 5.20; P, 6.27. Found: C, 63.57; H, 5.67; P, 6.03.

Procedure for Pd(dba)$_2$/Ligand 1−5-Catalyzed Reactions of 4-Bromobiphenyl with Morpholine and Dibutylamine. A mixture of 4-bromobiphenyl (233 mg, 1.00 mmol), morpholine (0.10 mL, 1.1 mmol) or dibutylamine (0.19 mL, 1.1 mmol), NaO^{t}Bu (116 mg, 1.20 mmol), Pd(dba)$_2$ (12 mg, 20 μmol), and ligands **1**−**5** (60 μmol) in toluene (4 mL) was heated at 105 °C for 75 min (morpholine substrate) or for 90 min (di-*n*-butylamine substrate). At the end of the reaction period the reactions were analyzed by GC−MS. Results are shown in Table 1.

Compound 14 (entry A, Table 2). A mixture of 4-bromo-*tert*-butylbenzene (319 mg, 1.50 mmol), *N*-methylbenzylamine (218 mg, 1.80 mmol), NaO^{t}Bu (173 mg, 1.80 mmol), Pd(dba)$_2$ (11 mg, 19 μmol), and ligand **1** (15 mg, 40 μmol) in toluene (4 mL) was heated at 105 °C for 90 min. The reaction was cooled to room temperature, taken up in diethyl ether (125 mL), washed with water (2 × 30 mL) and brine (30 mL), dried over $MgSO_4$, filtered, and concentrated under vacuum. The crude product was purified by column chromatography on silica gel using hexane (or hexanes/ethyl acetate) as the eluent to afford compound **14** (315 mg, 83% yield), after drying under vacuum, as a pale yellow solid. ^{1}H NMR ($CDCl_3$): δ 7.34−7.24 (m, 7H, ArH), 6.75 (d, 2H, J = 8.8 Hz, ArH), 4.51 (s, 2H, N−CH_2−Ar), 3.01 (s, 3H, N−CH_3), 1.31 (s, 9H, $C(CH_3)_3$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 147.6, 139.4, 128.5, 128.2, 126.8, 126.8, 125.9, 112.2, 57.0, 38.5, 33.7, 31.5. Anal. Calcd for $C_{18}H_{23}N$: C, 85.32; H, 9.15; N, 5.53. Found: C, 85.67; H, 9.77; N, 5.34.

Compound 15 (entry B, Table 2). Compound **15** (437 mg, 98% yield) was obtained as a pale yellow solid from the reaction of 4-bromobenzophenone (440 mg, 1.69 mmol), piperidine (0.20 mL, 2.0 mmol), NaO^{t}Bu (192 mg, 2.00 mmol), Pd(dba)$_2$ (19 mg, 33 μmol), and ligand **1** (32 mg, 90 μmol) in toluene (4 mL) at 105 °C for 60 min. The isolated sample contained trace amount of hexanes. ^{1}H NMR ($CDCl_3$): δ 7.90−7.70 (m, 4H, ArH), 7.51−7.27 (m, 3H, ArH), 6.86 (m, 2H, ArH), 3.36 (br, 4H, $-CH_2-N-CH_2-$), 1.65 (br s, 6H, N−C−$CH_2-CH_2-CH_2-$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 195.0, 154.1, 139.0, 132.6, 131.2, 129.4, 128.2, 128.0, 113.1, 48.6, 25.3, 24.3. Anal. Calcd for $C_{18}H_{19}NO$: C, 81.47; H, 7.22; N, 5.28. Found: C, 81.74; H, 7.58; N, 4.99.

Compound 16 (entry C, Table 2). Compound **16** (518 mg, 93% yield) was obtained as a colorless oil from the reaction of 4-bromo-*tert*-butylbenzene (319 mg, 1.50 mmol), dioctylamine (0.54 mL, 1.80 mmol), NaO^{t}Bu (173 mg, 1.80 mmol), Pd(dba)$_2$ (8.0 mg, 14 μmol), and ligand **1** (15 mg, 43 μmol) in toluene (4 mL) at 105 °C for 7 h. ^{1}H NMR ($CDCl_3$): δ 7.30 (d, 2H, J = 9.0 Hz, ArH), 6.66 (d, 2H, J = 9.0 Hz, ArH), 3.28 (br t, 4H, J = 8.0 Hz, CH_2-N-CH_2), 1.63 (br, 4H), 1.43−1.36 (br, 29H), 0.95 (br, 6H, 2 CH_3's). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 146.5, 138.0, 126.4, 111.7, 51.6, 34.1, 32.3, 32.0, 29.9, 29.8, 27.8, 27.7, 23.1, 14.6. Anal. Calcd for $C_{26}H_{47}N$: C, 83.57; H, 12.68; N, 3.75. Found: C, 83.44; H, 12.39; N, 3.71.

Compound 17 (entry D, Table 2). Compound **17** (299 mg, 91% yield) was obtained as a colorless oil from the reaction of 5-bromo-*m*-xylene (272 mg, 1.47 mmol), *N*-methylbenzylamine (214 mg, 1.77 mmol), NaO^{t}Bu (170 mg, 1.77 mmol), Pd(dba)$_2$ (17 mg, 30 μmol), and ligand **1** (28 mg, 80 μmol) in toluene (4 mL) at 105 °C for 2 h. Alternatively, this compound (278 mg, 83% yield) was obtained as a colorless oil from the reaction of 5-iodo-*m*-xylene (343 mg, 1.50 mmol), *N*-methylbenzylamine (214 mg, 1.77 mmol), NaO^{t}Bu (170 mg, 1.77 mmol), Pd(dba)$_2$ (17 mg, 30 μmol), and ligand **1** (28 mg, 80 μmol) in 1,4-dioxane (4 mL) at 105 °C for 3.5 h (entry E, Table 1). ^{1}H NMR ($CDCl_3$): δ 7.37−7.29 (m, 5H, ArH), 6.47 (br, 3H, ArH), 4.56 (s, 2H, N−CH_2−Ar), 3.02 (s, 3H, N−CH_3), 2.32 (s, 6H, Ar−$(CH_3)_2$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 150.0, 139.2, 138.7, 128.5, 126.8, 126.7, 118.7, 110.3, 56.6, 38.3, 21.7. Anal. Calcd for $C_{16}H_{19}N$: C, 85.28; H, 8.50; N, 6.22. Found: C, 85.32; H, 8.42; N, 5.98.

Compound 18 (entry F, Table 2). Compound **18** (272 mg, 88% yield) was obtained as a yellow oil from the reaction of 4-cyanobromobenzene (238 mg, 1.31 mmol), 2,4,6-trimethylaniline (212 mg, 1.56 mmol), NaO^{t}Bu (151 mg, 1.57 mmol), Pd(dba)$_2$ (15 mg, 26 μmol), and ligand **1** (25 mg, 72 μmol) in toluene (4 mL) at 105 °C for 2 h. A trace amount of diarylated product is generated in this reaction. The amount of diarylated product formed is greater if less than 1.2 equiv of 2,4,6-trimethylaniline is used. ^{1}H NMR ($CDCl_3$): δ 7.37 (d, 2H, J = 8.8, ArH), 6.95 (s, 2H, ArH), 6.43 (d, 2H, J = 8.8, ArH), 5.54 (br s, 1H, NH), 2.31 (s, 3H, CH_3), 2.16 (6H, 2 CH_3's). Anal. Calcd for $C_{16}H_{16}N_2$: C, 81.32; H, 6.82; N, 11.85. Found: C, 80.92; H, 7.19; N, 11.63.

Compound 19 (entry G, Table 2). Compound **19** (320 mg, 90% yield) was obtained as a colorless oil from the reaction of

4-ethoxybromobenzene (281 mg, 1.40 mmol), 2,4,6-trimethylaniline (227 mg, 1.68 mmol), NaO^{t}Bu (161 mg, 1.68 mmol), Pd(dba)$_2$ (16 mg, 28 μmol), and ligand **1** (27 mg, 78 μmol) in toluene (4 mL) at 105 °C for 21 h. ^{1}H NMR ($CDCl_3$): δ 6.91 (s, 2H, ArH), 6.72 (d, 2H, J = 8.6, ArH), 6.44 (d, 2H, J = 8.6, ArH), 4.9 (br, 1H, NH), 3.94 (q, 2H, J = 6.9, OCH_2), 2.29 (s, 3H, $ArCH_3$), 2.15 (s, 6H, 2 $ArCH_3$'s), 1.36 (t, 3H, J = 6.9, O−C−CH_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 151.8, 140.5, 136.5, 135.1, 134.6, 129.2, 115.5, 114.8, 63.9, 20.8, 18.2, 15.0. Anal. Calcd for $C_{17}H_{21}NO$: C, 79.96; H, 8.29; N, 5.49. Found: C, 80.27; H, 8.48; N, 5.24.

Compound 20 (entry H, Table 2). Compound **20** (339 mg, 92% yield) was obtained as a colorless solid from the reaction of 9-bromophenanthrene (352 mg, 1.37 mmol), aniline (153 mg, 1.64 mmol), NaO^{t}Bu (158 mg, 1.64 mmol), Pd(dba)$_2$ (16 mg, 28 μmol), and ligand **1** (26 mg, 75 μmol) in toluene (4 mL) at 105 °C for 3 h. The isolated sample contained a trace amount of solvents. ^{1}H NMR ($CDCl_3$): δ 8.74 (d, 1H, J = 8.0, ArH), 8.64 (m, 1H, ArH), 8.13 (d, 1H, J = 8.0, ArH), 7.73−7.54 (m, 6H, ArH), 7.34−7.24 (m, 2H, ArH), 7.06 (d, 2H, J = 8.4, ArH), 6.98 (t, 1H, J = 7.4, ArH), 5.95 (br, 1H, NH). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 144.6, 136.9, 132.5, 131.4, 129.4, 128.1, 127.8, 127.5, 126.9, 126.8, 126.6, 125.0, 123.2, 122.4, 122.3, 120.7, 117.9, 114.7. Anal. Calcd for $C_{20}H_{15}N$: C, 89.19; H, 5.61; N, 5.20. Found: C, 89.12; H, 5.82; N, 5.07.

Compound 21 (entry I-K, Table 2). Compound **21** (381 mg, 96% yield) was obtained as a colorless solid from the reaction of 2-(2′-bromophenyl)-2-methyl-1,3-dioxolane (318 mg, 1.31 mmol), 2-chloro-6-methylaniline (195 mg, 1.38 mmol), NaO^{t}Bu (152 mg, 1.58 mmol), Pd(dba)$_2$ (15 mg, 28 μmol), and ligand **1** (18 mg, 52 μmol) in toluene (4 mL) at 105 °C for 2 h. ^{1}H NMR ($CDCl_3$): δ 7.51 (m, 2H, ArH and NH), 7.36 (d, 1H, J = 7.9, ArH), 7.19 (d, 1H, J = 7.3, ArH), 7.13−7.06 (m, 2H, ArH), 6.83 (t, 1H, J = 7.3, ArH), 6.27 (d, 1H, J = 7.9, ArH), 4.17 (m, 2H, O−CH−CH−O), 3.97 (m, 2H, O−CH−CH−O), 2.23 (s, 3H, CH_3), 1.89 (s, 3H, CH_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 142.4, 137.4, 136.8, 131.2, 129.3, 128.8, 127.5, 126.8, 126.4, 125.3, 118.5, 113.5, 109.6, 64.1, 24.1, 18.8. Anal. Calcd for $C_{17}H_{18}ClNO_2$: C, 67.21; H, 5.97; N, 4.61. Found: C, 66.92; H, 5.83; N, 4.53.

Compound 22 (entry J, Table 2). Compound **22** (439 mg, 97% yield) was obtained as a colorless oil from the reaction of 2-bromoanisole (300 mg, 1.60 mmol), 2,6-diisopropylaniline (298 mg, 1.68 mmol), NaO^{t}Bu (161 mg, 1.68 mmol), Pd(dba)$_2$ (18 mg, 31 μmol), and ligand **1** (30 mg, 86 μmol) in toluene (4 mL) at 105 °C for 1 h. ^{1}H NMR ($CDCl_3$): δ 7.41−7.21 (m, 3 H, ArH), 6.94 (d, 1H, J = 7.4, ArH), 6.83−6.73 (m, 2H, ArH), 6.23 (d, 1H, J = 7.4, ArH), 5.72 (br, 1H, NH), 4.01 (s, 3H, OCH_3), 3.28 (heptet, 2H, J = 6.9, 2 C*H*Me$_2$'s), 1.25 (d, 12H, J = 6.9, 2 $(-CH_3)_2$'s). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 147.6, 146.2, 137.9, 135.4, 127.0, 123.7, 121.1, 116.7, 110.9, 109.7, 55.7, 28.1, 23.9. Anal. Calcd for $C_{19}H_{25}NO$: C, 80.52; H, 8.89; N, 4.94. Found: C, 79.93; H, 8.89; N, 4.85.

Procedure for Pd(dba)$_2$/Ligand 6−10-Catalyzed Reactions of 5-Chloro-*m*-xylene with Morpholine and *N*-Heptylmethylamine. A mixture of 5-chloro-*m*-xylene (0.14 mL, 1.0 mmol), morpholine(0.10 mL, 1.1 mmol) or *N*-methylheptylamine (0.19 mL, 1.1 mmol), NaO^{t}Bu (130 mg, 1.20 mmol), Pd(dba)$_2$ (12 mg, 20 μmol), and ligands **6**−**10** (60 μmol) in toluene (4 mL) was heated at 105 °C for 60 min. At the end of the reaction period the reactions were analyzed by GC−MS. Results are shown in Table 3.

Compound 23 (entry A, Table 4). Compound **23** (181 mg, 92% yield) was obtained as a yellow oil from the reaction of 5-chloro-*m*-xylene (0.14 mL, 1.0 mmol), morpholine (0.10 mL, 1.0 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 1 h. ^{1}H NMR ($CDCl_3$): δ 6.60 (s, 3 H, ArH), 3.88 (t, J = 4.8, 4H, $-O(CH_2)_2-$), 3.17 (t, J = 4.8, 4H, $-N(CH_2)_2-$), 2.34 (s, 6H, CH_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 151.3, 138.5, 121.8, 113.6, 66.8, 49.4, 21.5. Anal. Calcd for $C_{12}H_{17}NO$: C, 75.35; H, 8.96; N, 7.32. Found: C, 75.48; H, 9.23; N, 7.33.

Compound 24 (entry B, Table 4). Compound **24** (289 mg, 96% yield) was obtained as a yellow oil from the reaction of 4-chlorobenzophenone (217 mg, 1.00 mmol), *N*-benzylmethylamine (0.14 mL, 1.1 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 1 h. ^{1}H NMR ($CDCl_3$): δ 7.83 (d, J = 9.0, 2H, ArH), 7.75 (d, J = 6.8, 2H, ArH), 7.58−7.22 (m, 8H, ArH), 6.77 (d, J = 8.9, 2H, ArH), 4.69 (s, 2H, $-N-CH_2$-Ph), 3.19 (s, 3H, $-NCH_3$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 195.0, 152.7, 139.2, 137.5, 132.8, 131.1, 129.4, 128.8, 127.9, 127.2, 126.4, 125.3, 110.8, 56.0, 38.8. Anal. Calcd for $C_{21}H_{19}NO$: C, 83.69; H, 6.35; N, 4.65. Found: C, 83.38; H, 6.45; N, 4.46.

Compound 25 (entry C, Table 4). Compound **25** (238 mg, 90% yield) was obtained as a colorless cotton-like solid from the reaction of 4-chlorobenzonitrile (138 mg, 1.00 mmol), *N*-phenylpiperazine (0.17 mL, 1.11 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 1 h. Isolated compound contained trace amounts of solvents. ^{1}H NMR ($CDCl_3$): δ 7.50 (d, J = 8.8, 2H, ArH), 7.28 (m, 3H, ArH), 6.95 (d, J = 8.3, 2H, ArH), 6.89 (d, J = 8.0, 2H, ArH), 3.48 (br, 4H, $-NCH_2$'s), 3.31 (br, 4H, $-NCH_2$'s). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 153.2, 150.7, 133.5, 129.3, 120.4, 119.9, 116.4, 114.3, 100.6, 49.0, 47.2. Anal. Calcd for $C_{17}H_{17}N_3$: C, 77.54; H, 6.51; N, 15.96. Found: C, 77.34; H, 6.43; N, 16.03.

Compound 26 (entry D, Table 4). Compound **26** (311 mg, 97% yield) was obtained as a colorless oil from the reaction of 4-chlorobenzotrifluoride (0.13 mL, 0.97 mmol), dihexylamine (0.25 mL, 1.1 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 1 h. ^{1}H NMR ($CDCl_3$): δ 7.39 (d, J = 8.8, 2H, ArH), 6.59 (d, J = 8.8, 2H, ArH), 3.27 (t, J = 7.6, 4H, $-NCH_2$'s), 1.55 (br, 4H, $-CH_2CH_2$'s), 1.31 (br, 12H), 0.90 (t, J = 6.4, 6H, 2 CH_3's). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 150.1, 126.5, 110.5, 51.0, 31.7, 27.0, 26.8, 22.7, 14.0 (due to coupling to fluorine atoms, the two carbon atoms α and β to fluorine atoms could not be conclusively identified from the baseline). Anal. Calcd for $C_{19}H_{30}F_3N$: C, 69.27; H, 9.18; N, 4.25. Found: C, 69.22; H, 9.17; N, 4.42.

Compound 27 (entry E, Table 4). Compound **27** (277 mg, 89% yield) was obtained as a white crystalline solid from the reaction of 2-(2′-chlorophenyl)-2-methyl-1,3-dioxolane (198 mg, 1.00 mmol), 2-*tert*-butylaniline (0.17 mL, 1.1 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 2 h. ^{1}H NMR ($CDCl_3$): δ 7.47 (br t, J = 6.6, 2H, ArH), 7.29 (d, J = 6, 1H, ArH, partially overlap), 7.28 (br, 1H, NH), 7.18−7.06 (m, 3H, ArH), 6.90 (d, J = 8.1, 1H, ArH), 6.79 (t, J = 8.0, 1H, ArH), 4.12 (br, 2H, $-OCH_2CH_2O-$), 3.95 (br, 2H, $-OCH_2CH_2O-$), 1.82 (s, 3H, CH_3), 1.47 (s, 9H, $C(CH_3)_3$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 143.5, 142.9, 141.1, 128.9, 127.7, 127.1, 126.7, 126.4, 125.5, 123.2, 118.2, 115.8, 109.5, 64.1, 34.1, 30.2, 24.9. Anal. Calcd for $C_{20}H_{25}NO_2$: C, 77.14; H, 8.09; N, 4.50. Found: C, 77.09; H, 8.29; N, 4.46.

Compound 28 (entry F, Table 4). Compound **28** (222 mg, 96% yield) was obtained as an off-white solid from the reaction of 2-chloro-*p*-xylene (0.13 mL, 0.97 mmol), 2,4,6-trimethylaniline (0.14 mL, 0.99 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 1 h. ^{1}H NMR ($CDCl_3$): δ 7.02 (d, J = 7.4, 1H, ArH), 6.97 (s, 2H, ArH), 6.52 (d, J = 7.4, 1H, ArH), 5.98 (s, 1H, ArH), 4.84 (br, 1H, −NH), 2.34 (s, 3H, $-CH_3$), 2.29 (s, 3H, $-CH_3$), 2.17 (br, 9H, 3 CH_3's). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 144.2, 136.6, 136.0, 135.5, 134.9, 130.0, 129.2, 119.1, 118.4, 112.1, 21.3, 20.9, 18.2, 17.2. Anal. Calcd for $C_{17}H_{21}N$: C, 85.30; H, 8.84; N, 5.85. Found: C, 85.29; H, 9.07; N, 5.75.

Compound 29 (entry G, Table 4). Compound **29** (209 mg, 92% yield) was obtained as a yellow oil from the reaction of

2-chloro-*p*-xylene (0.13 mL, 0.97 mmol), octylamine (0.18 mL, 1.1 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 3 h. ^{1}H NMR ($CDCl_3$): δ 6.97 (d, J = 7.3, 1H, ArH), 6.50 (d, J = 7.3, 1H, ArH), 6.48 (br, 1H, ArH), 3.44 (br, 1H, −NH), 3.18 (t, J = 7.2, 2H, $-NCH_2-$), 2.35 (s, 3H, Ar$-CH_3$), 2.13 (s, 3H, Ar$-CH_3$), 1.69 (m, 2H, $-NCH_2CH_2-$), 1.6−1.2 (br, 10H, overlapped signals), 0.94 (br, 3H, CH_2CH_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 146.0, 136.6, 129.8, 118.6, 117.2, 110.5, 43.9, 31.8, 29.6, 29.4, 29.3, 27.2, 22.6, 21.5, 16.9, 14.1. Anal. Calcd for $C_{16}H_{27}N$: C, 82.34; H, 11.66; N, 6.00. Found: C, 82.23; H, 11.84; N, 5.91.

Compound 30 (entry H, Table 4). Compound **30** (183 mg, 83% yield) was obtained as a yellow oil from the reaction of 2-chloroanisole (0.12 mL, 0.94 mmol), octylamine (0.19 mL, 1.1 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) at 105 °C for 3 h. ^{1}H NMR ($CDCl_3$): δ 6.92 (t, J = 7.6, 1H, ArH), 6.81 (d, J = 7.6, 1H, ArH), 6.71 (d, J = 7.6, 1H, ArH), 6.67 (t, J = 7.6, 1H, ArH), 4.22 (br, 1H, −NH), 3.86 (s, 3H, $-OCH_3$), 3.16 (t, J = 7.2, 2H, $-NCH_2-$), 1.69 (pentet, 2H, $-NCH_2CH_2CH_2-$), 1.35 (br, 10H, 5 $-CH_2-$'s), 0.95 (br, 3H, CH_3). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 146.7, 138.5, 121.3, 115.9, 109.7, 109.3, 55.3, 43.7, 31.8, 29.5, 29.4, 29.2, 27.2, 22.6, 14.0. Anal. Calcd for $C_{15}H_{25}NO$: C, 76.55; H, 10.71; N, 5.95. Found: C, 76.74; H, 10.98; N, 5.94.

Compound 31 (entry I, Table 4). A mixture of 5-chloro-*m*-xylene (0.14 mL, 1.04 mmol), *N*-heptylmethylamine (0.19 mL, 1.13 mmol), NaO^{t}Bu (125 mg, 1.30 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (22 mg, 61 μmol) in toluene (4 mL) was heated to 105 °C for 1 h and analyzed by GC−MS. The reaction was cooled to room temperature, taken up in diethyl ether (125 mL), washed with water (30 mL) and brine (30 mL), dried over $MgSO_4$, filtered, and concentrated in vacuo. The crude product was purified by column chromatography on silica gel using hexanes as the eluent to afford compound **31**, after drying under vacuum, as a colorless oil (yield: 230 mg, 95%). Analogous reactions of 5-bromo-*m*-xylene (1 h, entry J, Table 4) and 5-iodo-*m*-xylene (15 min, entry K, Table 4) also afford the desired 5-(*N*-heptylmethylamino)-*m*-xylene in 93% and 91% isolated yields, respectively. ^{1}H NMR ($CDCl_3$): δ 6.33 (br, 3H, ArH), 3.25 (t, J = 7.6, 2H, $-NCH_2-$), 2.89 (s, 3H, $-N-CH_3$), 2.27 (s, 6H, Ar$(CH_3)_2$), 1.54 (br, 2H, $-NCH_2CH_2-$), 1.30 (br, 8H, $-(CH_2)_4CH_3$), 0.89 (br t, J = 6.6, 3H, $-CH_3$). ^{13}C{^{1}H} NMR ($CDCl_3$): δ 149.6, 138.6, 117.9, 110.1, 52.8, 38.3, 31.9, 29.2, 27.1, 26.7, 22.6, 21.8, 14.1. Anal. Calcd for $C_{16}H_{27}N$: C, 82.34; H, 11.66; N, 6.00. Found: C, 82.02; H, 11.92; N, 6.21.

Compound 32 (entry L, Table 4). Compound **32** (210 mg, 96% yield) was obtained as a yellow oil from the reaction of 5-chloro-1,3-benzodioxole (0.12 mL, 1.03 mmol), aniline (0.12 mL, 1.23 mmol), NaO^{t}Bu (130 mg, 1.35 mmol), Pd(dba)$_2$ (12 mg, 21 μmol), and ligand **6** (15 mg, 42 μmol) in toluene (4 mL) at 105 °C for 3 h. ^{1}H NMR ($CDCl_3$): δ 7.28 (t, J = 7.9, 2H, ArH), 7.00 (d, J = 8.9, 2H, ArH), 6.94 (t, J = 6.6, 1H, ArH), 6.81 (d, J = 8.4, 1H, ArH), 6.76 (d, J = 2.4, 1H, ArH), 6.61 (d/d, J = 8.1/2.4, 1H, ArH), 5.98 (s, 2H, $-OCH_2O-$), 5.57 (br s, 1H, NH). ^{13}C NMR ($CDCl_3$): δ 148.1, 144.5, 142.7, 137.2, 129.2, 119.9, 116.1, 112.8, 108.4, 102.4, 100.9.

X-ray Crystallography. Crystals were sealed in glass capillaries and then optically aligned on the goniostat of a Siemens P4 X-ray diffractometer. The reflections that were used for the unit cell determination were located and indexed by the automatic peak search routine provided with XSCANS.[36] The intensities of three standard reflections, which were measured after every 100 reflections, showed no indication of crystal decomposition or sample movement for all of these samples. The raw data were collected for Lorentz−polarization effects. Initial coordinates for the non-hydrogen atoms were determined by a combination of direct methods (for **11**, **13**) or heavy atom method (for **12**) and difference Fourier calculations performed with the algorithms provided in SHELXTL-IRIS operating on a Silicon Graphics Indigo workstation. The hydrogen atom positions were idealized with isotropic temperature factors at 1.2 times that of the adjacent carbon. The positions of methyl hydrogens were optimized by a rigid rotating group refinement with idealized tetrahedral angles. For **11**, there are three independent molecules (molecules 1−3) in the crystallographic asymmetric unit. For **12**, the crystallographic asymmetric unit also contained a molecule of methylene chloride, which was located in a general position within the unit cell. The *tert*-butyl substituent of **12** was refined using a two-site staggered disorder (70:30) of the three methyl carbons. The C−C bond lengths within the *tert*-butyl group were restrained at 1.54 ± 0.02 Å. For **13**, the crystallographic asymmetric unit contained a heptane molecule located in a general position. The individual positions of the carbon atoms within the heptane molecule were refined by restraining the C−C bond lengths to 1.54 ± 0.02 Å and the nonbonding distances between alternate carbons to 2.52 ± 0.02 Å. Crystal data and refinement parameters are summarized in Table 5. Further details of the crystallographic information are provided in the Supporting Information.

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Supporting Information Available: Tables of final positional parameters and isotropic and anisotropic displacement parameters for all atoms and bond lengths and angles for complexes **11**−**13**. This material is available free of charge via the Internet at http://pubs.acs.org.

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(36) XSCANS (version 2.0) is a diffractometer control system developed by Siemens Analytical X-ray Instruments, Madison, WI.