

III.2.20 Palladium-Catalyzed Homocoupling of Organic Electrophiles or Organometals

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A. INTRODUCTION

Although homocoupling can be catalyzed or mediated by a number of main group metals as well as transition metals, Pd-catalyzed processes are receiving special attention. Taking into account the specific properties of palladium and its compounds, it is not surprising that they have been used extensively for homocoupling of a wide variety of organic derivatives under mild reaction conditions.

Generally, the homocoupling can be classified into the following two groups: (i) coupling of organic electrophiles (halides, triflates, etc.) and (ii) coupling of organometallic compounds (lithium, boron, silicon, tin, mercury, etc.). The former process uses Pd^0 as the catalytically active species and requires the presence of reductants (amines, phosphines, zinc, electrons, etc.) in the reaction mixture to keep the catalytic cycle going. On the other hand, the latter process uses Pd^{II} as the catalytically active species and requires the presence of oxidants (CuCl_2 , peroxides, oxygen, etc.) (**Scheme 1**).

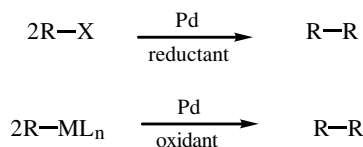
The aim of this section is to focus on the synthetic scope of Pd-catalyzed homocoupling as well as recent advances in this area.

B. Pd-CATALYZED COUPLING OF ALKENYL, ARYL, AND ALKYNYL ELECTROPHILES

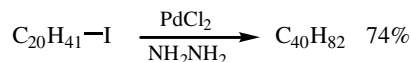
B.i. Homocoupling Reactions

Generally, homocoupling of aryl and alkenyl halides has been the most widespread. Other halide derivatives, such as alkyl or alkynyl halides, have seldom been used. This is either because of problems during homocoupling (alkyl halides may easily undergo dehydrohalogenation) or because the homocoupled product (diynes) could be obtained by more convenient methods. Nonetheless, a rare example of homocoupling of alkyl halides catalyzed by palladium chloride in the presence of hydrazine as the reductant was published^[1]; however, this procedure is of limited synthetic value (**Scheme 2**).

One of the first papers dealing with homocoupling of $\text{sp}^2\text{-C}$ halides was a mechanistic study of Pd-catalyzed dimerization of aryl iodides in the presence of trialkylamine as the



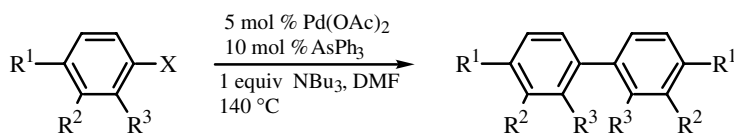
Scheme 1



Scheme 2

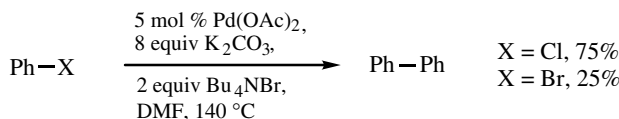
reductant.^[2] A considerable improvement of yields was achieved when the same reaction was conducted in the presence of triphenylarsine in DMF at 140 °C.^[3] A number of unsubstituted aryl halides (bromide and iodides) gave reasonable yields of the corresponding biaryls (**Scheme 3**). A system composed of palladium acetate, tetraalkylammonium halide, and a base (amine, potassium carbonate) in DMF has found wide application. This system was used for homocoupling of phenyl halides (**Scheme 4**) and for 1,8-diiodonaphthalene to afford a mixture of diiodobinaphthalene and perylene (**Scheme 5**). Diiodobinaphthalene in a separate reaction was intramolecularly cyclized to perylene.^[4]

This system was later used for a systematic study of homocoupling of variously substituted aryl and heteroaryl bromides.^{[5],[6]} The authors conducted a number of experiments to find the best conditions for homocoupling of various aryl halides. The influence of the base (K_2CO_3 , amines) and the reductant (isopropanol) was studied. It was demonstrated

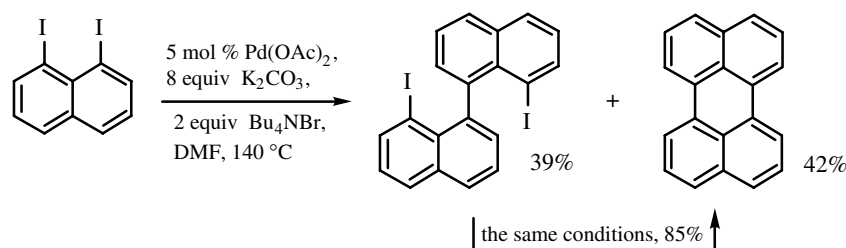


Yield (%)		Yield (%)	
X = Br; R ¹ = R ² = R ³ = H	68	X = I; R ¹ = COOH, R ² = R ³ = H	70
X = Br; R ¹ = R ² = H, R ³ = F	44	X = I; R ¹ = NO ₂ , R ² = H, R ³ = F	47
X = Br; R ¹ = Cl, R ² = R ³ = H	48	X = Br; R ¹ = NMe ₂ , R ² = R ³ = H	45
X = Br; R ¹ = Me, R ² = R ³ = H	58	X = Br; R ¹ = OMe, R ² = Br, R ³ = H	46
X = I; R ¹ = OMe, R ² = R ³ = H	58	X = I; R ¹ = Br, R ² = R ³ = H	41
X = Br; R ¹ = H, R ² = OMe, R ³ = H	57		

Scheme 3



Scheme 4



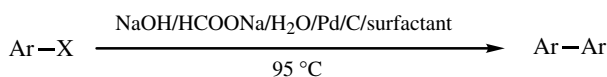
Scheme 5

that this procedure is a convenient method for homocoupling of ortho-, meta-, and para-substituted aryl halides with both an electron-donating as well as an electron-accepting functional group (**Table 1**). Also, this procedure was convenient for homocoupling of heteroaryl halides, including 2-bromo-5-nitropyridine, which usually reacted under the homocoupling conditions to give undesirable products (**Table 2**).

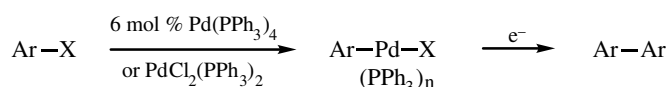
It was also recently demonstrated that homocoupling of aryl and heteroaryl iodides could be efficiently catalyzed either by a palladacycle catalyst in the presence of amine in DMF^[7] or by a (π -allyl)palladium complex and TBAF in DMSO.^[8] Also, homocoupling of a variety of substituted halothiophenes was achieved in the presence of a catalytic amount of Pd(OAc)₂ and diisopropylethylamine in toluene.^[9]

The successful homocoupling of aryl and heteroaryl bromides and chlorides was achieved by using palladium on charcoal in the presence of sodium hydroxide, sodium formate, and a surfactant (cetyltrimethylammonium bromide, etc.) (**Scheme 6**). The advantage of this procedure is that the homocoupling of aryl and heteroaryl halides can be successfully achieved (**Table 3**).^[10]

Yet another procedure for the preparation of biaryls is Pd-catalyzed electroreductive homocoupling^{[11],[12]} of aryl and heteroaryl halides (**Scheme 7** and **Table 4**^[11]).



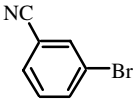
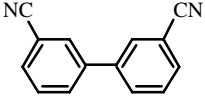
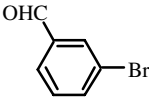
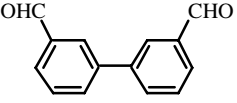
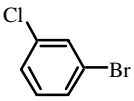
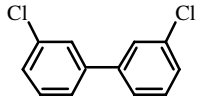
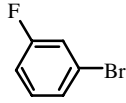
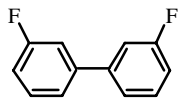
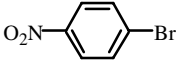
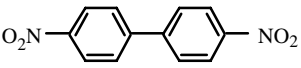
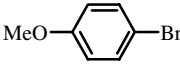
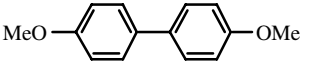
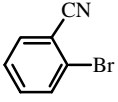
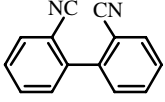
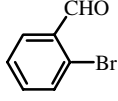
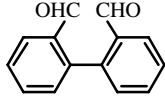
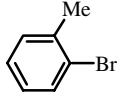
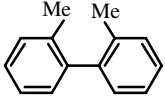
Scheme 6



Scheme 7

Another efficient method for the preparation of biaryls is Pd-catalyzed homocoupling of biaryliodonium salts in the presence of zinc dust (**Scheme 8**).^[13] In comparison with other methods, this procedure gives excellent yields of the corresponding biaryls; however, the efficiency is hampered by the fact that 1 equiv of aryl iodide does not participate in the reaction. This reaction proved to be very sensitive to the catalyst used. High yields are achieved only with Pd(acac)₂; the use of other palladium compounds results in considerably lower yields of biaryls, if any.

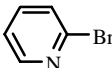
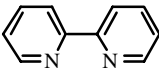
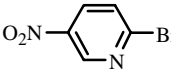
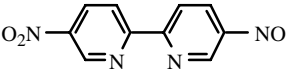
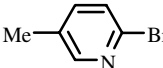
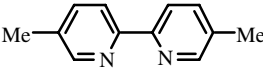
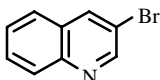
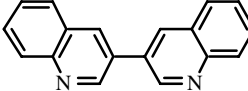
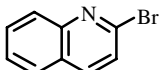
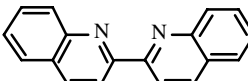
TABLE 1. Pd-Catalyzed Homocoupling of Aryl Halides

Starting Material	Conditions ^a	Product	Yield (%) ^b
	II		64 (57)
	III		67 (53)
	IV		83 (42)
	I		97 (86)
	I		74 (31)
	IV		95 (48)
	VI		89 (86)
	VI		69 (62)
	III		68 (60)

^a In all cases 0.5 equiv of Bu₄NBr was used, and the reactions were carried out at 115 °C in DMF or at 105 °C in toluene. **I**: 5 mol % Pd(OAc)₂, 1 equiv K₂CO₃, DMF/H₂O, isopropanol; **II**: 5 mol % Pd(OAc)₂, 1 equiv Et₃N, DMF, isopropanol; **III**: 5 mol % Pd(OAc)₂, 1 equiv Et₃N, DMF; **IV**: 5 mol % Pd(OAc)₂, 1 equiv K₂CO₃, DMF/H₂O; **V**: 5 mol % Pd(OAc)₂, 1 equiv (*i*-Pr)₂NEt, DMF, isopropanol; **VI**: 5 mol % Pd(OAc)₂, 1 equiv (*i*-Pr)₂NEt, DMF, **VII**: 5 mol % Pd(OAc)₂, 1 equiv (*i*-Pr)₂NEt, toluene, isopropanol.

^b GC yield. Isolated yields are given in parentheses.

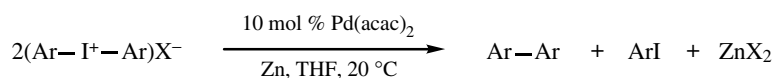
TABLE 2. Pd-Catalyzed Homocoupling of Heteroaryl Halides

Starting Material	Conditions ^a	Product	Yield (%) ^b
	I		92 (92)
	VII		— (53)
	I		100 (95)
	V		80 (79)
	V		64 (62)

^a For details see **Table 1**.^b GC yield. Isolated yield are given in parentheses.

Aryl triflates were homocoupled to biaryls in the presence of zinc^{[14],[15]} or under electroreductive conditions.^{[15],[16]} In some cases, the former method gave better yields of the biaryls, whereas in others the latter method was more successful (**Table 5**). It is noteworthy that in the case of the electroreductive formation of biaryls from chloroaryltriflates the coupling proceeded through the cleavage of the C—OTf bond leaving the halogen moiety intact.

In one case arylsulfonyl halides were used to prepare biaryls. The reaction was catalyzed by a palladium complex in the presence of titanium tetrakisopropoxide (**Scheme 9**).^[17] This procedure is convenient for the preparation of halogen-substituted biaryls, because the homocoupling proceeds through cleavage of the C—SO₂Cl bond.

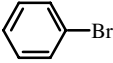
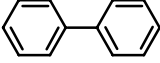
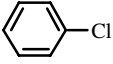
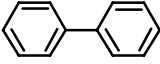
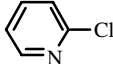
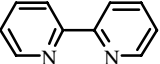
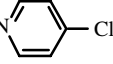
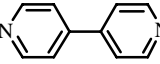
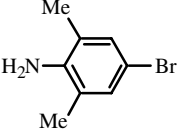
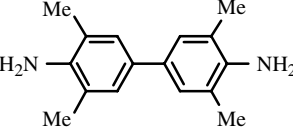
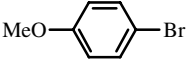
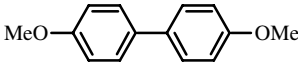
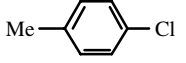
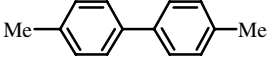
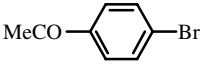
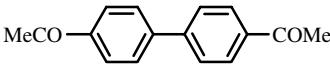


	Yield (%) ^a		Yield (%) ^a
Ar = Ph, X = Cl	96 (80)	Ar = 4- <i>t</i> -BuPh, X = Br	98 (93)
Ar = Ph, X = Br	94 (91)	Ar = 4-MeOPh, X = Br	88 (82)
Ar = Ph, X = I	50	Ar = 4-ClPh, X = Br	92 (90)
Ar = 4-MePh, X = Br	96 (91)	Ar = 4-NO ₂ Ph, X = Br	95 (91)

^a GC yield. Isolated yields are given in parentheses.

Scheme 8

TABLE 3. Preparation of Biaryls from Aryl Halides Using Sodium Formate, Pd/C, and Surfactant in Sodium Hydroxide Liquor^a

Starting Material	Amount of NaOH(g)	Product	Yield (%) ^b
	20		65
	60		48
	13.5		52
	13.5		46
	13.5		63
	64		49
	64		55
	20		41

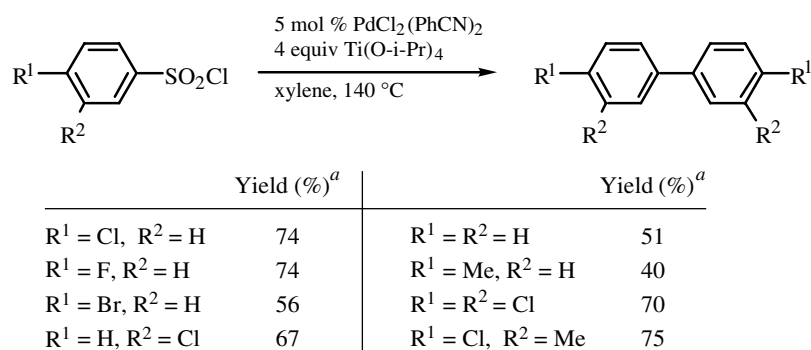
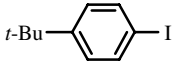
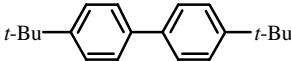
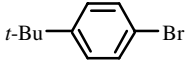
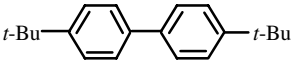
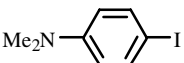
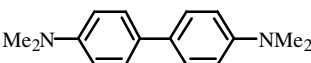
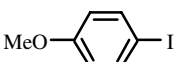
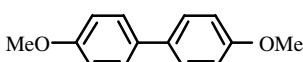
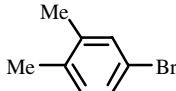
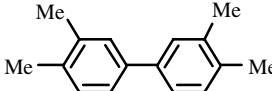
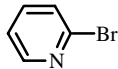
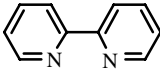
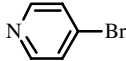
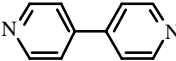
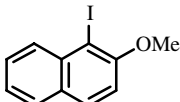
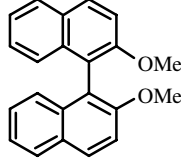
^a Aryl halide (0.1 mol), sodium formate (6.8 g), Pd/C (2 g), surfactant (4 g), 32% sodium hydroxide liquor, 95 °C.^b Isolated yield.^a GC yield.**Scheme 9**


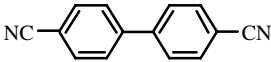

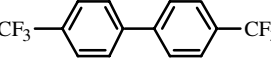

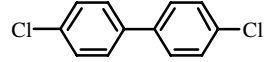
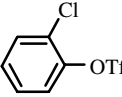
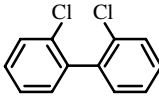
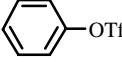
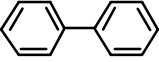
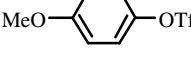
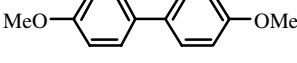
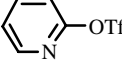
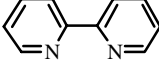
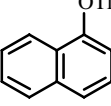
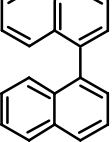
TABLE 4. Pd-Catalyzed Electroreductive Homocoupling of Aryl and Heteroaryl Halides

Starting Material	Pd Catalyst ^a	Product	Yield (%) ^b
	I		98
	I		99
	I		93
	I		87
	I		78
	II		91
	II		91
	II		53

^a Pd catalyst: **I** = Pd(PPh₃)₄; **II** = PdCl₂(PPh₃)₂.^b Isolated yield.

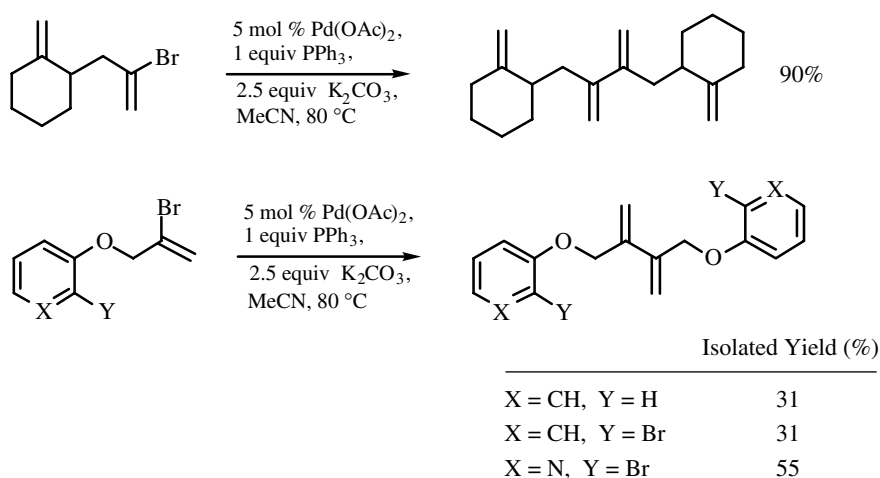
Homocoupling of vinyl halides is a possible pathway to obtain 1,3-dienes; however, this option has not been developed synthetically. A rare example is Pd-catalyzed inter- and intramolecular homocoupling of vinyl bromides in the presence of a stoichiometric amount of triphenyl phosphine and an excess of potassium carbonate.^{[18],[19]} The yields of the intermolecular coupling of vinyl bromides are from moderate to high and depend on the substrate (**Scheme 10**). The intramolecular coupling gives high yields of the corresponding exocyclic 1,3-dienes (**Scheme 11**). Also, Pd-catalyzed homocoupling of vinyl chloride to butadiene was reported.^[20]

TABLE 5. PdCl₂(PPh₃)₂-Catalyzed Homocoupling of Aryl and Heteroaryl Triflates in the Presence of Zn and Under Electroreductive Conditions

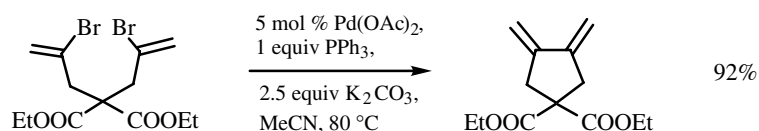
Starting Material	Product	Yield (%) ^a	
		Zn	Electroreduction
		— (85)	70 (55)
		— (76)	68 (45)
		17	— (57)
		n.d. ^b	— (34)
		30	83 (76)
		0	— (15)
		n.d. ^b	— (78)
		59	51

^a ¹H NMR yield. Isolated yields are given in parentheses.^b Not determined.**B.ii. Cross-Coupling Reactions**

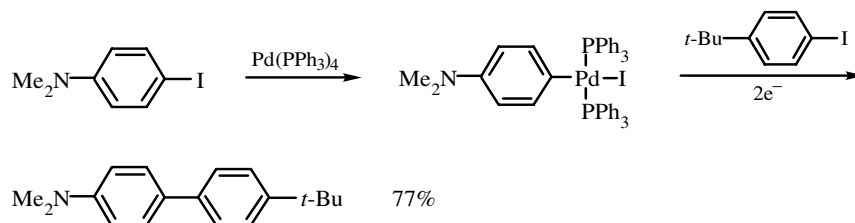
As a very rare example, electroreductive cross-coupling of two different aryl halides was achieved in the presence of a stoichiometric amount of a palladium complex (**Scheme 12**).^[11]



Scheme 10



Scheme 11



Scheme 12

C. Pd-CATALYZED COUPLING OF ALKENYL, ARYL, AND ALKYNYL ORGANOMETALS

C.i. Homocoupling Reactions

A number of organometallic compounds are suitable for the Pd-catalyzed homocoupling reaction. The homocoupling of group IV (Si, Sn, Pb) derivatives has been studied most extensively and developed into synthetically useful protocols. Also, derivatives of group III (B) and transition metals (Hg) have occasionally been used to obtain homocoupling products.

Recently, homocoupling of aryl boronic acids was reported to give good yields of the corresponding biaryls (Table 6). This paper included studies of effects of different bases and oxidants on the yield of homocoupling.^[21]

TABLE 6. Pd-Catalyzed Homocoupling of Arylboronic Acids^a

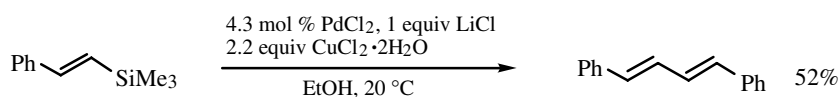
Starting Material	Product	Yield (%) ^b
		79
		83
		84
		58
		76

^a Reaction conditions: 4.7 mol % Pd(OAc)₂, 1.3 equiv Na₂CO₃, air(O₂), 20 °C.^b HPLC yield.

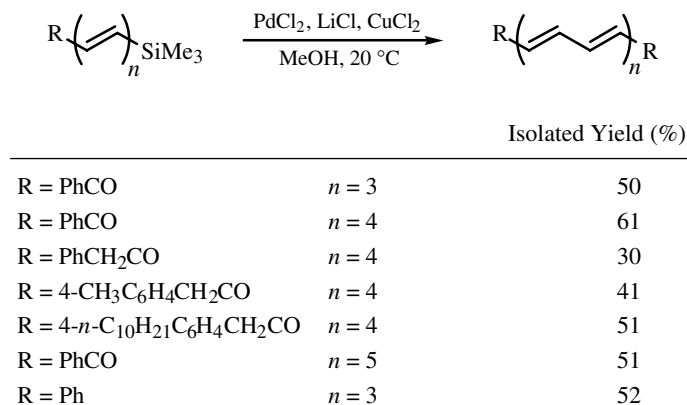
Vinylsilanes were one of the first organometallics used in the Pd-catalyzed homocoupling reaction with CuCl₂ as an oxidant (**Scheme 13**).^[22] Similar reaction conditions were used for the homocoupling of dienylyl, trienylyl, and tetraenylylsilanes to afford the corresponding polyenes (**Scheme 14**).^[23]

So far, the most intensive homocoupling studies were conducted with trialkylstannyl derivatives. Alkyl-, alkenyl-, aryl-, and alkynylstannanes have been homocoupled to give the corresponding dimers. There is no report of homocoupling of *n*-alkylstannanes, but cyclopropyltributylstannanes were easily coupled in the presence of a catalytic amount of a palladium complex to the corresponding biscyclopropanes in good yields (**Scheme 15**).^[24]

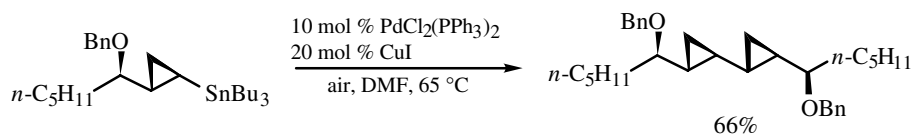
One of the first papers dealing with Pd-catalyzed homocoupling of alkenylstannanes utilized *t*-butylhydroperoxide as an oxidant. The reaction gave good yields of the corresponding dimers; however, in some cases, stereochemistry of the double bond was lost. It was also demonstrated that this methodology is suitable for the homocoupling of arylstannanes (**Table 7**).^[25]



Scheme 13



Scheme 14



Scheme 15

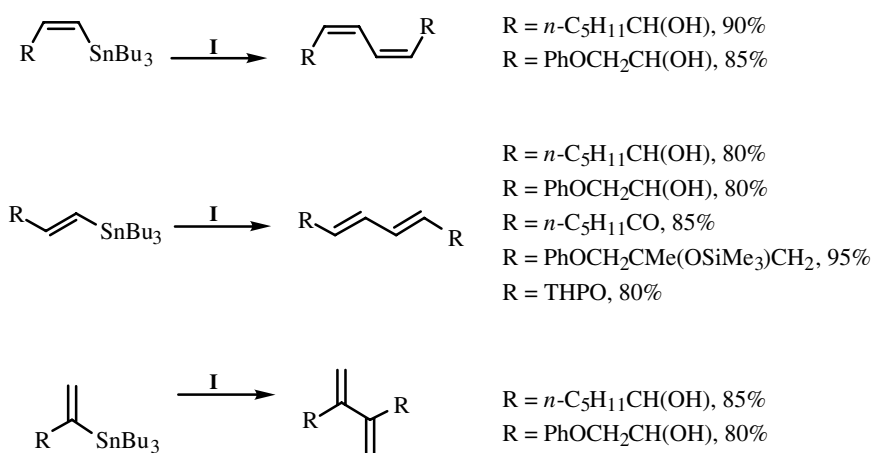
TABLE 7. Pd-Catalyzed Homocoupling of Alkenyl- and Arylstannanes^a

Starting Material	Product	Isolated Yield (%)
		80 ^b
		76
		77
		77
		83

^a Reaction conditions: 10 mol % Pd(OAc)₂, 2 equiv *t*-BuOOH, benzene, 25 °C.^b A mixture of *E,E* and *E,Z* isomers in 4:1 ratio.

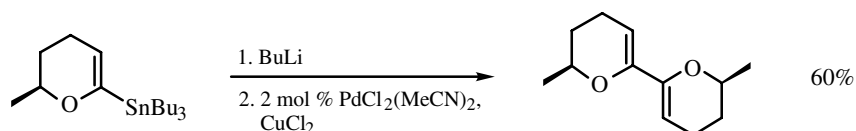
Later it was shown that Pd-catalyzed homocoupling of alkenylstannanes can use air as an oxidant. Under these conditions, all three types of isomeric vinylstannanes (*E*- and *Z*-1-alkenyl and 2-alkenylstannanes) with different functional groups underwent facile homocoupling in HMPA with retention of the stereochemistry on the double bond (**Scheme 16**).^[26] Air or oxygen, as the oxidation agent, has been used also in other Pd-catalyzed procedures for the homocoupling of various alkenyl-, aryl-, heteroaryl-, and alkynylstannanes.^{[27]–[29]} An especially active catalyst for the homocoupling was shown to be a palladium iminophosphine complex.^{[27],[29]}

It is also possible to conduct homocoupling of alkenylstannanes via organolithium intermediates (**Scheme 17**).^[30]



I: 5 mol % $\text{PdCl}_2(\text{MeCN})_2$, air, HMPA, 20 °C. In all cases isolated yields (%).

Scheme 16



Scheme 17

A general procedure for Pd-catalyzed homocoupling of different kinds of organostannanes (aryl-, heteroaryl-, alkenyl-, and alkynylstannanes) affording high yields of products was conducted in the presence of triphenylarsine in dichloroethane (**Table 8**).^[31] In this instance dichloroethane acts as an oxidant of the Pd^0 species to catalytically generate Pd^{II} species. *trans*-Diiodoethene as an oxidant in Pd-catalyzed homocoupling alkynylstannanes was used for the preparation of polyethyne and diynes.^[32]

It was also shown that aryl- and alkynyllead triacetates could be converted to biaryls and diynes in the Pd-catalyzed reaction (**Table 9**).^[33]

The last class of organometallic compounds that undergo Pd-catalyzed homocoupling are organomercury compounds. An early example of homocoupling of alkenylmercury

TABLE 8. Pd-Catalyzed Homocoupling of Tributylstannane Derivatives

Starting Material	Catalyst ^a	Product	Yield (%) ^b
	I		93
	I		85
	I		45
	I		68
	II		90

^a **I**: 10 mol % PdCl₂, 10 mol % AsPh₃, CH₂ClCH₂Cl; **II**: 10 mol % PdCl₂(PhCN)₂, CH₂ClCH₂Cl.^b Isolated yield.TABLE 9. Pd-Catalyzed Homocoupling of Lead Triacetate Derivatives^a

Starting Material	Product	Yield (%) ^b
		68
		65
		75
		81
		70

^a Reaction conditions: 5 mol % Pd₂(dba)₃, CHCl₃, 20 °C.^b Isolated yield.

TABLE 10. Dimerization of Alkenylmercury Chlorides ^a

Starting Material	Product	Yield (%) ^b
		98 ^c
		100 ^c
		96
		94
		100 ^c
		75 ^c
		100
		82
		95
		95

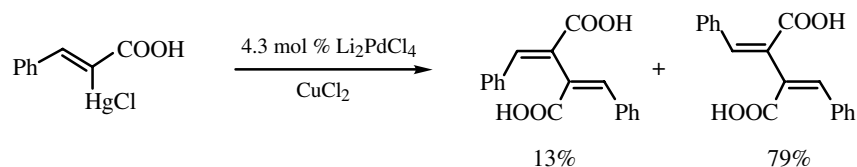
^a Reaction conditions: 50 mol % PdCl₂, 200 mol % LiCl, HMPA, 20 °C.

^b Isolated yield unless otherwise noted.^c GC yield.

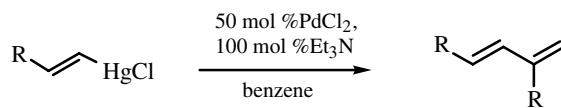
chloride used lithium tetrachloropalladate as the catalyst and copper(II) chloride as an oxidant (**Scheme 18**).^[34] Homocoupling of dipropenylmercury catalyzed by Pd(PPh₃)₄ was also reported.^[35] However, in both cases, loss of stereospecificity was observed.

The loss of stereospecificity can be prevented, if homocoupling is carried out with a stoichiometric amount of palladium chloride in the presence of lithium chloride in HMPA

(**Table 10**).^[36] The change in the reaction conditions (addition of triethylamine, absence of lithium chloride, benzene as a solvent) radically changes the course of the reaction and alkenylmercury chlorides are dimerized in head-to-tail fashion with excellent regioselectivity (**Scheme 19** and **Table 11**).^[37]



Scheme 18



Scheme 19

TABLE 11. Head-to-Tail Dimerization of Alkenylmercury Chlorides^a

Starting Material	Product	Yield (%) ^b
		98
		91
		91
		88 ^c
		62

^a Reaction conditions: 50 mol % PdCl₂, 100 mol % Et₃N, benzene, 20 °C.

^b GC yield unless noted.^c Isolated yield.

C.ii. Cross-Coupling Reactions

Cross-coupling of organostannanes is a rather rare reaction taking into account the reaction mechanism of homodimerization. Nonetheless, there have been two reports of Pd-catalyzed cross-coupling of alkenylstannanes with allylstannanes. The first procedure used *t*-BuOOH^[25] and the second one used oxygen^[28] as oxidants (**Table 12**). In both cases the coupling gives good yields of the 1,4-dienes and the stereochemistry at the double bond is retained. The cross-coupling with crotylstannane resulted in the formation of a mixture of S_N2 and S_N2' products in 3:1 ratio.

TABLE 12. Pd-Catalyzed Cross-Coupling of Alkenylstannanes with Allylstannanes

Alkenylstannane	Allylstannane	Procedure ^a	Product	Yield (%) ^b
		I		68
		II		84
		I		72
		I		53
				18
		I		77
		I		52
				16
		III		94
		III		72
		II		75
		II		73

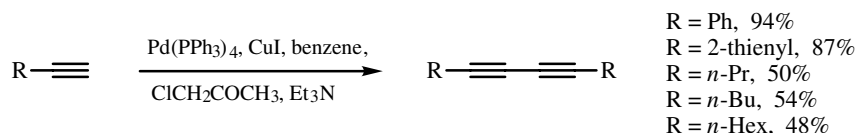
^a **I**: 10 mol % Pd(OAc)₂, 2 equiv *t*-BuOOH, benzene, 25 °C; **II**: 5 mol % Pd(OAc)₂, O₂, benzene, 20 °C;

III: 5 mol % PdCl₂(MeCN)₂, O₂, DMF, 20 °C.

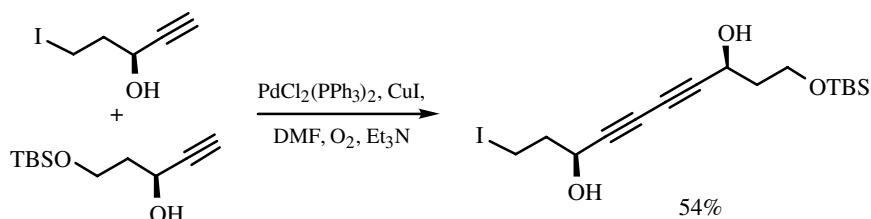
^b Isolated yield.

D. COUPLING OF TERMINAL ALKYNES

Terminal alkynes can very easily be dimerized to diynes under Glaser coupling conditions. However, this procedure is catalyzed by copper compounds. It therefore does not fall within the scope of this section, and details can be found elsewhere.^[38] However, a few Pd-catalyzed homocoupling reactions were reported. The initial report was made by Rossi et al.,^[39] who reported Pd-catalyzed homocoupling of alkyl- and aryl-substituted alkynes to diynes in the presence of chloroacetone as the oxidant (**Scheme 20**). This procedure gave high yields in the case of aryl- or heteroaryl-substituted alkynes, but only moderate yields for alkyl-substituted alkynes. Another report used Pd-catalyzed homocoupling of chiral terminal alkynes to chiral diynes in high yield.^[40] The same conditions were also used for cross-coupling of two different alkynes in 54% yield (**Scheme 21**) during synthesis of a natural compound.^[41]



Scheme 20

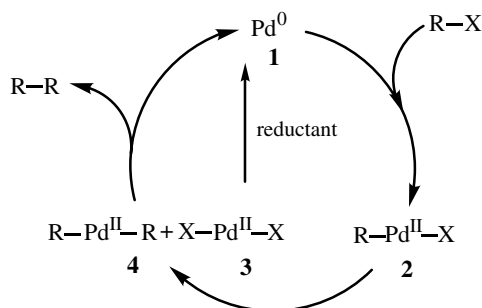


Scheme 21

E. MECHANISM

The overall mechanism of homocoupling reactions depends on the nature of homocoupled compounds. Initial steps for the homocoupling of organic electrophiles differ from that of organometals. However, it is noteworthy that during the course of the reaction both mechanisms proceed through identical intermediates that are responsible for the formation of homocoupling products. In this regard the most important step is reductive elimination of organyl moieties from diorganypalladium compound (see below).^{[42]–[45]}

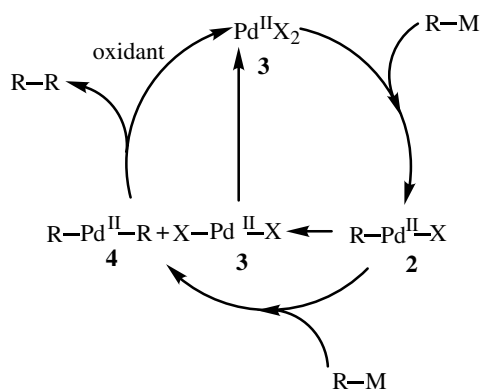
Pd-catalyzed homocoupling of organic electrophiles such as alkenyl, aryl, and alkynyl halides, triflates, and so on requires Pd⁰ and the presence of reductants. Although several reaction mechanisms have been proposed, the simplest one^[20] is outlined in **Scheme 22** (ligands are omitted for the sake of clarity). The reaction is assumed to proceed as follows: (i) oxidative addition of an organic electrophile to a Pd⁰ complex **1** to give a monoorganypalladium species **2**, (ii) disproportionation of **2** into Pd^{II} complex **3** and diorganypalladium species **4**, and (iii) reductive elimination of organyl



Scheme 22

moieties from **4** to furnish a homocoupling product and the Pd^0 complex **1** that may enter the catalytic cycle again. Compound **4** after reduction affords **1** as well. Although there has not been a report of observable disproportionation of **2** to **3** and **4** for organopalladium compounds, the identical phenomenon was reported for Ni compounds.^{[46]–[48]} Therefore, it is quite reasonable to assume that the same process might proceed in the case of Pd-catalyzed reactions. On the other hand, it should be mentioned that in the case of Ni-catalyzed homocoupling the reaction mechanism was shown to be dependent on the polarity of the solvent.^{[47],[49]} As for other reaction mechanisms for Pd-catalyzed homocoupling, one proceeding through the Pd^{IV} species^[7] and one for homocoupling in the presence of an electron source (a cathode or zinc powder) were proposed.^[15]

In comparison with the homocoupling of organic electrophiles, Pd-catalyzed homocoupling of organometals requires the presence of an oxidant. A generally accepted reaction mechanism is presented in **Scheme 23**.^{[25],[26]} The homocoupling of organometals proceeds as follows: (i) a reaction of Pd^{II} complex **3** with an organometal gives mono-organylpalladium species **2**, (ii) a reaction of **2** with another equivalent of the organometal affords **4**, and (iii) reductive elimination of organyl moieties from **4** results in the formation of a homocoupling product and Pd^0 complex that after oxidation to **3** enters the catalytic cycle again. Of course, disproportionation of compound **2** into **3** and **4** cannot be excluded. The above-mentioned reaction mechanism is in agreement with



Scheme 23

TABLE 13. Pd-Catalyzed Homocoupling of R—X According to Reductants

Reductant	R—X	Example Reference
NH ₂ NH ₂	Alkyl iodides	[1]
NR ₃	Aryl, heteroaryl, and alkenyl bromides and iodides, and vinyl chloride	[2],[3],[5]–[7],[9],[20]
NR ₃ , isopropanol	Aryl bromides and iodides	[5],[6]
K ₂ CO ₃	Aryl and alkenyl bromides and iodides	[4]–[6],[18],[19]
K ₂ CO ₃ , isopropanol	Aryl bromides	[5],[6]
HCOONa	Aryl chlorides and bromides	[10]
TBAF, DMSO	Aryl bromides and iodides	[8]
e [−]	Aryl bromides, iodides, and triflates	[11],[12],[15],[16]
Zn	Biarylodonium salts and triflates	[13]–[15]
Ti(<i>i</i> -PrO) ₄	Arylsulfonyl chlorides	[17]

results obtained from stoichiometric reactions of organolithium compounds with Pd^{II} complexes.^{[44],[45]}

Pd-catalyzed homocoupling of terminal alkynes proceeds in the presence of a catalytic amount of Cu(I) salts and amines. During this process a terminal alkyne reacts with copper(I) salt in the presence of an amine to give an alkynyl copper compound that reacts with the Pd catalyst. Therefore, the homocoupling of terminal alkynes falls into the category of homocoupling of organometals and follows the same reaction mechanism.

F. SUMMARY

Pd-catalyzed homocoupling of organic electrophiles proceeded under a number of different reaction conditions with various reductants (**Table 13**). From a practical point of view, the most commonly used ones were amines or potassium carbonate, or their combinations with other reductants, such as isopropanol. These reductants are suitable for the homocoupling of a variety of alkenyl and aryl halides.

TABLE 14. Pd-Catalyzed Homocoupling of R-Metal According to Oxidants

Oxidant	R-Metal	Example Reference
Air or O ₂	Aryl boronates, cyclopropyl-, alkenyl-, aryl-, heteroaryl-, and alkynylstannanes, and terminal alkynes	[21], [24], [26]–[29], [40], [41]
CuCl ₂	Alkenylsilanes, alkenylstannanes, alkenylmercury	[22],[23],[30],[34]
<i>t</i> -BuOOH	Alkenyl- and arylstannanes	[25]
1,2-Dichloroethane	Alkenyl-, aryl-, heteroaryl, and alkynylstannanes	[31]
<i>E</i> -1,2-Diiodoethene	Alkynylstannanes	[32]
Chloroacetone	Terminal alkynes	[39]

A number of oxidants were used for Pd-catalyzed homocoupling of organometals (**Table 14**). The most widely used oxidants were air or O₂ and copper(II) chloride, which were applied for the homocoupling of boronates, stannanes, and organomercury compounds. An interesting application is the use 1,2-dichloroethane and *E*-1,2-diiodoethene as oxidants. When a stoichiometric amount of a Pd^{II} compound was used for homo coupling, such as the case of organomercury compounds, it was not necessary to use any oxidants.^{[36],[37]} In one instance, it was reported that Pd⁰-catalyzed (Pd(PPh₃)₄) homo coupling of diorganomercury compounds with extrusion of metallic mercury proceeded without the presence of an oxidant.

Although it is not subject of this section, the same products (homocoupling products) could also be obtained by other methods. One such method is Pd-catalyzed cross-coupling of organic electrophiles (halides, triflates, etc.) with organometals (organozinc, organotin, organoboron compounds, etc.). The scope, functional group compatibility, and synthetic applications of this process can be found elsewhere.^{[38],[50],[51]}

REFERENCES

- [1] R. Nakajima, K. Morita, and T. Hara, *Bull. Chem. Soc. Jpn.*, **1981**, 54, 3599.
- [2] F. R. S. Clark, R. O. C. Norman, and B. C. Thomas, *J. Chem. Soc. Perkin Trans I*, **1975**, 121.
- [3] M. Brenda, A. Knebelkamp, A. Greiner, and W. Heitz, *Synlett*, **1991**, 809.
- [4] G. Dyker, *J. Org. Chem.*, **1993**, 58, 243.
- [5] V. Penalva, J. Hassan, L. Lavenot, C. Gozzi, and M. Lemaire, *Tetrahedron Lett.*, **1998**, 39, 2559.
- [6] J. Hassan, V. Penalva, L. Lavenot, C. Gozzi, and M. Lemaire, *Tetrahedron*, **1998**, 54, 13793.
- [7] F.-T. Luo, A. Jeevanandam, and M. S. Kumar, *Tetrahedron Lett.*, **1998**, 39, 7939.
- [8] D. Albanese, D. Landini, M. Penso, and S. Petricci, *Synlett*, **1999**, 199.
- [9] J. Hassan, L. Lavenot, C. Gozzi, and M. Lemaire, *Tetrahedron Lett.*, **1999**, 40, 857.
- [10] P. Bamfield and P. M. Quan, *Synthesis*, **1978**, 537.
- [11] S. Torii, H. Tanaka, and K. Morisaki, *Tetrahedron Lett.*, **1985**, 26, 1655.
- [12] C. Amatore, E. Carré, A. Jutand, H. Tanaka, and S. Torii, *Chem. Eur. J.*, **1997**, 2, 957.
- [13] M. Uchiyama, T. Suzuki, and Y. Yamazaki, *Chem. Lett.*, **1983**, 1165.
- [14] A. Jutand and A. Mosleh, *Synlett*, **1993**, 568.
- [15] A. Jutand and A. Mosleh, *J. Org. Chem.*, **1997**, 62, 261.
- [16] A. Jutand, S. Négri, and A. Mosleh, *J. Chem. Soc. Chem. Commun.*, **1992**, 1729.
- [17] M. Miura, H. Hashimoto, K. Itoh, and M. Nomura, *Chem. Lett.*, **1990**, 459.
- [18] R. Grigg, P. Stevenson, and T. Worakun, *J. Chem. Soc. Chem. Commun.*, **1985**, 971.
- [19] R. Grigg, P. Stevenson, and T. Worakun, *Tetrahedron*, **1988**, 44, 2049.
- [20] P. P. Nicholas, *J. Org. Chem.*, **1987**, 52, 5266.
- [21] K. A. Smith, E. M. Campi, W. R. Jackson, S. Marccucio, C. G. M. Naeslund, and G. B. Deacon, *Synlett*, **1997**, 131.
- [22] W. P. Weber, R. A. Felix, A. K. Willard, and K. E. Koenig, *Tetrahedron Lett.*, **1971**, 4701.
- [23] F. Babudri, A. R. Ciccimessere, G. M. Farinola, V. Fiandanese, G. Marchese, R. Musio, F. Naso, and O. Sciacovelli, *J. Org. Chem.*, **1997**, 62, 3291.
- [24] T. Itoh, S. Emoto, and M. Kondo, *Tetrahedron*, **1998**, 54, 5225.
- [25] S. Kanemoto, S. Matsubara, K. Oshima, K. Utimoto, and H. Nozaki, *Chem. Lett.*, **1987**, 5.

- [26] G. A. Tolstikov, M. S. Miftakhov, N. A. Danilova, Ya. L. Ve'lder, and L. V. Spirikhin, *Synthesis*, **1989**, 633.
- [27] E. Shirakawa, Y. Murota, Y. Nakao, and T. Hiyama, *Synlett*, **1997**, 1143.
- [28] L. Alcazar and R. J. K. Taylor, *Synlett*, **1997**, 791.
- [29] E. Shirakawa and T. Hiyama, *J. Organomet. Chem.*, **1999**, 576, 169.
- [30] G.-J. Boons, D. A. Entwistle, S. V. Ley, and M. Woods, *Tetrahedron Lett.*, **1993**, 34, 5649.
- [31] S.-K. Kang, E.-Y. Namkoong, and T. Yamaguchi, *Synth. Commun.*, **1997**, 27, 641.
- [32] M. E. Wright, M. J. Porsch, C. Buckley, and B. B. Cochran, *J. Am. Chem. Soc.*, **1997**, 119, 8393.
- [33] S.-K. Kang, U. Shivkumar, C. Ahn, S.-C. Choi, and J.-S. Kim, *Synth. Commun.*, **1997**, 27, 893.
- [34] H.-L. Elbe and G. Köbrich, *Chem. Ber.*, **1974**, 107, 1654.
- [35] E. Vedejs and P. D. Weeks, *Tetrahedron Lett.*, **1974**, 3207.
- [36] R. C. Larock, *J. Org. Chem.*, **1976**, 41, 2241.
- [37] R. C. Larock and B. Riefling, *J. Org. Chem.*, **1978**, 43, 1468.
- [38] K. Sonogashira, in *Comprehensive Organic Synthesis*, B. M. Trost and I. Fleming, Eds., Pergamon Press Ltd., Oxford, **1991**, Vol. 3, 551.
- [39] R. Rossi, A. Carpita, and C. Bigelli, *Tetrahedron Lett.*, **1985**, 26, 523.
- [40] S. Takano, T. Sugihara, and K. Ogasawara, *Synlett*, **1990**, 453.
- [41] S. Takano, T. Sugihara, and K. Ogasawara, *Tetrahedron Lett.*, **1991**, 32, 2797.
- [42] G. W. Parshall, *J. Am. Chem. Soc.*, **1974**, 96, 2360.
- [43] E. Negishi, T. Takahashi, and K. Akiyoshi, *J. Organomet. Chem.*, **1987**, 334, 181.
- [44] E. Negishi, K. Akiyoshi, and T. Takahashi, *J. Chem. Soc. Chem. Commun.*, **1986**, 477.
- [45] E. Negishi, T. Takahashi, and K. Akiyoshi, *J. Chem. Soc. Chem. Commun.*, **1987**, 1338.
- [46] T. Yamamoto, T. Kohara, and A. Yamamoto, *Bull. Chem. Soc. Jpn.*, **1981**, 54, 2010.
- [47] K. Osakada, R. Sato, and T. Yamamoto, *Organometallics*, **1994**, 13, 4645.
- [48] T. Yamamoto, S. Wakabayashi, and K. Osakada, *J. Organomet. Chem.*, **1992**, 428, 223.
- [49] T. T. Tsou and J. Kochi, *J. Am. Chem. Soc.*, **1979**, 101, 7547.
- [50] D. W. Knight, in *Comprehensive Organic Synthesis*, B. M. Trost and I. Fleming, Eds., Pergamon Press Ltd., Oxford, **1991**, Vol. 3, 481.
- [51] F. Diederich and P. J. Stang, Eds., *Metal-Catalyzed Cross-Coupling Reactions*, Wiley-VCH; Weinheim, **1998**, 1–97, 167–202, and 387–420.