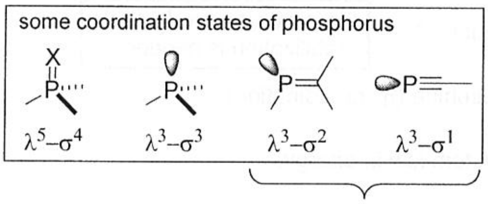
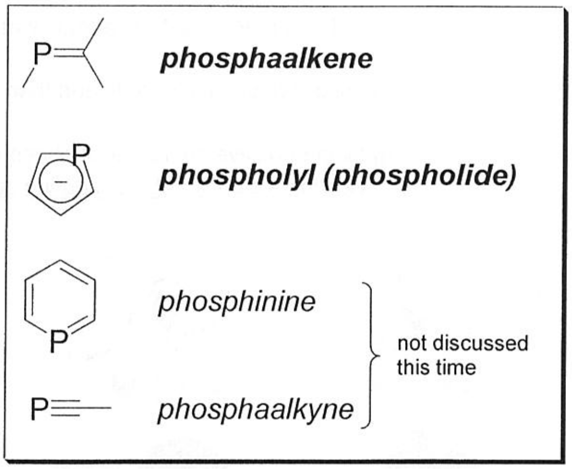
2008. Feb. 13th
Yamaguchi A. (D1)

Phosphaalkene and Phospholyl Ligands in Catalysis

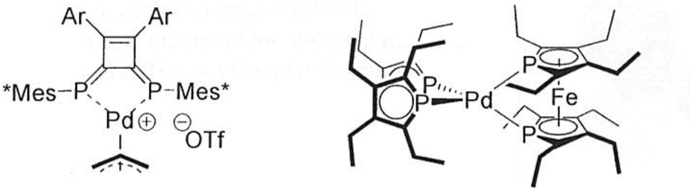


"low-coordinate phosphorus derivatives" ⟹



recent review: *Coord. Chem. Rev.* **2006**, *250*, 627.

The chemistry of low coordinate phosphorus species featuring P=C double bond rarely compare with those of classical trivalent compounds (phosphines).

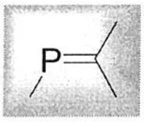


etc...

Contents

1. **nature of P=C double bond (general)**
2. **phophaalkene ligand**
3. **phospholyl ligand (as phosphametallocene)**

1. nature of P=C double bond (general)



(a) phosphorus is reluctant to give sp and sp^2 hybridization because overlap between 3s and 3p atomic orbitals is weak ⟸ large difference in spatial distribution of atomic orbitals

(b) in molecular orbital (MO) of lone pair, contribution of 3s is large

(c) spatial distribution of lone pair np at phosphorus

(d) lone pair is not the HOMO (in imine, lone pair at nitrogen is HOMO)

(e) similarly phosphinine & phospholide anion have lone pair at lower level than HOMO, which is π-system

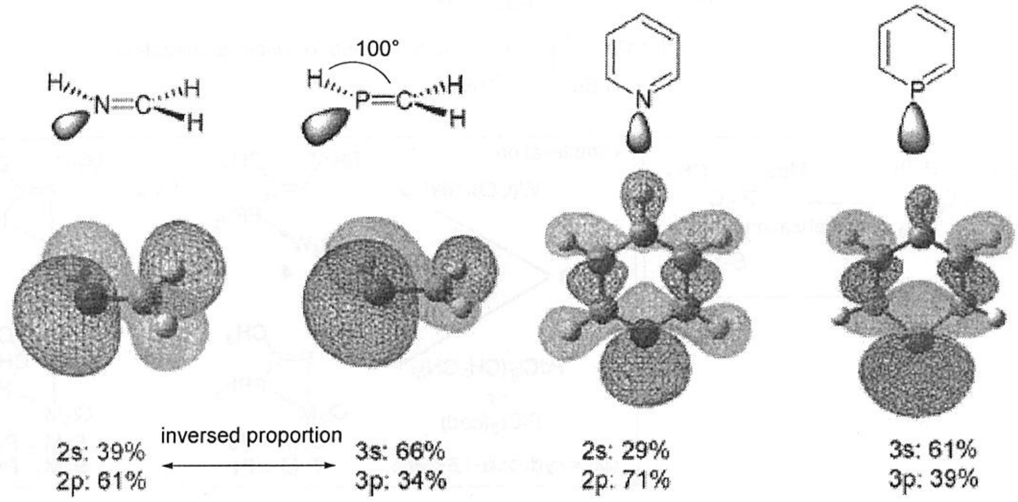
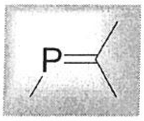


Fig 2. Molecular orbitals describing the lone pairs in $HN=CH_2$, $HP=PH_2$, pyridine and phosphinine with relative percentage of ns and np contributions



(f) EN by Pauling scale: phosphorus (2.1), carbon (2.5), nitrogen (3.0)

(g) π-electronegativity of phosphorus is higher than that of carbon (experimental)

⇐ this balance make the π-system aplolar

(h) π-bond of P=C is 45 kcal/mol, whereas C=C is 65 kcal/mol ⇐ kinetic or thermodynamic stabilization is needed

(i) act as weaker σ-donor ligand than classical trivalent phosphine (η^1 coordination)

(j) electropositive character of phosphorus makes the π* system low in energy, yielding a significant π-accepting capacity

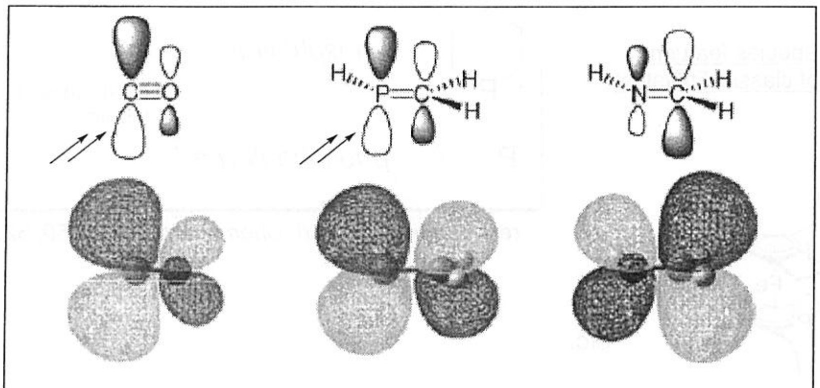


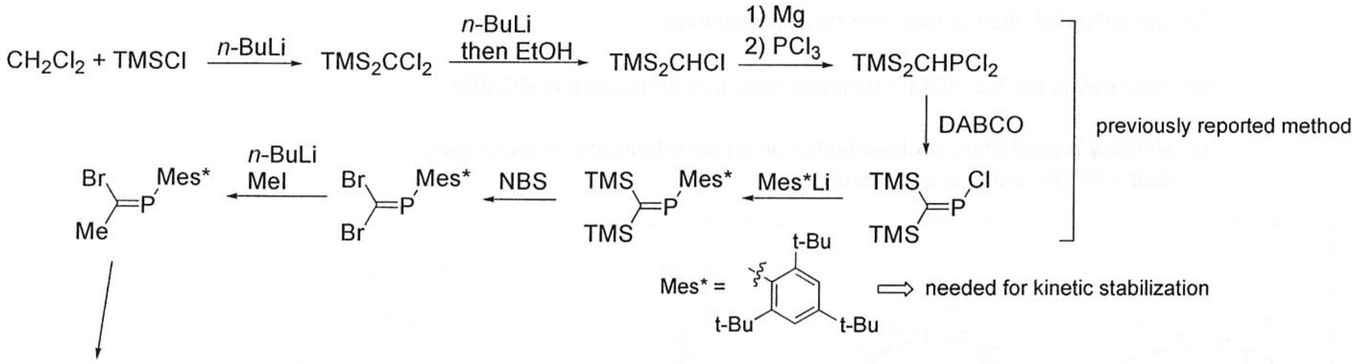
Fig. 4. A comparison between the LUMOs of CO, $HPCH_2$ and $HNCH_2$ illustrating the π-accepting capacity of low-coordinate-based phosphorus ligands.

⟹ π* orbital is mainly developed on the element bounding to the metal directly (CO and $HPCH_2$)

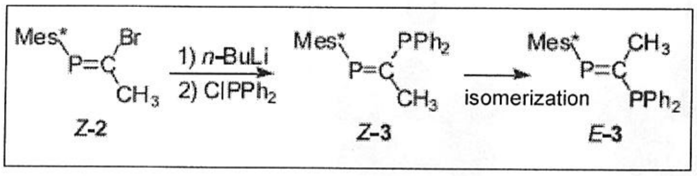
\# proof of P=C
(i) ^{31}P and ^{13}C NMR
(ii) existence of *E*/*Z* isomers
(iii) X-ray crystal structure — *Angew. Chem., Int. Ed. Engl.* **1981**, *20*, 731.

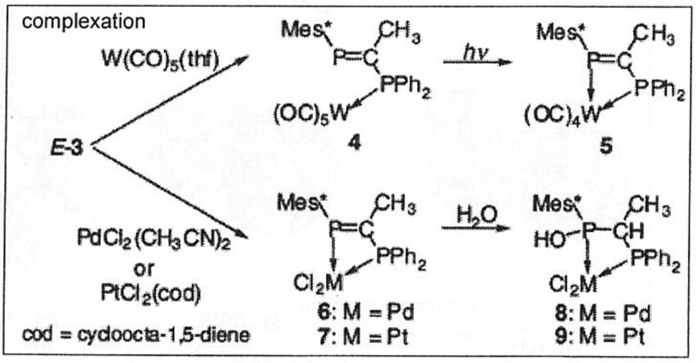
2. phophaalkene ligand

1,3-diphosphapropene Yoshifuji, M. et al. *Tetrahedron Lett.* **2003**, *44*, 8297.

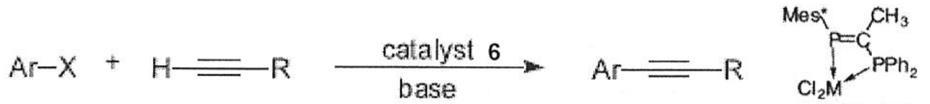


⟹ needed for kinetic stabilization





Sonogashira coupling



6: M = Pd
7: M = Pt

Table 1. Sonogashira coupling reaction (Eq. (1))[a]

only aryl iodide woked well

Entry	Catalyst	ArX	R	Base	Temp.	Time (h)	Yield (%)
1	6/CuI	PhI	Ph	Et_3N	rt	4	99
2	6/CuI	PhI	Ph	Et_2NH	rt	4	49
3	6	PhI	Ph	Et_3N	rt	4	11
4	6/CuI	PhI	$SiMe_3$	Et_3N	rt	4	93
5	6/CuI	2-PyBr	Ph	Et_3N	rt	4	4
6	6/CuI	p-$O_2NC_6H_4Br$	Ph	Et_3N	rt	4	–[b]
7	6/CuI	PhBr	Ph	Et_3N	Reflux	17	4

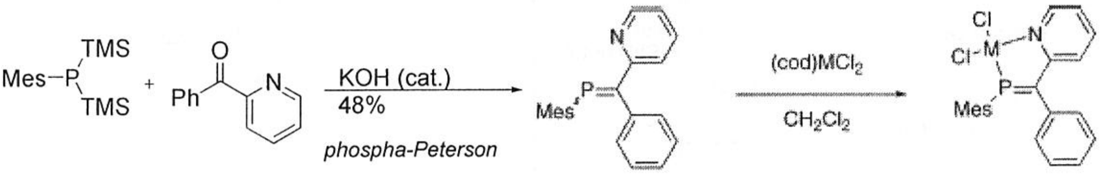
[a] Reaction conditions: iodobenzene (2.0 mmol), phenylacetylene (2.0 mmol), 6 (0.050 mmol), copper(I) iodide (0.050 mmol), base (8 mL).
[b] PhC≡C–C≡CPh was obtained in 18% isolated yield.

Low catalyst activity can be rationalized considering two factors:

(i) phosphaalkenes are poor σ-donors but strong π-acceptor ligands
(ii) highly electron rich metal centres are needed to promote the initial oxidative addition into Ar-Hal bond

P,N-chelate complex

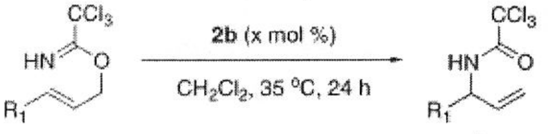
Dake G. R.; Gates, D. P. et al. *Organometallics* **2007**, *26*, 6481.



1

2a (M = Pt)
2b (M = Pd)

Overman-Claisen rearrangement



3a-e **4a-e**

entry	substrate	R1	2b (mol %)	yield (%)[a]
1	3a[b]	Me	5	91
2	3a[c]	Me	0	0
3	3a[c]	Me	5	84
4	3b[c]	n-Pr	5	86
5	3c[c]	n-Hep	5	72
6	3d[c]	$PhCH_2CH_2$	5	48
7	3e[c]	i-Pr	5	33

[a] Isolated yield. [b] Purified by distillation. [c] Purified by column chromatography.

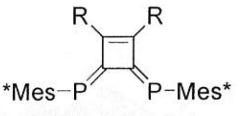
+ starting point to examine the potential catalytic activity

+ no involvement of changes in Pd oxidation state

+ not very superior to other catalyst system

diphosphinidenecyclobutene

Ozawa F. and Yoshifuji M. *Dalton Trans.*, **2006**, 4987.



diphosphinidenecyclobutene (DPCB)

(a) probably the most successful phosphaalkene ligands in catalysis

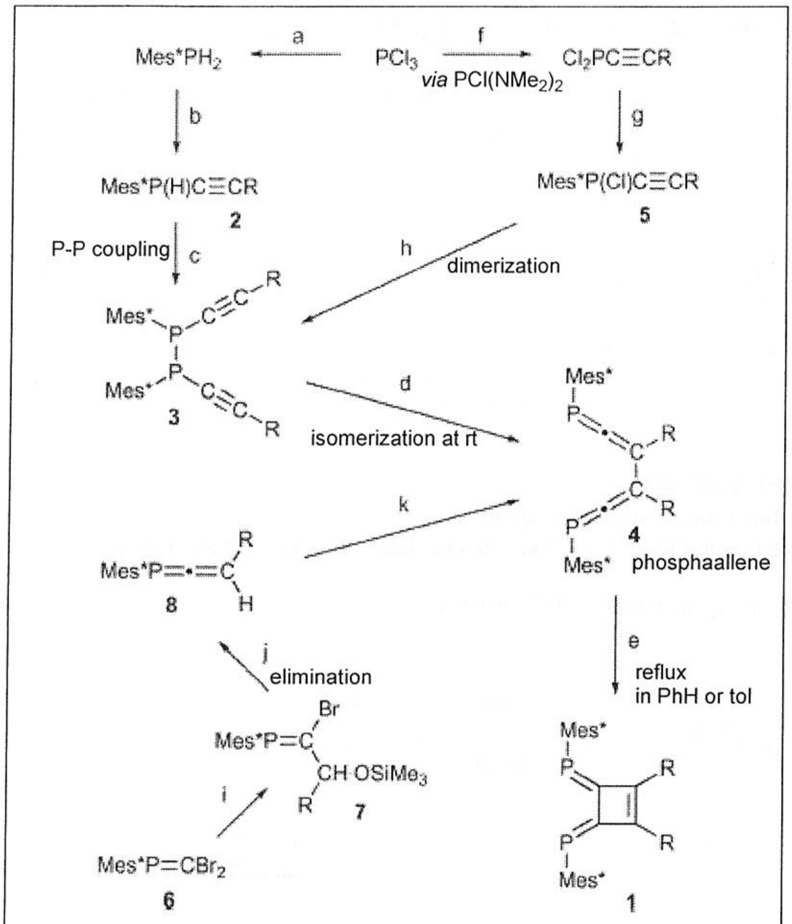
(b) extended π-conjugate system

(c) fairy stable toward the air and water

(d) form novel organometallic complex

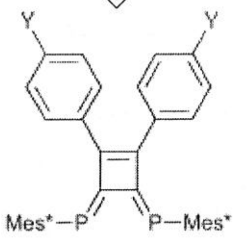
the first synthesis ——→ Appel et al. *Chem. Ber.* **1987**, *120*, 243.

3 routes have been developed

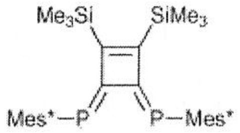


Scheme 1 *Reagents and conditions*: (a) (1) Mes*Li, (2) $LiAlH_4$; (b) (1) azobis(isobutyronitrile), CCl_4 or $CuCl_2$, CuI, THF, (2) RC≡CLi; (c) (1) *n*-BuLi, (2) $BrCH_2CH_2Br$, −78 °C; (d) room temperature; (e) reflux in benzene or toluene; (f) (1) Me_2NH, (2) RC≡CLi, (3) HCl (anhyd.); (g) Mes*Li; (h) Zn or *t*-BuLi; (i) (1) *n*-BuLi, (2) RCHO, (3) Me_3SiCl; (j) *t*-BuLi; (k) (1) *t*-BuLi, (2) Cu_2Cl_2 or $BrCH_2CH_2Br$.

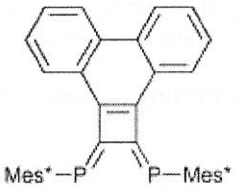
synthesized DPCBs ⇩



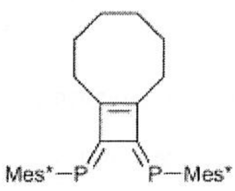
1a (Y = CF_3), **1b** (Y = H),
1c (Y = OMe), **1d** (Y = O-octyl)



1e



1f



1g

In particular, **1a-1d** bearing two phenyl or *p*-substituted phenyl groups at the 1,2-positions have been found to exhibit high performance in catalytic systems

electronic features

remarkable feature of DPCB ligands is the strong π-acceptor property toward transition metals, which is derived from extremely low-lying π* orbital over the diphosphinidenecyclobutene skeleton

comparison of ethylene ^{1}H shift upon complexation	^{1}H NMR of ethylene (δ)
free ethylene	5.30
common Pt(II) ethylene complex	3.7-4.5
[PtMe(CH_2=CH_2)(DPCB)]OTf	5.02-5.22

+ upfield shifts of ethylene protons upon coordination are due to π-back donation from Pt

+ significantly downfield chemical shifts are a good indication of the lack of dπ electrons on Pt and hence the strong π-accepting ability of DPCB ligands

Organometallics **2004**, *23*, 1325.

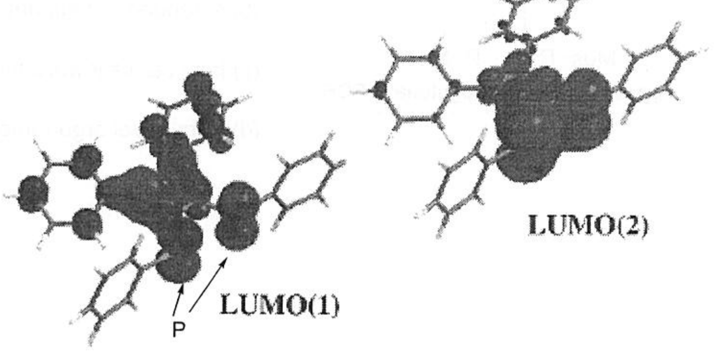
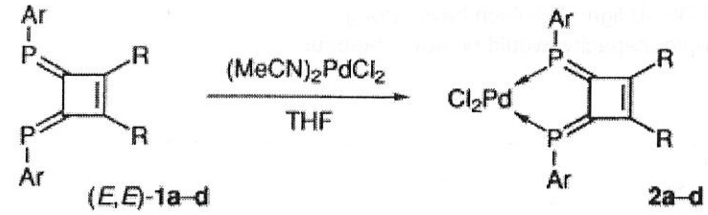
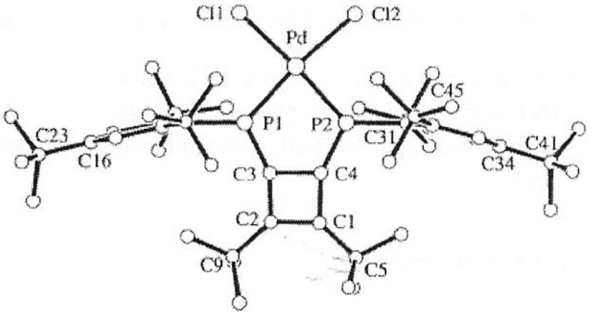


Figure 3. The π* orbitals of DPCB.

complexation (Pd)



a: R = H; **b**: R = SiMe₃; **c**: R = Ph; **d**: R = *t*-Bu.
Ar = 2,4,6-*t*-Bu₃C₆H₂

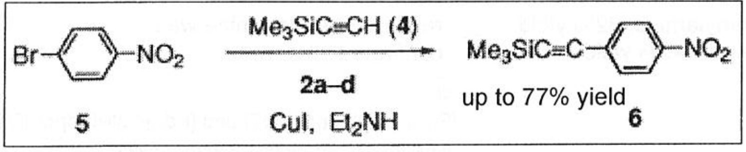


X-ray structure

- \+ P1, P2, C1-C4 are on the same plane
- \+ Pd deviates from the plane
- \+ Mes* groups are perpendicular to the coordination plane

Sonogashira coupling Yoshifuji et al. *Chem. Lett.* **1995**, *221*.

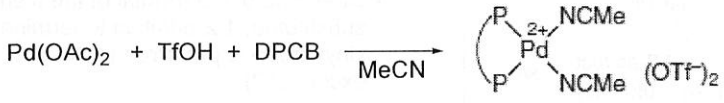
⟶ the first attempt to use phosphaalkene complex in catalysis

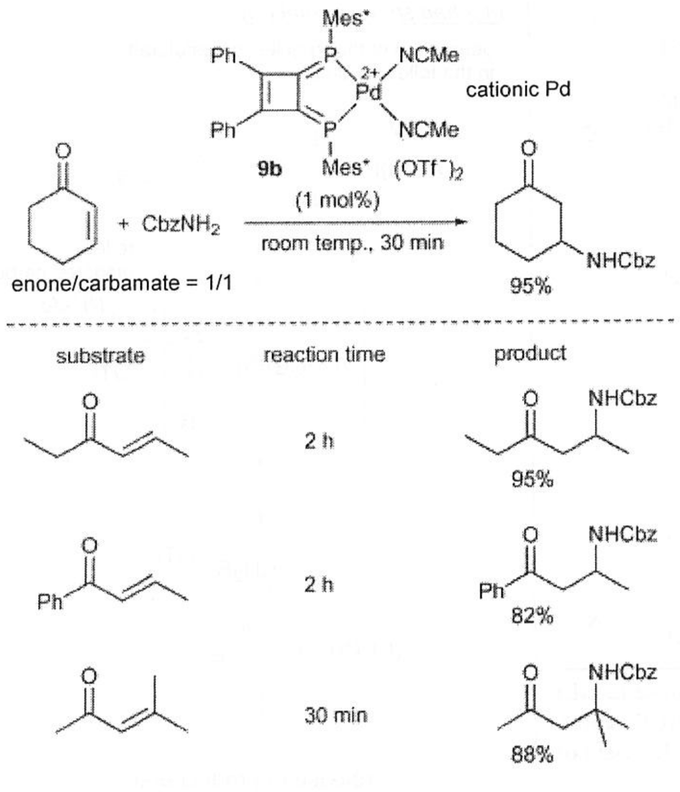


- \+ DPCB ligands might be not suitable for this kind of catalysis, (including oxidative addition in the reaction pathway) as previously mentioned

conjugate addition of Cbz-NH₂ Ozawa, F.; Yoshifuji, M. et al. *J. Organomet. Chem.* **2007**, *692*, 286.

preparation of catalyst

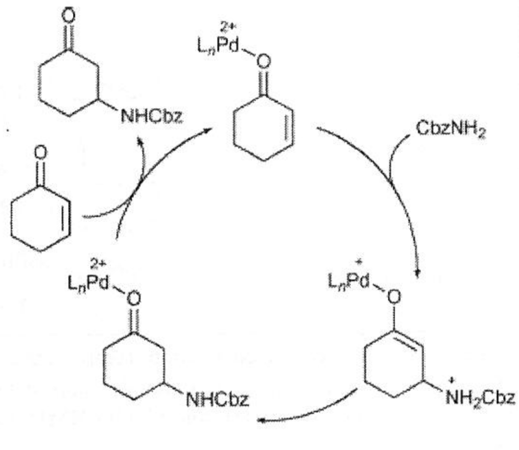




Scheme 3

- \+ use of DPCB-Pd complex as a strong Lewis acid
- \+ comparable catalytic activity to $PdCl_2(MeCN)_2$ or $[Pd(MeCN)_4](BF_4)_2$

proposed catalytic cycle

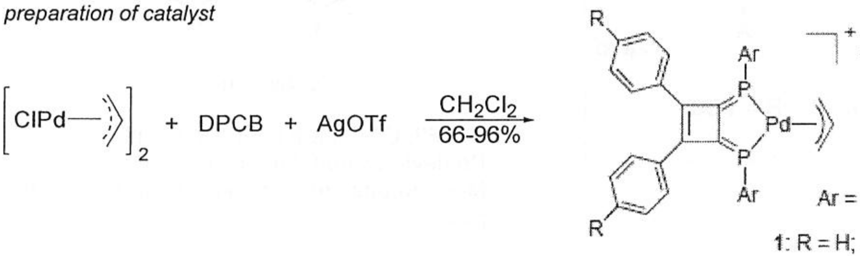


Scheme 4

catalytic allylation (hydroamination) Ozawa, F.; Yoshifuji, M. et al. *Angew. Chem., Int. Ed.* **2001**, *40*, 4501.

+ Pd-catalyzed addition of amine to 1,3-diene probably involves nucleophilic attack of the amine on an (η^3-allyl)Pd(II) or Pd(II)-diene complex ⇨ use of DPCB ligands, which have strong π-acceptor capacity, would be advantageous

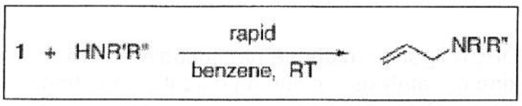
preparation of catalyst



can be stored at rt for 1 month

Ar = 2,4,6-tri-*tert*-butylphenyl

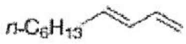
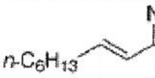
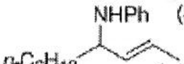
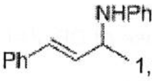
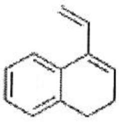
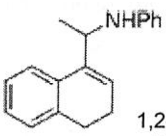
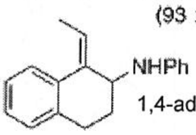
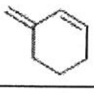
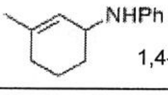
1: R = H; **2**: R = OMe; **3**: R = CF_3



diethylamine: 82% yield
aniline: 45% yield
⇨ reactivity of **1** to amine was confirmed

cf.
[Pd(η^3-allyl)(dppe)]OTf and [Pd(η^3-allyl)(dppf)]OTf were totally unreactive toward aniline

Table 2. Hydroamination of dienes with aniline catalyzed by **2**.[a]

Entry	Diene	Time [h]	Product(s)[b]	Yield [%][c]
1		6	 1,2-adduct (80 : 20)  1,4-adduct	80
2		5	 1,2-adduct	92
3		3	 1,4-adduct (88 : 12)  1,4-adduct	92
4		5	 1,4-adduct	96
5		6	 1,2-adduct (93 : 7)  1,4-adduct	85
6		24	 1,4-adduct	68

[a] All reactions were conducted at room temperature in toluene (2 mL) with diene (1.0 mmol), aniline (2.0 mmol), and catalyst (0.02 mmol). [b] The ratio of isomers was determined by ^1H NMR analysis. [c] Yield of isolated product.

+ diene/aniline = 1/2

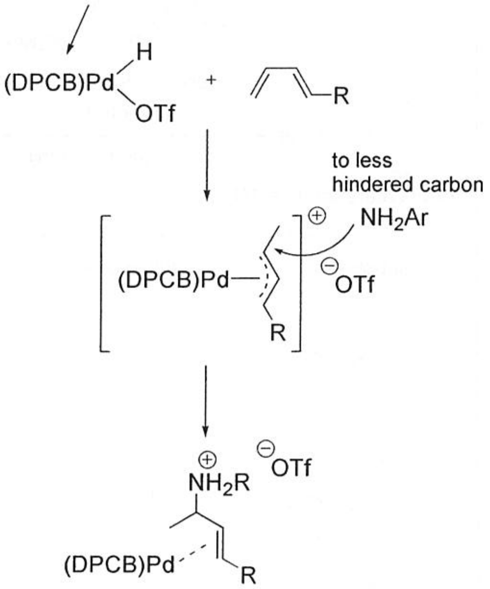
+ 2 mol% of catalyst

+ when one of the termini of the diene is substituted, 1,2-addition to terminal vinyl group is preferred (entry 6 is exception?)

+ otherwise, 1,4-addition is preferred

mechanism (speculation)

generation of this species is postulated in the following study

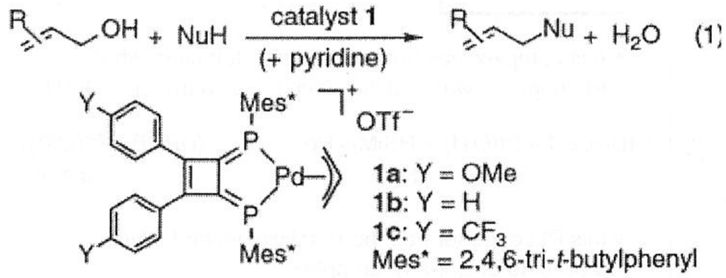


to less hindered carbon

release of product and regeneration of cat.

dehydrative allylation

Ozawa, F.; Yoshifuji, M. et al. *J. Am. Chem. Soc.* **2002**, *124*, 10968.
J. Organomet. Chem. **2006**, *691*, 3151.



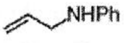
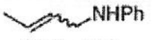
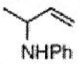
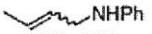
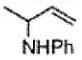
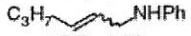
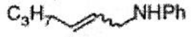
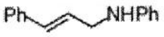
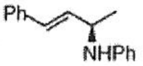
+ H_2O as leaving group (poor leaving ability)

+ most of the reports require rather severe conditions

+ most of the reports require activating agent, such as Lewis acid

* NuH = amine

Table 1. Catalytic Allylation of Aniline with Allylic Alcohols[a]

run	(allyl)OH	time (h)	(allyl)NHPh (%)[b]	(allyl)$_2$NPh (%)
1	**2a**	2	 96	3
2[c]	**2a**	2	91	8
3[d]	**2a**	2	82	16
4	**2b**	6	 (E/Z= 7/1) 85  10	4
5	**2c**	6	 (E/Z= 6/1) 84  11	4
6	**2d**	7	 (E/Z = 9/1) 97	3
7	**2e**	7	 (E/Z = 9/1) 96	3
8	**2f**	10	 90	8
9[e]	**2g**	3	 92 (98.5% ee)	<1

[a] Reaction conditions: 1.0 mmol (allyl)OH, 2.0 mmol $PhNH_2$, 0.1 mol % **1a**, 1 mL of toluene, 0.25 g of $MgSO_4$, room temperature. [b] Monoallylation products in runs 4−7 were obtained as a mixture of stereo- and/or regioisomers, whose ratio was determined by GLC. [c] **1b** was used in place of **1a**. [d] **1c** was used in place of **1a**. [e] **1a** was used in 2 mol %.

+ reaction proceeded at rt with only 0.1 mol% of catalyst
cf.
using $Pd(OAc)_2/4PPh_3$ (1mol%) and $Ti(Oi\text{-}Pr)_4$ (25 mol%), reactions proceeded at 50-80 °C

+ It was found later on that $MgSO_4$ is not essential

+ **1a** was the best catalyst

retention of the absolute stereochemistry
(probably double inversion)

substrates

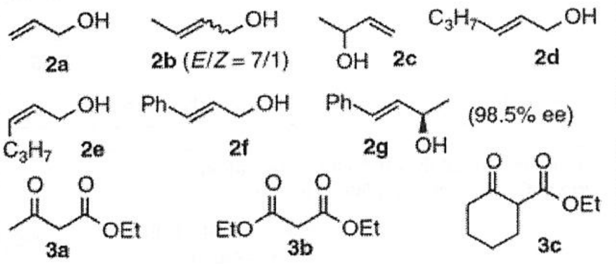
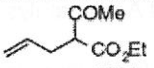
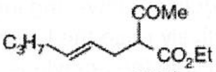
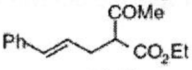
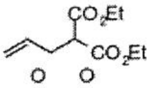
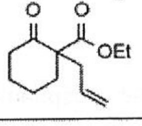
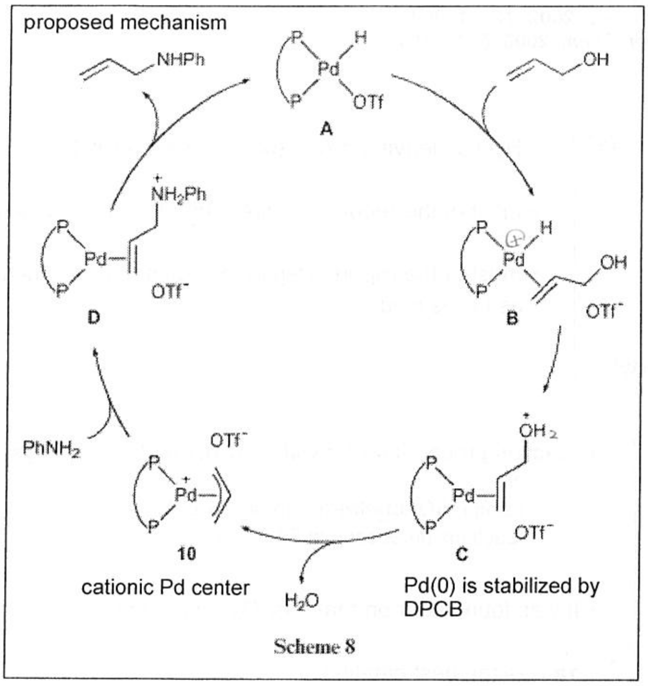


Table 2. Catalytic Allylation of Active Methylene Compounds[a]

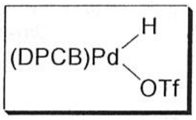
run	(allyl)OH	CH_2Z_2	time (h)	(allyl)CHZ_2 (%)	(allyl)$_2CZ_2$ (%)
1	**2a**	**3a**	3	 92	7
2	**2d**	**3a**	10	 93	<1
3	**2f**	**3a**	7	 85	12
4	**2a**	**3b**	12	 92	<1
5	**2a**	**3c**	12	 95	

[a] Reaction conditions: 2.0 mmol (allyl)OH, 4.0 mmol CH_2Z_2, 2 mol % **1a**, 10 mol % pyridine, 0.25 g of $MgSO_4$, 50 °C.

+ reaction took place using active methylene compounds with 2 mol% of **1a** and 10 mol% of pyridine



Scheme 8



this hydride species is assumed to be responsible for this catalysis

+ this complex was not isolated nor detected, while Pt congener was isolated (synthesized from MePtOTf)

$$(DPCB)MePt(OTf) + HSiMe_2Ph + H_2O \longrightarrow (DPCB)HPt(OTf) + \text{dimer}$$

+ this Pt congener has the reactivity toward allylic alcohol to give π-allyl complex

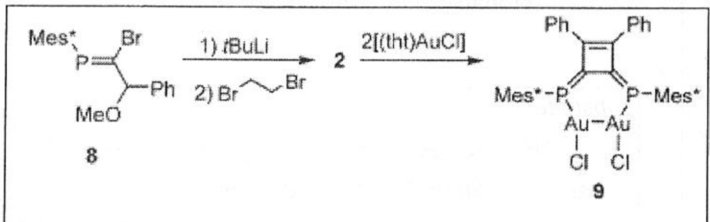
+ H shoud be very acidic, though *common* H of Pd-H is negatively charged

⇨ the factor that make the H of Pd-H acidic is needed

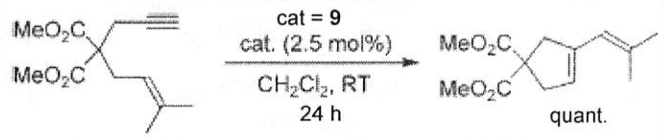
⇩

extremely low-lying π^* orbital, mainly located around the sp^2 phosphorus atoms, has considerable contribution

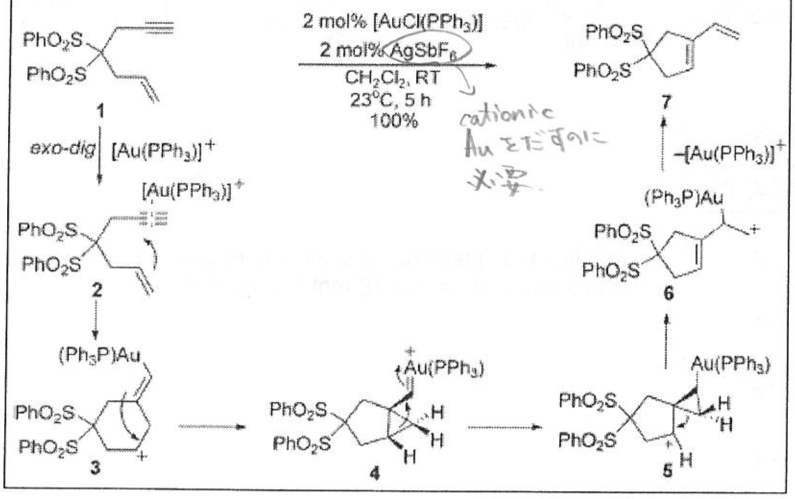
1,6-enyne cycloisomerization Ito, S.; Yoshifuji, M. et al. *Chem. Asian J.* **2006**, *1*, 693.



Scheme 2. Preparation of the DPCB–digold(I) complex.



cf. cationic Au-catalyzed cycloisomerization
Angew. Chem., *Int. Ed.* **2006**, *45*, 200.



+ normally 1,6-enyne cycloisomerizations catalyzed by Au need a Ag cocatalyst to generate reactive Au intermediates (Au^+)

+ cycloisomerization catalyzed by **9** proceeded without Ag cocatalyst

+ energetically low-lying lowest LUMO of DPCB would effectively raise the Lewis acidity of the Au complex to activate the acetylene moiety

3. phospholyl ligand (phosphametallocene)

(a) probably the most developed low-coordinate phosphorus ligand (as phosphametallocene ligand)

(b) having similar aromaticity as cyclopentadienyl anion, but reactivity is different

(c) η^1 vs η^5 coordination: dependent on the substituents at α-position of phosphorus

(d) act as both good π-donor and π-acceptor ligand

(e) currently admitted that phospholyl ligands are slightly less good π-donors than carbon analogues but usually exhibit greater π-accepting capacity

(f) highly spherical lone pair, modest σ-donor (no complexation with BH_3)

phosphaferrocene

- + phosphaferrocenyl backbone can be exploited to devise ligands possessing a planar-chirality
- + Fu was the first to use planar-chiral phosphaferrocene in asymmetric catalysis (*J. Org. Chem.* **1998**, *63,* 4168.)

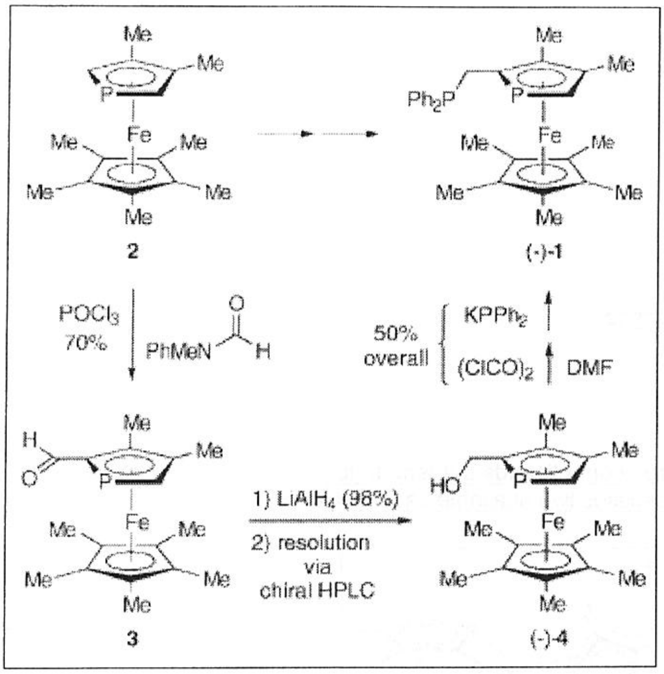
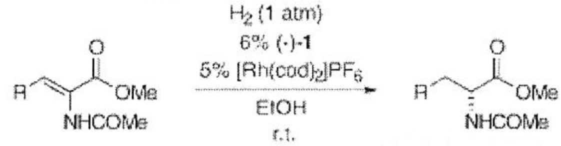


Table 1. Catalytic Asymmetric Hydrogenation in the Presence of Bisphosphine 1



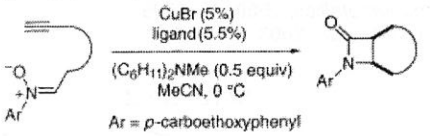
entry	R	% ee	yield
1	H	87	99
2	Ph	87	95
3	4-OMeC$_6$H$_4$	87	96
4	4-ClC$_6$H$_4$	85	95
5	4-NO$_2$C$_6$H$_4$	79	100
6	Me	88	96
7	Et	96	92
8	*i*-Pr	90	96

- + high catalyst loading
- + up to 96% ee

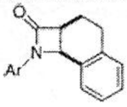
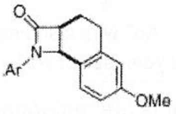
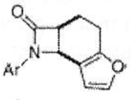
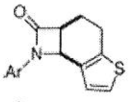
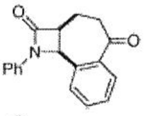
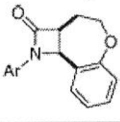
Intramolecular Kinugasa reaction

Fu, G. C. et al. *Angew. Chem., Int. Ed.* **2003**, *42*, 4082.
recent review: *Synlett*, **2007**, 2321.

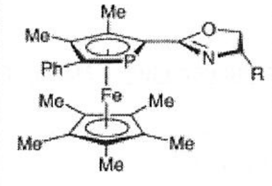
Table 2: Copper-catalyzed intramolecular Kinugasa reactions in the presence of planar-chiral phosphaferrocene–oxazoline ligands: Enantioselective synthesis of two new rings.[a]



Ar = *p*-carboethoxyphenyl

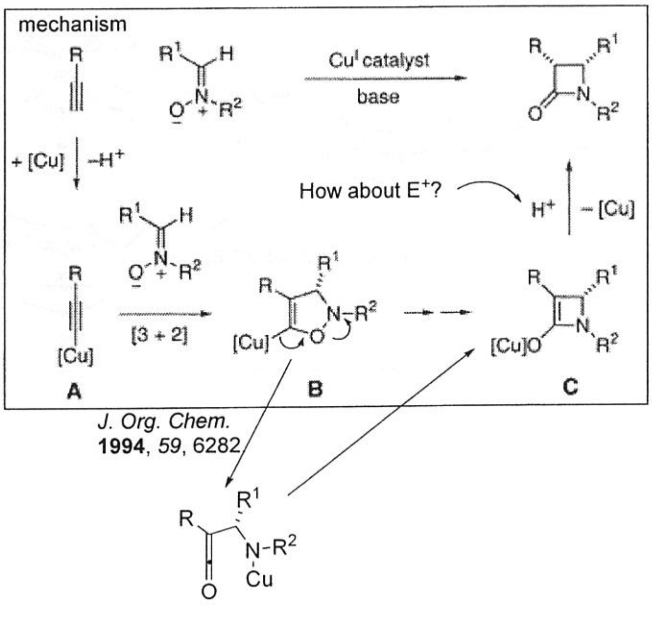
Entry	Product	Ligand	*ee* [%]	Yield [%]
1		**5a**	88	74
2		**5a**	86	60
3[b]		**5a**	90	46
4[b]		**5b**	90	64
5[b]		**5b**	85	53
6		**5b**	91	68

[a] All data are the average of two runs. [b] The reaction was run at room temperature.

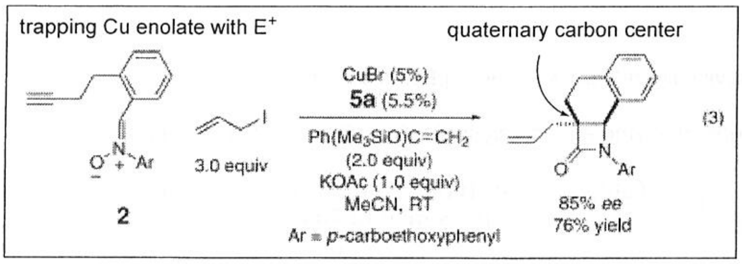


5a: R = *i*Pr; **5b**: R = *t*Bu

- + catalytic enantioselective synthesis of fused β-lactams from alkynyl nitrones
- + high enantioselectivity but low-modest yield



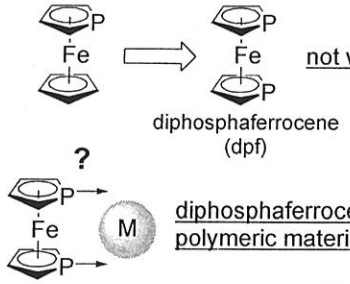
J. Org. Chem. **1994**, *59*, 6282



+ Ph(TMSO)C=CH$_2$ is used instead of amine base

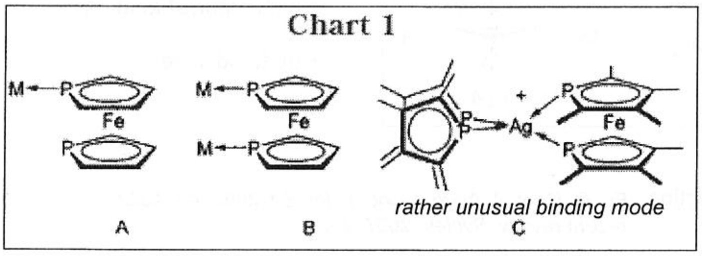
R$_3$NH$^{\oplus}$ など proton donor が できるのを防ぐ.

diphosphaferrocene



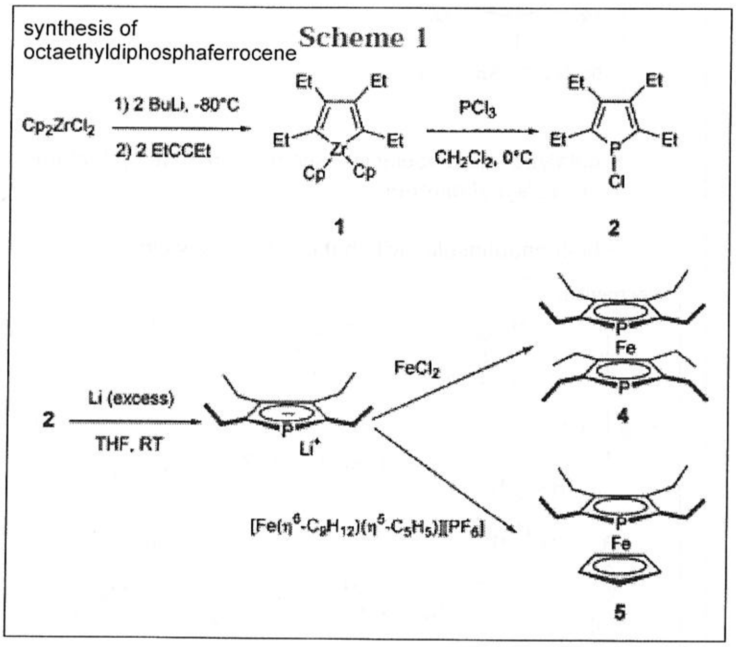
not well-developed like phosphaferrocene

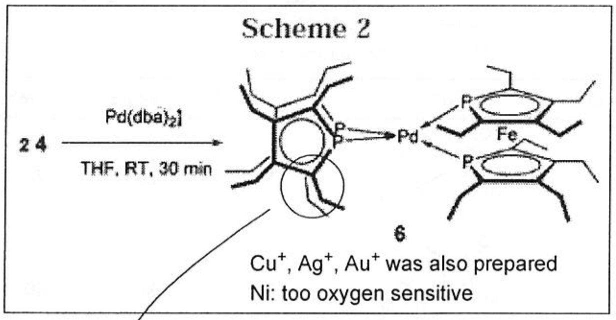
diphosphaferrocenes logically behave as 4-electron donor ligands but tend to form polymeric materials when the metal fragment possesses two available vacant sites



rather unusual binding mode

\# synthesis of diphosphaferrocene complex Mathey, F.; Le Floch, P. et al. *Organometallics,* **2000**, *19*, 4899.
New J. Chem., **2003**, *27* 1233.





Cu$^+$, Ag$^+$, Au$^+$ was also prepared
Ni: too oxygen sensitive

α-substituents are important for this unusual binding mode, preventing formation of polymeric material

theoretical study using DFT (Cu complex)

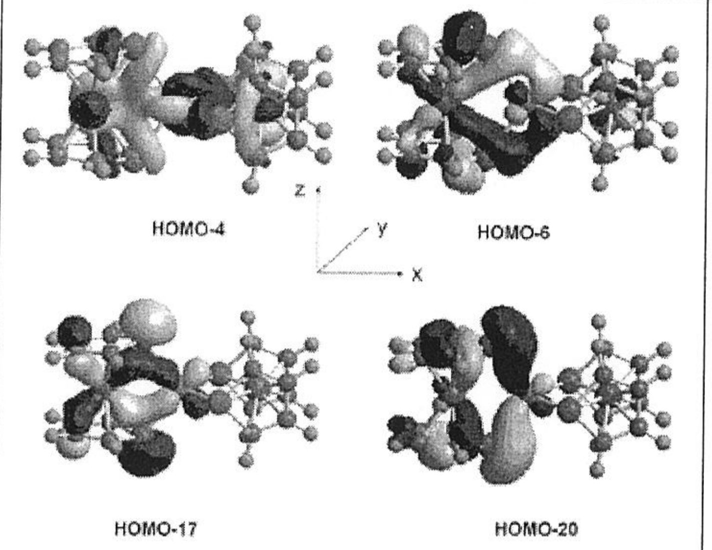
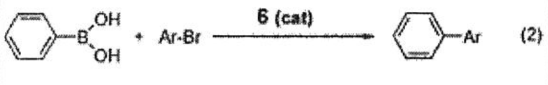


Fig. 3 Selected orbitals describing the bonding in $[Cu(dpf)2]^+$.

- + 9 orbitals mainly account for the binding of the dpf (diphosphaferrocene) ligands to the Cu
- + the orbitals which describe the lone pair at phosphorus and the π* orbital of the phospholide ligand (mainly 3pz contribution at P) as well as the MO which describe the P-Fe bond participates significantly to the bonding between Cu and dpf ligand
- + dative bonding between Fe and Cu doesn't occur, since no empty d orbitals are available at Cu (such bonding is often seen in ferrocenyl-based complexes)
- + deviation from the ideal in-plane coordination of the lone pair at phosphorus (θ = 50°, from X-ray analysis)
- + nondirectional bonding

Suzuki coupling



Ar = 4-MeCO-C_6H_4, 3-thienyl, 2-MeO-C_6H_4, C_6H_5.

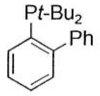
Table 3. Suzuki Coupling of Aryl Bromides[a]

aryl bromide	mol % Pd	t/h	conversion (%)	TON
4-bromoacetophenone	0.0001	1	77	770 000
4-bromoacetophenone	0.0001	20	98	980 000
3-bromothiophene	0.005	1	80	16 000
3-bromothiophene	0.005	20	96	19 200
2-bromoanisole	0.005	1	67	13 400
2-bromoanisole	0.005	20	96	19 200
bromobenzene	0.0001	1	46	460 000

[a] Reaction conditions: 1.0 equiv of aryl bromide, 1.5 equiv of phenylboronic acid, 2.0 equiv of K_2CO_3. Temperature: 110 °C. TON are expressed in mol product (mol Pd)$^{-1}$.

+ **6** proved to be highly active catalyst

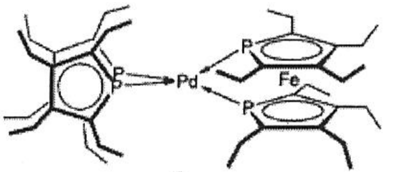
cf.



0.000001 mol% $Pd(OAc)_2$
24 h, 91% yield
Buchwald et al. *JACS* **1999**, *121*, 9550.

* Fu proposed that the bulkiness of P(*t*-Bu)$_3$ favors the formation of the 12-electron species [PdP(*t*-Bu)$_3$], which can be considered as the active species in the Suzuki coupling of arylboronic acid with aryl and vinyl halides and triflates *J. Am. Chem. Soc.* **2000**, *122*, 4020.

Does dpf ligands coorinate to Pd tightly?



6

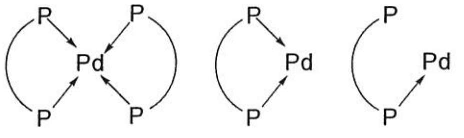
$\xrightarrow[\text{THF, rt}]{2L}$ 2dpf + PdL_2 quant.

L = dppe, dppp

⟹ hemilabile ligand

⇓

contribution to generation of active species?



18 e 14 e 12 e