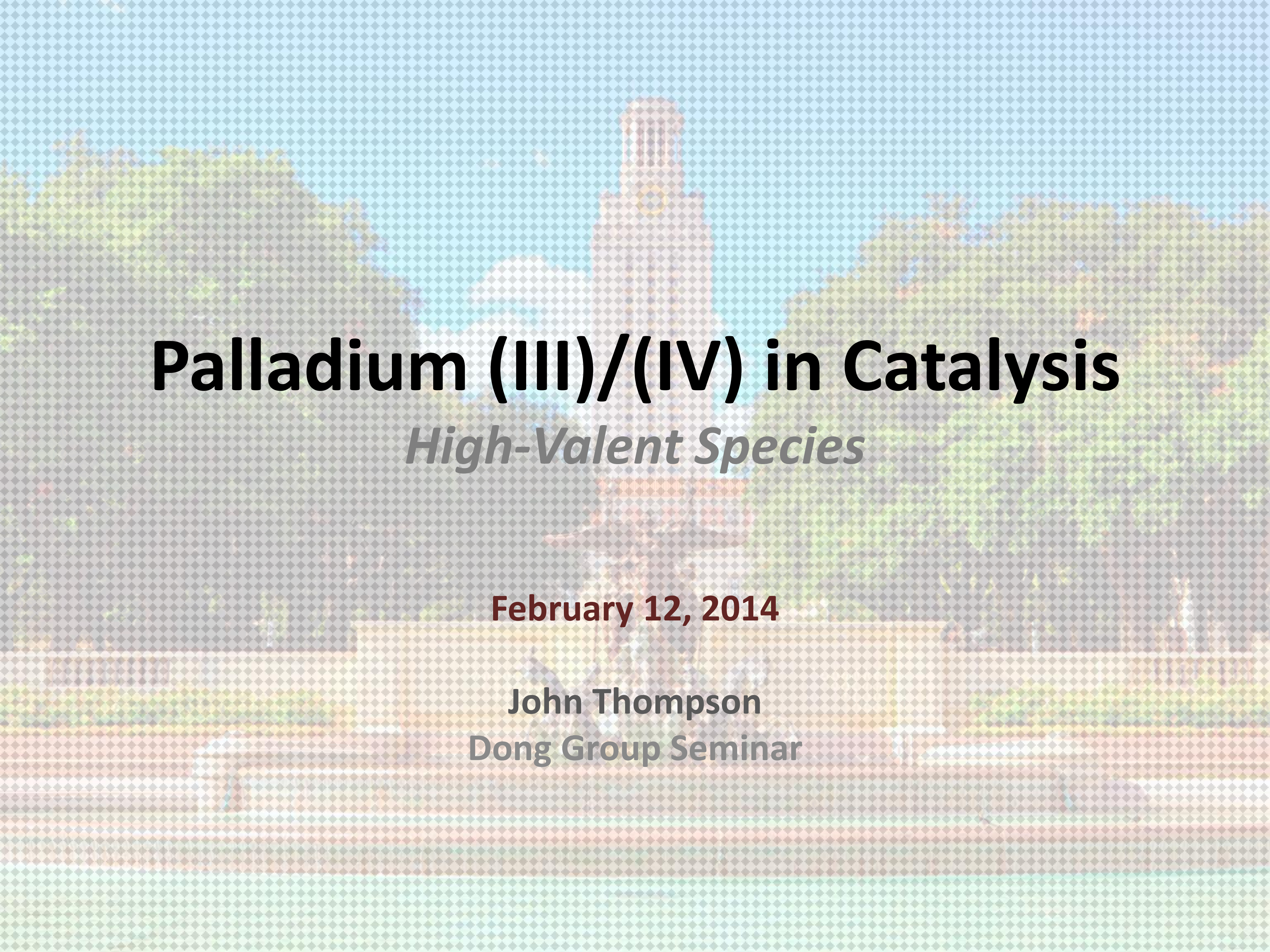


Palladium (III)/(IV) in Catalysis

High-Valent Species

February 12, 2014

John Thompson
Dong Group Seminar

Seminar Preview

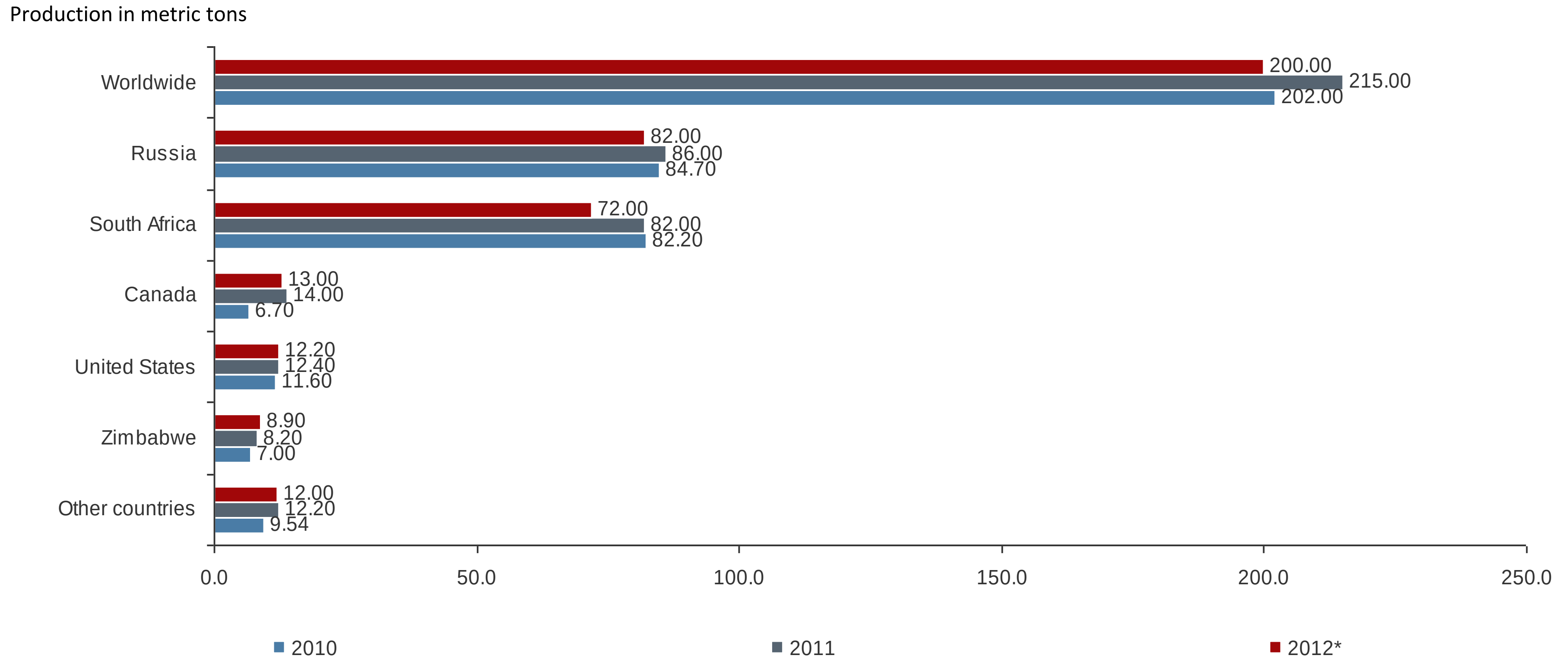
- Complementary Review to previous career seminars:
    - Yu – Zack
    - Sanford – Tao
    - Catellani – Dong Zhe

- **Goal**: To introduce the beginning of high-valent palladium chemistry, controlling reactivity and stability, and applications of this chemistry for synthesis and catalysis.

Pd(IV) Review: *Chem. Rev.*, **2010**, *110*, 824.
Pd(III) Review: *Top. Organometal. Chem.,* **2010**, *35*, 129.

Palladium mine production worldwide 2010-2012 by country
Worldwide

Global mine production of palladium from 2010 to 2012, by country (in metric tons)

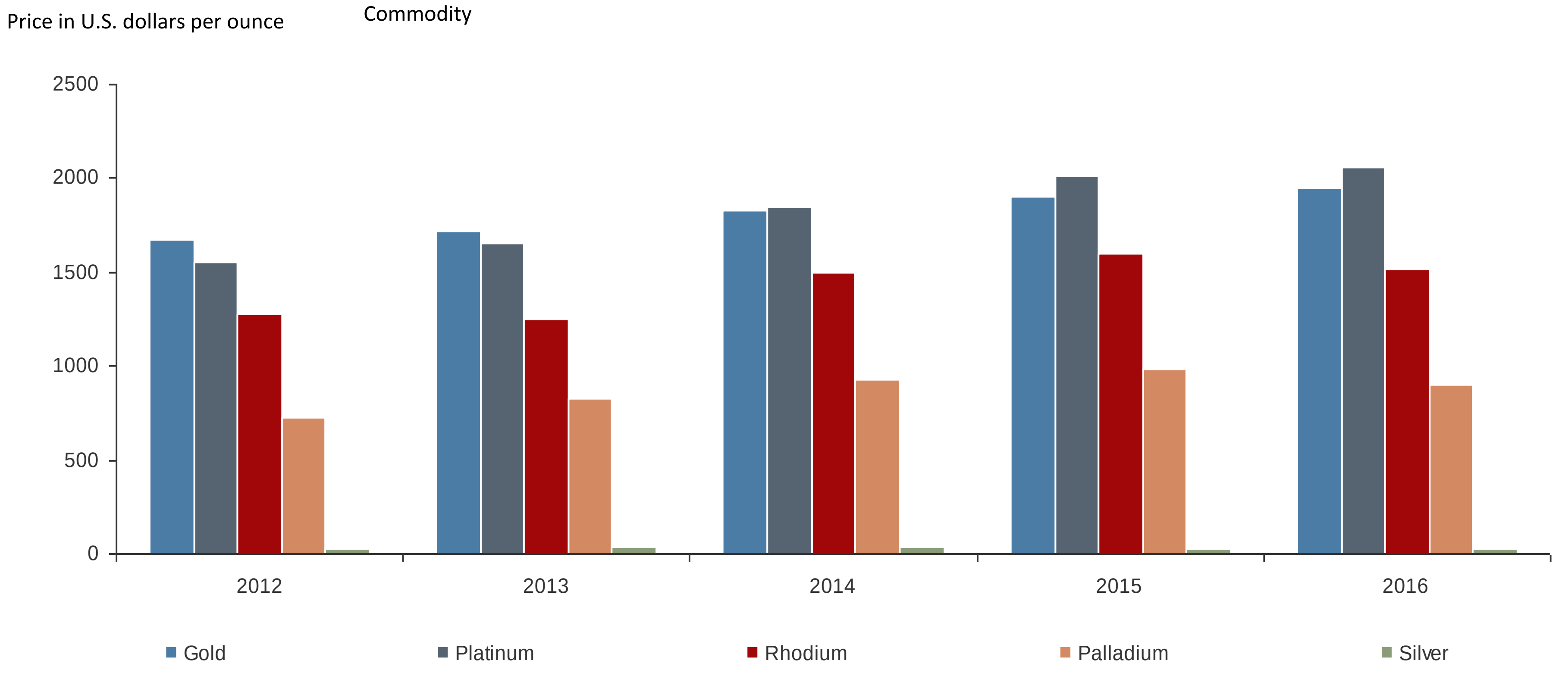


2010 figures were taken from the 2012 USGS report.* Estimated figures.

U.S. Geological Survey, USGS - Mineral Commodity Summaries 2013, page 121

Precious metal price forecast 2012-2016
Worldwide

Precious metal price forecast from 2012 to 2016 (in U.S. dollars per ounce)



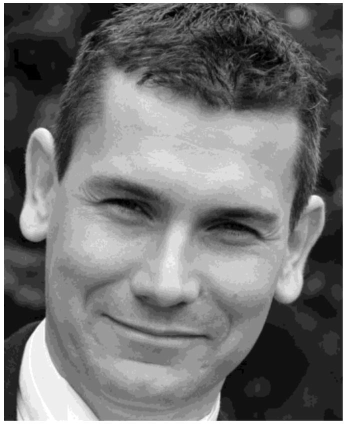
SBG Securities; Standard Bank, Commodity Spotlight Precious Metals, page 9

46
Pd
Palladium
106.42

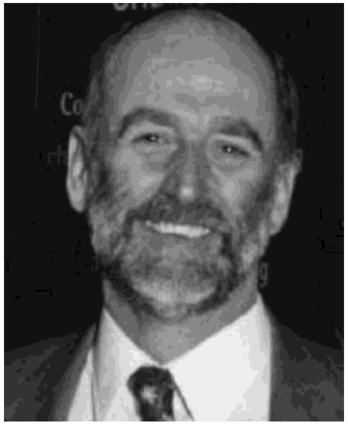
Publications with High-Valent Palladium (In Title)

- Palladium(IV)
  - JACS: 16
  - ACS: 53
- Palladium(III)
  - JACS: 8
  - ACS: 21

Review Article Authors:

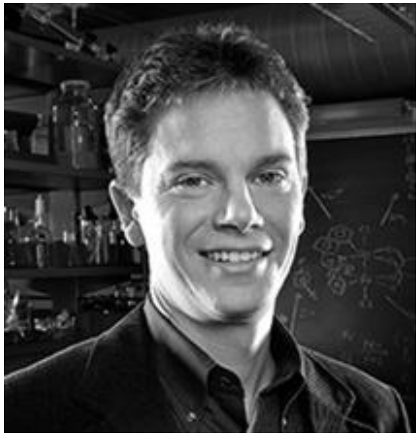


Richard Taylor



Ian Fairlamb

University of York, UK

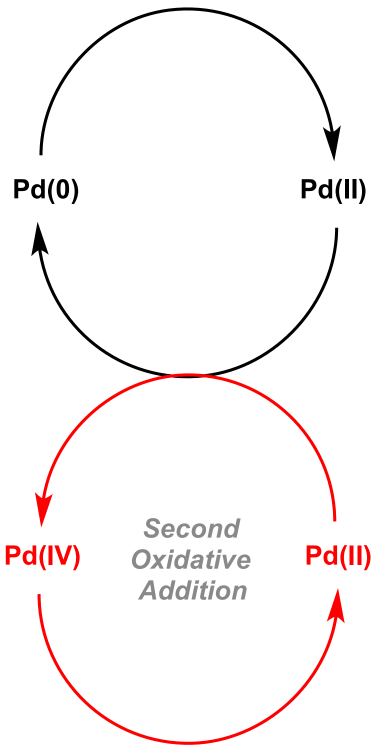


Tobias Ritter

Harvard University

Palladium in Catalysis

Normal Catalytic Cycle



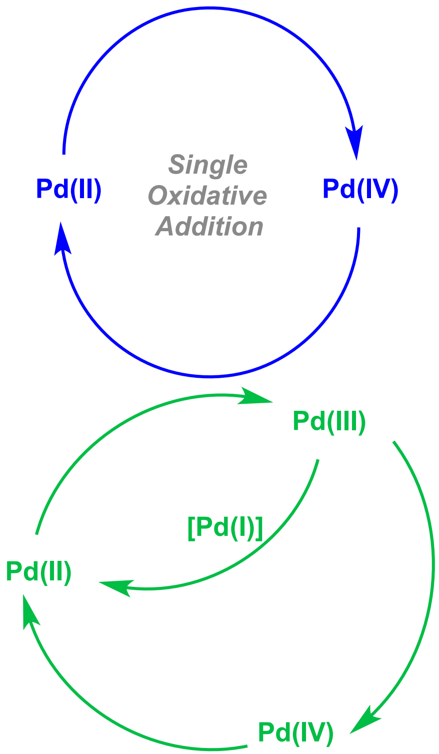
Pd(0)

Pd(II)

Pd(IV)

Second Oxidative Addition

Pd(II)



Pd(II)

Single Oxidative Addition

Pd(IV)

Pd(III)

[Pd(I)]

Pd(II)

Pd(IV)

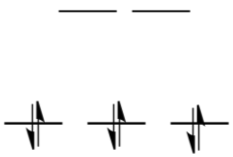
Overview

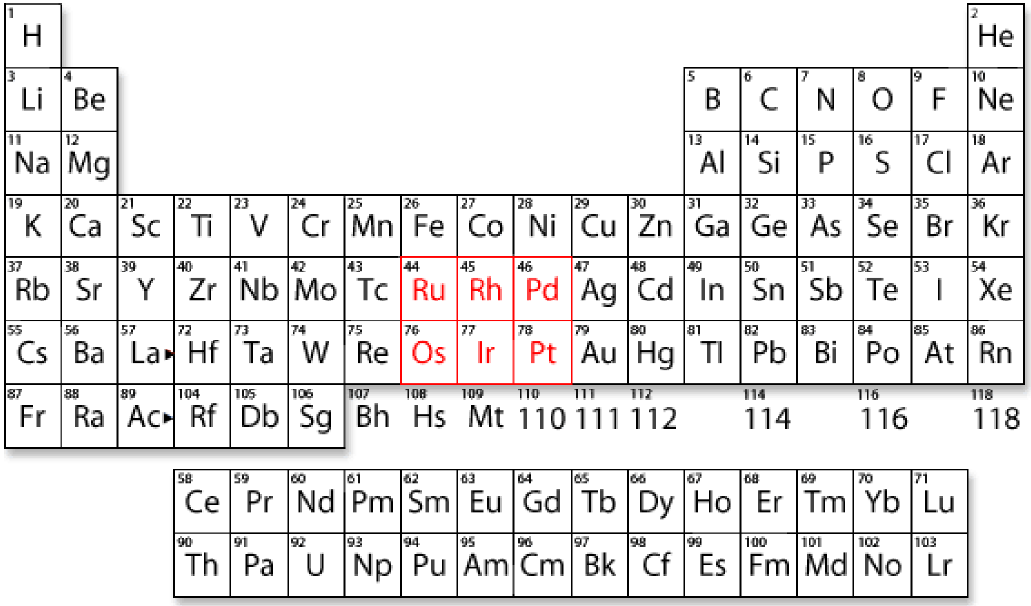
- Palladium(IV) Chemistry
    - Characteristics
    - Historical Background
    - Mechanism Aspects
    - Applications into Catalysis and Synthetic Efforts
    - Drawbacks and the Future

- Palladium(III) Chemistry
    - New Field
    - Isolation and Importance
    - Acceptance and Controversy
    - Outlook

Palladium (IV) Oxidation State

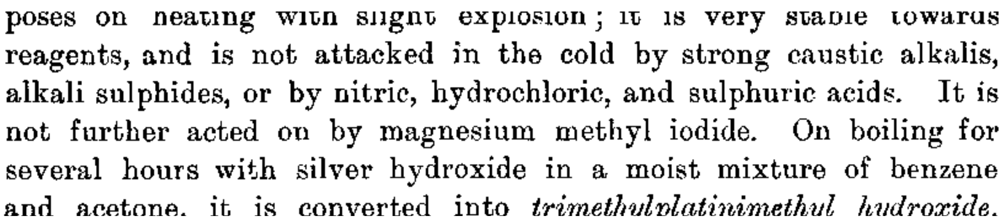
- Exists as Pd(0) to Pd(IV)
- Pd(IV) Complexes
    - Octahedral
    - Low-spin





1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La▸	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac▸	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 110	111 111	112 112		114 114		116 116		118 118
			58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
			90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

- Counter-part Pt(IV)
    - Thermodynamically stable
    - Kinetically inert
    - First organometallic species discovered in 1907 [$PtMe_3X$]



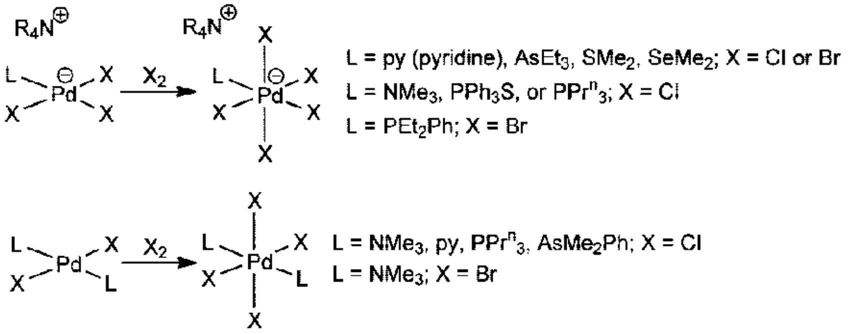
poses on heating with slight explosion; it is very stable towards reagents, and is not attacked in the cold by strong caustic alkalis, alkali sulphides, or by nitric, hydrochloric, and sulphuric acids. It is not further acted on by magnesium methyl iodide. On boiling for several hours with silver hydroxide in a moist mixture of benzene and acetone, it is converted into *trimethylplatinimethyl hydroxide.*

First organometallic Pd(IV) → 1975

Proc. Chem. Soc., **1907**, *23*, 86.

Inorganic Pd(IV) Complexes

- Most well studied and characterized are halogen salts.

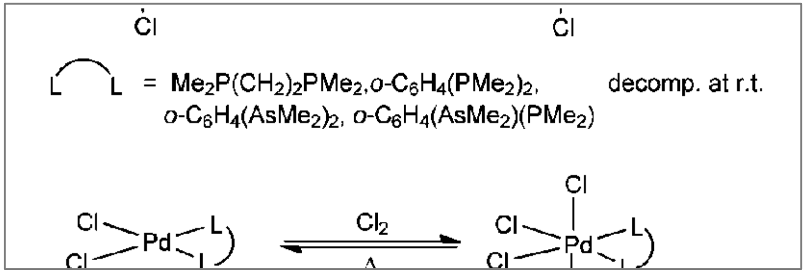


L = py (pyridine), $AsEt_3$, SMe_2, $SeMe_2$; X = Cl or Br
L = NMe_3, PPh_3S, or PPr^n_3; X = Cl
L = PEt_2Ph; X = Br

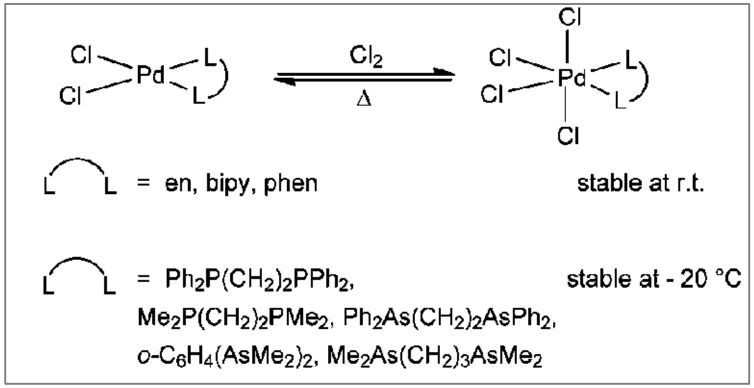
L = NMe_3, py, PPr^n_3, $AsMe_2Ph$; X = Cl
L = NMe_3; X = Br

Stability

- Neutral ligand complexes of Pd(IV) usually decompose very easily.



= $Me_2P(CH_2)_2PMe_2$, o-$C_6H_4(PMe_2)_2$, o-$C_6H_4(AsMe_2)_2$, o-$C_6H_4(AsMe_2)(PMe_2)$ decomp. at r.t.



= en, bipy, phen stable at r.t.

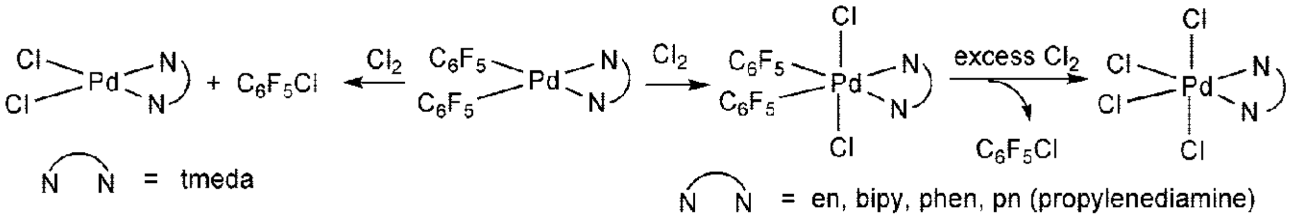
= $Ph_2P(CH_2)_2PPh_2$, $Me_2P(CH_2)_2PMe_2$, $Ph_2As(CH_2)_2AsPh_2$, o-$C_6H_4(AsMe_2)_2$, $Me_2As(CH_2)_3AsMe_2$ stable at - 20 °C

- Importance: Trans X_2 in $[Pd(L\text{-}L)_2X_2]$ more kinetically stable

J. Chem. Soc., Dalton Trans., **1983**, 113.

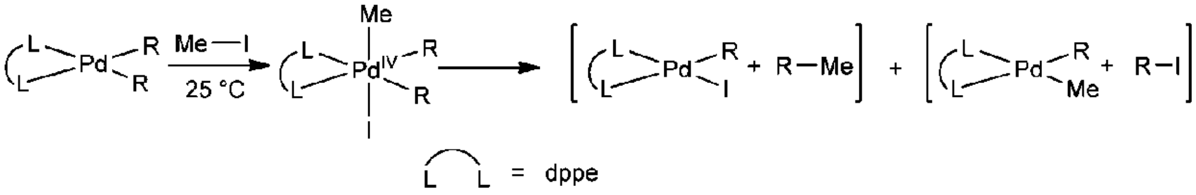
Organometallic Pd(IV) Complexes

- First report 1975 by Uson:



  - Larger sterically hindered ligands made Pd(IV) intermediate too unstable, promoting reductive elimination

- Yamamoto 1977: first use of phosphine ligands

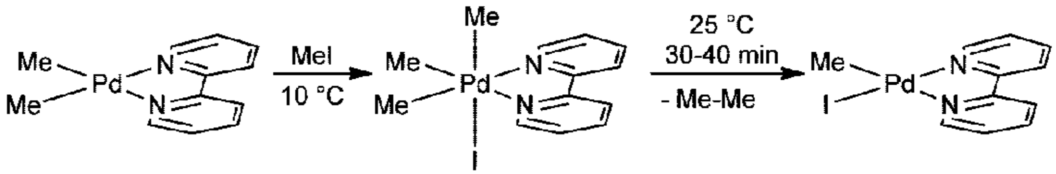


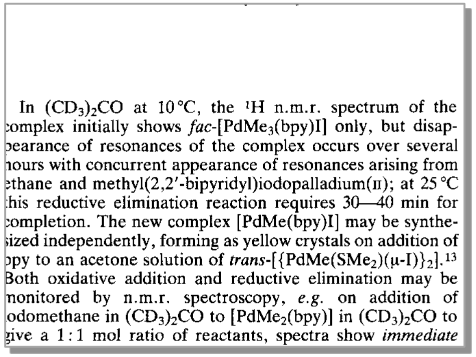
  - Phosphorous ligands rarely used with Pd(IV)

J. Organometal. Chem. **1975**, *96*, 307
Bull. Chem. Soc. Jpn. **1977**, *50*, 1319.

Isolation and Stability

- 1986: Canty

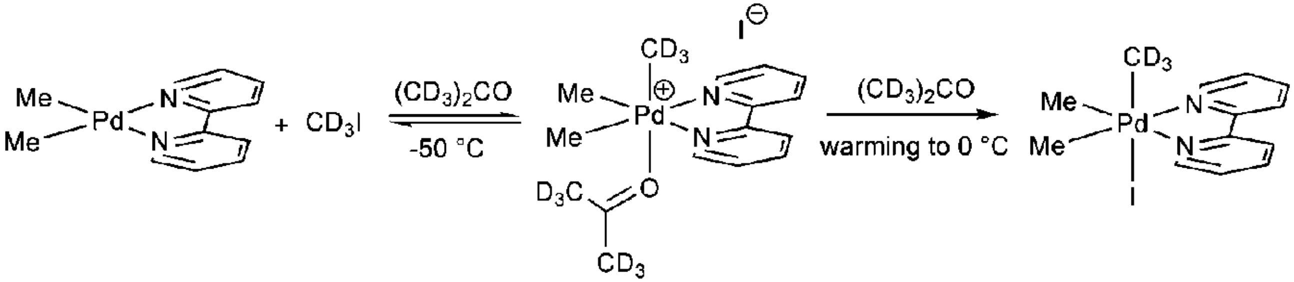




In $(CD_3)_2CO$ at 10 °C, the ^1H n.m.r. spectrum of the complex initially shows *fac*-$[PdMe_3(bpy)I]$ only, but disappearance of resonances of the complex occurs over several hours with concurrent appearance of resonances arising from ethane and methyl(2,2′-bipyridyl)iodopalladium(II); at 25 °C this reductive elimination reaction requires 30—40 min for completion. The new complex [PdMe(bpy)I] may be synthesized independently, forming as yellow crystals on addition of bpy to an acetone solution of *trans*-$[\{PdMe(SMe_2)(\mu\text{-}I)\}_2]$.[13] Both oxidative addition and reductive elimination may be monitored by n.m.r. spectroscopy, *e.g.* on addition of iodomethane in $(CD_3)_2CO$ to $[PdMe_2(bpy)]$ in $(CD_3)_2CO$ to give a 1:1 mol ratio of reactants, spectra show *immediate*

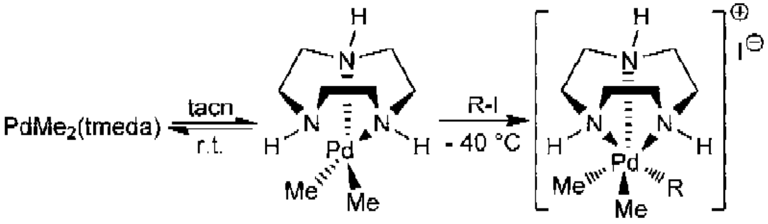
  - Stable to store below -20°C
  - Elimination of ethane in solution

  - Proposed mechanism to Pd(IV):



J. Chem. Soc., Chem. Commun. **1986**, 1722.
Organometallics, **1990,** *9*, 826.

Increasing Pd(IV) Stability



- Tridentate ligands make complexes thermally stable to 150°C
    - Bidentate complexes require very low temperature storage

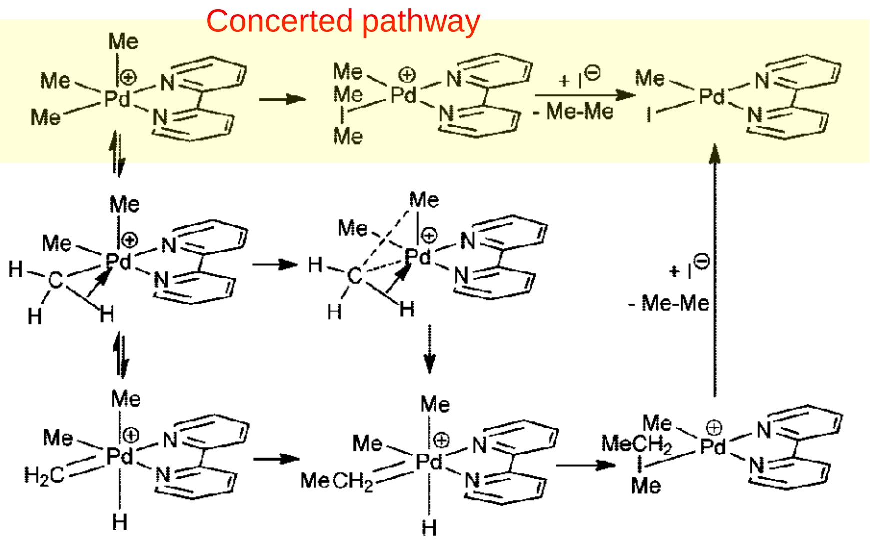
Stability of Pd(IV) complexes is dictated by rigidity of the ligands and their complexes.

- Numerous other allyl, benzyl, and alkyl complexes with various nitrogen or phosphorous based ligands have been prepared to date.

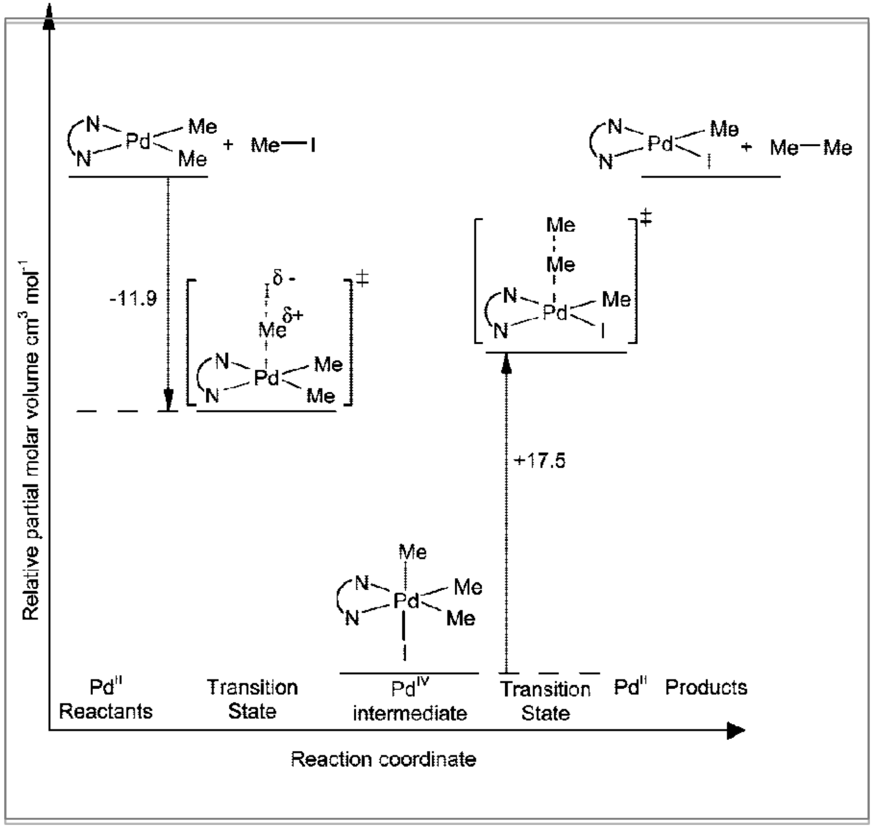
Mendeleev Commun. **2002**, 14.

O.A. and R.E. with Pd(IV) intermediates

- Oxidative Addition: via S_N2 pathway with proposed cationic intermediate as seen previously.
- Reductive Elimination: concerted pathway favored from electronics.



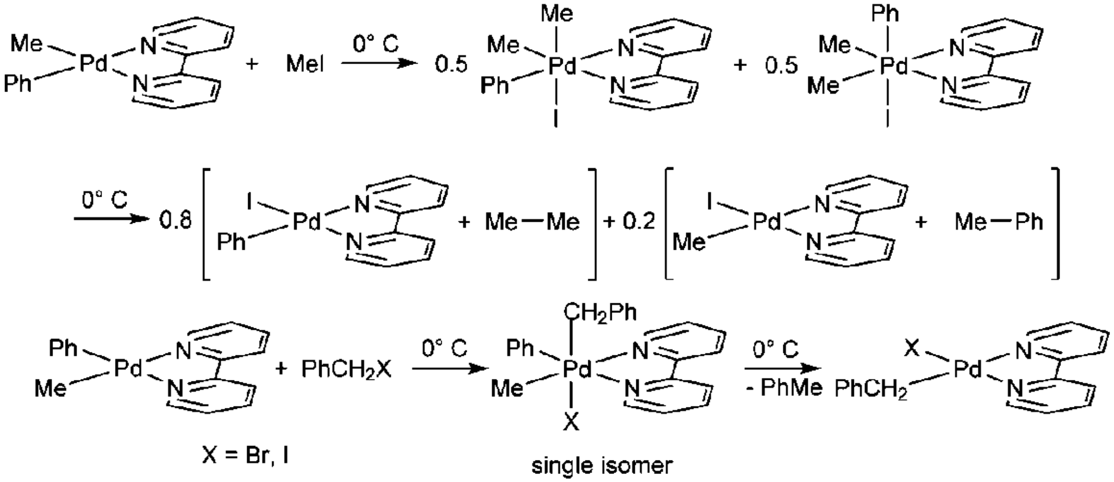
Alternative Pathways



Organometallics, **1988**, *7*, 1363.

Reductive Elimination from Pd(IV)

- In cases with alkyl and halogen substitutents:
  - R.E. occurs almost exclusively through C-C bond formation (rarely C-X)



(1)

(2)

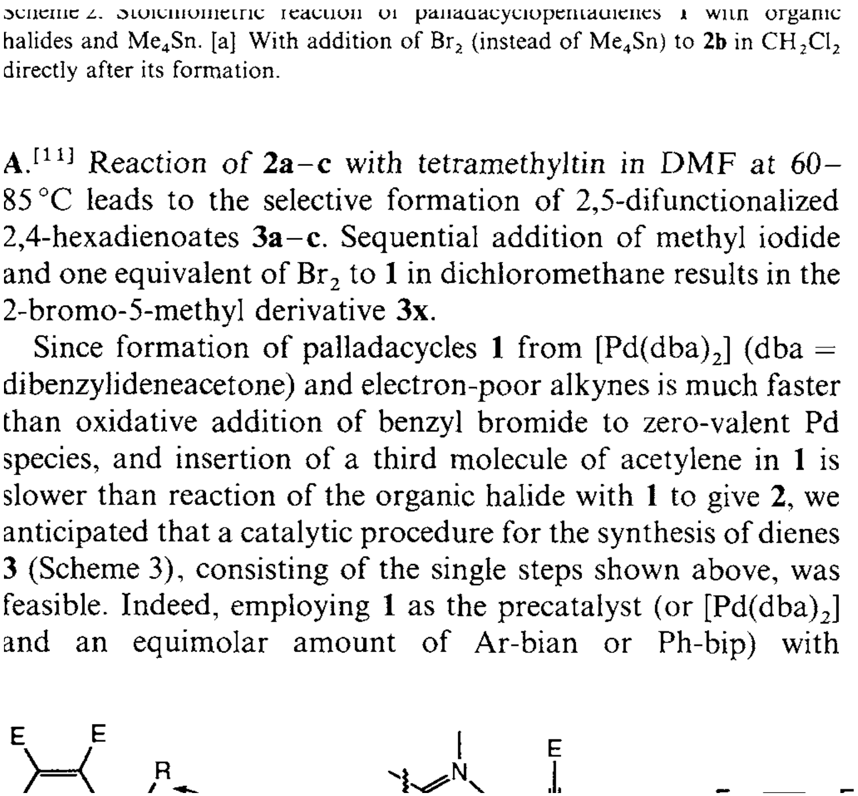
(1) - 4:1 ratio of ethane to toluene

(1) - Pd bound to 3 different groups → only product is toluene

Canty *Organometallics*, **1994**, *13*, 2053.

Oxidative Addition of Pd(II) to Pd(IV)

- Direct synthesis of conjugated dienes from alkynes

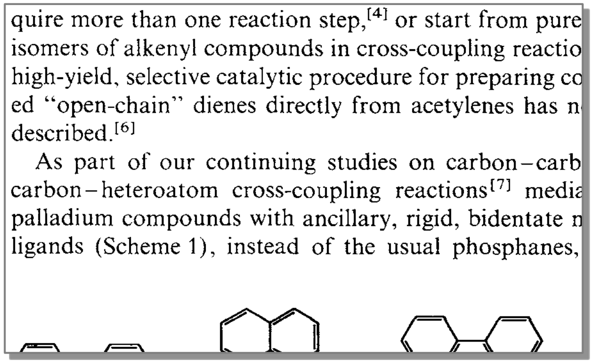


Scheme 2. Stoichiometric reaction of palladacyclopentadienes 1 with organic halides and Me_4Sn. [a] With addition of Br_2 (instead of Me_4Sn) to **2b** in CH_2Cl_2 directly after its formation.

A.[11] Reaction of **2a**–**c** with tetramethyltin in DMF at 60–85 °C leads to the selective formation of 2,5-difunctionalized 2,4-hexadienoates **3a**–**c**. Sequential addition of methyl iodide and one equivalent of Br_2 to **1** in dichloromethane results in the 2-bromo-5-methyl derivative **3x**.

Since formation of palladacycles **1** from $[Pd(dba)_2]$ (dba = dibenzylideneacetone) and electron-poor alkynes is much faster than oxidative addition of benzyl bromide to zero-valent Pd species, and insertion of a third molecule of acetylene in **1** is slower than reaction of the organic halide with **1** to give **2**, we anticipated that a catalytic procedure for the synthesis of dienes **3** (Scheme 3), consisting of the single steps shown above, was feasible. Indeed, employing **1** as the precatalyst (or $[Pd(dba)_2]$ and an equimolar amount of Ar-bian or Ph-bip) with

Catalytic 3-component synthesis



quire more than one reaction step,[4] or start from pure isomers of alkenyl compounds in cross-coupling reactio high-yield, selective catalytic procedure for preparing co ed "open-chain" dienes directly from acetylenes has n described.[6]

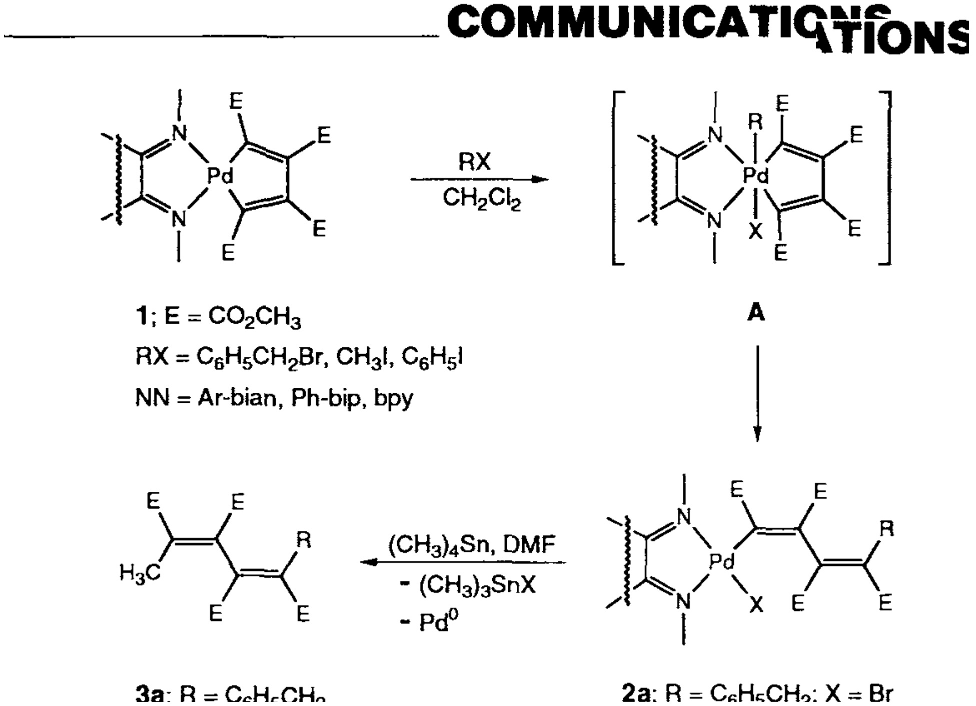
As part of our continuing studies on carbon–carb carbon–heteroatom cross-coupling reactions[7] media palladium compounds with ancillary, rigid, bidentate n ligands (Scheme 1), instead of the usual phosphanes,

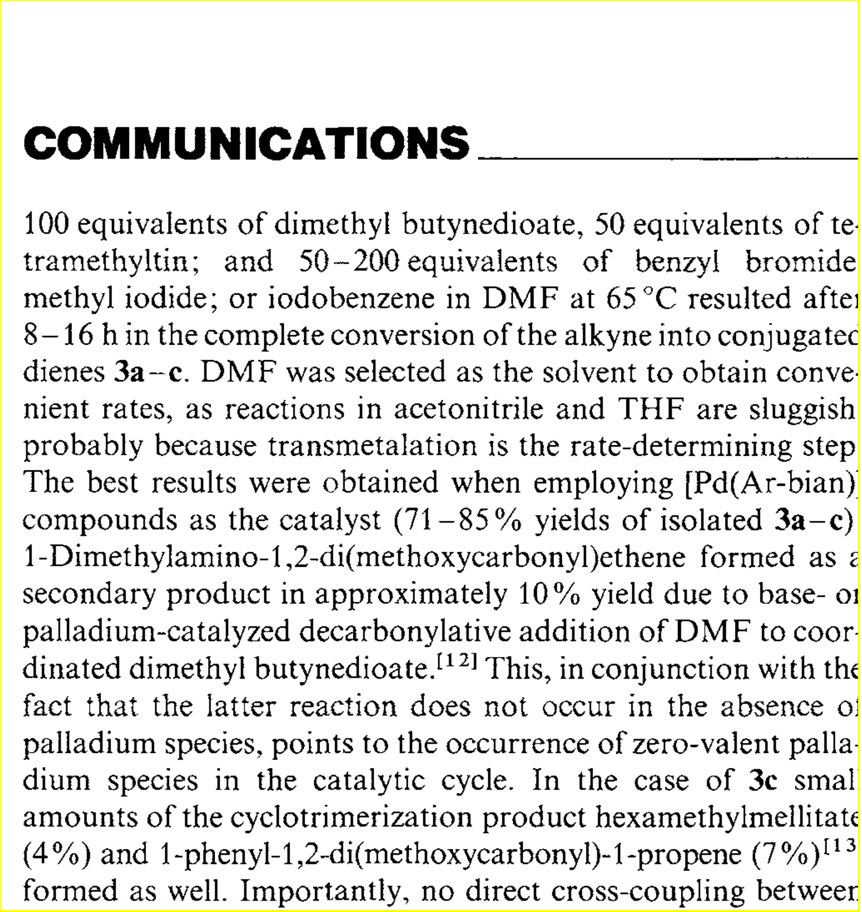
Yields: 71-76%

Elsevier. *Angew. Chem. Int. Ed. Engl.*, **1997**, ***36***, **1743.**

Catalysis with Pd(0), Pd(II), and Pd(IV)

- Using $Pd(dba)_2$ and electron poor alkynes, palladacycles could be generated faster than O.A. of benzyl bromide → ***catalytic process***





COMMUNICATIONS

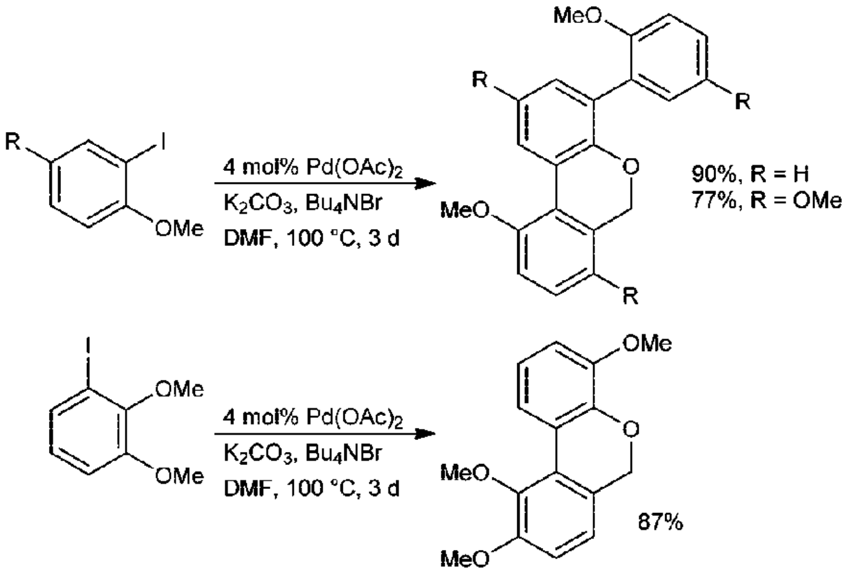
100 equivalents of dimethyl butynedioate, 50 equivalents of tetramethyltin; and 50–200 equivalents of benzyl bromide methyl iodide; or iodobenzene in DMF at 65 °C resulted after 8–16 h in the complete conversion of the alkyne into conjugated dienes **3a**–**c**. DMF was selected as the solvent to obtain convenient rates, as reactions in acetonitrile and THF are sluggish probably because transmetalation is the rate-determining step The best results were obtained when employing [Pd(Ar-bian)] compounds as the catalyst (71–85% yields of isolated **3a**–**c**) 1-Dimethylamino-1,2-di(methoxycarbonyl)ethene formed as a secondary product in approximately 10% yield due to base- or palladium-catalyzed decarbonylative addition of DMF to coordinated dimethyl butynedioate.[12] This, in conjunction with the fact that the latter reaction does not occur in the absence of palladium species, points to the occurrence of zero-valent palladium species in the catalytic cycle. In the case of **3c** small amounts of the cyclotrimerization product hexamethylmellitate (4%) and 1-phenyl-1,2-di(methoxycarbonyl)-1-propene (7%)[13 formed as well. Importantly, no direct cross-coupling between

- DFT studies show process is energetically feasible!
- Process also uses 50eq. of Tin.

Elsevier. *Angew. Chem. Int. Ed. Engl.*, **1997**, ***36***, **1743.**

Questions about Pd(IV) in Synthesis

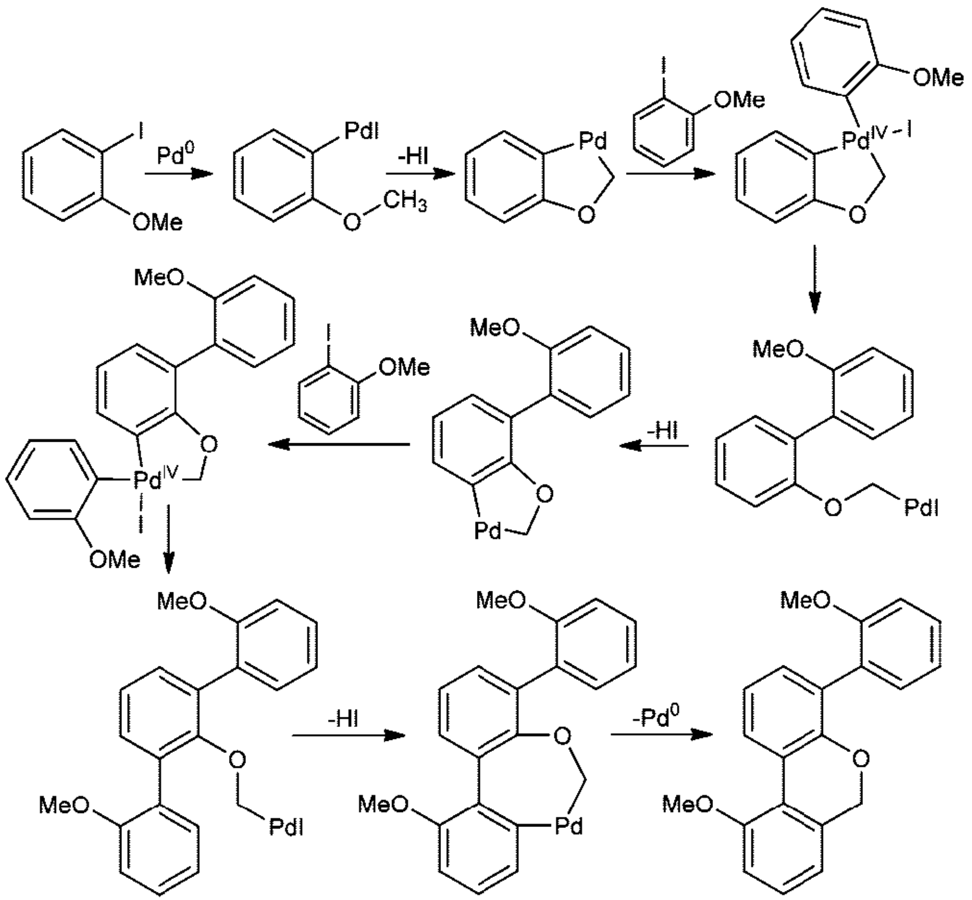
- C-H activation at aryl methoxy group.
- Forms dibenzo-pyrans in high yields.



Dyker *Angew. Chem. Int. Ed. Engl.*, **1992,** *31*, **1023.**

Questions about Pd(IV) in Synthesis

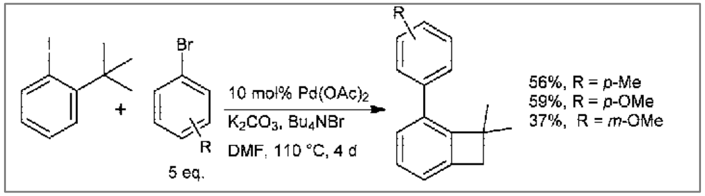
- Proposed Mechanism



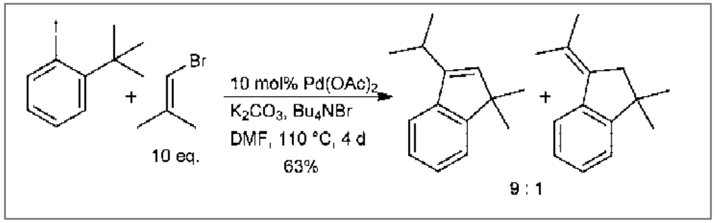
Dyker *Angew. Chem. Int. Ed. Engl.*, **1992,** *31*, **1023.**

sp^2-sp^2 coupling issues

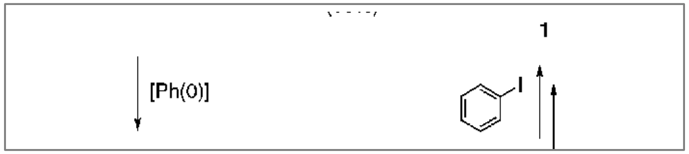
- Many new reactions forming sp^2-sp^2 bonds were published suggesting Pd(IV) intermediates



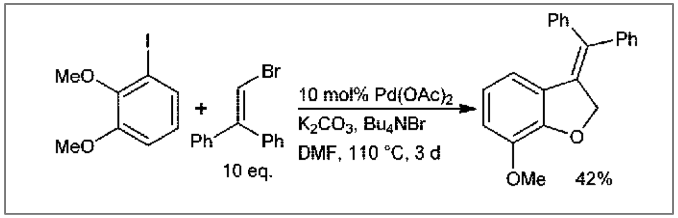
Dyker, G. *Angew. Chem., Int. Ed. Eng. Engl.* **1992**, *31*, 1023.



Dyker, G. *Angew. Chem., Int. Ed. Engl*. **1994**, *33*, 103.



Catellani, M. *J. Organomet. Chem*. **1991**, *401*, C30.

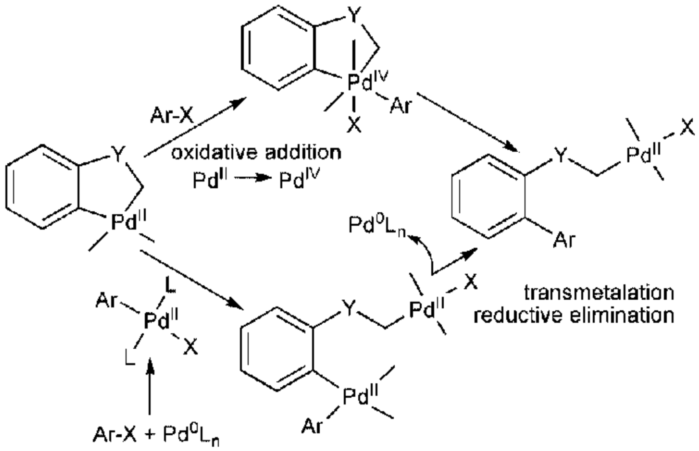


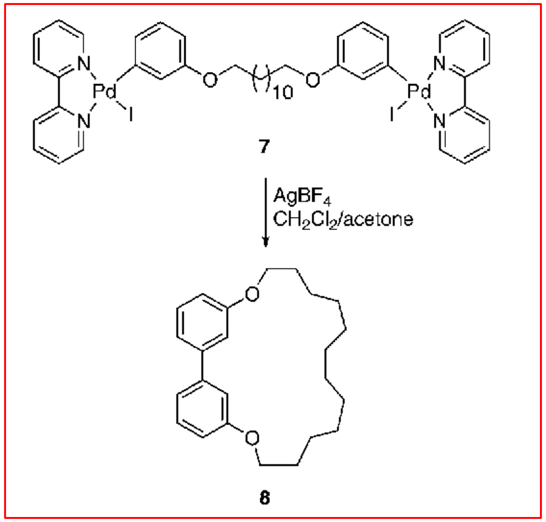
Dyker, G. *J. Org. Chem*. **1993**, *58*, 6426.

What about opposing pathway with transmetallation of aryl ligands?

DTF rebuttle

- DFT calculations on model substrates to probe Oxidative Addition forming Pd(IV) intermediates or Pd-Pd transmetallation





Osakada, K. *Organometallics* 2003, 5254.

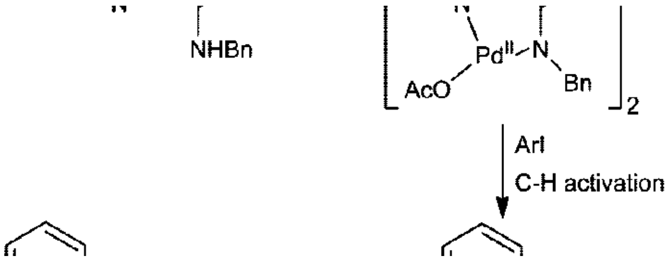
- Authors found alkenyl and aryl electrophiles react more readily with Pd(0) precursors than Pd(II) metallacycles
- Transmetallation between the two Pd(II) complexes was facile

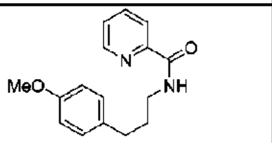
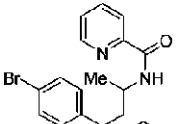
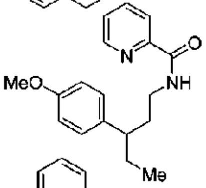
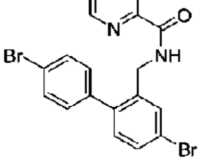
- Previous sp^2-sp^2 publications may actually not involve Pd(IV)

Echavarren *JACS,* **2008**, *128*, 5033.

Applications of sp^2-Pd(IV) Complexes (Daugulis)

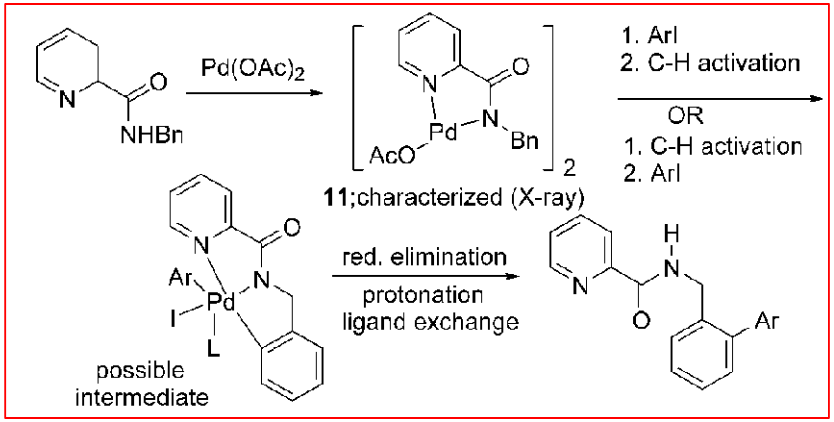
- Chelation directed arylation of C-H bonds



Entry	Amide, ArI	Time Temp	Arylated Amide	Yield
1	R = n-Pr (**7**) Ar = 4-MeOC$_6$H$_4$	6 h 130 °C		76%
2	R = s-Bu (**8**) Ar = 4-BrC$_6$H$_4$	1 h 150 °C		72%
3	R = n-Amyl (**9**) Ar = 4-MeOC$_6$H$_4$	12 h 150 °C		54%
4	R = 3-Bromo-benzyl (**10**) Ar = 4-BrC$_6$H$_4$	5 h 150 °C		81%

- 8-Aminoquinoline was also used as a directing group

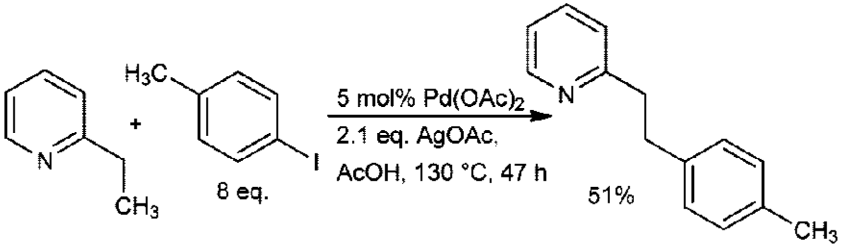
- Proposed Mechansim:



Daugulis *JACS*, **2005**, *127*, 13154.

Continuing Activation of Unactivated C-H bonds

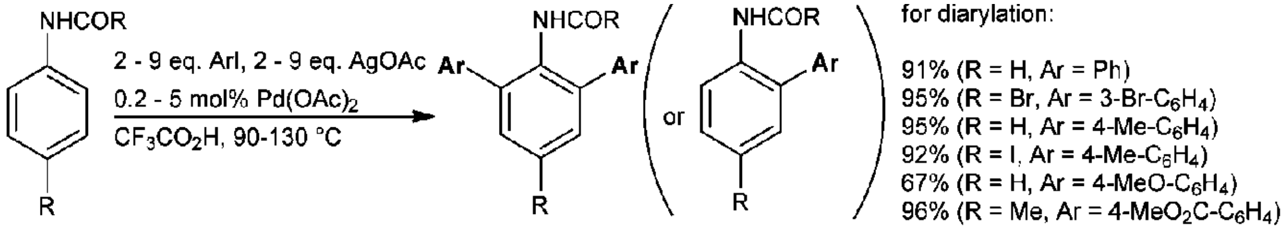
- Daugulis group has even achieved catalytic coupling of unactivated C-H bonds
  - Pyridine as directing group:



Daugulis *Org. Lett.*, **2005**, *7*, 3657.

Continuing Activation of Unactivated C-H bonds

- Daugulis group has even achieved catalytic coupling of unactivated C-H bonds
    - Pyridine as directing group:
    - Analines



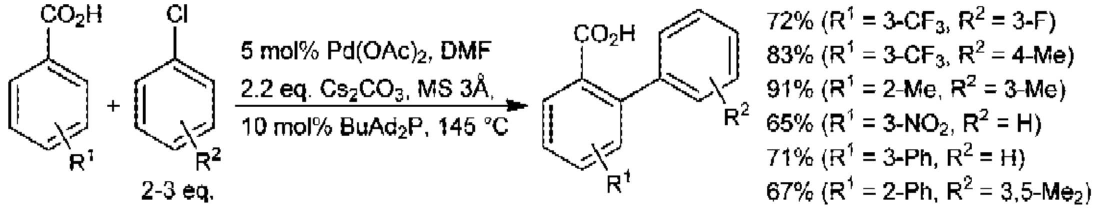
for diarylation:

91% (R = H, Ar = Ph)
95% (R = Br, Ar = 3-Br-C_6H_4)
95% (R = H, Ar = 4-Me-C_6H_4)
92% (R = I, Ar = 4-Me-C_6H_4)
67% (R = H, Ar = 4-MeO-C_6H_4)
96% (R = Me, Ar = 4-MeO$_2$C-C_6H_4)

Angew. Chem. Int. Ed. **2005**, *44*, **4026.**

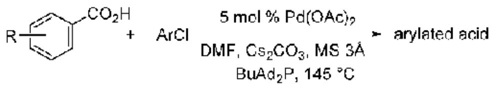
Continuing Activation of Unactivated C-H bonds

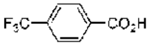
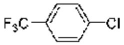
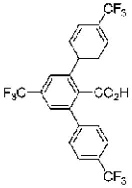
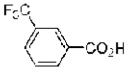
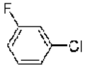
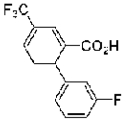
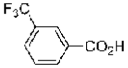
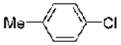
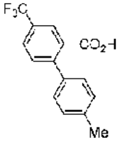
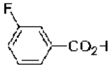
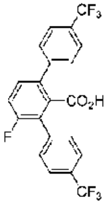
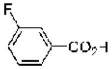
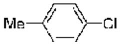
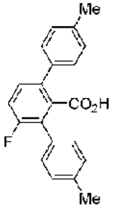
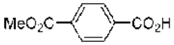
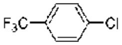
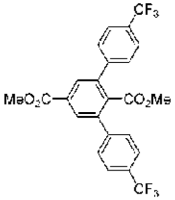
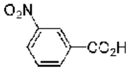
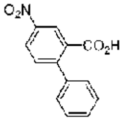
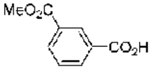
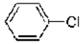
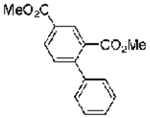
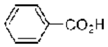
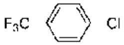
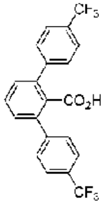
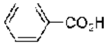
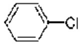
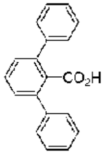
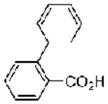
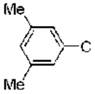
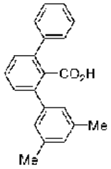
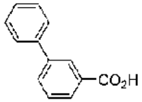
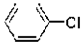
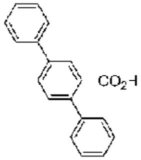
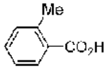
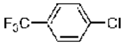
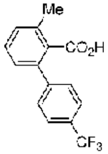
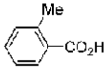
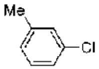
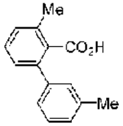
- Daugulis group has even achieved catalytic coupling of unactivated C-H bonds
    - Pyridine as directing group:
    - Analines
    - Benzoic Acids



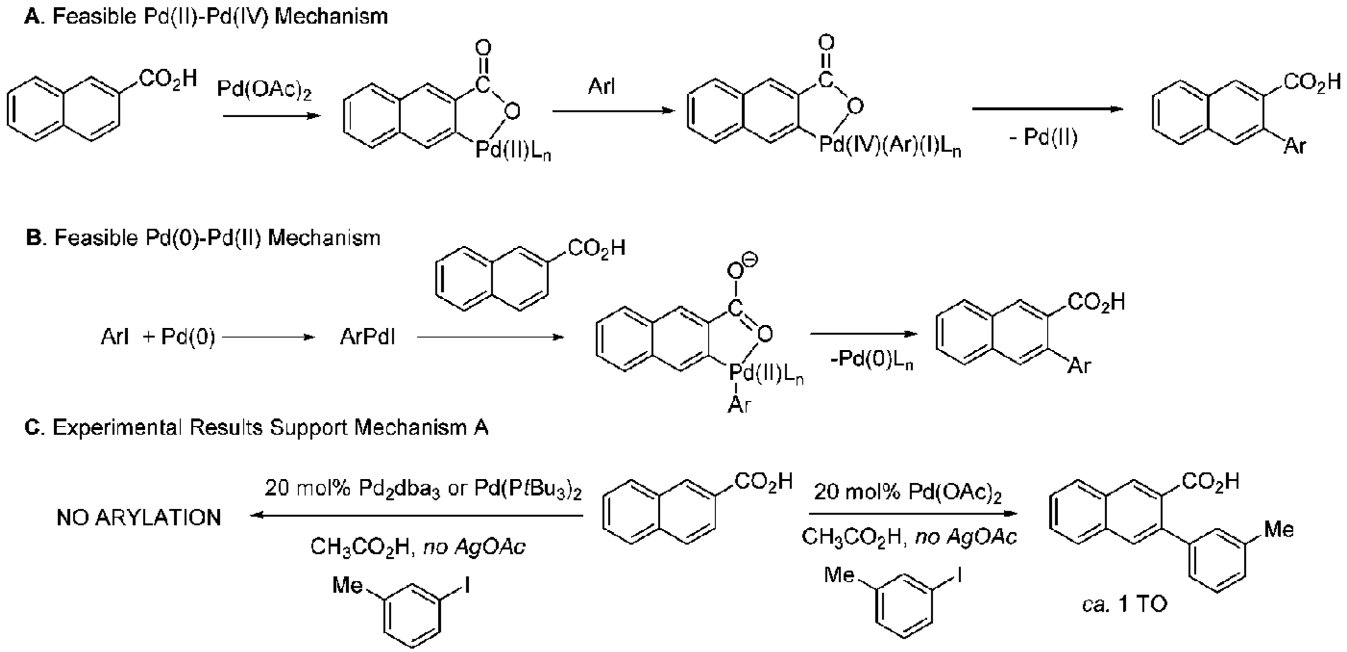
72% (R^1 = 3-CF_3, R^2 = 3-F)
83% (R^1 = 3-CF_3, R^2 = 4-Me)
91% (R^1 = 2-Me, R^2 = 3-Me)
65% (R^1 = 3-NO_2, R^2 = H)
71% (R^1 = 3-Ph, R^2 = H)
67% (R^1 = 2-Ph, R^2 = 3,5-Me_2)

JACS, **2007**, *129*, 9879.



Entry	Acid	Aryl Chloride	Arylated Acid	Yield
1				75%
2				72%
3				83%
4				91%
5				67%
6[b]				79%
7				65%
8[b]				75%
9				82%
10[c]				71%
11				67%
12				71%
13				72%
14				91%

Benzoic Acid Arylation Significance



- Reactivity promotes Pd(IV) Intermediate, but does not exclude sigma-bond metathesis.

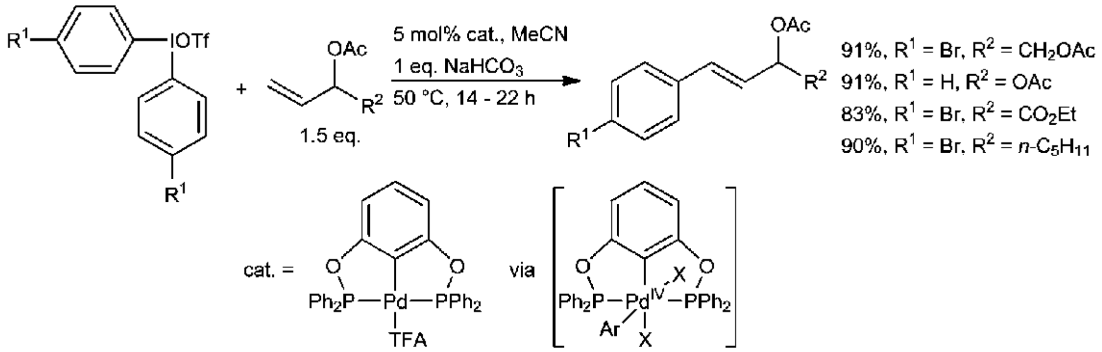
Daugulis *JACS*, **2007**, *129*, 9879.

Pd(IV) in Heck Reactions

- Pd(IV) intermediates in Heck reactions are rare and controversial, leading even to a retraction of a paper

- DFT studies showed Pd(0)/Pd(II) and Pd(II)/Pd(IV) cycles have similar energy levels
    - Pd(II)/Pd(IV) requires weak ligands
    - Pd(IV)-H intermediate is without precedence

- Most catalysts involve PCP ligands

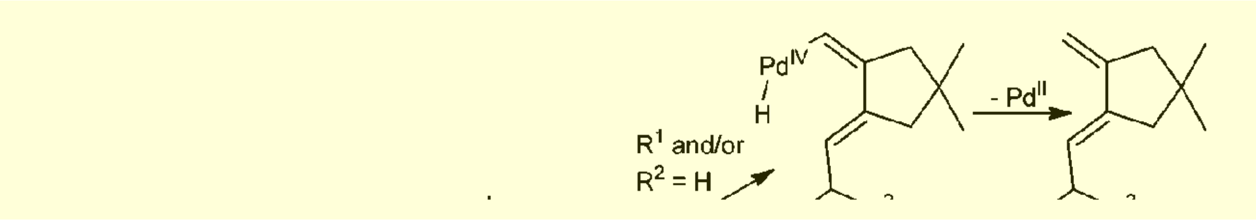


- Mild conditions and DFT modeling promote Pd(IV)!

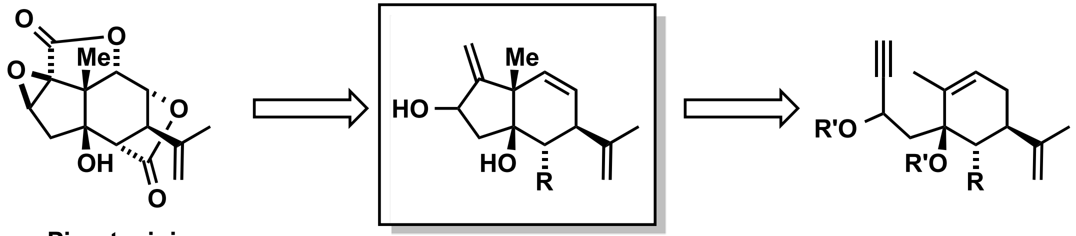
Martin, JML. *Chem.-Eur. J.* **2001**, *7*, 1703.
Szabo, KJ. *Org. Lett.* **2009**, *11*, 2852.

Isomerization Reactions

- First example: Trost and Lautens
  - High Yields, moderate conditions
  - $Pd(PPh_3)_4$ was inactive
  - Lewis acidic Pd(II) complexes worked cleanly and tolerated excess ligands
    - Pd(IV) palladacycles proposed



- Applied methodology to the synthesis of picrotoxane skeleton

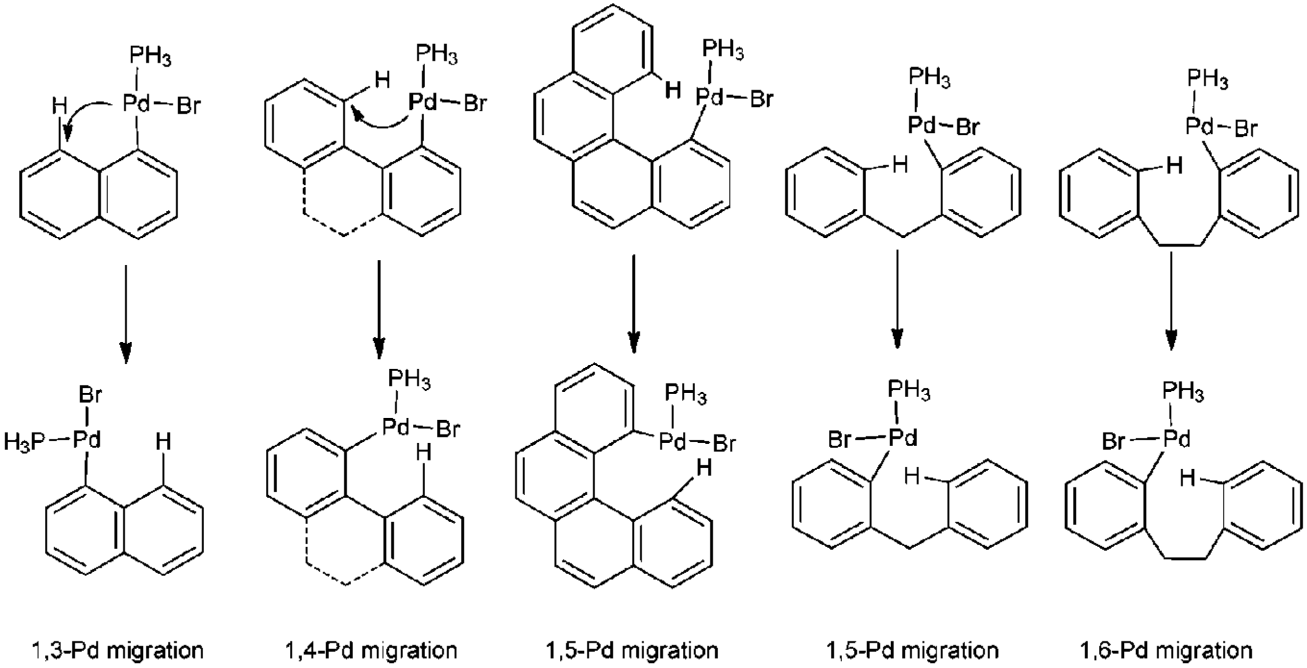


Picrotoxinin

Trost, Lautens. *JACS*, **1985**, *107*, 1781.

Pd(IV) Hydride

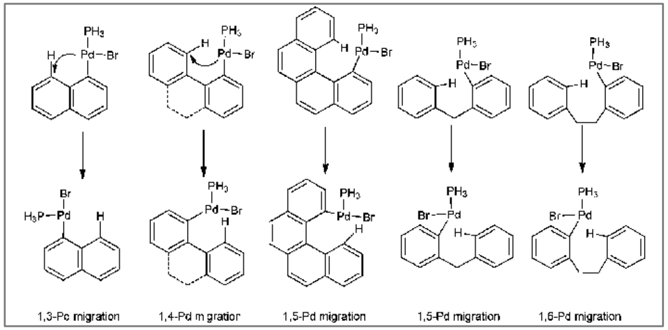
- No definitive evidence of a Pd(IV) hydride has been established.
- DFT study of intramolecular palladium migrations to verify possible Pd(IV) intermediate



Dedieu, A. *Organometallics*, **2006**, *25*, 3130.

Pd(IV) Hydride

- 1,3-Pd migration → *Sterically hindered* → High energy Pd^{IV} transition state, Direct transfer → **Pd^{IV} mechanism only**
- 1,4-Pd migration
  - *Geometrically constrained (i.e. phenanthrene)* → Pd^{IV} transition state, Direct transfer
  - *Geometrically unconstrained (i.e. biphenyl)* → Pd^{II} transition state, Direct transfer, Pd^{II} transition state, Direct transfer
  - → **Both Pd^{II} and Pd^{IV} mechanisms competing**
- 1,5-Pd migration
  - *Geometrically constrained (i.e.benzo[c]phenanthrene)* → Low energy Pd^{II} transition state, Direct Transfer, Absence of a Pd^{IV} mechanism
  - *Geometrically unconstrained (i.e. benzylbenzene)* → Low energy Pd^{II} transition state, Direct transfer, Pd^{IV} transition state, Two-step transfer
  - → **Pd^{II} favoured**
- 1,6-Pd migration → Low energy Pd^{II} transition state, Direct transfer; Pd^{IV} transition state, Two-step transfer → **Pd^{II} favoured**

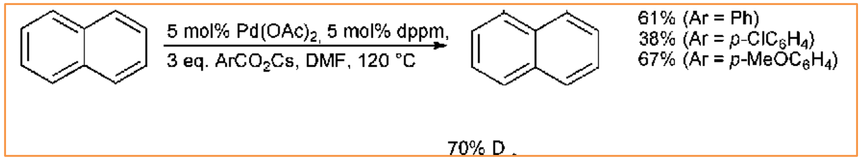


- Study extended later to aryl/alkyl processes
- Pd(IV) intermediate via O.A. then R.E or through Pd(IV) transition state is Possible!

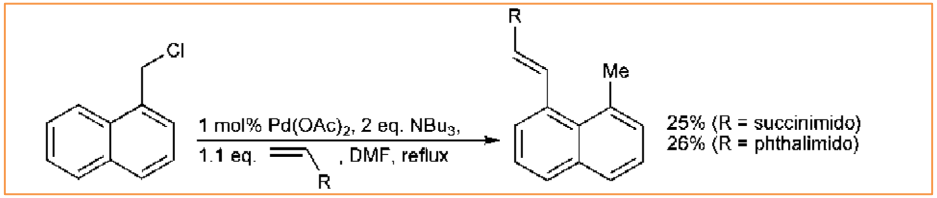
Dedieu, A. *Organometallics*, **2006**, *25*, 3130.

Pd(IV) Hydride Shift Applications

- Forward and Reverse hydride shifts



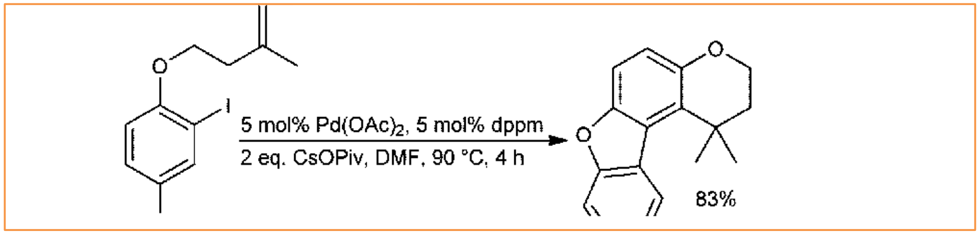
Larock, RC. *Tetrahedron* **2008**, *64*, 6090.



Hu, HW. *Tet. Lett.* **2000**, *41*, 725.

- Hydride shifts Intra- and Intermolecularly

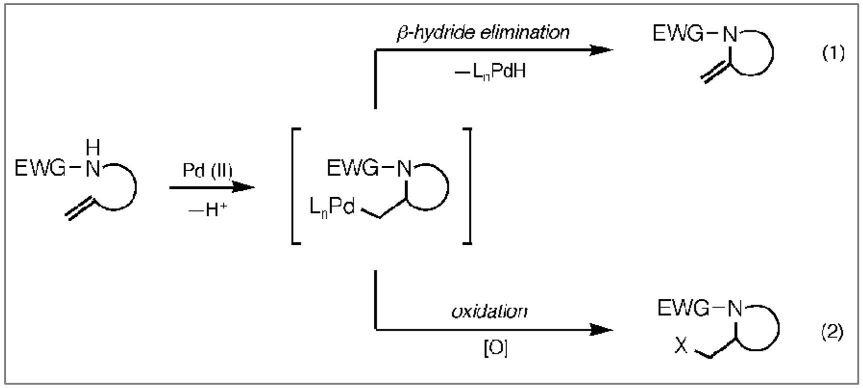
Larock. *JACS.* **2004**, *126*, 7460.



Larock. *Org. Lett.* **2005**, *7*, 701.

Oxidative Difunctionalization of Alkenes

- Combines alkene amination with Pd(II)/Pd(IV) cycle



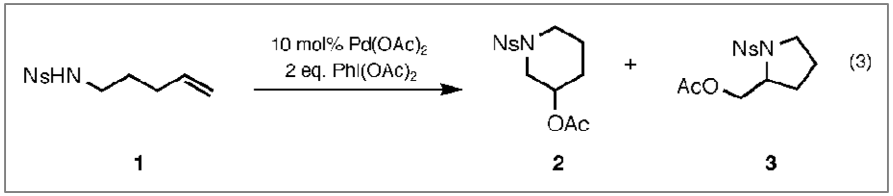
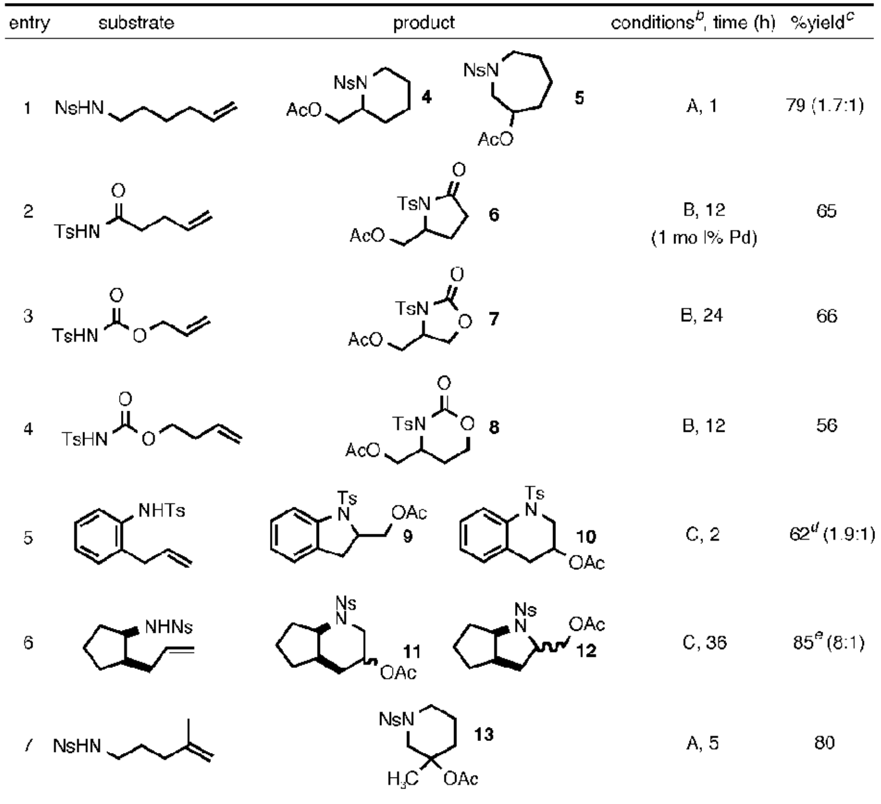


Table 1. Palladium(II)-Catalyzed Aminoacetoxylation of Alkenes[a]



entry	substrate	product	conditions[b], time (h)	%yield[c]
1	NsHN	**4**, **5**	A, 1	79 (1.7:1)
2	TsHN	**6**	B, 12 (1 mol% Pd)	65
3	TsHN	**7**	B, 24	66
4	TsHN	**8**	B, 12	56
5	NHTs	**9**, **10**	C, 2	62[d] (1.9:1)
6	NHNs	**11**, **12**	C, 36	85[e] (8:1)
7	NsHN	**13**	A, 5	80

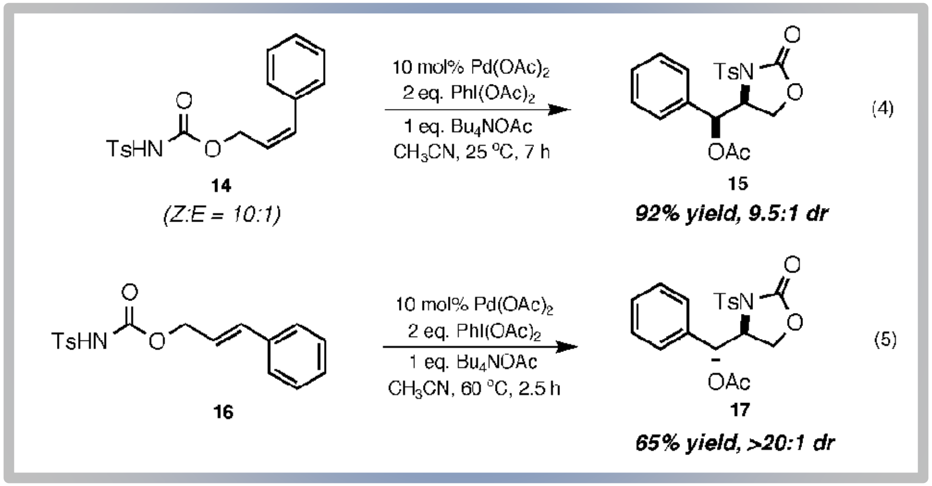
---

[a] All reactions run with 1 equiv of substrate (0.2 M) and 2 equiv of $PhI(OAc)_2$ at 25 °C. All regio- and diastereoselectivities calculated by ^1H NMR. [b] Condition A: 10 mol % $Pd(OAc)_2$, 1 equiv of Bu_4NOAc, CH_2Cl_2. Condition B: 5 mol % $PdCl_2(PhCN)_2$, CH_2Cl_2. Condition C: 10 mol % $Pd(OAc)_2$, 1:1 $AcOH/Ac_2O$. [c] Isolated yields. [d] 1 equiv of $PhI(OAc)_2$ used. [e] Product **11** obtained as 2.3:1 (β: R) mixture of diastereomers.

Alexanian, EJ; Sorensen, *EJ. JACS.* **2005**, *127*, 7690

Oxidative Difunctionalization of Alkenes

- Mechanism Insight



14 *(Z:E = 10:1)*

15 ***92% yield, 9.5:1 dr***

16

17 ***65% yield, >20:1 dr***

- Pd(IV) evidence: Cu(OAc)$_2$, common oxidant for Pd(0)/Pd(II) catalysis was ineffective

Propose Mechanism

Alexanian, EJ; Sorensen, *EJ. JACS.* **2005**, *127*, 7690

Significant Issues

- Low stability of Pd(IV) results in poor selectivity

- Most catalyst loads require 10 mol% of Pd(II)
    - Need to increase TON
    - New catalyst strategies

- Requires expensive additives and oxidants (which normally are required in excess)

- Reducing Conditions leads to Pd(0)→Pd(II) cycles

- Selectively activating C-H/C-C bonds without directing groups

- Functional groups are well tolerated
- No enantioselective processes have been accomplished

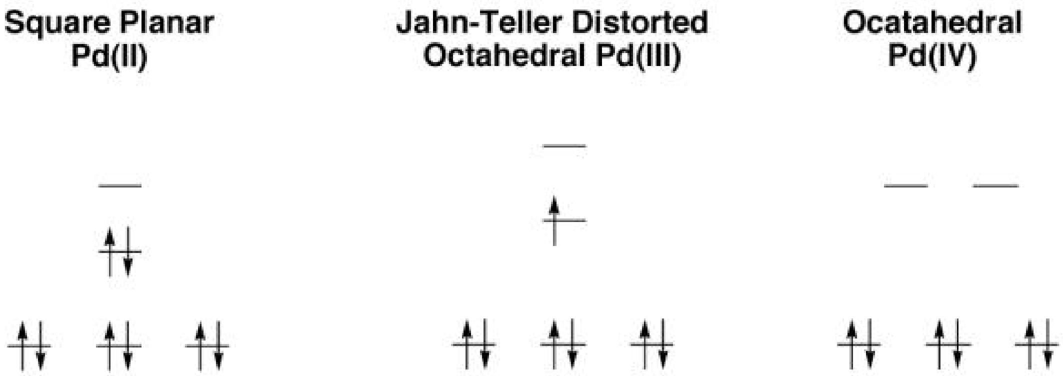
Overview

- Palladium(IV) Chemistry
  - Characteristics
  - Historical Background
  - Mechanism Aspects
  - Applications into Catalysis and Synthetic Efforts
  - Drawbacks and the Future

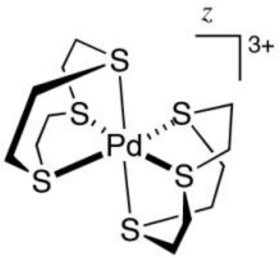
- Palladium(III) Chemistry
  - New Field
  - Isolation and Importance
  - Acceptance and Controversy
  - Outlook

Emergence of Palladium(III)

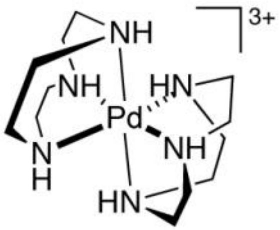
- One-electron oxidation of Pd(II) gives d^7 low spin Pd(III)



- Platinum(III) and Palladium(III) complexes are rarely proposed in catalysis
- Pd(III) & EPR: often the radical is hard to characterize as metal-centered or distributed through the ligands



1



2

Isolation and X-ray structures of mononuclear Pd(III) complexes

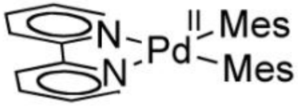
J Chem Soc, Chem Commun. **1987**, 987.
J Organomet Chem. **1987**, *323*, 261.
Can J Chem. **1999**, *77*, 1638.

Pd(III) in Oxidative C-H Coupling Reactions

- To the right, Pd(0)→Pd(II) oxidative coupling of aryl C-H bonds

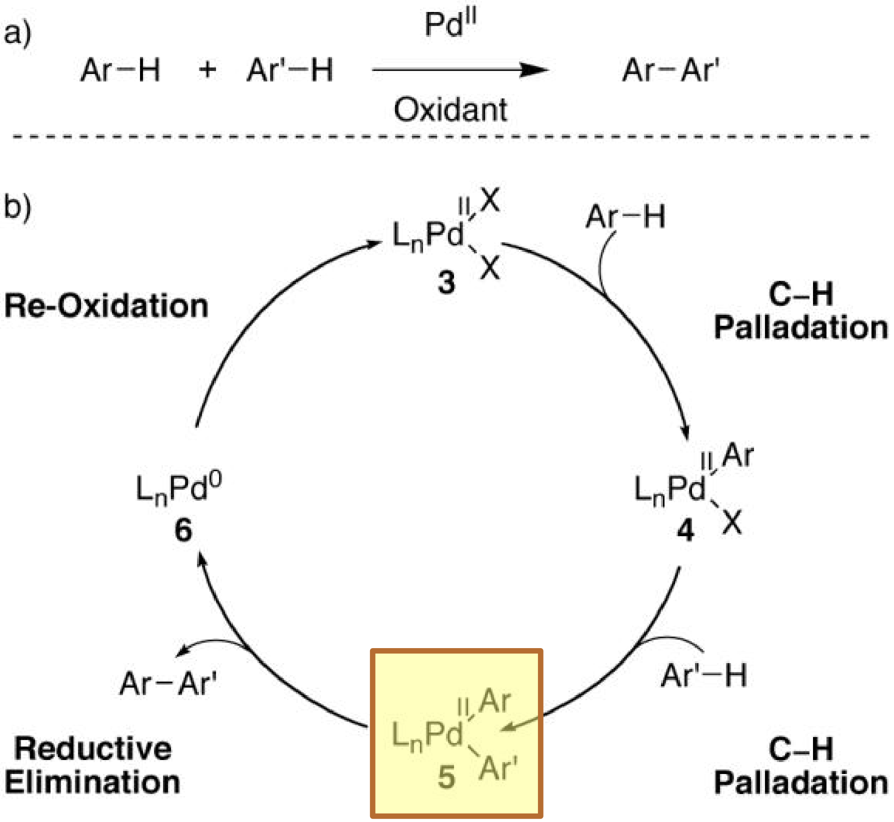
- Intermediate 5 is proposed to undergo reductive elimination

- **Under the oxidative conditions, could 5 be oxidized further prior to C-C bond formation?**

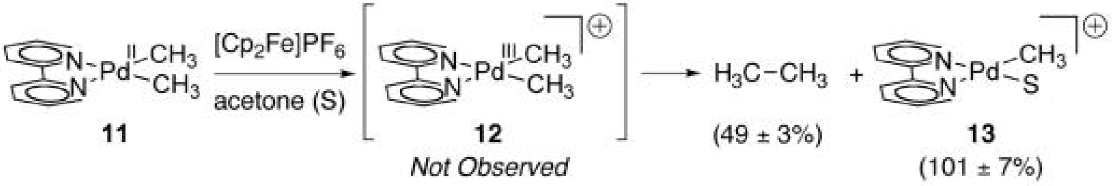


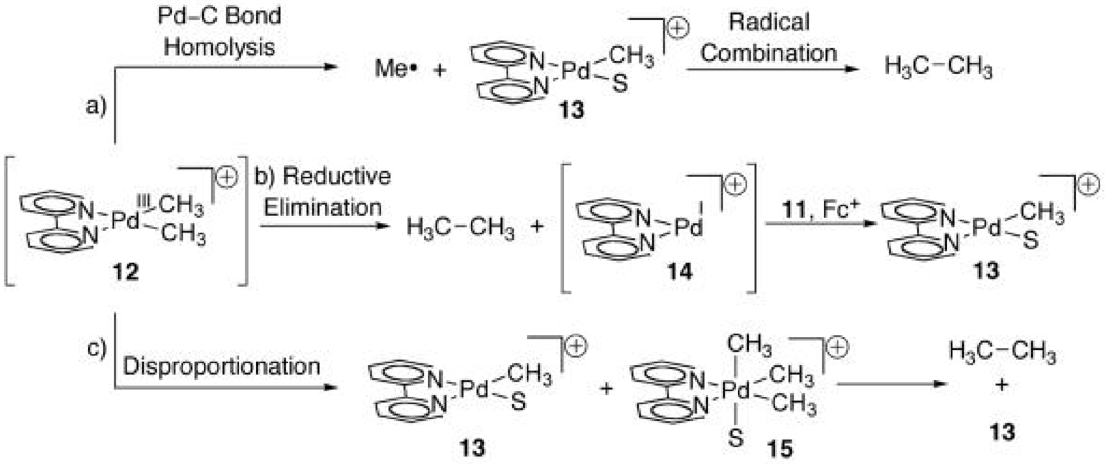
7

$E_{1/2} = 0.57$ V vs. Fc/Fc^+



How does Pd(III) function mechanistically?





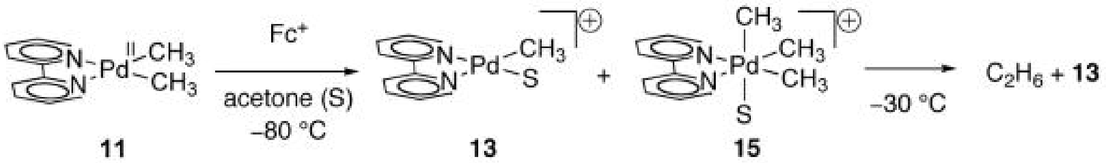
A) Radical traps had no effect

B vs C) Oxidation of Pd(II) carried out at -80°C

Saw Pd(II) and Pd(IV) form!

Sanford. *J Am Chem Soc*. **2009,** *131*, 15618.

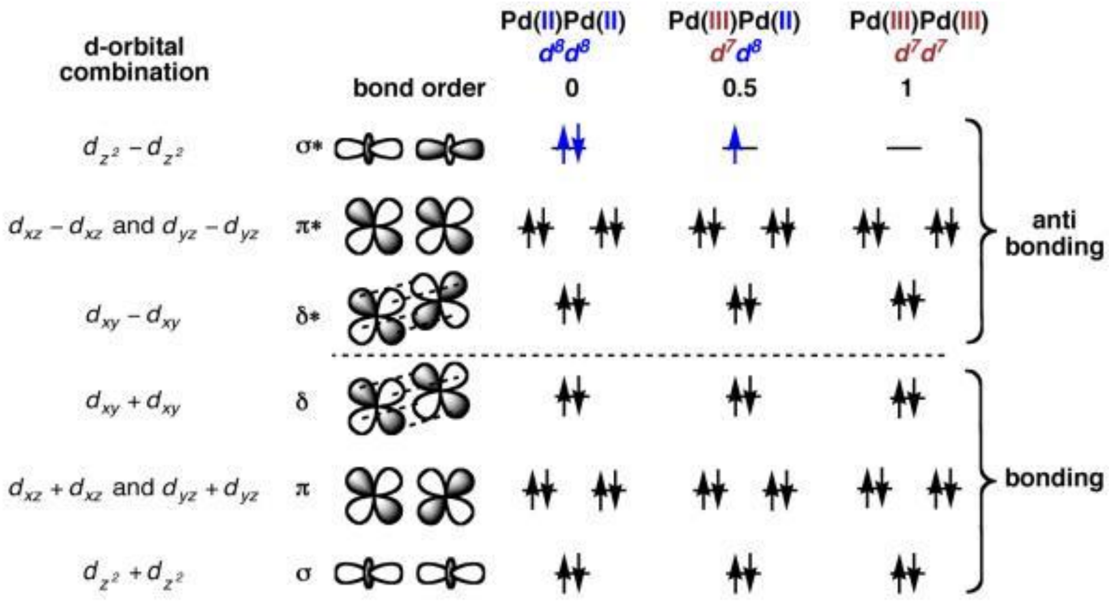
Mononuclear Pd(III) in Catalysis



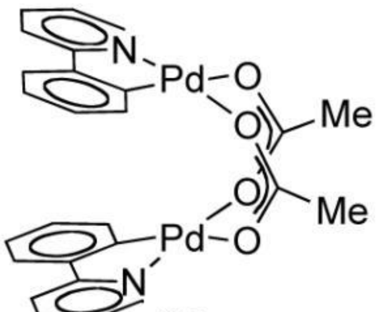
- Therefore in common Ag(I) oxidative palladium chemistry, the proposal is that:
  1) Ag(I) coordinates to Pd(II)
  2) Electron transfer produces Pd(III) and Ag mirror
  3) Disproportionation of Pd(III) to Pd(II) and Pd(IV)
  4) Reductive Elimination of Pd(IV) to Pd(II) forms product

Mechanism could be present also in Carbon-Heteroatom bond forming reactions and could explain rate accelerations of Kumada and Negishi coupling reactions

Dinuclear Palladium(III) Complexes



- Based on molecular orbitals, there should be no $[Pd(II)]_2$ dimers
- However DFT calculations showed a weak interaction with Pd(II) acetate dimers
- Complexes with Pd(III) should be feasible then



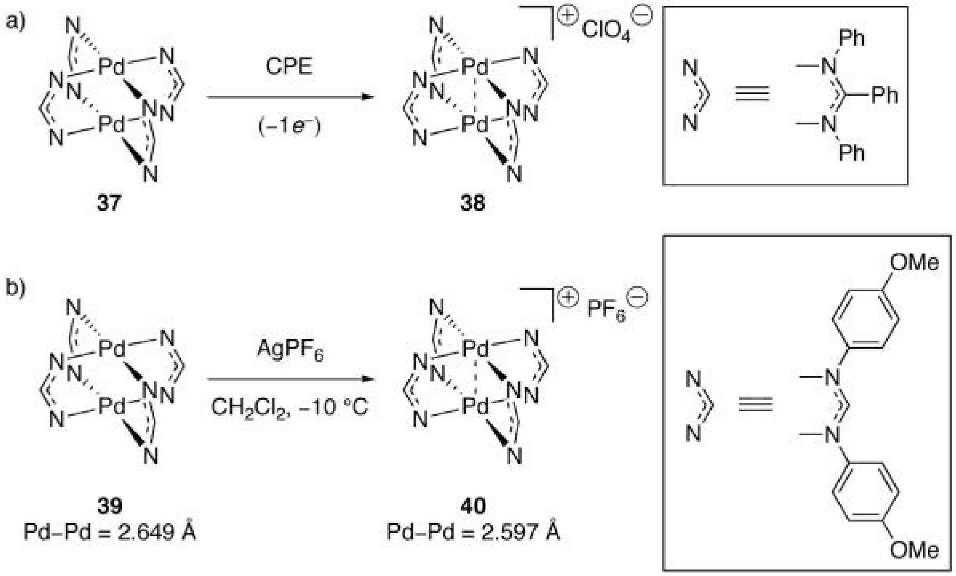
36

Computed Pd–Pd Bond Order: 0.11

Multiple Bonds Between Metal Atoms. Springer Science and Business Media, Inc.; New York: 2005.

Bercaw JE, Durrell AC, Gray HB, Green JC, Hazari N, Labinger JA, Winkler JR. *Inorg Chem*. **2010**, *49*, 1801.

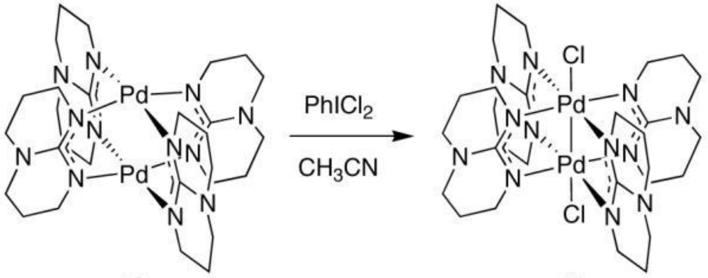
Pd(II)/Pd(III) and P(III)/Pd(III) Complexes



37 **38**

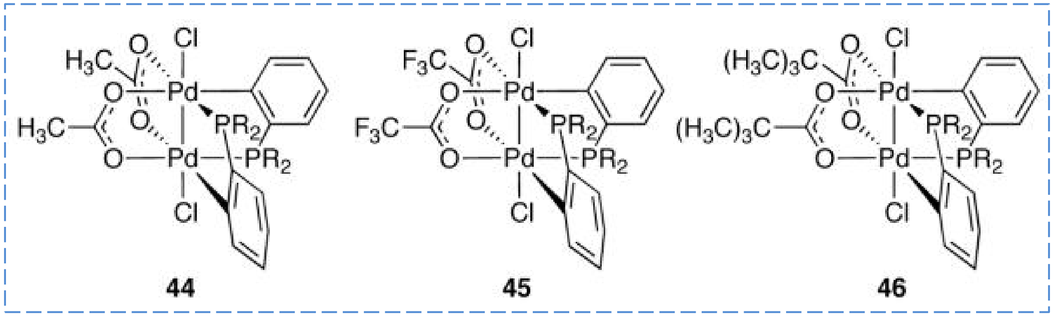
39
Pd–Pd = 2.649 Å

40
Pd–Pd = 2.597 Å



42
Pd–Pd = 2.55 Å

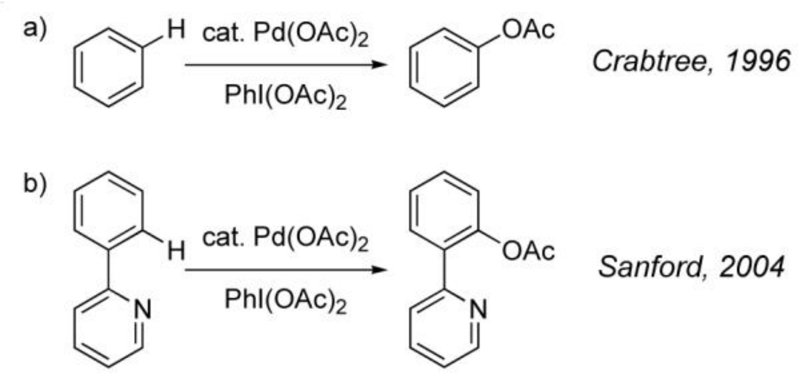
43
Pd–Pd = 2.39 Å



44 **45** **46**

Pd(III) Dimers in Catalysis

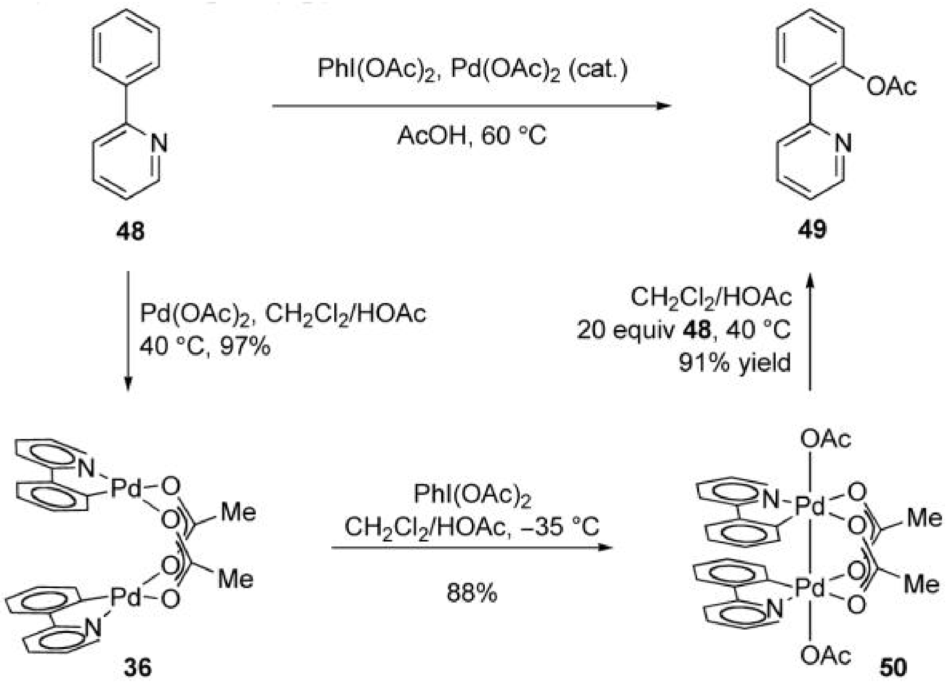
- Often proposed that Pd(III) dimers are precatalysts to lower-valent Pd species
- Pd-catalyzed aromatic C-H acetoxylations previously proposed Pd(IV) intermediates



Sanford MS. *J Am Chem Soc*. **2004**, *126*, 2300.
Ritter T. *J Am Chem Soc*. **2009**, *131*, 17050.

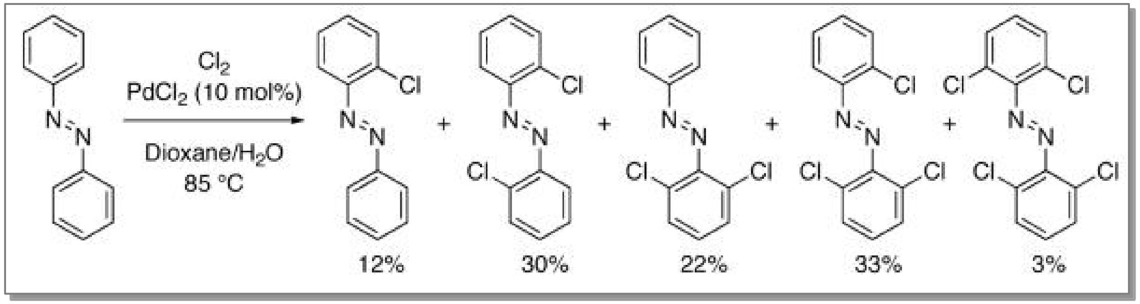
Pd(III) Dimers in Catalysis

- Often proposed that Pd(III) dimers are precatalysts to lower-valent Pd species
- Pd-catalyzed aromatic C-H acetoxylations previously proposed Pd(IV) intermediates
  - *Ritter proposes that Pd(III) dimers could be the intermediates*

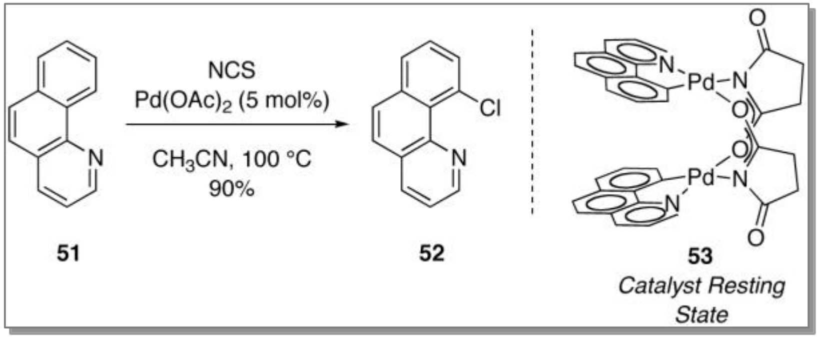


Sanford MS. *J Am Chem Soc*. **2004**, *126*, 2300.
Ritter T. *J Am Chem Soc*. **2009**, *131*, 17050.

Pd(III) Dimers in C-H Chlorinations



Fahey DR. *J Chem Soc D.* **1970,** 417.

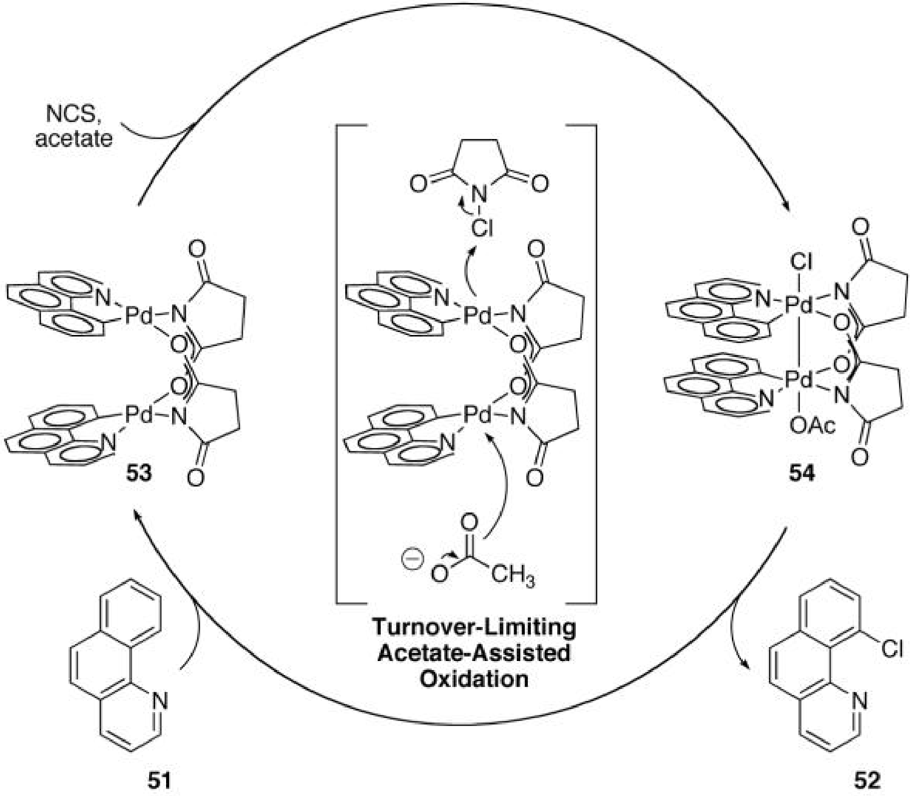


Sanford MS. *J Am Chem Soc*. *2004*, *126*, 2300.
J Am Chem Soc. **2007**, *129*, 15142.
Org Lett. **2006**, *8*, 2523.
Tetrahedron. **2006**, *62*, 11483.

Fahey DR. *J Chem Soc D.* **1970,** 417.

Ritter's Mechanism of $Pd(OAc)_2$ Chlorination

- Rate Law shows oxidation is turnover limiting step / first order in dinuclear catalyst
- Co-catalysis by acetate ions?



rate = k [**53**] [NCS] [AcO^-]

Ritter. *JACS*, **2010**, *132*, 14530.

Pd(III) in Review

- 1-electron oxidants certainly favor Pd(III) intermediates in catalysis

- Pd(III) complexes are established to undergo disproportionation to Pd(II) and Pd(IV) so they may only be short lived intermediates in synthesis
    - *Hard to utilize currently*

- Likewise Pd(III) dimers are isolated for X-ray crystallography, but no results disprove that they just undergo disproportionation like previous systems

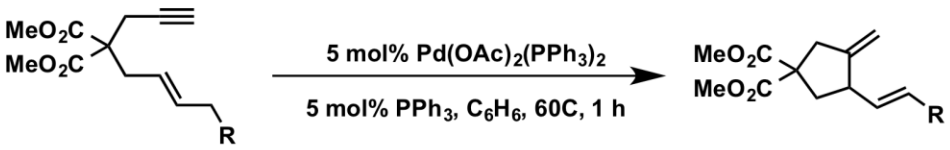
- Until the Pd(IV) intermediate can be ruled out of a mechanistic pathway, Pd(III) catalysis will always be challenged

- **Ritter’s work is a nice change of pace to challenge traditional thinking**

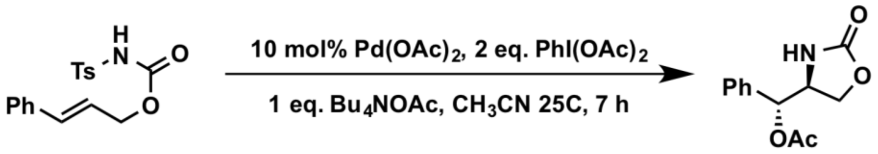
Questions?

Group Questions (MAJOR HINT – They use Pd(IV)!)

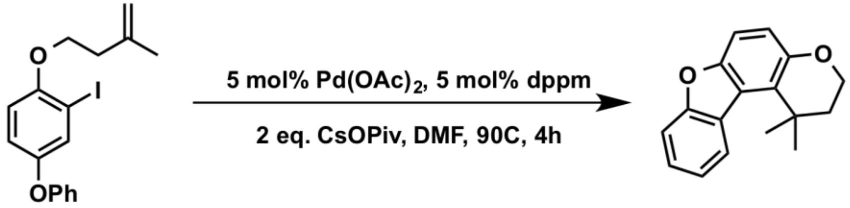
1. Predict the mechanism of the enyne carbocyclization.



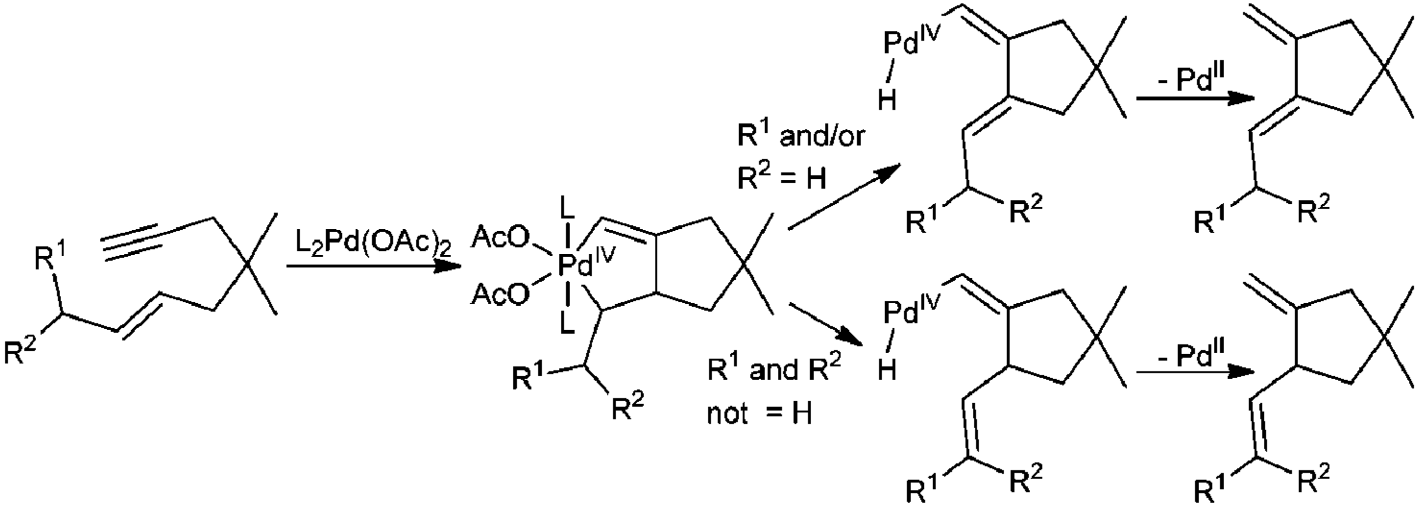
2. Propose a mechanism for the reaction below.



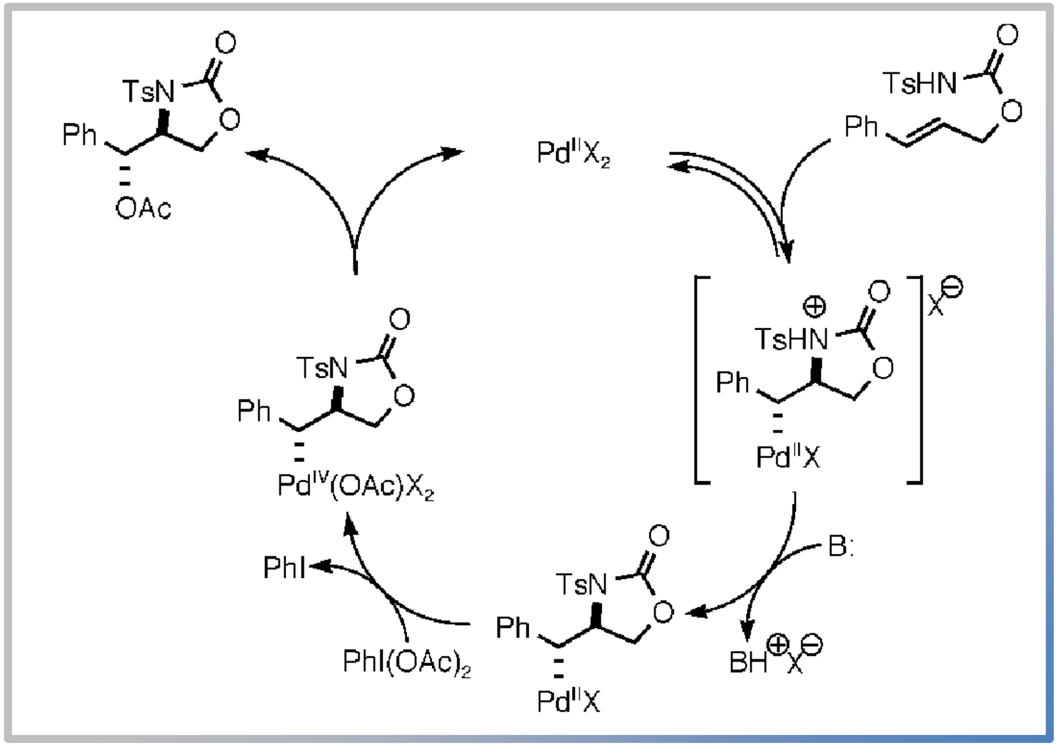
3. Propose a mechanism for the reaction below. (Hint: Pd^{IV}-H shift)



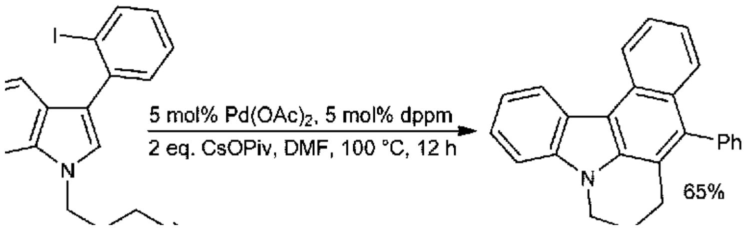
Question 1

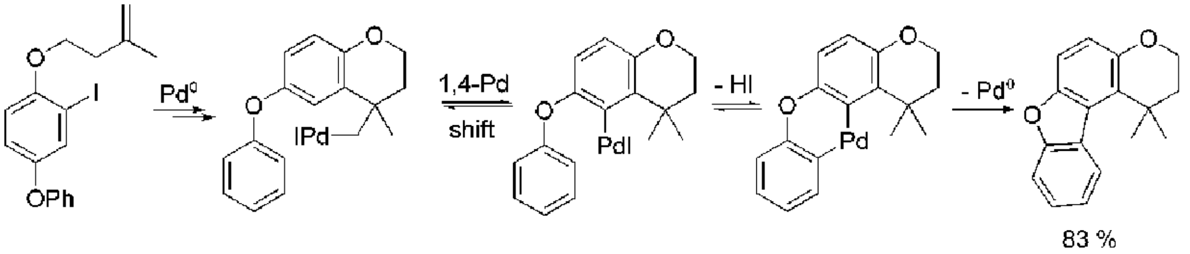

R1
R2
L2Pd(OAc)2
AcO
AcO
L
PdIV
L
R1
R2
R1 and/or
R2 = H
R1 and R2
not = H
PdIV
H
R1
R2
- PdII
R1
R2
PdIV
H
R1
R2
- PdII
R1
R2

Question 2


TsN
O
O
Ph
OAc
$Pd^{II}X_2$
TsHN
O
O
Ph
$\oplus$
TsHN
O
O
Ph
$Pd^{II}X$
$X^{\ominus}$
TsN
O
O
Ph
$Pd^{IV}(OAc)X_2$
PhI
$PhI(OAc)_2$
TsN
O
O
Ph
$Pd^{II}X$
B:
$BH^{\oplus}X^{\ominus}$

Question 3


I
N
5 mol% Pd(OAc)$_2$, 5 mol% dppm
2 eq. CsOPiv, DMF, 100 °C, 12 h
N
Ph
65%


O
I
OPh
Pd^0
O
IPd
O
1,4-Pd
shift
O
PdI
O
- HI
O
Pd
O
- Pd^0
O
O
83 %