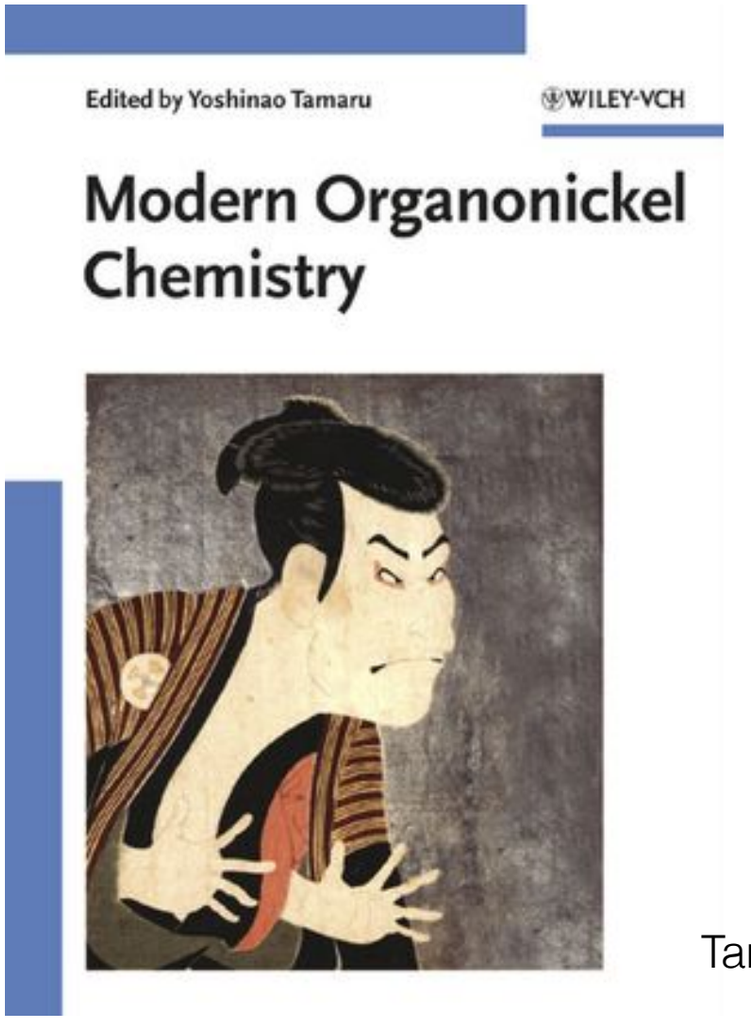
Development of Nickel Precatalysts in Modern Cross Coupling Chemistry (Part 1)

Sam Kasmali

Nickel in Pre-Cross Coupling Era



Kabuki actor dressed like the devil?

Tamaru, Y. *Modern Organonickel Chemistry*; Wiley-VCH, **2005**

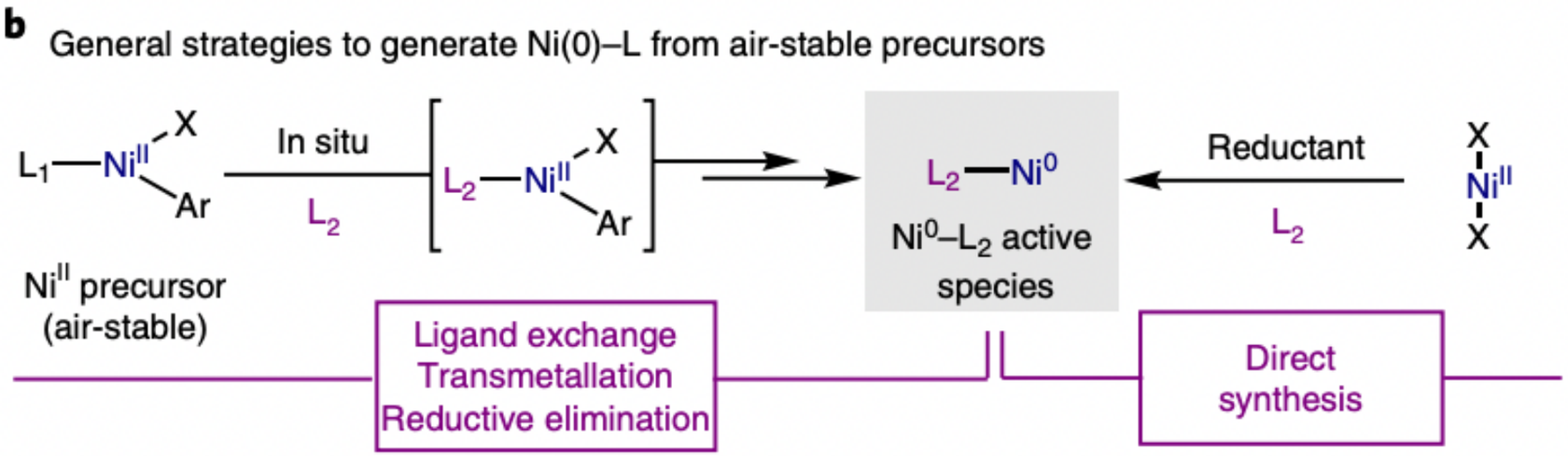
Nickel has wings (Mond, 1890)

$$\mathbf{Ni_{(s)}} + 4\,\mathbf{CO_{(g)}} \longrightarrow \mathbf{Ni(CO)_{4(l)}}$$

See also
Wilke *et al*. *ACIE* **1988**, *27*, 185–206
Nobel prize in chemistry in 1912

Scope

1



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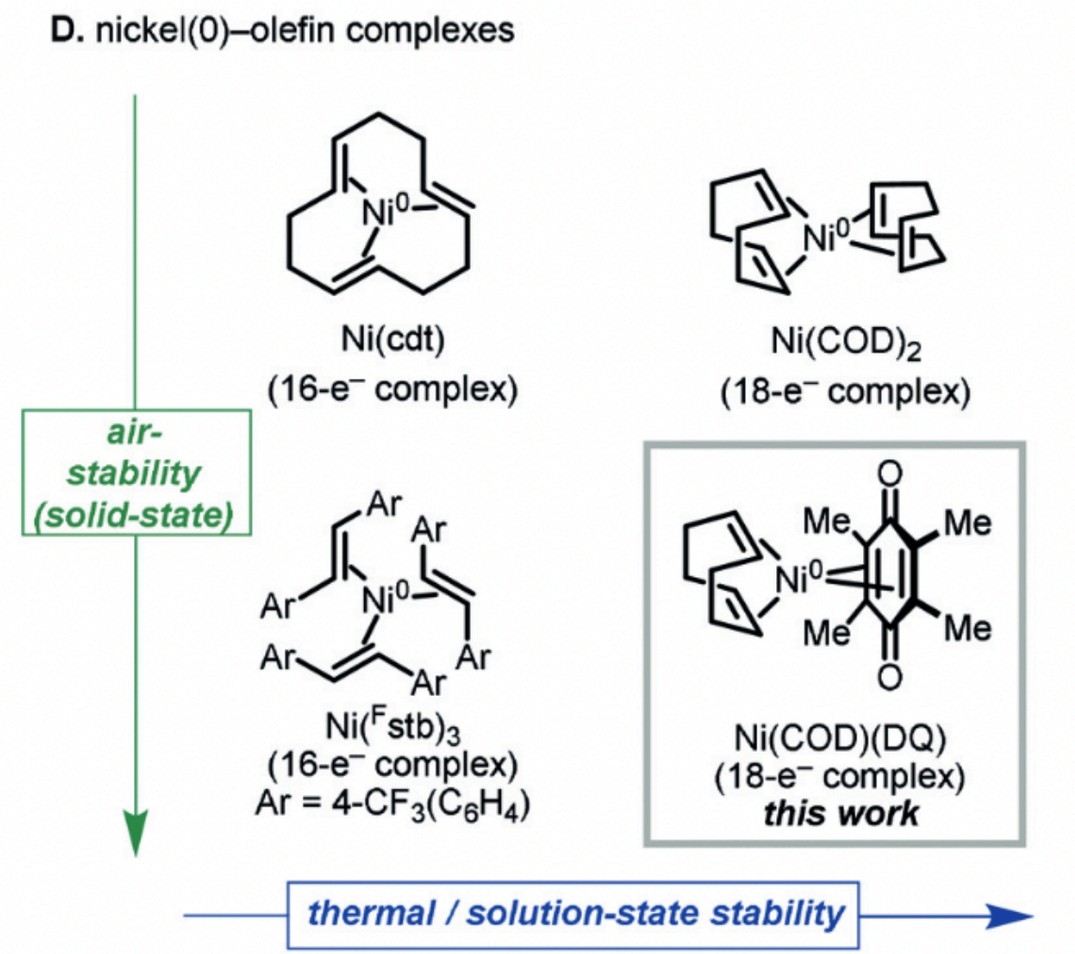

3

[Ni](alkyl)$_2$

Doyle 2015, (TMEDA)Ni(*o*-Tolyl)Cl

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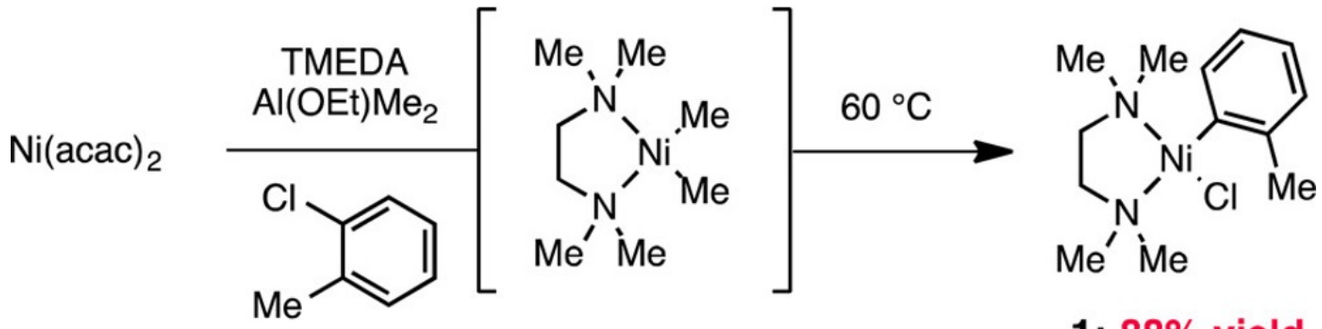


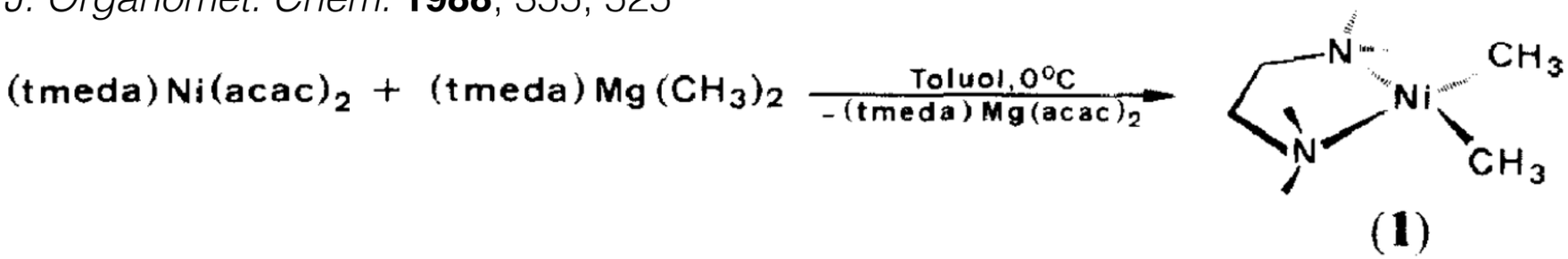
1: 88% yield
(gram scale)

- one-pot synthesis w/o purification
- commercial starting materials
- air-stable, crystalline solid

Doyle *et al*. *OL* **2015**, *17*, 2166–2169

Precedent

Wilke *et al*. *J. Organomet. Chem.* **1988**, 355, 525

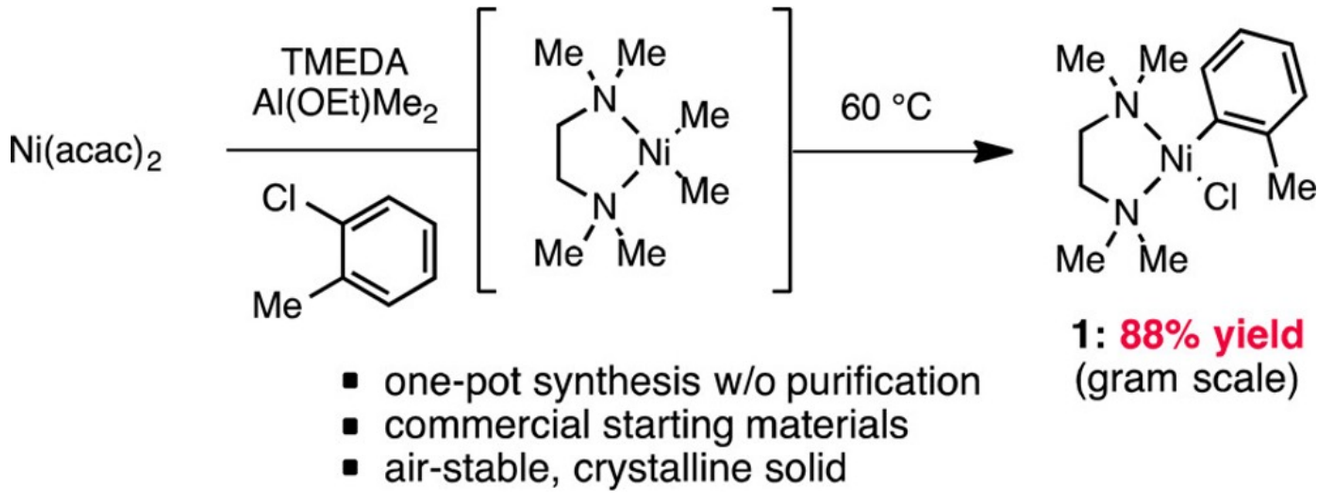


(1)

(1)

(tmeda)Ni(acac)$_2$ reacts with the main group metal compounds (tmeda)Mg-(CH$_3$)$_2$, (tmeda){Al(CH$_3$)$_3$}$_2$, and (C$_2$H$_5$O)Al(CH$_3$)$_2$ at 0 °C to give (tmeda)Ni-(CH$_3$)$_2$ (**1**), which can be isolated as fine yellow crystals in 50–80% yield. Complex **1**, which is the simplest dialkyl nickel(II) compound with a "hard" donor ligand, is surprisingly stable and decomposes only at 79 °C. **1** is converted by bipy to (bipy)Ni(CH$_3$)$_2$ and by Me$_2$PC$_2$H$_4$PMe$_2$ to (Me$_2$PC$_2$H$_4$PMe$_2$)Ni(CH$_3$)$_2$. Upon reaction of **1** with strong π-acceptor molecules (acrylic acid methylester, methyl vinyl ketone, acrylonitrile, tetracyanoethene, tetrafluoroethene, maleic anhydride) reductive elimination of the methyl groups takes place to give the complexes (tmeda)Ni(π-ligand)$_n$ (n = 1, 2) and ethane.

Doyle 2015, (TMEDA)Ni(*o*-Tolyl)Cl



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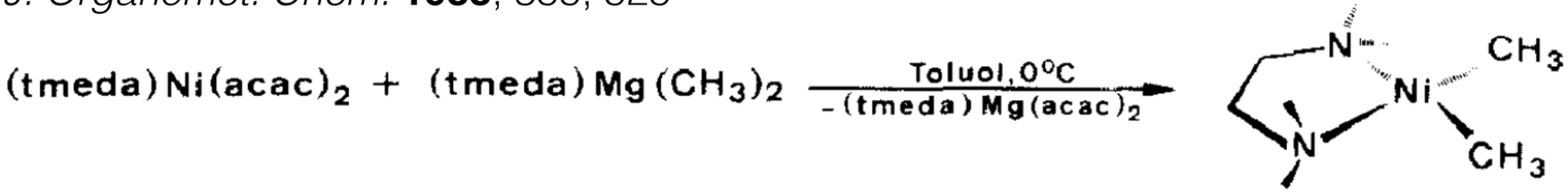
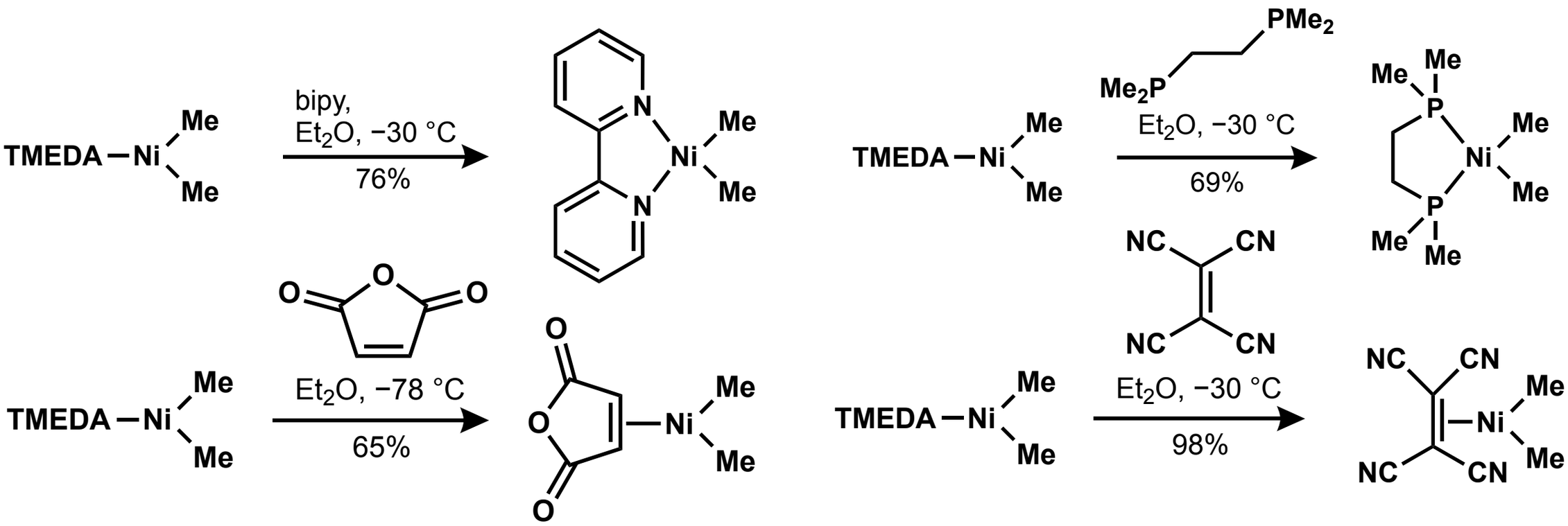
Wilke *et al*. *J. Organomet. Chem.* **1988**, 355, 525





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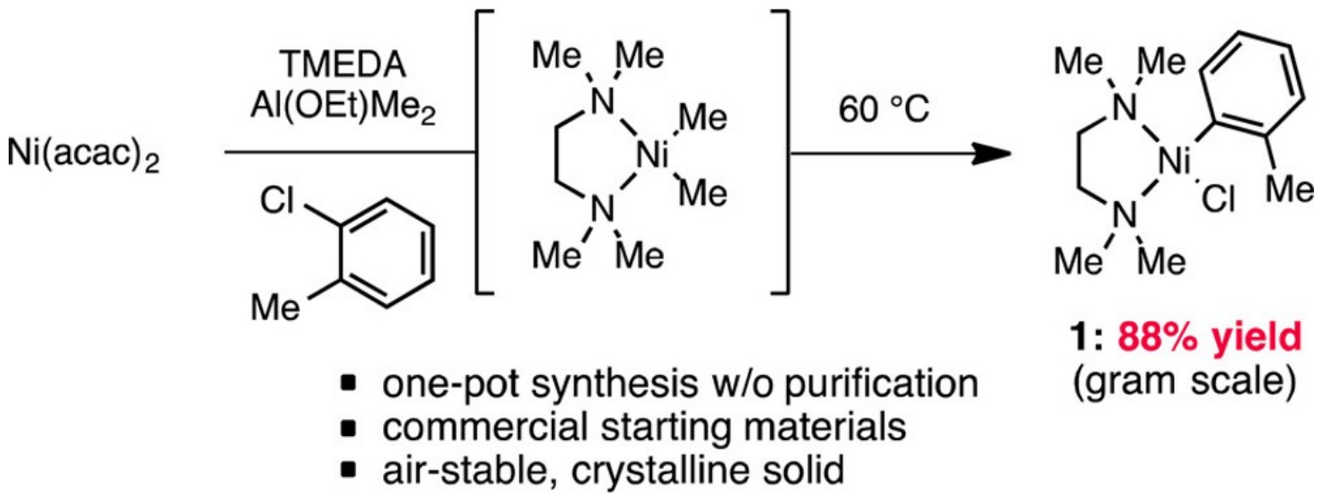

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Doyle *et al*. *OL* **2015**, *17*, 2166–2169

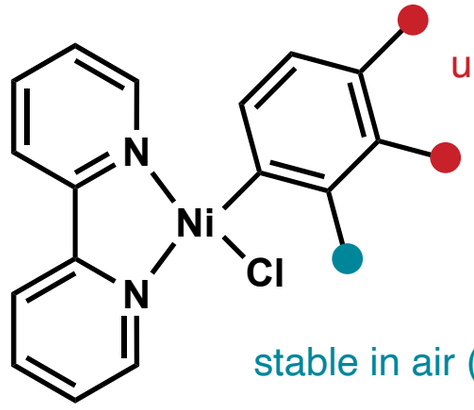
Precedent

Yamamoto *et al*. *J. Organomet. Chem.* **1975**, 84, 93

(2) Tolyl(dipyridyl)nickel chloride (V, o-tolyl-; VI, m-tolyl-; VII, p-tolyl-)

The green solution of I in chlorotoluenes such as *o*-chlorotoluene, *m*-chlorotoluene and *p*-chlorotoluene changes at 40-50° to red with sudden evolution of n-butane. The complexes can be precipitated from the red solution by addition of n-hexane. The *o*-tolyl complex V can be recrystallized either from acetone or from chlorobenzene. The *m*- and *p*-tolyl complexes VI and VII can be recrystallized from chlorobenzene and were isolated as orange-red crystals containing the solvent of crystallization (*m*-tolyl(dip)NiCl(C_6H_5Cl)$_n$ (VIII) and *p*-tolyl(dip)-NiCl($\frac{1}{2}C_6H_5Cl$) (IX)). The amounts of chlorobenzene in VIII varied, depending on drying conditions.

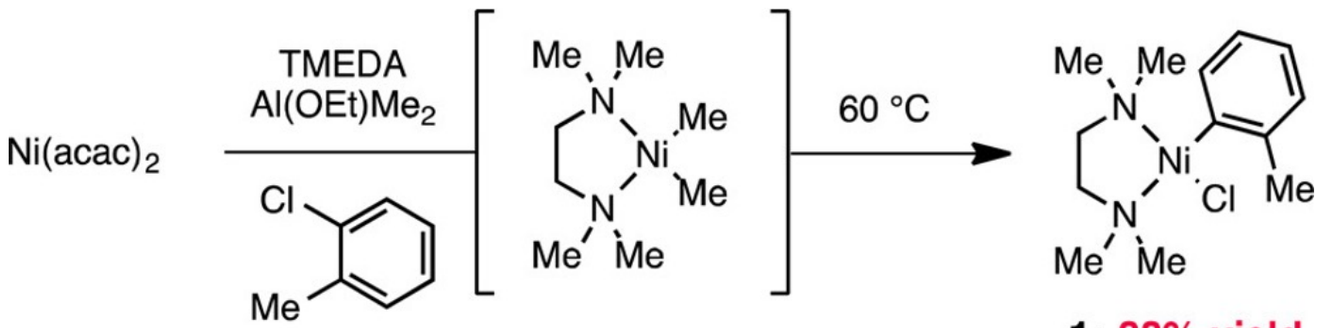
The complexes V and VIII are stable under air and no color changes under air were observed even after 24 h. Complex IX, in contrast to V and VIII, was found to be air sensitive like complex II and it decomposed to a yellow-white powder in a few hours.



unstable in air

stable in air (24 h)

Doyle 2015, (TMEDA)Ni(*o*-Tolyl)Cl



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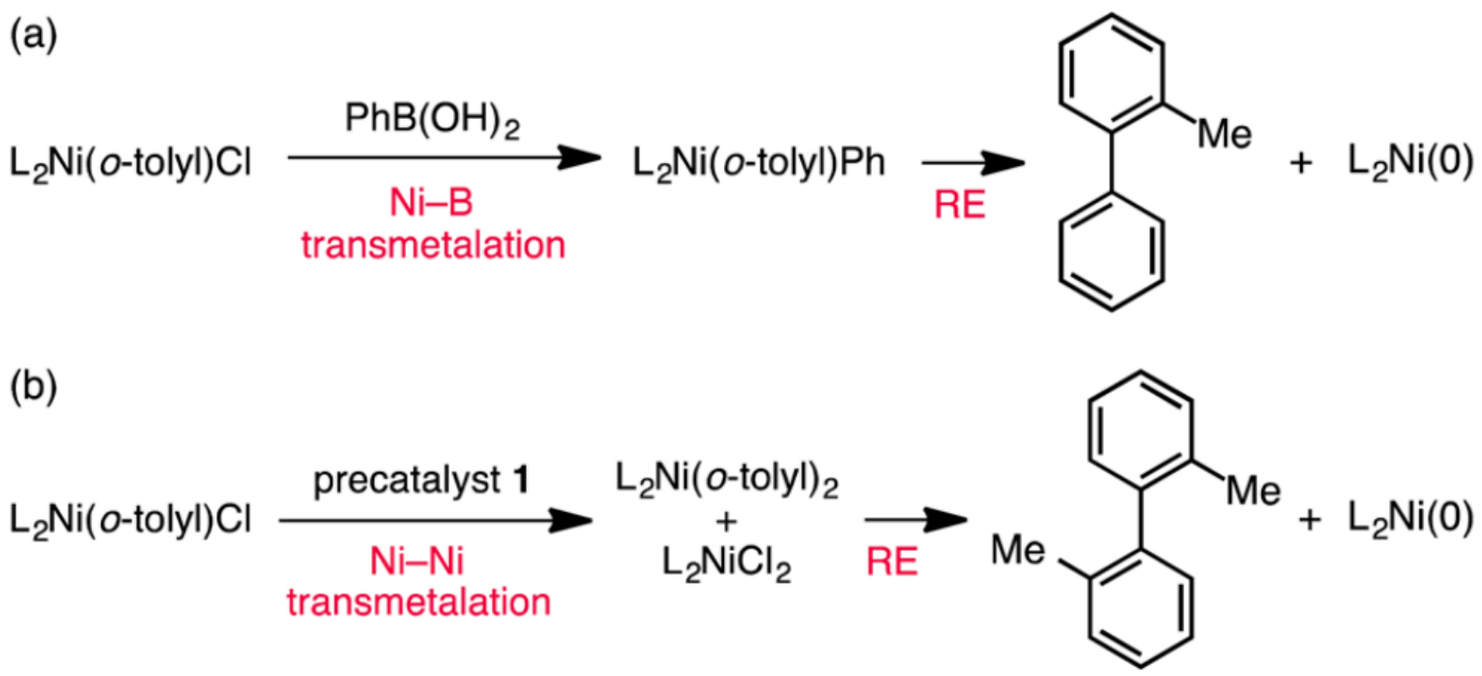
Doyle *et al*. *OL* **2015**, *17*, 2166–2169

Activation



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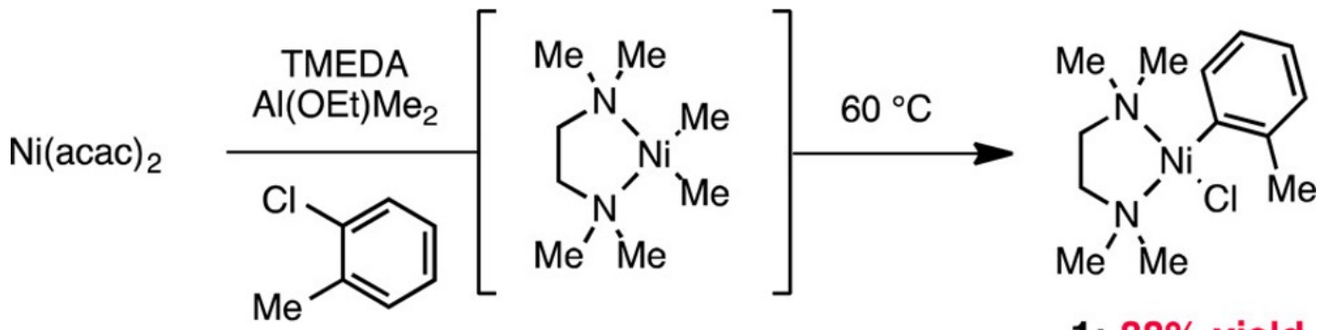

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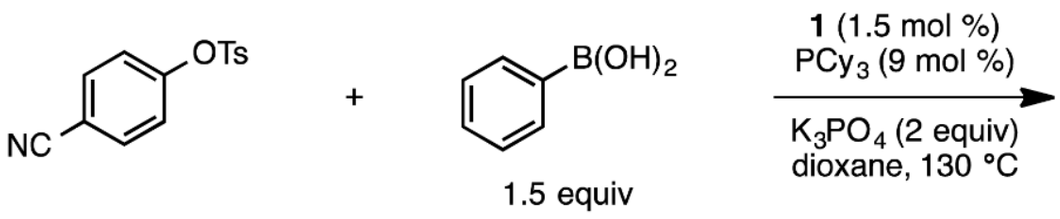
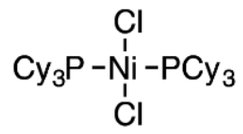
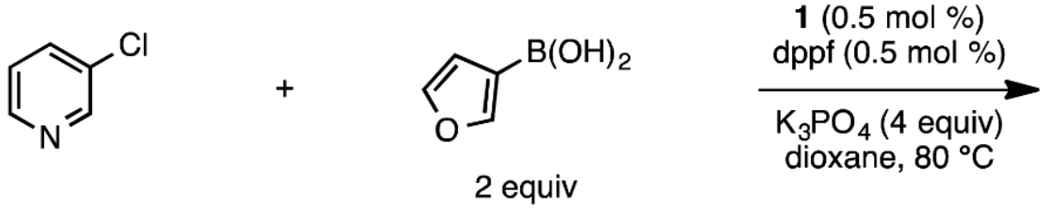
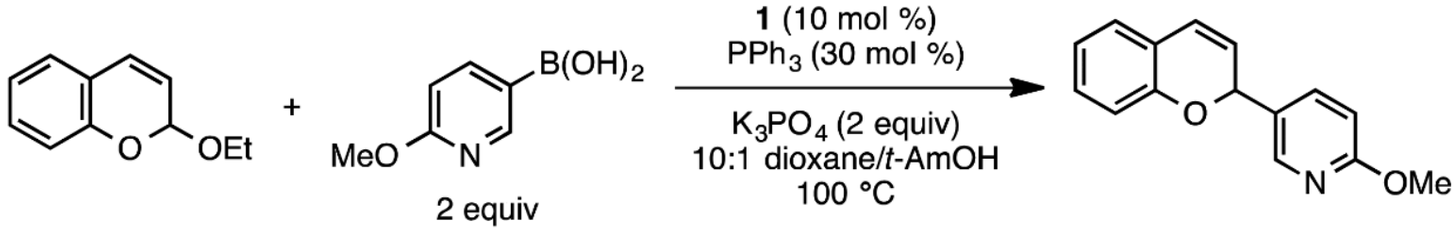
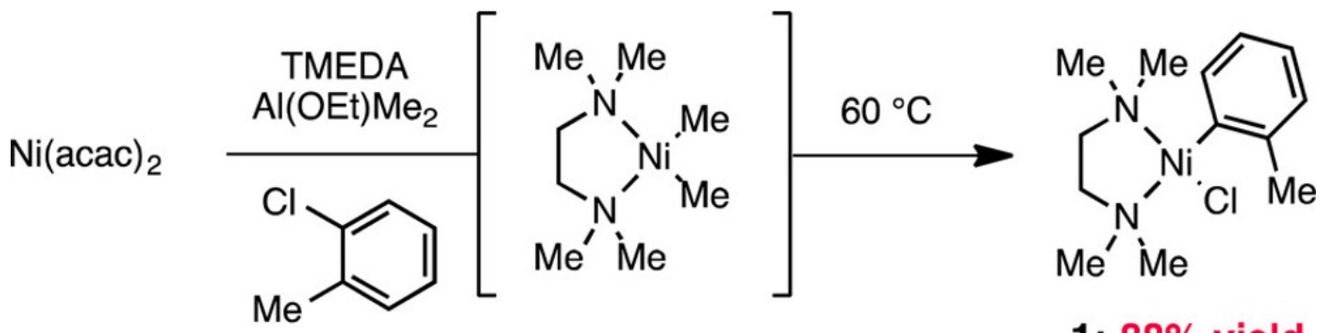
Doyle *et al*. *OL* **2015**, *17*, 2166–2169

Examples

reaction[a]	yield w/ precatalyst 1	literature precatalyst (literature yield)
	**98% yield** **(87% yield)**[b]	 (96% yield) *ref 14a*
	**96% yield**	[(dppf)Ni(cinnamyl)Cl] (91% yield) *ref 9*
	**43% yield**	Ni(cod)2 PPh3 (68% yield) *ref 20*

Doyle 2015, (TMEDA)Ni(*o*-Tolyl)Cl



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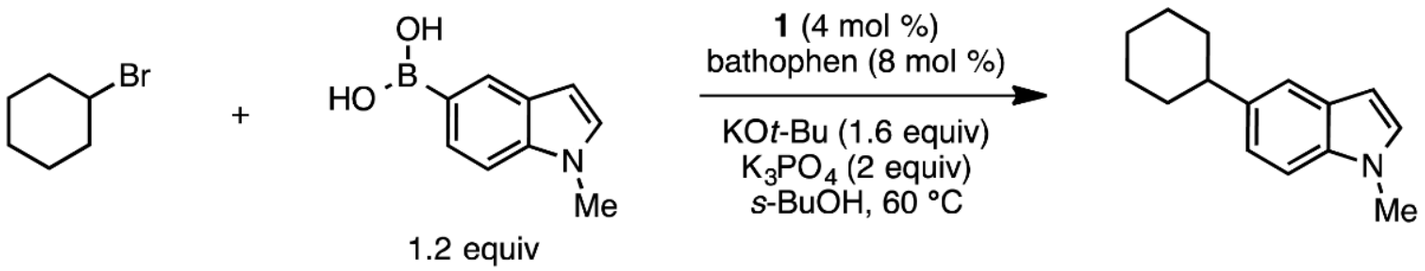
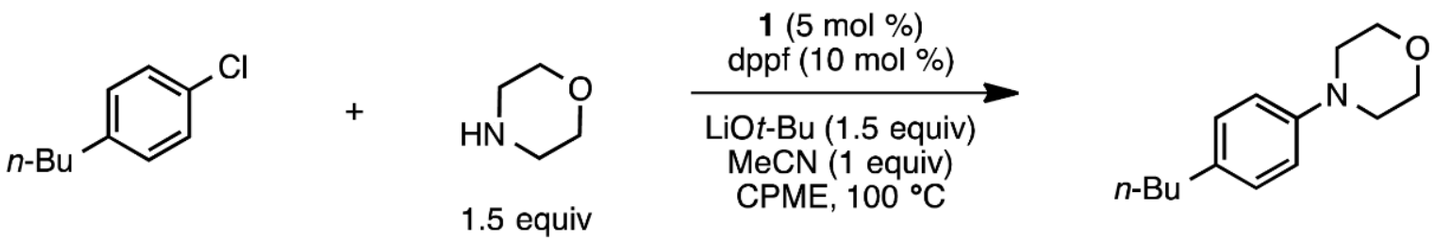
	**80% yield**	$Ni(cod)_2$ bathophen (67% yield) *ref 22*
	**83% yield**	[(dppf)Ni(*o*-tolyl)Cl] (85% yield) *ref 11*

Yang 2007, $(Ph_3P)_2Ni(Ar)Cl$

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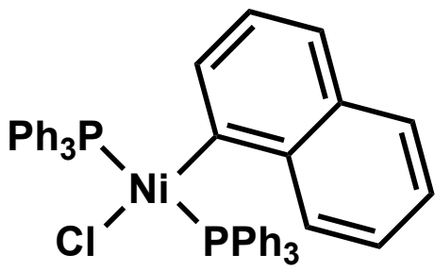
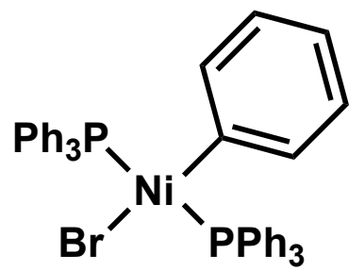


Suzuki-Miyaura

Yang *et al*. *Tetrahedron Lett.* **2007**, *48*, 2427



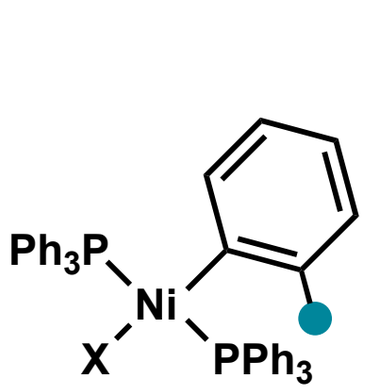
Amination

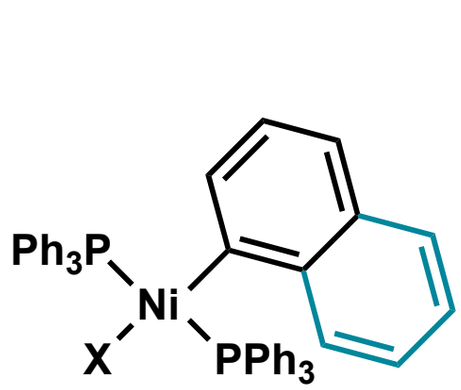
Yang *et al*. *JOC.* **2007**, *72*, 6324

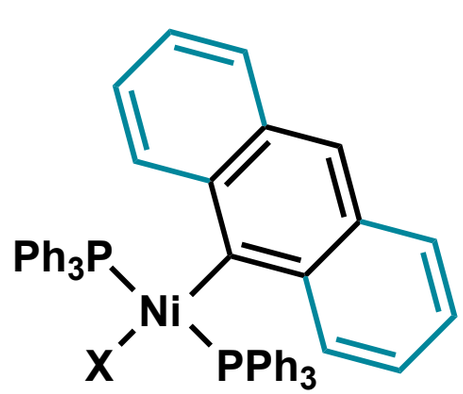
Precedent

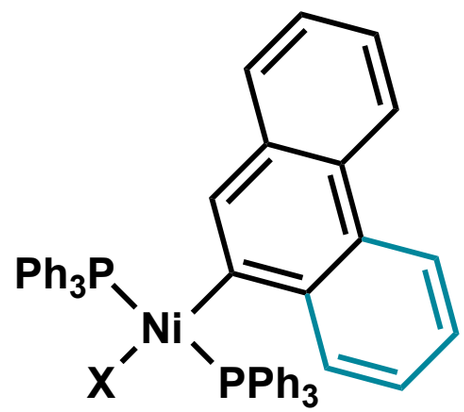
Shaw *et al. J. Chem. Soc.* **1960**, 1718-1729

to prepare derivatives of *meta*- and *para*-substituted phenyls and of 2-naphthyl gave similar products. However, *ortho*-substituted phenyls, 1-naphthyl, 9-phenanthryl, and 9-anthryl all form surprisingly stable compounds of the types *trans*-$[(PR_3)_2NiArX]$ and also, in some cases, *trans*-$[(PR_3)_2NiAr_2]$. These complexes were, with a few exceptions, stable in boiling ethyl alcohol and benzene solution and appear to be stable indefinitely in the solid state (some of them have remained unchanged after more than a year's storage in air at room temperature). The mesityl derivatives are particularly stable; for instance, the complex *trans*-[(PEt$_3$)$_2$Ni(mesityl)Cl] sublimes in air at 150°/1 atm. on a Kofler block

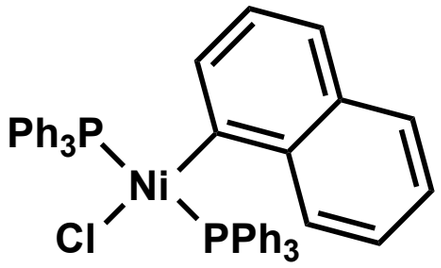






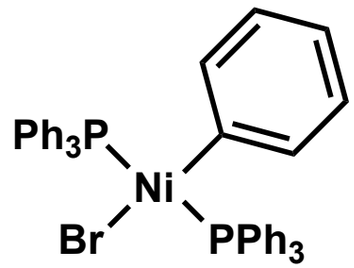


Yang 2007, $(Ph_3P)_2Ni(Ar)Cl$



Suzuki-Miyaura

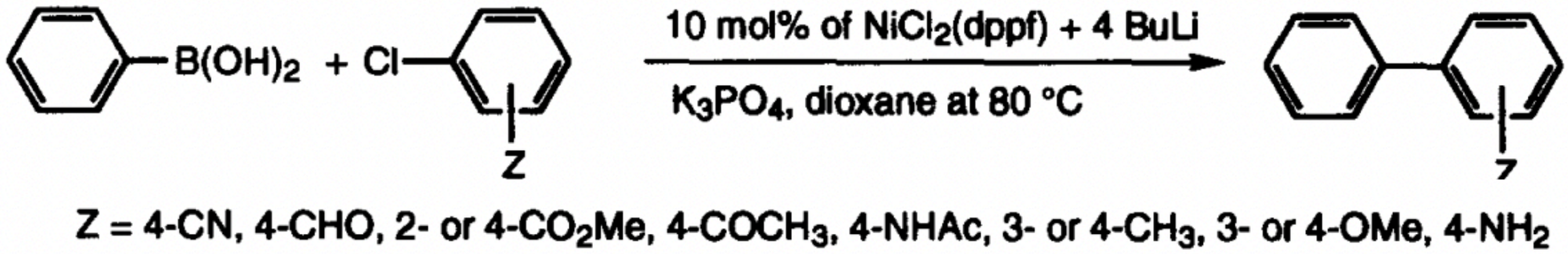
Yang *et al*. *Tetrahedron Lett.* **2007**, *48*, 2427



Amination

Yang *et al*. *JOC.* **2007**, *72*, 6324

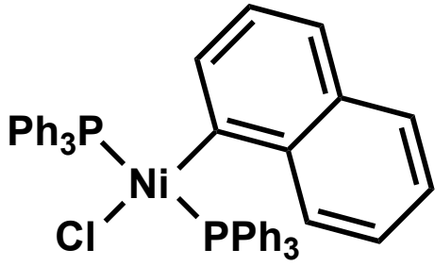
Prior art



Miyaura *et al*. *Tetrahedron Lett.* **1996**, *37*, 2993

reaction,[7f–i] Ni(0) species could be formed from the Ni(II) via the homocoupling of the organometals used. However, for the other processes not involving the organometals (e.g., typically in the Ni(II)-catalyzed arylamination), in situ generation of Ni-(0) species would be problematic. Therefore the treatment of Ni(II) precatalysts with external reductants has been an inevitable step. The reported modes included addition of zinc dust[7a,b] and pretreatment of butyllithium or the Grignard reagent[7c–e] and NaH.[8d–h] Also, the Ni(0)-on-charcoal from Ni(II) pretreated

Yang 2007, $(Ph_3P)_2Ni(Ar)Cl$



Suzuki-Miyaura

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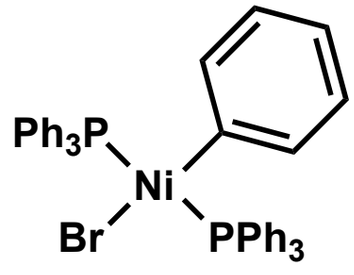

Amination

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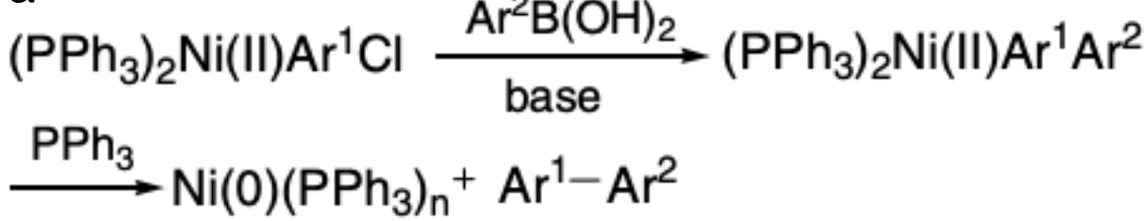
Activation

Suzuki-Miyaura



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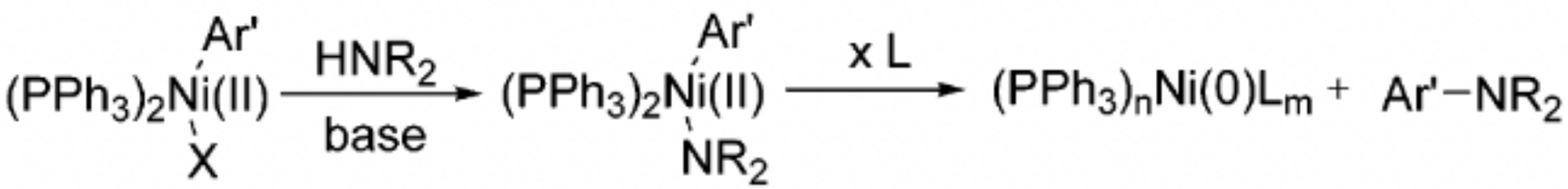

L NHC ligand

Hartwig 2012, (dppf)NiCl(cinnamyl)

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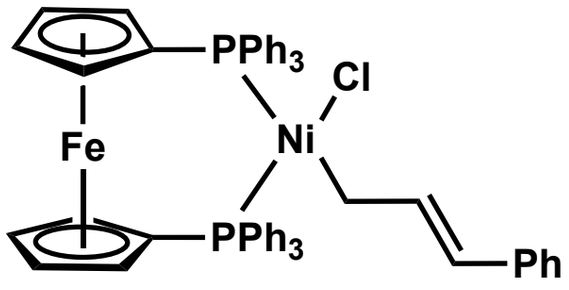
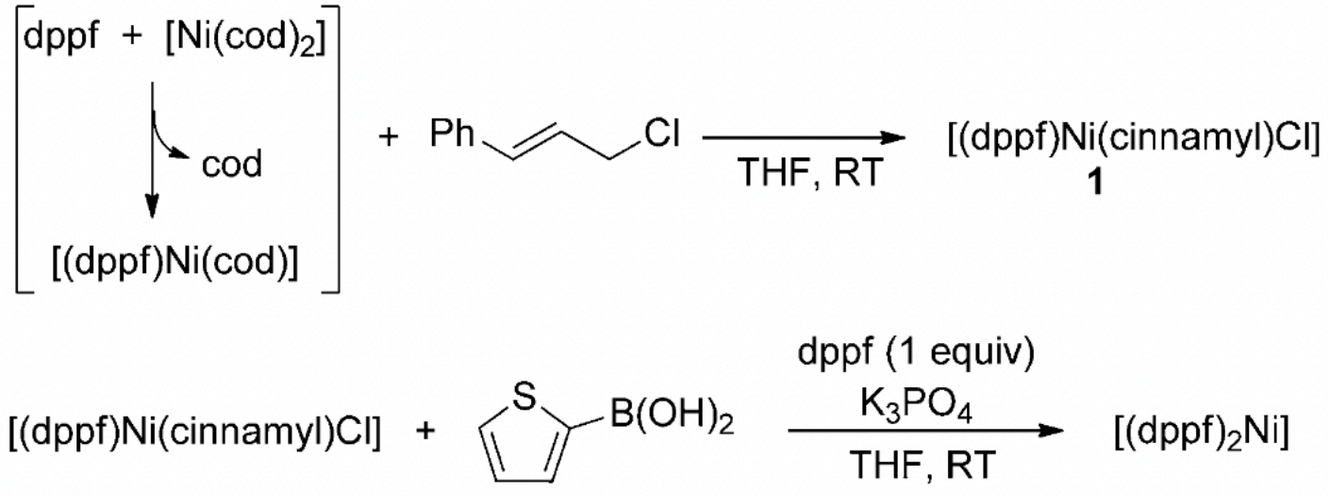
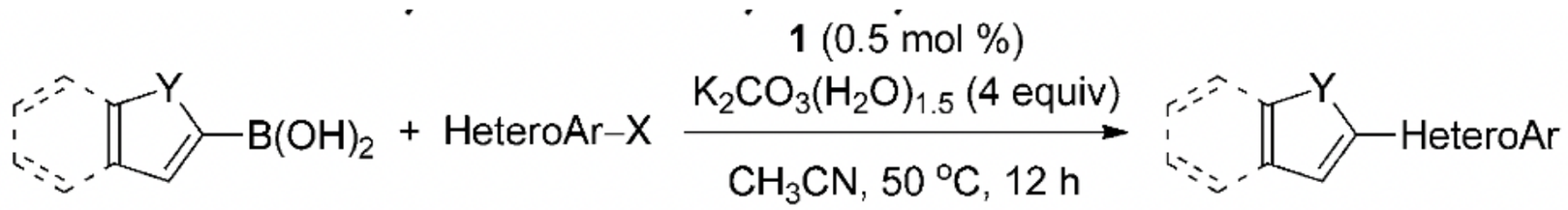
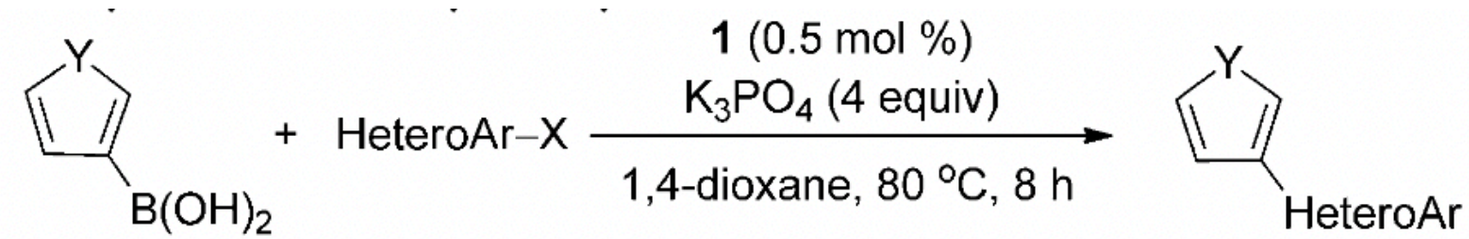


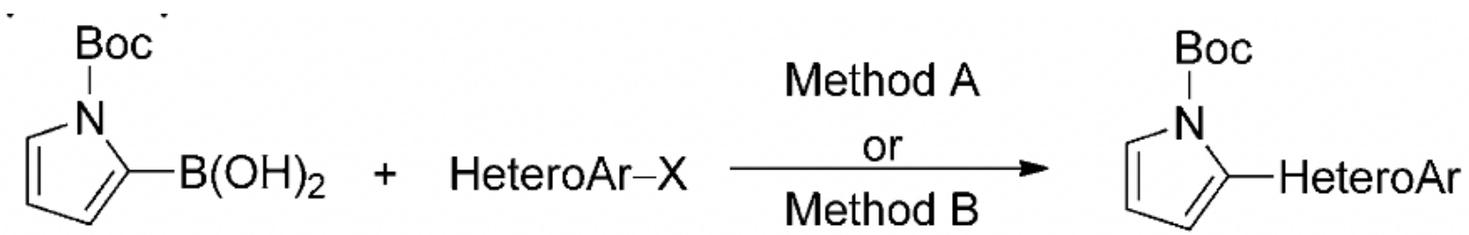
Hartwig *et al. ACIE* **2012**, *51*, 12837



Examples







Jamison 2013, $(Cy_2PhP)_2Ni(o\text{-Tolyl})Cl$

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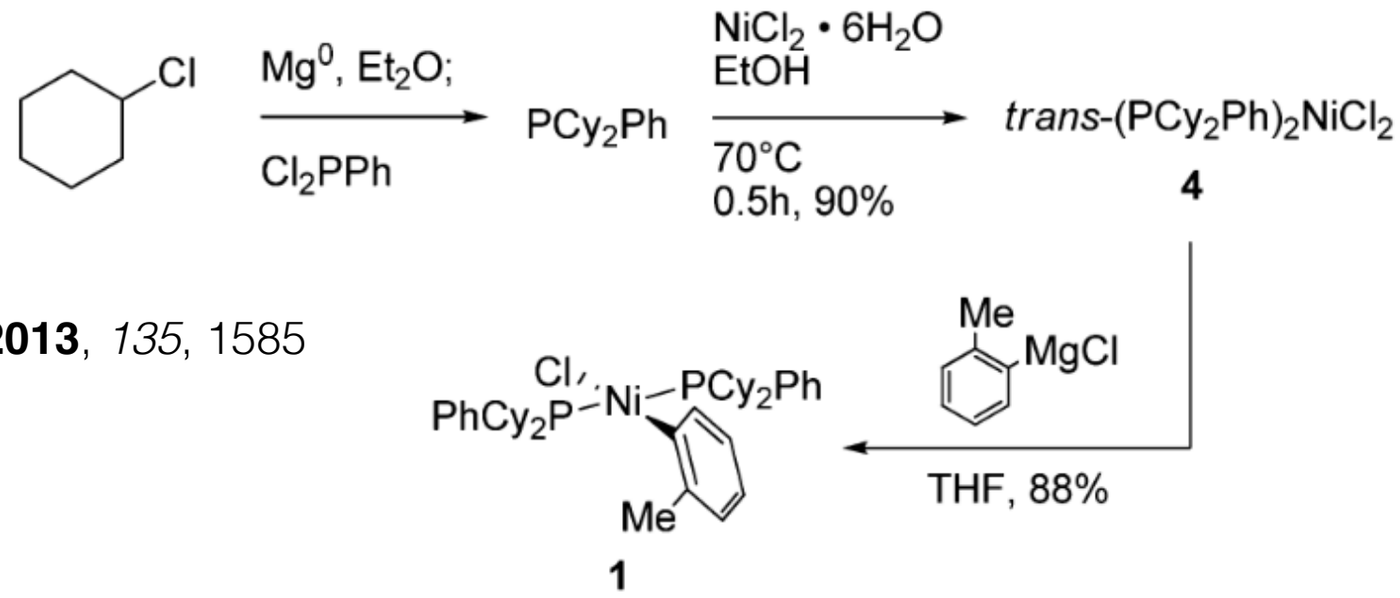

Jamison *et al. JACS* **2013**, *135*, 1585

Precedent

Shaw *et al. J. Chem. Soc.* **1960**, *1718-1729*

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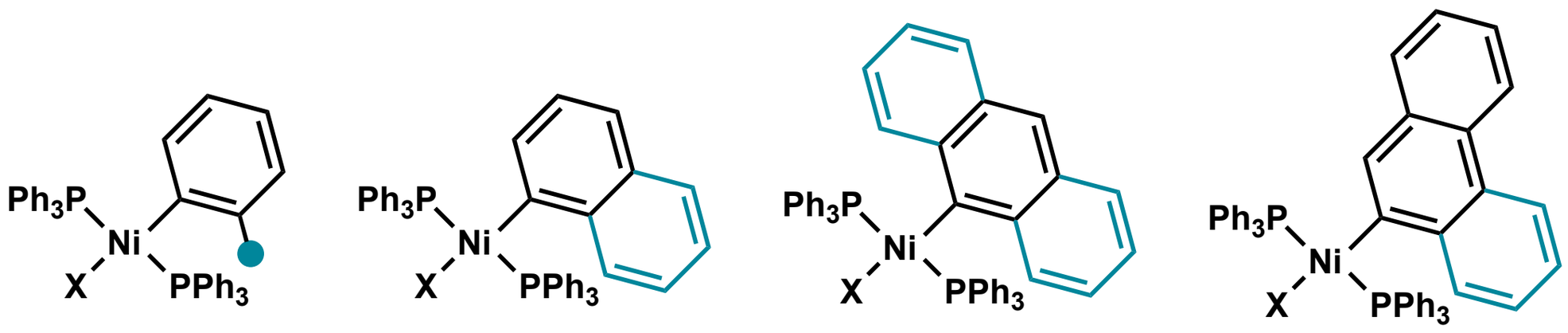

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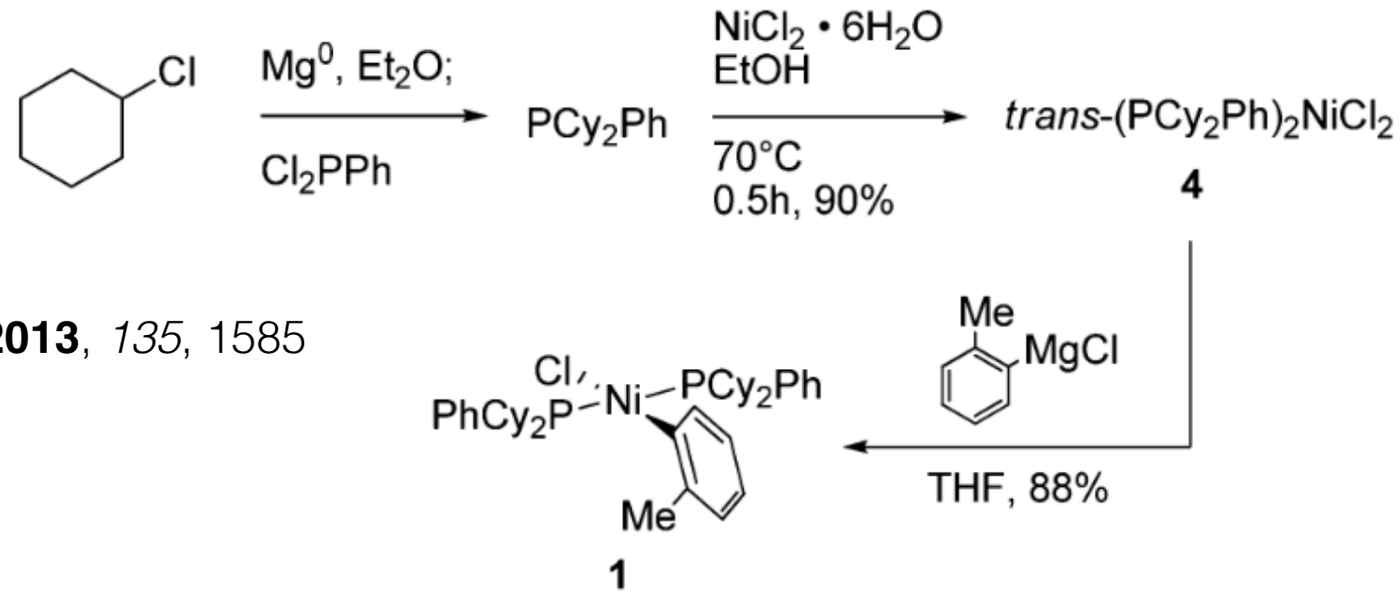

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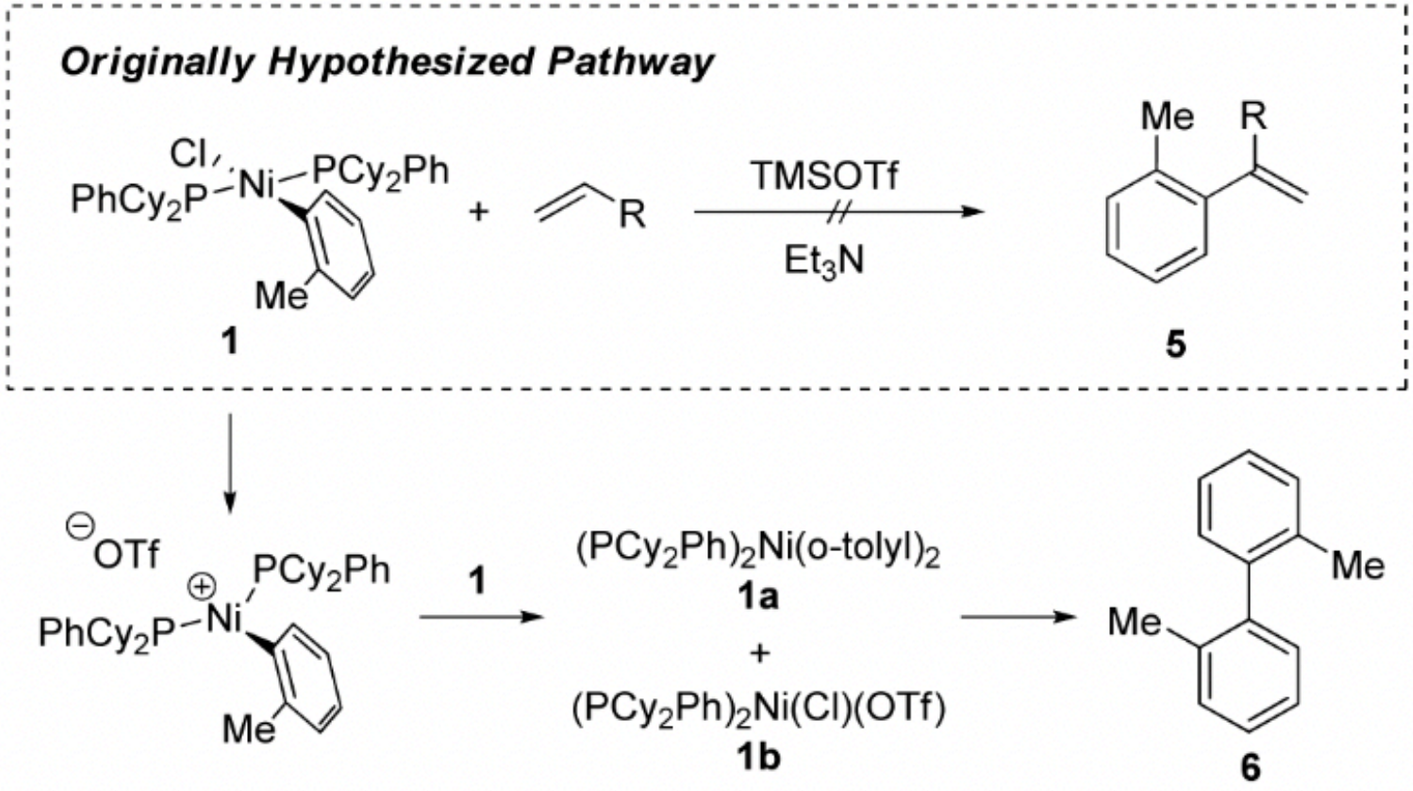
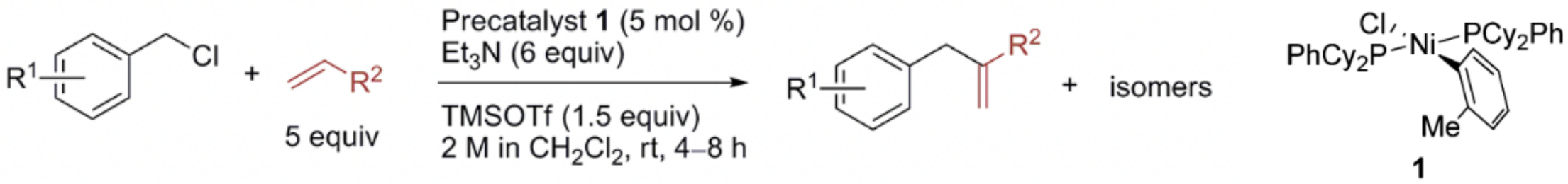
Novelty
Activation pathway



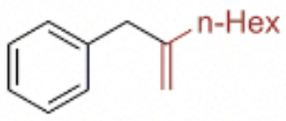
Jamison 2013, $(Cy_2PhP)_2Ni(o\text{-Tolyl})Cl$



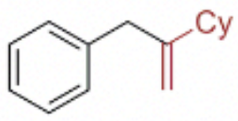
Jamison *et al. JACS* **2013**, *135*, 1585

Examples

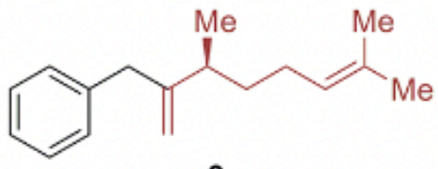
unsubstituted



7
92% yield, 98:2

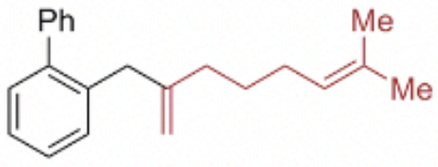


8
70% yield, 93:7

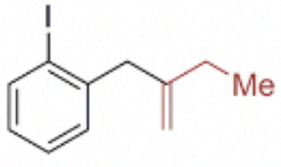


9
47% yield, 93:7

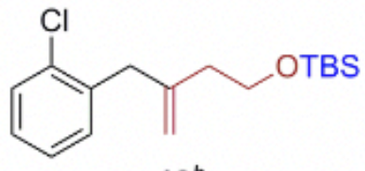
ortho-substituted



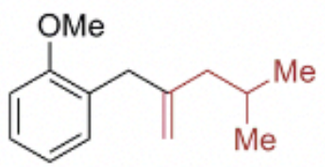
10
87% yield, 96:4



11
84% yield, 95:5

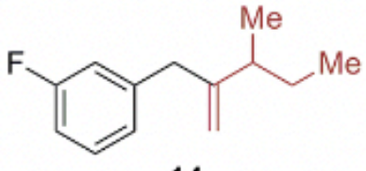


12[b]
90% yield, 96:4

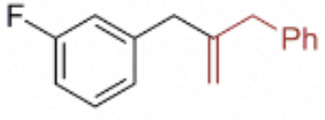


13
69% yield, 95:5

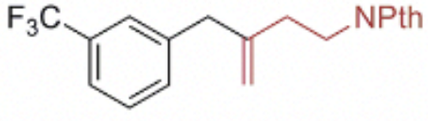
meta-substituted



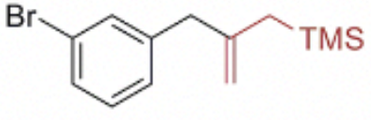
14
75% yield, 96:4



15
92% yield, 97:3

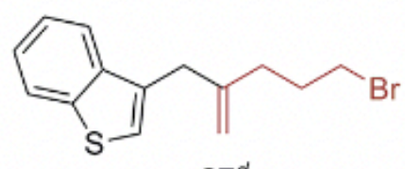


16[c]
83% yield, 99:1

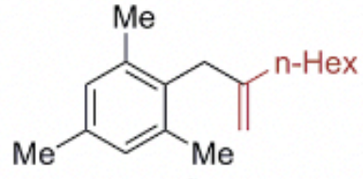


17
50% yield, 97:3

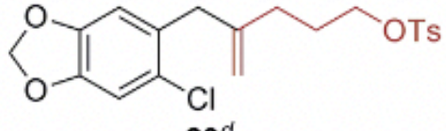
multiply-substituted and heteroaromatic



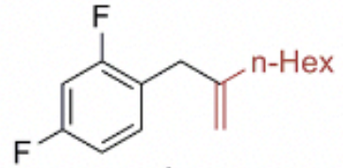
27[d]
78% yield, 94:6



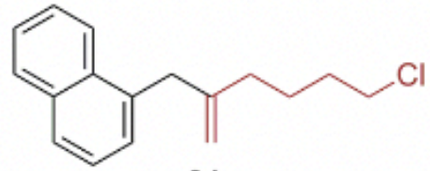
28[g]
41% yield, 96:4



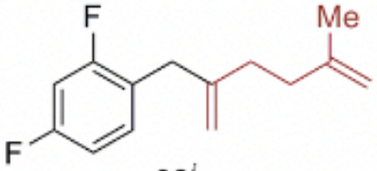
29[d]
52% yield, >95:5



30[h]
89% yield, 97:3



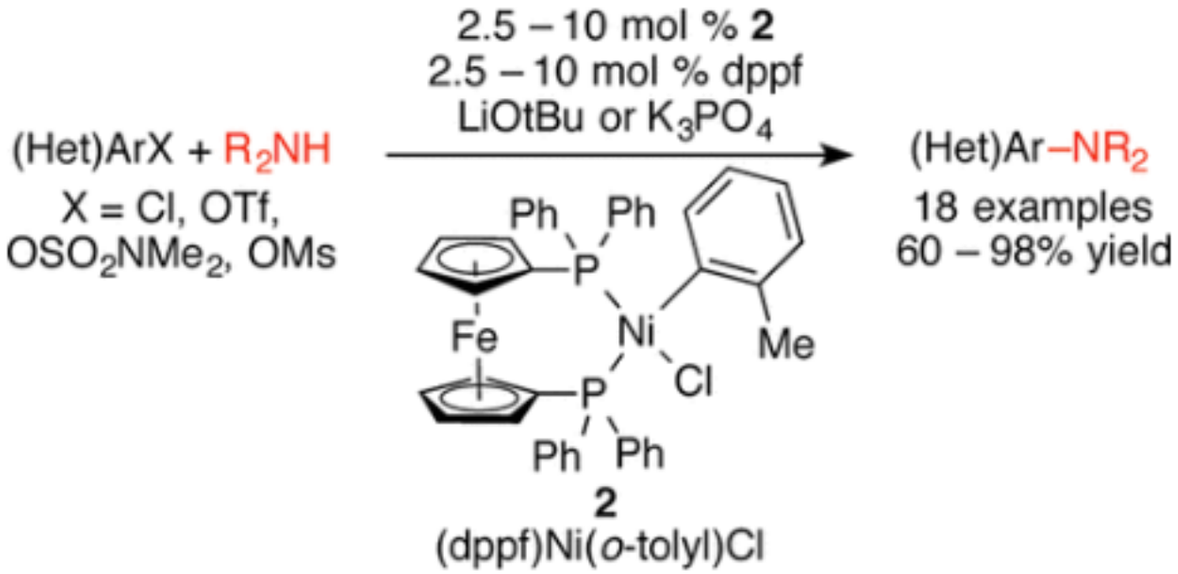
31
90% yield, 83:17



32[i]
61% yield, 97:3

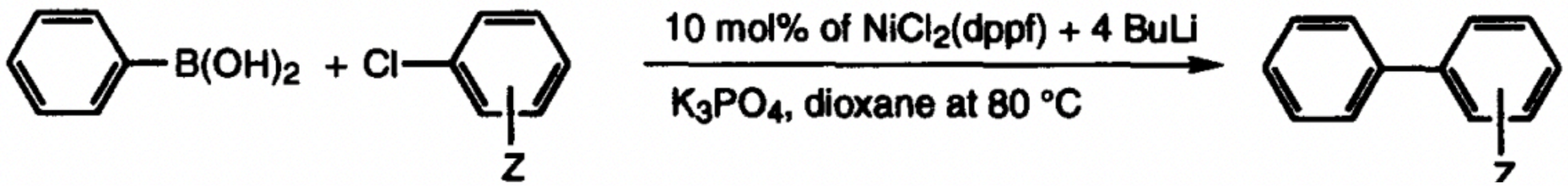
Buchwald 2014, (dppf)Ni(*o*-Tolyl)Cl

Buchwald 2014, (dppf)Ni(*o*-Tolyl)Cl

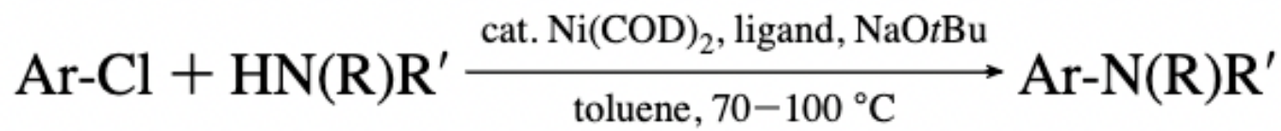


Buchwald *et al. OL* **2014**, *16*, 220

Prior art



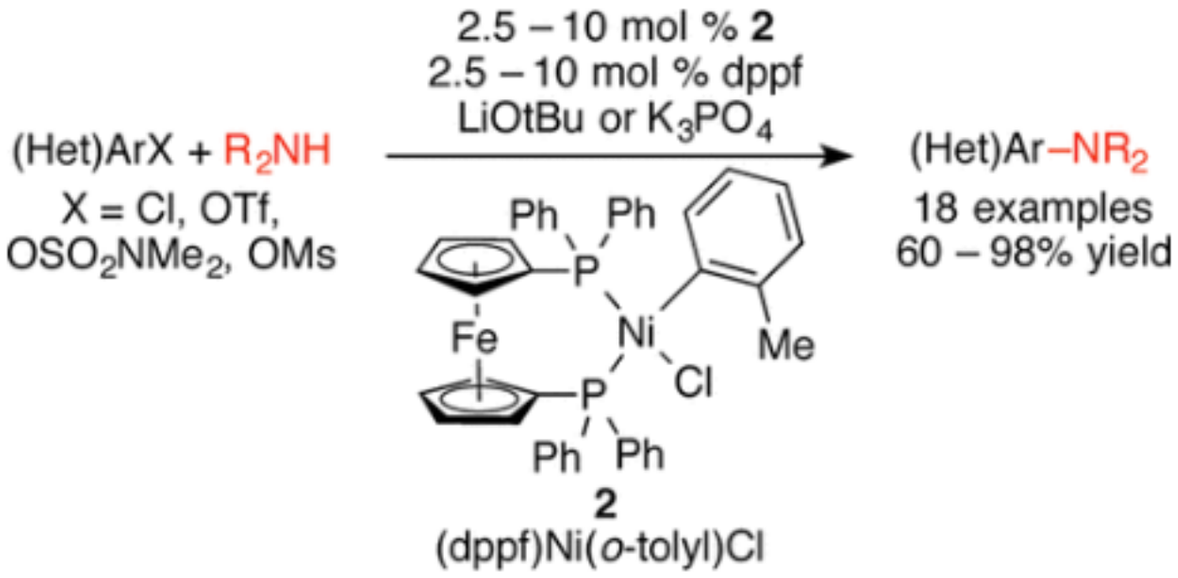
Miyaura *et al*. *Tetrahedron Lett.* **1996**, *37*, 2993



Buchwald *et al. JACS* **1997**, *119*, 6054

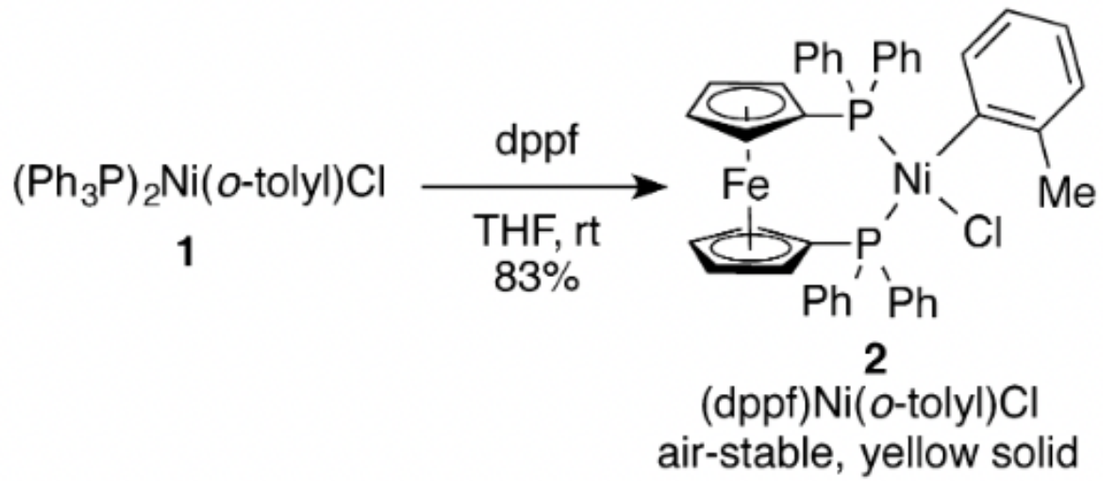
Ligand dppf

Buchwald 2013, (dppf)Ni(*o*-Tolyl)Cl

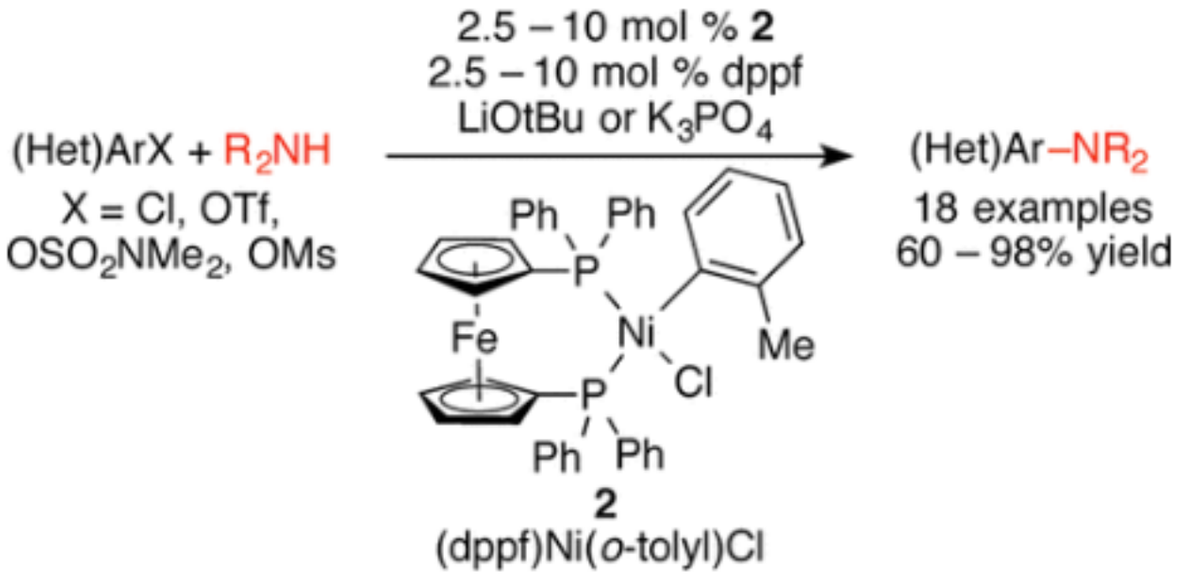


Buchwald *et al. OL* **2014**, *16*, 220

Prep

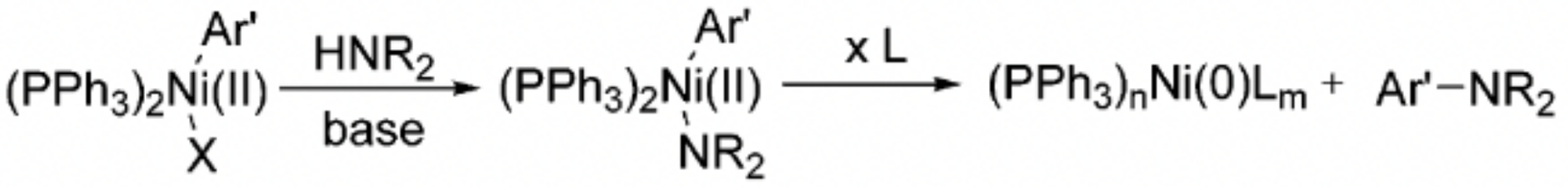


Buchwald 2013, (dppf)Ni(*o*-Tolyl)Cl



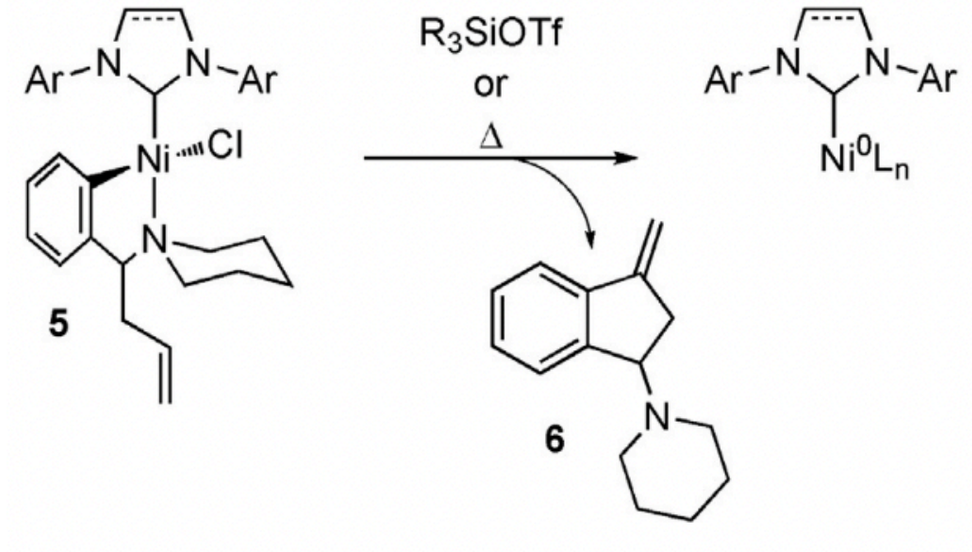
Buchwald *et al. OL* **2014**, *16*, 220

Activation



Jamison 2018, (NHC)Ni(Ar)Cl

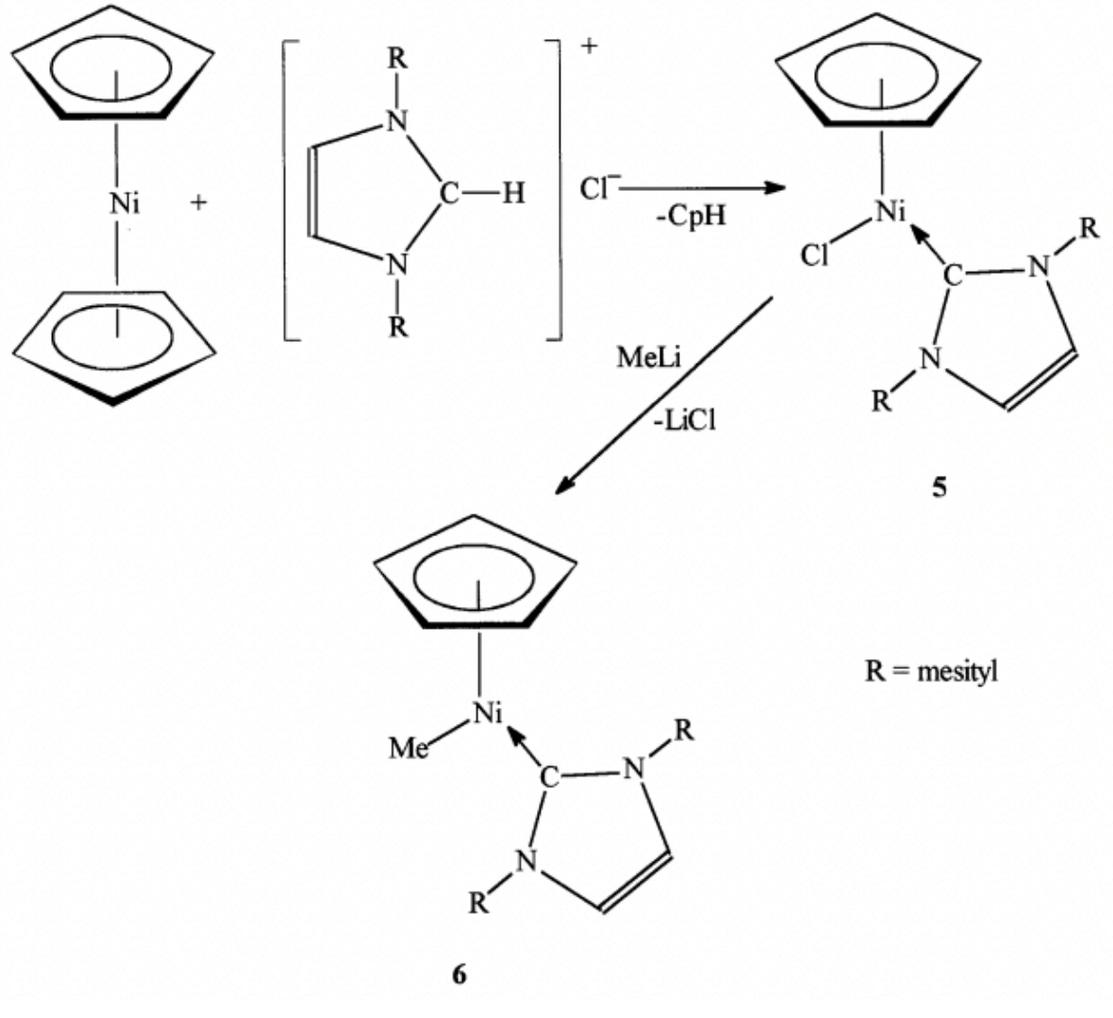
Jamison 2018, (NHC)Ni(Ar)Cl



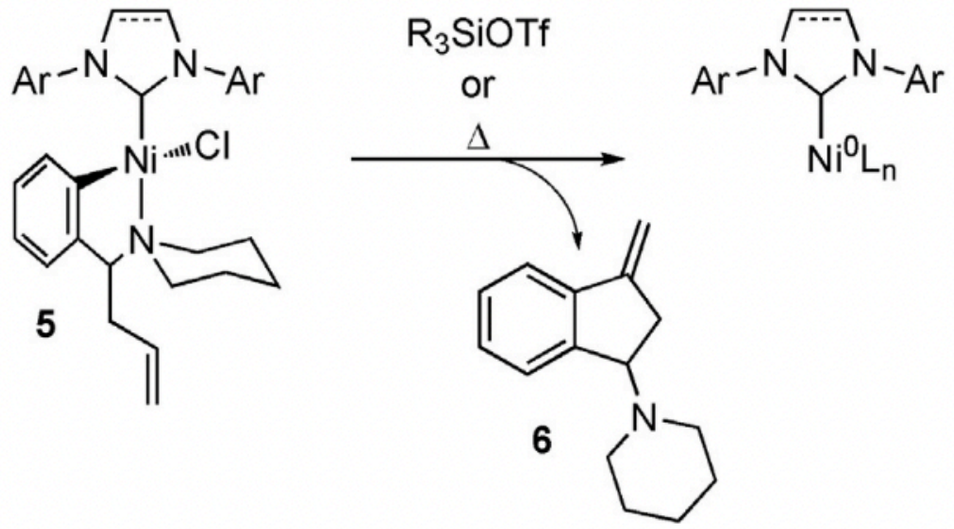
Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Precedent

Cowley *et al. J. Organomet. Chem.* **2000**, *596*, 3-5

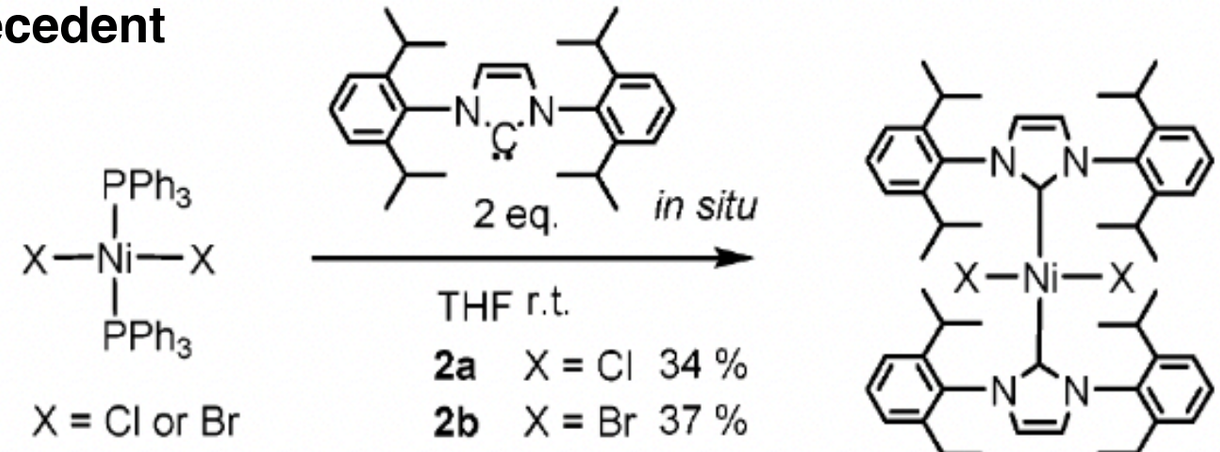


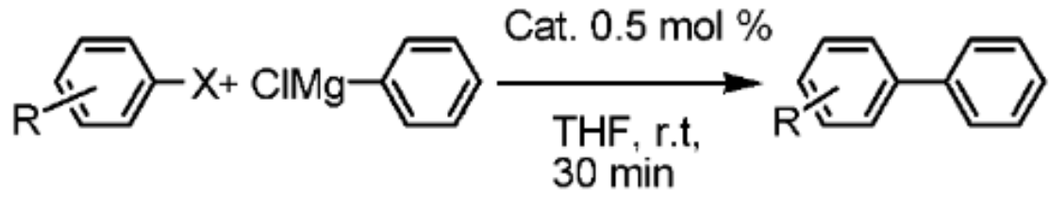
Jamison 2018, (NHC)Ni(Ar)Cl



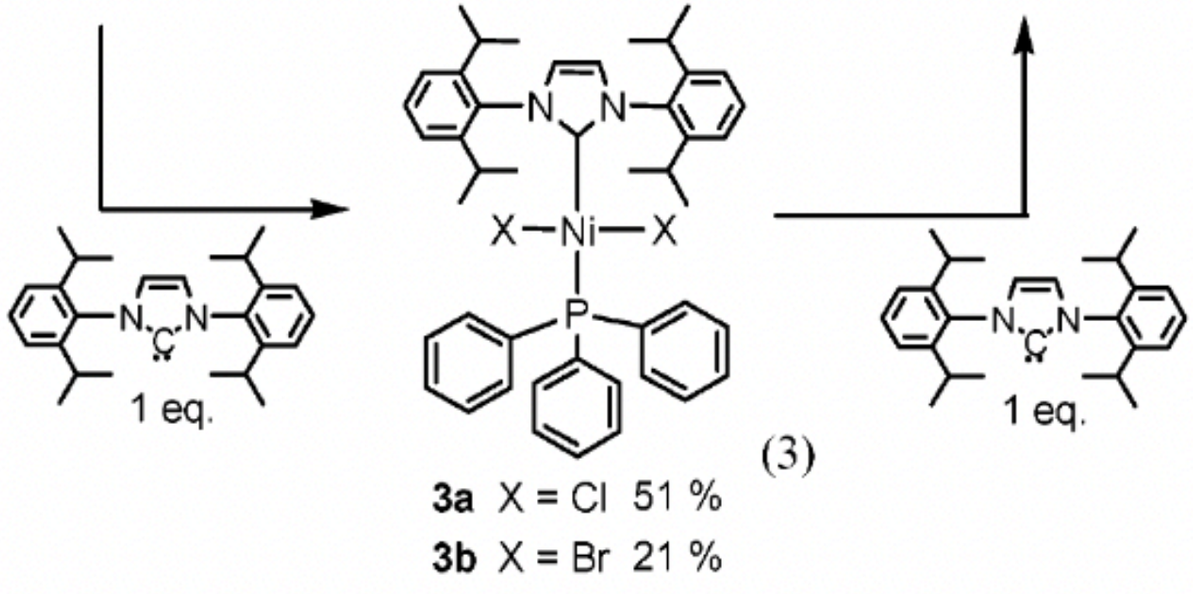
Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Precedent

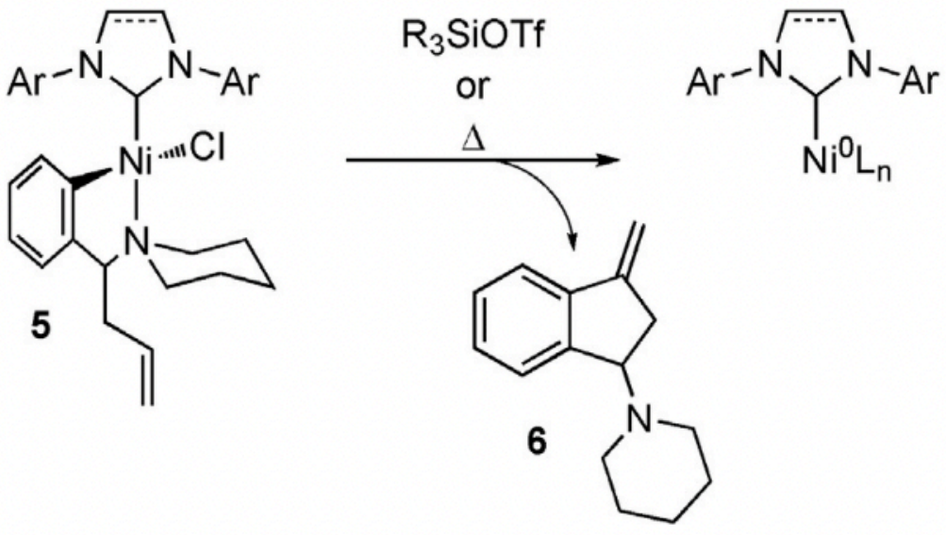




Matsubara *et al. Organometallics* **2006**, *25*, 3422

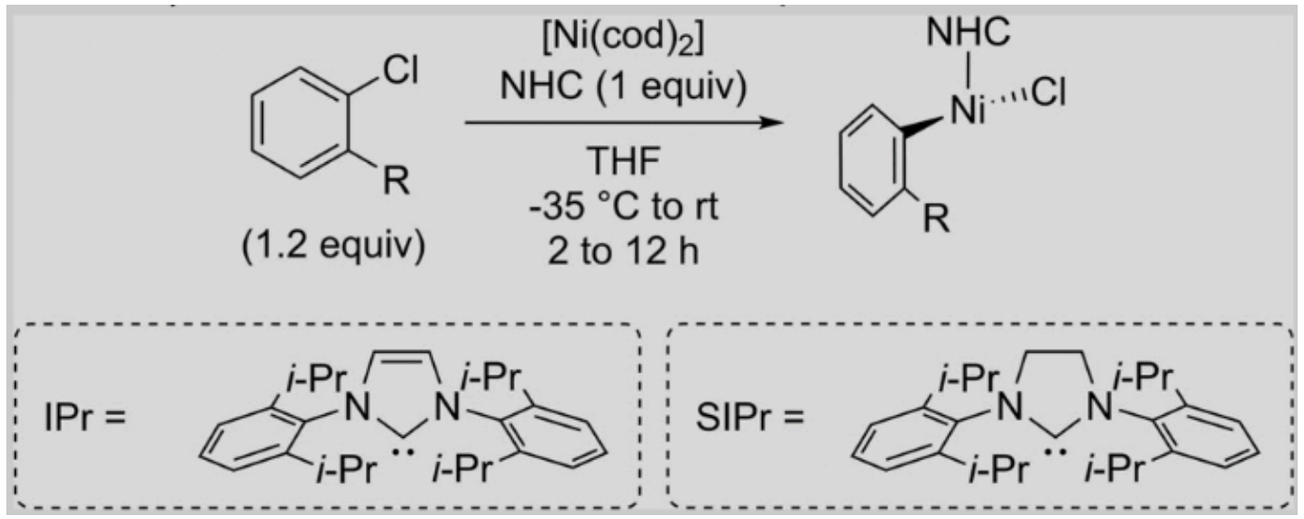


Jamison 2018, (NHC)Ni(Ar)Cl

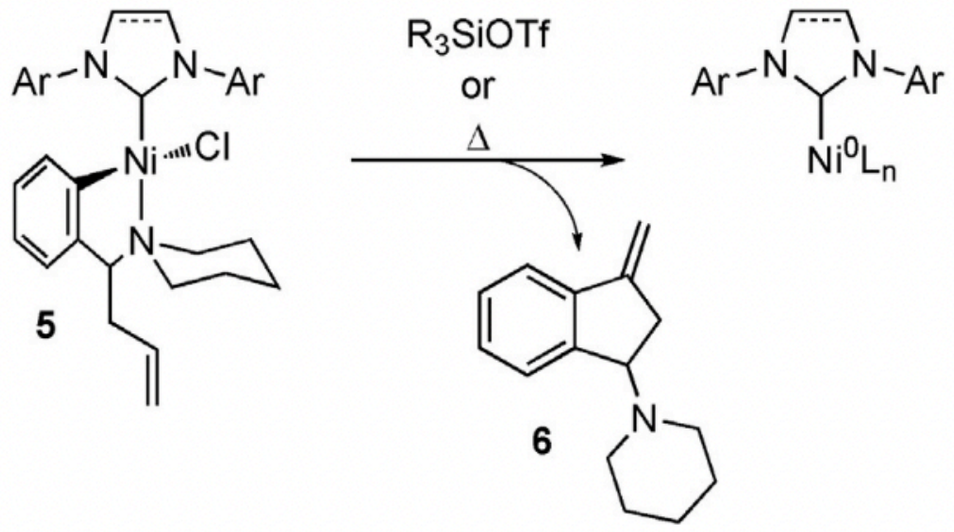


Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Preparation

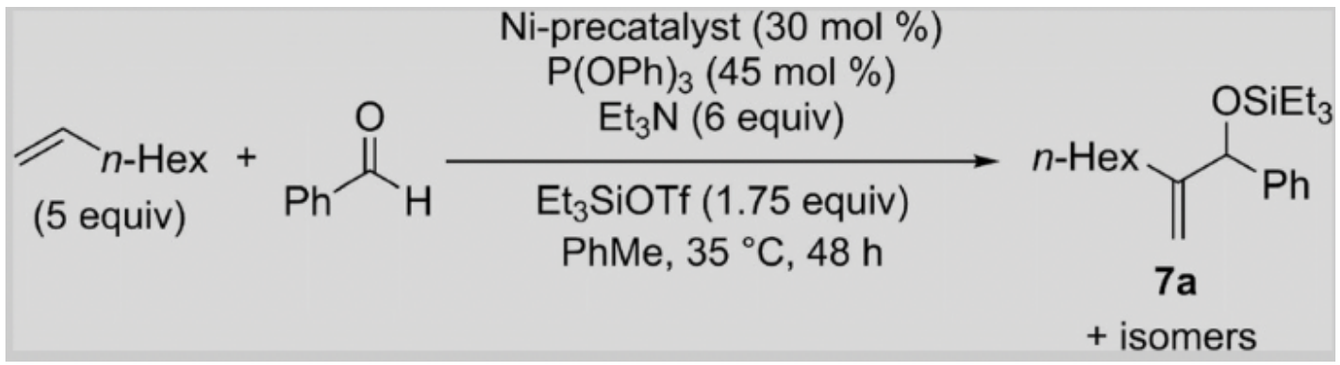


Jamison 2018, (NHC)Ni(Ar)Cl



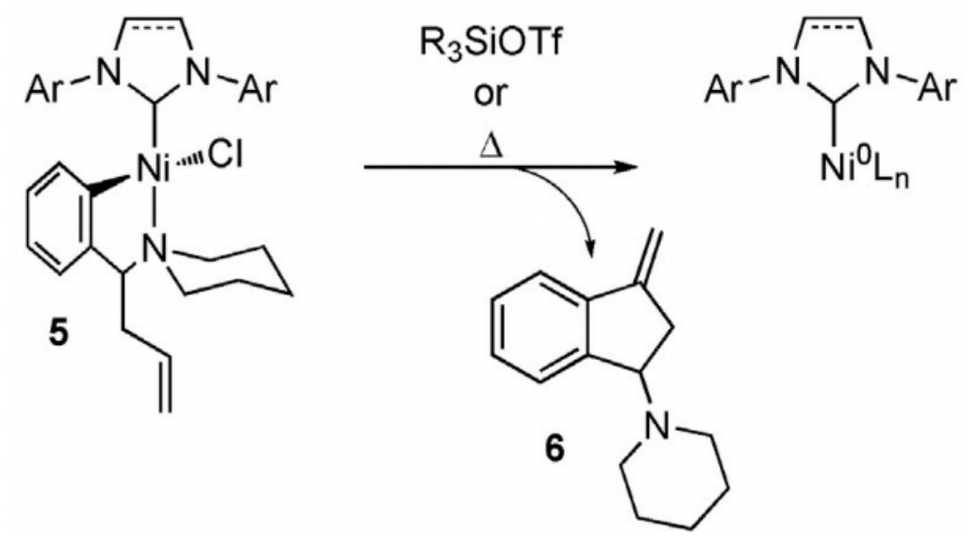
Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Examples



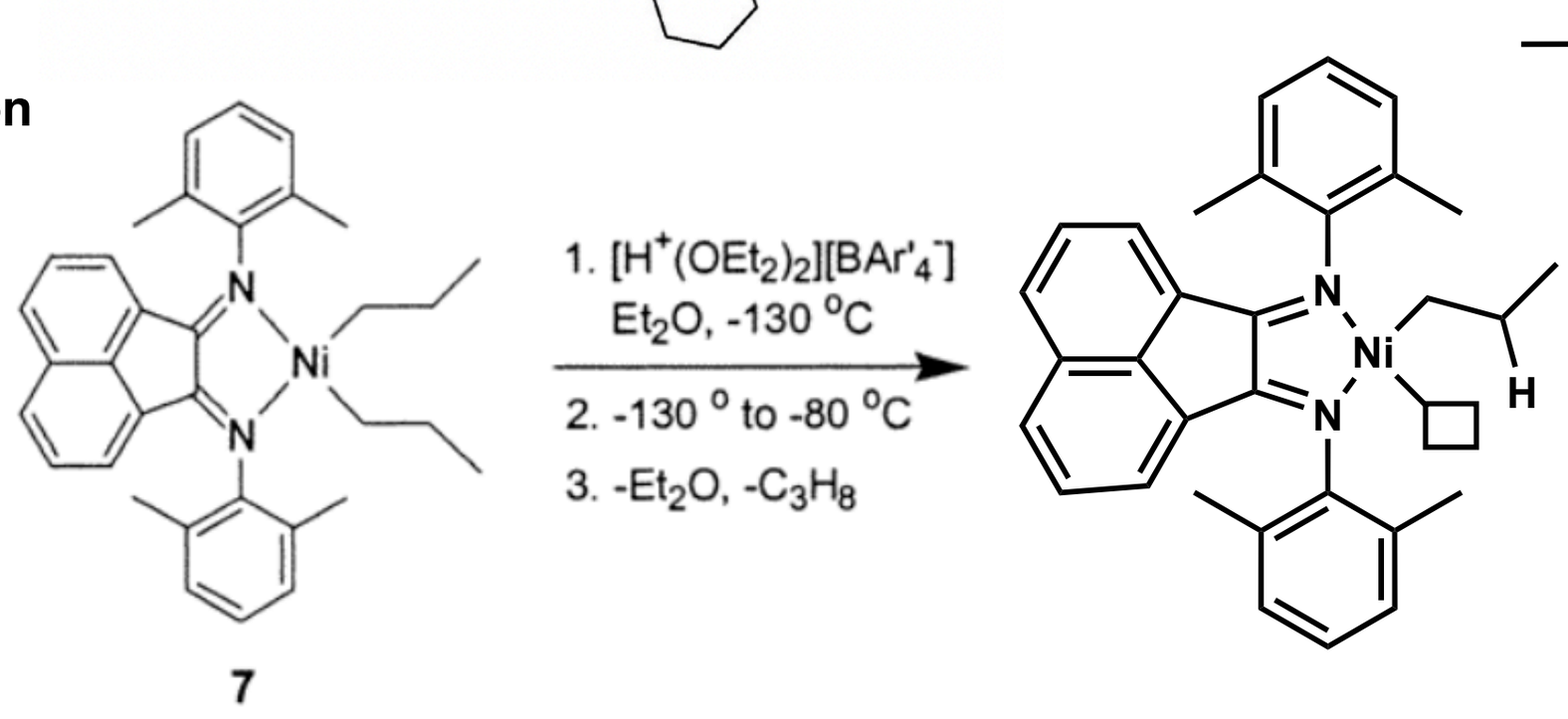
5 IPr 93% (**7a**)

Jamison 2018, (NHC)Ni(Ar)Cl

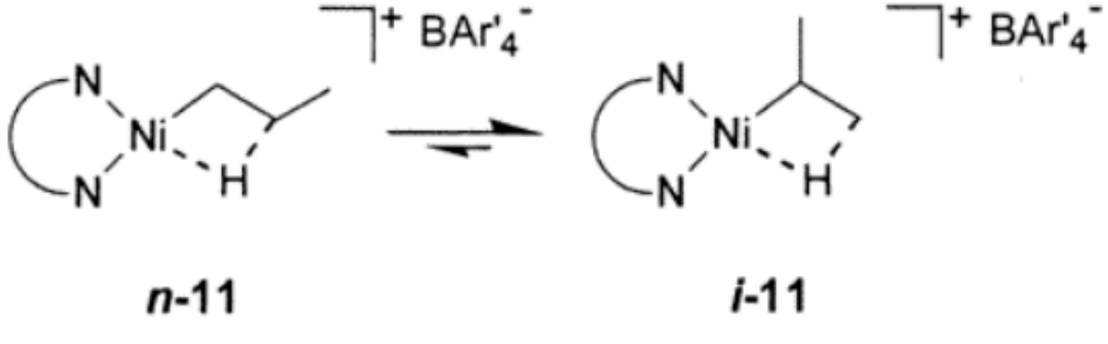


Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Activation



Agostic Ni complex

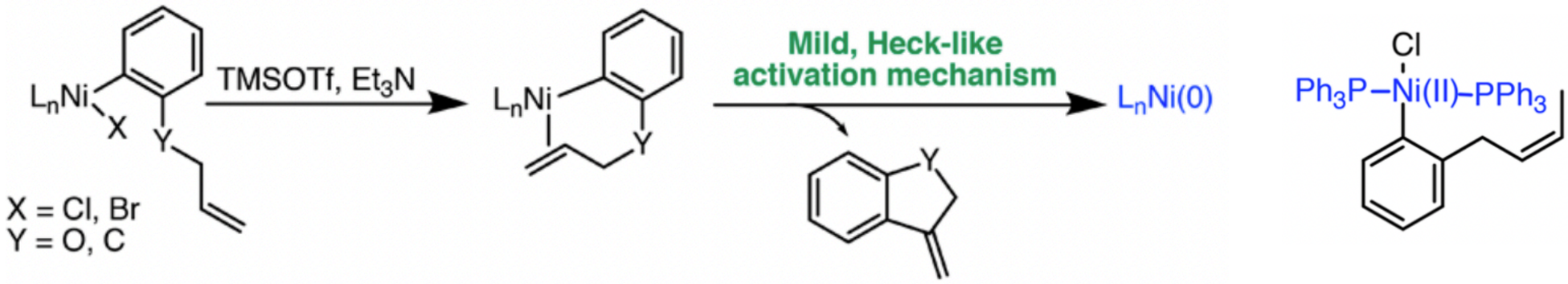


1	:	20

Brookhart *et al*. *JACS* **2003**, *125*, 3068

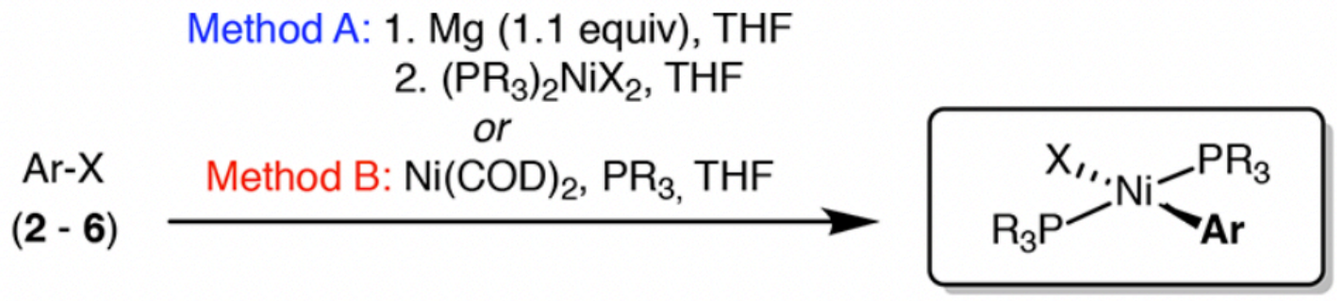
Jamison 2018, $(PPh_3)_2Ni(Ar)Cl$

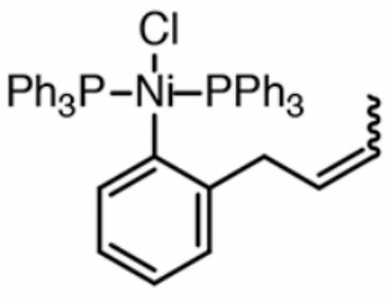
Jamison 2018, $(PPh_3)_2Ni(Ar)Cl$



Jamison *et al. Organometallics* **2018**, *37*, 2716

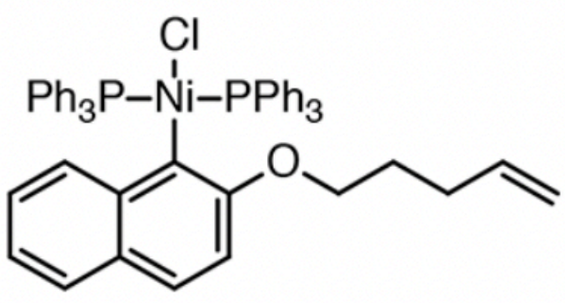
Preparation





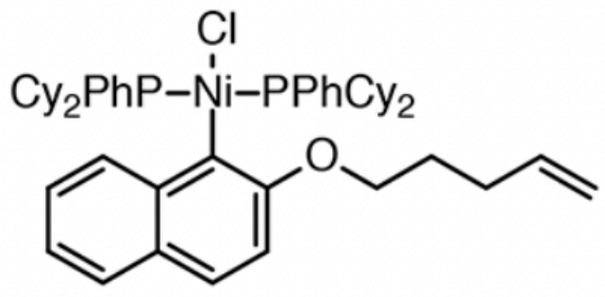
Ni-2

Method A: 35%
Method B: 28%



Ni-5a

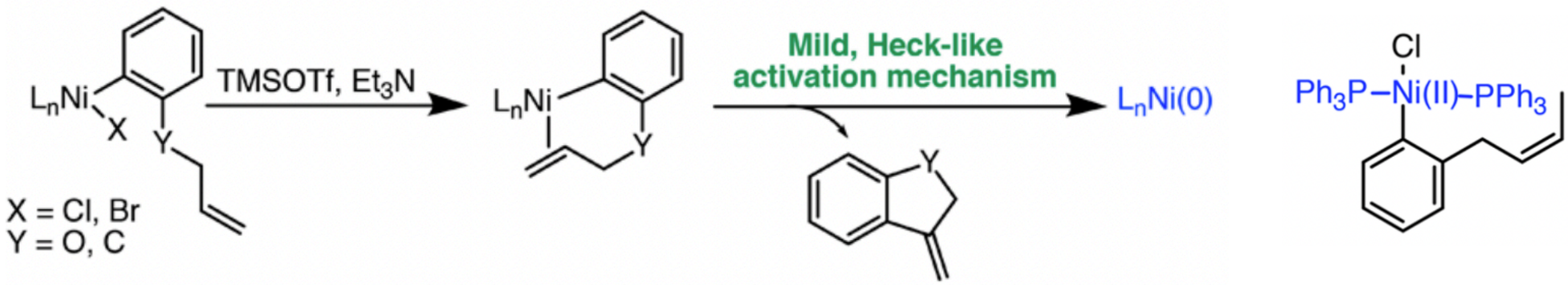
Method A[b]: 59%



Ni-5b

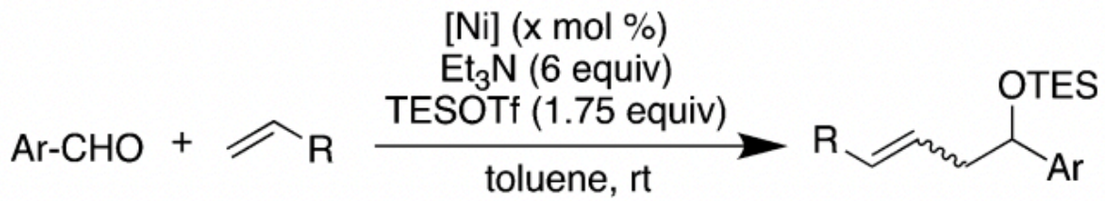
Method A[b]: 68%

Jamison 2018, $(PPh_3)_2Ni(Ar)Cl$

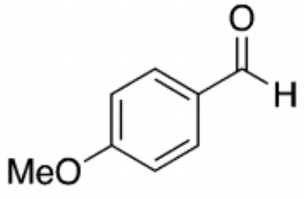
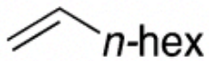
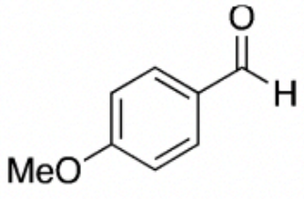
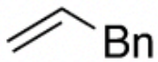
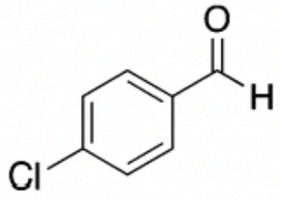
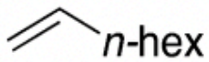


Jamison *et al. Organometallics* **2018**, *37*, 2716

Examples

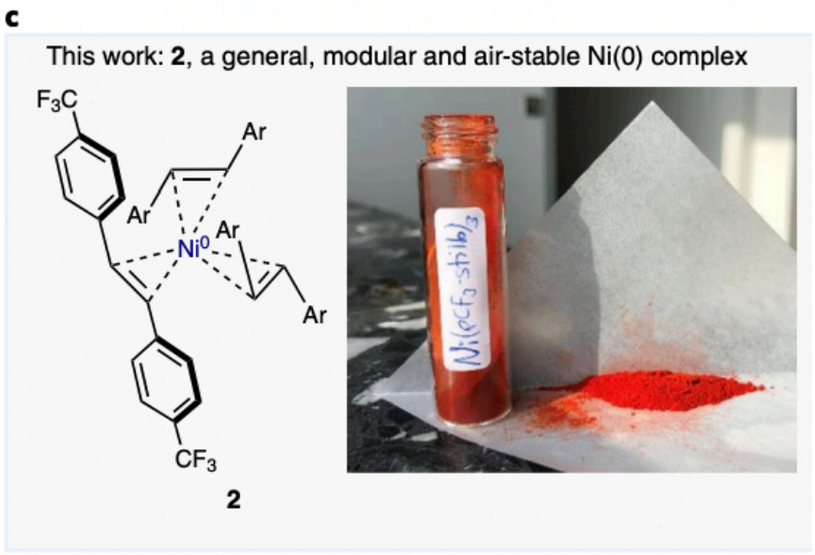


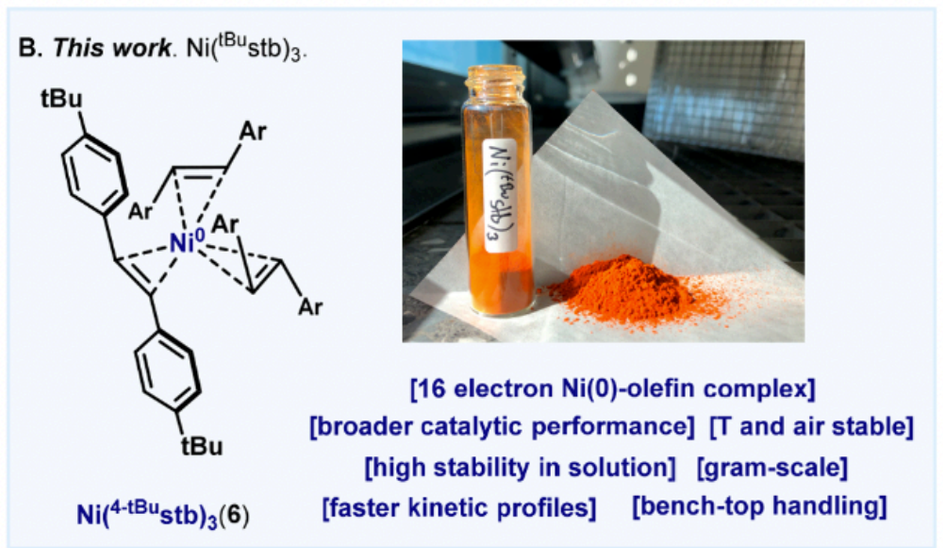
12

Entry	Ar-CHO	R	Time (h)	Catalyst loading (mol%)	%Yield of 12[a] using Ni-2	% Yield of 12[a] using $Ni(COD)_2/PPh_3$
1			18	5	98	60
2			18	20	96	85
3			24	5	97	66
4			24	20	95	88
5			18	5	22	9
6			18	20	47	36

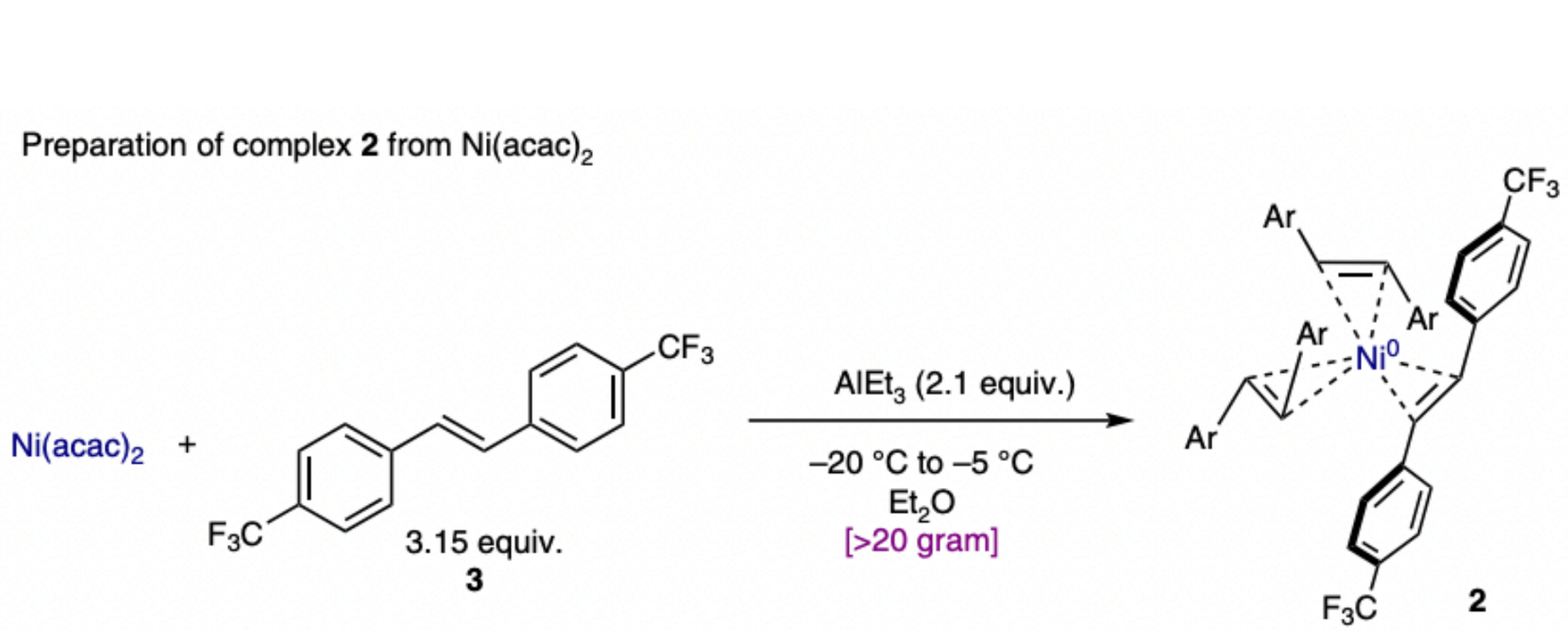
Cornella 2020, Ni(^{R}stb)$_3$

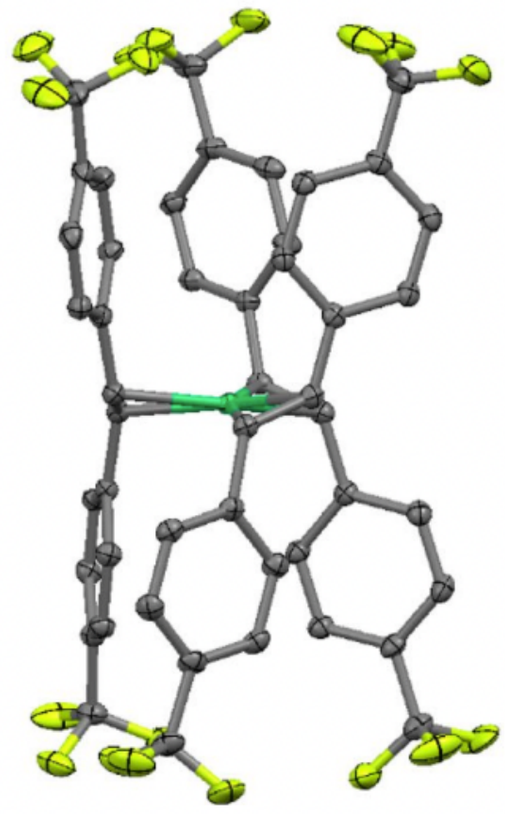
Cornella 2020, Ni(^{R}stb)$_3$





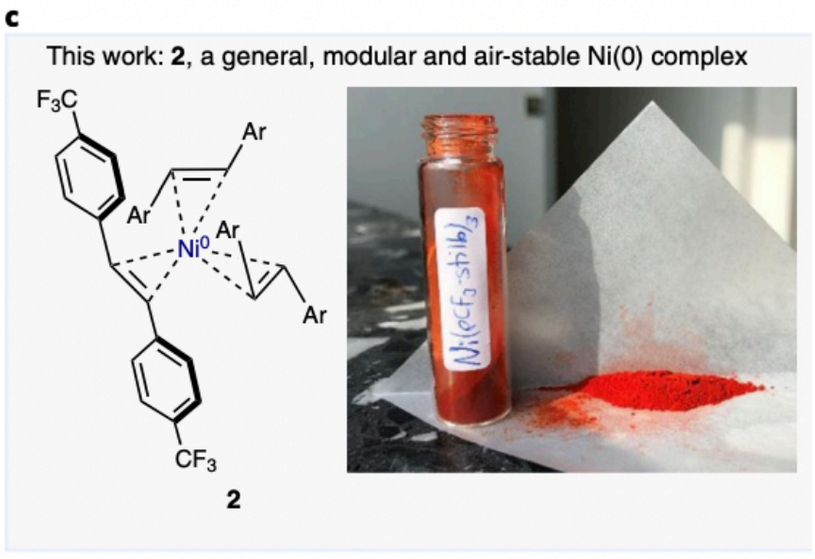
Preparation and structure

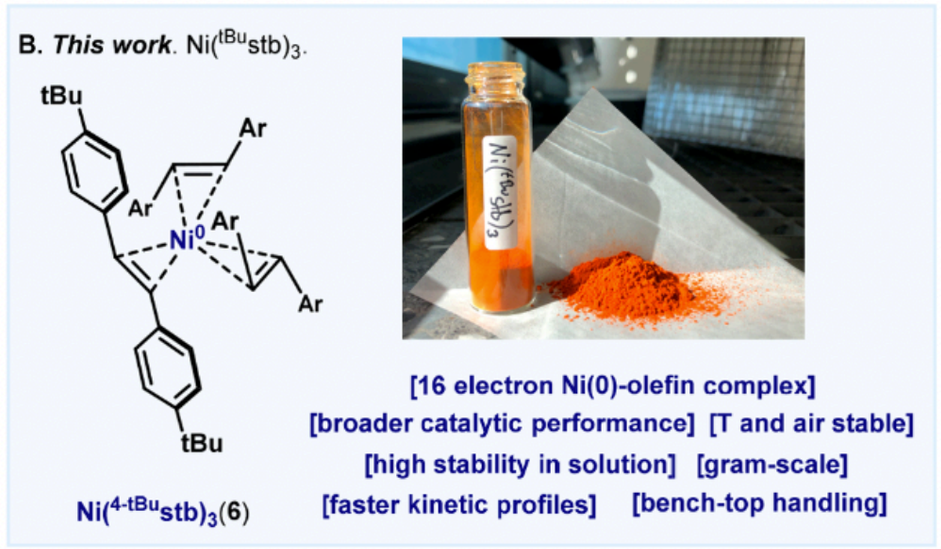




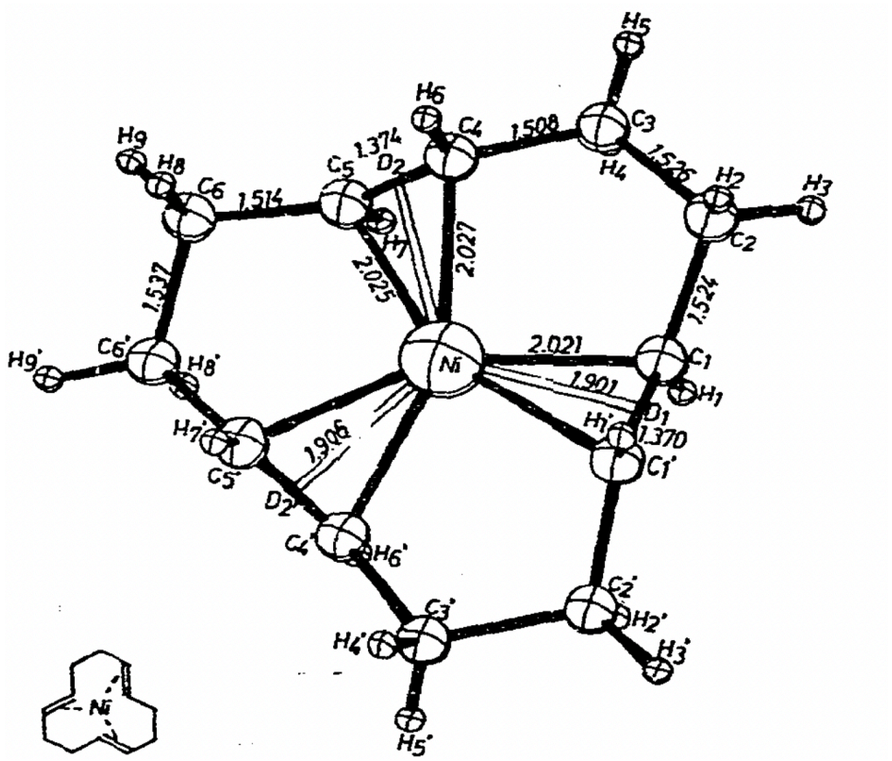
Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al. Nat. Catal.* **2020**, *3*, 6

Cornella 2020, Ni(^{R}stb)$_3$

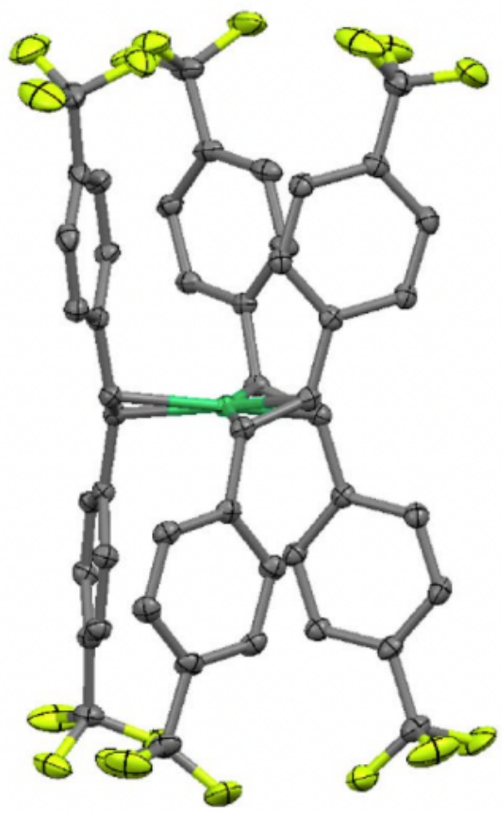




Preparation and structure

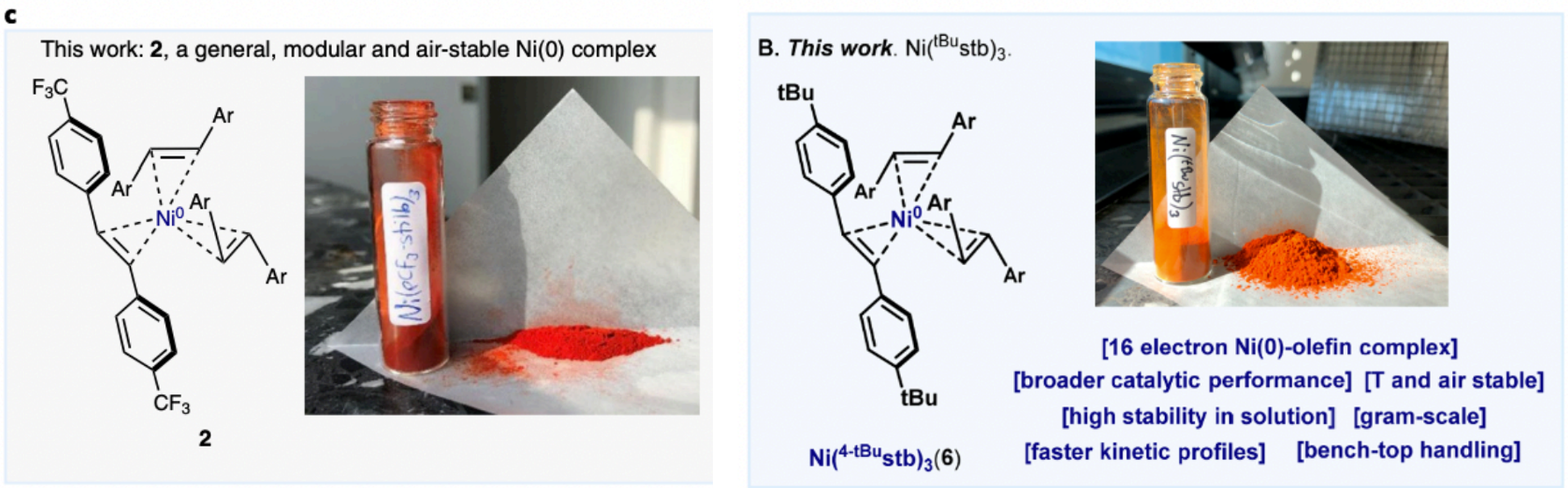


Krüger *et al*. *J. Organomet. Chem.* **1972**, *44*, 397



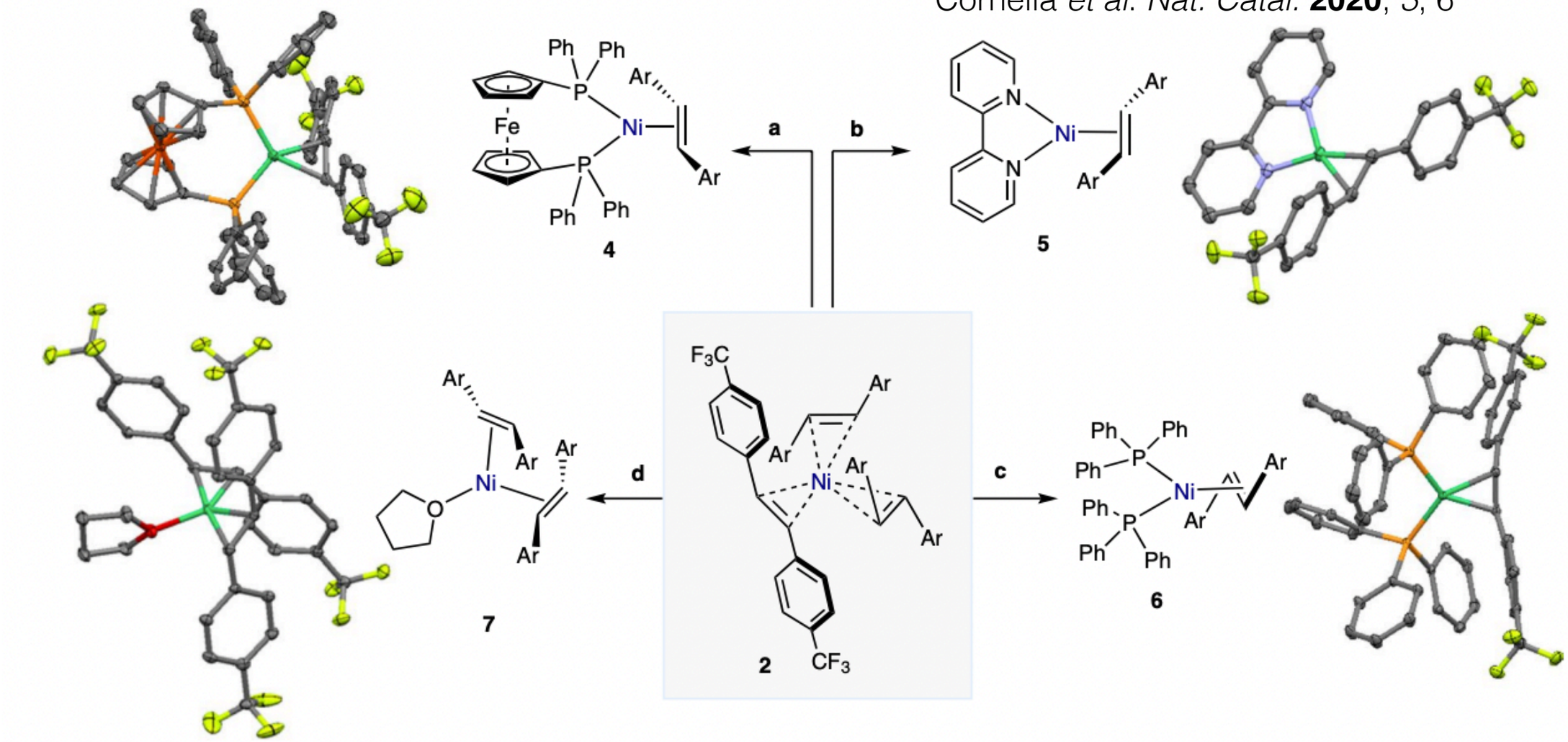
Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al*. *Nat. Catal.* **2020**, *3*, 6

Cornella 2020, Ni(^{R}stb)$_3$



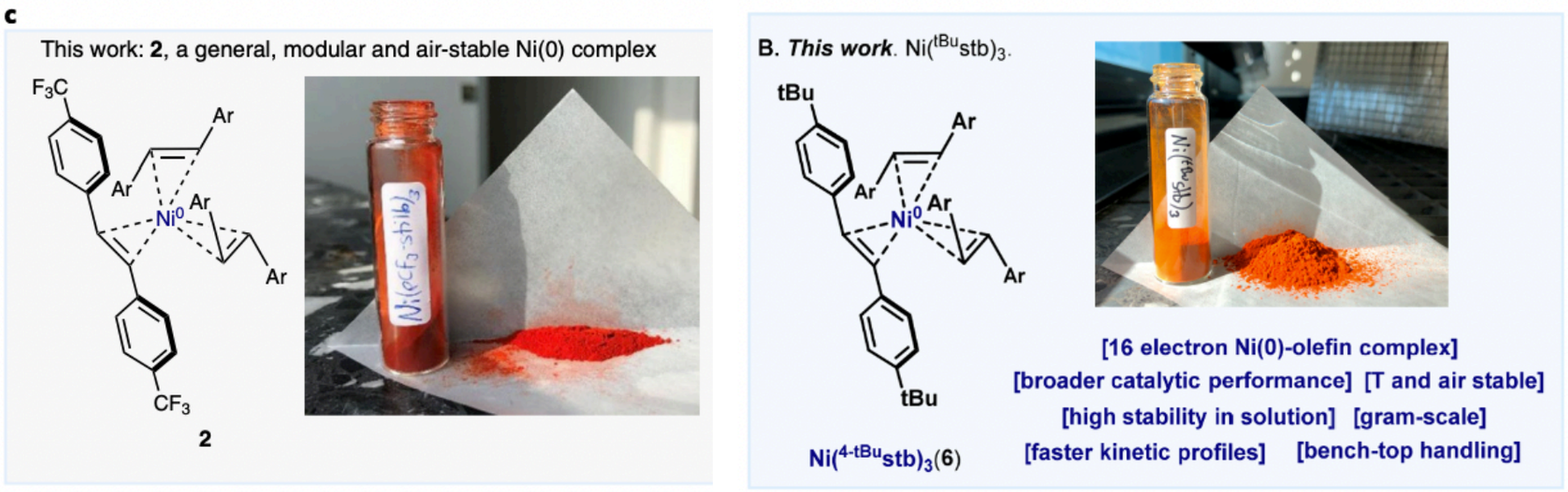
Ligand exchange

Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al. Nat. Catal.* **2020**, *3*, 6



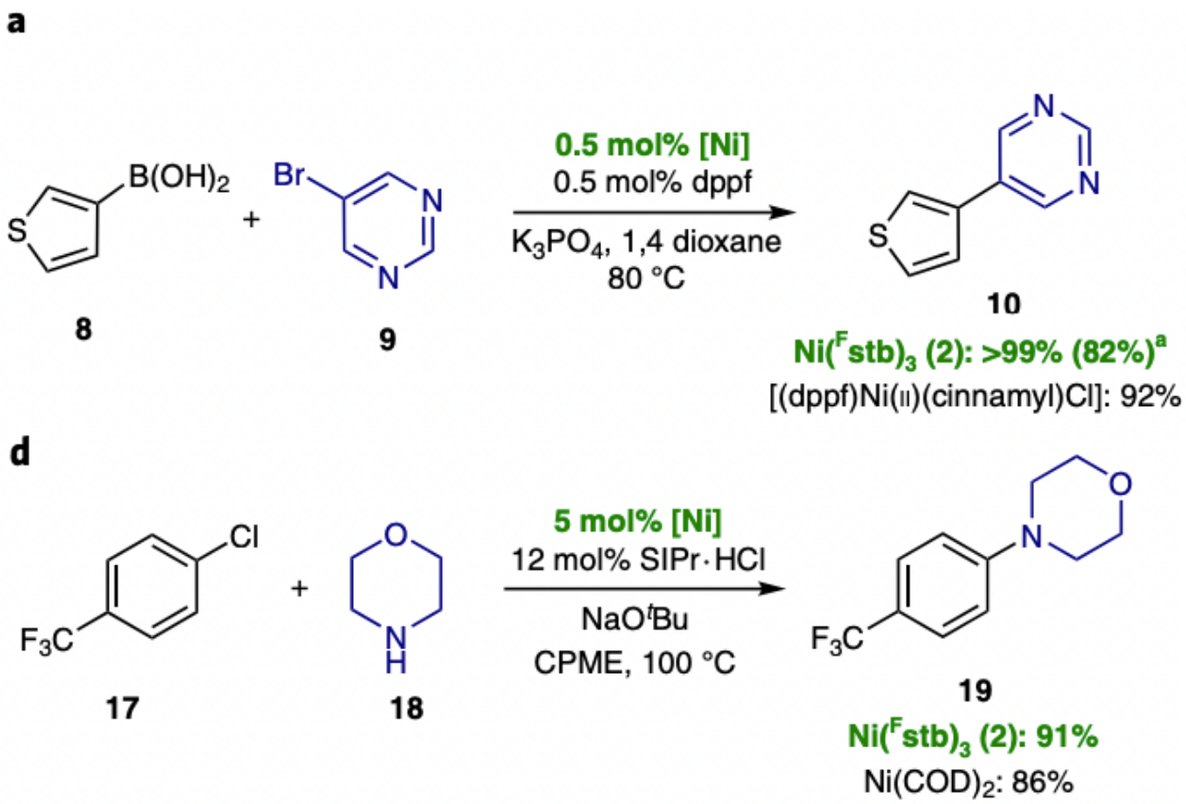
(a) 1:1 THF, 25 °C, quant. (b)1:1 THF, 25 °C, quant. (c)1:2 THF, 25 °C, quant. (d)THF slow xtal, -20 to -78 °C

Cornella 2020, Ni(^{R}stb)$_3$

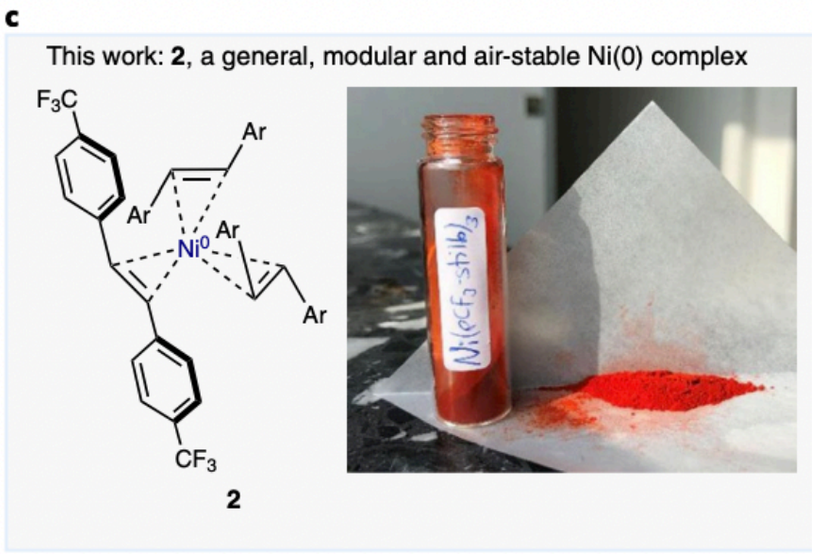


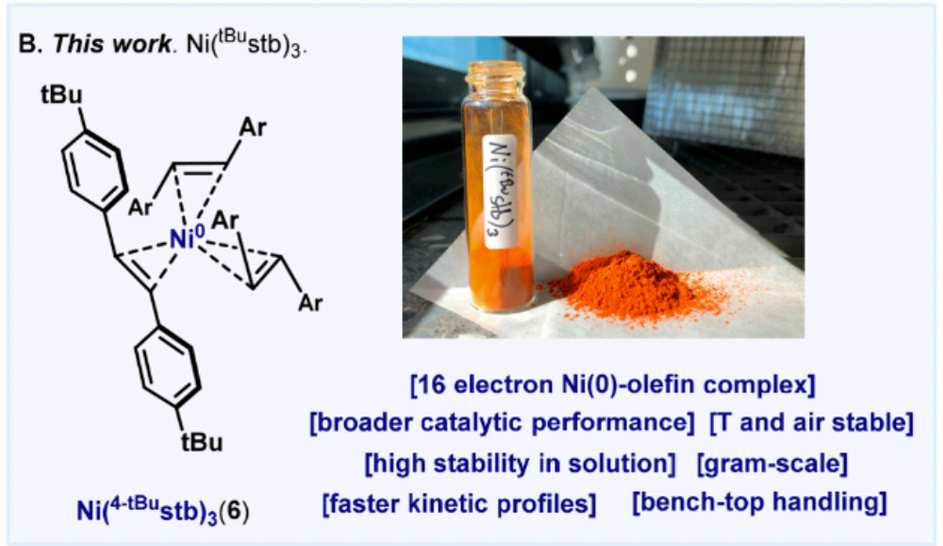
Examples

Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al. Nat. Catal.* **2020**, *3*, 6



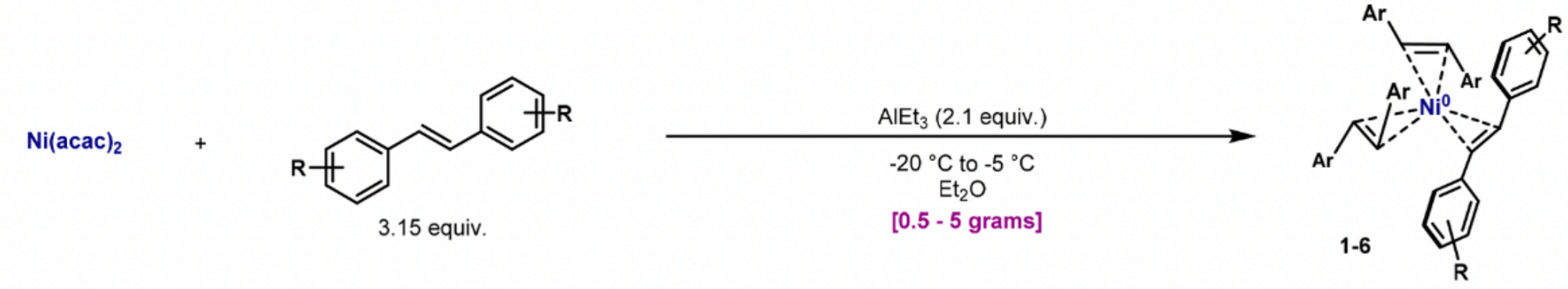
Cornella 2020, Ni(^{R}stb)$_3$



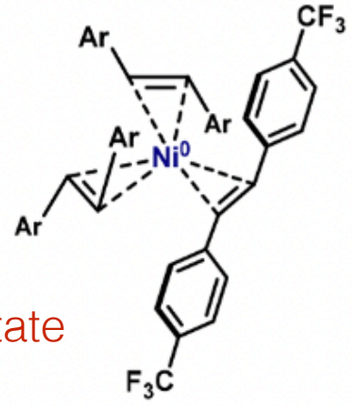


Improved studies

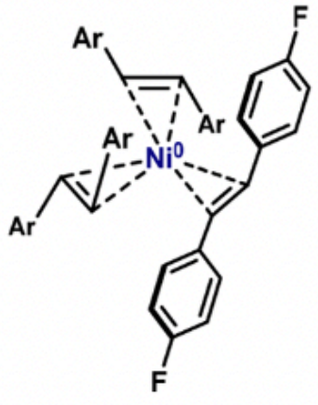
Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al. Nat. Catal.* **2020**, *3*, 6



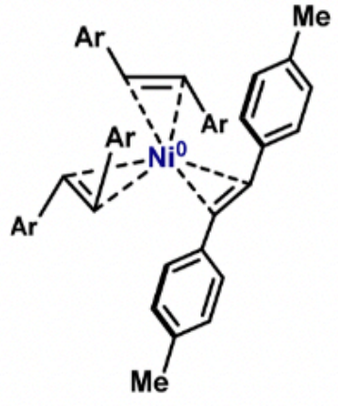
Solid state



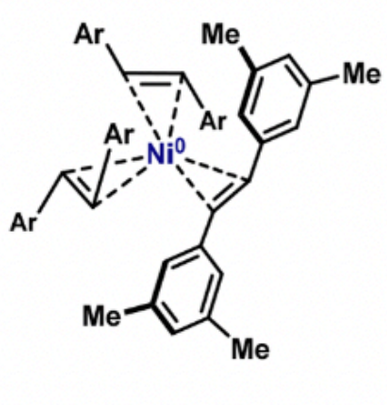
Ar = 4-CF_3-C_6H_4
2, 95% (**Ni($^{4\text{-}CF3}$stb)$_3$**)
air-stable:
at -18 °C: > 3 months
at 25 °C: (<1 week)



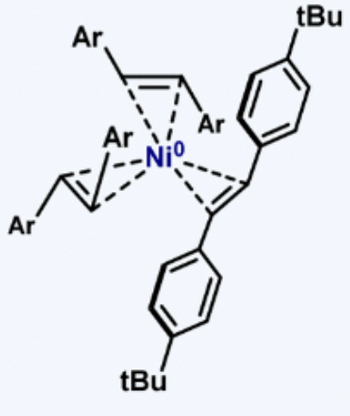
Ar = 4-F-C_6H_4
3, 67% (**Ni($^{4\text{-}F}$stb)$_3$**)
air-stable:
at -18 °C: > 3 months
at 25 °C: (<1 week)



Ar = 4-Me-C_6H_4
4, 74% (**Ni($^{4\text{-}Me}$stb)$_3$**)
air-stable:
at -18 °C: > 3 months
at 25 °C: (<1 week)



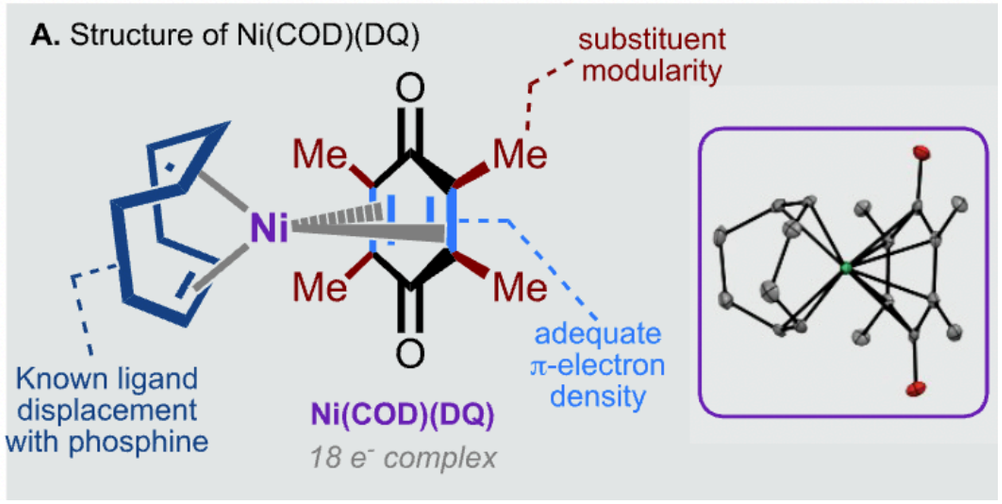
Ar = 3,5-Me-C_6H_4
5, 77% (**Ni($^{3,5\text{-}Me}$stb)$_3$**)
air-stable:
at -18 °C: 1 month
at 25 °C: (<1 week)



Ar = 4-tBu-C_6H_4
6, 95%, (**Ni($^{4\text{-}tBu}$stb)$_3$**)
air-stable:
at -18 °C: > 3 months
at 25 °C: 1 month

Engle 2020, Ni(COD)DQ

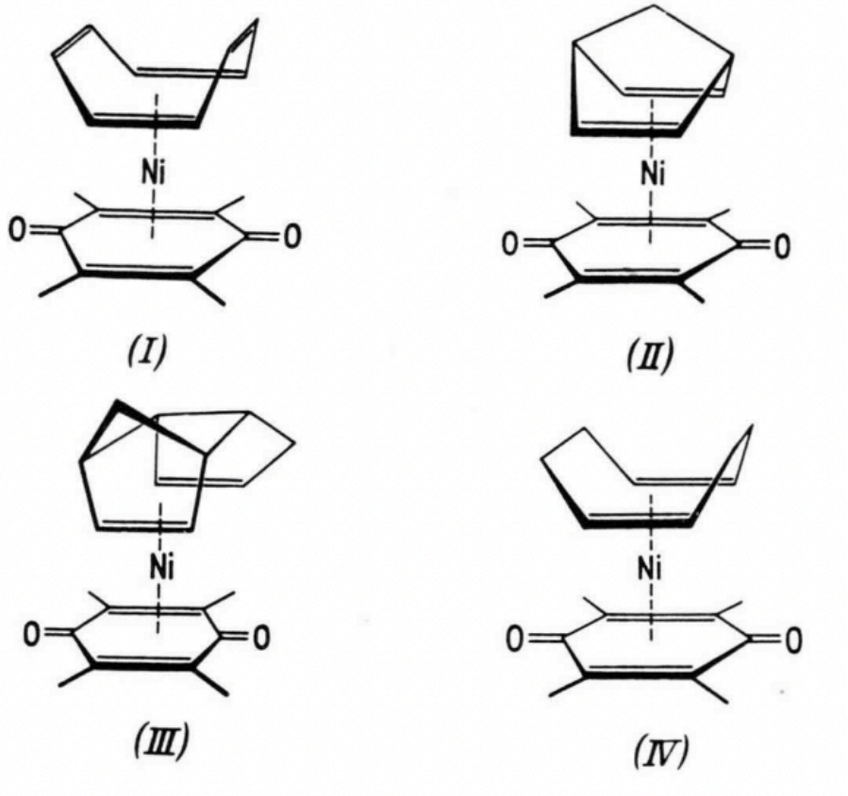
Engle 2020, Ni(COD)DQ



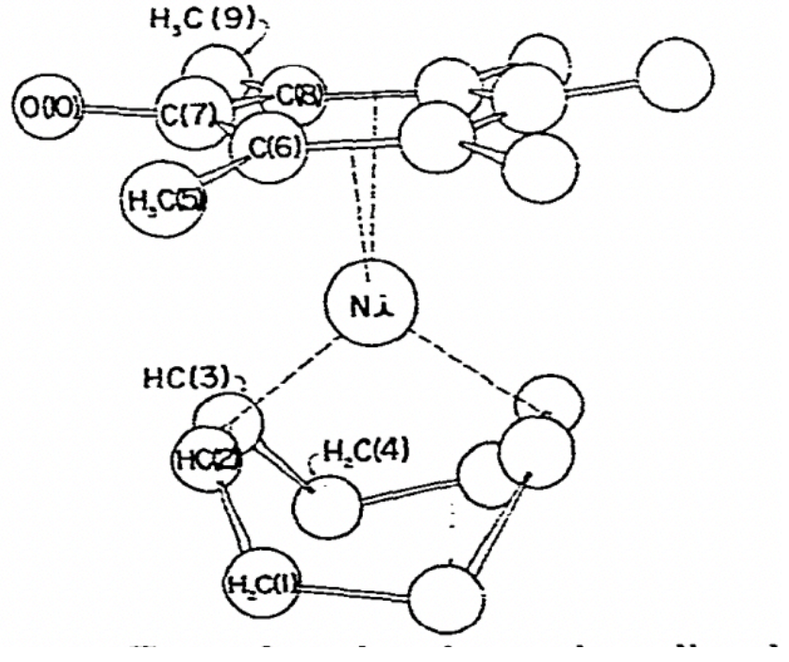
Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Precedent

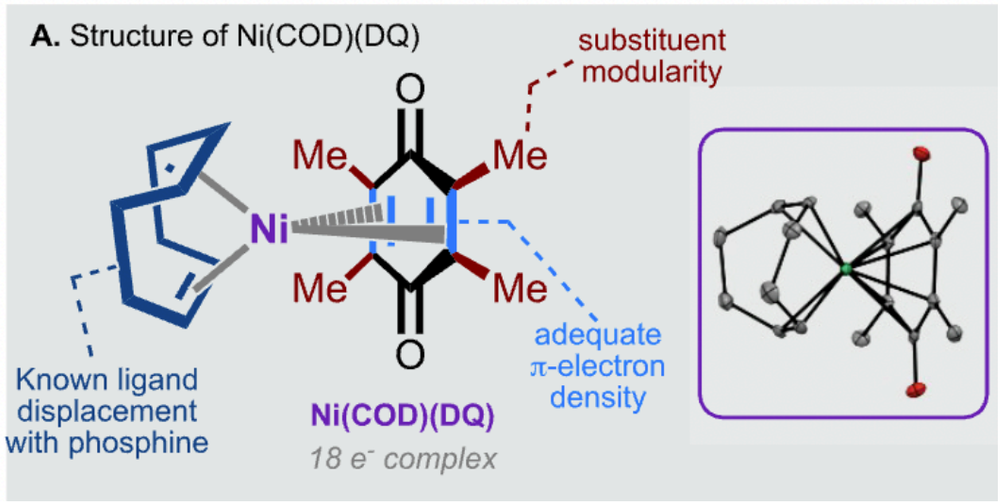
Schrauzer *et al. Naturforsch. B* **1962**, *17*, 73-76



Dahl *et al. J. Organometal. Chem.* **1965**, *3*, 200-221

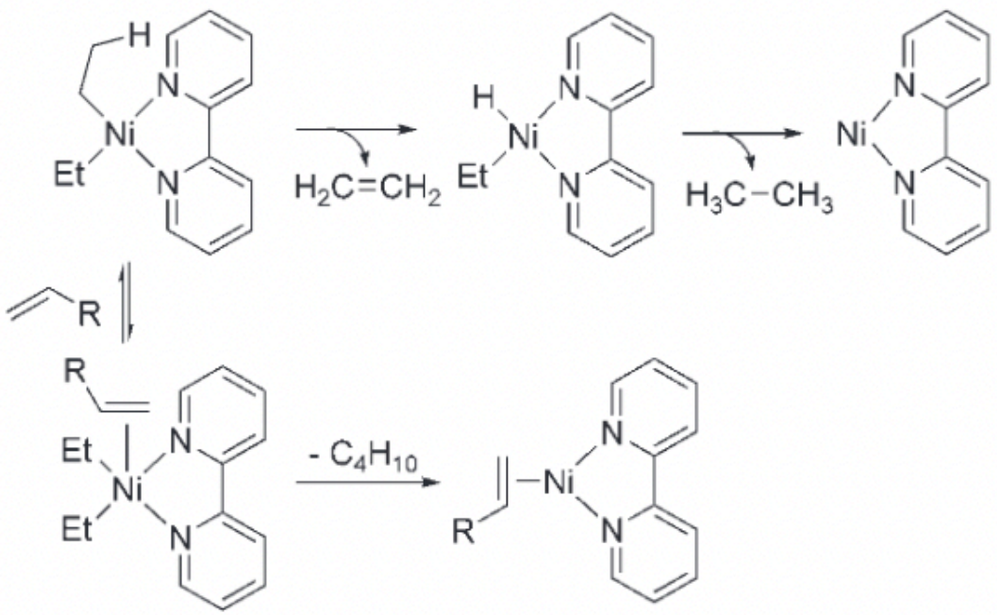


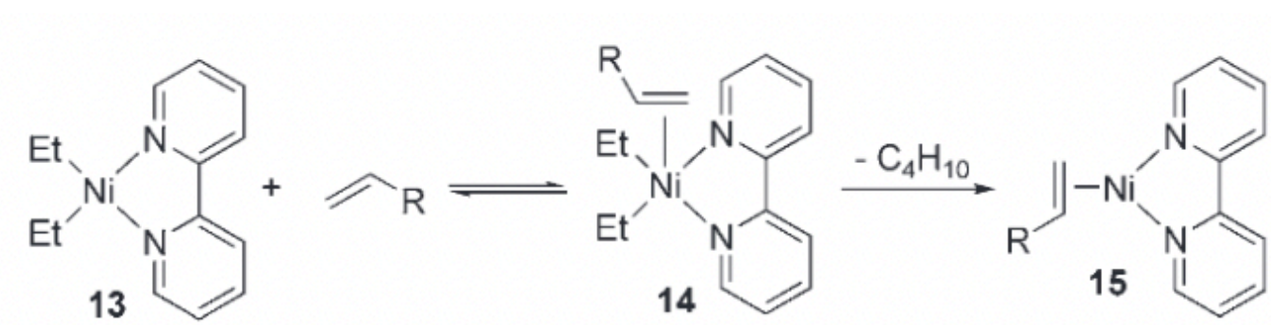
Engle 2020, Ni(COD)DQ

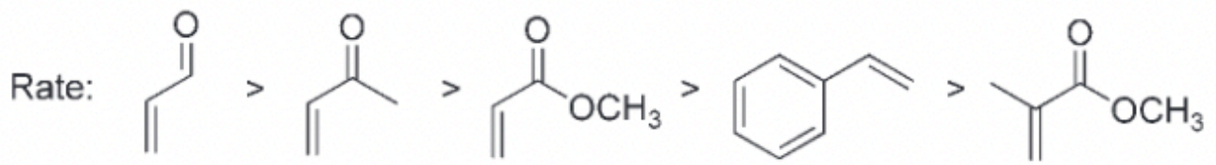


Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

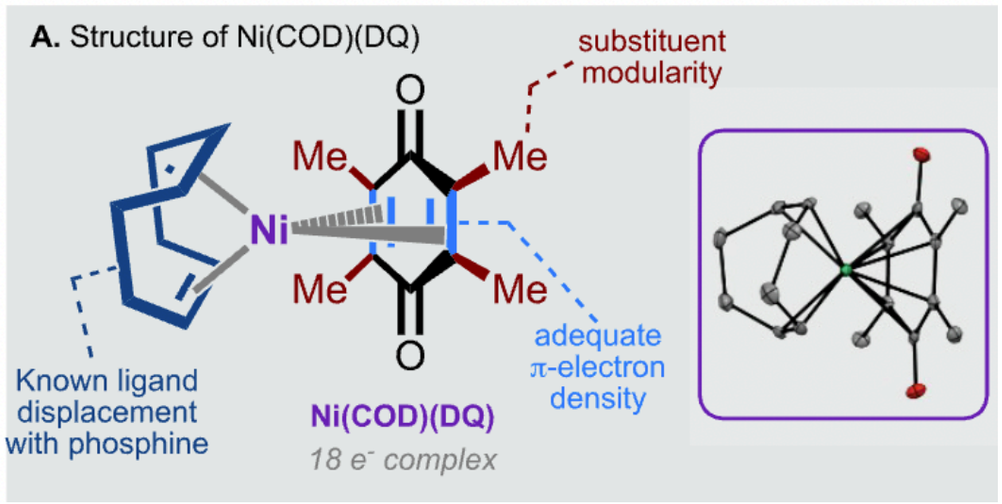
Precedent
Yamamoto *et al. JACS* **1971**, *93*, 3350
Rovis *et al. ACIE* **2008**, *47*, 840
(review)





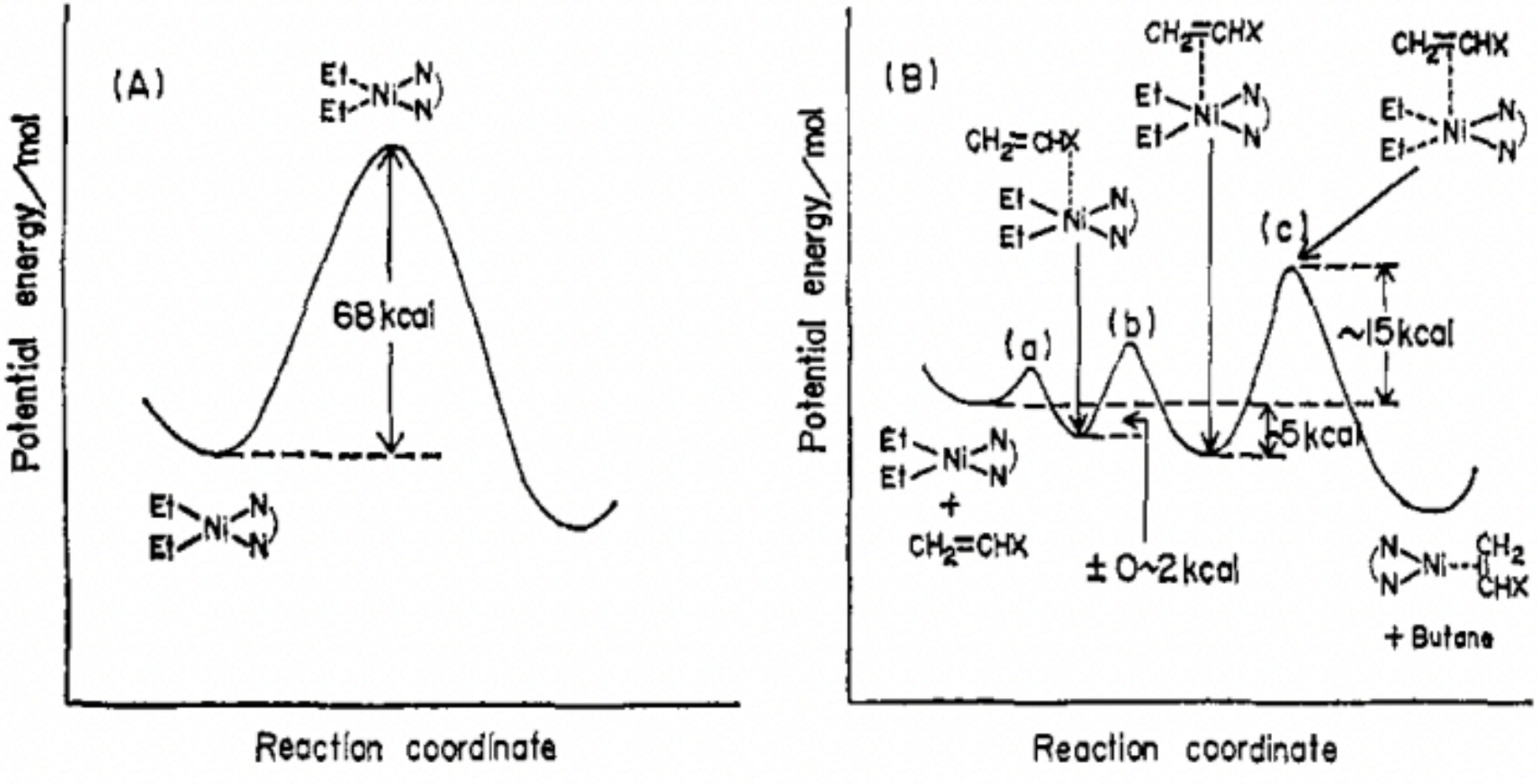


Engle 2020, Ni(COD)DQ

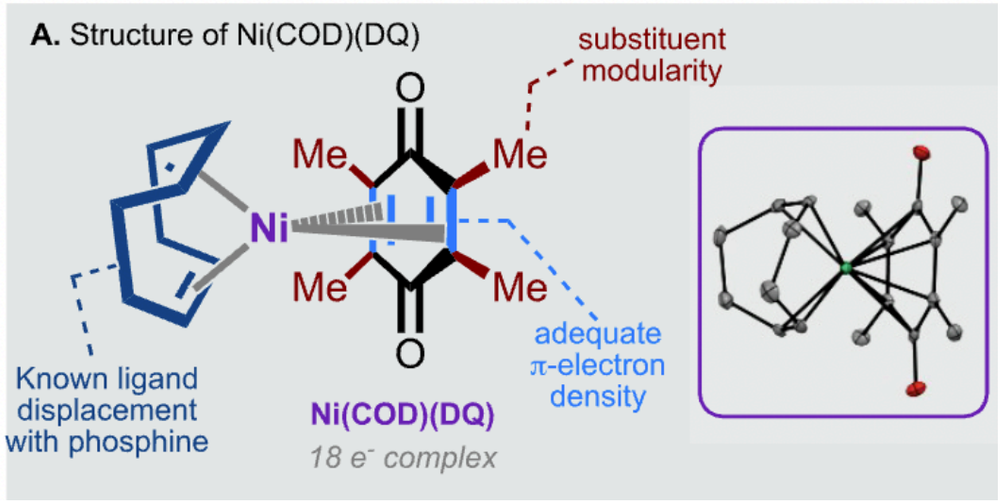


Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Precedent
Yamamoto *et al. JACS* **1971**, *93*, 3350



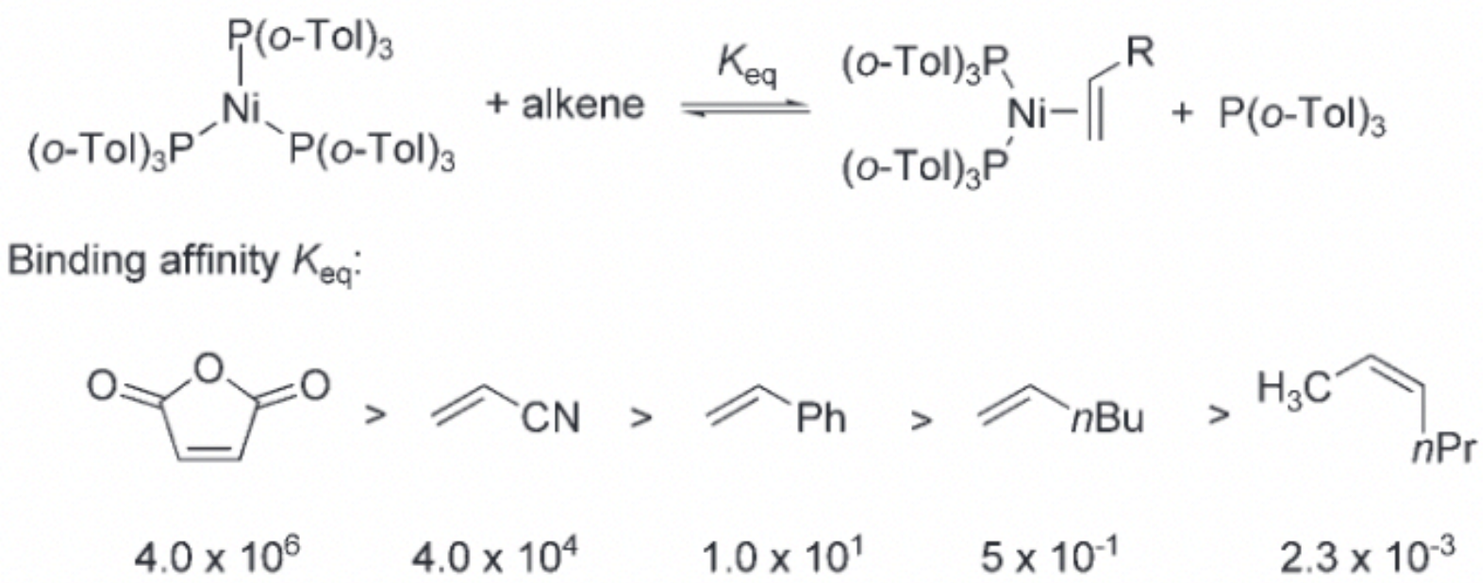
Engle 2020, Ni(COD)DQ



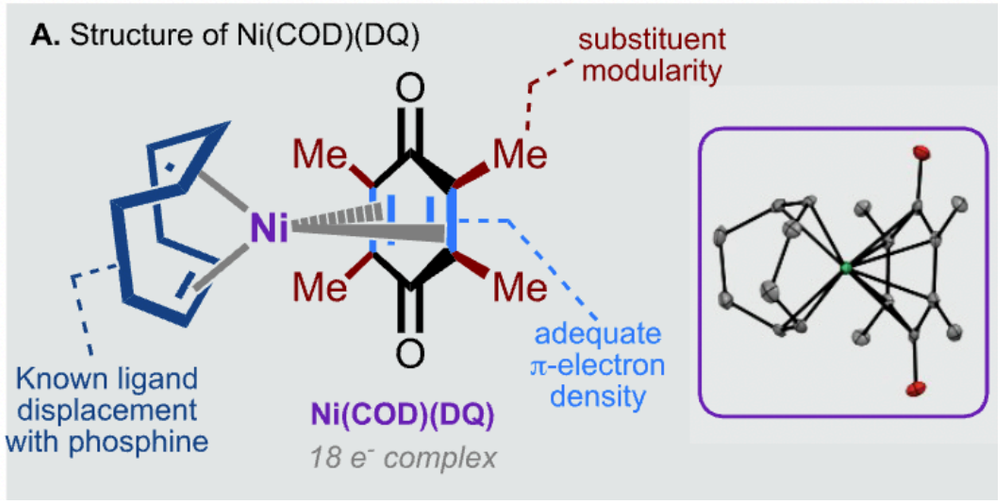
Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Precedent

Tolman *et al. JACS* **1974**, *96*, 2780
Rovis *et al. ACIE* **2008**, *47*, 840
(review)



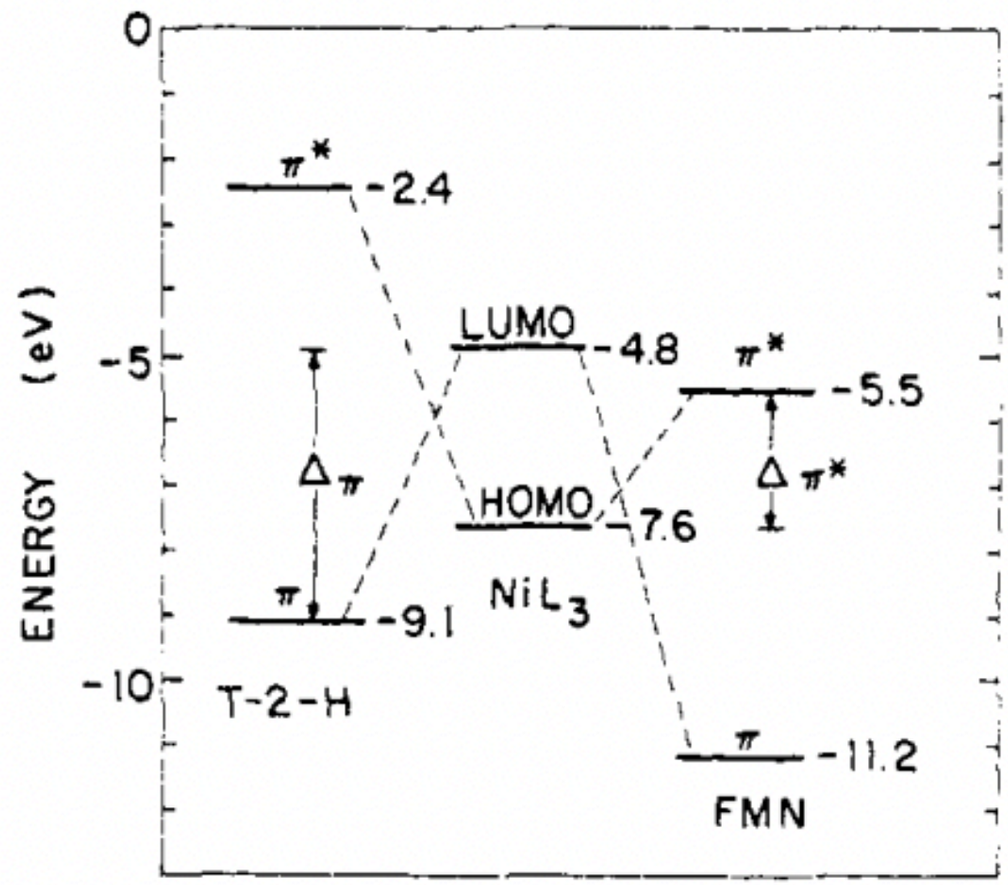
Engle 2020, Ni(COD)DQ

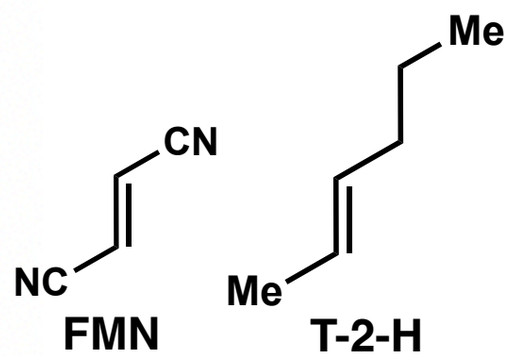


Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

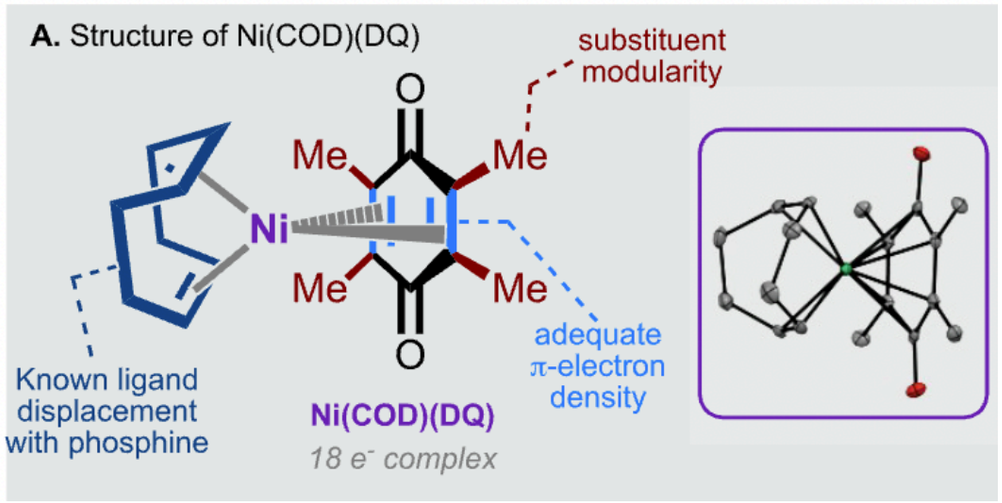
Precedent

Tolman *et al. JACS* **1974**, *96*, 2780



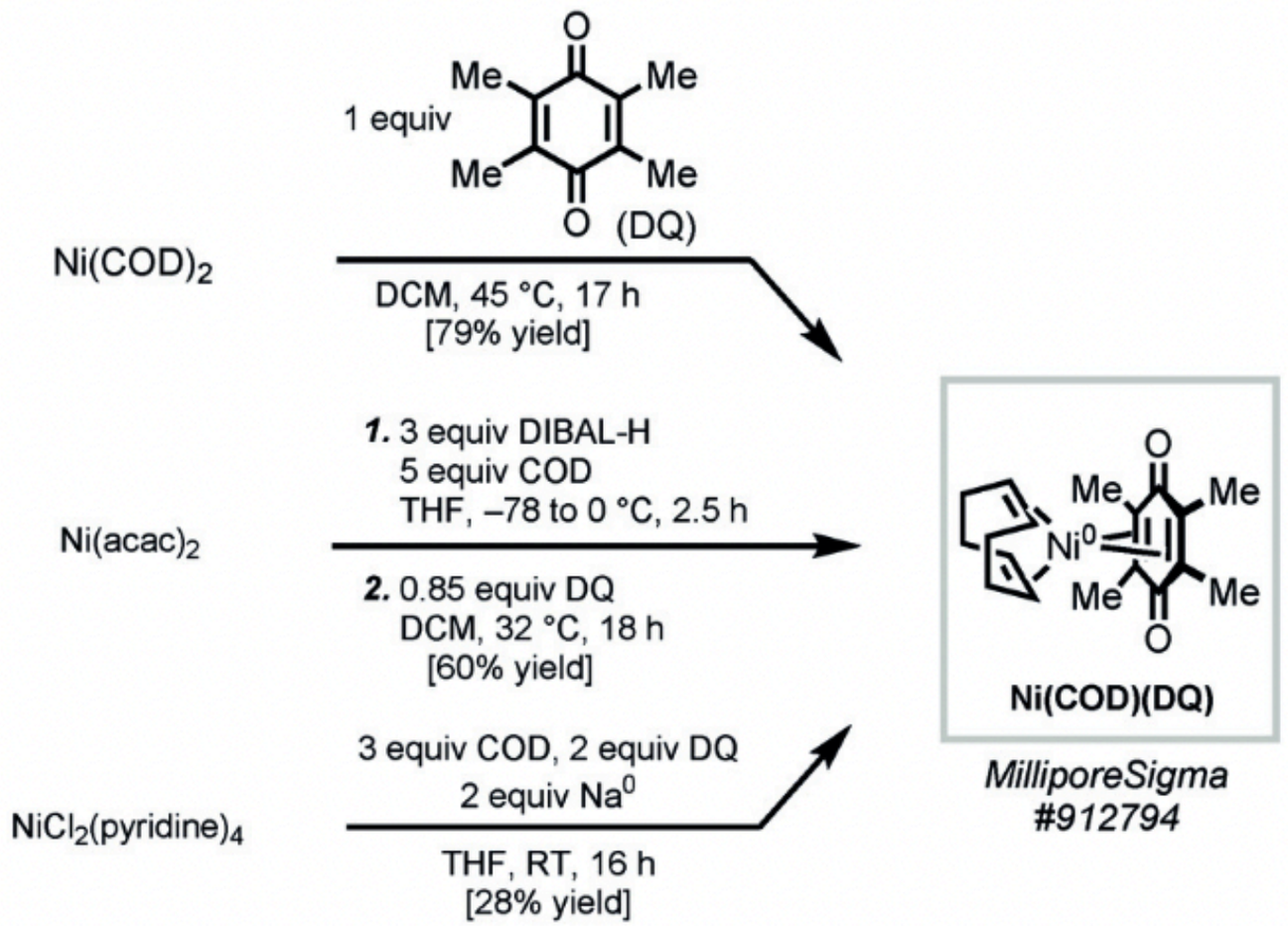


Engle 2020, Ni(COD)DQ

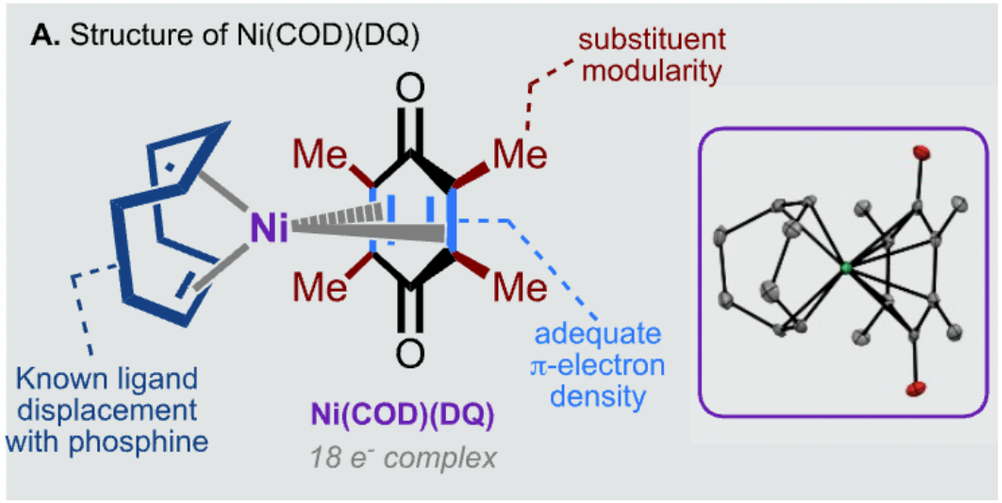


Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Preparation

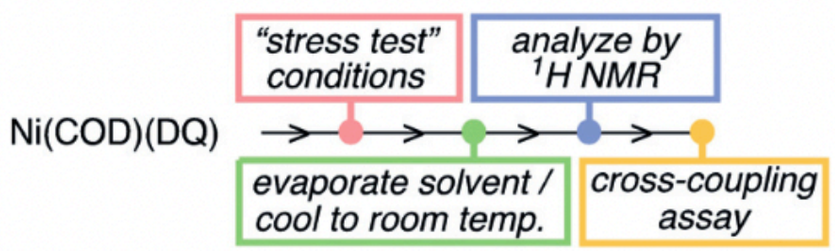


Engle 2020, Ni(COD)DQ



Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

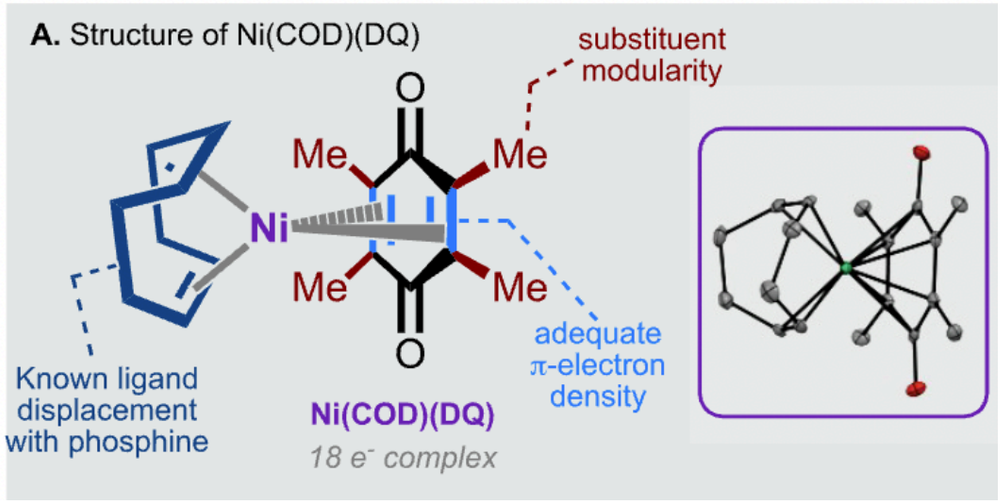
Notes on stability



Entry	Conditions	Yield of **1a** (%)
1	(none)	>99
2	MeOH, air, 5 h	94
3	H_2O, air, 5 h	98
4	MeOH/H_2O, air, 5 h	>99
5	oven (90 °C), air, 4 h	98
6	silica gel, air	95

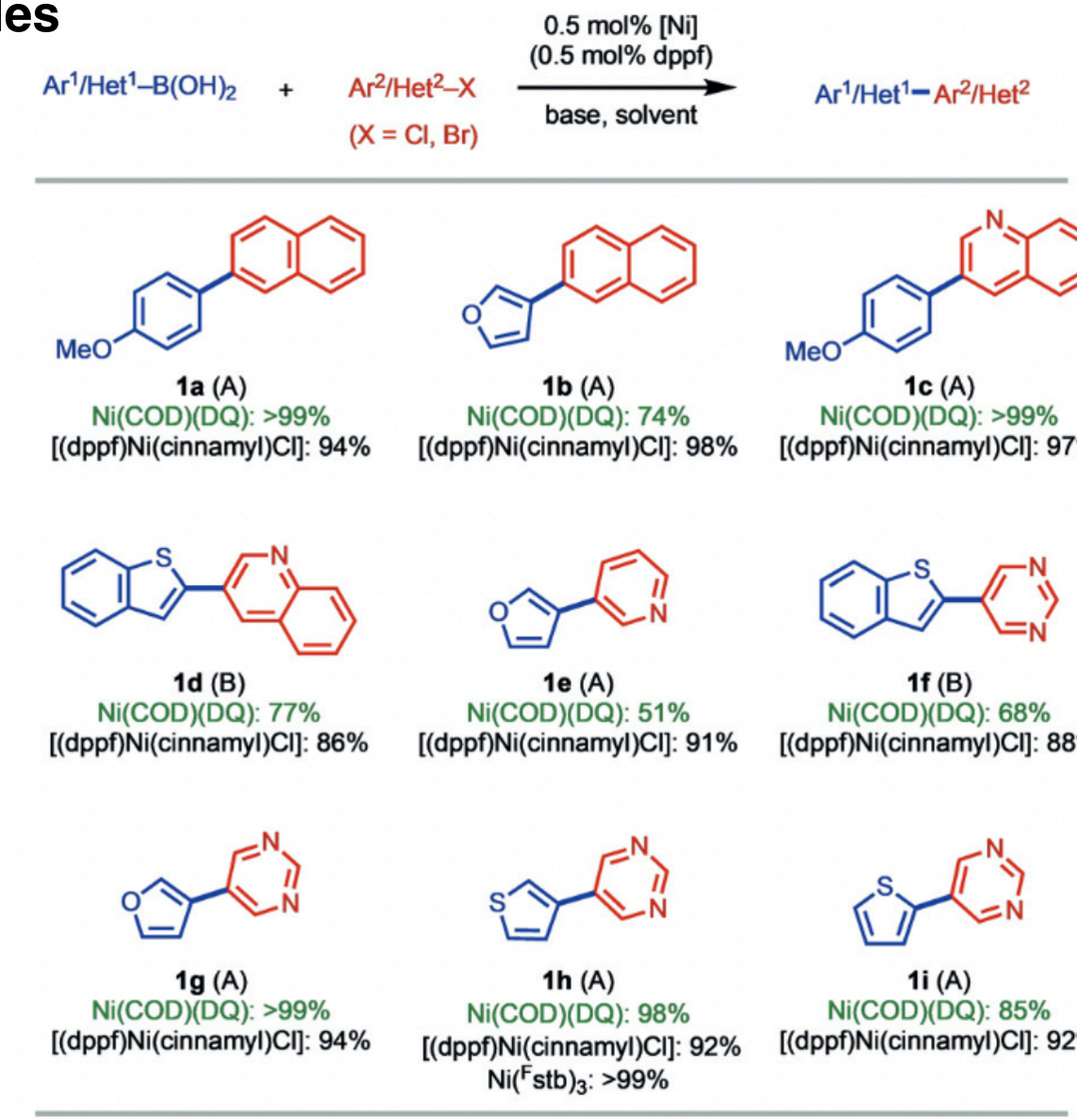
And >3 months solid state

Engle 2020, Ni(COD)DQ

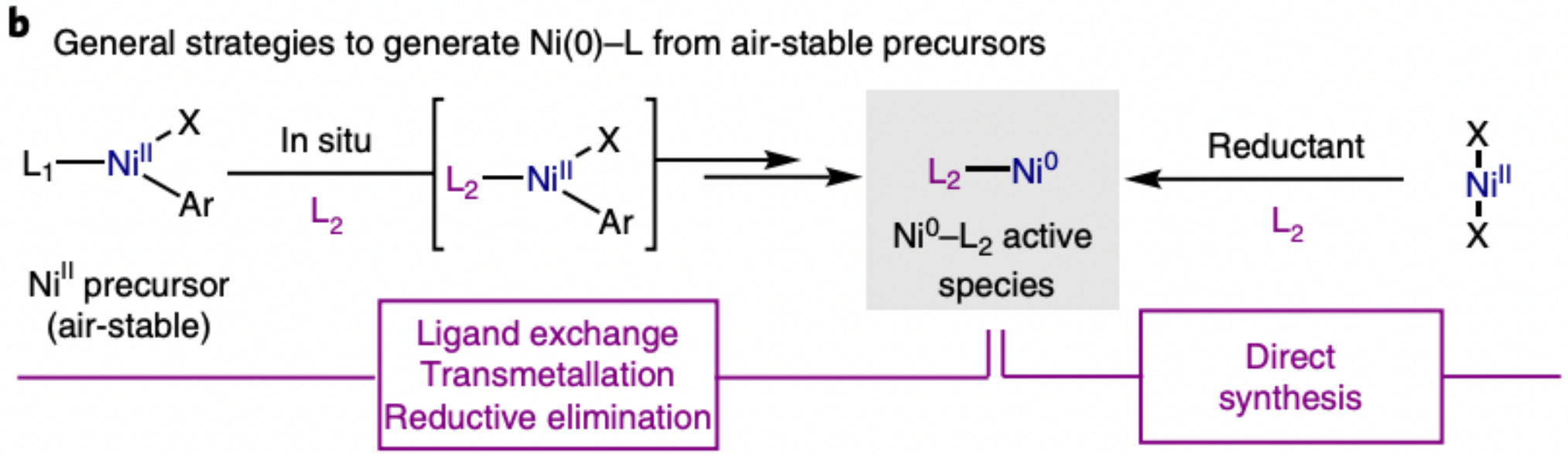


Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Examples



Conclusion



Doyle *et al*. *OL* **2015**, *17*, 2166–2169

Yang *et al*. *Tetrahedron Lett.* **2007**, *48*, 2427

Yang *et al*. *JOC.* **2007**, *72*, 6324

Hartwig *et al. ACIE* **2012**, *51*, 12837

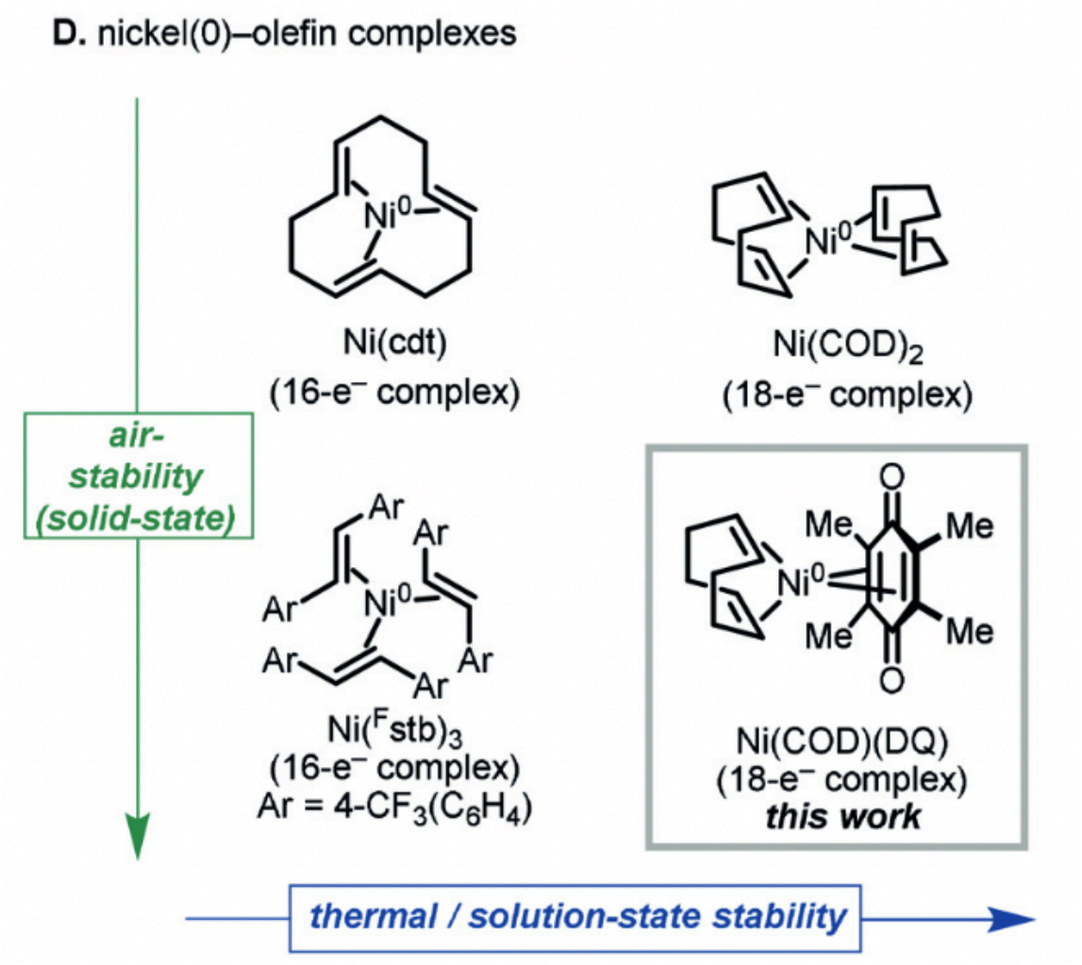
Jamison *et al. JACS* **2013**, *135*, 1585

Buchwald *et al. OL* **2014**, *16*, 220

Jamison *et al. ChemCatChem* **2018**, *10*, 2873

Jamison *et al. Organometallics* **2018**, *37*, 2716

Conclusion



Cornella *et al. Organometallics* **2020**, *39*, 3295
Cornella *et al. Nat. Catal.* **2020**, *3*, 6

Engle *et al. ACIE* **2020**, *59*, 7409
Engle *et al. ACR* **2024**, *57*, 312

Supporting Information