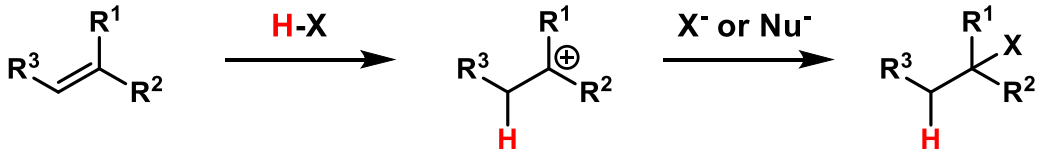
Mechanistic Studies into Cobalt-Nickel Catalyzed Olefin Hydroarylation

Jacob Lacharity

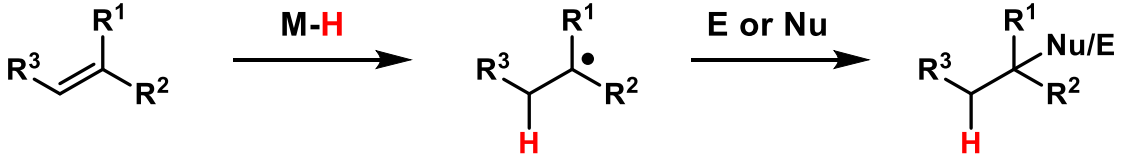
Current Topics in Organic Chemistry
Zakarian Group Meeting
October 4th, 2018

Hydrogen Atom Transfer (HAT) vs Markonikov Hydration:

Markovnikov hydrofunctionalization:

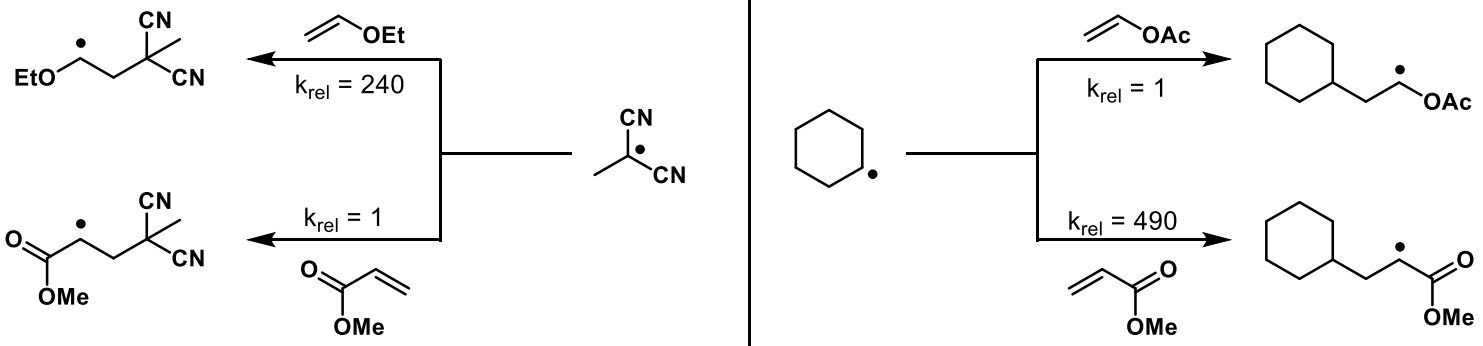


Metal-Hydride HAT:

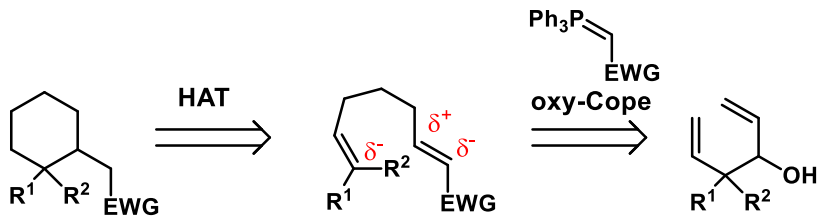


Shenvi, R.A. *Chem. Rev.* **2016**, *116*, 8912-9000.

Polarity Reversal for Radical Functionalizations:

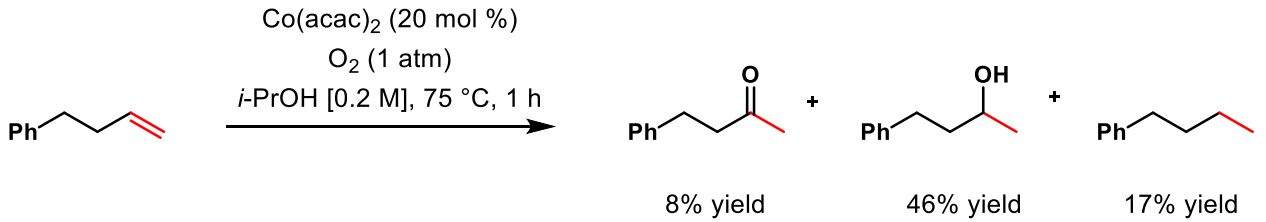


Implications for synthesis planning:

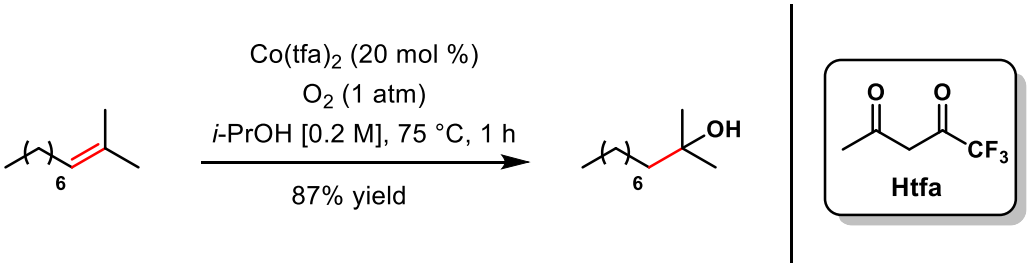


Shenvi, R.A. *Chem. Rev.* **2016**, *116*, 8912-9000.

The Mukaiyama Hydration:



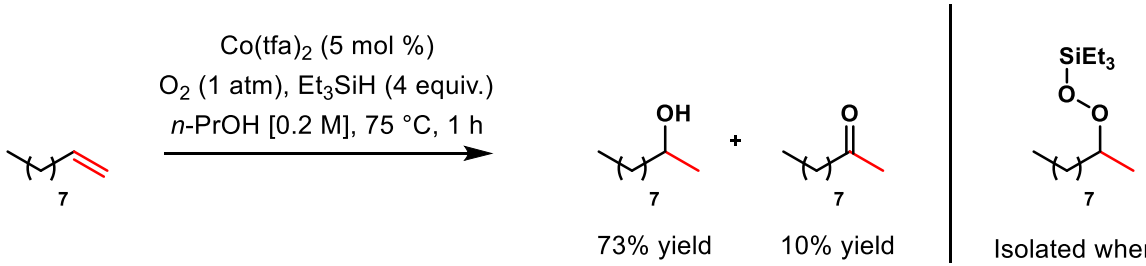
Mukiyama, T. *Chem. Lett.* **1989**, *18*, 449–452.



- ***Co^{II} redox potential is a critical parameter***
- ***0-0.5 V potential required for catalytic activity***

Mukiyama, T. *Chem. Lett.* **1989**, *18*, 515–518.

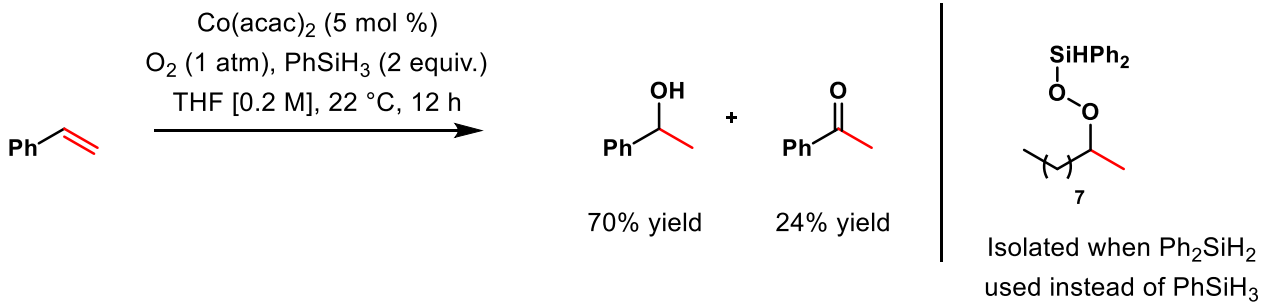
Isayama, S. *Bull. Chem Soc. Jpn.* **1990**, *63*, 179–186.



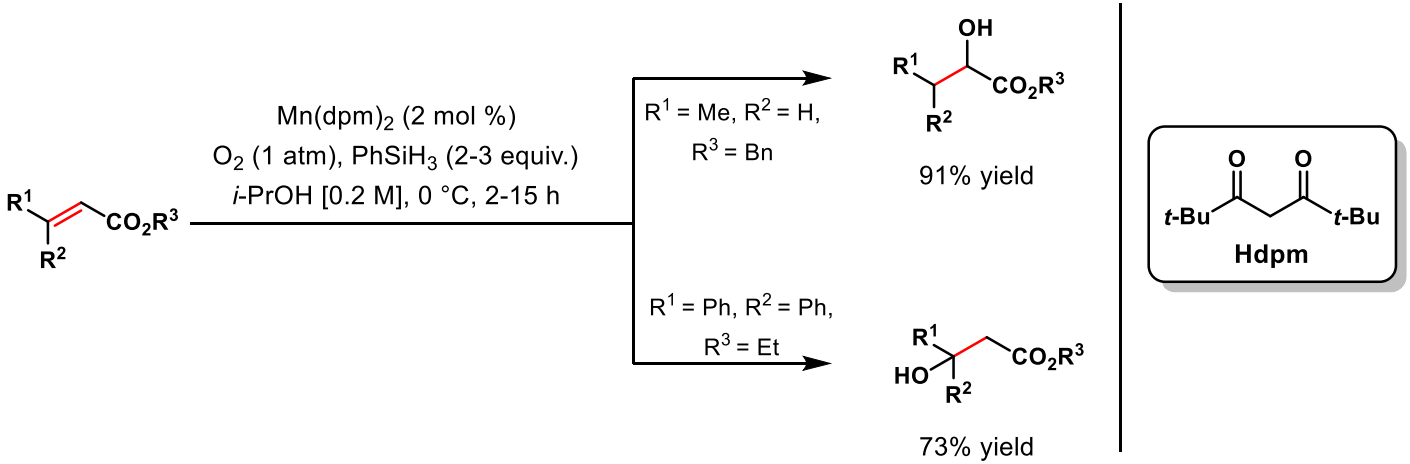
Isolated when $(CH_2Cl)_2$ used instead of *n*-PrOH

Mukiyama, T. *Chem. Lett.* **1989**, *18*, 569–572.
Mukiyama, T. *Chem. Lett.* **1989**, *18*, 573–576.
Isayama, S. *Bull. Chem. Soc. Jpn.* **1990**, *63*, 1305-1310.
Mukaiyama, T. *Chem. Lett.* **1989**, *18*, 1071-1074.

The Mukaiyama Hydration:

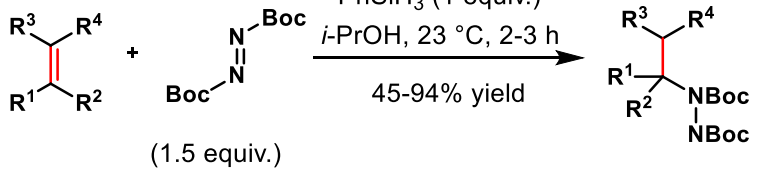


Mukaiyama, T. *Chem. Lett.* **1989**, *18*, 1071-1074.

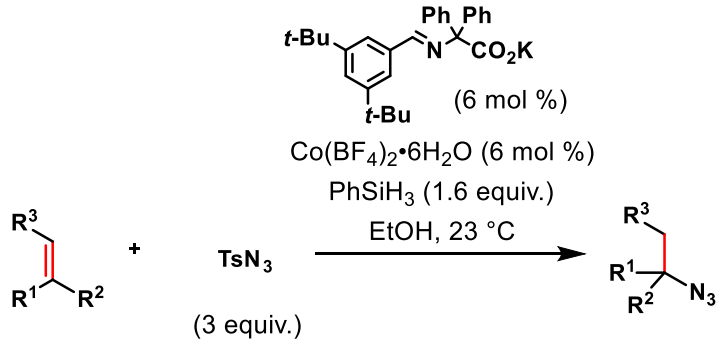


Mukaiyama, T. *Chem. Lett.* **1990**, *19*, 1869-1972.

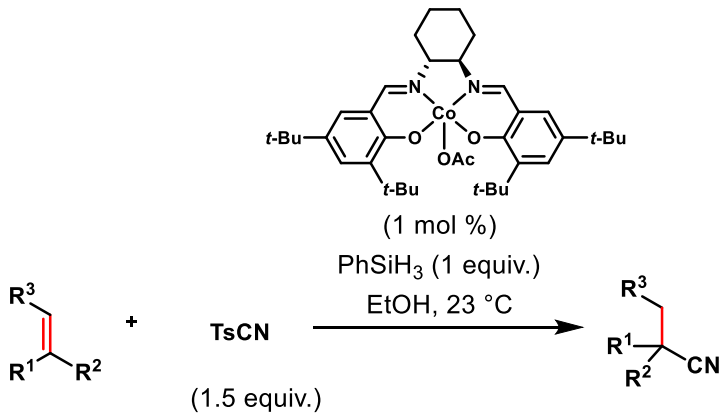
Extensions of Mukaiyama's Seminal Work:



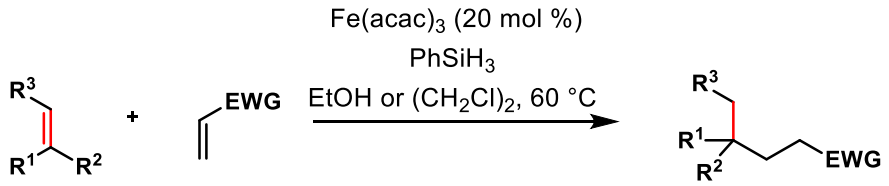
Carreira, E.M. *Angew. Chem. Int. Ed.* **2004**, *43*, 4099-4102



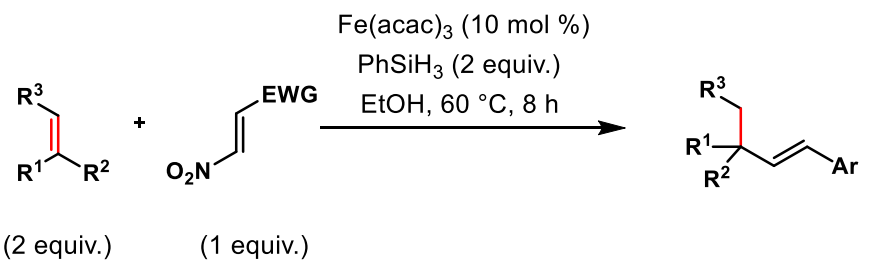
Carreira, E.M. *J. Am. Chem. Soc.* **2006**, *128*, 11693-11712.



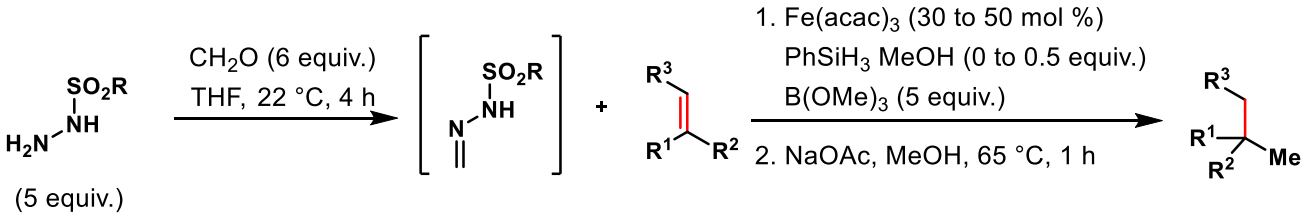
Carreira, E.M. *Angew. Chem. Int. Ed.* **2009**, *131*, 13214-13215



Baran, P.S. *J. Am. Chem. Soc.* **2014**, *136*, 1304-1307.

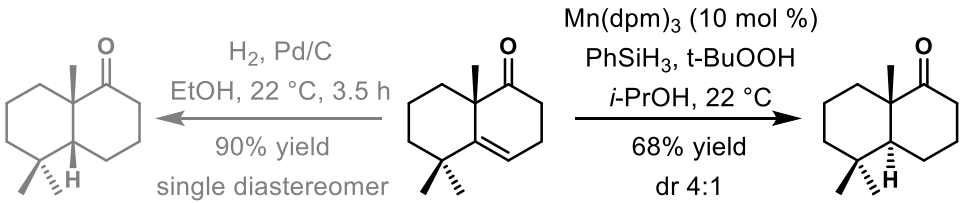


Cui, S. *Org. Lett*. **2015**, *17*, 4572–4575.

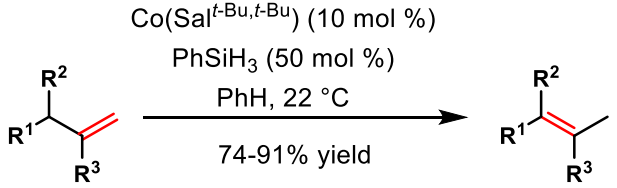


Baran, P.S. *J. Am. Chem. Soc.* **2015**, *137*, 8046–8049.

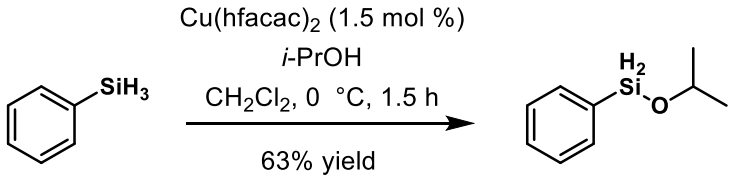
Shenvi's Work:



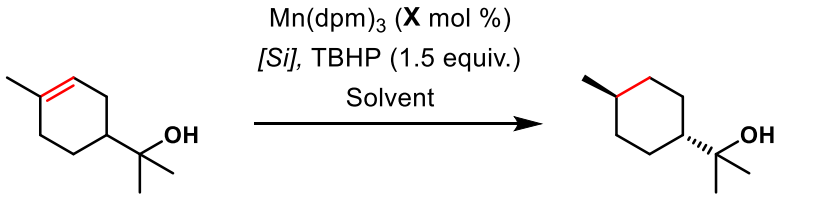
Shenvi, R.A. *J. Am. Chem. Soc.* **2014,** *136,* 1300-1303.



Shenvi, R.A. *J. Am. Chem. Soc.* **2014**, *136,* 16788−16791.



isopropoxy(phenyl)silane



$Mn(dpm)_3$ (10 mol %)
$PhSiH_3$ (1 equiv.), *i*-PrOH, 22 °C, 1 h

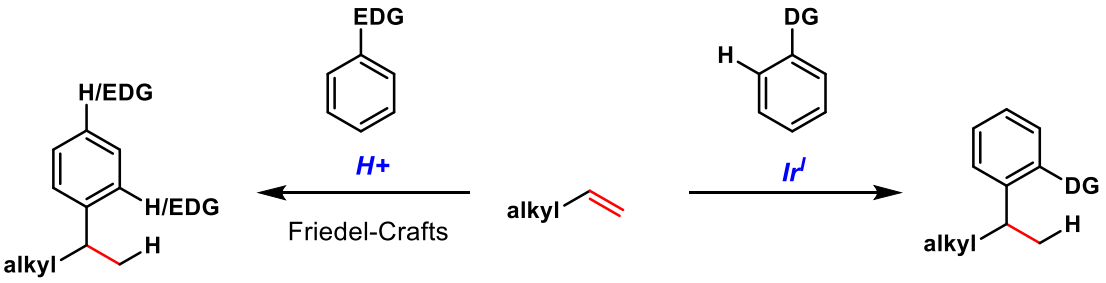
89% yield, dr 7.5:1

$Mn(dpm)_3$ (1 mol %)
$Ph(i\text{-}PrOSiH_2)$ (1.5 equiv.),
hexanes, –30 °C, 1 h

71% yield, dr 11.3:1

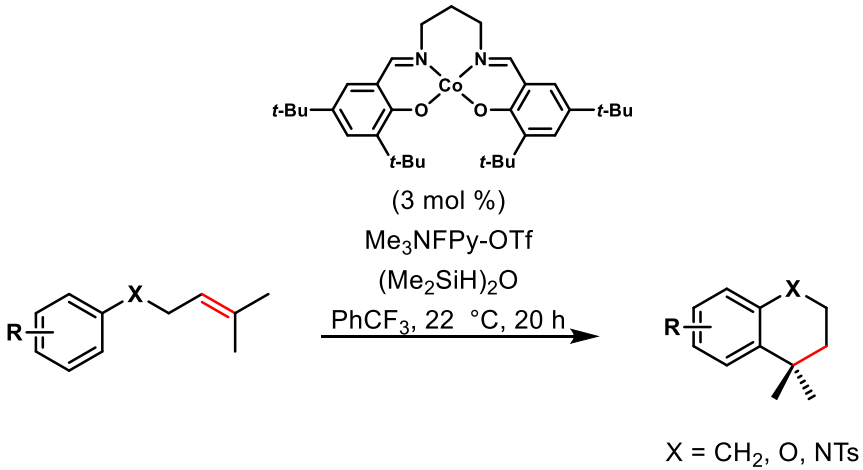
Shenvi, R.A. *J. Am. Chem. Soc.* **2016,** *138,* 4692-4971.

Branch-Selective Hydroarylation of Unactivated Olefins:

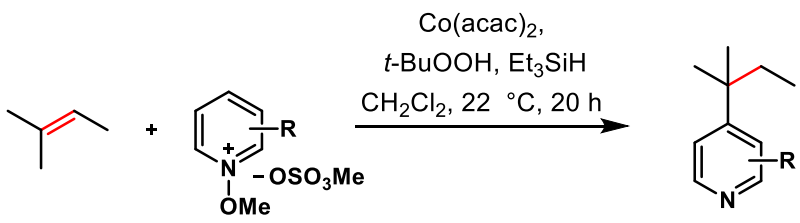


Fagnou, K. *Science of Synthesis* **2010,** *45,* 627.

Bower. J.F.. *J. Am. Chem. Soc.* **2014***, 136,* 10258.
Bower. J.F. *Angew. Chem. Int. Ed.*. **2015***, 54,* 14866.
Shibata, T. *J. Am. Chem. Soc.* **2012***, 134,* 17474.
Nishimura, T. *J. Am. Chem. Soc.* **2015***, 137,* 5899.
Nishimura, T. *J. Am. Chem. Soc.* **2016**, *138*, 4010.



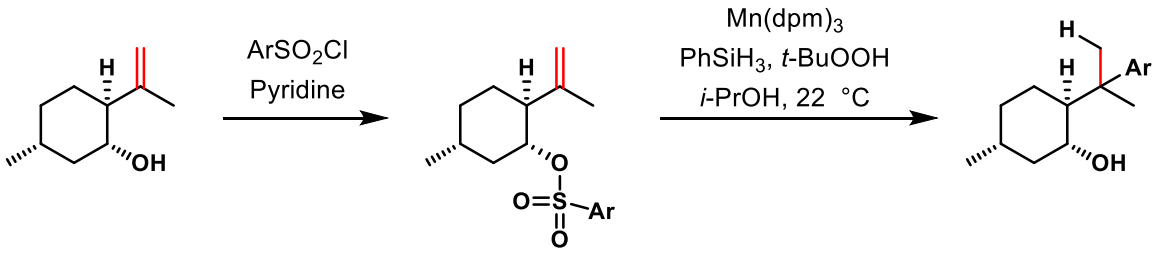
Shigehisa, H. *Org. Lett.* **2016,** *18,* 3622-3625.



Herzon, S.B. *J. Am. Chem. Soc.* **2016,** *138,* 8718-8721.

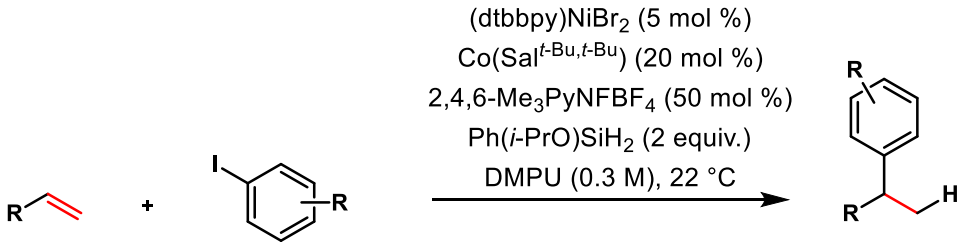
Shenvi's Hydroarylations:

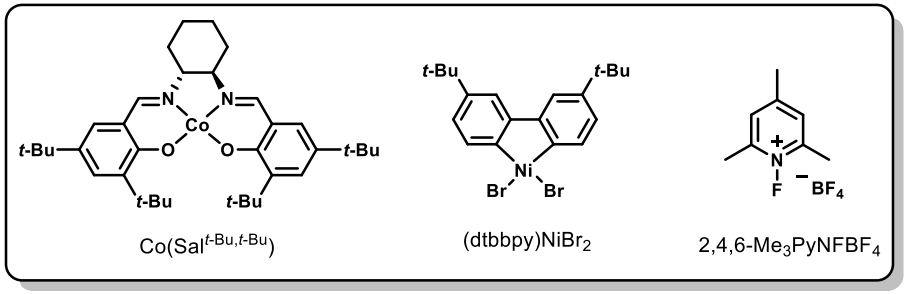
Intramolecular variant:



Shenvi, R.A. *Org. Lett.* **2016,** *18,* 2620-2623.

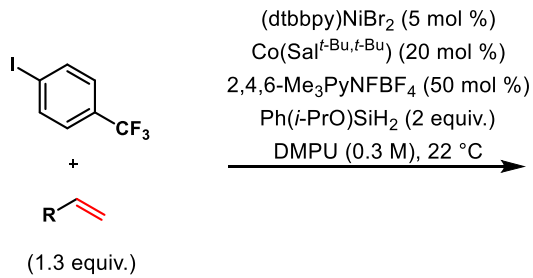
Intermoleular Variant:

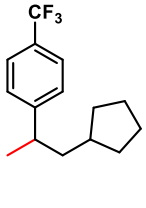




Shenvi, R.A. *J. Am. Chem. Soc.* **2016,** *138,* 12779-12782.

Scope of the Hydroarylation:





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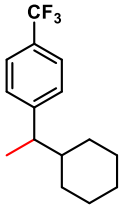

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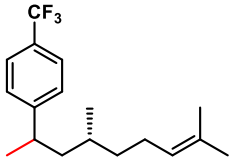

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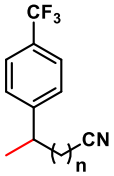
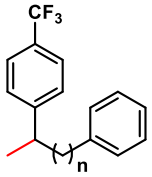
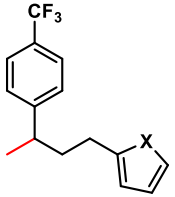


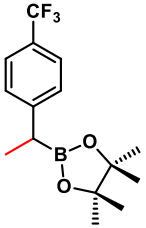
n = 1 31%
n = 2 75%



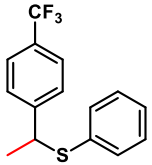
n = 1 66%
n = 2 70%



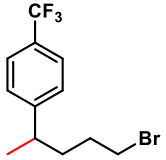
X = O 68%
X = S 65%



33%



42%



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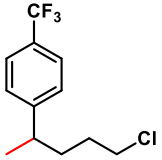
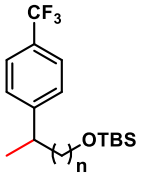
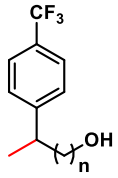


67%



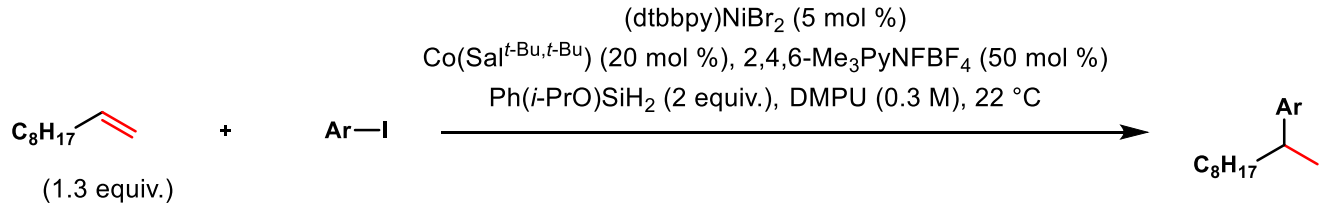
n = 1 43%
n = 2 86%

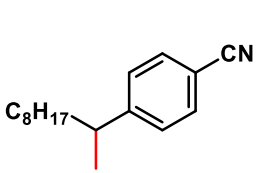


n = 1 20%
n = 2 36%
n = 3 53%

Shenvi, R.A. *J. Am. Chem. Soc.* **2016,** *138,* 12779-12782.

Scope of the Hydroarylation (Cont'd):





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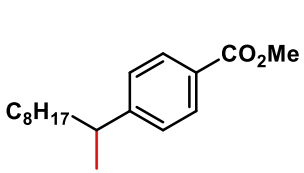

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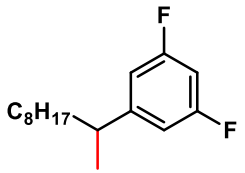
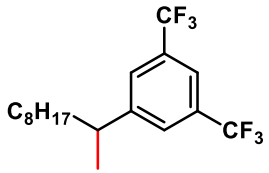


70%



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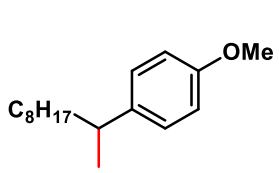

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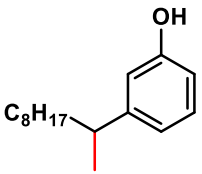
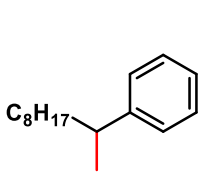
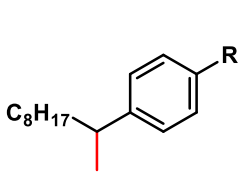


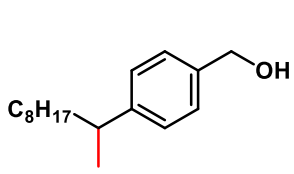
68%



55%



R = Me 48%
R = *i*-Pr 47%



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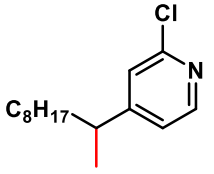

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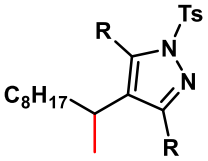
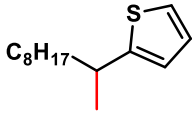
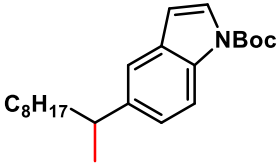


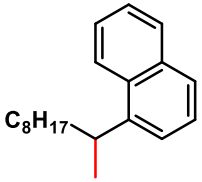
R = H 67%
R = Me 0%



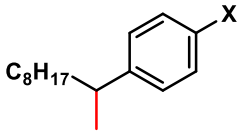
62%



59%



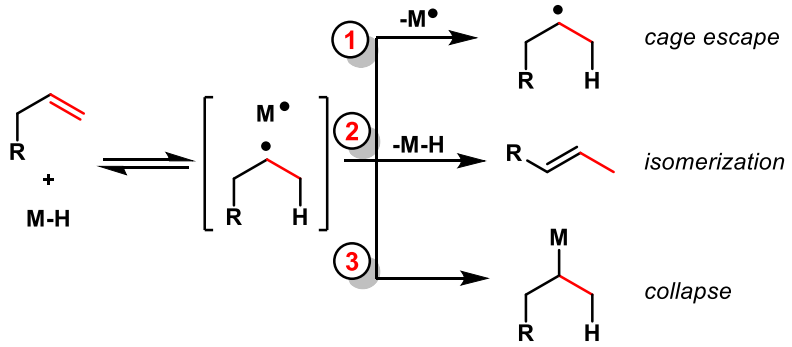
32%



X = Cl 68%
X = F 0%

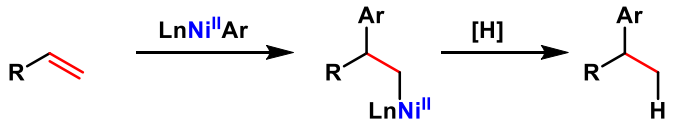
Shenvi, R.A. *J. Am. Chem. Soc.* **2016,** *138,* 12779-12782.

Mechanistic Possibilities:

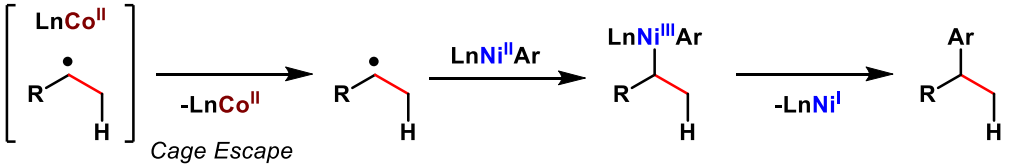


- *MH-HAT mechanism proposes reversible formation of C-radical/ metal pair*
- *Three available possibilities for this caged pair*
- *Unclear whether 1st or 3rd pathway operating in this circumstance*

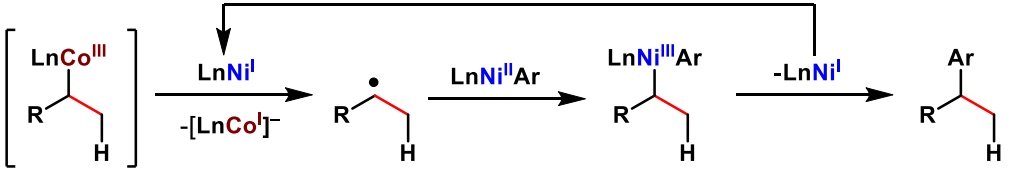
a) Ni-Catalyzed Reductive Heck



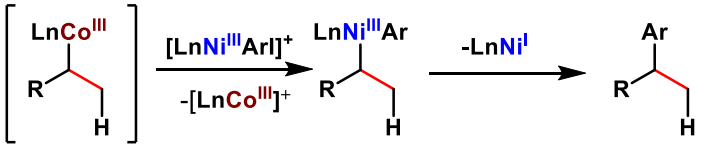
b) Radical Cage Escape



c) Radical Chain

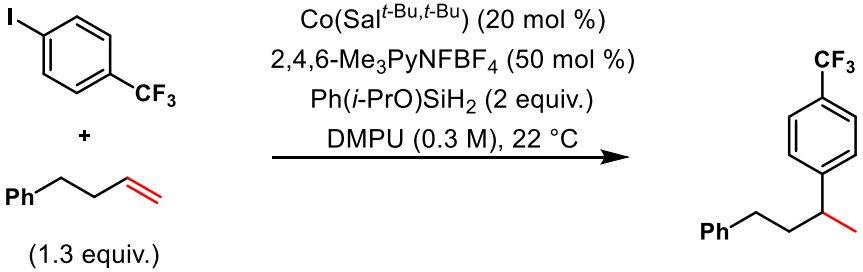


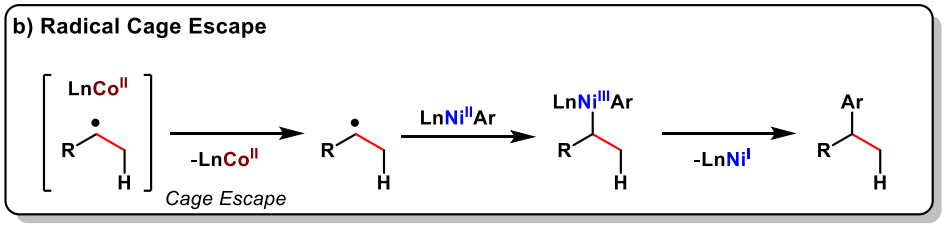
d) Cage rebound

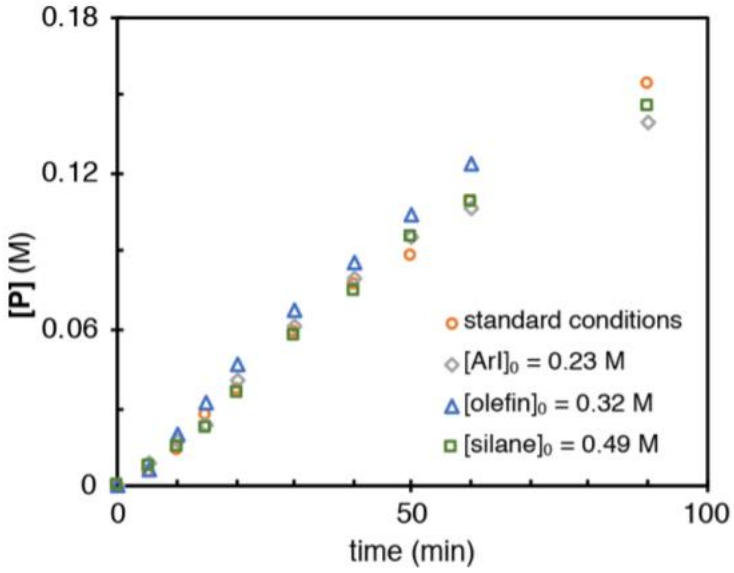


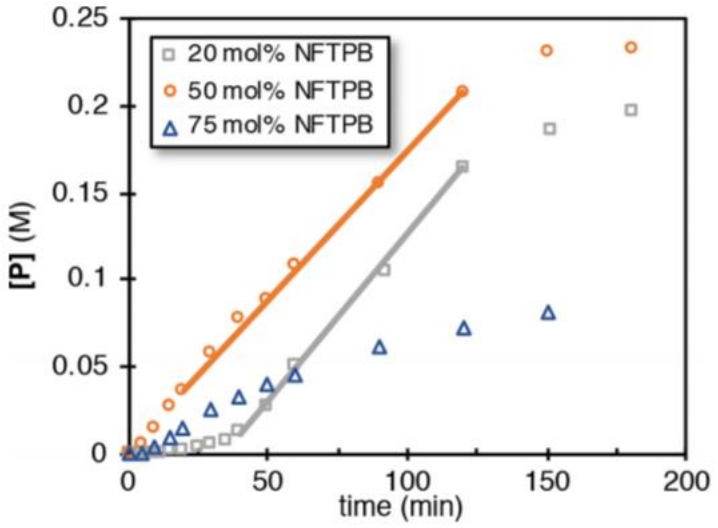
Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

Exclusion of the Cage-Escape Pathway:









Standard concentrations:
$[ArI]_0 = 0.32$ M
$[olefin]_0 = 0.42$ M
$[silane]_0 = 0.64$ M

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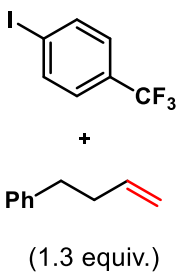
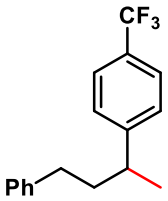
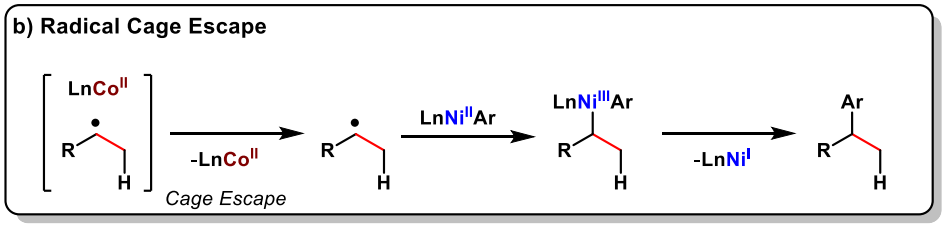
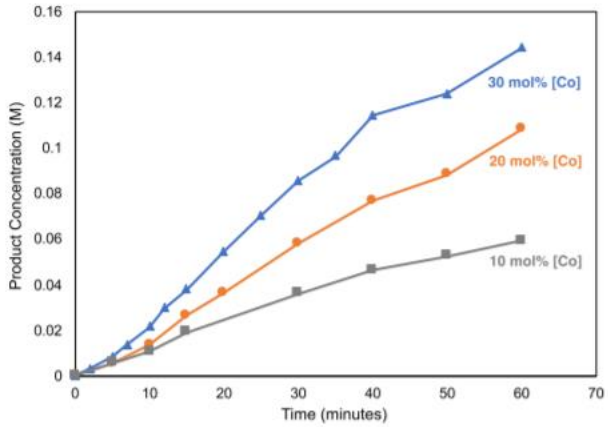
Exclusion of the Cage-Escape Pathway:

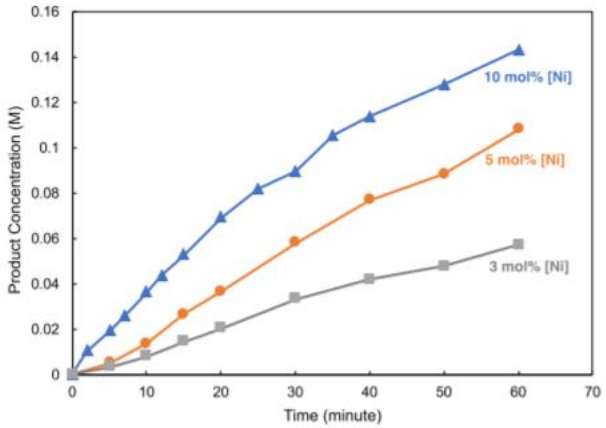


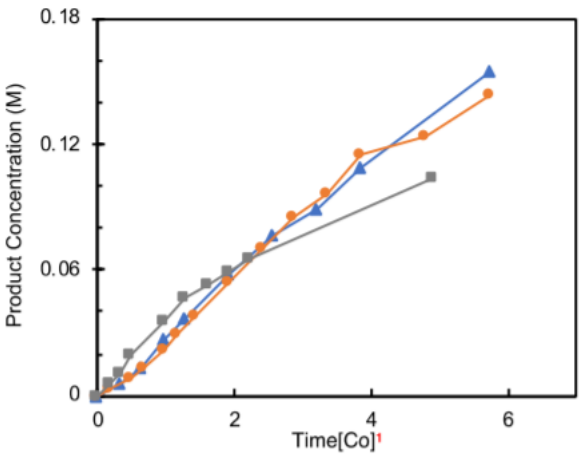
(dtbbpy)$NiBr_2$ (5 mol %)
$Co(Sal^{t\text{-}Bu,t\text{-}Bu})$ (20 mol %)
2,4,6-$Me_3PyNFBF_4$ (50 mol %)
Ph(*i*-PrO)SiH_2 (2 equiv.)
DMPU (0.3 M), 22 °C

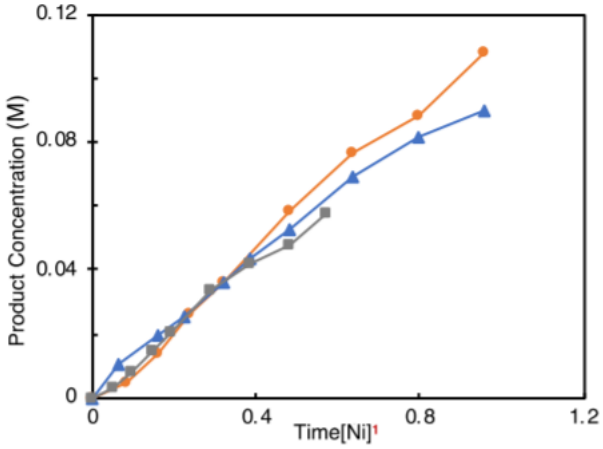






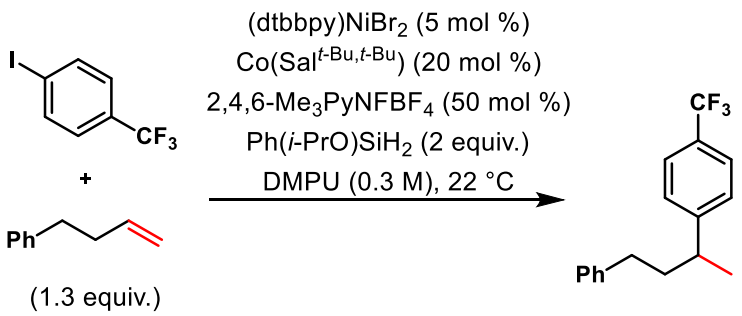


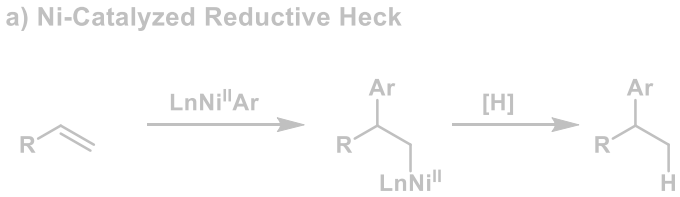


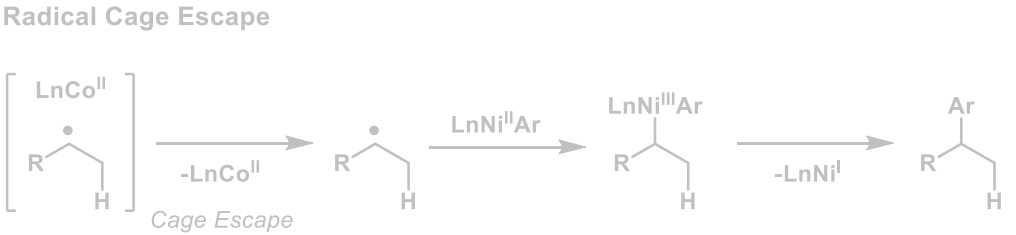


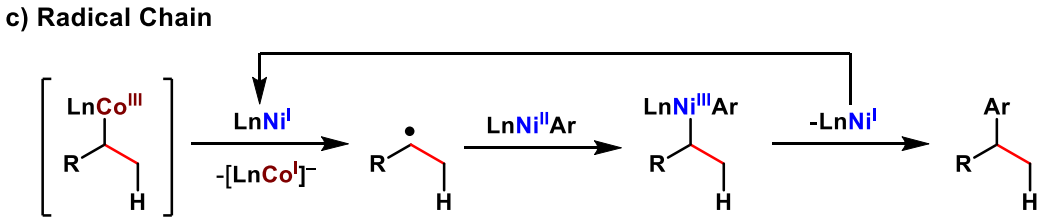
Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

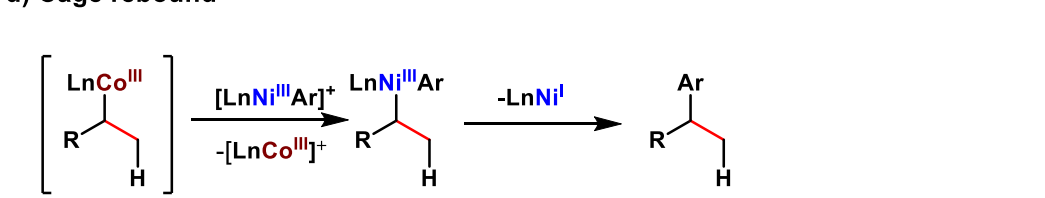
Exclusion of the Cage-Escape Pathway:





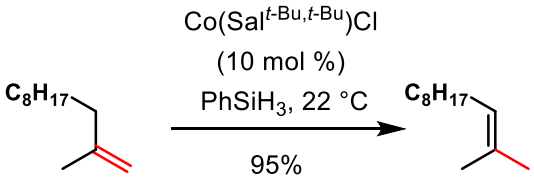


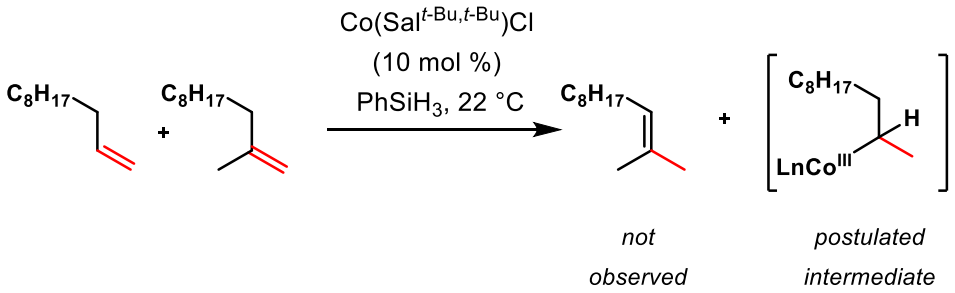


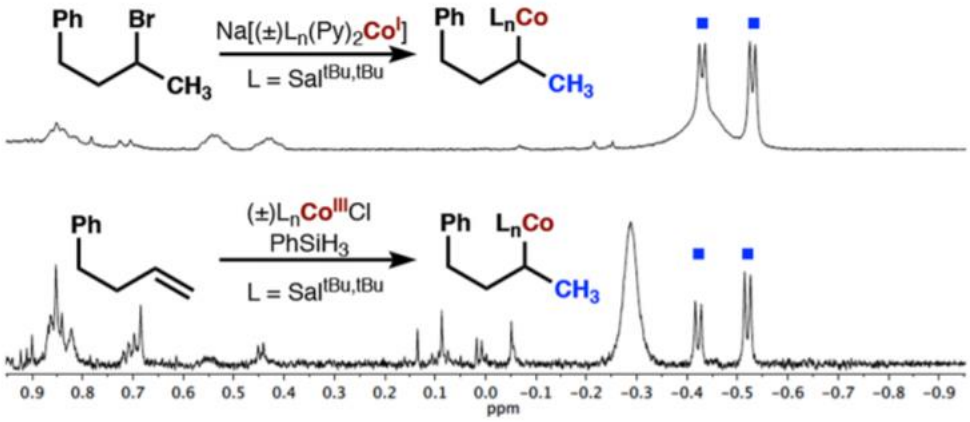


Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

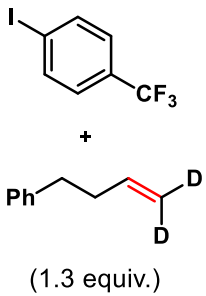
Evidence for an Organocobalt Species:

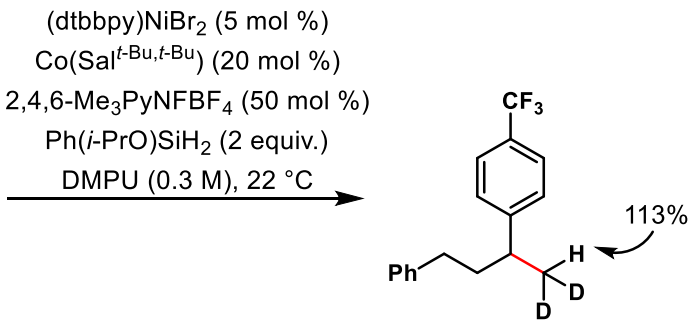






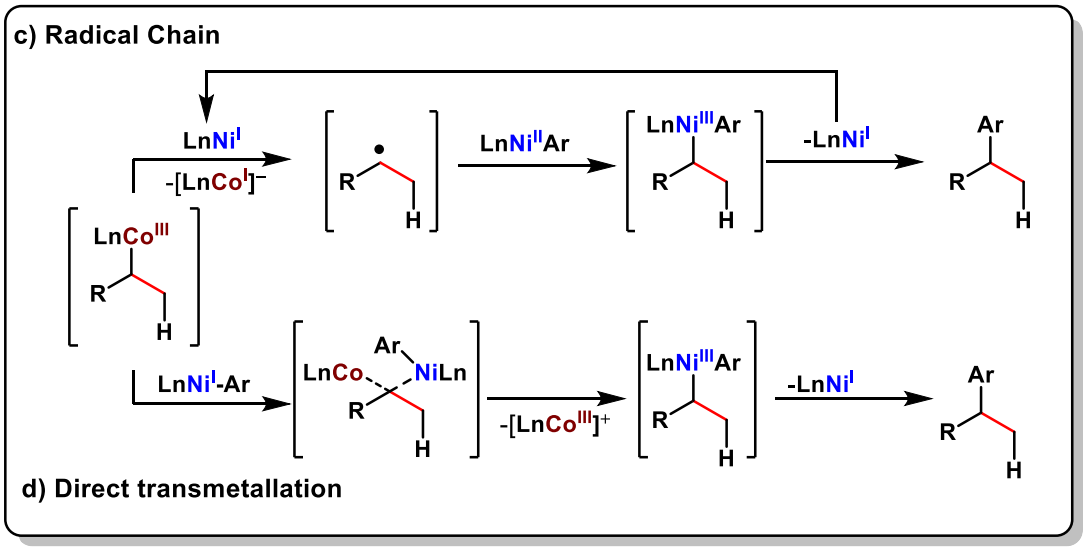
Ln= (Sal$^{t\text{-Bu},t\text{-Bu}}$)

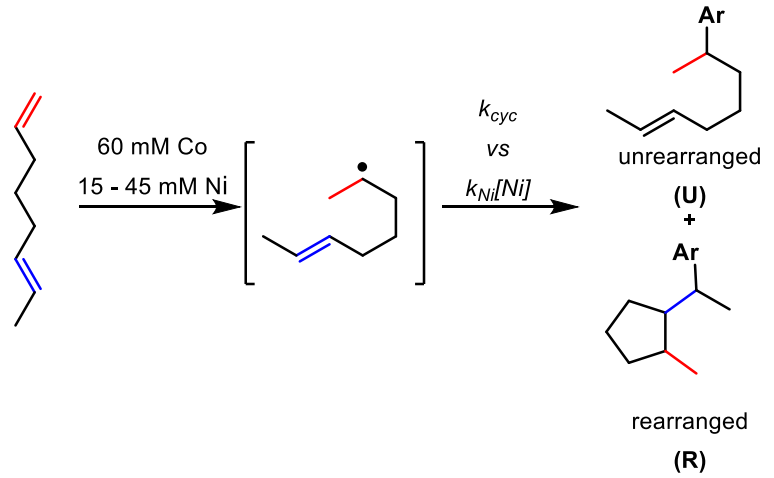


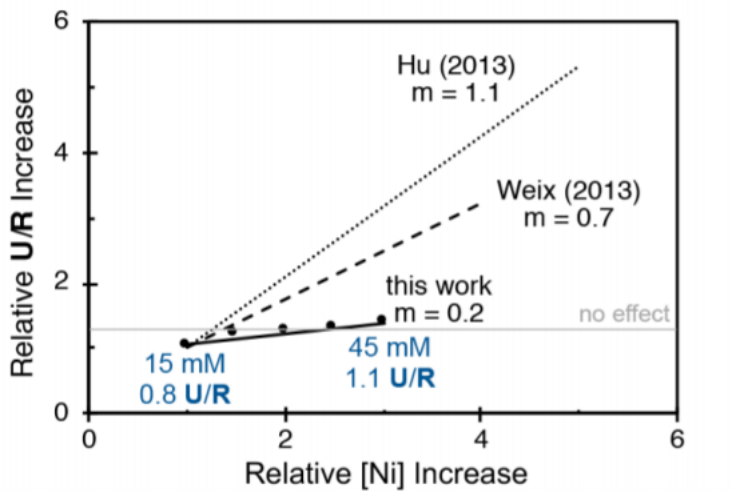


Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

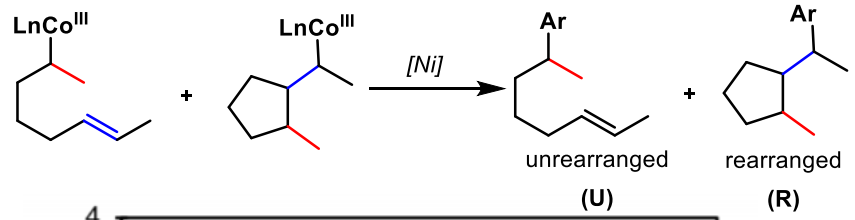
Exclusion of the Radical Chain Mechanism:

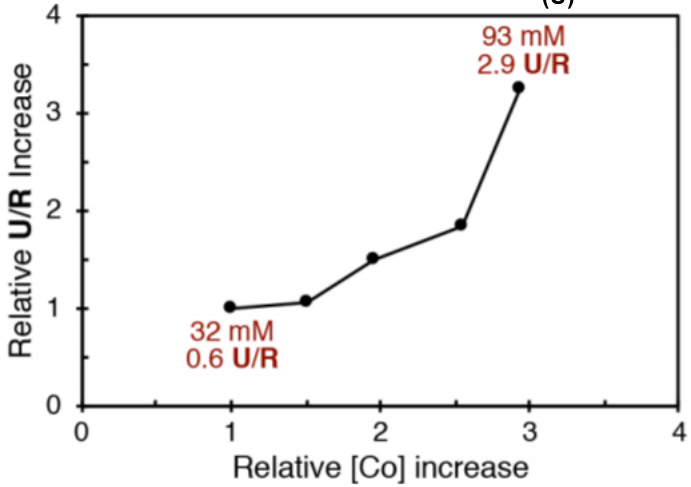






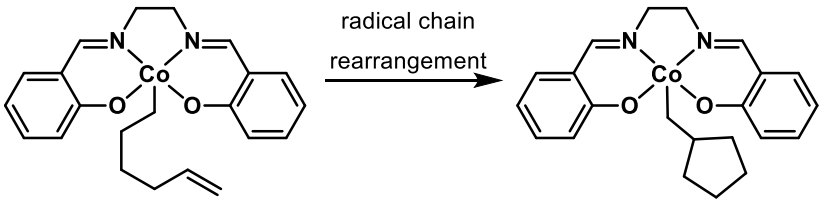
$$U/R = k_{Ni}[Ni]/ k_{cyc}$$





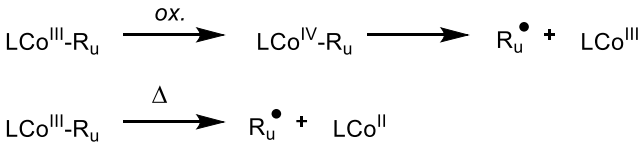
Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

A Cobalt Radical Chain:

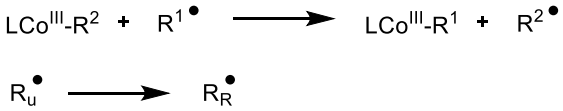


R_u-Co(salen) R_R-Co(salen)

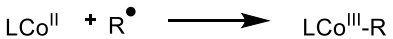
Initiation:



Propagation:



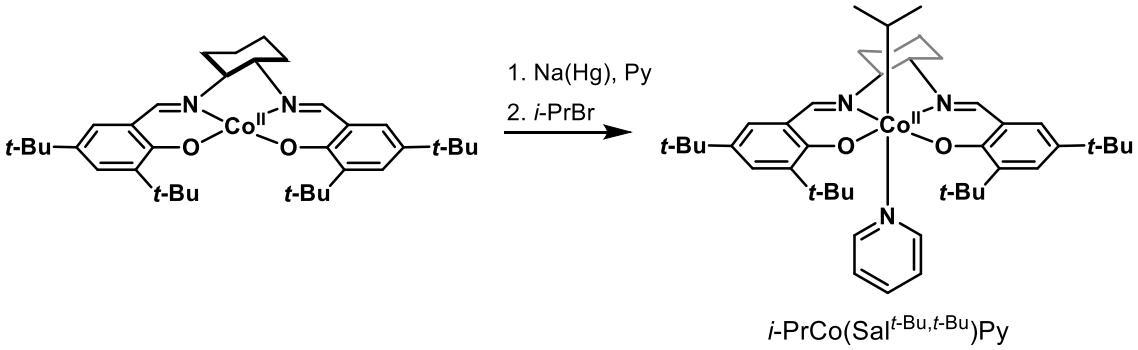
Termination:



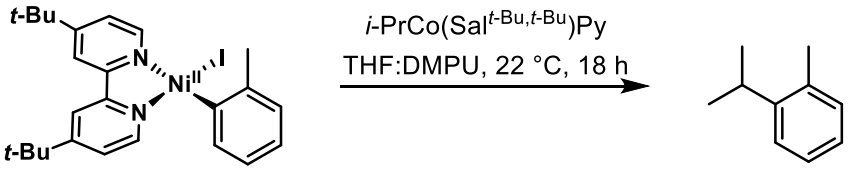
Kochi, J.K. *J. Am. Chem. Soc.* **1986,** *108, 4790-4804*.
Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

Probing Direct Transmetalation:

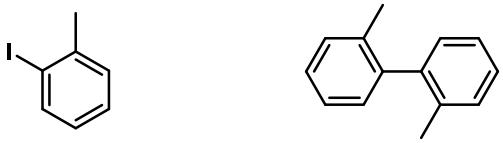
Stoichiometric experiment:



i-PrCo(Sal$^{t\text{-Bu},t\text{-Bu}}$)Py



10% yield



observed by-products

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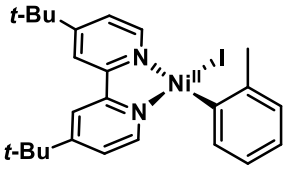
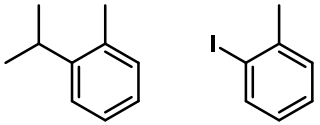
The Role of the Oxidant:

Stoichiometric experiment:



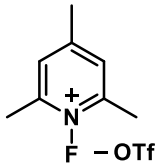
[ox]
DMPU, 22 °C, 3 h

i-PrCo(Sal$^{t\text{-Bu},t\text{-Bu}}$)Py

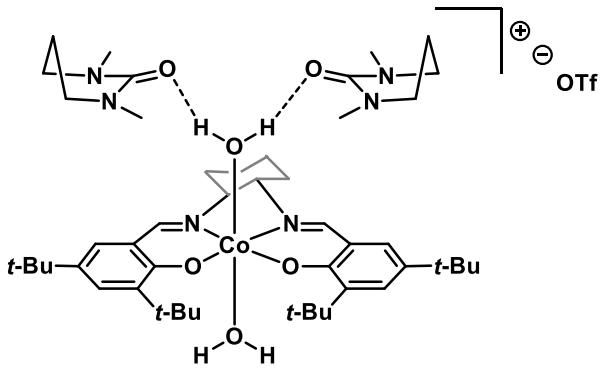


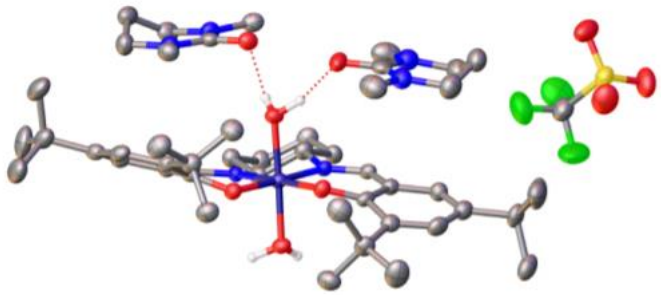
[ox]		
none	10%	25%
2,4,6-Me_3NFPyBF_4	17%	78%
AcFcBF_4 (1 equiv.)	18%	18%
AcFcBF_4 (2 equiv.)	41%	44%

Co(Sal$^{t\text{-Bu},t\text{-Bu}}$)



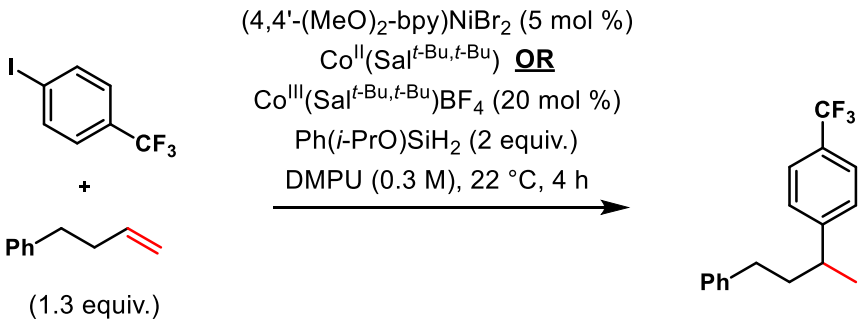
DMPU (10 equiv)
C_6D_6, 22 °C, 1 h



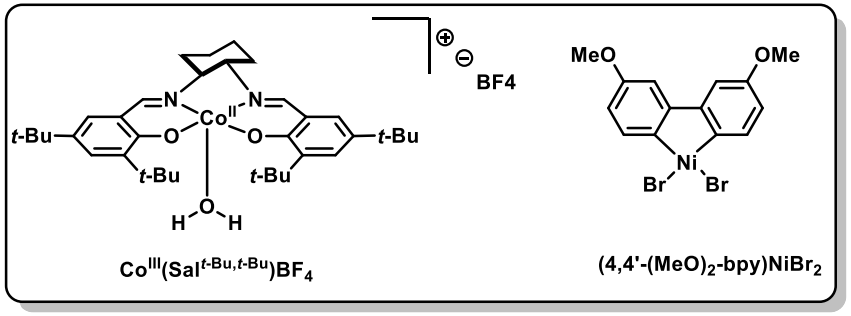


Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

The Role of the Oxidant:



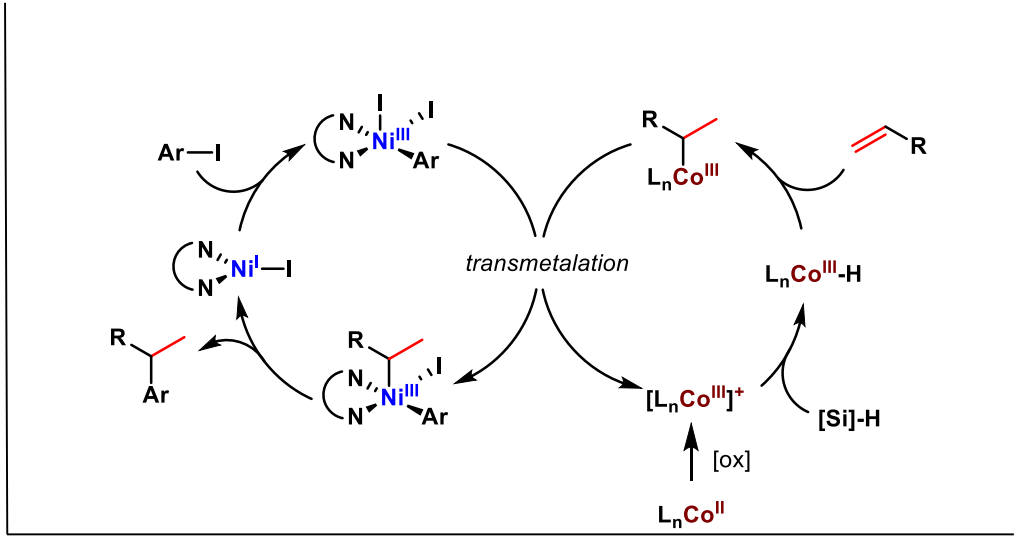
$Co(II) + 2,4,6\text{-}Me_3NFPyBF_4$	82% yield
$Co(III)BF_4$	56% yield
$Co(III)BF_4 + Mn^0$	76% yield

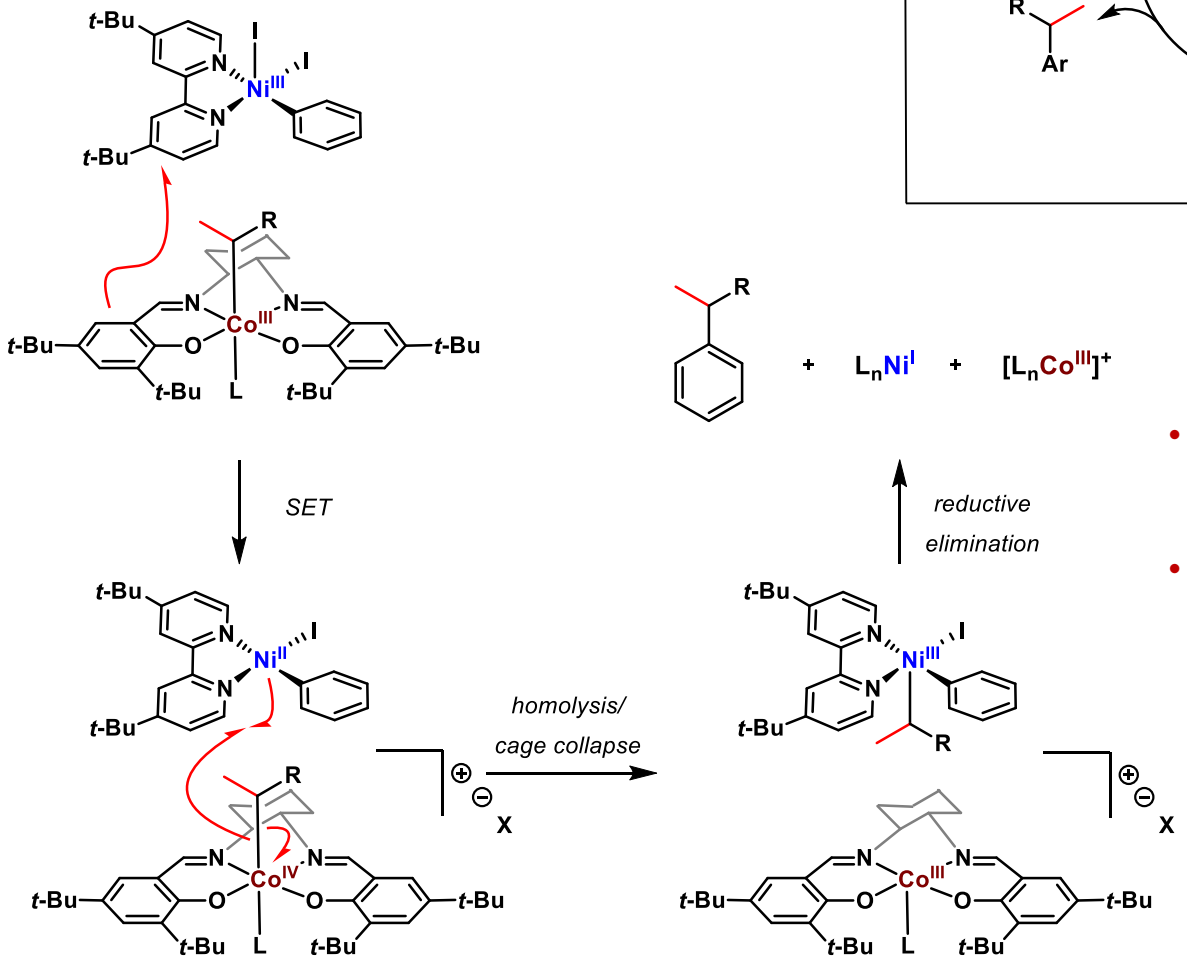


Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

The Full Picture:

Possible Transmetalation Mechanism:



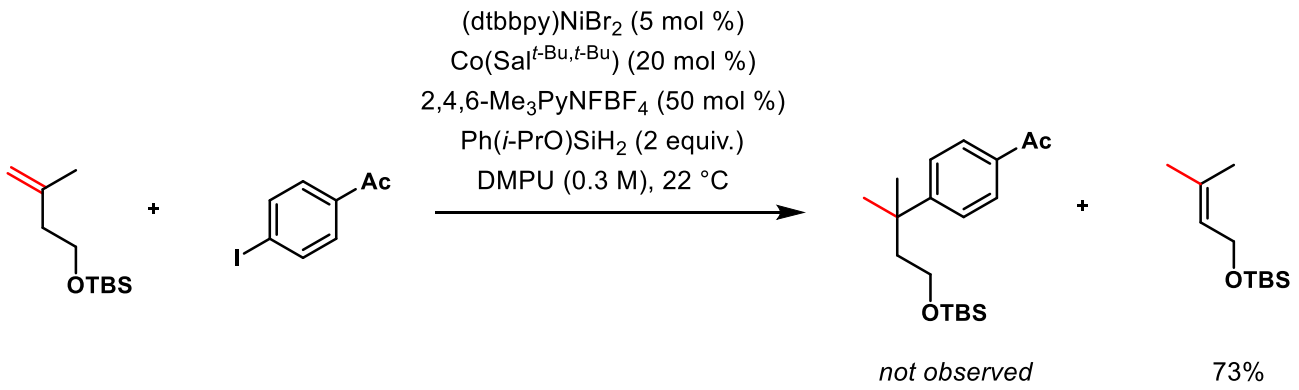


- *$(bpy)_3$Ni(III) complexes are stronger one-electron oxidants than analogous Fe(III) complexes*
- *Organocobalt complexes can be oxidized by Fe(III), so it is not difficult to imagine how an ArNi(III)X complex could oxidize an organocobalt(III) species*

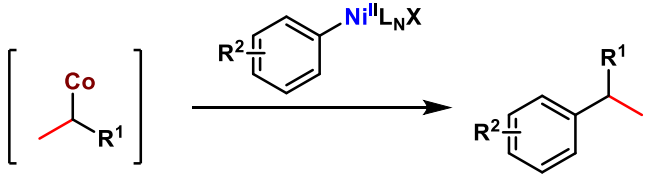
Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.

Enabling the Use of Internal Olefins:

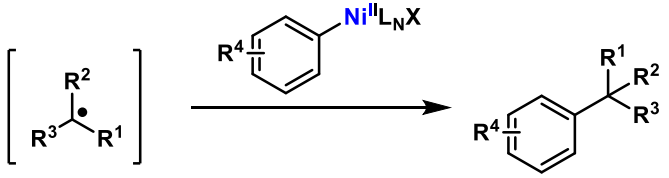
Previous Reaction Conditions:



Transmetalation (Previous work):

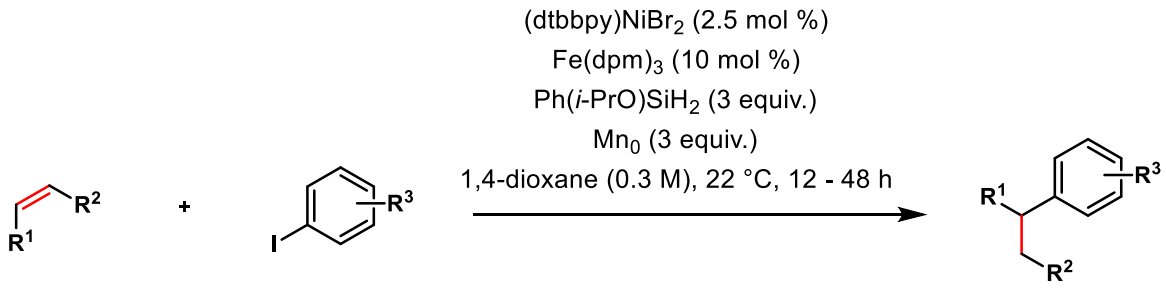


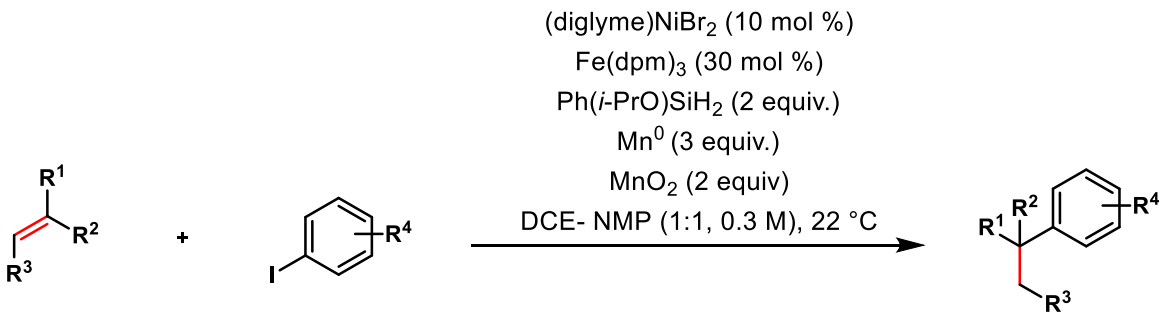
Free Radical Capture (This work):

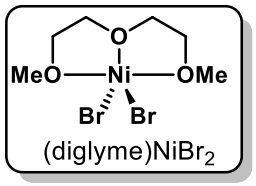


Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 11317-11324.

Enabling the Use of Internal Olefins:



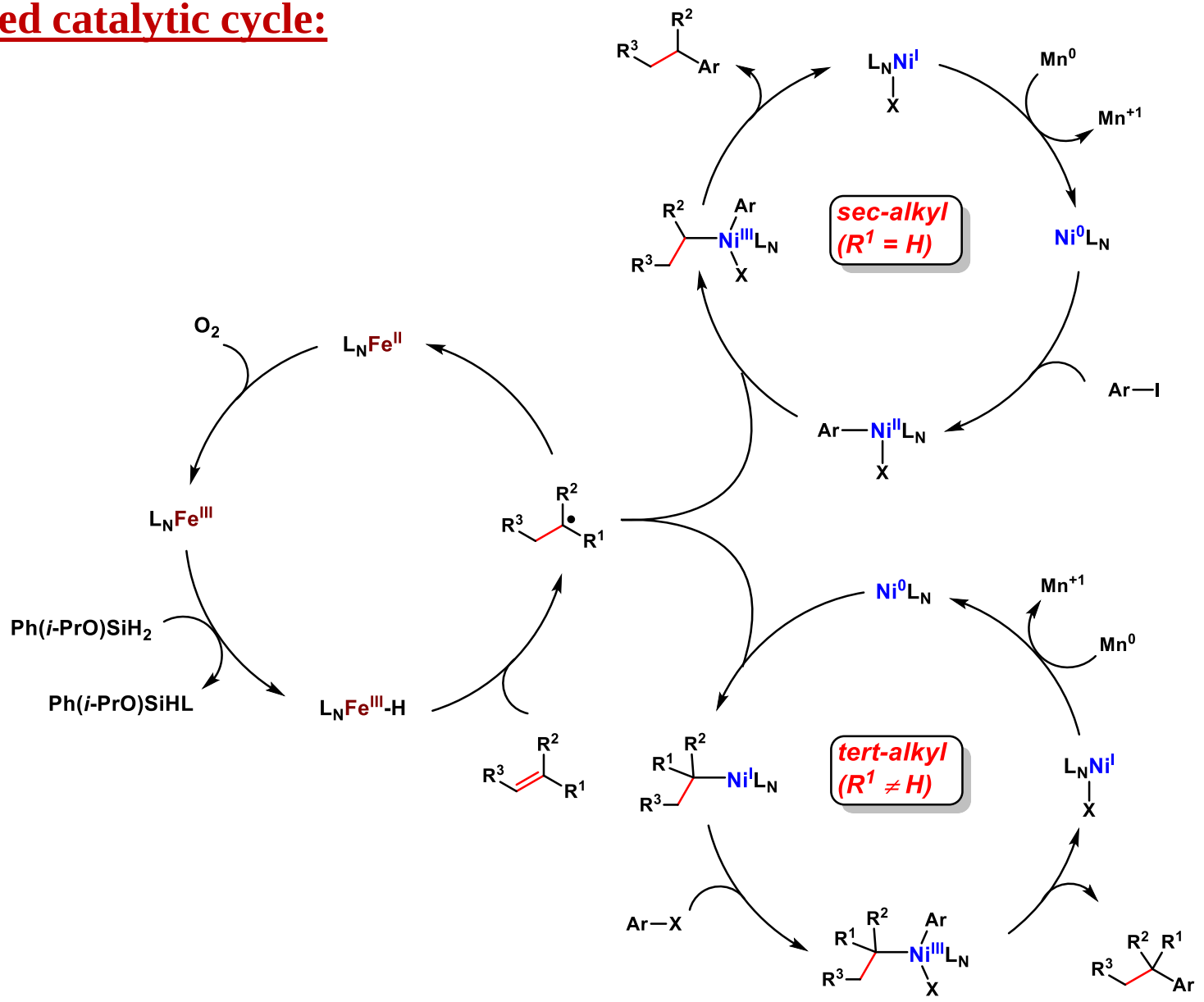




Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 11317-11324.

Enabling the Use of Internal Olefins:

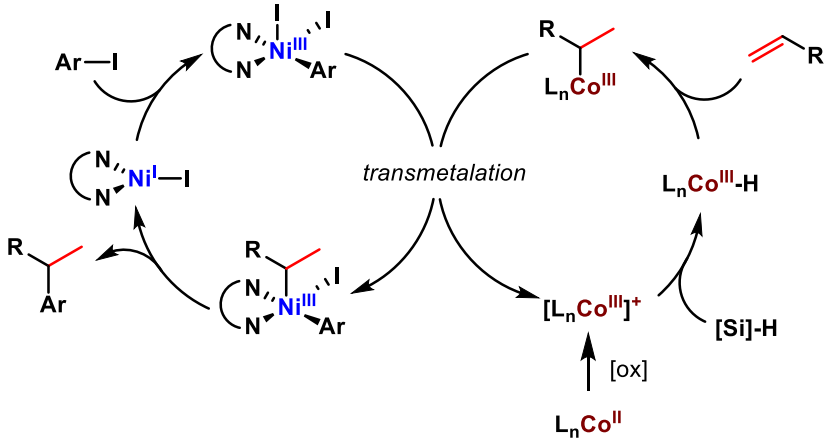
Proposed catalytic cycle:



Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 11317-11324.

Conclusions:

- *Cobalt-nickel catalyzed hydroarylation of terminal olefins proceeds via direct organocobalt to nickel transmetalation*
- *Eludicated mechanism using combination of reaction progress kinetic analysis (RPKA), radical clock experiments, and synthesis and subsequent reactivity studies of arylnickel(II) and organocobalt(III) complexes*
- *Exogenous oxidant could be excluded from the reaction conditions if a Co(III) precatalyst was used*
- *Use of an Fe(III) catalyst expands the scope of the reaction to include internal olefins, allowing for the formation of quarternary centers*



Shenvi, R.A. *J. Am. Chem. Soc.* **2018,** *140,* 12056-12068.