Iron and Cobalt Metal-π Complex Synthesis and Reactivity

Tropical Seminar I

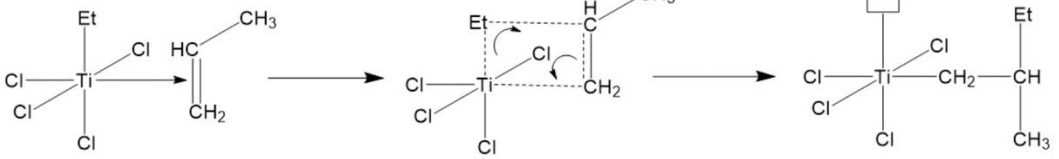
01/21/2025

Maya Lebowitz



JAX Beach Dec. 2021

Large Scale Applications of Metal-π Intermediates (Iron's Day Will Come)

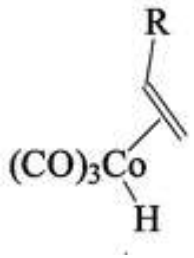


Zeigler-Natta Polymerization

Nobel Prize 1963

Almost 80 million tons of polymer per year

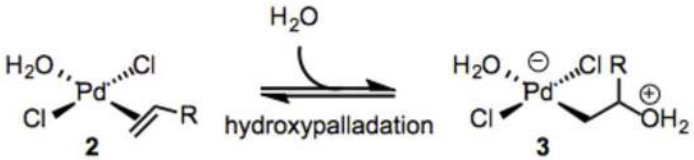
Groppo, E. et al. *Catalysis Today* **2023**, *418*, 114077.



Oxo Process (and its derivatives)

10 million metric tons per year

Huo, Y.-X. et al. *Biotechnol. Biofuels Bioprod.* **2022**, *15*, 80.



Wacker Oxidation

>1 million tons per year

Facile Access to Acetaldehyde from Feedstock Chemicals

Angew. Chem. Int. Ed. **2009**, *48*, 9034–9037.



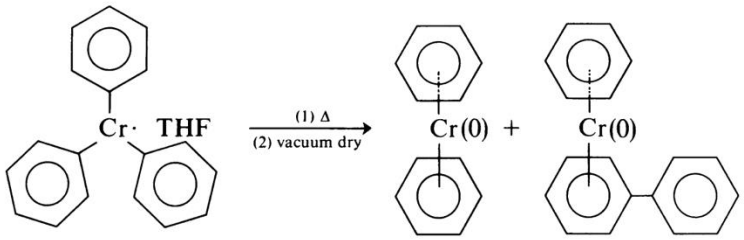
Asymmetric Hydrogenation

Atom Economical Source for Chiral Information

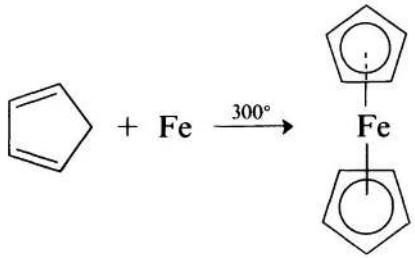
Widely Used in Industry

Diéguez, M. et al. *Angew. Chem. Int. Ed.* **2024**, *63*, e202315872.

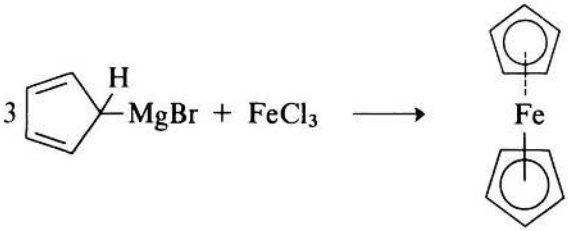
Preparation of Metal-π Complexes



σ to π *R*edistribution



Direct Synthesis



Substitution Reactions

$M(CO)nX + \text{olefin} \longrightarrow$ mixed olefin halide π-complex

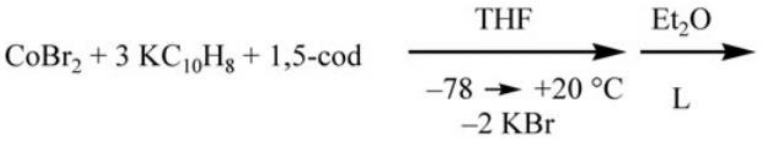
$M(CO)nCp + \text{olefin} \longrightarrow$ mixed olefin-cyclopentadienyl π-complex

$HM(CO)n + \text{diolefin} \longrightarrow$ allyl π-complex

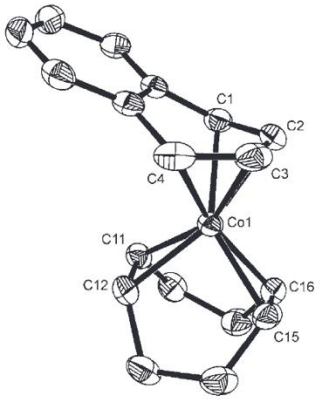
Metal/Ligand Exchange

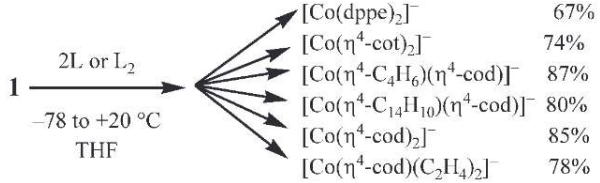
Tsutsui, M. *Introduction to Metal π-Complex Chemistry*, 1970th edition.; Springer

Interesting Coordination Complexes



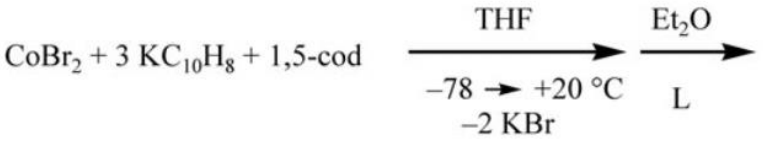
$$[K(L)(thf)_x][\mathbf{1}] + 2\ C_{10}H_8$$



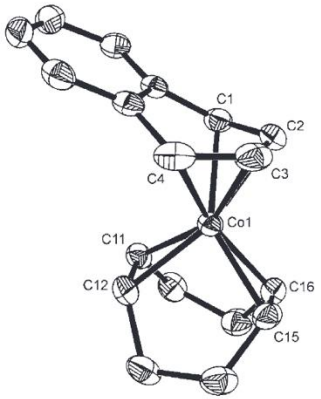


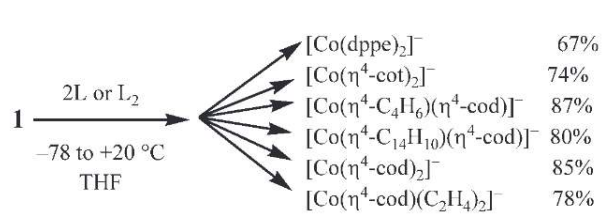
Ellis, J. E. et al. *Angew. Chem. Int. Ed.* **2006**, *45*, 7268–7271.

Interesting Coordination Complexes

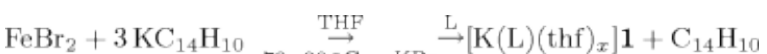


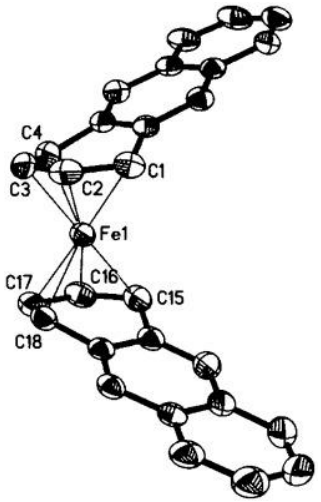
$[K(L)(thf)_x][\mathbf{1}] + 2\ C_{10}H_8$

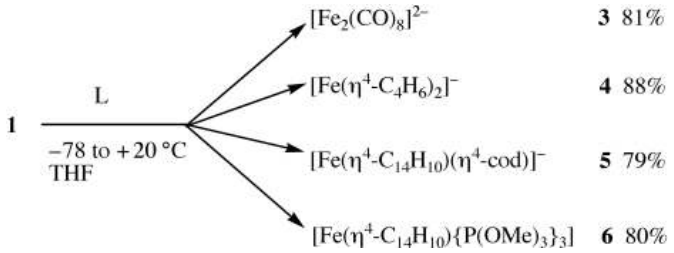




Ellis, J. E. et al. *Angew. Chem. Int. Ed.* **2006**, *45*, 7268–7271.







Ellis, J. E. et al. *Angew. Chem.* **2007**, *119*, 6244–6248.

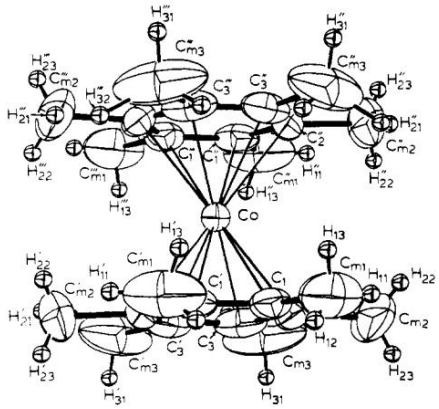
Interesting Coordination Complexes

$$\mathrm{Co(CO)_5{}^+[WCA]^- + 2\,arene \rightarrow Co(arene)_2{}^+[WCA]^- + 5\,CO}$$

$$\mathrm{(arene)Co(CO)_2{}^+[WCA]^- + arene \rightarrow Co(arene)_2{}^+[WCA]^- + 2\,CO}$$

$$\mathrm{Co_2(CO)_8 + 2\,Ag^+[WCA]^- + 2\,arene \rightarrow Co(arene)_2{}^+[WCA]^- + 2\,Ag + 8\,CO}$$

Krossing, I. et al. *Angew. Chem. Int. Ed.* **2018**, *57*, 9310–9314.



Muetterties, E. L. et al. *J. Am. Chem. Soc.* **1980**, *102*, 2979–2986.

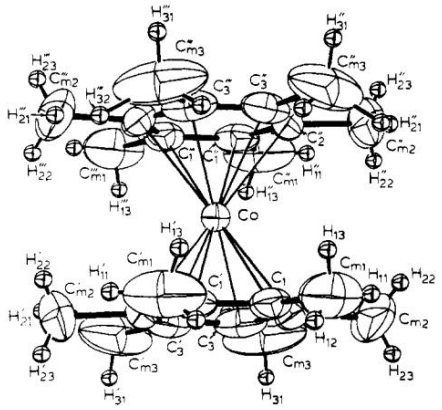
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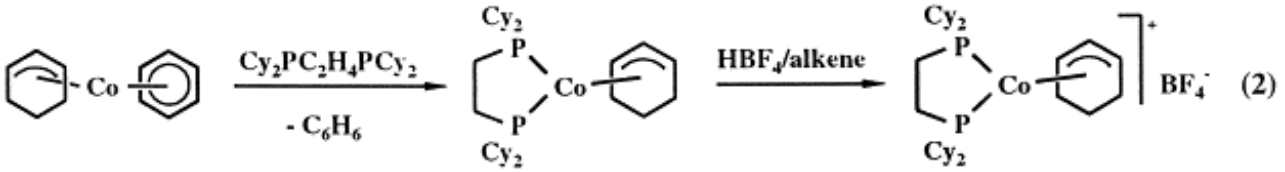
$$(arene)Co(CO)_2{}^+[WCA]^- + arene \rightarrow Co(arene)_2{}^+[WCA]^- + 2\,CO$$

$$Co_2(CO)_8 + 2\,Ag^+[WCA]^- + 2\,arene \rightarrow Co(arene)_2{}^+[WCA]^- + 2\,Ag + 8\,CO$$

Krossing, I. et al. *Angew. Chem. Int. Ed.* **2018**, *57*, 9310–9314.



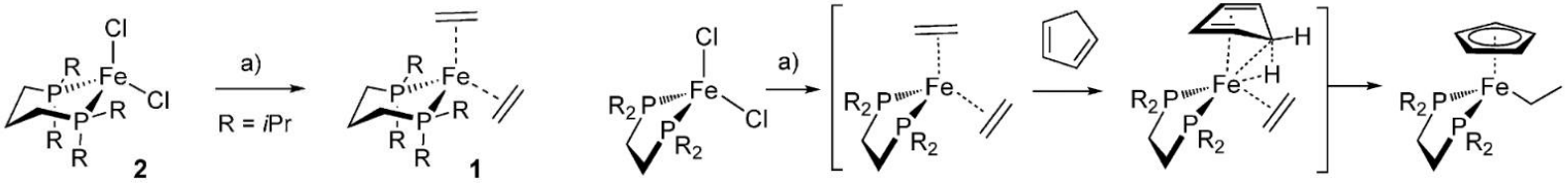
Muetterties, E. L. et al. *J. Am. Chem. Soc.* **1980**, *102*, 2979–2986.



3 4 5

Jolly, P. W. et al. *J. Organomet. Chem.* **1998**, *568*, 205–211.

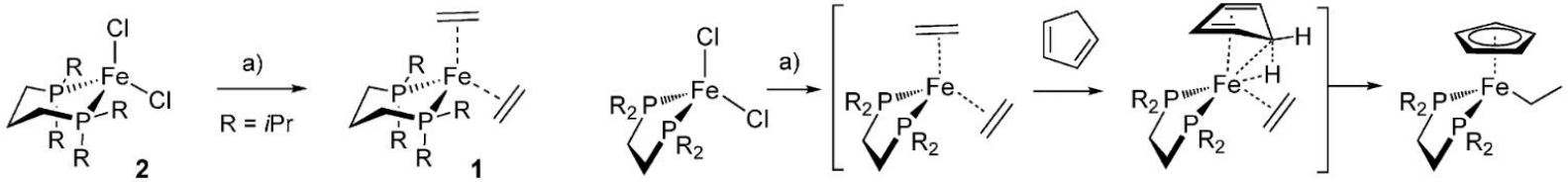
Iron Alkyl and Olefin Complexes



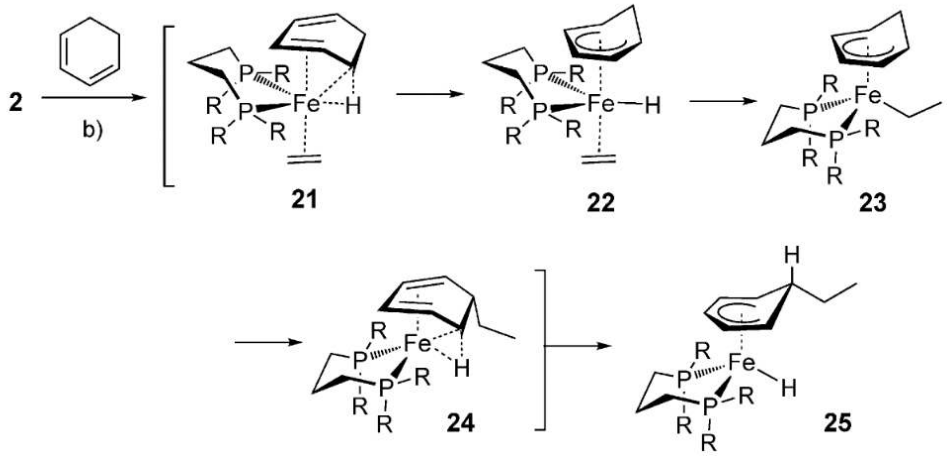
Scheme 1. a) EtMgBr, THF, ethylene, −5 °C, 77–97%.

Fürstner, A. et al. *Angew. Chem. Int. Ed.* **2015**, *54*, 1521–1526.

Iron Alkyl and Olefin Complexes

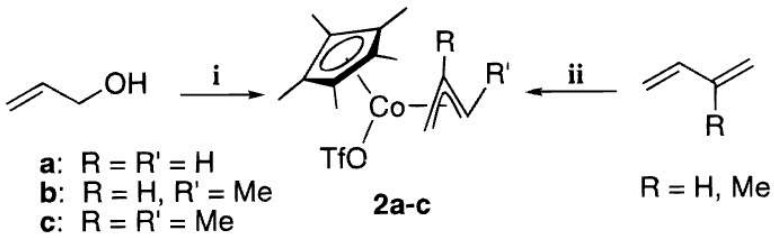


Scheme 1. a) EtMgBr, THF, ethylene, −5 °C, 77–97%.



Fürstner, A. et al. *Angew. Chem. Int. Ed.* **2015**, *54*, 1521–1526.

Cobalt [3+2+2] Cycloaddition



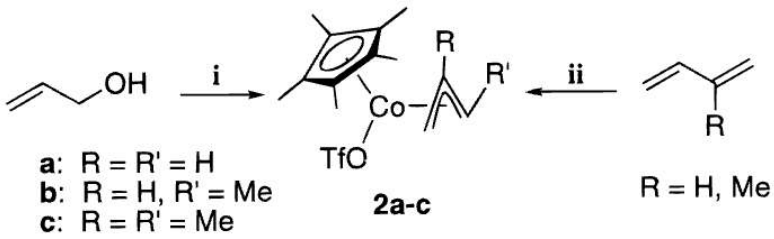
(1)

Conditions: **i**. $(C_5Me_5)Co(C_2H_4)_2$ (**1**), TfOH, Et_2O, -78 °C→RT, 4h
ii. $(C_5Me_5)Co(C_2H_4)_2$ (**1**), hexane, 65 °C, 4-12h; then step **i**.

In-Situ Catalyst Generation Possible from
$(\eta^5\text{-}C_5Me_5)Co(\eta^2\text{-}C_2H_4)_2$

Stryker, J. M. et al . *J. Am. Chem. Soc.* **1998**, *120*, 9702–9703.

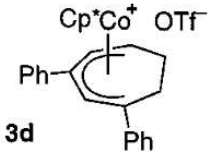
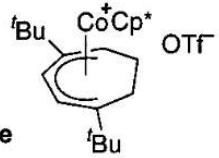
Cobalt [3+2+2] Cycloaddition



(1)

Conditions: **i**. $(C_5Me_5)Co(C_2H_4)_2$ (**1**), TfOH, Et_2O, -78 °C→RT, 4h
ii. $(C_5Me_5)Co(C_2H_4)_2$ (**1**), hexane, 65 °C, 4-12h; then step **i**.

Table 1. [3 + 2 + 2] Allyl/Alkyne Cycloaddition[a]

Entry	Allyl complex/	Alkyne	Product	Yield[b]
4	**2a**	Ph—≡—H	 **3d**	59
5	**2a**	^{t}Bu—≡—H	 **3e**	88

Air-Stable

Regioisomers Only Observed with Disubstituted Alkynes

[a]Conditions: CH_2Cl_2, excess alkyne (PhC≡CH, 3 equiv; tBuC≡CH, 10 equiv), -78 °C→RT, 12h. [b]Yield of spectroscopically homogeneous material obtained from chromatography. Yields in parenthesis are overall yields obtained from complex **1**, without isolation of the allyl triflate complex **2**. [c]Conditions: **i**. $(C_5Me_5)Co(C_2H_4)_2$ (**1**), THF, 0 °C→RT 6h; **ii**. AgOTf or $AgBF_4$, HC≡CH, acetone, RT, 0.5h.

Stryker, J. M. et al . *J. Am. Chem. Soc.* **1998**, *120*, 9702–9703.

Cobalt [5+2] Cycloaddition

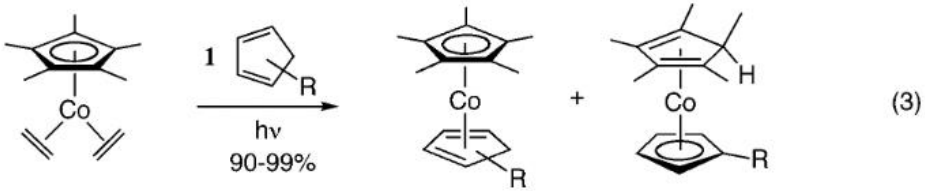
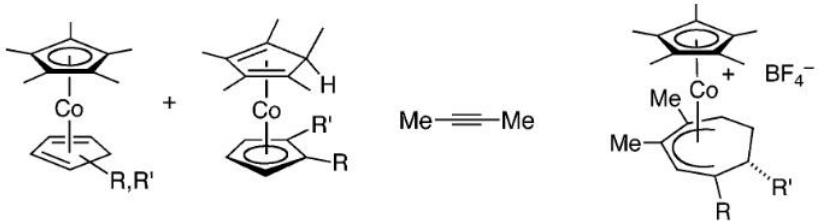
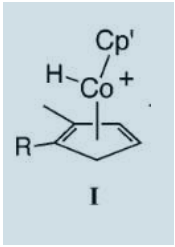


Table 1. Ring Expansion of Coordinated Cyclopentadienes[a]

Entry	Substrate	Alkyne	Product(s)	Yield[b]
1	**2a/2a'**	R, R' = H	**3a**	70
2	**2b/2b'**	R = Me, R' = H	**3b**	55
3	**2c/2c'**	R = H, R' = *tert*-Bu	**3c**	50
4	**2d/2d'**	R, R' = Me	**3d**	33





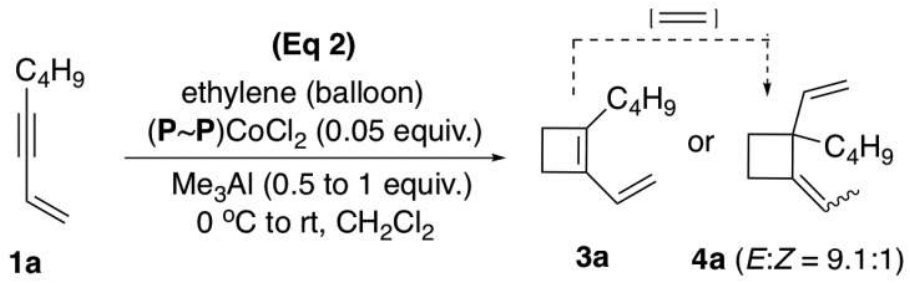
Proposed Intermediate

Favorable Hydride Migration to the Less Substituted Ring

[a] Conditions: $HBF_4 \cdot OEt_2$, alkyne (≥2 equiv), CH_2Cl_2, −78 °C→rt.[9] [b] Yields of isolated, purified products. No significant formation of isomeric products is observed. [c] Formed as a 4:1 mixture with isomeric $[(C_5H_5)Co(1\text{-Me-3-}tert\text{-Bu-}(1\text{-}5)\eta^5\text{-cycloheptadienyl})][BF_4^-]$.

Dzwiniel, T. L.; Stryker, J. M. *J. Am. Chem. Soc.* **2004**, *126*, 9184–9185.

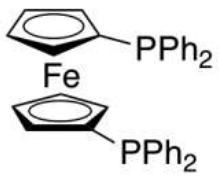
[2+2] Cycloaddition and Tandem Hydrovinylation



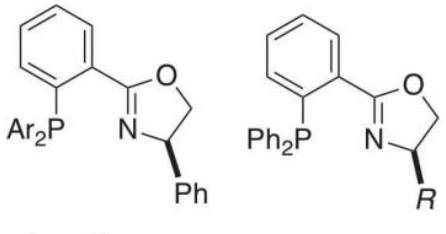
Activator Necessary; Must be Cationic Complex

Up to 98:2 er

To 3a: Low Temp. and Short Rxn Times
To 4a: RT and Longer Rxn Times



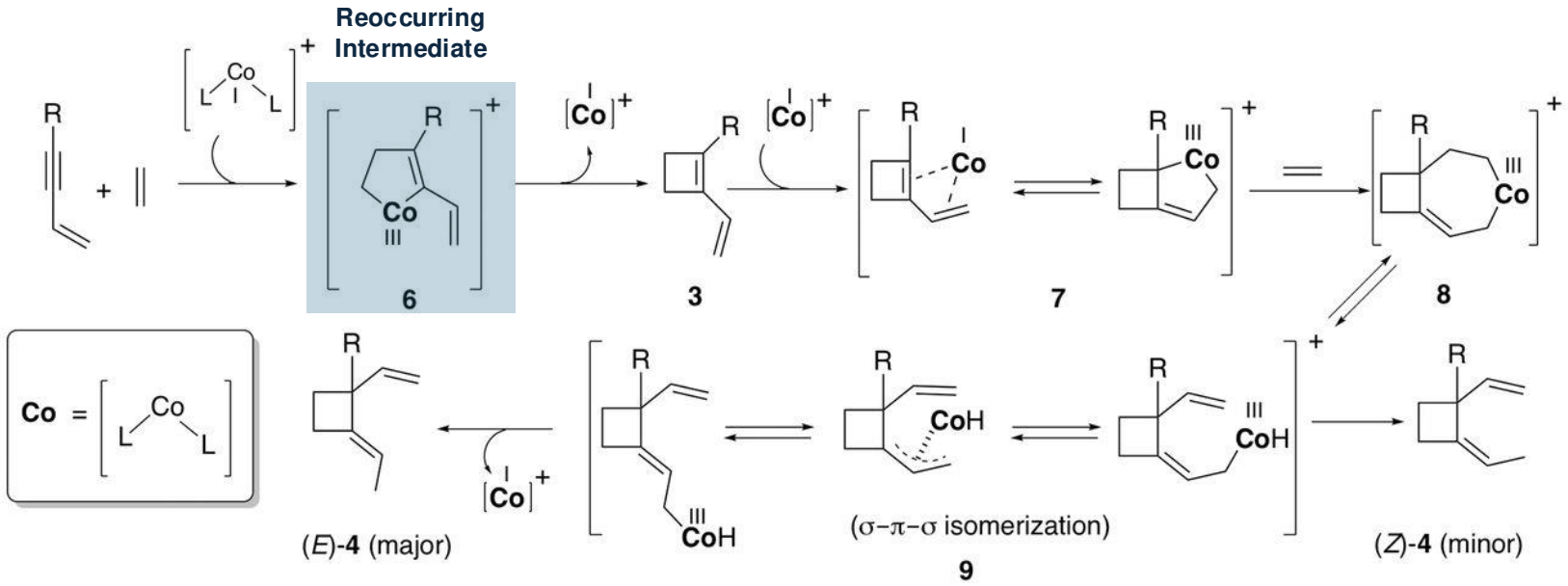
Best Ligand for Achiral Variant



Best for [2+2] and Tandem Hydrovinylation; Paired with Et_2AlCl

Pagar, V. V.; RajanBabu, T. V. *Science* **2018**, *361*, 68–72.

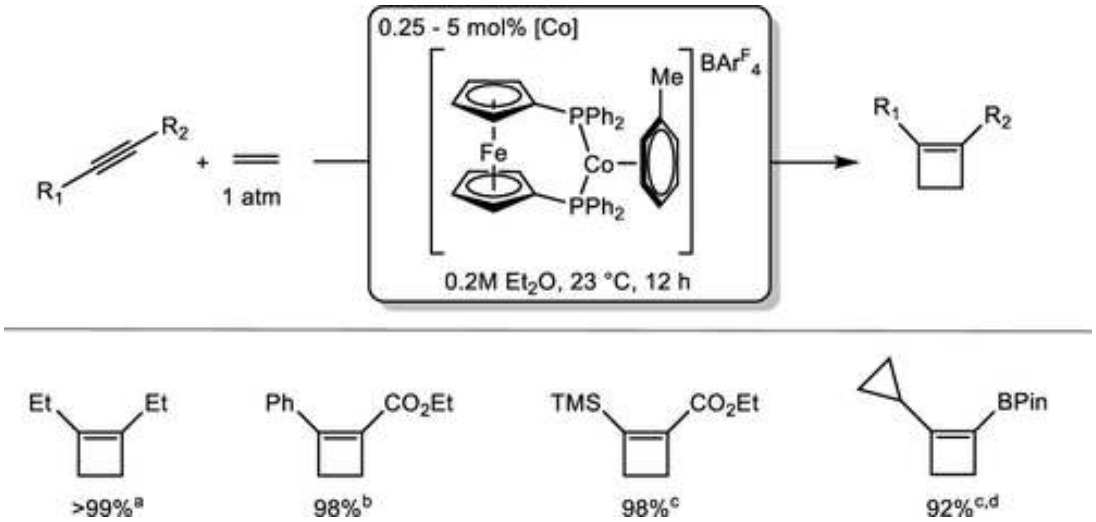
[2+2] Cycloaddition and Tandem Hydrovinylation



Pagar, V. V.; RajanBabu, T. V. *Science* **2018**, *361*, 68–72.

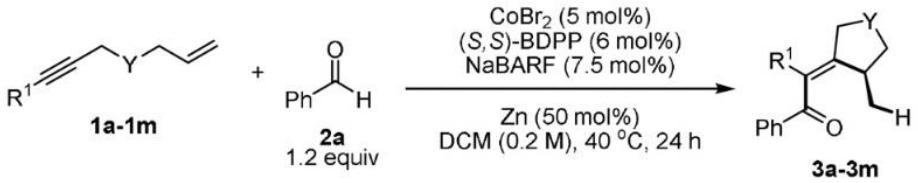
[2+2] Cycloaddition Accessed with Well-Defined Co(I) Catalyst

Well-Defined Cationic Co(I) Support
Proposed Oxidation and Charge State

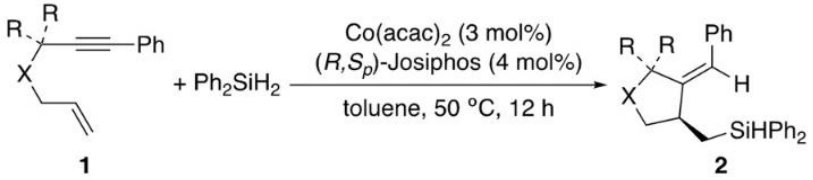


Chirik, P. J. et al. *Organometallics* **2021**, *40*, 3599–3607.

Extensive Investigation into 1,6-Enyne Reactivity



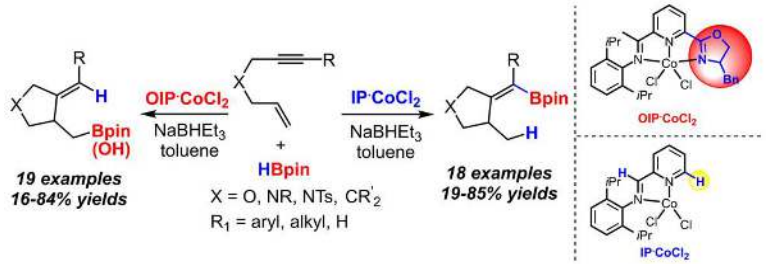
Lautens, M. et al. *Angew. Chem. Int. Ed.* **2020**, *59*, 16409–16413.



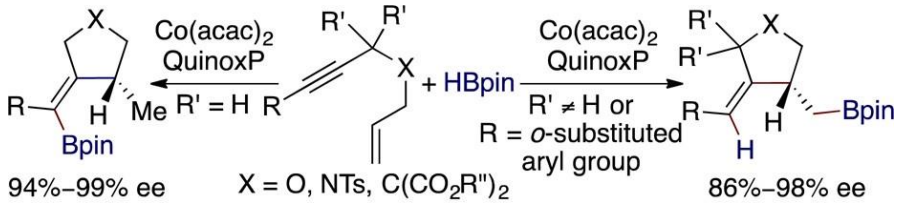
You, Y.; Ge, S. *Angew.Chem. Int.Ed.* **2021**, *60*, 12046–12052.



Cheng, C.-H. et al. *Org. Lett.* **2014**, *16*, 4208–4211.

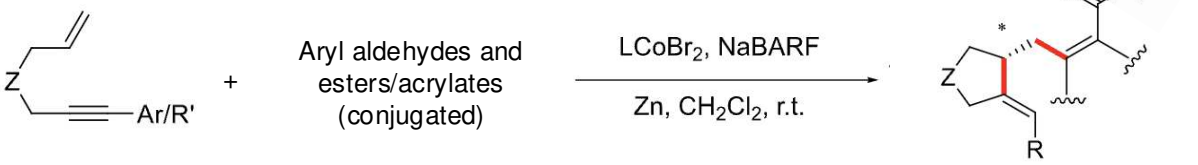


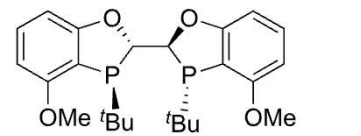
Xi, T.; Lu, Z. *ACS Catal.* **2017**, *7*, 1181–1185.



Ge, S. et al. *J. Am. Chem. Soc.* **2017**, *139*, 6526–6529.

Hydrofunctionalizations Using 1,6 Enynes





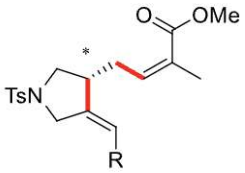
L = (2*S*,2'*S*,3*S*,3'*S*)-MeO-BIBOP

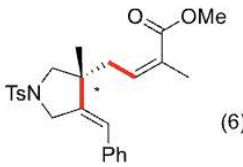


(4)



(7)

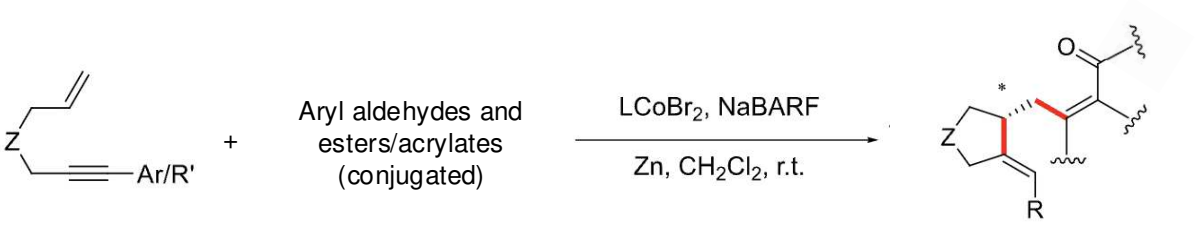


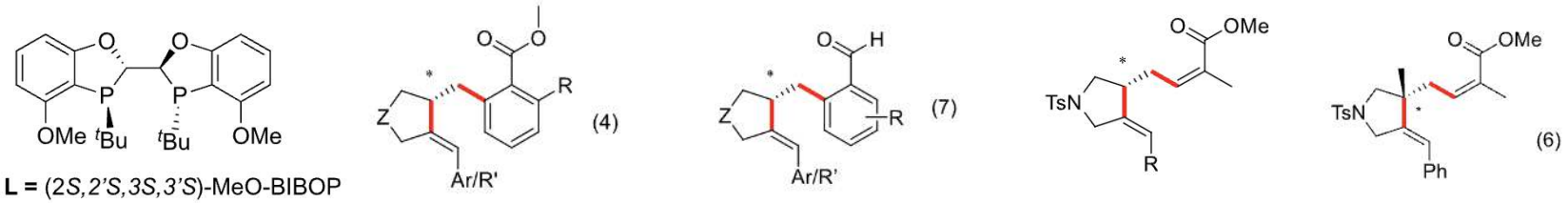


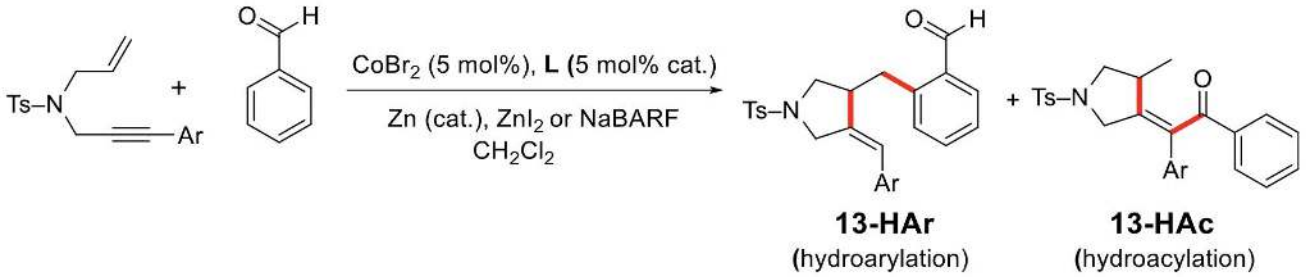
(6)

Ghosh, K. K.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2024**, *146*, 18753–18770.

Hydrofunctionalizations Using 1,6 Enynes







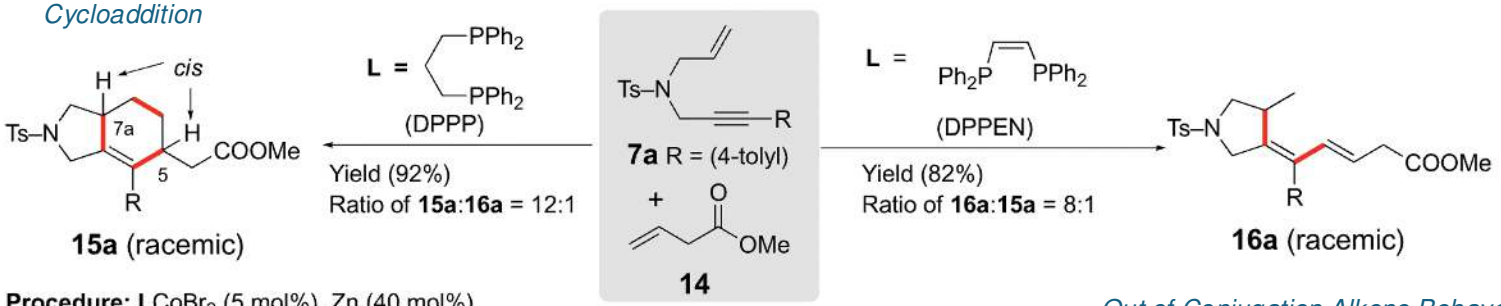
P_2 Bite Angle < 90°
% yield HAr > HAc

P_2 Bite Angle > 90°
% yield HAr < HAc

Ghosh, K. K.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2024**, *146*, 18753–18770.

Hydrofunctionalizations Using 1,6 Enynes

Wide-Bite Angle Shown to Previously Support [2+2] Cycloaddition



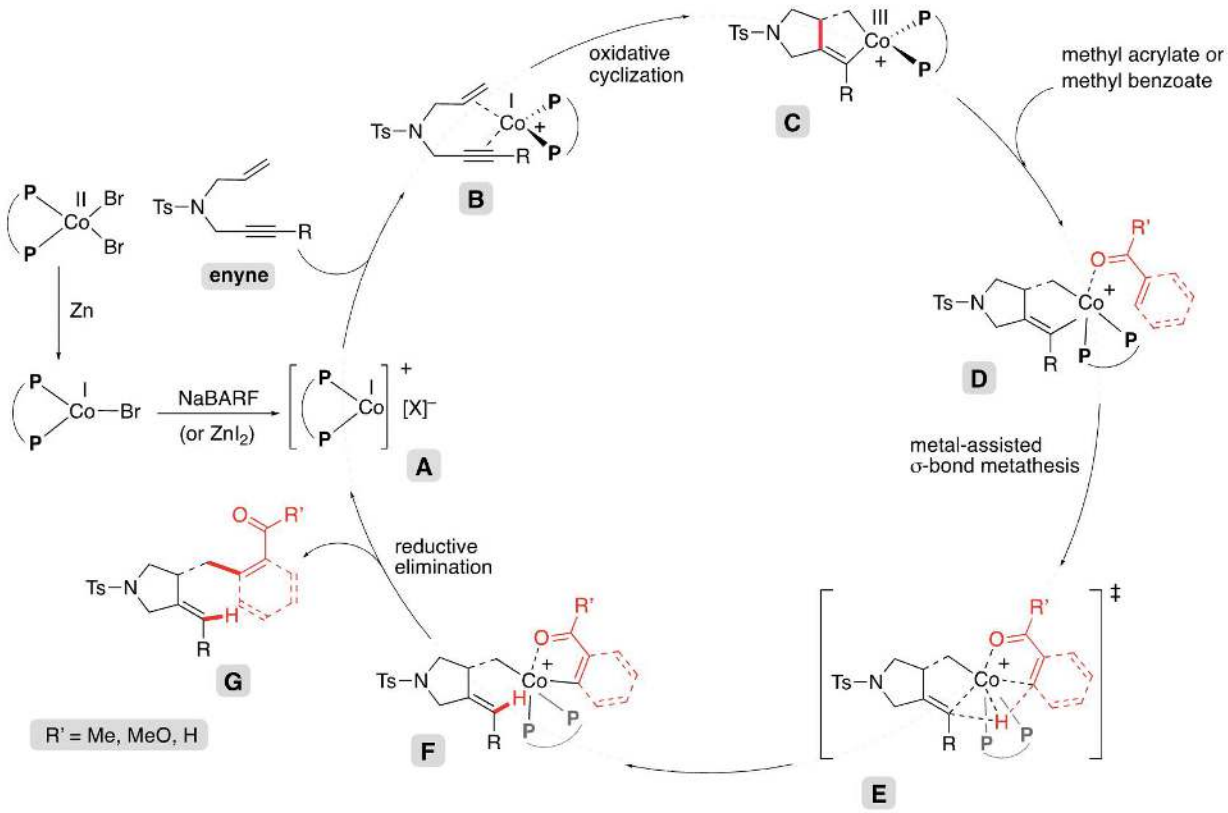
Procedure: L$CoBr_2$ (5 mol%), Zn (40 mol%)
NaBARF (6 mol%), CH_2Cl_2(0.33 M), rt, 24 h

Authors Argue Sterics for Diverging Selectivities

Out of Conjugation Alkene Behaves in the Typical Migratory Insertion Beta-Hydride Elimination Fashion

Ghosh, K. K.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2024**, *146*, 18753–18770.

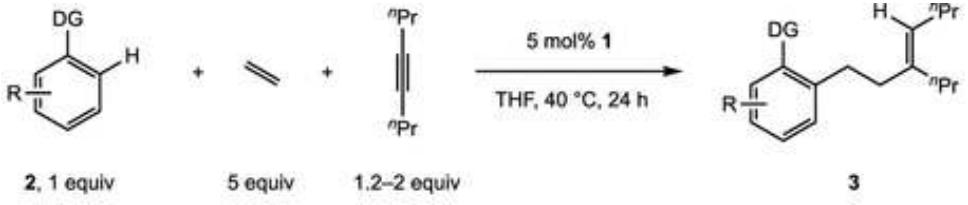
Hydrofunctionalizations Using 1,6 Enynes



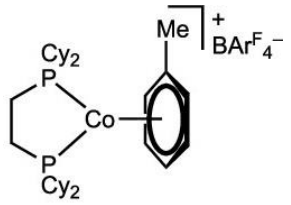
Alkene interception for [2+2+2]

Ghosh, K. K.; RajanBabu, T. V. *J. Am. Chem. Soc.* **2024**, *146*, 18753–18770.

Transitioning from 1,6 Enynes to Discrete Alkene and Alkyne Units



2, 1 equiv 5 equiv 1.2–2 equiv **3**

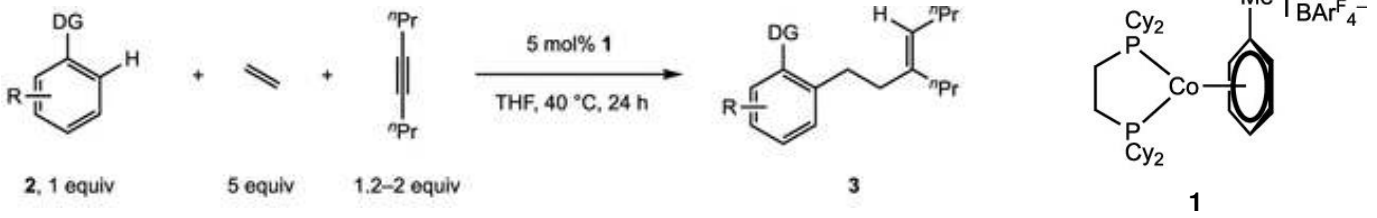


1

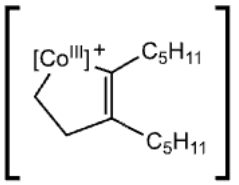
No External Base Necessary

Chirik, P. J. et al. *J. Am. Chem. Soc.* **2022**, *144*, 4530–4540.

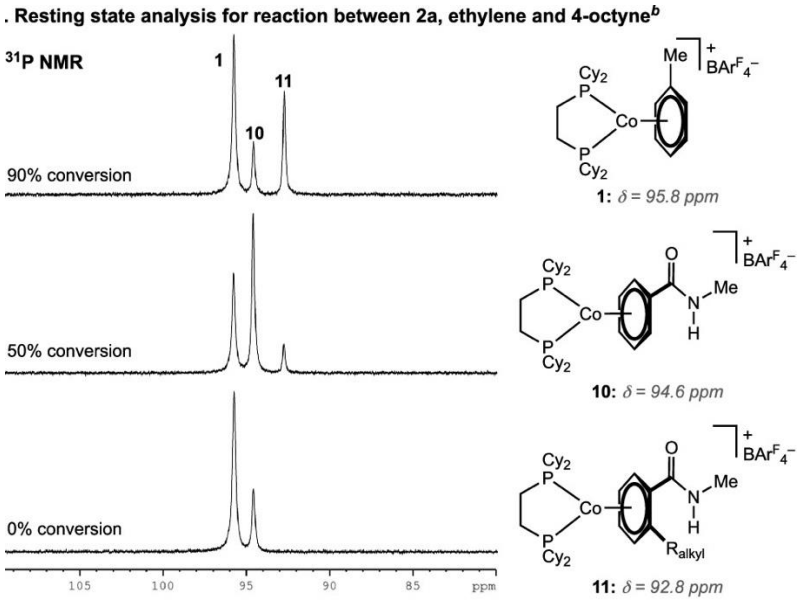
Transitioning from 1,6 Enynes to Discrete Alkene and Alkyne Units



No External Base Necessary



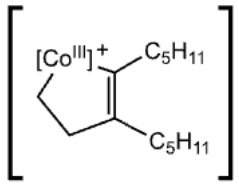
int-VI



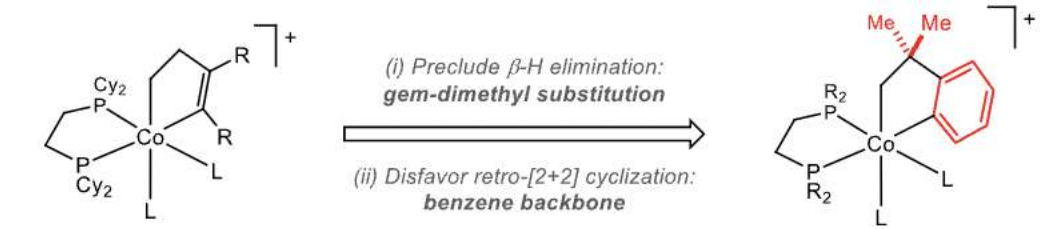
[2+2] Cyclization or Displacement of Arenes Are Potentially Rate Limiting

Chirik, P. J. et al. *J. Am. Chem. Soc.* **2022**, *144*, 4530–4540.

C-H Activation From Isolable Metallacycle



int-VI



Putative catalytic intermediate

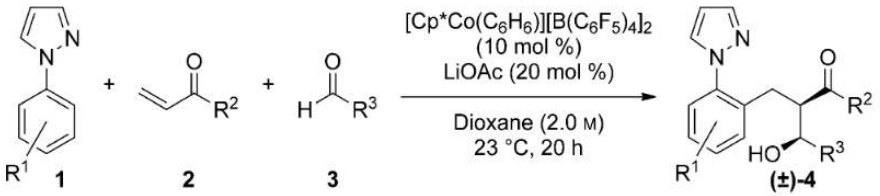
Discrete Co(III) metallacycle

Isolable Metallacycle!

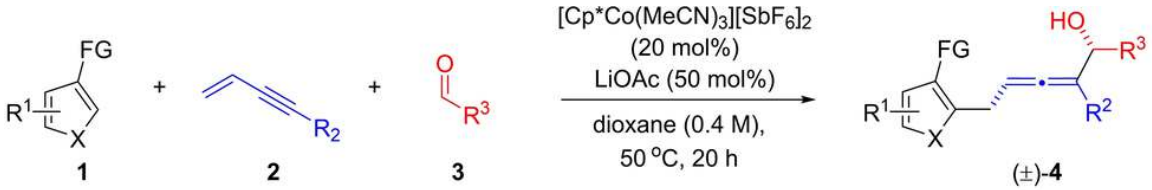
C-H activation is Fast and Reversible
Product Forming Reductive Elimination is Irreversible

Chirik, P. J. et al. *J. Am. Chem. Soc.* **2022**, *144*, 19186–19195.

Alternative Three Component Couplings

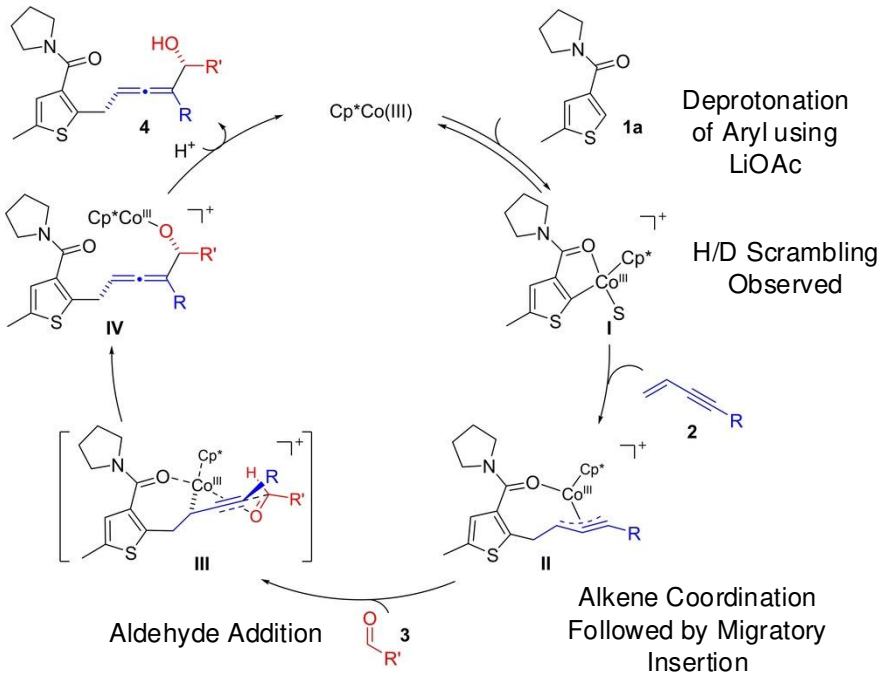


Ellman, J. A. et al. *Angew. Chem. Int. Ed.* **2016**, *55*, 12650–12654.



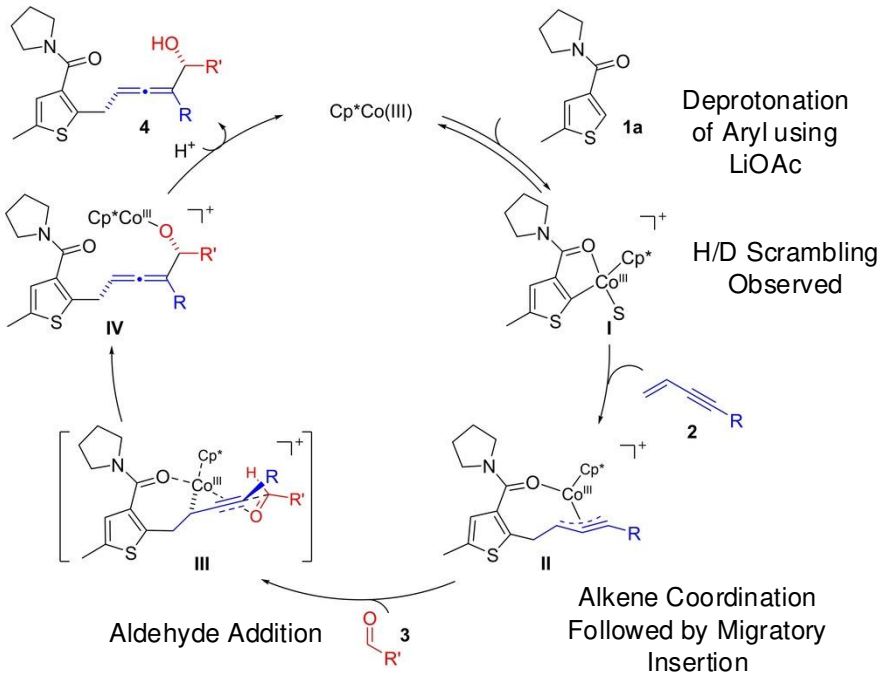
Ellman, J. A. et al. *Angew. Chem.* **2022**, *134*, e202202364.

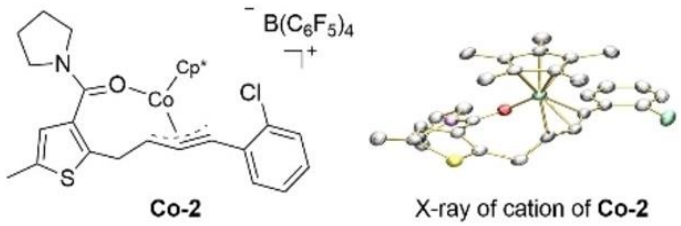
Alternative Three Component Couplings



Ellman, J. A. et al. *Angew. Chem.* **2022**, *134*, e202202364.

Alternative Three Component Couplings

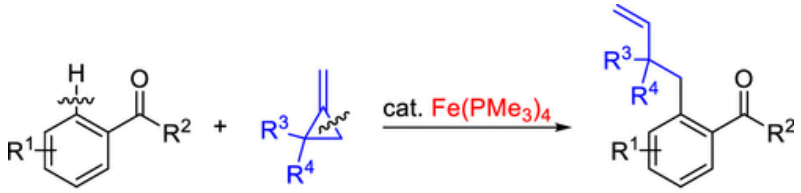


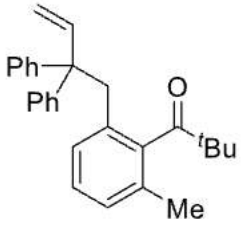


Comparable Yield in Rxn Conditions

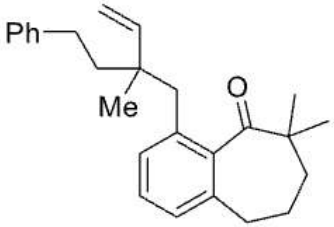
Ellman, J. A. et al. *Angew. Chem.* **2022**, *134*, e202202364.

Fe-Catalyzed Allylation of Aromatic Ketones

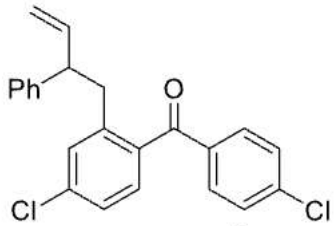




4fj, not detected



4nl, 67%[c,d]

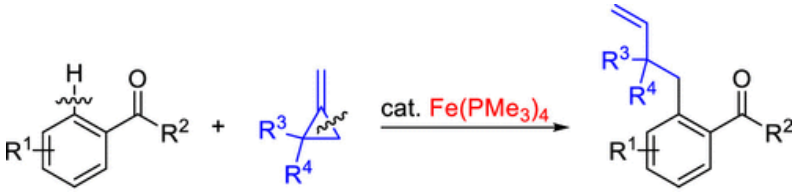


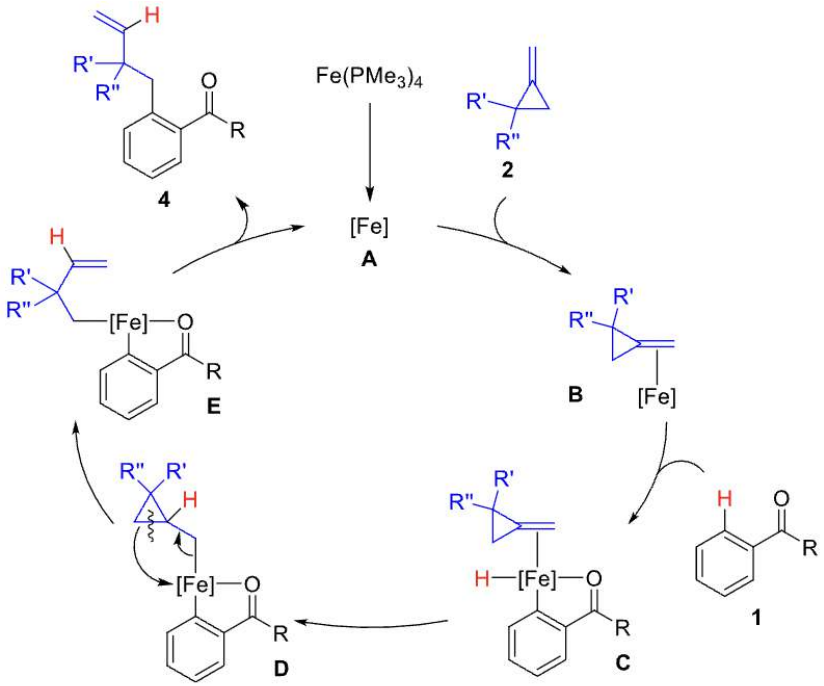
4ra, 51%[e,f]

Representative Examples

Kakiuchi, F. et al. *J. Am. Chem. Soc.* **2021**, *143*, 4543–4549.

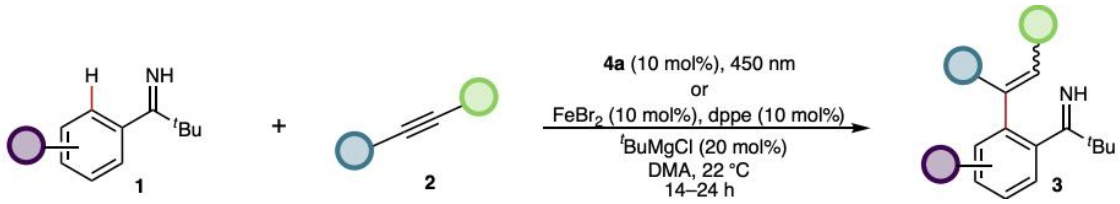
Fe-Catalyzed Allylation of Aromatic Ketones

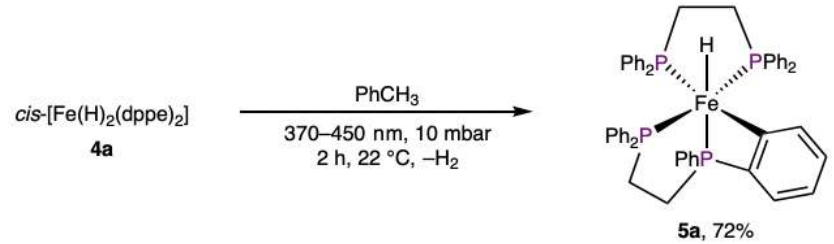


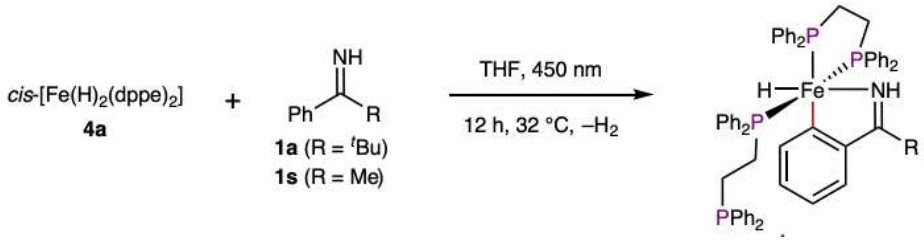


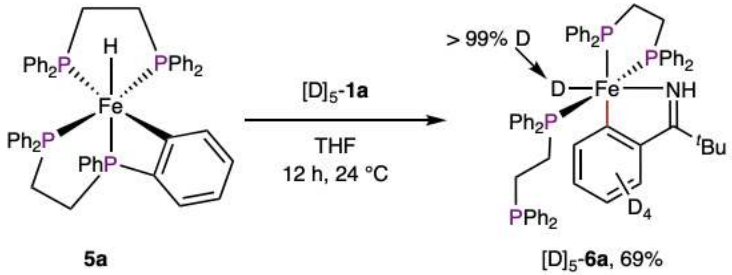
Kakiuchi, F. et al. *J. Am. Chem. Soc.* **2021**, *143*, 4543–4549.

Iron-Catalyzed Arene Alkenylation



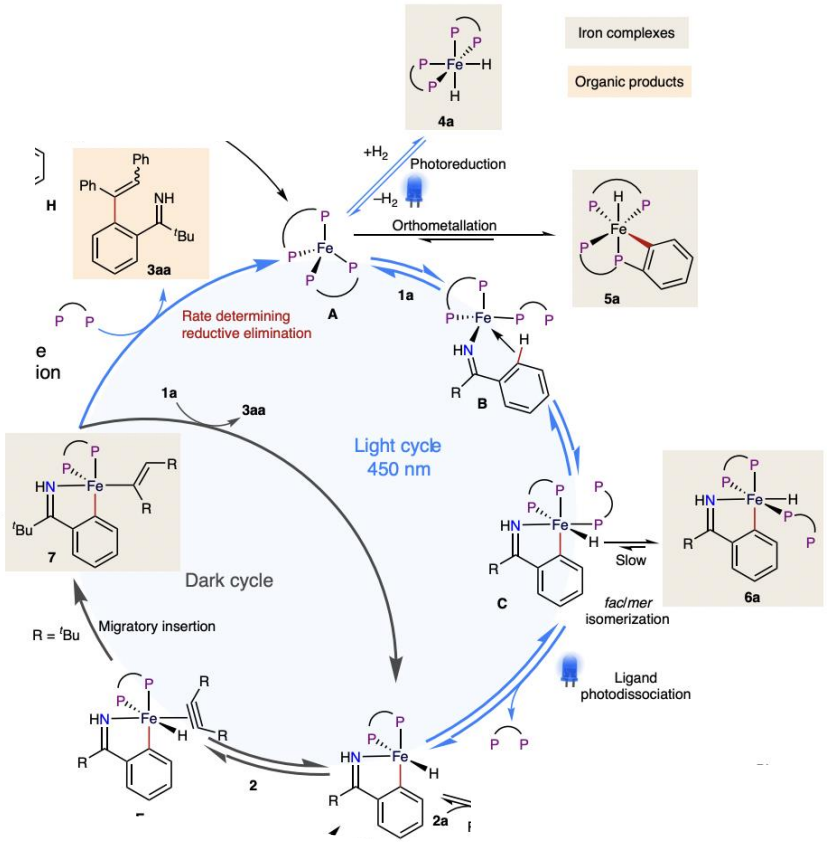






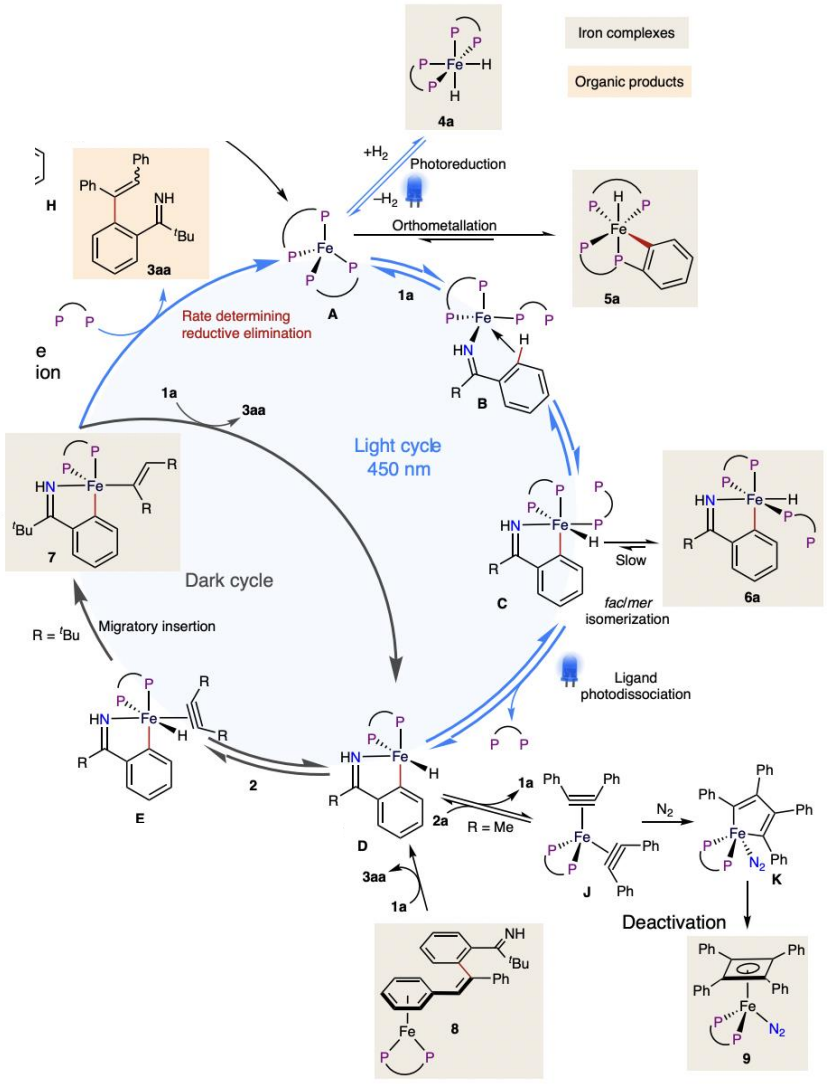
Ackermann, L. et al. *Nat. Catal.* **2024**, *7*, 273–284.

Iron-Catalyzed Arene Alkenylation



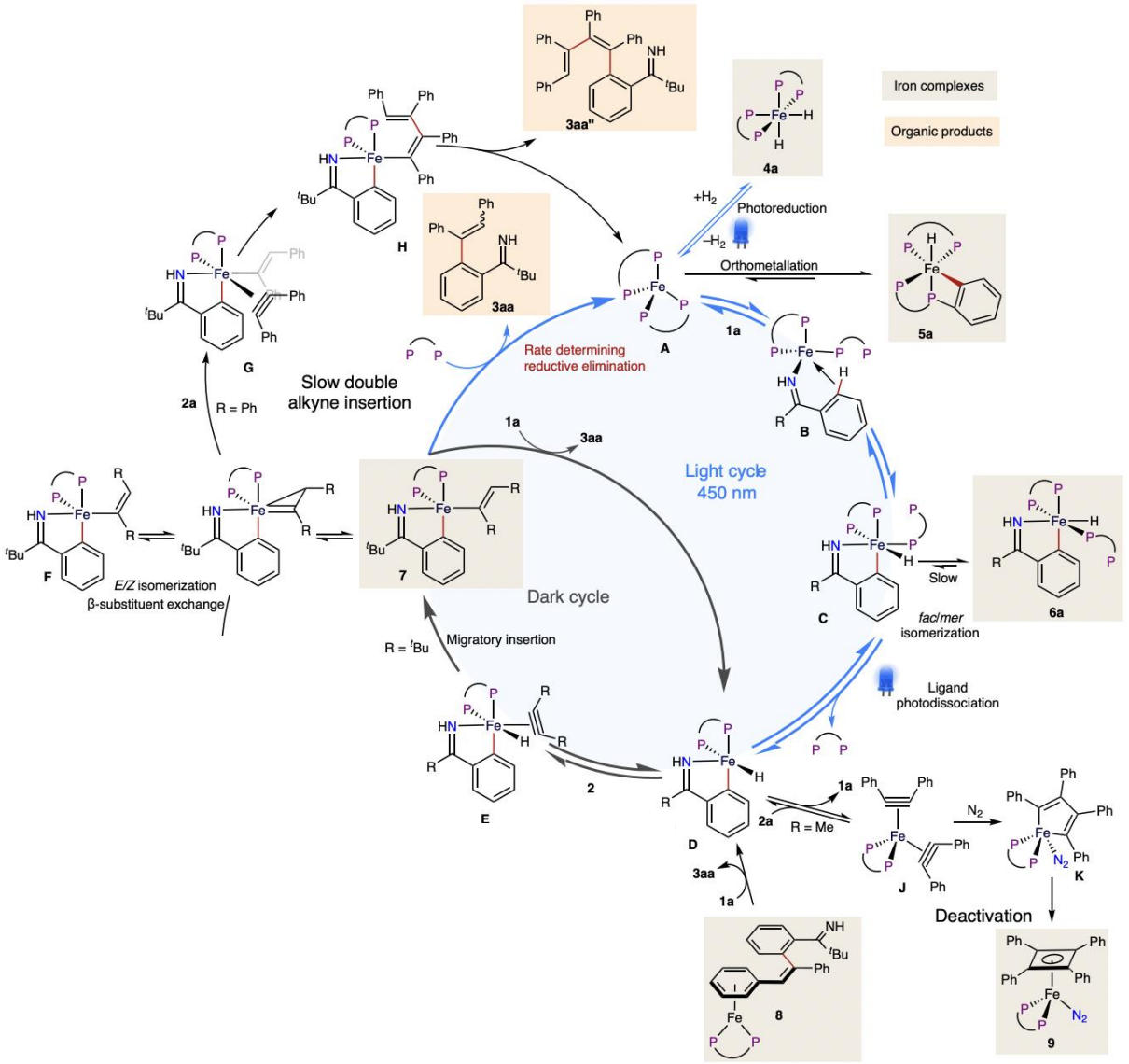
Ackermann, L. et al. *Nat. Catal.* **2024**, *7*, 273–284.

Iron-Catalyzed Arene Alkenylation



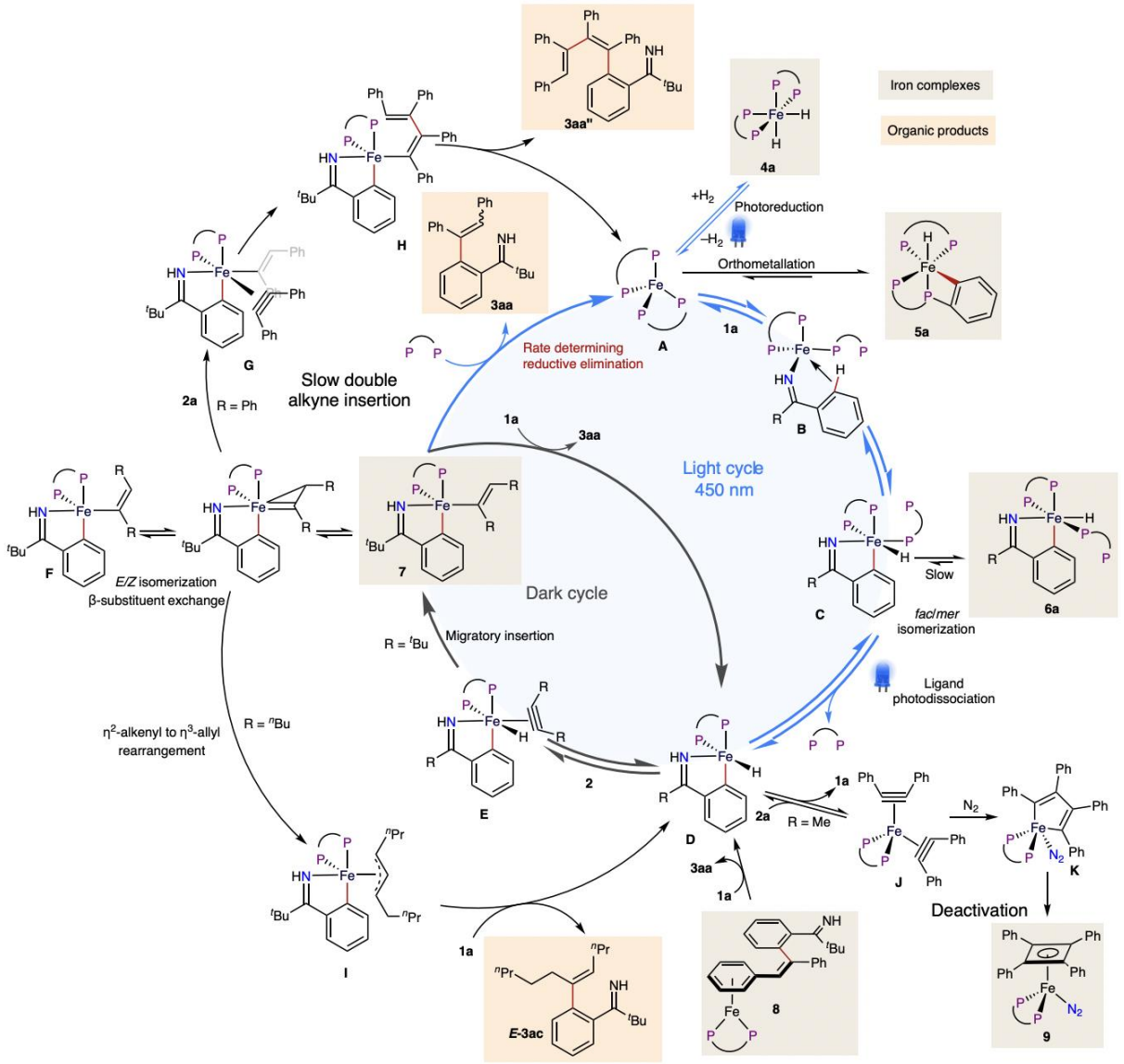
Ackermann, L. et al. *Nat. Catal.* **2024**, *7*, 273–284.

Iron-Catalyzed Arene Alkenylation



Ackermann, L. et al. *Nat. Catal.* **2024**, *7*, 273–284.

Iron-Catalyzed Arene Alkenylation



Ackermann, L. et al. *Nat. Catal.* **2024**, *7*, 273–284.

Thanks:)