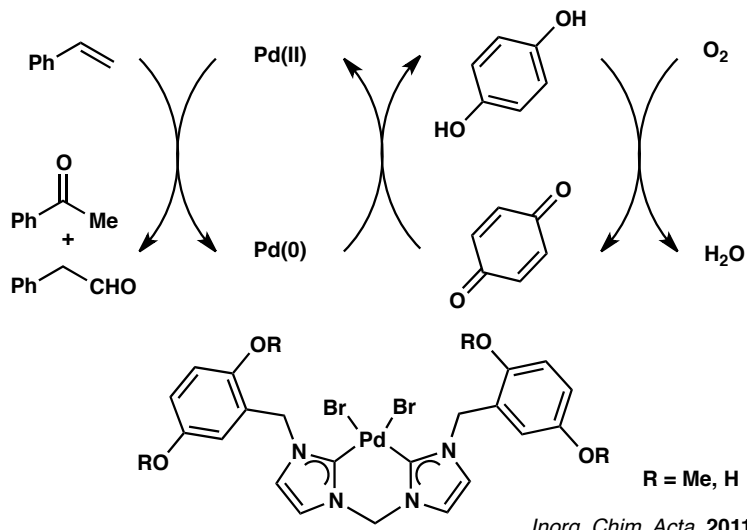


Introduction: the Wacker example and non-innocent ligands

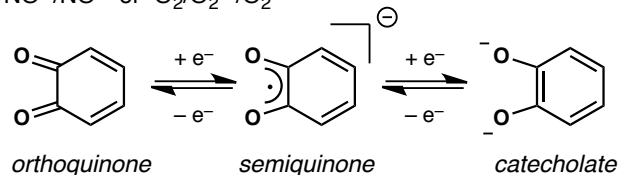


Appending quinone moieties into a palladium complex could improve the rate of the reaction by proximity effect. However, both NHC complexes (R = Me or H) failed to catalyze oxidation of styrene, as well as the oxidized (quinone) version. Introducing a redox-active substructure in a ligand is not that simple!

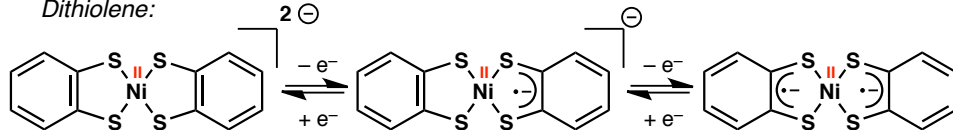
Non-Innocent ("Suspect") Ligands (Jørgensen, 1966):

Ligands that have an ambiguous oxidation state:

$\text{NO}^+/\text{NO}^\bullet/\text{NO}^-$ or $\text{O}_2/\text{O}_2^{\bullet-}/\text{O}_2^{2-}$



Dithiolene:



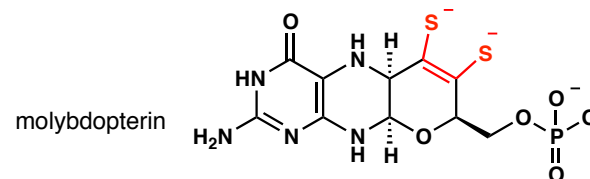
The complex is better described by radical ligands than oxidation of Ni(II) to Ni(IV)

"Although we loved these ligands, by the end of the 1960s, we knew that they were "guilty" as charged."

H. B. Gray, *Inorg. Chem.*, **2011**, 50, 974.

Modern experimental (EPR, Raman, X-ray crystallography...) and computational methods can often identify the appropriate oxidation state of the metal and the ligand.

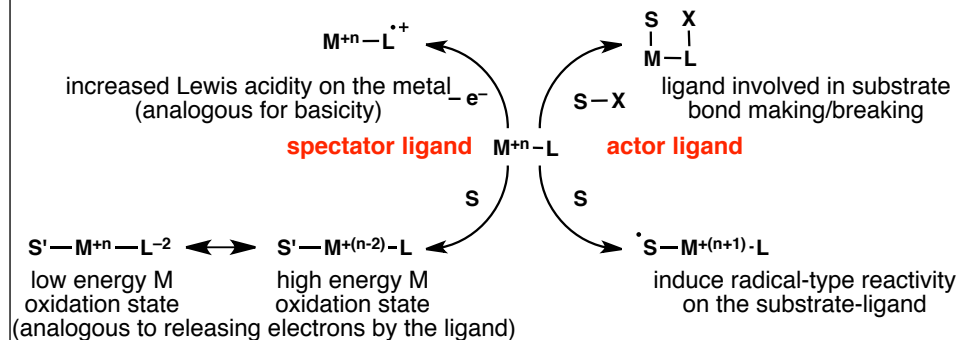
Biological relevance: Several enzymes contain non-innocent ligands like molybdenum oxotransferases (see Michaudel Group Meeting 2012)



Redox-active ligands recently regained an increasing attention from the inorganic community and have been the topic of a recent Forum issue in *Inorganic Chemistry* (Chirik, *Inorg. Chem.*, **2011**, 50 (20), 9737–9914.) and a special issue in the *European Journal of Inorganic Chemistry* (de Bruin, *Eur. J. Inorg. Chem.*, **2012**, 3, 340–580.)

For two recent and exhaustive reviews, see Crabtree, *Chem. Soc. Rev.*, **2013**, 42, 1440; de Bruin, *ACS Catal.*, **2012**, 2, 270.

Four Different Categories of Redox-Active Ligands :



This group meeting will not discuss:

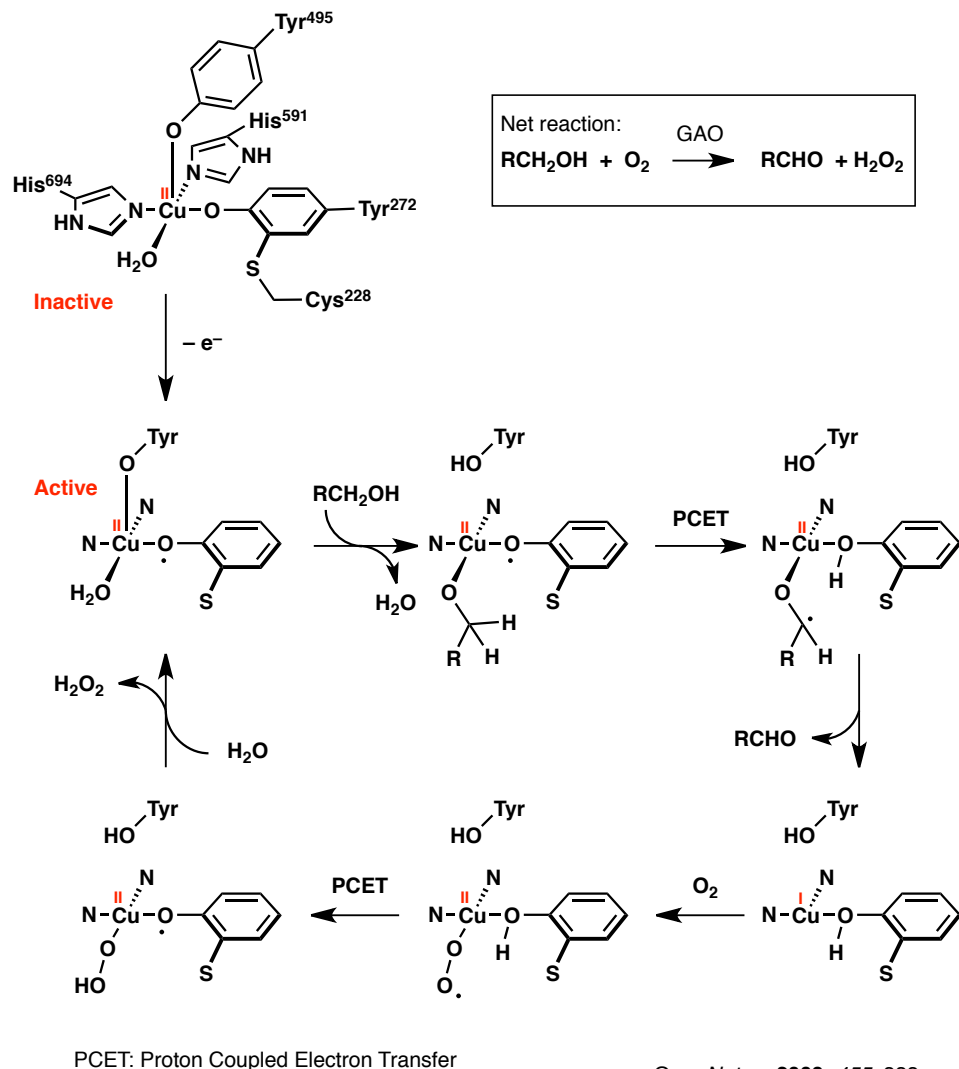
* electrochemical recognition of cations or anions by a ligand.

* redox-switchable hemilabile ligands or reactive fragment redox-switchable ligands. (For a review, see: Mirkin, *Angew. Chem., Int. Ed.*, **1998**, 37, 894.)

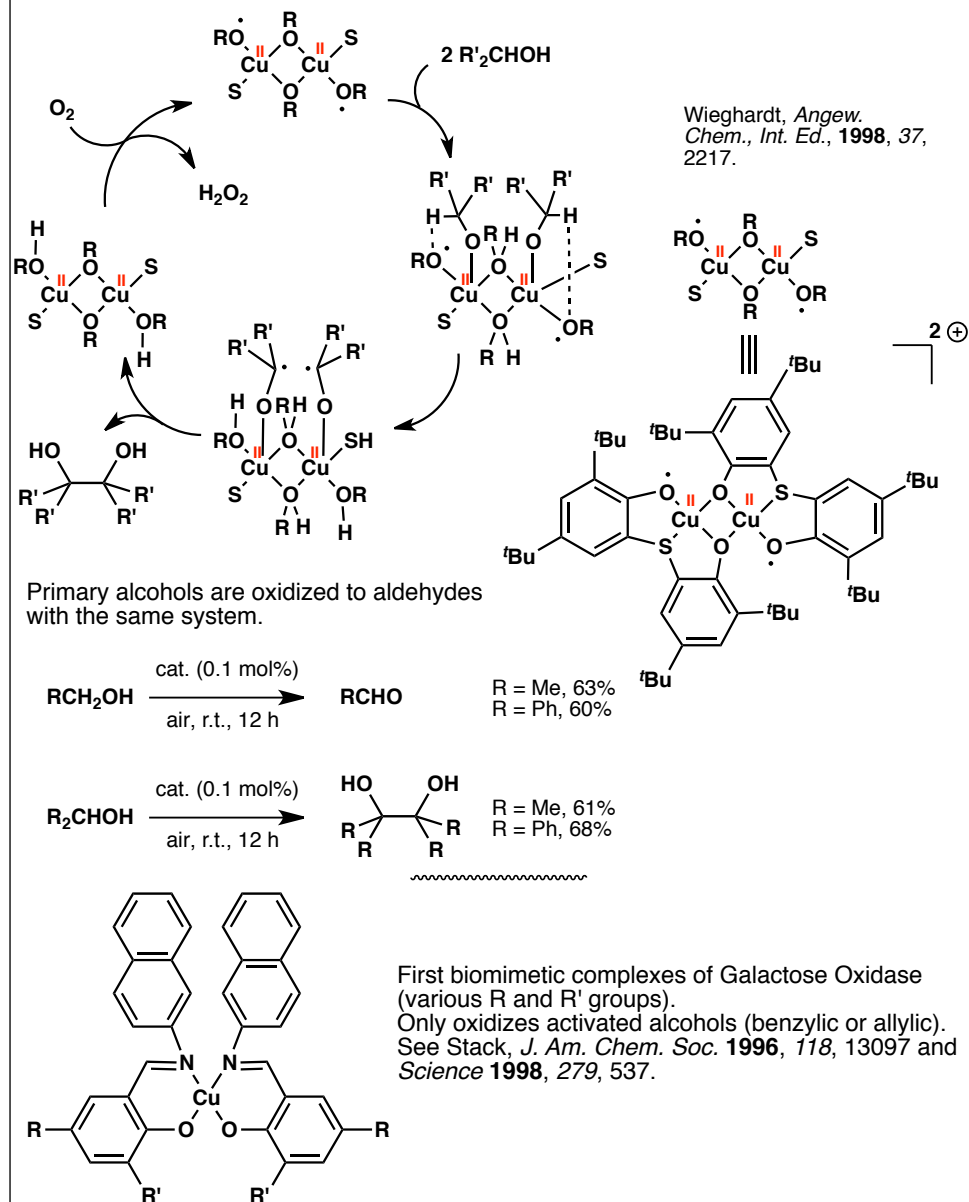
Actor Ligands:

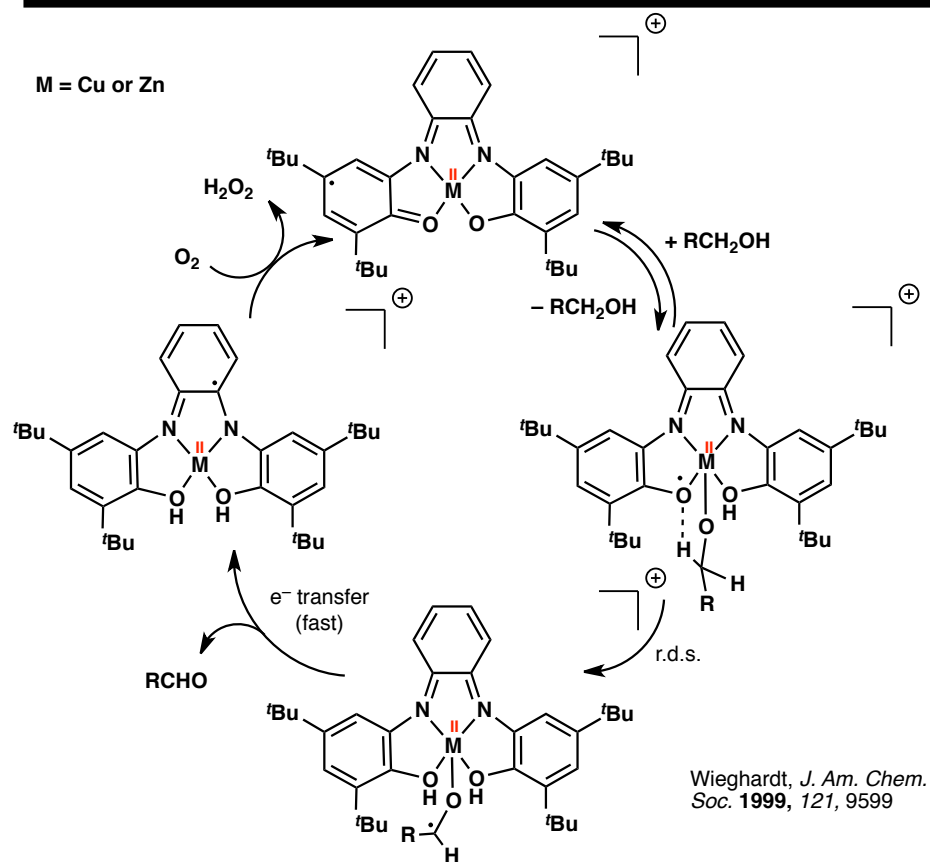
Cooperative Ligand-Centered Reactivity:

Mechanism of Galactose-Oxidase

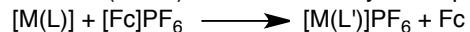


Biomimetic Alcohol Oxidation

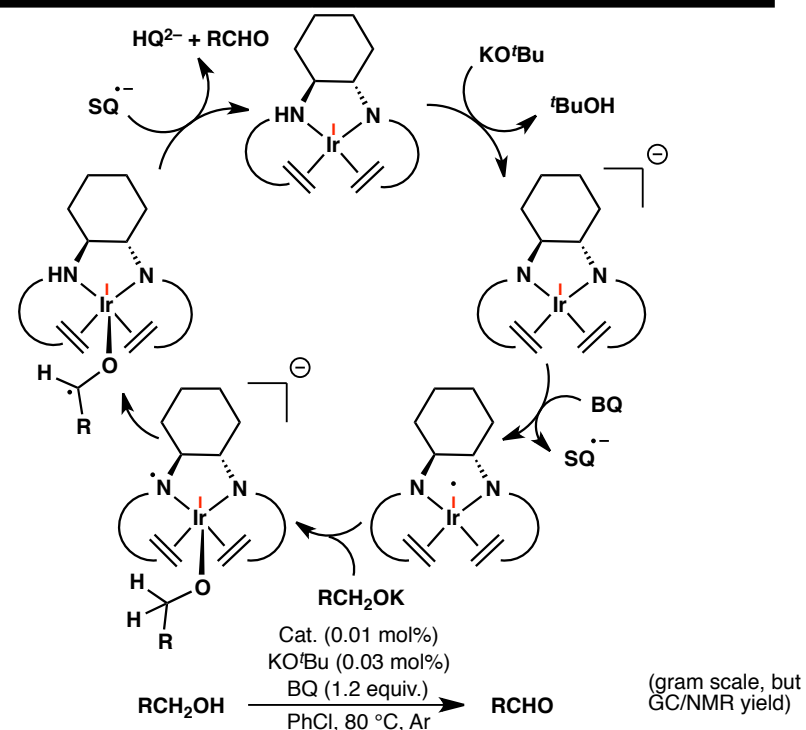
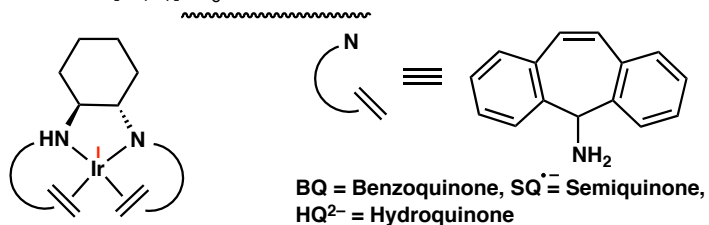




EPR spectroscopy, magnetic and electrochemical data provides evidence of ligand participation. It is also of note that Zn^{2+} is d^{10} and cannot accommodate any redox catalysis. Catalyst is more efficient with Cu than with Zn and even MeOH can be oxidized (>95%). The active catalyst was prepared by oxidation with ferrocenium:

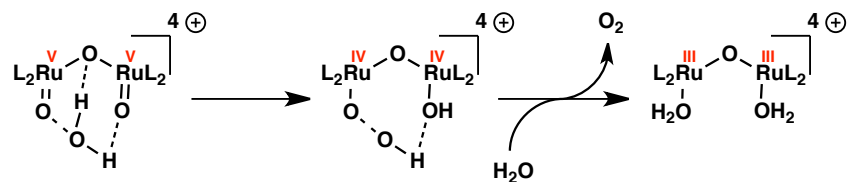


Angew. Chem., Int. Ed., **2007**, *46*, 3567.

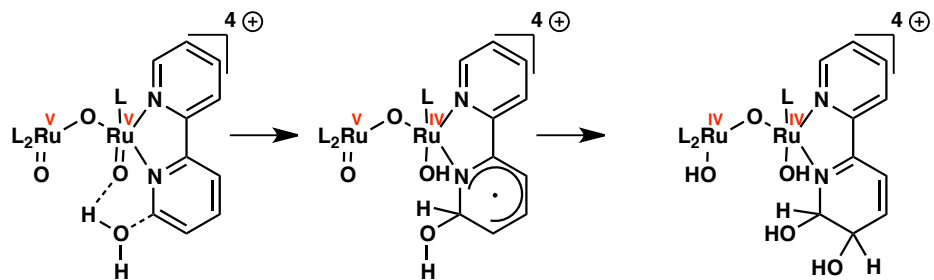
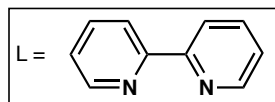


Substrate	Product	Yield (Time)	Substrate	Product	Yield (Time)
		94% (3 min)			> 98% (2 h)
		> 98% (3 h)			> 98% (1 h)
CH ₃ OH	CH ₂ O	64% (4 h)			> 98% (10 min) BQ (2 equiv.)
CH ₃ CH ₂ OH	CH ₃ CHO	94% (4 h)			> 98% (5 min) BQ (2 equiv.)

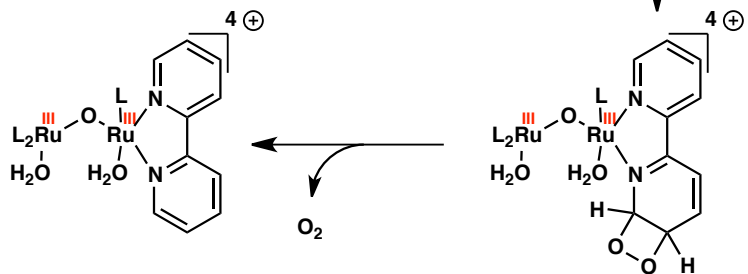
Mechanism of Water Oxidation with Ru "Blue Dimer": Redox-Active Ligand or Not?



Meyer, *J. Am. Chem. Soc.*, **2000**, *122*, 8464.

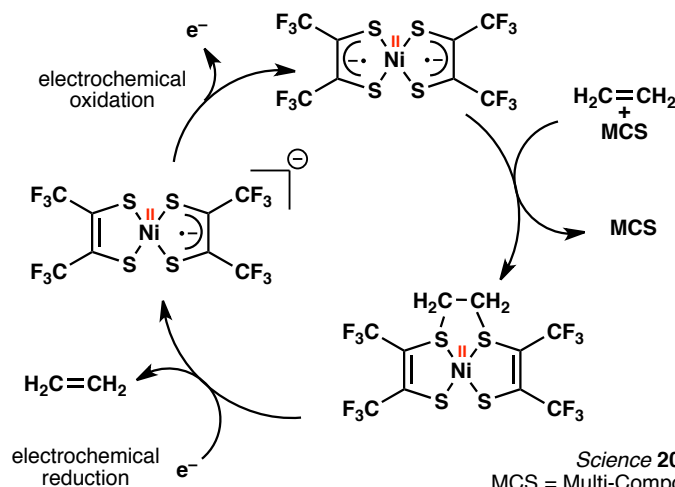


Hurst, *Inorg. Chem.*, **2008**, *47*, 1753.



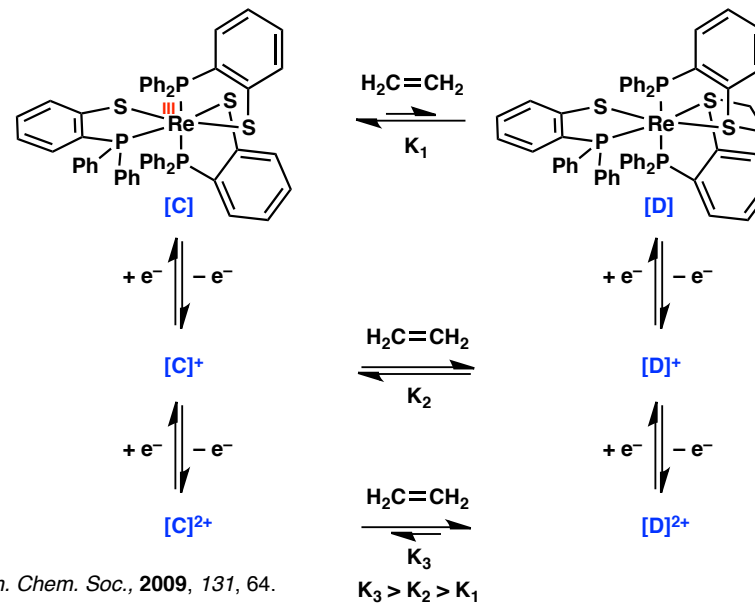
The original Meyer mechanism is still regarded as more likely, but the Hurst mechanism is still under consideration.

Purification of Ethene Gas Streams:



Science **2001**, *291*, 106.
MCS = Multi-Component Stream

Improved system: Fixation of ethene faster with oxidized complex [C]²⁺ and release requires less energy with to reduce complex [D]²⁺ into [D].

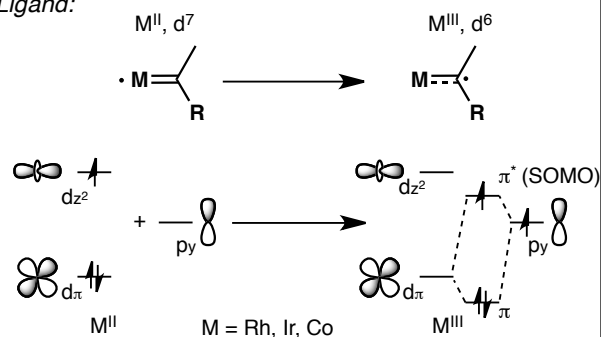


J. Am. Chem. Soc., **2009**, *131*, 64.

$K_3 > K_2 > K_1$

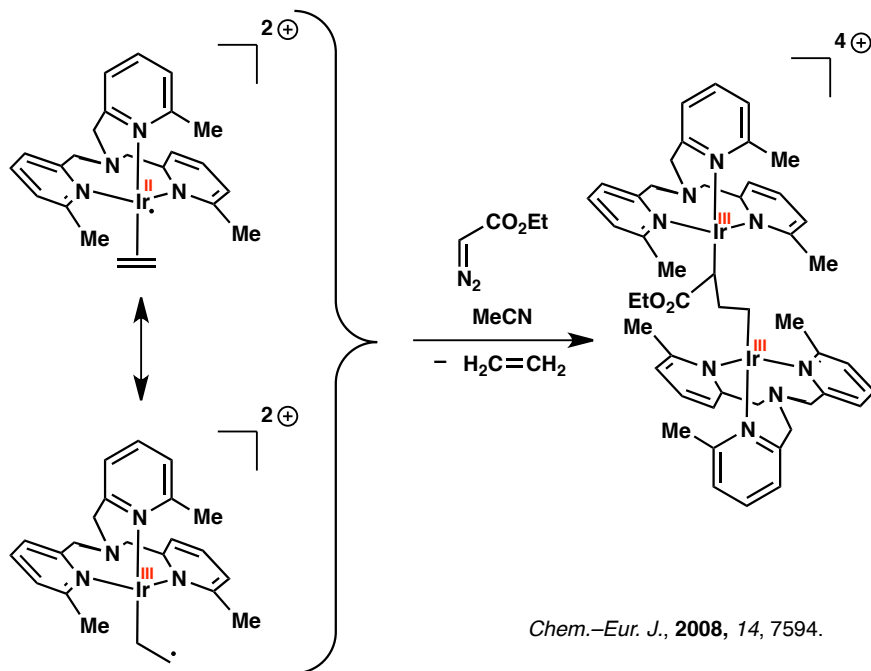
Cooperative Substrate-Centered Radical-Type Reactivity:

Carbenoid Redox-Active Actor Ligand:



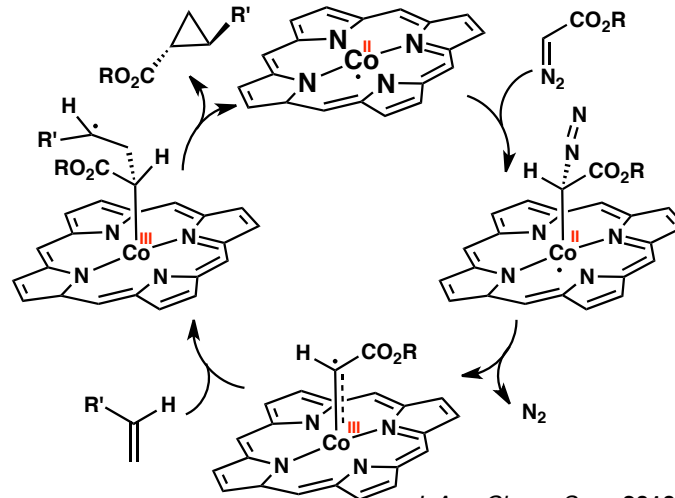
Chem. Soc. Rev., 2013, 42, 1440

Electronic configuration of metalloradicals of group 9

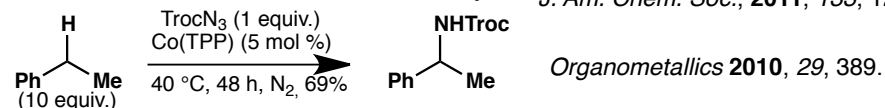
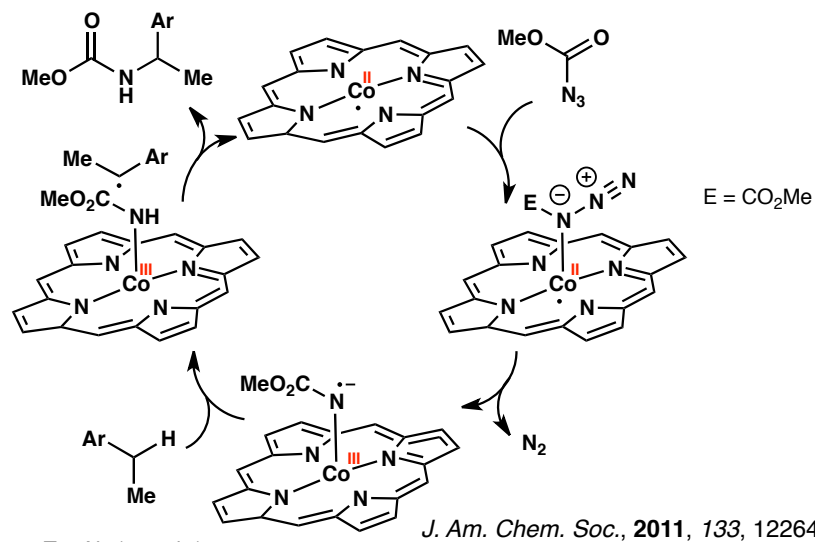


Reactivity of radical carbenoid is different from both Fischer (electrophilic, carbon-centered LUMO) and Schrock (nucleophilic, carbon-centered HOMO) carbenes.

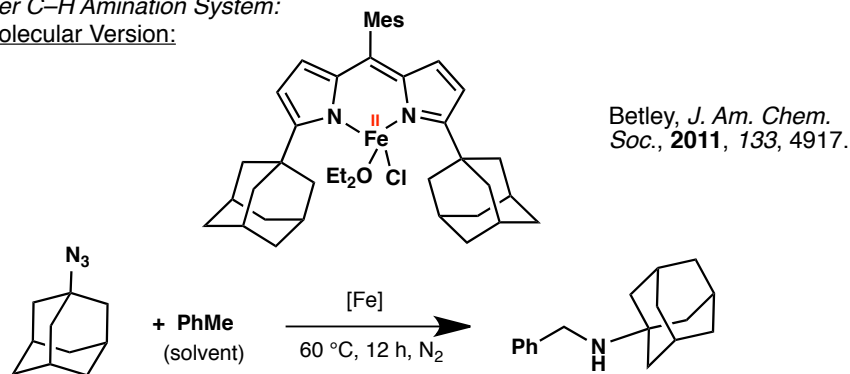
Cyclopropanation with Redox Non-Innocent Carbene:



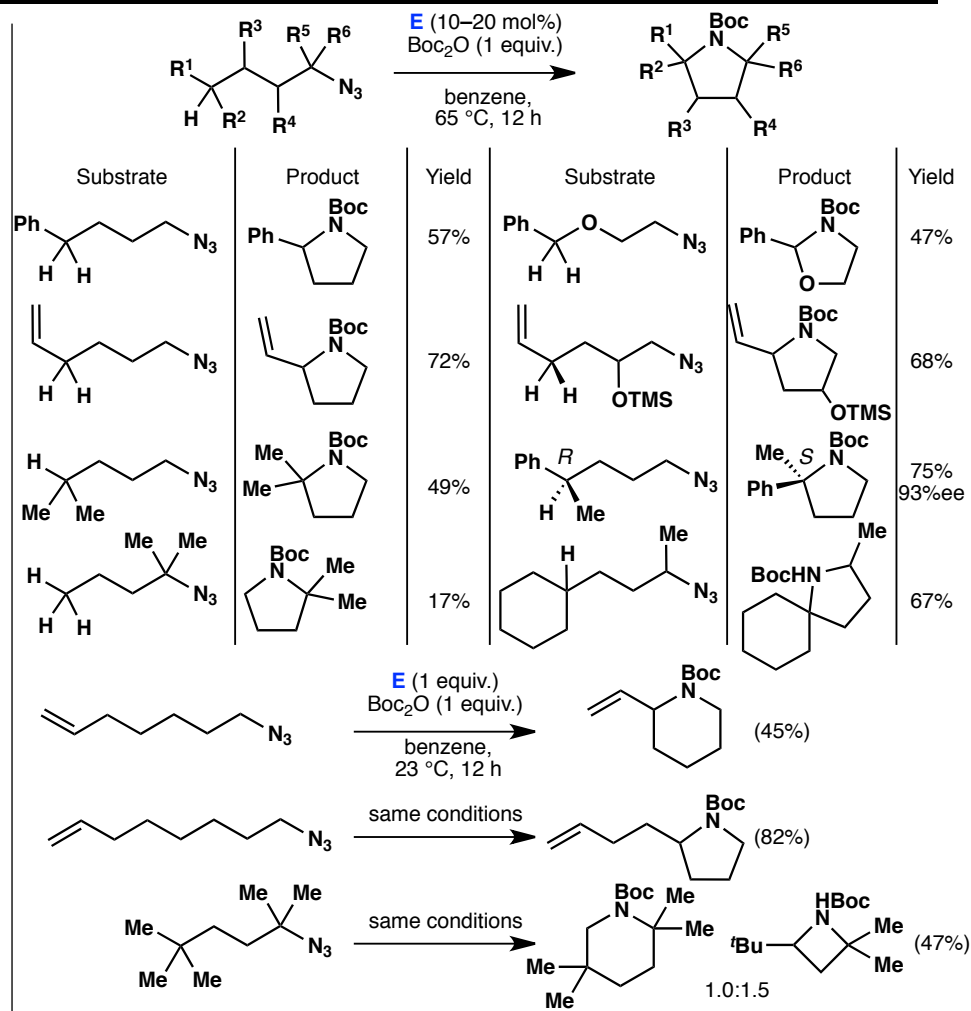
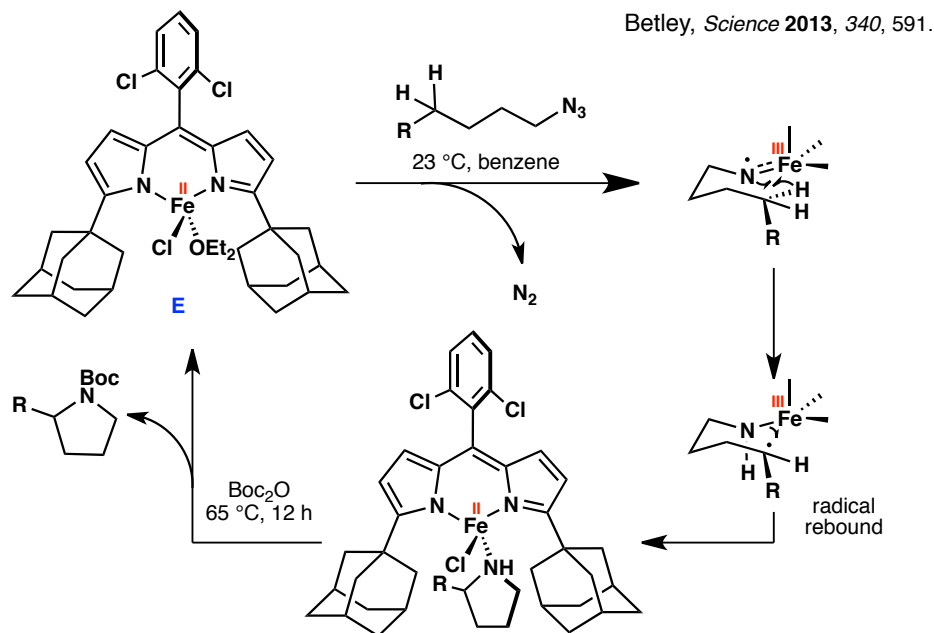
C-H Amination of Benzylic C-H Bonds:



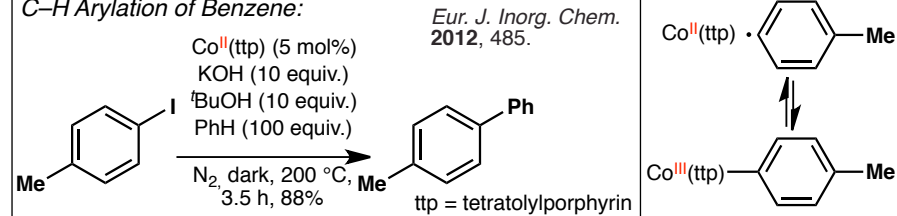
Another C–H Amination System:
Intermolecular Version:



Intramolecular Version:

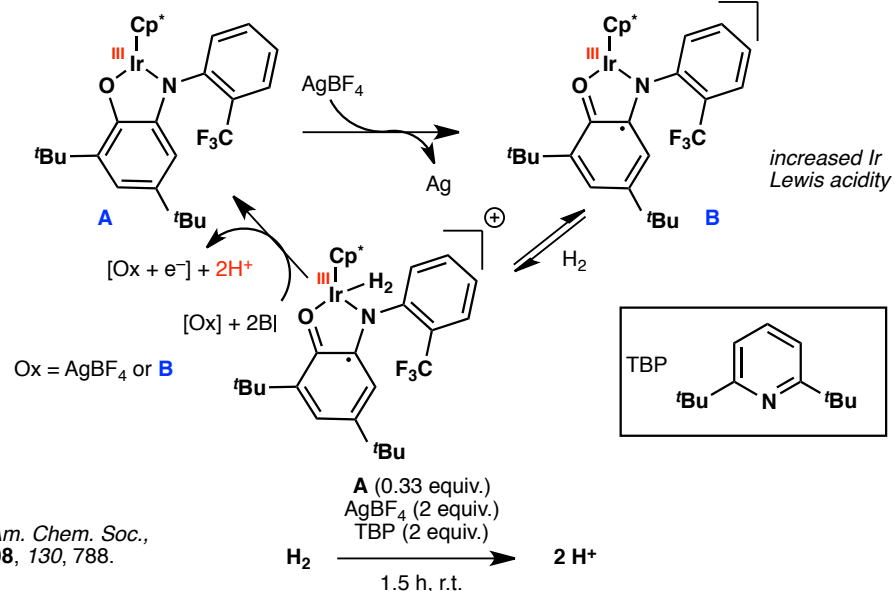


C–H Arylation of Benzene:



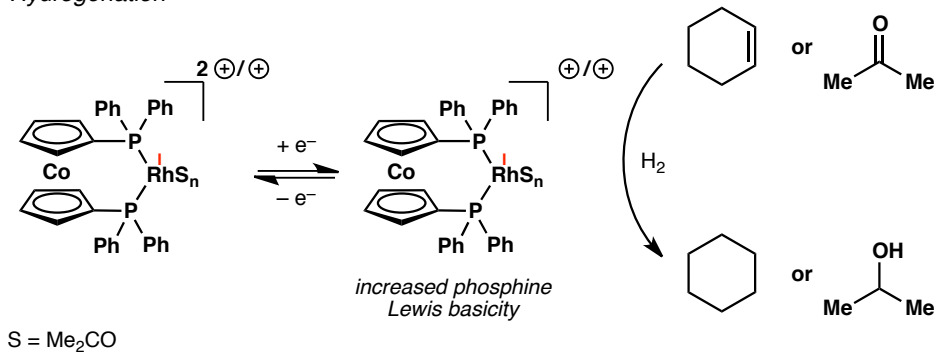
Spectator Ligands:

Modification of the Lewis Acid-Base Properties of the Metal

 H_2 oxidation:

J. Am. Chem. Soc.,
2008, 130, 788.

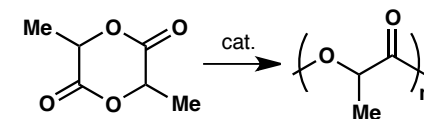
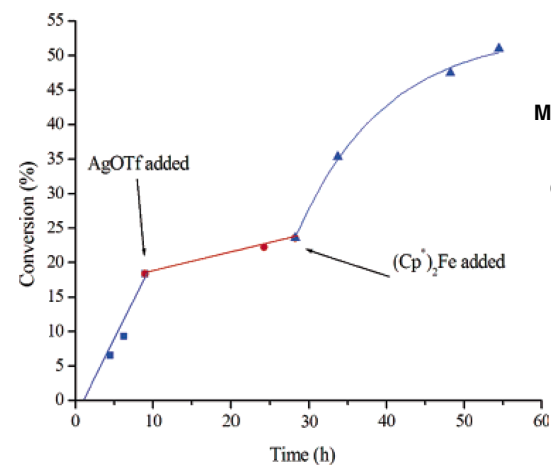
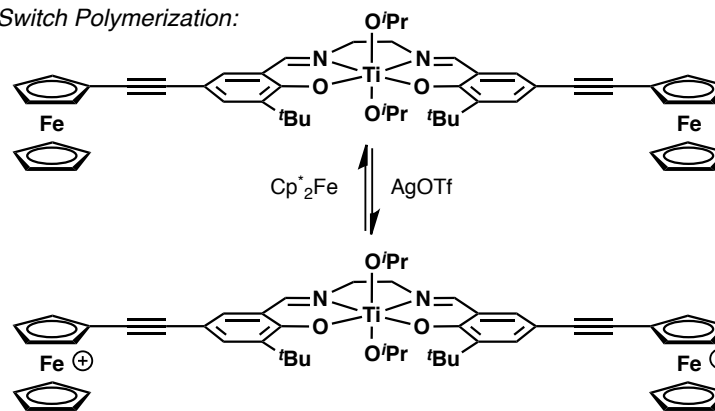
Hydrogenation



J. Am. Chem. Soc., 1995, 117, 3617.

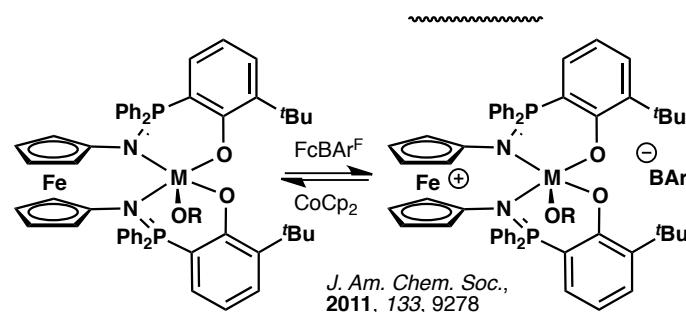
Cobaltocenium reduction enhances electron density on Rh, which facilitates the oxidative addition of H_2 (r.d.s.) and leads to 16-fold rate increase compared to the oxidized form of the complex. Interestingly, the oxidized complex catalyzes the hydrosilylation of alkene faster than the reduced form.

Redox Switch Polymerization:



Redox-switches could be useful for block copolymerization.

J. Am. Chem. Soc.,
2006, 128, 7410.



J. Am. Chem. Soc.,
2011, 133, 9278

For M = Y, R = ^tBu, ferrocenium stops lactide polymerization. While, for M = In, R = Ph, it is the opposite behavior! R.d.s. is different depending on which complex is used.

Redox Non-Innocent Ligands as Electron-Reservoirs:

Redox-Active Ligands Confer Nobility on Base-Metal Catalysts:

Precious metals most efficiently catalyze two electron reactions, since they typically undergo ± 2 e⁻ oxidation state changes (Ir^I, Ir^{III}, Ir^V or Pd⁰, Pd^{II}, Pd^{IV}) whereas base-metal undergo ± 1 e⁻ oxidation state changes (Co^I, Co^{II}, Co^{III} or Fe^{II}, Fe^{III}). However, the price of precious metals is increasing due to their low abundance.

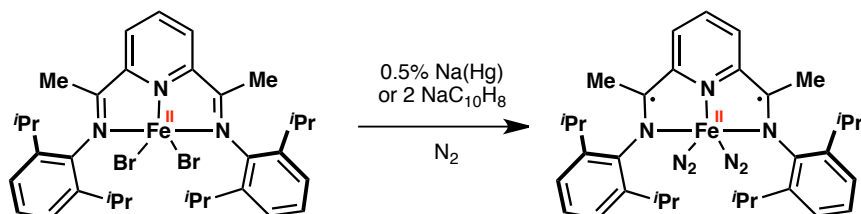
Abundance in Earth's crust (ppb by weight)

Mn	Fe	Co	Ni	Cu	Zn
1.1×10^6 ppb	6.3×10^7 ppb	3.0×10^4 ppb	9.0×10^4 ppb	6.8×10^4 ppb	7.9×10^4 ppb
Tc	Ru	Rh	Pd	Ag	Cd
–	1.0 ppb	0.7 ppb	6.3 ppb	80 ppb	1.5×10^2 ppb
Re	Os	Ir	Pt	Au	Hg
2.6 ppb	1.8 ppb	0.4 ppb	37 ppb	3.1 ppb	67 ppb

Source: http://www.webelements.com/periodicity/abundance_crust/

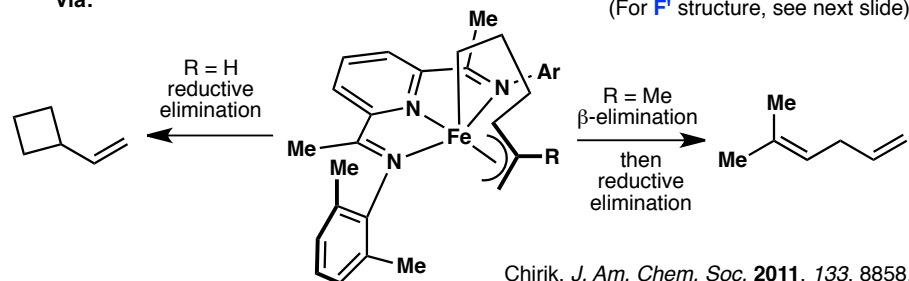
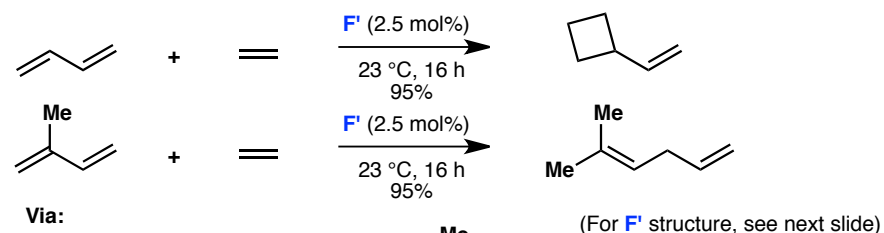
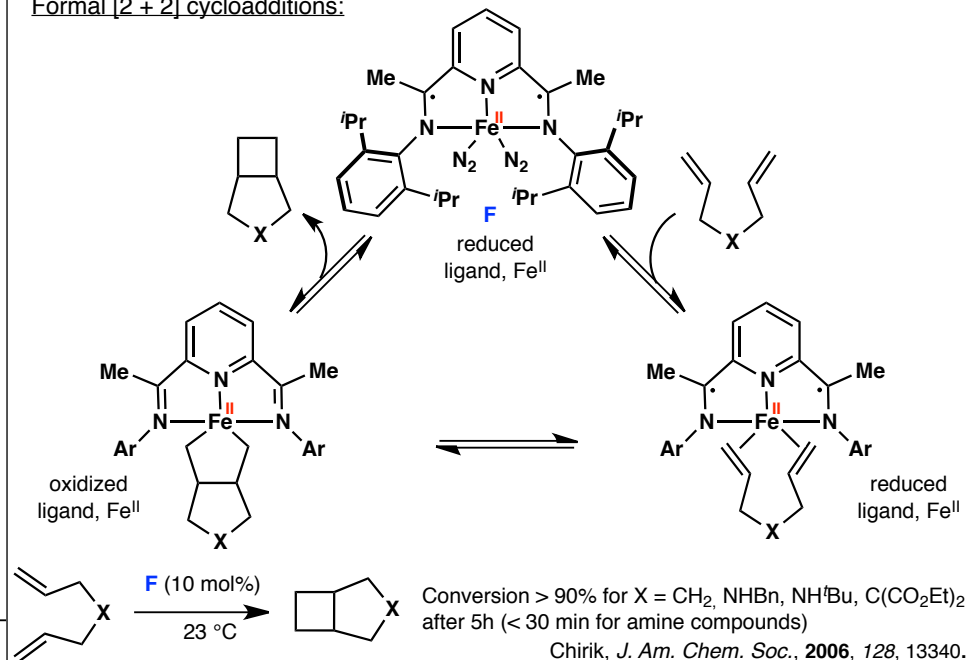
Chirik and Wieghardt have proposed that redox active ligands may be able to confer nobility on base metals by playing the role of electron sinks.

Science, 2010, 327, 794.

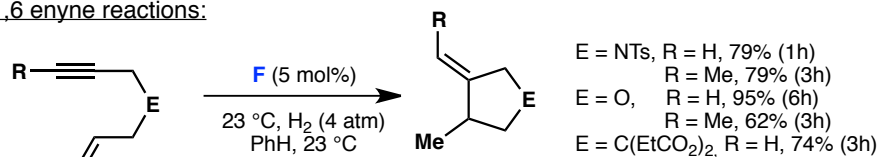
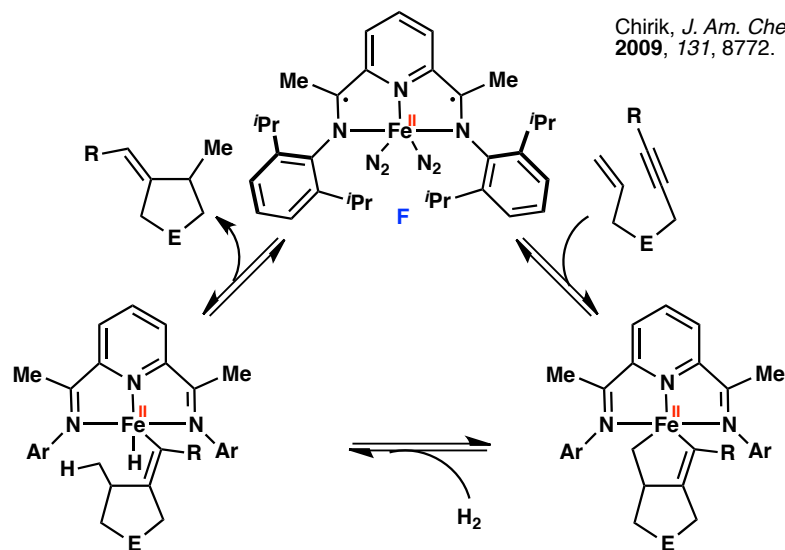
Bis(aryliminopyridine) Pincer Ligand:

This ligand framework can store two reducing equivalents in an iron(II) complex. It has been used for several reactions:

- * Formal [2 + 2] cycloadditions
- * 1,6-enyne reactions
- * Hydrogenation and hydrosilylation
- * Oxidative additions into C–C bonds

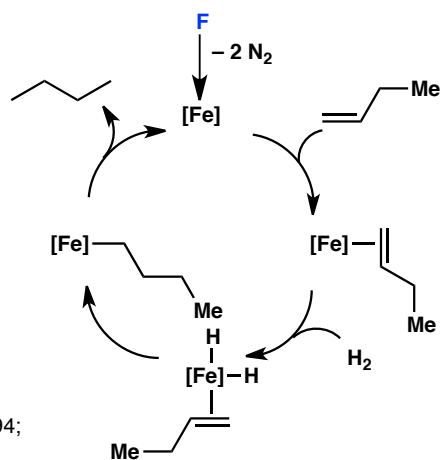
Formal [2 + 2] cycloadditions:

1,6 enyne reactions:

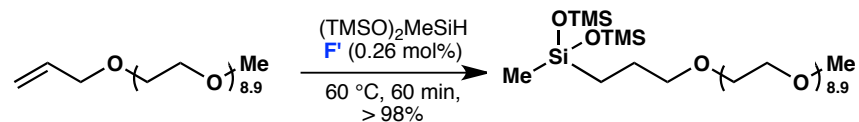
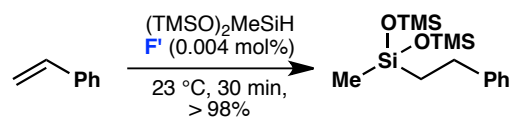
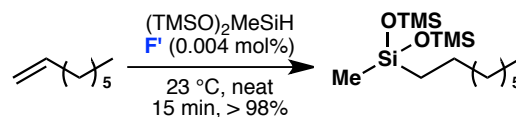
Chirik, *J. Am. Chem. Soc.*, 2009, 131, 8772.

Hydrogenation and hydrosilylation:

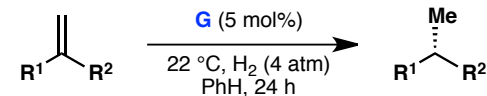
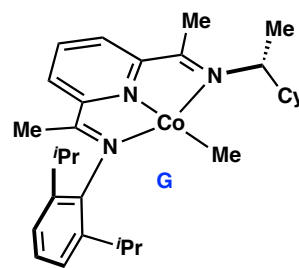
This catalyst enables the hydrogenation of olefins in the presence of unprotected amines, various carbonyls, ethers and fluorinated hydrocarbons.

Chirik, *J. Am. Chem. Soc.*, 2004, 126, 13794; *Organometallics*, 2008, 27, 1470.

Anti Markovnikov Hydrosilylation:

Chirik, *Science*, 2012, 335, 567.

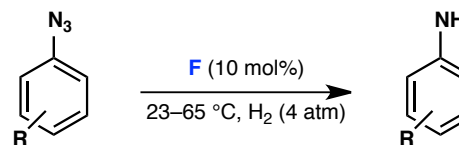
Enantioselective Hydrogenation:



$R^1 = \text{Ar}, R^2 = \text{Alk}$
Up to >98% yield, 96% ee

Chirik, *J. Am. Chem. Soc.*, 2012, 134, 4561.

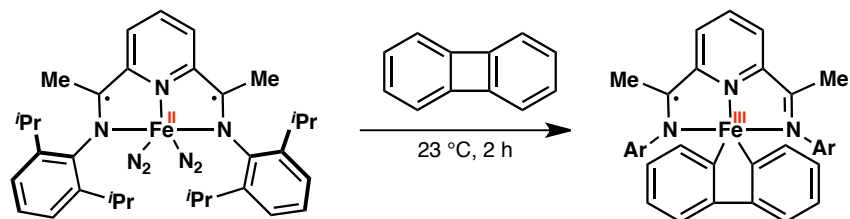
Reduction of Azides:



$R: 2,6\text{-}i\text{Pr}_2 > 2,5\text{-}t\text{Bu}_2 > 2,6\text{-Et}_2 \gg 2,4,6\text{-Me}_3$

Chirik, *J. Am. Chem. Soc.*, 2006, 128, 5302.

Oxidative additions into C–C bonds:

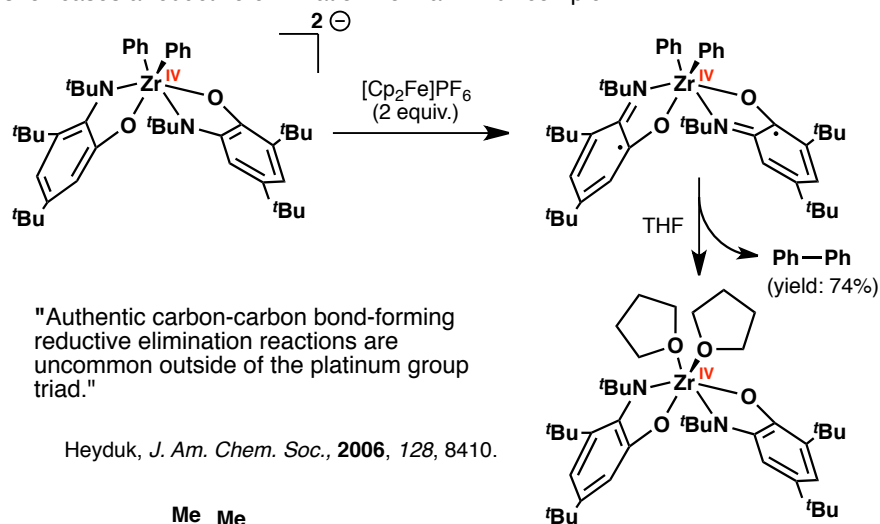


In this case, both ligand and metal give one electron. This is another way for this bis(imino)pyridine frame to adjust to the electronic requirements of a metal complex and a specific redox process.

Chirik, *J. Am. Chem. Soc.*, **2012**, *134*, 17125.

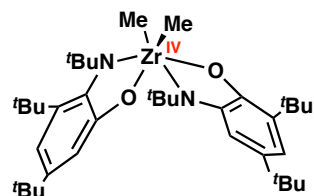
C–C Bond Formation:

This paper set a key precedent for the field of redox-active ligands, because it showcases a reductive elimination from a Zr^{IV} d⁰ complex!!



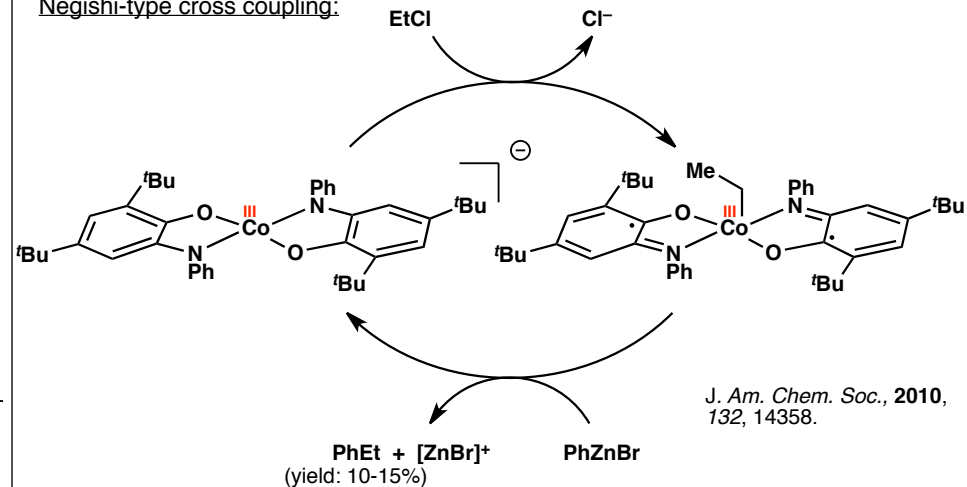
"Authentic carbon-carbon bond-forming reductive elimination reactions are uncommon outside of the platinum group triad."

Heyduk, *J. Am. Chem. Soc.*, **2006**, *128*, 8410.



The dimethyl equivalent yields 23% of a mixture of methane (79%) and ethane (21%), so about 5% yield for the Me–Me coupling.

Negishi-type cross coupling:



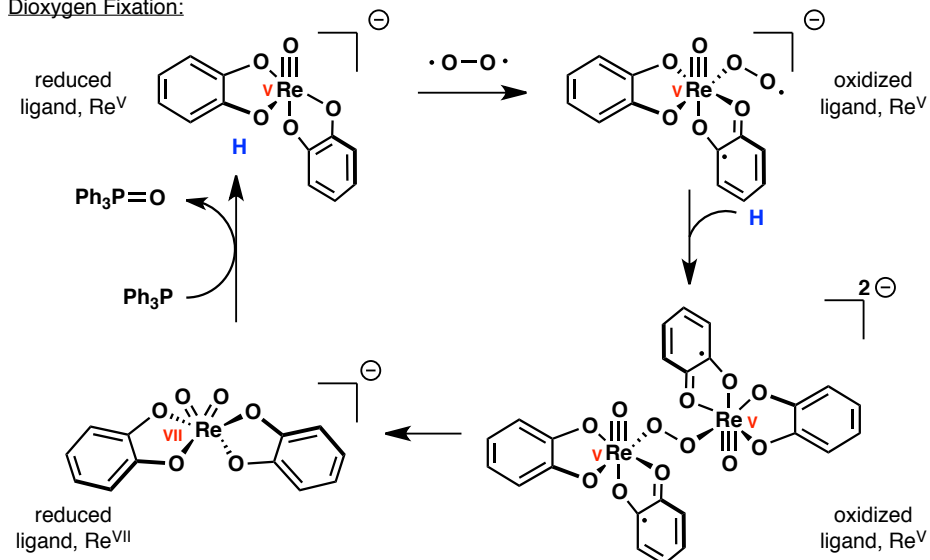
J. Am. Chem. Soc., **2010**, *132*, 14358.

Reaction also works with hexylzinc bromide in similar yields.

Miscellaneous Reactions:

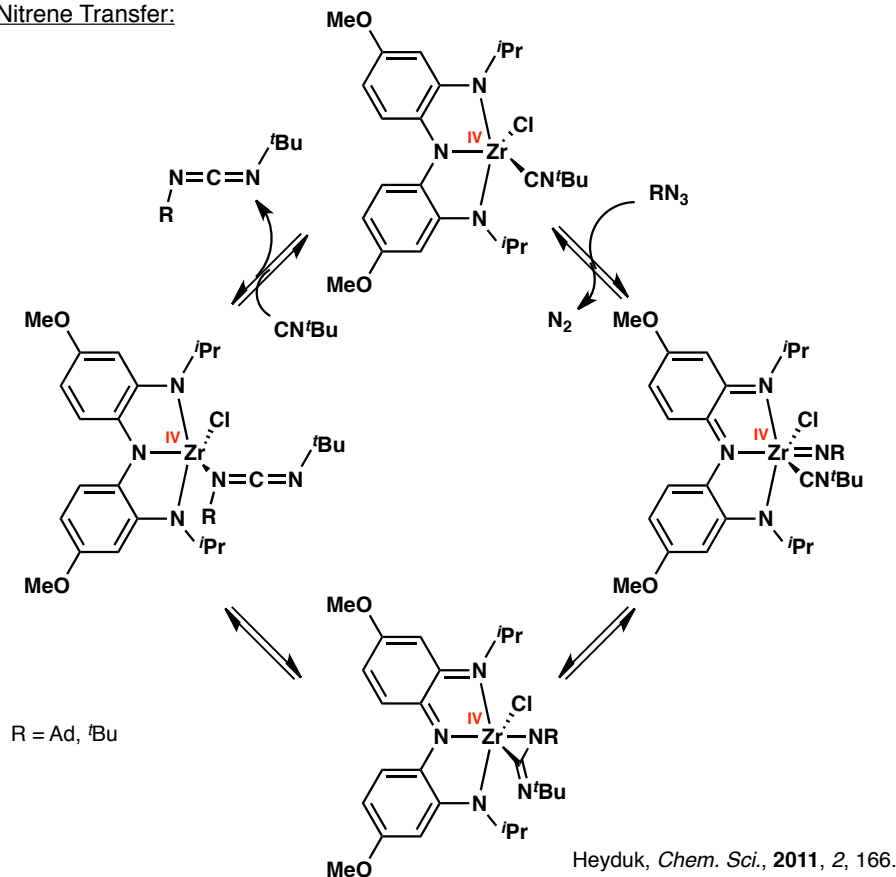
J. Am. Chem. Soc., **2010**, *132*, 3879.

Dioxygen Fixation:



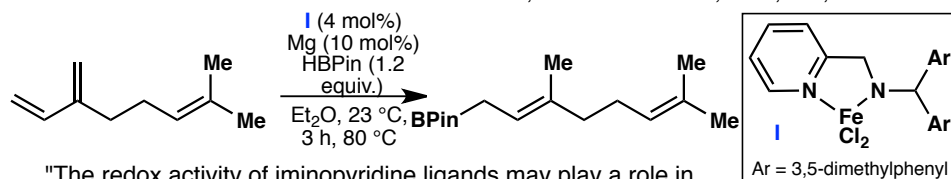
The ligand facilitates spin-crossover in the formally "spin-forbidden" reaction between triplet oxygen and the closed-shell (singlet) d² rhenium(V).

Nitrene Transfer:



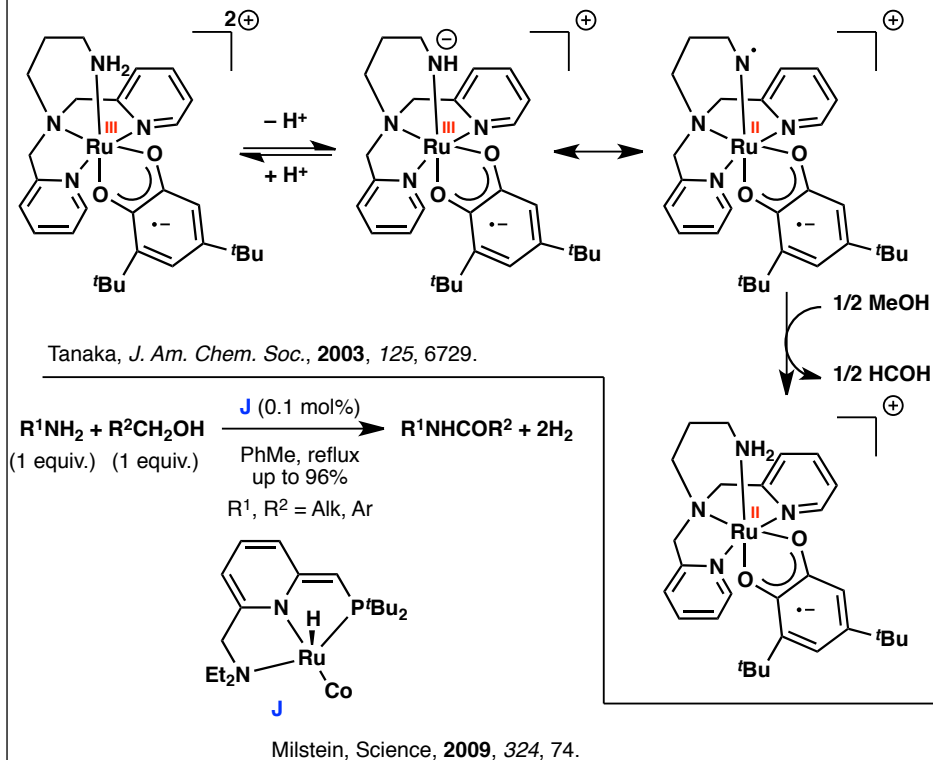
Coupling of ^tBuNC with AdN₃ reacted to completion in 2 h at 55 °C with 10 mol% of catalyst.

Hydroboration of 1,3 Diene:



"The redox activity of iminopyridine ligands may play a role in effecting efficient catalysis".

The elegant work of Milstein and Tanaka on base assisted redox-active ligand catalysis for alcohol oxidation is also notable:



Further Reading:

"Oxidative Addition" to a Zirconium(IV) Redox-Active Ligand Complex: Heyduk, *Inorg. Chem.*, **2005**, *44*, 5559.

Catalytic Reactivity of a Zirconium(IV) Redox-Active Ligand Complex with 1,2-Diphenylhydrazine: Heyduk, *J. Am. Chem. Soc.*, **2008**, *130*, 2728.

Four-Electron Oxidative Formation of Aryl Diazenes Using a Tantalum Redox-Active Ligand Complex: Heyduk, *Angew. Chem., Int. Ed.*, **2008**, *47*, 4715.

Iron Diazoalkane Chemistry: N–N Bond Hydrogenation and Intramolecular C–H Activation: Chirik, *J. Am. Chem. Soc.*, **2007**, *129*, 7212.

Reaction of a Redox-Active Ligand Complex of Nickel with Dioxygen Probes Ligand-Radical Character: *J. Am. Chem. Soc.*, **2009**, *131*, 15582.