

Outline:

1. Carbonate Formation from Epoxides
2. Reductive Methylation/Formylation
3. An introduction to oxidative cyclometallations
4. Carboxylation with various functional handles
5. A few slides dedicated to the work of the Martin group in recent years up to 2017

Not Covered:

- CO₂ as a catalyst
- CO₂ fixation into various feedstock chemicals
 - Organocatalytic, photochemical, or electrochemical methods utilizing CO₂ as a reagent without transition metal catalysis.

A Few Useful Reviews:

Sakakura, K. *Chem. Rev.* **2007**, 107, 6, 2365–2387.
<https://doi.org/10.1021/cr068357u>

Beller, M. *Nature Communications*, **2015**, 6, 5933.
<https://doi.org/10.1038/ncomms6933>

Martín, R. *Angew. Chem. Int. Ed.* **2018**, 57 (49), 15948–15982.
<https://doi.org/10.1002/anie.201803186>

For a review discussing the utility of CO₂ as an alternative for CO in organic reactions, see:

Bandini, M. *ChemCatChem* **2023**, <https://doi.org.proxy2.library.illinois.edu/10.1002/cctc.202300827>

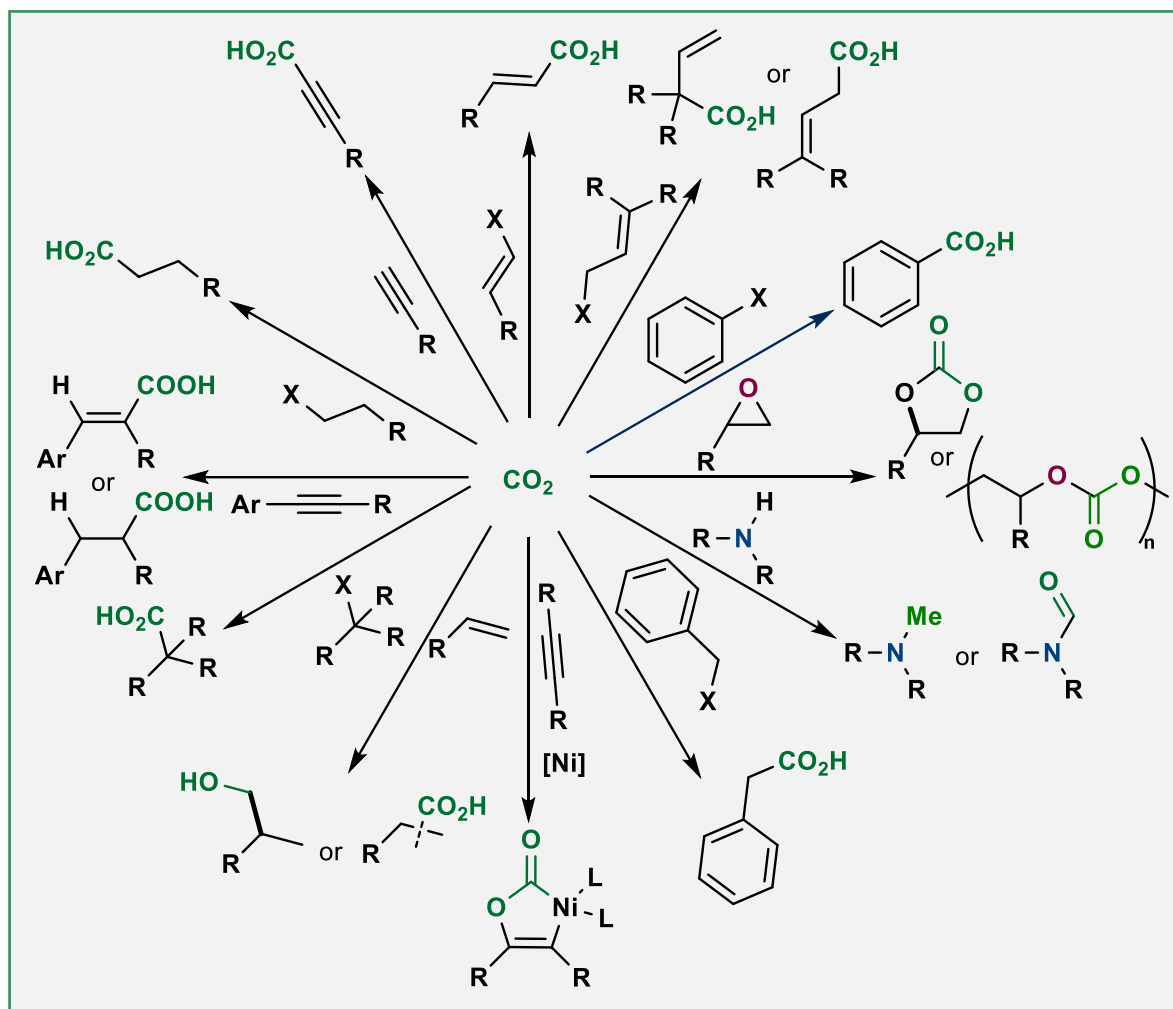
For an in-depth look at the organometallics behind carbonylation complex formation, see:

Gibson, D. *Chem. Rev.* **1996**, 96, 6, 2063–2096.
<https://doi.org/10.1021/cr940212c>

For an interesting perspective on CO₂-promoted reactions (not covered) see:

Das, S. *ACS Catal.* **2021**, 11, 6, 3414–3442.
<https://doi.org/10.1021/acscatal.0c05681>

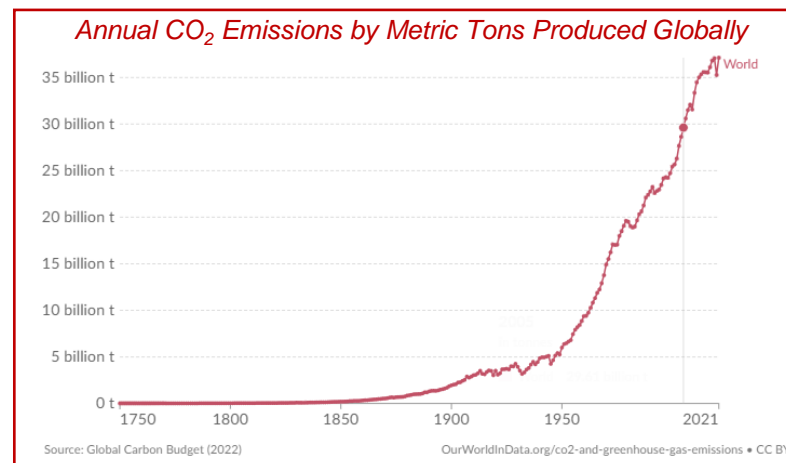
An Overview of Transition Metal Catalyzed Reactions Using CO₂ as a Building Block



This seminar will attempt to cover all of these transformations, however, let the caveat be made: this field is incredibly expansive between disciplines. There are numerous additional examples than the examples shown, and likely numerous ways of performing that transformation depicted with different catalytic systems.

The Importance of CO₂ Valorization:

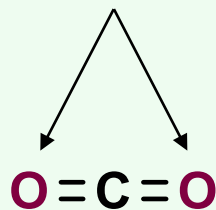
- Carbon dioxide is among the most prominent greenhouse gases produced, coming in at over 37 billion metric tons produced globally every year as of 2021.
- CO₂ is produced in large quantities by fossil fuel combustion, sugar fermentation, and most prominently from the respiration of all living organisms. Since the boom of the second industrial revolution, these numbers have risen drastically in the last 150 years.
- Being as CO₂ is produced in such large quantities and is posited to be contributing largely to changes in atmospheric temperature and global climate, the valorization of such a feedstock chemical would be exceptionally useful not only to the chemical community, but the global community at large.
- While efforts to directly alter CO₂ into other feedstock C1 and C2 chemicals is a prevalent and exciting field, the focus of this topic will be on the utility of CO₂ directly as a building block in organic synthesis.



The Reactivity Challenge of CO₂:

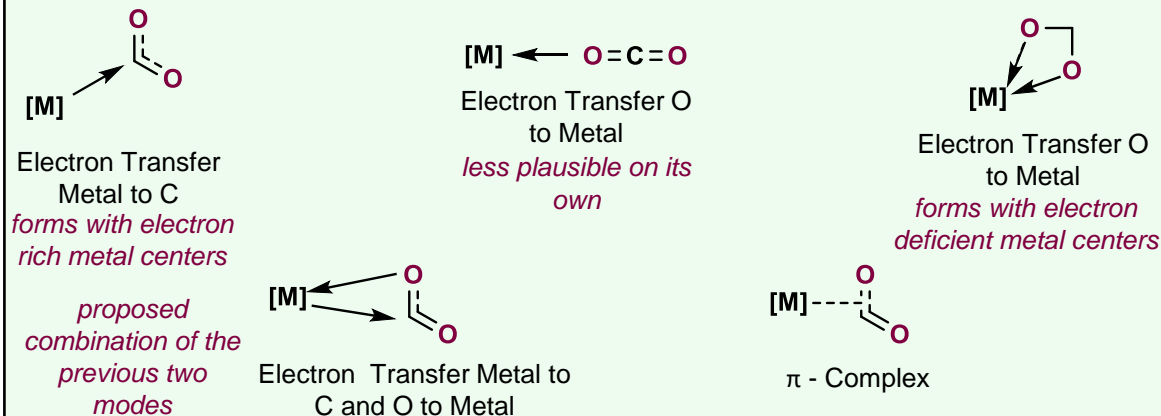
- Carbon dioxide is the most stable form of oxidized carbon compounds, making it inherently difficult to develop mild reactions utilizing it. CO₂ reactivity often requires high energy input rendering it neither practical or benign. This subsequently can also lead to challenges with reversibility, where these forcing conditions can facilitate the expulsion of CO₂. However, transition metal catalysis has made great strides in helping to make CO₂ valorization a more practical and synthetically useful endeavor.

The oxygen atoms on CO₂ can react as weak nucleophilic Lewis Bases



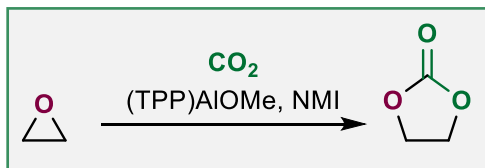
The carbon atom is an electrophilic Lewis acid center

Available Chelation Modes Between Transition Metal Centers and CO₂



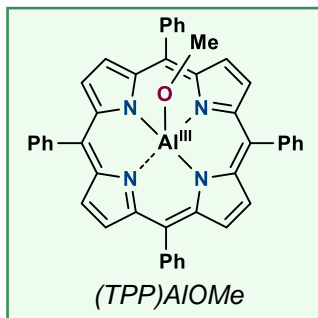
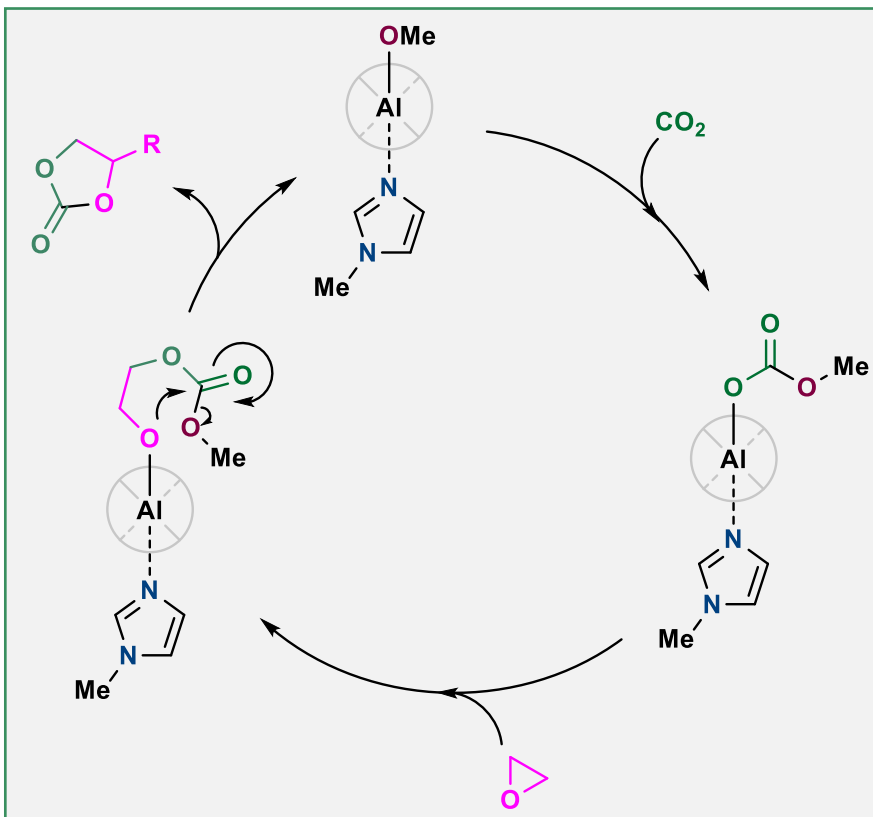
Carbonate Formation from Epoxides

Inoue, 1983: The Seminal Report

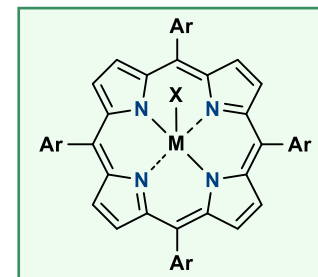
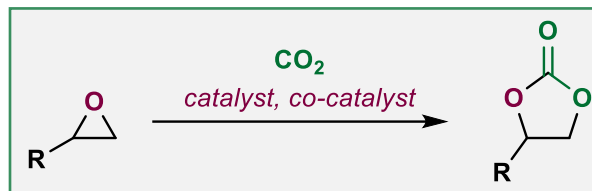


The first report showed reversible addition of CO_2 into ethylene oxide at ambient temperature. No yields reported.

Proposed Mechanism:

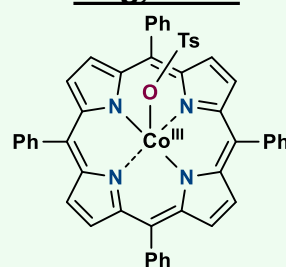


Subsequent Metalloporphyrin Systems



Nucleophilic co-catalysts such as TBAB, TBAI, PTAT, etc. were determined to be quite useful for activating the epoxide upon coordination to the metal center. There are reports in which these nucleophilic tetralkylammonium salts are capable of performing these transformations without a metal catalyst, albeit requiring molten temperatures.

Jing, 2007:

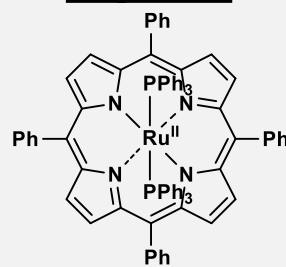


- CO_2 (7 barr)
- Room Temperature w/ PTAT
- Up to 930 TON
- 93% yield
- Solvents Required
- Other metals were screened, and catalytic activity was ranked as follows:



Jing, H. J. *Molecular Catalysis*. 2007, 261, 2, 262–266. <https://doi.org/10.1016/j.molcata.2006.06.011>

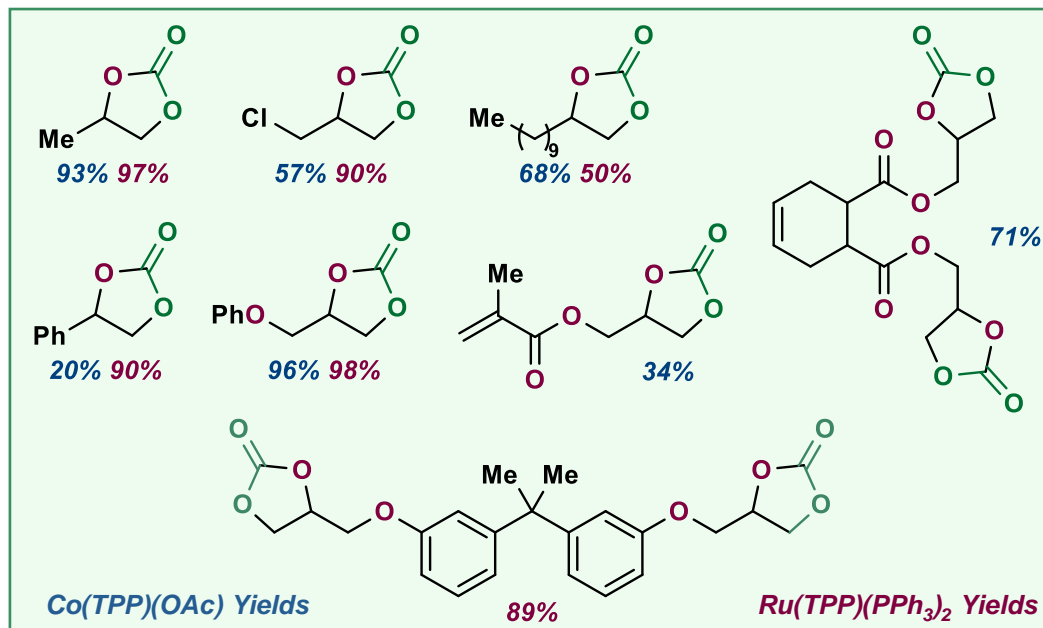
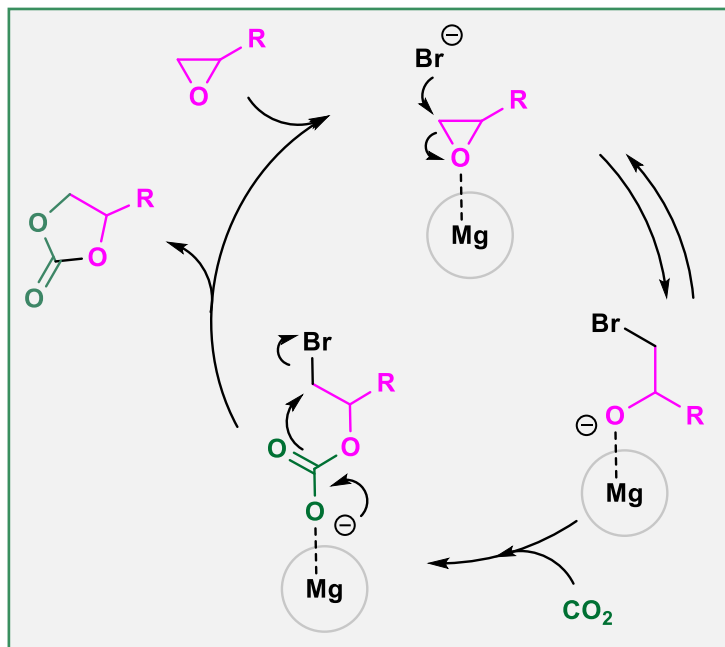
Jing, 2007:



- 0.05 mmol catalyst
- Up to 960 TON
- Up to 84% yield
- CO_2 (667 kPa)
- 50 °C w/ PTAT & EDA additive
- Solvent free

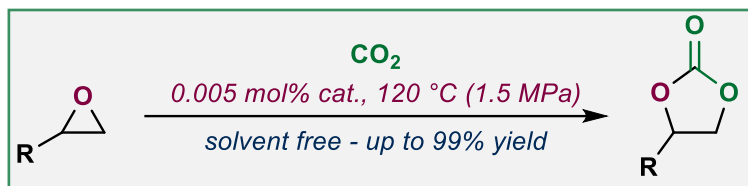
Utilization of Bifunctional Catalysis for Improved TON

Jing, 2007: *Co-Catalyst Mechanistic Rationale and Substrate Scope*



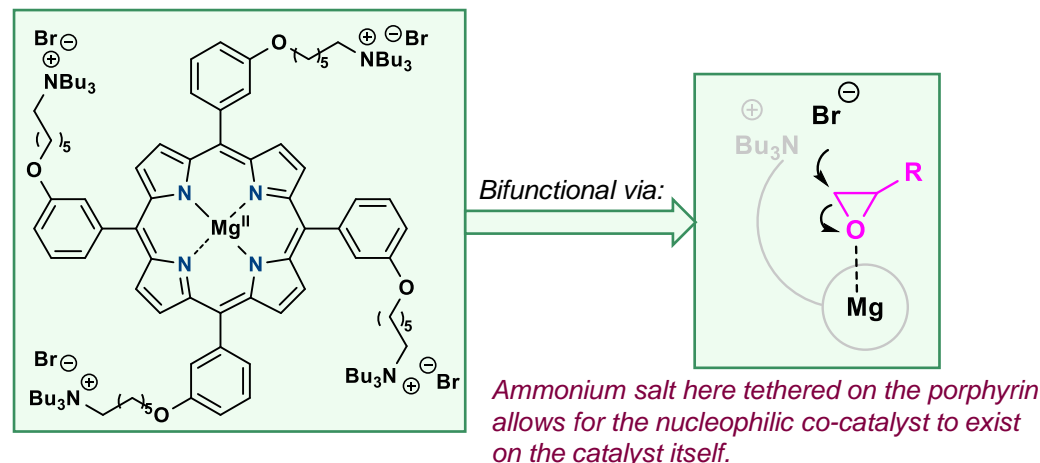
Jing, H. *Chinese Journal of Catalysis*. **2007**, 28, 4, 287–288. [https://doi.org/10.1016/S1872-2067\(07\)60024-2](https://doi.org/10.1016/S1872-2067(07)60024-2)
 Jing, H. *J. Molecular Catalysis*. **2007**, 261, 2, 262–266. <https://doi.org/10.1016/j.molcata.2006.06.011>

Sakai, 2012: *Bifunctional Catalyst Control*



• **TON of 103,000!**

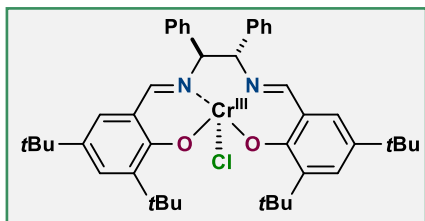
Within this paper, other divalent metalloporphyrins utilizing zinc are also shown to be highly active. The bifunctional catalyst showed compatibility with various onium salt groups tethered.



Sakai, T. *Chem. Commun.*, **2012**, 48, 4489. <https://doi.org/10.1039/C2CC30591G>

Expanding Beyond Poyphyrins

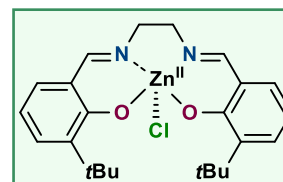
Nguyen, 2001: Cr^{III} Salen System



- CO₂ (8 barr)
- 100 C w/ DMAP
- Up to 916 TON
- Up to quantitative yields by HNMR yields
- Solvent Free

Nguyen, S. J. *Am. Chem. Soc.* **2001**, 123, 11498-11499. <https://doi.org/10.1021/ja0164677>

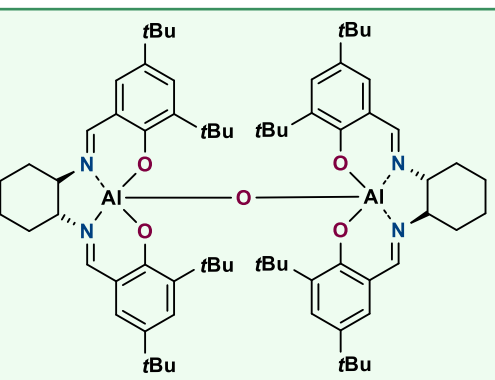
Kleij, 2011: Zn^{II} Salen System



- CO₂ (2 barr)
- Room Temperature w/ NBu₄
- Up to quantitative yields by HNMR yields
- Solvents Required

Kleij, A. *ChemCatChem*, **2011**, 3, 831-834. <https://doi.org/10.1002/cctc.201100031>

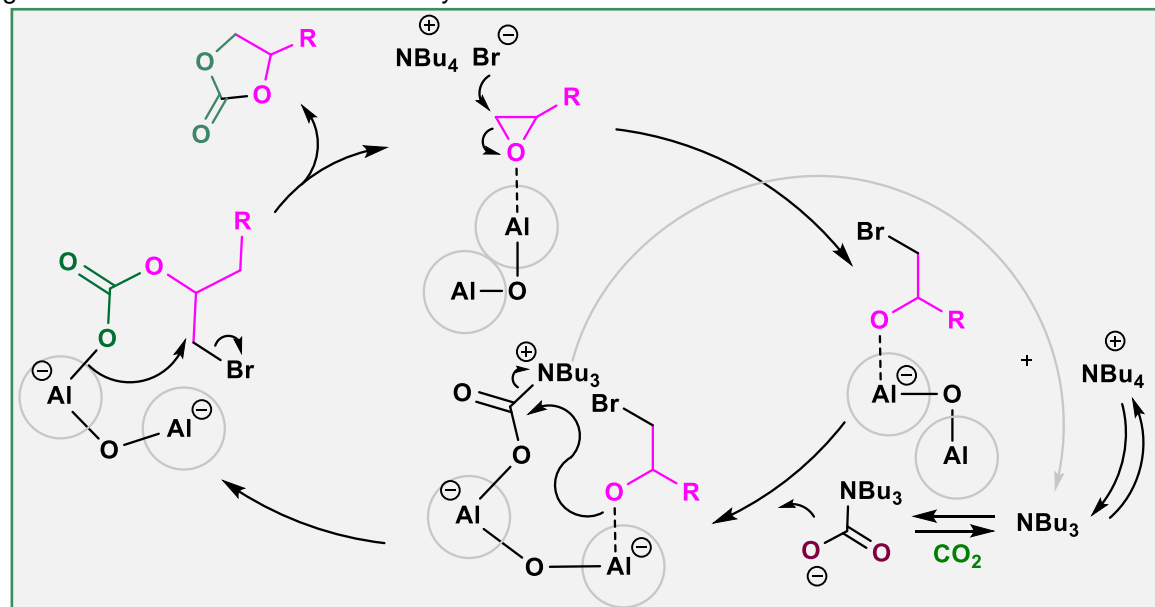
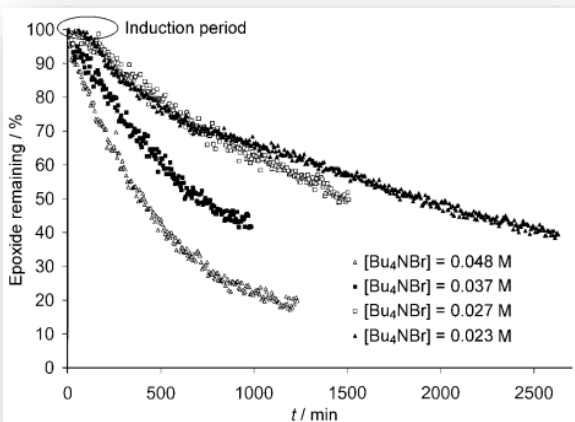
North, 2009: Bimetallic Aluminum Salen System and Mechanism Studies



- Up to 850 TON
- Solvent Free

- CO₂ (1 barr)
- Room Temperature w/ NBu₄Br

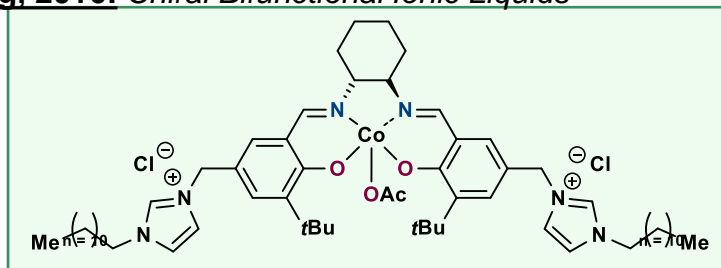
Mechanistic studies were performed, and interestingly, the reaction was determined to be second order with respect to the nucleophilic co-catalyst. This suggests that mechanistically, the co-catalyst is not only opening the activated epoxide, but is likely performing an additional function. Close analysis of the reaction neat in propylene oxide as a solvent revealed the formation of tributylamine over time. Interestingly, as the amount of this tributylamine decreased, so did catalytic activity. Upon restoration of more co-catalyst, the catalysis would restore. The authors posit the following mechanistic mode for these salen systems:



North, M. *Angew Chem Int.* **2009**, 48, 16, 2946-2948. <https://doi.org/10.1002/anie.200805451>

Asymmetric Variations

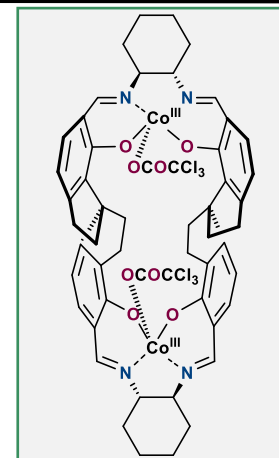
Jing, 2016: Chiral Bifunctional Ionic Liquids



- CO₂ (1.2 MPa)
- Room Temperature
- Up to 497 TON
- Up to 50% yield, 50% highest ee
- Catalyst is a chiral ionic liquid, no solvent needed

Jing, 2016: Co^{III} Spiro-Salen System

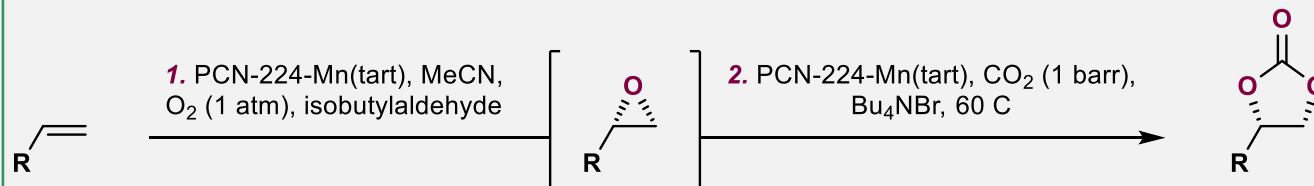
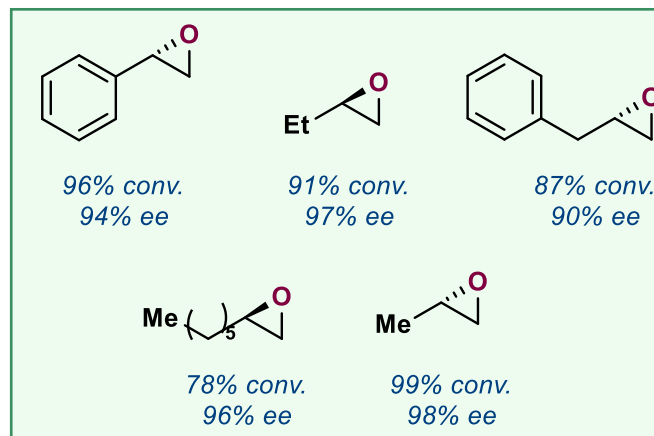
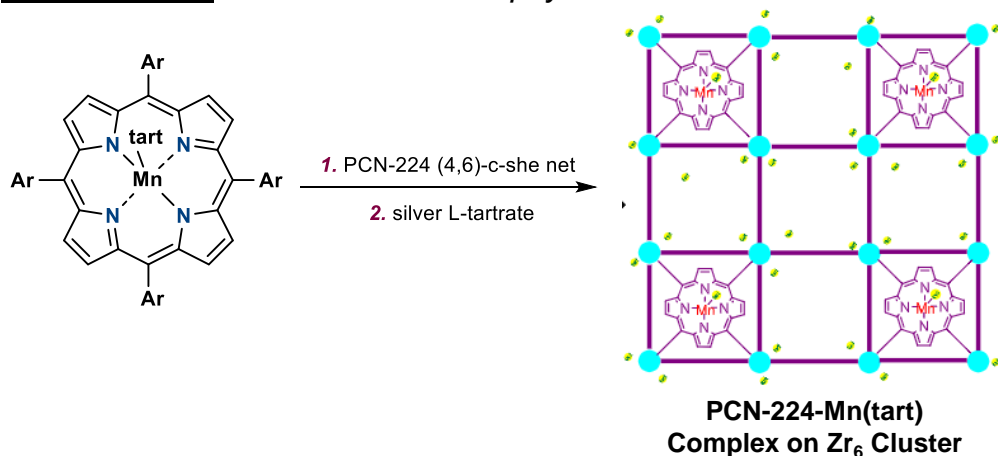
- CO₂ (0.8 MPa)
- Room Temperature w/ TBAF co-catalyst
- Up to 50% conversion, 68% highest ee
- Solvent Free



Jing, H. *J. Molecular Catalysis*. **2016**, 411, 34-39. <https://doi.org/10.1016/j.molcata.2015.10.008>

Sakai, T. *Chem. Commun.*, **2012**, 48, 4489. <https://doi.org/10.1039/C2CC30591G>

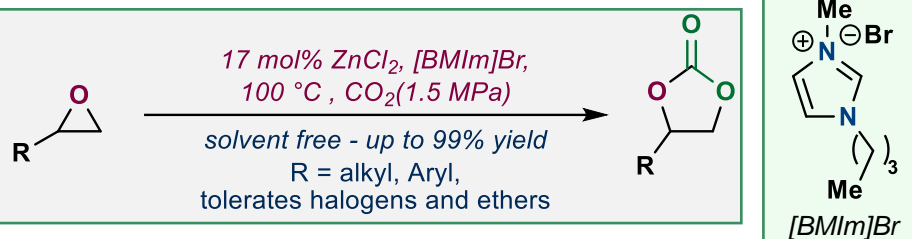
Morsali, 2021: Zr MOF with Mn Porphyrin Catalyst Embedded for Exceptional ee



Can be run as individual or steps or as a one pot procedure with no noticeable drops in conversion or ee

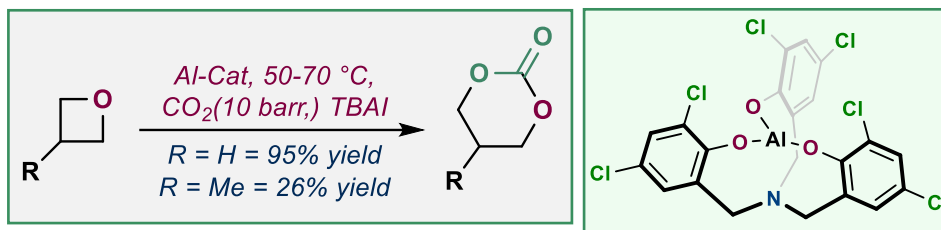
Morsali, A. *Inorg. Chem.* **2021**, 60, 1, 206–218. <https://doi.org/10.1021/acs.inorgchem.0c02811>

Hu, 2004: ZnCl₂ Ligand-Free Variation



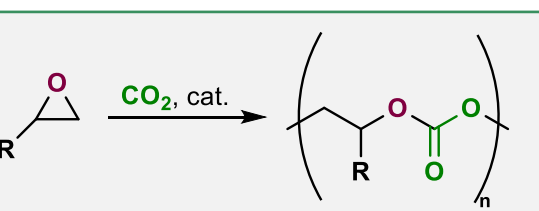
Hu, B. *Tetrahedron*. **2004**, 45, 45, 8307-8310. <https://doi.org/10.1016/j.tetlet.2004.09.074>

Kleij, 2013: Demonstrated the Application to Oxetanes



Kleij, A. *J. Am. Chem. Soc.* **2013**, 135, 4, 1228-1231. <https://doi.org/10.1021/ja311053h>

Formation of Polycarbonates from oxiranes and CO₂:



- **M_n = Number Average Molecular Weight**
The statistical average MW of all the polymer chains in a given sample.

- **M_w = Weight Average Molecular Weight**
Takes into account the mol weight of a chain in determining contributions to the molecular weight average.

- **M_w/M_n = Polydispersity**

A measure of the heterogeneity of sizes of molecules or particles in a mixture.

Coates, G.W. *J. Am. Chem. Soc.* **2003**, 125, 11911-11924. <https://doi.org/10.1021/ja030085e>

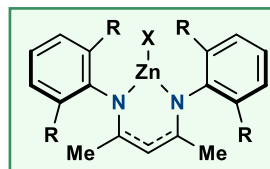
Williams, C.K. *Angew. Chem. Int. Ed.* **2009**, 48, 931-933. <https://doi.org/10.1002/anie.200803896>

Nozaki, K. *J. Am. Chem. Soc.* **2013**, 135, 23, 8456-8459. <https://doi.org/10.1021/ja4028633>

Cyclic carbonate synthesis vis Ni and Pd porphyrins:

Hung, C. *Dalton Trans* **2019**, 48, 7527. <https://doi.org/10.1039/C9DT00104B>

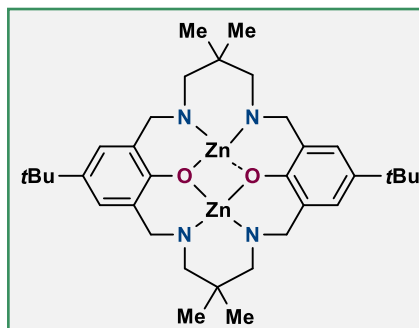
Coates, 1998: Zn β-diiminate catalyst system



- CO₂ (7 barr)
- 50 °C
- Up to 494 TON
- M_n = 25.5 x 10⁻³, M_w/M_n = 1.1

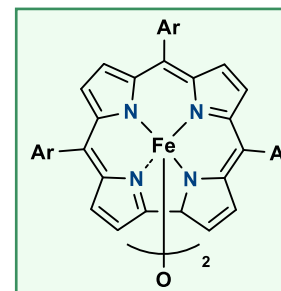
Coates, G.W. *J. Am. Chem. Soc.* **1998**, 120, 11018-11019. <https://doi.org/10.1021/ja982601k>

Williams, 2009: Dimetallic Zn system



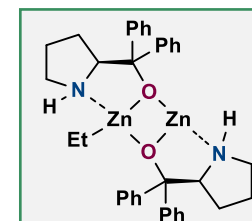
- CO₂ (1 barr)
- 100 °C
- Up to 527 TON
- M_n = 7,360, M_w/M_n = 1.2

Nozaki, 2013: Fe-corrole catalyst



- CO₂ (20 barr)
- 60 °C
- TOF = 1,004
- M_n = 29,000, M_w/M_n = 1.3

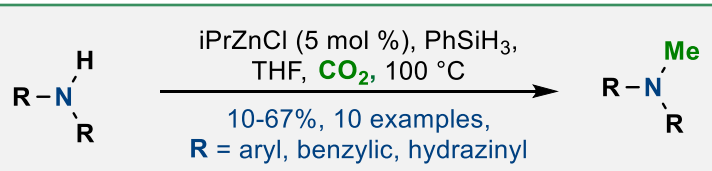
Nozaki, 1999: Dimeric zinc catalyst



- CO₂ (30 barr)
- 40 °C
- Up to 74% ee
- M_n = 12,000, M_w/M_n = 1.3

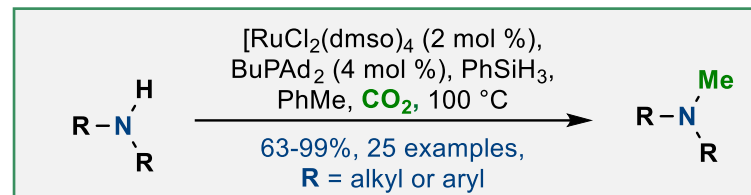
Nozaki, K. *J. Am. Chem. Soc.* **1999**, 121, 47, 11008-11009. <https://doi.org/10.1021/ja992433b>

Cantat, 2013: *i*PrZnCl catalyzed methylation



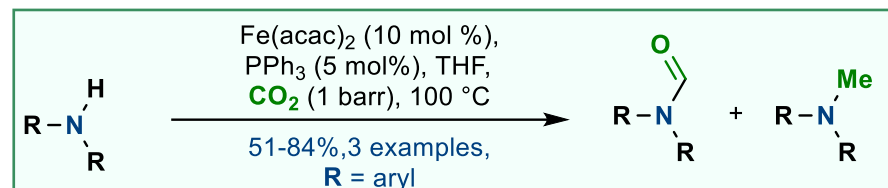
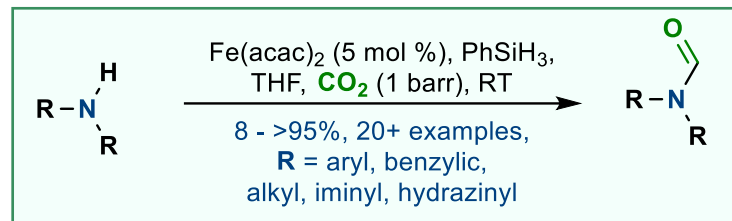
Cantat, T. *Chem. Sci.* **2013**, 4, 2127. <https://doi.org/10.1039/C3SC22240C>

Beller, 2013: [RuCl₂(dmsO)₄] catalyzed methylation



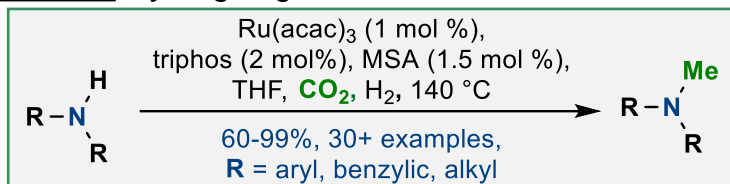
Beller, M. *Angew. Chem. Int. Ed.* **2013**, 52, 9568–9571. <https://doi.org/10.1002/anie.201301349>

Cantat, 2014: Fe(acac)₂ catalyzed Formylation or Methylation



Cantat, T. *Catal. Sci. Technol.* **2014**, 4, 1529. <https://doi.org/10.1039/C4CY00130C>

Beller, 2013: hydrogen gas as a reductant



Beller, M. *Angew. Chem. Int. Ed.* **2013**, 52, 12156–12160. <https://doi.org/10.1002/anie.201306850>

Additional Miscellaneous Reports:

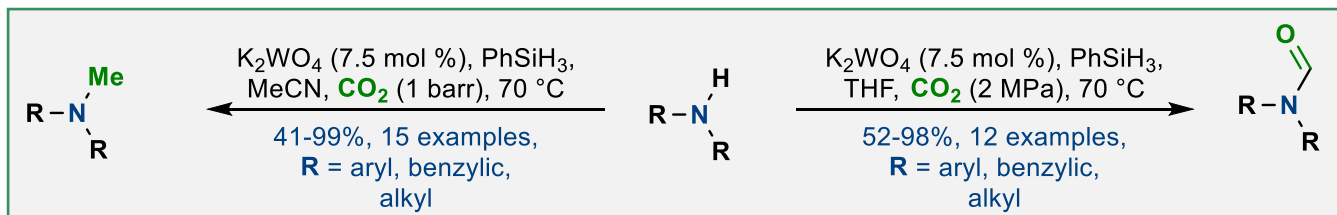
García, 2015: [(*dippe*)Ni(μ -H)]₂ and [Ni(Cod)₂]/dcype catalyzed methylation

García, J. *Organometallics* **2015**, 34, 4, 763–769. <https://doi.org/10.1021/om501176u>

Kobayashi, 2016: Bis(*tzNHC*)Rh]OTf catalyzed methylation

Kobayashi, S. *Adv. Synth. Catal.* **2016**, 358, 452–458. <https://doi.org/10.1002/adsc.201500875>

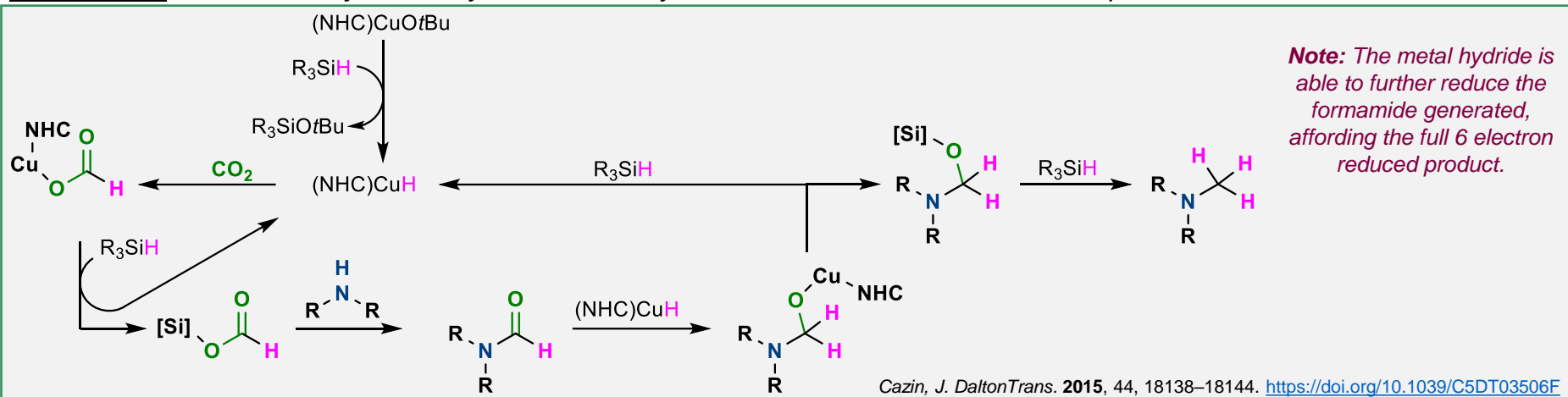
He, 2018: Tungstate catalysis allowing for pressure switched methylation or formylation



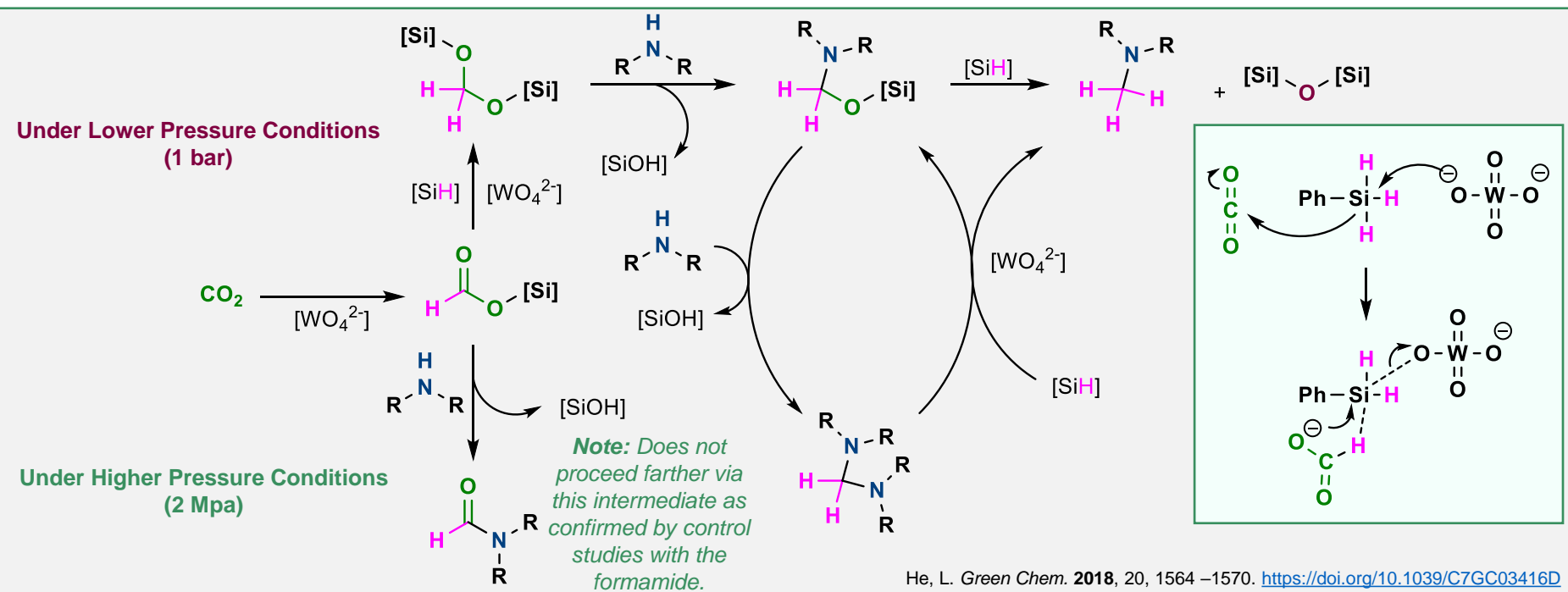
He, L. *Green Chem.* **2018**, 20, 1564–1570. <https://doi.org/10.1039/C7GC03416D>

Mechanistic Look at Methylation and Formylation

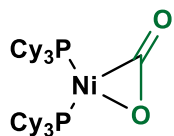
Cazin, 2015: *Cu^I NHC catalyzed methylation and formylation. Mechanistic Outline for M-H species*



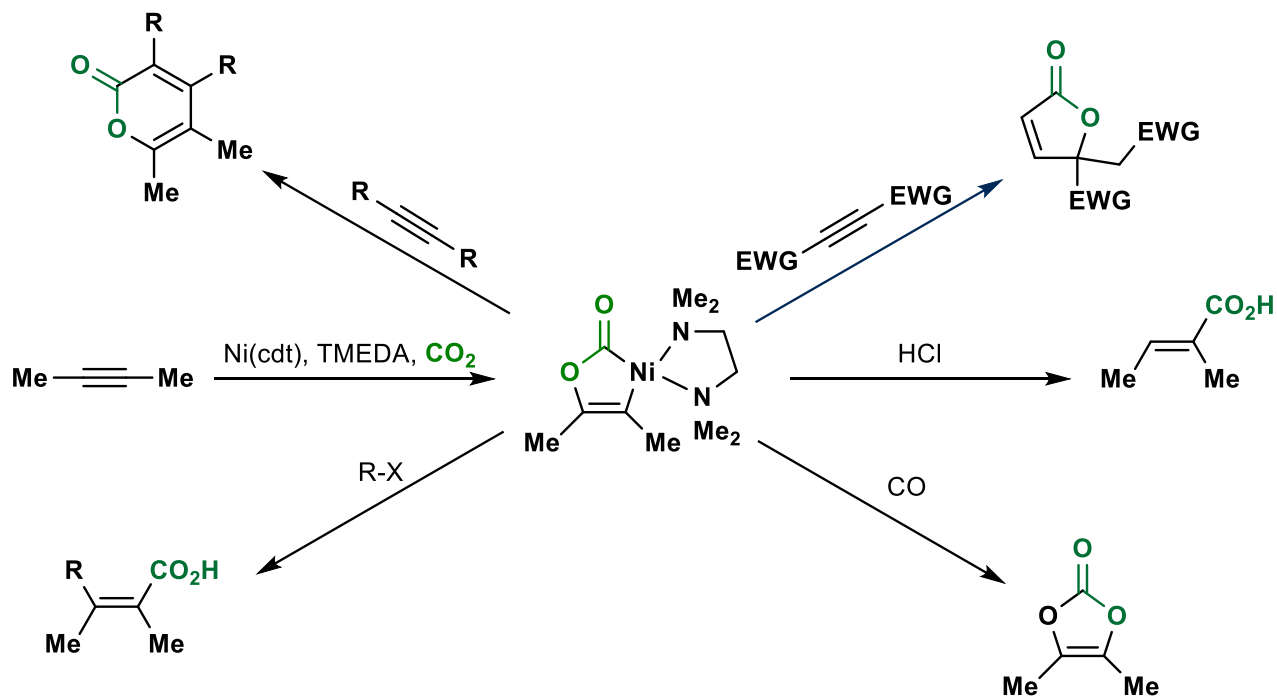
Tungstate Formylation vs Methylation Mechanistic Rationale



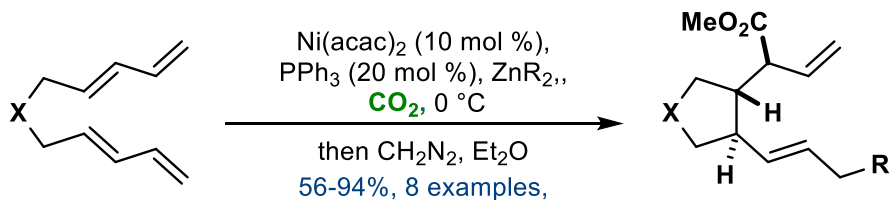
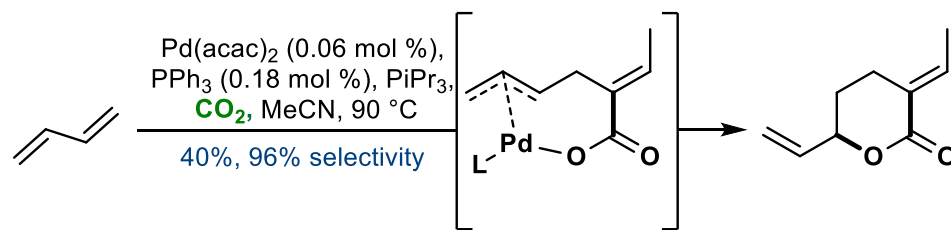
Oxidative Cyclometallations

Aresta, 1975:

The Aresta complex, depicted above, was a landmark discovery for carboxylative chemistry. Isolating and characterizing this low valent nickel species would lay the groundwork to inspire CO₂ valorization for decades to come.

Oxanickelacyclopentene Formation and Reactivity:

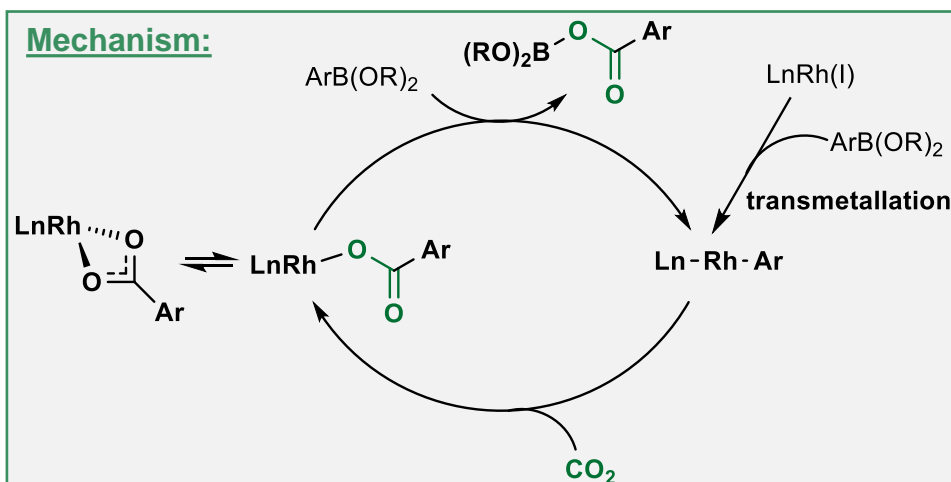
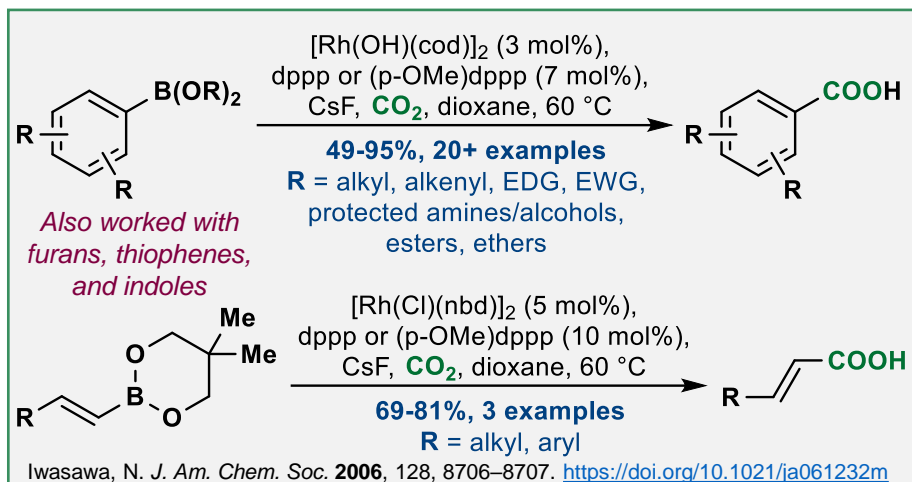
Aresta, M. *Chem. Soc. Chem. Commun.* **1975**, 636–637.
<https://doi.org/10.1039/C39750000636>

Mori, 2002: Ring closing carboxylationBehr, 1983:

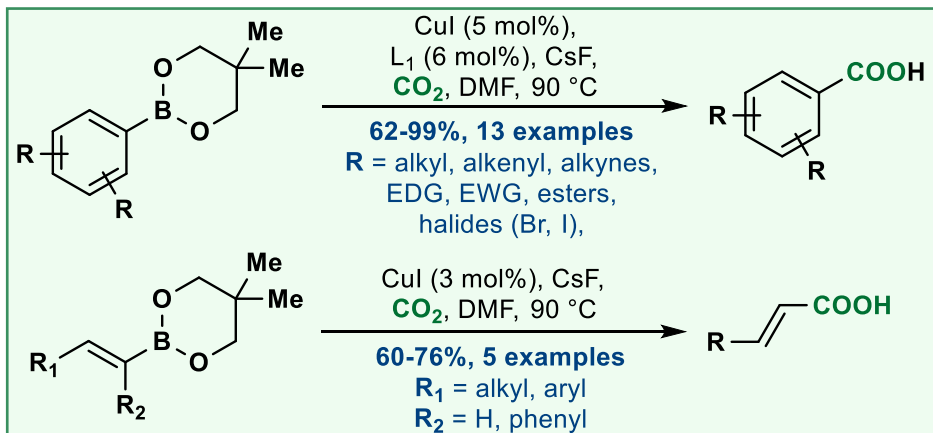
Mori, M. *J. Am. Chem. Soc.* **2002**, 124, 34, 10008–10009. <https://doi.org/10.1021/ja026620c>

Carboxylation Reactions with Boronic Esters

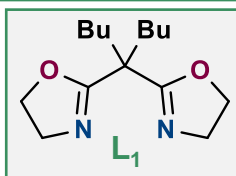
Iwasawa, 2006: *Rh*^I catalyzed carboxylation of aryl and alkenyl boronic esters with CO₂



Iwasawa, 2008: *Cu*^I-catalyzed carboxylation

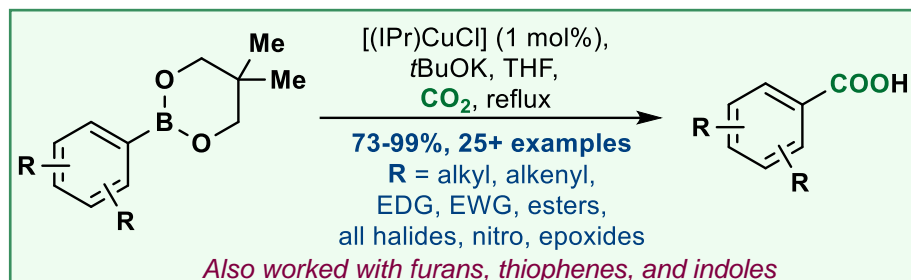


The authors note a number of substrates that were compatible with the copper system that did not work with the rhodium system in the substrate scope. (Nitro arenes, benzothiophenes, alkylnl substitution, and R₂ substituted viny boronic esters)



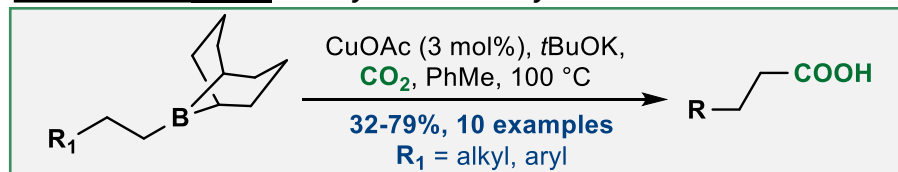
Iwasawa, N. *Org. Lett.* **2008**, 10, 13, 2697–2700. <https://doi.org/10.1021/ol800829c>

Hou, 2008: *Cu*^I-NHC system



Hou, Z. *Angew. Chem. Int. Ed.* **2008**, 47, 5792–5795. <https://doi.org/10.1002/anie.200801857>

Sawamura, 2011: *Cu*^I system for alkyl boranes

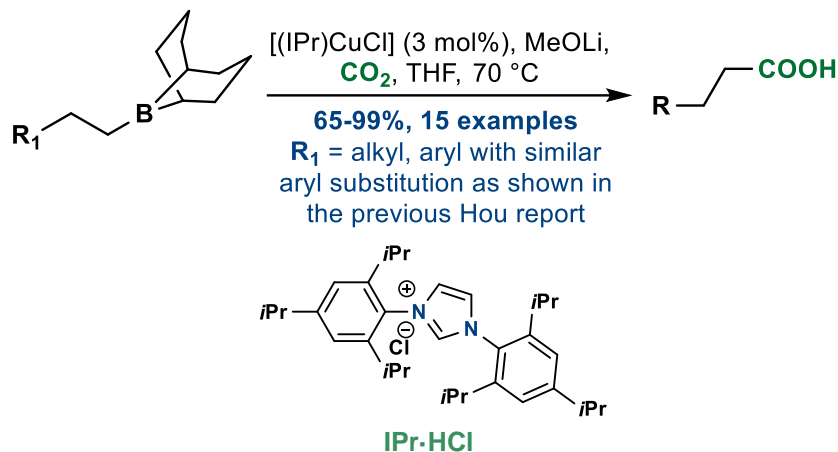


Authors perform hydroboration followed by this reaction directly to perform formal hydrocarboxylation of olefins

Sawamura, M. *Org. Lett.* **2011**, 13, 1086–1088. <https://doi.org/10.1021/ol103128x>

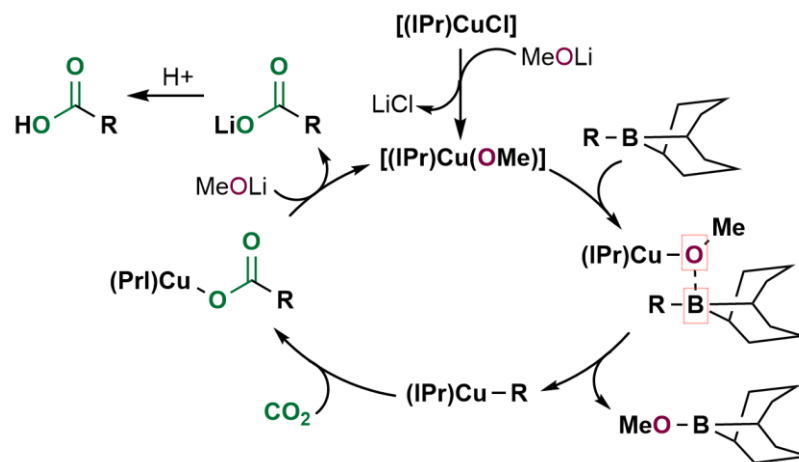
Carboxylation Reactions with Boronic Esters & C-H Bonds

Hou, 2011: Cu^I NHC System for alkyl boronic esters

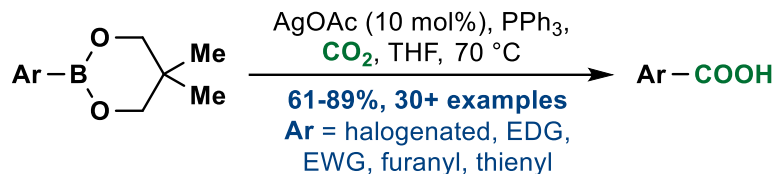


Hou, Z. *Angew. Chem. Int. Ed.* **2011** 50, 8114–8117. <https://doi.org/10.1002/anie.201101769>

Mechanism of Cu-mediated Carboxylations:

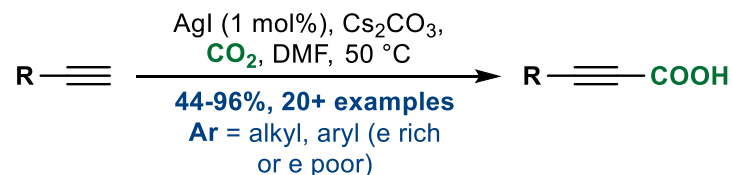


Lu, 2012: Silver catalyzed carboxylation of arylboronic esters



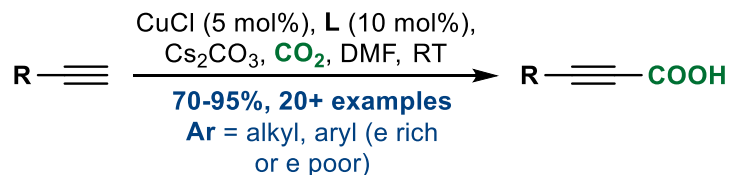
Lu, X. *Chem. Commun.* **2012**, 48, 6292–6294. <https://doi.org/10.1039/C2CC32045B>

Lu, 2011: Silver catalyzed carboxylation of Terminal Alkynes



Lu, X. *Org. Lett.* **2011**, 13, 9, 2402–2405. <https://doi.org/10.1021/ol200638z>

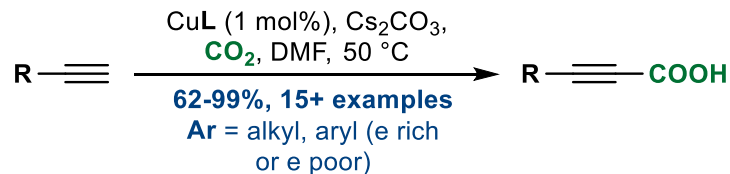
Zhang, 2010: Copper catalyzed carboxylation of arylboronic esters



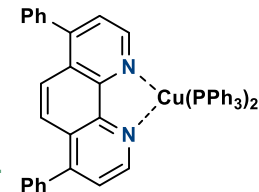
NHC ligand is denoted as L13 in the paper
N,N-tetramethylethylenediamine worked well for most of their substrate scope

Zhang, Y. *Proc. Natl Acad. Sci. USA* **2010**, 107, 20184–20189. <https://doi.org/10.1073/pnas.1010962107>

Lange, 2010: Copper catalyzed carboxylation of arylboronic esters



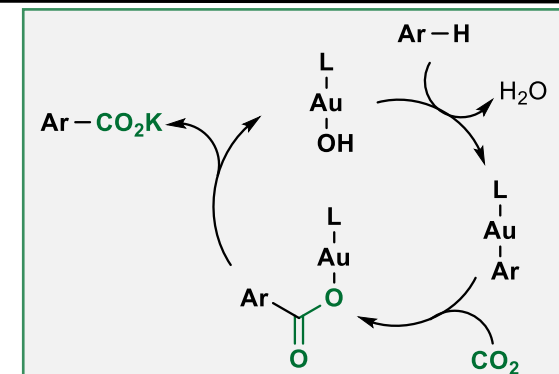
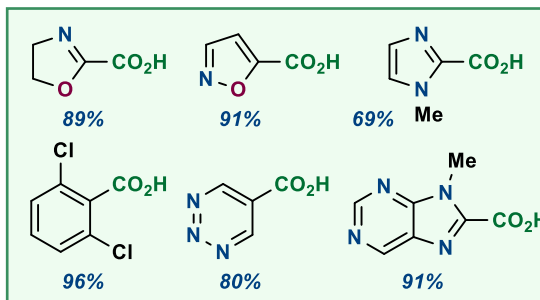
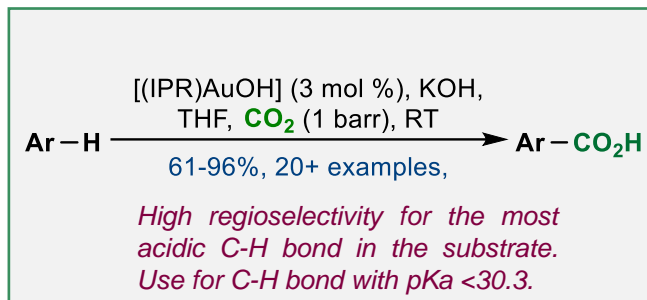
Phenanthroline L



Lange, P. *Adv. Synth. Catal.* **2010**, 352, 2913–2917. <https://doi.org/10.1002/adsc.201000564>

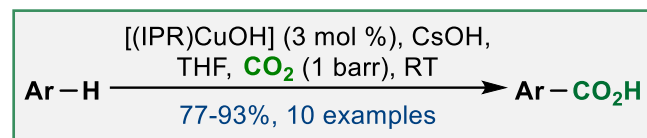
Carboxylations into Aryl C-H and Benzylic C-H Bonds

Nolan, 2010: Au NHC system for aryl C-H carboxylation

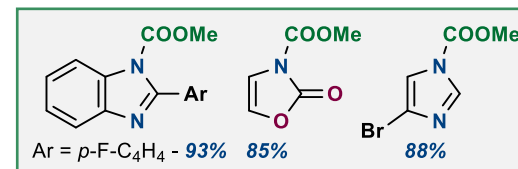


Nolan, S. *J. Am. Chem. Soc.* **2010**, 132, 26, 8858–8859. <https://doi.org/10.1021/ja103429q>

Nolan, 2010: Cu^I NHC system for aryl C-H or N-H carboxylation

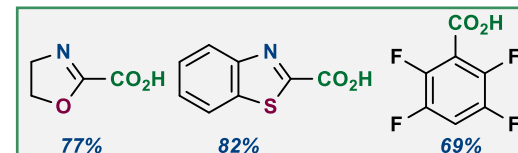


High regioselectivity for the most acidic C-H bond in the substrate. Use for C-H bond with pKa <27.3.



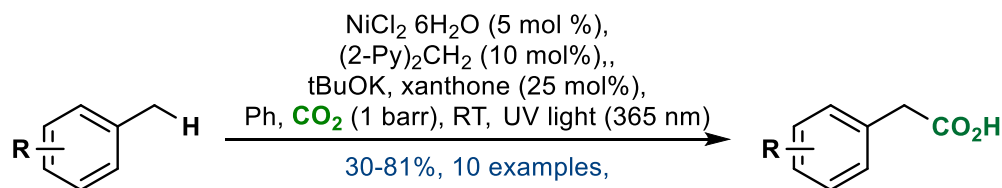
**Substrates were methylated to help get yields*

**Yields taken directly as acid*

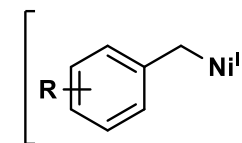


Nolan, S. *Angew. Chem. Int. Ed.* **2010**, 49, 8674–8677. <https://doi.org/10.1002/anie.201004153>

Murakami, 2019: Cu^I NHC system for aryl C-H or N-H carboxylation



Works best with electron rich arenes, but can tolerate a few relatively electron poor substrates.

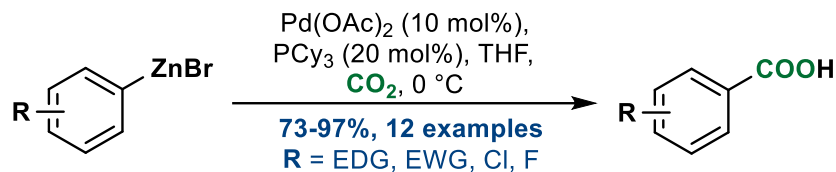


Mechanistically, the reaction works by using the base and xanthone as an initiator to generate a benzylic radical which can form the depicted Ni^I species. This species can then undergo CO₂ insertion to form the nickel carboxylate, which can then incorporate CO₂ before being reduced back to Ni⁰.

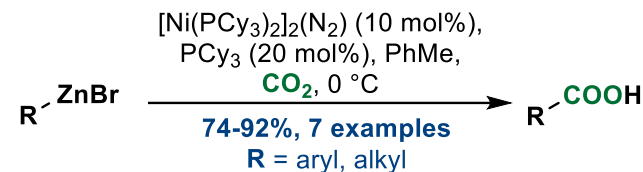
Murakami, M. *J. Am. Chem. Soc.* **2019**, 141, 50, 19611–19615. <https://doi.org/10.1021/jacs.9b12529>

Carboxylations into Aryl, Alkenyl, and Alkyl Halides

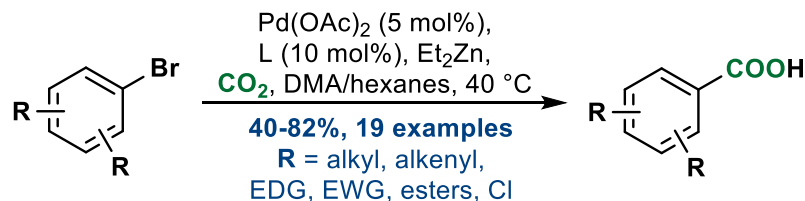
Dong, 2008: Pd catalyzed Negishi-carboxylation



Dong, V. *J. Am. Chem. Soc.* **2008**, 130, 25, 7826–7827. <https://doi.org/10.1021/ja803435w>

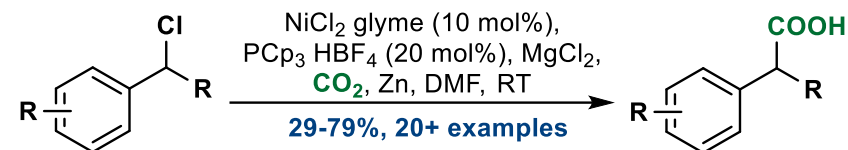


Martin, 2009: Pd catalyzed direct carboxylation of aryl bromides



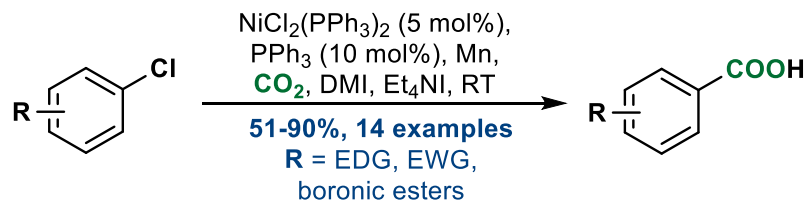
Martin, R. *J. Am. Chem. Soc.* **2009**, 131, 44, 15974–15975. <https://doi.org/10.1021/ja905264a>

Martin, 2013: Ni-catalyzed direct carboxylation of benzyl halides

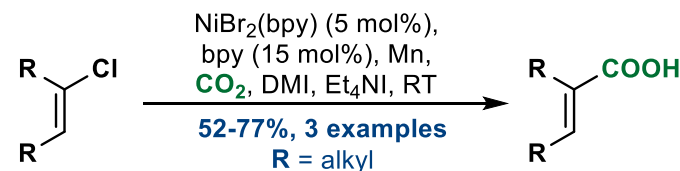


Martin, R. *J. Am. Chem. Soc.* **2013**, 135, 4, 1221–1224. <https://doi.org/10.1021/ja311045f>

Tsuji, 2012: Ni catalyzed direct carboxylation of aryl and vinyl chlorides

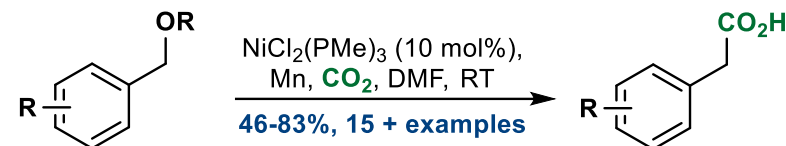
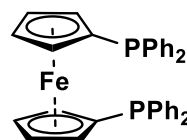
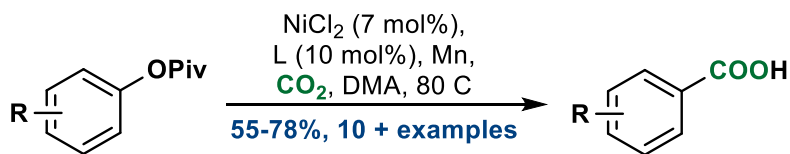


Aryl chlorides, bromides, and triflates all worked with this method.



Tsuji, Y. *J. Am. Chem. Soc.* **2012**, 134, 22, 9106–9109. <https://doi.org/10.1021/ja303514b>

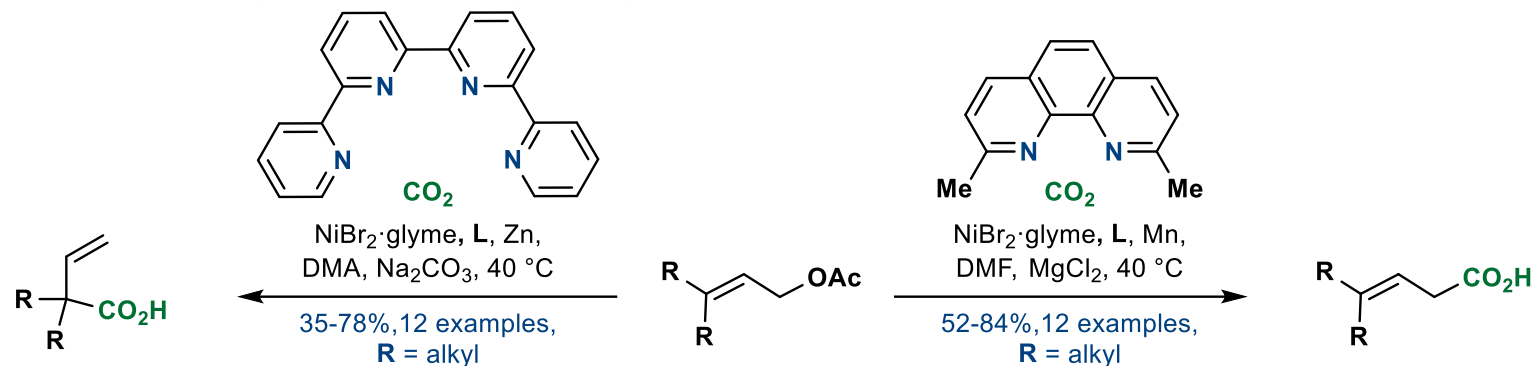
Martin, 2014: Ni catalyzed direct carboxylation of aryl and vinyl chlorides



Ac, Bz, CONEt₂, and COAd were all viable for the reaction

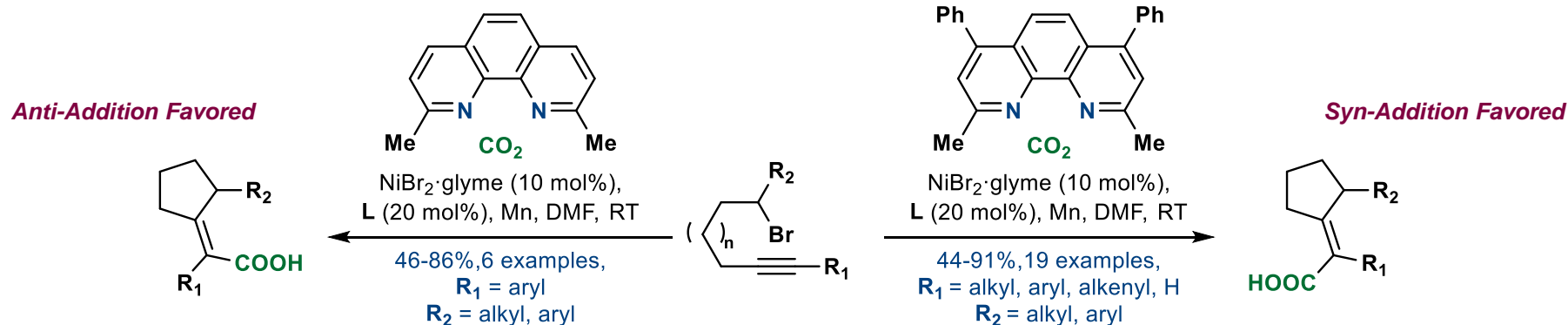
Martin, R. *J. Am. Chem. Soc.* **2014**, 136, 3, 1062–1069. <https://doi.org/10.1021/ja410883p>

Martín, 2014: Ni-catalyzed, ligand-controlled regiodivergent reductive carboxylation



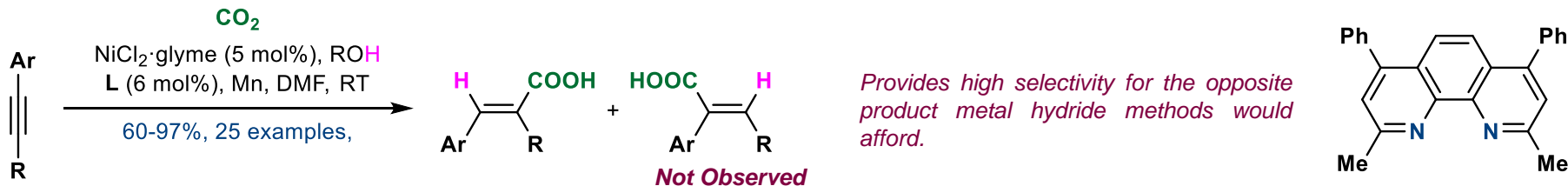
Martín, R. *J. Am. Chem. Soc.* **2014**, 136, 51, 17702–17705. <https://doi.org/10.1021/ja509077a>

Martín, 2015: Ni-catalyzed, divergent cyclization/carboxylation of unactivated primary and secondary alkyl halides with CO₂



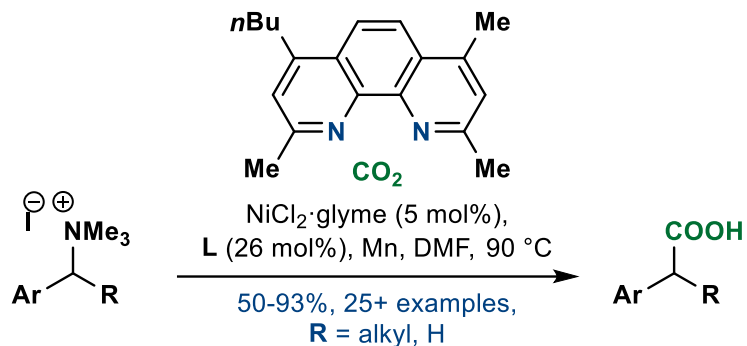
Martín, R. *J. Am. Chem. Soc.* **2015**, 137, 20, 6476–6479. <https://doi.org/10.1021/jacs.5b03340>

Martín, 2015: Ni-catalyzed, Hydrocarboxylation of Alkynes



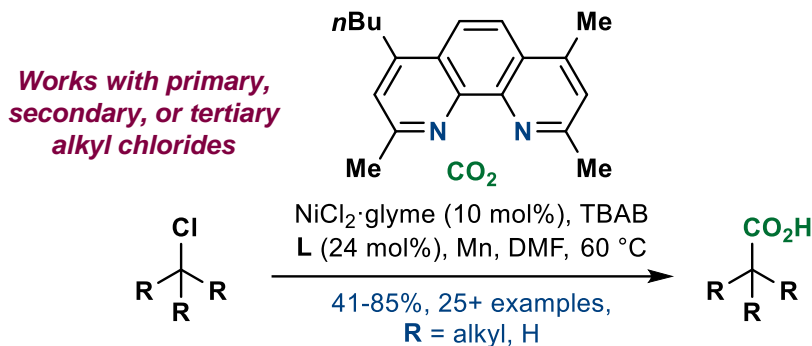
Martín, R. *J. Am. Chem. Soc.* **2015**, 137, 28, 8924–8927. <https://doi.org/10.1021/jacs.5b05513>

Martín, 2016: Ni-catalyzed carboxylation of C-N Bonds



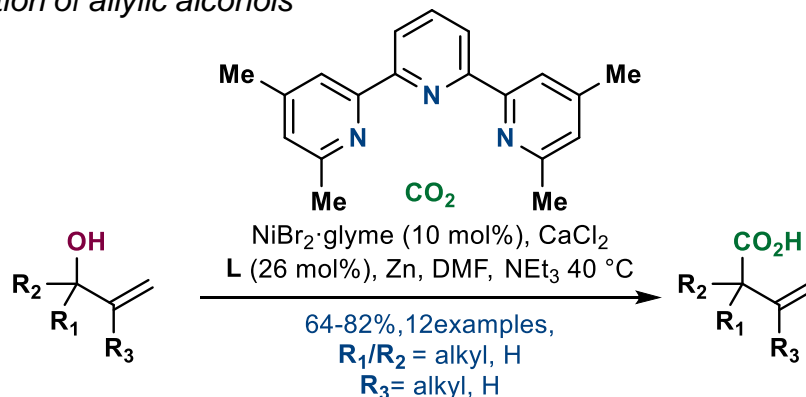
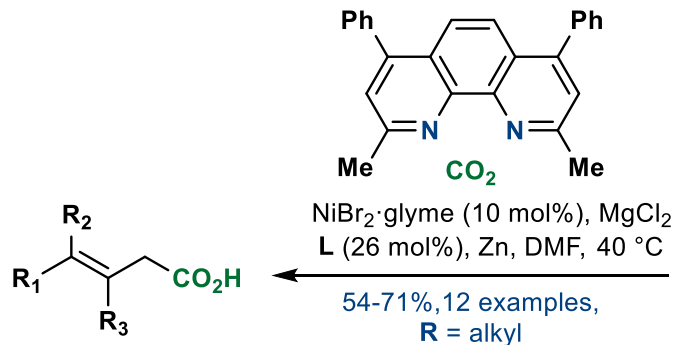
Martín, R. *Angew. Chem. Int. Ed.* **2016**, 55, 5053-5057. <https://doi.org/10.1002/anie.201600697>

Martín, 2016: Ni-catalyzed carboxylation of unactivated alkyl chlorides



Martín, R. *J. Am. Chem. Soc.* **2016**, 138, 24, 7504–7507. <https://doi.org/10.1021/jacs.6b04088>

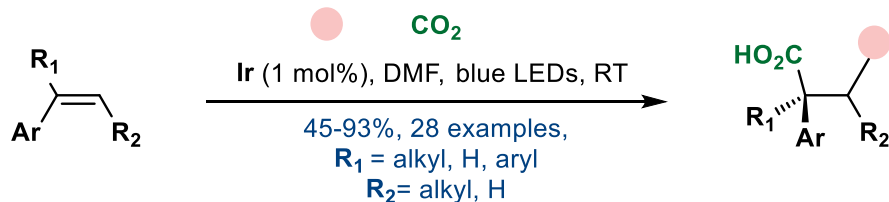
Martín, 2017: Ni-catalyzed, site-selective catalytic carboxylation of allylic alcohols



Martín, R. *Angew. Chem. Int. Ed.* **2017**, 56 (23), 6558-6562. <https://doi.org/10.1002/anie.201702857>

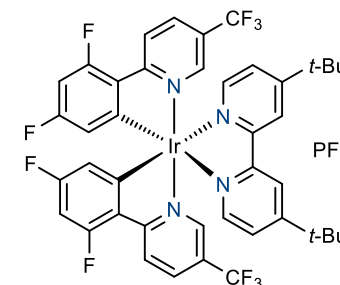
Martín, 2017: Catalytic intermolecular dicarboxylation of styrenes

Radical Entity



Radical Entities:

- Sulfonates
- Trifluoroborates
- oxalates



Martín, R. *Angew. Chem. Int. Ed.* **2017**, 56 (36), 10915-10919. <https://doi.org/10.1002/anie.201706263>