May Lab **Dual Photoredox Catalysis in Organic Chemistry**

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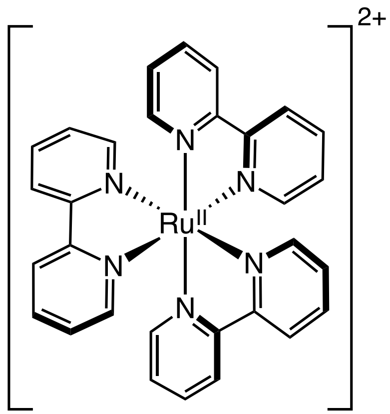
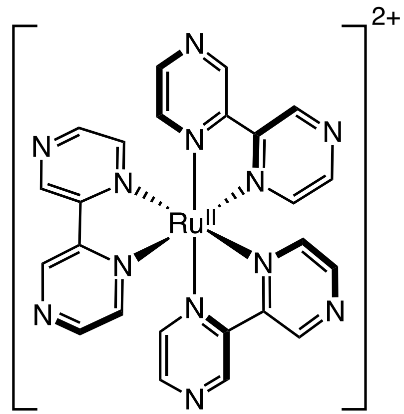
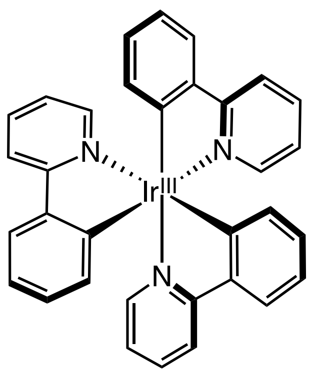


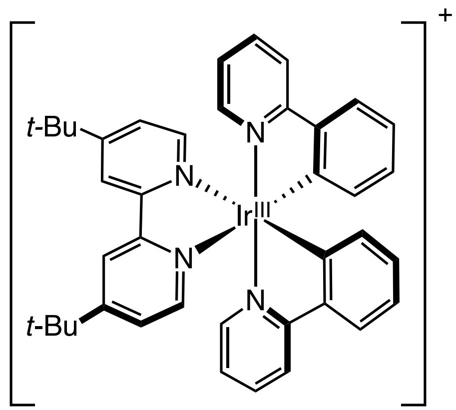
$Ru(bpy)_3^{2+}$



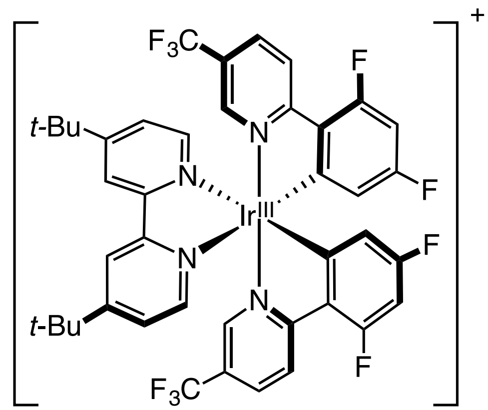
$Ru(bpz)_3^{2+}$



$Ir(ppy)_3$



$Ir(ppy)_2(dtbbpy)^+$



$Ir[dF(CF_3)ppy]_2(dtbbpy)^+$

Reviews: (a) *Chem. Rev*. **2013**, *113*, 5322—5363
(b) *J. Org. Chem*. **2016**, *81*, 6898—6926
(c) *Acc. Chem. Res.* **2016**, ASAP, DOI: 10.1021/acs.accounts6b00351

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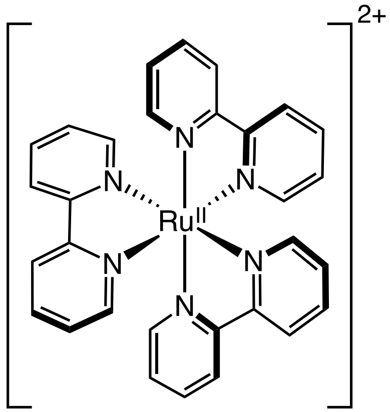
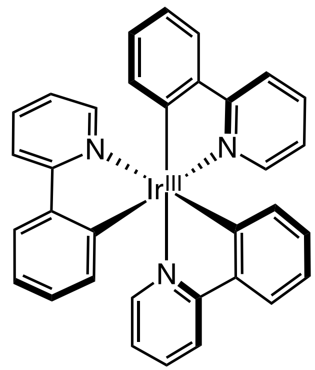


$Ru(bpy)_3^{2+}$

- Absorption at 452 nm (visible light)
- Stable, long-lived excited state (τ = 1100 ns)
- Single electron transfer (SET) catalsyt
- Effective excited state oxidant and reductant



$Ir(ppy)_3$

- Max absorption at 375 nm (visible light)
- Long-lived excited state (τ = 1.9 μs)
- Single electron transfer (SET) catalsyt
- Effective excited state oxidant and reductant
- Triplet energy of 56 $kcal/mol^{-1}$

Advantages: Excited species served as both oxidants and reductants.
Low catalyst loading.
Radical intermediates could be generated at milder condition.
Organic molecules generally do not absorb visible light.

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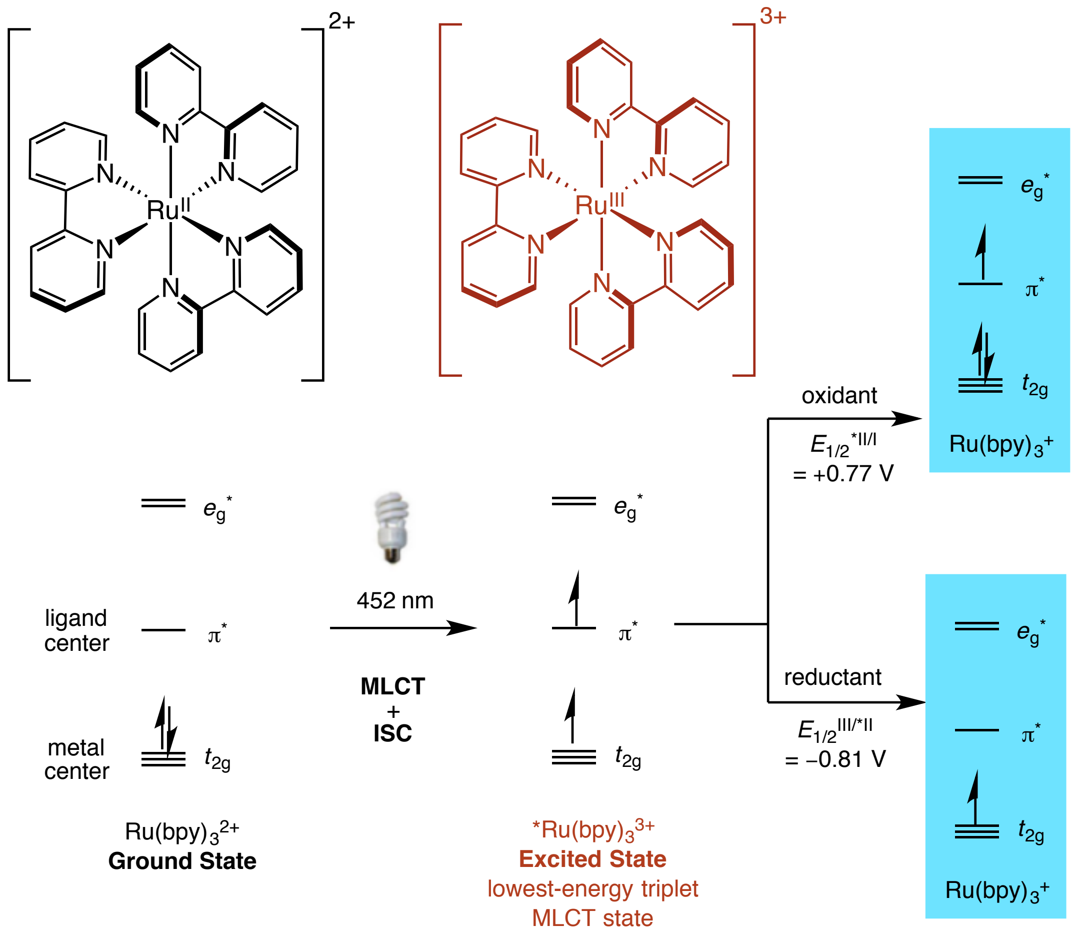
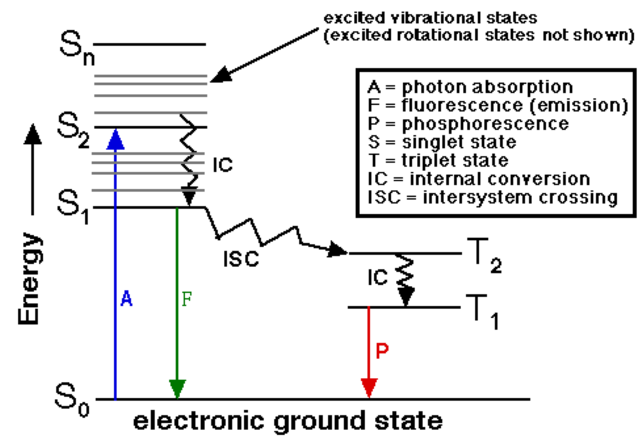
Simplified Molecular Orbital Depiction of $Ru(bpy)_3^{2+}$





Jablonski diagram

MLCT = Metal to Ligand Charge Transfer.

ISC = Intersystem Crossing

Ref: MacMillan *et al. Chem. Rev.* **2013**, *113*, 5322—5363
For $Ir(ppy)_3$: MacMillan *et al. J. Org. Chem.* **2016**, *81*, 6898—6926
Jablonski diagram: http://www.shsu.edu/~chm_tgc/chemilumdir/JABLON.GIF

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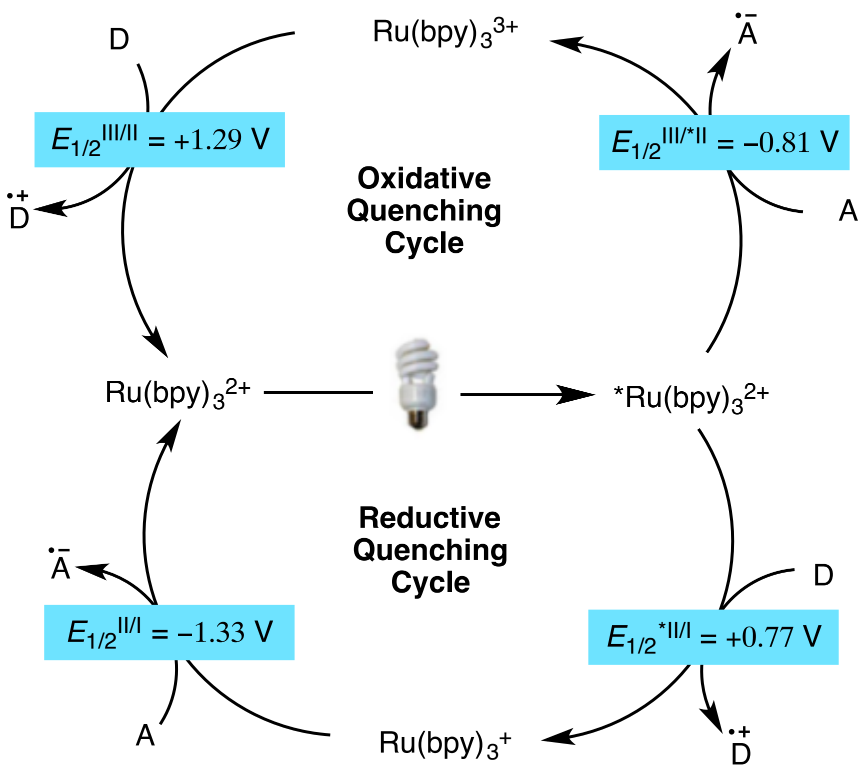
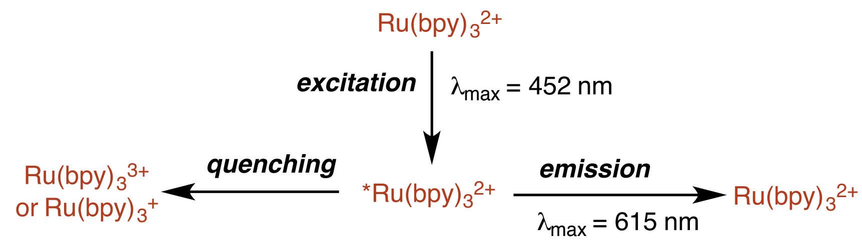
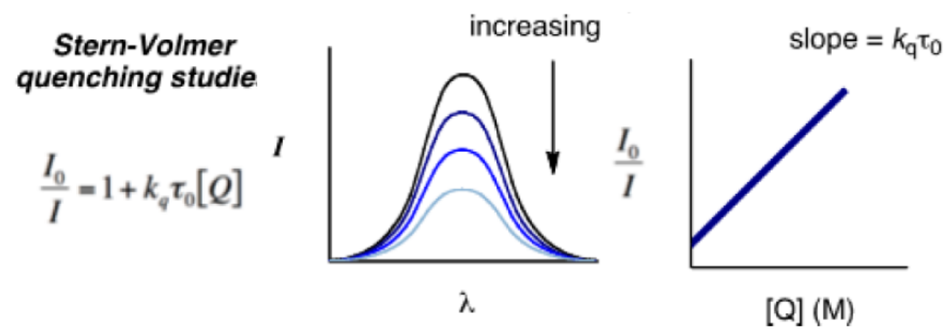
Oxidative and Reductive Quenching Cycle of $Ru(bpy)_3^{2+}$







Fluorescence Quenching (Stern-Volmer) Studies

Common oxidative quenchers: viologens, polyhalomethanes, dinitro- and dicyanobenzenes

Common reductive quenchers: tertiary amines.

Ref: *Modern Molecular Photochemistry*; Benjamin/Cummings: Menlo Park, CA, 1978

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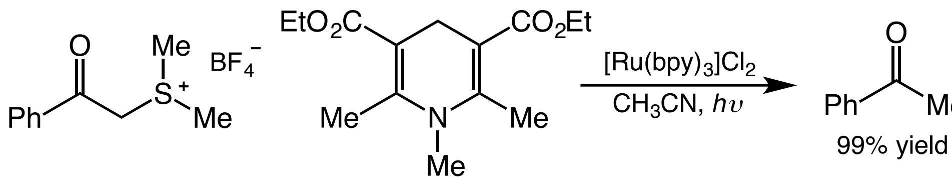
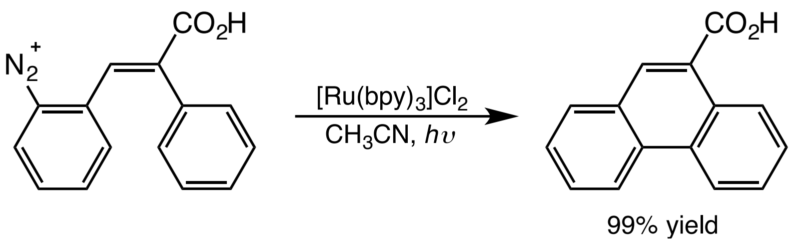
Early Work:

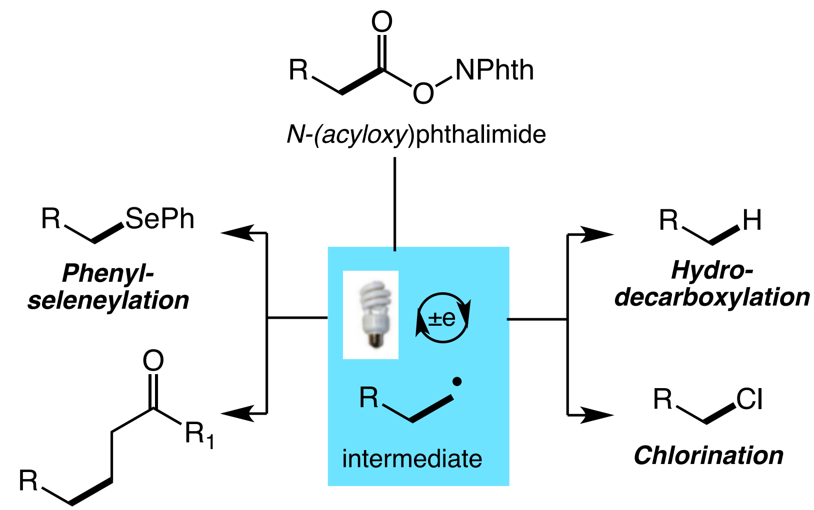
Kellogg, 1978 - Reductive desulfuration

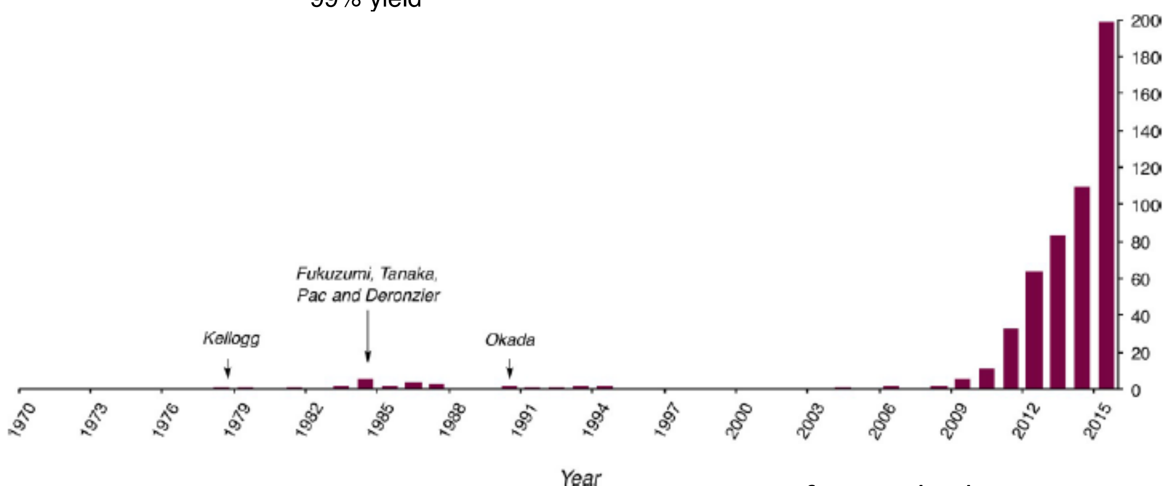


Deronzier, 1984 - Photocatalytic Pschorr reaction



Okada, 1991 - Reductive decarboxylation of redox-active esters





Ref: *Tetrahedron Lett.* ***1978***, *19*, 1255—1258
J. Chem. Soc., Perkin Trans. 2 **1984**, 1093—1098
J. Am. Chem. Soc. **1991**, *113*, 9401—9402

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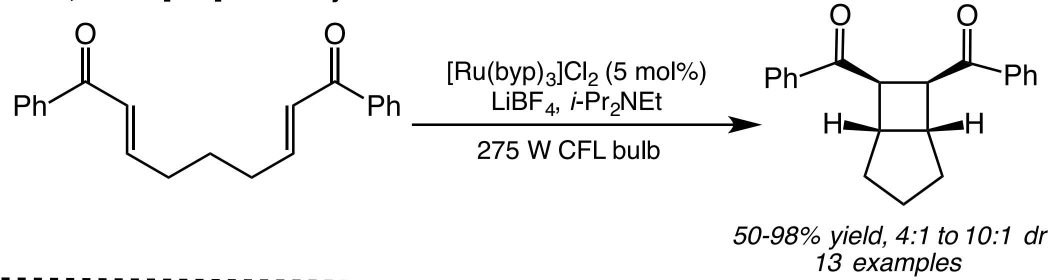
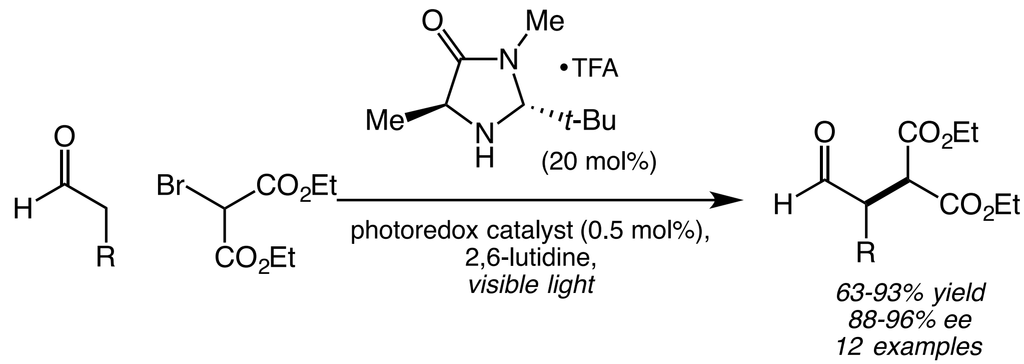
Recently Work:

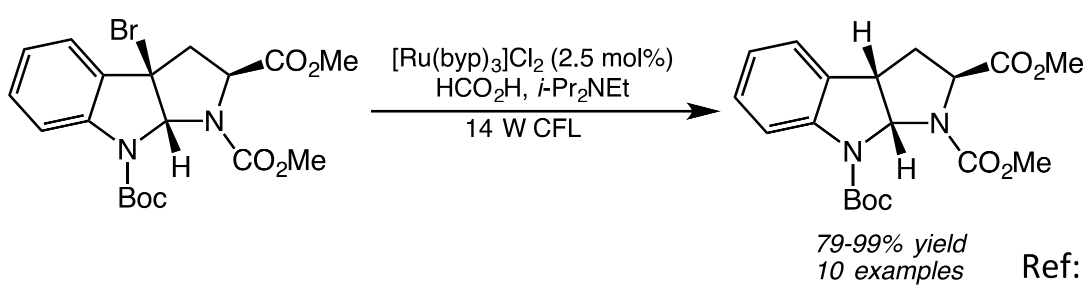
(a) Yoon, 2008 - [2+2] Enone cycloadditions



(b) MacMillan, 2008 - Asymmetric catalytic α-alkylation of aldehydes



(c) Stephenson, 2009 - Reductive dehalogenation of activated alkyl halides



Ref: *JACS*, **2008**, *130*, 12886—12887
Science, **2008**, *322*, 77—80
JACS, **2009**, *131*, 8756—8757

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Photoredox catalysts without co-catalysts

Net Reductive Reaction
-Reduction of Electron-Deficient Olefins
-Dehalogenation
-Reduction of Hydrazides and Hydrazines

Net Oxidative Reaction
-Oxidation of Benzylic Alcohols to Aldehydes
-Oxidative Hydroxylation of Arylboronic acids
-
Net Neutral Reactions
-Atom Transfer Radical Additions (ATRA) Cycle.

Ref: MacMillan *et al. Chem. Rev.* **2013**, *113*, 5322—5363
J. Org. Chem. **2016**, *81*, 6898—6926

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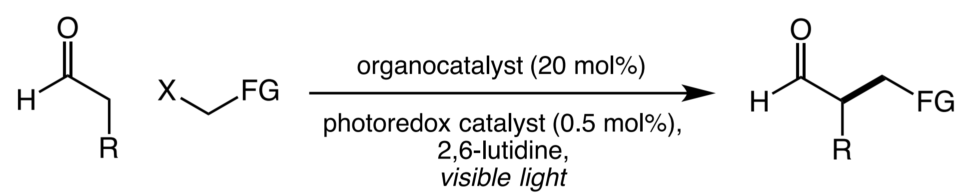
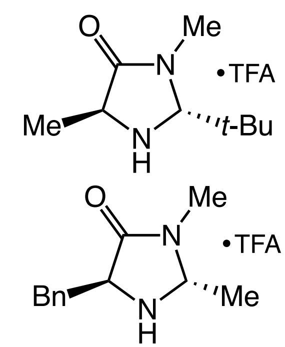
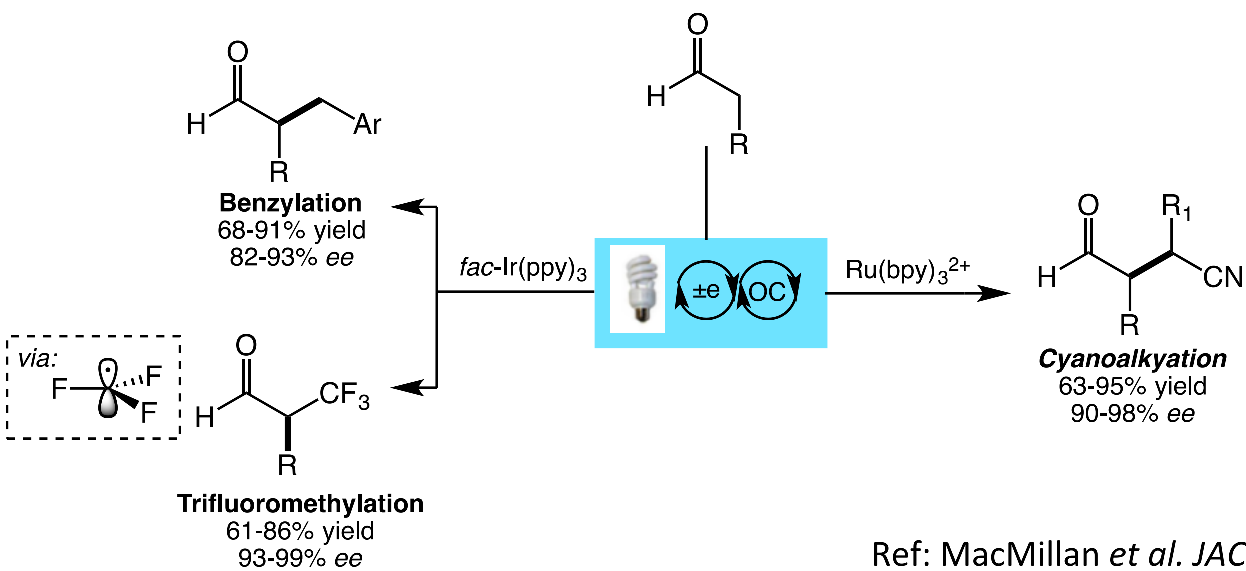
Photoredox Catalysis and Enamine Catalysis:
The Asymmetric *α*-Alkylation of Aldehyde



examples of organocatalyst





Ref: MacMillan *et al.* *JACS*, **2009**, *131*, 10875—10877
JACS, **2010**, *132*, 13600—13603
ACIE, **2015**, *54*, 9668—9672

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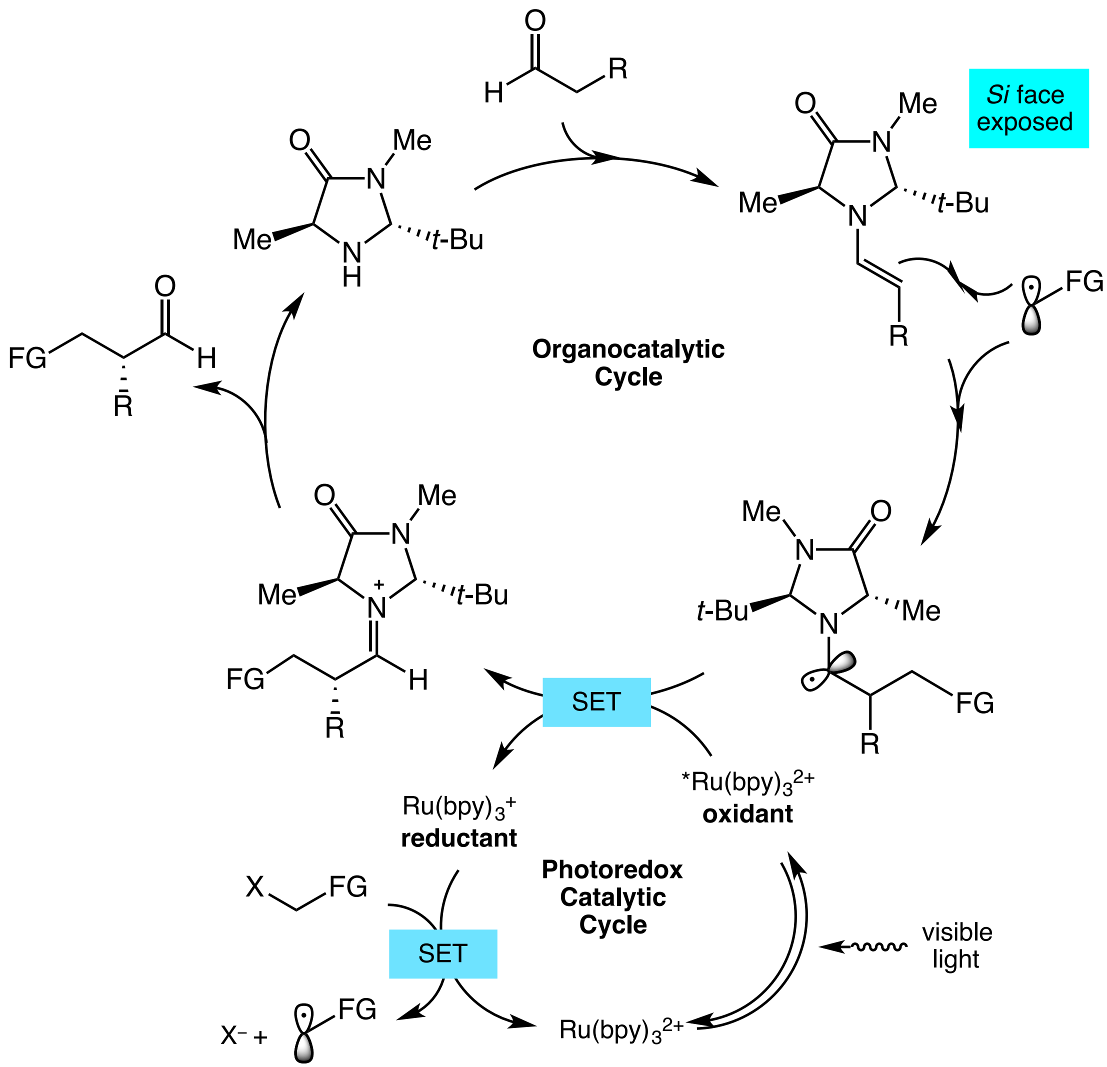
General Mechanism of Dual Catalysis System



Ref: MacMillan *et al. Chem. Rev.* **2013**, *113*, 5322—5363
For Ir(ppy)$_3$: MacMillan *et al. J. Org. Chem.* **2016**, *81*, 6898—6926

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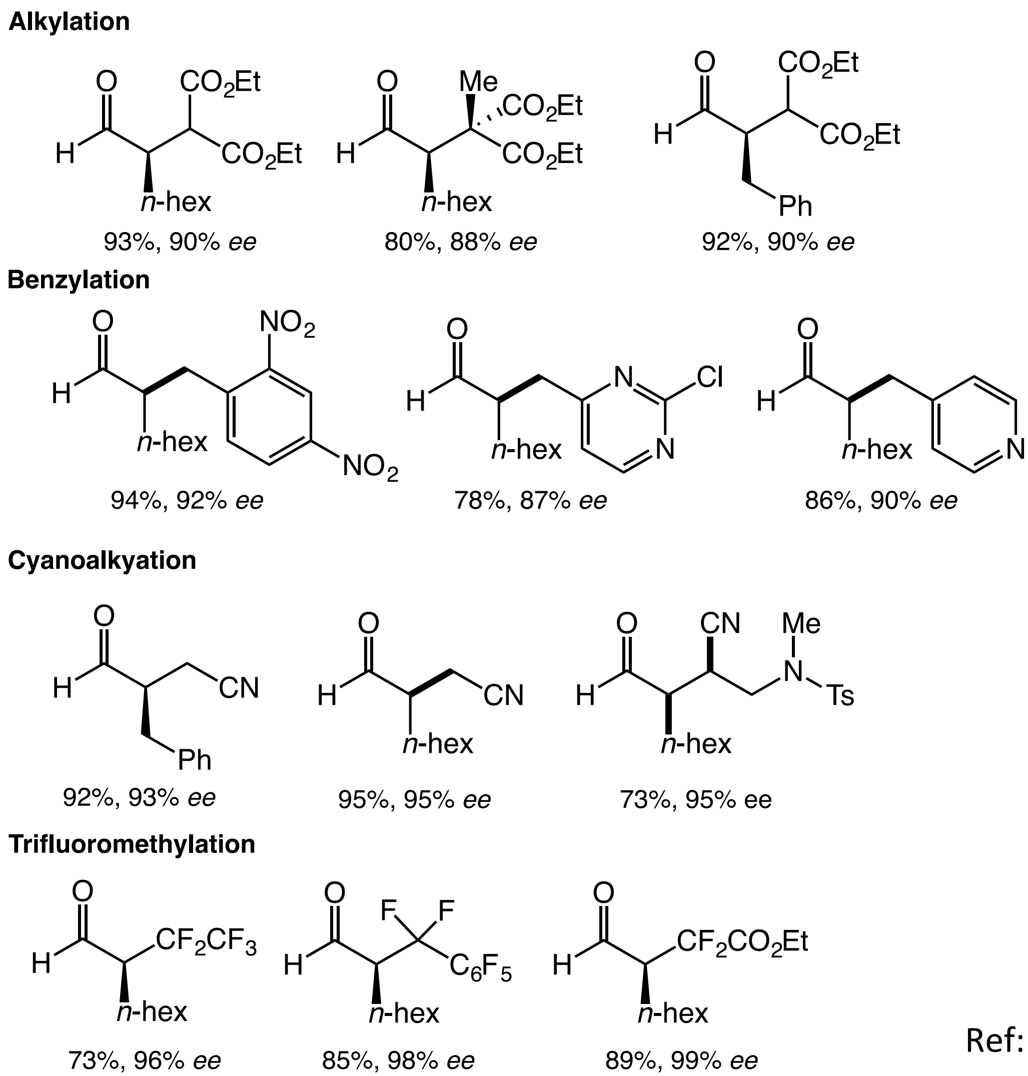
Selected examples of dual photoredox catalyst and organocatalyst



Ref: *JACS*, **2009**, *131*, 10875—10877
JACS, **2010**, *132*, 13600—13603
ACIE, **2015**, *54*, 9668—9672

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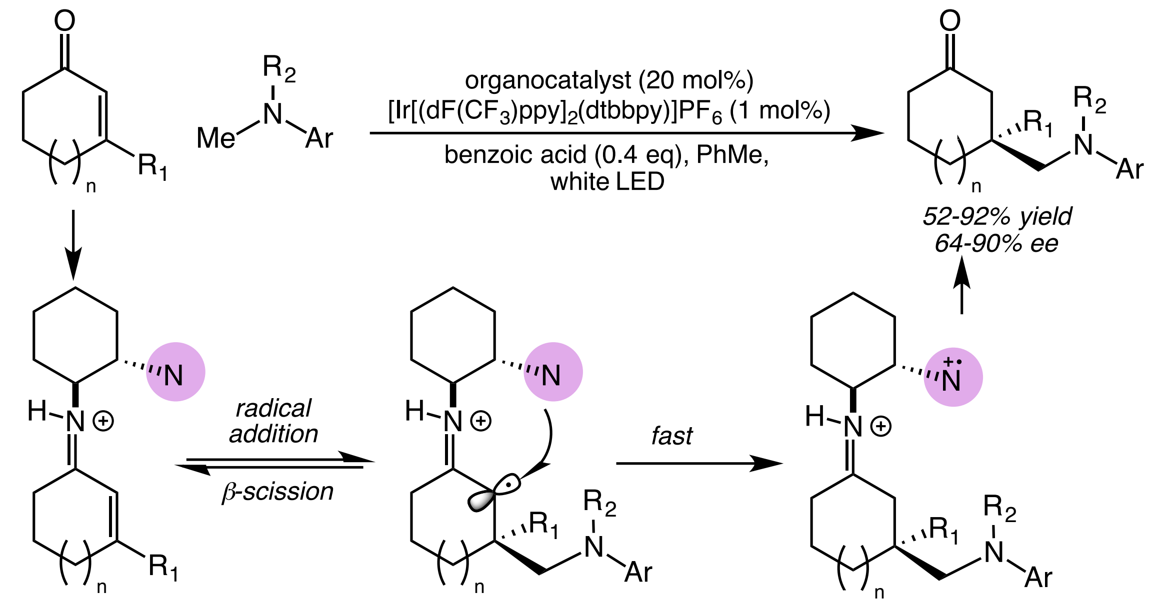
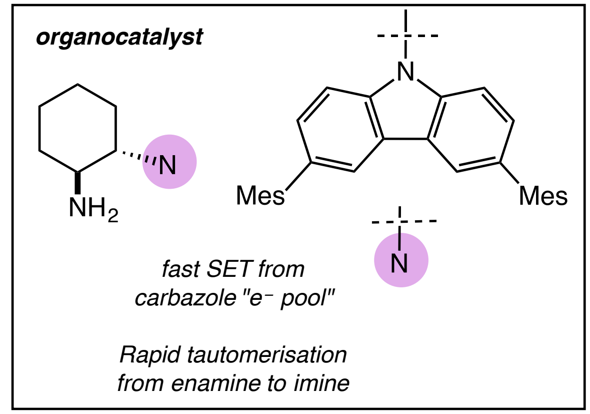
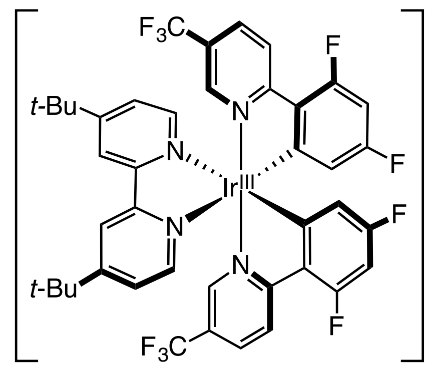
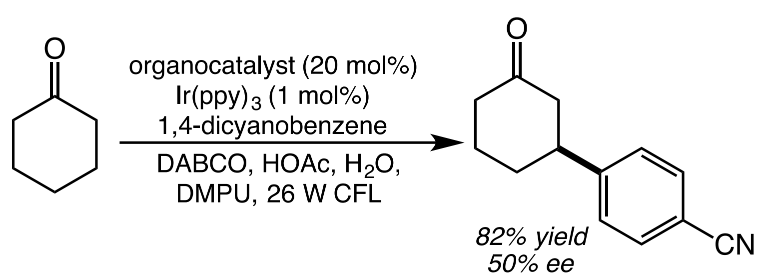


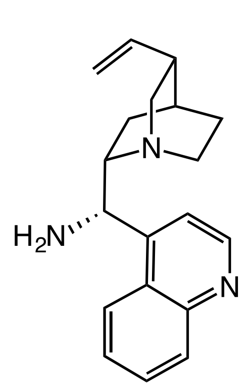


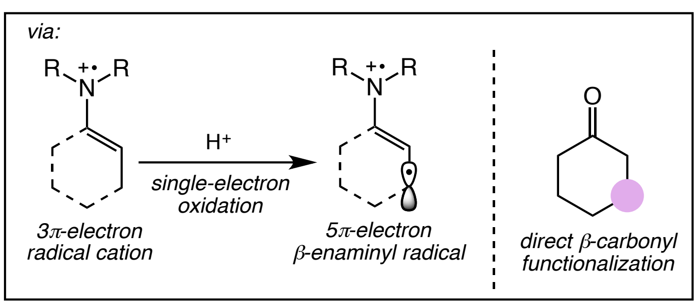


[Ir[(dF(CF3)ppy]2(dtbbpy)]$^{+}$

Asymmetric β-arylation of ketones







Ref: *Nature* **2016**, *532*, 218—222
Science **2007**, *316*, 582—585

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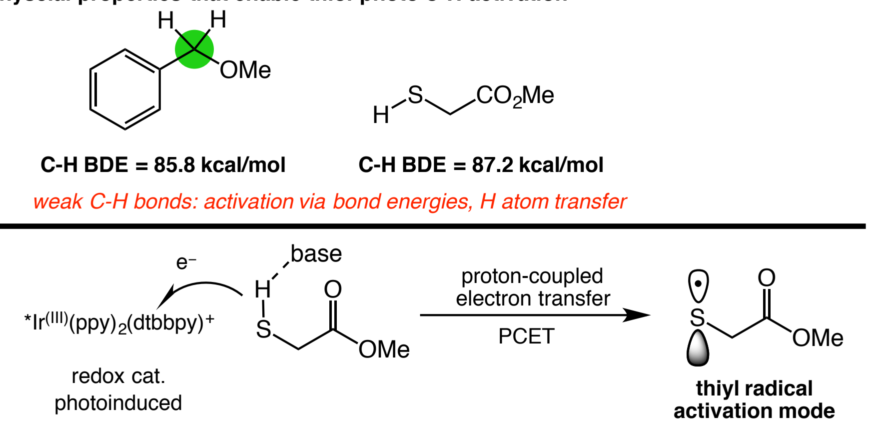
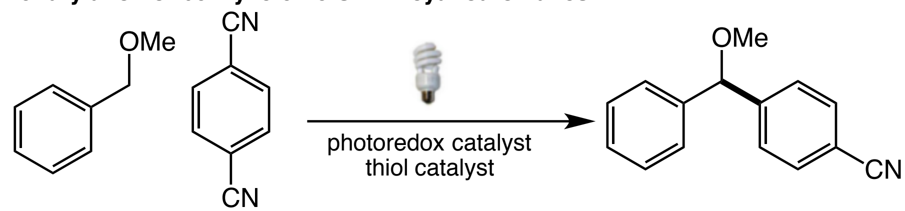
Photoredox Catalysis and thiol catalyst: A Coupling of Benzylic Ethers with Schiff Bases

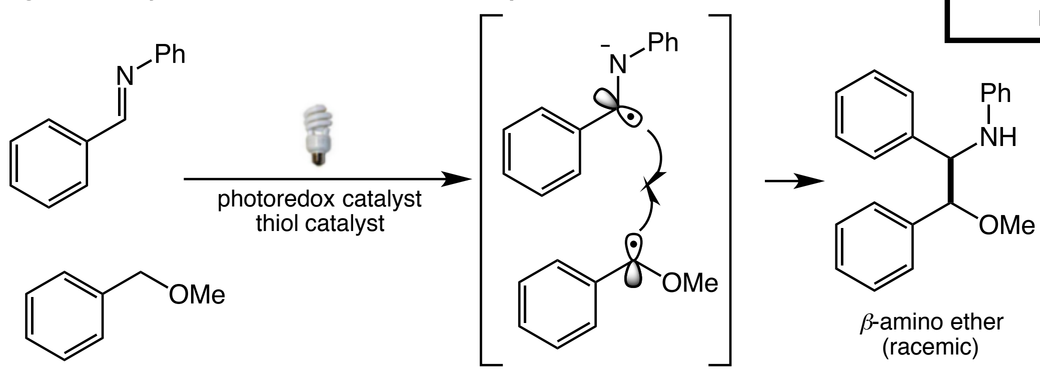
Physcial properties that enable thiol-photo C-H activation

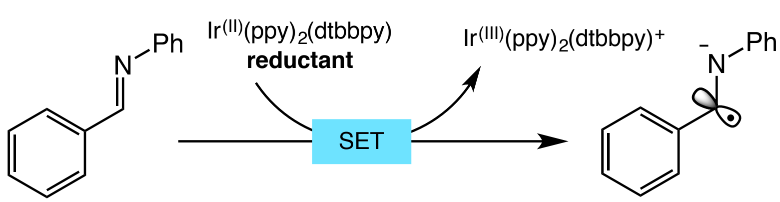


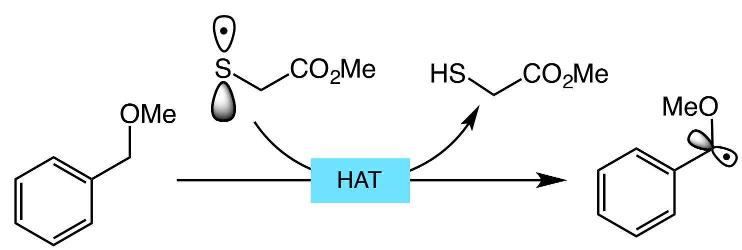
Diret arylation of benzylic ethers with cyanoaromatics



Merger of benzylic ethers with Schiff bases *via* photoredox







Ref: *JACS*, **2014**, *136*, 16986—16989

For Ir(ppy)$_3$: *J. Org. Chem.* **2016**, *81*, 6898—6926

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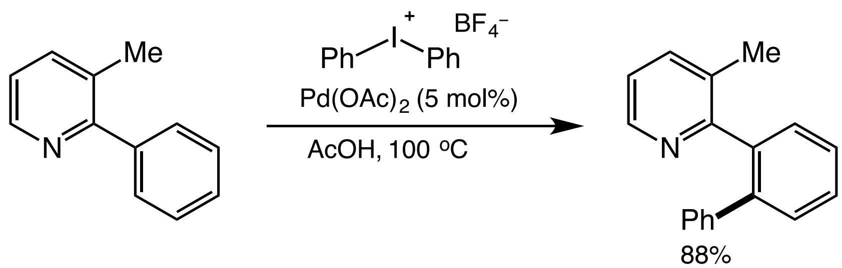
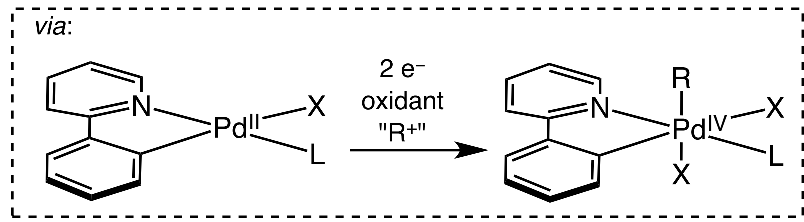
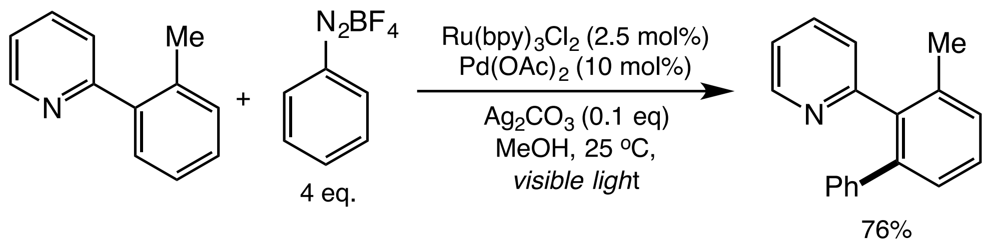
Photoredox Catalysis and Palladium:
C-H Arylation with Aryldiazonium Salts

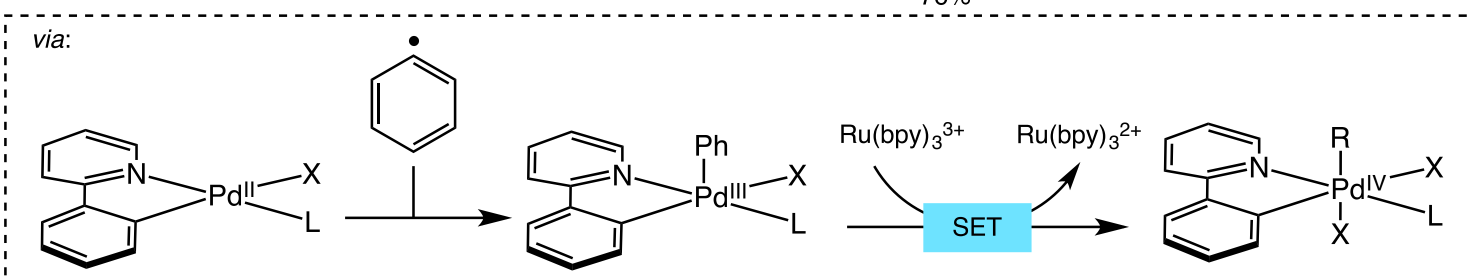
w/o photoredox catalyst





w/ photoredox catalyst





Ref: Sanford et al. *JACS.* **2011**, *133*, 18566
Chem. Rev. **2010**, *110*, 1147

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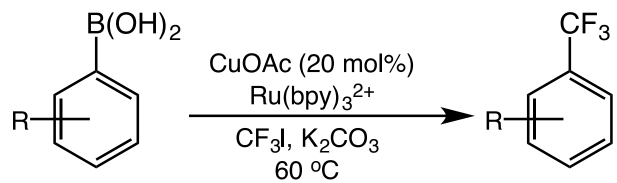
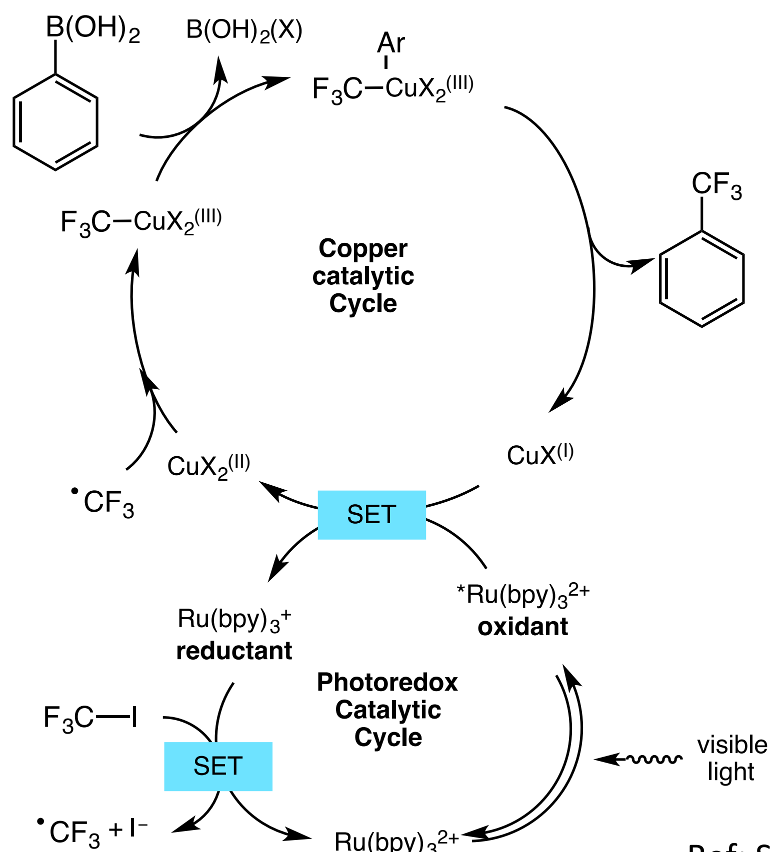
Photoredox Catalysis and Copper:
Trifluoromethylation of Boronic Acid



Mechanism:



Ref: Sanford *et al*. *JACS*, **2012**, *134*, 9034—9047

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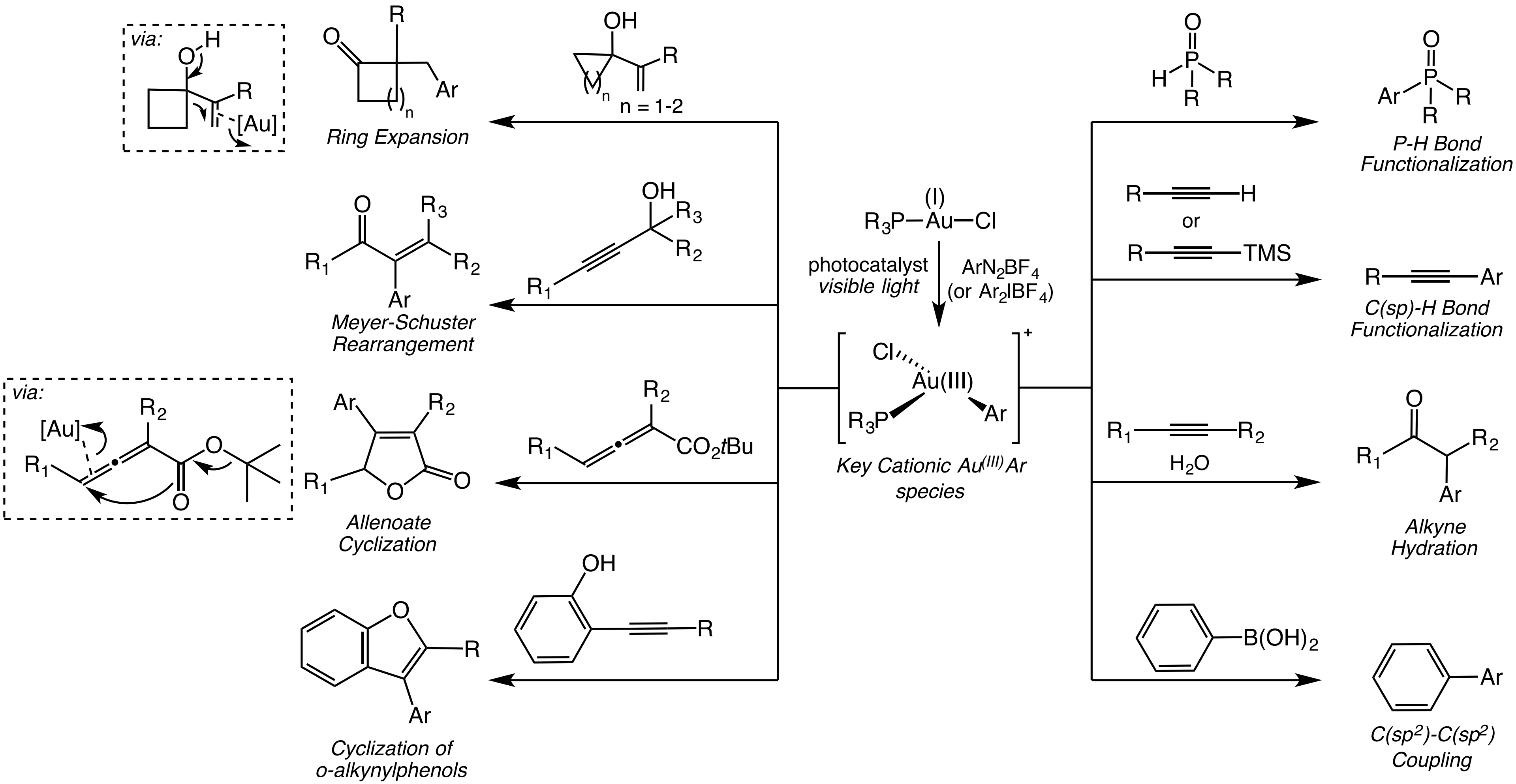
Photoredox Catalysis and Gold:
Current State of the Art in the transformation



Review: Glorius *et al, J. Org. Chem.* **2016**, *81*, 6898—6926

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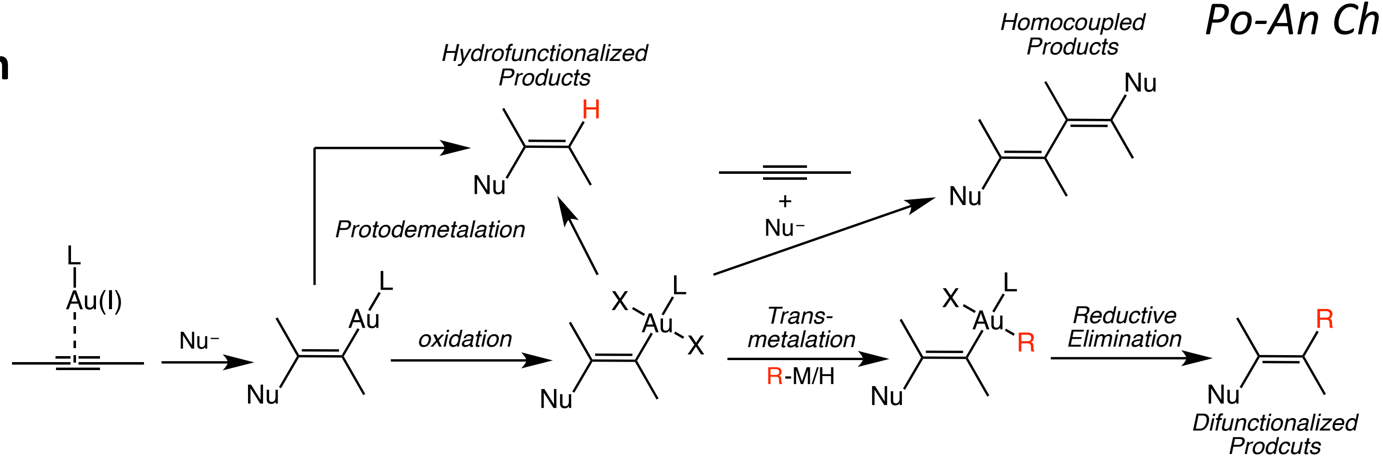
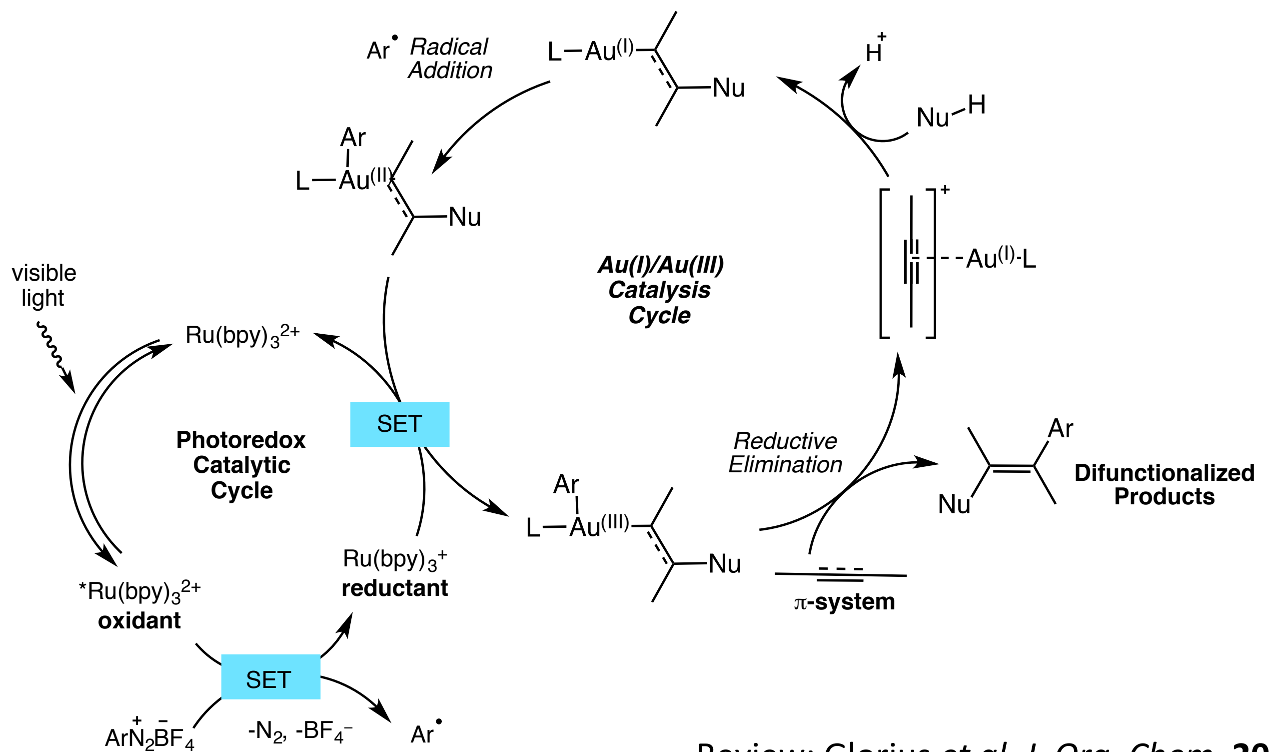
Mechanism





Review: Glorius *et al, J. Org. Chem.* **2016**, *81*, 6898—6926

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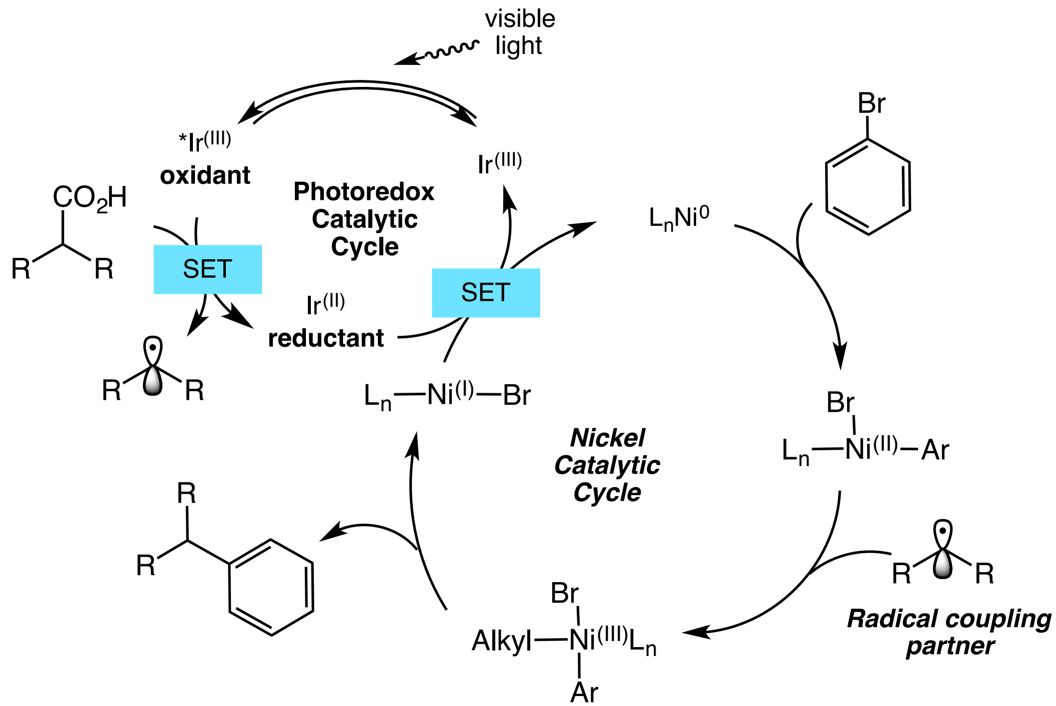
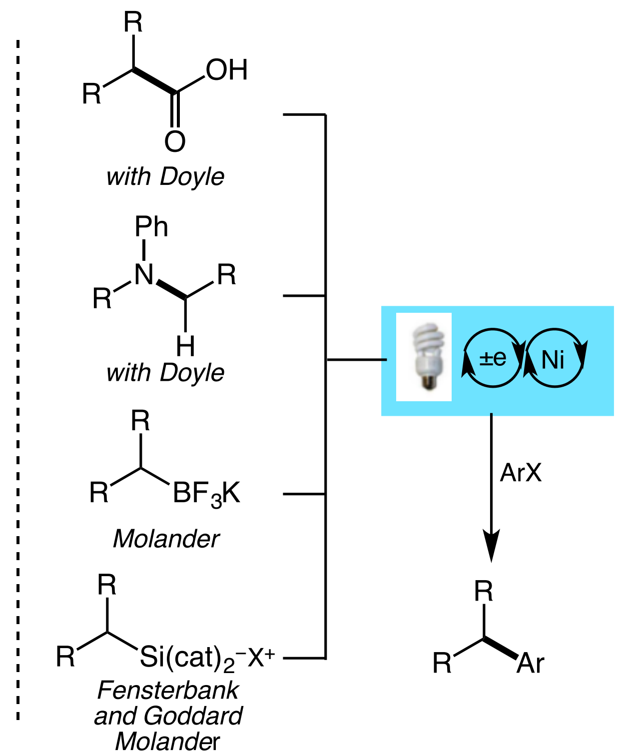
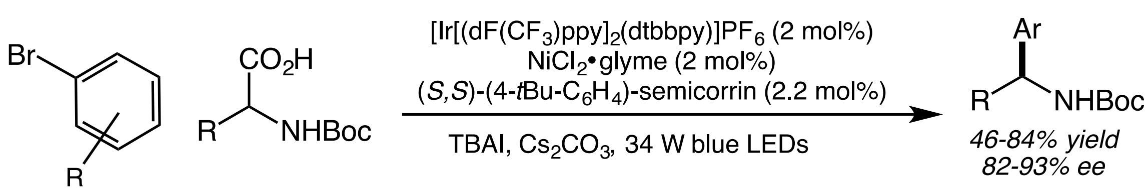
Photoredox Catalysis and Nickel: Selected C-C bond formation





Enantioselective decarboxylative C(sp²)-C(sp³) coupling



Ref: *Chem. Rev.* **2013**, *113*, 5322—5363

For Ir(ppy)$_3$: *J. Org. Chem.* **2016**, *81*, 6898—6926

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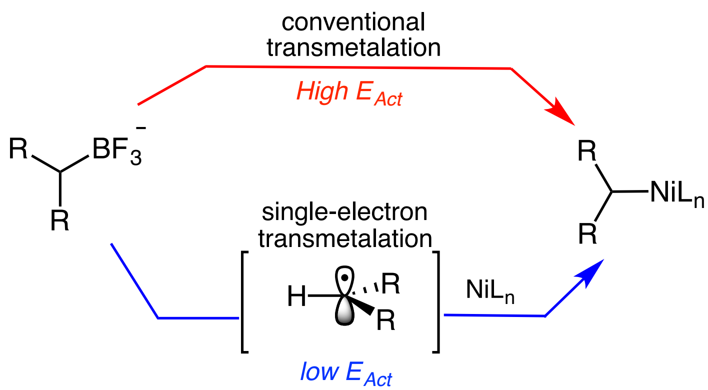
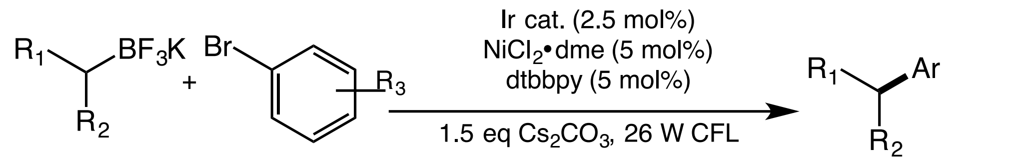
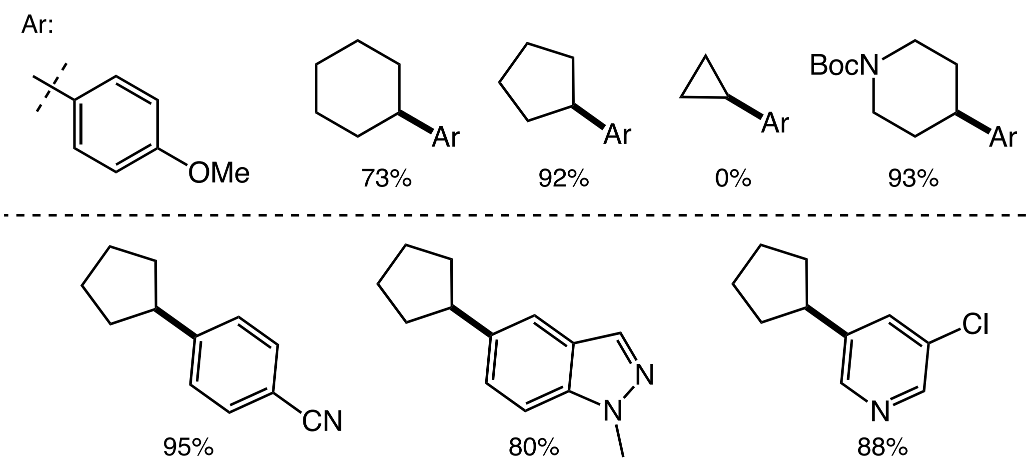
Molander's work



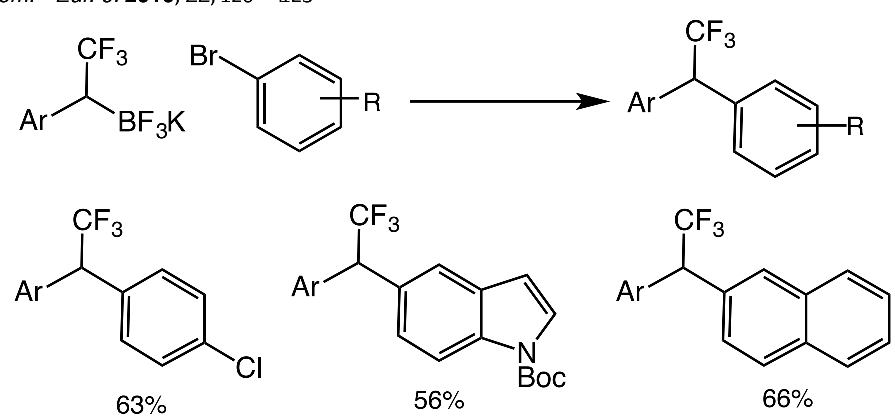
Conventional approach	*SET approach*
*high temp.	*room temp.
*strong base	*lower barrier
*isomeriaztion	*regioselective
*β-hydride elimination	*minimal side products



JACS, **2015**, *137*, *2195*—2198



Chem. - Eur. J. **2016**, *22*, 120—123



*when a chiral ligand was employed and computational studies suggest that rapid dissociation occurs.

Ref: *Science*, **2014**, *345, 433—436*
JACS, **2015**, *137, 2195*—2198
Org. Lett. **2015**, *17*, 3294—3297
Chem. – Eur. J. **2016**, *22*, 120—123

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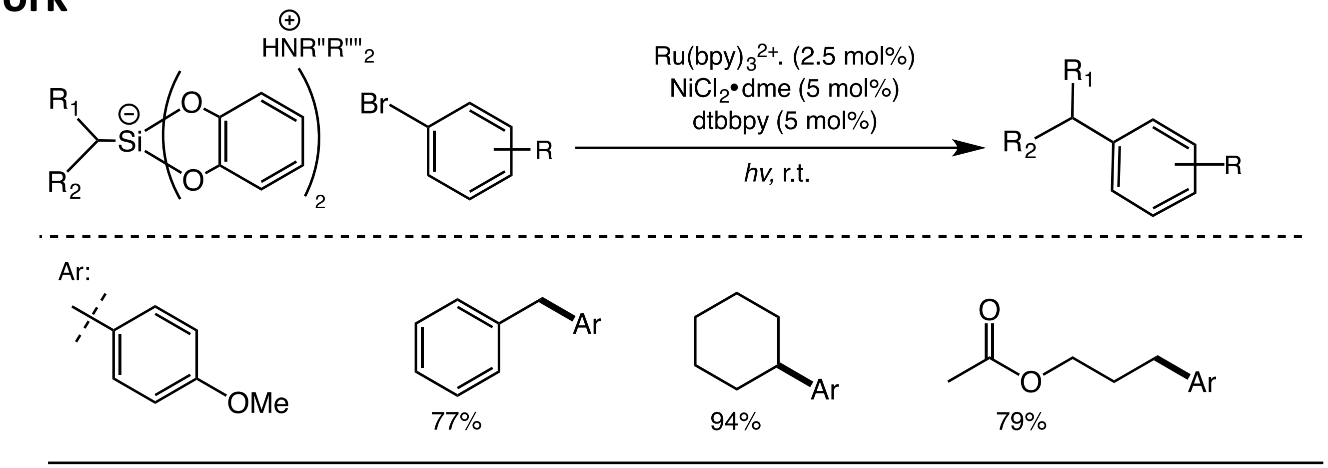
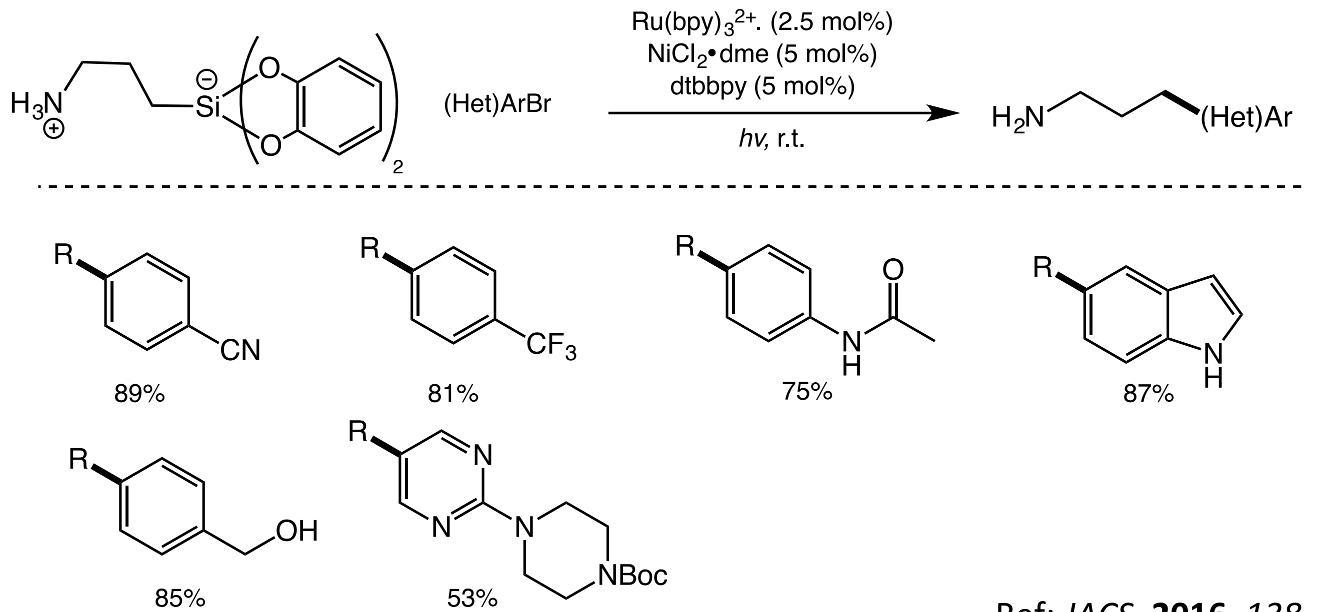
Molander's work





Ref: *JACS*, **2016**, *138*, 475—478
Also see: *ACIE*, **2015**, *54*, 11414—11418
Org. Lett. **2016**, *18*, 1606—1609

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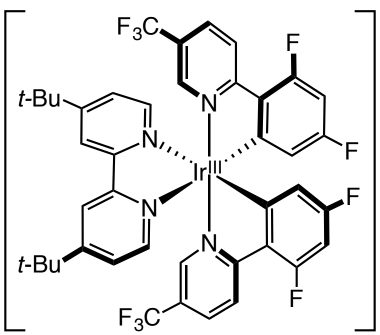
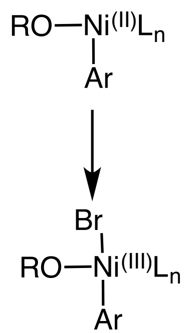
Photoredox Catalysis and Nickel: Selected C-X bond formation

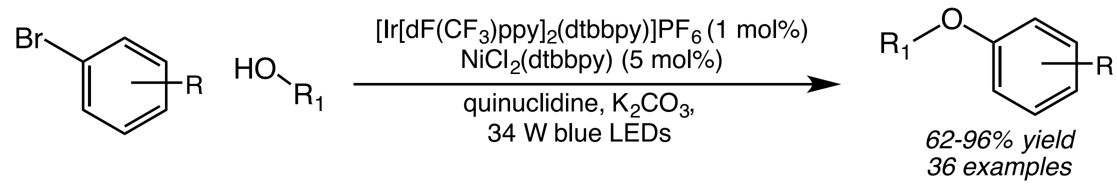


[Ir[(dF(CF$_3$)ppy]$_2$(dtbbpy)]$^+$

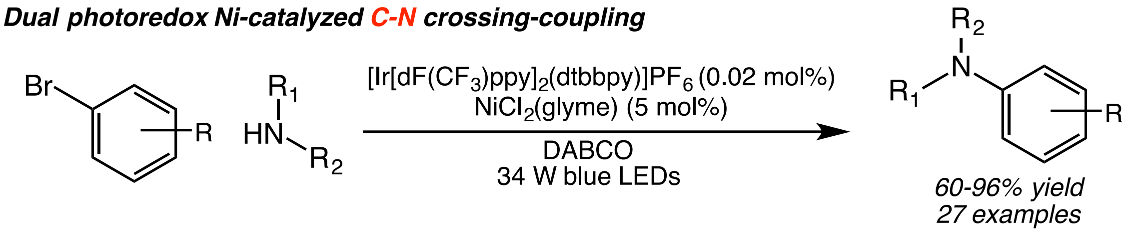
intermediate



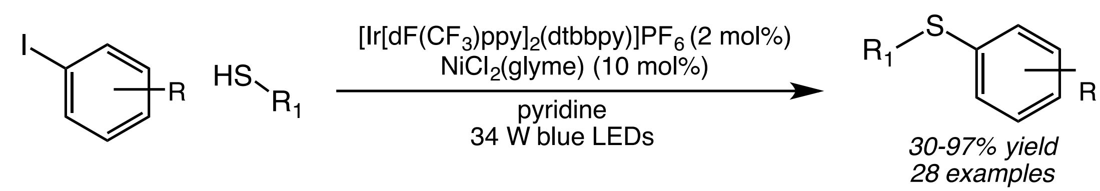
Dual photoredox Ni-catalyzed C-O crossing-coupling



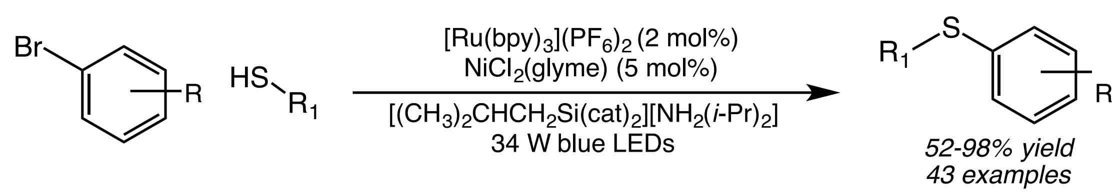
Dual photoredox Ni-catalyzed C-N crossing-coupling



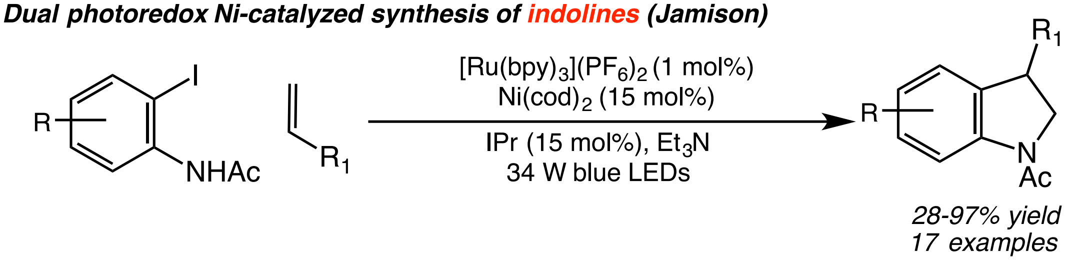
Dual photoredox Ni-catalyzed C-S crossing-coupling (Johannes and Oderinde)



Dual photoredox Ni-catalyzed C-S crossing-coupling (Molander)



Dual photoredox Ni-catalyzed synthesis of indolines (Jamison)



Nature, **2015**, *524*, 330—334
JACS, **2015**, *137*, 9531—9534
Org. Lett. **2016**, *18*, 876—879
JACS, **2016**, *138*, 1760—1763
Science, **2016**, DOI:10.1126/science.aag0209

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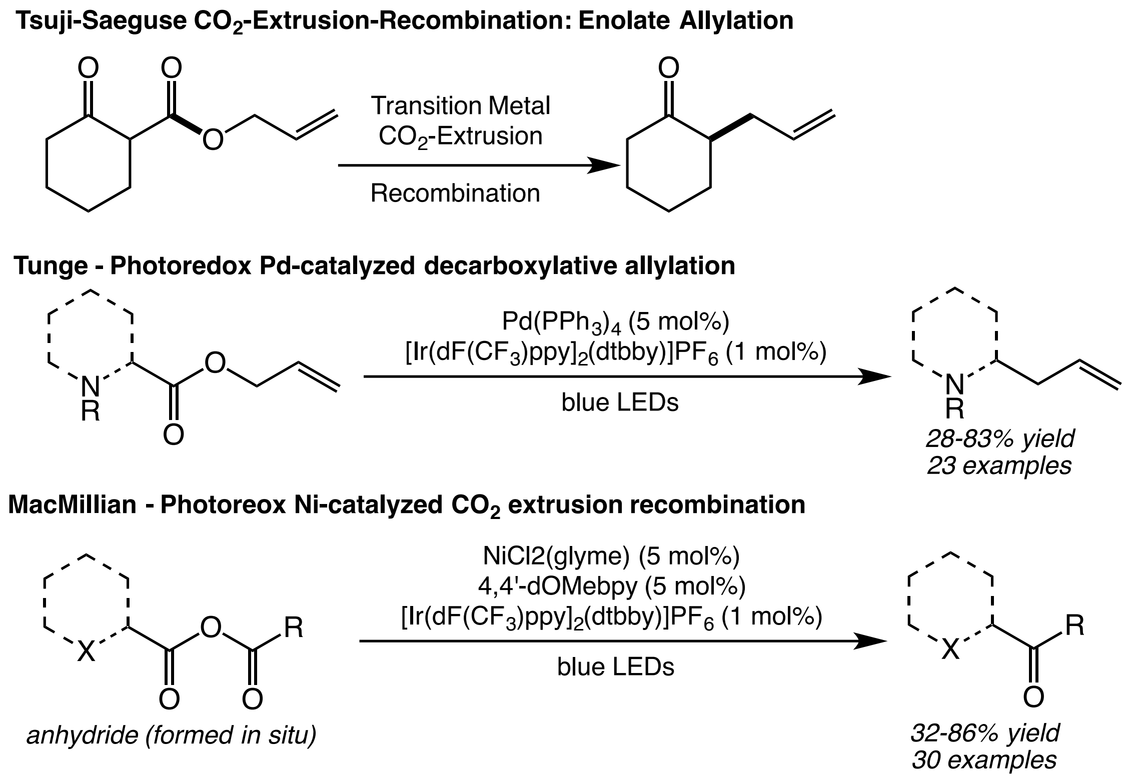
Photoredox Catalysis and Nickel: CO_2 Extrusion-Recombination



Ref: *Chem. Rev.* **2011**, *111*, 1846
JACS, **2014**, *136*, 13606—13609
JACS, **2015**, *137*, 11938—11941

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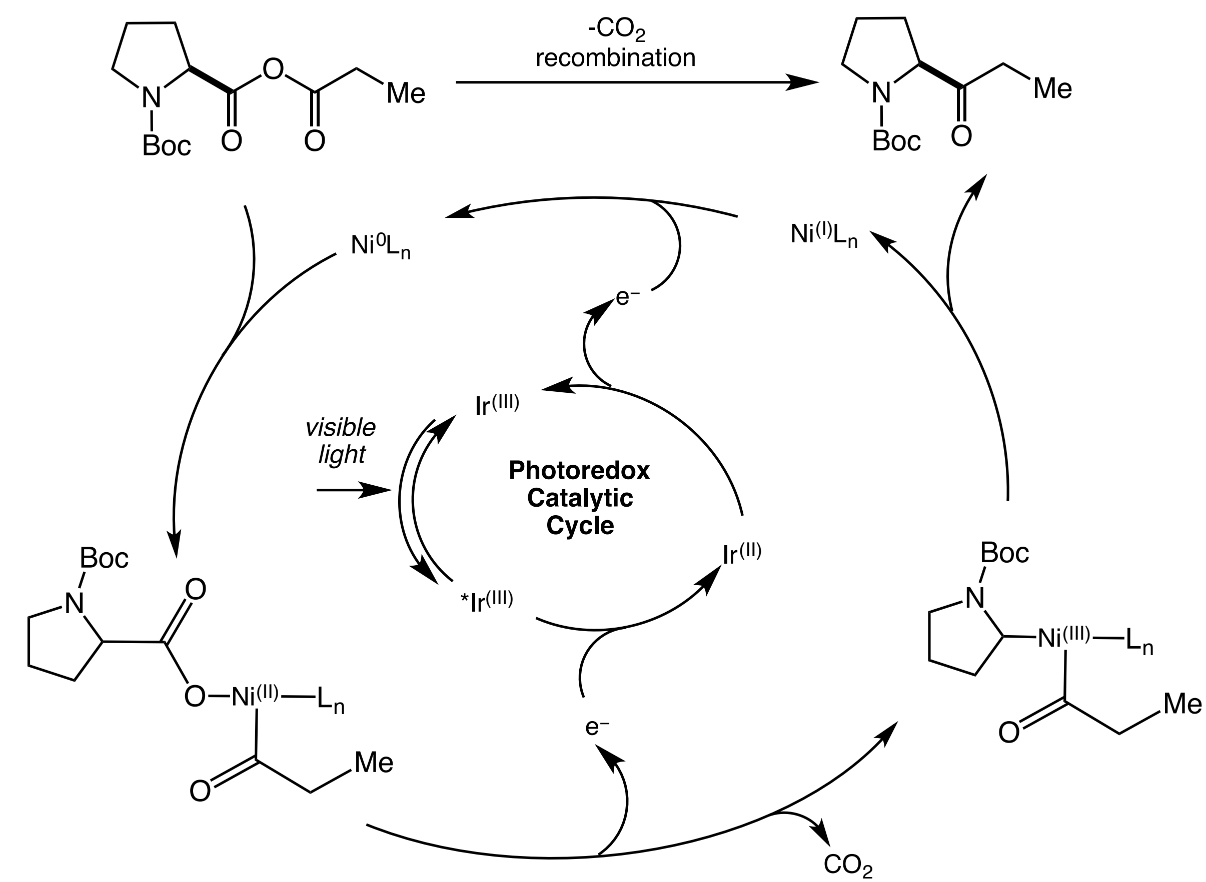
General Mechanism of CO_2 Extrusion-Recombination



Ref: *JACS*, **2015**, *137*, 11938—11941

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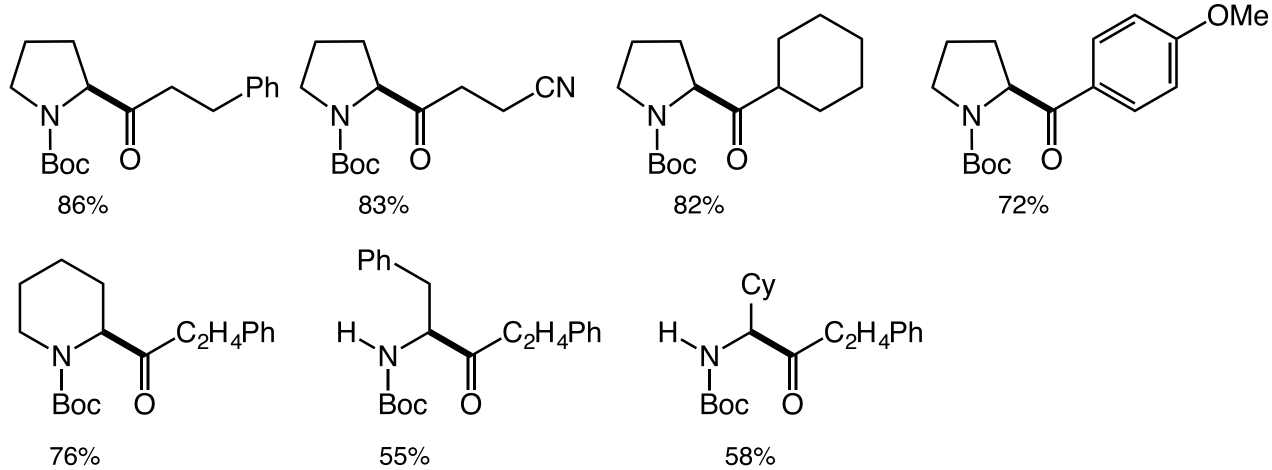
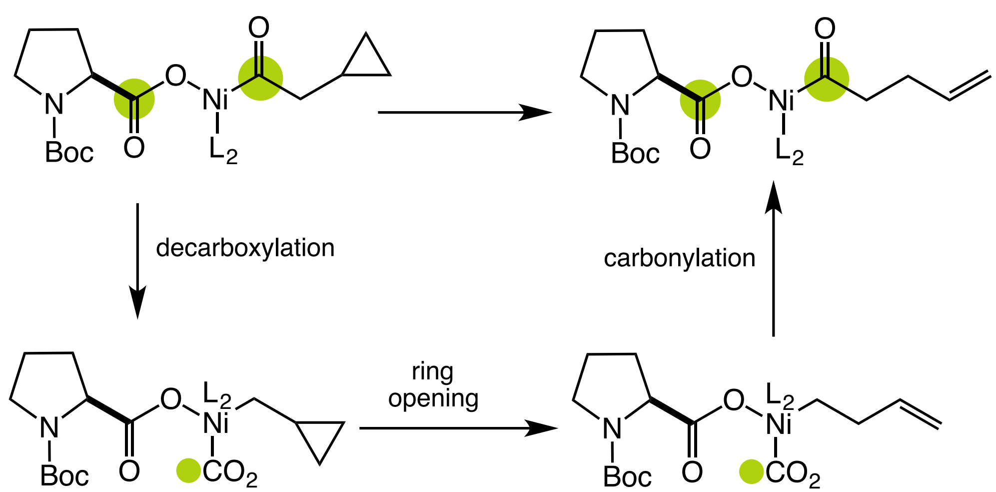
Selected examples of CO_2 Extrusion-Recombination



Proposed Mechanism Based on Cyclopropyl [13]C-labeling Studies



Ref: *JACS*, **2015**, *137*, 11938—11941

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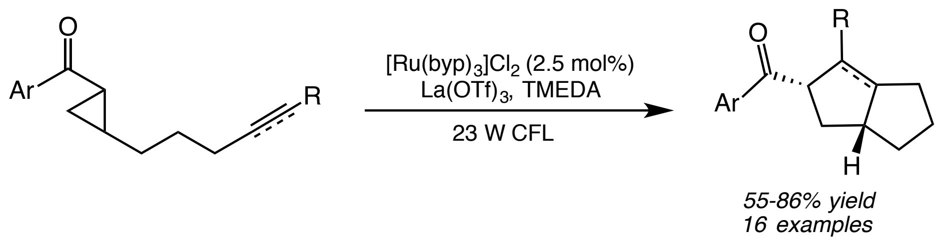
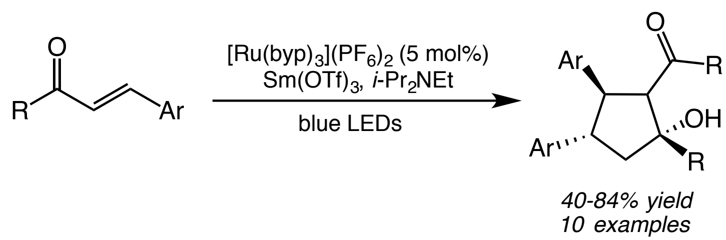
Photoredox Catalysis and Lewis Acid:

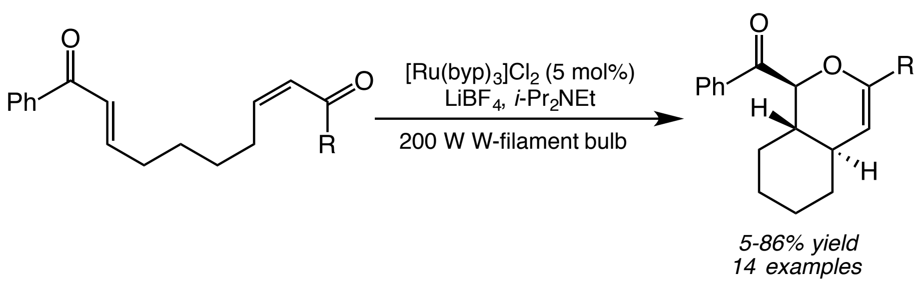
(a) Yoon - Photoredox Lewis acid-catalyzed [3+2] cycloadditions



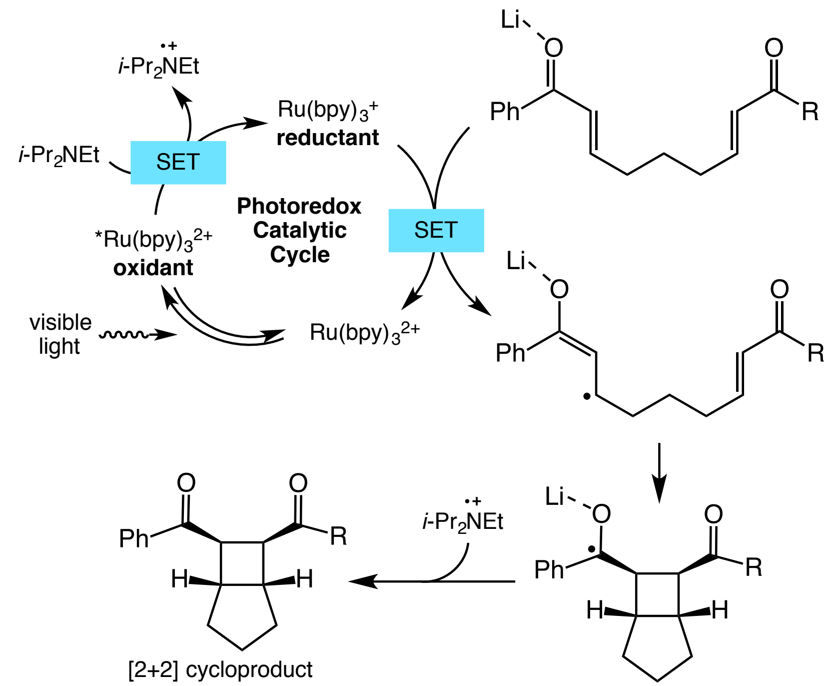
(b) Xia - Photoredox Lewis acid-catalyzed reductive cyclization



(c) Yoon - Photoredox Lewis acid-catalyzed hetero-Diels Alder



(d) Yoon - Photoredox Lewis acid-catalyzed [2+2] cycloadditions



The radical intermediate could be stabilized by the Lewis acid => suppressing back-electron transfer

Ref: Yoon *et al*, *JACS*, **2008**, *130*, 12886—12887
JASC, **2011**, *133*, 1162—1164

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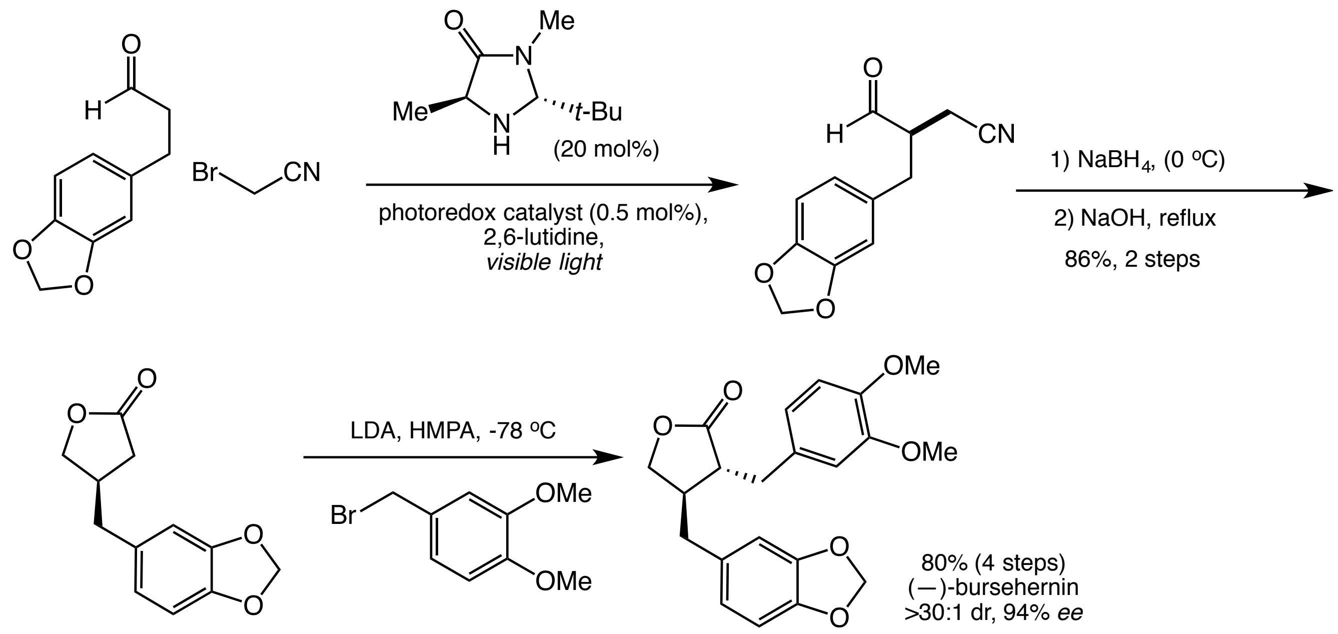
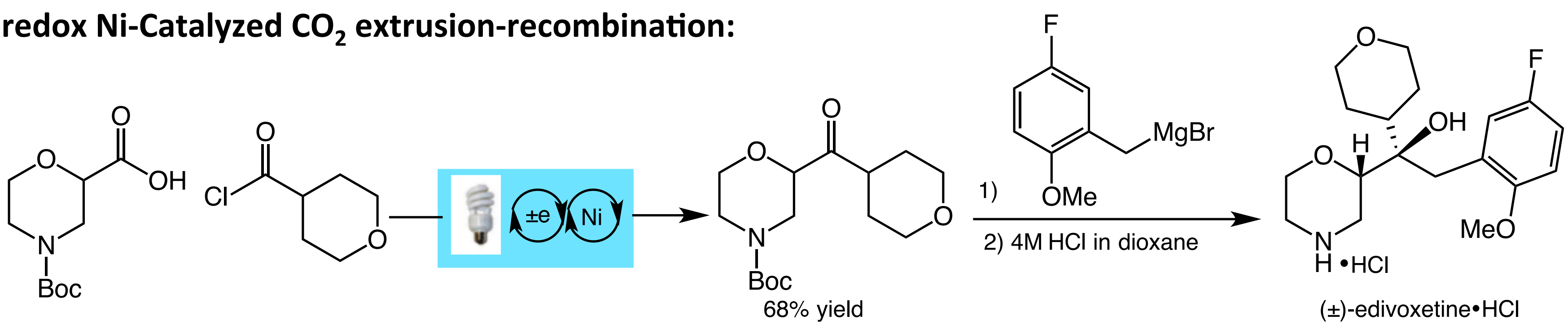
Applications:



Photoredox Ni-Catalyzed CO_2 extrusion-recombination:



Ref: *JACS*, **2015**, *137*, 11948—11941

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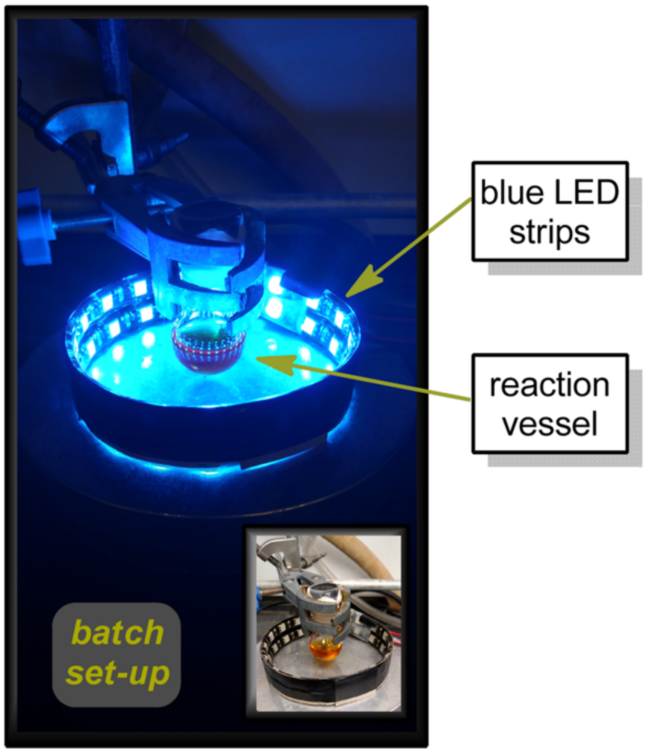
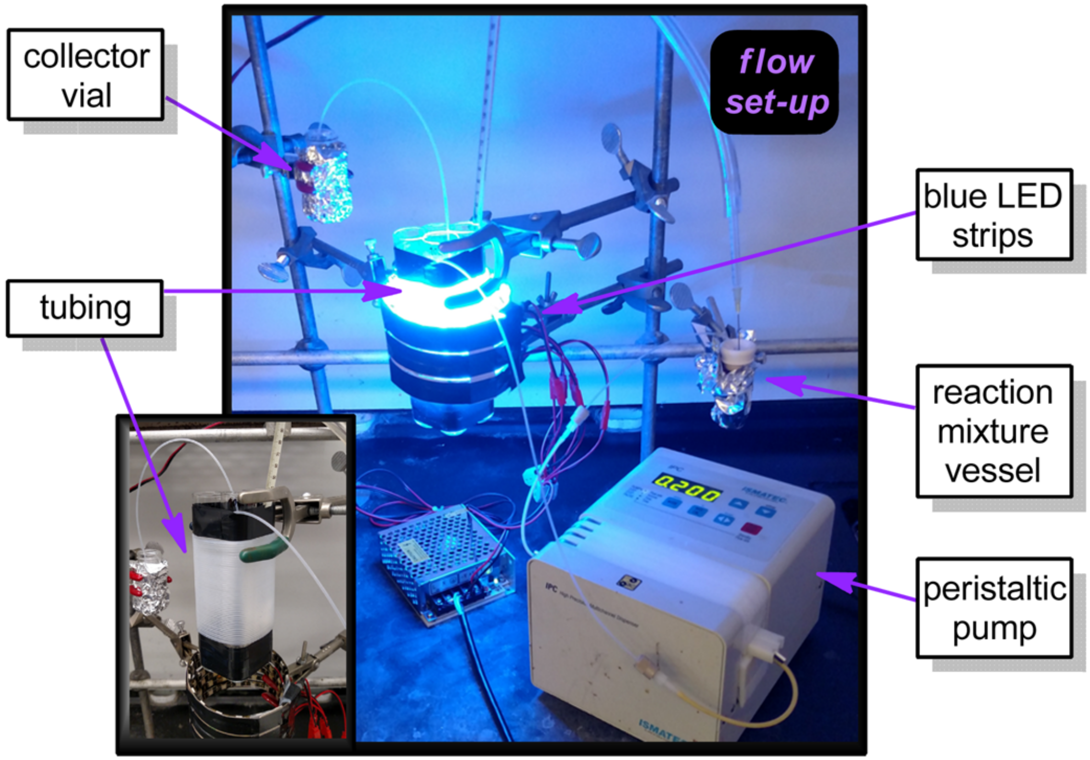
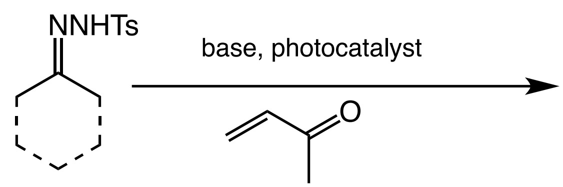
General Set-ups for Batch and Flow Photocatalytic Reactions

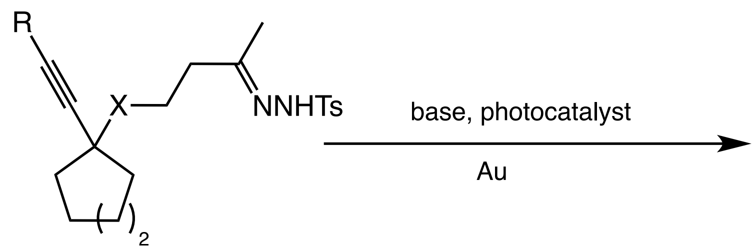


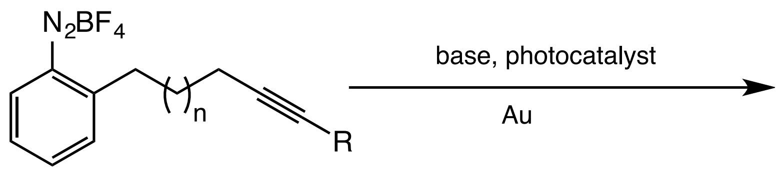


Ref: Acc. Chem. Res. DOI: 10.1021/acs.accounts.6b00270

Ideas


NNHTs
base, photocatalyst
O


R
X
NNHTs
2
base, photocatalyst
Au


N2BF4
n
R
base, photocatalyst
Au

Thank you for your attention