

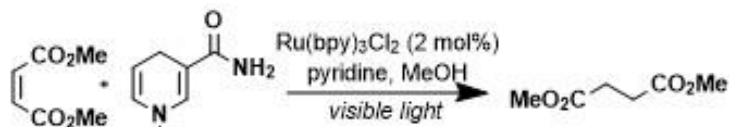
Visible-Light Photoredox Catalysis (VLPC)

Davis Plasko

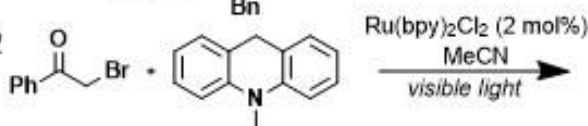
Reference: MacMillan, D. et al. *Chem. Rev.* **2013**, *113*, 5322-5363
Bode Research Group OC VI (HS 2015) <http://www.bode.ethz.ch/>

Initial VLPC reactions

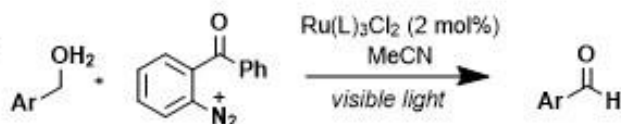
- Pac, C. et al. *JACS* **1981**, *103*, 6495
-reduction of electron-poor alkenes



- Fukuzumi, S. et al. *J. Phys. Chem.* **1990**, *94*, 722
-reductive dehalogenation of α -bromocarbonyl compounds

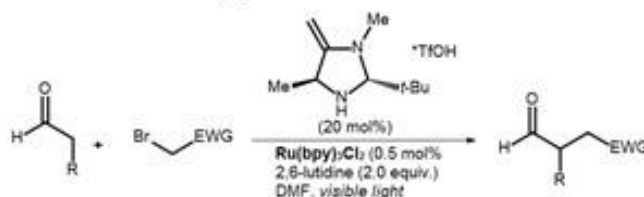


- Cano-Yelo, H.; Deronzier, A. *Tet. Lett.* **1984**, *94*, 5517
-oxidation of benzylic alcohols to aldehydes

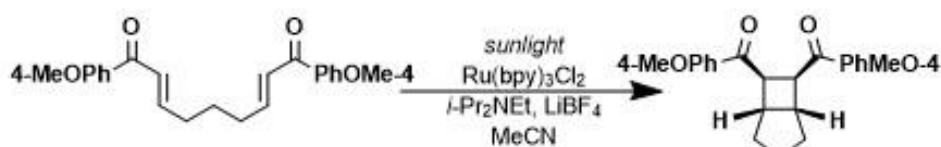


Crossing the Rubicon

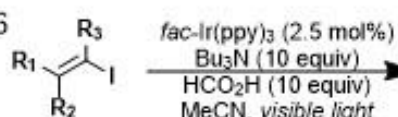
- MacMillan, D. W. C. *Science* **2008**, *322*, 77
- α -alkylation of aldehydes



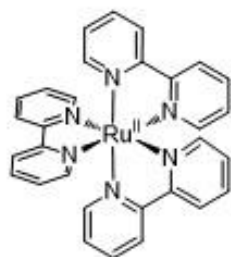
- Yoon, T. P. et al. *J. Am. Chem. Soc.* **2008**, *130*, 12886
-[2+2] cycloaddition



- Stephenson, C. R. J. et al. *J. Am. Chem. Soc.* **2009**, *131*, 8756
-reductive dehalogenation



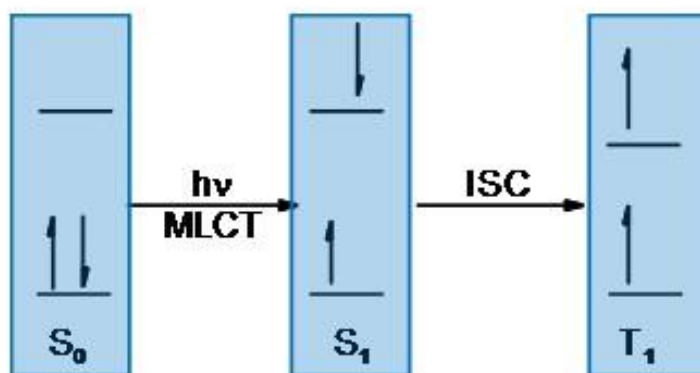
Catalysts



Ru(bpy)₃²⁺
 $\lambda_{\text{max}} = 452 \text{ nm}$
 $\tau = 1100 \text{ ns}$

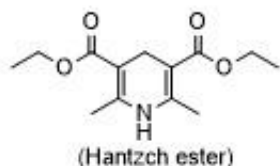
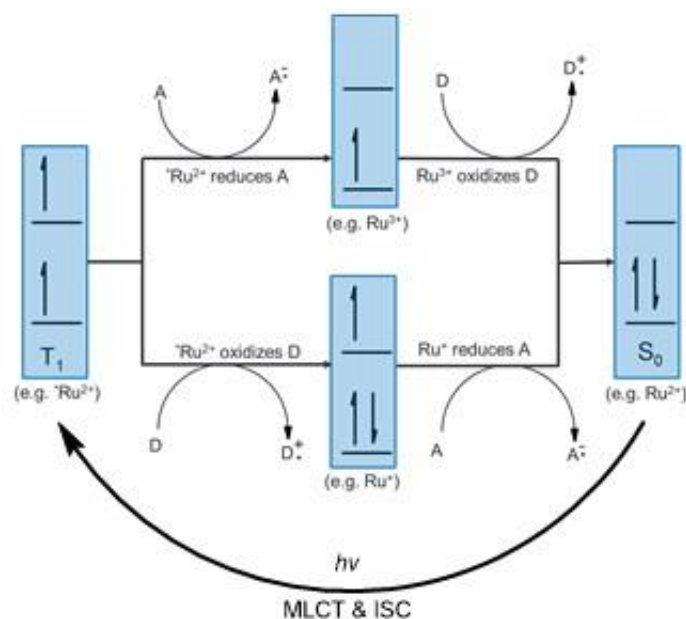


fac-Ir(ppy)₃
 $\lambda_{\text{max}} = 375 \text{ nm}$
 $\tau = 1900 \text{ ns}$



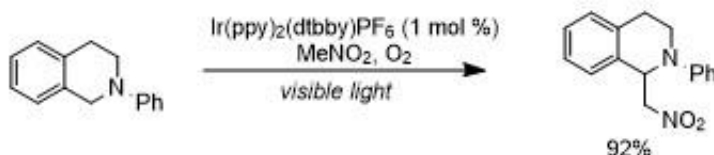
- Mostly ruthenium or iridium polypyridyl complexes
- Absorb visible light through a metal-to-ligand charge transfer (MLCT) and then rapid intersystem crossing (ISC) to give photo-excited state
- Decay to singlet ground state spin-forbidden
- Long lifetimes (131 ns-2300ns) allow for unique reactivities

- From the singlet excited state there are two possible cycles, reductive quenching (top) and oxidative quenching (bottom)
- Often A (acceptor) or D (donor) are sacrificial (not used in the product of the reaction)
- In net oxidative and net reductive reactions the use of a stoichiometric, sacrificial acceptor/donor molecule is necessary, such as Hantzsch ester



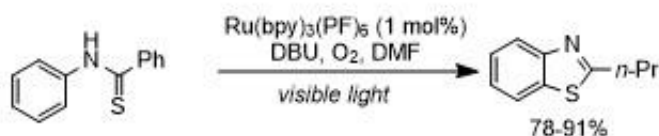
Net Oxidative Reactions

Aza-Henry

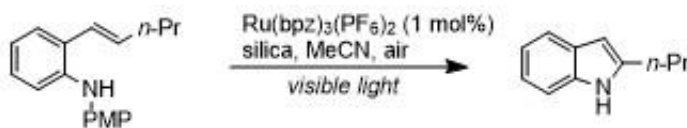


Stephenson, *JACS* **2010**, *132*, 1464
Wang, *ACIE* **2012**, *51*, 8050

Oxidative cyclizations



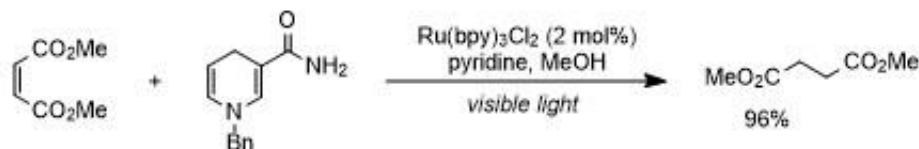
Li, *Org. Lett.* **2012**, *14*, 98



Zheng, *ACIE* **2012**, *51*, 9562

Net Reductive Reactions

Alkene reduction

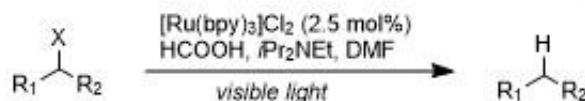


Pac, *JACS*, **1981** *103*, 6495

Ring opening/allylation

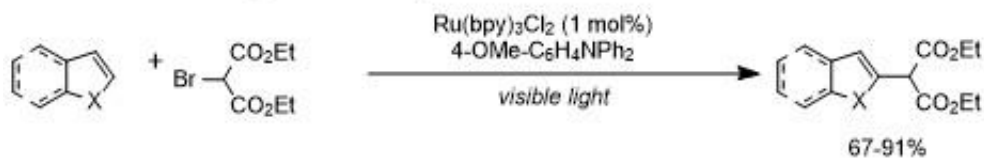


Guidon, *Synlett*, **1998**, 213



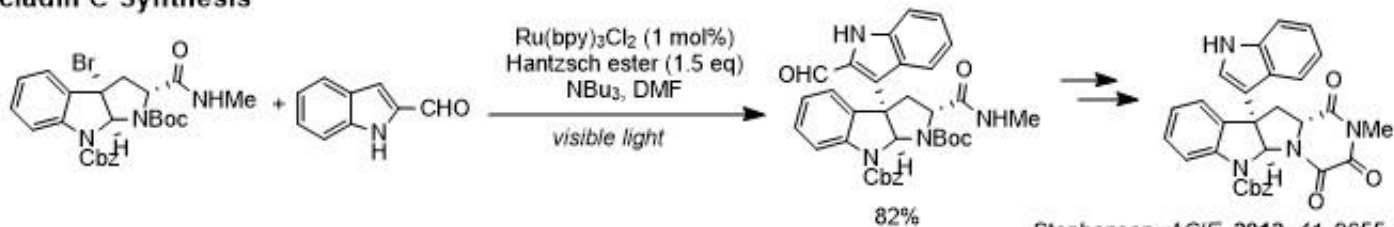
Stephenson, *JACS*, **2009**, *131*, 8756

Reductive dehalogenation alkylation



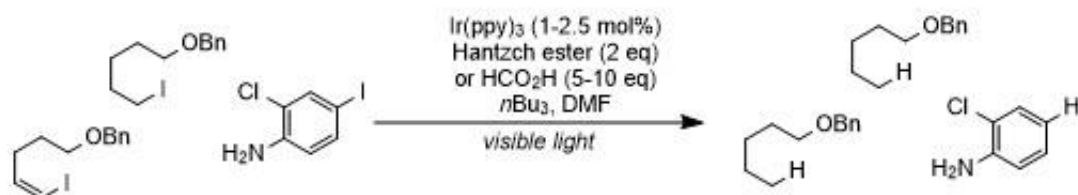
Stephenson, *Org. Lett.*, 2010, 12, 368

Gliocladin C Synthesis



Stephenson, *ACIE*, 2012, 41, 9655

- Ruthenium catalysts can only reductively dehalogenate activated halides, iridium catalysts generally have a greater reduction potential and can be employed with unactivated halides

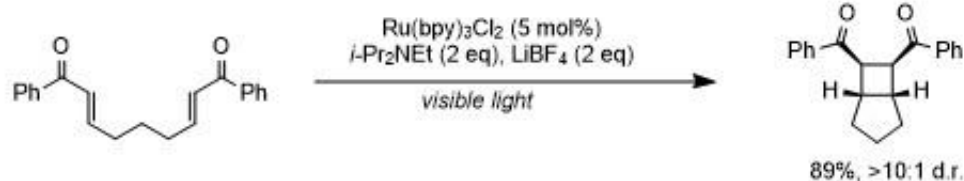


Stephenson, *ACIE*, 2012, 4, 854

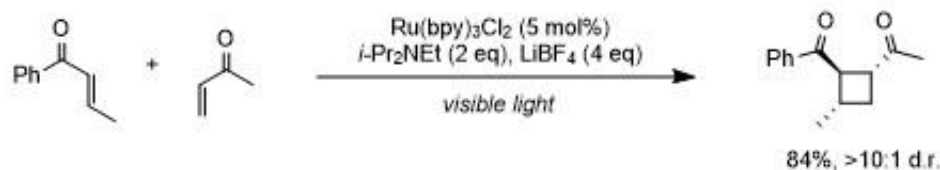
Redox Neutral Reactions

- The starting materials interact in both the reductive and oxidative steps of the pathway and leads to unique reactivities not often found elsewhere

[2+2] Cycloadditions



Yoon, *JACS*, 2009, 131, 14604
Org. Lett. 2012, 14, 1110
Science 2014, 344, 392

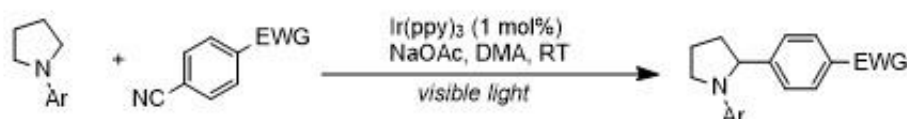


[4+2] Cycloadditions



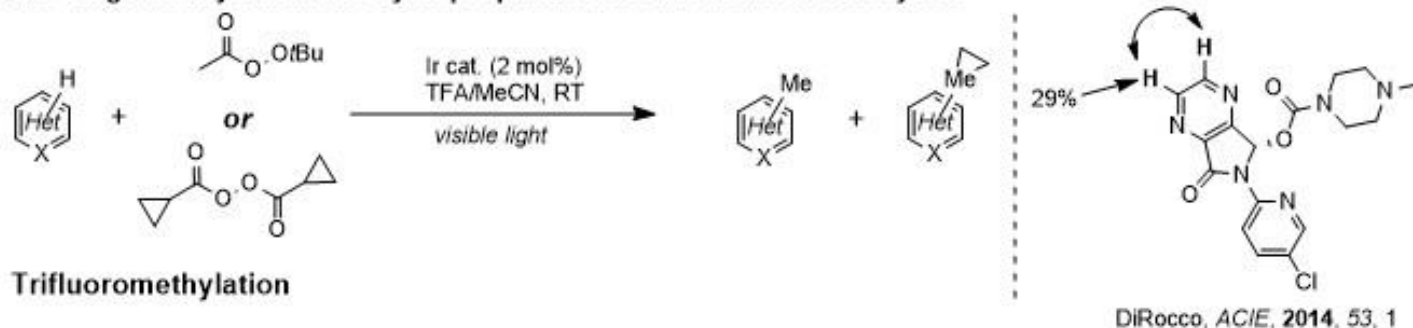
Yoon, *JACS* 2011, 133, 19350

C-H Arylation of Amines

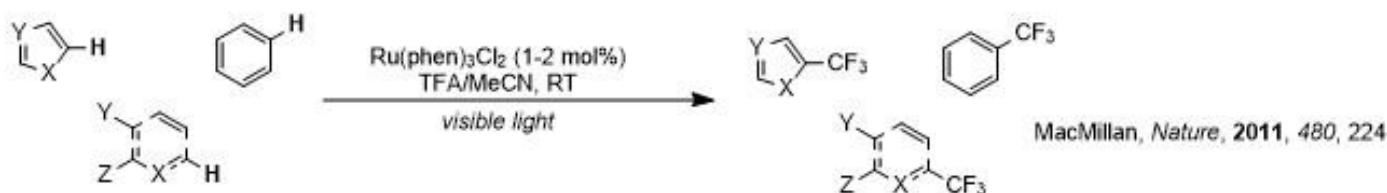


MacMillan, *Science* 2011, 334, 1114

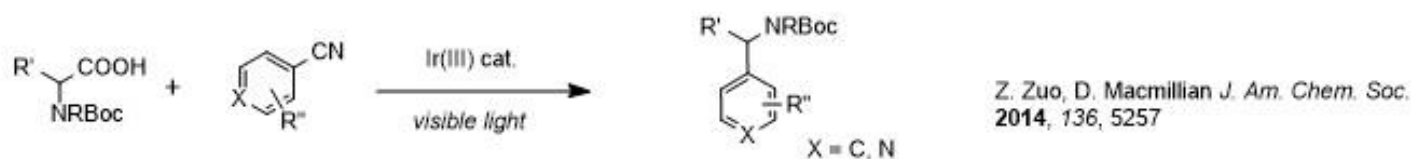
Late-Stage methylation and cyclopropanation of bioactive heterocycles



Trifluoromethylation

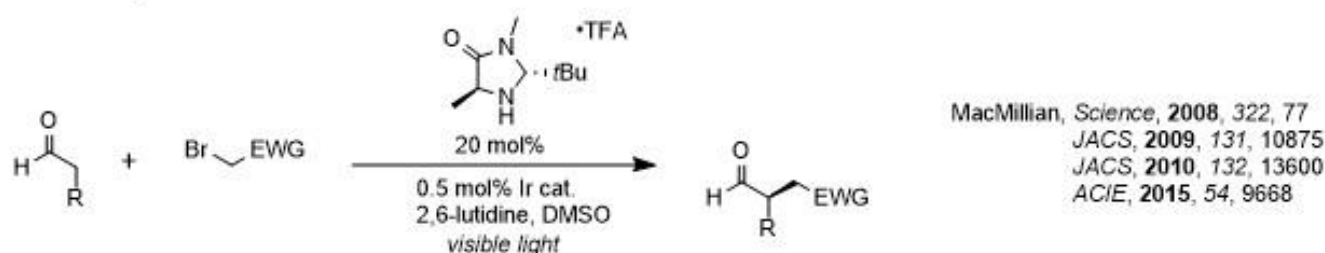


Decarboxylative couplings

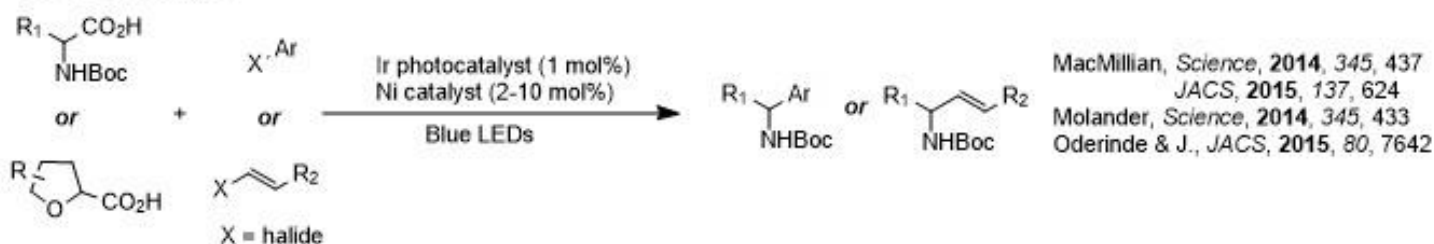


Dual Catalysis

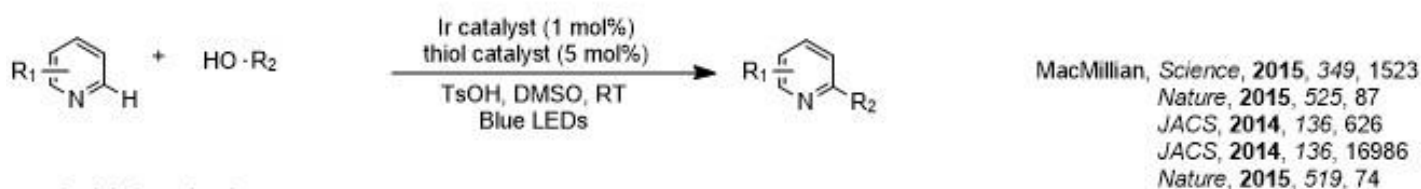
Enamine Catalysis



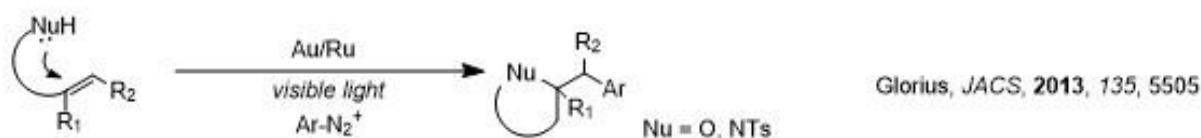
Nickel Catalysis



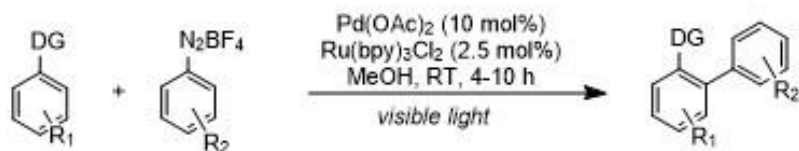
Hydrogen atom transfer (HAT) catalysis



Gold Catalysis

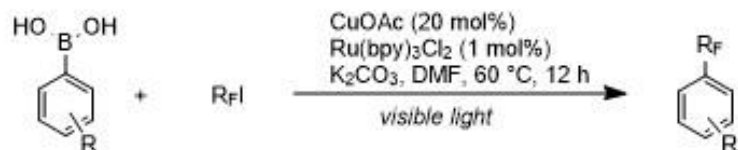


Palladium Catalysis



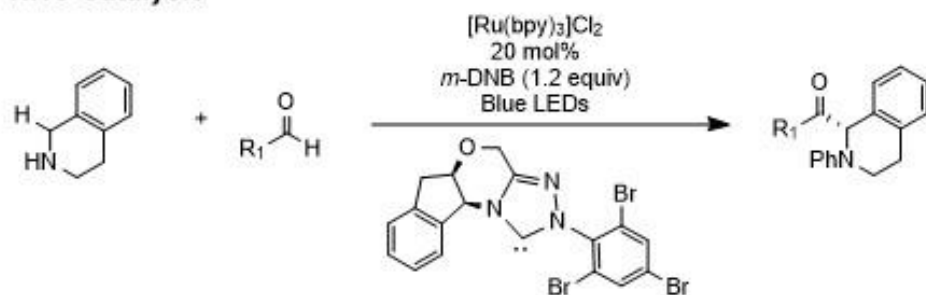
Sanford, *JACS*, **2011**, *133*, 18566

Copper Catalysis



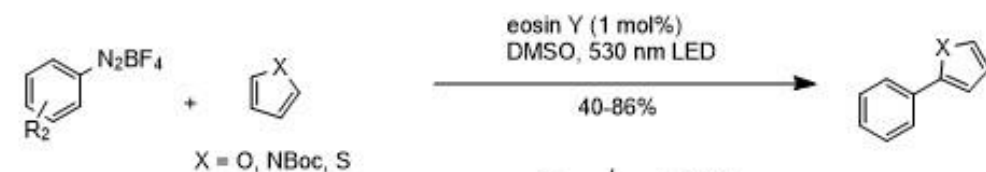
Sanford, *JACS*, **2012**, *134*, 9034

NHC Catalysis

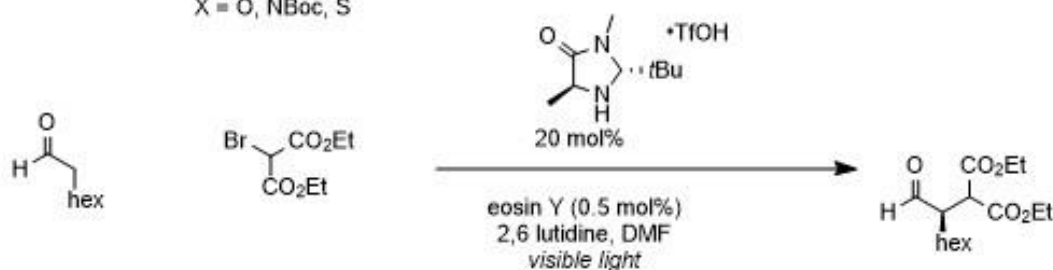


Rovis, *JACS*, **2012**, *134*, 8094

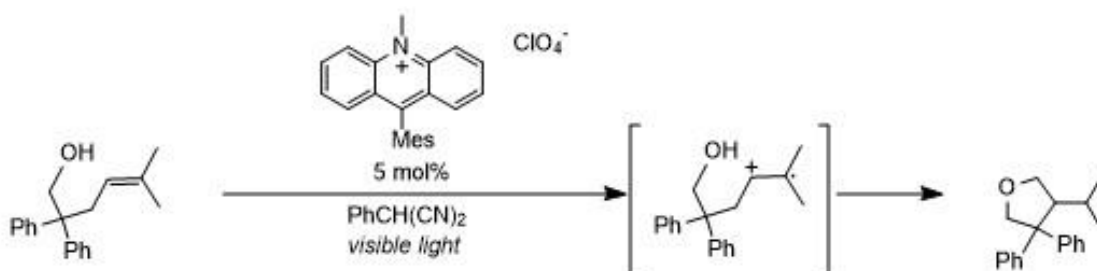
Organic Photoredox Catalysis



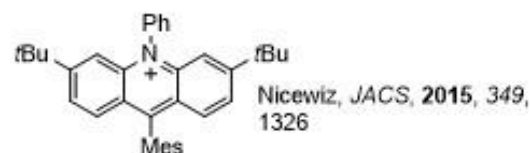
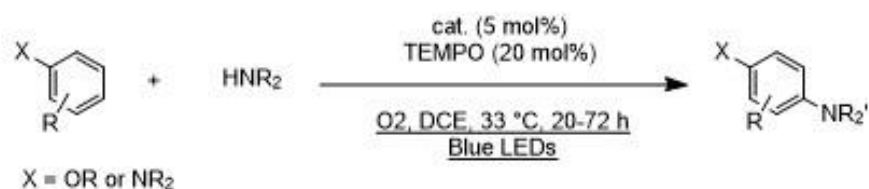
Konig, *JACS*, **2012**, *134*, 2958



Zeitler *ACIE*, **2011**, *50*, 951

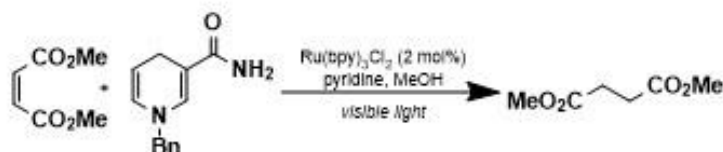


Nicewicz, *JACS*, **2012**, *134*, 18577



Role of Redox Potentials

- Lets use Pac's olefin reduction in 1981 to describe redox potentials



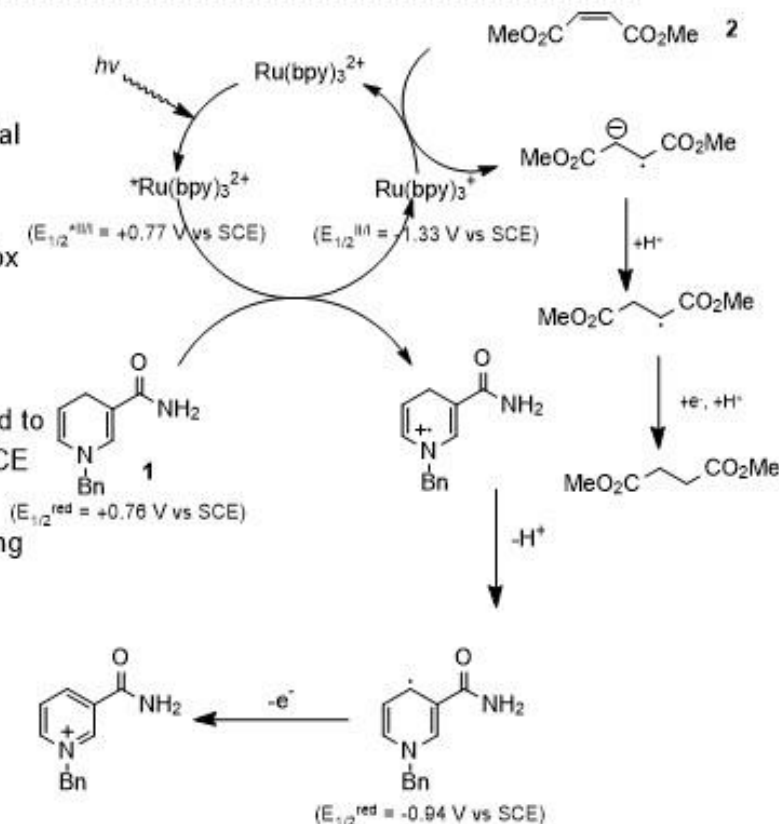
- The photocatalytic cycle starts with the excitation of $\text{Ru}(\text{bpy})_3^{2+}$ to $^*\text{Ru}(\text{bpy})_3^{2+}$ that has a redox potential of +0.77 V vs SCE (saturated calomel electrode)

- BNAH (1) which has similarities to NADH, has a redox potential of +0.76 V vs SCE; just low enough for $^*\text{Ru}(\text{bpy})_3^{2+}$ to oxidize BNAH

- While BNAH is oxidized, the photocatalyst is reduced to $\text{Ru}(\text{bpy})_3^+$ that has a redox potential of -1.33 V vs SCE

- Therefore, $\text{Ru}(\text{bpy})_3^+$ is an exceptionally good reducing agent and can reduce dimethyl maleate (2) while oxidizing the photocatalyst back to $\text{Ru}(\text{bpy})_3^{2+}$ finishing the photocatalytic cycle

- Whether the α -carbonyl radical is reduced by the dihydropyridyl radical or a second equivalent of $\text{Ru}(\text{bpy})_3^+$ is not known as the dihydropyridyl radical is also a good reducing agent with a redox potential of -0.94 V vs SCE



entry	photocatalyst	$E_{1/2}$ (M^+/M^*)	$E_{1/2}$ (M^*/M')	$E_{1/2}$ (M^+/M)	$E_{1/2}$ (M/M')	excited-state lifetime τ (ns)	excitation λ_{max} (nm)	emission λ_{max} (nm)
1	$\text{Ru}(\text{bpm})_3^{2+}$	-0.21	+0.99	+1.69	-0.91	131 [§]	454	639 [§]
2	$\text{Ru}(\text{bpz})_3^{2+}$	-0.26	+1.45	+1.86	-0.80	740	443	591
3	$\text{Ru}(\text{bpy})_3^{2+}$	-0.81	+0.77	+1.29	-1.33	1100	452	615
4	$\text{Ru}(\text{phen})_3^{2+}$	-0.87	+0.82	+1.26	-1.36	500	422	610 [§]
5	$\text{Ir}[\text{dF}(\text{CF}_3)\text{ppy}]_2(\text{dtbbpy})^+$	-0.89	+1.21	+1.69	-1.37	2300	380	470
6	$\text{Ir}(\text{ppy})_2(\text{dtbbpy})^+$	-0.96	+0.66	+1.21	-1.51	557		581
7	$\text{Cu}(\text{dap})_2^+$	-1.43		+0.62		270		670 [§]
8	<i>fac</i> - $\text{Ir}(\text{ppy})_3$	-1.73	+0.31	+0.77	-2.19	1900	375	494 [§]

[§]All potentials are given in V vs SCE. Measurements performed at room temperature in acetonitrile unless with ^{§§}