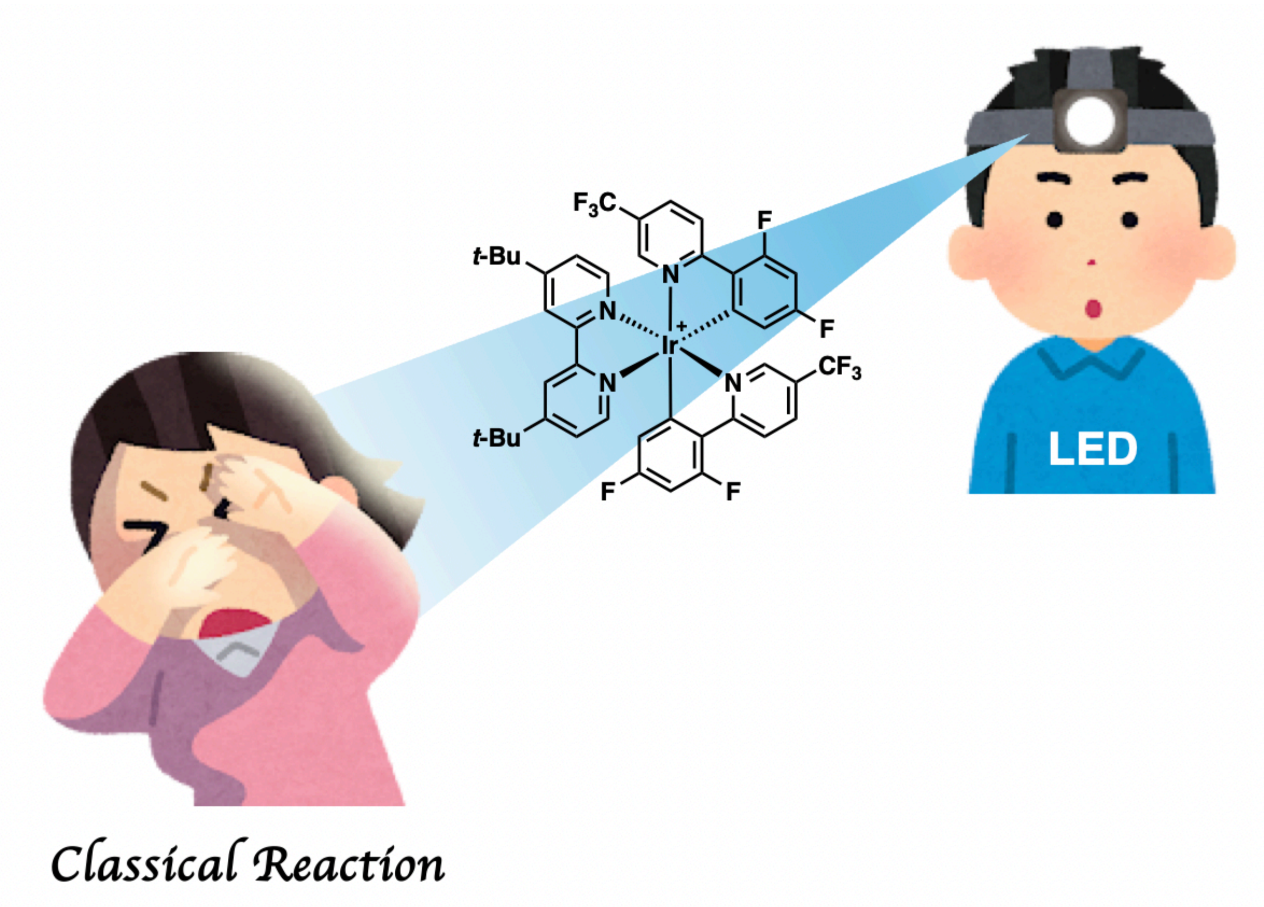
Brightening up "Classical" Reactions by Irradiating Visible Light

（光反応を応用した「古典的」反応の再興）



2024/12/6 (Fri.)
Hayato Akao

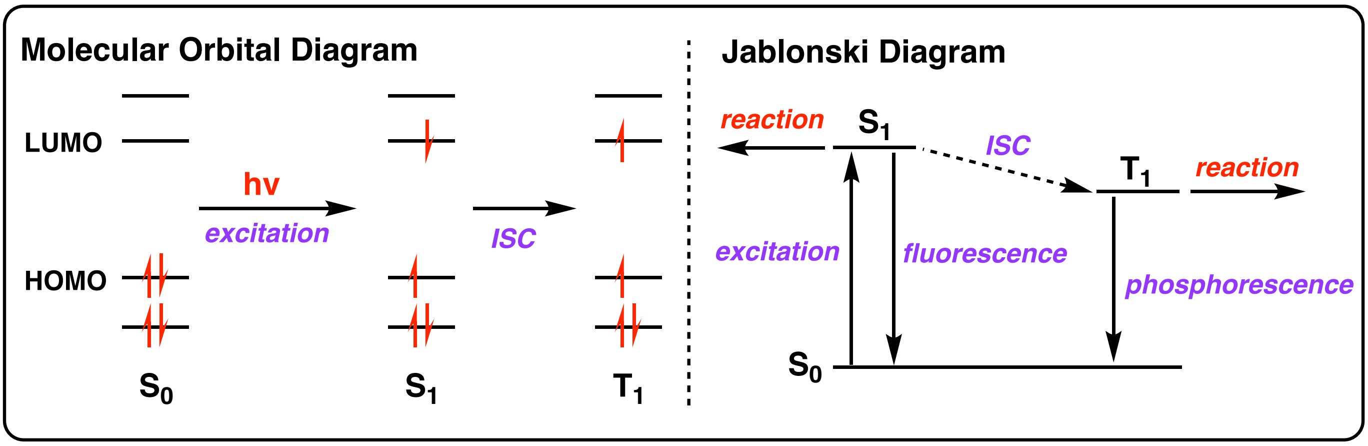
Contents

1. Introduction

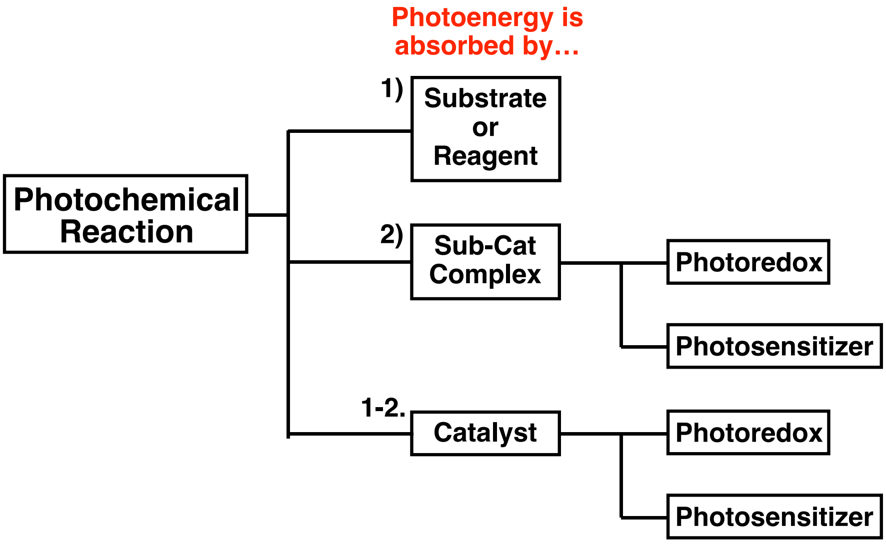
1-1. Photochemical Reaction

Photoreaction = Reaction which starts with light energy.

$$S \xrightarrow{\text{(cat), } h\nu} P$$

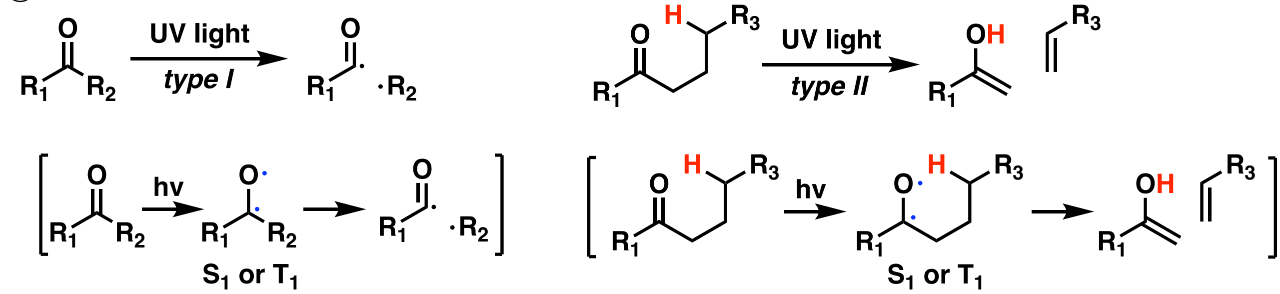


Classification of Photochemical Reaction



Examples of 1) [Photoenergy is absorbed by Substrate (Reagent).]

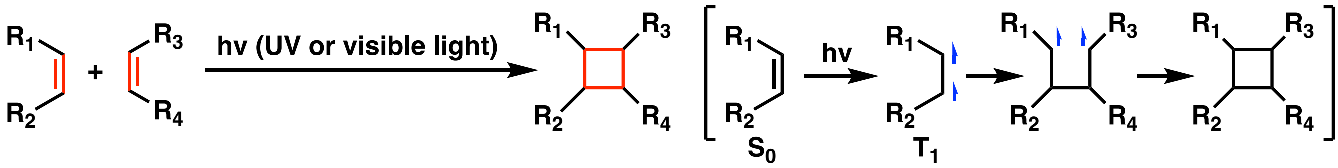
① Norrish reaction[1)2)]



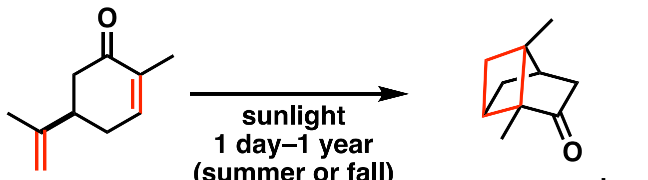
Reference
1) Norrish, R. G. W. et al. *Nature*, **1936**, *138*, 1016.
2) Norrish, R. G. W. et al. *Nature*, **1937**, *140*, 195.

1. Introduction

② (2+2) Photocycloaddition

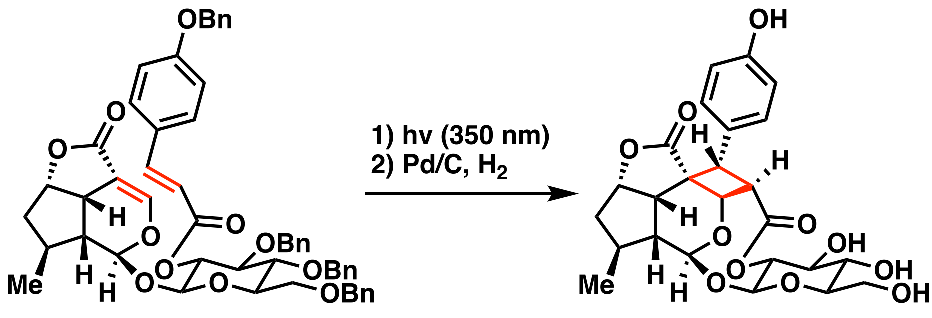


First Report [Ciamician (1908)[3)]]



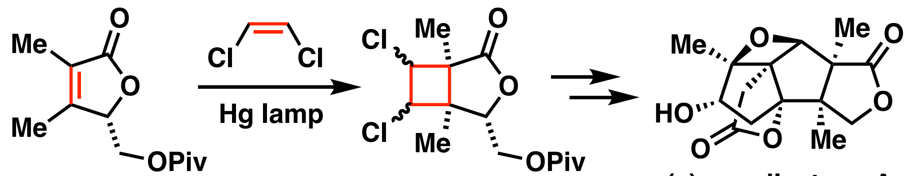
Application to Natural Product Synthesis

MacMillan (2005)[4)]



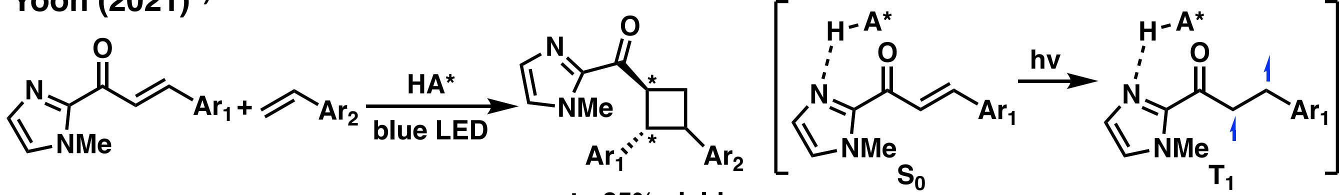
❌ Regioselectivity
❌ Diastereoselectivity
❌ Enantioselectivity

Inoue (2006)[5)]



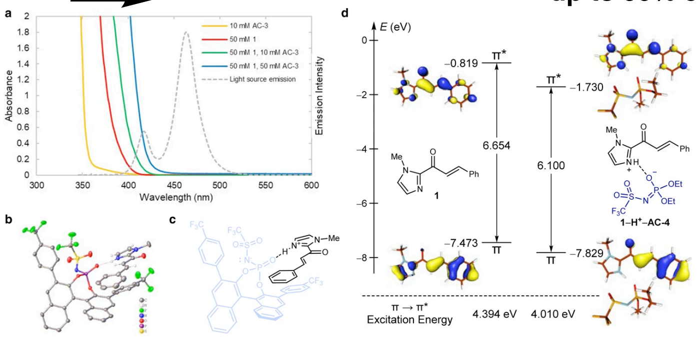
<u>Example of 2)</u> [Photoenergy is absorbed by Sub-Cat complex.]

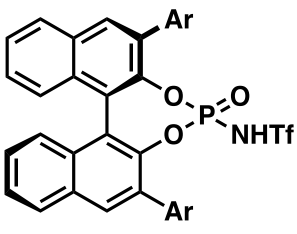
Yoon (2021)[6)]



up to 85% yield
up to 99% ee

bathochromic shift





HA*
Ar = 4-$(CF_3)C_6H_4$

⭕ Regioselectivity
❌ Diastereoselectivity
⭕ Enantioselectivity

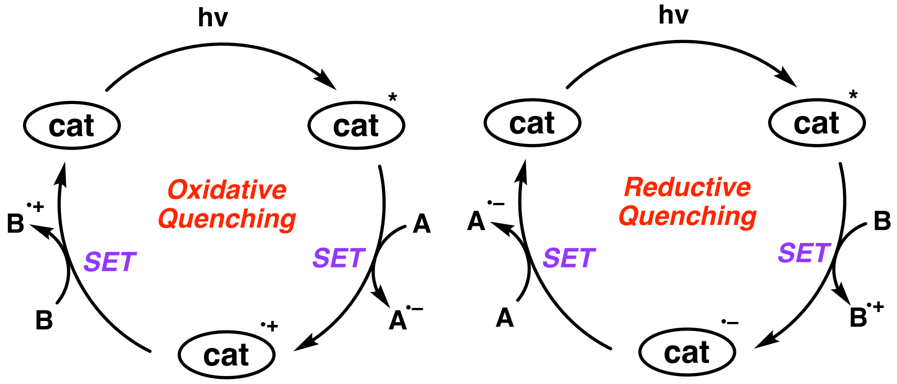
Reference

3) Ciamician, G. et al. *Ber*. **1908**, *41*, 1928.
4) MacMillan. D, W. C. et al. *J. Am. Chem. Soc.* **2005**, *127*, 3696-3697.
5) Inoue, M. et al. *Angew. Chem. Int. Ed.* **2006**, *45*, 4843-4848.
6) Yoon, T. P. et al. *Nat. Commun.* **2021**, *12*, 5735.

1. Introduction

1-2. Photocatalytic Reaction[7]

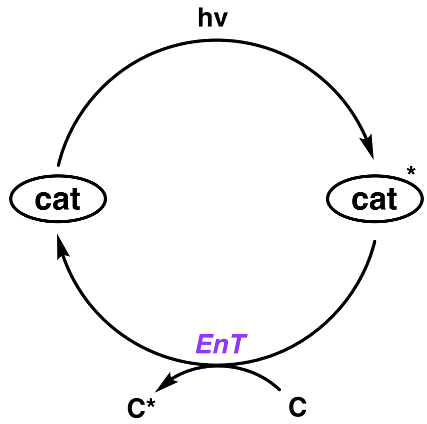
① Photoredox Catalyst



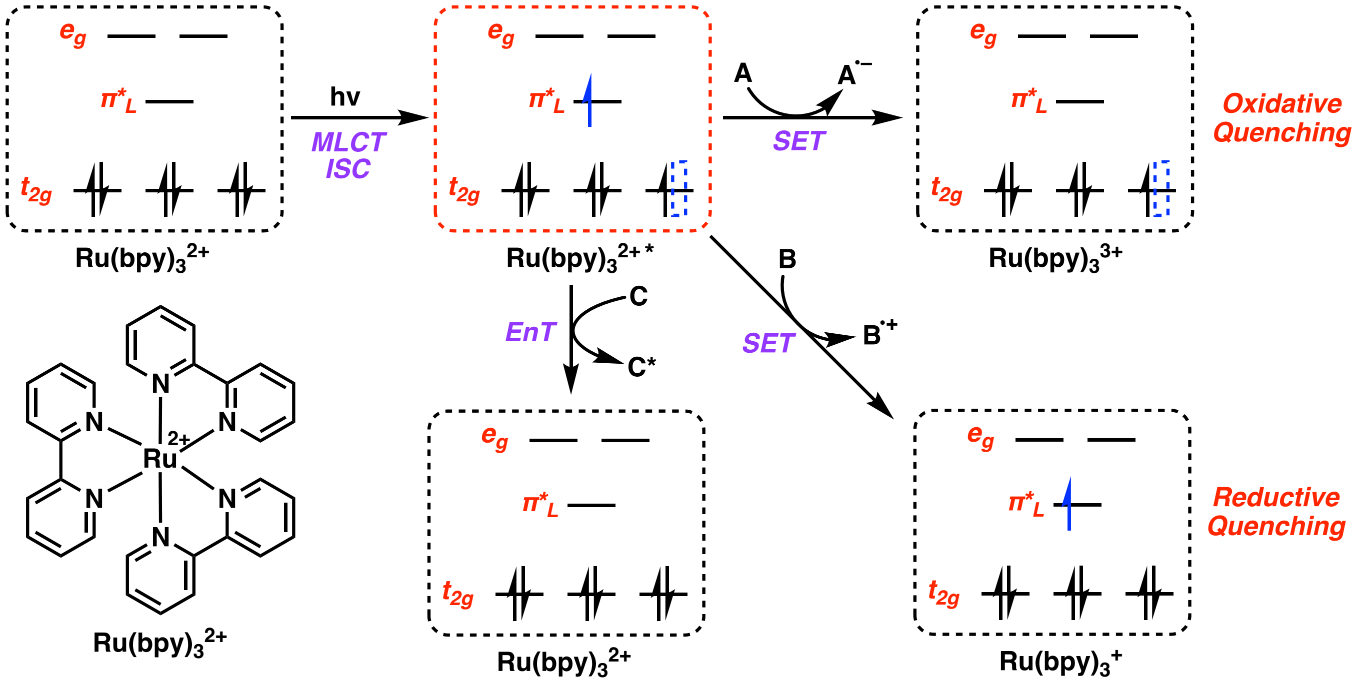
cat is an excited state **reductant**

cat is an excited state **oxidant**

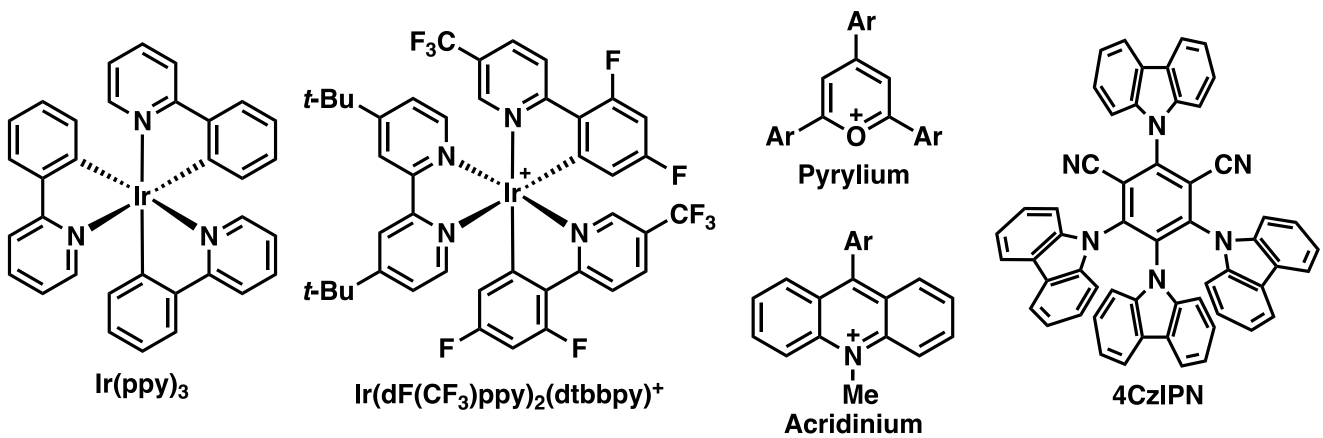
② Photosensitizer



Molecular Orbital Diagram



Examples of Photocatalyst



Refference
7) Nicewicz. D. A. et al. *Chem. Rev.* **2016**, *116*, 10075-10166.

1. Introduction

Photophysical and Electrochemical Properties

Transition Metal Catalysis[8)]

compound	$E_{1/2}$ (C^+/C)/V [a]	$E_{1/2}$ (C^+/C^*)/V [a]	$E_{1/2}$ (C/C^-)/V [a]	$E_{1/2}$ (C^*/C^-)/V [a]	λ_{em}/nm	τ/ns	ref.
$[Ru(bpy)_3]^{2+}$	1.29[b]	−0.81	−1.33[b]	0.77	615[b]	930[b]	[9]
$[Ir(ppy)_3]$	0.77[b]	−1.73	−2.19[b]	0.31	510[c]	1.9·10³ [c]	[9]
$[Cu(dap)_2]^+$	0.62[b]	−1.43	–	–	670[c]	270[c]	[20]
$[Cr(L^{tBu})_3]$	0.15[d]	−1.91	–	–	630[d]	2.2 [d]	[32]
$[Mo(L^{Me})_3]$	−0.02[d]	−2.2	–	–	597[f]	225[f]	[33,34]
$[Mo(L^{tBu})_3]$	−0.08[d]	−2.3	–	–	585[f]	1040, 2370[f]	[34]
$[Cr(ddpd)_2]^{3+}$	–	–	−0.73[b]	0.87	775[g]	898 · 10³ [g]	[47]
$[Cr(dpq)_2]^{3+}$	–	–	−0.39[b]	–	724, 747[g]	1.2 · 10⁶ [g]	[51]
$[Cr(tpe)_2]^{3+}$	–	–	−0.50[b]	1.25	748[h]	4.5 · 10⁶ [h]	[52]
$[Re(L^{Me})_3]^+$	1.36[b]	−1.6	–	–	480[b]	8[b]	[56]
$[Re(phen)(CO)_3(L^1)]$	1.09[b]	–	–	–	571[c]	740[c]	[120]
$[Re(NHC\text{–}py)(CO)_3(Cl)]$	0.99[b]	–	–	–	522[c,e]	140[c]	[65,121]
$[Re(NHC\text{–}qu)(CO)_3(Cl)]$	1.27[b]	–	–	–	494[c]	5[c]	[65,122]
$[Ir(ppy)_2(NacNac^{NMe2})]$	0.14[b]	−2.2	−2.3[b]	–	634[b]	760[b]	[71,72]
$[Ir(sppy)_3]$	0.77[g]	−1.89	–	–	508[g]	1.6 · 10³ [g]	[73,75]
$[Pt(NHC\text{-}ArO\text{-}cbz^H)]$	–	–	–	–	446[i]	6.1 · 10³ [i]	[77]
$[Pt(NHC\text{-}ArO\text{-}cbz^{tBu})]$	0.85[i]	−2.13	−2.56[i]	–	447[i]	6.7 · 10³ [i]	[77]
[Pt(S–quinoline)(Cl)(dmso)]	1.25[b]	−1.22	−1.35[b]	1.12	~540[b]	–	[86]
[Pt(O–quinoline)(Cl)(dmso)]	1.58[b]	−1.29	−1.43[b]	1.42	~490, ~530[b]	–	[86]
$[Ce(Cl)_6]^{3-}$	0.41[b]	−3.07	–	–	356, 387[b]	22.1[b]	[88]
$[Ce(guanidinate^{iPr})_3]$	0.16[c]	−2.54	–	–	459[j]	83[j]	[92]
$[Ce(guanidinate^{iPr})(amide)_2]$	0.47[c]	−1.92	–	–	518[j]	56[j]	[92]

Organocatalysis[7)]

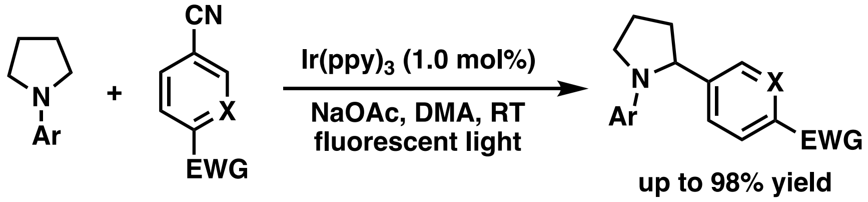
					excited state energies (eV)		ground state redox potentials (V vs SCE)		excited state redox potentials (V vs SCE): S_1		excited state redox potentials (V vs SCE): T_1	
abbreviation	λ_{max}^{abs}(nm)	τ_f(ns)	ϕ_f	ϕ_{ISC}	$E_{0,0}^{S_1}$	$E_{0,0}^{T_1}$ [a]	$E_{1/2}^{red}$	$E_{1/2}^{ox}$	$E_{red}^{S_1}$	$E_{ox}^{S_1}$	$E_{red}^{T_1}$	$E_{ox}^{T_1}$
DCB	290[21]	9.7[22]			4.01[22]	3.04[23]	−1.46[22]		+2.55[22]		+1.58[b,22,23]	
DCN	325[24]	10.3[25]			3.57[25]	2.41[23]	−1.27[25]		+2.3[b,25]		+1.14[b,25,23]	
DCA	422[26]	14.9[25]	0.76[c,27]	0.0085[28]	2.90[25]	1.81[27]	−0.91[25]		+1.99[b,25]		+0.9[b,25,27]	
BP	335[d,29]	0.008[30]		1.0[31]	3.22[30]	3.0[30]	−1.72[31]	+2.39[31]	+1.5[b,31,30]	−0.83[b,31,30]	+1.28[b,31,30]	−0.61[b,31,30]
MK	365[e,32]				2.98[e,32]	2.7[30]	−2.20[f,34]	+0.86[35]	+0.76[b,34,32]	−2.12[b,35,32]	+0.48[b,34,30]	−1.84[b,35,30]
FLN	377[36]	16.2[31]		0.97[31]		2.31[31]	−1.35[31]	+1.7[31]			+0.96[b,31]	−0.61[b,31]
XO	340[37]	<0.0[31]		1.0[31]	3.4[30]	3.22[30]	−1.65[31]	+1.8[31]	+1.76[b,31,30]	−1.61[b,31,30]	+1.57[b,31,30]	−1.42[b,31,30]
TXO	360[38]	2[31]		0.99[31]	3.14[30]	2.8[30]	−1.62[31]	+1.69[31]	+1.52[b,31,30]	−1.45[b,31,30]	+1.18[b,31,30]	−1.11[b,31,30]
TCBQ	450[39]			1.0[40]		2.46[41]	0.00[42]				+2.46[b,42,41]	
DDQ	~400[43]			1.0[44]		2.67[43]	+0.49[42]				+3.18[43]	
AQ	326[e,45]			1.04[46]		2.73[46,47]	−0.96[42]				+1.77[b,42,46]	
TPT^+	415[g,48]	4.38[25]	0.58[g,48]	0.42[48]	2.83[25]	2.3[h,49]	−0.32[25]		+2.55[b,48,25]		+2.02[b,48,49]	
p-$OMeTPT^+$	422,470[h,50]	4.0[9]	0.95[9] 0.49[51]	0.03[52]	2.34[i,50]	2.21[h,49]	−0.50[j,50]		+1.84[b,50]		+1.71[b,50,49]	
$TTPP^+$	414[50]	3.6[g,54]	0.03[54]	0.94[52]	2.64[i,50]	2.28[55]	−0.19[j,50]		+2.45[b,50]		+2.09[b,50,55]	
p-$OMeTTPP^+$	455[50]				2.23[i,50]		−0.33[j,50]		+1.9[b,50]			
NMQ+	315[56]	20[57]	0.79[k,58]		3.50[22]		−0.85[59]		+2.70[59]			
QuCN+	329[60]	45[61]			3.32[22]		−0.60[62] −0.79[63]		+2.72[61]			
Acr-Me+		37,[57] 34[25]	1.0[l,64]		2.80[25]		−0.46[25]		+2.32[65]			
Ph-Acr-Me+	424[66]	1.5[66]	0.063[66]				−0.54[m,67]					
Mes-Acr-Me+	425[68]	6[69]	0.035[69] 0.08[n,70]	0.38[69]	LE: 2.67[69] CT: 2.57[69]	LE: 1.94[69]	−0.49[68] −0.57[71]		LE: +2.18[69] CT: +2.08[69]		LE: +1.45[69] CT: +1.88[72]	
AO	425[73]					2.58[73]	−2.4[73]				+0.60[o,73]	
AOH^+	495[73]	1.8[75]	0.18[l,76]		2.58[d,77] 2.43[p,78]	2.07[77] 2.13[p,78]	−1.18[o,73]				+0.95[o,73]	
$AcrF^+$	470[p,78]		0.54[l,64]		2.56[p,78]	2.22[p,78]						
PF	393[l,79]											
PFH^+	470[p,78]	~5[l,80]	0.39[l,76]	0.10[l,81]	2.56[p,78]	2.22[p,78]	−0.74[l,79]		+1.82[b,79,78]		+1.48[b,79,78]	
PTh	<300[82]	0.81-2.3[82]			2.8[q,83]	2.4[83]		+0.68[83]		−2.1[83]		−1.7[b,83]
MB^+	650[r,84] 664[l,85]	1.0[s,86] 0.6[d,87,88]		0.52[e,89]	1.89[88]	1.50[88] 1.85[77]	−0.30[d,f,77]	+1.13[d,f,77]	+1.56[d,f,77]	−0.73[d,f,77]	+1.60[d,f,77] +1.14[b,77,88]	−0.68[d,f,77] −0.33[b,77,88]
[FL][t,u]	FLH_2:437[l,93] FL^{2-}: 491[l,93]	4.2[d,90] 4.73[d,77]	FLH_2: 0.2[93] FL^{2-}: 0.93[93]	0.03[77]	2.42[d,77]	1.94[77]	−1.17[d,f,77] −1.22[d,f,90]	+0.87[d,f,77] +0.83[d,f,90]	+1.25[d,f,77]	−1.55[d,f,77]	+0.77[d,f,77]	−1.07[d,f,77]
[EY][u,t]	520[d,90] 533[e,91]	2.1[d,90] 2.66[d,77]	0.48[d,77] 0.19[v,64]	0.32[d,77]	2.31[d,90]	1.91[77]	−1.08[d,f,77] −1.13[d,f,90]	+0.76[d,f,77] +0.72[d,f,90]	+1.23[d,f,77]	−1.58[d,f,77]	+0.83[d,f,77]	−1.15[d,f,,77]
[RB][u,t]	549[92]	0.50[77]	0.09[d,77]	0.77[d,77]	2.17[d,77]	1.8[77]	−0.99[d,f,77] −0.78[94]	+0.84[d,f,77]	+1.18[d,f,77]	−1.33[d,f,77]	+0.81[d,f,77]	−0.96[d,f,77]
[RhB]	550[l,95]	2.45[d,,77]	0.58[d,77] 0.97[e,64]	0.12[d,77] 0.0024[95]	2.22[d,77]	1.80[77]	−0.96[d,f,77]	+0.91[d,f,77]	+1.26[d,f,77]	−1.31[d,f,77]	+0.84[d,f,77]	−0.89[d,f,77]
[Rh6G]	530[e,96]	4.13[d,97]	0.90[l,98]	0.002[99]	2.32[100]	2.09[99]	−1.14[f,100]	+1.23[102]	+1.18[f,100]	−1.09[b,100,102]	+0.95[b,99,100]	−0.86[b,99,102]

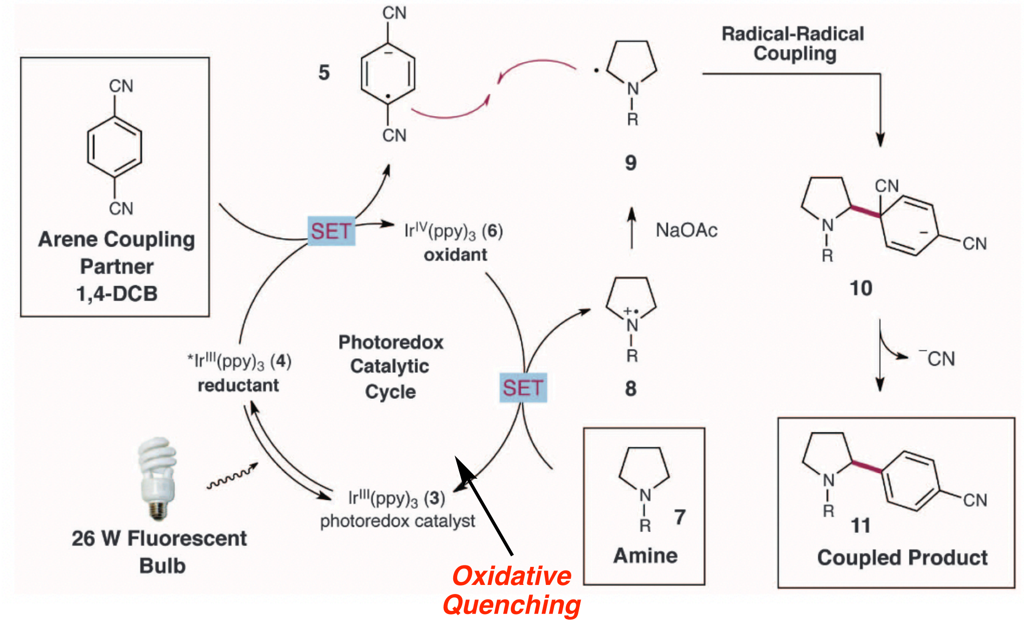
Reference

8) Wenger, O. S. et al. *Coord. Chem. Rev.* **2020**, *405*, 213129.

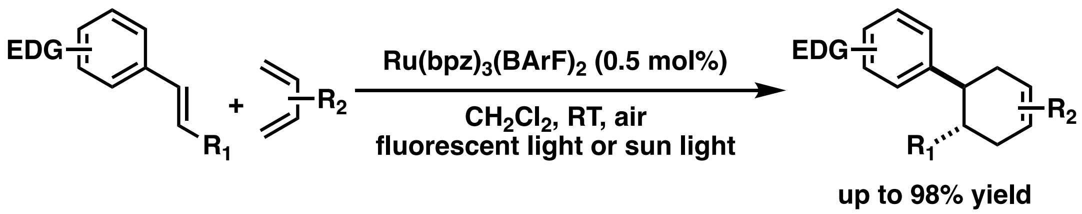
1. Introduction

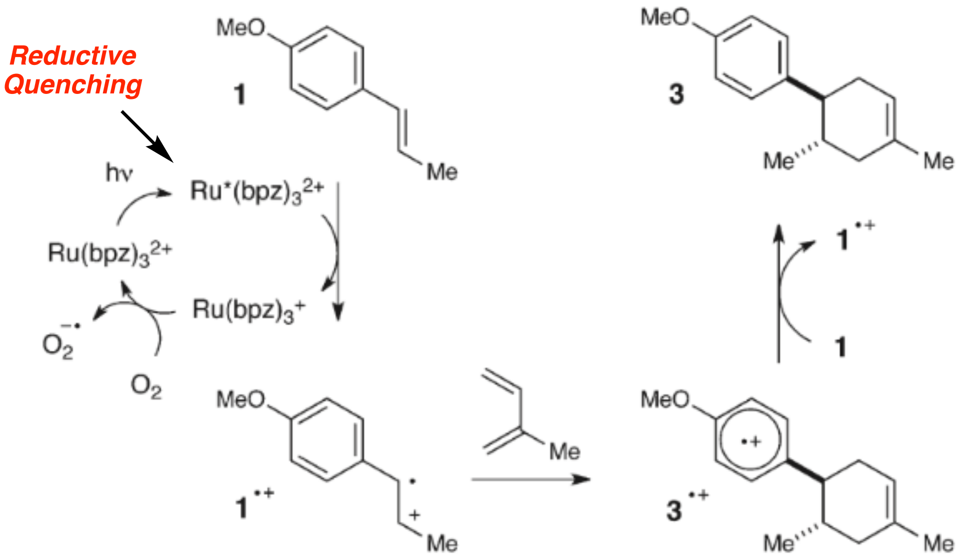
Example 1. α-Amino C-H Arylation [MacMillan (2011)[9]]





Example 2. Radical Cation (4+2) Cycloaddition [Yoon (2011)[10]]



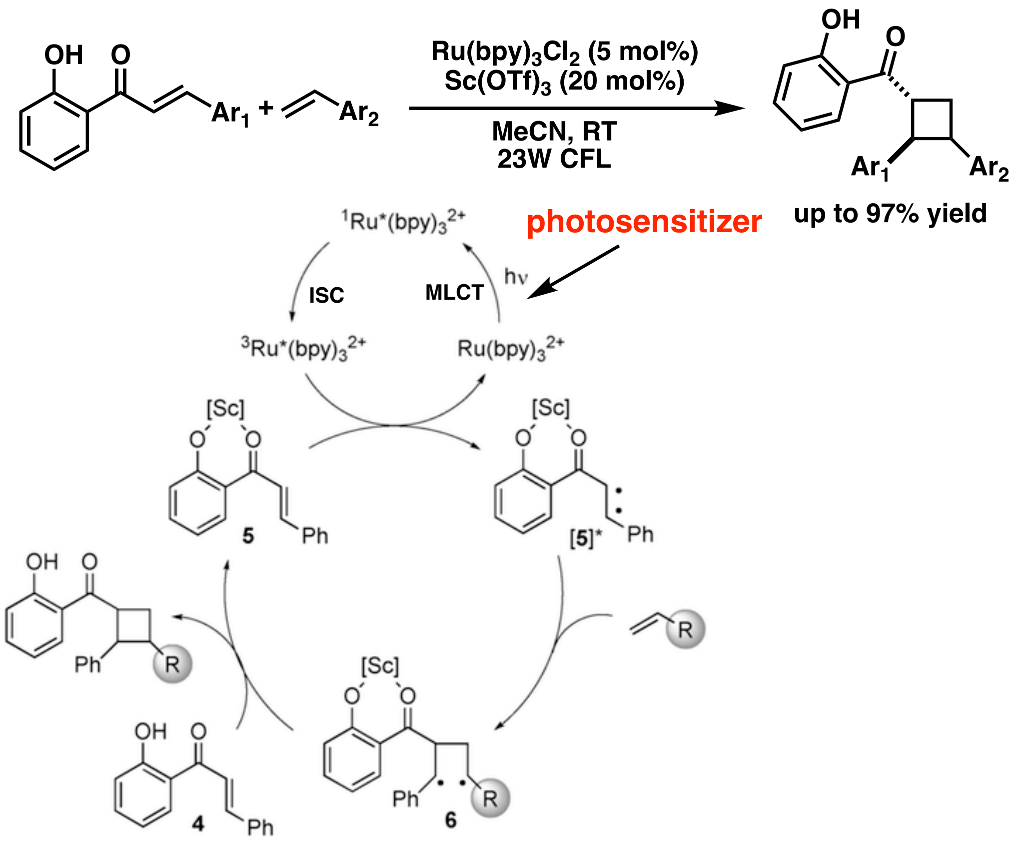


Reference

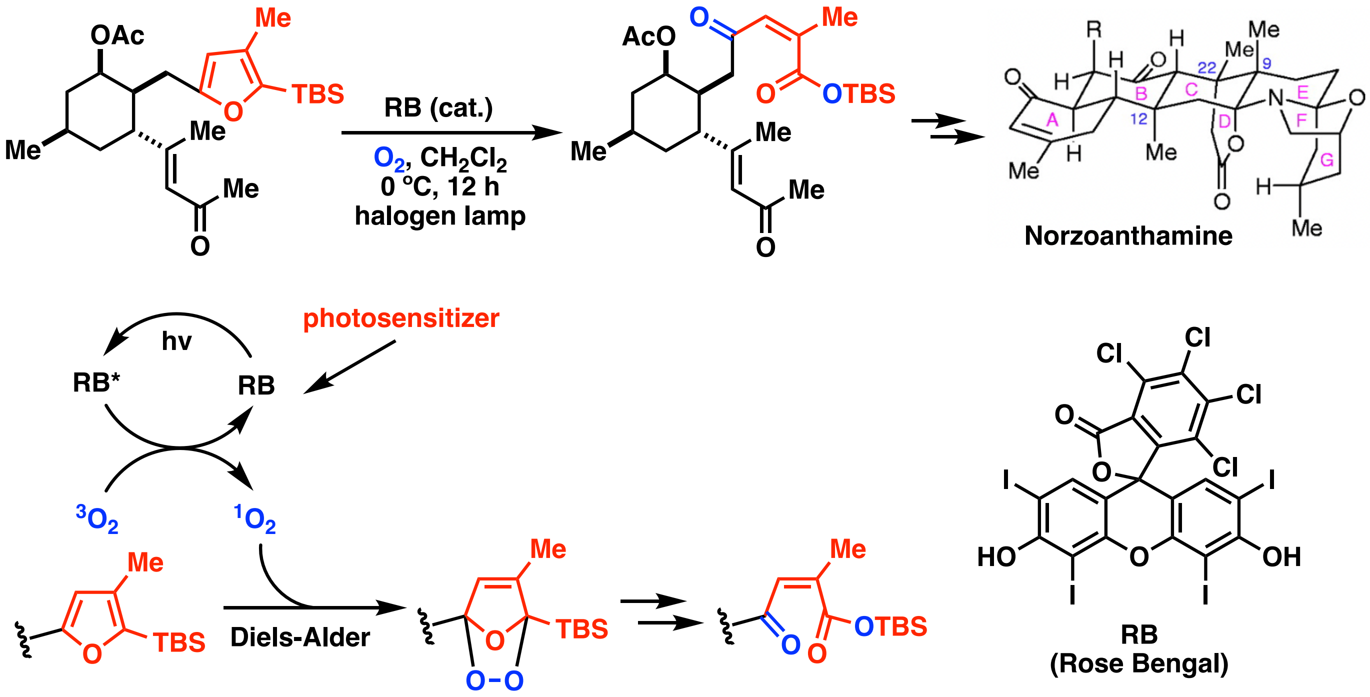
9) MacMillan, D. W. C. et al. *Science.* **2011**, *334*, 1114-1117.
10) Yoon, T. P. et al. *J. Am. Chem. Soc.* **2011**, *133*, 19350-19353.

1. Introduction

Example 3. (2+2) Photocycloaddition [Yoon (2017)[11)]]



Example 4. Singlet Oxygen [Tanino (2004)[12)]]



Reference

11) Yoon, T. P. et al. *Angew. Chem. Int. Ed.* **2017**, *56*, 11891-11895.

12) Tanino, K. et. al. *Science* **2004**, *305*, 495.

1. Introduction

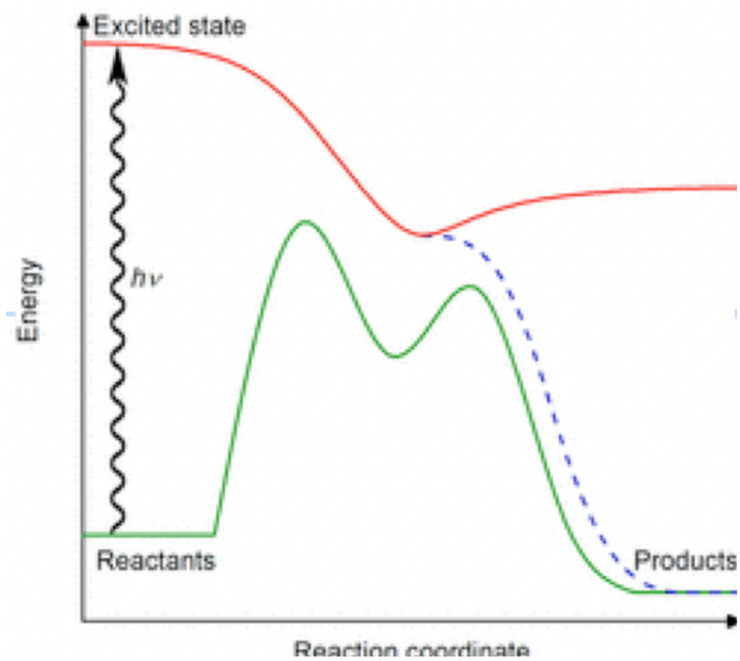
1-3. Application of Photochemistry to "Classical" Reaction

"Classical" Reaction × **Photo Chemistry** ⇨

Environmentally Friendly
- Reduce Waste
- Don't Use Toxic Reagent

Mild Condition
- Higher Chemoselectivity
- Broaden Scope
- Natural Product Synthesis
- Late Stage Functionalization

❌ Stoichiomeric Waste
❌ Use of Toxic Reagent
❌ Harsh Condition
❌ Low Chemoselectivity

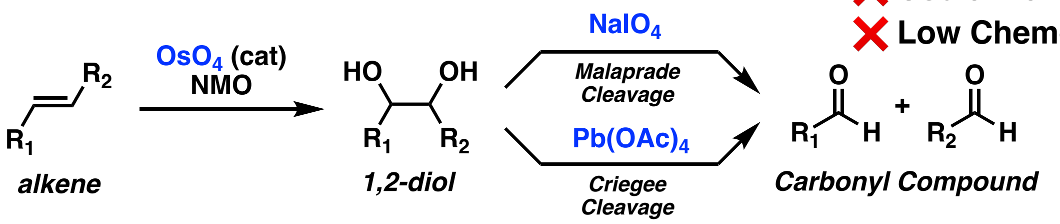


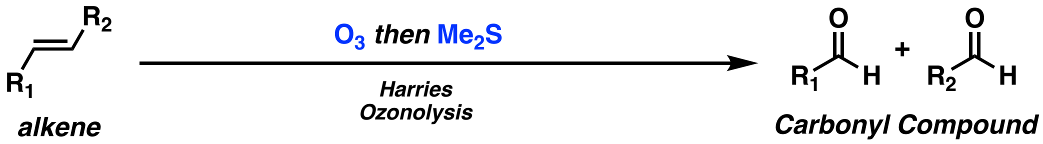
	"Classical"		Photochemical
Topic 1. Oxidative Cleavage 1,2-Dihydroxydation	O_3, OsO_4	⇨	$ArNO_2$ + purple LED
Topic 2. Decarboxylation	$Pb(OAc)_4$ (stoichiometric)	⇨	$[Ir^{III}]$, $[Cu^{II}]$, $[Fe^{III}]$ + blue LEDs (catalytic)
Topic 3. Nucleophilic Addition	[Cr] + Mn^0 ↑ (stoichiometric)	⇨	[Cr] + $[Ir^{III}]$ + HE + blue LEDs ↑ (catalytic) ↑ (stoichiometric)
Topic 4. Pinacol Coupling	SmI_2 (stoichiometric)	⇨	SmI_2 (catalytic) + ligand + blue LEDs
Topic 5. Proposal	?	⇨	???

2. Oxidative Cleavage / 1,2-Dihydroxylation of Alkenes

2-1 "Classical" Reaction

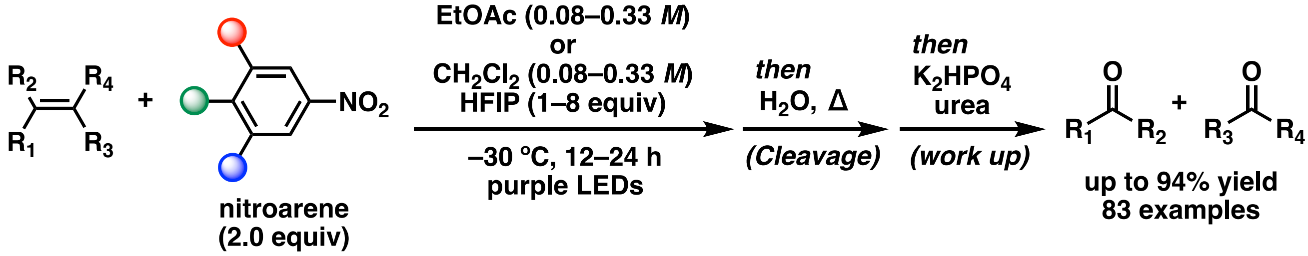
❌ Use of Toxic Reagent
❌ Low Chemoselectivity



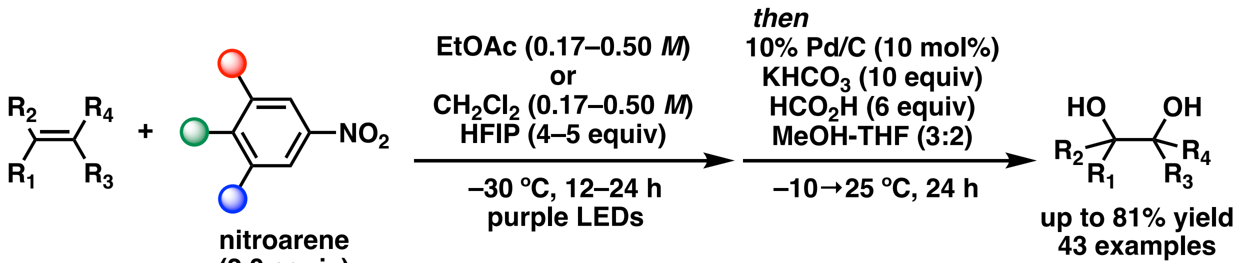


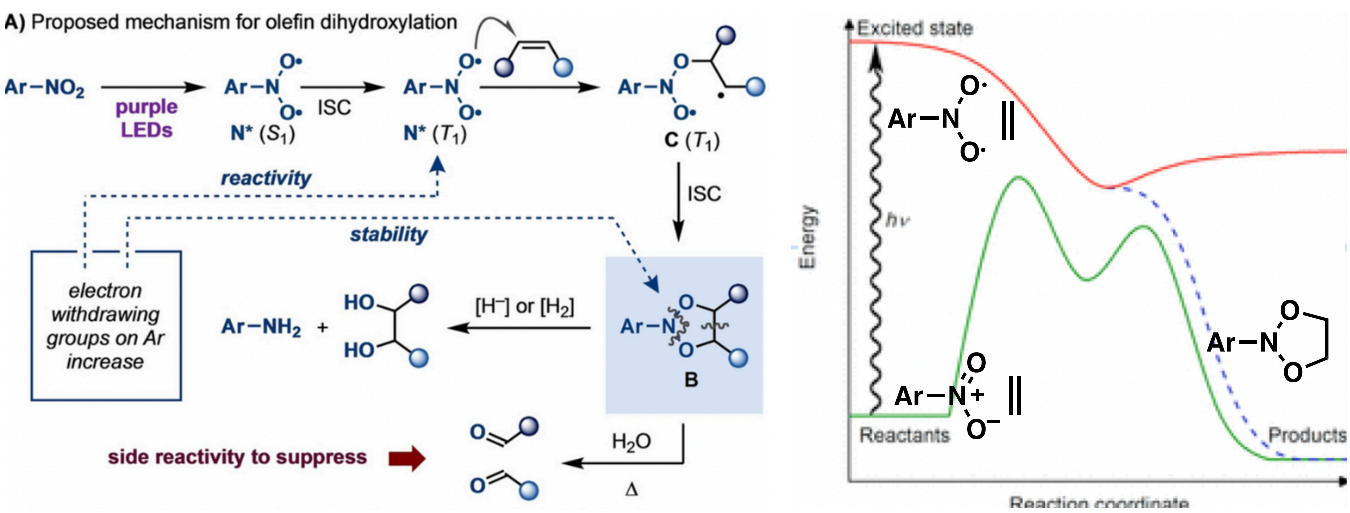
2-2 Photochemical Reaction

Oxidative Clevage of Alkene [Leonori (2022)[13)]]



Dihydroxylation of Alkene [Leonori (2022)[14)]]





Reference

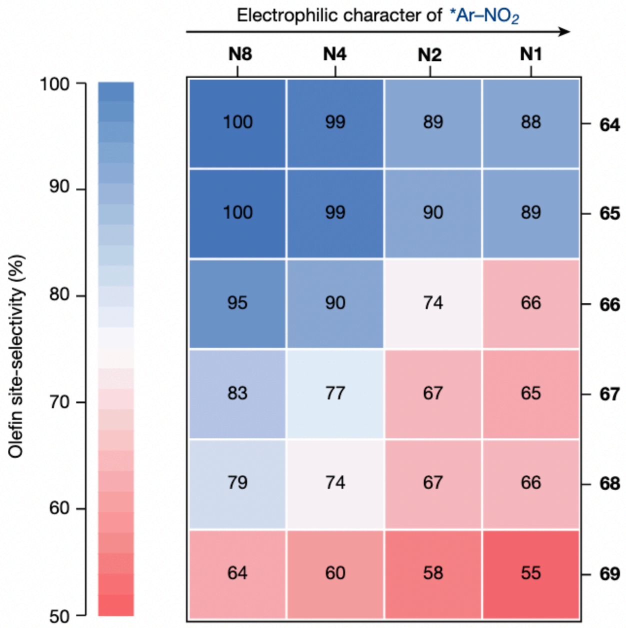
13) Leonori, D. et al. *Nature.* **2022**, *610*, 81-86.

14) Leonori, D. et al. *Angew. Chem. Int. Ed.* **2022**, *62*, e202214508.

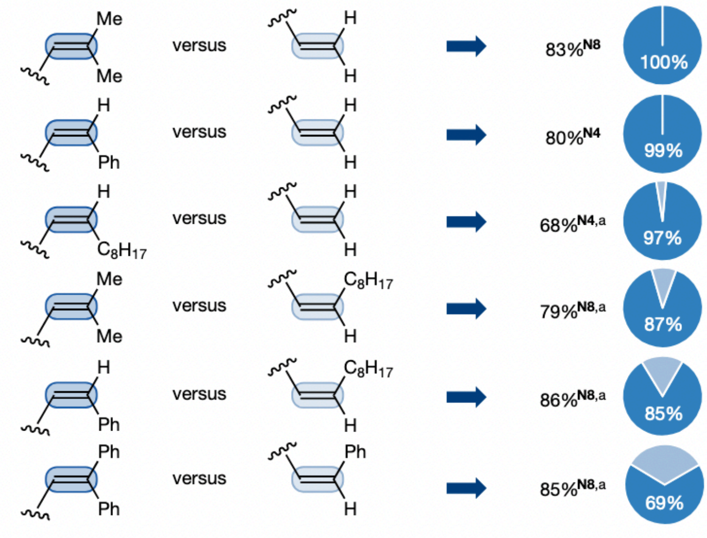
2. Oxidative Cleavage/Dihydroxylation of Alkenes

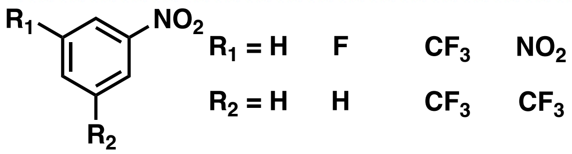
2-2 Overcoming Limitation of Classical Reaction

High Turnability of Nitroarene = Regioselective Oxidative Cleavage



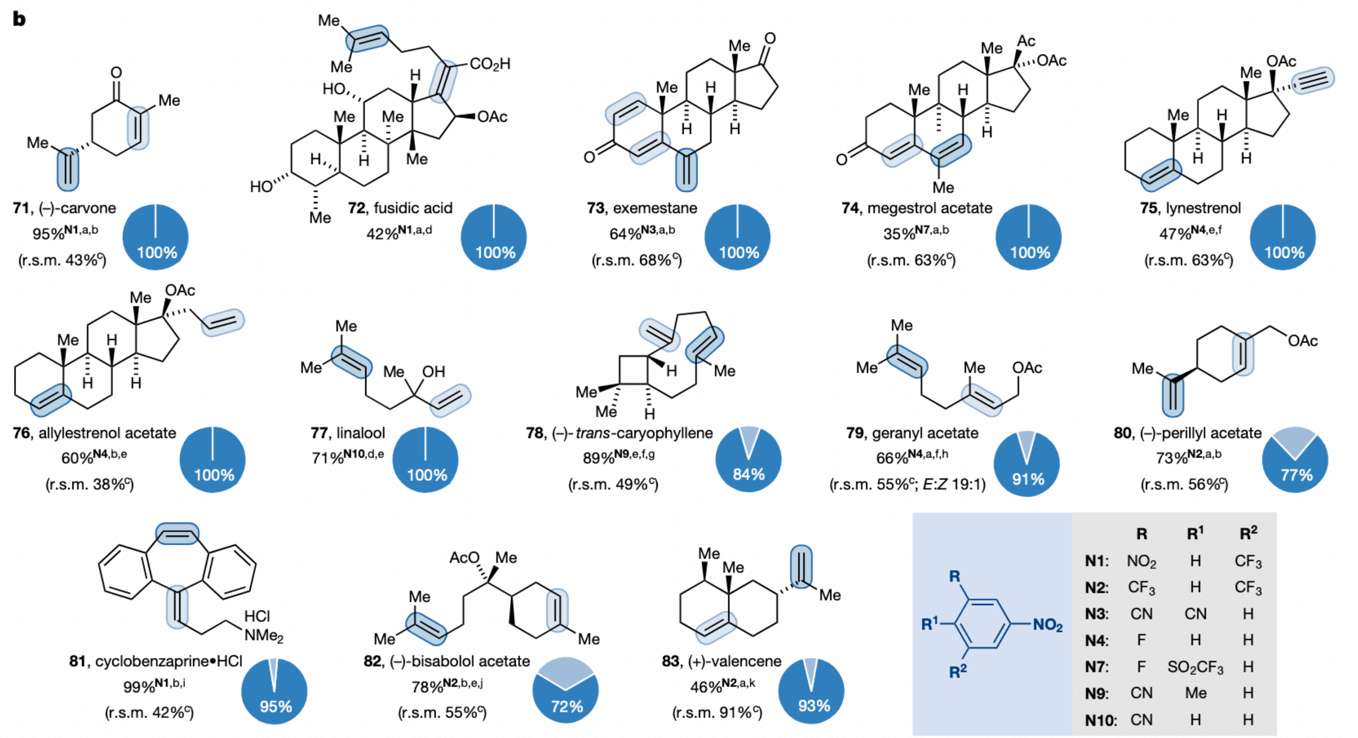
electron rich vs electron poor





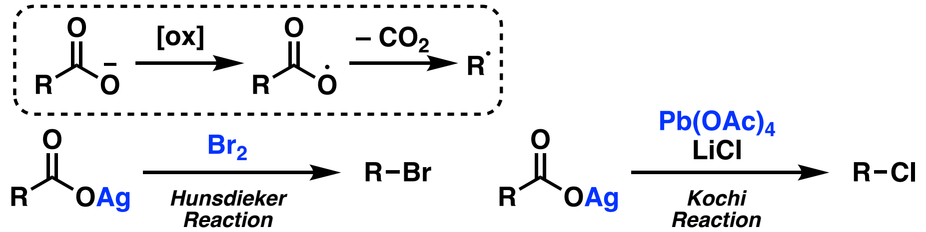
Less electrophilic nitroarene increases regioselectivity.

Oxidative Cleavage of Complex Molecules

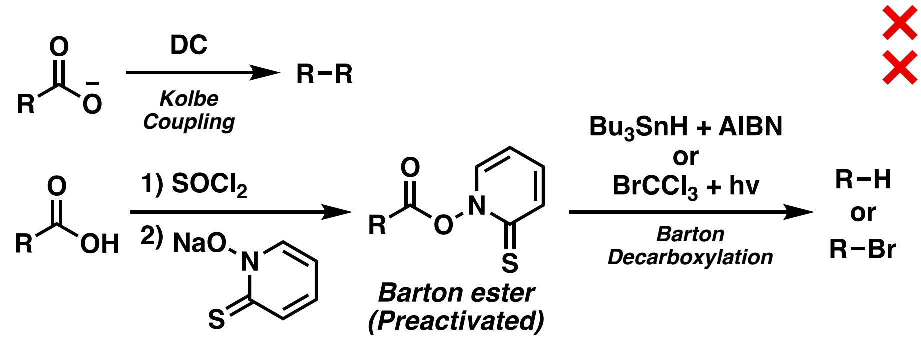


3. Oxidative Decarboxylative Reaction

3-1 "Classical" Reaction

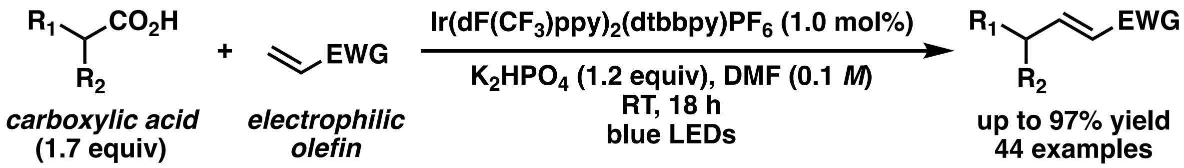


❌ Harsh Condition
❌ Low Chemoselectivity

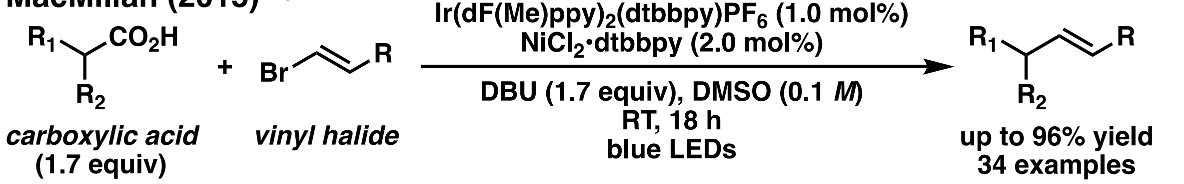


3-2 Photochemical Reaction

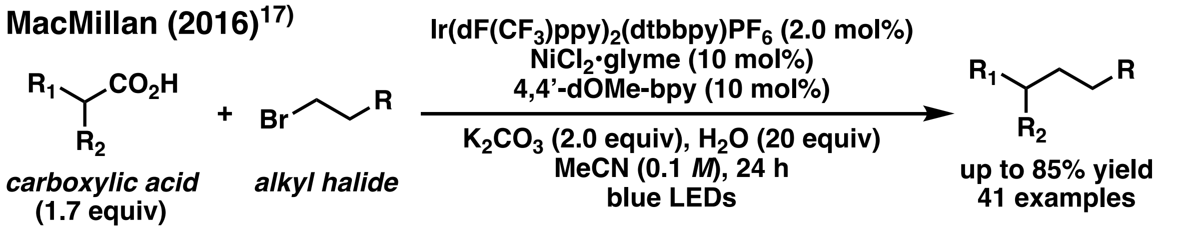
MacMillan (2014)[15]

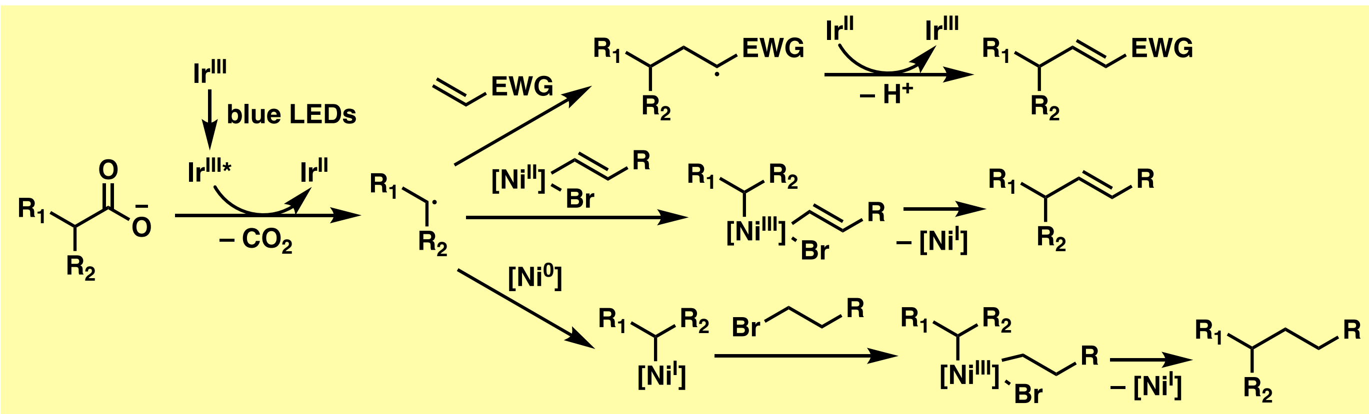


MacMillan (2015)[16]



MacMillan (2016)[17]





Key point : Oxidant is present in Catalytic Amount.

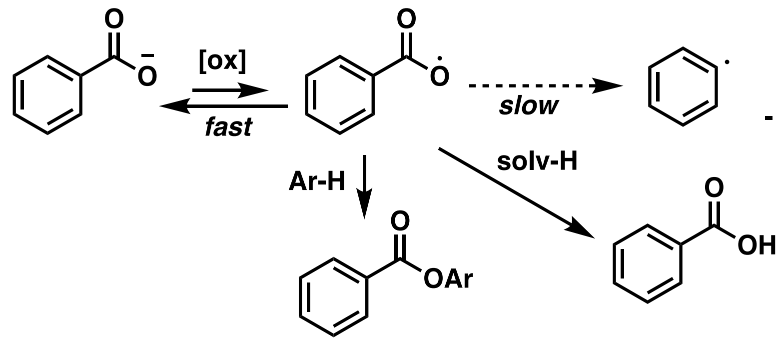
Reference

15) MacMillan, D. W. C. et al. *J. Am. Chem. Soc.* **2014**, *136*, 10886-10889.
16) MacMillan, D. W. C. et al. *J. Am. Chem. Soc.* **2015**, *137*, 624-627.
17) MacMillan, D. W. C. et al. *Nature.* **2016**, *536*, 322-325.

3. Oxidative Decarboxylative Reaction

3-3 Overcoming Limitation : Generation of Aryl Radical (•Ar)

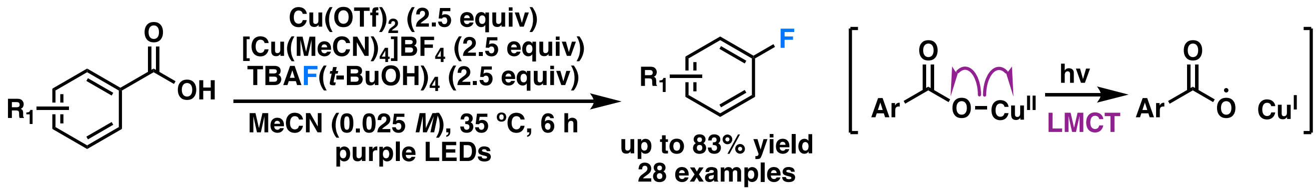
Problem

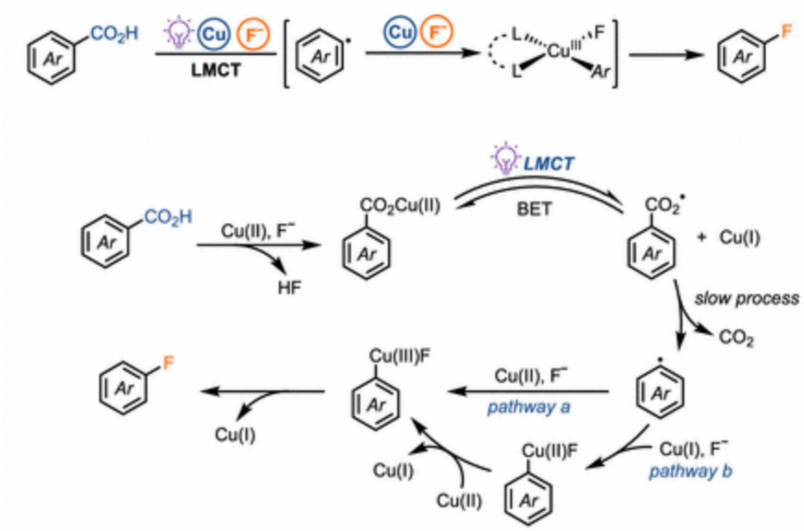


- Slow CO_2 extrusion
  (Undesired side reactions occur.)

Approach. Decarboxylation via Cu-LMCT

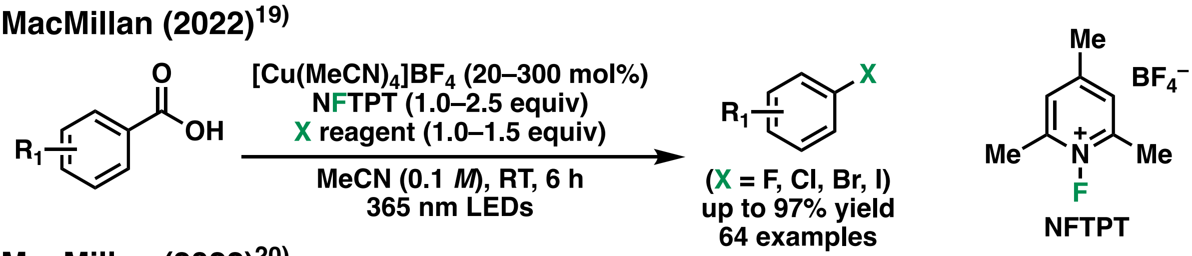
Ritter (2021)[18) : Stoichiometric Reaction



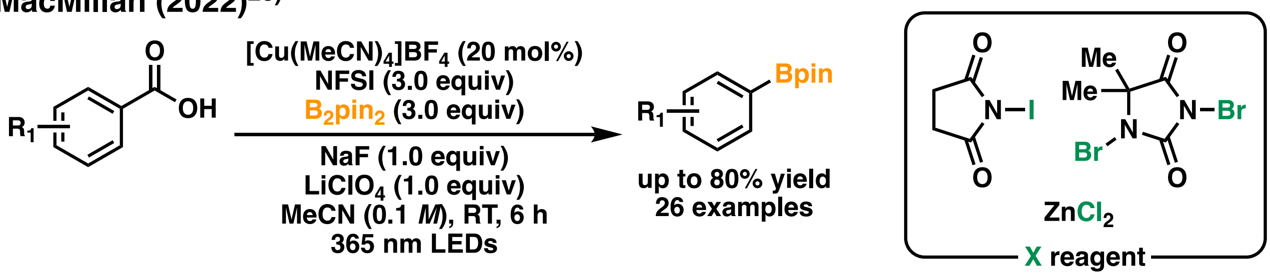


Key point
- Rapid geometric reorganization and ligand exchange of newly formed Cu(I).
  → Suppress BET process.
- $[Cu(MeCN)_4]BF_4$ can trap aryl radical fast.
  → Suppress side reaction.
- MeCN has strong C-H bond.
  → Suppress competitive HAT process.

MacMillan (2022)[19)



MacMillan (2022)[20)

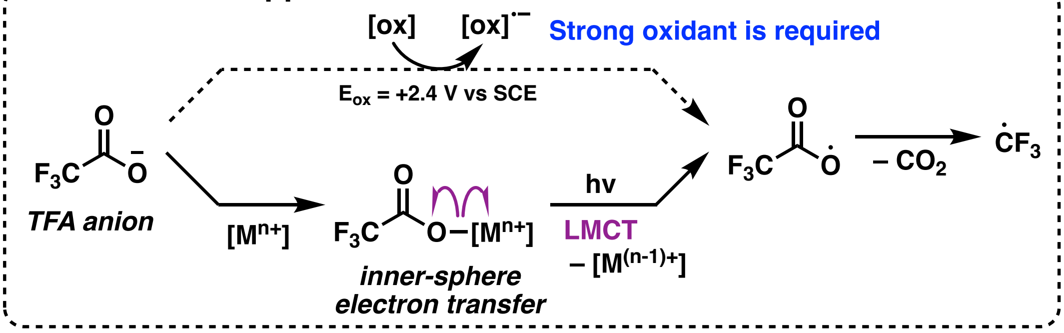


Reference
18) Ritter, T. et al. *J. Am. Chem. Soc.* **2021**, *143*, 5349-5354.
19) MacMillan, D. W. C. et al. *J. Am. Chem. Soc.* **2022**, *144*, 8296-8305.
20) MacMillan, D. W. C. et al. *J. Am. Chem. Soc.* **2022**, *144*, 6163-6172.

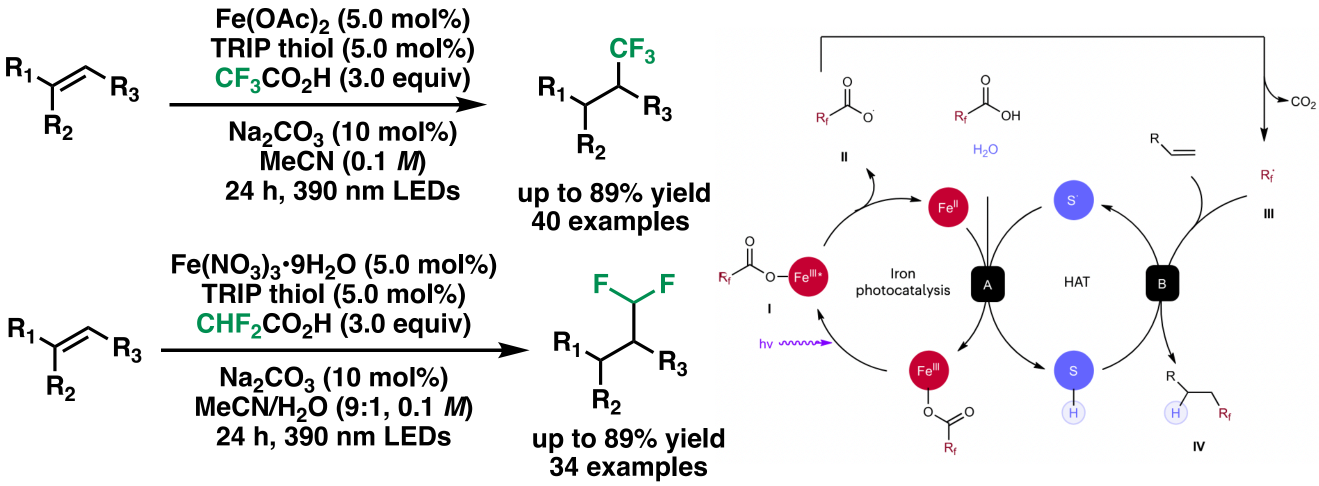
3. Oxidative Decarboxylative Reaction

3-4 Overcoming Limitation : Generation of Trifluoromethyl Radical (·CF_3)

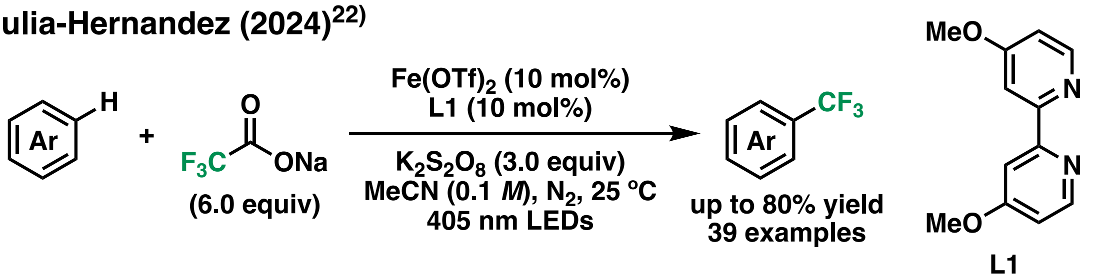
Problem and Approach

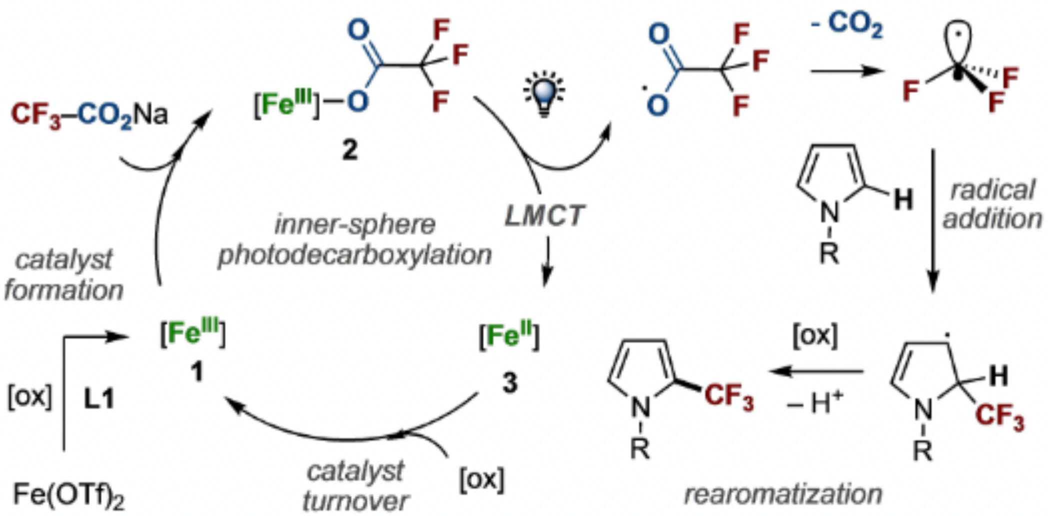


West (2023)[21)]



Julia-Hernandez (2024)[22)]





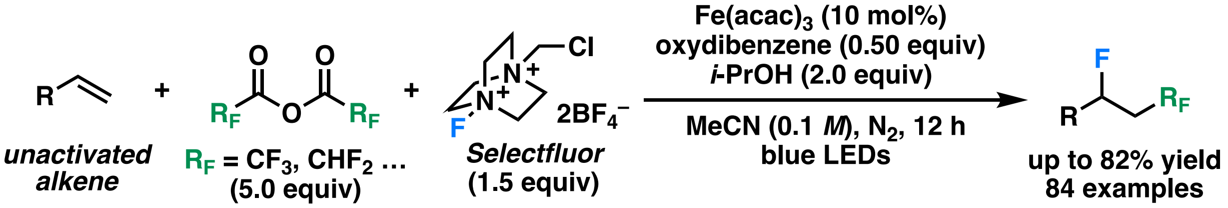
Reference

21) West, J. G. et al. *Nat. Chem.* **2023**, *15*, 1683-1692.

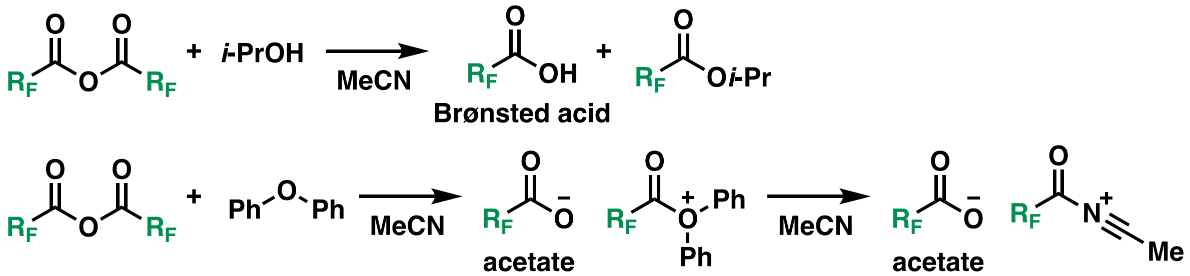
22) Julia-Hernandez, F. et al. *Angew. Chem. Int. Ed.* **2024**, *63*, e202311984.

3. Oxidative Decalboxylative Reaction

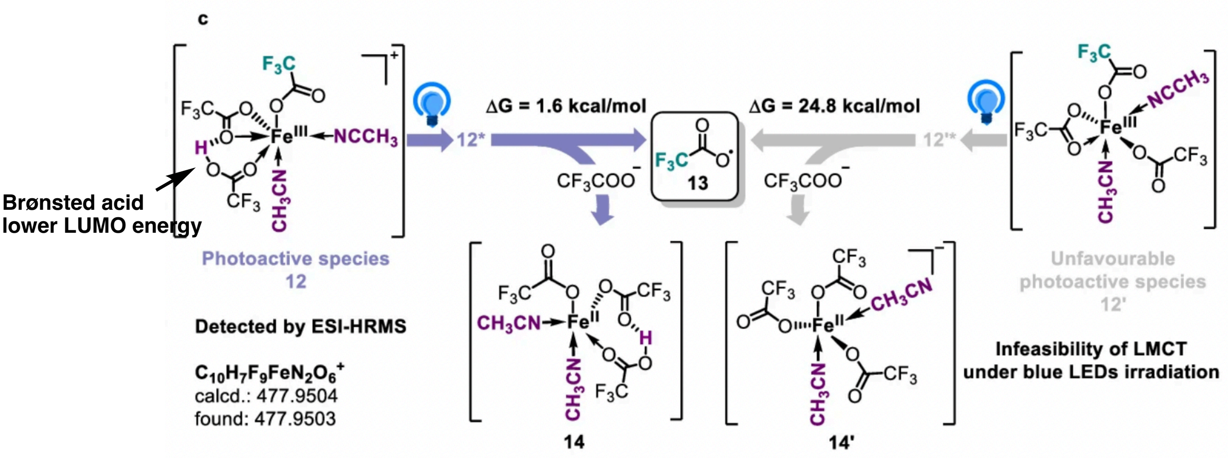
Niu (2024)[23) : Brønsted Acid Unlocked LMCT



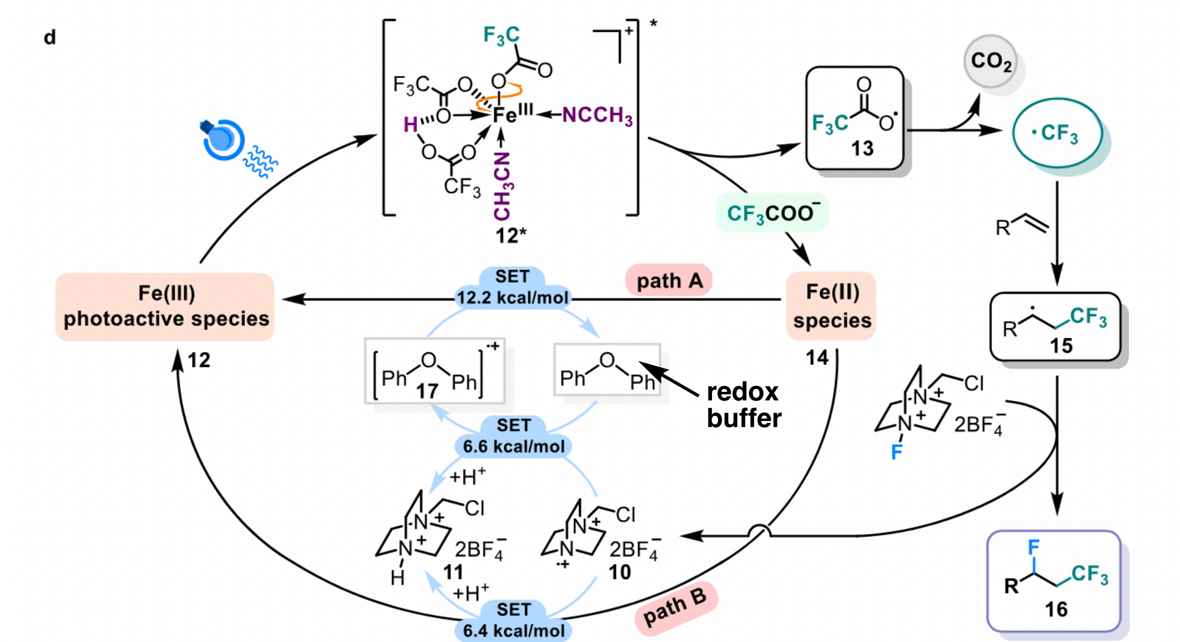
Balanced Construction of $R_FCO_2H + R_FCO_2^-$



Brønsted Acid Unlocked Photoactive Species



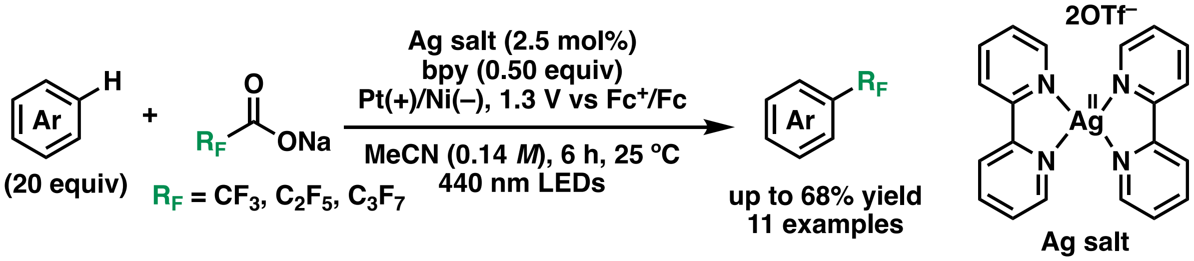
Mechanism



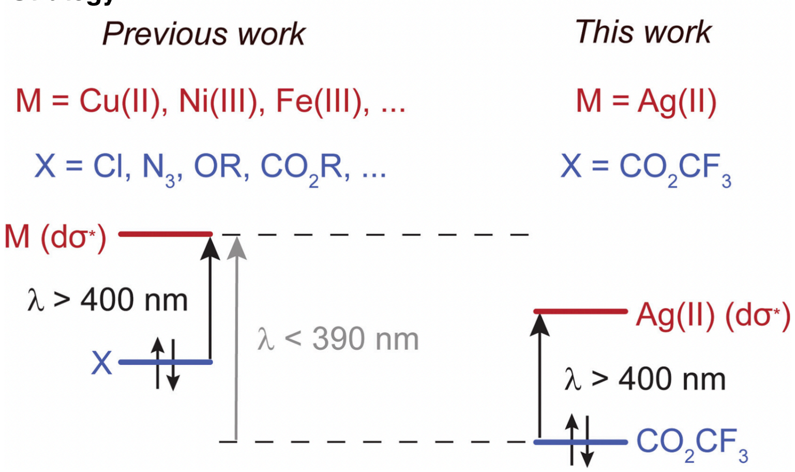
Reference
23) Niu, L. et al. *Nat. Commun.* **2024**, *15*, 6115.

3. Oxidative Decalboxylative Reaction

Nocera (2024)[24) : Ag^{II} catalysis

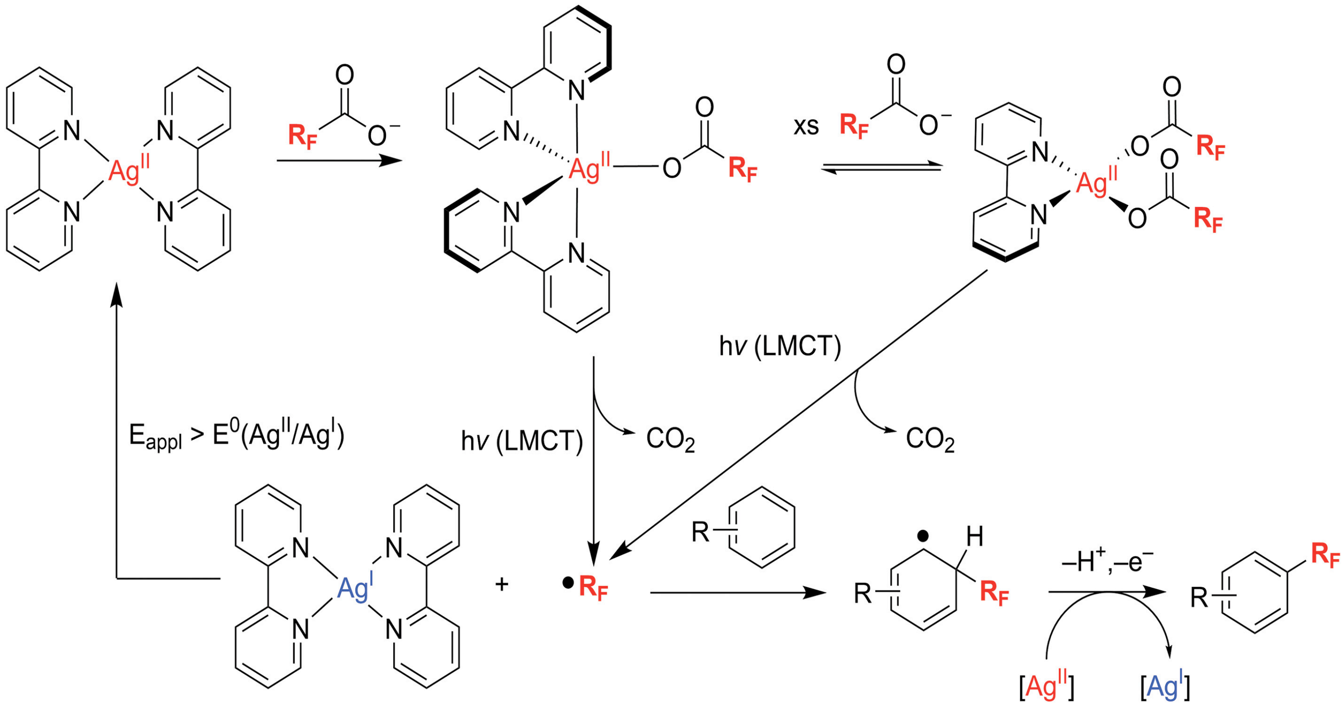


Strategy



Ag^{II} has lower-energy unoccupied orbital.
→ Longer wavelength light can be used.

Mechanism

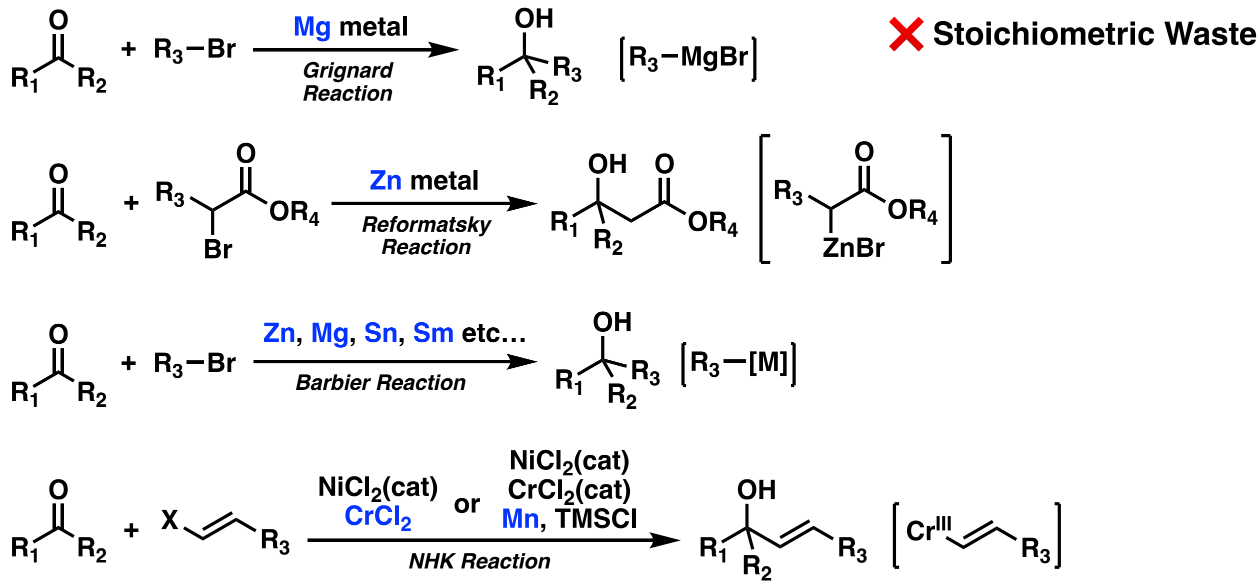


Reference

24) Nocera, D. G. et al. *Science.* **2024**, *383*, 279-284.

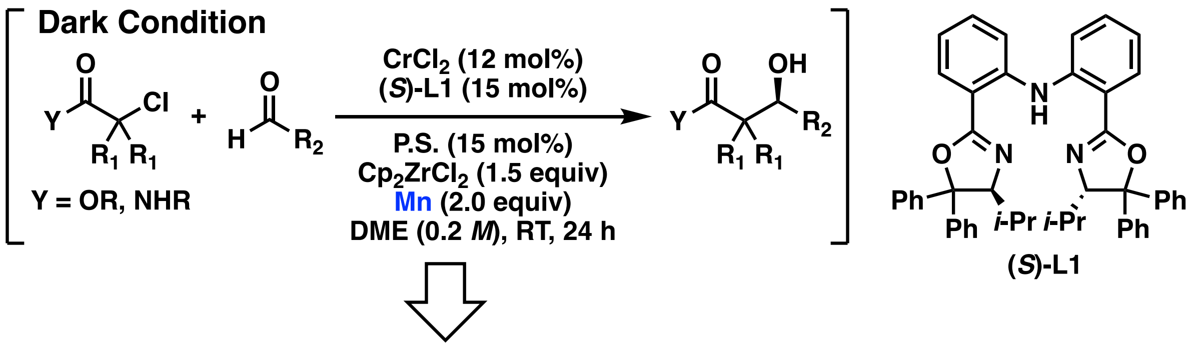
4. Nucleophilic Addition

4-1 "Classical" Reaction

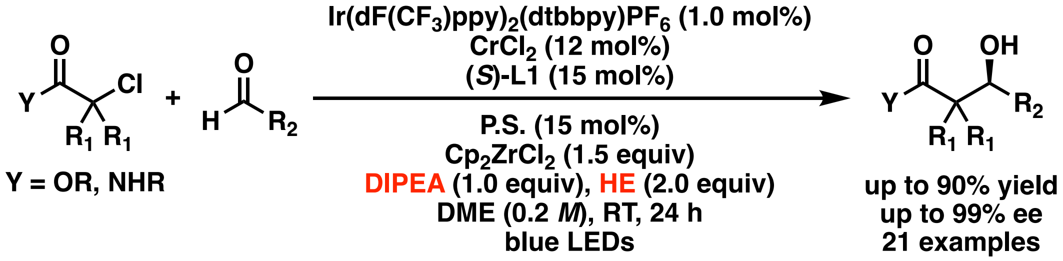


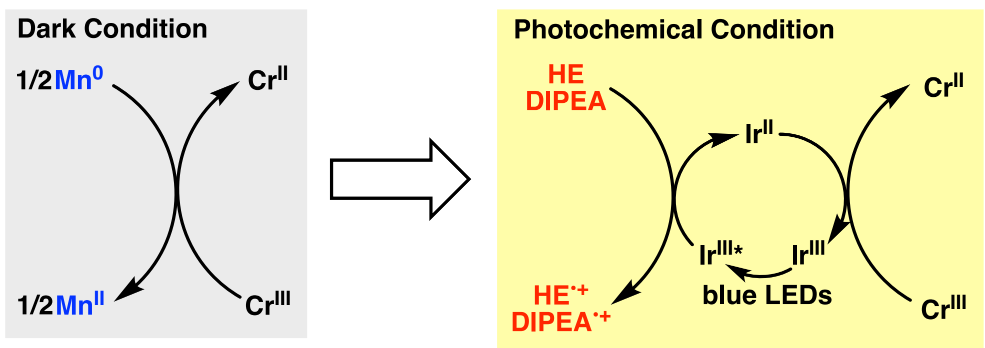
4-2 Photochemical Reaction

4-2-1 Asymmetric Reformatsky-type Reaction [Wang (2024)[25]]



Photochemical Condition



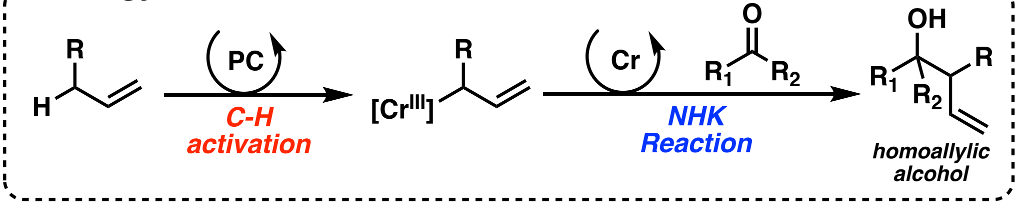


Reference

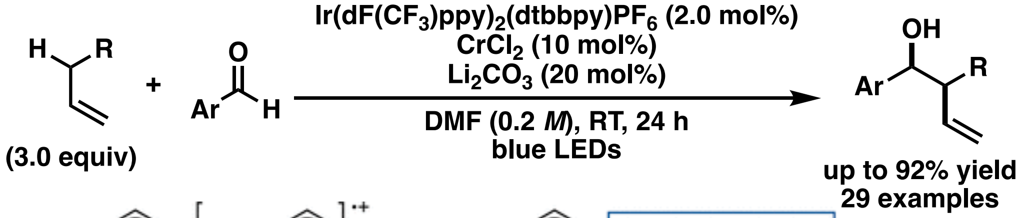
25) Wang, Z. et al. *Angew. Chem. Int. Ed.* **2024**, *63*, e202406109.

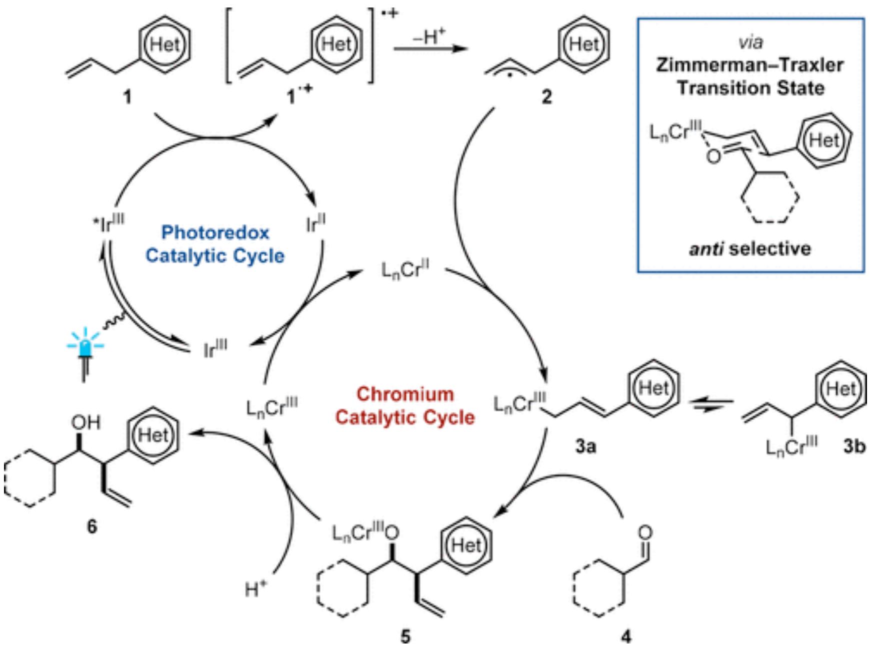
4-2-2 NHK Reaction

Strategy

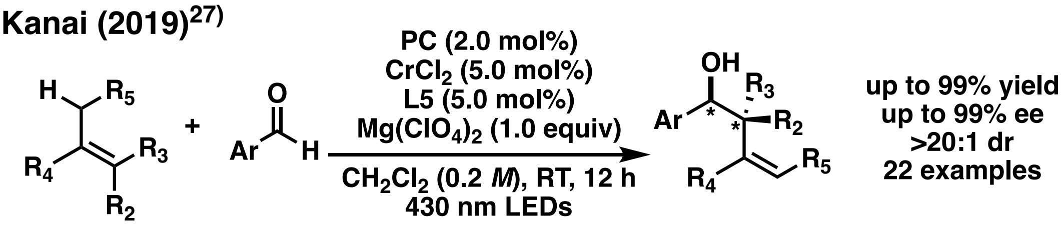


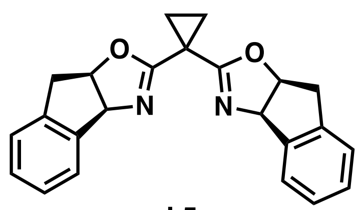
Glorius (2018)[26)]



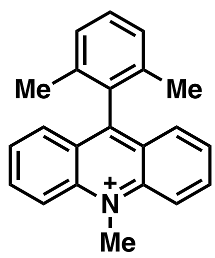


Kanai (2019)[27)]





L5

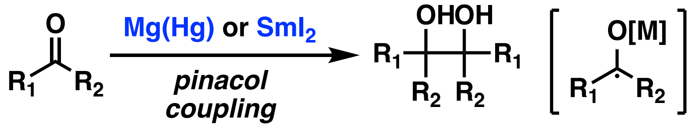


PC

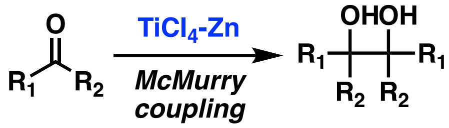
Reference
26) Glorius, F. et al. *J. Am. Chem. Soc.* **2018**, *140*, 12705-12709.
27) Kanai, M. et al. *Chem. Sci.* **2019**, *10*, 3459-3465.

5. Pinacol-type Coupling

4-1 “Classical” Reaction

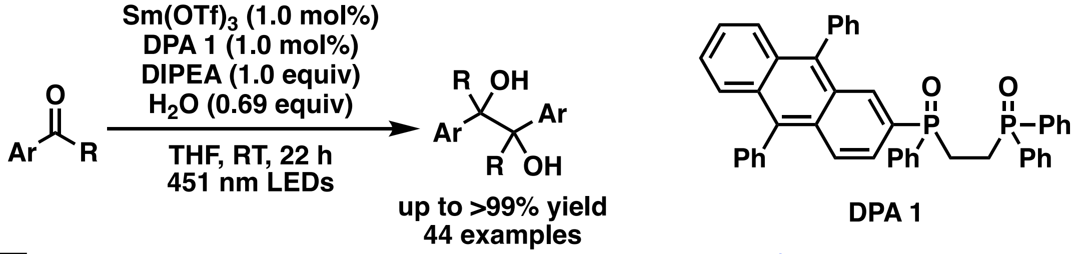


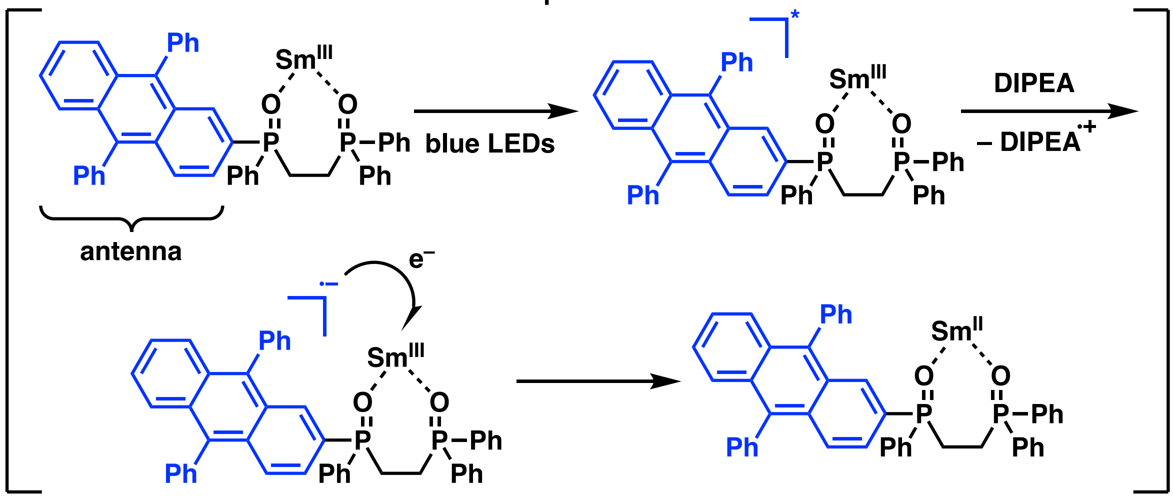
❌ Stoichiometric Waste



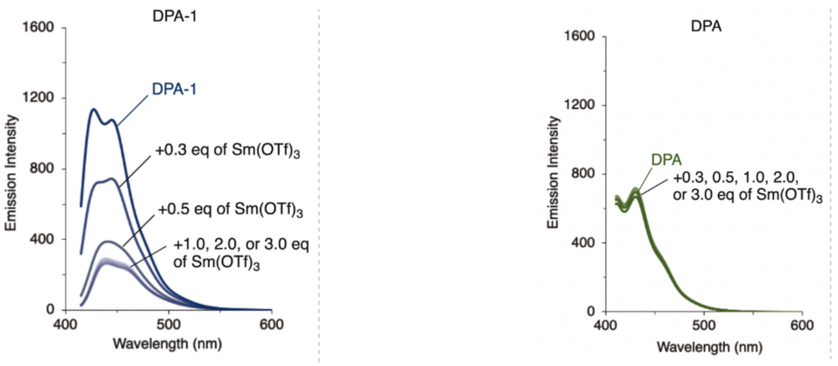
4-2 Photochemical Reaction

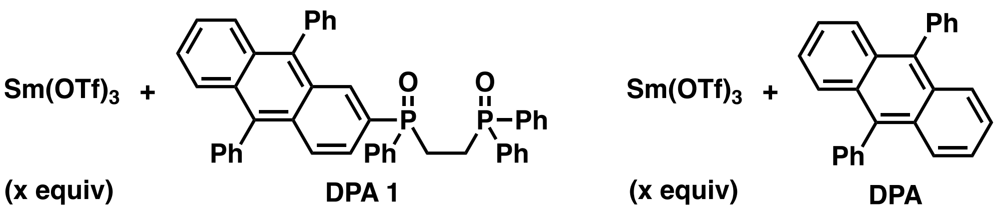
Nemoto (2024)[28]





Effect of Antenna Ligand (Stern-Volmer experiment)





Reference

28) Nemoto, T. et al. *J. Am. Chem. Soc.* **2024**, *146*, 20904-20912.