

XU GROUP
Department of Chemistry, Peking University

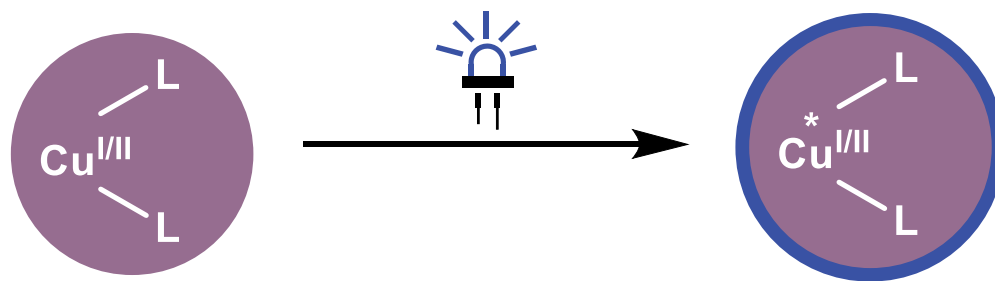
Selected Weekly Literature Presentations

Disclaimer:

These slides contain personal interpretations and may include errors or subjective views.

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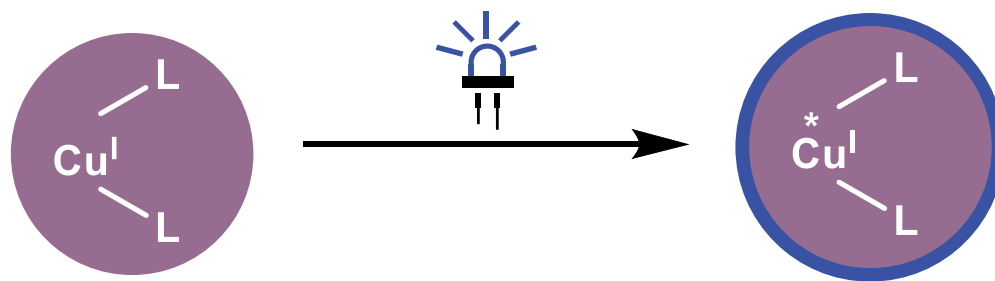
Photoactive Copper Complex in Organic Transformations



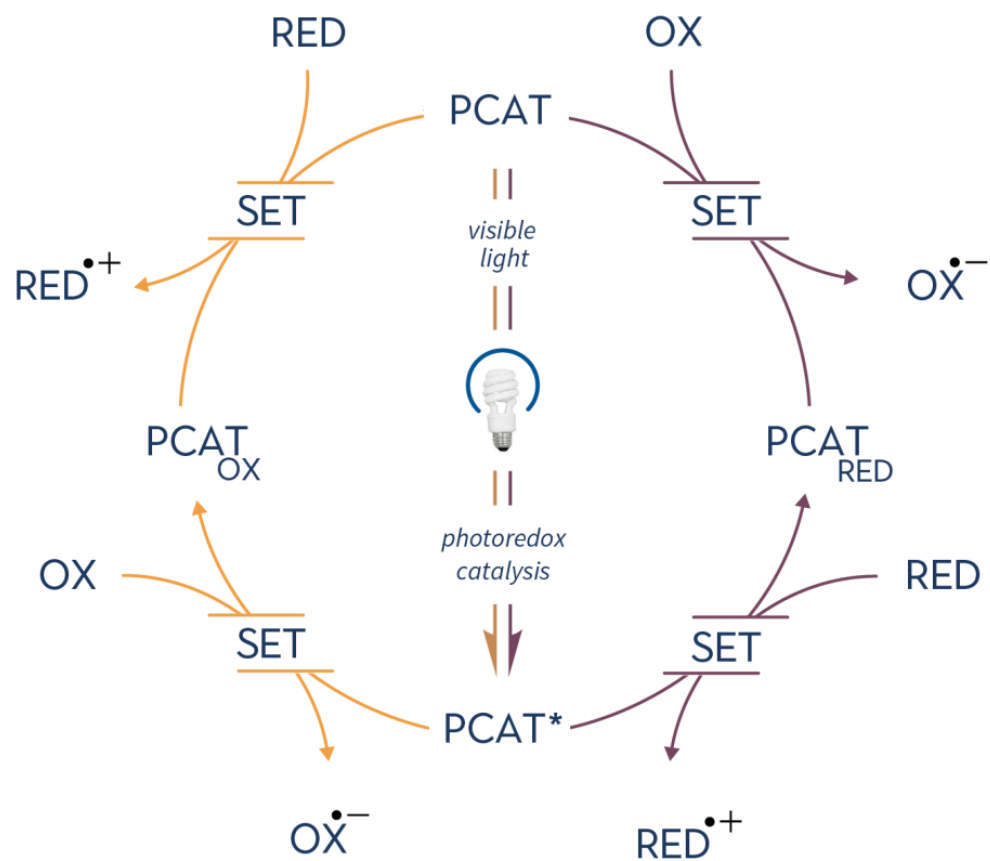
Qingrui Zeng

2024.06.15

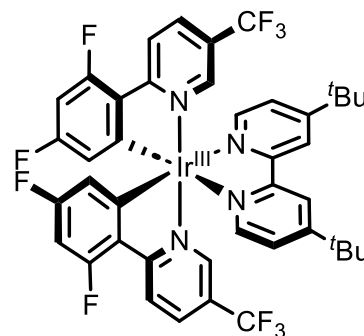
Cu(I) Complexes as Standalone Photocatalysts



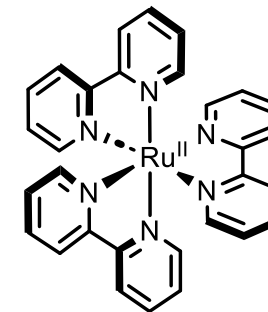
Visible-light Photoredox Catalysis



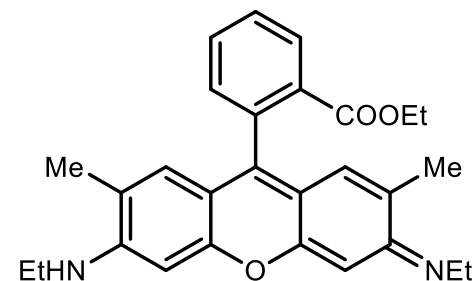
Chromophores



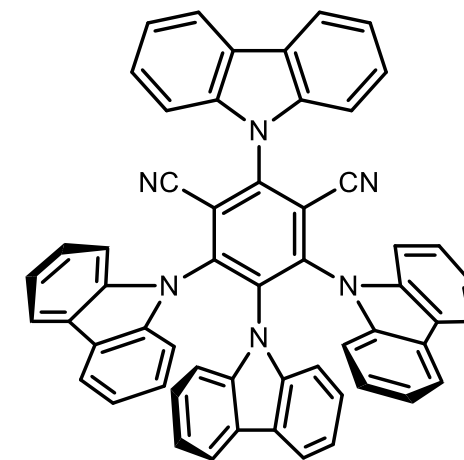
$[\text{Ir}(\text{dF}(\text{CF}_3)\text{ppy})_2(\text{dtbbpy})]^+$
 $\lambda = 380 \text{ nm}$



$[\text{Ru}(\text{bpy})_3]^{2+}$
 $\lambda = 452 \text{ nm}$

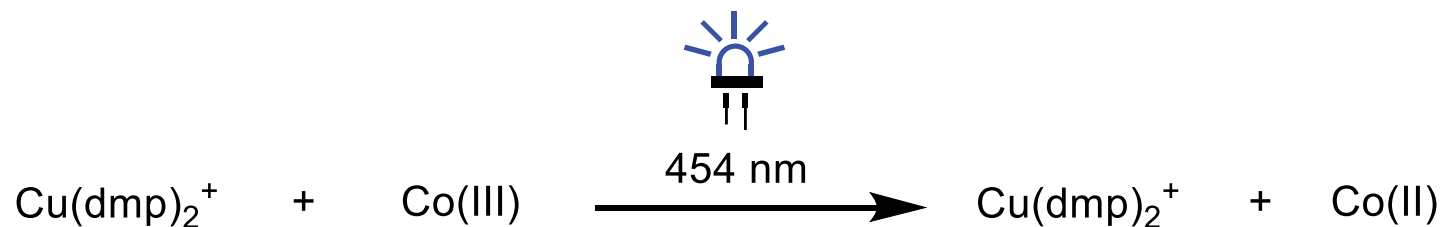


Rhodamine 6G
 $\lambda = 530 \text{ nm}$

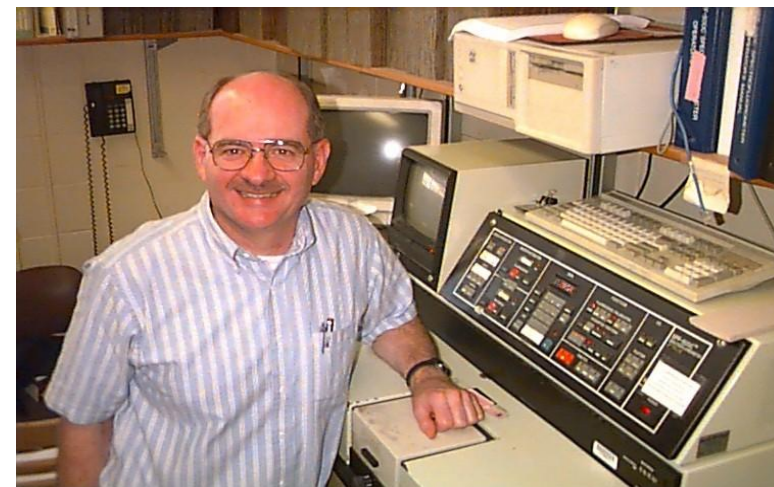
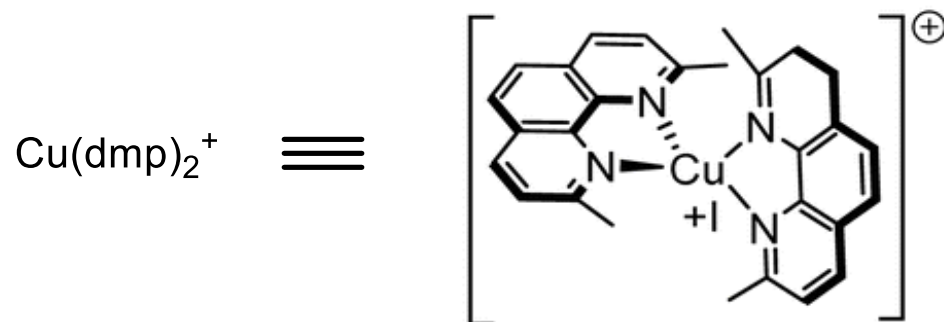


4CzIPN
 $\lambda = 435 \text{ nm}$

Pioneer of Photocatalysis with Copper Complex



Co(III) was in $\text{K}[\text{cis-Co(IDA)}_2] \cdot 1.5\text{H}_2\text{O}$

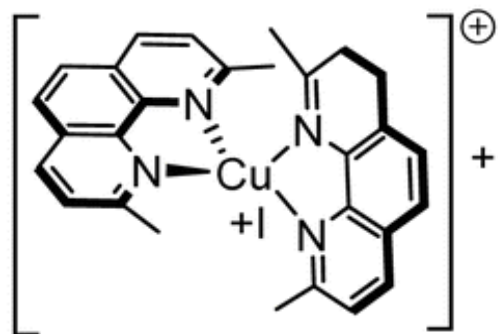


David R. McMillin

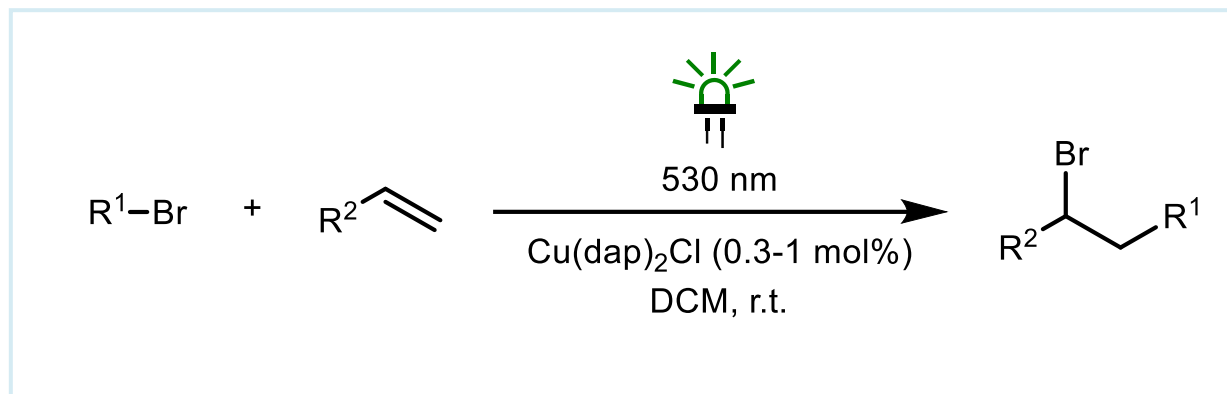
*“has a rather low-lying metal-to-ligand charge transfer excited state and could be expected to **participate in some interesting photoredox chemistry**”*

McMillin, D.R. *et al. Inorg. Chem.* **1977**, *16*, 943–945.

Hibernation



excited-state
lifetime ≤ 270 ns



25 years

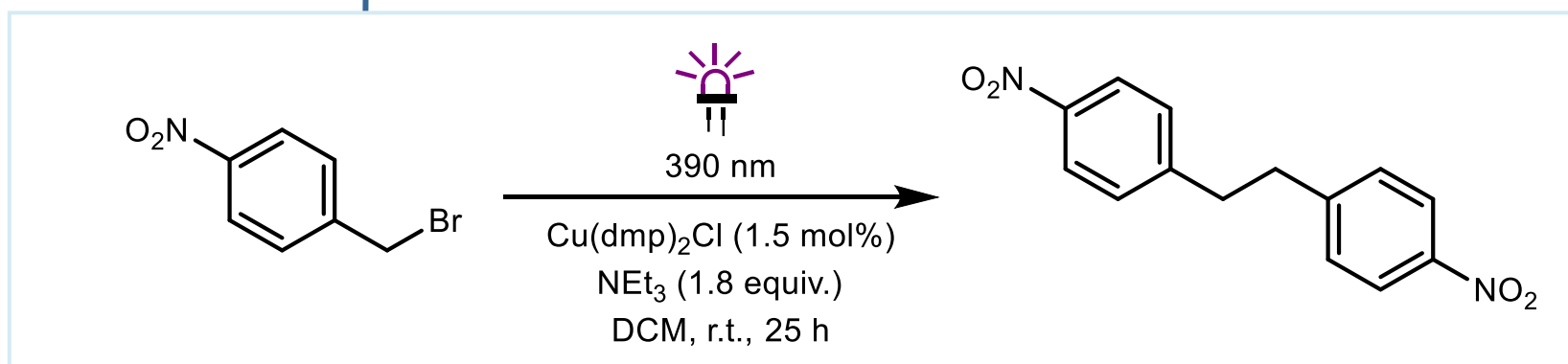
1987

2012

"renaissance"

1977

"the first application of a photoactivatable copper complex inorganic synthesis"

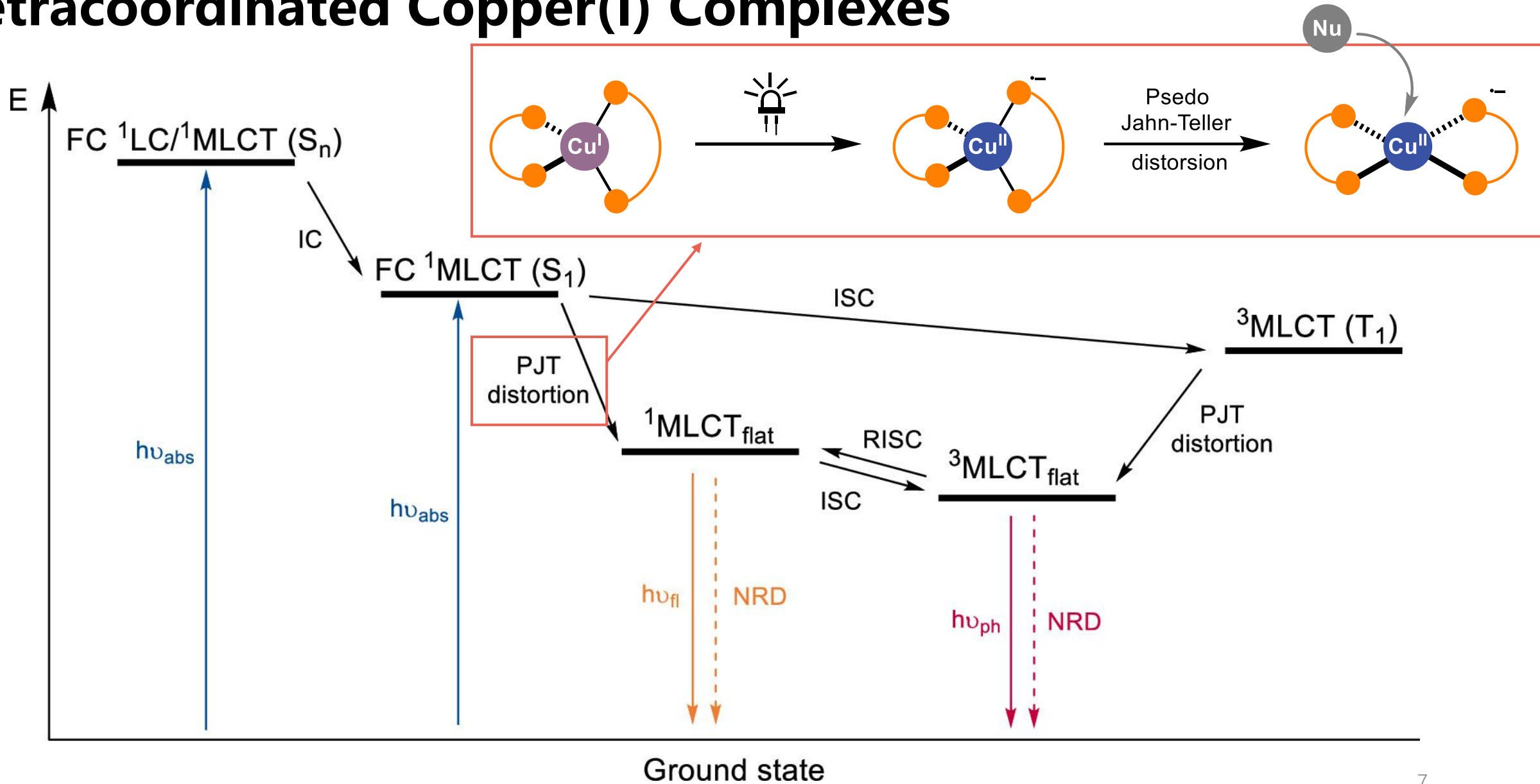


WHY?

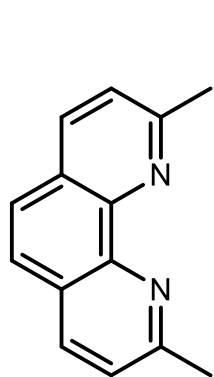
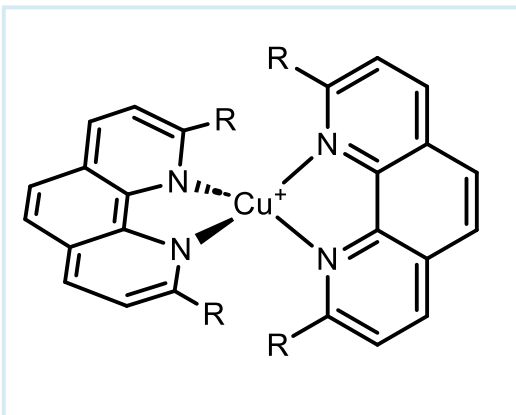
Sauvage, J. -P. *et al.* *J. Chem. Soc., Chem. Commun.* **1987**, 546–548.

Reiser, O. *et al.* *Chem. –Eur. J.*, **2012**, 18, 7336–7340.

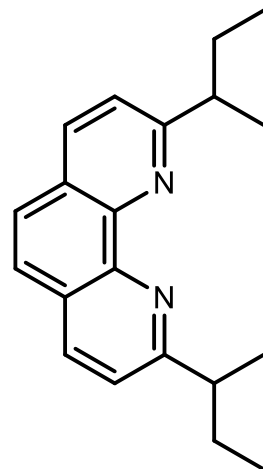
General Photophysical Scheme of Tetracoordinated Copper(I) Complexes



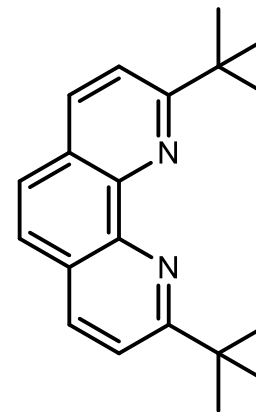
Strategy 1: Bulky Substituents



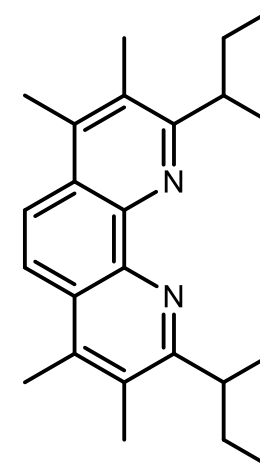
$\lambda_{em} = 730 \text{ nm}$
 $\tau_{em} = 90 \text{ ns}$



$\lambda_{em} = 690 \text{ nm}$
 $\tau_{em} = 400 \text{ ns}$

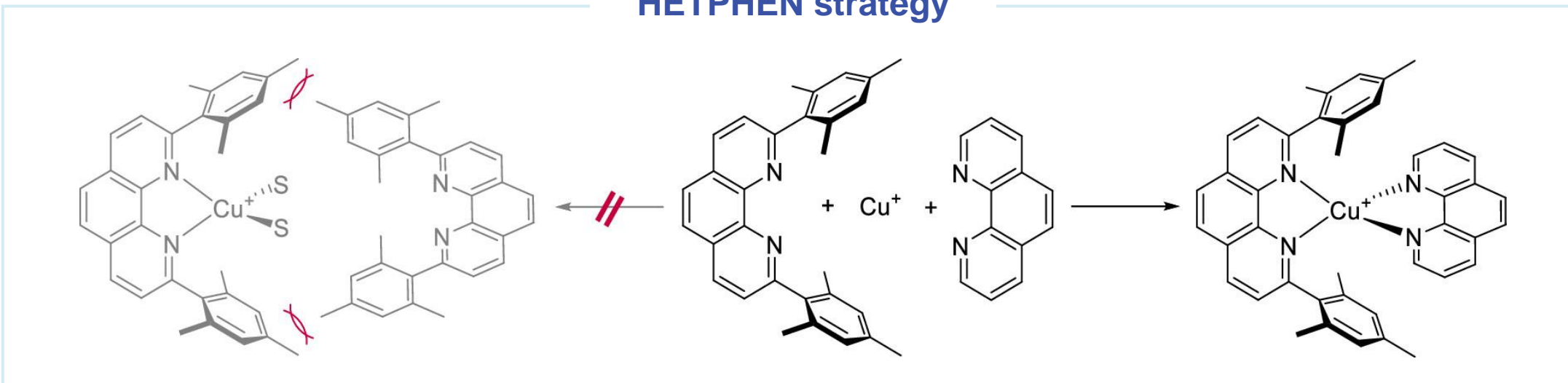


$\lambda_{em} = 599 \text{ nm}$
 $\tau_{em} = 1900 \text{ ns}$

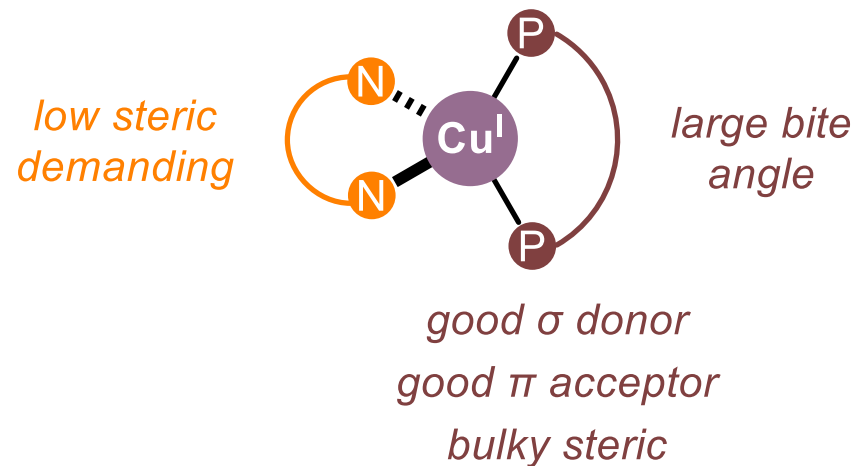


$\lambda_{em} = 631 \text{ nm}$
 $\tau_{em} = 2800 \text{ ns}$

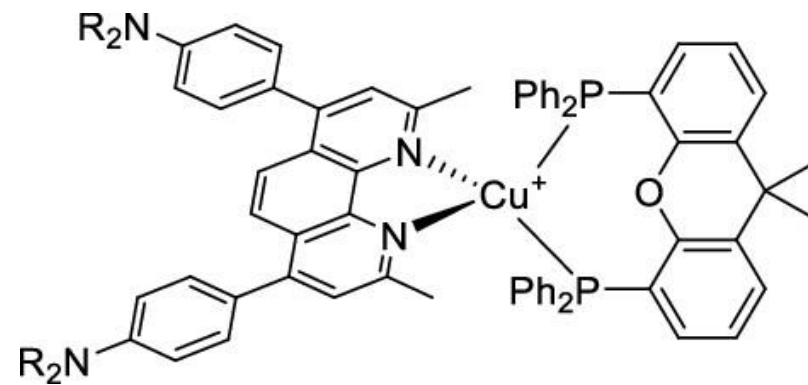
HETPHEN strategy



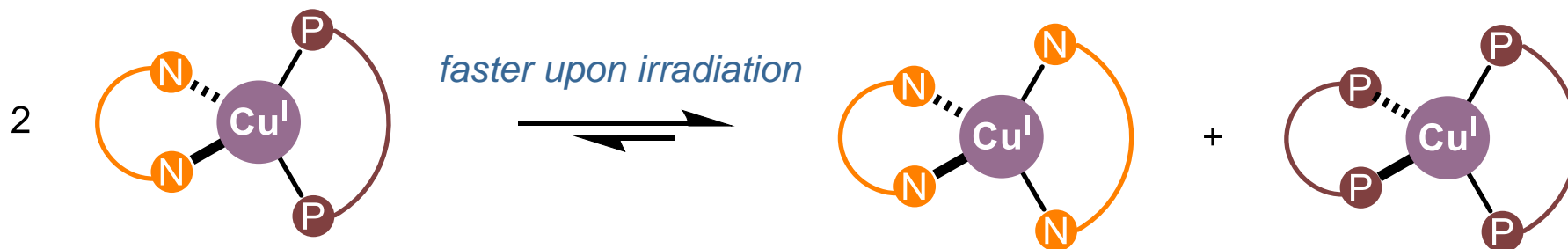
Strategy 2: Heteroleptic



For example:

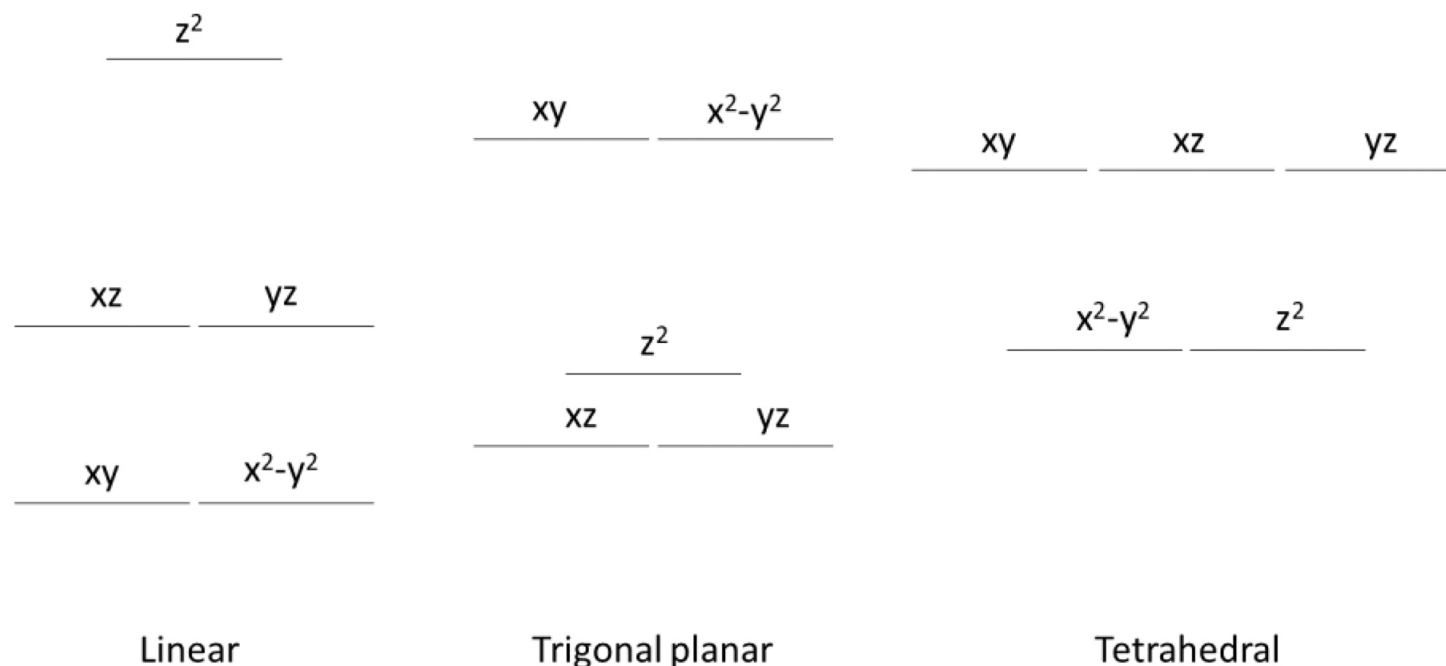


stability issues

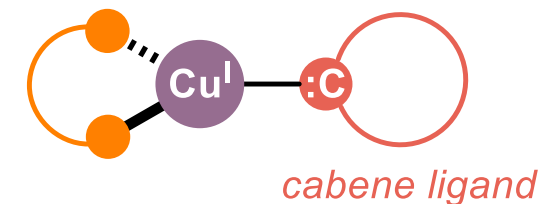
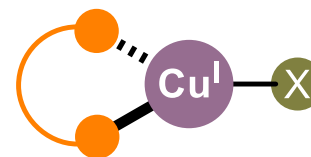


Three and Two-Coordinate Copper(I) Complexes

Crystal field splitting of the d orbitals of relevant geometries for copper(I) complexes



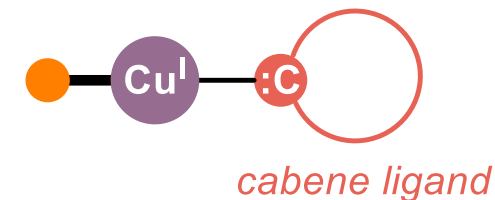
Three



$X = \text{Cl}, \text{Br}, \text{I}$

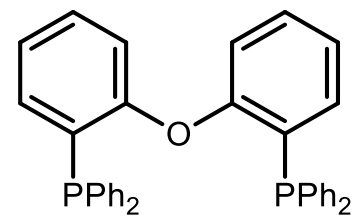
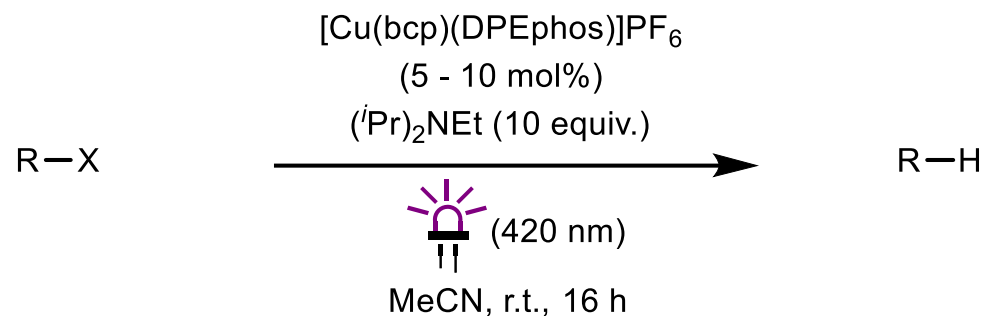
- These complexes are also prone to **pseudo-Jahn-Teller distortion**.

Two

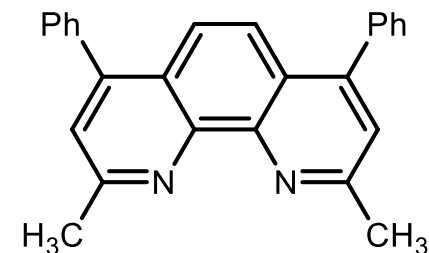


- > 90% of two-coordinate complexes bear at least 1 carbene ligand**
- These complexes **avoids** the pseudo-Jahn-Teller distortion

C-H Bond Formation

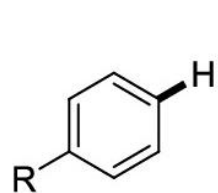


DPEphos

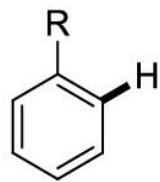


bcp

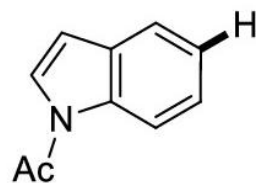
from Ar-I



R = Ph, 93%
 R = CH₂OTBS, 82%
 R = OBn, 85%
 R = CO₂Me, 90%
 R = BPin, 92%

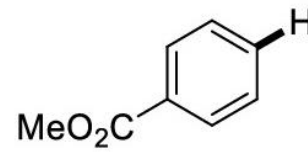


R = NHAc, 99%
 R = OTBS, 60%



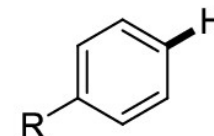
75%

from Ar-Cl



15%

from Ar-Br



R = CO₂Me, 55-64%
 R = COMe, 95%
 R = CHO, 63%
 R = OMe, 10%

$E_{\text{red}}(\text{PhI}) = -1.91 \text{ V vs SCE}$

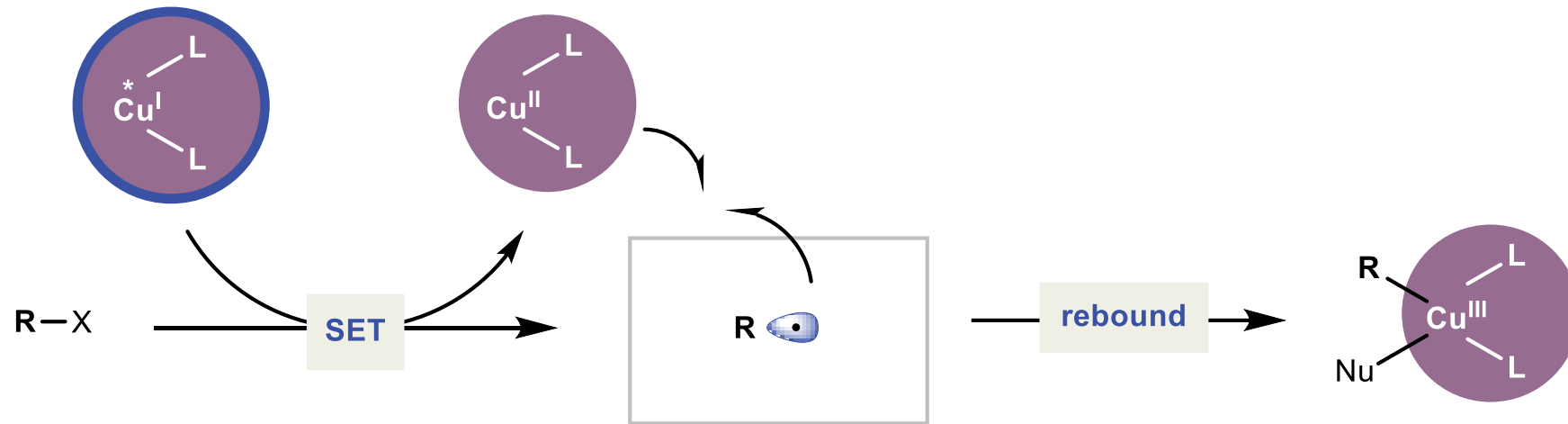
$E_{\text{red}}(\text{Cu(0)}) = -1.64 \text{ V vs SCE}$



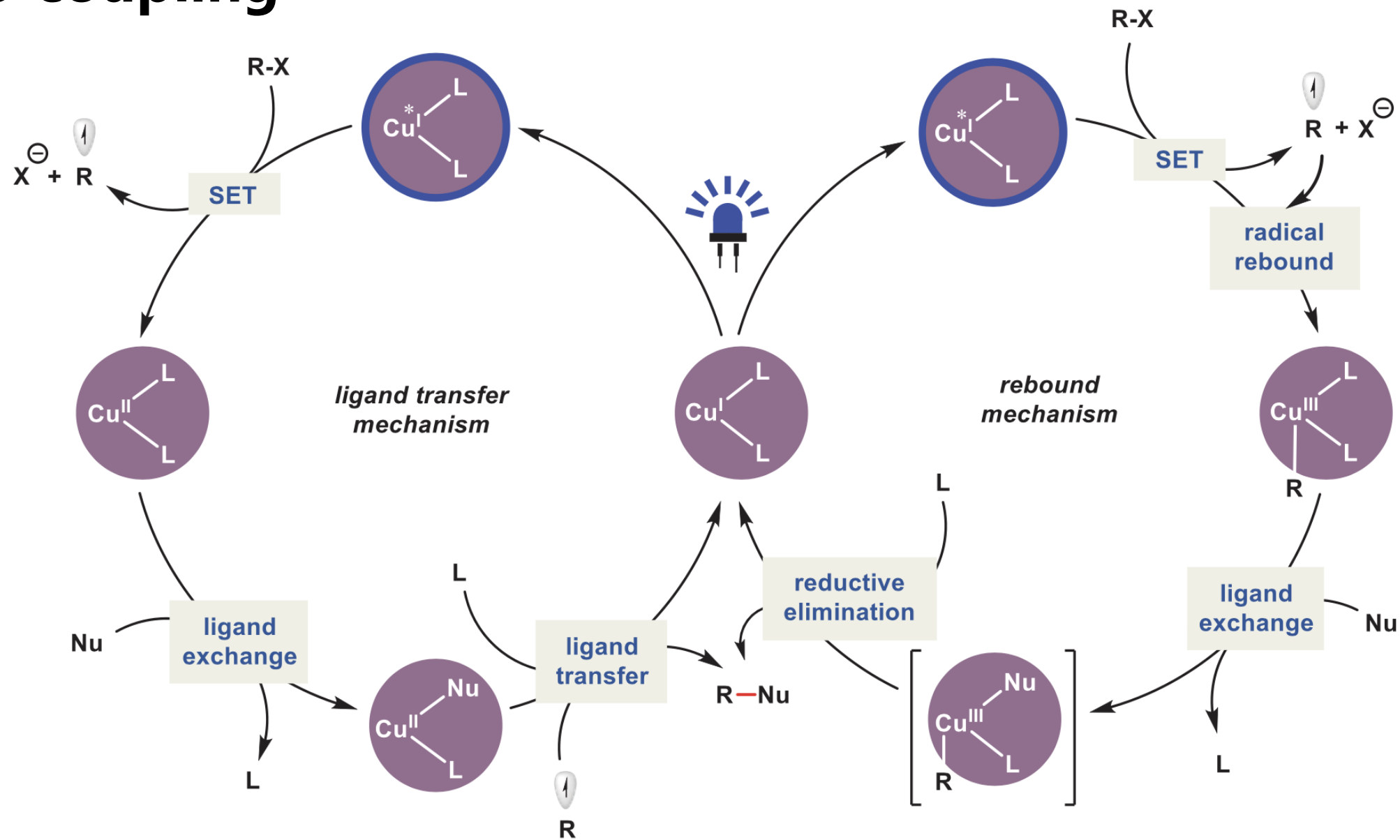
Cu(I)/Cu(I)* / Cu(0) reductive quenching cycle

Evano, G. *et al. Org. Lett.* **2017**, *19*, 3576–3579.

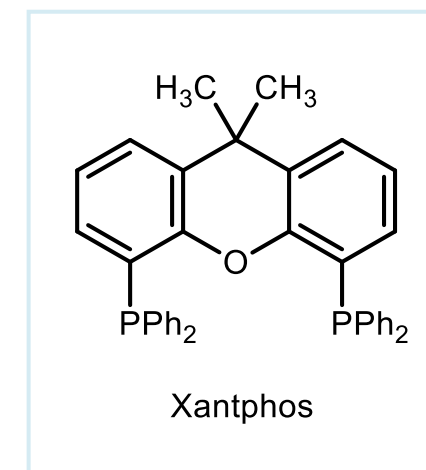
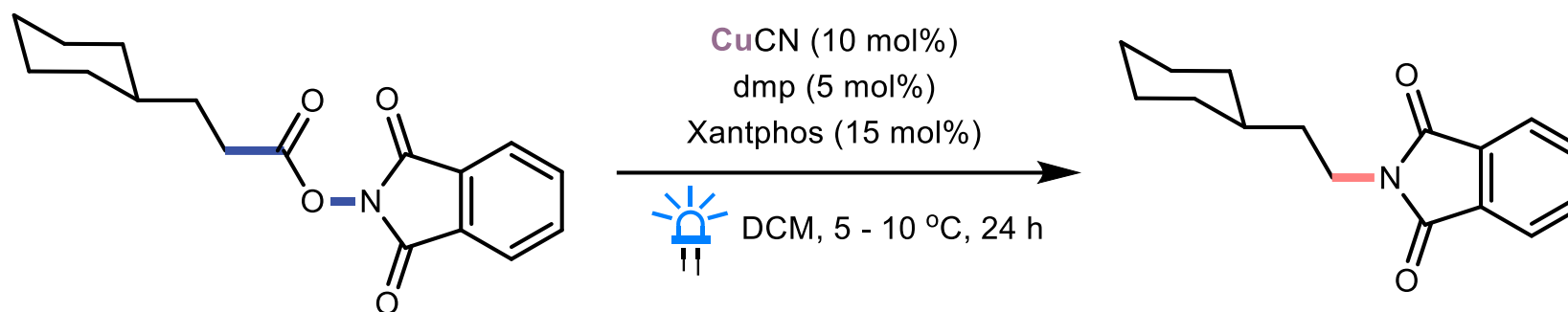
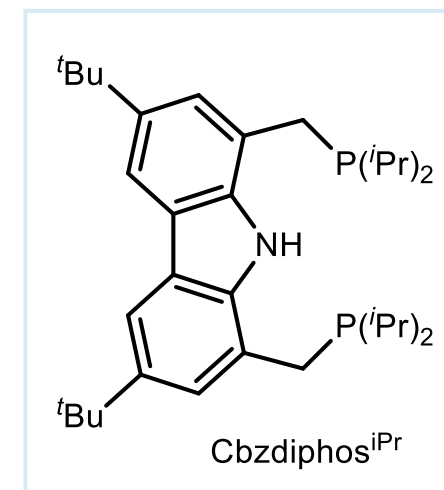
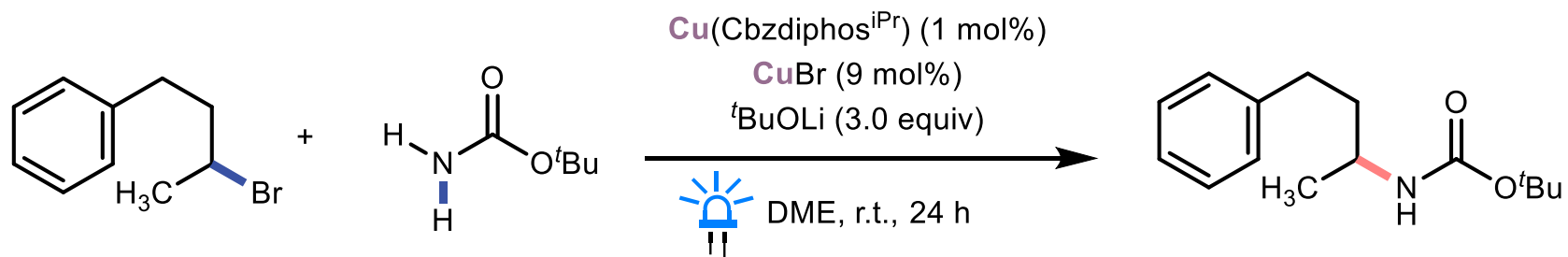
Radical Rebound



The Mechanistic Paradigm of Cu(I) Photocatalysts for Cross-coupling



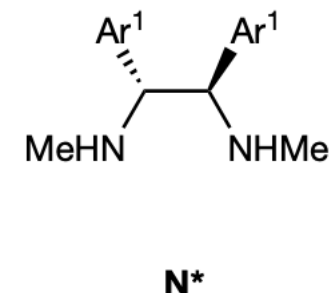
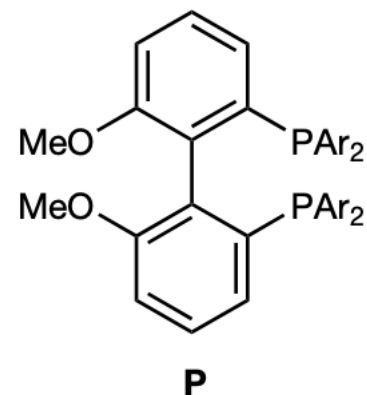
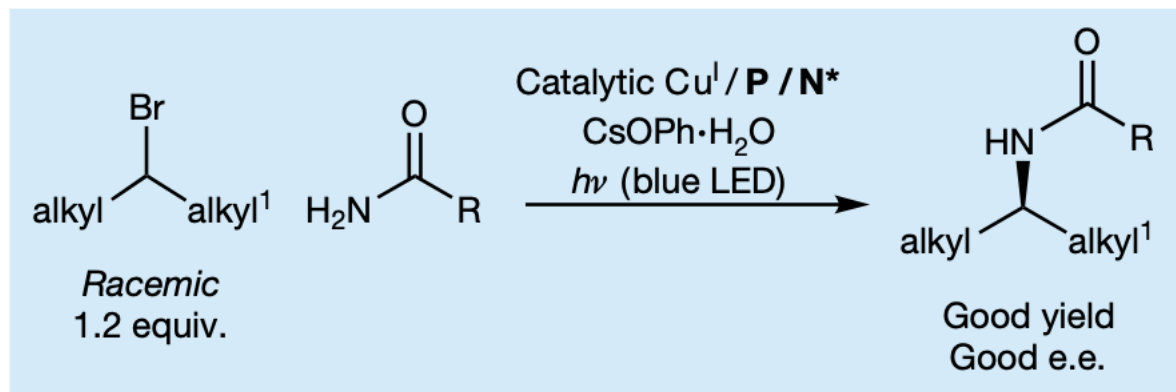
C(sp³)-N(sp³) Cross-coupling



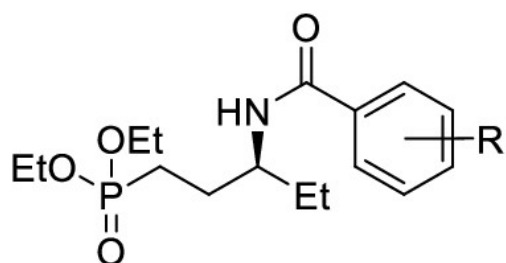
Peters, J. C.; Fu, G. C. *et al. J. Am. Chem. Soc.* **2017**, *139*, 18101–18106.

Hu, X. *et al. Angew. Chem., Int. Ed.* **2018**, *57*, 13624–13628.

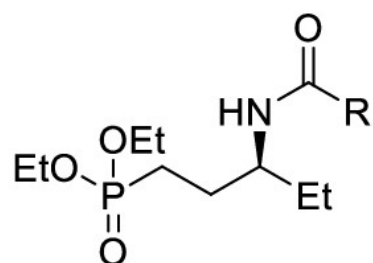
Enantioselective Synthesis of Chiral Secondary Amides



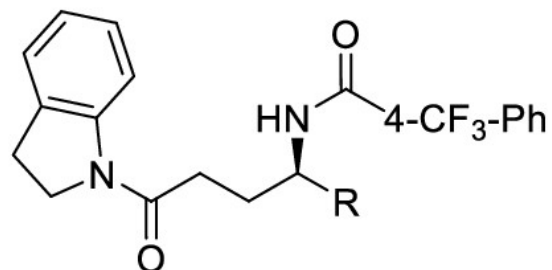
Selected example



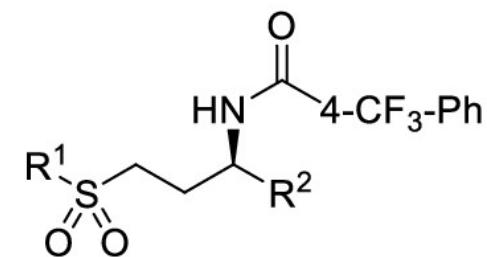
R = 3-OMe, 81%, 89% e.e.
R = 4-CF₃, 95%, 93% e.e.
R = 3,4-F, 91%, 92% e.e.



R = CH₂Ph, 75%, 91% e.e.
R = furan-3-yl, 76%, 90% e.e.



R = (CH₂)₂Ph, 67%, 95% e.e.
R = (CH₂)₄OAc, 72%, 95% e.e.
R = (CH₂)₄Cl, 70%, 92% e.e.

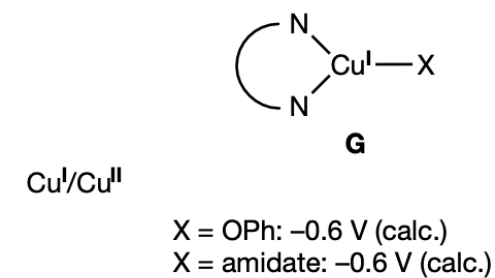
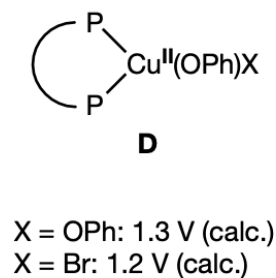
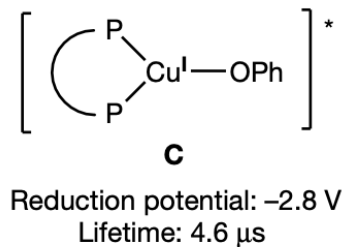
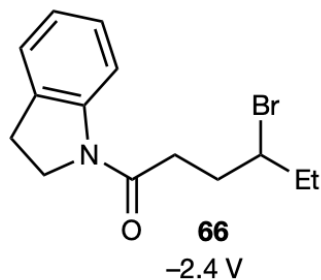
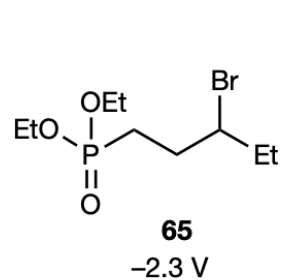
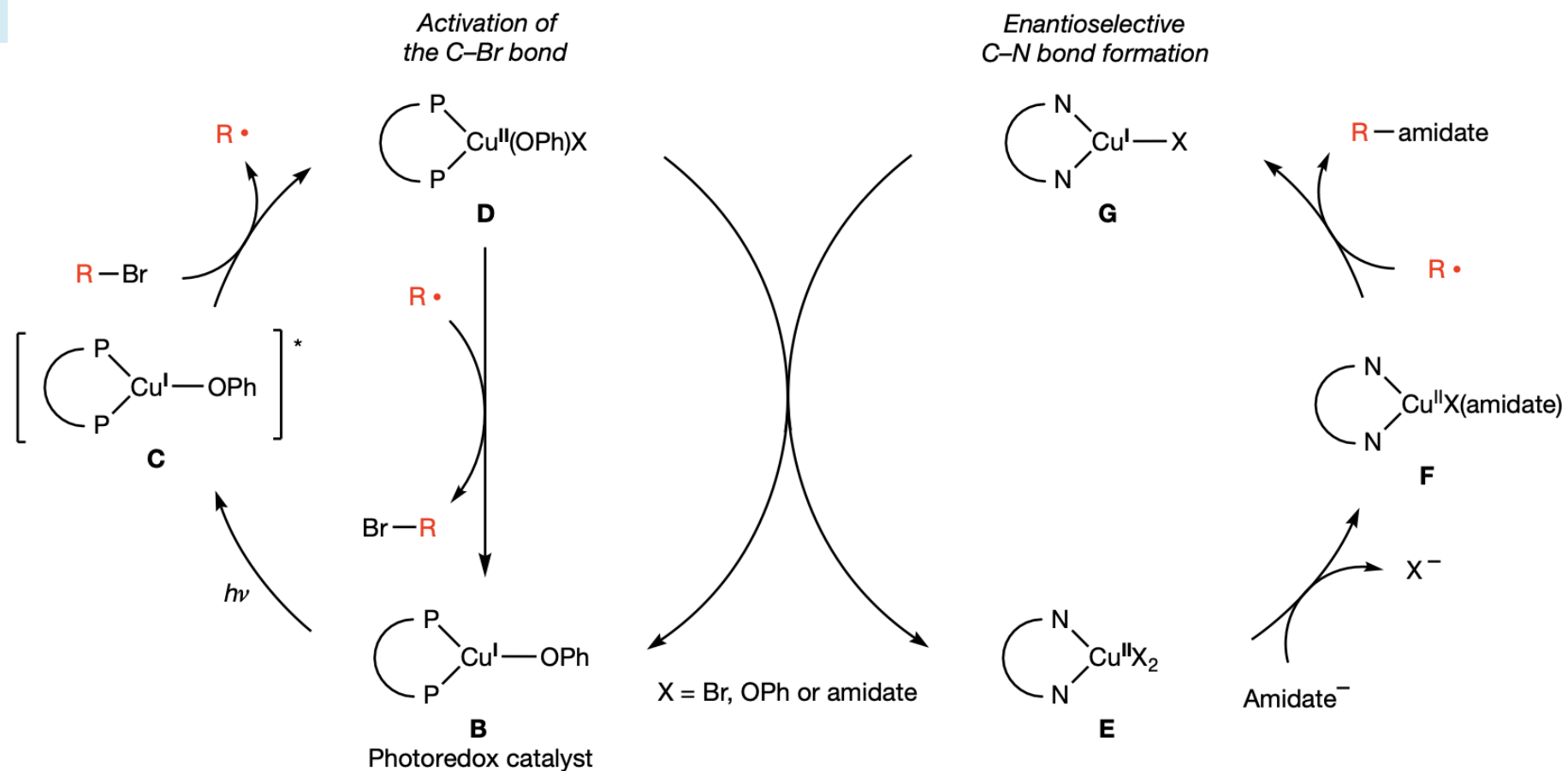


R¹ = Me₂N, R² = Me, 85%, 89% e.e.
R¹ = ^tBu, R² = Et, 72%, 97% e.e.

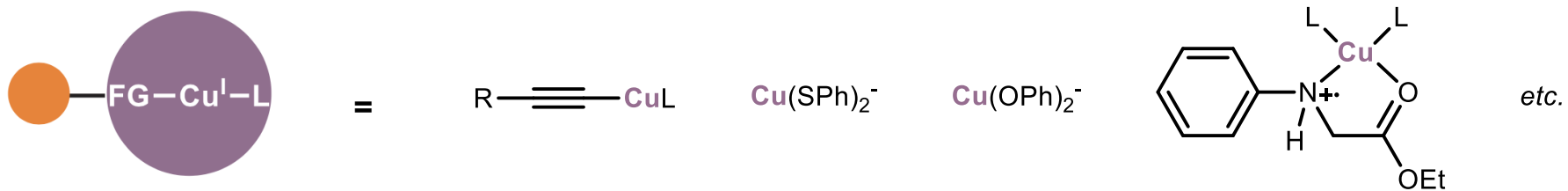
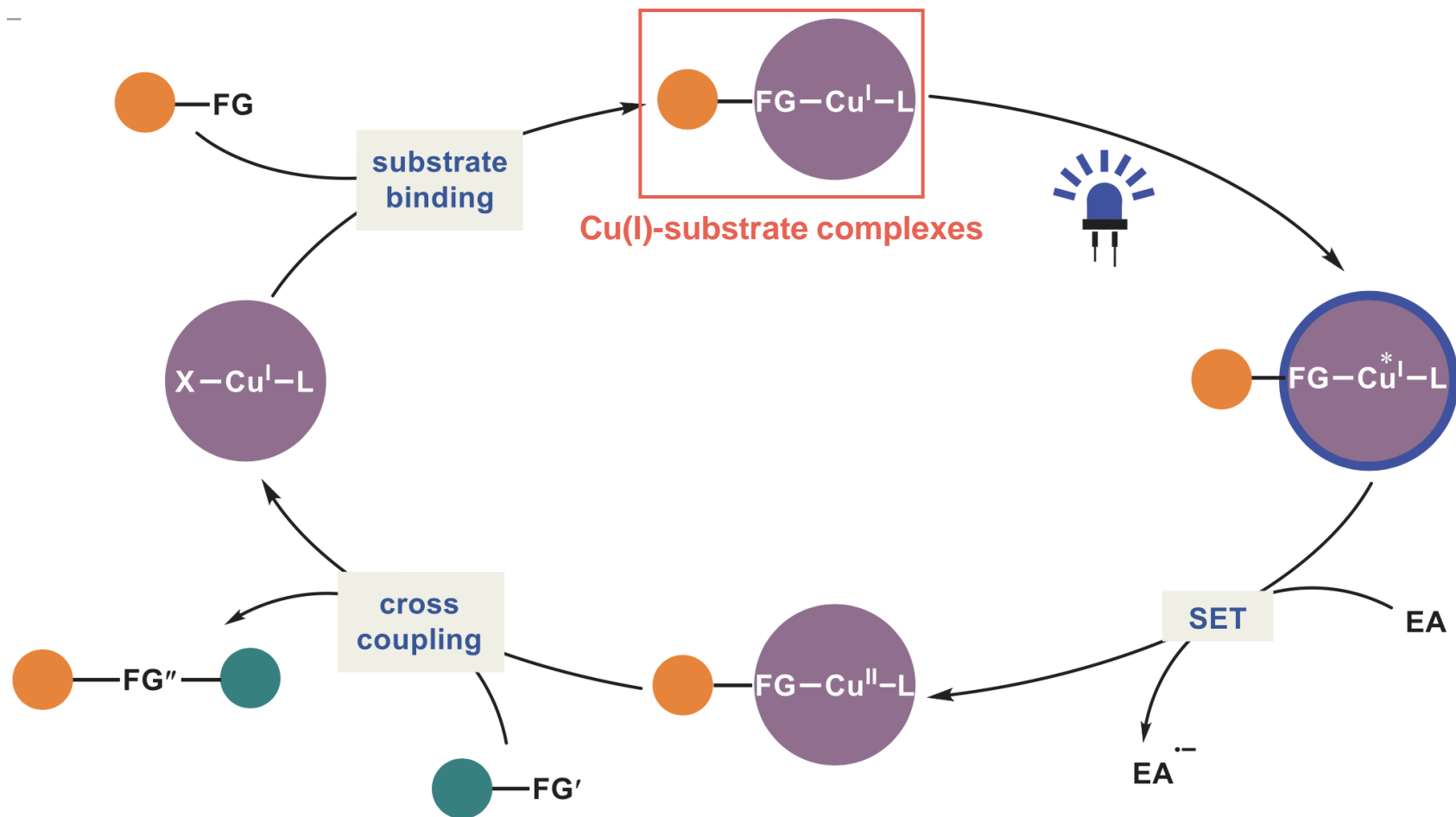
Peters, J. C.; Fu, G. C. *et. al* Nature **2021**, 596, 250–256.

Enantioselective Synthesis of Chiral Secondary Amides

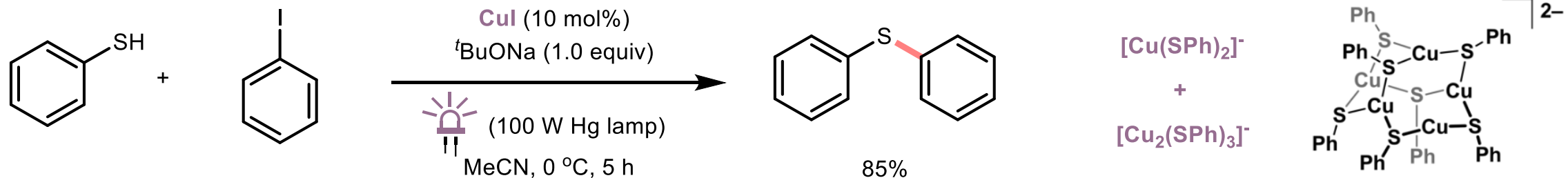
Mechanism



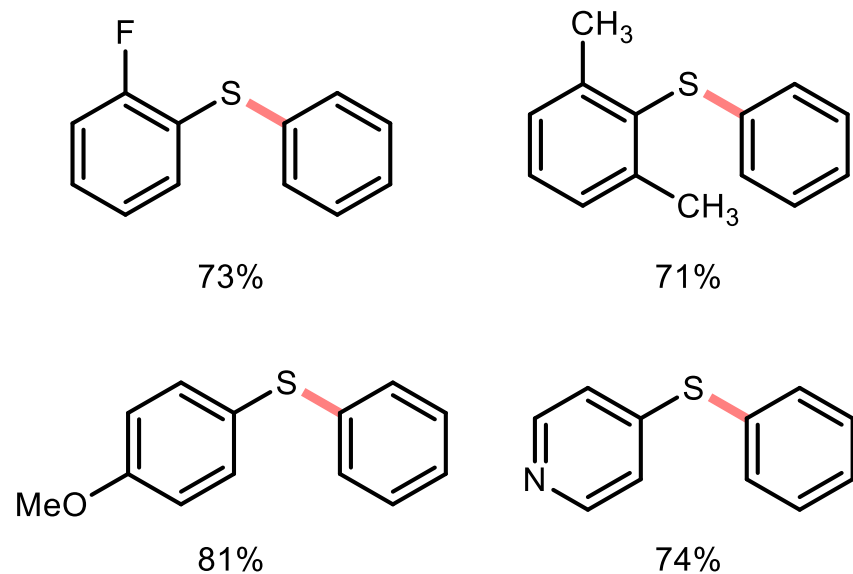
In situ-generated Cu(I)-Substrate Complexes



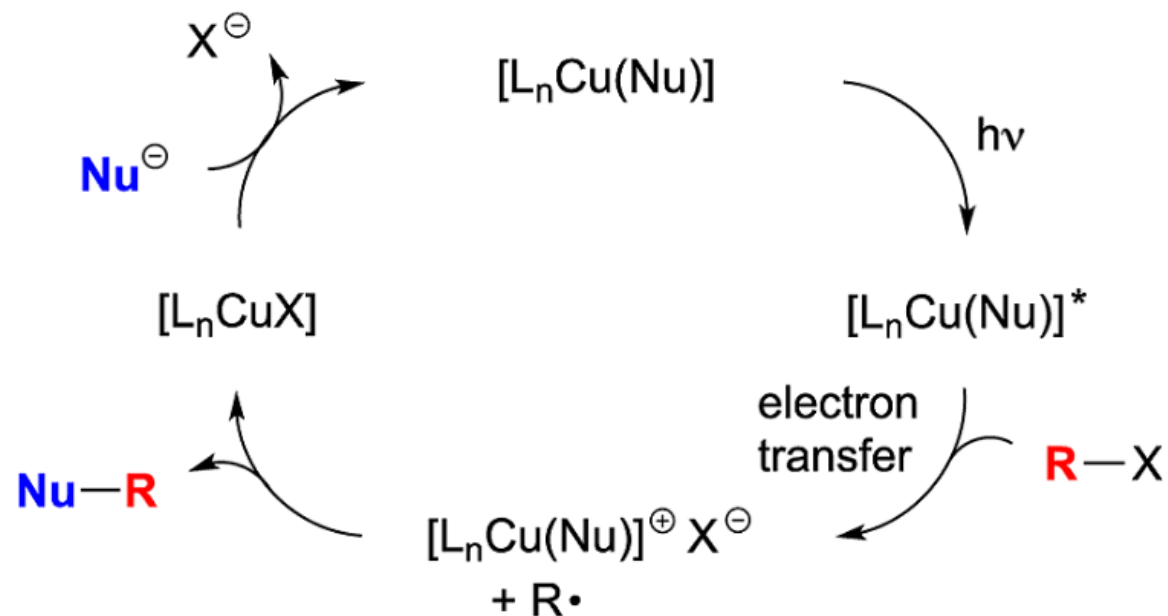
In situ-generated Cu(I)-Substrate Complexes



Selected example



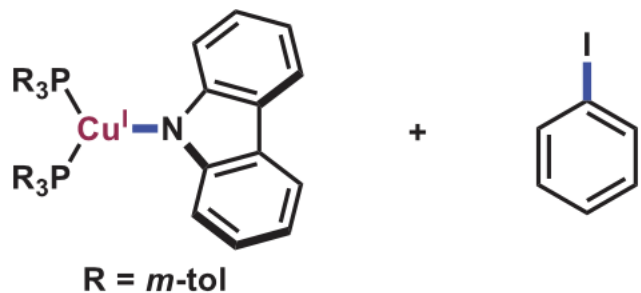
Mechanism



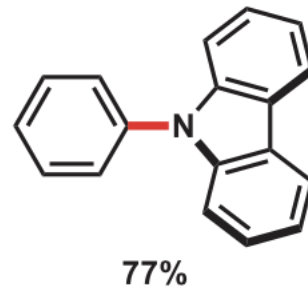
Fu, G. C.; Peters, J. C. *et al. J. Am. Chem. Soc.* **2013**, *135*, 9548–9552.

In situ-generated Cu(I)-Substrate Complexes

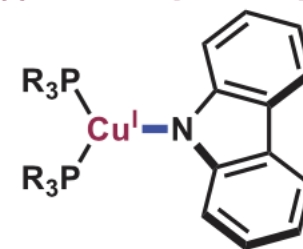
A Fu and Peters, 2012



13 W CFL
CH₃CN, rt, 10 h

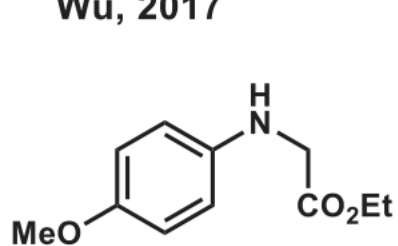


UV-light-absorbing
Cu(I)-nucleophile species

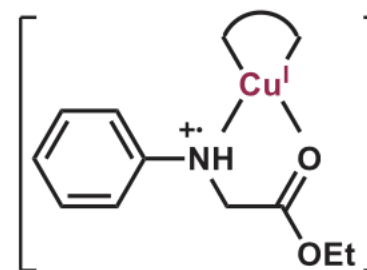
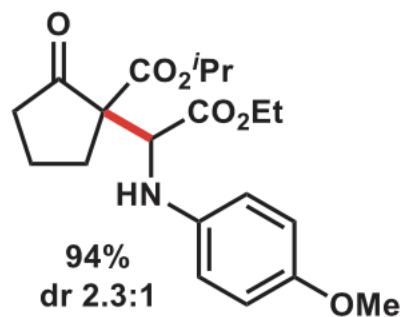


$E_{\text{red}} \approx -2.6 \text{ V vs SCE}$

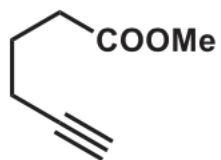
B Wu, 2017



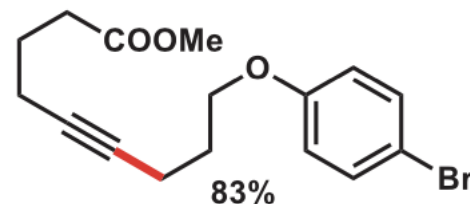
$\text{Cu}(\text{OTf})_2$
(5 mol%)
air, blue LEDs
MeCN, rt



C Lalic, 2018



CuCl (10 mol%)
 $t\text{Bu}_3\text{-TERPY}$ (20 mol%)
 K_2CO_3 (3.0 equiv)
blue LED
CH₃CN/MeOH (3:1)

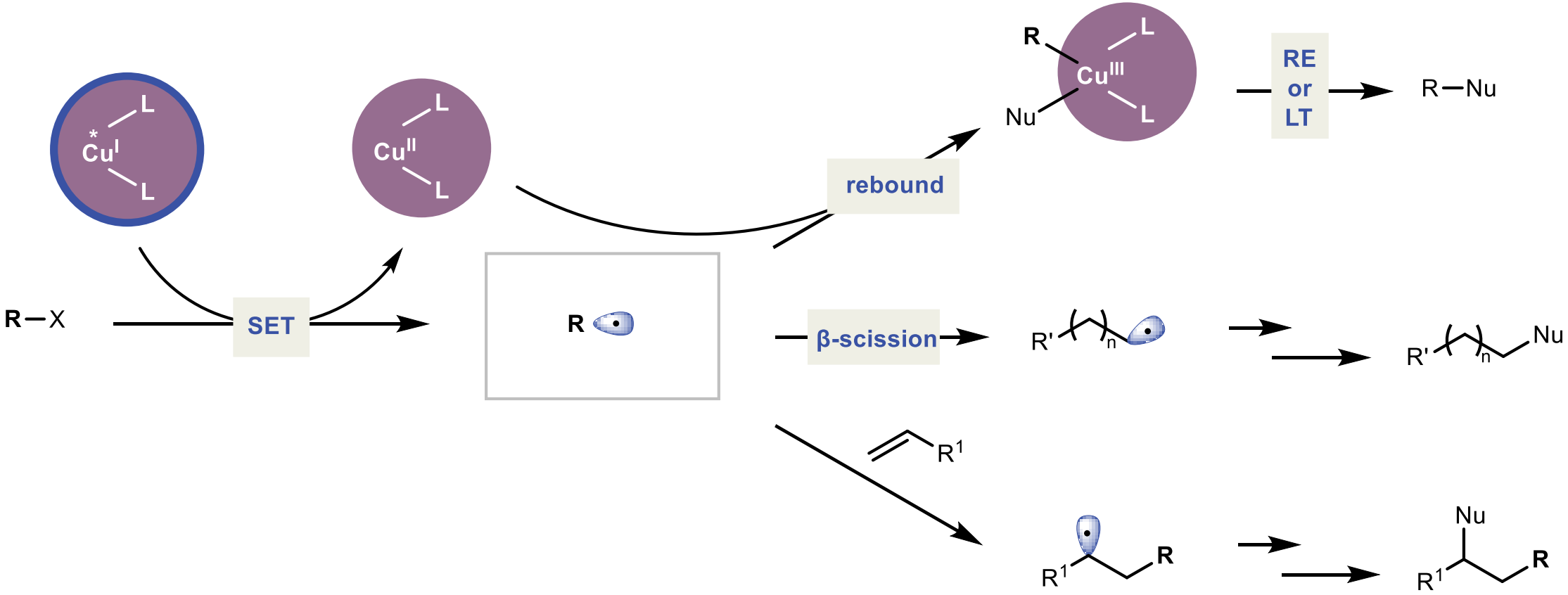


$\text{R} \equiv \text{CuL}$

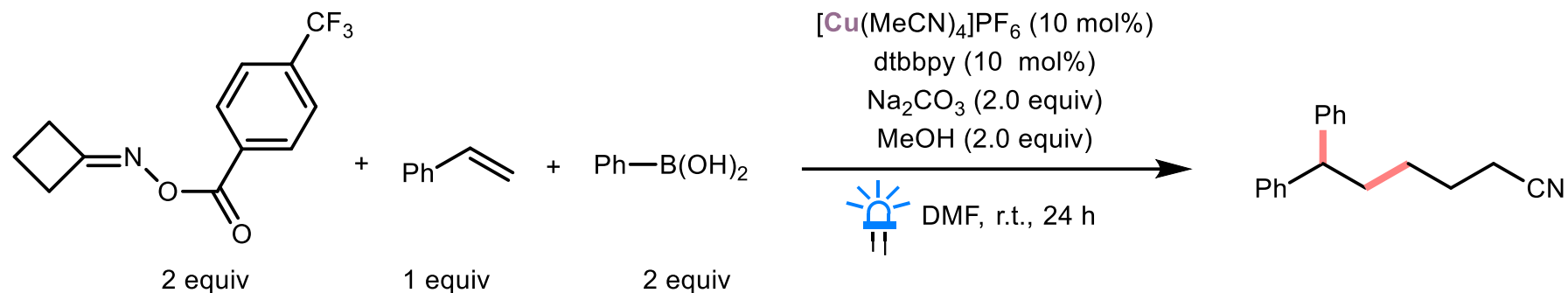
"Cu-acetylide"
for $\text{R} = \text{Ph}$,

$E_{\text{red}} = -2.048 \text{ V vs SCE}$

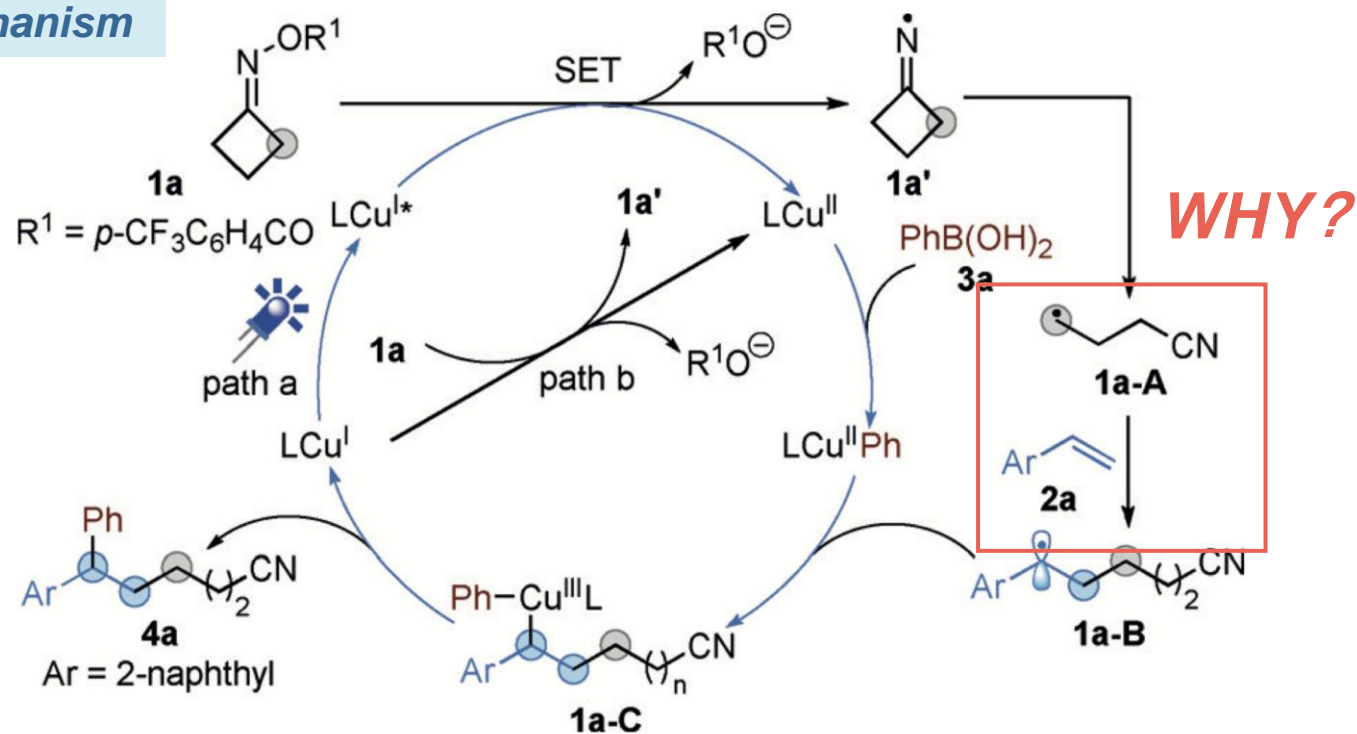
Before Rebound



C(sp²)-C(sp³) Cross Coupling



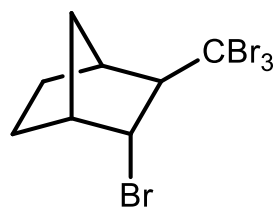
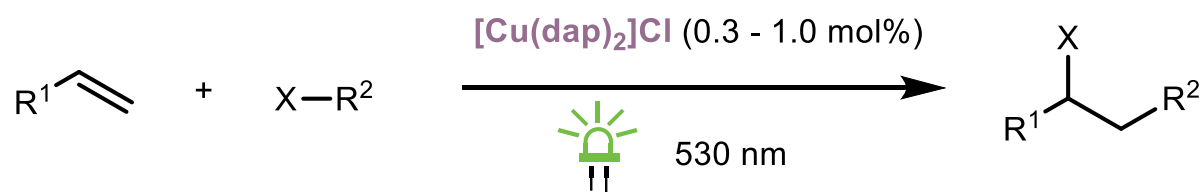
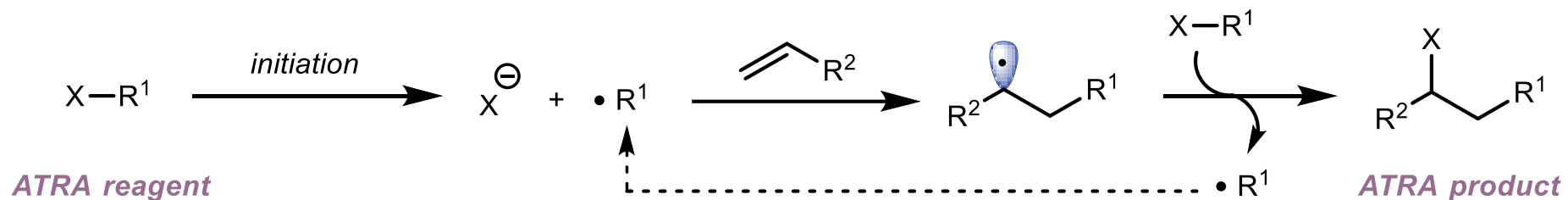
Mechanism



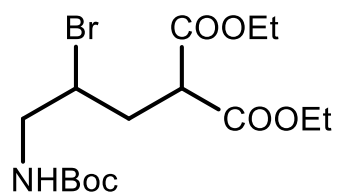
Xiao, W. *et al.* *Angew. Chem. Int. Ed.* **2018**, *57*, 15505–15509.

Bifunctionalization of Olefins

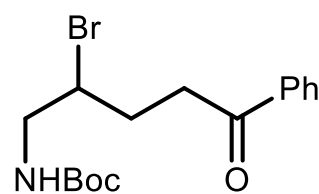
ATRA Reaction



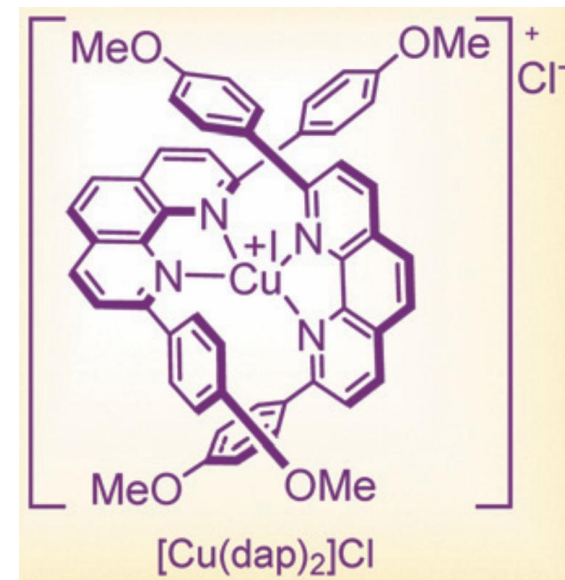
82%



75%

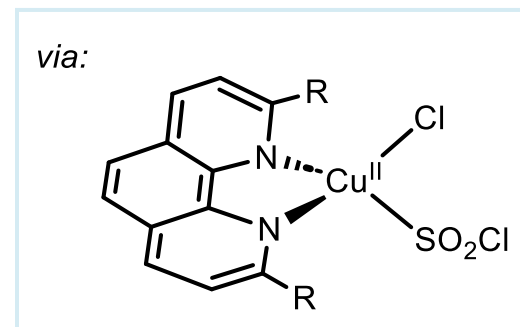
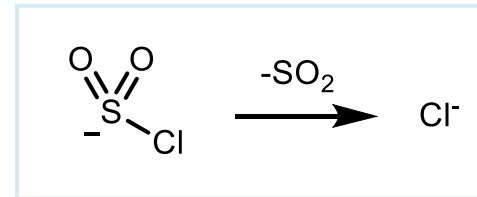
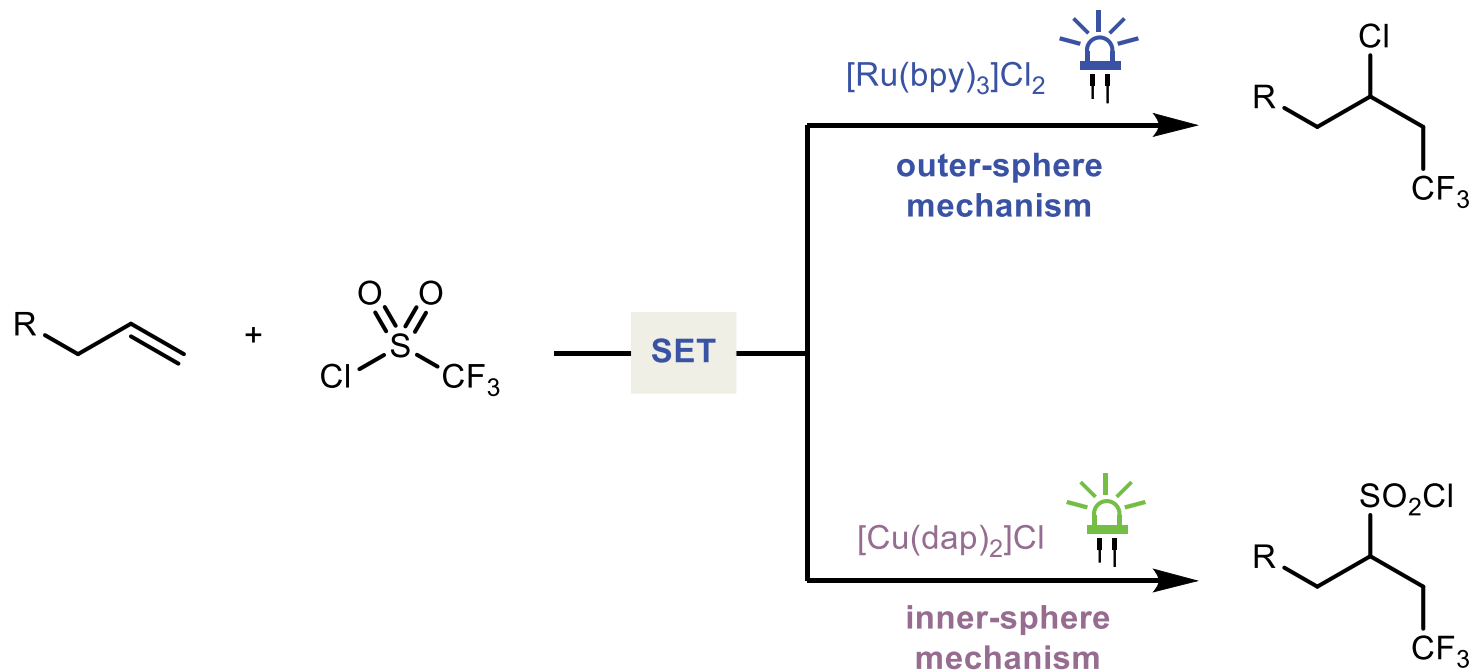


98%

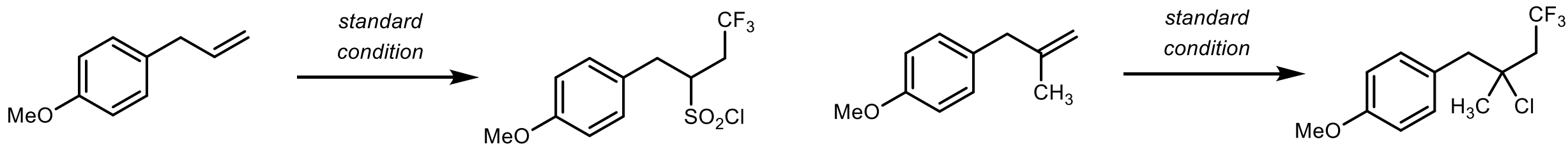


Reiser, O. *et al. Chem. –Eur. J.*, **2012**, *18*, 7336–7340.

Copper Makes the Difference

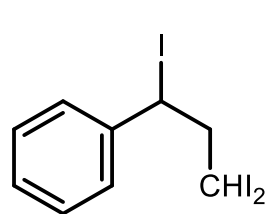
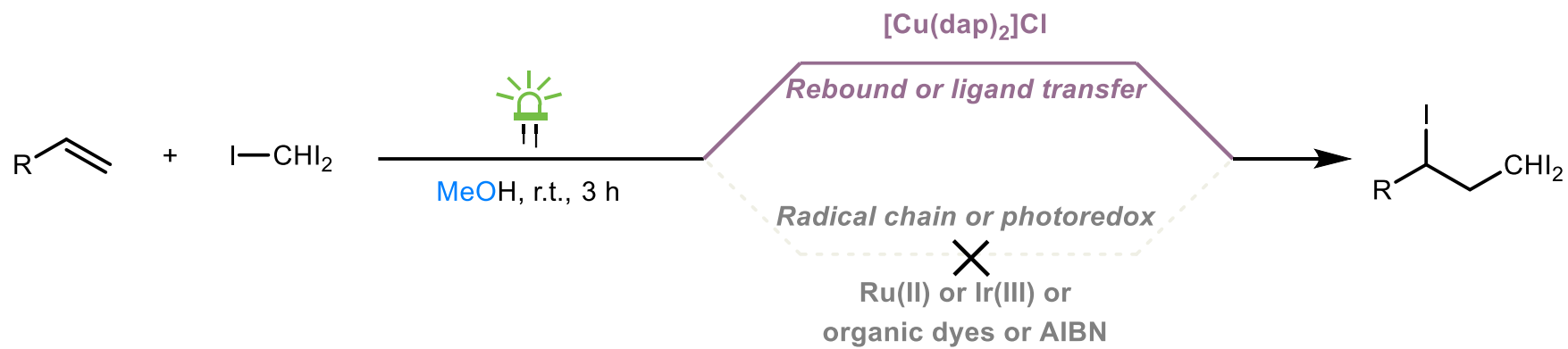


The binding of SO_2Cl to copper appears to be weak

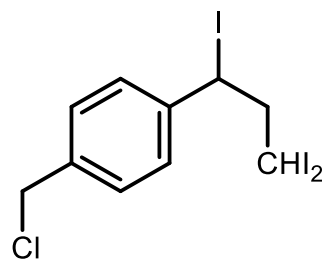


Reiser, O. *et al. Angew. Chem., Int. Ed.* **2015**, *54*, 6999–7002.

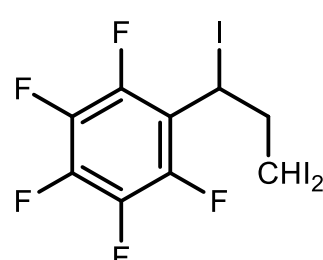
Copper Makes the Difference



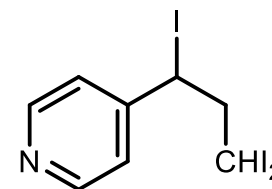
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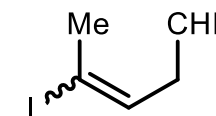
70%



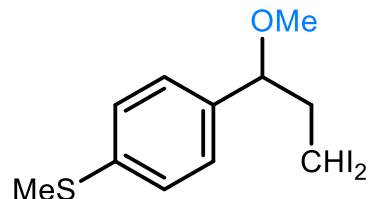
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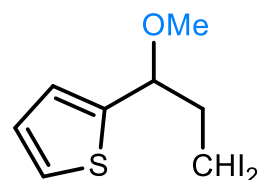
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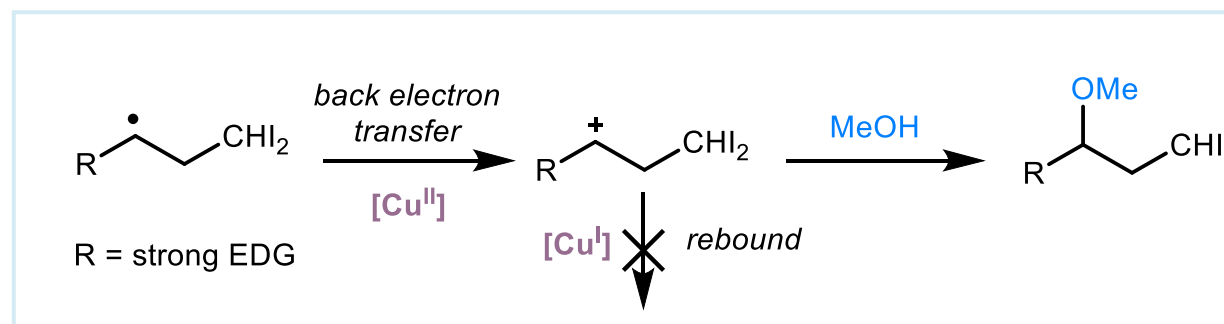
82%
d.r. = 83:17



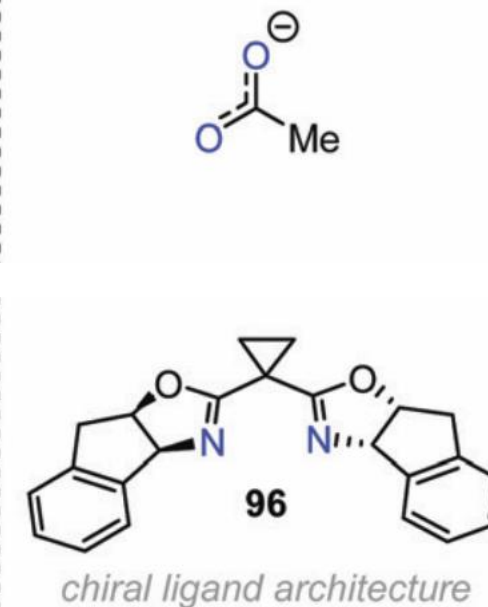
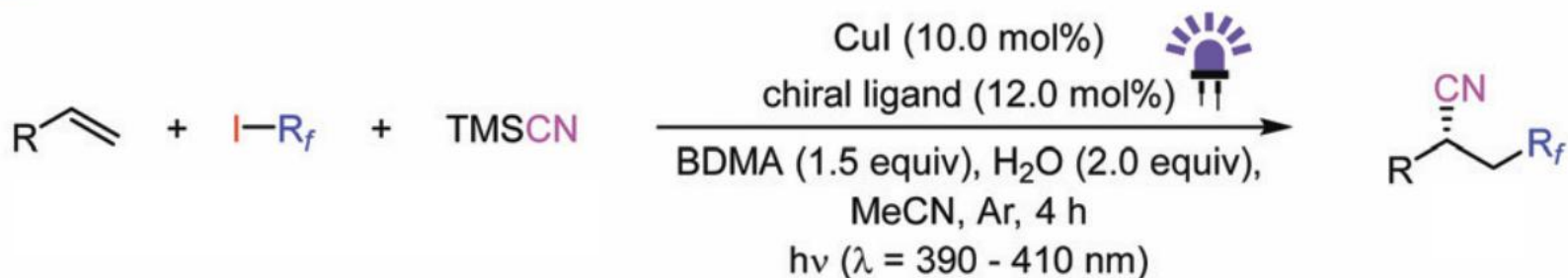
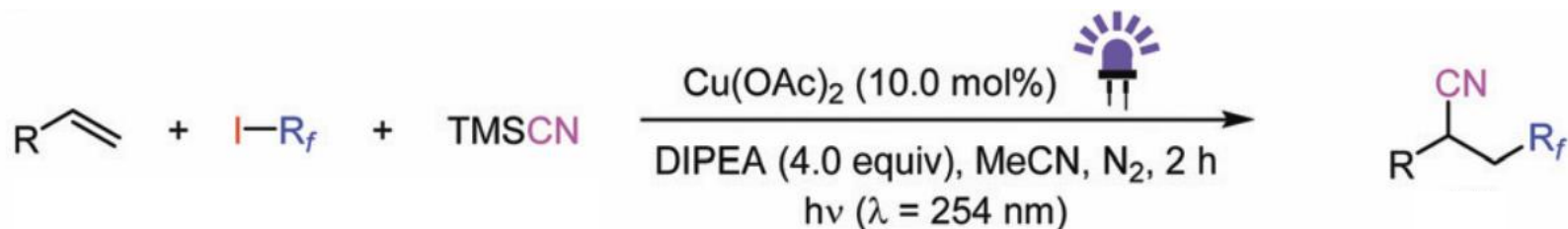
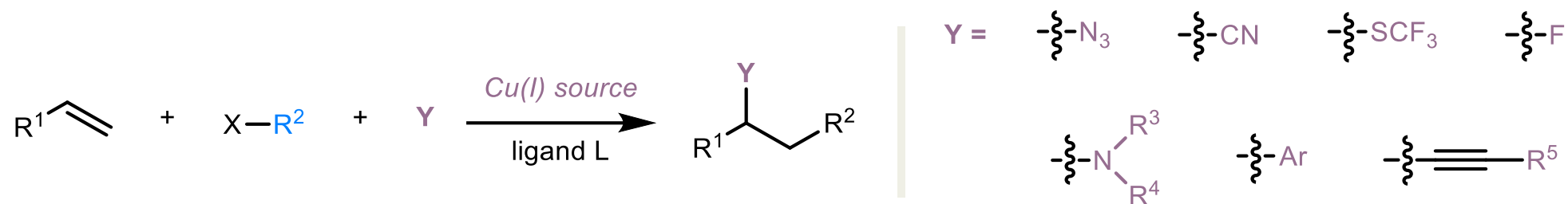
43%



57%



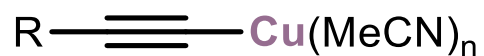
Three-component Copper Photo-ATRA reactions



Wang, R. et al. *Chem. Commun.*, **2017**, 53, 12317–12320.

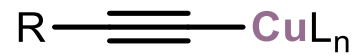
Xu, Z. et al. *ACS Catal.*, **2019**, 9, 4470–4476.

Recall



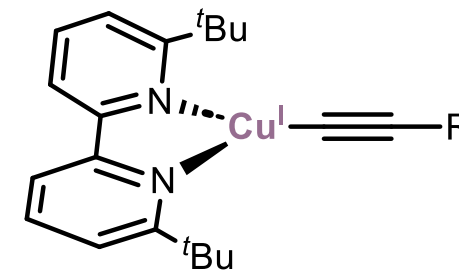
highly reductive

$$E_{\text{red}} = -2.05 \text{ V vs. SCE in MeCN}$$



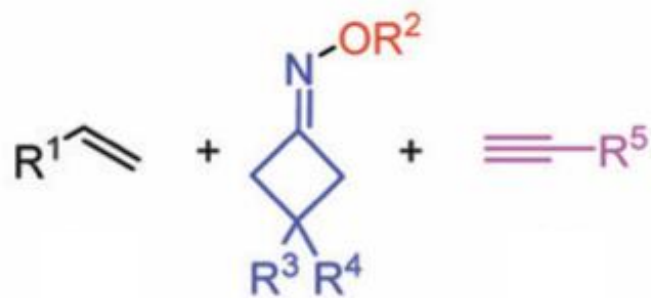
less effective

$$E_{\text{red}} = -0.89 \text{ V vs. SCE in DMF}$$



highly reductive

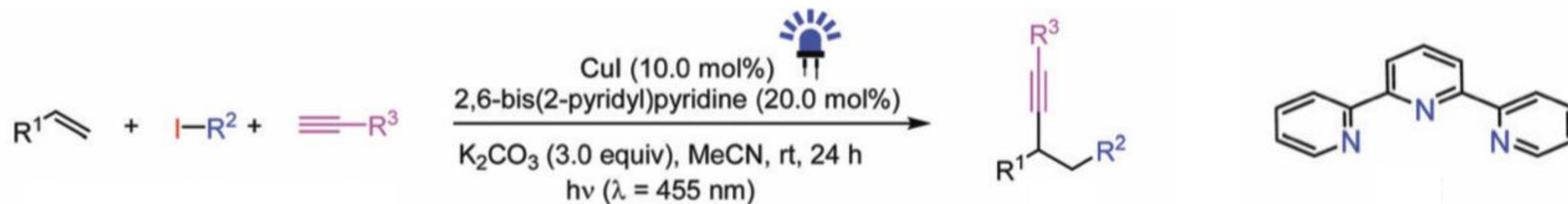
$$E_{\text{red}} = -2.82 \text{ V vs. SCE in DMF}$$



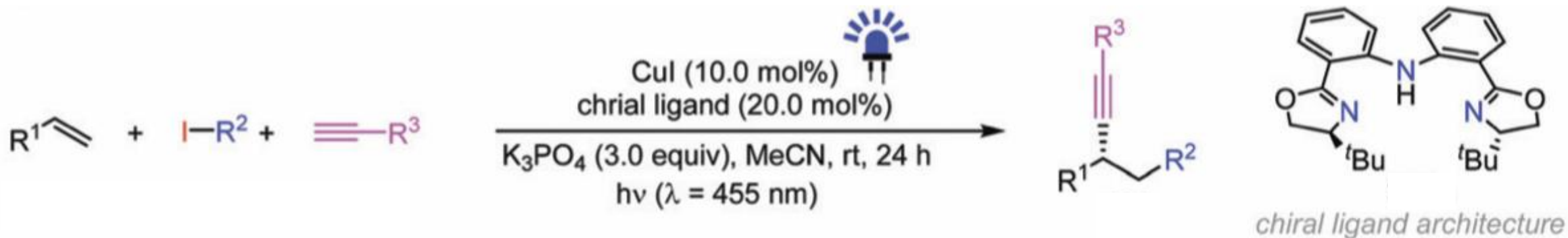
$$E_{\text{red}} = -2.18 \text{ V vs. SCE in DMF}$$

Xiao, W.-J. *et al. Org. Lett.*, **2019**, *21*, 4359–4364.

Three-component Copper Photo-ATRA reactions

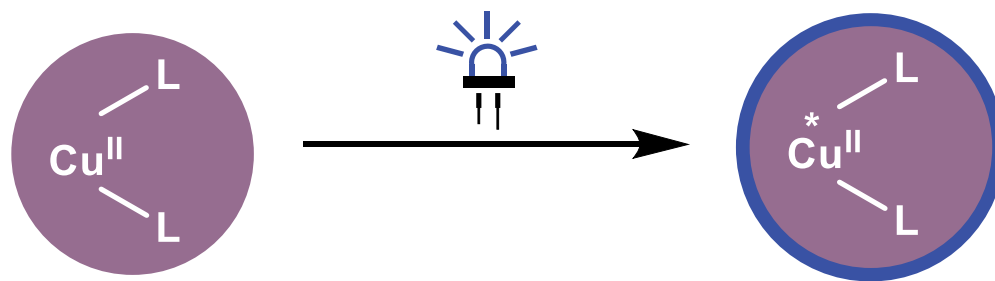


Zhang, D. *et al. J. Org. Chem.*, **2020**, 85, 3213–3223.



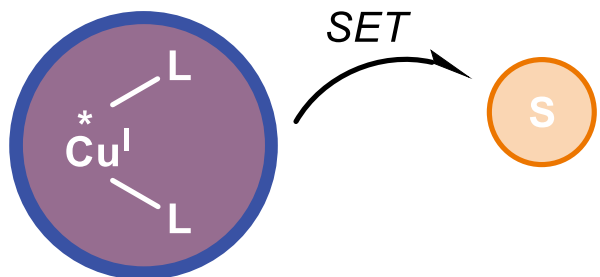
Zhang, D. *et al. Org. Lett.*, **2020**, 22, 1490–1494.

Cu(II) Complexes as Standalone Photocatalysts

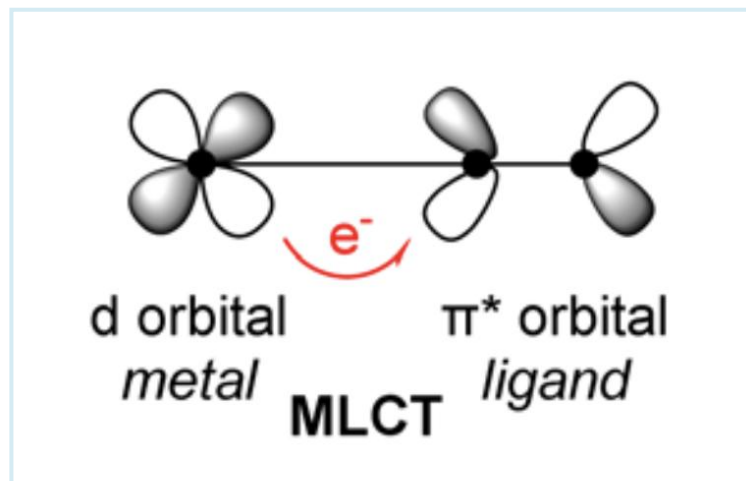


Contrast

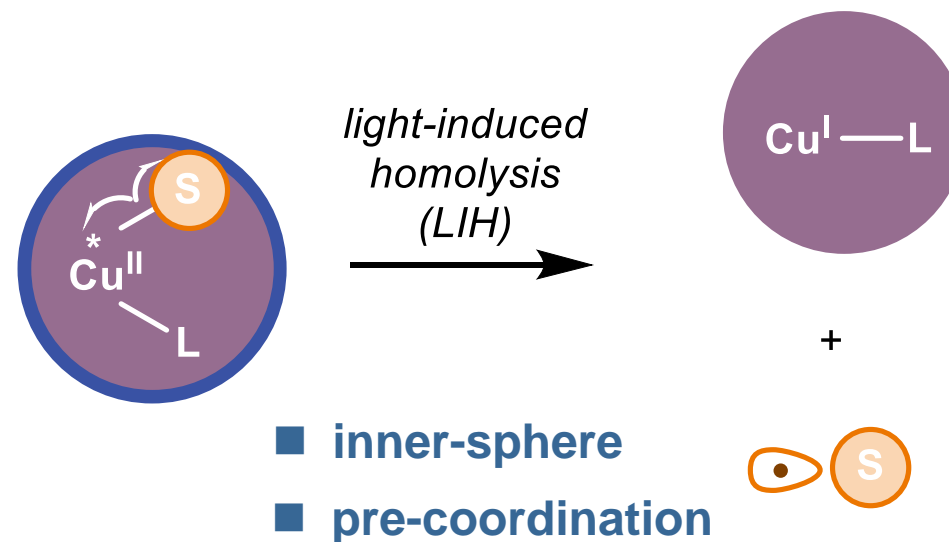
Excited Cu(I) complex



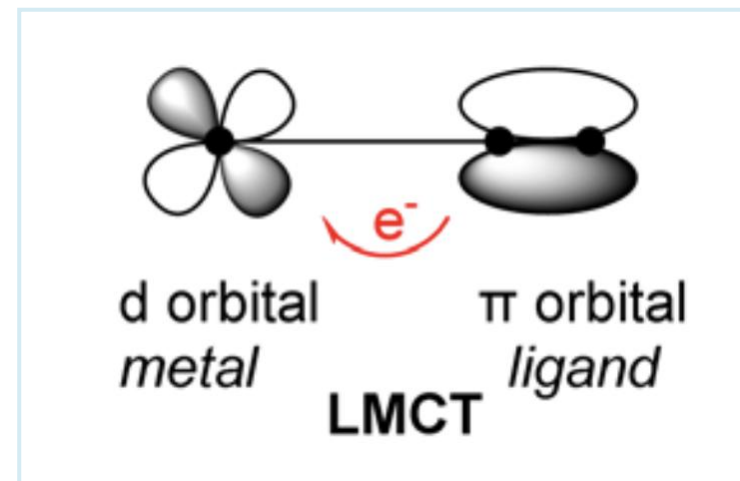
- outer-sphere
- bimolecular quenching
- Need long-lived excited state



Excited Cu(II) complex



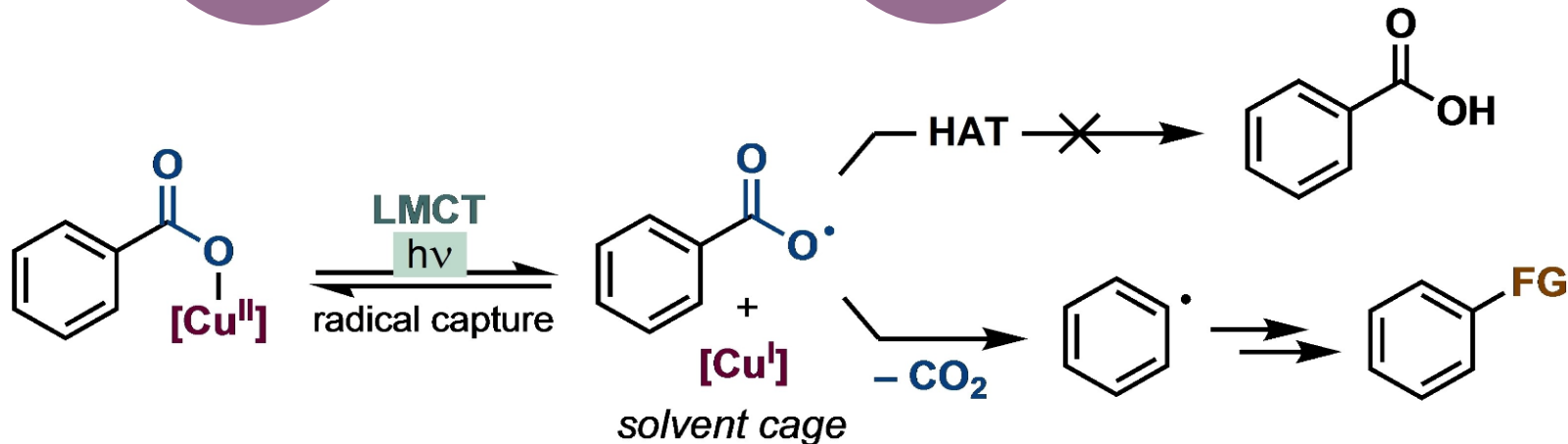
- inner-sphere
- pre-coordination



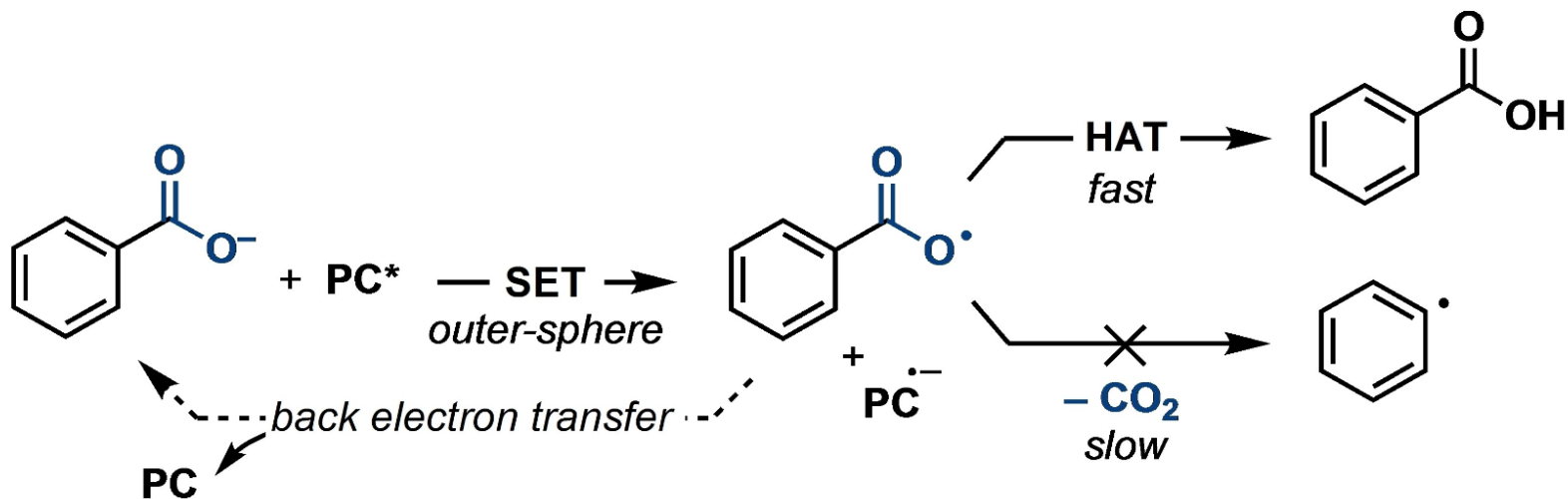
Contrast



LMCT



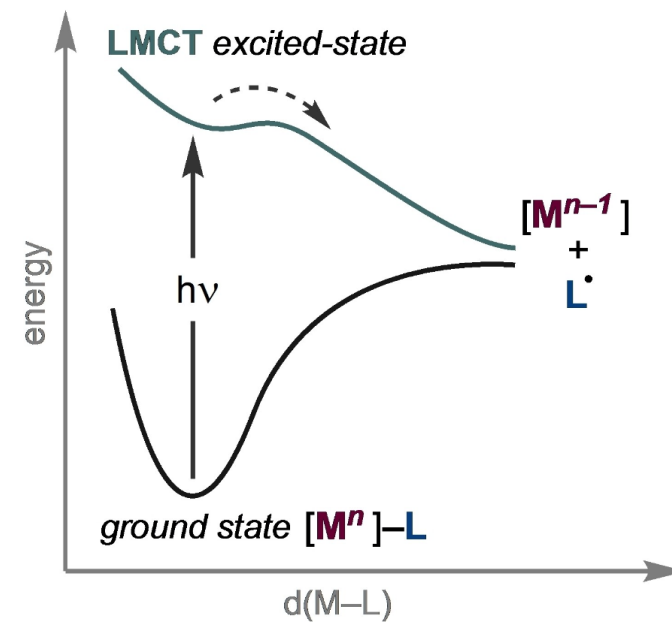
Photoredox



Questions



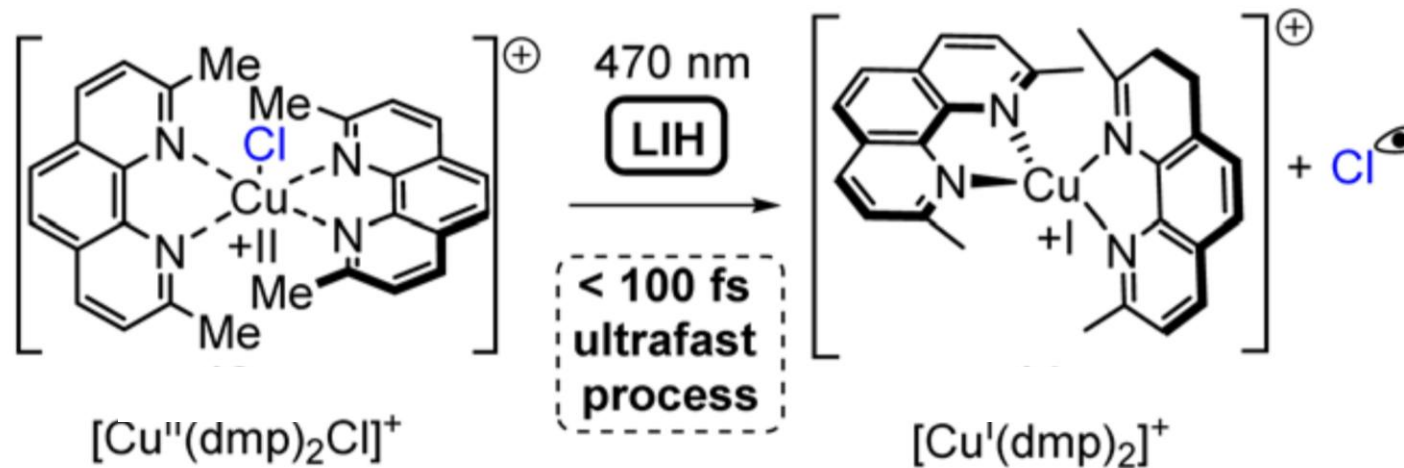
- Which metal–(ligand)–substrate complexes can undergo light-induced homolysis reactions?
- On what time scale does the homolysis reaction occur?
- How efficient is the homolysis process?
- How to make transformations catalytic?



Answers



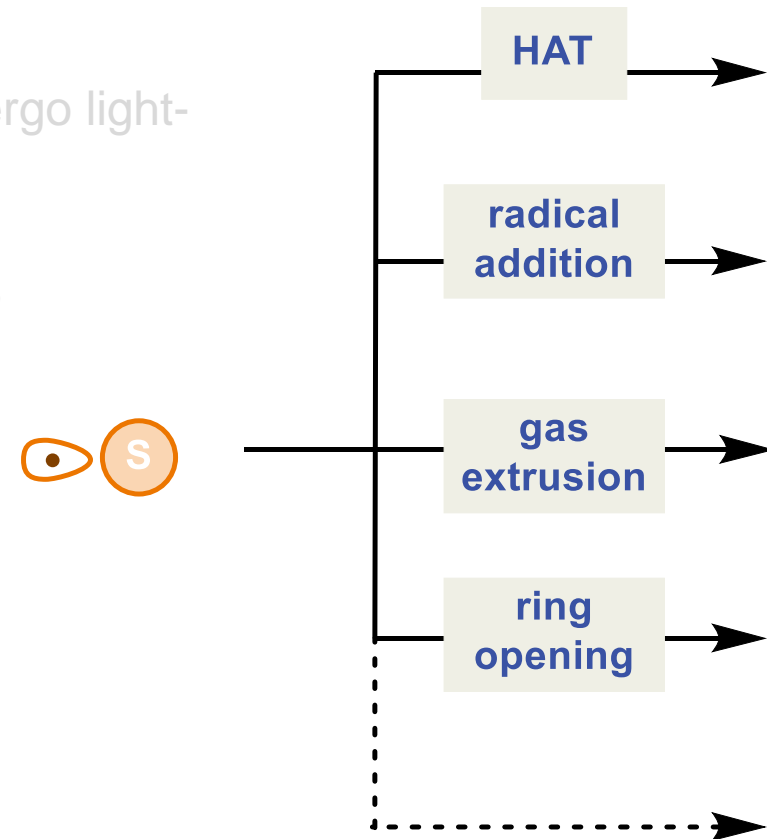
- Which metal–(ligand)–substrate complexes can undergo light-induced homolysis reactions?
- On **what time scale** does the homolysis reaction occur?



Answers



- Which metal–(ligand)–substrate complexes can undergo light-induced homolysis reactions?
- On what time scale does the homolysis reaction occur?
- How **efficient** is the homolysis process?

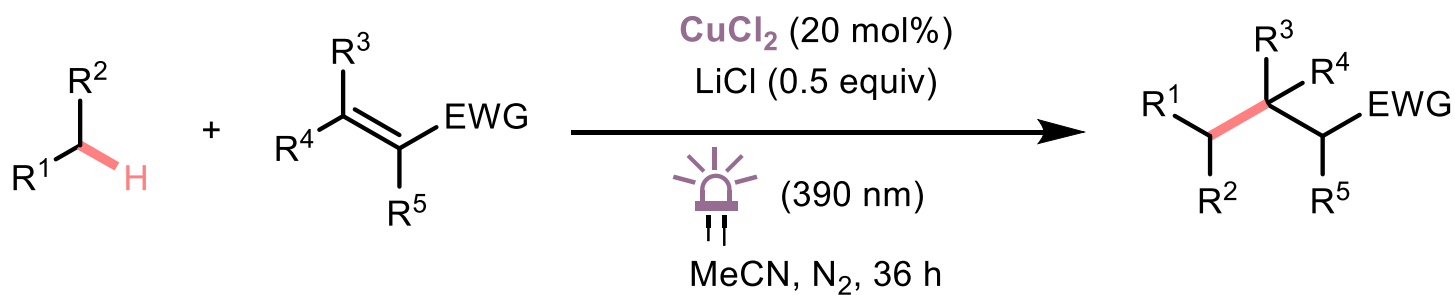


Answers

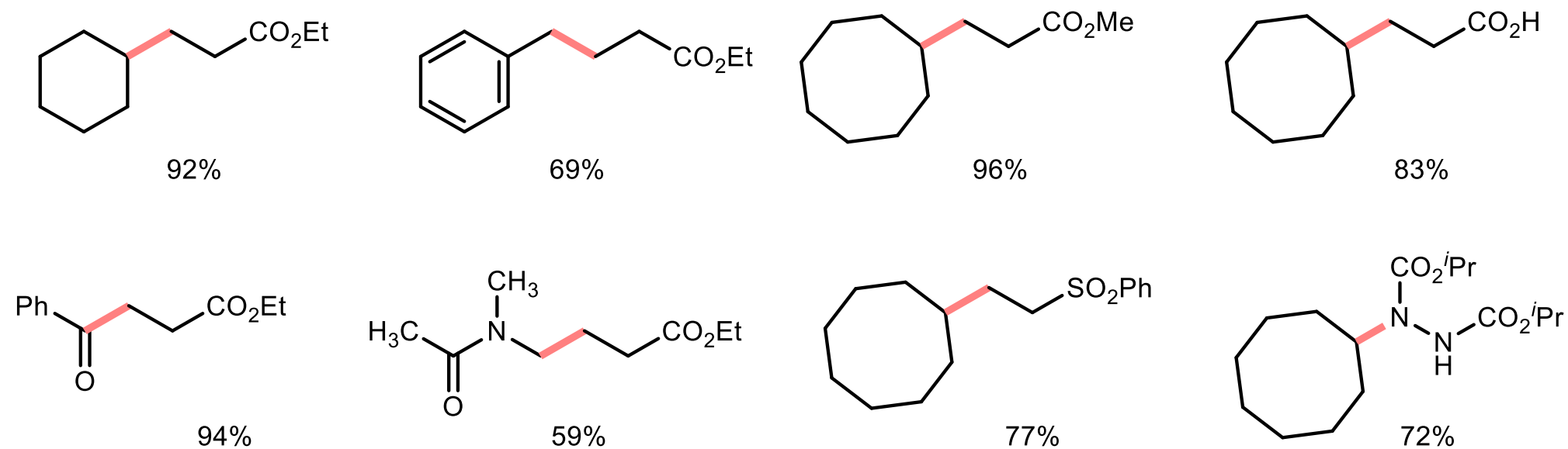


- Which metal–(ligand)–substrate complexes can undergo light-induced homolysis reactions?
- On what time scale does the homolysis reaction occur?
- How efficient is the homolysis process?
- How to make transformations **catalytic**?

CuCl₂-mediated Activation of Aliphatic Compound

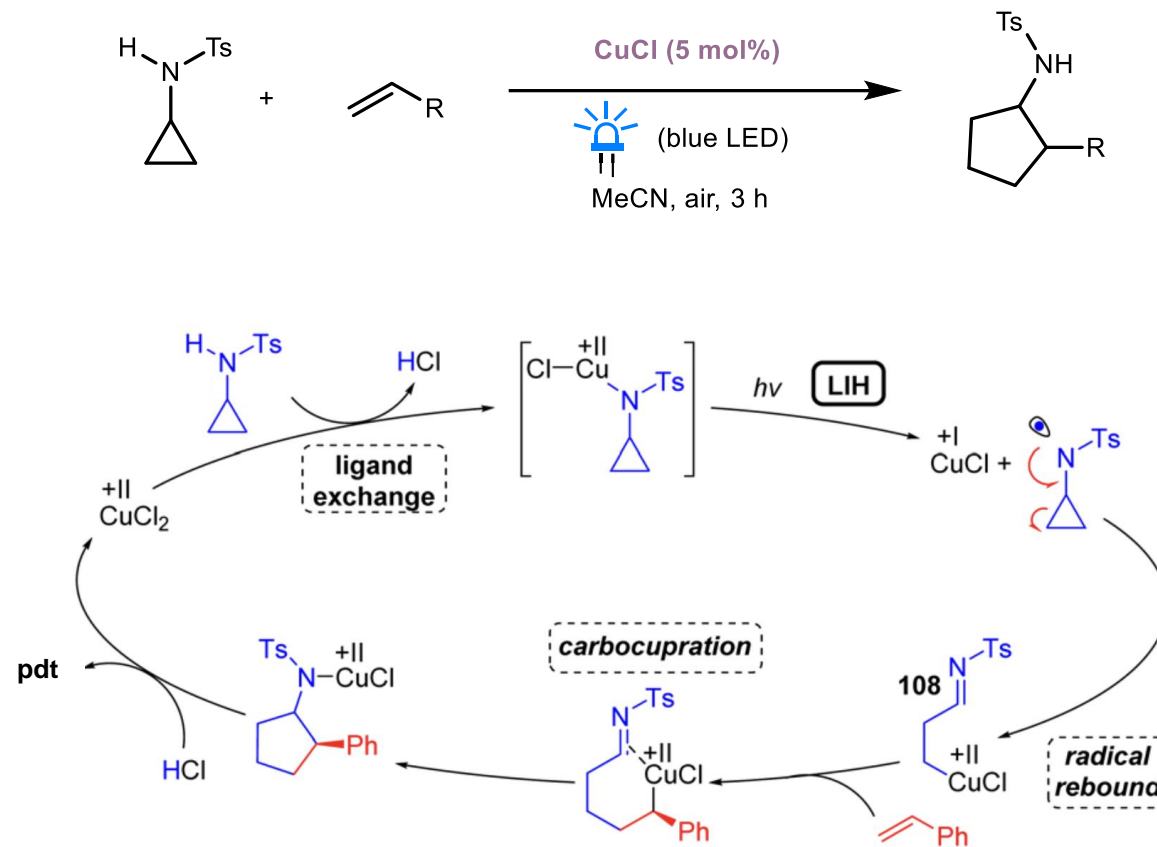
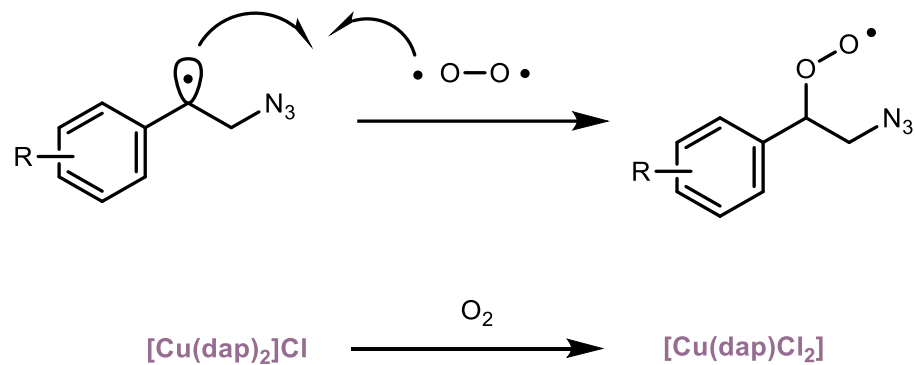
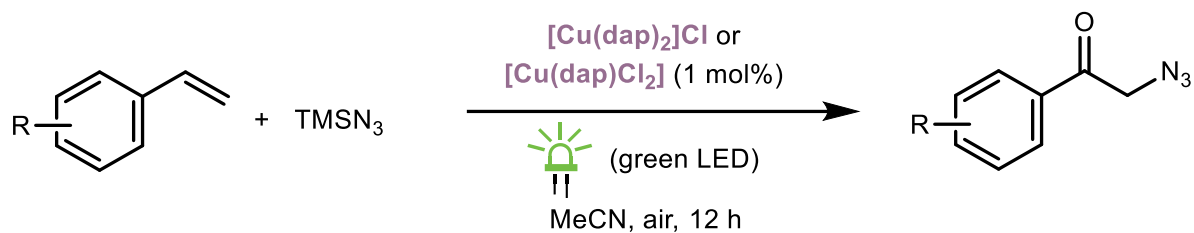


Selected example:



Rovis, T. *et al. J. Am. Chem. Soc.*, **2021**, *143*, 2729– 2735.

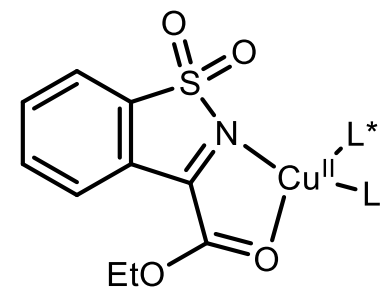
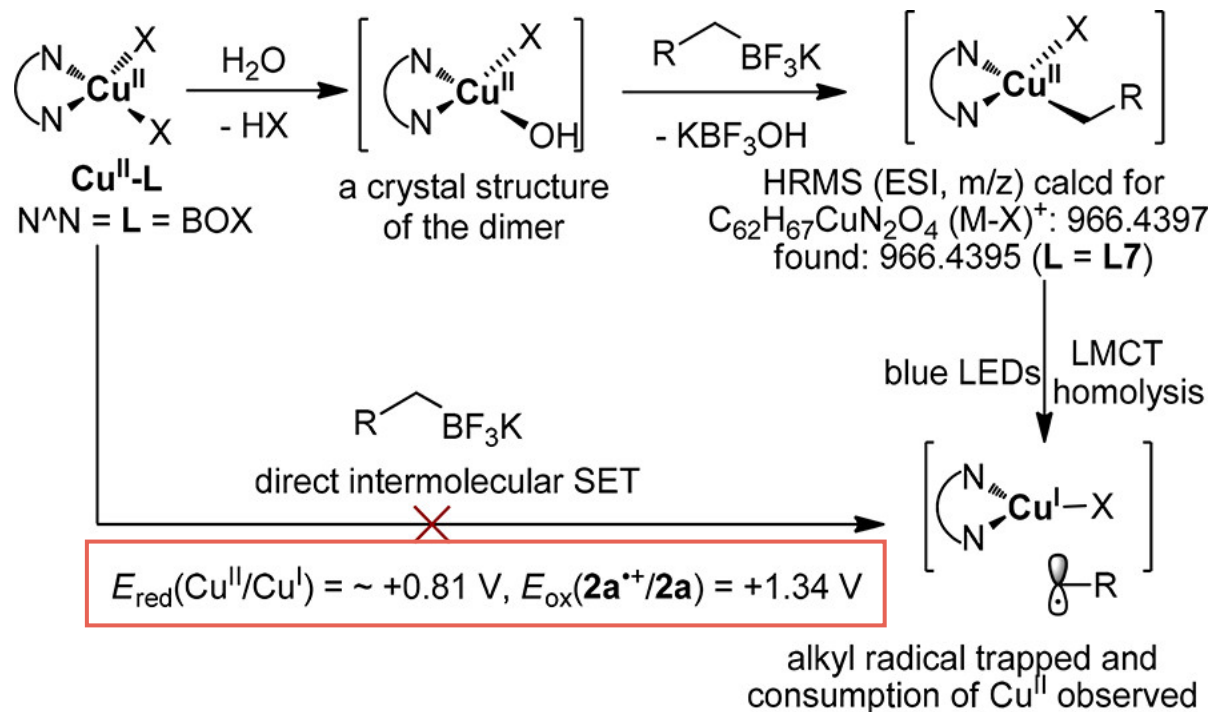
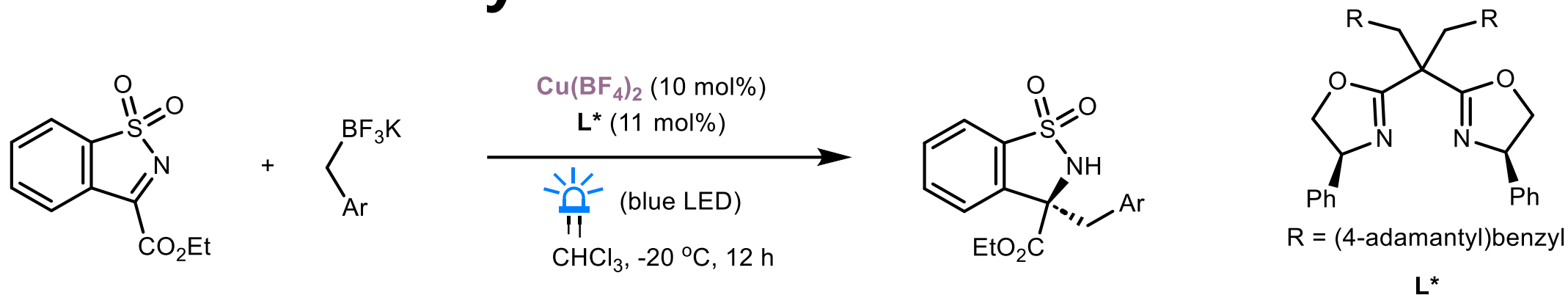
CuCl₂-mediated Activation of Aliphatic Compound



Reiser, O. *et al. Angew. Chem., Int. Ed.*, **2018**, *57*, 8288–8292.

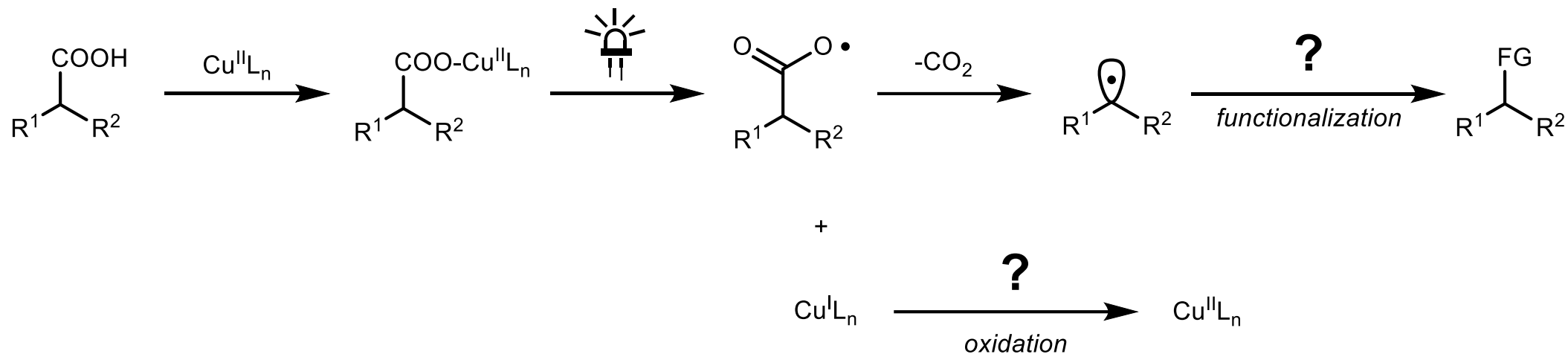
Verma, A. K. *et al. J. Org. Chem.*, **2022**, *87*, 6263–6272.

Enantioselective Alkylation of Imines



Cu(II) also plays a role of Lewis acid.

Decarbonative Functionalization of Carboxylic Acid



Goals

- Value-added building blocks



- Find good **radicalophiles**

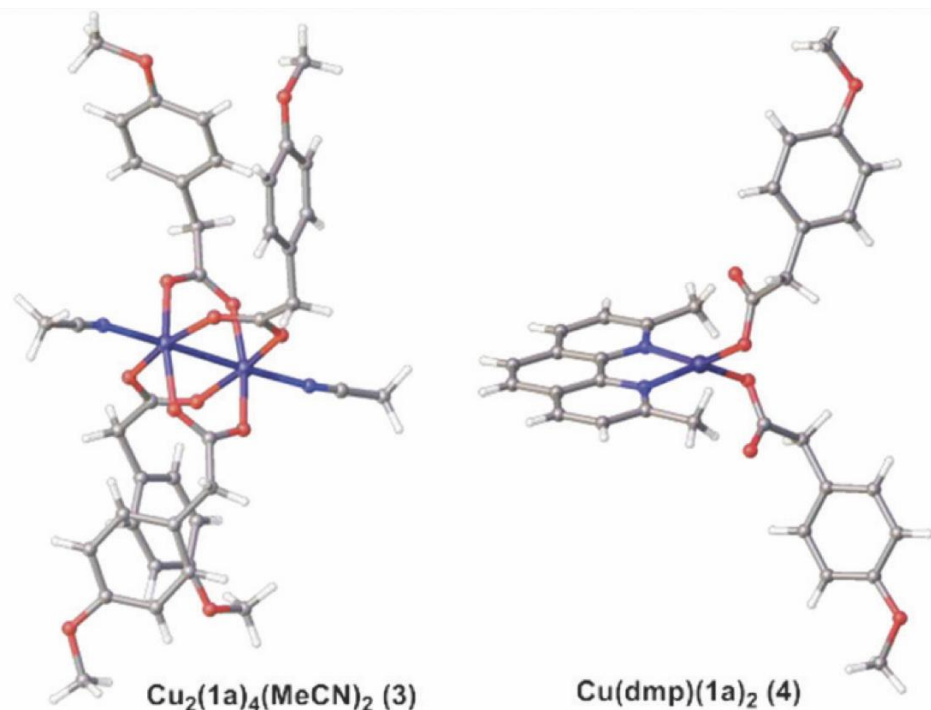
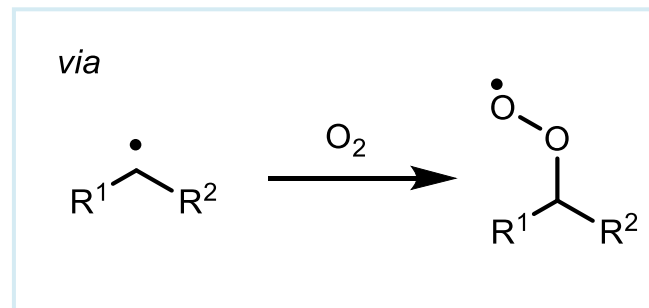
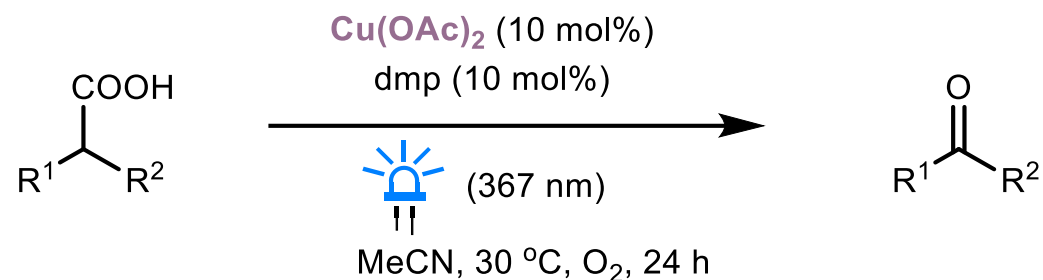


- Achieve catalytic turnover



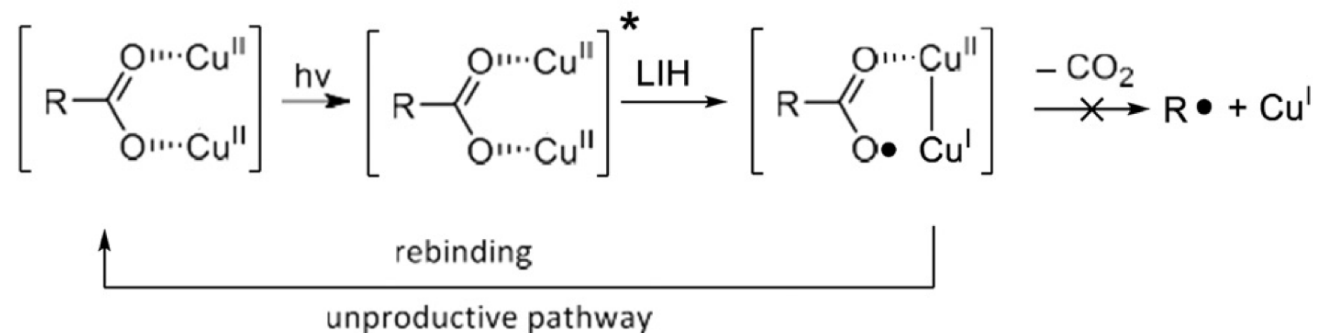
- Find **suitable oxidants**

Decarbonlative Oxygenation of Carboxylic Acid



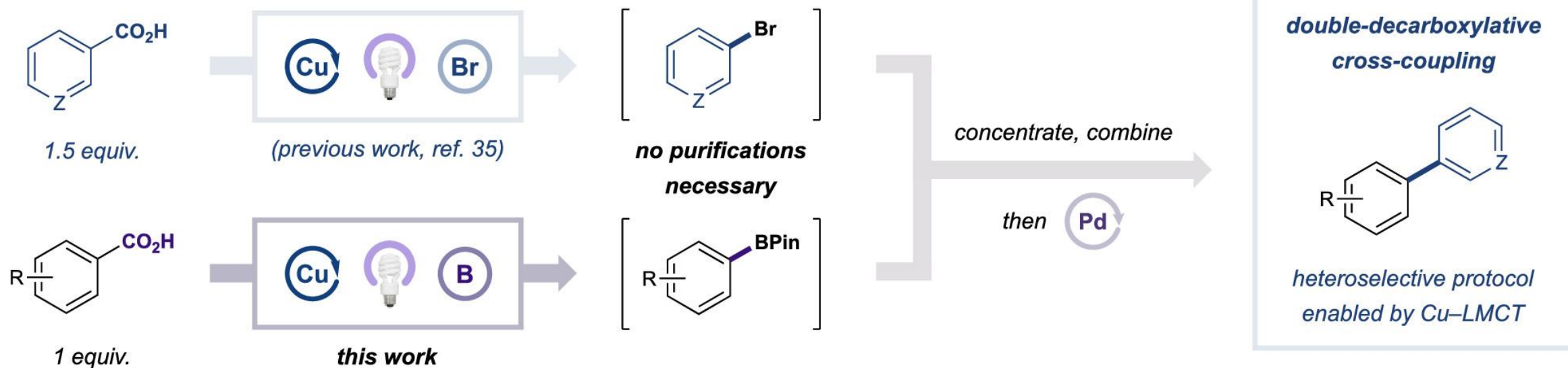
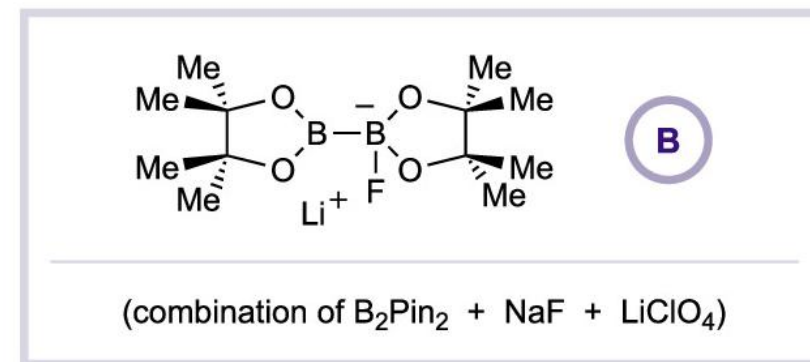
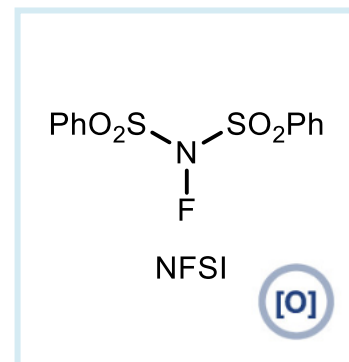
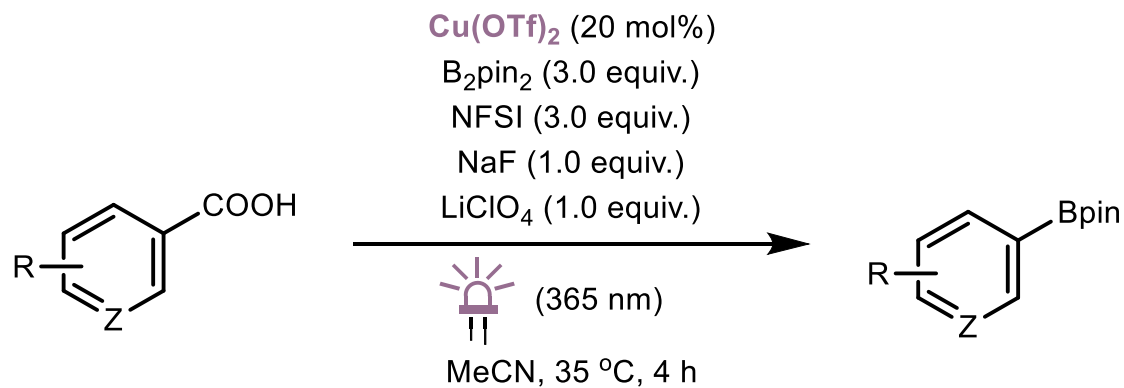
w/o dmp

w/ dmp

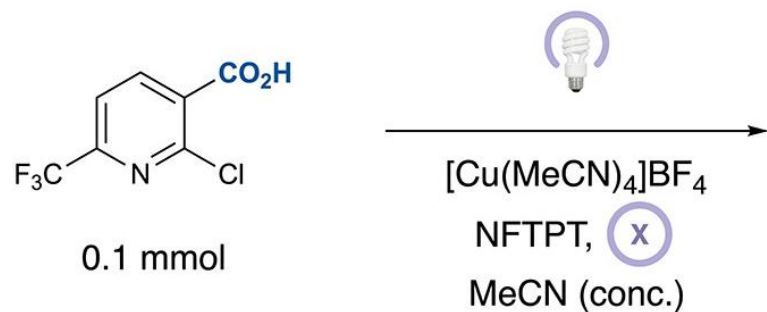


Reiser, O. *et al. Chem. Commun.* **2022**, 58, 4456–4459.

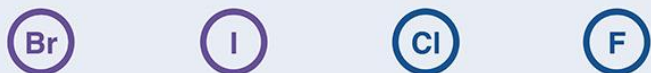
Decarbonlative Borylation of Carboxylic Acid



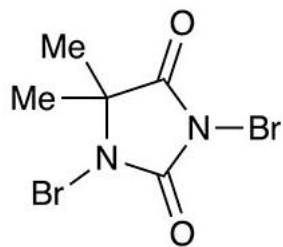
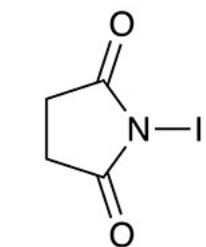
Decarbonlative Halogenation of Carboxylic Acid



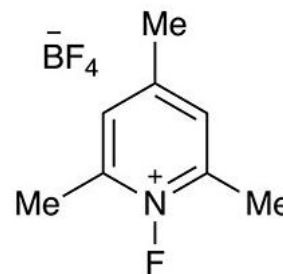
>10 examples with all four halogenations



	 56% yield ^a	 70% yield	 62% yield ^a	 51% yield ^a
Cu	20 mol%	20 mol%	100 mol%	300 mol%
Ox	1 equiv.	1 equiv.	1.5 equiv.	2 equiv.
X	NIS (1 equiv.)	DBDMH (0.75 equiv.)	ZnCl ₂ (1 equiv.)	—
<i>conc.</i>	0.1 M, 4 h	0.1 M, 4 h	0.1 M, 12 h	0.05 M, 24 h



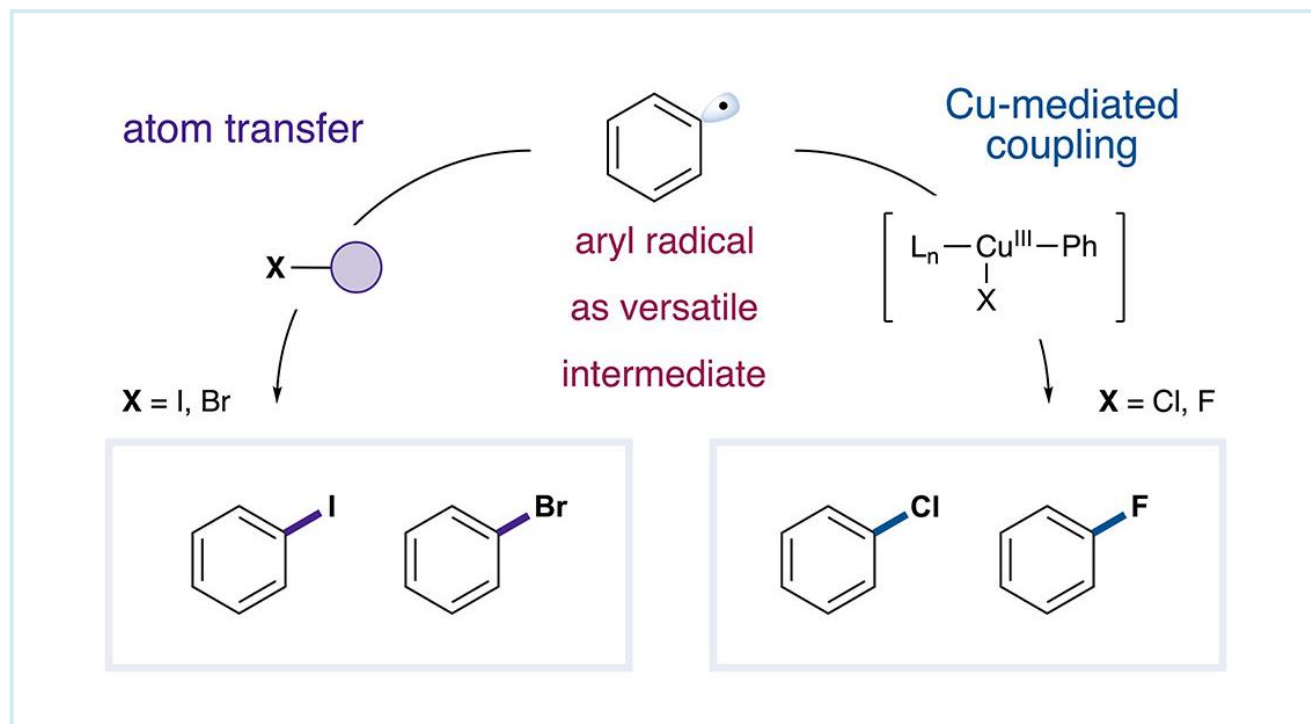
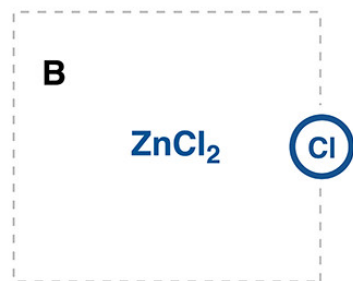
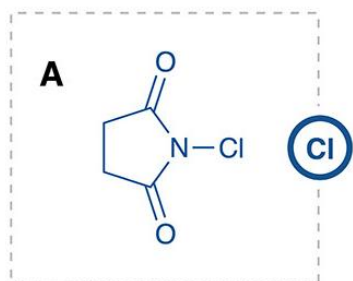
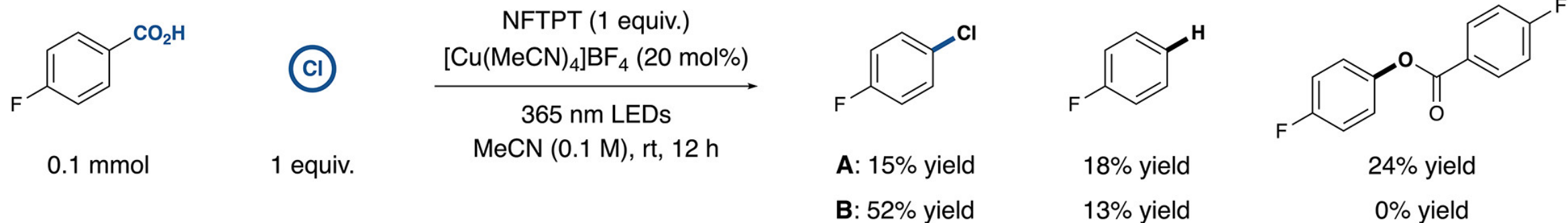
ZnCl₂



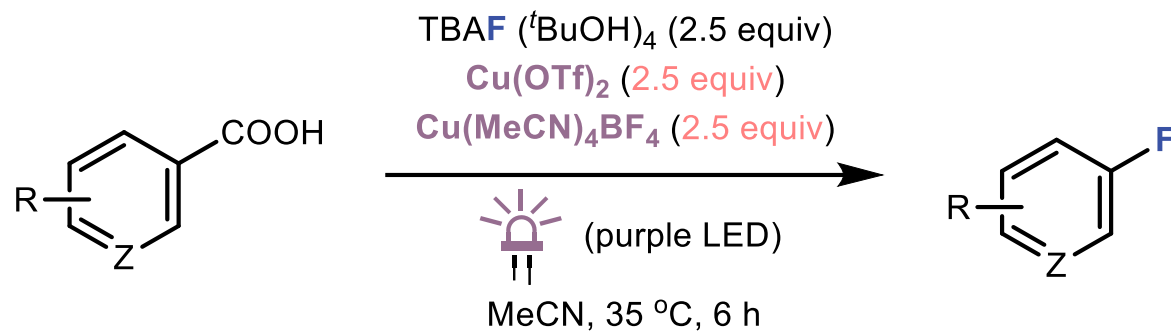
NFTPT

MacMillan, D. W. C. *et al.* *J. Am. Chem. Soc.*, **2022**, *144*, 6163–6172.

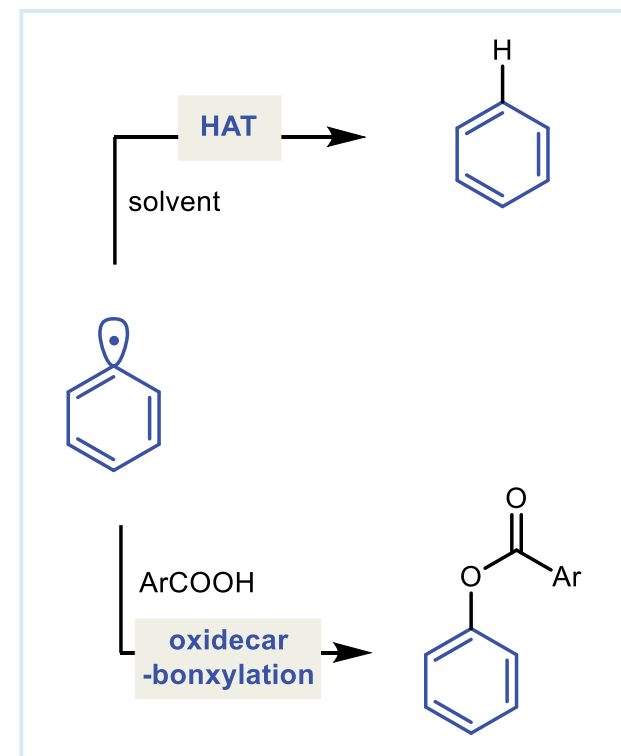
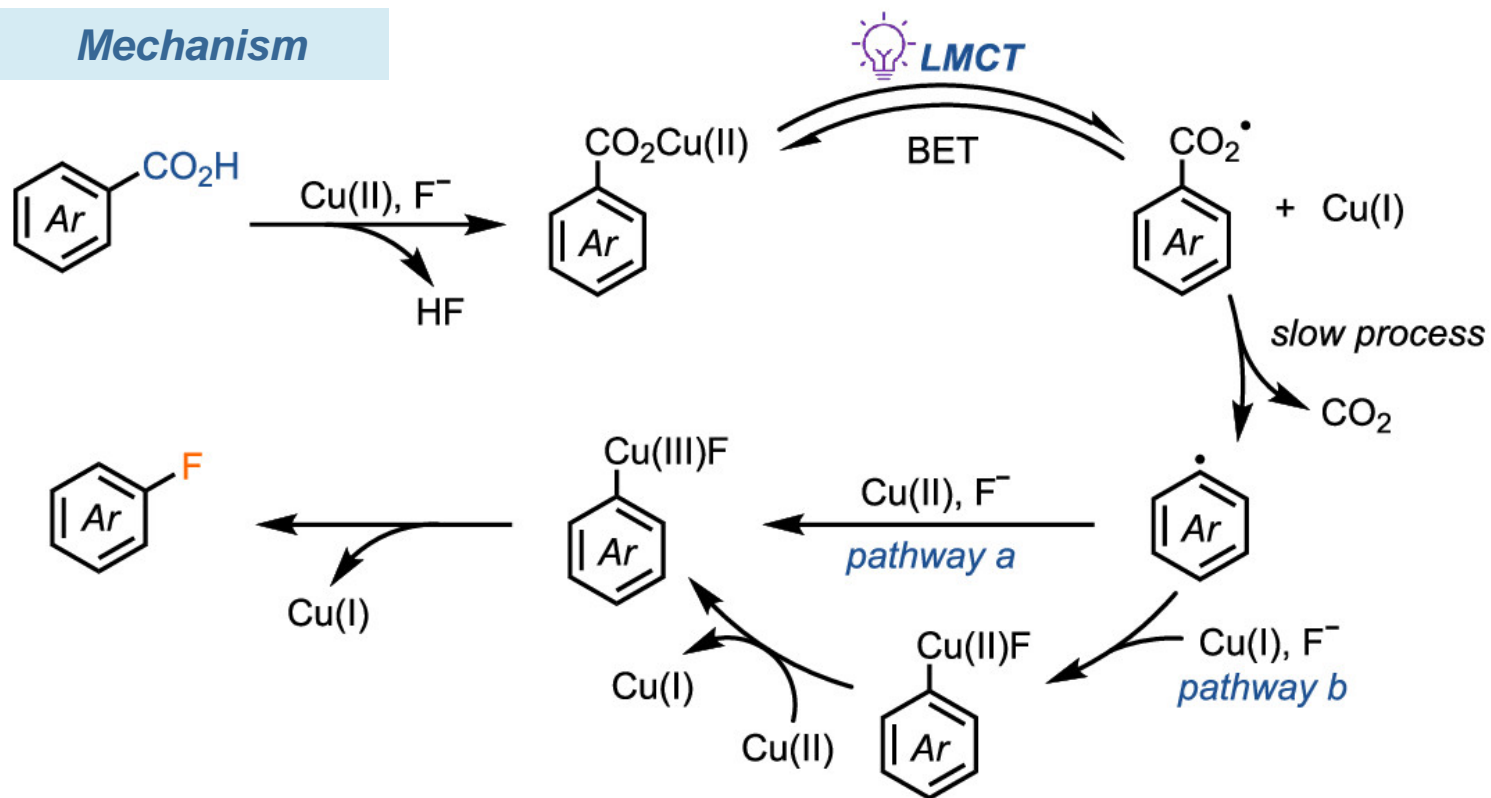
N-chlorosuccinimide vs. ZnCl₂ as Chlorination Reagent



Decarbonlative Fluorination of Carboxylic Acid

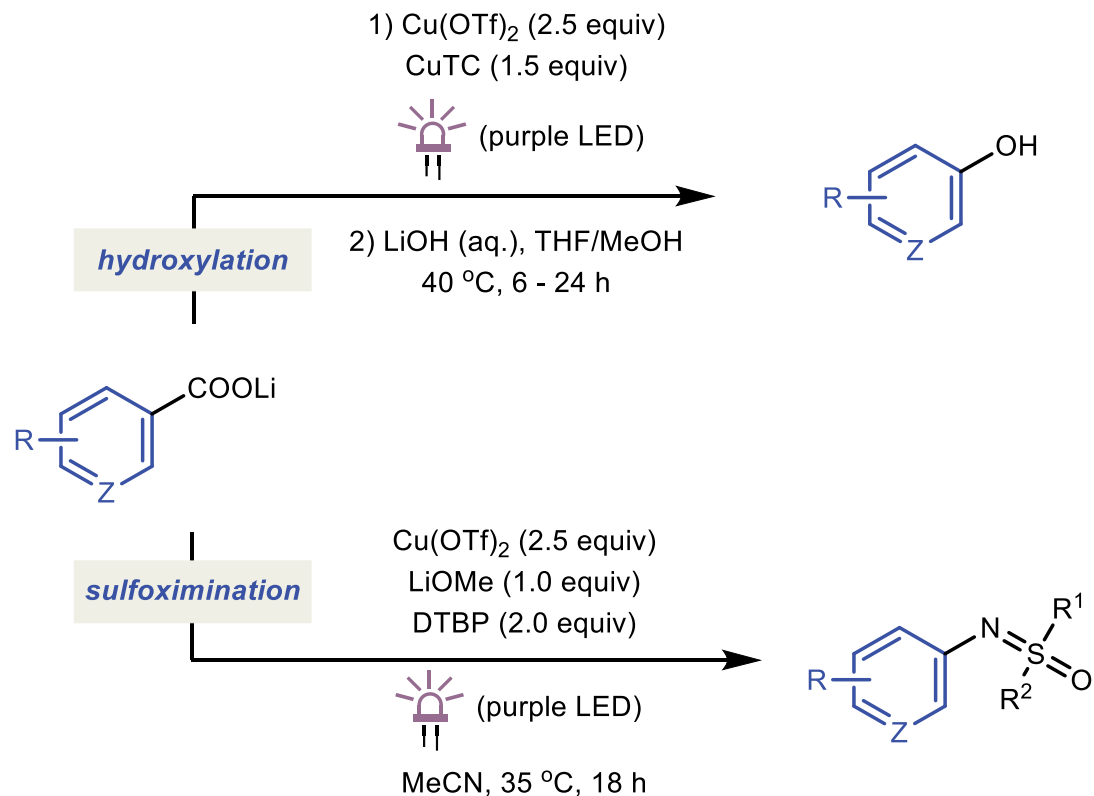


Mechanism



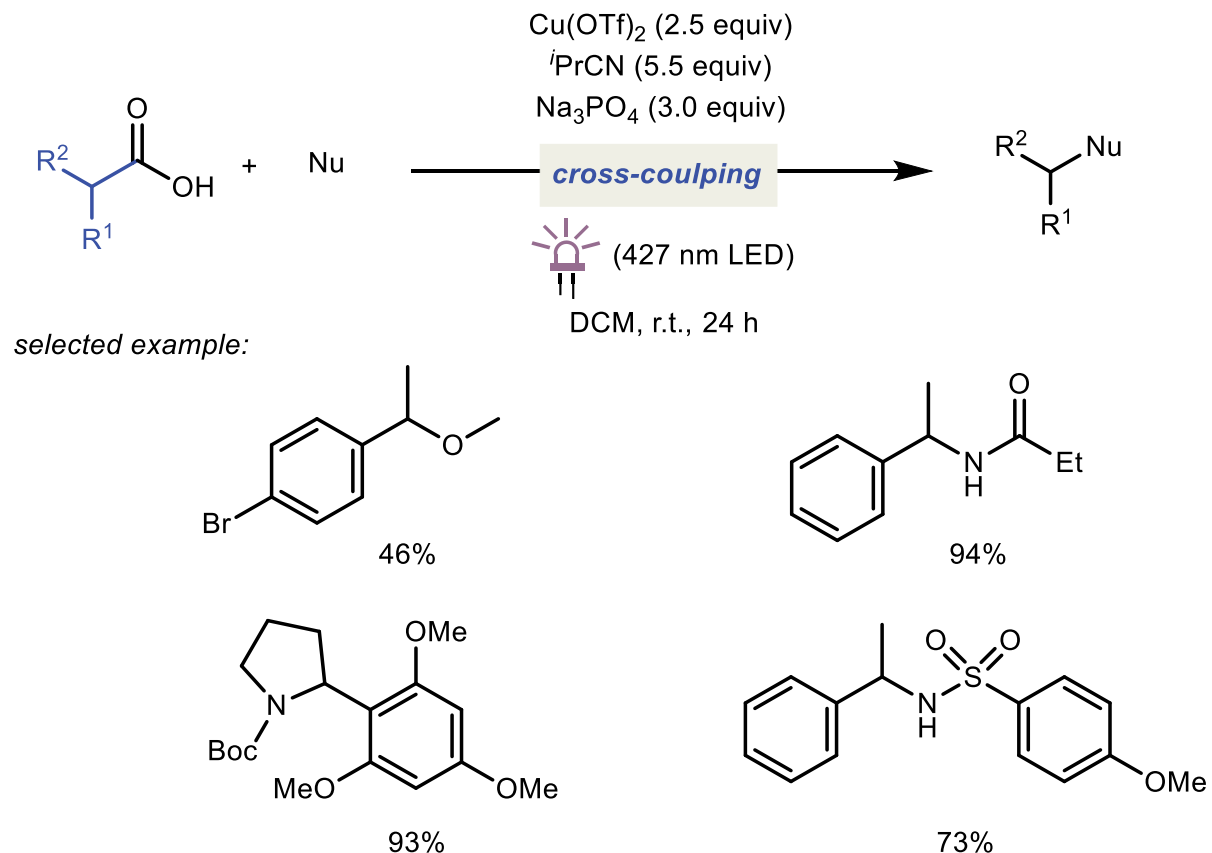
Decarbonlative Functionalization of Carboxylic Acid

Ritter et al. 2021



Ritter et al. 2022

Yoon et al. 2021

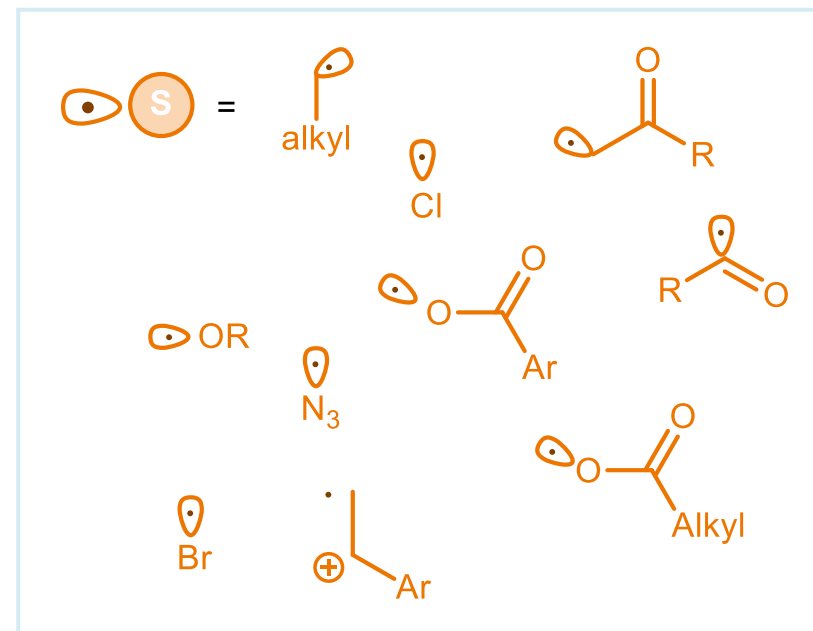
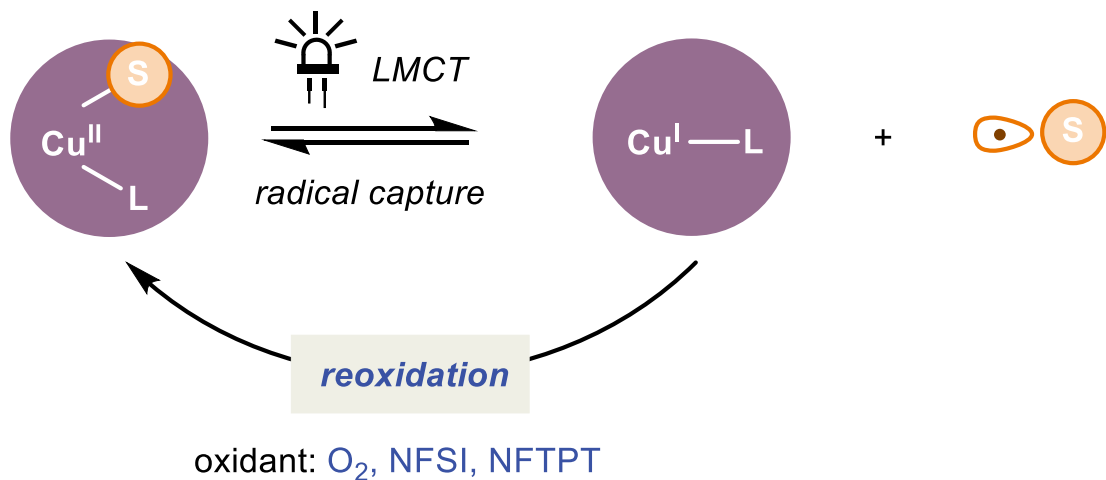
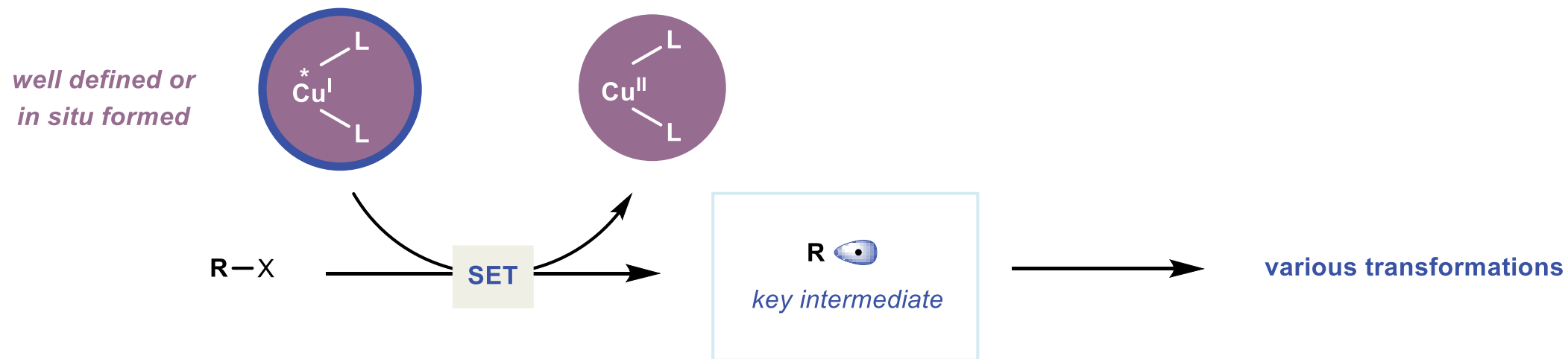


Ritter, T. et al. *Angew. Chem., Int. Ed.*, **2021**, 60, 24012–24017.

Ritter, T. et al. *Chem. Sci.*, **2022**, 13, 13611–13616.

Yoon, T. P. et al. *Nat. Chem.*, **2022**, 14, 94–99.

Summary



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