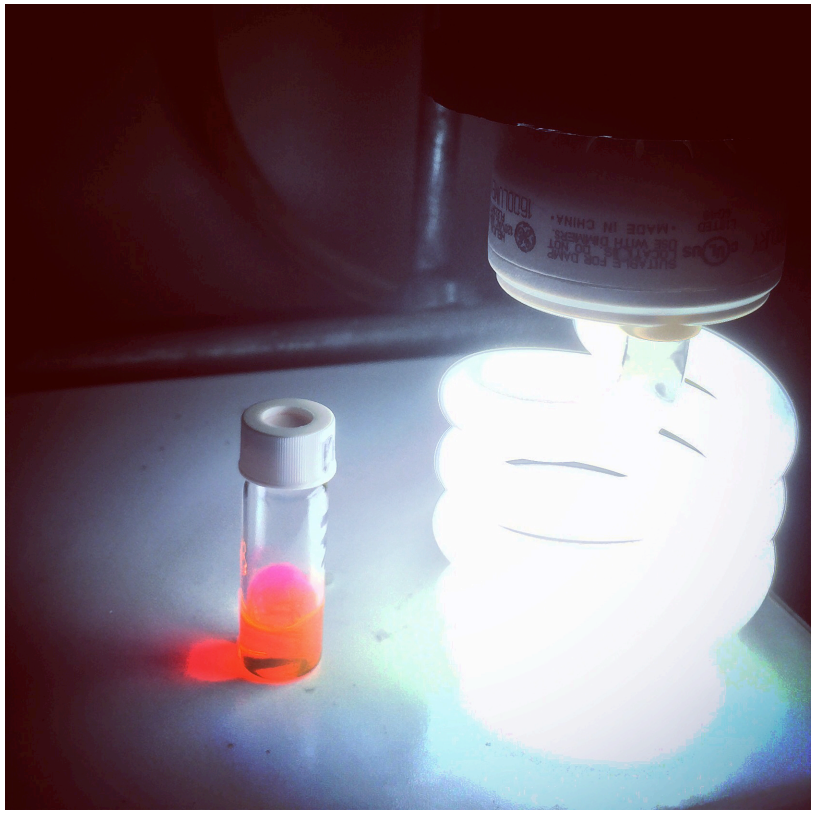
A brief overview of Transition Metal Photoredox Catalysis as a tool for organic synthesis



Literature Review Presentation
Dimitri Caputo
7th December 2016

Outline

1. Introduction
2. Photoredox catalysis
3. Functional group interconversion
4. C-C bond formation
5. Conclusions

Introduction

Contemporary definition

"Photoredox catalysis is a branch of catalysis that harnesses the energy of visible light to accelerate a chemical reaction via a single-electron transfer."

- Wikipedia

Introduction

Contemporary definition

"Photoredox catalysis is a branch of catalysis that harnesses the energy of visible light to accelerate a chemical reaction via a single-electron transfer."

- Wikipedia

"In a general sense, this approach relies on the ability of metal complexes and organic dyes to engage in single-electron transfer processes with organic substrates upon photoexcitation with visible light."

-MacMillan

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.*, **2013**, *113*, 5322

Introduction

Contemporary definition

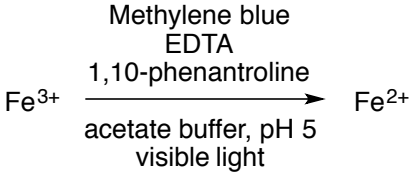
"Photoredox catalysis is a branch of catalysis that harnesses the energy of visible light to accelerate a chemical reaction via a single-electron transfer."

- Wikipedia

"In a general sense, this approach relies on the ability of metal complexes and organic dyes to engage in single-electron transfer processes with organic substrates upon photoexcitation with visible light."

-MacMillan

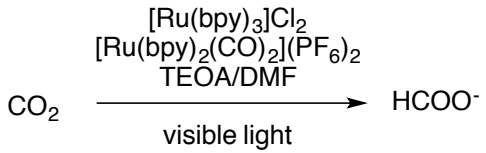
Early reports: late 1950's

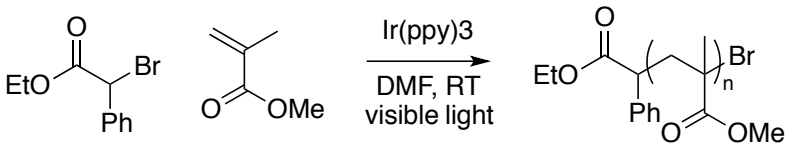


C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.*, **2013**, *113*, 5322
G. K. Oster, G. Oster, *J. Am. Chem. Soc.*, **1959**, *81*, 5543

Introduction

Applications in CO_2 reduction, radical polymerization initiation…

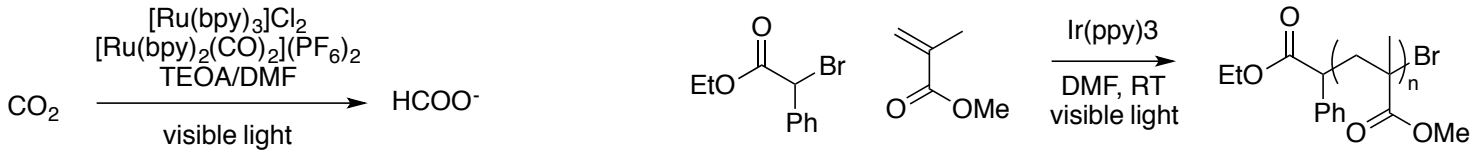




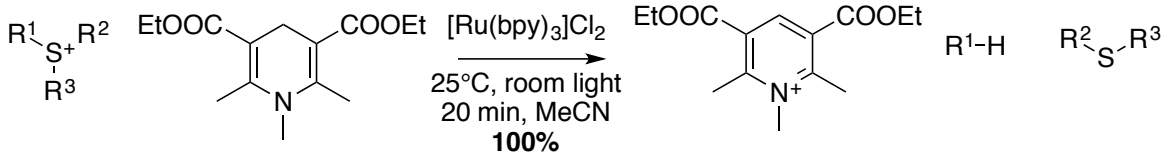
J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, *77*, 1617-1622
H. Ishida, T. Terada, K. Tanaka, T. Tanaka, *Inorg. Chem.*, **1990**, *29*, 905-911
B. P. Fors, C. J. Hawker, *Angew. Chem. Int. Ed.*, **2012**, *51*, 8850-8853

Introduction

Applications in CO_2 reduction, radical polymerization initiation…



Early applications in organic chemistry:

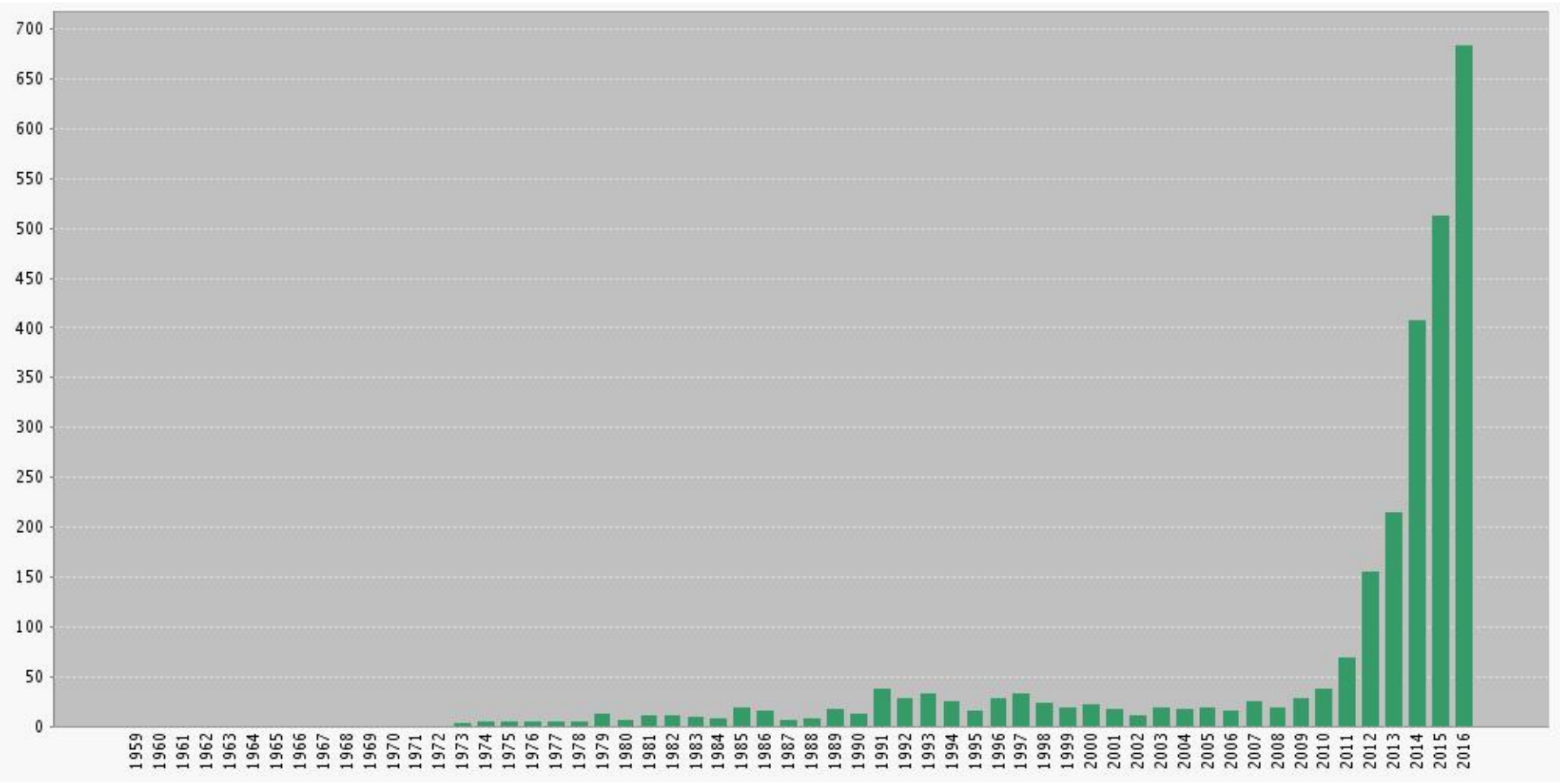


J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, *77*, 1617-1622

H. Ishida, T. Terada, K. Tanaka, T. Tanaka, *Inorg. Chem.*, **1990**, *29*, 905-911

B. P. Fors, C. J. Hawker, *Angew. Chem. Int. Ed.*, **2012**, *51*, 8850-8853

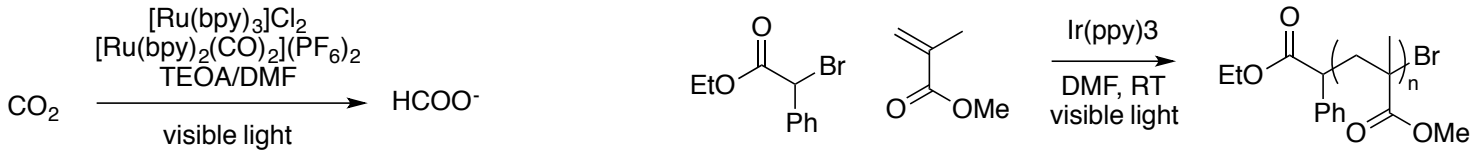
Publications in the field: exponential increase since 2008



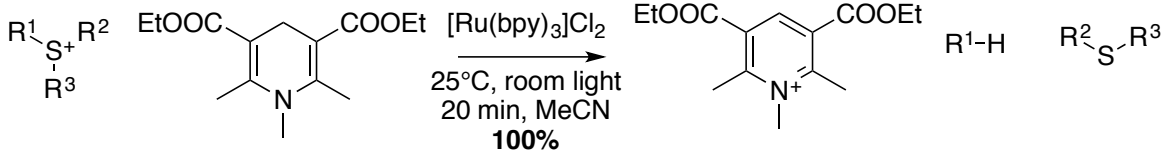
Citation report from Web Of Science™,
Basic search by topic with "photoredox", 23rd November 2016

Introduction

Applications in CO2 reduction, radical polymerization initiation…



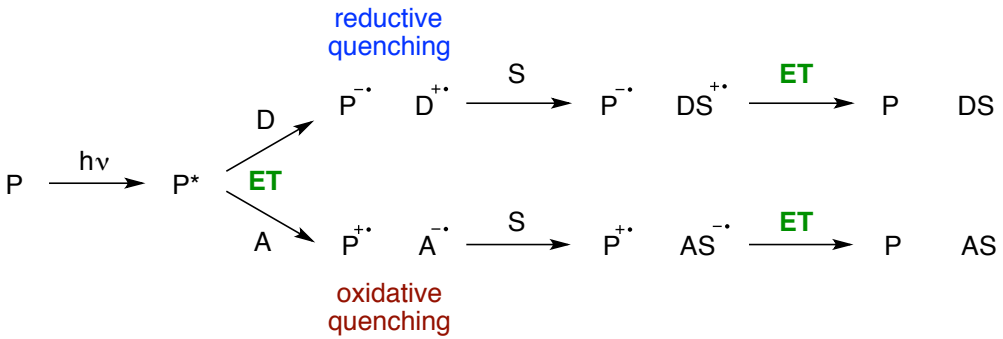
Early applications in organic chemistry:



How does it work?

J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, *77*, 1617-1622
H. Ishida, T. Terada, K. Tanaka, T. Tanaka, *Inorg. Chem.*, **1990**, *29*, 905-911
B. P. Fors, C. J. Hawker, *Angew. Chem. Int. Ed.*, **2012**, *51*, 8850-8853

Photoredox catalysis: general process



P = photocatalyst, photoredox catalyst

D = electron donor species (amine, alcohol, thiol, electron-rich arene…)

A = electron acceptor species (carbonyl, halide, electron-poor arene)

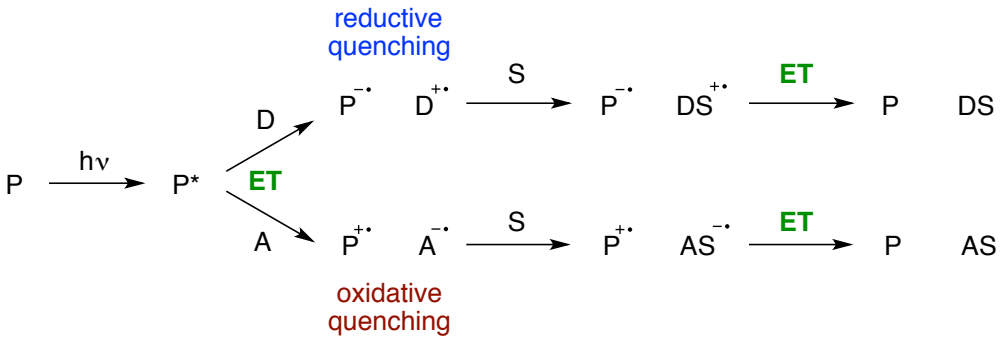
S = Redox neutral substrate

"Transition metal mediated photoredox catalysis", S. Crossley, Shenvi Lab Group Meeting, 14/09/2015

J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, *77*, 1617-1622

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.*, **2013**, *113*, 5322

Photoredox catalysis: general process

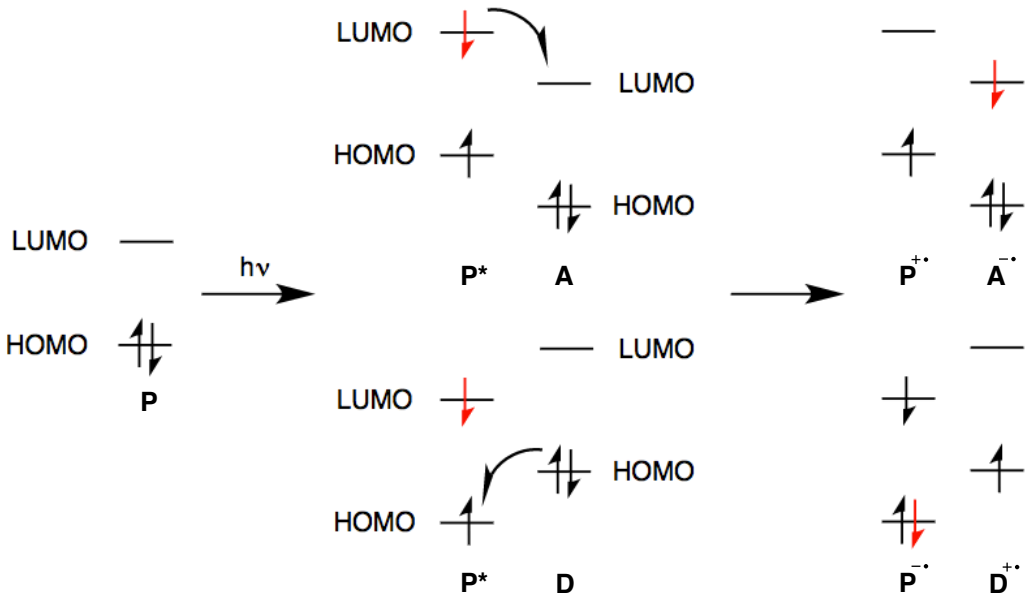


P = photocatalyst, photoredox catalyst

D = electron donor species (amine, alcohol, thiol, electron-rich arene…)

A = electron acceptor species (carbonyl, halide, electron-poor arene)

S = Redox neutral substrate

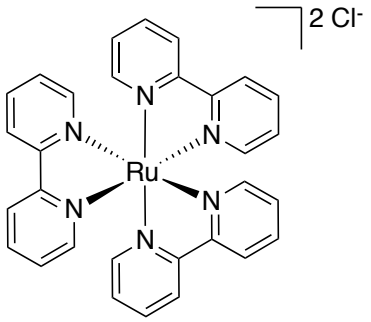


"Transition metal mediated photoredox catalysis", S. Crossley, Shenvi Lab Group Meeting, 14/09/2015

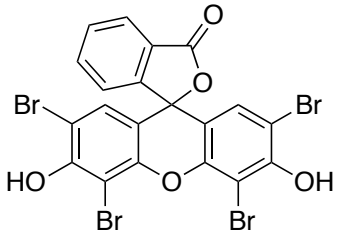
J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, *77*, 1617-1622

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.*, **2013**, *113*, 5322

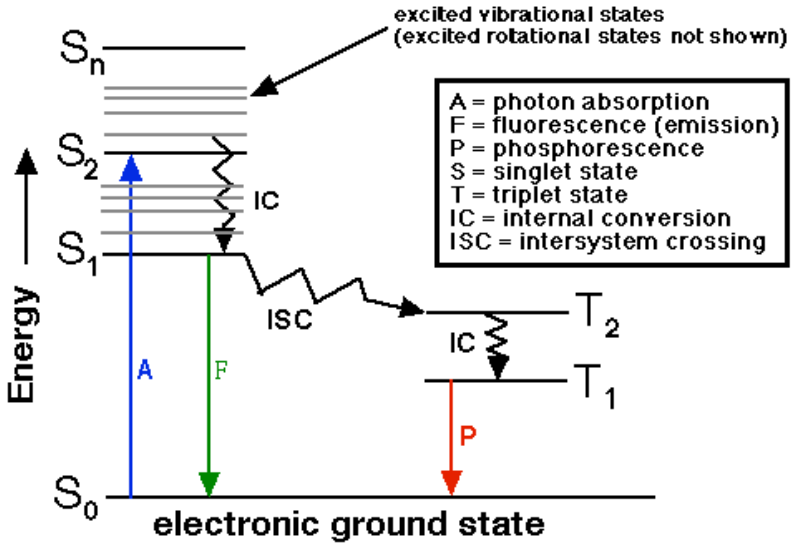
Photoredox catalysis: what about the catalyst?



Metal-ligand complex



Organic dye



http://www.shsu.edu/~chm_tgc/chemilumdir/JABLON.GIF

TM Photoredox catalysis: metals and ligands

Mostly Ru^{2+} and Ir^{3+}

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: metals and ligands

Mostly Ru^{2+} and Ir^{3+}

Electronic configuration

Ru^{2+}: $[Kr]3f^{14}4d^{6}$ Ir^{3+}: $[Xe]4f^{14}5d^{6}$

d^6 complexes

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: metals and ligands

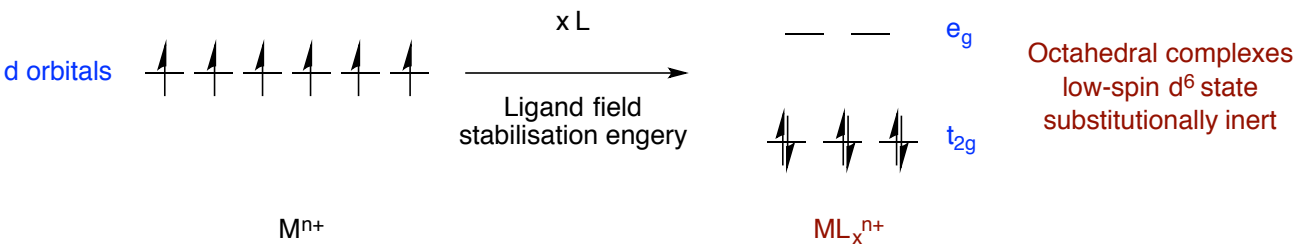
Mostly Ru^{2+} and Ir^{3+}

Electronic configuration

Ru^{2+}: $[Kr]3f^{14}4d^{6}$ Ir^{3+}: $[Xe]4f^{14}5d^{6}$

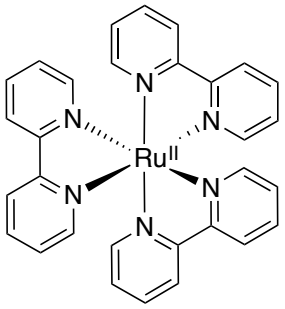
d^6 complexes

Ligand field theory:



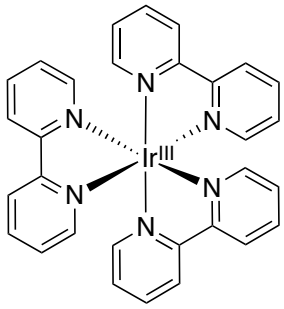
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: intrinsic properties of metal



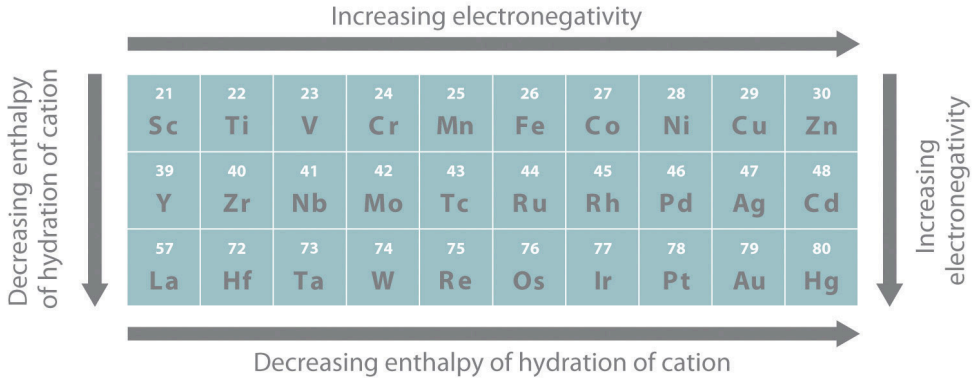
$Ru(bpy)_3^{2+}$

Ru(II)*/Ru(III) = – 0.81 V
Ru(II)*/Ru(I) = 0.77 V



$Ir(bpy)_3^{3+}$

Ir(III)*/Ir(IV) = – 0.88 V
Ir(III)*/Ir(II) = 1.81 V



Similar reducing properties

Ir complex stronger oxidant than Ru complex

(same set of ligand)

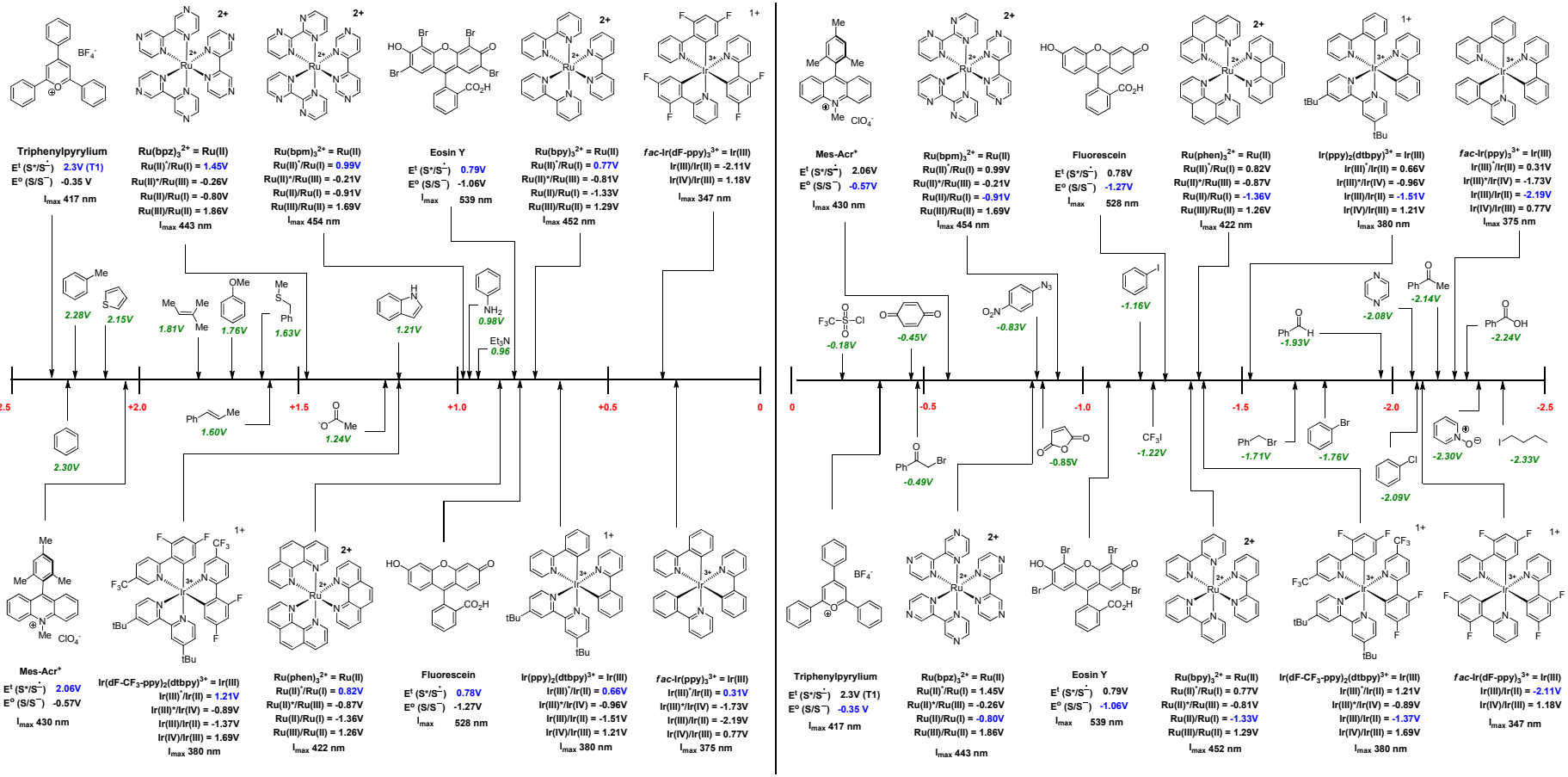
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
"Chemistry: Principles, Patterns, and Applications", Chapter 23, B. A. Averill, P. Eldredge,

Electrochemical Series of Photocatalysts and Common Organic Compounds

Excited State Oxidations

E^* (V vs SCE))

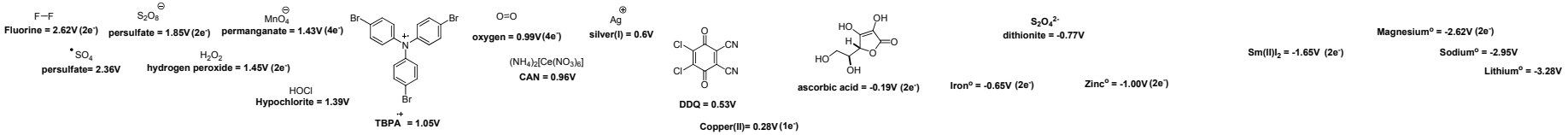
Reduced State Reductions



Common Oxidizing Agents

E^* (V vs SCE))

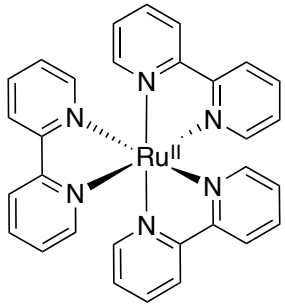
Common Reducing Agents



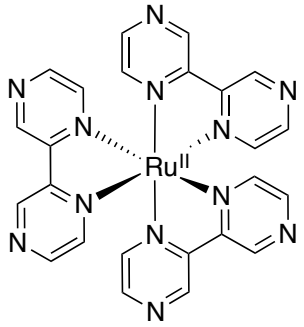
compiled by D. DiRocco 2014

MERCK

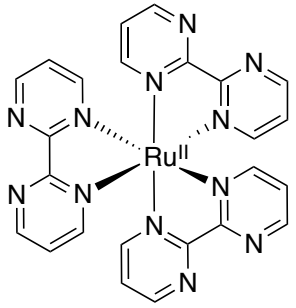
TM Photoredox catalysis: metals and ligands



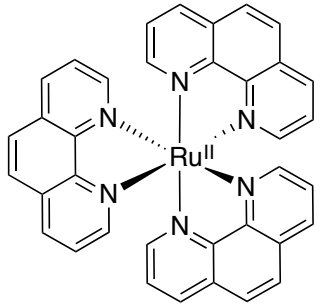
$Ru(bpy)_3^{2+}$



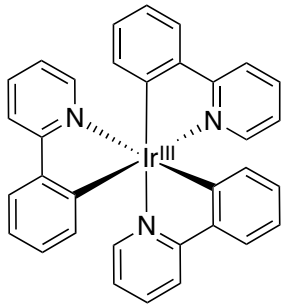
$Ru(bpz)_3^{2+}$



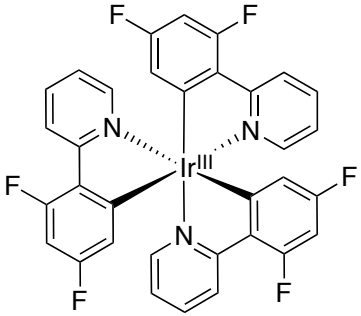
$Ru(bpm)_3^{2+}$



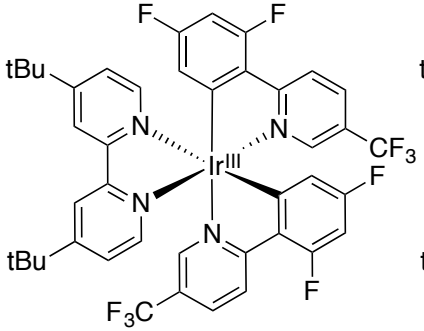
$Ru(phen)_3^{2+}$



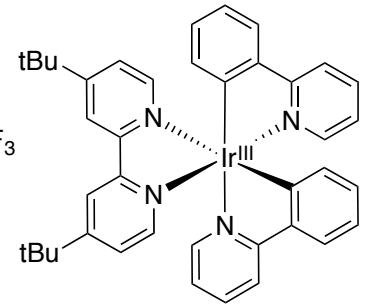
fac-$Ir(ppy)_3$



fac-$Ir(dF\text{-}ppy)_3$

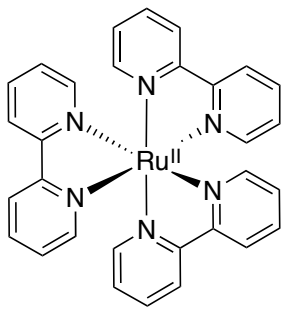


$Ir(dF\text{-}CF_3\text{-}ppy)_2(dtbpy)^+$

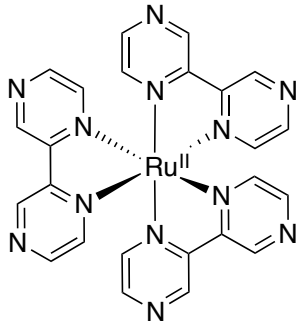


$Ir(ppy)_2(dtbpy)^+$

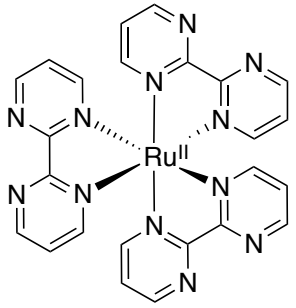
TM Photoredox catalysis: metals and ligands



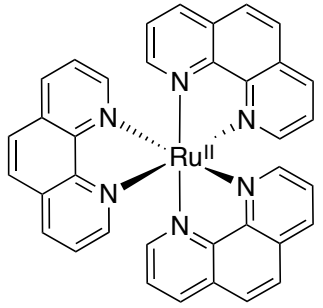
$Ru(bpy)_3^{2+}$



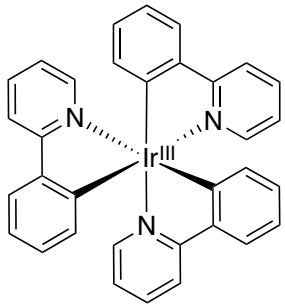
$Ru(bpz)_3^{2+}$



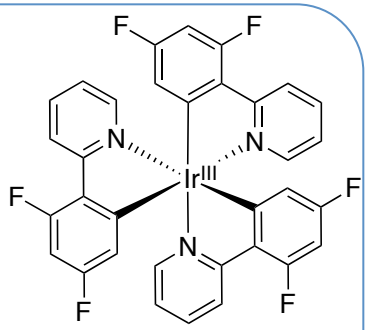
$Ru(bpm)_3^{2+}$



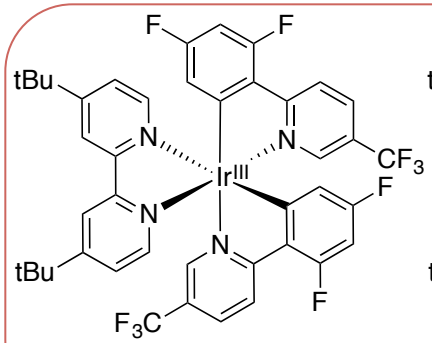
$Ru(phen)_3^{2+}$



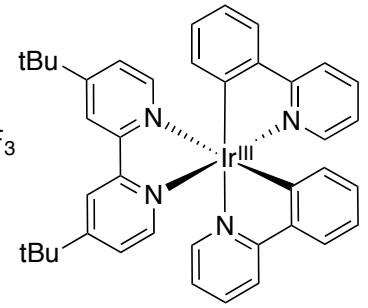
fac-Ir(ppy)$_3$



fac-Ir(dF-ppy)$_3$

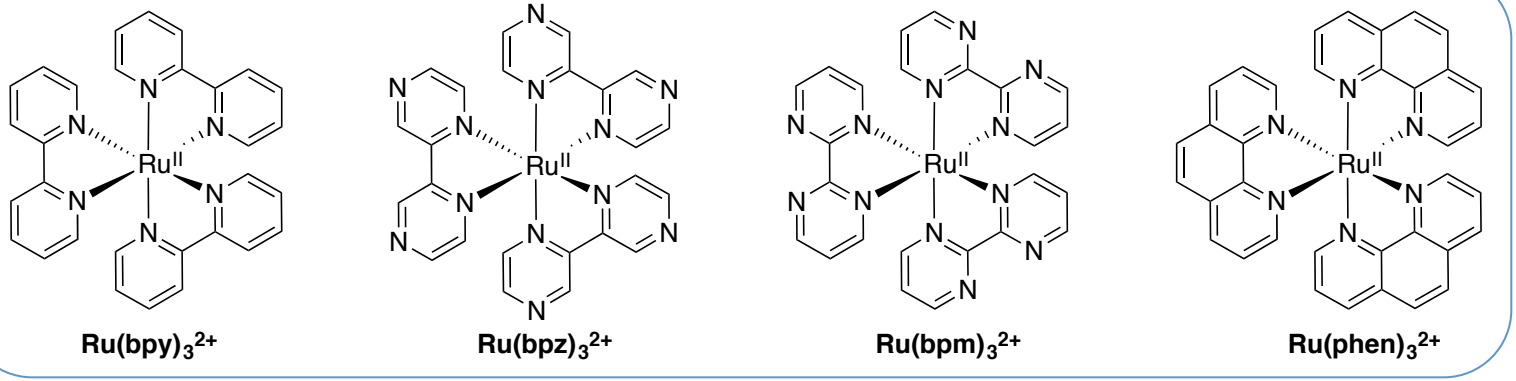


Ir(dF-CF$_3$-ppy)$_2$(dtbpy)$^+$



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

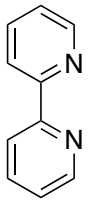
TM Photoredox catalysis: metals and ligands



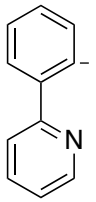
Ru complexes: homoleptic

Ir complexes: homoleptic and heteroleptic

TM Photoredox catalysis: usual ligand type



Type bpy
neutral
LL



Type ppy
anionic
LX

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
E. Y. Li, Y.-M. Cheng, C.-C. Hsu, P.-T. Chou, G.-H. Lee, *Inorg. Chem.,* **2006**, *45*, 9631
P. G. Bomben, K. C. D. Robson, P. A. Sedach, C. P. Berlinguette, *Inorg. Chem.*, **2009**, *48*, 9631

TM Photoredox catalysis: usual ligand type

Type bpy
neutral
LL

Type ppy
anionic
LX

Found in Ru^{2+}

Strong e^- donation
Found in Ir^{3+} (better stabilisation)

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
E. Y. Li, Y.-M. Cheng, C.-C. Hsu, P.-T. Chou, G.-H. Lee, *Inorg. Chem.,* **2006**, *45*, 9631
P. G. Bomben, K. C. D. Robson, P. A. Sedach, C. P. Berlinguette, *Inorg. Chem.*, **2009**, *48*, 9631

TM Photoredox catalysis: usual ligand type

Type bpy
neutral
LL

Type ppy
anionic
LX

Found in Ru^{2+}

Strong e^- donation
Found in Ir^{3+} (better stabilisation)

Heteroleptic complexes: Spin-Orbit coupling disrupted, MLCT less efficient
SO (Ir) > SO (Ru) ➔ compensation

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
E. Y. Li, Y.-M. Cheng, C.-C. Hsu, P.-T. Chou, G.-H. Lee, *Inorg. Chem.,* **2006**, *45*, 9631
P. G. Bomben, K. C. D. Robson, P. A. Sedach, C. P. Berlinguette, *Inorg. Chem.*, **2009**, *48*, 9631

TM Photoredox catalysis: usual ligand type

Type bpy
neutral
LL

Type ppy
anionic
LX

Found in Ru^{2+}

Strong e^- donation
Found in Ir^{3+} (better stabilisation)

Heteroleptic complexes: Spin-Orbit coupling disrupted, MLCT less efficient
SO (Ir) > SO (Ru) ➔ compensation

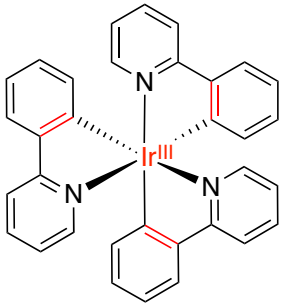
Ru complexes mostly homoleptic and LL ligands

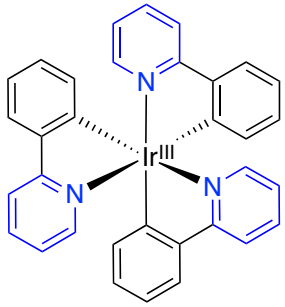
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
E. Y. Li, Y.-M. Cheng, C.-C. Hsu, P.-T. Chou, G.-H. Lee, *Inorg. Chem.,* **2006**, *45*, 9631
P. G. Bomben, K. C. D. Robson, P. A. Sedach, C. P. Berlinguette, *Inorg. Chem.*, **2009**, *48*, 9631

TM Photoredox catalysis: heteroleptic VS homoleptic

Heteroleptic: spatial modification of HOMO/LUMO

$Ir(ppy)_3$*



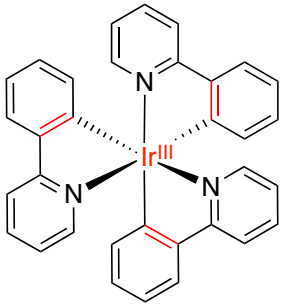


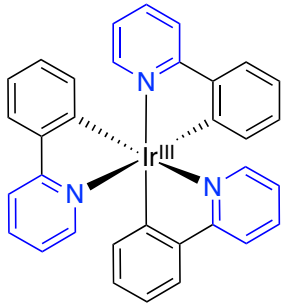
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
A. B. Tamayo et al., *J. Am. Chem. Soc.*, **2003**, *125*, 7377-7387
M. S. Lowry et al., *Chem. Mater.*, **2005**, *17*, 5712-5719

TM Photoredox catalysis: heteroleptic VS homoleptic

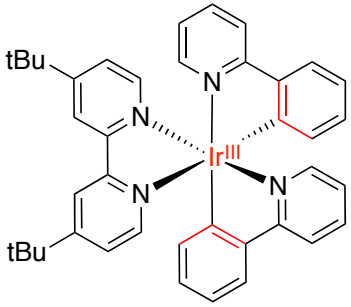
Heteroleptic: spatial modification of HOMO/LUMO

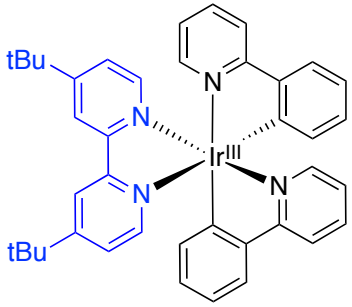
$Ir(ppy)_3$*





$Ir(ppy)_2(dtbbpy)$*

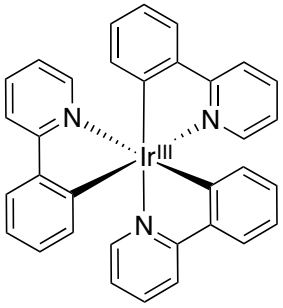




HOMO LUMO

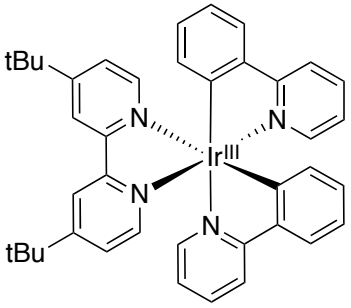
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
A. B. Tamayo et al., *J. Am. Chem. Soc.*, **2003**, *125*, 7377-7387
M. S. Lowry et al., *Chem. Mater.*, **2005**, *17*, 5712-5719

TM Photoredox catalysis: effects of ligand on redox potentials



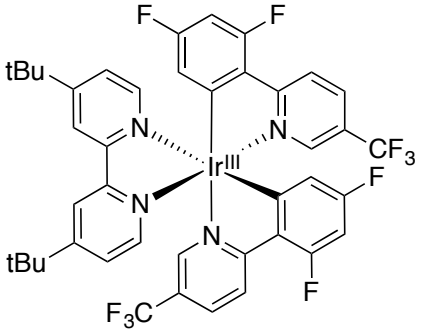
fac-Ir(ppy)$_3$

Ir(III)*/Ir(IV) = – 1.73 V
Ir(III)*/Ir(II) = 0.31 V



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

Ir(III)*/Ir(IV) = – 0.96 V
Ir(III)*/Ir(II) = 0.66 V

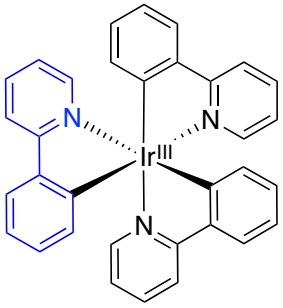


Ir(dF-CF$_3$-ppy)$_2$(dtbpy)$^+$

Ir(III)*/Ir(IV) = – 0.89 V
Ir(III)*/Ir(II) = 1.21 V

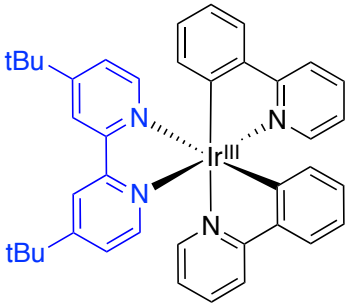
"Electrochemical Series of Photocatalysts and Common Organic Coumpounds", D. DiRocco, 2014, Merck
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: effects of ligand on redox potentials



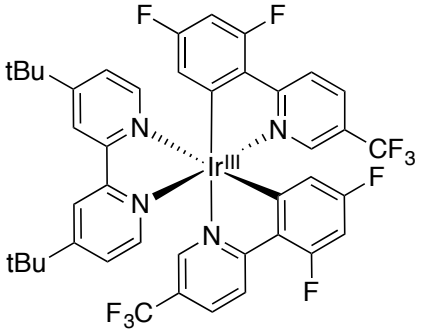
fac-Ir(ppy)$_3$

Ir(III)*/Ir(IV) = – 1.73 V
Ir(III)*/Ir(II) = 0.31 V



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

Ir(III)*/Ir(IV) = – 0.96 V
Ir(III)*/Ir(II) = 0.66 V



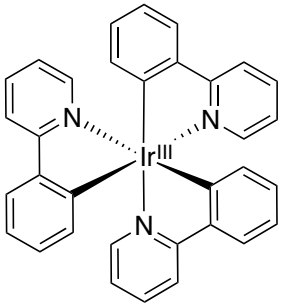
Ir(dF-CF$_3$-ppy)$_2$(dtbpy)$^+$

Ir(III)*/Ir(IV) = – 0.89 V
Ir(III)*/Ir(II) = 1.21 V

LL to LX ligand: electron density on the metal increases ➔ Reductive power increases

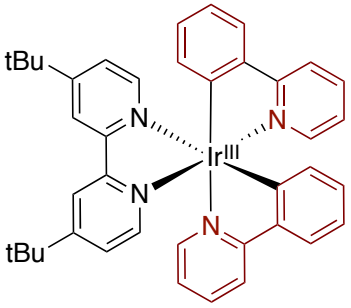
"Electrochemical Series of Photocatalysts and Common Organic Coumpounds", D. DiRocco, 2014, Merck
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: effects of ligand on redox potentials



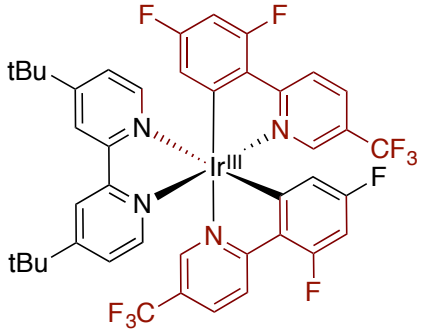
fac-Ir(ppy)$_3$

Ir(III)*/Ir(IV) = – 1.73 V
Ir(III)*/Ir(II) = 0.31 V



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

Ir(III)*/Ir(IV) = – 0.96 V
Ir(III)*/Ir(II) = 0.66 V



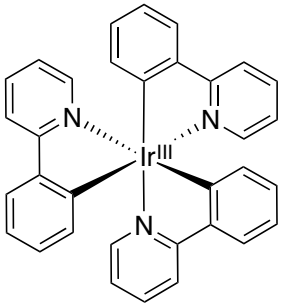
Ir(dF-CF$_3$-ppy)$_2$(dtbpy)$^+$

Ir(III)*/Ir(IV) = – 0.89 V
Ir(III)*/Ir(II) = 1.21 V

LL to LX ligand: electron density on the metal increases ➔ Reductive power increases
EWG on ligands: electron density on the metal decreases ➔ Oxidative power increases

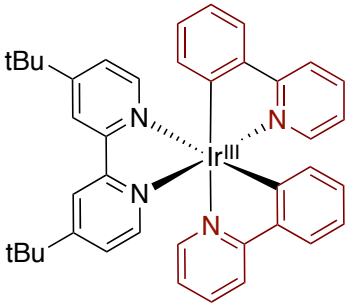
"Electrochemical Series of Photocatalysts and Common Organic Coumpounds", D. DiRocco, 2014, Merck
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

TM Photoredox catalysis: effects of ligand on redox potentials



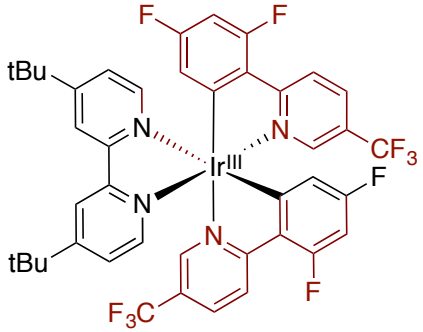
fac-Ir(ppy)$_3$

Ir(III)*/Ir(IV) = – 1.73 V
Ir(III)*/Ir(II) = 0.31 V



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

Ir(III)*/Ir(IV) = – 0.96 V
Ir(III)*/Ir(II) = 0.66 V



Ir(dF-CF$_3$-ppy)$_2$(dtbpy)$^+$

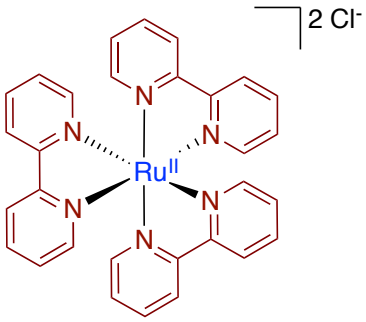
Ir(III)*/Ir(IV) = – 0.89 V
Ir(III)*/Ir(II) = 1.21 V

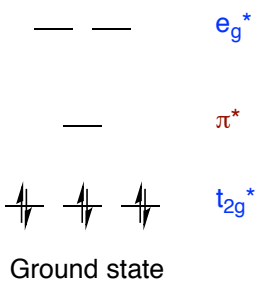
LL to LX ligand: electron density on the metal increases ➔ Reductive power increases
EWG on ligands: electron density on the metal decreases ➔ Oxidative power increases

TM/ligand complexes = tunable catalysts

"Electrochemical Series of Photocatalysts and Common Organic Coumpounds", D. DiRocco, 2014, Merck
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

Photoredox catalysis: active species

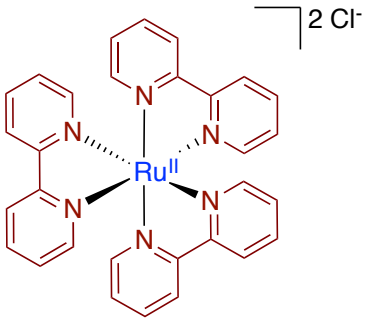


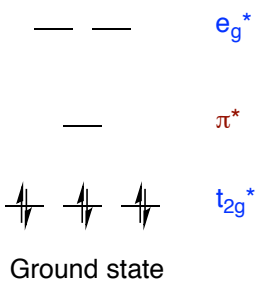


$[Ru(bpy)_3]Cl_2$
octahedral, d^6
low-spin configuration
(substitutionally inert)
λ_{max} = 452 nm

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
N. H. Damrauer, G. Cerullo, A. Yeh, T. R. Boussie, C. V. Shank, J. K. McCusker, *Science*, **1997**, *275*, 54-57

Photoredox catalysis: active species

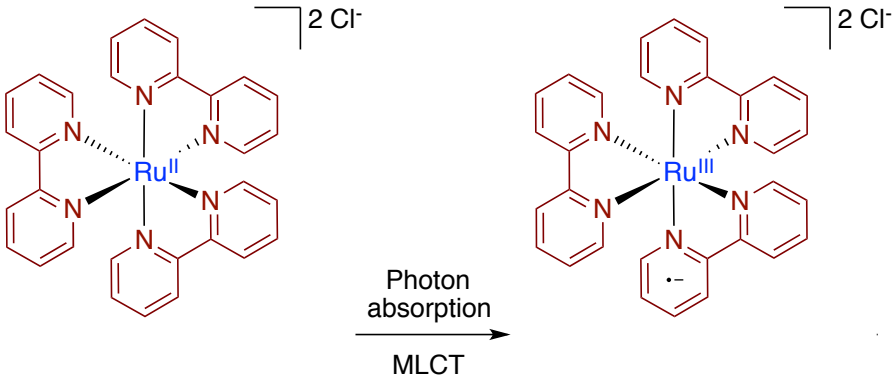




$[Ru(bpy)_3]Cl_2$
octahedral, d^6
low-spin configuration
(substitutionally inert)
λ_{max} = 452 nm

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
N. H. Damrauer, G. Cerullo, A. Yeh, T. R. Boussie, C. V. Shank, J. K. McCusker, *Science*, **1997**, *275*, 54-57

Photoredox catalysis: active species



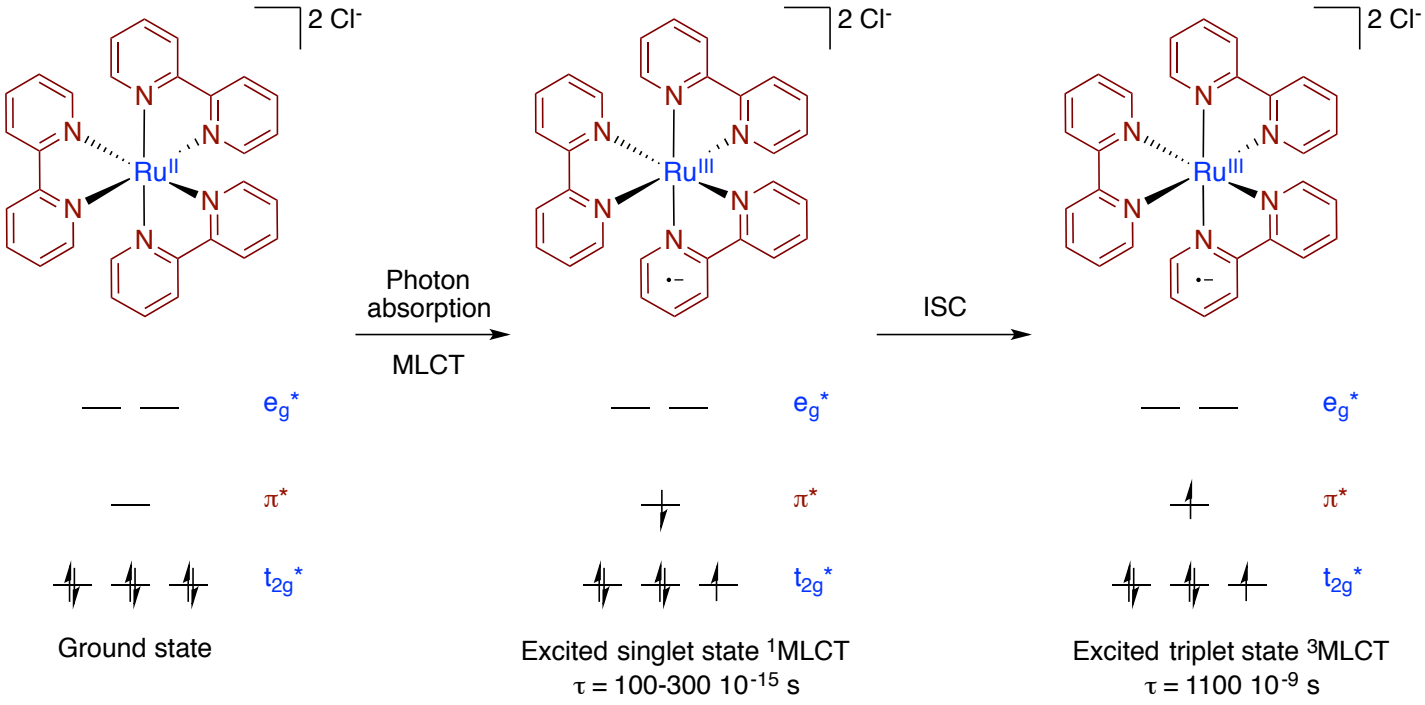
Ground state

Excited singlet state ^{1}MLCT
τ = 100-300 10^{-15} s

$[Ru(bpy)_3]Cl_2$
octahedral, d^6
low-spin configuration
(substitutionally inert)
λ_{max} = 452 nm

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
N. H. Damrauer, G. Cerullo, A. Yeh, T. R. Boussie, C. V. Shank, J. K. McCusker, *Science*, **1997**, *275*, 54-57

Photoredox catalysis: active species



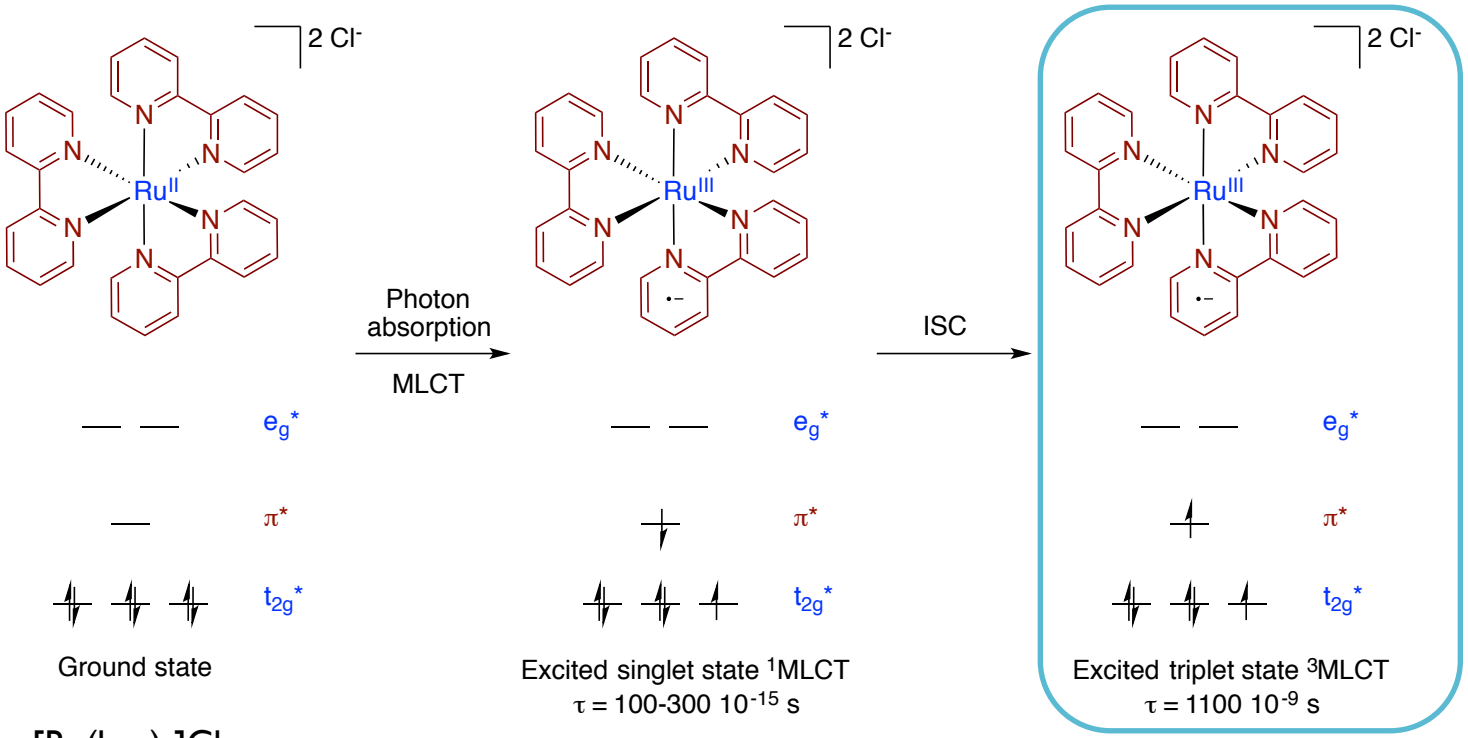
$[Ru(bpy)_3]Cl_2$
octahedral, d^6
low-spin configuration
(substitutionally inert)
λ_{max} = 452 nm

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363

"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

N. H. Damrauer, G. Cerullo, A. Yeh, T. R. Boussie, C. V. Shank, J. K. McCusker, *Science*, **1997**, *275*, 54-57

Photoredox catalysis: active species



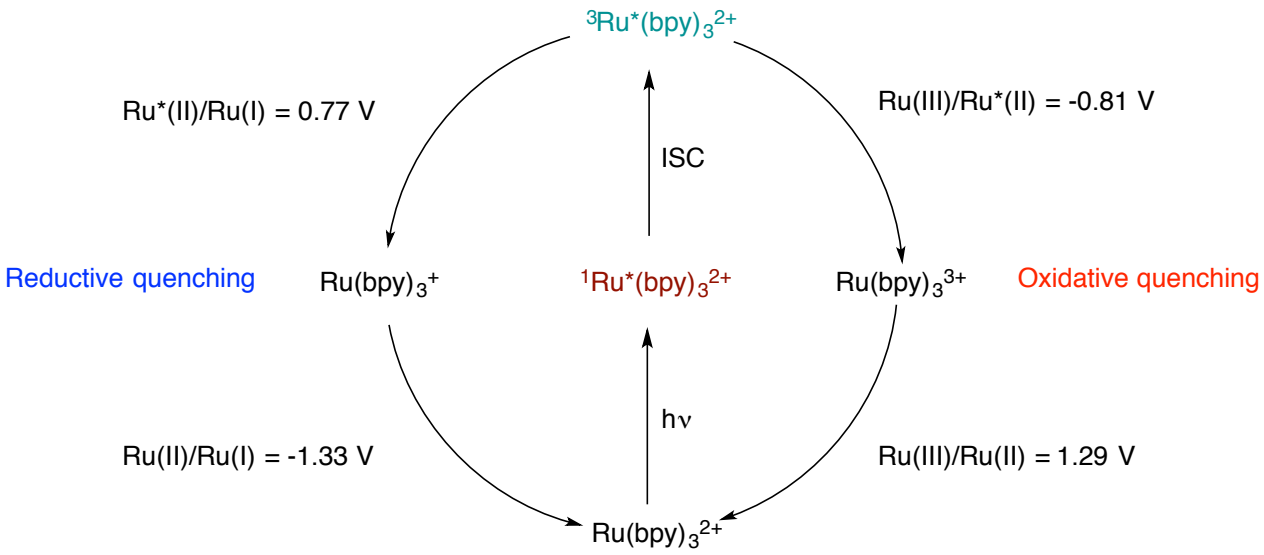
$[Ru(bpy)_3]Cl_2$
octahedral, d^6
low-spin configuration
(substitutionally inert)
λ_{max} = 452 nm

$\tau(^1MLCT) < \tau(^3MLCT)$

^3MLCT active species = P*

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363
"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015
N. H. Damrauer, G. Cerullo, A. Yeh, T. R. Boussie, C. V. Shank, J. K. McCusker, *Science*, **1997**, *275*, 54-57

Photoredox catalysis: Thermodynamics and kinetics

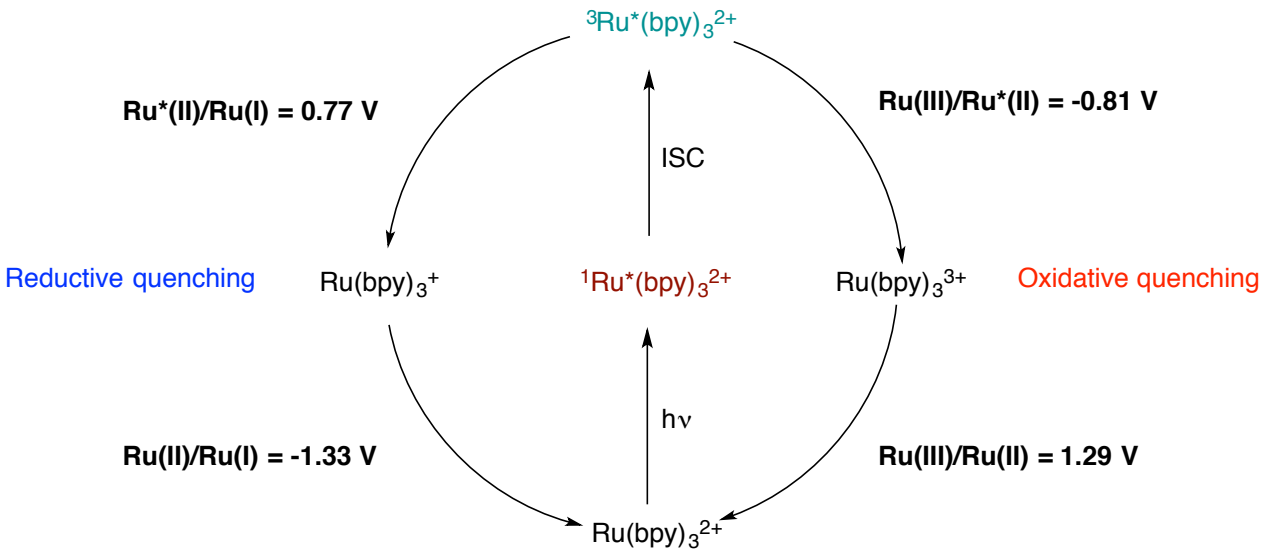


"Behind the scenes with Transition Metal Photocatalysts", E. R. Welin, MacMillan Group Meetings, 12/02/2015

C. K. Prier, D. A. Rankic, D. W. C. MacMillan, *Chem. Rev.,* **2013**, *113*, 5322-5363

J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, 77, 1617-1622

Photoredox catalysis: Thermodynamics and kinetics

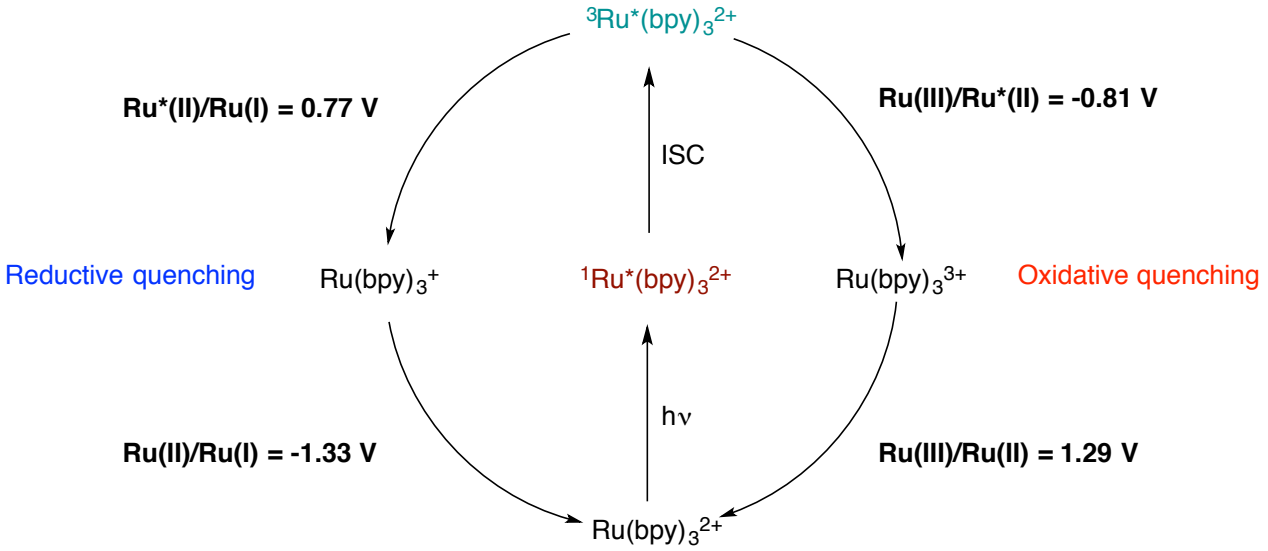


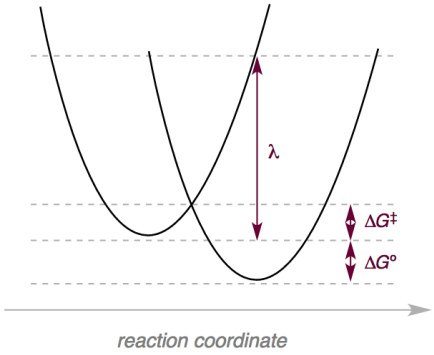
R. A. Marcus, *J. Chem. Phys.*, **1956**, *24*, 966

A Very Brief Introduction of the Concepts of Marcus Theory, V. Shurtleff, MacMillan Group Meetings, 26/06/2016

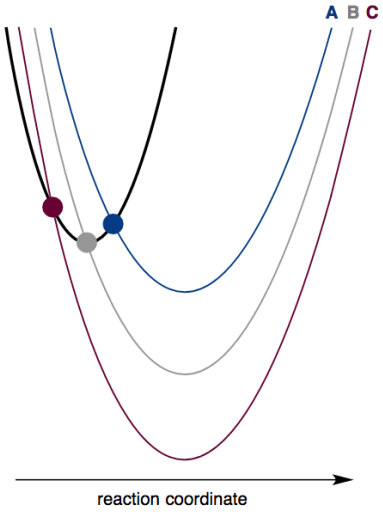
J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, 77, 1617-1622

Photoredox catalysis: Thermodynamics and kinetics





Beware of the Marcus inversion



A $\Delta G^\circ < 0$ (somewhat negative)
$\Delta G^\ddagger > 0$, rate k_A

B $\Delta G^\circ = -\lambda$ (quite negative)
$\Delta G^\ddagger = 0$, rate $k_B > k_A$

C $\Delta G^\circ << 0$ (very negative)
$\Delta G^\ddagger > 0$, rate $k_C < k_B$

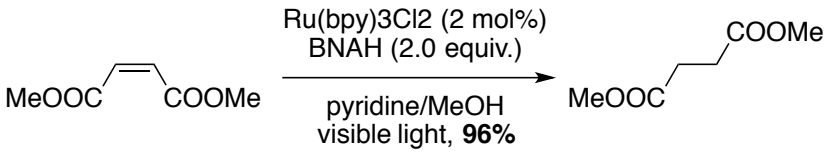
R. A. Marcus, *J. Chem. Phys.*, **1956**, *24*, 966

A Very Brief Introduction of the Concepts of Marcus Theory, V. Shurtleff, MacMillan Group Meetings, 26/06/2016

J. W. Tucker, C. R. J. Stephenson, *J. Org. Chem.*, ***2012***, 77, 1617-1622

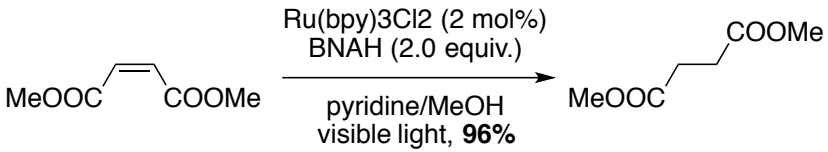
Functional group interconversion

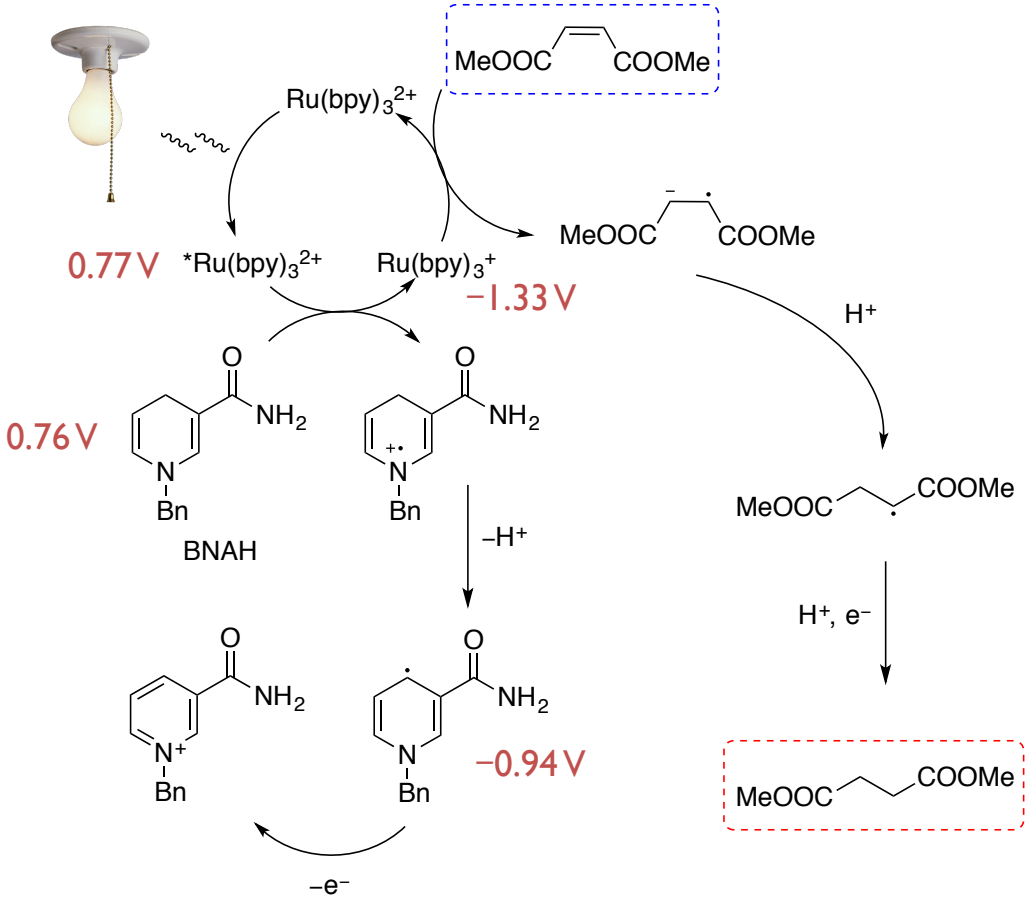
Reduction of electron-deficient olefins



C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.*, **1981**, *103*, 6495-6497

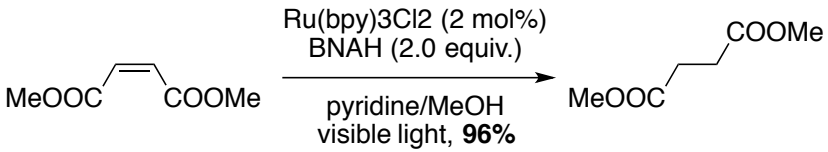
Reduction of electron-deficient olefins

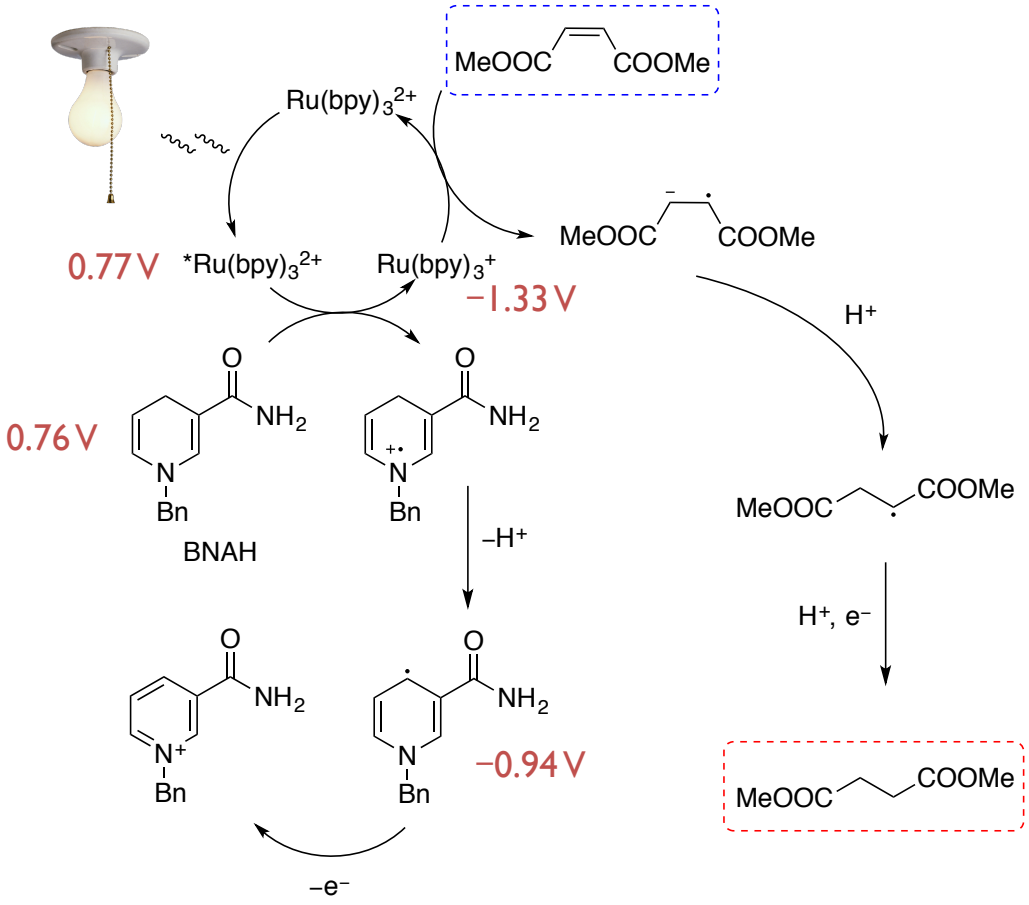


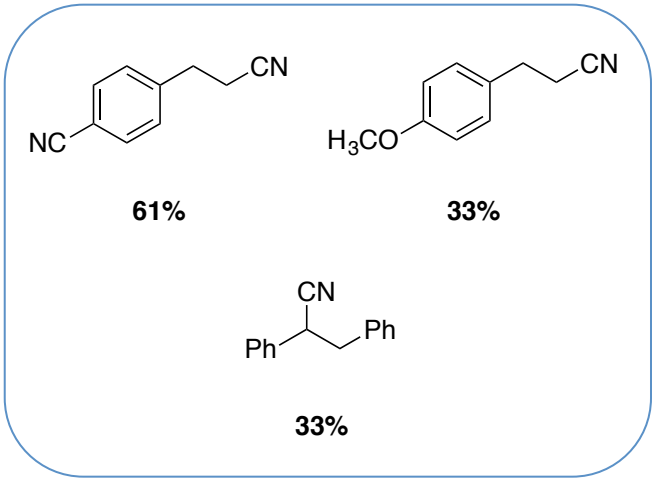


C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.*, **1981**, *103*, 6495-6497

Reduction of electron-deficient olefins

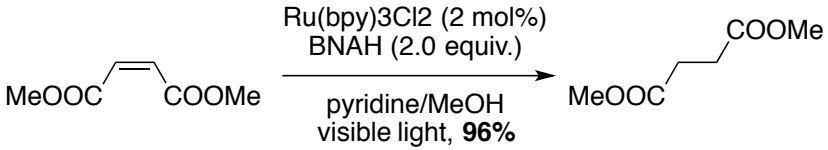


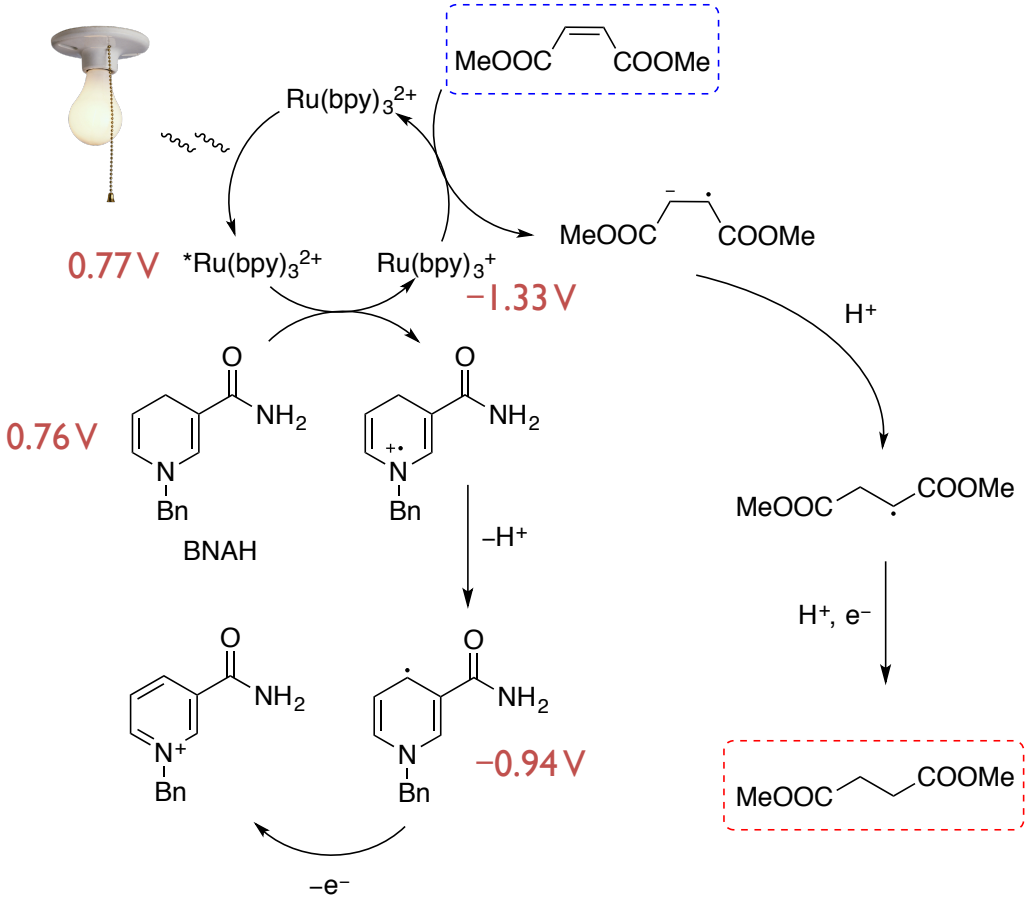


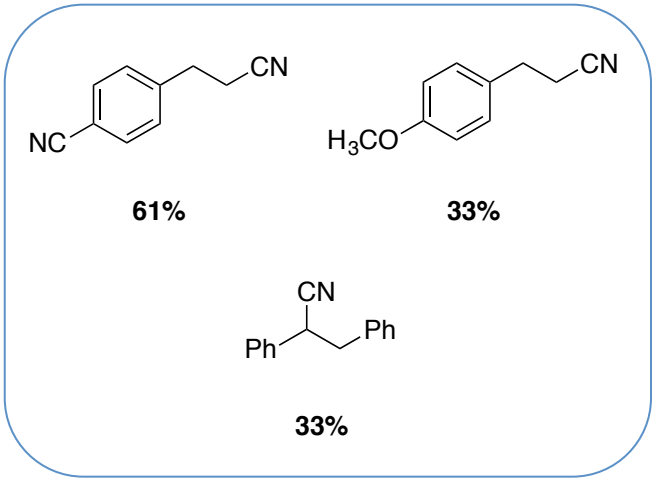


C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.*, **1981**, *103*, 6495-6497

Reduction of electron-deficient olefins



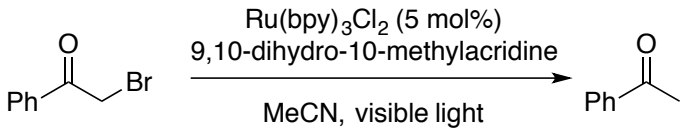




- SM doesn't quench *Ru(bpy)$_3^{2+}$
  ➔ Reductive quenching
- BNAH-4,4-d_2: next to no deuteration
  CH_3OD, CD_3OD: deuteration
  ➔ Direct H transfer negligeable
- Last ET from Ru(bpy)+ or BNA•

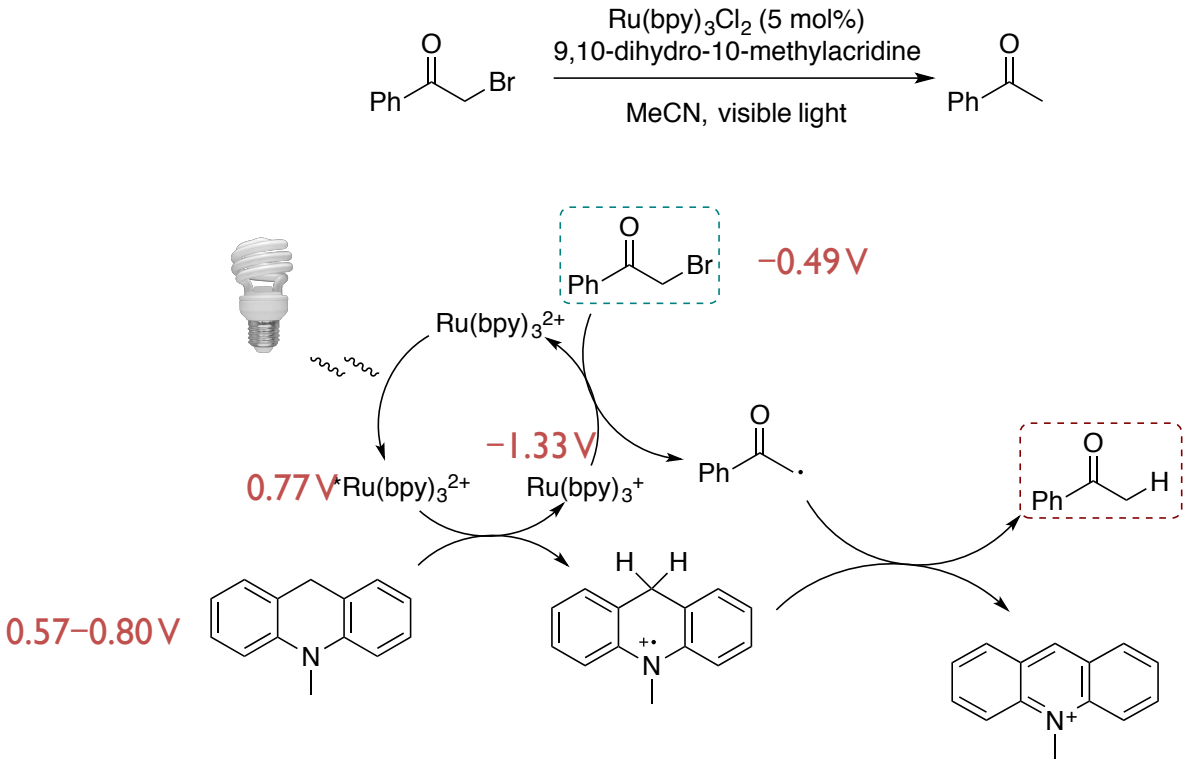
C. Pac, M. Ihama, M. Yasuda, Y. Miyauchi, H. Sakurai, *J. Am. Chem. Soc.*, **1981**, *103*, 6495-6497

Reductive dehalogenation: activated halides



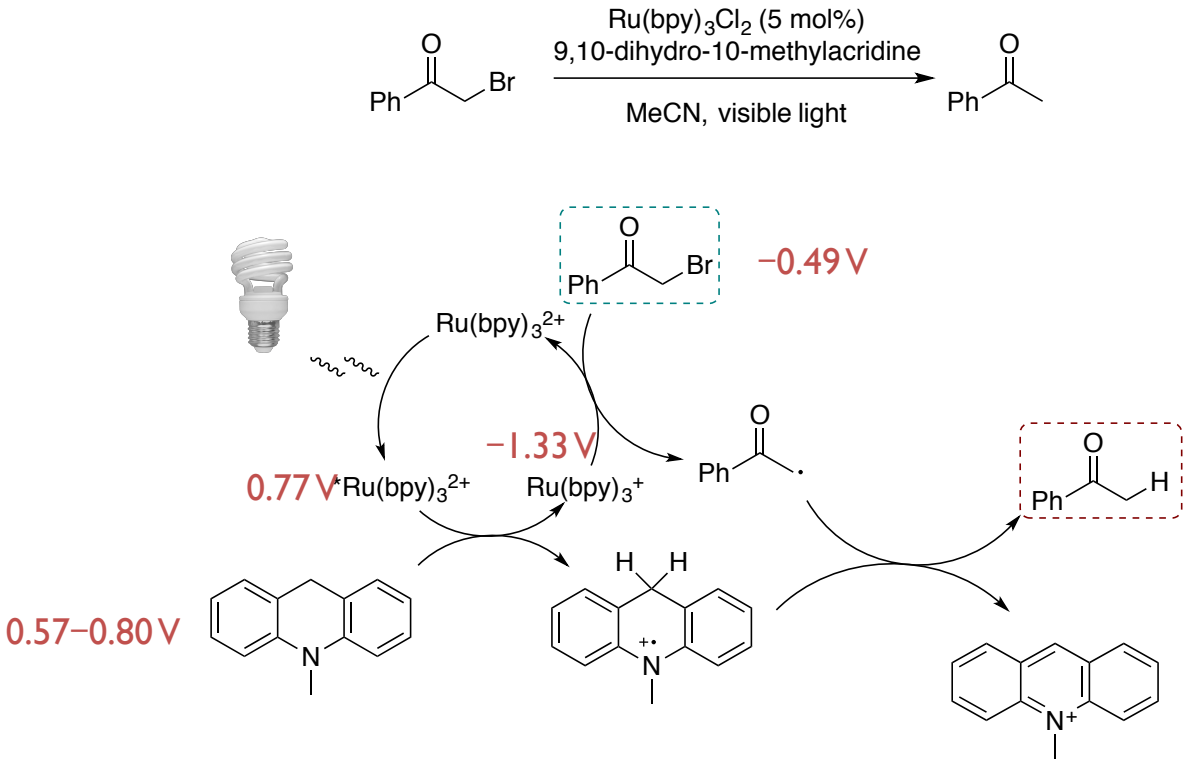
S. Fukuzumi, S. Mochizuki, T. Tanaka, *J. Phys. Chem.*, **1990**, *94*, 722-726
S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Am. Chem. Soc.*, **1987**, *109*, 305-316

Reductive dehalogenation: activated halides



S. Fukuzumi, S. Mochizuki, T. Tanaka, *J. Phys. Chem.*, **1990**, *94*, 722-726
S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Am. Chem. Soc.*, **1987**, *109*, 305-316

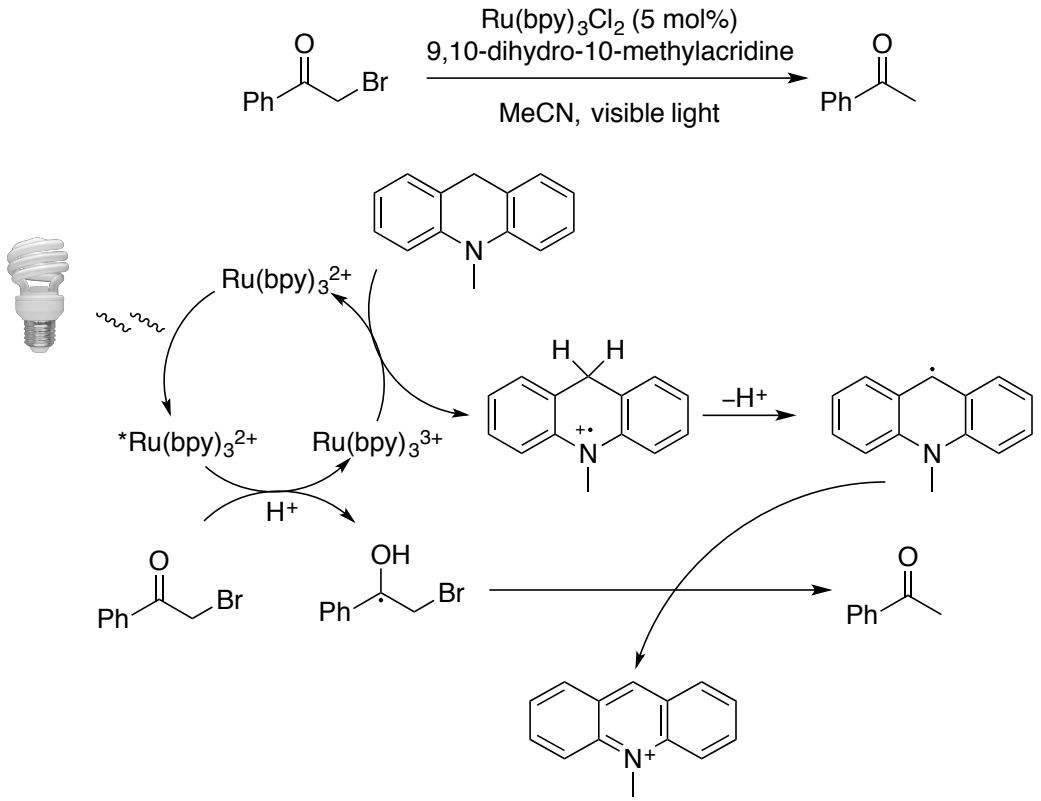
Reductive dehalogenation: activated halides



- Bromide doesn't quench $Ru(bpy)_3^{2+}$
  ➔ reductive quenching
- Addition of $HClO_4$: quenching by $AcrH_2$ decreases
  ➔ $AcrH_2$ → $AcrH_3^+$ (weaker reductant)
- More $HClO_4$: increase of quenching and reaction conversion

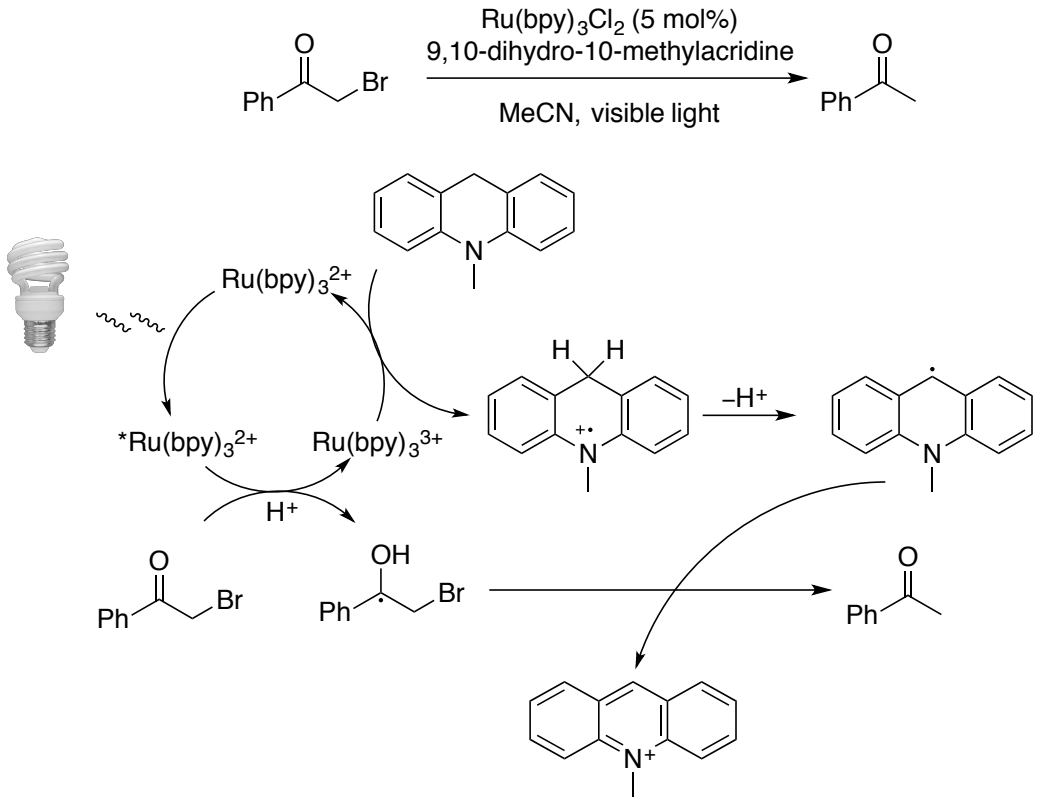
S. Fukuzumi, S. Mochizuki, T. Tanaka, *J. Phys. Chem.*, **1990**, *94*, 722-726
S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Am. Chem. Soc.*, **1987**, *109*, 305-316

Reductive dehalogenation: activated halides



S. Fukuzumi, S. Mochizuki, T. Tanaka, *J. Phys. Chem.*, **1990**, *94*, 722-726
S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Am. Chem. Soc.*, **1987**, *109*, 305-316

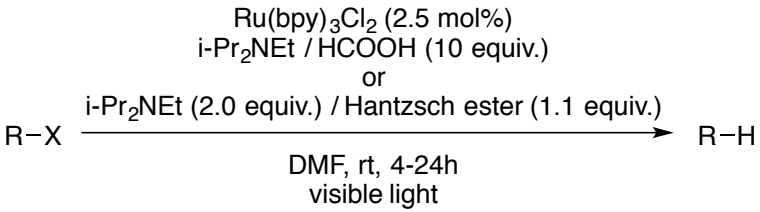
Reductive dehalogenation: activated halides



- Large quantities of $HClO_4$
  ➔ induces oxidative quenching
- Reduction of phenacyl chloride possible

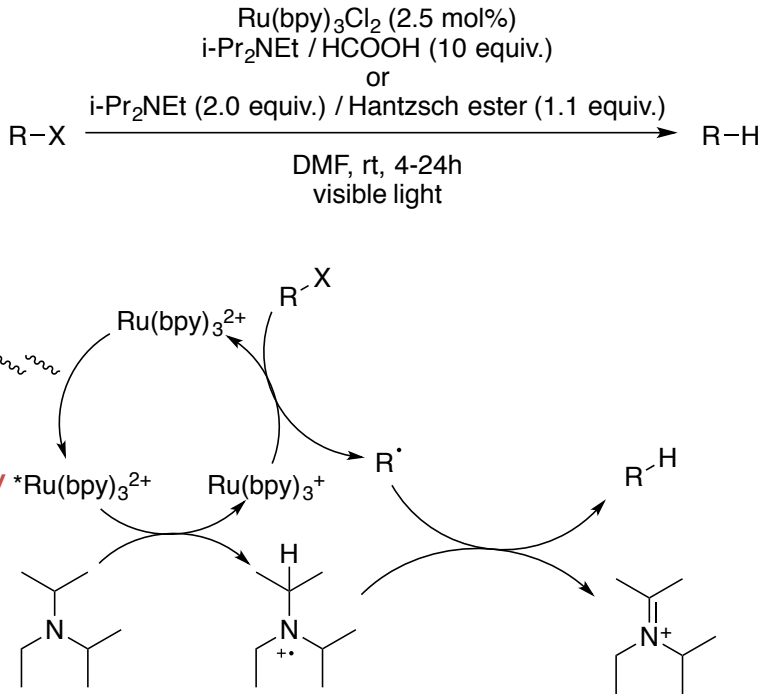
S. Fukuzumi, S. Mochizuki, T. Tanaka, *J. Phys. Chem.*, **1990**, *94*, 722-726
S. Fukuzumi, S. Mochizuki, K. Hironaka, T. Tanaka, *J. Am. Chem. Soc.*, **1987**, *109*, 305-316

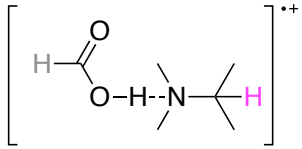
Reductive dehalogenation: activated halides



J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *J. Am. Chem. Soc.*, **2009**, *131*, 8756–8757
U. Pischel et al., *J. Am. Chem. Soc.*, **2000**, *122*, 2027-2043

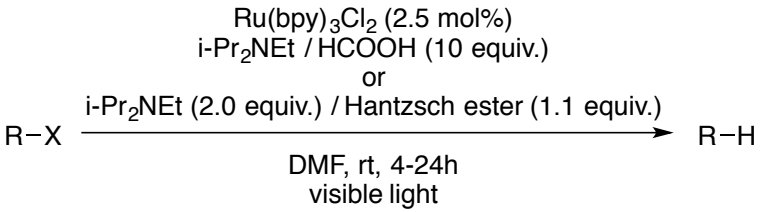
Reductive dehalogenation: activated halides

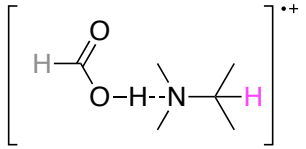


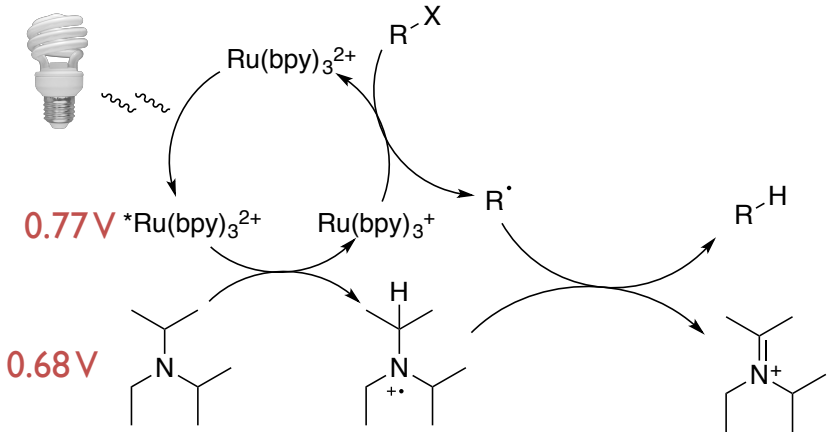


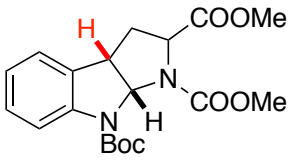
J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *J. Am. Chem. Soc.*, **2009**, *131*, 8756–8757
U. Pischel et al., *J. Am. Chem. Soc.*, **2000**, *122*, 2027-2043

Reductive dehalogenation: activated halides

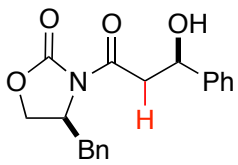




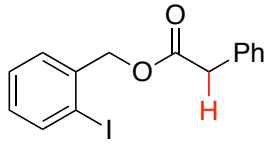




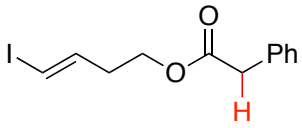
95%



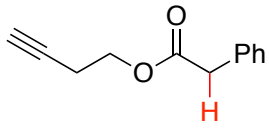
95% from Br
80% from Cl



88% from Cl
Hantzsch ester



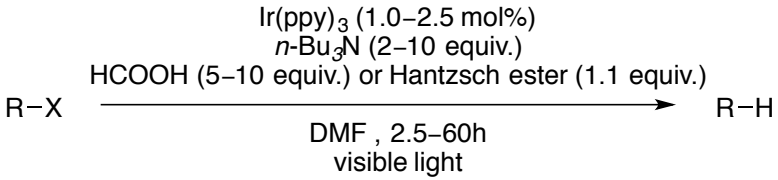
81% from Cl
Hantzsch ester

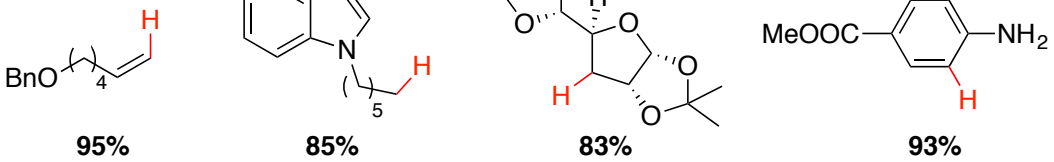


89% from Cl
Hantzsch ester

J. M. R. Narayanam, J. W. Tucker, C. R. J. Stephenson, *J. Am. Chem. Soc.*, **2009**, *131*, 8756–8757
U. Pischel et al., *J. Am. Chem. Soc.*, **2000**, *122*, 2027-2043

Reductive dehalogenation: unactivated iodides

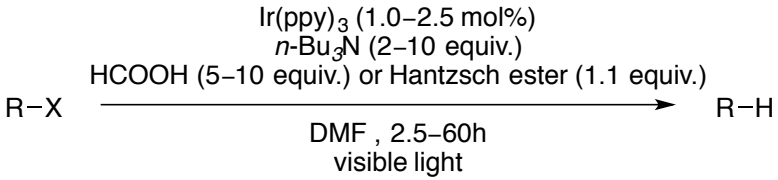


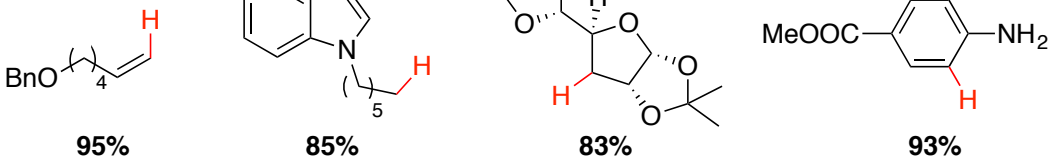


95% **85%** **83%** **93%**

J. D. Nguyen, E. M. D'Amato, J. M. R. Narayanam, C. R. J. Stephenson, Nature Chem., **2012**, *4*, 854–859

Reductive dehalogenation: unactivated iodides



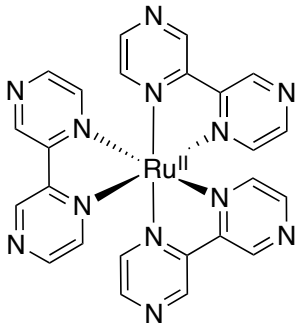


95% **85%** **83%** **93%**

Use of $Ir(ppy)_3$: better reducing power E = -1.73 V

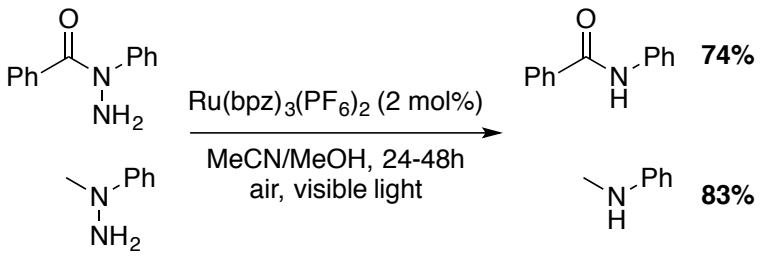
-1.59 V < E (iodobenzene) < -2.24 V

J. D. Nguyen, E. M. D'Amato, J. M. R. Narayanam, C. R. J. Stephenson, Nature Chem., **2012**, *4*, 854–859

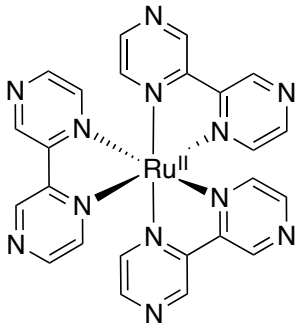


Ru*(II)/Ru(I) = 1.45 V

Reduction of hydrazides and hydrazines

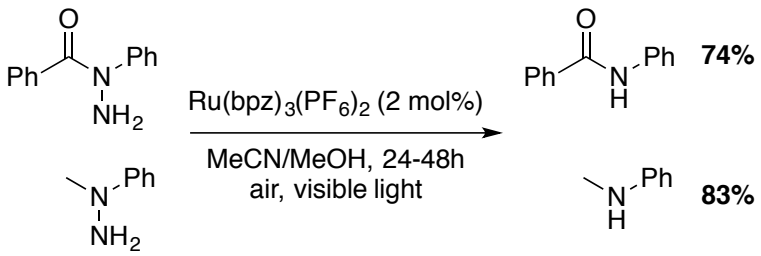


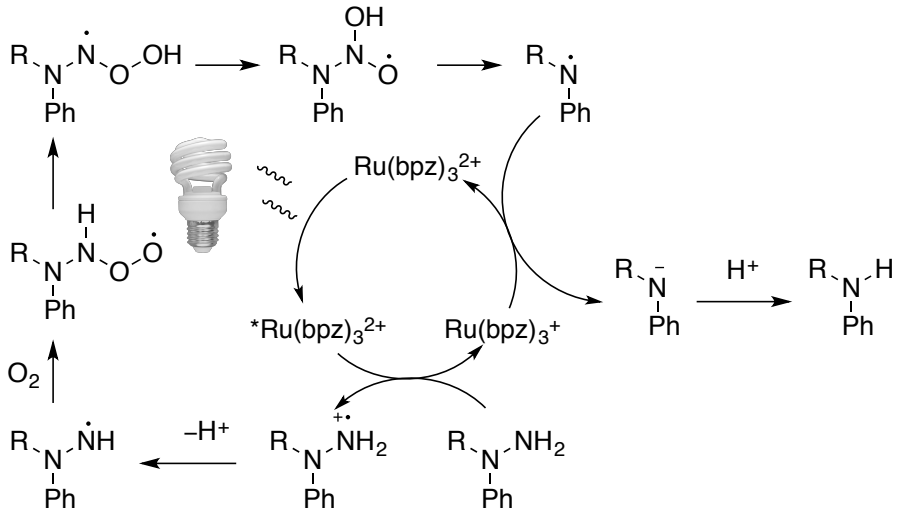
M. Zhu, N. Zheng, *Synthesis*, **2011**, *14*, 2223-2236



Ru*(II)/Ru(I) = 1.45 V

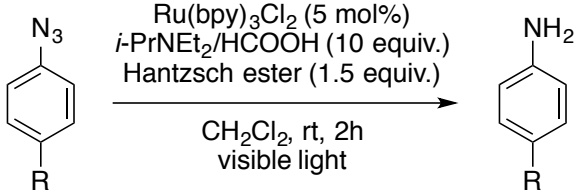
Reduction of hydrazides and hydrazines





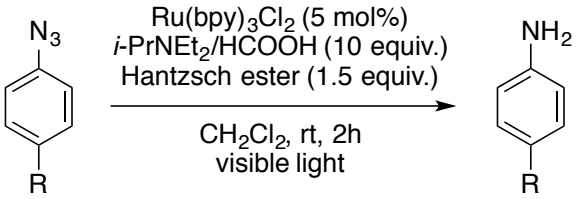
M. Zhu, N. Zheng, *Synthesis*, **2011**, *14*, 2223-2236

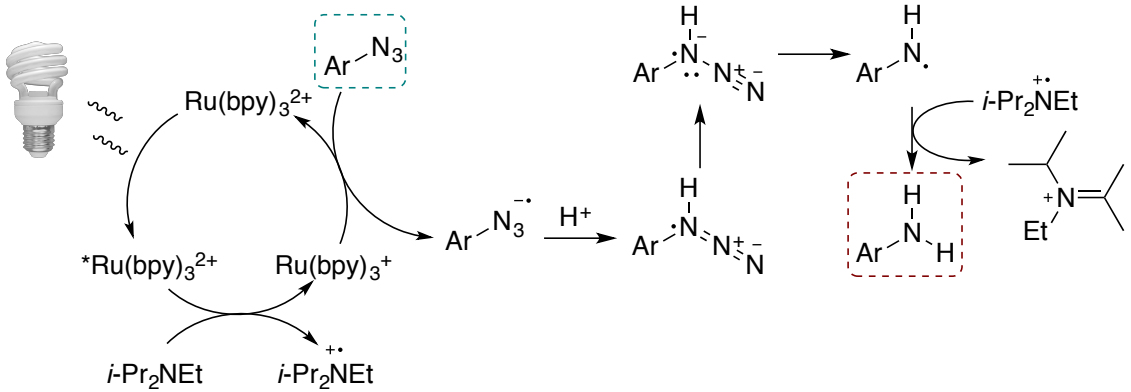
Reduction of azides



Y. Chen, A. S. Kamlet, J. B. Steinman, D. R. Liu, *Nature Chem.*, **2011**, *3*, 146-153

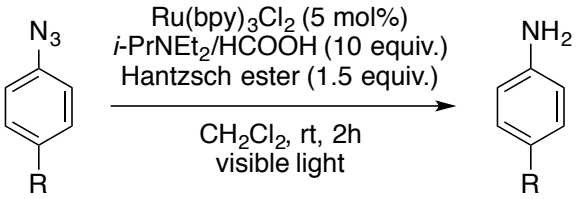
Reduction of azides

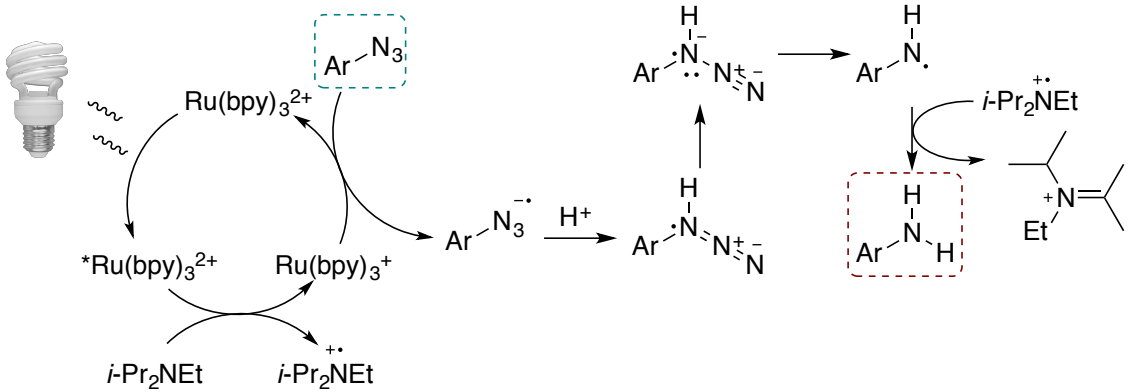




Y. Chen, A. S. Kamlet, J. B. Steinman, D. R. Liu, *Nature Chem.*, **2011**, *3*, 146-153

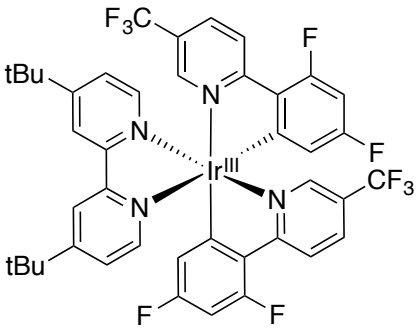
Reduction of azides



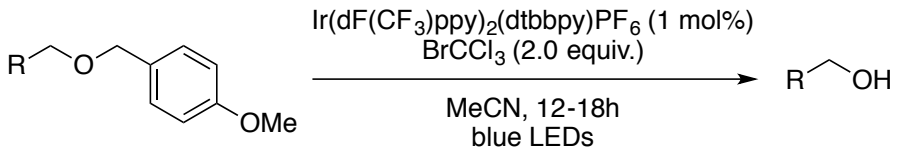


- Work in aqueous media, linked to DNA, sugars
- Chemoselective: inert to halides, mesylates, aldehydes, free hydroxyl, carboxylic acids, amides, alkenes, alkynes

Y. Chen, A. S. Kamlet, J. B. Steinman, D. R. Liu, *Nature Chem.*, **2011**, *3*, 146-153

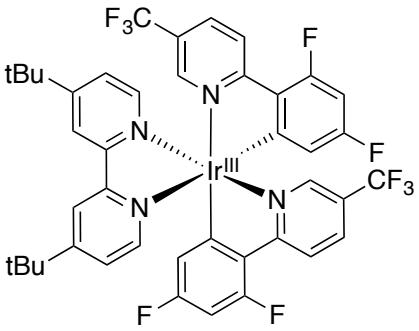


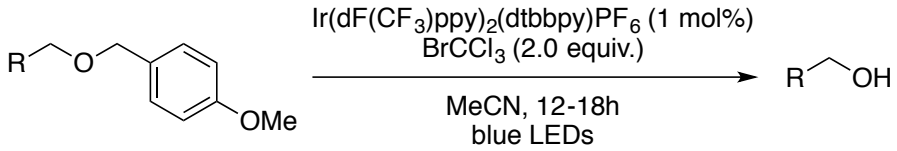
Deprotection of p-Methoxybenzylether

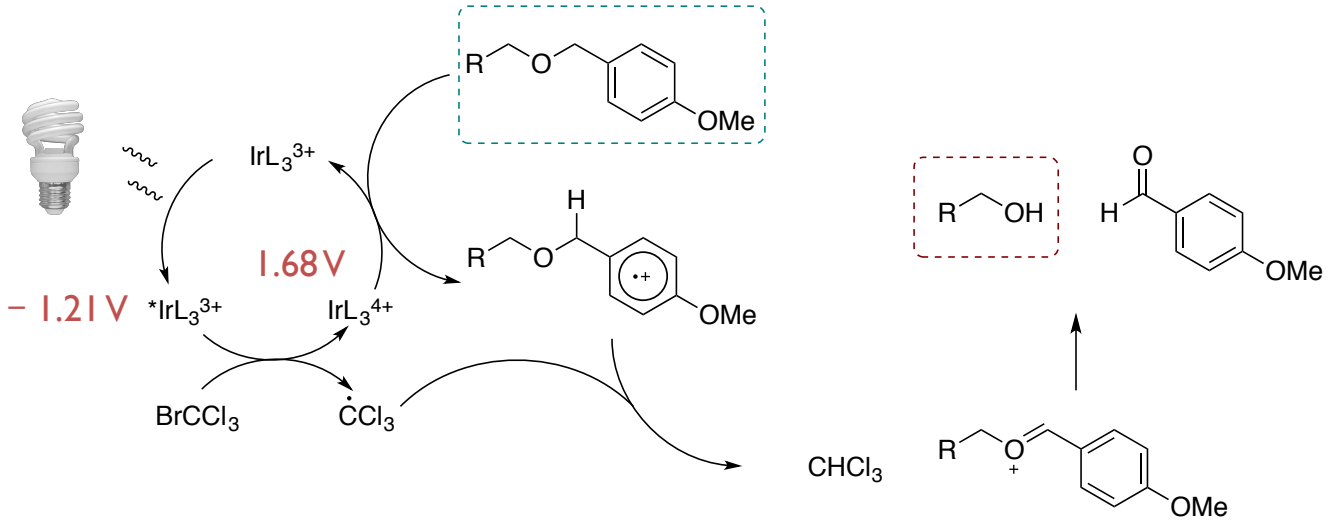


J. W. Tucker, J. M. R. Narayanam, P. S. Shah, C. R. J. Stephenson, *Chem. Commun.*, **2011**, *47,* 5040-5042

Deprotection of p-Methoxybenzylether

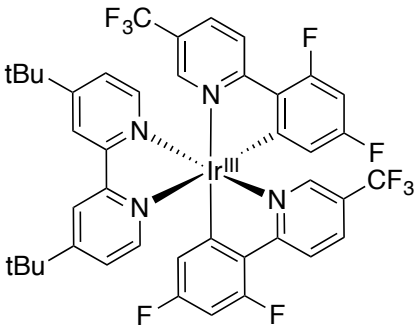


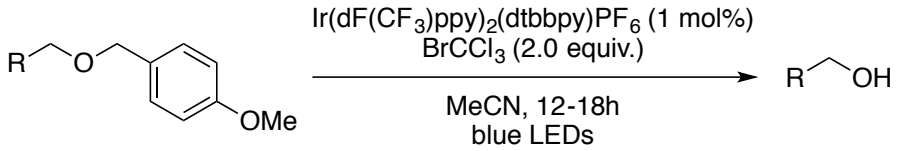


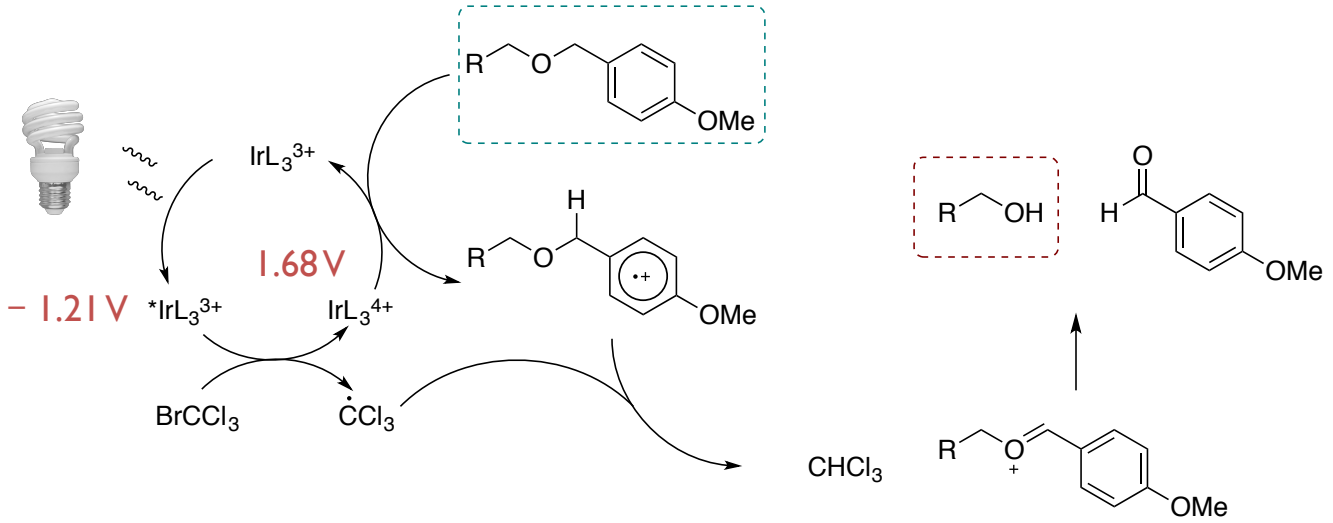


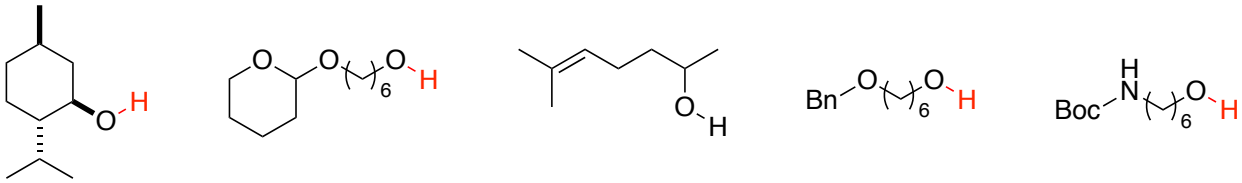
J. W. Tucker, J. M. R. Narayanam, P. S. Shah, C. R. J. Stephenson, *Chem. Commun.*, **2011**, *47,* 5040-5042

Deprotection of p-Methoxybenzylether





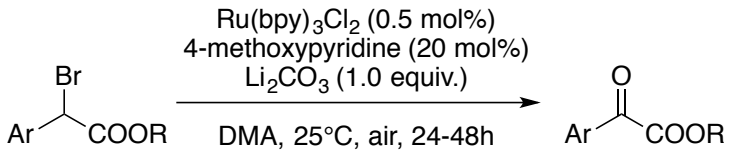




69% **80%**[a] **84%** **92%**[a] **79%**[a]

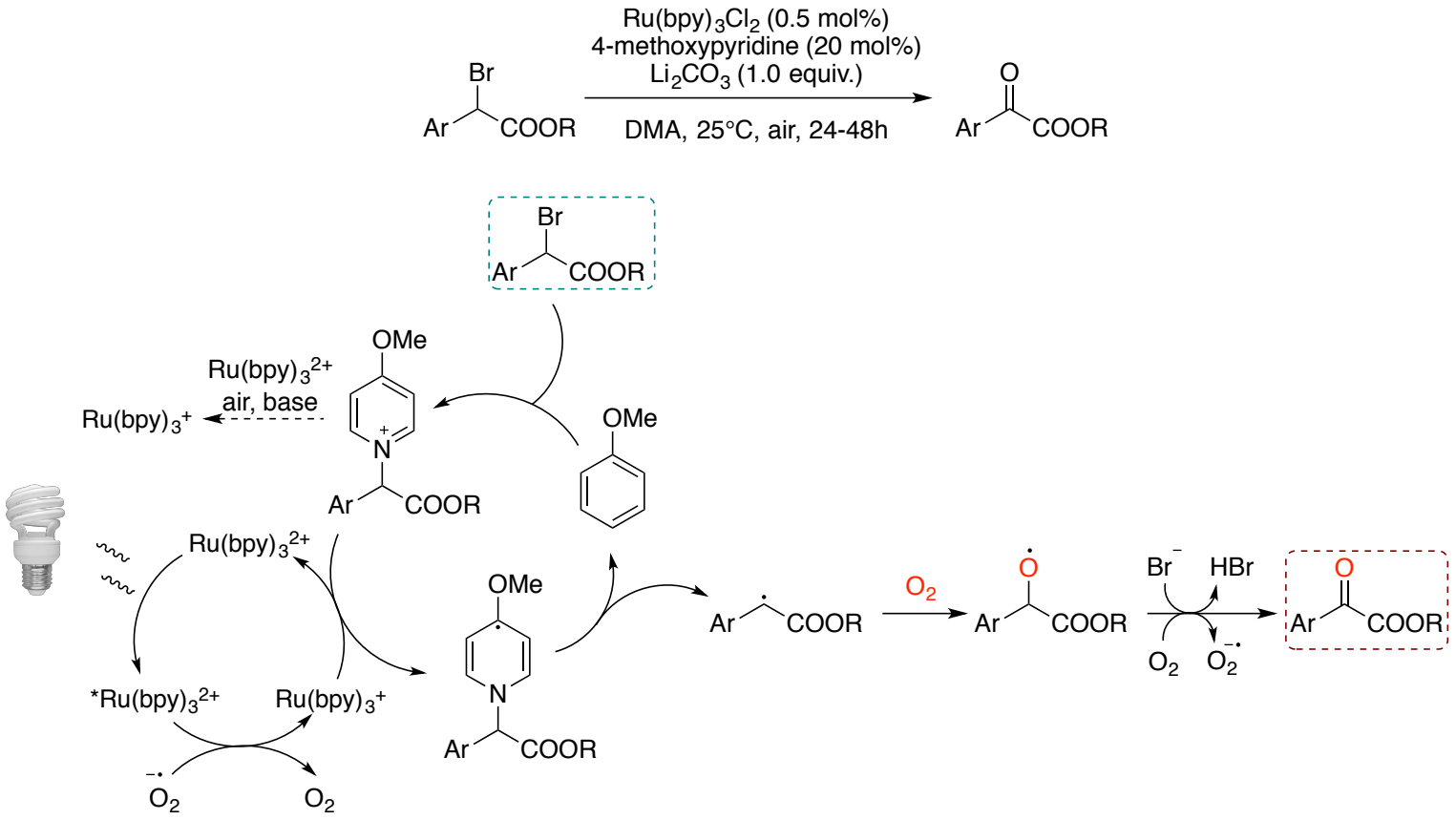
J. W. Tucker, J. M. R. Narayanam, P. S. Shah, C. R. J. Stephenson, *Chem. Commun.*, **2011**, *47,* 5040-5042

Aerobic oxitation of benzylic halides



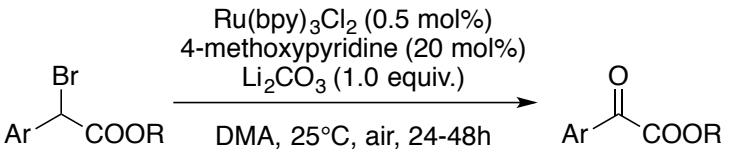
Y. Su, L. Zhang, N. Jiao, *Org. Lett.*, **2011**, *13*, 2168-2171

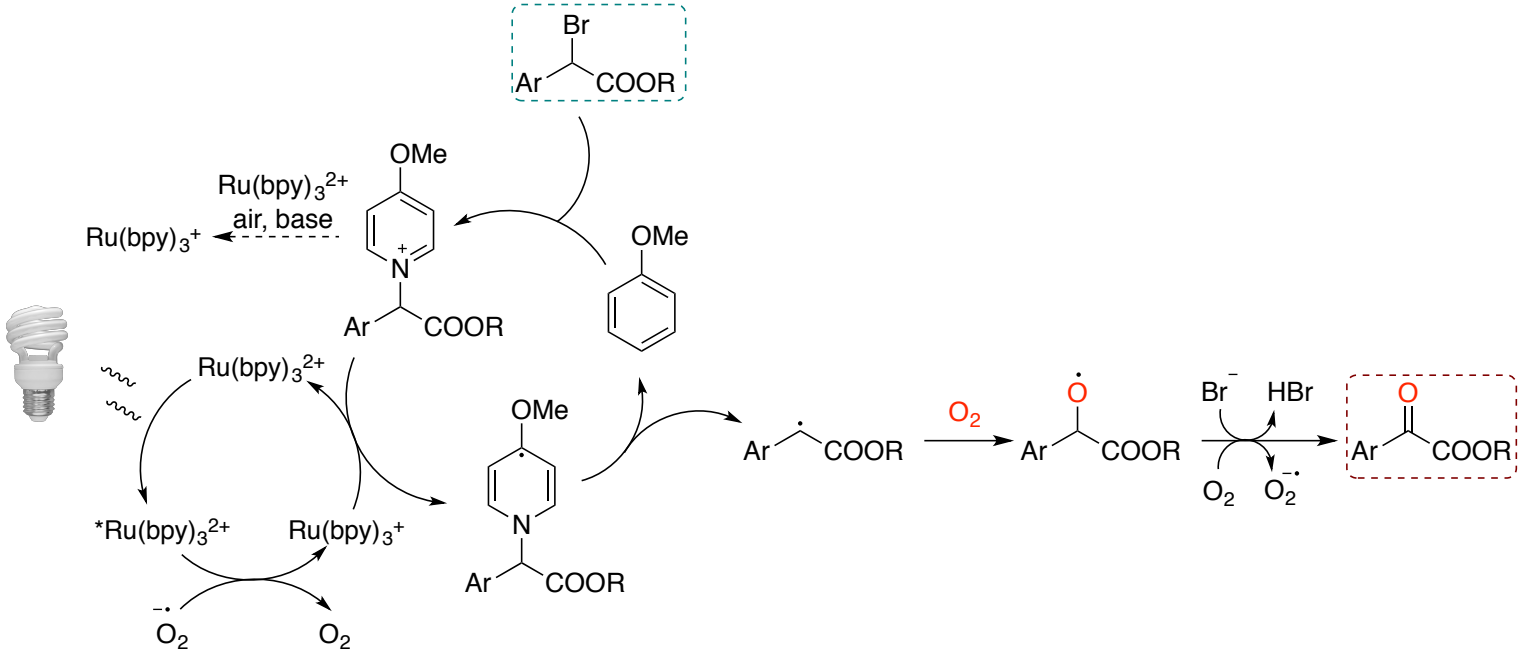
Aerobic oxitation of benzylic halides

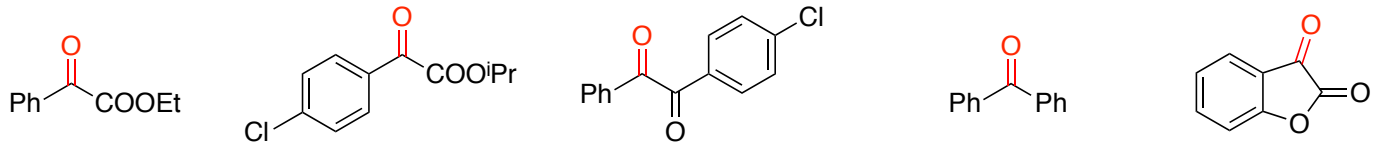


Y. Su, L. Zhang, N. Jiao, *Org. Lett.*, **2011**, *13*, 2168-2171

Aerobic oxitation of benzylic halides





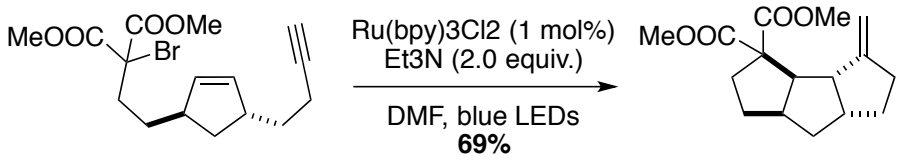


75% **75%** **82%** from Cl **40%** 2.5 equiv. of pyridine Cs_2CO_3 **0%**

Y. Su, L. Zhang, N. Jiao, *Org. Lett.*, **2011**, *13*, 2168-2171

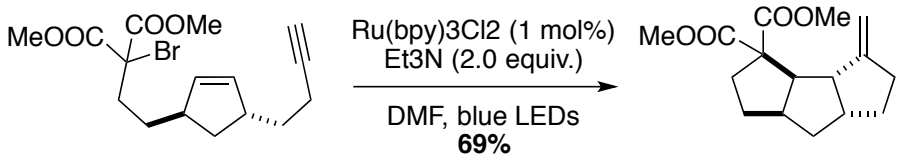
C-C Bond Formation

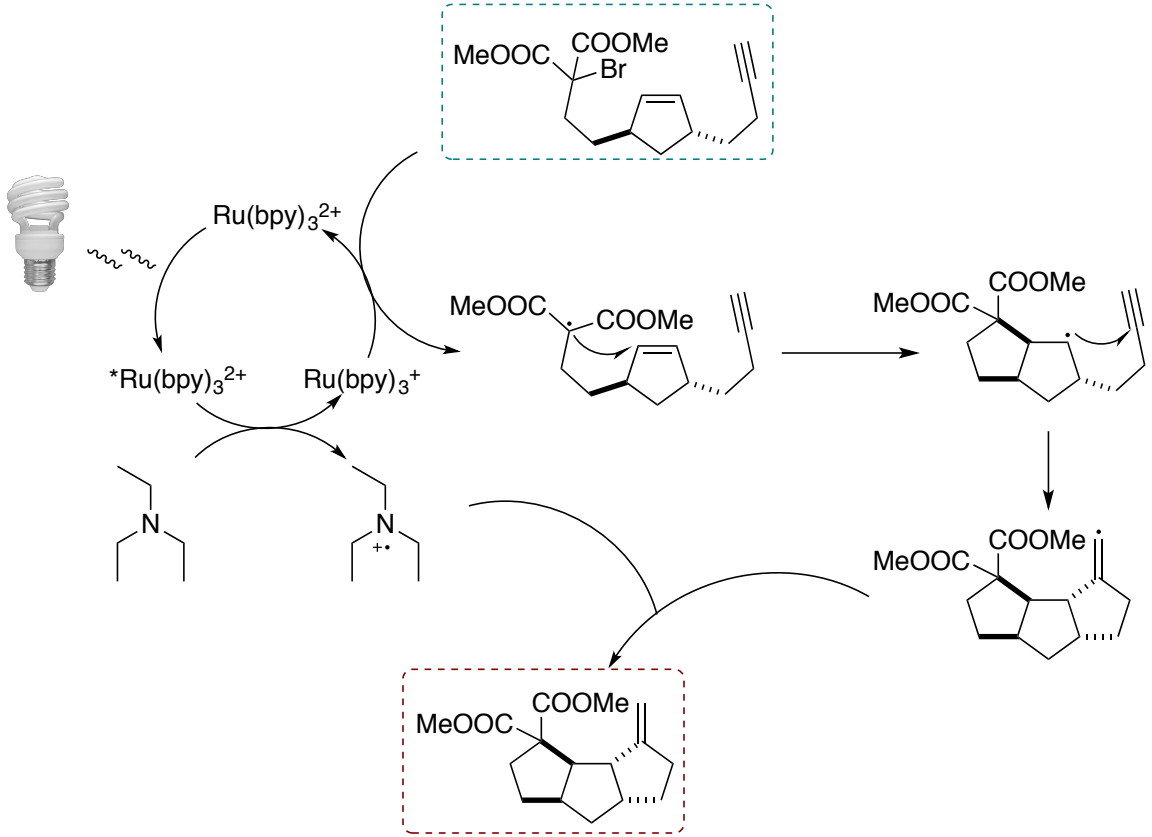
Reductive radical cyclization



J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

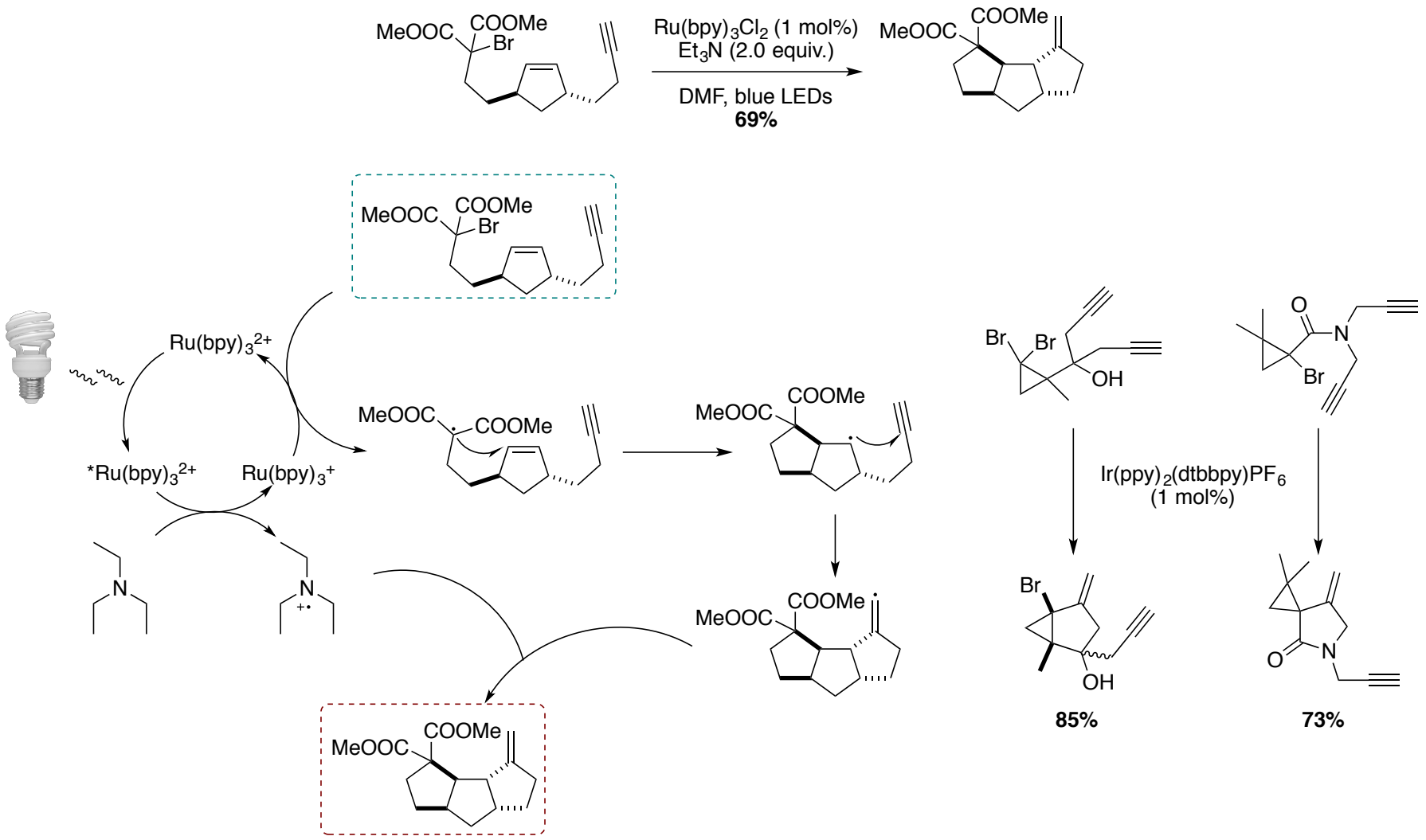
Reductive radical cyclization





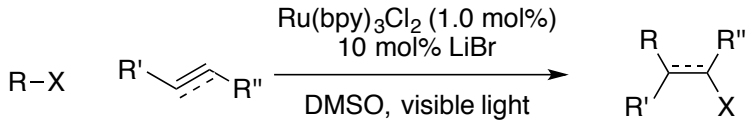
J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

Reductive radical cyclization



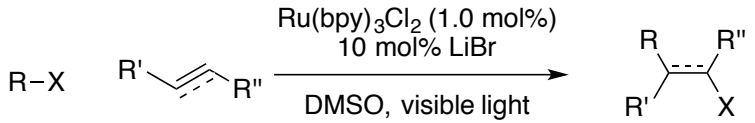
J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

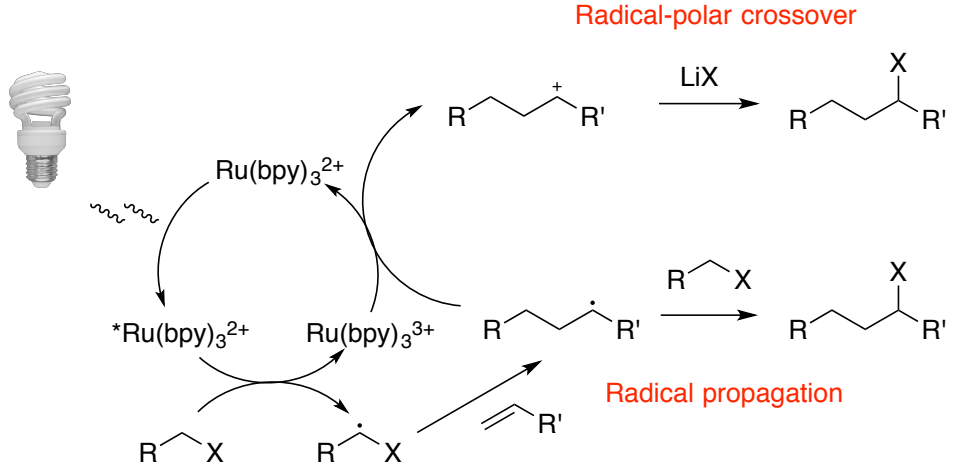
Atom Transfer Radical Addition



J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

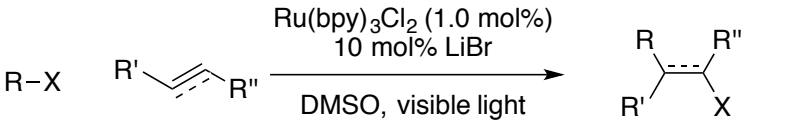
Atom Transfer Radical Addition



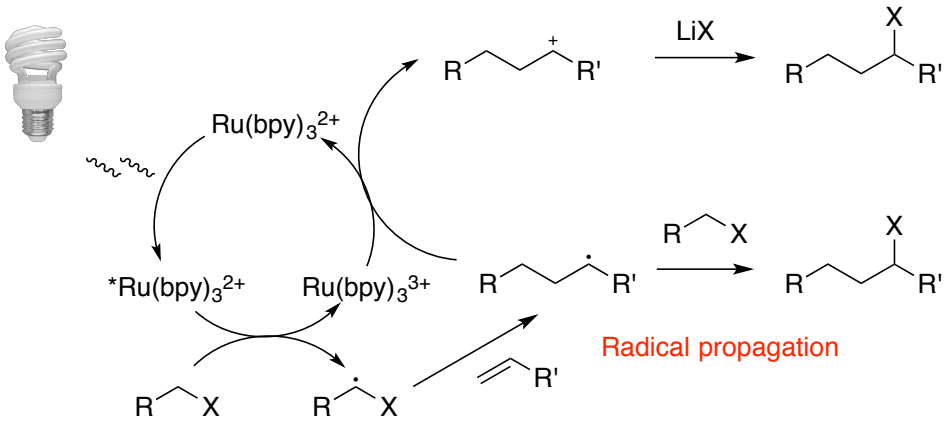


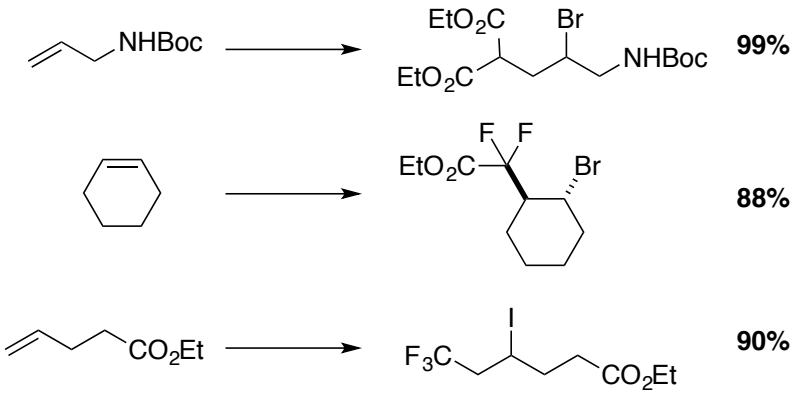
J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

Atom Transfer Radical Addition



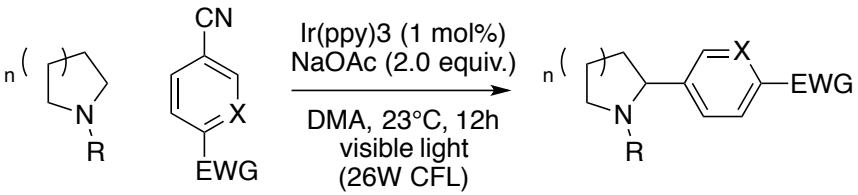
Radical-polar crossover





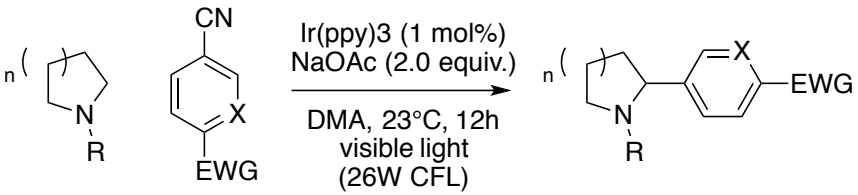
J. W. Tucker, J. D. Nguyen, J. M. R. Narayanam, S. W. Krabbe, C. R. J. Stephenson, *Chem. Commun*, **2010**, *46*, 4985-4987

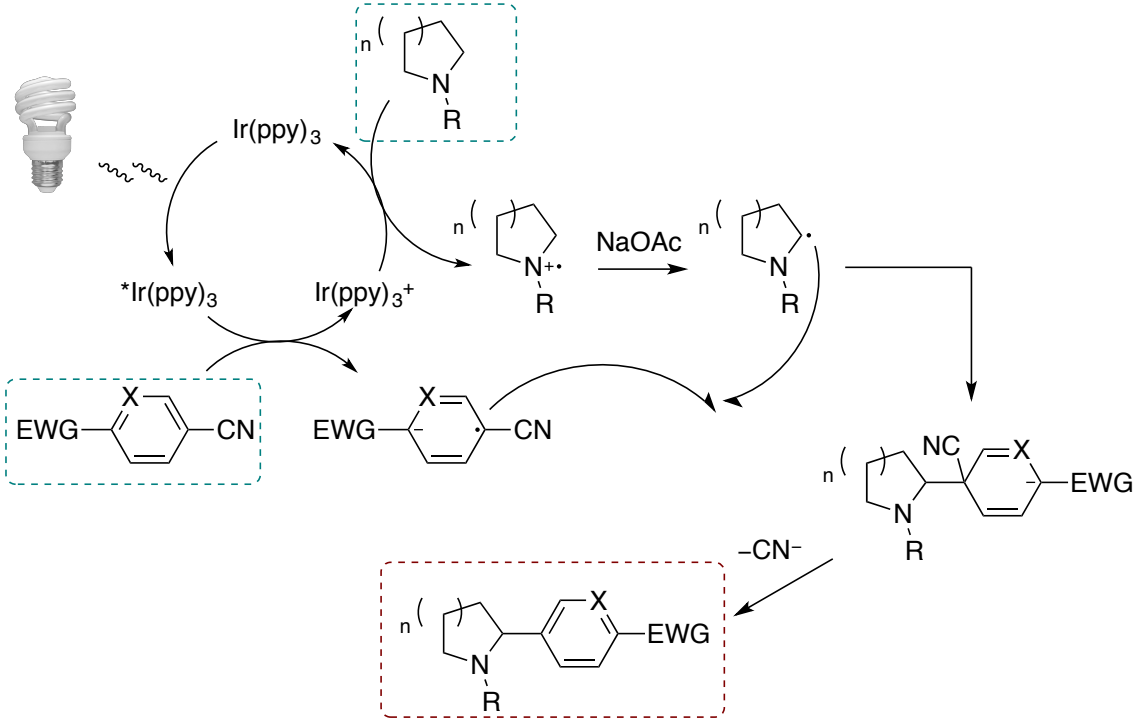
α-Amino C-H arylation



A. McNally, C. K. Prier, D.W. C. MacMillan, *Science*, **2011**, *334*, 1114-1117

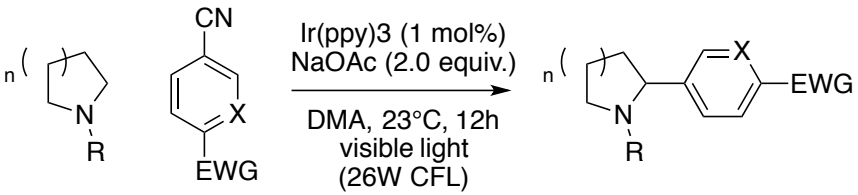
α-Amino C-H arylation

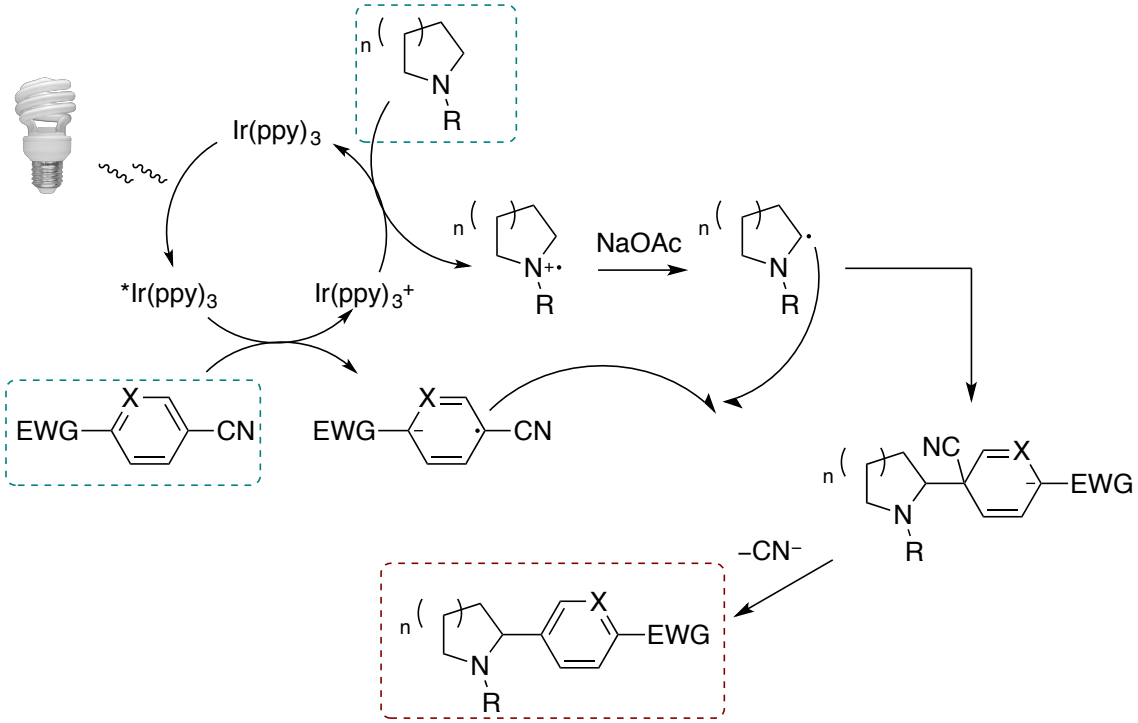


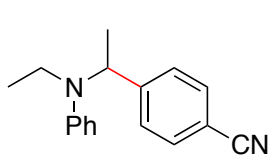


A. McNally, C. K. Prier, D.W. C. MacMillan, *Science*, **2011**, *334*, 1114-1117

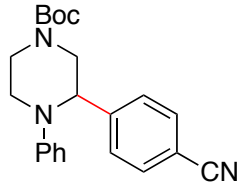
α-Amino C-H arylation



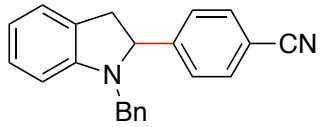




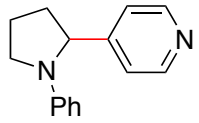
94%



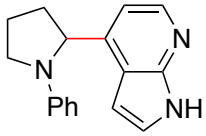
95%



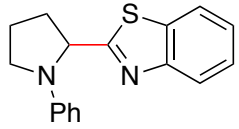
90% (6.7:1 r.r.)



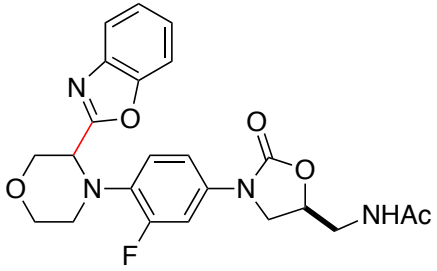
72%



61%



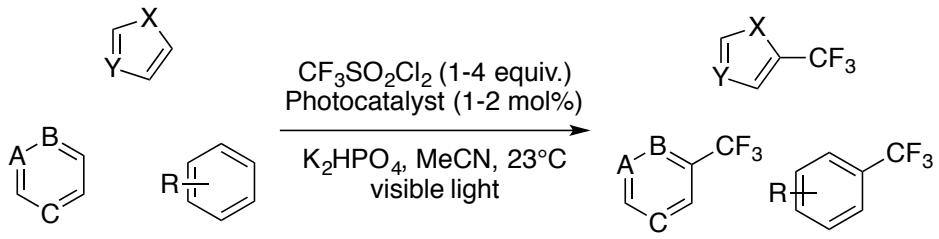
79%



58%

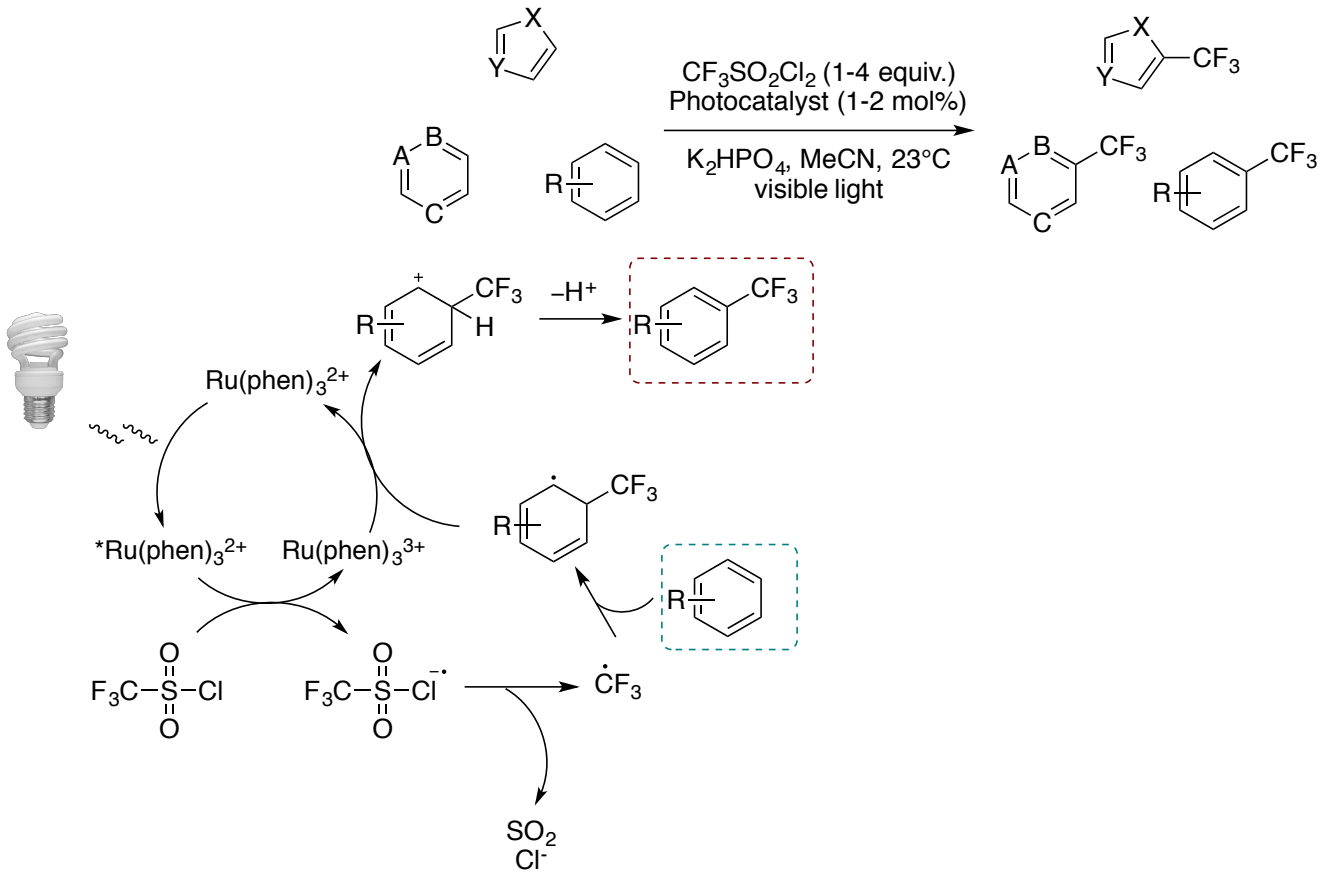
A. McNally, C. K. Prier, D.W. C. MacMillan, *Science*, **2011**, *334*, 1114-1117

Trifluoromethylation of Arenes via Direct C-H functionalization



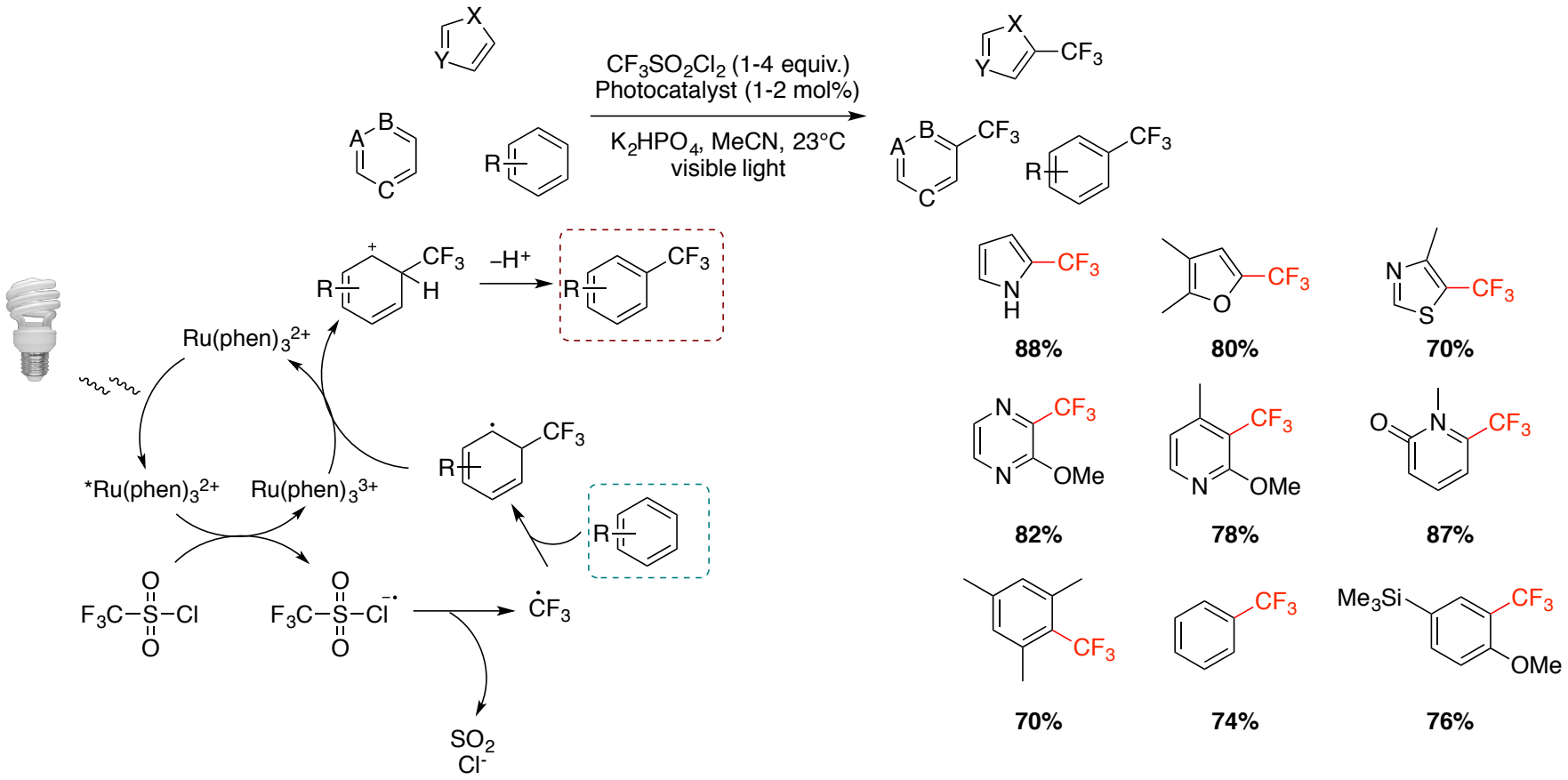
D.A. Nagib, D.W. C. MacMillan, *Nature*, **2011**, *480*, 224-228

Trifluoromethylation of Arenes via Direct C-H functionalization



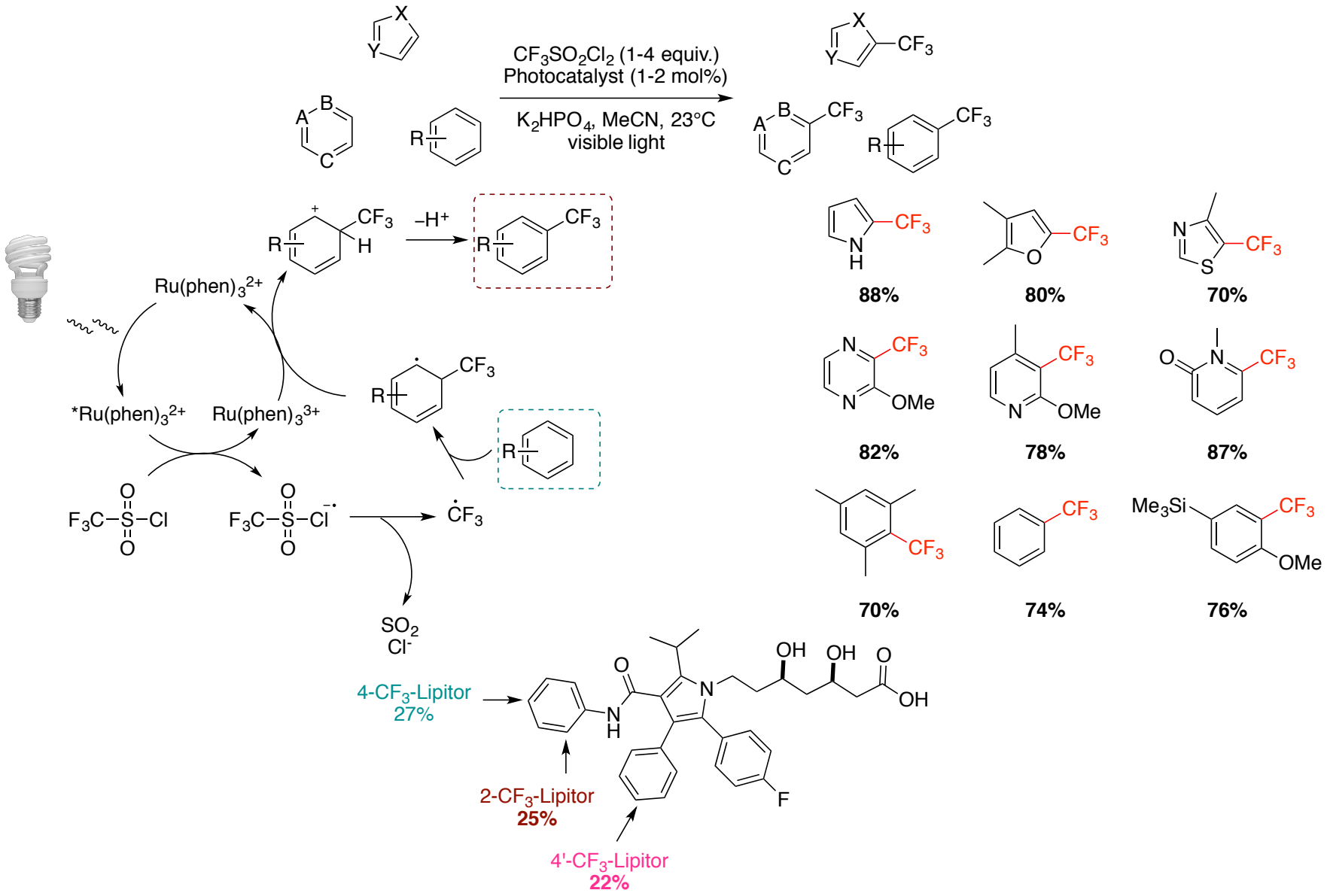
D.A. Nagib, D.W. C. MacMillan, *Nature*, **2011**, *480*, 224-228

Trifluoromethylation of Arenes via Direct C-H functionalization



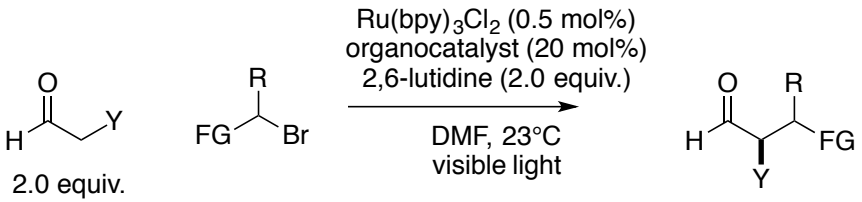
D.A. Nagib, D.W. C. MacMillan, *Nature*, **2011**, *480*, 224-228

Trifluoromethylation of Arenes via Direct C-H functionalization



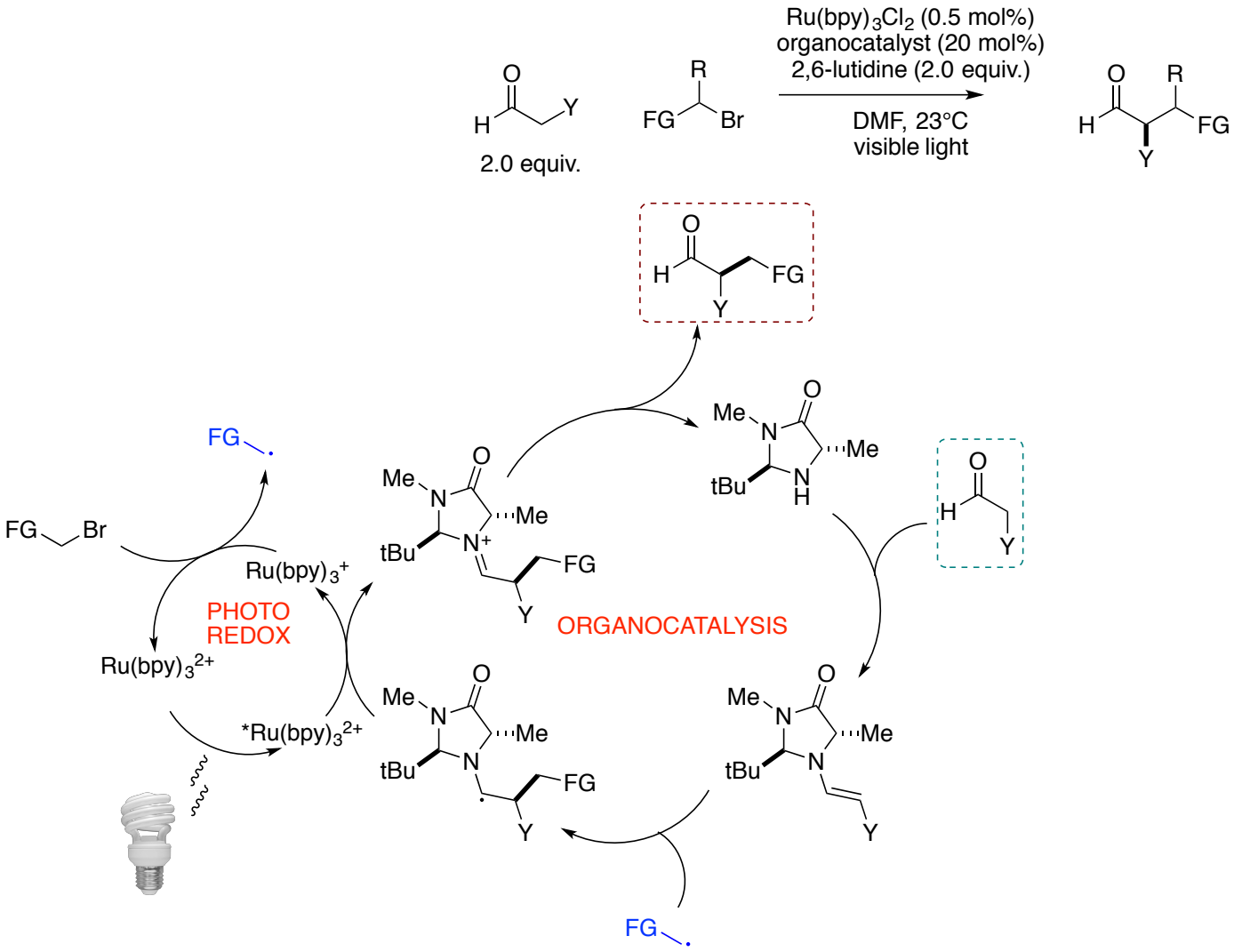
D.A. Nagib, D.W. C. MacMillan, *Nature*, **2011**, *480*, 224-228

Merging Photoredox and Organocatalysis: Enantioselective α-Alkylation of Aldehydes



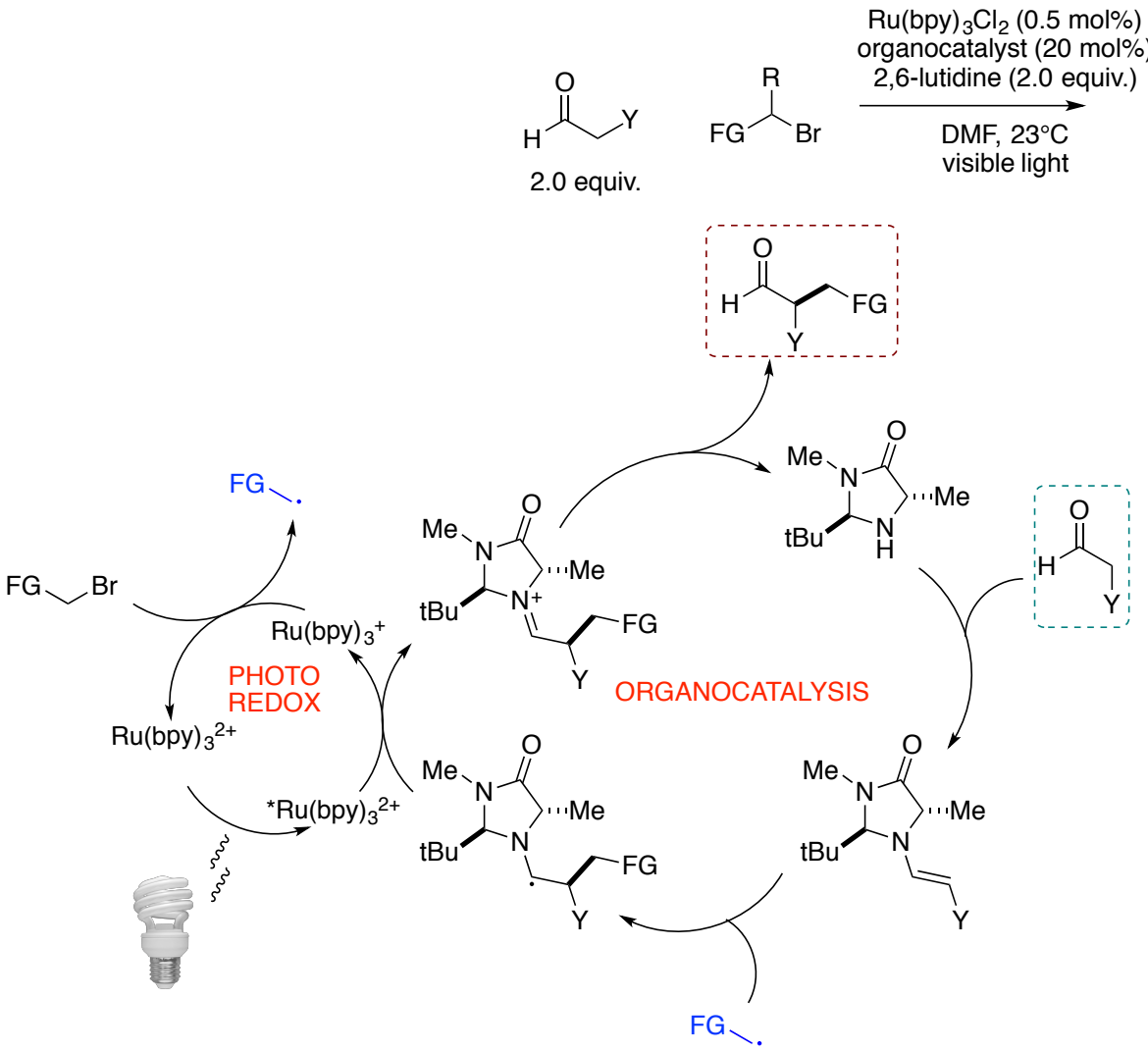
D. A. Nicewicz, D. W. C. MacMillan, *Science*, **2008**, *322*, 77-80

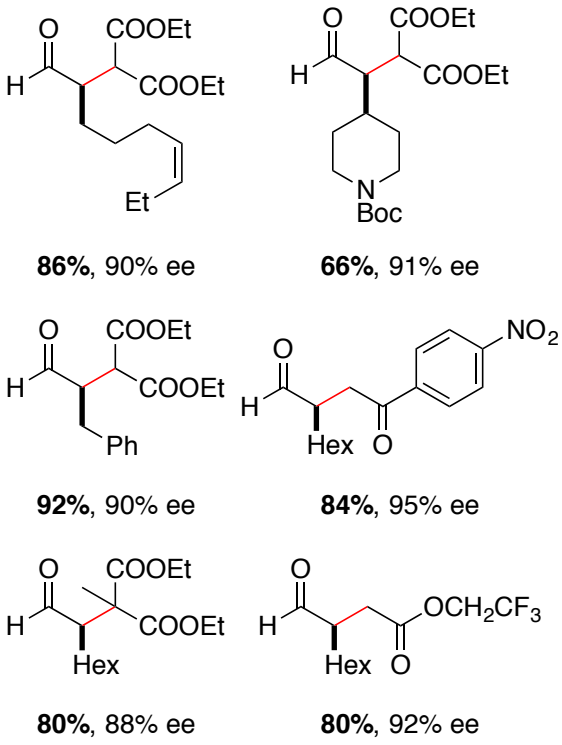
Merging Photoredox and Organocatalysis: Enantioselective α-Alkylation of Aldehydes



D.A. Nicewicz, D.W. C. MacMillan, *Science*, **2008**, *322*, 77-80

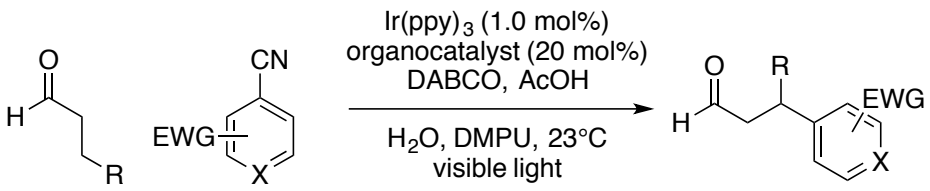
Merging Photoredox and Organocatalysis: Enantioselective α-Alkylation of Aldehydes

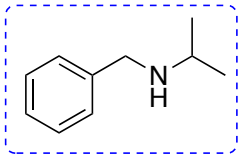


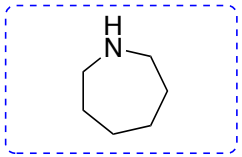


D.A. Nicewicz, D.W. C. MacMillan, *Science*, **2008**, *322*, 77-80

β-Arylation of Aldehydes and Ketones

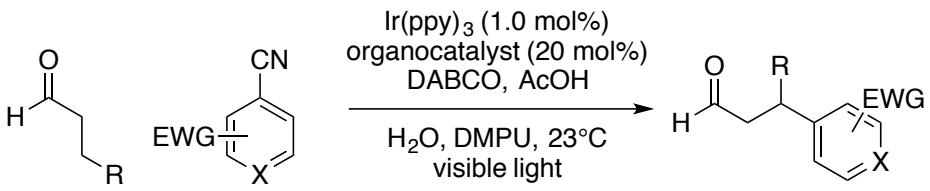


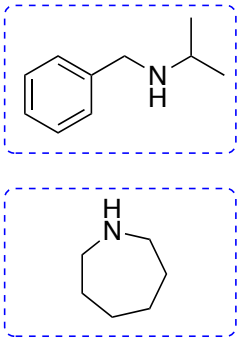


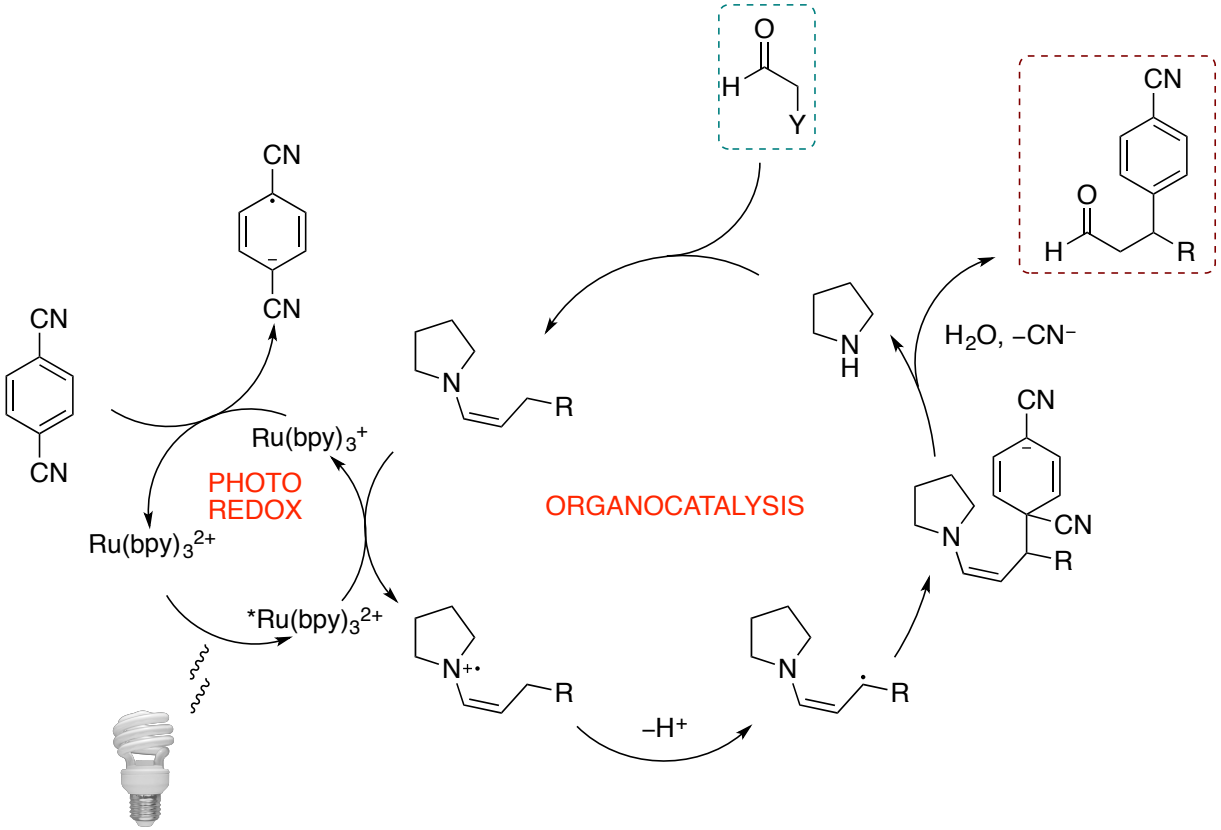


M. T. Pirnot, D. A. Rankic, D. B. C. Martin, D. W. C. MacMillan, *Science*, **2013**, *339*, 1593-1596

β-Arylation of Aldehydes and Ketones

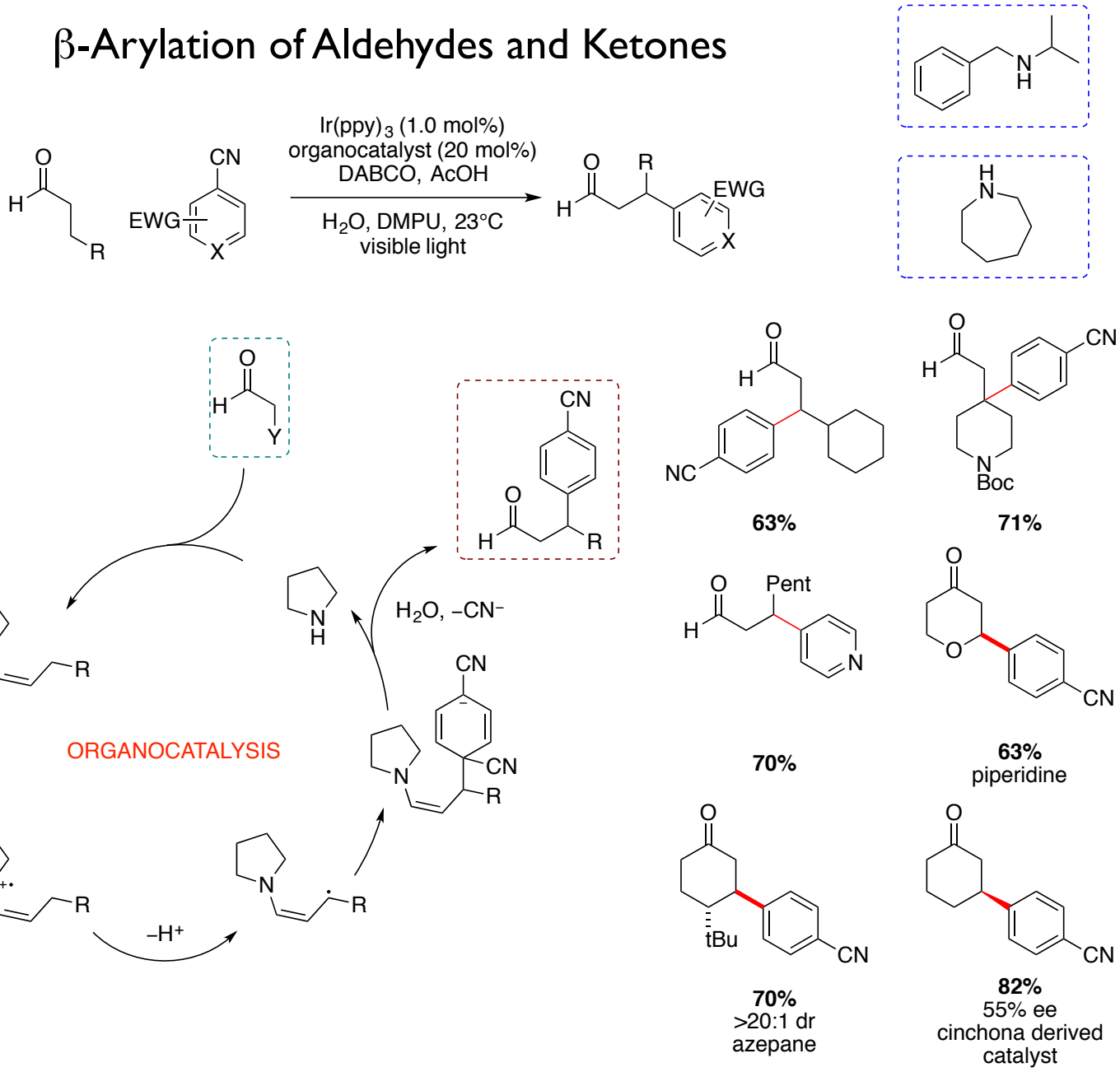






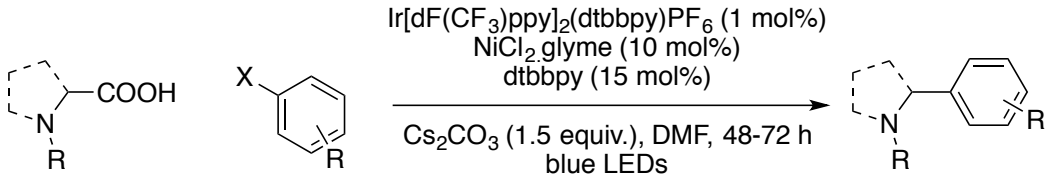
M. T. Pirnot, D. A. Rankic, D. B. C. Martin, D. W. C. MacMillan, *Science*, **2013**, *339*, 1593-1596

β-Arylation of Aldehydes and Ketones



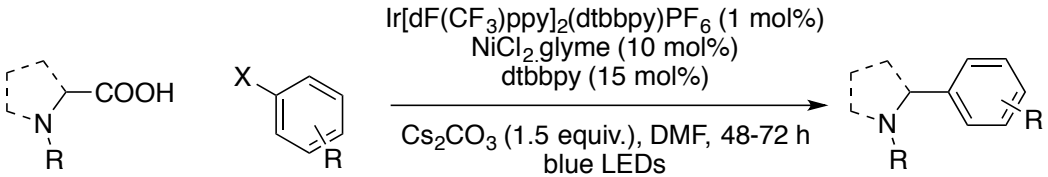
M. T. Pirnot, D. A. Rankic, D. B. C. Martin, D. W. C. MacMillan, *Science*, **2013**, *339*, 1593-1596

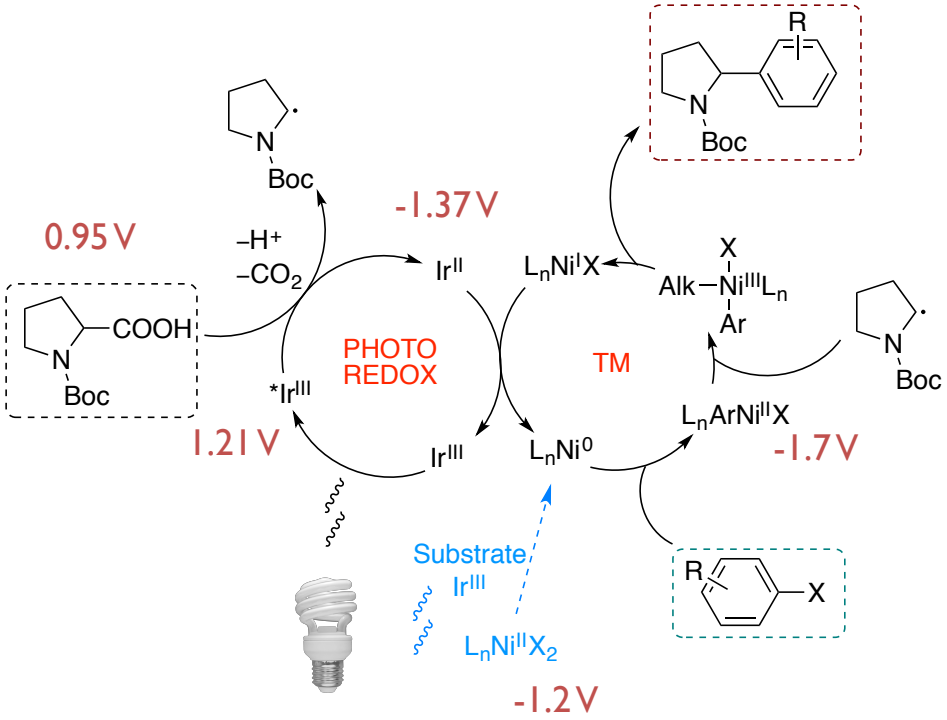
Merging Photoredox and TM catalysis: Coupling of α-carboxyl sp^3 carbon with Aryl Halides



Z. Zuo, D. T. Ahneman, L. Chu, J. A. Terrett, A. G. Doyle, D. W. C. MacMillan, *Science*, **2014**, *345*, 437-440

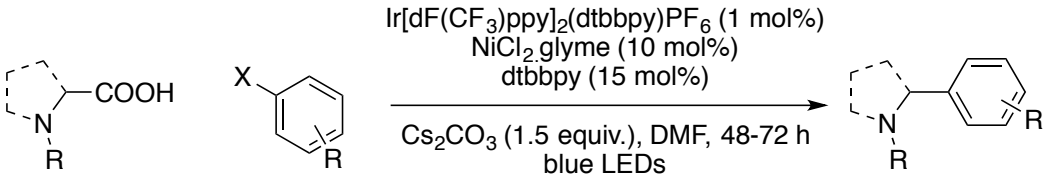
Merging Photoredox and TM catalysis: Coupling of α-carboxyl sp^3 carbon with Aryl Halides

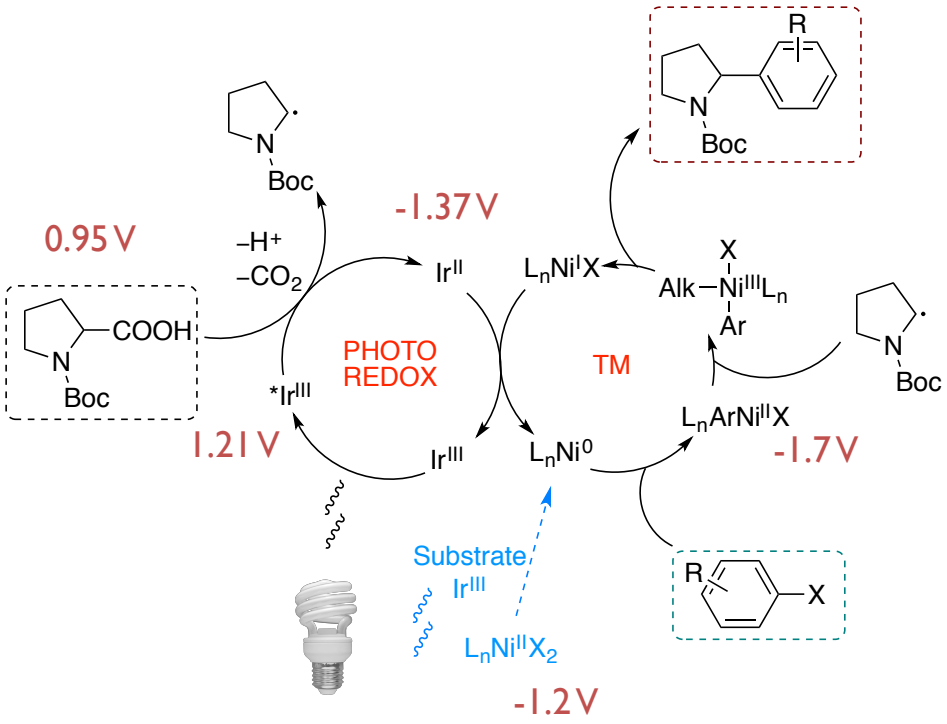


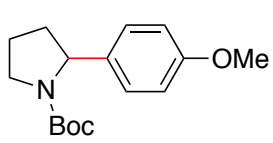


Z. Zuo, D. T. Ahneman, L. Chu, J. A. Terrett, A. G. Doyle, D. W. C. MacMillan, *Science*, **2014**, *345*, 437-440

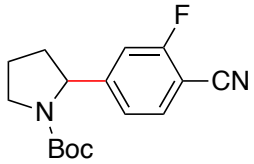
Merging Photoredox and TM catalysis: Coupling of α-carboxyl sp^3 carbon with Aryl Halides



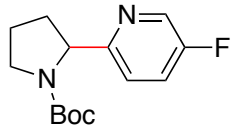




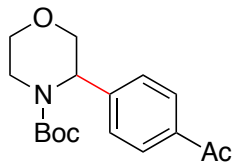
78%
from ArI



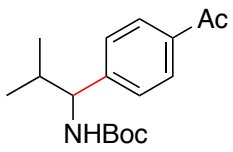
75%
from ArBr



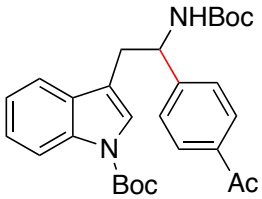
78%
from ArCl



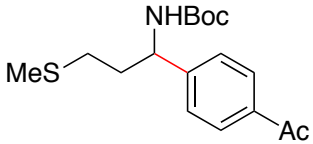
61%
from ArBr



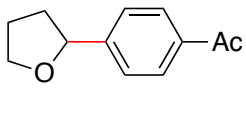
72%
from ArBr



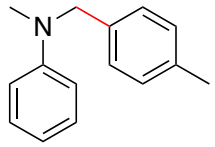
83%
from ArBr



83%
from ArBr



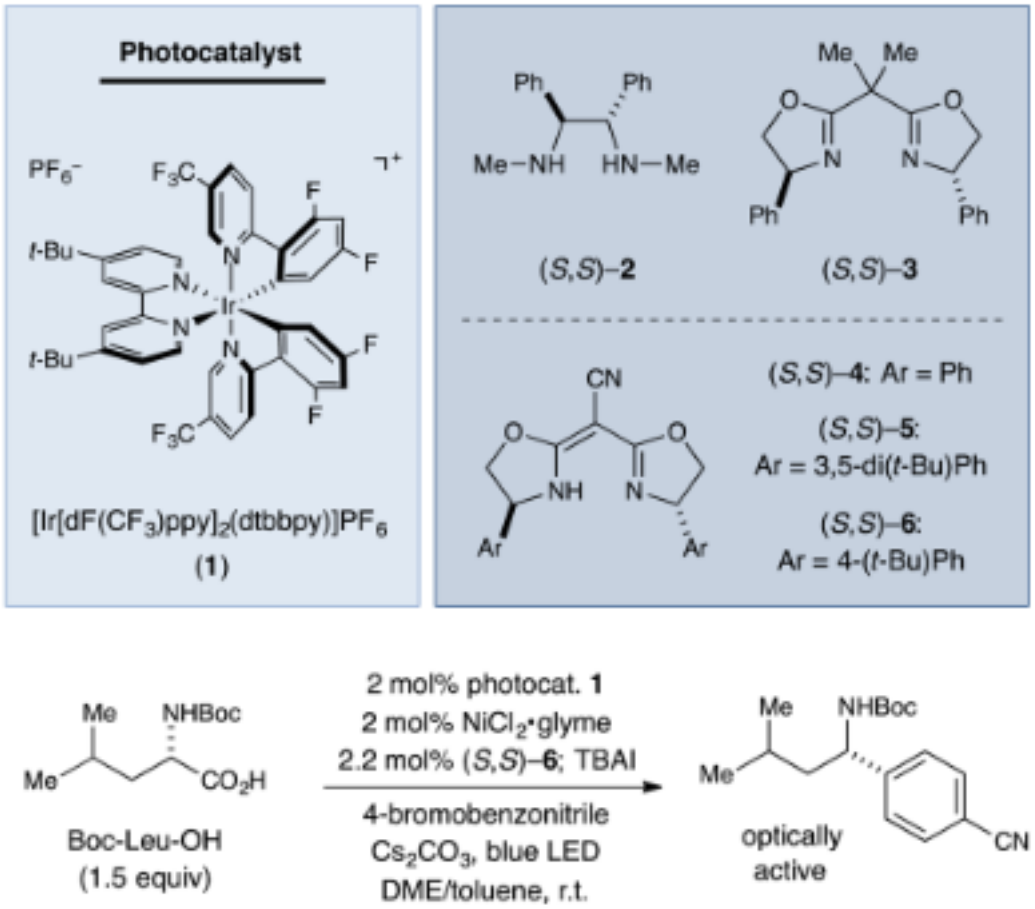
82%
from ArBr



84%
from ArBr
and
dimethylaniline

Z. Zuo, D. T. Ahneman, L. Chu, J. A. Terrett, A. G. Doyle, D. W. C. MacMillan, *Science*, **2014**, *345*, 437-440

Enantioselective Coupling of α-carboxyl sp^3 carbon with Aryl Halides

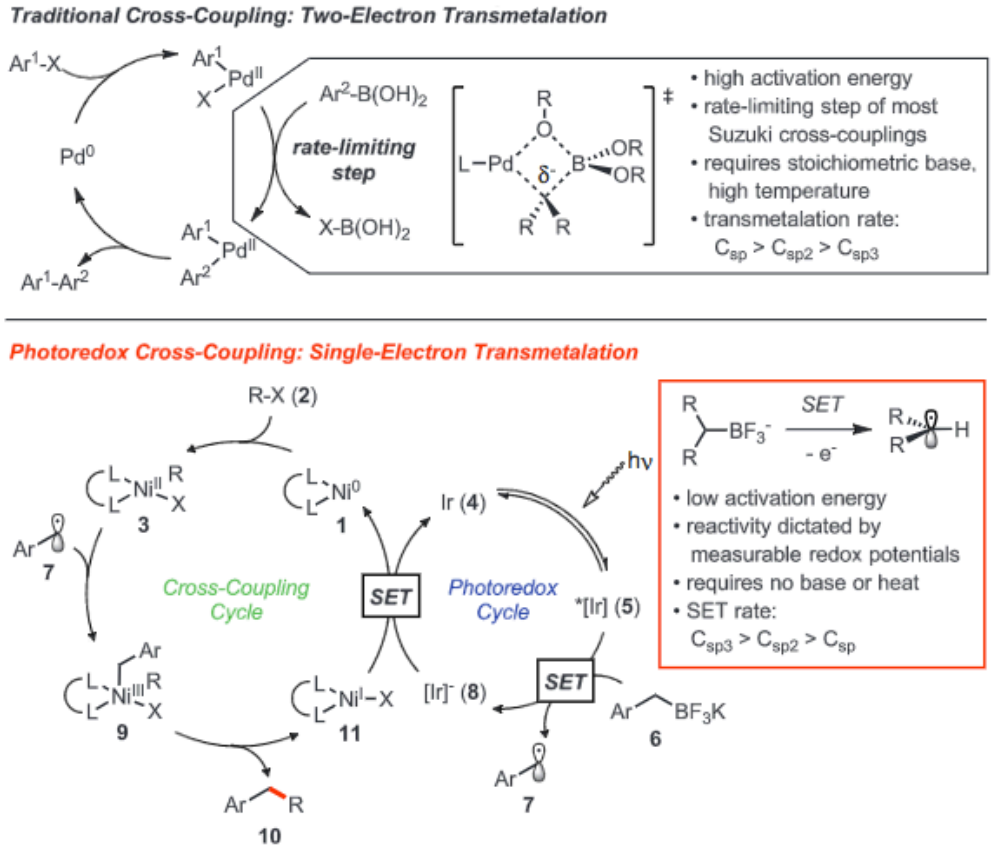


Z. Zuo, H. Cong, W. Li, J. Choi, G. C. Fu, D. W. C. MacMillan, *J. Am. Chem. Soc.*, **2016**, *138*, 1832-1835

Photoredox-Assisted Suzuki-type Cross Coupling

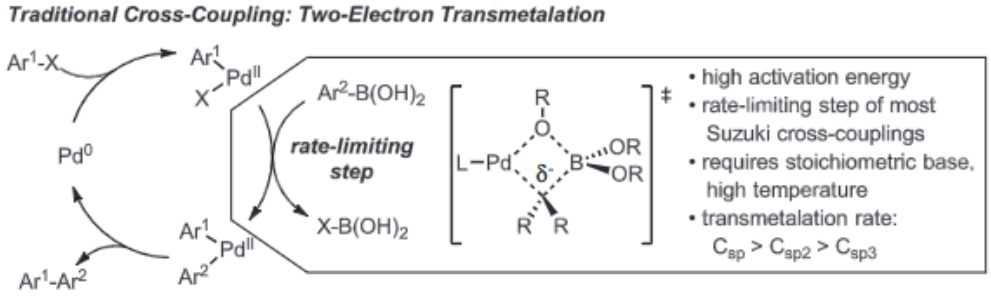
J. C. Tellis, D. N. Primer, G. A. Molander, *Science*, **2014,** *345*, 433-436

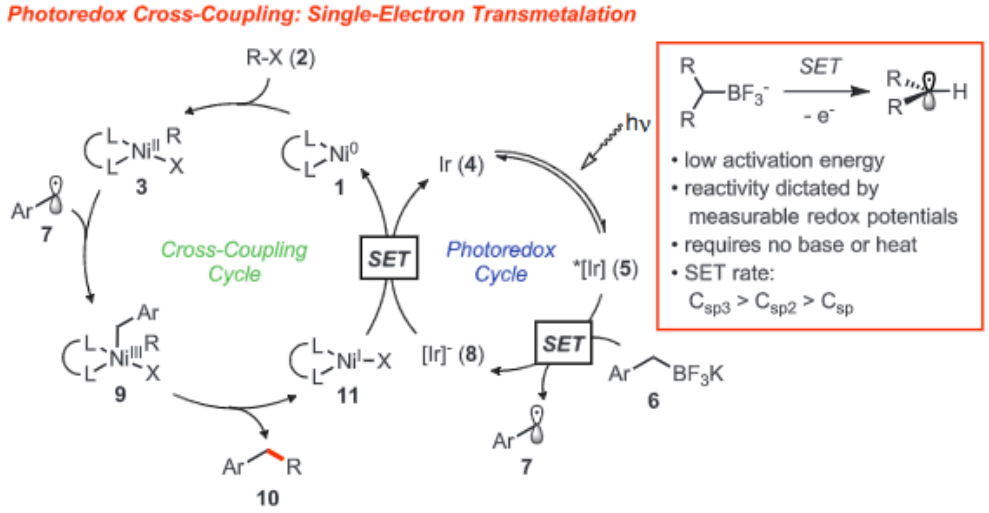
Photoredox-Assisted Suzuki-type Cross Coupling

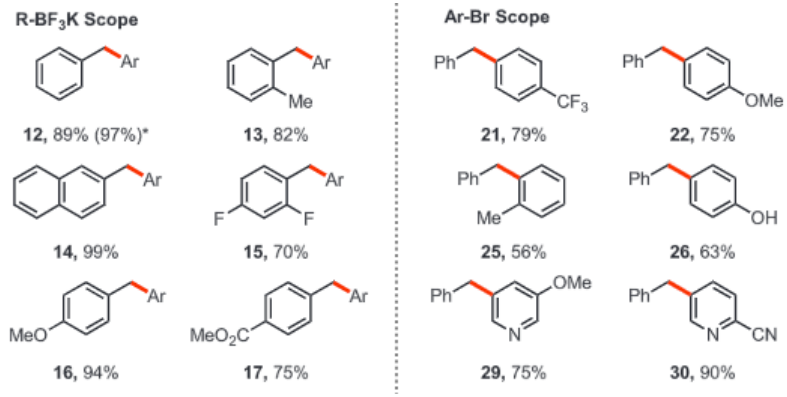


J. C. Tellis, D. N. Primer, G. A. Molander, *Science*, **2014,** *345*, 433-436

Photoredox-Assisted Suzuki-type Cross Coupling

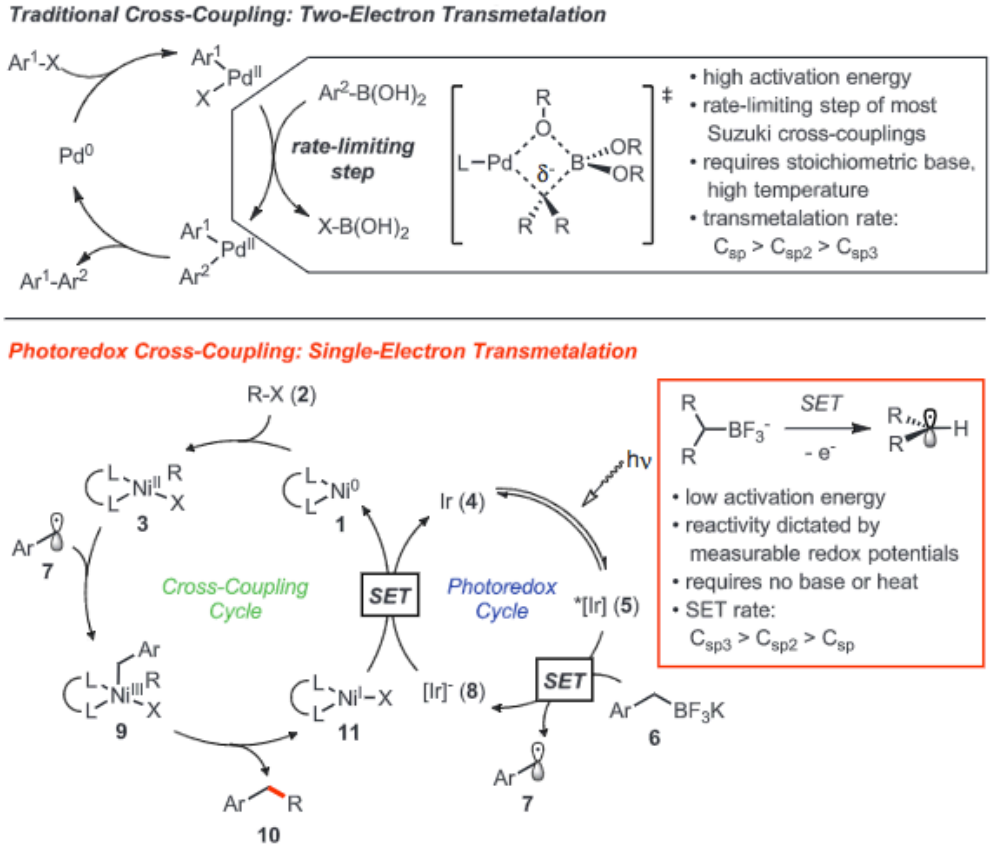


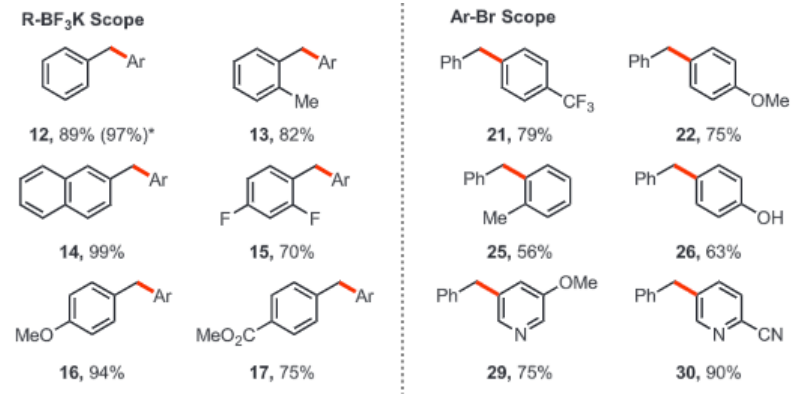


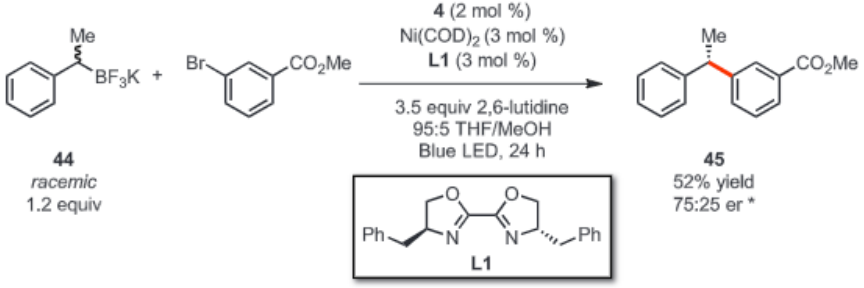


J. C. Tellis, D. N. Primer, G. A. Molander, *Science*, **2014,** *345*, 433-436

Photoredox-Assisted Suzuki-type Cross Coupling

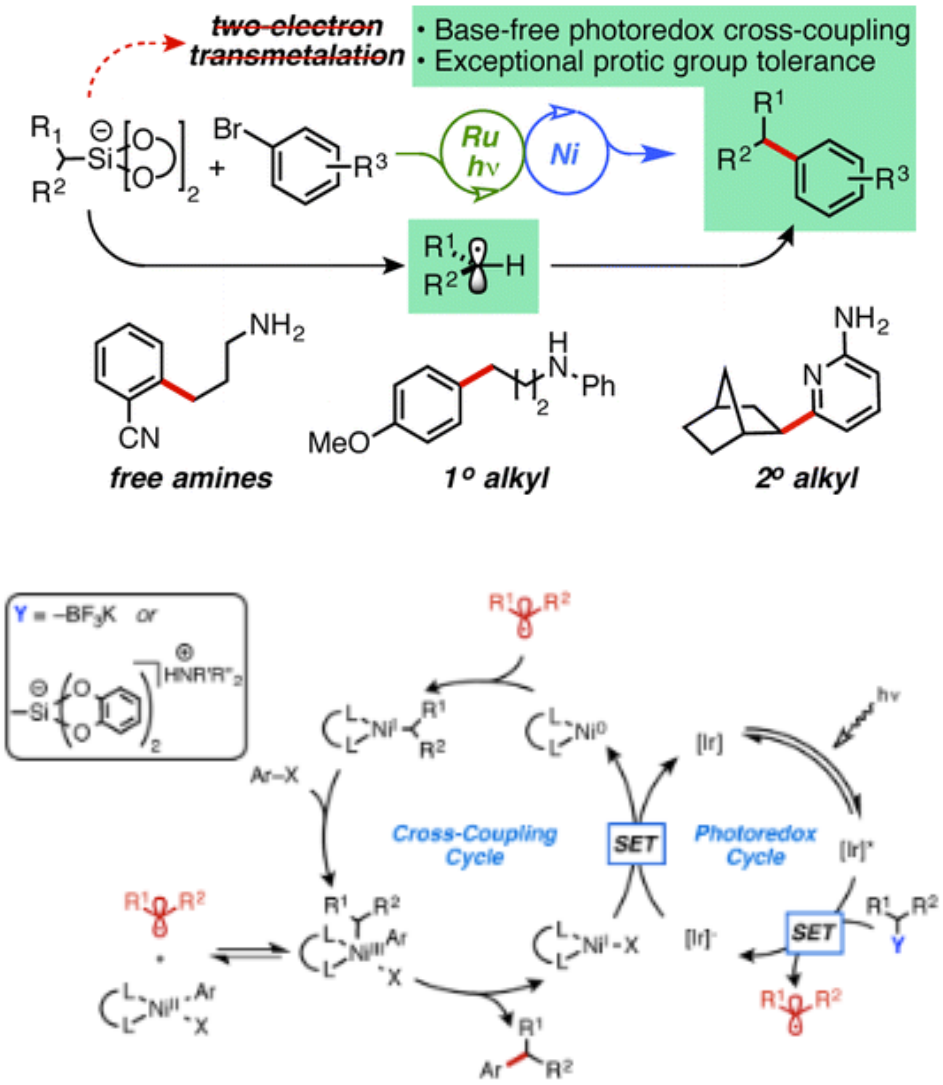






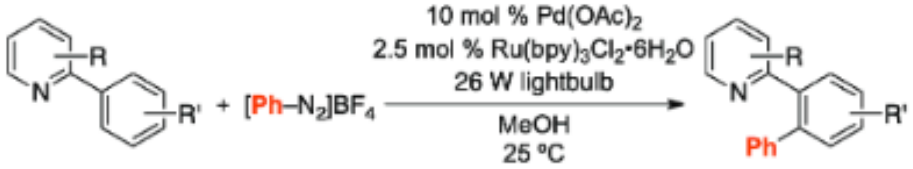
J. C. Tellis, D. N. Primer, G. A. Molander, *Science*, **2014,** *345*, 433-436

Photoredox-Assisted Hiyama-type Cross Coupling

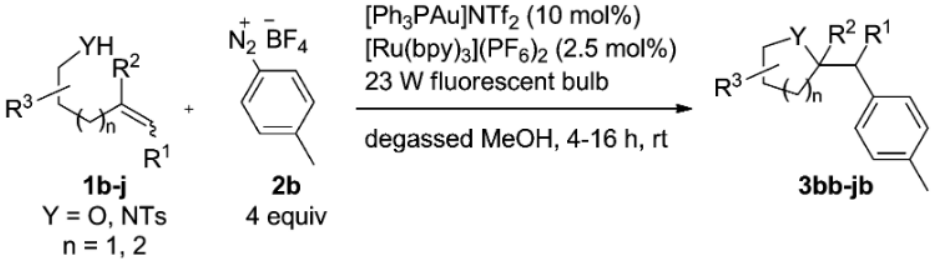


M. Jouffroy, D. N. Primer, G. A. Molander, *J. Am. Chem. Soc.*, **2016**, *138*, 475-478

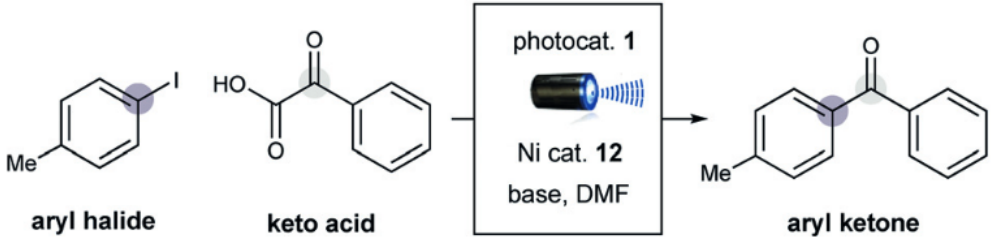
Dual Photoredox and TM



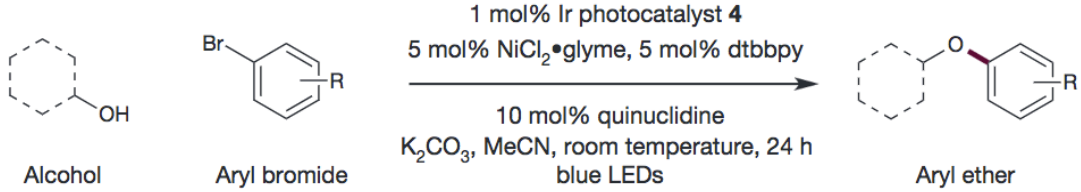
Sanford, *J. Am. Chem. Soc.*, **2011**, *133*, 18566–18569



Glorius, *J. Am. Chem. Soc.*, **2013**, *135*, 5505–5508



MacMillan, *Angew. Chem. Int. Ed.*, **2015**, *54*, 7929–7933



MacMillan, *Nature*, **2015**, *524*, 330–334

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Mild conditions

Room temperature

Stable/commercial reagents

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Mild conditions

Room temperature

Stable/commercial reagents

Combination with other types of catalysis

Organocatalysis, TM catalysis, HAT

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Mild conditions

Room temperature

Stable/commercial reagents

Combination with other types of catalysis

Organocatalysis, TM catalysis, HAT

Rational design

Catalyst

Reaction

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Mild conditions

Room temperature

Stable/commercial reagents

Combination with other types of catalysis

Organocatalysis, TM catalysis, HAT

Rational design

Catalyst

Reaction

Types of catalysts

Cu, Fe, W, …

Metal-free: organic dyes

Conclusions

Extremely versitile

CC, CN, CO, CP, CB bond formation, FGI…

[2+2], [4+2] cycloadditions, oxidative & reductive couplings…

Mild conditions

Room temperature

Stable/commercial reagents

Combination with other types of catalysis

Organocatalysis, TM catalysis, HAT

Rational design

Catalyst

Reaction

Types of catalysts

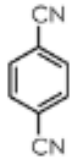
Cu, Fe, W, …

Metal-free: organic dyes

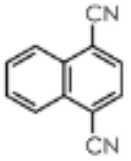
« Organic Photoredox Chemistry »

N. A. Romero and D. A. Nicewicz, *Chem. Rev.*, **2016**, *16*, 10075−10166

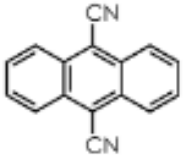
CYANOARENES



DCB
1,4-dicyanobenzene

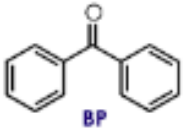


DCN
1,4-dicyanonaphthalene

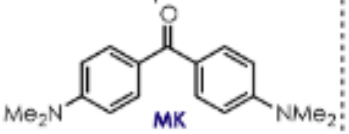


DCA
9,10-dicyanoanthracene

BENZOPHENONES

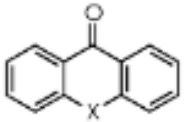


BP
benzophenone



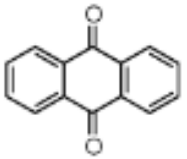
MK
Michler's Ketone

FLN
fluorenone

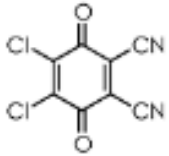


XO
xanthone (X=O)
TXO
thioxanthone (X=S)

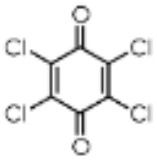
QUINONES



AQ
anthraquinone

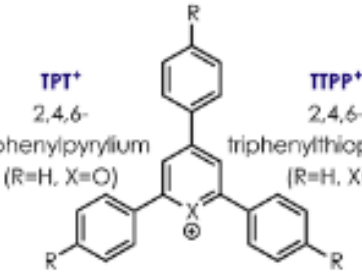


DDQ
2,3-Dichloro-5,6-dicyano-1,4-benzoquinone



TCBQ
p-Chloranil

PYRYLIUMS



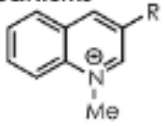
TPT⁺
2,4,6-triphenylpyrylium (R=H, X=O)

TTPP⁺
2,4,6-triphenylthiopyrylium (R=H, X=S)

p-MeO-TPT⁺
2,4,6-tris-(4-methoxyphenyl)pyrylium (R=OMe, X=O)

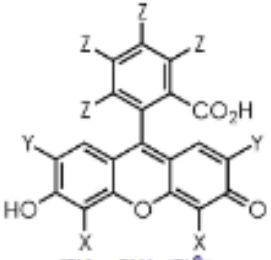
p-MeO-TTPP⁺
2,4,6-tris-(4-methoxyphenyl)thiopyrylium (R=OMe, X=S)

QUINOLINIUMS

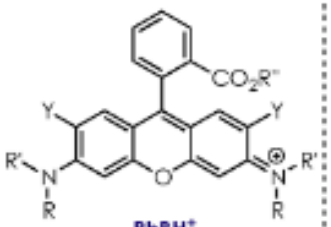


NMQ⁺
N-methylquinolinium
QuCN⁺
3-cyano-1-methylquinolinium (R = CN)

XANTHENES

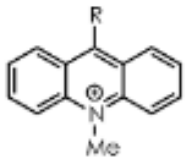


[FL] = FLH_2/FL^{2-}
Fluorescein (X,Y,Z=H)
[EY] = EYH_2/EY^{2-}
Eosin Y (X,Y=Br; Z=H)
[RB] = EYH_2/EY^{2-}
Rose Bengal (X,Y=I; Z=Cl)

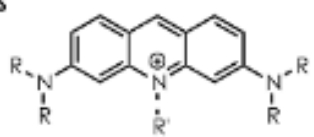


RhBH⁺
Rhodamine B (Y,R''=H; R,R'=Et)
Rh6G-H⁺
Rhodamine 6G (Y=Me; R'=H; R,R''=Et)

ACRIDINIUMS

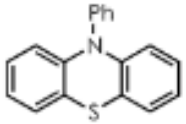


Acr-Me⁺
10-methylacridinium (R=H)
Ph-Acr-Me⁺
10-methyl-9-phenylacridinium (R=Ph)
Mes-Acr-Me⁺
10-methyl-9-mesitylacridinium (R=mesityl)

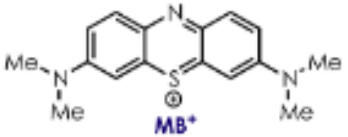


AO/AOH⁺
acridine orange (R=Me; no R')/(R=Me, R'=H)
AcrF⁺
acriflavin (R=H; R'=Me)
PF/PFH⁺
proflavin (R=H; no R')/(R=H; R'=H)

THIAZINES



PTh
10-phenylphenothiazine



MB⁺
Methylene Blue

DAP^{2+}
2,7-dimethyldiazapyrenium

PDI perylene diimide
PDI-a (R = 2,6-diisopropylphenyl)
PDI-b (R = 2,5-di-*tert*-butylphenyl)