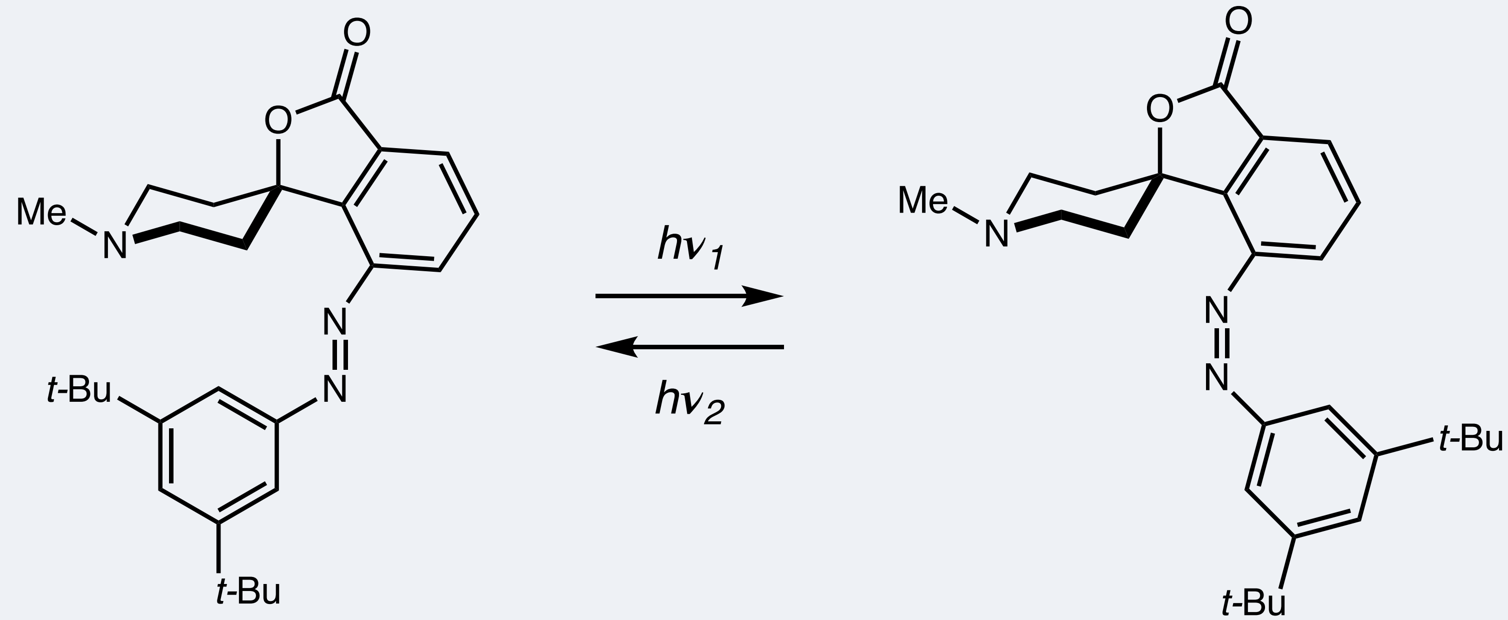
Switchable Catalysis



Tiffany Chen

MacMillan Lab

June 5, 2018

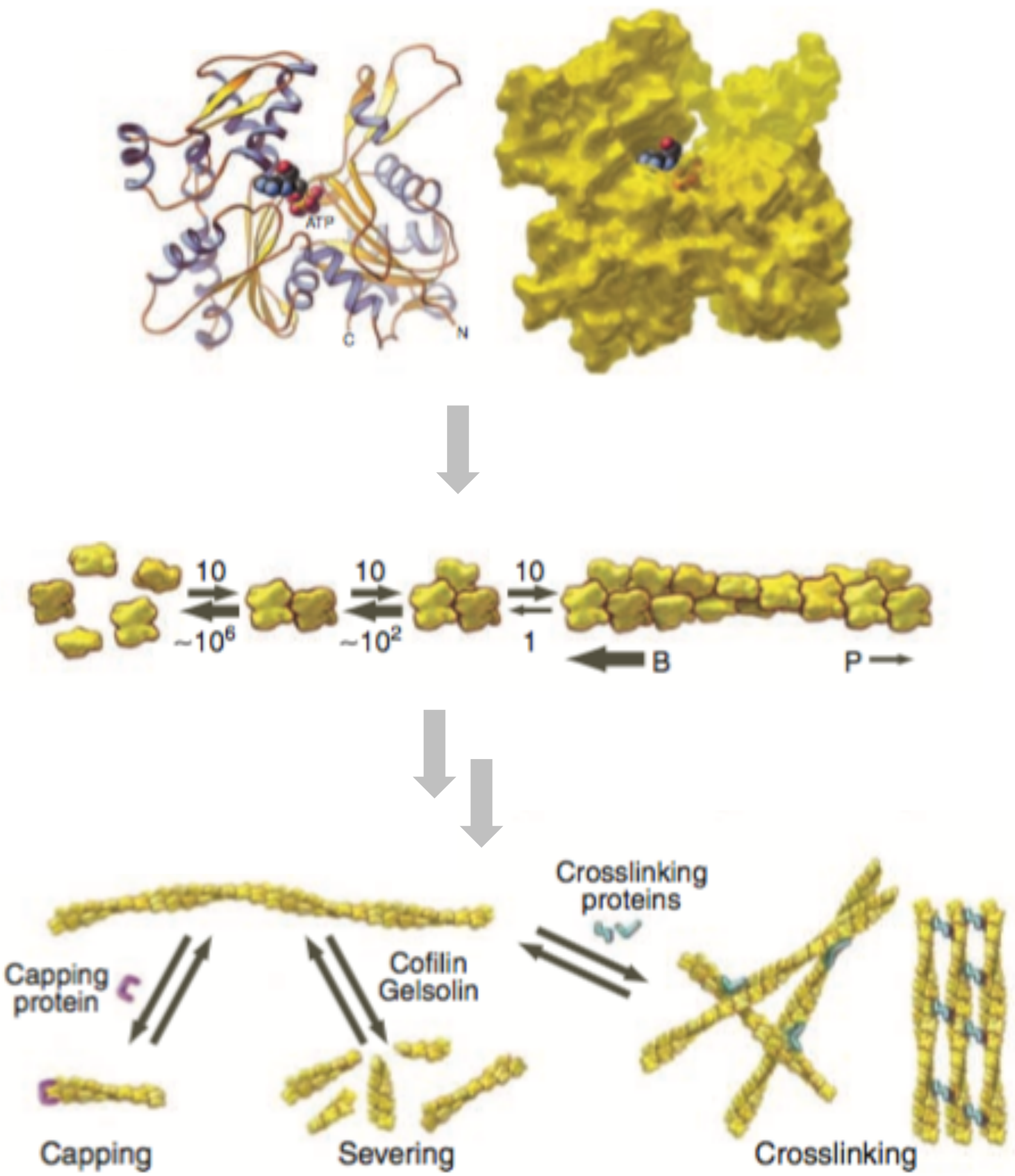
Switchable Catalysis: Inspiration from Nature

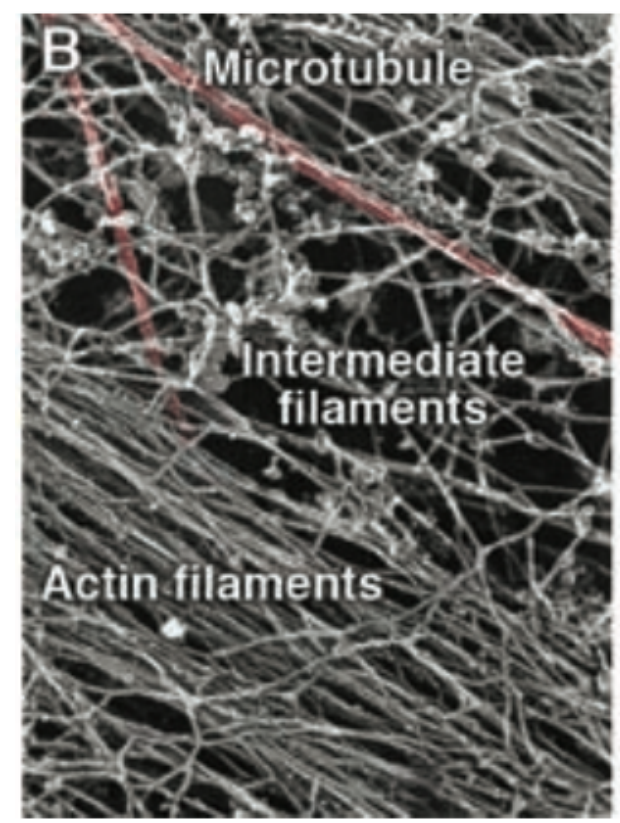
the synthetic machinery of natural systems makes complex polymers with fine temporal and spatial control

example: actin filament polymerization provides structure and allows cells to move

initiation, chain-growth, and cross-linking

regulated by >100 accessory proteins





Pollard, T.D.; Cooper, J.A. *Science* **2009**, 326, 1208.

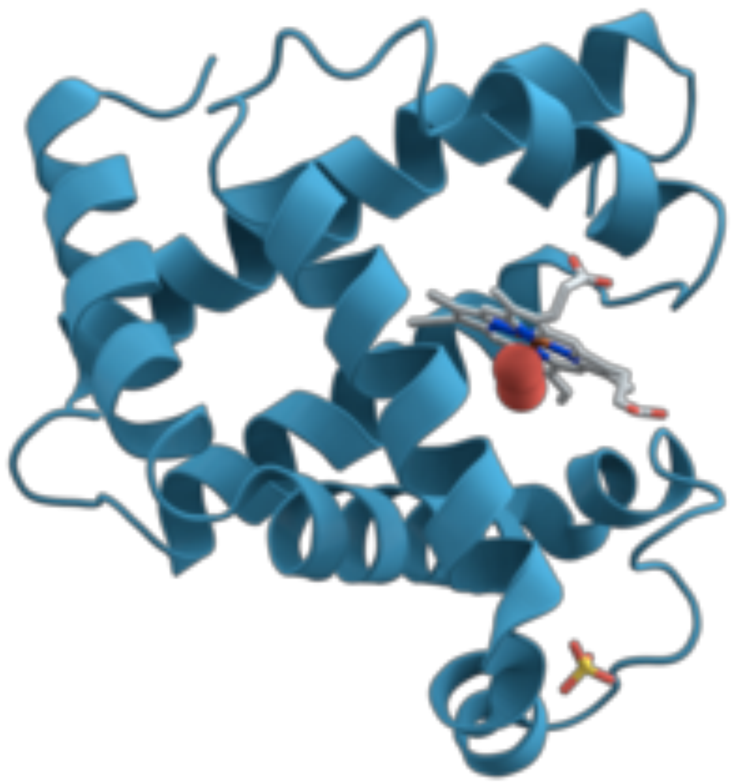
Switchable Catalysis: Inspiration from Nature

the synthetic machinery of natural systems makes complex polymers with fine temporal and spatial control

*enzymatic activity modulated through **feedback loops** and **trigger-induced effects***

to prevent parallel reactions in Nature from interfering with one another:

- operations must be controlled
- function must be switchable
- switching must be reversible



Switchable Catalysis: Inspiration from Nature

switchable catalysis

toggling chemical reactivity of a catalyst between multiple distinct states

through application of external stimuli

basic requirements for switches:

- bistability: occurrence of 2 forms of molecule that can be interconverted by an external stimulus
- fast response times
- thermal stability
- fatigue resistance

Stoll, R.S.; Hecht, S. *Angew. Chem. Int. Ed.* **2010**, 49, 5054.

Switchable Catalysis

- switchable catalysis: biological inspiration
- types of switchable external stimuli
  - **light**
  - **pH**
  - ion coordination
  - **redox switching**
  - mechanical forces

Switchable Catalysis

- switchable catalysis: biological inspiration
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Light-Gated Catalysis

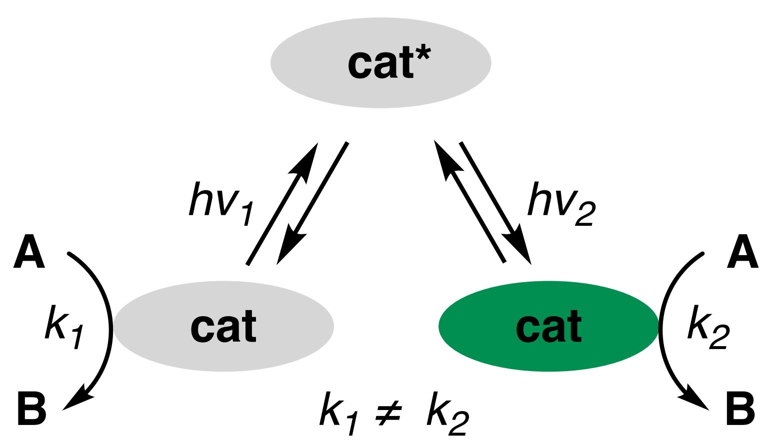
light is an attractive external regulator: low-cost, ubiquitous, noninvasive, precise control

initiates and regulates complex processses with precision in Nature

(e.g., photosynthesis, vision)

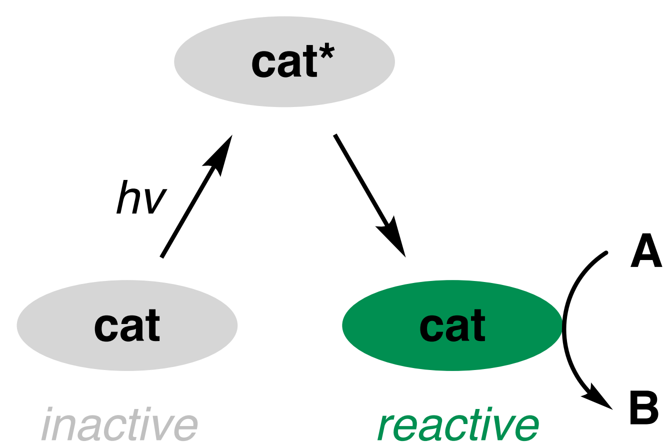
types of photocontrol of catalytic activity

photoswitchable catalysis



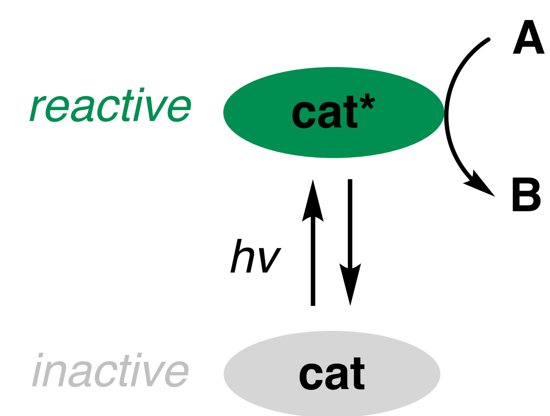
reversible toggling between active and inactive catalytic states

photocaged catalysis



irreversible formation of active catalytic state

photocatalysis



transient excited state is reactive

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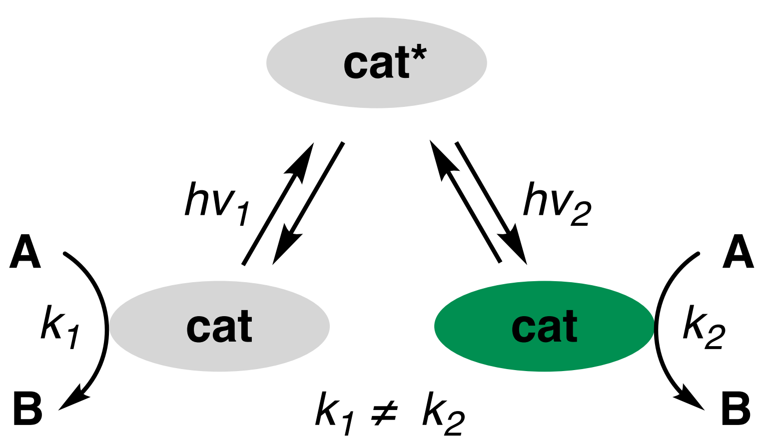

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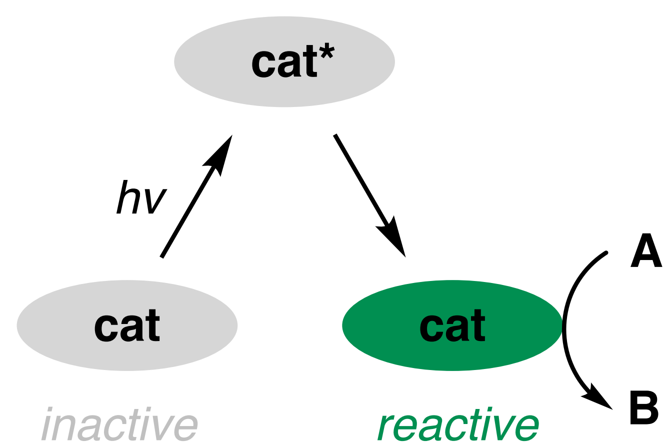

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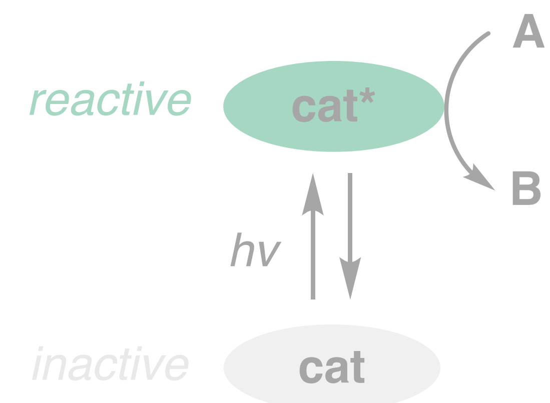

transient excited state is reactive

catalytic activity from ground-state species

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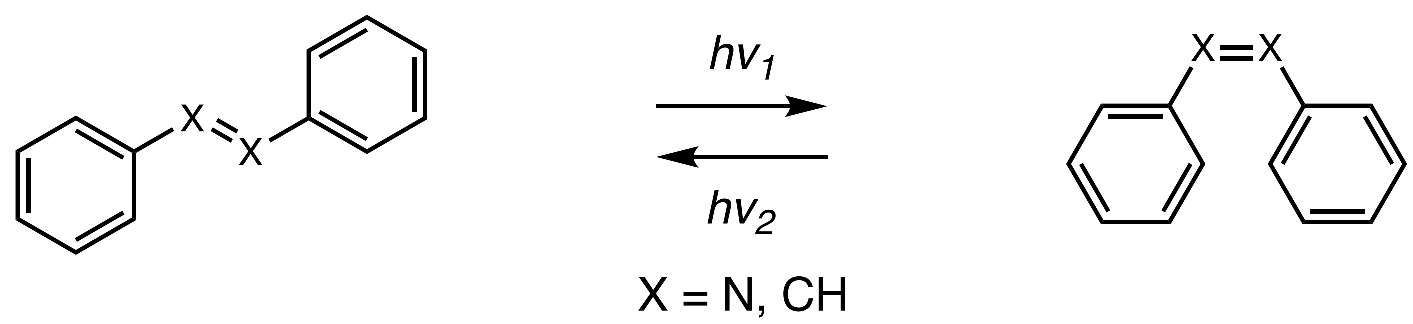
Nelson, B.M.; Biewlawski, C.W. *ACS Catal.* **2013**, 3, 1874.

Light-Gated Catalysis

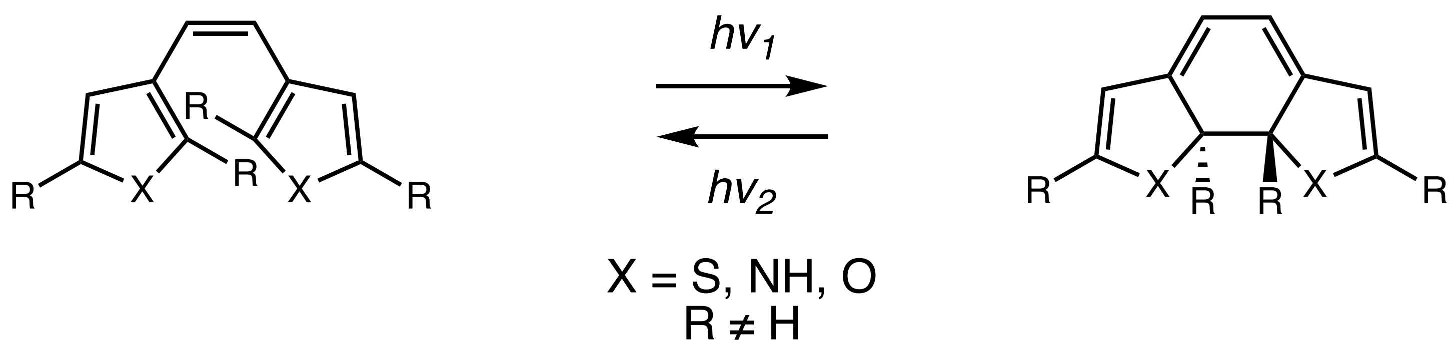
a ***photoswitchable catalyst*** *involves a catalytically active species*

that undergoes a reversible photochemical transformation altering its catalytic properties

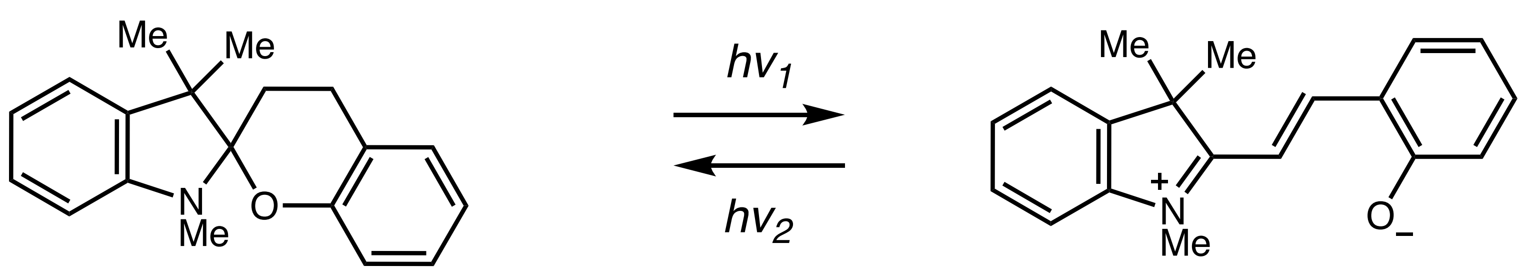
azobenzene/stilbene



diarylethene



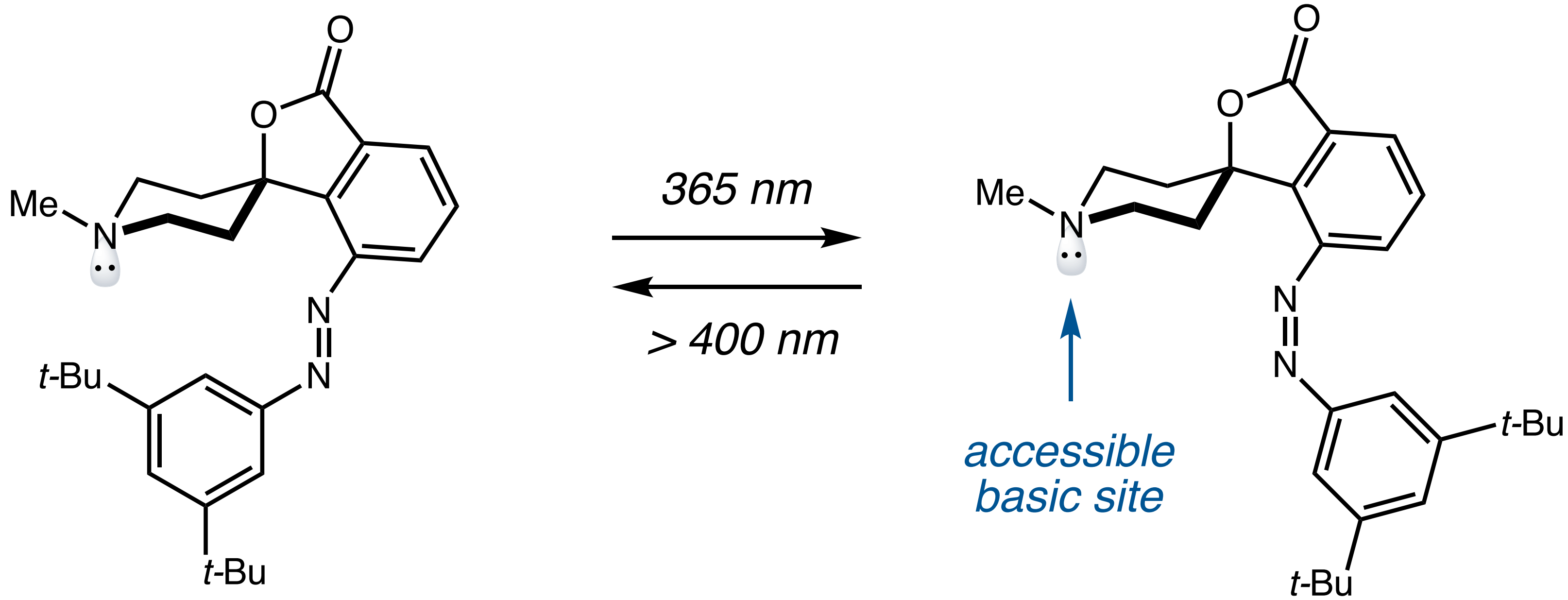
spiropyran

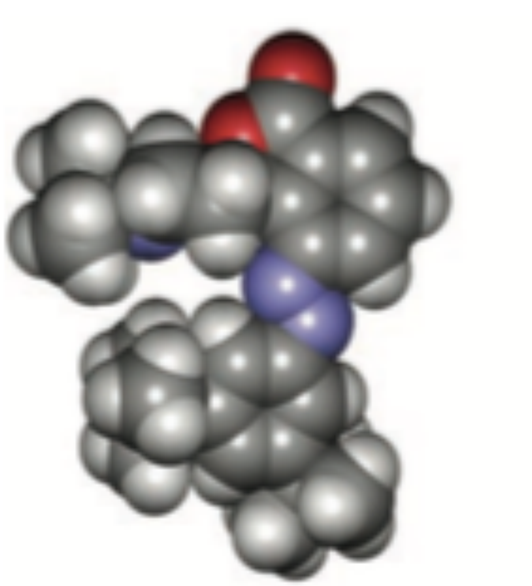


Nelson, B.M.; Biewlawski, C.W. *ACS Catal.* **2013**, 3, 1874.

Light-Gated Catalysis

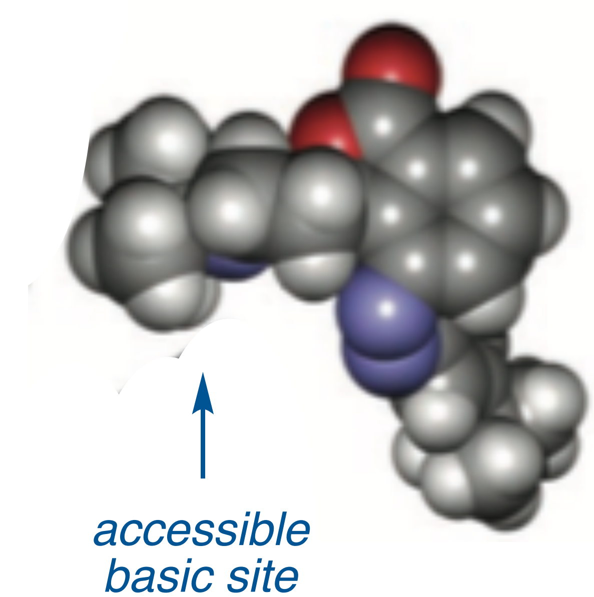
photoswitchable base catalysis





basicity of deshielded Z isomer increases

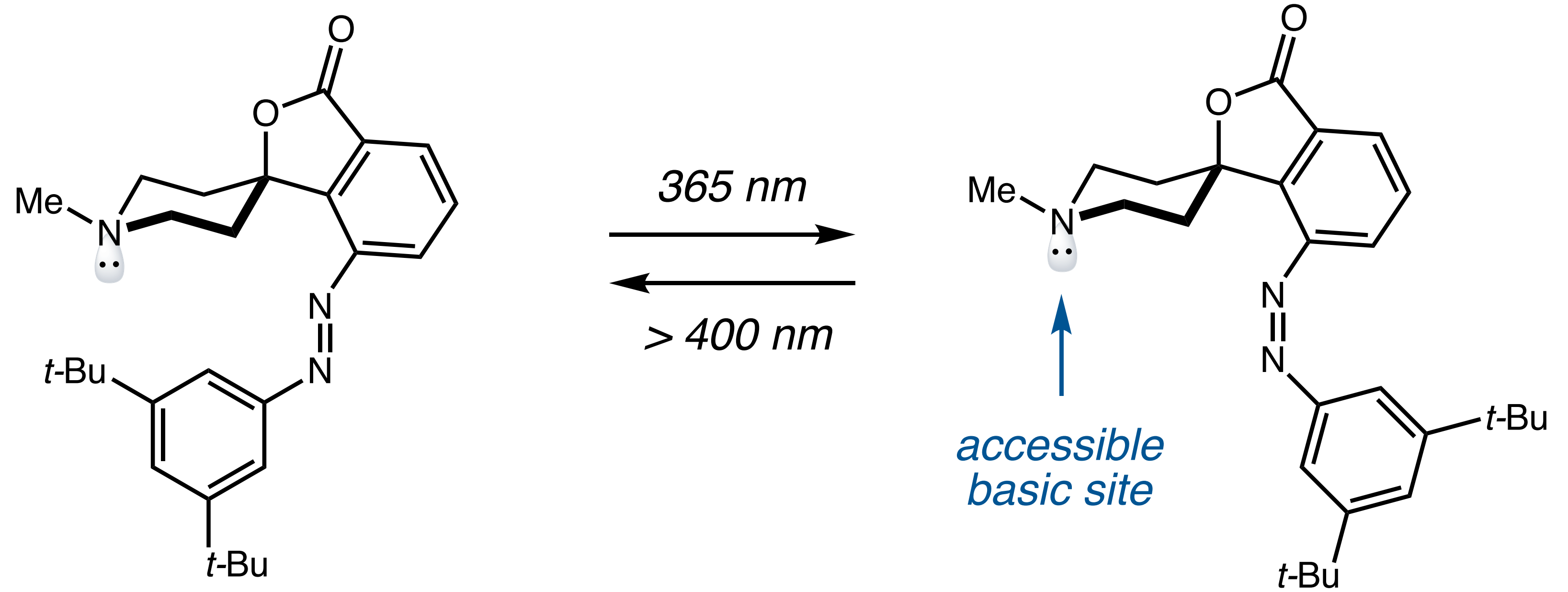
by almost an order of magnitude

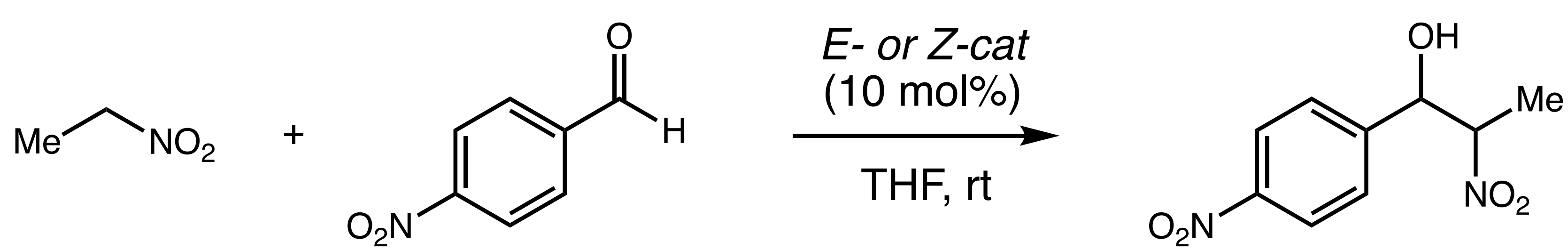


Peters, M.V.; Stoll, R.S.; Kuhn, A.; Hecht, S. *Angew. Chem. Int. Ed.* **2008**, 47, 5968.

Light-Gated Catalysis

photoswitchable base catalysis





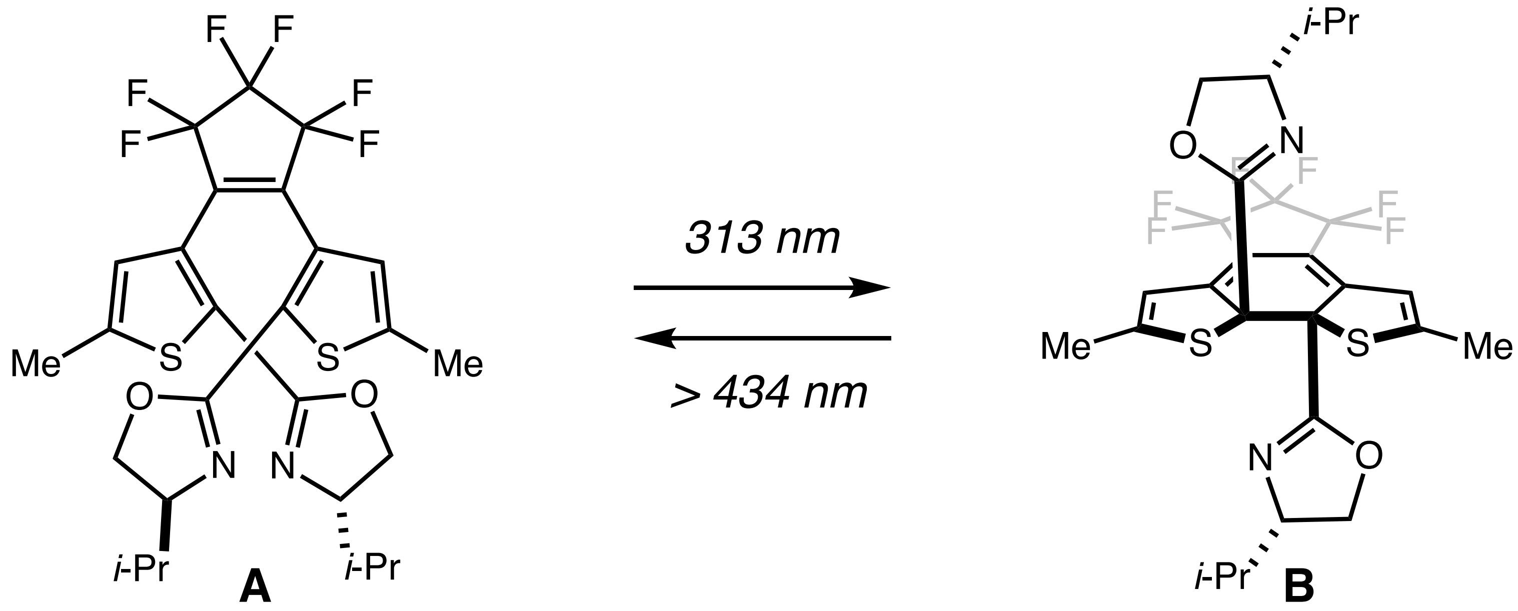
$k_Z/k_E = 35.5$

photoreversible steric shielding in a small molecule catalyst

Peters, M.V.; Stoll, R.S.; Kuhn, A.; Hecht, S. *Angew. Chem. Int. Ed.* **2008**, 47, 5968.

Light-Gated Catalysis

chiral Cu chelation
high enantioselectivity



no Cu chelation
low enantioselectivity

large geometrical change induces change in orientation

of key sites on catalyst (cooperative effect)

Light-Gated Catalysis

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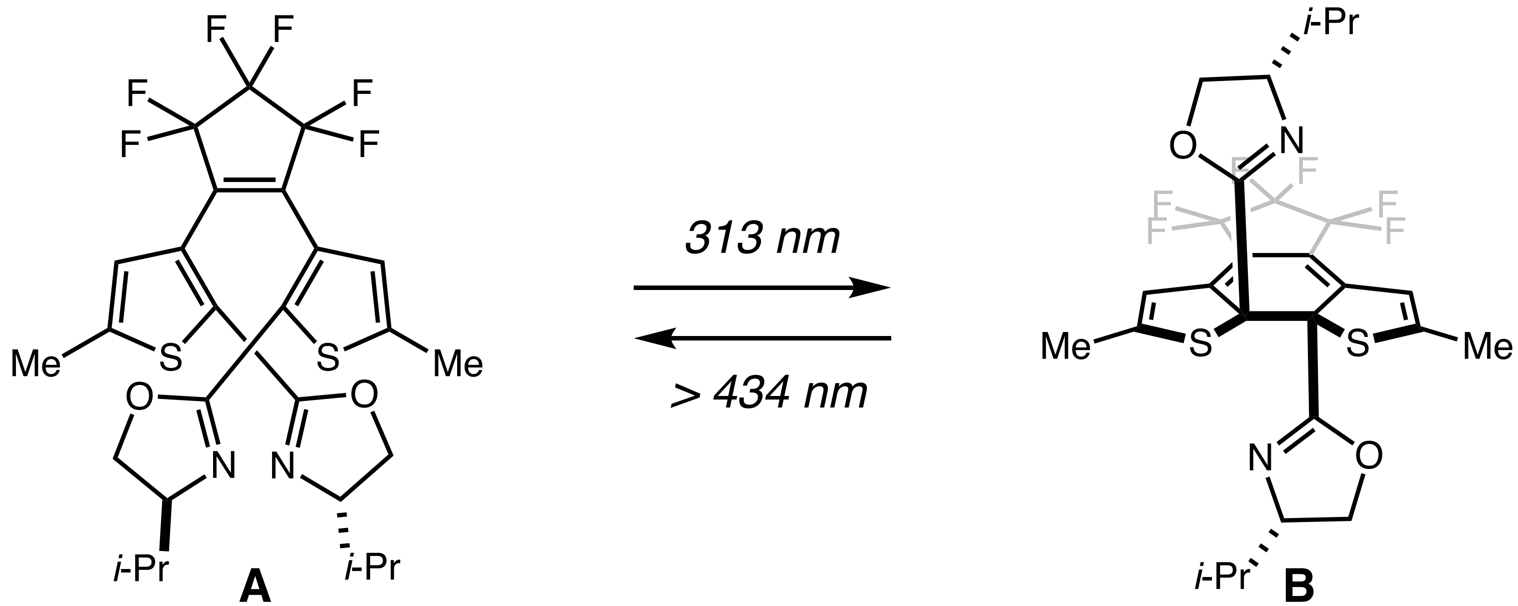
high enantioselectivity



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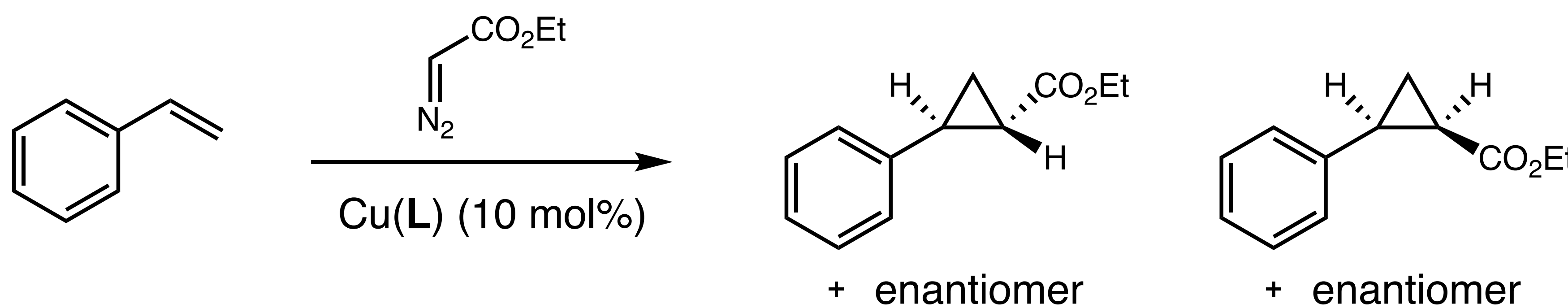

ligand	*trans*	*cis*	*d.r.*
A	30	50	55:45
B	5	5	63:37

in situ photoinduced ring-opening

first in situ photoswitching of stereoselective catalysis

Sud, D.; Norsten, T.B.; Branda, N.R. *Angew. Chem. Int. Ed.* **2005**, 44, 2019.

Light-Gated Catalysis

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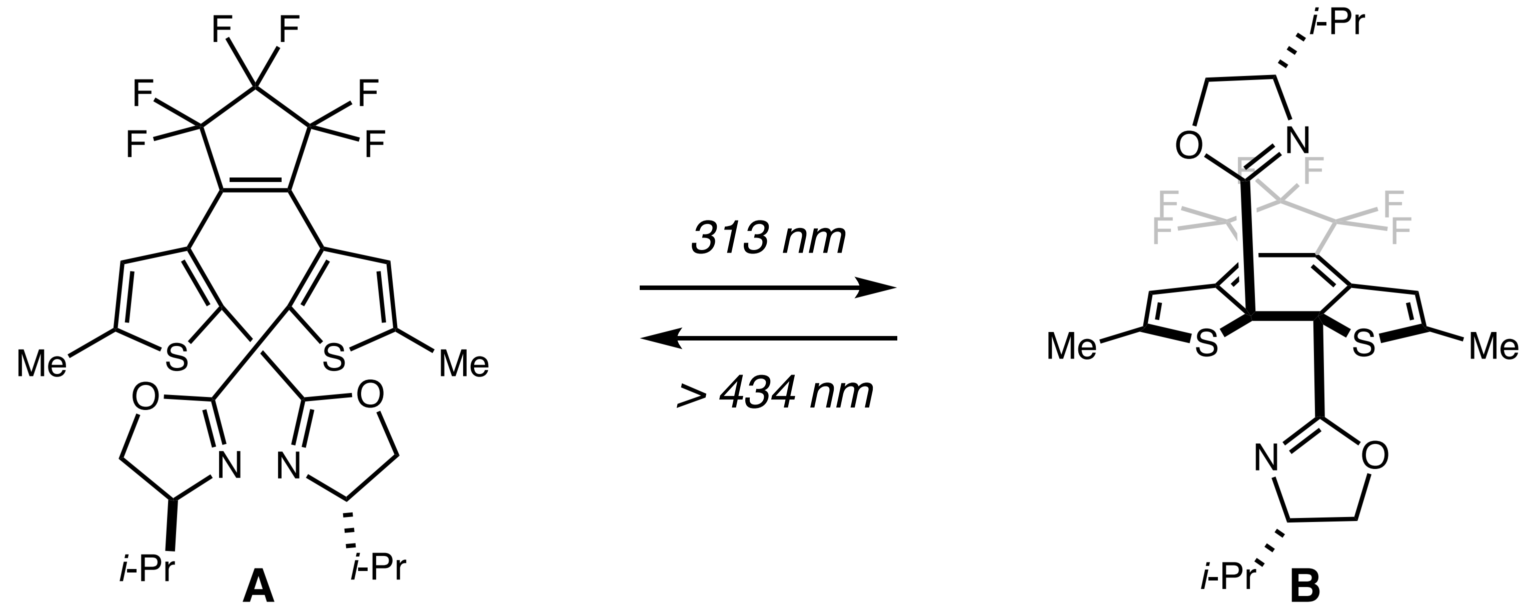

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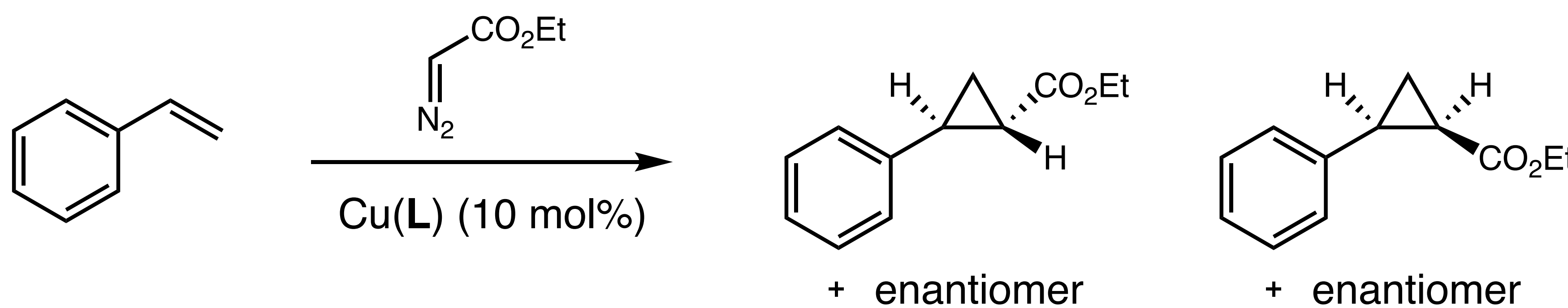

ligand	*trans*	*cis*	*d.r.*
A	30	50	55:45
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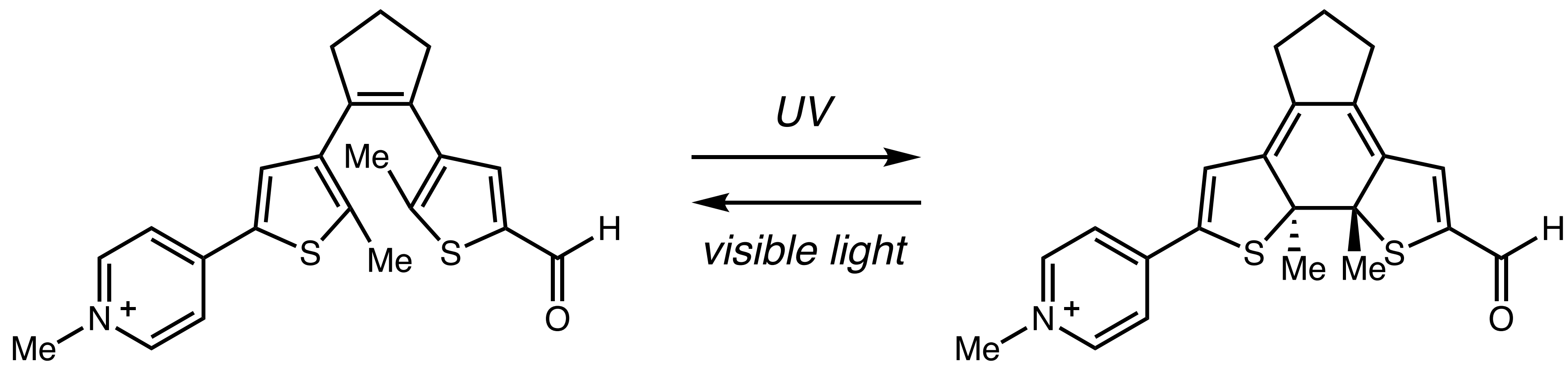
limitation: photoinduced ring-closing inefficient with Cu(I)

only 23% of closed form at stationary state at 313 nm

Sud, D.; Norsten, T.B.; Branda, N.R. *Angew. Chem. Int. Ed.* **2005**, 44, 2019.

Light-Gated Catalysis

photoinduced changes in electronic properties to alter catalytic activity



electronically insulated
(inactive)

electronically connected
(active)

mimic of bioactive form of vitamin B6
(pyridoxal 5'-phosphate, PLP)

proof-of-concept: photoinduced regulation of biomimetic, small molecule cofactors

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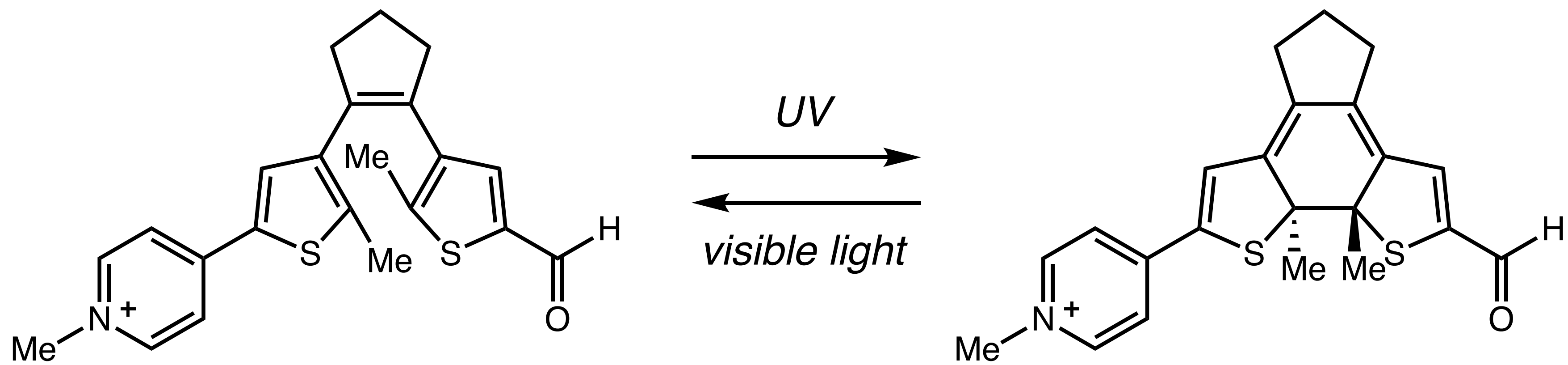

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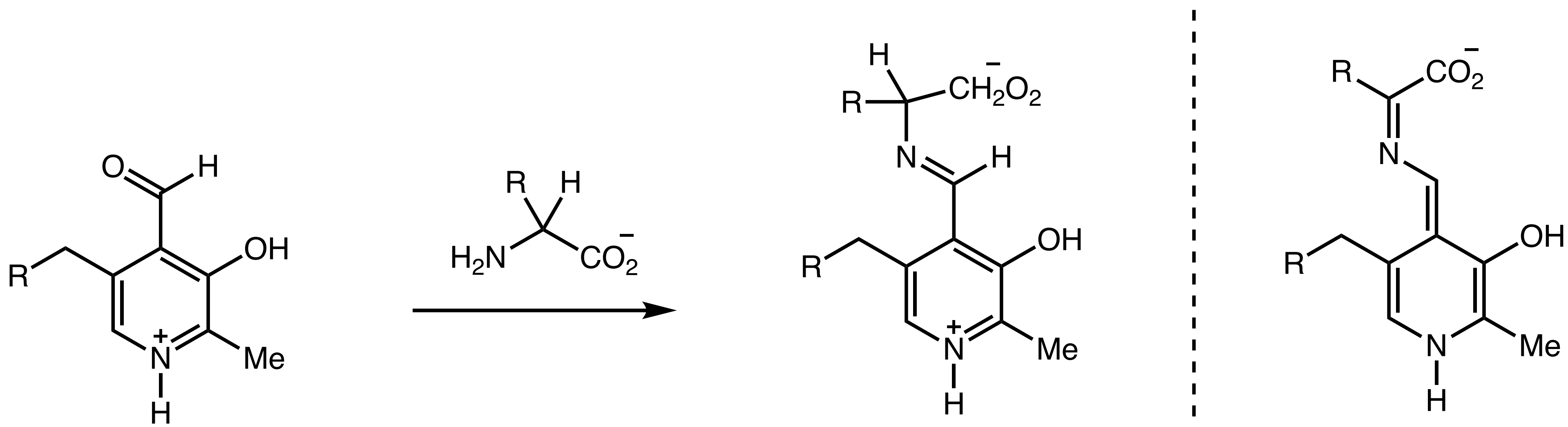

PLP

enzyme cofactor responsible for
amino acid metabolism

aldimine

quinonoid

Wilson, D.; Branda, N.R. *Angew. Chem. Int. Ed.* **2012**, 51, 5431.

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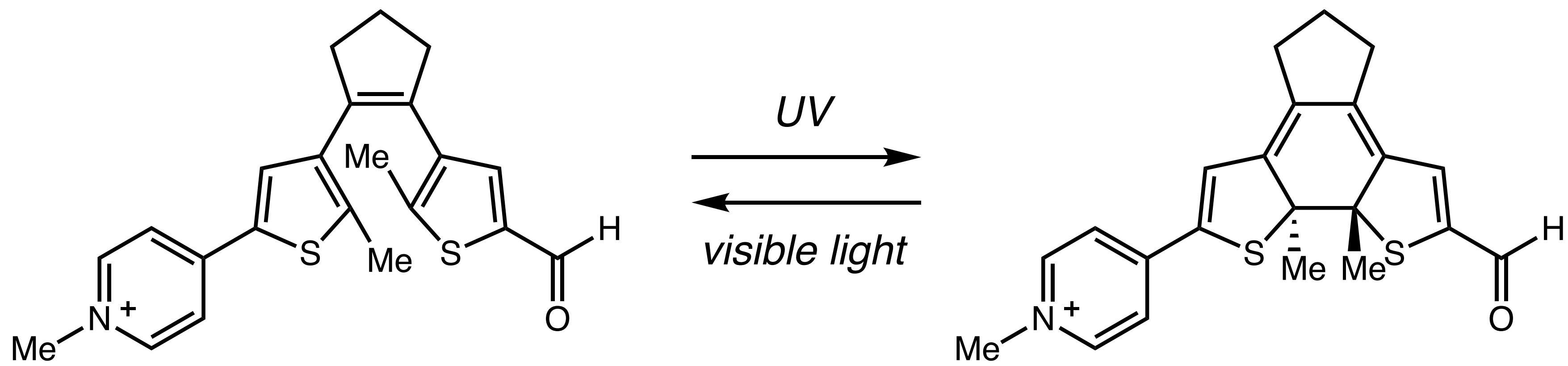

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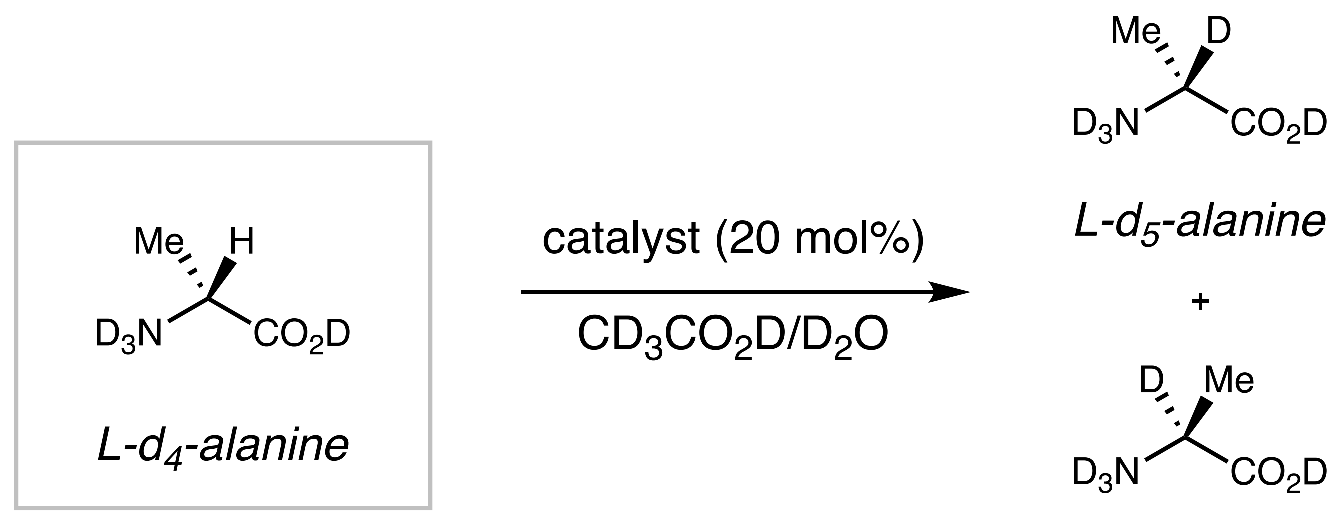
(inactive)

electronically connected
(active)

catalytic activity for racemization of L-alanine

dependent on electronic connectivity

between functional groups



L-d_4-alanine

L-d_5-alanine + *D-d_5-alanine*

D-d_5-alanine

H/D-exchange to monitor catalytic racemization

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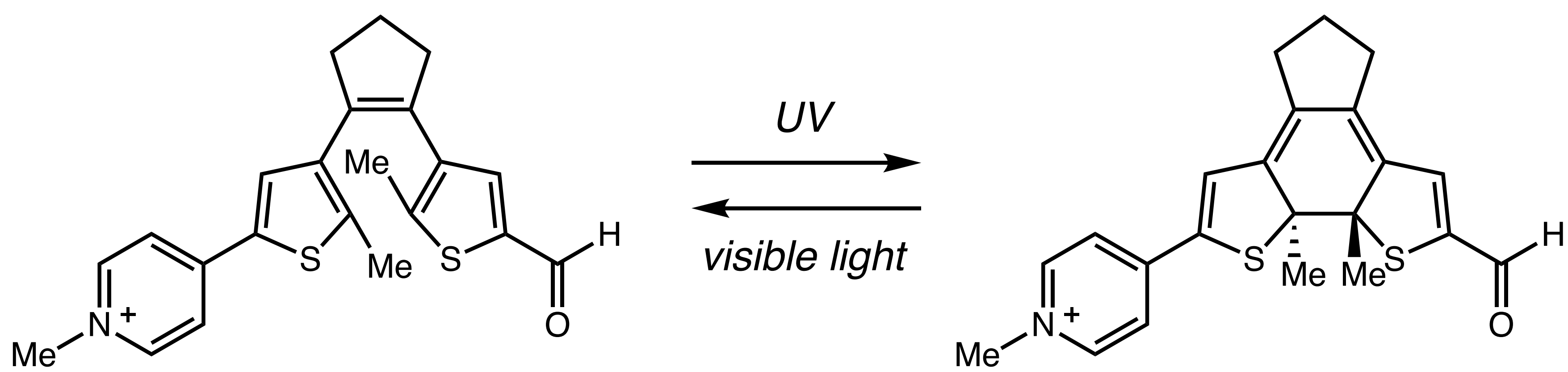

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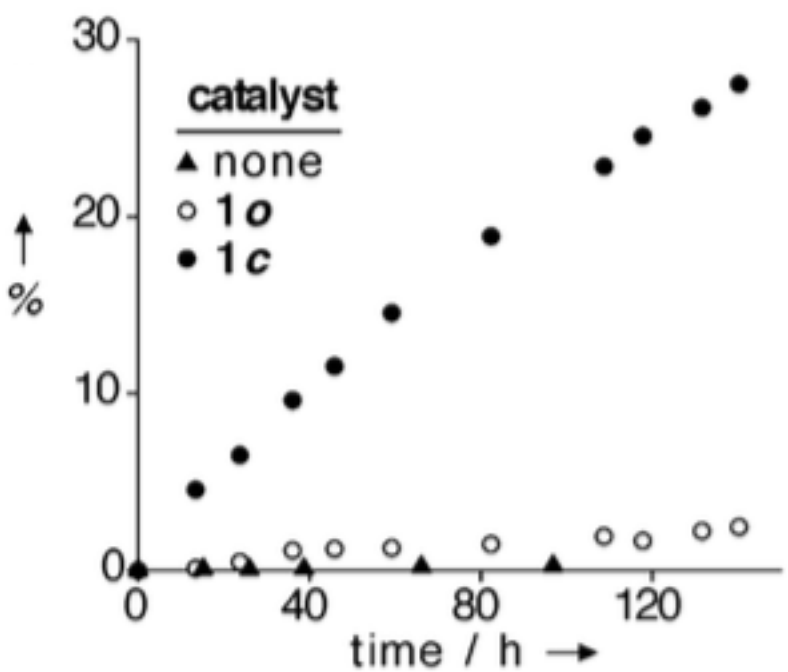

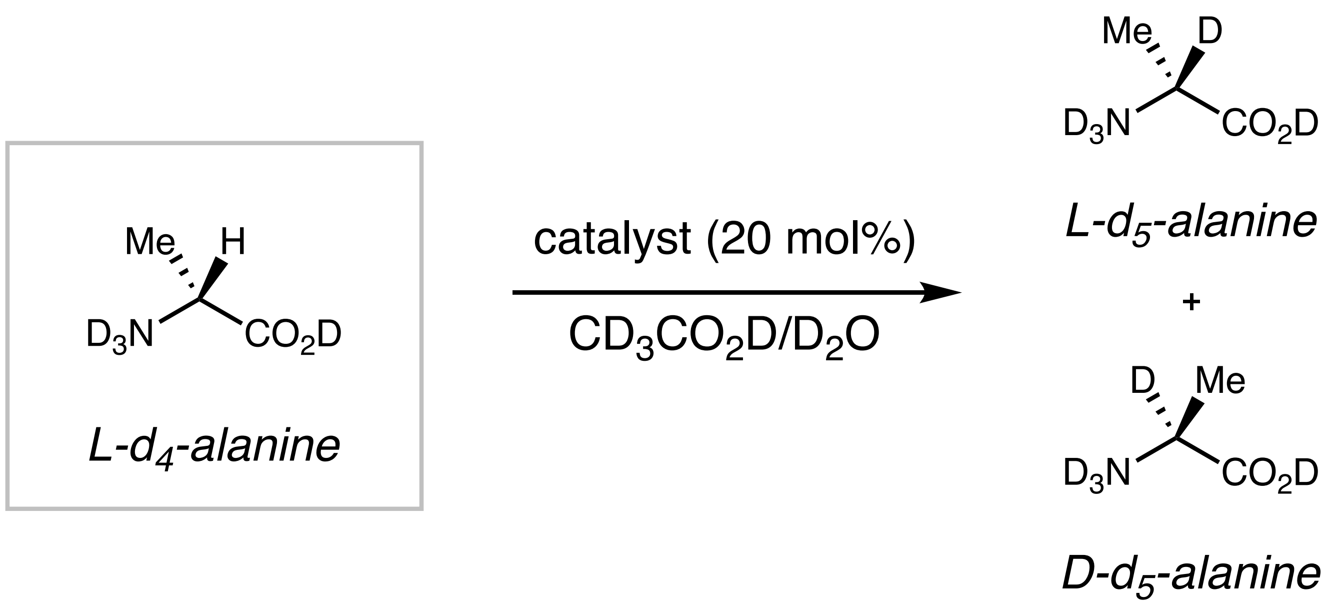

after 140 h at 40 ºC:

- 30% conversion with ring-closed catalyst
- < 3% conversion with ring-opened

Wilson, D.; Branda, N.R. *Angew. Chem. Int. Ed.* **2012**, 51, 5431.

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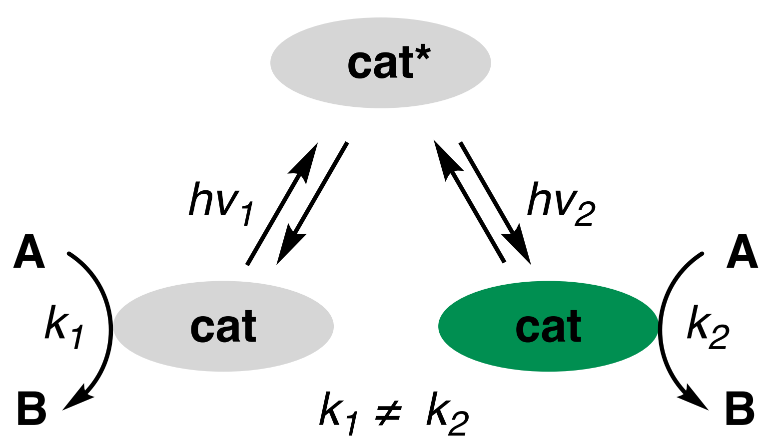

reversible toggling between active and inactive catalytic states

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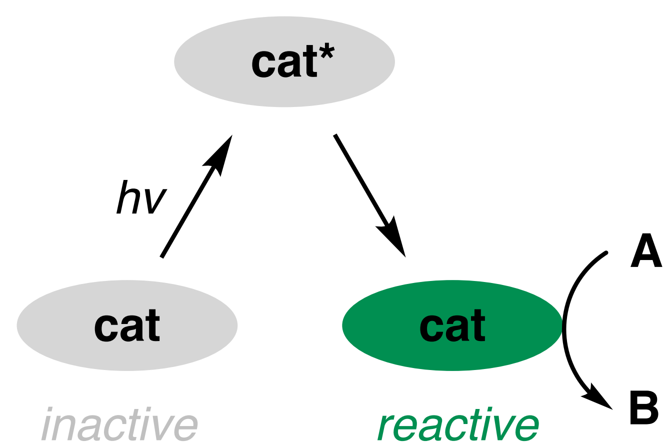

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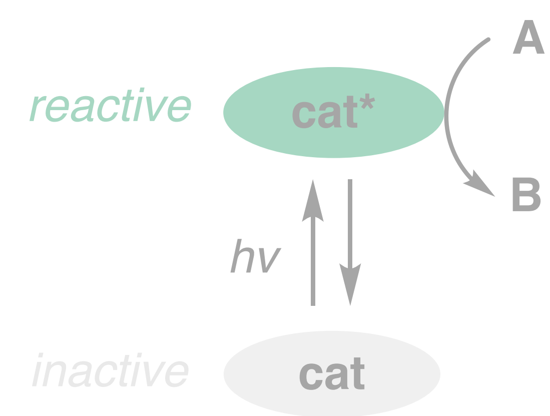

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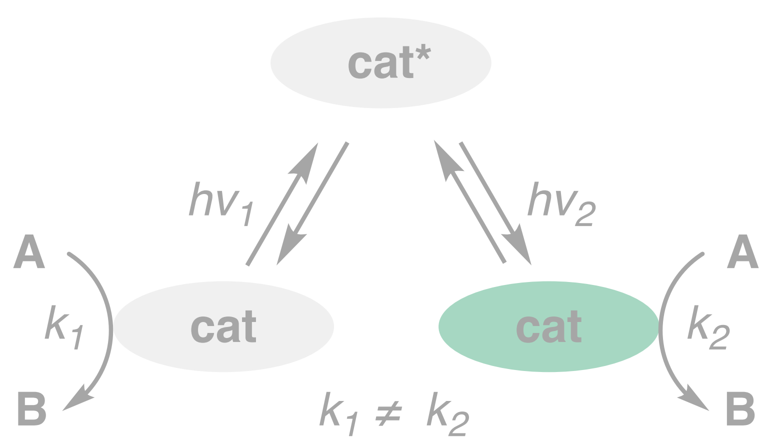

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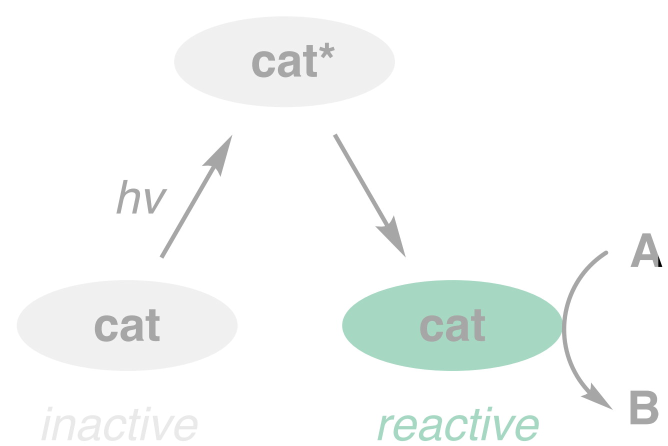

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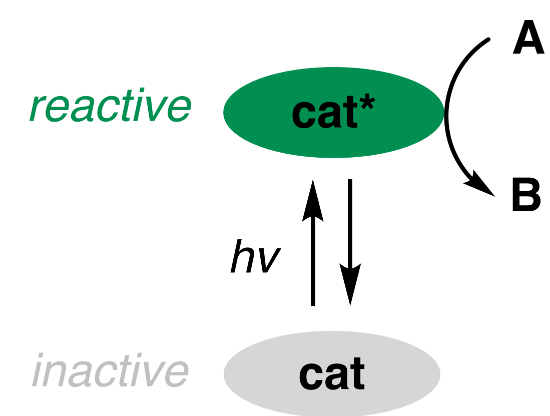

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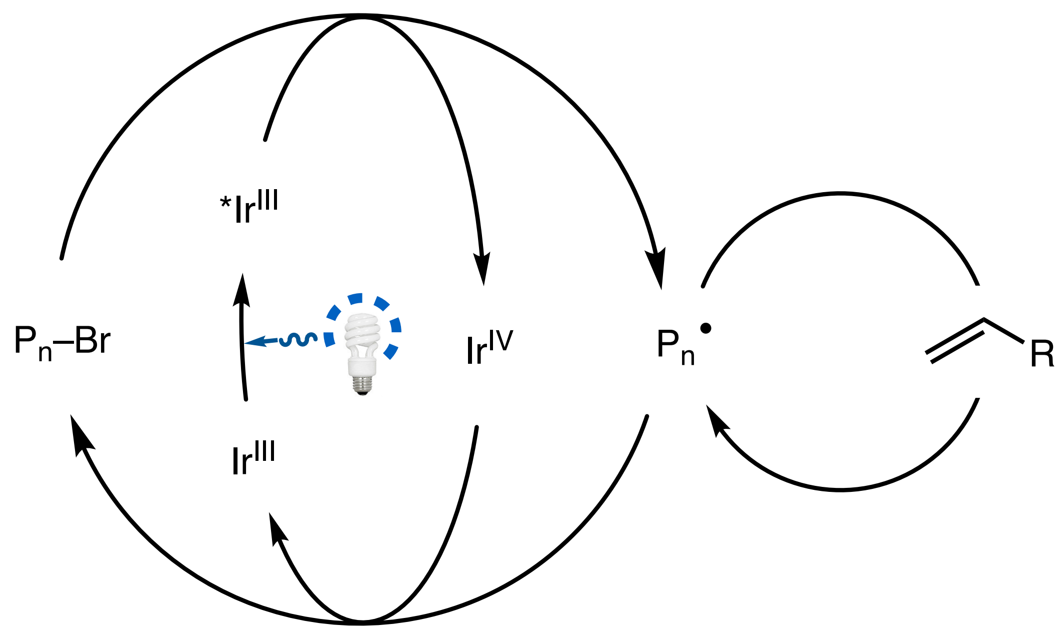
Photocontrolled Living Radical Polymerization

light used to reversibly activate/deactivate living radical polymerization

- why light? high degree of temporal control over chain growth
- highly responsive external control

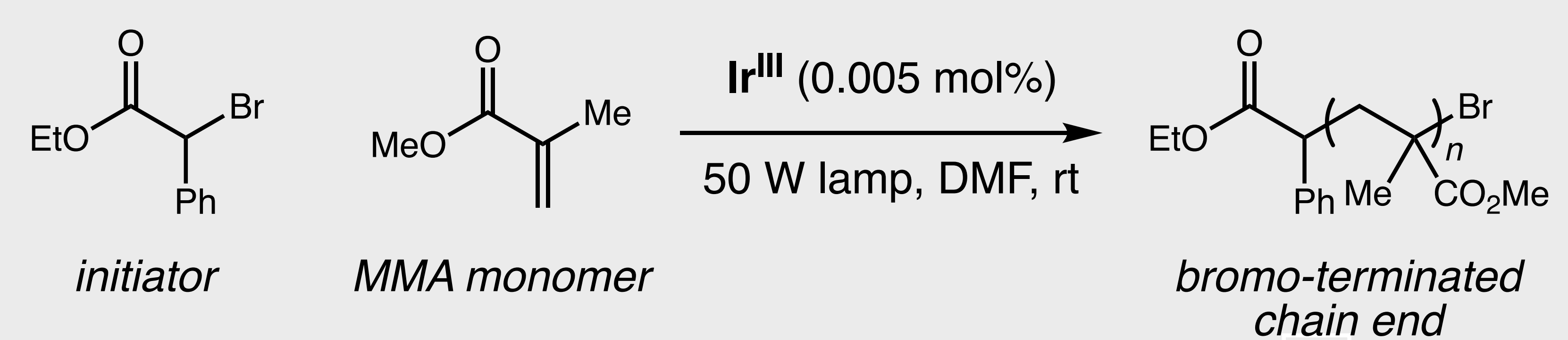


$\mathbf{Ir^{III}}$ = *fac*-[Ir(ppy)$_3$]

in absence of light, no excited state Ir

polymerization rests in bromo-capped dormant state

reactivation upon reexposure to light



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

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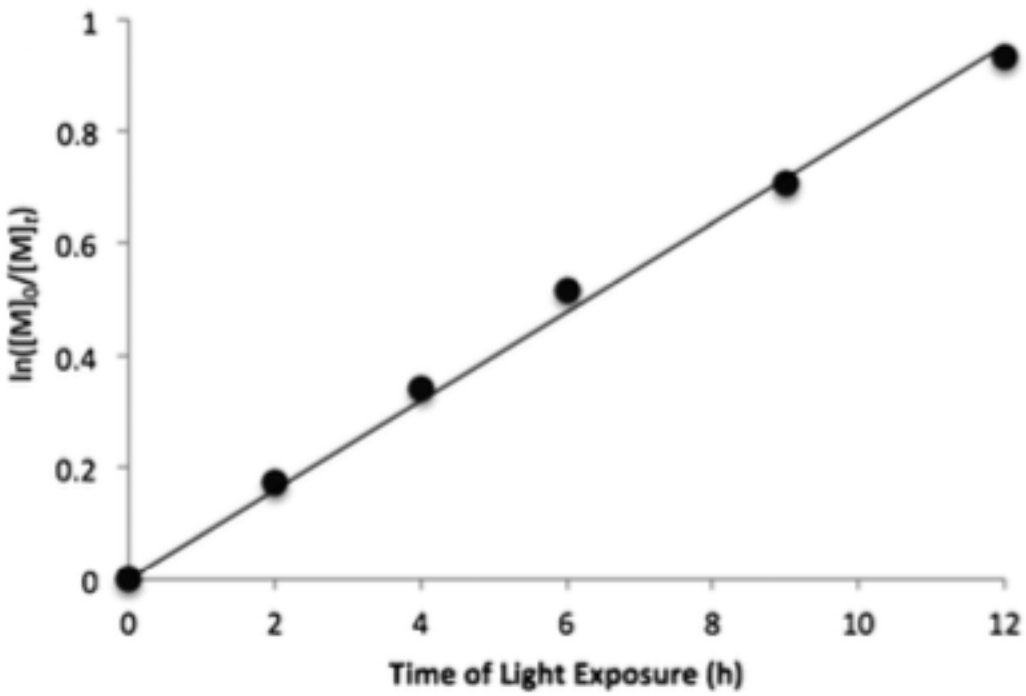
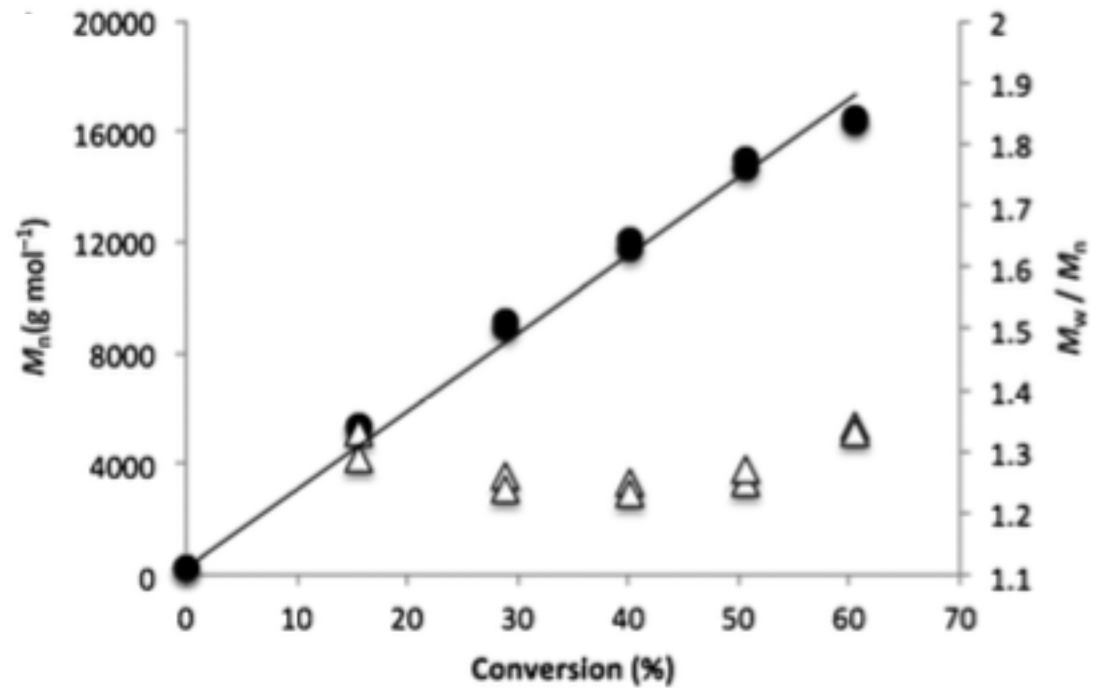


ln([M$_0$]/[M$_t$]) vs. time of light exposure



linear relationship between M_n and conversion

- polymerization stops immediately without light
- existing chain ends reactivated
- no new chain ends initiated during polymerization

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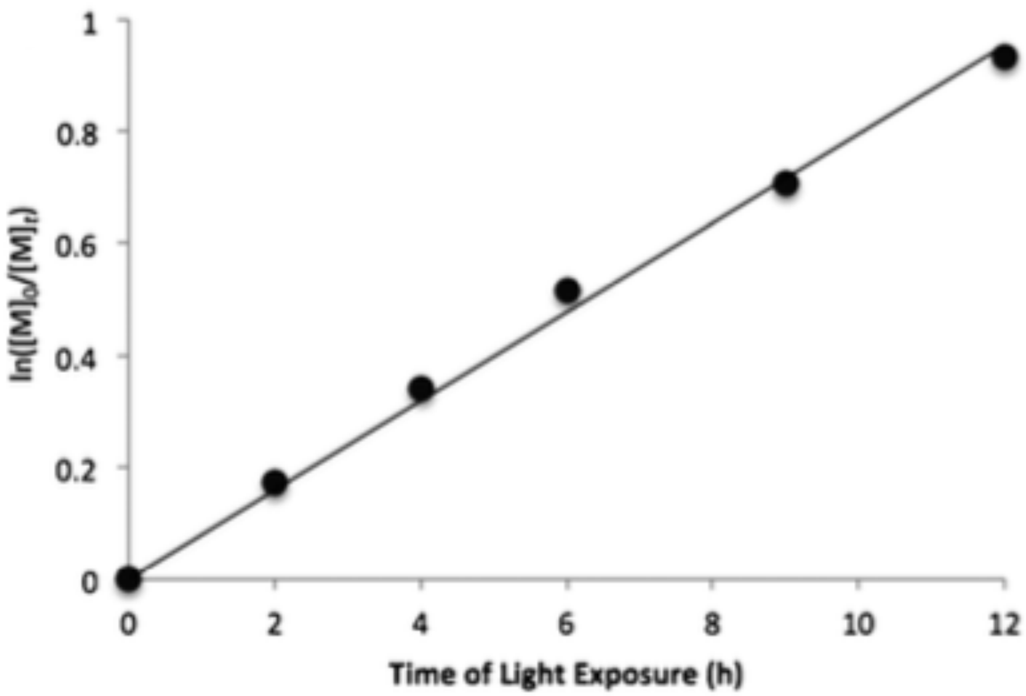
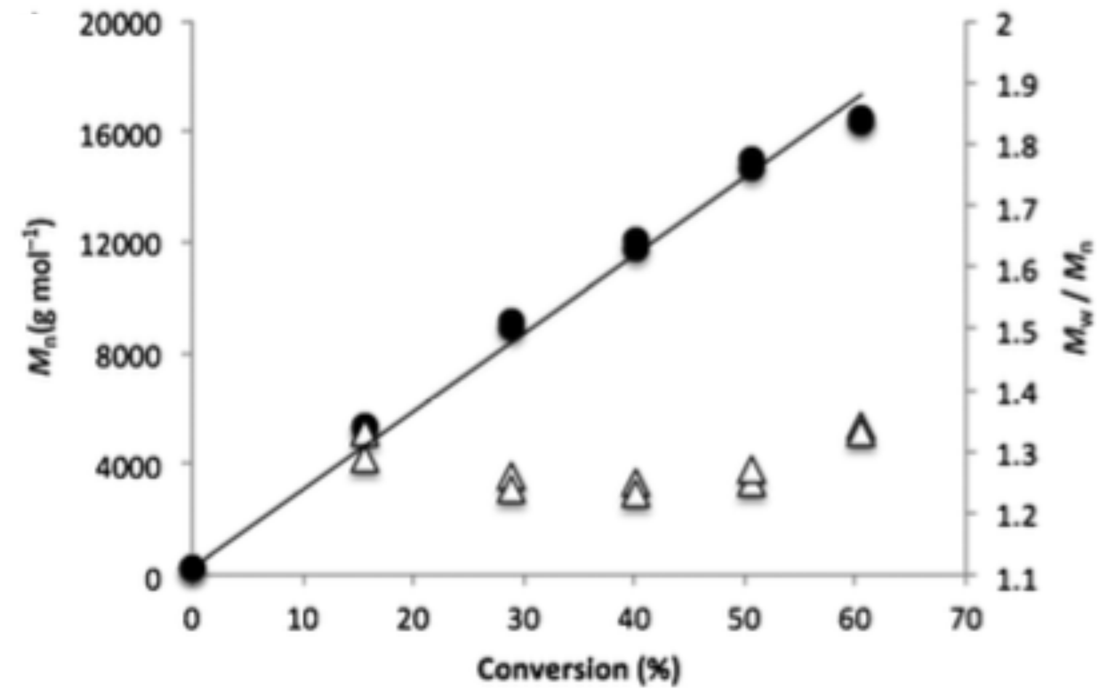


ln([M_0]/[M_t]) vs. time of light exposure



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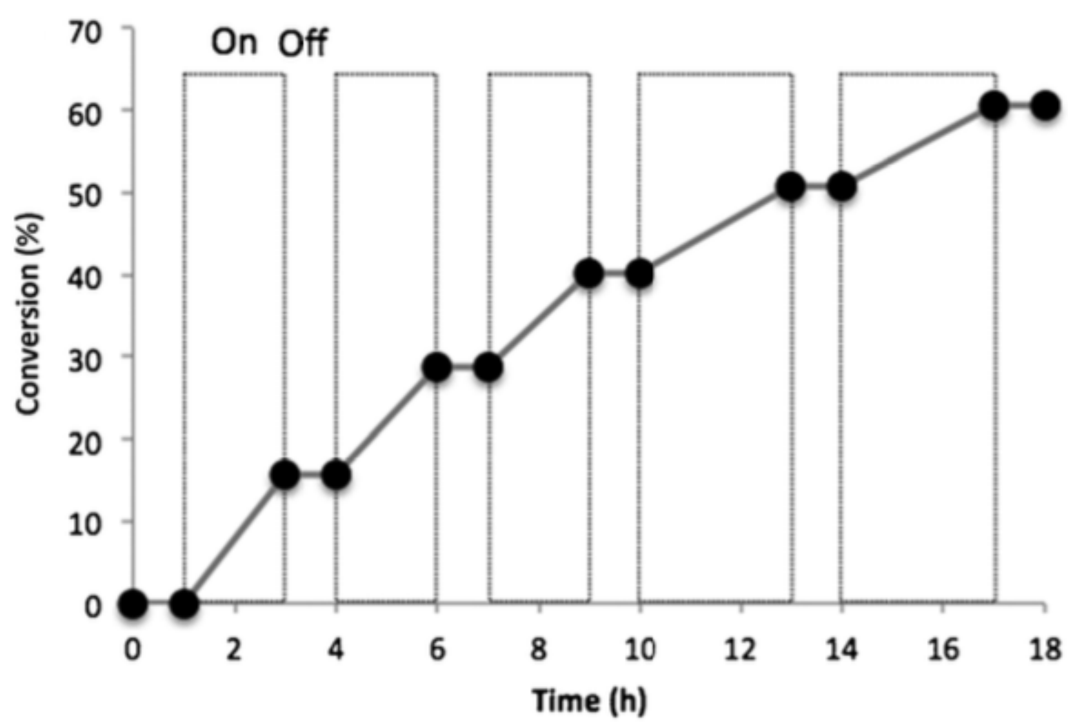

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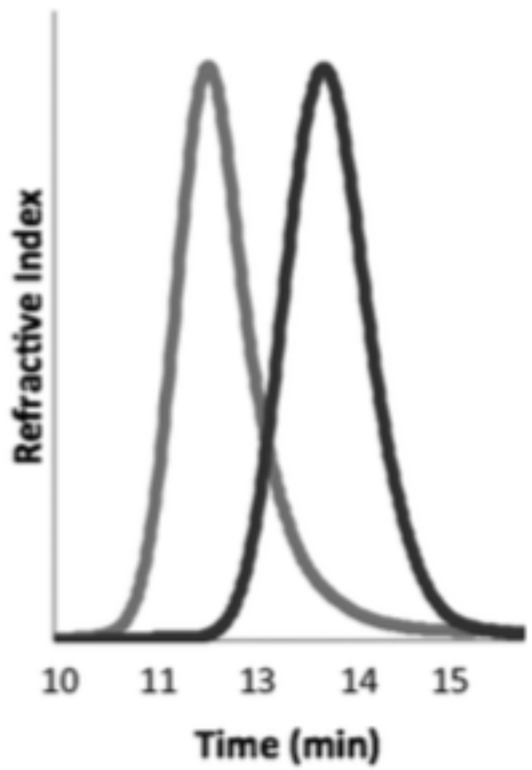
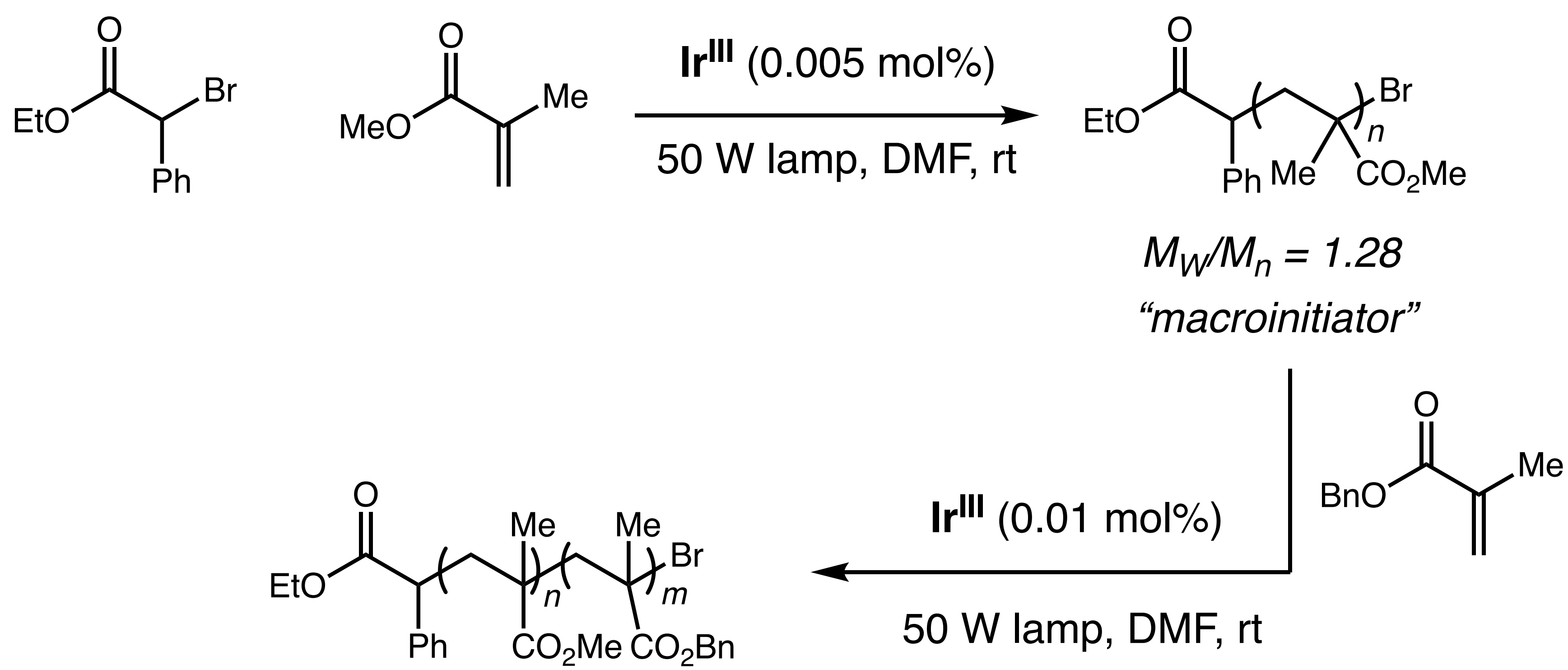
Photocontrolled Living Radical Polymerization

light used to reversibly activate/deactivate living radical polymerization

- a living polymerization should give efficient block copolymer formation





- efficient block copolymer formation - LRP
- little to no starting macroinitiator
- minimal termination occurring during polymerization

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

Switchable Catalysis

- switchable catalysis: biological inspiration
- types of switchable external stimuli
  - ***light***
  - pH
  - ion coordination
  - redox switching
  - mechanical forces

Switchable Catalysis

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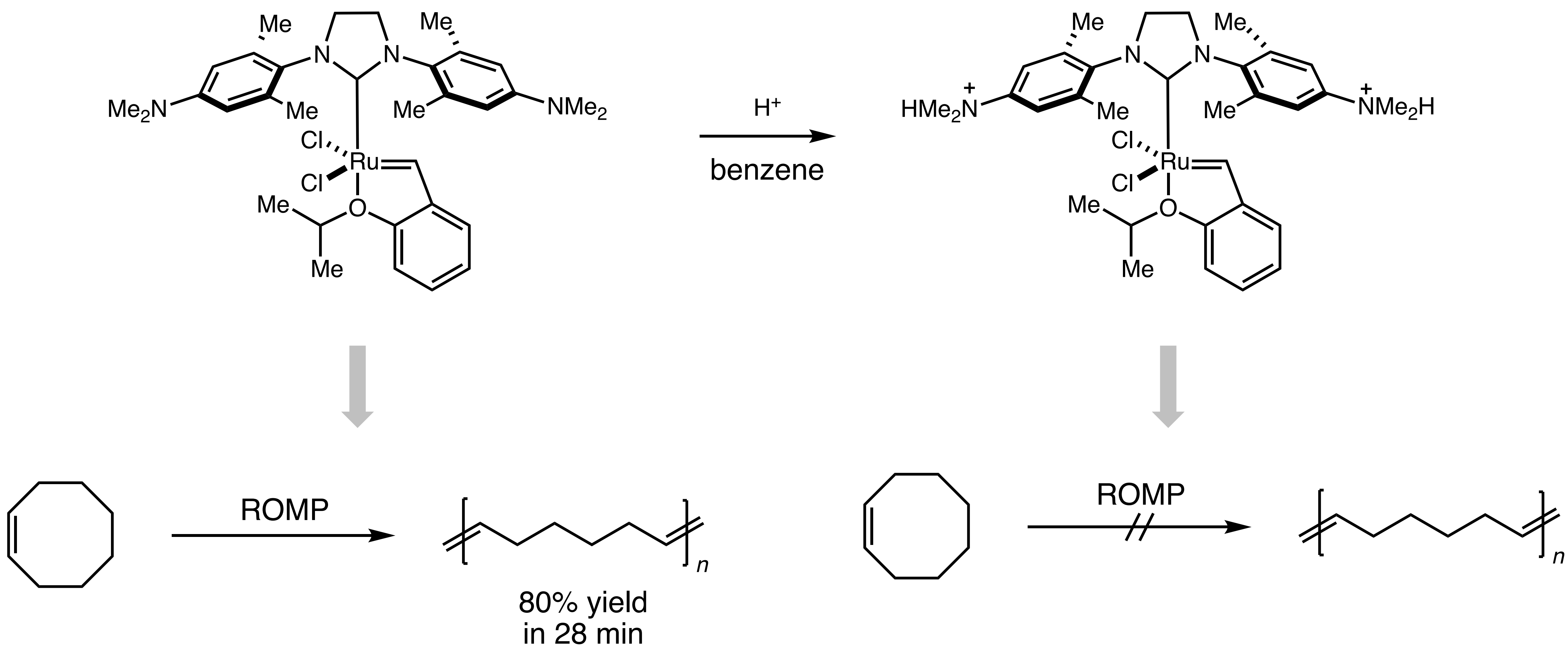
pH-Driven Switching

chemically driven processes based on changes in pH common in both Nature and molecular machines

in catalysis, pH-switching can modify ***catalyst solubility***



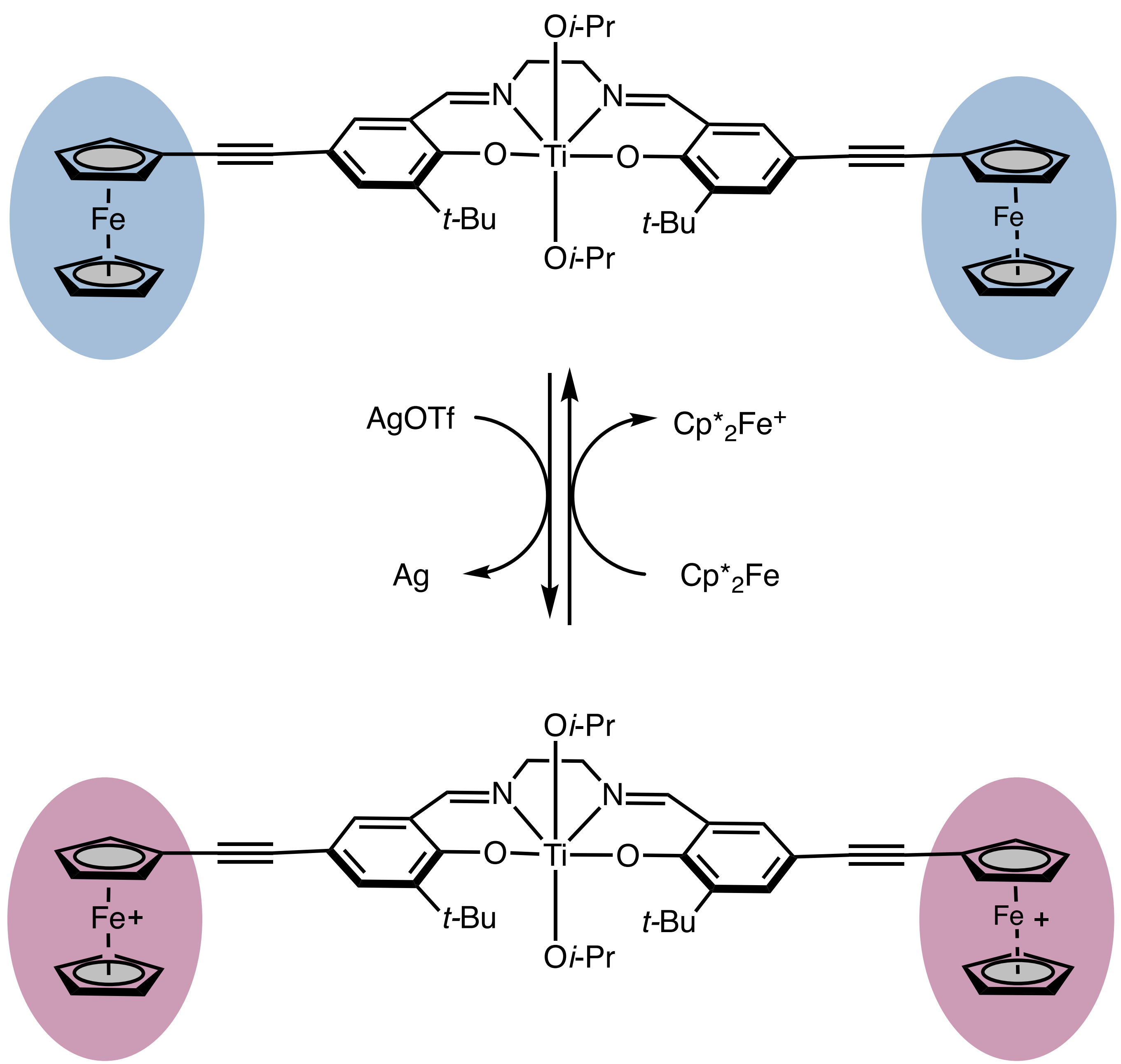
catalyst removal after metathesis can be challenging

after protonation, efficient removal of Ru catalyst by filtration

Balof, S.L.; P'Pool, S.J.; Berger, N.J.; Valente, E.J.; Shiller, A.M.; Schanz, H.-J. *Dalton Trans.* **2008**, 5791.

Redox Switching

control of oxidation state of redox-active ligands to mediate catalytic activity



Gregson, K.A.G.; Gibson, V.C.; Long, N.J.; Marshall, E.L.; Oxford, P.J.; White, A.J.P. *J. Am. Chem. Soc.* **2006**, 128, 7410.

Redox Switching

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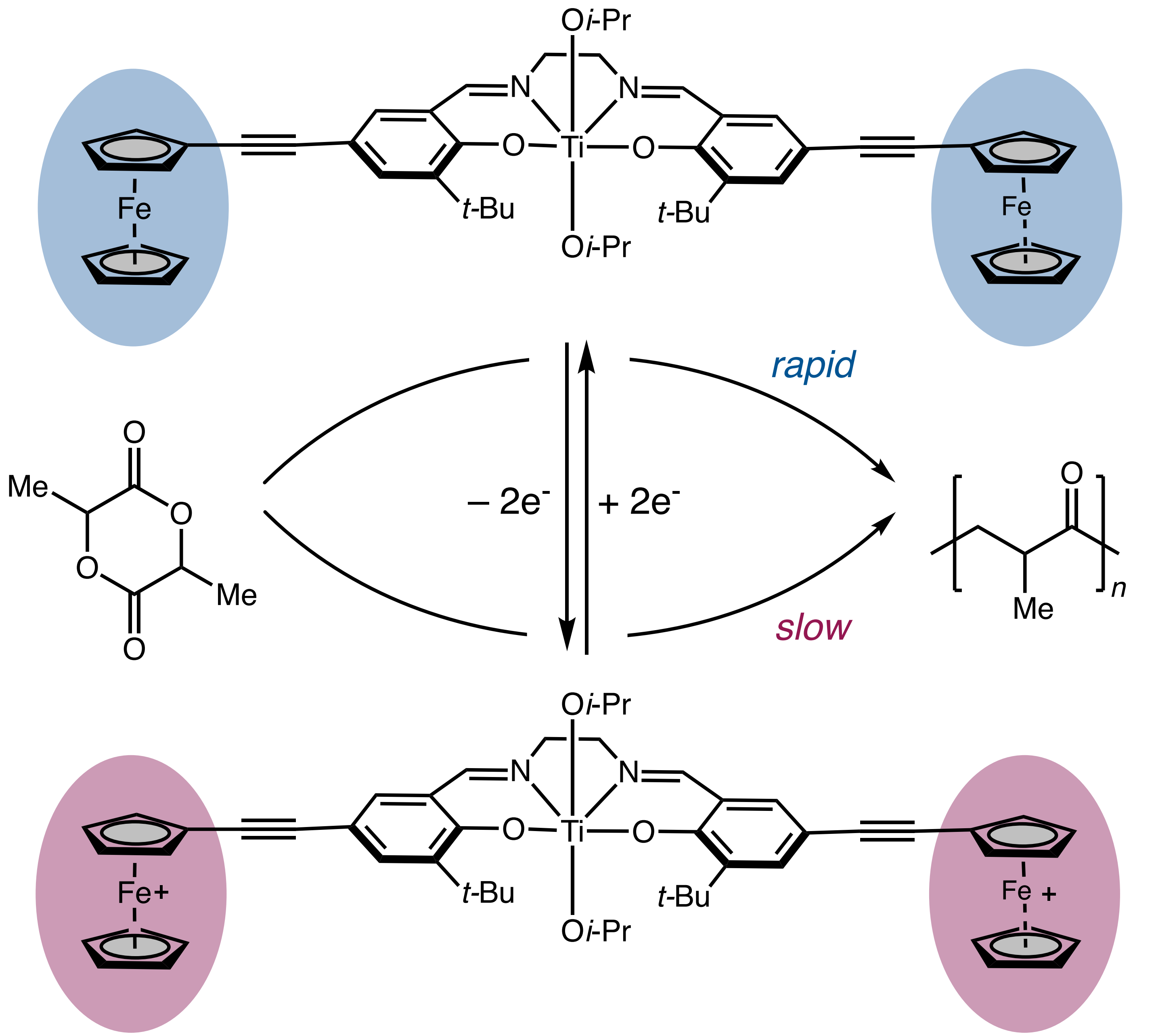


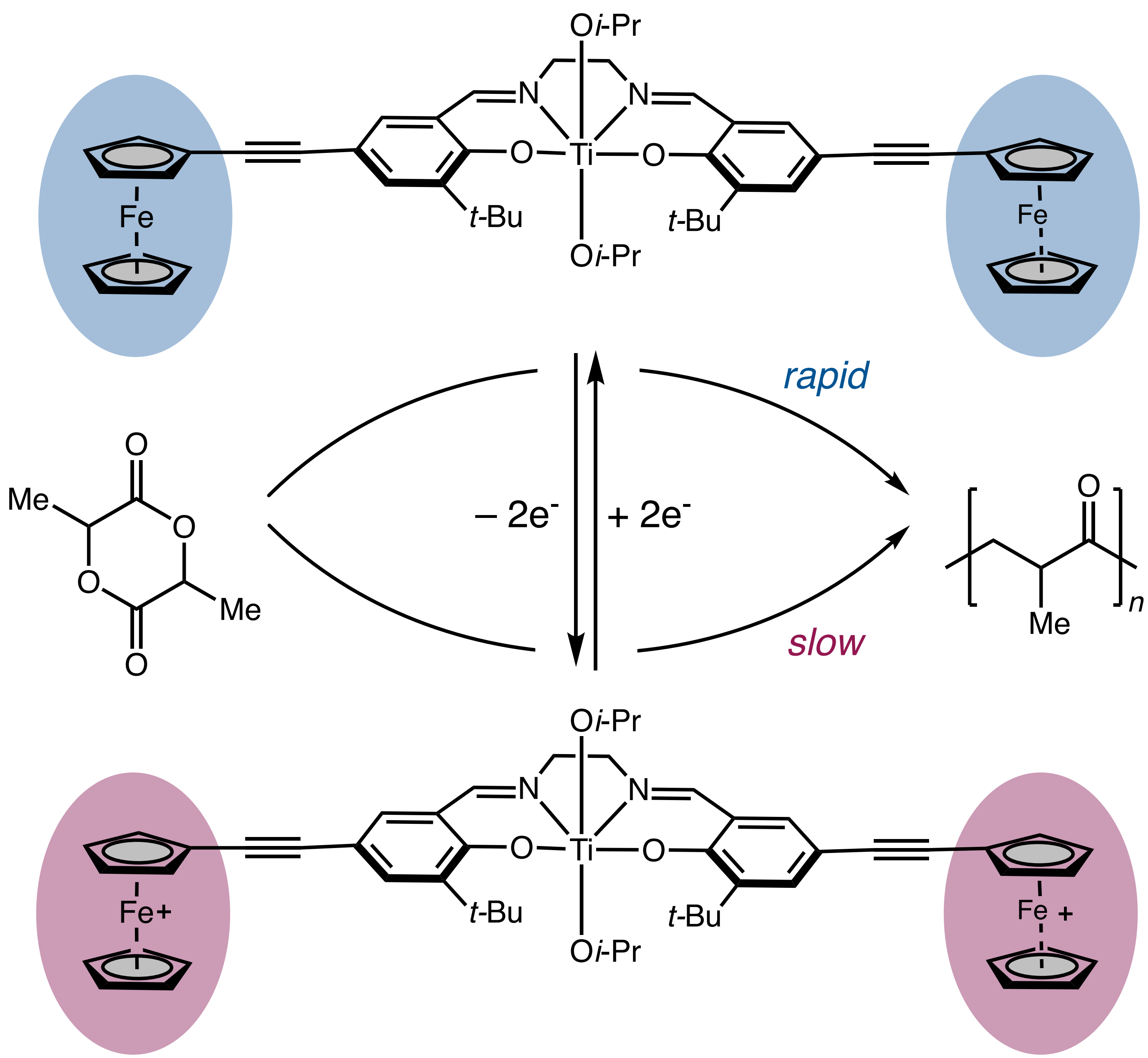
k_{red}/k_{ox} = ~ 30

- lactide polymerization known to be slow for e-deficient Ti^{IV}-salen catalysts

Gregson, K.A.G.; Gibson, V.C.; Long, N.J.; Marshall, E.L.; Oxford, P.J.; White, A.J.P. *J. Am. Chem. Soc.* **2006**, 128, 7410.

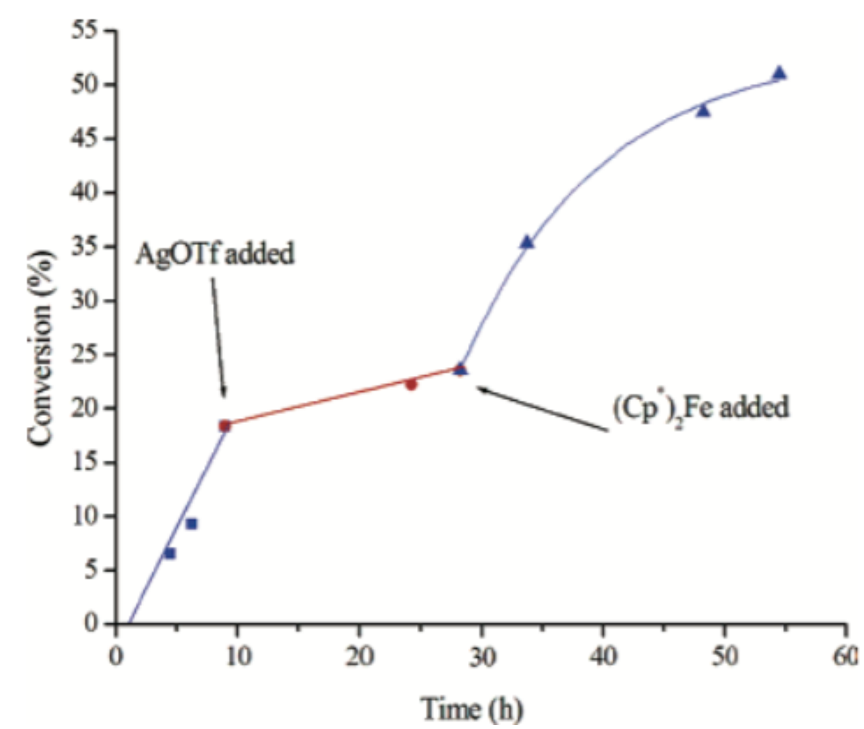
Redox Switching

control of oxidation state of redox-active ligands to mediate catalytic activity



reversible nature of redox event

demonstrates switching effect



before oxidation: $k_{app} = 4.73 \times 10^{-6}\ s^{-1}$

after $(Cp^*)_2Fe$ *added*: $k_{app} = 4.98 \times 10^{-6}\ s^{-1}$

k_{app} *= rate of propagation*

Gregson, K.A.G.; Gibson, V.C.; Long, N.J.; Marshall, E.L.; Oxford, P.J.; White, A.J.P. *J. Am. Chem. Soc.* **2006**, 128, 7410.

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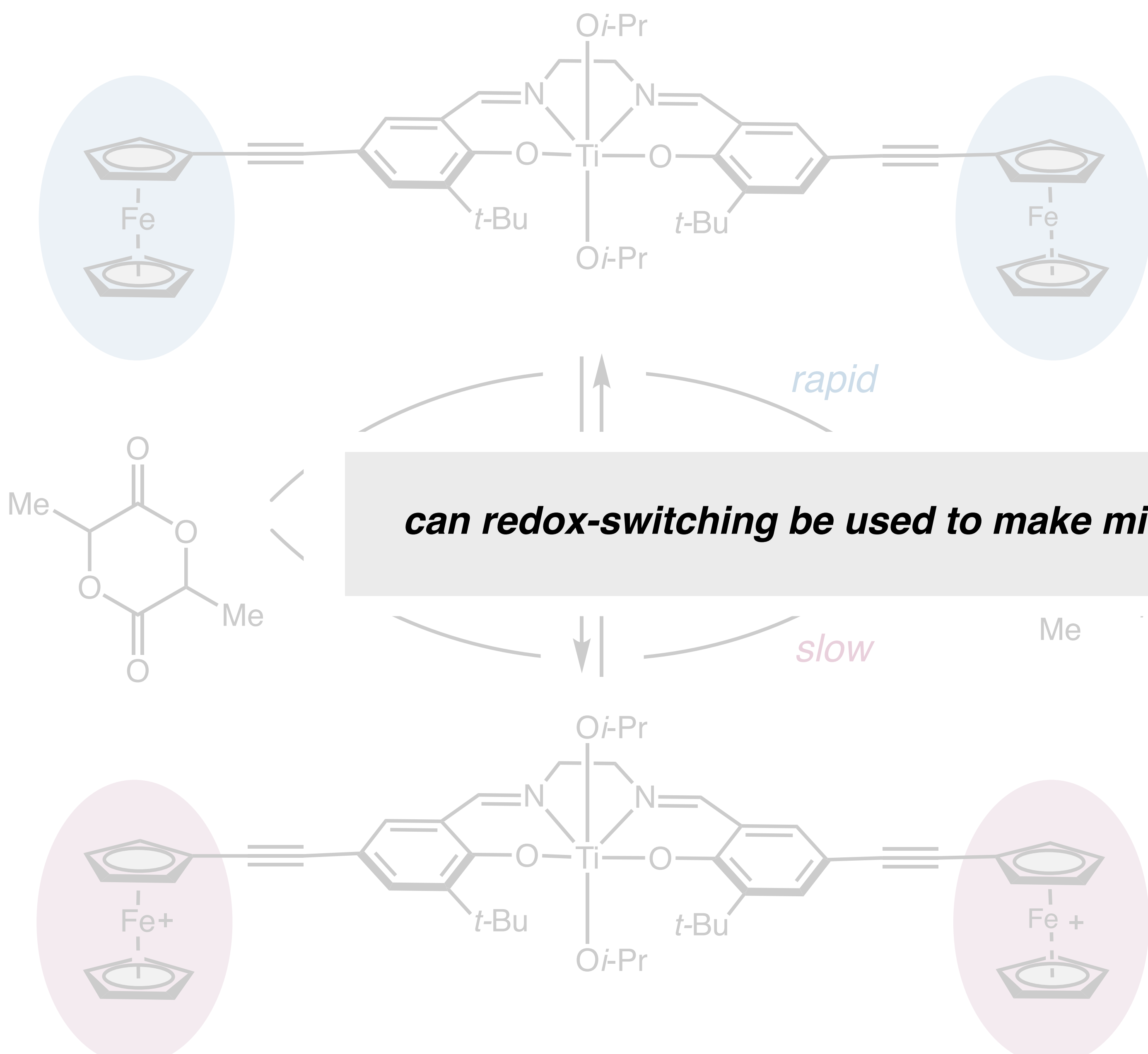
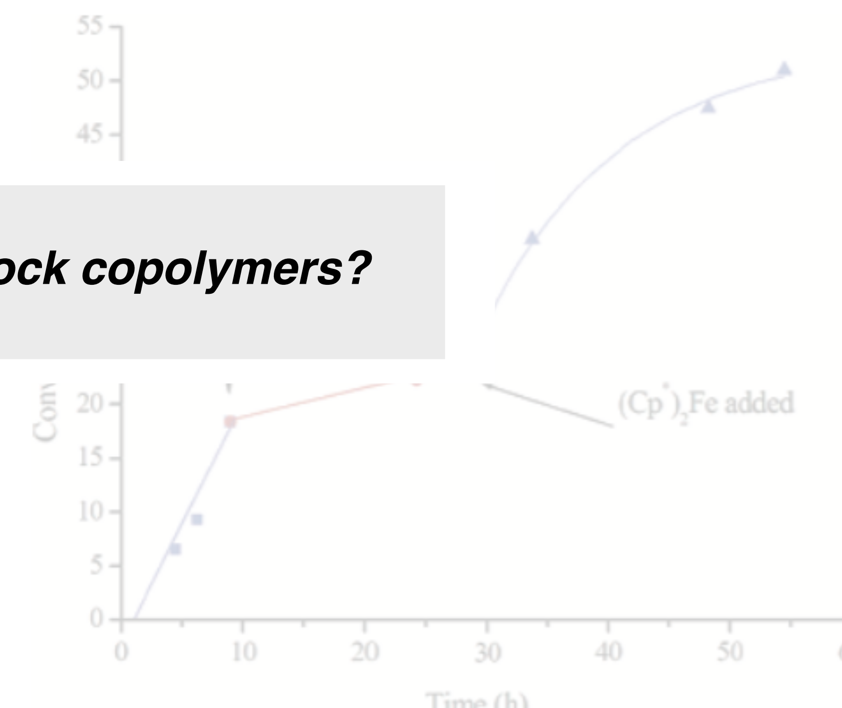


can redox-switching be used to make micro-block copolymers?



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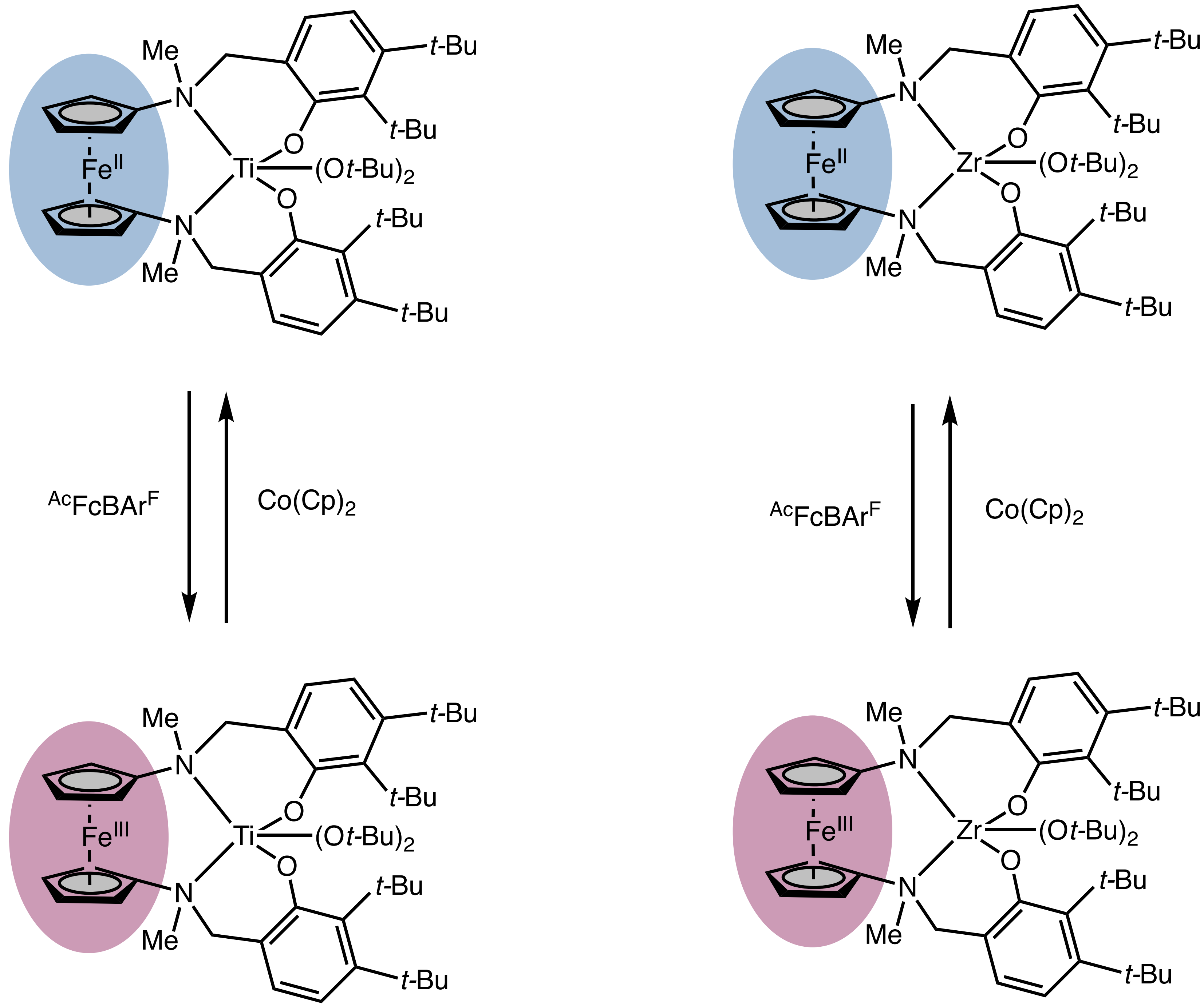
Redox Switching

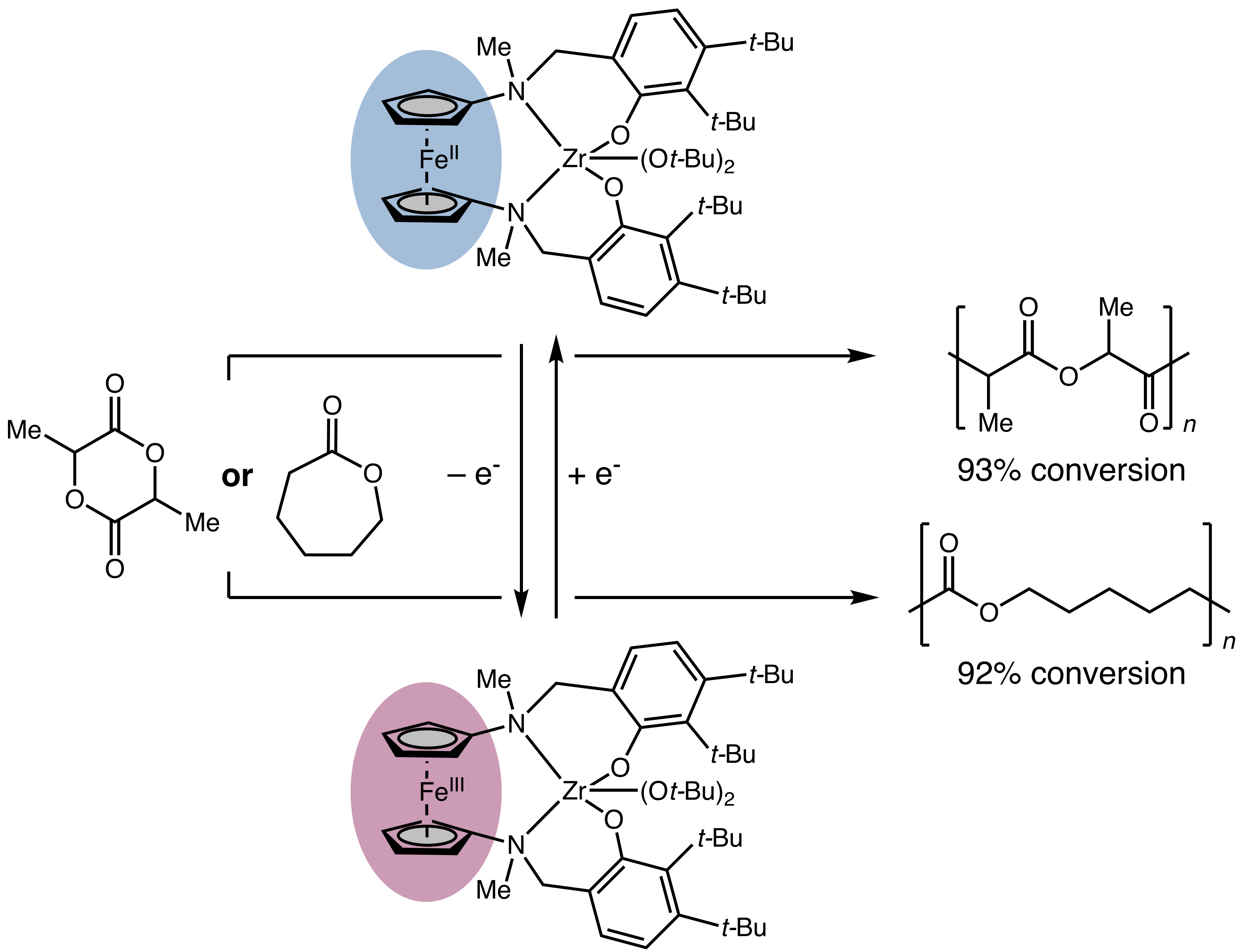
block copolymer synthesis via redox switching of ligands



Wang, X.; Thevenon, A.; Brosmer, J.L.; Yu, I.; Khan, S.I.; Mehrkhodavandi, P.; Diaconescu, P.L. *J. Am. Chem. Soc.* **2014**, 136, 11264.

Redox Switching

change in oxidation state changes binding profile of catalyst



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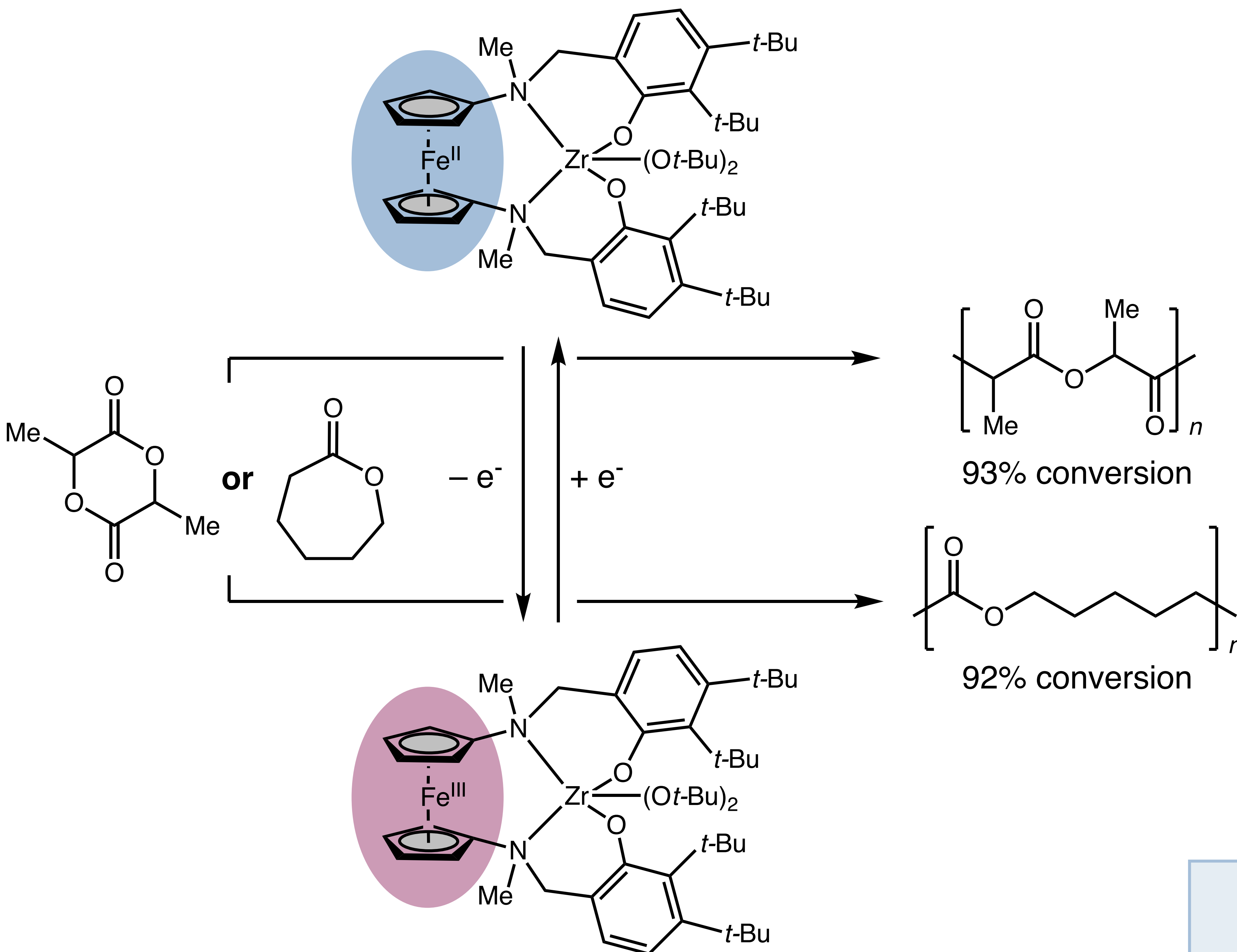
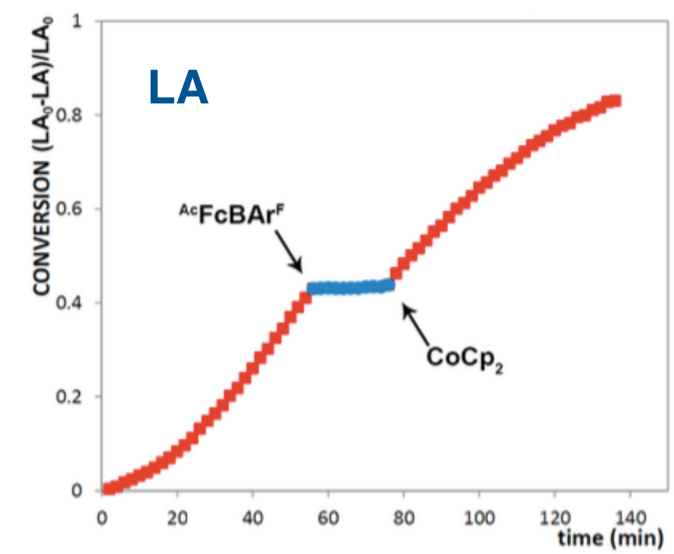
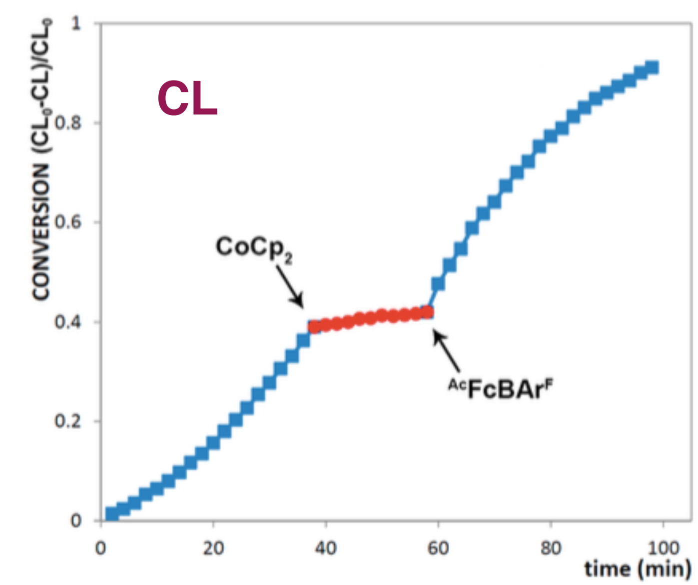






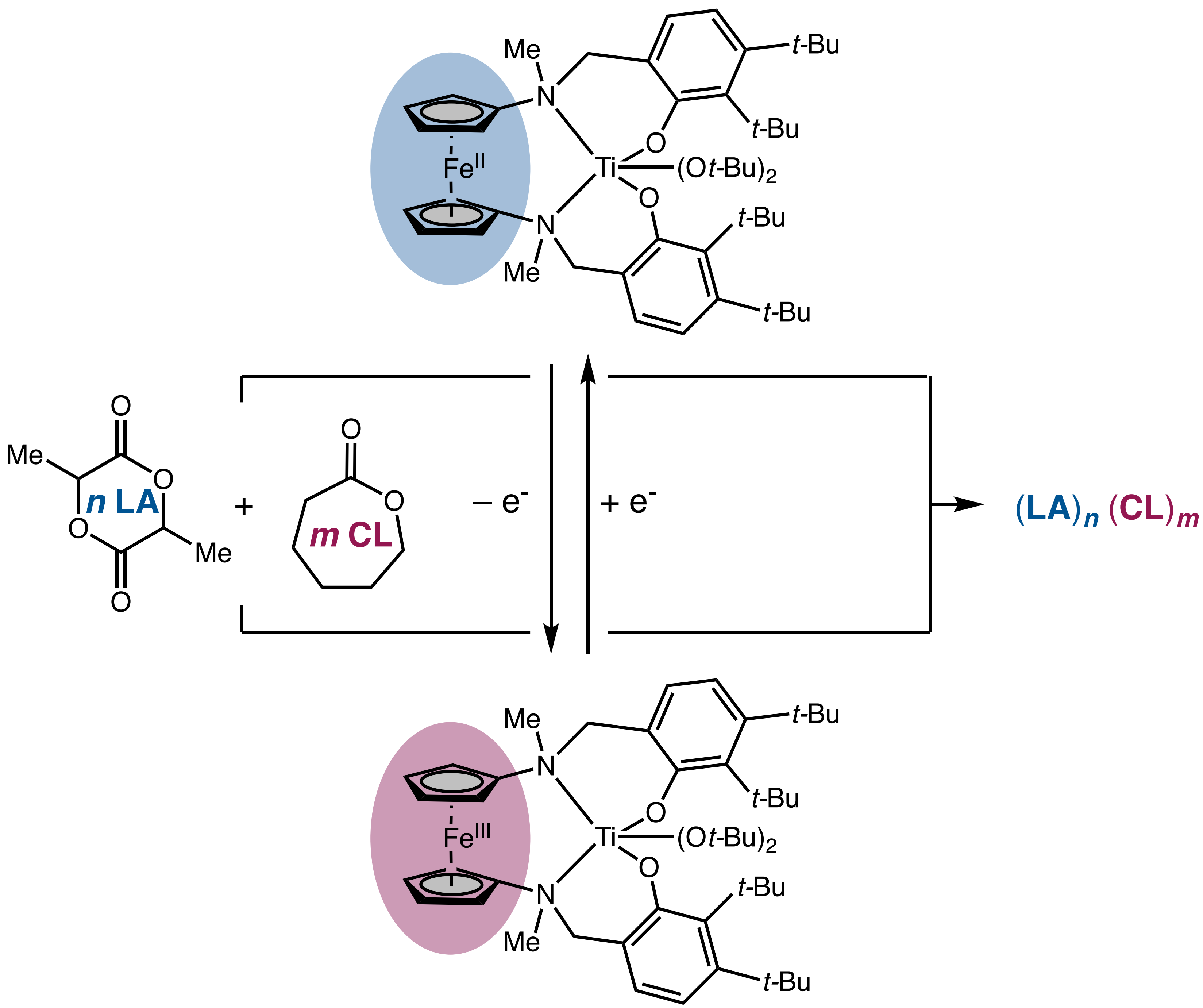
minimal change in rate of reaction

before/after changing oxidation state of Fe

Wang, X.; Thevenon, A.; Brosmer, J.L.; Yu, I.; Khan, S.I.; Mehrkhodavandi, P.; Diaconescu, P.L. *J. Am. Chem. Soc.* **2014**, 136, 11264.

Redox Switching

in situ redox-switching to achieve a block copolymer

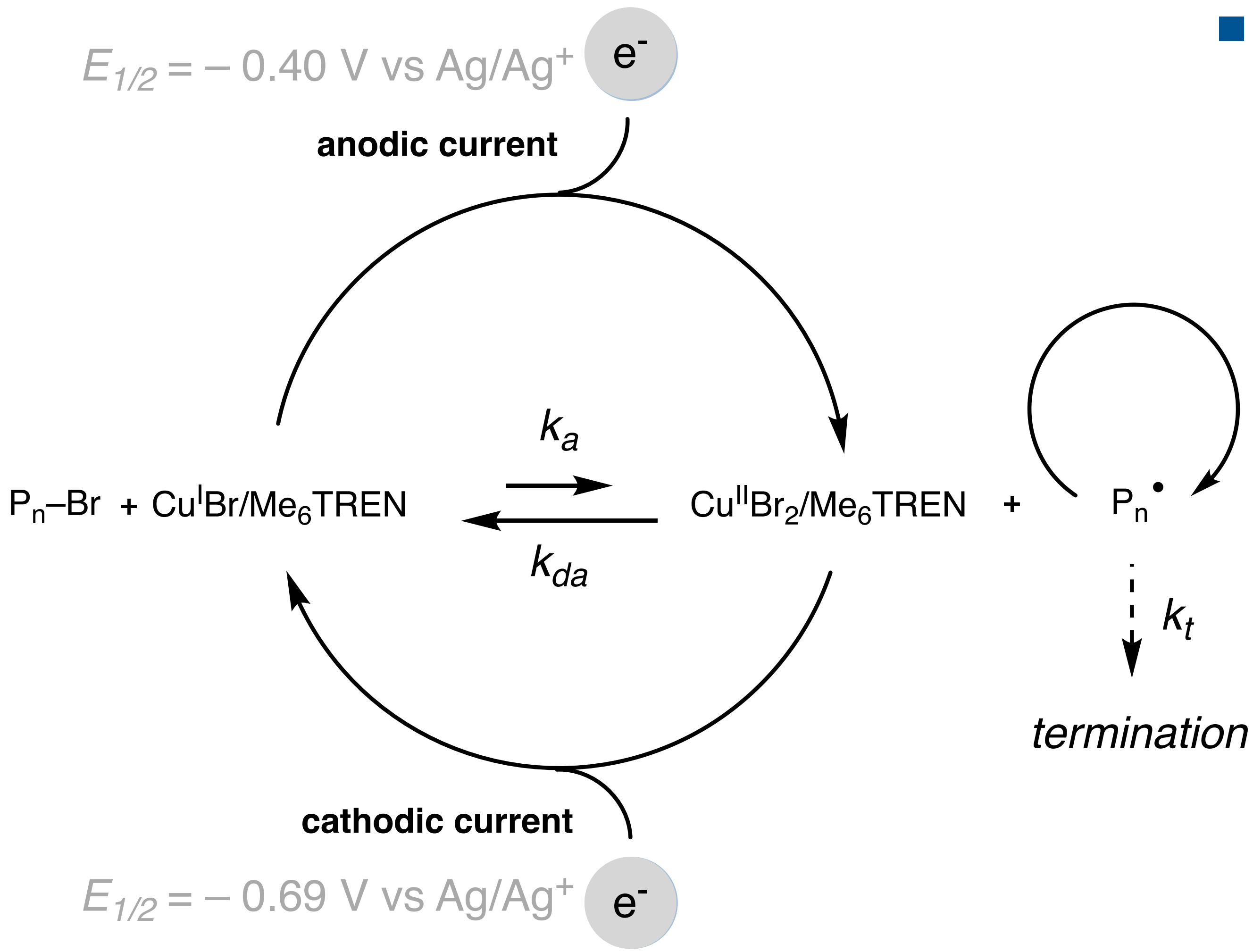


- ox. Zr complex did not polymerize caprolactone in mixed monomer pool
- more Lewis acidic Zr = increases bond strengths of all intermediates for ox. compound

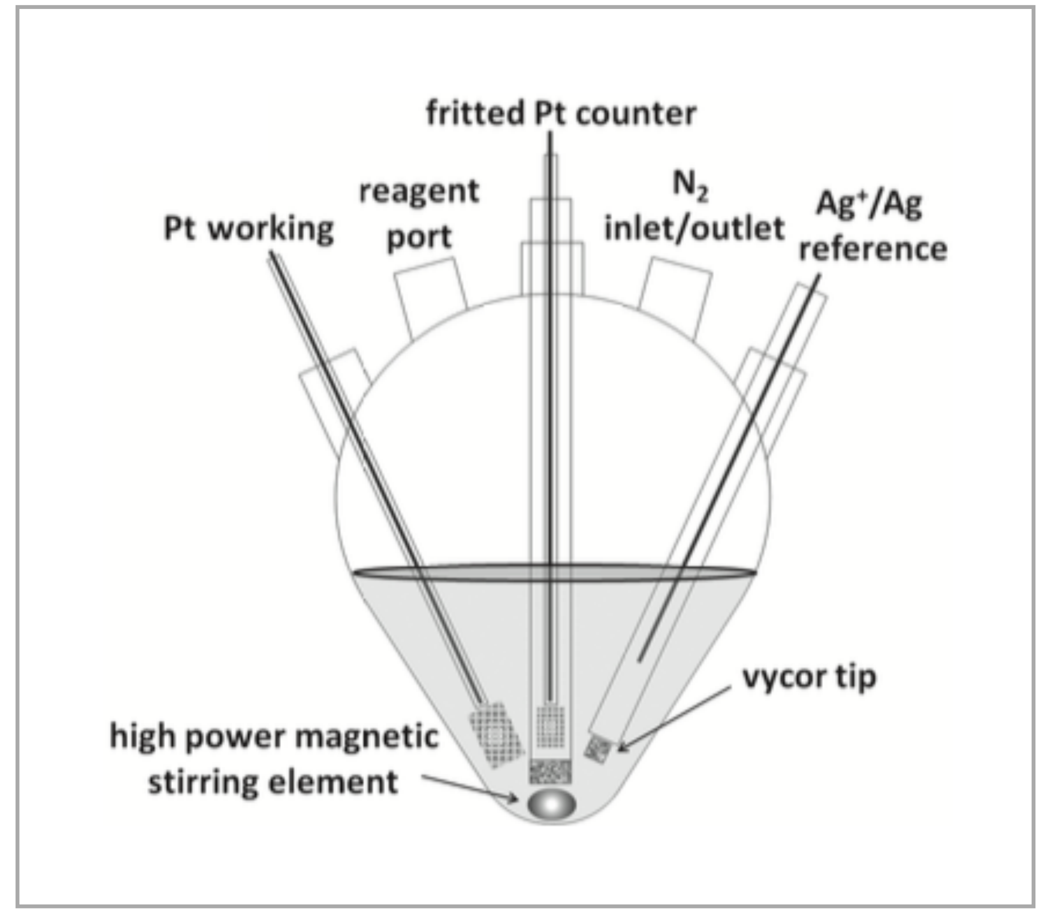
Wang, X.; Thevenon, A.; Brosmer, J.L.; Yu, I.; Khan, S.I.; Mehrkhodavandi, P.; Diaconescu, P.L. *J. Am. Chem. Soc.* **2014**, 136, 11264.

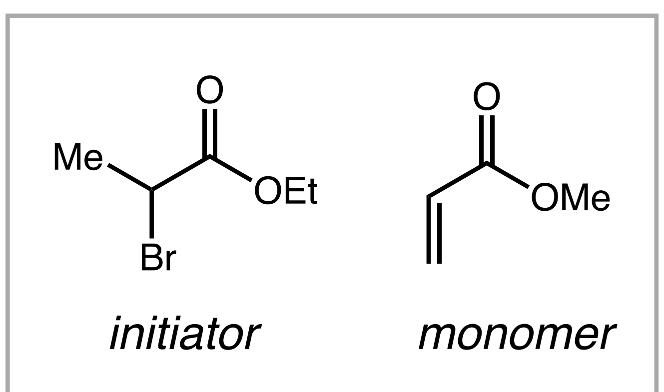
Electrochemically Mediated Atom Transfer Radical Polymerization

redox control of activity of metal catalyst



- in absence of potential, equilibrium favors starting materials



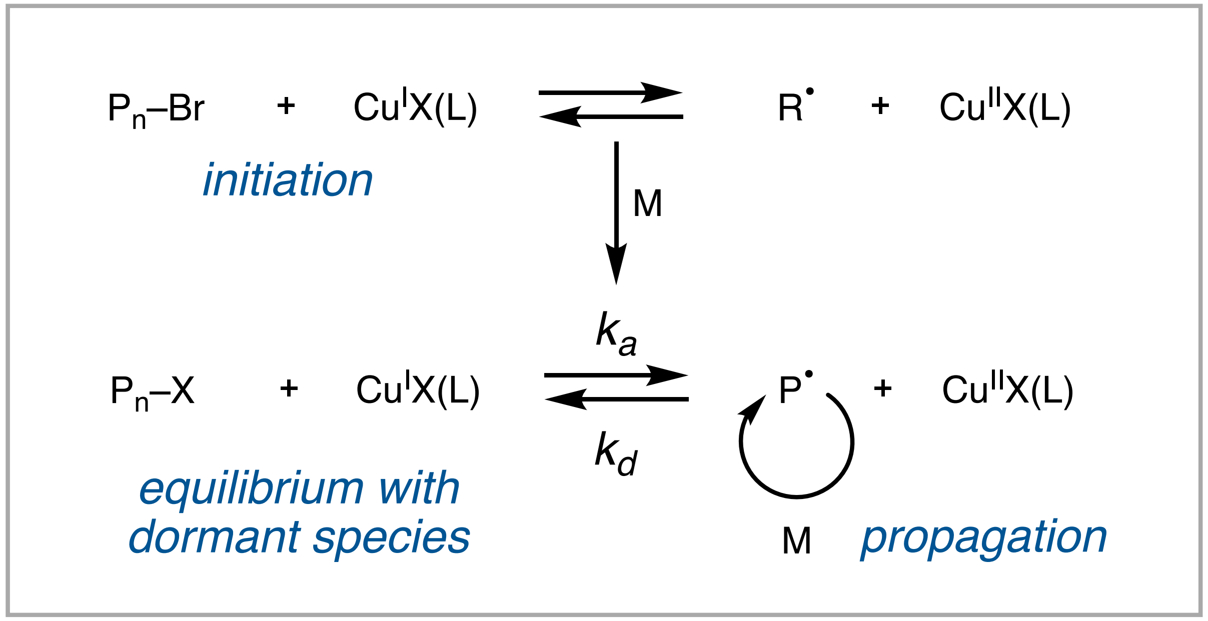


- extent of reduction dictated by applied potential (E_{app})
- shifting E_{app} to more positive values deactivates polymerization

Magenau, A.J.D.; Strandwitz, N.C.; Gennaro, A.; Matyjaszewski, K. *Science* **2011**, 332, 81.

Electrochemically Mediated Atom Transfer Radical Polymerization

redox control of activity of metal catalyst



ATRP depends on active/dormant equilibrium

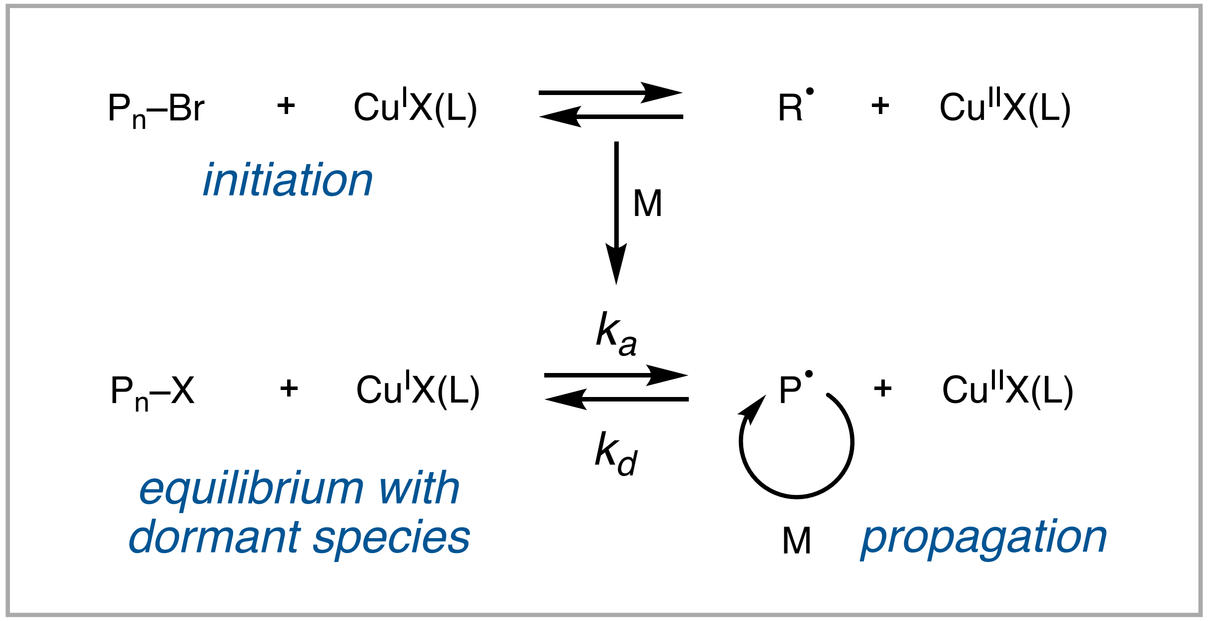
between (lower oxidation state) activators and alkyl halides (P_n–Br)

and between (higher oxidation state) deactivators and radicals ($P_n^•$)

Matyjaszewski, K.; Xia, J. *Chem. Rev.* **2001**, 101, 2921.

Electrochemically Mediated Atom Transfer Radical Polymerization

redox control of activity of metal catalyst



ATRP depends on active/dormant equilibrium

between (lower oxidation state) activators and alkyl halides (P_n–Br)

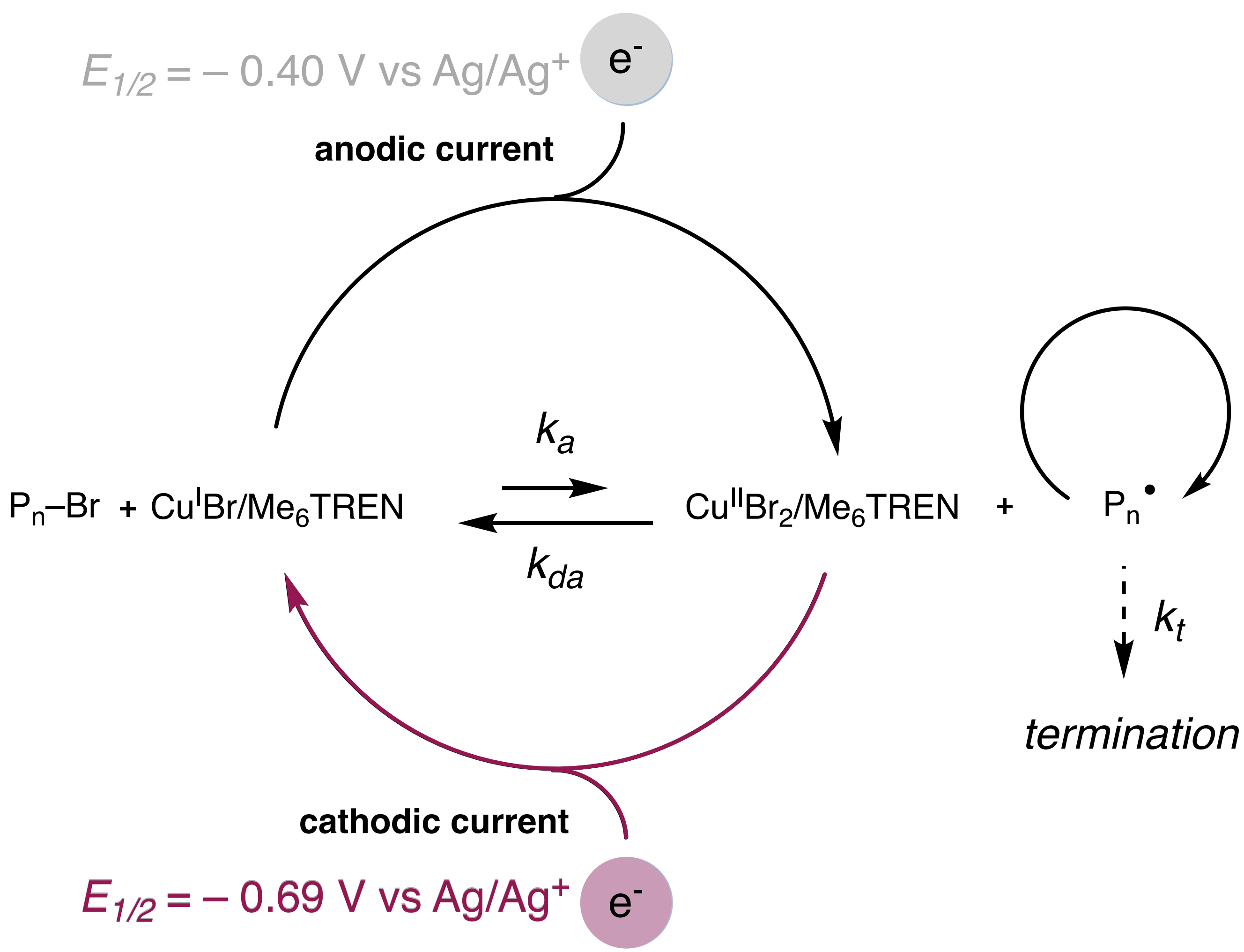
and between (higher oxidation state) deactivators and radicals ($P_n^{\bullet}$)

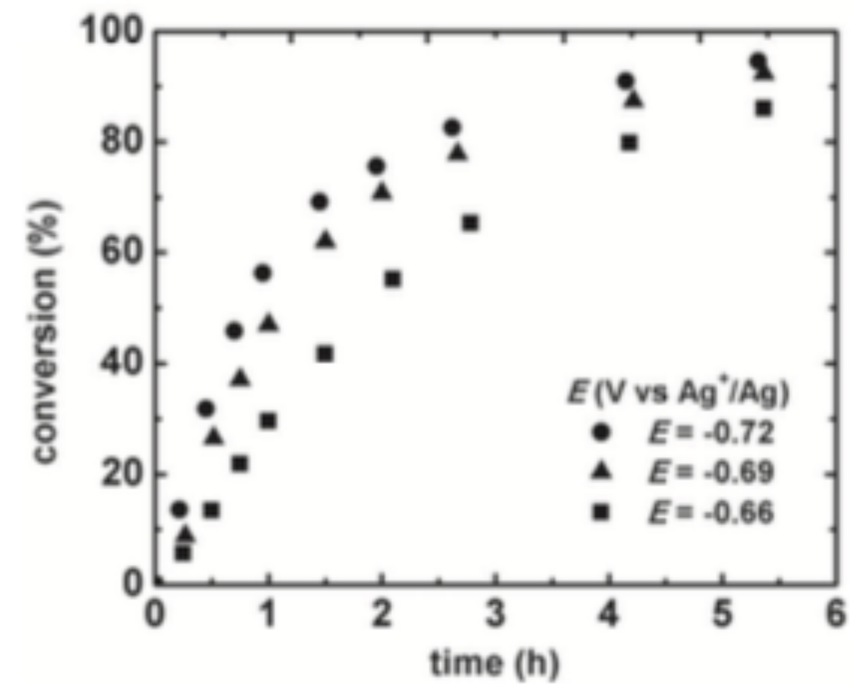
$$K_{ATRP} = k_a/k_{da}$$

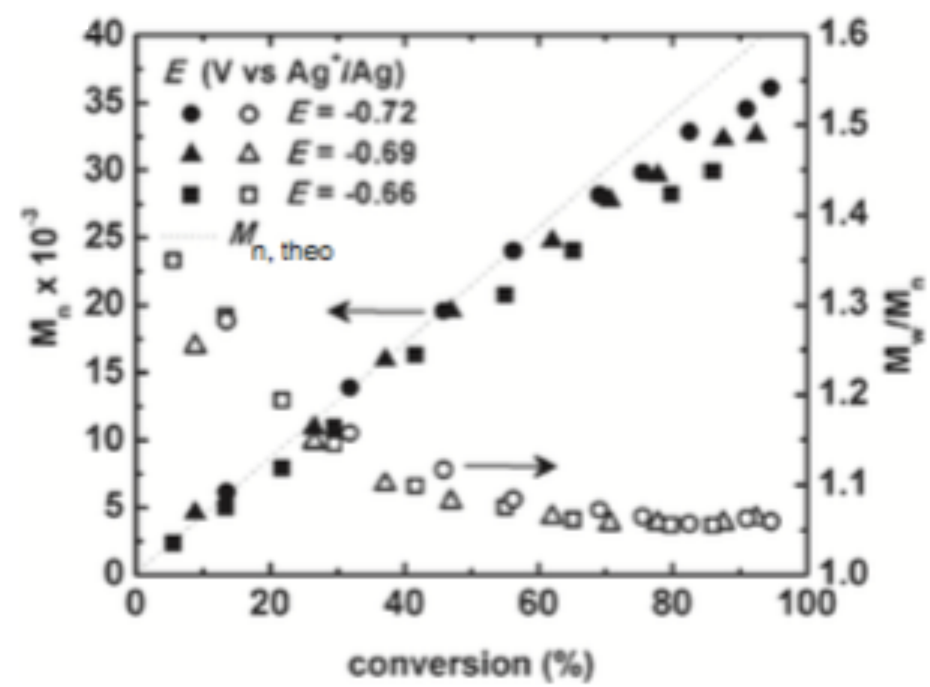
- concerted atom transfer mechanism via inner-sphere electron transfer
- favoring dormant state mediates polymerization, allowing for simultaneous growth of each polymer chain
- excess reducing agent used to regenerate $Cu^{I}X$ activators from $Cu^{II}X_2$ deactivators (ARGET)

Matyjaszewski, K.; Xia, J. *Chem. Rev.* **2001**, 101, 2921.

Electrochemically Mediated Atom Transfer Radical Polymerization





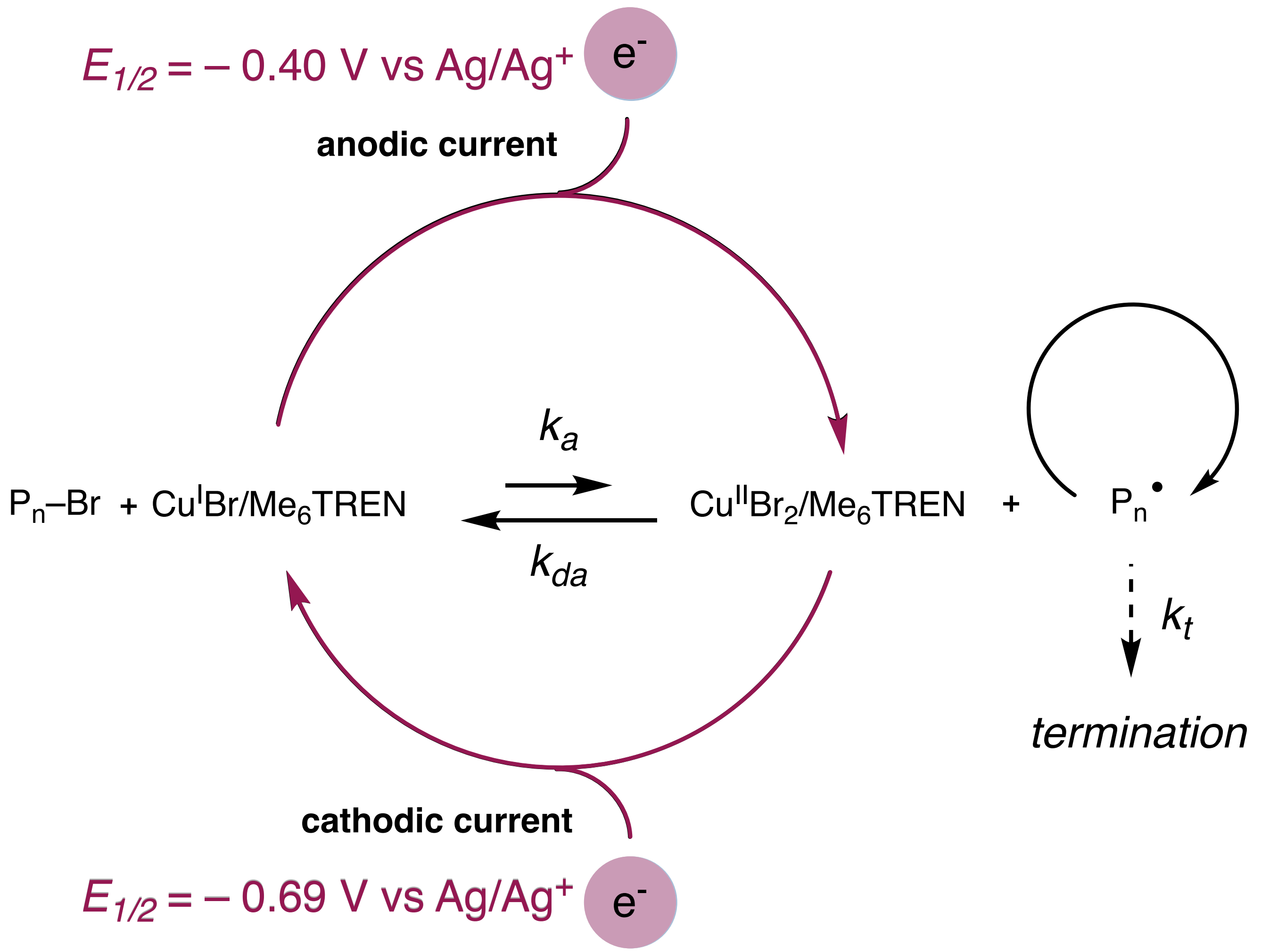


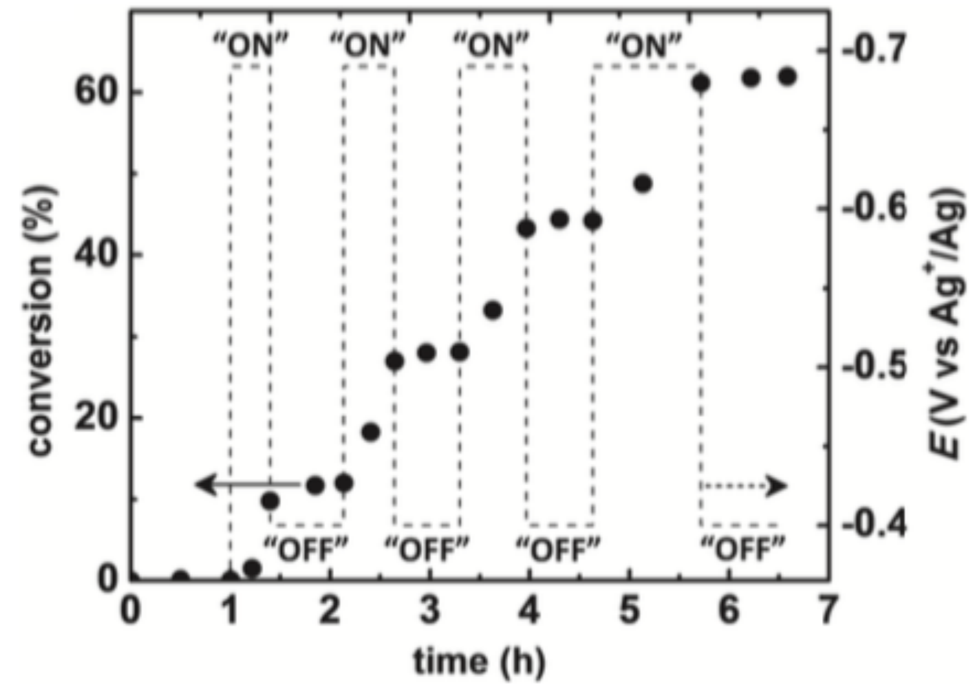
- applying potential of – 0.69 V: 80% conversion in 2 h
- low dispersity at high conversion (M_w/M_n = 1.06)

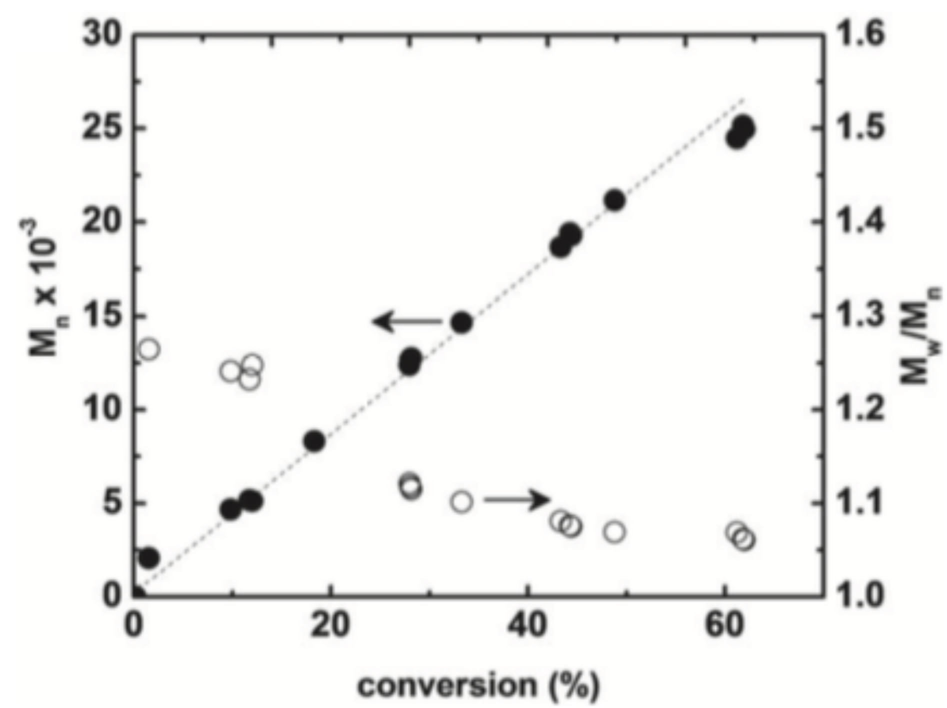
Magenau, A.J.D.; Strandwitz, N.C.; Gennaro, A.; Matyjaszewski, K. *Science* **2011**, 332, 81.

Electrochemically Mediated Atom Transfer Radical Polymerization

toggling between $E_{1/2}$ = –0.69 V and $E_{1/2}$ = –0.40 V exhibits responsive on/off switching of polymerization







repetitive stepping of E_{app} acts as

electrochemical switch to modulate Cu oxidation state

Magenau, A.J.D.; Strandwitz, N.C.; Gennaro, A.; Matyjaszewski, K. *Science* **2011**, 332, 81.

Switchable Catalysis

- switchable catalysis: biological inspiration
- types of switchable external stimuli
  - **light**
  - **pH**
  - ion coordination
  - **redox switching**
  - mechanical forces