HHS Public Access

Author manuscript

SynOpen. Author manuscript; available in PMC 2021 November 24.

Published in final edited form as:

SynOpen. 2021 ; 5(3): 173–228. doi:10.1055/s-0040-1706051.

C–H Bond Functionalization of Amines: A Graphical Overview of Diverse Methods

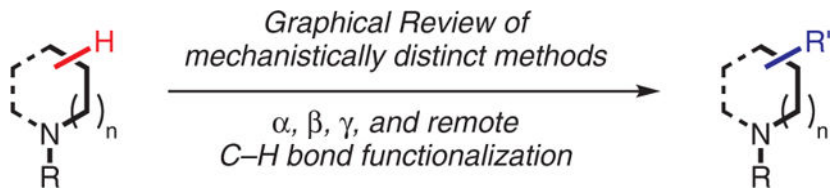
Subhradeep Dutta, **Bowen Li**, **Dillon R. L. Rickertsen**, **Daniel A. Valles**, **Daniel Seidel**

Center for Heterocyclic Compounds, Department of Chemistry, University of Florida, Gainesville, FL 32611, USA

Abstract

This Graphical Review provides a concise overview of the manifold and mechanistically diverse methods that enable the functionalization of sp^3 C–H bonds in amines and their derivatives.

Graphical Abstract



Keywords

C–H bond functionalization; amines; heterocycles; catalysis; synthesis

1 Introduction

The development of methods for the C–H bond functionalization of amines continues to be a topic of significant interest. Given the potential to lead to real-world applications, coupled with the intellectually stimulating nature of the field, this sustained high level of interest is hardly surprising. A plethora of approaches have emerged over the years, exhibiting significant mechanistic diversity. In addition, an almost overwhelming number of contributions continue to be published at an ever-accelerating pace, making it challenging to keep up with what has already been accomplished, and to put new discoveries into perspective. The rapid speed of development can also obscure what has already been done well versus which transformations need further improvement (regarding scope, ease of use, cost, scalability, etc.), and which worth-while unsolved challenges remain to be addressed.

seidel@chem.ufl.edu .

Conflict of Interest

The authors declare no conflict of interest.

The goal of this Graphical Review is to provide a concise overview of the manifold methods that achieve the functionalization of sp^3 C–H bonds in amines and their protected derivatives (e.g., amides, carbamates, *N*-aryl amines, etc.). We aim to cover the most important methods while highlighting the underlying mechanisms. Throughout, we have attempted to trace the origin of each approach back to a seminal report or important literature precedent. A focus is placed on historical contributions, key innovations, and the most recent cutting-edge advances. While reactions are grouped by mechanism, clear categorization of a given process is not always possible. Clearly, certain transformations would fit well into different categories. Due to the format of this review and the vast number of contributions published to date, this overview could not possibly be comprehensive, nor does it aim to be. Coverage extends to the end of 2020, with selected contributions from early 2021. We hope that this review will offer something of value to novices and experts alike. Feedback from the community is welcomed, so that a future, updated version of this review can be improved upon.

Regarding the structure of this Graphical Review, abbreviated references including prior reviews are provided within the Figures at the appropriate places. Full references are shown in the reference section and are grouped by Figure number. A note on the use of color: Amine substrates are shown in black, while groups that are being added are colored in light or dark blue. Catalysts are shown in purple or green. Other colors are used on occasion to highlight certain aspects (e.g., green for directing groups, red for hydrogens that are being functionalized, and orange for curly arrows).

Acknowledgment

We are grateful to the current and former members of the Seidel research group who have contributed to the development of this field.

Funding Information

Financial support from the NIH-NIGMS (grant no. R01GM101389) is gratefully acknowledged.

Biographies

Subhradeep Dutta was born and raised in West Bengal, India. He earned a B.Sc. degree in chemistry from Calcutta University (India) in 2016 and an M.Sc. degree in chemistry from the Indian Institute of Technology Kanpur (IITK) in 2018 under the guidance of Prof. Basker Sundararaju. In August 2018, he moved to the University of Florida (USA) for his graduate studies, joining the group of Prof. Daniel Seidel. His research focuses on developing methods towards the C–H bond functionalization of cyclic amines.

Bowen Li was born and raised in Shandong, P. R. of China. He earned a B.Sc. degree in the School of Chemistry and Chemical Engineering at Shanghai Jiao Tong University (P. R. of China) working with Prof. Wanbin Zhang. In 2019, he moved to the University of Florida (USA) for his graduate studies, joining the group of Prof. Daniel Seidel. His research focuses on asymmetric catalysis and C–H bond functionalization.

Dillon Rickertsen was born in Denver, Colorado, USA. He earned a B.Sc. degree in the Department of Chemistry at the University of Colorado, Denver (USA), working with Prof. Scott Reed. In 2019, he moved to the University of Florida for his graduate studies, joining the group of Prof. Daniel Seidel. His research is focused on developing methodologies for the C–H bond functionalization of amines.

Daniel Valles was born in Caracas, Venezuela and raised in Weston, Florida, USA. He attended the California Institute of Technology (Caltech) (USA) working with Prof. Peter Dervan, Prof. Sarah Reisman, and Dr. Scott Virgil. In 2018, he started his Ph.D. research at the University of Florida under the direction of Prof. Daniel Seidel. His research focuses on the functionalization of C–H bonds on cyclic amines.

Daniel Seidel studied chemistry at the Friedrich-Schiller-Universität Jena (Germany) and at the University of Texas at Austin (USA) (Diplom 1998). He performed his graduate studies in the lab of Prof. Jonathan L. Sessler, obtaining his Ph.D. in 2002. From 2002–2005, he was an Ernst Schering Postdoctoral Fellow in the group of Prof. David A. Evans at Harvard University (USA). He started his independent career at Rutgers University (USA) in 2005

and was promoted to Associate Professor in 2011 and Full Professor in 2014. In the summer of 2017, his research group moved to the University of Florida (USA).

References

(1). (a)Peterson DJ; Hays HR J. Org. Chem 1965, 30, 1939.(b)Lepley AR; Giumanini AG J. Org. Chem 1966, 31, 2055.(c)Ahlbrecht H; Dollinger H Tetrahedron Lett. 1984, 25, 1353.(d)Gessner VH; Strohmann C J. Am. Chem. Soc 2008, 130, 14412. [PubMed: 18842047] (e)Kessar SV; Singh P; Vohra R; Kaur NP; Singh KN J. Chem. Soc., Chem. Commun 1991, 568.(f)Kessar SV; Vohra R; Kaur NP Tetrahedron Lett. 1991, 32, 3221.(g)De Ceglie MC; Musio B; Affortunato F; Moliterni A; Altomare A; Florio S; Luisi R Chem. Eur. J 2011, 17, 286. [PubMed: 21207624] (h)Singh KN; Singh P; Singh P; Deol YS Org. Lett 2012, 14, 2202. [PubMed: 22506630] (i)Lepley AR; Khan WA J. Org. Chem 1966, 31, 2061.(j)Lepley AR; Khan WA Chem. Commun 1967, 1198.(k)Kessar SV; Singh P Chem. Rev 1997, 97, 721. [PubMed: 11848886] (l)Katritzky AR; Qi M Tetrahedron 1998, 54, 2647.(m)Ferey V; Toupet L; Le Gall T; Mioskowski C Angew. Chem., Int. Ed. Engl 1996, 35, 430.(n)Vedejs E; Kendall JT J. Am. Chem. Soc 1997, 119, 6941.(o)Ebden MR; Simpkins NS; Fox DNA Tetrahedron 1998, 54, 12923.(p)Kessar SV; Singh P; Singh KN; Venugopalan P; Kaur A; Bharatam PV; Sharma AK J. Am. Chem. Soc 2007, 129, 4506. [PubMed: 17385855] (q)Harmata M; Carter KW; Jones DE; Kahraman M Tetrahedron Lett. 1996, 37, 6267.(r)Kovács E; Huszka B; Gáti T; Nyerges M; Faigl F; Mucsi Z J. Org. Chem 2019, 84, 7100. [PubMed: 31084024] (s)Kovács E; Faigl F; Mucsi Z J. Org. Chem 2020, 85, 11226. [PubMed: 32786621]

(2). (a)Keefer LK; Fodor CH J. Am. Chem. Soc 1970, 92, 5747.(b)Seebach D; Enders D Angew. Chem., Int. Ed. Engl 1972, 11, 301.(c)Seebach D; Enders D Angew. Chem., Int. Ed. Engl 1972, 11, 1101.(d)Seebach D; Wykypiel W Synthesis 1979, 423.(e)Seebach D; Enders D J. Med. Chem 1974, 17, 1225. [PubMed: 4416026] (f)Fraser RR; Passannanti S Synthesis 1976, 540.(g)Wykypiel W; Seebach D Tetrahedron Lett. 1980, 21, 1927.(h)Savignac P; Dreux M; Leroux Y Tetrahedron Lett. 1974, 15, 2651.(i)Savignac P; Leroux Y J. Organomet. Chem 1973, 57, C47.(j)Magnus P; Roy G Synthesis 1980, 575.(k)Seebach D; Yoshifuji M Helv. Chim. Acta 1981, 64, 643.(l)Beak P; Zajdel WJ J. Am. Chem. Soc 1984, 106, 1010.(m)Meyers AI; Edwards PD; Rieker WF; Bailey TR J. Am. Chem. Soc 1984, 106, 3270.(n)Meyers AL; Dickman DA; Boes M Tetrahedron 1987, 43, 5095.(o)Meyers AI Tetrahedron 1992, 48, 2589.(p)Seebach D; Enders D Angew. Chem., Int. Ed. Engl 1975, 14, 15.(q)Beak P; Reitz DB Chem. Rev 1978, 78, 275.(r)Beak P; Zajdel WJ; Reitz DB Chem. Rev 1984, 84, 471.(s)Clayden J Organolithiums: Selectivity for Synthesis, In Tetrahedron Organic Chemistry Series, Vol. 23; Clayden J, Ed.; Pergamon: Amsterdam, 2002, 9.(t)Fraser RR; Boussard G; Postescu ID; Whiting JJ; Wigfield YY Can. J. Chem 1973, 51, 1109.(u)Lyle RE; Saavedra JE; Lyle GG; Fribush HM; Marshall JL; Lijinsky W; Singer GM Tetrahedron Lett. 1976, 17, 4431.(v)Seebach D; Lubosch W Angew. Chem., Int. Ed. Engl 1976, 15, 313.(w)Seebach D; Hassel T Angew. Chem., Int. Ed. Engl 1978, 17, 274.(x)Meyers AI; Ten Hoeve W J. Am. Chem. Soc 1980, 102, 7125.(y)Seebach D; Lohmann J-J; Syfrig MA; Yoshifuji M Tetrahedron 1983, 39, 1963.(z)Gawley RE; Hart G; Goicoechea-Pappas M; Smith AL J. Org. Chem 1986, 51, 3076.(aa)Gawley RE; Rein K; Chemburkar S J. Org. Chem 1989, 54, 3002.(ab)Meyers AI; Milot G J. Org. Chem 1993, 58, 6538.(ac)Nain Singh K; Singh P; Kaur A Synth. Commun 2006, 36, 3339.

(3). (a)Beak P; Lee W-K Tetrahedron Lett. 1989, 30, 1197.(b)Beak P; Lee WK J. Org. Chem 1990, 55, 2578.(c)Beak P; Lee WK J. Org. Chem 1993, 58, 1109.(d)Xiao D; Lavey BJ; Palani A; Wang C; Aslanian RG; Kozlowski JA; Shih N-Y; McPhail AT; Randolph GP; Lachowicz JE; Duffy RA Tetrahedron Lett. 2005, 46, 7653.(e)Aeyad T; Williams JD; Meijer AJHM; Coldham I Synlett 2017, 28, 2765.(f)Beak P; Wu S; Yum EK; Jun YM J. Org. Chem 1994, 59, 276. (g)Dieter RK; Li S Tetrahedron Lett. 1995, 36, 3613.(h)Dieter RK; Li S J. Org. Chem 1997, 62, 7726.(i)Dieter RK; Dieter JW; Alexander CW; Bhinderwala NS J. Org. Chem 1996, 61, 2930. [PubMed: 11667147] (j)Dieter RK; Velu SE J. Org. Chem 1997, 62, 3798.(k)Dieter RK; Lu K; Velu SE J. Org. Chem 2000, 65, 8715. [PubMed: 11112594] (l)Barker G; O'Brien P; Campos KR Org. Lett 2010, 12, 4176. [PubMed: 20718476] (m)Kwong A; Firth JD; Farmer TJ; O'Brien P Tetrahedron 2021, 81, 131899.(n)Stead D; O'Brien P; Sanderson AJ Org. Lett 2005, 7, 4459. [PubMed: 16178558] (o)Berkheij M; van der Sluis L; Sewing C; den Boer DJ; Terpstra

JW; Hiemstra H; Iwema Bakker WI; van den Hoogenband A; van Maarseveen JH Tetrahedron Lett. 2005, 46, 2369.(p)Hodgson DM; Humphreys PG; Xu Z; Ward JG Angew. Chem. Int. Ed 2007, 46, 2245.(q)Li X; Leonori D; Sheikh NS; Coldham I Chem. Eur. J 2013, 19, 7724. [PubMed: 23677770] (r)Pizzuti MG; Minnaard AJ; Feringa BL Org. Biomol. Chem 2008, 6, 3464. [PubMed: 19082145] (s)Krishnan S; Bagdanoff JT; Ebner DC; Ramtohul YK; Tambar UK; Stoltz BM J. Am. Chem. Soc 2008, 130, 13745. [PubMed: 18798630] (t)Dieter RK; Sharma RR; Ryan W Tetrahedron Lett. 1997, 38, 783.(u)Dieter RK; Lu K J. Org. Chem 2002, 67, 847. [PubMed: 11856028] (v)Coldham I; Leonori D Org. Lett 2008, 10, 3923. [PubMed: 18683935]

(4). (a)Kerrick ST; Beak P J. Am. Chem. Soc 1991, 113, 9708.(b)Beak P; Kerrick ST; Wu S; Chu J J. Am. Chem. Soc 1994, 116, 3231.(c)Dearden MJ; Firkin CR; Hermet J-PR; O'Brien P J. Am. Chem. Soc 2002, 124, 11870. [PubMed: 12358529] (d)Campos KR; Klapars A; Waldman JH; Dormer PG; Chen C-Y J. Am. Chem. Soc 2006, 128, 3538. [PubMed: 16536525] (e)Seel S; Thaler T; Takatsu K; Zhang C; Zipse H; Straub BF; Mayer P; Knochel P J. Am. Chem. Soc 2011, 133, 4774. [PubMed: 21388211] (f)Kasten K; Seling N; O'Brien P Org. React 2019, 100, 255.(g)Wong JYF; Barker G Tetrahedron 2020, 76, 131704.(h)Gallagher DJ; Beak P J. Org. Chem 1995, 60, 7092.(i)Wilkinson TJ; Stehle NW; Beak P Org. Lett 2000, 2, 155. [PubMed: 10814270] (j)Phuan P-W; Ianni JC; Kozlowski MC J. Am. Chem. Soc 2004, 126, 15473. [PubMed: 15563175] (k)Coldham I; Leonori D J. Org. Chem 2010, 75, 4069. [PubMed: 20469892] (l)Sheikh NS; Leonori D; Barker G; Firth JD; Campos KR; Meijer AJHM; O'Brien P; Coldham I J. Am. Chem. Soc 2012, 134, 5300. [PubMed: 22339321] (m)Kizirian J-C; Caille J-C; Alexakis A Tetrahedron Lett. 2003, 44, 8893.(n)Hermet J-PR; Porter DW; Dearden MJ; Harrison JR; Koplin T; O'Brien P; Parmene J; Tyurin V; Whitwood AC; Gilday J; Smith NM Org. Biomol. Chem 2003, 1, 3977. [PubMed: 14664387] (o)McGrath MJ; Bilke JL; O'Brien P Chem. Commun 2006, 2607.(p)McGrath MJ; O'Brien P J. Am. Chem. Soc 2005, 127, 16378. [PubMed: 16305208]

(5). (a)Coldham I; Raimbault S; Whittaker DTE; Chovatia PT; Leonori D; Patel JJ; Sheikh NS Chem. Eur. J 2010, 16, 4082. [PubMed: 20175161] (b)Millet A; Larini P; Clot E; Baudoin O Chem. Sci 2013, 4, 2241.(c)Cordier CJ; Lundgren RJ; Fu GC J. Am. Chem. Soc 2013, 135, 10946. [PubMed: 23869442] (d)Mu X; Shibata Y; Makida Y; Fu GC Angew. Chem. Int. Ed 2017, 56, 5821.(e)Beak P; Basu A; Gallagher DJ; Park YS; Thayumanavan S Acc. Chem. Res 1996, 29, 552.(f)Campos KR Chem. Soc. Rev 2007, 36, 1069. [PubMed: 17576475] (g)Mitchell EA; Peschiulli A; Lefevre N; Meerpoel L; Maes BUW Chem. Eur. J 2012, 18, 10092. [PubMed: 22829434] (h)Coldham I; Dufour S; Haxell TFN; Howard S; Vennall GP Angew. Chem. Int. Ed 2002, 41, 3887.(i)Beng TK; Gawley RE J. Am. Chem. Soc 2010, 132, 12216. [PubMed: 20806976] (j)Millet A; Dailler D; Larini P; Baudoin O Angew. Chem. Int. Ed 2014, 53, 2678. (k)Watson RT; Gore VK; Chandupatla KR; Dieter RK; Snyder JP J. Org. Chem 2004, 69, 6105. [PubMed: 15373496] (l)Klapars A; Campos KR; Waldman JH; Zewge D; Dormer PG; Chen C-Y J. Org. Chem 2008, 73, 4986. [PubMed: 18507444] (m)Barker G; McGrath JL; Klapars A; Stead D; Zhou G; Campos KR; O'Brien P J. Org. Chem 2011, 76, 5936. [PubMed: 21714542]

(6). (a)Jun C-H Chem. Commun 1998, 1405.(b)Wang D-H; Hao X-S; Wu D-F; Yu J-Q Org. Lett 2006, 8, 3387. [PubMed: 16836412] (c)Pan S; Endo K; Shibata T Org. Lett 2011, 13, 4692. [PubMed: 21812393] (d)Chatani N; Asaumi T; Ikeda T; Yorimitsu S; Ishii Y; Kakiuchi F; Murai S J. Am. Chem. Soc 2000, 122, 12882.(e)Pastine SJ; Gribkov DV; Sames D J. Am. Chem. Soc 2006, 128, 14220. [PubMed: 17076471] (f)Chatani N; Asaumi T; Yorimitsu S; Ikeda T; Kakiuchi F; Murai S J. Am. Chem. Soc 2001, 123, 10935. [PubMed: 11686697] (g)Tsuchikama K; Kasagawa M; Endo K; Shibata T Org. Lett 2009, 11, 1821. [PubMed: 19354323] (h)Schinkel M; Wang L; Bielefeld K; Ackermann L Org. Lett 2014, 16, 1876. [PubMed: 24635222] (i)Lahm G; Opatz T Org. Lett 2014, 16, 4201. [PubMed: 25057785] (j)Spangler JE; Kobayashi Y; Verma P; Wang D-H; Yu J-Q J. Am. Chem. Soc 2015, 137, 11876. [PubMed: 26322957] (k)Tran AT; Yu J-Q Angew. Chem. Int. Ed 2017, 56, 10530.(l)Antermite D; Affron DP; Bull JA Org. Lett 2018, 20, 3948. [PubMed: 29897773] (m)Reyes RL; Sato M; Iwai T; Sawamura M J. Am. Chem. Soc 2020, 142, 589. [PubMed: 31820960] (n)Su B; Bunescu A; Qiu Y; Zuend SJ; Ernst M; Hartwig JF J. Am. Chem. Soc 2020, 142, 7912. [PubMed: 32216373] (o)He J; Wasa M; Chan KSL; Shao Q; Yu J-Q Chem. Rev 2017, 117, 8754. [PubMed: 28697604] (p)Sambiagio C; Schönbauer D; Blieck R; Dao-Huy T; Pototschnig G; Schaaf P; Wiesinger T; Zia MF; Wencel-Delord J; Besset T; Maes BUW; Schnürch M Chem. Soc. Rev 2018, 47, 6603. [PubMed: 30033454] (q)Zhang M;

Wang Q; Peng Y; Chen Z; Wan C; Chen J; Zhao Y; Zhang R; Zhang AQ Chem. Commun 2019, 55, 13048.(r)Kapoor M; Singh A; Sharma K; Hsu MH Adv. Synth. Catal 2020, 362, 4513.

(7). (a)Topczewski JJ; Cabrera PJ; Saper NI; Sanford MS Nature 2016, 531, 220. [PubMed: 26886789] (b)Cabrera PJ; Lee M; Sanford MS J. Am. Chem. Soc 2018, 140, 5599. [PubMed: 29652497] (c)Aguilera EY; Sanford MS Angew. Chem. Int. Ed 2021, 60, 11227.(d)Zaitsev VG; Shabashov D; Daugulis O J. Am. Chem. Soc 2005, 127, 13154. [PubMed: 16173737] (e)Zhang S-Y; He G; Nack WA; Zhao Y; Li Q; Chen G J. Am. Chem. Soc 2013, 135, 2124. [PubMed: 23350845] (f)Zhang S-Y; He G; Zhao Y; Wright K; Nack WA; Chen G J. Am. Chem. Soc 2012, 134, 7313. [PubMed: 22486219] (g)He G; Zhao Y; Zhang S; Lu C; Chen G J. Am. Chem. Soc 2012, 134, 3. [PubMed: 22191666] (h)He G; Zhao Y; Zhang S; Lu C; Chen G J. Am. Chem. Soc 2017, 139, 561. [PubMed: 28004919] (i)Verma P; Richter JM; Chekshin N; Qiao JX; Yu J-Q J. Am. Chem. Soc 2020, 142, 5117. [PubMed: 32098471] (j)Nadres ET; Daugulis O J. Am. Chem. Soc 2012, 134, 7. [PubMed: 22206416] (k)Ye X; He Z; Ahmed T; Weise K; Akhmedov NG; Petersen JL; Shi X Chem. Sci 2013, 4, 3712.(l)Li Q; Zhang S-Y; He G; Nack WA; Chen G Adv. Synth. Catal 2014, 356, 1544.(m)Wang P-L; Li Y; Wu Y; Li C; Lan Q; Wang X-S Org. Lett 2015, 17, 3698. [PubMed: 26181629] (n)Huang Z; Wang C; Dong G Angew. Chem. Int. Ed 2016, 55, 5299.(o)Coomber CE; Benhamou L; Bučar D-K; Smith PD; Porter MJ; Sheppard TD J. Org. Chem 2018, 83, 2495. [PubMed: 29241011]

(8). (a)Reddy BVS; Reddy LR; Corey EJ Org. Lett 2006, 8, 3391. [PubMed: 16836413] (b)Tran LD; Daugulis O Angew. Chem. Int. Ed 2012, 51, 5188.(c)Affron DP; Davis OA; Bull JA Org. Lett 2014, 16, 4956. [PubMed: 25191995] (d)Affron DP; Bull JA Eur. J. Org. Chem 2016, 139.(e)Maetani M; Zoller J; Melillo B; Verho O; Kato N; Pu J; Comer E; Schreiber SL J. Am. Chem. Soc 2017, 139, 11300. [PubMed: 28732448] (f)He J; Li S; Deng Y; Fu H; Laforteza BN; Spangler JE; Homs A; Yu J-Q Science 2014, 343, 1216. [PubMed: 24626923] (g)He G; Chen G Angew. Chem. Int. Ed 2011, 50, 5192.(h)Rodríguez N; Romero-Revilla JA; Fernández-Ibáñez MÁ; Carretero JC Chem. Sci 2013, 4, 175.(i)Chen K; Hu F; Zhang S-Q; Shi B-F Chem. Sci 2013, 4, 3906.(j)Zhang S-Y; Li Q; He G; Nack WA; Chen G J. Am. Chem. Soc 2013, 135, 12135. [PubMed: 23919290] (k)Wang B; Nack WA; He G; Zhang S-Y; Chen G Chem. Sci 2014, 5, 3952.(l)Gong W; Zhang G; Liu T; Giri R; Yu J-Q J. Am. Chem. Soc 2014, 136, 16940. [PubMed: 25384178] (m)Zhang L-S; Chen G; Wang X; Guo Q-Y; Zhang X-S; Pan F; Chen K; Shi Z-J Angew. Chem. Int. Ed 2014, 53, 3899.(n)Zhang Q; Yin X-S; Chen K; Zhang S-Q; Shi B-F J. Am. Chem. Soc 2015, 137, 8219. [PubMed: 26067591] (o)Ye S; Yang W; Coon T; Fanning D; Neubert T; Stamos D; Yu J-Q Chem. Eur. J 2016, 22, 4748. [PubMed: 26841330] (p)Xu J-W; Zhang Z-Z; Rao W-H; Shi B-F J. Am. Chem. Soc 2016, 138, 10750. [PubMed: 27529372] (q)Zhan B-B; Li Y; Xu J-W; Nie X-L; Fan J; Jin L; Shi B-F Angew. Chem. Int. Ed 2018, 57, 5858.(r)Noisier AFM; Brimble MA Chem. Rev 2014, 114, 8775. [PubMed: 25144592] (s)He G; Wang B; Nack WA; Chen G Acc. Chem. Res 2016, 49, 635. [PubMed: 27015079] (t)Wang W; Lorion MM; Shah J; Kapdi AR; Ackermann L Angew. Chem. Int. Ed 2018, 57, 14700.(u)Tong H-R; Li B; Li G; He G; Chen G CCS Chem. 2020, 3, 1797.

(9). (a)Wang H; Tong H-R; He G; Chen G Angew. Chem. Int. Ed 2016, 55, 15387.(b)Jain P; Verma P; Xia G; Yu J-Q Nat. Chem 2017, 9, 140. [PubMed: 28282045] (c)Jiang H-J; Zhong X-M; Yu J; Zhang Y; Zhang X; Wu Y-D; Gong L-Z Angew. Chem. Int. Ed 2019, 58, 1803.(d)Greßies S; Klauck FJR; Kim JH; Daniliuc CG; Glorius F Angew. Chem. Int. Ed 2018, 57, 9950.(e)Chen L; Yang Y; Liu L; Gao Q; Xu S J. Am. Chem. Soc 2020, 142, 12062. [PubMed: 32597651]

(10). (a)Wu Y; Chen Y-Q; Liu T; Eastgate MD; Yu J-Q J. Am. Chem. Soc 2016, 138, 14554. [PubMed: 27786439] (b)Liu Y; Ge H Nat. Chem 2017, 9, 26.(c)Kapoor M; Liu D; Young MC J. Am. Chem. Soc 2018, 140, 6818. [PubMed: 29787251] (d)Chen Y-Q; Wang Z; Wu Y; Wisniewski SR; Qiao JX; Ewing WR; Eastgate MD; Yu J-Q J. Am. Chem. Soc 2018, 140, 17884. [PubMed: 30500192] (e)Chen Y-Q; Singh S; Wu Y; Wang Z; Hao W; Verma P; Qiao JX; Sunoj RB; Yu J-Q J. Am. Chem. Soc 2020, 142, 9966. [PubMed: 32363869] (f)Yada A; Liao W; Sato Y; Murakami M Angew. Chem. Int. Ed 2017, 56, 1073.(g)St John-Campbell S; Ou AK; Bull JA Chem. Eur. J 2018, 24, 17838. [PubMed: 30255961] (h)St John-Campbell S; Bull JA Org. Biomol. Chem 2018, 16, 4582. [PubMed: 29796566] (i)Niu B; Yang K; Lawrence B; Ge H ChemSusChem 2019, 12, 2955. [PubMed: 30958921] (j)Trowbridge A; Walton SM; Gaunt MJ Chem. Rev 2020, 120, 2613. [PubMed: 32064858]

(11). (a)McNally A; Haffemayer B; Collins BSL; Gaunt MJ Nature 2014, 510, 129. [PubMed: 24870240] (b)Smalley AP; Gaunt MJ J. Am. Chem. Soc 2015, 137, 10632. [PubMed: 26247373] (c)Willcox D; Chappell BGN; Hogg KF; Calleja J; Smalley AP; Gaunt MJ Science 2016, 354, 851. [PubMed: 27856900] (d)Smalley AP; Cuthbertson JD; Gaunt MJ J. Am. Chem. Soc 2017, 139, 1412. [PubMed: 28064488] (e)Whitehurst WG; Blackwell JH; Hermann GN; Gaunt MJ Angew. Chem. Int. Ed 2019, 58, 9054.(f)Zhuang Z; Yu J-Q J. Am. Chem. Soc 2020, 142, 12015. [PubMed: 32605367] (g)Calleja J; Pla D; Gorman TW; Domingo V; Haffemayer B; Gaunt MJ Nat. Chem 2015, 7, 1009. [PubMed: 26587717] (h)Cabrera-Pardo JR; Trowbridge A; Nappi M; Ozaki K; Gaunt MJ Angew. Chem. Int. Ed 2017, 56, 11958.(i)Chen K; Wang D; Li Z-W; Liu Z; Pan F; Zhang Y-F; Shi Z-J Org. Chem. Front 2017, 4, 2097.(j)Png ZM; Cabrera-Pardo JR; Peiró Cadahía J; Gaunt MJ Chem. Sci 2018, 9, 7628. [PubMed: 30393523] (k)Lin H; Pan X; Barsamian AL; Kamenecka TM; Bannister TD ACS Catal. 2019, 9, 4887.(l)Rodrigalvarez J; Nappi M; Azuma H; Flodén NJ; Burns ME; Gaunt MJ Nat. Chem 2020, 12, 76. [PubMed: 31863014] (m)He C; Whitehurst WG; Gaunt MJ Chem 2019, 5, 1031.

(12). (a)Li Q; Liskey CW; Hartwig JF J. Am. Chem. Soc 2014, 136, 8755. [PubMed: 24836159] (b)Lee M; Sanford MS J. Am. Chem. Soc 2015, 137, 12796. [PubMed: 26439251] (c)Howell JM; Feng K; Clark JR; Trzepkowski LJ; White MC J. Am. Chem. Soc 2015, 137, 14590. [PubMed: 26536374] (d)Zhao J; Nanjo T; de Lucca EC; White MC Nat. Chem 2019, 11, 213. [PubMed: 30559371] (e)Clark JR; Feng K; Sookezian A; White MC Nat. Chem 2018, 10, 583. [PubMed: 29713037] (f)Oeschger R; Su B; Yu I; Ehinger C; Romero E; He S; Hartwig J Science 2020, 368, 736. [PubMed: 32409470] (g)Su B; Lee T; Hartwig JF J. Am. Chem. Soc 2018, 140, 18032. [PubMed: 30354144] (h)Mack JBC; Gipson JD; Du Bois J; Sigman MS J. Am. Chem. Soc 2017, 139, 9503. [PubMed: 28660763] (i)Mbofana CT; Chong E; Lawniczak J; Sanford MS Org. Lett 2016, 18, 4258. [PubMed: 27529646] (j)Nanjo T; de Lucca EC; White MC J. Am. Chem. Soc 2017, 139, 14586. [PubMed: 28921954] (k)Hartwig JF; Larsen MA ACS Cent. Sci 2016, 2, 281. [PubMed: 27294201] (l)Dalton T; Faber T; Glorius F ACS Cent. Sci 2021, 7, 245. [PubMed: 33655064]

(13). (a)Clerici MG; Maspero F Synthesis 1980, 305.(b)Nugent WA; Ovenall DW; Holmes SJ Organometallics 1983, 2, 161.(c)Herzon SB; Hartwig JF J. Am. Chem. Soc 2007, 129, 6690. [PubMed: 17474747] (d)Herzon SB; Hartwig JF J. Am. Chem. Soc 2008, 130, 14940. [PubMed: 18937477] (e)Kubiak R; Prochnow I; Doye S Angew. Chem. Int. Ed 2009, 48, 1153.(f)Bexrud JA; Eisenberger P; Leitch DC; Payne PR; Schafer LL J. Am. Chem. Soc 2009, 131, 2116. [PubMed: 19173650] (g)Nako AE; Oyamada J; Nishiura M; Hou Z Chem. Sci 2016, 7, 6429. [PubMed: 28451099] (h)Reznichenko AL; Hultzsch KC J. Am. Chem. Soc 2012, 134, 3300. [PubMed: 22264172] (i)Roesky PW Angew. Chem. Int. Ed 2009, 48, 4892.(j)Kruger K; Tillack A; Beller M ChemSusChem 2009, 2, 715. [PubMed: 19672919] (k)Chong E; Garcia P; Schafer L Synthesis 2014, 46, 2884.(l)Hannedouche J; Schulz E Organometallics 2018, 37, 4313.(m)Edwards PM; Schafer LL Chem. Commun 2018, 54, 12543.(n)Eisenberger P; Ayinla RO; Lauzon JM; Schafer LL Angew. Chem. Int. Ed 2009, 48, 8361.(o)Bytschkov I; Doye S Eur. J. Org. Chem 2001, 4411.(p)Ramanathan B; Odom AL J. Am. Chem. Soc 2006, 128, 9344. [PubMed: 16848465] (q)Zi G; Zhang F; Song H Chem. Commun 2010, 46, 6296.(r)Reznichenko AL; Emge TJ; Audörsch S; Klauber EG; Hultzsch KC; Schmidt B Organometallics 2011, 30, 921.(s)Payne PR; Garcia P; Eisenberger P; Yim JC-H; Schafer LL Org. Lett 2013, 15, 2182. [PubMed: 23600625] (t)Luhning LH; Strehl J; Schmidtmann M; Doye S Chem. Eur. J 2017, 23, 4197. [PubMed: 28124797] (u)Geik D; Rosien M; Bielefeld J; Schmidtmann M; Doye S Angew. Chem. Int. Ed 2021, 60, 9936.

(14). (a)Leonard NJ; Hay AS; Fulmer RW; Gash VW J. Am. Chem. Soc 1955, 77, 439.(b)Leonard NJ; Morrow DF J. Am. Chem. Soc 1958, 80, 371.(c)Leonard NJ; Hauck FP J. Am. Chem. Soc 1957, 79, 5279.(d)Van Tamelen EE; Foltz RL J. Am. Chem. Soc 1969, 91, 7372.(e)Gutzwiller J; Pizzolato G; Uskoković M J. Am. Chem. Soc 1971, 93, 5907.(f)Openshaw HT; Whittaker N J. Chem. Soc 1963, 1449.(g)Bartlett MF; Lambert BF; Taylor WI J. Am. Chem. Soc 1964, 86, 729.(h)Barczaibeke M; Dornyei G; Kajtar M; Szantay C Tetrahedron 1976, 32, 1019.(i)Sakai S; Kubo A; Haginiwa J Tetrahedron Lett. 1969, 10, 1485.(j)Butler RN Chem. Rev 1984, 84, 249.

(15). (a)Rosenblatt DH; Moore KA; Streaty RA; Hayes AJ; Harrison BL J. Org. Chem 1963, 28, 2790. (b)Chen CK; Hortmann AG; Marzabadi MR J. Am. Chem. Soc 1988, 110, 4829.(c)Moriarty RM; Vaid RK; Duncan MP; Ochiai M; Inenaga M; Nagao Y Tetrahedron Lett. 1988, 29, 6913.(d)Shen H; Zhang XH; Liu Q; Pan J; Hu W; Xiong Y; Zhu XM Tetrahedron Lett. 2015, 56, 5628.(e)Tsang

ASK; Todd MH Tetrahedron Lett. 2009, 50, 1199.(f)Chu LL; Qing FL Chem. Commun 2010, 46, 6285.(g)Allen JM; Lambert TH J. Am. Chem. Soc 2011, 133, 1260. [PubMed: 21204541] (h)Xie ZY; Liu L; Chen WF; Zheng HB; Xu QQ; Yuan HQ; Lou HX Angew. Chem. Int. Ed 2014, 53, 3904.(i)Richter H; Mancheño OG Eur. J. Org. Chem 2010, 4460.(j)Fang L; Li ZH; Jiang ZJ; Tan ZY; Xie YY Eur. J. Org. Chem 2016, 3559.(k)Zhdankin VV; Kuehl CJ; Krasutsky AP; Bolz JT; Mismash B; Woodward JK; Simonsen AJ Tetrahedron Lett. 1995, 36, 7975.(l)Huang WZ; Ni CF; Zhao YC; Hu JB New J. Chem 2013, 37, 1684.(m)Oss G; de Vos SD; Luc KNH; Harper JB; Nguyen TV J. Org. Chem 2018, 83, 1000. [PubMed: 29231724] (n)Zhang RP; Qin Y; Zhang L; Luo SZ J. Org. Chem 2019, 84, 2542. [PubMed: 30753779] (o)Chen WL; Wang LY; Li YJ Eur. J. Org. Chem 2020, 103.(p)Singh P; Batra A; Singh KN; Mritunjay M Synthesis 2021, 53, 1556.

(16). (a)Murahashi S-I; Imada Y Chem. Rev 2019, 119, 4684. [PubMed: 30875202] (b)Largeron M Eur. J. Org. Chem 2013, 5225.(c)Franck B; Randau D Angew. Chem., Int. Ed. Engl 1966, 5, 131. [PubMed: 4956377] (d)Gupta RN; Spenser ID Can. J. Chem 1969, 47, 445.(e)Claxton GP; Allen L; Grisar JM Org. Synth 1977, 56, 118.(f)Kessler H; Moehrle H; Zimmermann G J. Org. Chem 1977, 42, 66.(g)Nutt RF; Joullie MM J. Am. Chem. Soc 1982, 104, 5852.(h)Davis BG; Maughan MAT; Chapman TM; Villard R; Courtney S Org. Lett 2002, 4, 103. [PubMed: 11772101] (i)Gravel E; Poupon E; Hocquemiller R Tetrahedron 2006, 62, 5248.(j)Gomm A; Lewis W; Green AP; O'Reilly E Chem. Eur. J 2016, 22, 12692. [PubMed: 27411957] (k)Gu R; Flidrova K; Lehn J-M J. Am. Chem. Soc 2018, 140, 5560. [PubMed: 29616806] (l)van der Heijden G; van Schaik TB; Mouarrawis V; de Wit MJM; Velde CMLV; Ruijter E; Orru RVA Eur. J. Org. Chem 2019, 5313.(m)Nomura Y; Ogawa K; Takeuchi Y; Tomoda S Chem. Lett 1977, 693.(n)Ogawa K; Nomura Y; Takeuchi Y; Tomoda S J. Chem. Soc., Perkin Trans 1 1982, 3031.(o)Ochiai M; Inenaga M; Nagao Y; Moriarty RM; Vaid RK; Duncan MP Tetrahedron Lett. 1988, 29, 6917.(p)Boto A; Hernández R; Suárez E Tetrahedron Lett. 1999, 40, 5945.(q)Huang W-J; Singh OV; Chen C-H; Chiou S-Y; Lee S-S Helv. Chim. Acta 2002, 85, 1069.(r)Castedo L; Riguera R; Rodriguez MJ Tetrahedron 1982, 38, 1569.(s)Su F; Mathew SC; Möhlmann L; Antonietti M; Wang X; Blechert S Angew. Chem. Int. Ed 2011, 50, 657.(t)Wendlandt AE; Stahl SS Org. Lett 2012, 14, 2850. [PubMed: 22594886] (u)Chen B; Wang L; Gao S ACS Catal. 2015, 5, 5851.(v)Mitsui H; Zenki S-I; Shiota T; Murahashi S-I J. Chem. Soc., Chem. Commun 1984, 874.(w)Murahashi S; Mitsui H; Shiota T; Tsuda T; Watanabe S J. Org. Chem 1990, 55, 1736.(x)Matassini C; Parmeggiani C; Cardona F; Goti A Org. Lett 2015, 17, 4082. [PubMed: 26225452] (y)Lisnyak VG; Lynch-Colameta T; Snyder SA Angew. Chem. Int. Ed 2018, 57, 15162.

(17). (a)Murahashi S; Naota T; Yonemura K J. Am. Chem. Soc 1988, 110, 8256.(b)Boess E; Wolf LM; Malakar S; Salamone M; Bietti M; Thiel W; Klussmann M ACS Catal. 2016, 6, 3253.(c)Li ZP; Li CJ J. Am. Chem. Soc 2004, 126, 11810. [PubMed: 15382913] (d)Volla CMR; Vogel P Org. Lett 2009, 11, 1701. [PubMed: 19296636] (e)Li ZP; Li CJ J. Am. Chem. Soc 2005, 127, 6968. [PubMed: 15884937] (f)Xie J; Huang ZZ Angew. Chem. Int. Ed 2010, 49, 10181.(g)Xu ZW; Yu XQ; Feng XJ; Bao M J. Org. Chem 2011, 76, 6901. [PubMed: 21761905] (h)Wang YD; Zhu J; Guo R; Lindberg H; Wang YM Chem. Sci 2020, 11, 12316. [PubMed: 34094439] (i)Li CJ Acc. Chem. Res 2009, 42, 335. [PubMed: 19220064] (j)Yeung CS; Dong VM Chem. Rev 2011, 111, 1215. [PubMed: 21391561] (k)Zhang C; Tang CH; Jiao N Chem. Soc. Rev 2012, 41, 3464. [PubMed: 22349590] (l)Girard SA; Knauber T; Li CJ Angew. Chem. Int. Ed 2014, 53, 74.(m)Qin Y; Zhu LH; Luo SZ Chem. Rev 2017, 117, 9433. [PubMed: 28697602] (n)Huang CY; Kang H; Li JB; Li CJ J. Org. Chem 2019, 84, 12705. [PubMed: 31441304] (o)Zhang JS; Liu L; Chen TQ; Han LB ChemSusChem 2020, 13, 4776. [PubMed: 32667732]

(18). (a)Murahashi SI; Komiya N; Terai H; Nakae T J. Am. Chem. Soc 2003, 125, 15312. [PubMed: 14664574] (b)Scott M; Sud A; Boess E; Klussmann M J. Org. Chem 2014, 79, 12033. [PubMed: 25203932] (c)Basle O; Li CJ Green Chem. 2007, 9, 1047.(d)Meng QY; Liu Q; Zhong JJ; Zhang HH; Li ZJ; Chen B; Tung CH; Wu LZ Org. Lett 2012, 14, 5992. [PubMed: 23194402] (e)Alagiri K; Kumara RGS; Prabhu KR Chem. Commun 2011, 47, 11787.(f)Wang TT; Schrempp M; Berndhauser A; Schiemann O; Menche D Org. Lett 2015, 17, 3982. [PubMed: 26252357] (g)Sonobe T; Oisaki K; Kanai M Chem. Sci 2012, 3, 3249.(h)Li X; Zhao H; Chen XW; Jiang HF; Zhang M Org. Chem. Front 2020, 7, 425.(i)Wang FF; Luo CP; Deng GJ; Yang L Green Chem. 2014, 16, 2428.(j)Brzozowski M; Forni JA; Savage GP; Polyzos A Chem. Commun 2015, 51, 334.(k)Sharma K; Borah A; Neog K; Gogoi P ChemistrySelect 2016, 1, 4620.(l)Groll B; Schaaf P; Schnürch M Monatsh. Chem 2017, 148, 91. [PubMed: 28127095] (m)Zhang Y; Wei BW;

Wang WX; Deng LL; Nie LJ; Luo HQ; Fan XL RSC Adv. 2017, 7, 1229.(n)Zhu ZQ; Xiao LJ; Chen Y; Xie ZB; Zhu HB; Le ZG Synthesis 2018, 50, 2775.(o)Ramana DV; Chandrasekharam M Adv. Synth. Catal 2018, 360, 4080.(p)Odachowski M; Greaney MF; Turner NJ ACS Catal. 2018, 8, 10032.(q)Peng K; Dong ZB Adv. Synth. Catal 2021, 363, 1185.(r)Afsina CMA; Aneeja T; Neetha M; Anilkumar G Eur. J. Org. Chem 2021, 1776.

(19). (a)Dominguez E; Lete E J. Heterocycl. Chem 1984, 21, 525.(b)Rao SN; Reddy NNK; Samanta S; Adimurthy S J. Org. Chem 2017, 82, 13632. [PubMed: 29205037] (c)Nobuta T; Tada N; Fujiya A; Kariya A; Miura T; Itoh A Org. Lett 2013, 15, 574. [PubMed: 23331076] (d)Nobuta T; Fujiya A; Yamaguchi T; Tada N; Miura T; Itoh A RSC Adv. 2013, 3, 10189.(e)Huang HM; Li YJ; Ye Q; Yu WB; Han L; Jia JH; Gao JR J. Org. Chem 2014, 79, 1084. [PubMed: 24393026] (f)Kumar RA; Saidulu G; Prasad KR; Kumar GS; Sridhar B; Reddy KR Adv. Synth. Catal 2012, 354, 2985.(g)Li LT; Li HY; Xing LJ; Wen LJ; Wang P; Wang B Org. Biomol. Chem 2012, 10, 9519. [PubMed: 23143045] (h)Liu D; Lei AW Chem. Asian J 2015, 10, 806. [PubMed: 25683644] (i)Deb ML; Borpatra PJ; Saikia PJ; Baruah PK Synlett 2017, 28, 461.(j)Debnath S; Das T; Gayen S; Ghosh T; Maiti DK ACS Omega 2019, 4, 20410. [PubMed: 31815245]

(20). (a)Shu XZ; Yang YF; Xia XF; Ji KG; Liu XY; Liang YM Org. Biomol. Chem 2010, 8, 4077. [PubMed: 20664883] (b)Meng QY; Zhong JJ; Liu Q; Gao XW; Zhang HH; Lei T; Li ZJ; Feng K; Chen B; Tung CH; Wu LZ J. Am. Chem. Soc 2013, 135, 19052. [PubMed: 24160446] (c)Zhong JJ; Meng QY; Liu B; Li XB; Gao XW; Lei T; Wu CJ; Li ZJ; Tung CH; Wu LZ Org. Lett 2014, 16, 1988. [PubMed: 24628016] (d)Gao XW; Meng QY; Li JX; Zhong JJ; Lei T; Li XB; Tung CH; Wu LZ ACS Catal. 2015, 5, 2391.(e)Chen XW; Li YB; Chen L; Zhu ZZ; Li B; Huang YB; Zhang M J. Org. Chem 2019, 84, 3559. [PubMed: 30788969] (f)Niu LB; Wang SC; Liu JM; Yi H; Liang XA; Liu TY; Lei AW Chem. Commun 2018, 54, 1659.(g)Zhou AX; Mao LL; Wang GW; Yang SD Chem. Commun 2014, 50, 8529.(h)Cao L; Zhao H; Tan ZD; Guan RQ; Jiang HF; Zhang M Org. Lett 2020, 22, 4781. [PubMed: 32493014] (i)Sun X; Hu Y; Nie SZ; Yan YY; Zhang XJ; Yan M Adv. Synth. Catal 2013, 355, 2179.(j)Nie SZ; Sun X; Wei WT; Zhang XJ; Yan M; Xiao JL Org. Lett 2013, 15, 2394. [PubMed: 23621093] (k)Sun X; Lv XH; Ye LM; Hu Y; Chen YY; Zhang XJ; Yan M Org. Biomol. Chem 2015, 13, 7381. [PubMed: 26065641] (l)Fu NK; Li LJ; Yang Q; Luo SZ Org. Lett 2017, 19, 2122. [PubMed: 28394132] (m)Khusnutdinova JR; Ben-David Y; Milstein D J. Am. Chem. Soc 2014, 136, 2998. [PubMed: 24521458] (n)He KH; Li Y ChemSusChem 2014, 7, 2788. [PubMed: 25139249] (o)Chen C; Chen X; Zhao H; Jiang H; Zhang M Org. Lett 2017, 19, 3390. [PubMed: 28608699] (p)Chen B; Wu LZ; Tung CH Acc. Chem. Res 2018, 51, 2512. [PubMed: 30280898] (q)Tang S; Zeng L; Lei AW J. Am. Chem. Soc 2018, 140, 13128. [PubMed: 30260638] (r)Wang HM; Gao XL; Lv ZC; Abdelilah T; Lei AW Chem. Rev 2019, 119, 6769. [PubMed: 31074264]

(21). (a)Li ZP; Li CJ Org. Lett 2004, 6, 4997. [PubMed: 15606119] (b)Li ZP; MacLeod PD; Li CJ Tetrahedron: Asymmetry 2006, 17, 590.(c)Zhang G; Ma YX; Wang SL; Kong WD; Wang R Chem. Sci 2013, 4, 2645.(d)Dubs C; Hamashima Y; Sasamoto N; Seidel TM; Suzuki S; Hashizume D; Sodeoka M J. Org. Chem 2008, 73, 5859. [PubMed: 18578499] (e)Zhang JM; Tiwari B; Xing C; Chen XK; Chi YGR Angew. Chem. Int. Ed 2012, 51, 3649.(f)Zhang G; Ma YX; Wang SL; Zhang YH; Wang R J. Am. Chem. Soc 2012, 134, 12334. [PubMed: 22800571] (g)Ma YX; Zhang G; Zhang JL; Yang DX; Wang R Org. Lett 2014, 16, 5358. [PubMed: 25260156] (h)Huang TY; Liu XH; Lang JW; Xu J; Lin LL; Feng XM ACS Catal. 2017, 7, 5654.(i)Zhao YL; Wang Y; Luo YC; Fu XZ; Xu PF Tetrahedron Lett. 2015, 56, 3703.(j)Cheng MX; Yang SD Synlett 2017, 28, 159.(k)Gandhi S Org. Biomol. Chem 2019, 17, 9683. [PubMed: 31710329] (l)Phillips AMF; da Silva M; Pombeiro AJL Catalysts 2020, 10, 529.(m)Rostoll-Berenguer J; Blay G; Pedro JR; Vila C Adv. Synth. Catal 2021, 363, 602.

(22). (a)Schreiber SL Tetrahedron Lett. 1980, 21, 1027.(b)Xu XL; Li XN; Ma L; Ye N; Weng BJ J. Am. Chem. Soc 2008, 130, 14048. [PubMed: 18826314] (c)Wang SJ; Wang ZY; Zheng XQ Chem. Commun 2009, 47, 7372.(d)Shu XZ; Xia XF; Yang YF; Ji KG; Liu XY; Liang YM J. Org. Chem 2009, 74, 7464. [PubMed: 19731925] (e)Xia XF; Shu XZ; Ji KG; Yang YF; Shaukat A; Liu XY; Liang YM J. Org. Chem 2010, 75, 2893. [PubMed: 20345090] (f)Takasu N; Oisaki K; Kanai M Org. Lett 2013, 15, 1918. [PubMed: 23578034] (g)Griffiths RJ; Kong WC; Richards SA; Burley GA; Willis MC; Talbot EPA Chem. Sci 2018, 9, 2295. [PubMed: 29719703] (h)He Y; Yang JT; Liu QM; Zhang XY; Fan XS J. Org. Chem 2020, 85, 15600. [PubMed: 33180489] (i)Rong XN; Guo JW; Hu ZQ; Huang LH; Gu YG; Cai YP; Liang G; Xia QQ Eur. J. Org. Chem 2021, 701.(j)Wang F; Zhang XY; He Y; Fan XS J. Org. Chem 2020, 85,

2220. [PubMed: 31880446] (k)Jiang F; Achard M; Bruneau C Chem. Eur. J 2015, 21, 14319. [PubMed: 26385286] (l)Cai YG; Zhang RH; Sun DL; Xu S; Zhou QG Synlett 2017, 28, 1630. (m)Zhou MJ; Zhu SF; Zhou QL Chem. Commun 2017, 53, 8770.(n)He Y; Wang F; Zhang XY; Fan XS Chem. Commun 2017, 53, 4002.(o)Liu GQ; Opatz T Adv. Heterocycl. Chem 2018, 125, 107.(p)Shi XN; Chen X; Wang MH; Zhang XY; Fan XS J. Org. Chem 2018, 83, 6524. [PubMed: 29756782] (q)He Y; Zheng Z; Liu YJ; Qiao JJ; Zhang XY; Fan XS Chem. Commun 2019, 55, 12372.(r)He KX; Zhang T; Zhang SW; Sun Z; Zhang YX; Yuan Y; Jia XD Org. Lett 2019, 21, 5030. [PubMed: 31247738]

(23). (a)Konstantinova LS; Rakitin OA; Rees CW Chem. Rev 2004, 104, 2617. [PubMed: 15137802] (b)Rakitin OA Chem. Heterocycl. Compd. (Engl. Transl.) 2020, 56, 837.(c)Rees CW; Marcos CF; Polo C; Torroba T; Rakitin OA Angew. Chem., Int. Ed. Engl 1997, 36, 281.(d)Marcos CF; Polo C; Rakitin OA; Rees CW; Torroba T Chem. Commun 1997, 879.(e)Rees CW; White AJP; Williams DJ; Rakitin OA; Marcos CF; Polo C; Torroba T J. Org. Chem 1998, 63, 2189. (f)Konstantinova LS; Obruchnikova NV; Rakitin OA; Rees CW; Torroba T J. Chem. Soc., Perkin Trans 1 2000, 3421.(g)Barriga S; Konstantinova SL; Marcos FC; Rakitin AO; Rees WC; Torroba T; White JPA; Williams JD J. Chem. Soc., Perkin Trans 1 1999, 2237.(h)Konstantinova LS; Berezin AA; Lysov KA; Rakitin OA Russ. Chem. Bull., Int. Ed 2006, 55, 147.(i)Amelichev SA; Konstantinova LS; Lyssenko KA; Rakitin OA; Rees CW Org. Biomol. Chem 2005, 3, 3496. [PubMed: 16172686] (j)Konstantinova LS; Amelichev SA; Rakitin OA Russ. Chem. Bull., Int. Ed 2006, 55, 2081.(k)Konstantinova LS; Rakitin OA; Rees CW; Souvorova LI; Golovanov DG; Lyssenko KA Org. Lett 2003, 5, 1939. [PubMed: 12762691] (l)Konstantinova LS; Bastrakov MA; Starosotnikov AM; Glukhov IV; Lysov KA; Rakitin OA; Shevelev SA Mendeleev Commun. 2010, 20, 353.

(24). (a)Lounasmaa M; Koskinen A Heterocycles 1984, 22, 1591.(b)Grierson D Org. React 1990, 39, 85.(c)Langlois N; Gueritte F; Langlois Y; Potier P J. Am. Chem. Soc 1976, 98, 7017. [PubMed: 965661] (d)Han-ya Y; Tokuyama H; Fukuyama T Angew. Chem. Int. Ed 2011, 50, 4884.(e)Ahond A; Cave A; Kan-Fan C; Husson HP; De Rostolan J; Potier P J. Am. Chem. Soc 1968, 90, 5622.(f)Aimi N; Yamanaka E; Endo J; Sakai S; Haginiwa J Tetrahedron 1973, 29, 2015.(g)Kende AS; Liu K; Jos Brands KM J. Am. Chem. Soc 1995, 117, 10597.(h)Wenkert E; Chauncy B; Wentland SH Synth. Commun 1973, 3, 73.(i)Beugelmans R; Negron G; Roussi G J. Chem. Soc., Chem. Commun 1983, 31.(j)Chastanet J; Roussi G Heterocycles 1985, 23, 653.(k)Chastanet J; Roussi G J. Org. Chem 1985, 50, 2910.(l)Chastanet J; Roussi G J. Org. Chem 1988, 53, 3808.(m)Davoren JE; Gray DL; Harris AR; Nason DM; Xu W Synlett 2010, 2490. (n)Takano S; Sugihara Y; Ogasawara K Heterocycles 1992, 34, 1519.(o)Mirzayans PM; Krenske EH; Williams CM Aust. J. Chem 2014, 67, 1309.(p)Bernier D; Wefelscheid UK; Woodward S Org. Prep. Proced. Int 2009, 41, 173.(q)Cui L; Peng Y; Zhang L J. Am. Chem. Soc 2009, 131, 8394. [PubMed: 19492799] (r)Cui L; Ye L; Zhang L Chem. Commun 2010, 46, 3351.(s)Noey EL; Luo YD; Zhang LM; Houk KN J. Am. Chem. Soc 2012, 134, 1078. [PubMed: 22191473]

(25). (a)Nishiguchi T; Tachi K; Fukuzumi K J. Org. Chem 1975, 40, 237.(b)Yoshida T; Okano T; Otsuka S J. Chem. Soc., Chem. Commun 1979, 870.(c)Murahashi SI; Naota T; Taki H J. Chem. Soc., Chem. Commun 1985, 613.(d)Gu XQ; Chen W; Morales-Morales D; Jensen CM J. Mol. Catal. A: Chem 2002, 189, 119.(e)Zhang XW; Fried A; Knapp S; Goldman AS Chem. Commun 2003, 2060.(f)Kamiguchi S; Nakamura A; Suzuki A; Kodomari M; Nomura M; Iwasawa Y; Chihara T J. Catal 2005, 230, 204.(g)Yi CS; Lee DW Organometallics 2009, 28, 947. [PubMed: 20119477] (h)Wang ZH; Tonks I; Belli J; Jensen CM J. Organomet. Chem 2009, 694, 2854.(i)Brayton DF; Jensen CM Chem. Commun 2014, 50, 5987.(j)Lu YSJ; Zhang XW; Malakar S; Krogh-Jespersen K; Hasanayn F; Goldman AS J. Org. Chem 2020, 85, 3020. [PubMed: 31990556] (k)Wang YL; Qian L; Huang ZD; Liu GX; Huang Z Chin. J. Chem 2020, 38, 837.(l)Fujita K; Tanaka Y; Kobayashi M; Yamaguchi R J. Am. Chem. Soc 2014, 136, 4829. [PubMed: 24660903] (m)Yamaguchi R; Ikeda C; Takahashi Y; Fujita K J. Am. Chem. Soc 2009, 131, 8410. [PubMed: 19480425] (n)Wu JJ; Talwar D; Johnston S; Yan M; Xiao JL Angew. Chem. Int. Ed 2013, 52, 6983.(o)Talwar D; Gonzalez-de-Castro A; Li HY; Xiao JL Angew. Chem. Int. Ed 2015, 54, 5223.(p)Manas MG; Sharninghausen LS; Lin E; Crabtree RH J. Organomet. Chem 2015, 792, 184.(q)Zhang DL; Iwai T; Sawamura M Org. Lett 2020, 22, 5240. [PubMed: 32610931] (r)Tseng KNT; Rizzi AM; Szymczak NK J. Am. Chem. Soc 2013, 135, 16352. [PubMed: 24144014] (s)Hale LVA; Malakar T; Tseng KNT; Zimmerman PM; Paul A; Szymczak NK ACS Catal. 2016, 6, 4799.(t)Muthaiah S; Hong SH Adv. Synth. Catal 2012,

354, 3045.(u)Dutta I; Yadav S; Sarbajna A; De S; Holscher M; Leitner W; Bera JK J. Am. Chem. Soc 2018, 140, 8662. [PubMed: 29956921] (v)Wang QF; Chai HN; Yu ZK Organometallics 2018, 37, 584.(w)Stubbs JM; Hazlehurst RJ; Boyle PD; Blacquiere JM Organometallics 2017, 36, 1692.(x)Kojima M; Kanai M Angew. Chem. Int. Ed 2016, 55, 12224.(y)Maier AFG; Tussing S; Schneider T; Florke U; Qu ZW; Grimme S; Paradies J Angew. Chem. Int. Ed 2016, 55, 12219.(z)Wu Y; Yi H; Lei AW ACS Catal. 2018, 8, 1192.(aa)Chen WD; Tang H; Wang WL; Fu Q; Luo JF Adv. Synth. Catal 2020, 362, 3905.(ab)Yang RC; Yue SS; Tan W; Xie YF; Cai H J. Org. Chem 2020, 85, 7501. [PubMed: 32368910] (ac)Huang YQ; Song HJ; Liu YX; Wang QM Chem. Eur. J 2018, 24, 2065. [PubMed: 29210122] (ad)Liu TT; Wu KK; Wang LD; Yu ZK Adv. Synth. Catal 2019, 361, 3958.(ae)Kato S; Saga Y; Kojima M; Fuse H; Matsunaga S; Fukatsu A; Kondo M; Masaoka S; Kanai M J. Am. Chem. Soc 2017, 139, 2204. [PubMed: 28139917] (af)Kim J; Kim S; Choi G; Lee GS; Kim D; Choi J; Ihee H; Hong SH Chem. Sci 2021, 12, 1915.(ag)He KH; Tan FF; Zhou CZ; Zhou GJ; Yang XL; Li Y Angew. Chem. Int. Ed 2017, 56, 3080.(ah)Chakraborty S; Brennessel WW; Jones WD J. Am. Chem. Soc 2014, 136, 8564. [PubMed: 24877556] (ai)Bolig AD; Brookhart M J. Am. Chem. Soc 2007, 129, 14544. [PubMed: 17985901]

(26). (a)Grigg R; Mitchell TRB; Sutthivaiyakit S; Tongpenyai N J. Chem. Soc., Chem. Commun 1981, 611.(b)Sundararaju B; Tang Z; Achard M; Sharma GVM; Toupet L; Bruneau C Adv. Synth. Catal 2010, 352, 3141.(c)Sundararaju B; Achard M; Sharma GVM; Bruneau C J. Am. Chem. Soc 2011, 133, 10340. [PubMed: 21671630] (d)Boudiar T; Sahli Z; Sundararaju B; Achard M; Kabouche Z; Doucet H; Bruneau C J. Org. Chem 2012, 77, 3674. [PubMed: 22420762] (e)Murugesh V; Bruneau C; Achard M; Sahoo AR; Sharma GVM; Suresh S Chem. Commun 2017, 53, 10448.(f)Murugesh V; Sahoo AR; Achard M; Sharma GVM; Bruneau C; Suresh S Adv. Synth. Catal 2021, 363, 453.(g)Chen Y; Wan HL; Huang Y; Liu S; Wang FY; Lu CF; Nie JQ; Chen ZX; Yang GC; Ma C Org. Lett 2020, 22, 7797. [PubMed: 32990447] (h)Yuan KD; Jiang F; Sahli Z; Achard M; Roisnel T; Bruneau C Angew. Chem. Int. Ed 2012, 51, 8876. (i)Sahli Z; Sundararaju B; Achard M; Bruneau C Green Chem. 2013, 15, 775.(j)Bruneau C. Top. Organomet. Chem 2014, 48, 195.(k)Irrgang T; Kempe R Chem. Rev 2019, 119, 2524. [PubMed: 30457320]

(27). (a)Rügheimer L Ber. Dtsch. Chem. Ges 1891, 24, 2186.(b)Rügheimer L Ber. Dtsch. Chem. Ges 1892, 25, 2421.(c)Poirier RH; Morin RD; McKim AM; Bearse AE J. Org. Chem 1961, 26, 4275. (d)Platonova AY; Seidel D Tetrahedron Lett. 2015, 56, 3147. [PubMed: 26207074] (e)Burrows EP; Hutton RF; Burrows WD J. Org. Chem 1962, 27, 316.(f)Sainsbury M; Dyke SF; Brown DW; Lugton WGD Tetrahedron 1968, 24, 427.(g)Dannhardt G; Mayer KK; Obergrusberger I; Roelcke J Arch. Pharm.(Weinheim Ger.) 1986, 319, 977.(h)Cook AG; Switek KA; Cutler KA; Witt AN Lett. Org. Chem 2004, 1, 1.(i)Polackova V; Veverkova E; Toma S; Bogdal D Synth. Commun 2009, 39, 1871.(j)Xue X; Yu A; Cai Y; Cheng J-P Org. Lett 2011, 13, 6054. [PubMed: 22014326] (k)Moura NMM; Nunez C; Santos SM; Faustino MAF; Cavaleiro JAS; Paz FAA; Neves M; Capelo JL; Lodeiro C Chem. Eur. J 2014, 20, 6684. [PubMed: 24782336] (l)Burrows WD; Burrows EP J. Org. Chem 1963, 28, 1180.(m)Oda M; Fukuchi Y; Ito S; Thanh NC; Kuroda S Tetrahedron Lett. 2007, 48, 9159.(n)Pahadi NK; Paley M; Jana R; Waetzig SR; Tunge JA J. Am. Chem. Soc 2009, 131, 16626. [PubMed: 19886656] (o)Mao H; Xu R; Wan J; Jiang Z; Sun C; Pan Y Chem. Eur. J 2010, 16, 13352. [PubMed: 21053212] (p)Deb I; Das D; Seidel D Org. Lett 2011, 13, 812. [PubMed: 21247142] (q)Ma L; Paul A; Breugst M; Seidel D Chem. Eur. J 2016, 22, 18179. [PubMed: 27712000]

(28). (a)Ardill H; Grigg R; Sridharan V; Surendrakumar S; Thianpatanagul S; Kanajun S J. Chem. Soc., Chem. Commun 1986, 602.(b)Grigg R; Gunaratne HQN; Henderson D; Sridharan V Tetrahedron 1990, 46, 1599.(c)Ardill H; Fontaine XLR; Grigg R; Henderson D; Montgomery J; Sridharan V; Surendrakumar S Tetrahedron 1990, 46, 6449.(d)Mantelingu K; Lin Y; Seidel D Org. Lett 2014, 16, 5910. [PubMed: 25413125] (e)Rahman M; Bagdi AK; Mishra S; Hajra A Chem. Commun 2014, 50, 2951.(f)Deb I; Seidel D Tetrahedron Lett. 2010, 51, 2945.(g)Kang Y; Richers MT; Sawicki CH; Seidel D Chem. Commun 2015, 51, 10648.(h)Cheng Y-F; Rong H-J; Yi C-B; Yao J-J; Qu J Org. Lett 2015, 17, 4758. [PubMed: 26378343] (i)Vasu D; Fuentes de Arriba AL; Leitch JA; de Gombert A; Dixon DJ Chem. Sci 2019, 10, 3401. [PubMed: 30996928] (j)Wittland C; Arend M; Risch N Synthesis 1996, 367.(k)Yang H-T; Tan Y-C; Ge J; Wu H; Li J-X; Yang Y; Sun XQ; Miao C-B J. Org. Chem 2016, 81, 11201. [PubMed: 27766870] (l)Zheng

K; Zhuang S; You M; Shu W; Wu A; Wu Y ChemistrySelect 2017, 2, 10762.(m)Strada A; Fredditori M; Zanoni G; Protti S Molecules 2019, 24, 1318.

(29). (a)Ma L; Chen W; Seidel D J. Am. Chem. Soc 2012, 134, 15305. [PubMed: 22963652] (b)Das D; Sun AX; Seidel D Angew. Chem. Int. Ed 2013, 52, 3765.(c)Zheng Q-H; Meng W; Jiang G-J; Yu Z-X Org. Lett 2013, 15, 5928. [PubMed: 24237286] (d)Lin W; Cao T; Fan W; Han Y; Kuang J; Luo H; Miao B; Tang X; Yu Q; Yuan W; Zhang J; Zhu C; Ma S Angew. Chem. Int. Ed 2014, 53, 277.(e)Lin W; Ma S Org. Chem. Front 2014, 1, 338.(f)Chen W; Wilde RG; Seidel D Org. Lett 2014, 16, 730. [PubMed: 24328366] (g)Haldar S; Mahato S; Jana CK Asian J. Org. Chem 2014, 3, 44.(h)Chen W; Kang Y; Wilde RG; Seidel D Angew. Chem. Int. Ed 2014, 53, 5179.(i)Zheng K-L; Shu W-M; Ma J-R; Wu Y-D; Wu A-X Org. Lett 2016, 18, 3526. [PubMed: 27396906] (j)Mandal S; Dwari S; Jana CK J. Org. Chem 2018, 83, 8874. [PubMed: 30025457] (k)Chen W; Seidel D Org. Lett 2014, 16, 3158. [PubMed: 24857691] (l)Zhu Z; Seidel D Org. Lett 2016, 18, 631. [PubMed: 26785064] (m)Yan J-M; Bai Q-F; Xu C; Feng G Synthesis 2016, 48, 3730.(n)Haldar S; Saha S; Mandal S; Jana CK Green Chem. 2018, 20, 3463.(o)Jiang D; Wu Z; Wang J Chin. J. Chem 2020, 38, 135.(p)Seidel D Org. Chem. Front 2014, 1, 426. [PubMed: 24955245] (q)Seidel D Acc. Chem. Res 2015, 48, 317. [PubMed: 25560649] (r)Mahato S; Jana CK Chem. Rec 2016, 16, 1477. [PubMed: 27185195] (s)Das D; Seidel D Org. Lett 2013, 15, 4358. [PubMed: 23957378] (t)Mandal S; Mahato S; Jana CK Org. Lett 2015, 17, 3762. [PubMed: 26204435] (u)Zhou S; Tong R Chem. Eur. J 2016, 22, 7084. [PubMed: 26990887] (v)Huang J; Li L; Xiao T; Mao Z.-w.; Zhou L Asian J. Org. Chem 2016, 5, 1204.(w)Du Y; Yu A; Jia J; Zhang Y; Meng X Chem. Commun 2017, 53, 1684.(x)Yi C-B; She Z-Y; Cheng Y-F; Qu J Org. Lett 2018, 20, 668. [PubMed: 29363983] (y)Haldar S; Jana CK Org. Biomol. Chem 2019, 17, 1800. [PubMed: 30516776] (z)Rahman I; Deka B; Thakuria R; Deb ML; Baruah PK Org. Biomol. Chem 2020, 18, 6514. [PubMed: 32804185]

(30). (a)Zhang C; De C K; Mal R; Seidel D J. Am. Chem. Soc 2008, 130, 416. [PubMed: 18081292] (b)Dieckmann A; Richers MT; Platonova AY; Zhang C; Seidel D; Houk KN J. Org. Chem 2013, 78, 4132. [PubMed: 23517448] (c)Richers MT; Deb I; Platonova AY; Zhang C; Seidel D Synthesis 2013, 45, 1730.(d)Zheng L; Yang F; Dang Q; Bai X Org. Lett 2008, 10, 889. [PubMed: 18260668] (e)Richers MT; Breugst M; Platonova AY; Ullrich A; Dieckmann A; Houk KN; Seidel D J. Am. Chem. Soc 2014, 136, 6123. [PubMed: 24689802] (f)Jarvis CL; Richers MT; Breugst M; Houk KN; Seidel D Org. Lett 2014, 16, 3556. [PubMed: 24927364] (g)Mahato S; Haque MA; Dwari S; Jana CK RSC Adv. 2014, 4, 46214.(h)Kirkeby EK; Roberts AG Chem. Commun 2020, 56, 9118.(i)Zhang C; Das D; Seidel D Chem. Sci 2011, 2, 233.(j)Ma L; Seidel D Chem. Eur. J 2015, 21, 12908. [PubMed: 26220197] (k)Kang Y; Chen W; Breugst M; Seidel D J. Org. Chem 2015, 80, 9628. [PubMed: 26348653] (l)Chen W; Seidel D Org. Lett 2016, 18, 1024. [PubMed: 26895555] (m)Zhu Z; Seidel D Org. Lett 2017, 19, 2841. [PubMed: 28510444] (n)Li J; Qin C; Yu Y; Fan H; Fu Y; Li H; Wang W Adv. Synth. Catal 2017, 359, 2191.(o)Li J; Fu Y; Qin C; Yu Y; Li H; Wang W Org. Biomol. Chem 2017, 15, 6474. [PubMed: 28737793] (p)Zhu Z; Chandak HS; Seidel D Org. Lett 2018, 20, 4090. [PubMed: 29939750] (q)Paul A; Chandak HS; Ma L; Seidel D Org. Lett 2020, 22, 976. [PubMed: 31984752] (r)Rickertsen DRL; Ma L; Paul A; Abboud KA; Seidel D SynOpen 2020, 4, 123. [PubMed: 34327302] (s)Zhu Z; Lv X; Anesini JE; Seidel D Org. Lett 2017, 19, 6424. [PubMed: 29144764] (t)Liu Y; Wu J; Jin Z; Jiang H Synlett 2018, 29, 1061.(u)Afanasyev OI; Podyacheva E; Rudenko A; Tsygankov AA; Makarova M; Chusov D J. Org. Chem 2020, 85, 9347. [PubMed: 32515592]

(31). (a)Pinnow J Ber. Dtsch. Chem. Ges 1895, 28, 3039.(b)Ruiz MDR; Vasella A Helv. Chim. Acta 2011, 94, 785.(c)Meth-Cohn O; Naqui MA Chem. Commun 1967, 1157.(d)Ryabukhin SV; Plaskon AS; Volochnyuk DM; Shivanyuk AN; Tolmachev AA J. Org. Chem 2007, 72, 7417. [PubMed: 17715977] (e)Verboom W; Reinhoudt DN; Visser R; Harkema S J. Org. Chem 1984, 49, 269.(f)Nijhuis WHN; Verboom W; Abu El-Fadl A; Harkema S; Reinhoudt DN J. Org. Chem 1989, 54, 199.(g)Nijhuis WHN; Verboom W; Abu El-Fadl A; Van Hummel GJ; Reinhoudt DN J. Org. Chem 1989, 54, 209.(h)Verboom W; Hamzink MRJ; Reinhoudt DN; Visser R Tetrahedron Lett. 1984, 25, 4309.(i)Noguchi M; Yamada H; Sunagawa T J. Chem. Soc., Perkin Trans 1 1998, 3327.(j)Reinhoudt DN; Visser GW; Verboom W; Benders PH; Pennings MLM. J. Am. Chem. Soc 1983, 105, 4775.(k)Jiang S; Janousek Z; Viehe HG Tetrahedron Lett. 1994, 35, 1185.(l)Jiang S; Janousek Z; Viehe HG Bull. Soc. Chim. Belg 1993, 102, 663.(m)De Boeck B; Janousek Z; Viehe HG Tetrahedron 1995, 51, 13239.(n)Polonka-Balint A; Saraceno C; Ludányi K; Bényei A; Matyus P Synlett 2008, 2846.(o)Foldi AA; Ludanyi K; Benyei AC;

Matyus P Synlett 2010, 2109.(p)Barluenga J; Fananas-Mastral M; Aznar F; Valdes C Angew. Chem. Int. Ed 2008, 47, 6594.(q)Meth-Cohn O; Suschitzky H Adv. Heterocycl. Chem 1972, 14, 211.(r)Meth-Cohn O Adv. Heterocycl. Chem 1996, 65, 1.(s)Matyus P; Elias O; Tapolcsanyi P; Polonka-Balint A; Halasz-Dajka B Synthesis 2006, 2625.(t)Platonova AY; Glukhareva TV; Zimovets OA; Morzherin YY Chem. Heterocycl. Compd. (Engl. Transl.) 2013, 49, 357.

(32). (a)Peng B; Maulide N Chem. Eur. J 2013, 19, 13274. [PubMed: 24027042] (b)Haibach MC; Seidel D Angew. Chem. Int. Ed 2014, 53, 5010.(c)Kwon SJ; Kim DY Chem. Rec 2016, 16, 1191. [PubMed: 27062480] (d)An X-D; Xiao J Org. Chem. Front 2021, 8, 1364.(e)Zhang C; Murarka S; Seidel DJ Org. Chem 2009, 74, 419.(f)Mori K; Ohshima Y; Ehara K; Akiyama T Chem. Lett 2009, 38, 524.(g)Murarka S; Zhang C; Konieczynska MD; Seidel D Org. Lett 2009, 11, 129. [PubMed: 19067554] (h)Zhou G; Zhang J Chem. Commun 2010, 46, 6593.(i)Jurberg ID; Peng B; Woestefeld E; Wasserloos M; Maulide N Angew. Chem. Int. Ed 2012, 51, 1950.(j)Haibach MC; Deb I; De C K; Seidel D J. Am. Chem. Soc 2011, 133, 2100. [PubMed: 21280625] (k)Wang P-F; Huang Y-P; Wen X; Sun H; Xu Q-L Eur. J. Org. Chem 2015, 6727.(l)Wang P-F; Jiang C-H; Wen X; Xu Q-L; Sun H J. Org. Chem 2015, 80, 1155. [PubMed: 25543720] (m)Li S-S; Zhou L; Wang L; Zhao H; Yu L; Xiao J Org. Lett 2018, 20, 138. [PubMed: 29239184] (n)Liu S; Qu J; Wang B Chem. Commun 2018, 54, 7928.(o)Bai G; Dong F; Xu L; Liu Y; Wang L; Li S-S Org. Lett 2019, 21, 6225. [PubMed: 31361504] (p)Wang S; Shen Y-B; Li L-F; Qiu B; Yu L; Liu Q; Xiao J Org. Lett 2019, 21, 8904. [PubMed: 31697087] (q)An X-D; Duan K; Li X-J; Yang J-M; Lu Y-N; Liu Q; Xiao J J. Org. Chem 2019, 84, 11839. [PubMed: 31433189] (r)Suh CW; Kwon SJ; Kim DY Org. Lett 2017, 19, 1334. [PubMed: 28234485] (s)Li S-S; Lv X; Ren D; Shao C-L; Liu Q; Xiao J Chem. Sci 2018, 9, 8253. [PubMed: 30542574] (t)Lv X; Hu F; Duan K; Li S-S; Liu Q; Xiao J J. Org. Chem 2019, 84, 1833. [PubMed: 30608677] (u)Shen Y-B; Li L-F; Xiao M-Y; Yang J-M; Liu Q; Xiao J J. Org. Chem 2019, 84, 13935. [PubMed: 31533423] (v)Mori K; Kurihara K; Yabe S; Yamanaka M; Akiyama T J. Am. Chem. Soc 2014, 136, 3744. [PubMed: 24564435]

(33). (a)Murarka S; Deb I; Zhang C; Seidel D J. Am. Chem. Soc 2009, 131, 13226. [PubMed: 19711900] (b)Kang YK; Kim SM; Kim DY J. Am. Chem. Soc 2010, 132, 11847. [PubMed: 20701277] (c)Kang YK; Kim DY Adv. Synth. Catal 2013, 355, 3131.(d)Kang YK; Kim DY Chem. Commun 2014, 50, 222.(e)Suh CW; Kim DY Org. Lett 2014, 16, 5374. [PubMed: 25280134] (f)Zhou G; Liu F; Zhang J Chem. Eur. J 2011, 17, 3101. [PubMed: 21328507] (g)Mori K; Ehara K; Kurihara K; Akiyama T J. Am. Chem. Soc 2011, 133, 6166. [PubMed: 21466211] (h)Cao W; Liu X; Wang W; Lin L; Feng X Org. Lett 2011, 13, 600. [PubMed: 21218793] (i)Lv J; Luo S Chem. Commun 2013, 49, 847.(j)He Y-P; Du Y-L; Luo S-W; Gong L-Z Tetrahedron Lett. 2011, 52, 7064.(k)Mori K; Isogai R; Kamei Y; Yamanaka M; Akiyama T J. Am. Chem. Soc 2018, 140, 6203. [PubMed: 29741877] (l)Wang M ChemCatChem 2013, 5, 1291.(m)Xiao M; Zhu S; Shen Y; Wang L; Xiao J Chin. J. Org. Chem 2018, 38, 328.(n)Cao W; Liu X; Guo J; Lin L; Feng X Chem. Eur. J 2015, 21, 1632. [PubMed: 25421053] (o)He Y-P; Wu H; Chen D-F; Yu J; Gong L-Z Chem. Eur. J 2013, 19, 5232. [PubMed: 23512426] (p)Mao Z; Mo F; Lin X Synlett 2016, 27, 546.(q)Du H-J; Lin C; Wen X; Xu Q-L Tetrahedron 2018, 74, 7480.

(34). (a)Ten Broeke J; Douglas AW; Grabowski EJJ J. Org. Chem 1976, 41, 3159.(b)Heathcock CH; Hansen MM; Ruggeri RB; Kath JC J. Org. Chem 1992, 57, 2544.(c)Heathcock CH Proc. Natl. Acad. Sci. U.S.A 1996, 93, 14323. [PubMed: 8962049] (d)Tantillo D. J. Org. Lett 2016, 18, 4482.(e)Pastine SJ; McQuaid KM; Sames D J. Am. Chem. Soc 2005, 127, 12180. [PubMed: 16131169] (f)Vadola PA; Sames D J. Am. Chem. Soc 2009, 131, 16525. [PubMed: 19852462] (g)Sugiishi T; Nakamura H J. Am. Chem. Soc 2012, 134, 2504. [PubMed: 22283631] (h)Cui Y; Lin W; Ma S Chem. Sci 2019, 10, 1796. [PubMed: 30842847] (i)Huang Y-W; Frontier AJ Org. Lett 2016, 18, 4896. [PubMed: 27652822] (j)Lecomte M; Evano G Angew. Chem. Int. Ed 2016, 55, 4547.(k)Machida M; Mori K Chem. Lett 2018, 47, 868.(l)Zhang X; Anderson JC Angew. Chem. Int. Ed 2019, 58, 18040.(m)Kataoka M; Otawa Y; Ido N; Mori K Org. Lett 2019, 21, 9334. [PubMed: 31710232] (n)Ye J; Ma S Org. Chem. Front 2014, 1, 1210.

(35). (a)Shang M; Chan JZ; Cao M; Chang Y; Wang Q; Cook B; Torker S; Wasa M J. Am. Chem. Soc 2018, 140, 10593. [PubMed: 30045617] (b)Millot N; Santini CC; Fenet B; Basset JM Eur. J. Inorg. Chem 2002, 3328.(c)Chen G-Q; Kehr G; Daniliuc CG; Bursch M; Grimme S; Erker G Chem. Eur. J 2017, 23, 4723. [PubMed: 28164392] (d)Zhang J; Park S; Chang S J. Am. Chem. Soc 2018, 140, 13209. [PubMed: 30269485] (e)Zhou M; Park S; Dang L Org. Chem. Front 2020, 7, 944.(f)Chang Y; Cao M; Chan JZ; Zhao C; Wang Y; Yang R; Wasa M J. Am. Chem. Soc 2021,

143, 2441. [PubMed: 33512998] (g)Chan JZ; Yesilcimen A; Cao M; Zhang Y; Zhang B; Wasa M J. Am. Chem. Soc 2020, 142, 16493. [PubMed: 32830966] (h)Chan JZ; Chang Y; Wasa M Org. Lett 2019, 21, 984. [PubMed: 30693779] (i)Li R; Chen Y; Jiang K; Wang F; Lu C; Nie J; Chen Z; Yang G; Chen Y-C; Zhao Y; Ma C Chem. Commun 2019, 55, 1217.(j)Maier AFG; Tussing S; Zhu H; Wicker G; Tzvetkova P; Flörke U; Daniliuc CG; Grimme S; Paradies J Chem. Eur. J 2018, 24, 16287. [PubMed: 30230618] (k)Tian J-J; Zeng N-N; Liu N; Tu X-S; Wang X-C ACS Catal. 2019, 9, 295.(l)Fang H; Xie K; Kemper S; Oestreich M Angew. Chem. Int. Ed 2021, 60, 8542.(m)Zhou L; Shen Y-B; An X-D; Li X-J; Li S-S; Liu Q; Xiao J Org. Lett 2019, 21, 8543. [PubMed: 31633932] (n)Chang Y; Yesilcimen A; Cao M; Zhang Y; Zhang B; Chan JZ; Wasa M J. Am. Chem. Soc 2019, 141, 14570. [PubMed: 31480842] (o)Zhou L; An X-D; Yang S; Li X-J; Shao C-L; Liu Q; Xiao J Org. Lett 2020, 22, 776. [PubMed: 31965804] (p)Ma Y; Lou S-J; Hou Z Chem. Soc. Rev 2021, 50, 1945. [PubMed: 33325932] (q)Basak S; Winfrey L; Kustiana BA; Melen RL; Morrill LC; Pulis AP Chem. Soc. Rev 2021, 50, 3720. [PubMed: 33533343]

(36). (a)Fandrick DR; Hart CA; Okafor IS; Mercadante MA; Sanyal S; Masters JT; Sarvestani M; Fandrick KR; Stockdill JL; Grinberg N; Gonnella N; Lee H; Senanayake CH Org. Lett 2016, 18, 6192. [PubMed: 27934338] (b)Wittig G; Schmidt HJ; Renner H Chem. Ber 1962, 95, 2377. (c)Wittig G; Hesse A Liebigs Ann. Chem 1971, 746, 174.(d)Wittig G; Häusler G Liebigs Ann. Chem 1971, 746, 185.(e)Chen W; Ma L; Paul A; Seidel D Nat. Chem 2018, 10, 165. [PubMed: 29359746] (f)Chen W; Paul A; Abboud KA; Seidel D Nat. Chem 2020, 12, 545. [PubMed: 32231260] (g)Majewski M; Gleave DM J. Organomet. Chem 1994, 470, 1.(h)Scully FE J. Org. Chem 1980, 45, 1515.(i)Paul A; Seidel D J. Am. Chem. Soc 2019, 141, 8778. [PubMed: 31117670] (j)Kim JH; Paul A; Ghiviriga I; Seidel D Org. Lett 2021, 23, 797. [PubMed: 33464093] (k)Chen W; Seidel D Org. Lett 2021, 23, 3729. [PubMed: 33881883] (l)Paul A; Kim JH; Daniel SD; Seidel D Angew. Chem. Int. Ed 2021, 60, 1625.(m)Shen Z; Walker MM; Chen S; Parada GA; Chu DM; Dongbang S; Mayer JM; Houk KN; Ellman JA J. Am. Chem. Soc 2021, 143, 126. [PubMed: 33373212]

(37). (a)Corey EJ; Felix AM J. Am. Chem. Soc 1965, 87, 2518. [PubMed: 14327161] (b)Earle RH; Hurst DT; Viney M J. Chem. Soc. C 1969, 2093.(c)Axten JM; Krim L; Kung HF; Winkler JD J. Org. Chem 1998, 63, 9628.(d)Garner R Tetrahedron Lett. 1968, 9, 221.(e)Krogsgaard-Larsen N; Begtrup M; Herth MM; Kehler J Synthesis 2010, 4287.(f)Mahoney SJ; Fillion E Chem. Eur. J 2012, 18, 68. [PubMed: 22161978] (g)Doyle MP; Protopopova MN; Winchester WR; Daniel KL Tetrahedron Lett. 1992, 33, 7819.(h)Doyle MP; Winchester WR; Hoorn JAA; Lynch V; Simonsen SH; Ghosh R J. Am. Chem. Soc 1993, 115, 9968.(i)Watanabe N; Anada M; Hashimoto S.-i.; Ikegami S Synlett 1994, 1031.(j)Doyle MP; Kalinin AV Synlett 1995, 1075.(k)Doyle MP; Yan M; Phillips IM; Timmons DJ Adv. Synth. Catal 2002, 344, 91.(l)Davies HML; Hansen T; Hopper DW; Panaro SA J. Am. Chem. Soc 1999, 121, 6509.(m)Axten JM; Ivy R; Krim L; Winkler JD J. Am. Chem. Soc 1999, 121, 6511.(n)Davies HML; Venkataramani C Org. Lett 2001, 3, 1773. [PubMed: 11405708] (o)Davies HML; Venkataramani C; Hansen T; Hopper DW J. Am. Chem. Soc 2003, 125, 6462. [PubMed: 12785786] (p)Davies HML; Hopper DW; Hansen T; Liu Q; Childers SR Bioorg. Med. Chem. Lett 2004, 14, 1799. [PubMed: 15026075] (q)Santi M; Müller STR; Folgueiras-Amador AA; Uttry A; Hellier P; Wirth T Eur. J. Org. Chem 2017, 1889.(r)Souza LW; Squitieri RA; Dimirjian CA; Hodur BM; Nickerson LA; Penrod CN; Cordova J; Fettinger JC; Shaw JT Angew. Chem. Int. Ed 2018, 57, 15213.(s)Asako S; Ishihara S; Hirata K; Takai K J. Am. Chem. Soc 2019, 141, 9832. [PubMed: 31184481] (t)Gomes LFR; Veiros LF; Maulide N; Afonso CAM Chem. Eur. J 2015, 21, 1449. [PubMed: 25412838] (u)Doyle MP; Kalinin AV Tetrahedron Lett. 1996, 37, 1371.(v)Lee S; Lim H-J; Cha KL; Sulikowski GA Tetrahedron 1997, 53, 16521.(w)Sulikowski GA; Lee S Tetrahedron Lett. 1999, 40, 8035. (x)Toumieux S; Compain P; Martin OR; Selkti M Org. Lett 2006, 8, 4493. [PubMed: 16986933] (y)Morin MST; Toumieux S; Compain P; Peyrat S; Kalinowska-Tluscik J Tetrahedron Lett. 2007, 48, 8531.(z)He J; Hamann LG; Davies HML; Beckwith RE J. Nat. Commun 2015, 6, 5943. (aa)Zhou AZ; Chen K; Arnold FH ACS Catal. 2020, 10, 5393.(ab)Davies HML; Beckwith RE J. Chem. Rev 2003, 103, 2861.(ac)Davies HML; Manning JR Nature 2008, 451, 417. [PubMed: 18216847] (ad)Doyle MP; Duffy R; Ratnikov M; Zhou L Chem. Rev 2010, 110, 704. [PubMed: 19785457] (ae)Davies HML; Morton D Chem. Soc. Rev 2011, 40, 1857. [PubMed: 21359404] (af)Sultanova RM; Khanova MD; Zlotskii SS Chem. Heterocycl. Compd. (Engl. Transl.) 2015, 51, 775.

(38). (a)Hofmann AW Chem. Ber 1883, 16, 558.(b)Löffler K; Freytag C Chem. Ber 1909, 42, 3427. (c)De Armas P; Carrau R; Concepción JI; Francisco CG; Hernández R; Suárez E Tetrahedron Lett. 1985, 26, 2493.(d)Francisco CG; Herrera AJ; Suárez E J. Org. Chem 2003, 68, 1012. [PubMed: 12558429] (e)Martínez C; Muñiz K Angew. Chem. Int. Ed 2015, 54, 8287.(f)Liu T; Myers MC; Yu J-Q Angew. Chem. Int. Ed 2017, 56, 306.(g)Becker P; Duhamel T; Stein CJ; Reiher M; Muñiz K Angew. Chem. Int. Ed 2017, 56, 8004.(h)Zhang Z; Zhang X; Nagib DA Chem 2019, 5, 3127. [PubMed: 32296736] (i)Wolff ME Chem. Rev 1963, 63, 55.(j)Stella L Angew. Chem., Int. Ed. Engl 1983, 22, 337.(k)Jeffrey JL; Sarpong R Chem. Sci 2013, 4, 4092.(l)Stateman L; Nakafuku K; Nagib DA Synthesis 2018, 50, 1569. [PubMed: 29755145] (m)Wawzonek S; Thelen PJ J. Am. Chem. Soc 1950, 72, 2118.(n)Corey EJ; Hertler WR J. Am. Chem. Soc 1960, 82, 1657.(o)Fan R; Pu D; Wen F; Wu J J. Org. Chem 2007, 72, 8994. [PubMed: 17929871] (p)Qin Q; Yu S Org. Lett 2015, 17, 1894. [PubMed: 25853884] (q)Paz NR; Rodríguez-Sosa D; Valdés H; Marticorena R; Melián D; Copano MB; González CC; Herrera AJ Org. Lett 2015, 17, 2370. [PubMed: 25932748] (r)Wappes EA; Fosu SC; Chopko TC; Nagib DA Angew. Chem. Int. Ed 2016, 55, 9974.(s)Short MA; Shehata MF; Sanders MA; Roizen JL Chem. Sci 2020, 11, 217.

(39). (a)Hey DH; Turpin DG J. Chem. Soc 1954, 2471.(b)Lewin AH; Dinwoodie AH; Cohen T Tetrahedron 1966, 22, 1527.(c)Cohen T; McMullen CH; Smith K J. Am. Chem. Soc 1968, 90, 6866.(d)Shaaban S; Oh J; Maulide N Org. Lett 2016, 18, 345. [PubMed: 26757174] (e)Snieckus V; Cuevas JC; Sloan CP; Liu H; Curran DP J. Am. Chem. Soc 1990, 112, 896.(f)Curran DP; Abraham AC Tetrahedron 1993, 49, 4821.(g)Murakami M; Hayashi M; Ito Y J. Org. Chem 1992, 57, 793.(h)Williams L; Booth SE; Undheim K Tetrahedron 1994, 50, 13697.(i)Yoshimitsu T; Arano Y; Nagaoka H J. Am. Chem. Soc 2005, 127, 11610. [PubMed: 16104731] (j)Yoshikai N; Mieczkowski A; Matsumoto A; Ilies L; Nakamura E J. Am. Chem. Soc 2010, 132, 5568. [PubMed: 20361736] (k)Tian H; Yang H; Zhu C; Fu H Sci. Rep 2016, 6, 19931. [PubMed: 26822836] (l)Sarkar S; Cheung KPS; Gevorgyan V Chem. Sci 2020, 11, 12974. [PubMed: 34123240] (m)Robertson J; Peplow MA; Pillai J Tetrahedron Lett. 1996, 37, 5825.(n)Khan TA; Tripoli R; Crawford JJ; Martin CG; Murphy JA Org. Lett 2003, 5, 2971. [PubMed: 12889921] (o)Beckwith ALJ; Bowry VW; Bowman WR; Mann E; Parr J; Storey JMD Angew. Chem. Int. Ed 2004, 43, 95.(p)Dénès F; Beaufils F; Renaud P Org. Lett 2007, 9, 4375. [PubMed: 17887768] (q)Yoshimitsu T; Matsuda K; Nagaoka H; Tsukamoto K; Tanaka T Org. Lett 2007, 9, 5115. [PubMed: 17975923] (r)Yoshimitsu T; Atsumi C; Iimori E; Nagaoka H; Tanaka T Tetrahedron Lett. 2008, 49, 4473.(s)Wertjes WC; Wolfe LC; Waller PJ; Kalyani D Org. Lett 2013, 15, 5986. [PubMed: 24256509] (t)Hollister KA; Conner ES; Spell ML; Deveaux K; Maneval L; Beal MW; Ragains JR Angew. Chem. Int. Ed 2015, 54, 7837.(u)Chen J-Q; Wei Y-L; Xu G-Q; Liang Y-M; Xu P-F Chem. Commun 2016, 52, 6455.(v)Liu P; Tang J; Zeng X Org. Lett 2016, 18, 5536. [PubMed: 27774791] (w)Huang F-Q; Dong X; Qi L-W; Zhang B Tetrahedron Lett. 2016, 57, 1600.

(40). (a)Weinberg NL; Brown EA J. Org. Chem 1966, 31, 4058.(b)Shono T; Matsumura Y; Tsubata K J. Am. Chem. Soc 1981, 103, 1172.(c)Yoshida J; Suga S; Suzuki S; Kinomura N; Yamamoto A; Fujiwara K J. Am. Chem. Soc 1999, 121, 9546.(d)Suga S; Okajima M; Yoshida J Tetrahedron Lett. 2001, 42, 2173.(e)Suga S; Suzuki S; Yoshida J J. Am. Chem. Soc 2002, 124, 30. [PubMed: 11772058] (f)Kim S; Shoji T; Kitano Y; Chiba K Chem. Commun 2013, 49, 6525.(g)Shoji T; Kim S; Chiba K Angew. Chem. Int. Ed 2017, 56, 4011.(h)Suga S; Matsumoto K; Ueoka K; Yoshida JI J. Am. Chem. Soc 2006, 128, 7710. [PubMed: 16771464] (i)Yoshida J; Isoe S Tetrahedron Lett. 1987, 28, 6621.(j)Sugawara M; Mori K; Yoshida JI Electrochim. Acta 1997, 42, 1995.(k)Suga S; Watanabe M; Song CH; Yoshida JI Electrochemistry 2006, 74, 672.(l)Mitsudo K; Yamamoto J; Akagi T; Yamashita A; Haisa M; Yoshioka K; Mandai H; Ueoka K; Hempel C; Yoshida J; Suga S Beilstein J. Org. Chem 2018, 14, 1192. [PubMed: 29977386] (m)Yoshida J; Ashikari Y; Matsumoto K; Nokami T J. Synth. Org. Chem. Jpn 2013, 71, 1136.(n)Jones AM; Banks CE Beilstein J. Org. Chem 2014, 10, 3056. [PubMed: 25670975] (o)Yoshida J; Kataoka K; Horcajada R; Nagaki A Chem. Rev 2008, 108, 2265. [PubMed: 18564879]

(41). (a)Semmelhack MF; Schmid CR J. Am. Chem. Soc 1983, 105, 6732.(b)Li C; Zeng CC; Hu LM; Yang FL; Yoo SJ; Little RD Electrochim. Acta 2013, 114, 560.(c)Wang F; Rafiee M; Stahl SS Angew. Chem. Int. Ed 2018, 57, 6686.(d)Lennox AJJ; Goes SL; Webster MP; Koolman HF; Djuric SW; Stahl SS J. Am. Chem. Soc 2018, 140, 11227. [PubMed: 30141925] (e)Gao

PS; Weng XJ; Wang ZH; Zheng C; Sun B; Chen ZH; You SL; Mei TS Angew. Chem. Int. Ed 2020, 59, 15254.(f)Kashiwagi Y; Kurashima F; Kikuchi C; Anzai J; Osa T; Bobbitt JM Chem. Commun 1999, 1983.(g)Kashiwagi Y; Anzai J Chem. Pharm. Bull 2001, 49, 324.(h)Nutting JE; Rafiee M; Stahl SS Chem. Rev 2018, 118, 4834. [PubMed: 29707945] (i)Wang F; Stahl SS Acc. Chem. Res 2020, 53, 561. [PubMed: 32049487]

(42). (a)Norrish RGW; Bamford CH Nature 1937, 140, 195.(b)Yang NC; Yang DDH J. Am. Chem. Soc 1958, 80, 2913.(c)Clasen RA; Searles S Chem. Commun 1966, 289.(d)Cohen SG; Parola A; Parsons GH Chem. Rev 1973, 73, 141.(e)Hasegawa T; Aoyama H; Omote Y Tetrahedron Lett. 1975, 16, 1901.(f)Lindemann U; Wulff-Molder D; Wessig P Tetrahedron: Asymmetry 1998, 9, 4459.(g)Gramain JC; Remuson R; Vallee D J. Org. Chem 1985, 50, 710.(h)Giese B; Wettstein P; Stahelin C; Barbosa F; Neuburger M; Zehnder M; Wessig P Angew. Chem. Int. Ed 1999, 38, 2586.(i)Wu JF; Zhang W; Wang CL Synthesis 2009, 1821.(j)Roque JB; Kuroda Y; Jurczyk J; Xu LP; Ham JS; Gottemann LT; Roberts CA; Adpressa D; Sauri J; Joyce LA; Musaev DG; Yeung CS; Sarpong R ACS Catal. 2020, 10, 2929. [PubMed: 33569242] (k)Ham JS; Park B; Son M; Roque JB; Jurczyk J; Yeung CS; Baik MH; Sarpong R J. Am. Chem. Soc 2020, 142, 13041. [PubMed: 32627545] (l)Griesbeck AG; Heckroth H; Schmickler H Tetrahedron Lett. 1999, 40, 3137.(m)Rey V; Pierini AB; Peñéñory AB J. Org. Chem 2009, 74, 1223. [PubMed: 19138117] (n)Nishio T; Tabata M; Koyama H; Sakamoto M Helv. Chim. Acta 2005, 88, 78.(o)Nishio T; Koyama H; Sasaki D; Sakamoto M Helv. Chim. Acta 2005, 88, 996.(p)Nishio T; Sakurai N; Iba K; Hamano Y; Sakamoto M Helv. Chim. Acta 2005, 88, 2603.(q)Nechab M; Mondal S; Bertrand MP Chem. Eur. J 2014, 20, 16034. [PubMed: 25345694]

(43). (a)Davidson RS Chem. Commun 1966, 575.(b)Hoshikawa T; Yoshioka S; Kamijo S; Inoue M Synthesis 2013, 45, 874.(c)Kamijo S; Takao G; Kamijo K; Hirota M; Tao K; Murafuji T Angew. Chem. Int. Ed 2016, 55, 9695.(d)Kamijo S; Takao G; Kamijo K; Tsuno T; Ishiguro K; Murafuji T Org. Lett 2016, 18, 4912. [PubMed: 27668684] (e)Perry IB; Brewer TF; Sarver PJ; Schultz DM; DiRocco DA; MacMillan DWC Nature 2018, 560, 70. [PubMed: 30068953] (f)Si XJ; Zhang LM; Hashmi ASK Org. Lett 2019, 21, 6329. [PubMed: 31373208] (g)Schultz DM; Levesque F; DiRocco DA; Reibarkh M; Ji YN; Joyce LA; Dropinski JF; Sheng HM; Sherry BD; Davies IW Angew. Chem. Int. Ed 2017, 56, 15274.(h)Sarver PJ; Bacauanu V; Schultz DM; DiRocco DA; Lam YH; Sherer EC; MacMillan DWC Nat. Chem 2020, 12, 459. [PubMed: 32203440] (i)Yu JP; Zhao CY; Zhou R; Gao WC; Wang S; Liu K; Chen SY; Hu KQ; Mei L; Yuan LY; Chai ZF; Hu HS; Shi WQ Chem. Eur. J 2020, 26, 16521. [PubMed: 32901978] (j)Srivastava V; Singh PK; Singh PP Tetrahedron Lett. 2019, 60, 1333.(k)Roberts BP Chem. Soc. Rev 1999, 28, 25.(l)Nagatomo M; Yoshioka S; Inoue M Chem. Asian J 2015, 10, 120. [PubMed: 25274043] (m)Capaldo L; Ravelli D Eur. J. Org. Chem 2017, 2056.(n)Capaldo L; Quadri LL; Ravelli D Green Chem. 2020, 22, 3376.

(44). (a)Condie AG; Gonzalez-Gomez JC; Stephenson CRJ J. Am. Chem. Soc 2010, 132, 1464. [PubMed: 20070079] (b)Rueping M; Zhu SQ; Koenigs RM Chem. Commun 2011, 47, 12709. (c)Freeman DB; Furst L; Condie AG; Stephenson CR J. Org. Lett 2012, 14, 94.(d)Rueping M; Zhu SQ; Koenigs RM Chem. Commun 2011, 47, 8679.(e)Rueping M; Vila C; Koenigs RM; Poscharny K; Fabry DC Chem. Commun 2011, 47, 2360.(f)Zhao GL; Yang C; Guo L; Sun HN; Chen C; Xia WJ Chem. Commun 2012, 48, 2337.(g)Rueping M; Koenigs RM; Poscharny K; Fabry DC; Leonori D; Vila C Chem. Eur. J 2012, 18, 5170. [PubMed: 22431393] (h)DiRocco DA; Rovis T J. Am. Chem. Soc 2012, 134, 8094. [PubMed: 22548244] (i)Bergonzini G; Schindler CS; Wallentin CJ; Jacobsen EN; Stephenson CR J. Chem. Sci 2014, 5, 112.(j)Pan YH; Kee CW; Chen L; Tan CH Green Chem. 2011, 13, 2682.(k)Liu Q; Li YN; Zhang HH; Chen B; Tung CH; Wu LZ Chem. Eur. J 2012, 18, 620. [PubMed: 22162148] (l)Pan YH; Wang S; Kee CW; Dubuisson E; Yang YY; Loh KP; Tan CH Green Chem. 2011, 13, 3341.(m)Fu WJ; Guo WB; Zou GL; Xu C J. Fluorine Chem 2012, 140, 88.(n)Lin SX; Sun GJ; Kang Q Chem. Commun 2017, 53, 7665.(o)Zhang T; Liang WW; Huang YX; Li XR; Liu YZ; Yang B; He CX; Zhou XC; Zhang JM Chem. Commun 2017, 53, 12536.(p)Kohls P; Jadhav D; Pandey G; Reiser O Org. Lett 2012, 14, 672. [PubMed: 22260623] (q)Miyake Y; Nakajima K; Nishibayashi Y Chem. Eur. J 2012, 18, 16473. [PubMed: 23150225] (r)Espelt LR; Wiensch EM; Yoon TP J. Org. Chem 2013, 78, 4107. [PubMed: 23537318] (s)Sharma S; Sharma A Org. Biomol. Chem 2019, 17, 4384. [PubMed: 30951059] (t)Romero NA; Nicewicz DA Chem. Rev 2016, 116, 10075. [PubMed: 27285582]

(45). (a)McNally A; Prier CK; MacMillan DWC Science 2011, 334, 1114. [PubMed: 22116882] (b)Noble A; MacMillan DWC J. Am. Chem. Soc 2014, 136, 11602. [PubMed: 25026314] (c)Joe CL; Doyle AG Angew. Chem. Int. Ed 2016, 55, 4040.(d)Leng LY; Fu Y; Liu P; Ready JM J. Am. Chem. Soc 2020, 142, 11972. [PubMed: 32573218] (e)Prier CK; MacMillan DWC Chem. Sci 2014, 5, 4173. [PubMed: 26236461] (f)Ahneman DT; Doyle AG Chem. Sci 2016, 7, 7002. [PubMed: 28058105] (g)McManus JB; Onuska NPR; Nicewicz DA J. Am. Chem. Soc 2018, 140, 9056. [PubMed: 29986129] (h)McManus JB; Onuska NPR; Jeffreys MS; Goodwin NC; Nicewicz DA Org. Lett 2020, 22, 679. [PubMed: 31904980] (i)Holmberg-Douglas N; Choi Y; Aquila B; Huynh H; Nicewicz DA ACS Catal. 2021, 11, 3153.(j)Cohen SG; Chao HM J. Am. Chem. Soc 1968, 90, 165.(k)Lewis FD; Ho TI; Simpson JT J. Org. Chem 1981, 46, 1077. (l)Masuda Y; Ito M; Murakami M Org. Lett 2020, 22, 4467. [PubMed: 32432879] (m)Thullen SM; Rovis T J. Am. Chem. Soc 2017, 139, 15504. [PubMed: 29048886] (n)Shaw MH; Twilton J; MacMillan DWC J. Org. Chem 2016, 81, 6898. [PubMed: 27477076] (o)Guillemard L; Wencel-Delord J Beilstein J. Org. Chem 2020, 16, 1754. [PubMed: 32765795]

(46). (a)Dai C; Meschini F; Narayanam JMR; Stephenson CRJ J. Org. Chem 2012, 77, 4425. [PubMed: 22458307] (b)Ide T; Barham JP; Fujita M; Kawato Y; Egami H; Hamashima Y Chem. Sci 2018, 9, 8453. [PubMed: 30542595] (c)Kobayashi F; Fujita M; Ide T; Ito Y; Yamashita K; Egami H; Hamashima Y ACS Catal. 2021, 11, 82.(d)Wakaki T; Sakai K; Enomoto T; Kondo M; Masaoka S; Oisaki K; Kanai M Chem. Eur. J 2018, 24, 8051. [PubMed: 29645304] (e)Grainger R; Heightman TD; Ley SV; Lima F; Johnson CN Chem. Sci 2019, 10, 2264. [PubMed: 30881651] (f)Shaw MH; Shurtleff VW; Terrett JA; Cuthbertson JD; MacMillan DWC Science 2016, 352, 1304. [PubMed: 27127237] (g)Le C; Liang YF; Evans RW; Li XM; MacMillan DWC Nature 2017, 547, 79. [PubMed: 28636596] (h)Rohe S; Morris AO; McCallum T; Barriault L Angew. Chem. Int. Ed 2018, 57, 15664.(i)Li WP; Duan YQ; Zhang ML; Cheng J; Zhu CJ Chem. Commun 2016, 52, 7596.(j)Choi GJ; Zhu QL; Miller DC; Gu CJ; Knowles RR Nature 2016, 539, 268. [PubMed: 27732585] (k)Ye JT; Kalvet I; Schoenebeck F; Rovis T Nat. Chem 2018, 10, 1037. [PubMed: 30061617] (l)Ashley MA; Yamauchi C; Chu JCK; Otsuka S; Yorimitsu H; Rovis T Angew. Chem. Int. Ed 2019, 58, 4002.(m)Ryder ASH; Cunningham WB; Ballantyne G; Mules T; Kinsella AG; Turner-Dore J; Alder CM; Edwards LJ; McKay BSJ; Grayson MN; Cresswell AJ Angew. Chem. Int. Ed 2020, 59, 14986.(n)Treacy SM; Rovis T J. Am. Chem. Soc 2021, 143, 2729. [PubMed: 33576606] (o)Xu P; Chen PY; Xu HC Angew. Chem. Int. Ed 2020, 59, 14275.

(47). (a)Han GH; McIntosh MC; Weinreb SM Tetrahedron Lett. 1994, 35, 5813.(b)Ito R; Umezawa N; Higuchi T J. Am. Chem. Soc 2005, 127, 834. [PubMed: 15656611] (c)Kim Y; Heo J; Kim D; Chang S; Seo S Nat. Commun 2020, 11, 4761. [PubMed: 32958762] (d)Osberger TJ; Rogness DC; Kohrt JT; Stepan AF; White MC Nature 2016, 537, 214. [PubMed: 27479323] (e)Roque JB; Kuroda Y; Gottemann LT; Sarpong R Science 2018, 361, 171. [PubMed: 30002251] (f)Roque JB; Kuroda Y; Gottemann LT; Sarpong R Nature 2018, 564, 244. [PubMed: 30382193] (g)Roque JB; Sarpong R; Musaev DG J. Am. Chem. Soc 2021, 143, 3889. [PubMed: 33656336] (h)Kaname M; Yoshifuji S; Sashida H Tetrahedron Lett. 2008, 49, 2786.(i)Xia XF; Shu XZ; Ji KG; Shaukat A; Liu XY; Liang YM J. Org. Chem 2011, 76, 342. [PubMed: 21141942] (j)Paciaroni NG; Ratnayake R; Matthews JH; Norwood VM; Arnold AC; Dang LH; Luesch H; Huigens RW Chem. Eur. J 2017, 23, 4327. [PubMed: 27900785] (k)Morcillo SP Angew. Chem. Int. Ed 2019, 58, 14044.(l)Zhang YJ; Sun S; Su YJ; Zhao J; Li YH; Han B; Shi F Org. Biomol. Chem 2019, 17, 4970. [PubMed: 31049547] (m)Smolobochkin AV; Gazizov AS; Burilov AR; Pudovik MA; Sinyashin OG Russ. Chem. Rev 2019, 88, 1104.(n)Su JK; Ma XX; Ou ZL; Song QL ACS Cent. Sci 2020, 6, 1819. [PubMed: 33145418]

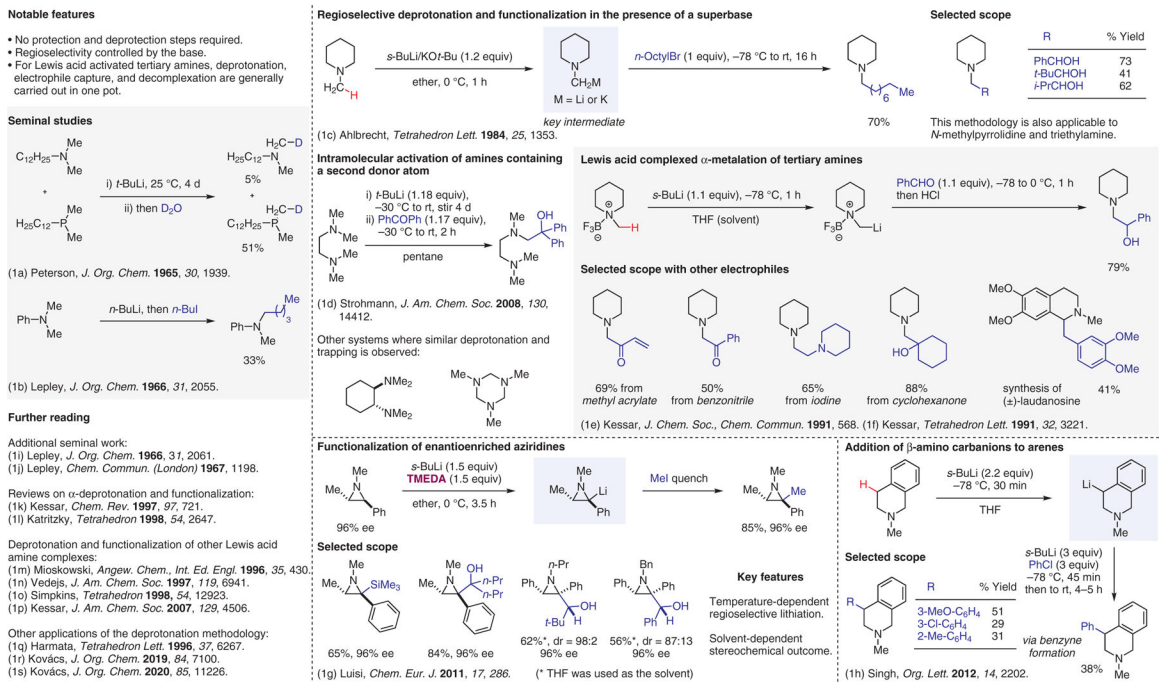


Figure 1.
Deprotonation of tertiary amines.[1]

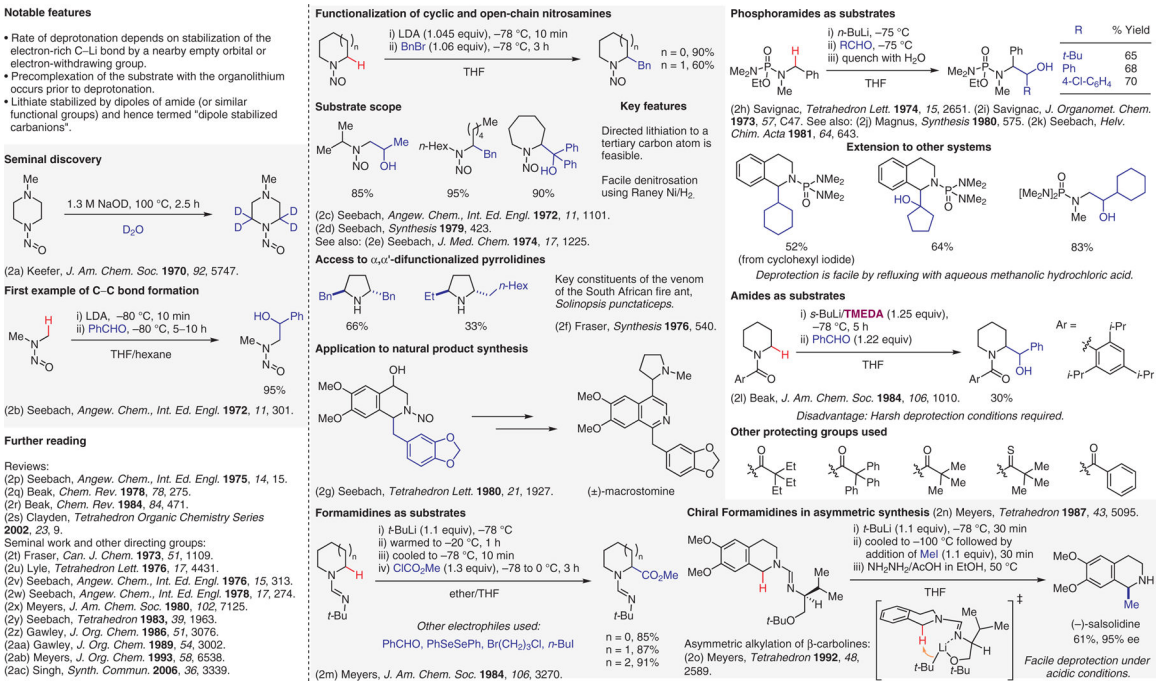


Figure 2.
Deprotonation of protected amines, part I.[2]

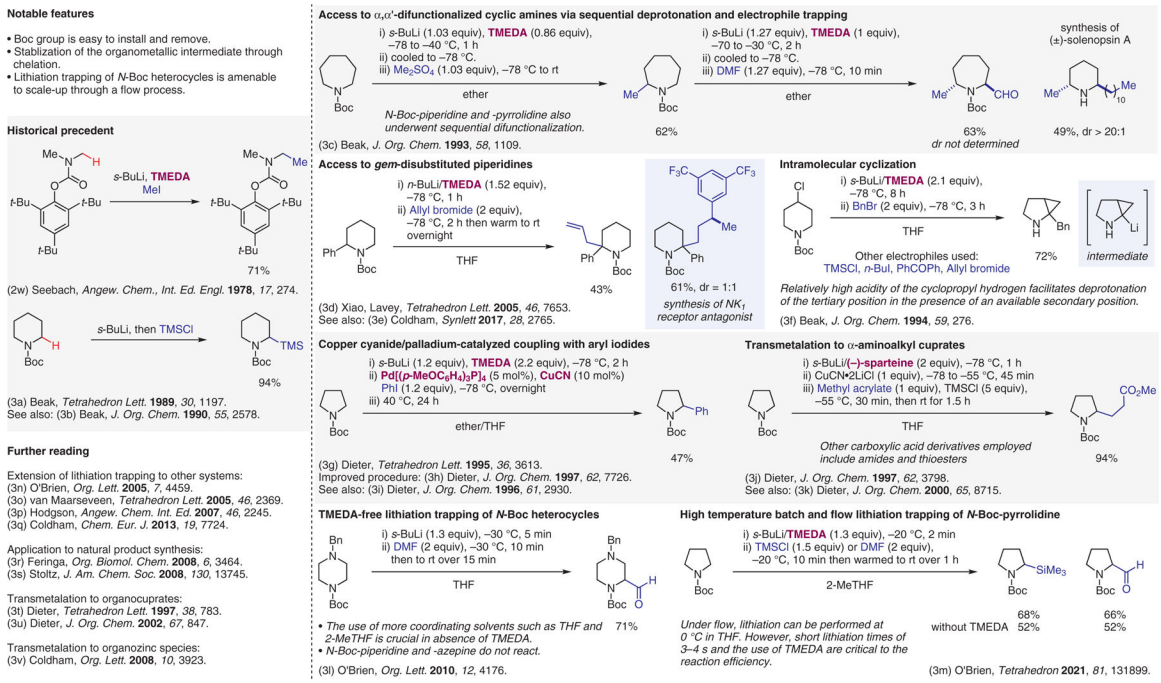


Figure 3.
Deprotonation of protected amines, part II.[3]

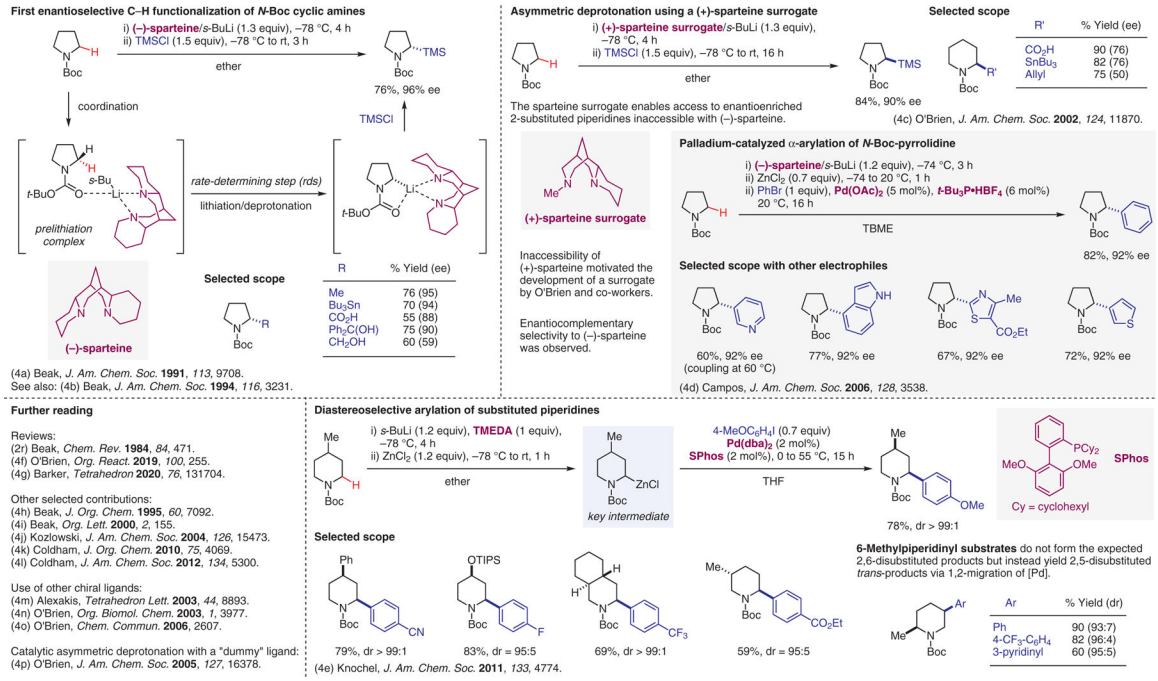


Figure 4.
Deprotonation of protected amines, part III.[4]

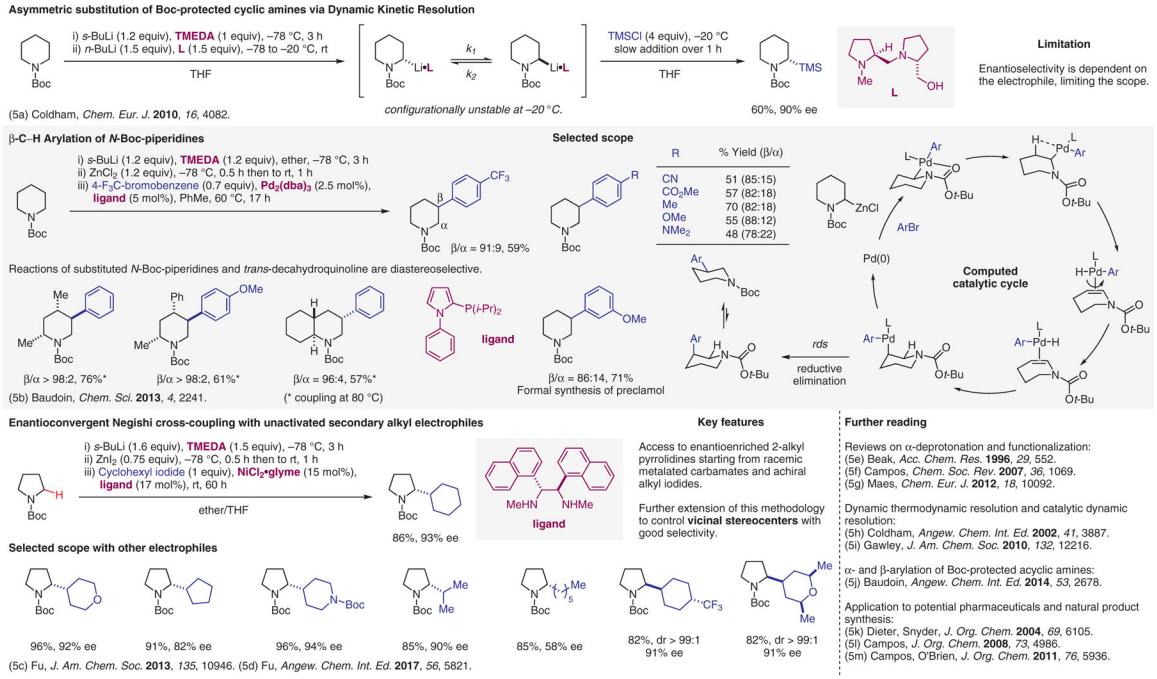


Figure 5.
Deprotonation of protected amines, part IV.[5]

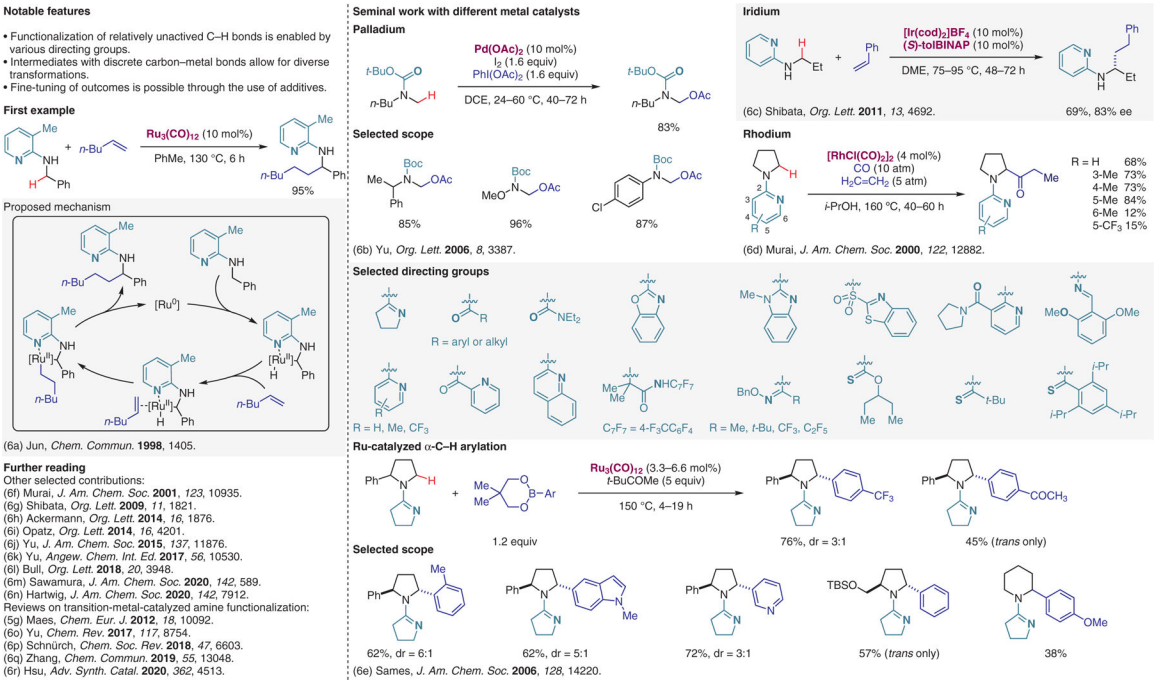


Figure 6.
Transition-metal-catalyzed reactions with substrates containing directing groups, part I.[6]

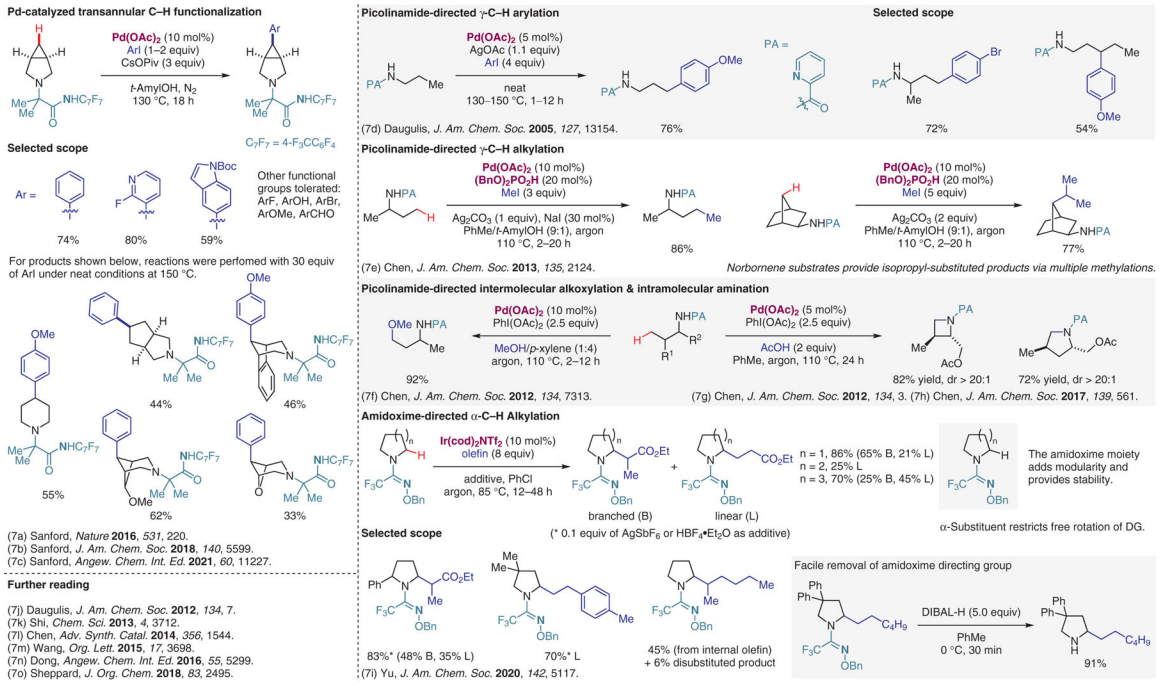


Figure 7.

Transition-metal-catalyzed reactions with substrates containing directing groups, part II.[7]

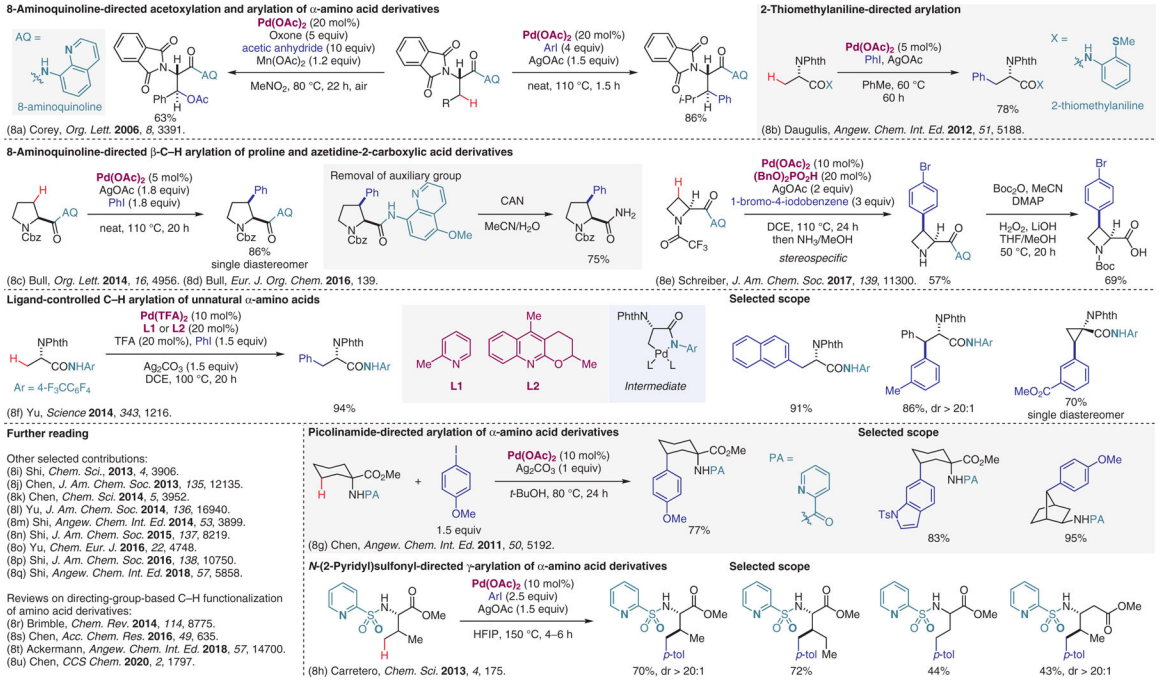


Figure 8.

Transition-metal-catalyzed reactions with substrates containing directing groups, functionalization of amino acid derivatives.[8]

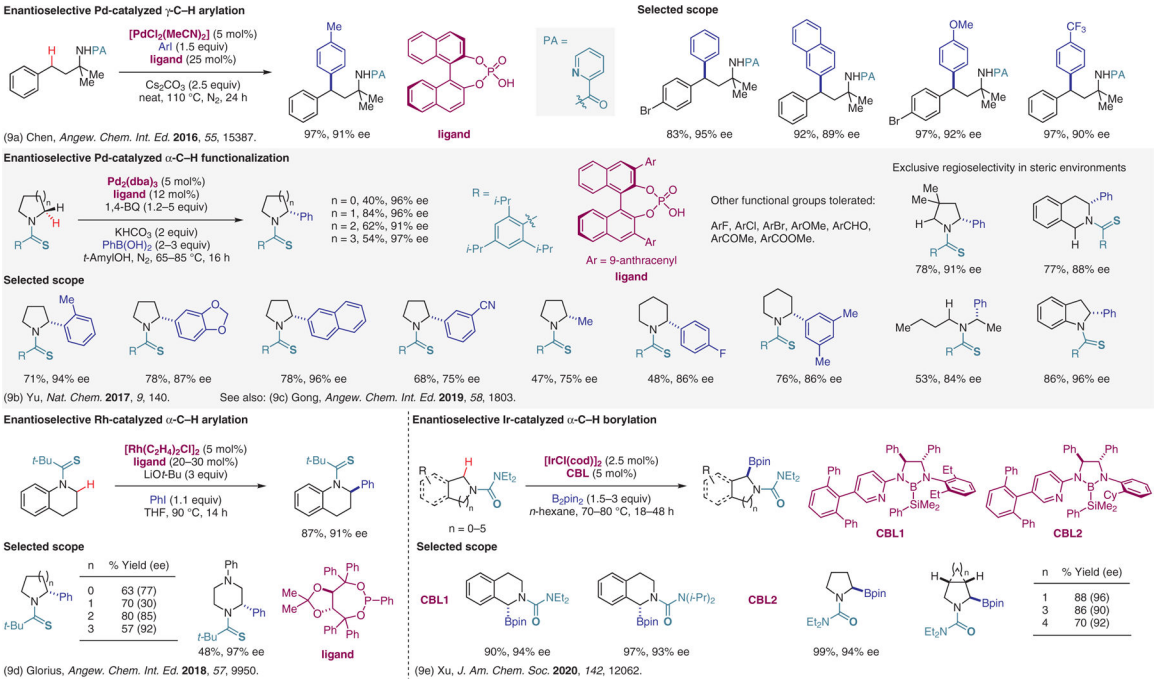


Figure 9.

Transition-metal-catalyzed reactions with substrates containing directing groups, catalytic enantioselective approaches.[9]

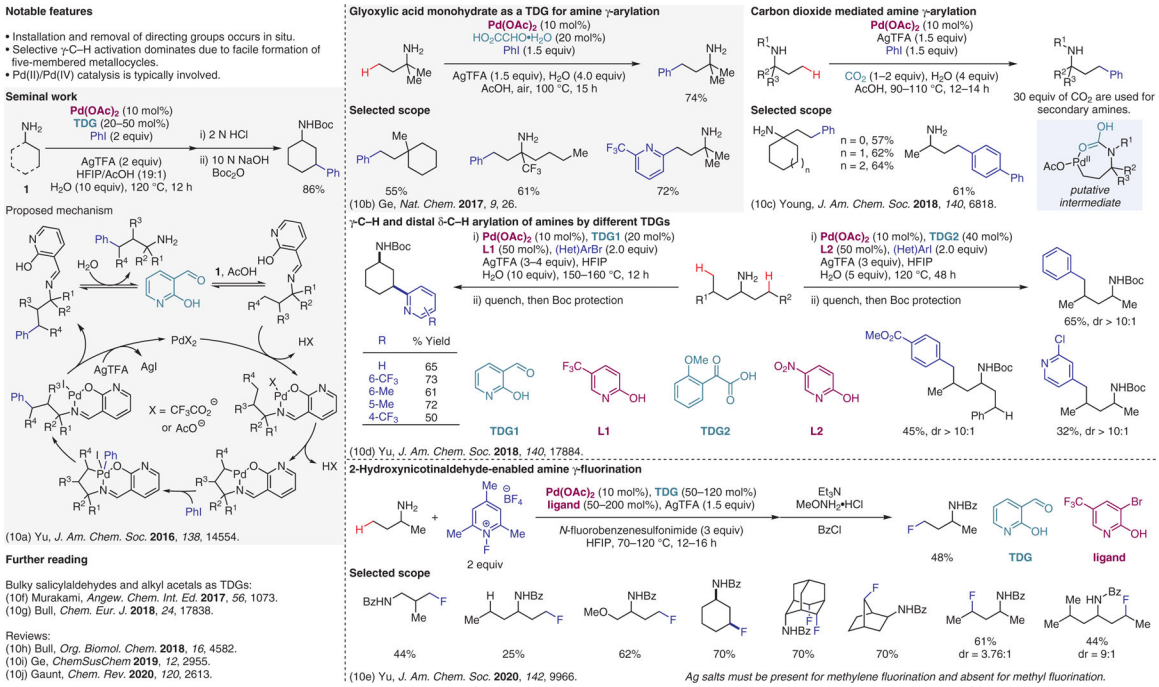


Figure 10.

Transition-metal-catalyzed reactions involving transient directing groups (TDGs).[10]

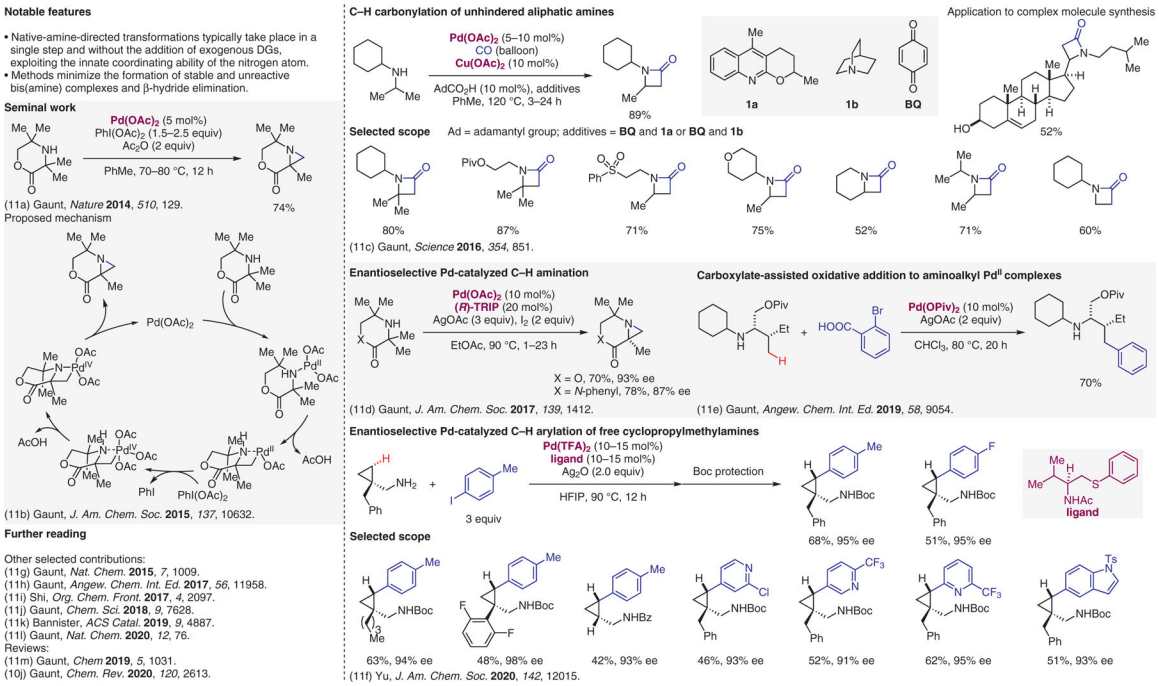


Figure 11.

Native-amine-directed transition-metal-catalyzed reactions.[11]

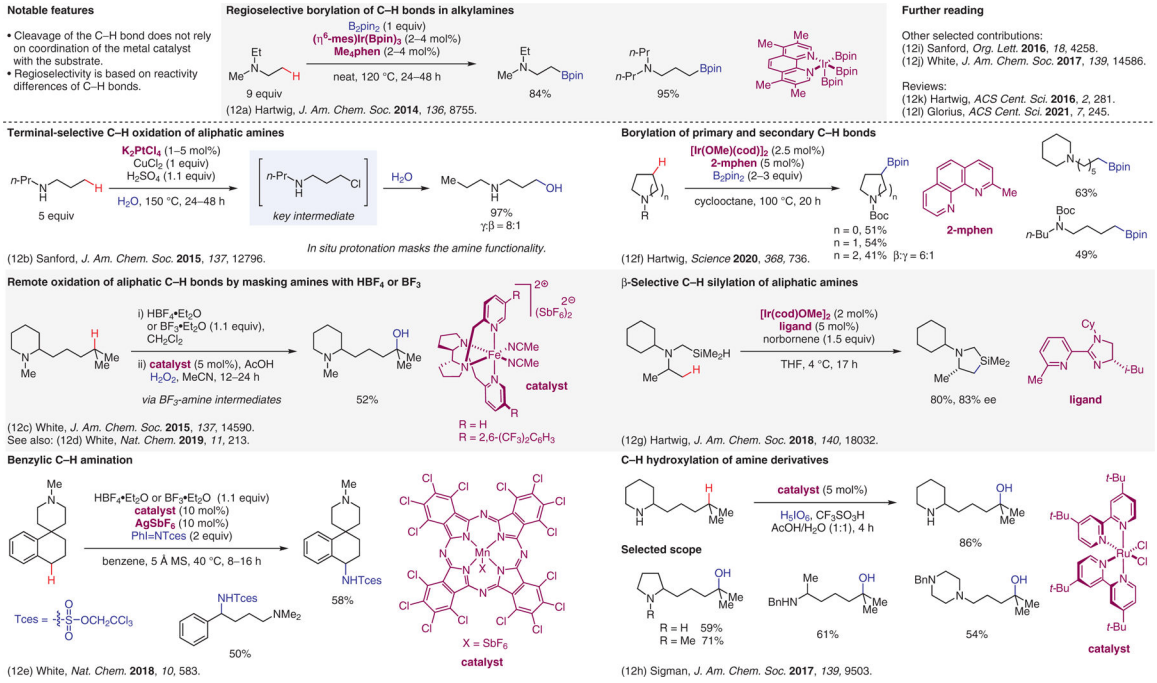


Figure 12.
Undirected transition-metal-catalyzed reactions.[12]

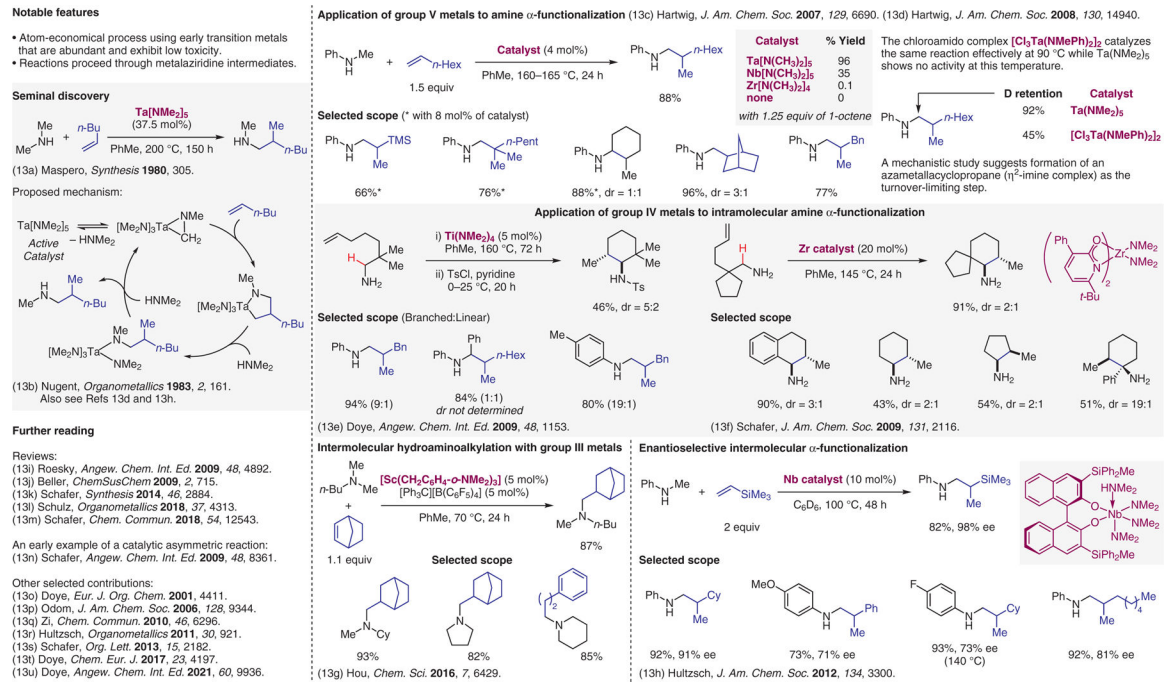


Figure 13.
Hydroaminoalkylation.[13]

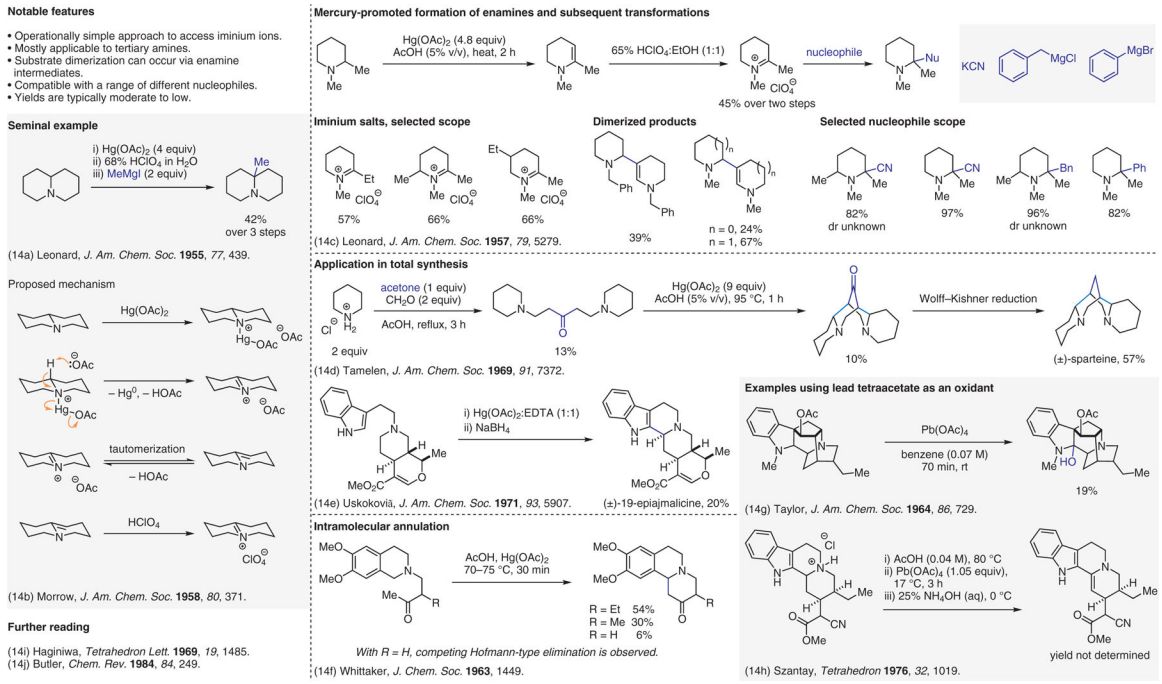


Figure 14.
Oxidative methods, stoichiometric metal-based oxidants.[14]

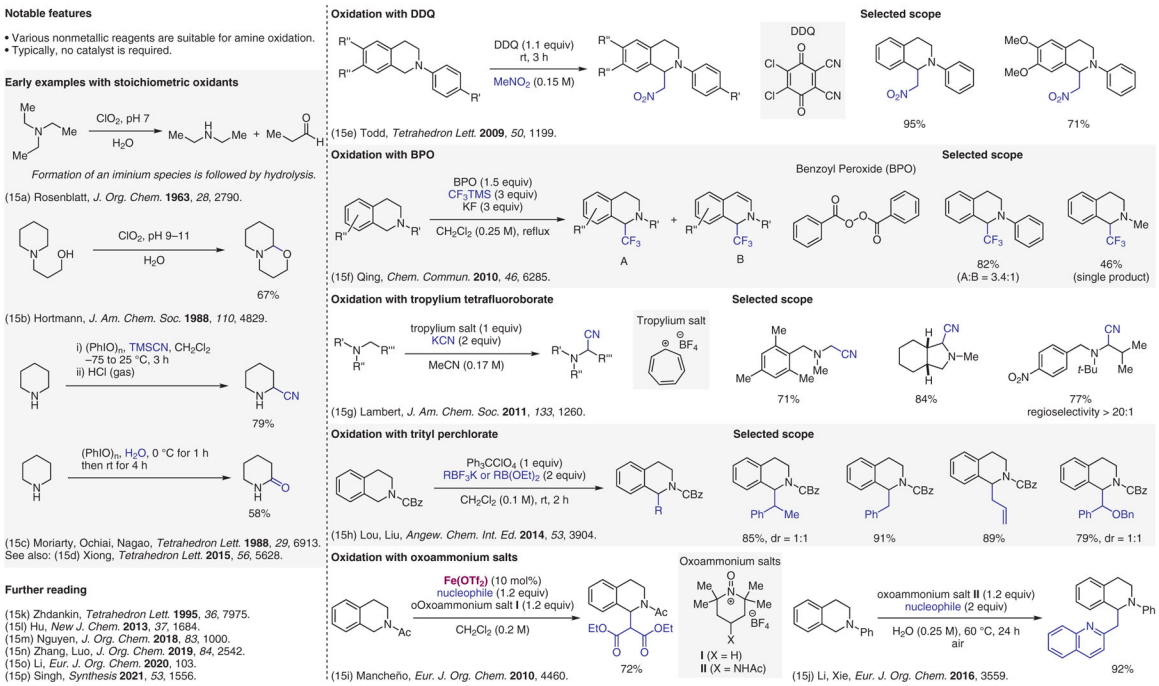


Figure 15.
Oxidative methods, stoichiometric nonmetallic oxidants.[15]

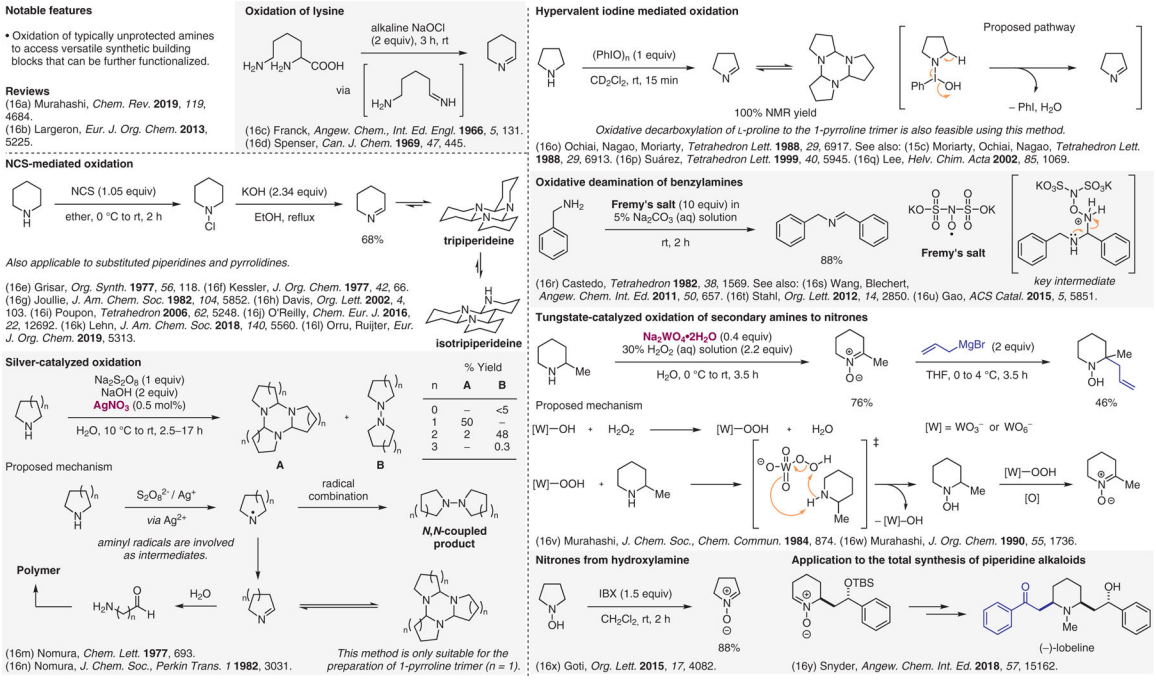


Figure 16.
Oxidative preparation of building blocks.[16]

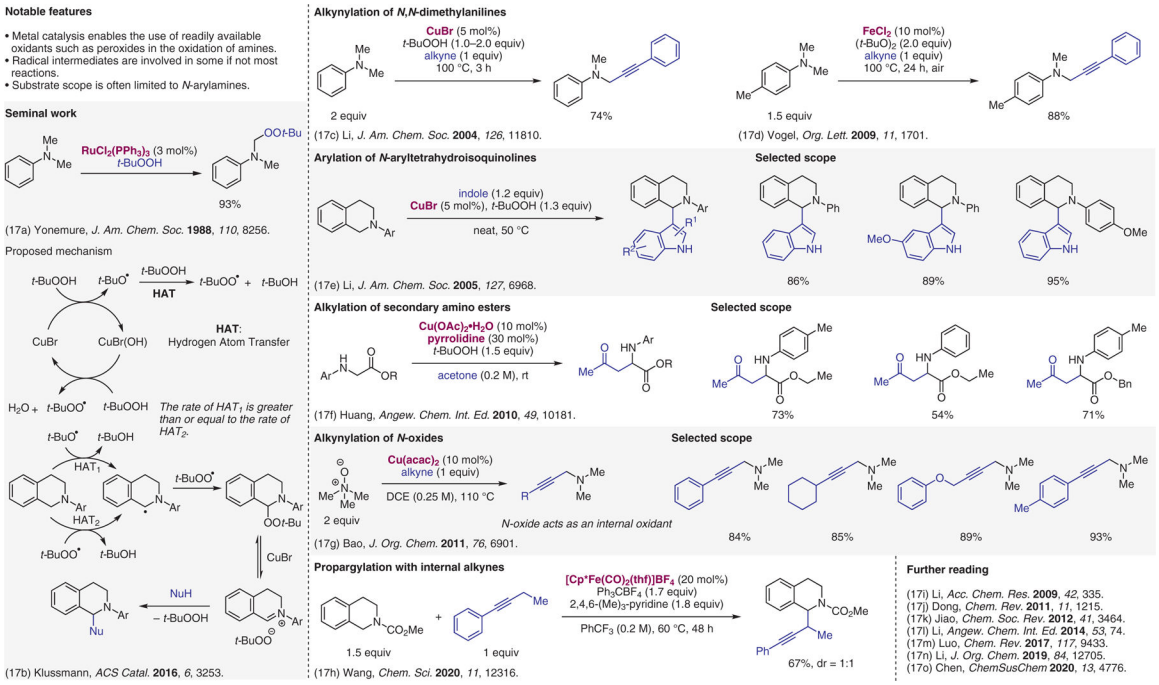


Figure 17.
Metal-catalyzed cross-dehydrogenative-coupling (CDC) reactions.[17]

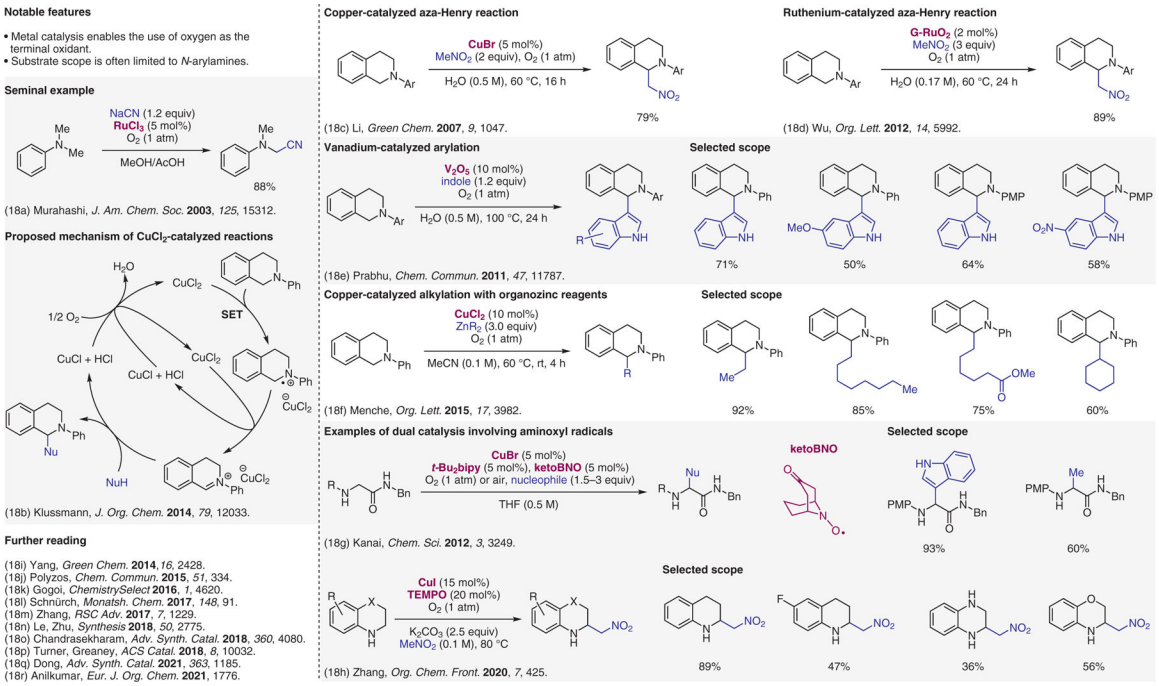


Figure 18.

Metal-catalyzed cross-dehydrogenative-coupling (CDC) reactions with oxygen as the terminal oxidant.[18]

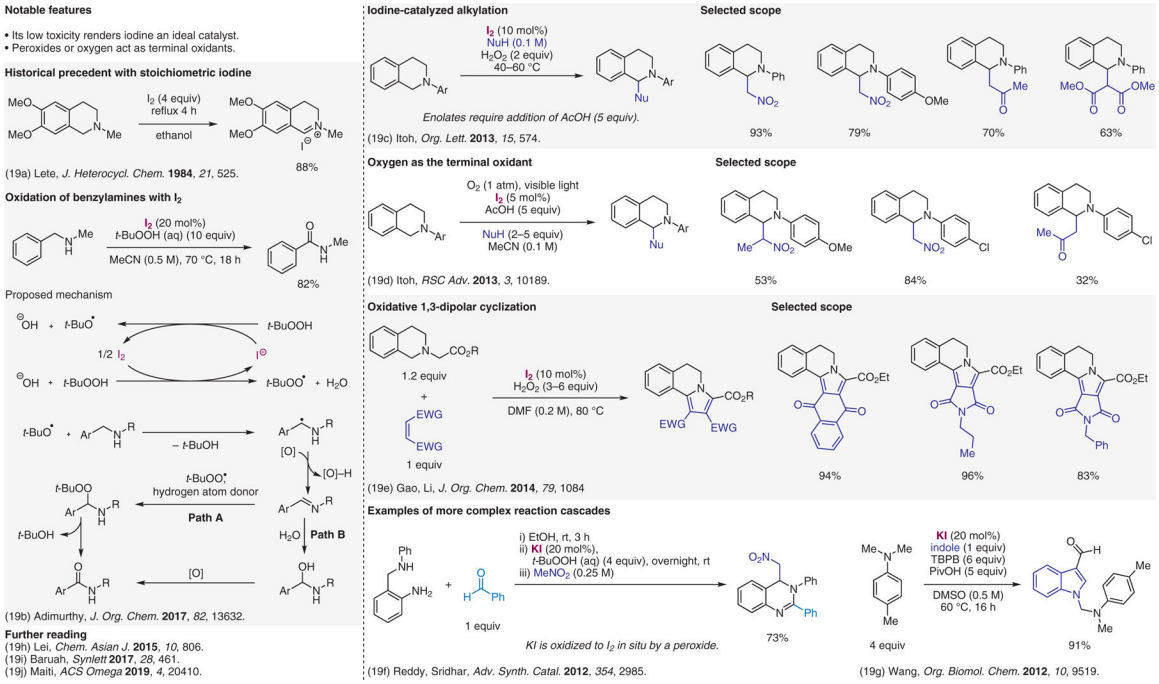


Figure 19.
Iodine-catalyzed cross-dehydrogenative-coupling (CDC) reactions.[19]

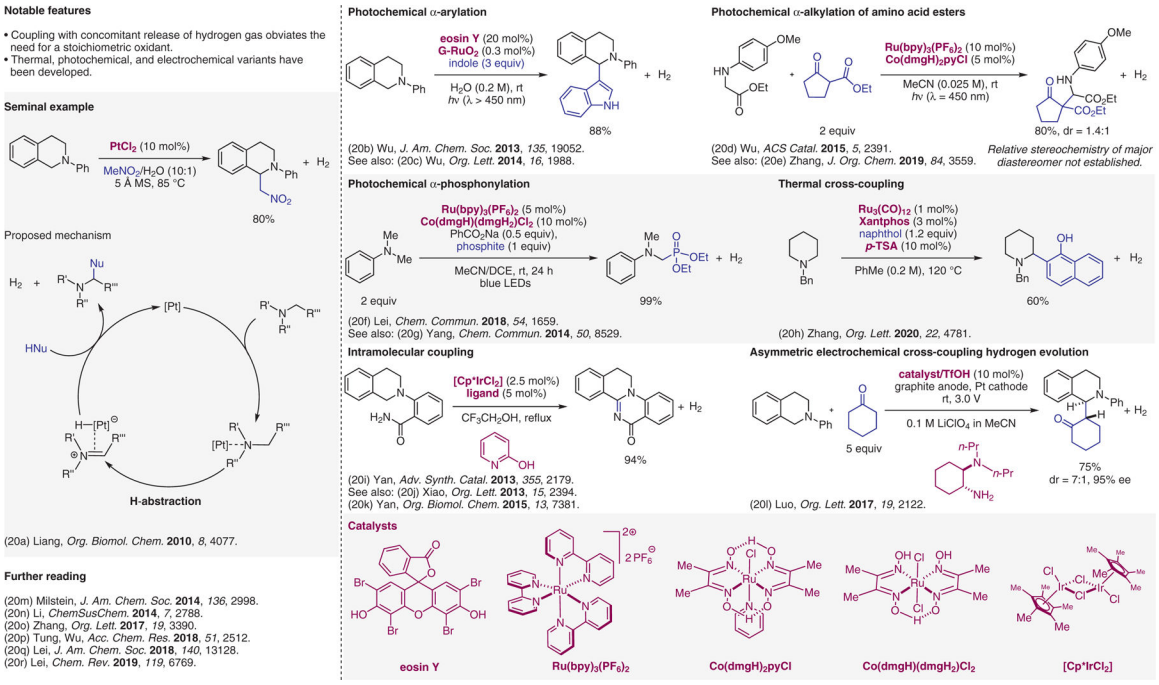


Figure 20.

Acceptorless cross-dehydrogenative-coupling (CDC) reactions with hydrogen evolution.[20]

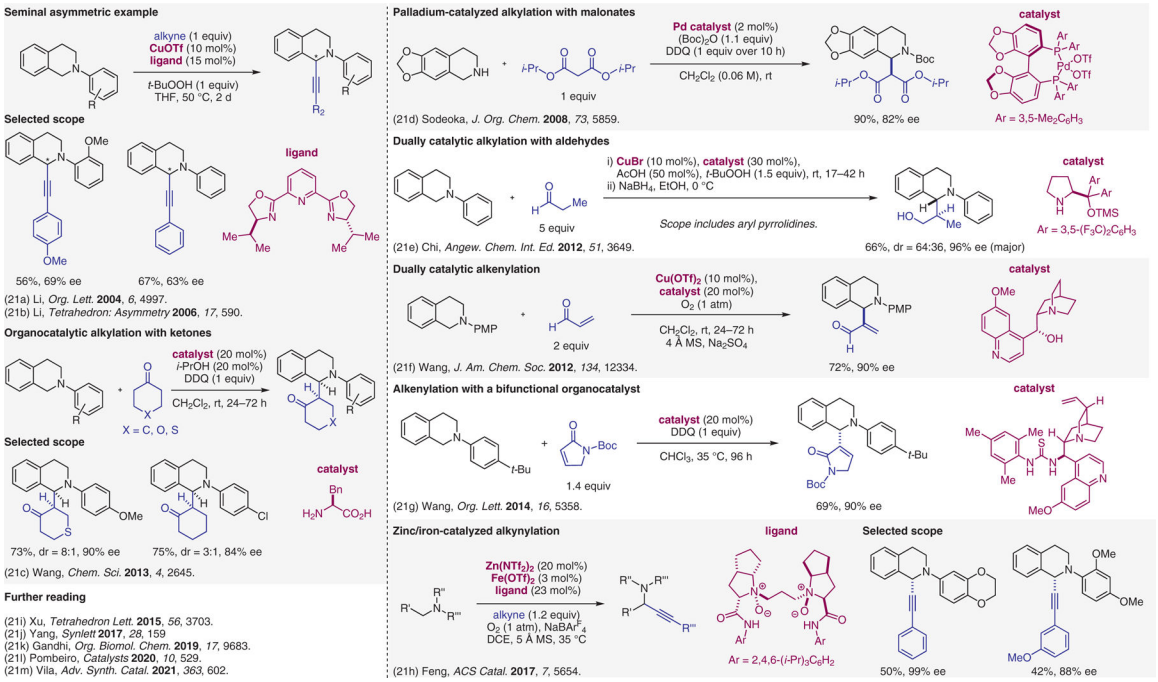


Figure 21.

Catalytic enantioselective cross-dehydrogenative-coupling (CDC) reactions.[21]

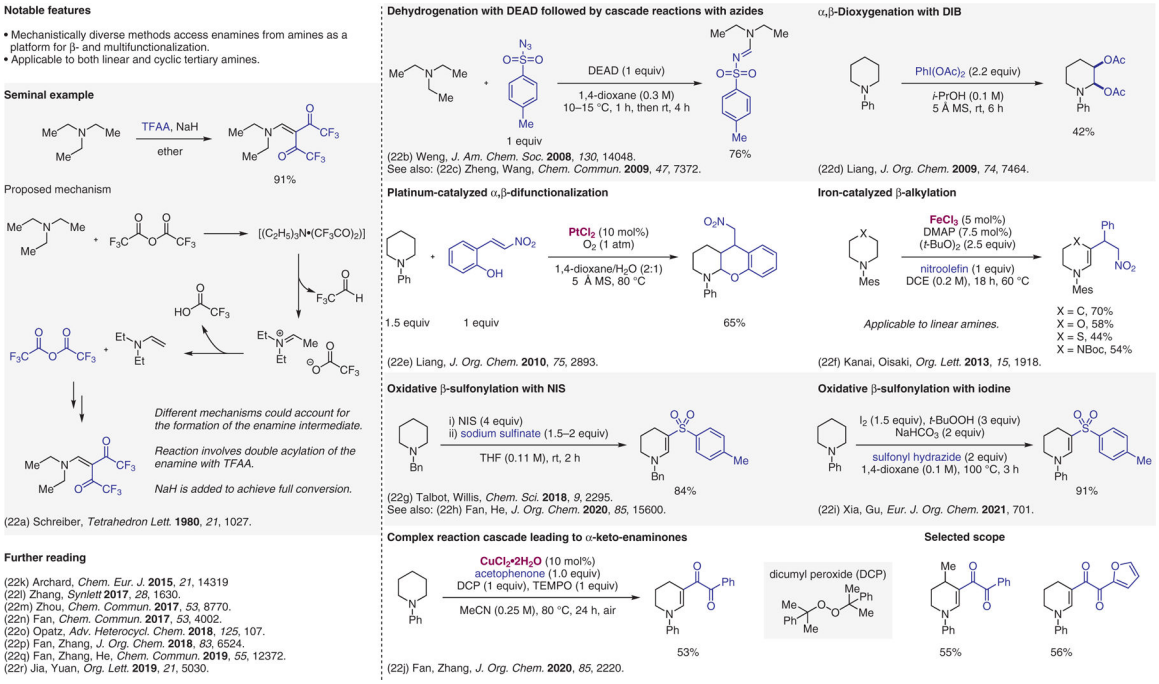


Figure 22.
Oxidative β-functionalization.[22]

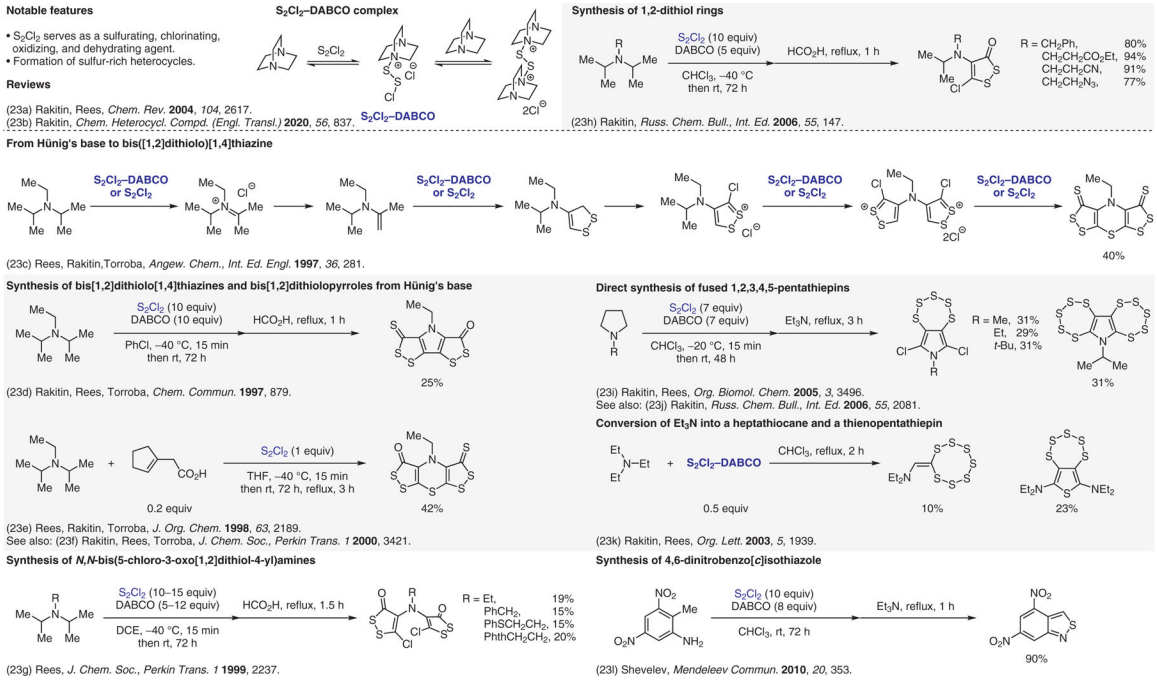


Figure 23.
Oxidative formation of sulfur-rich heterocycles.[23]

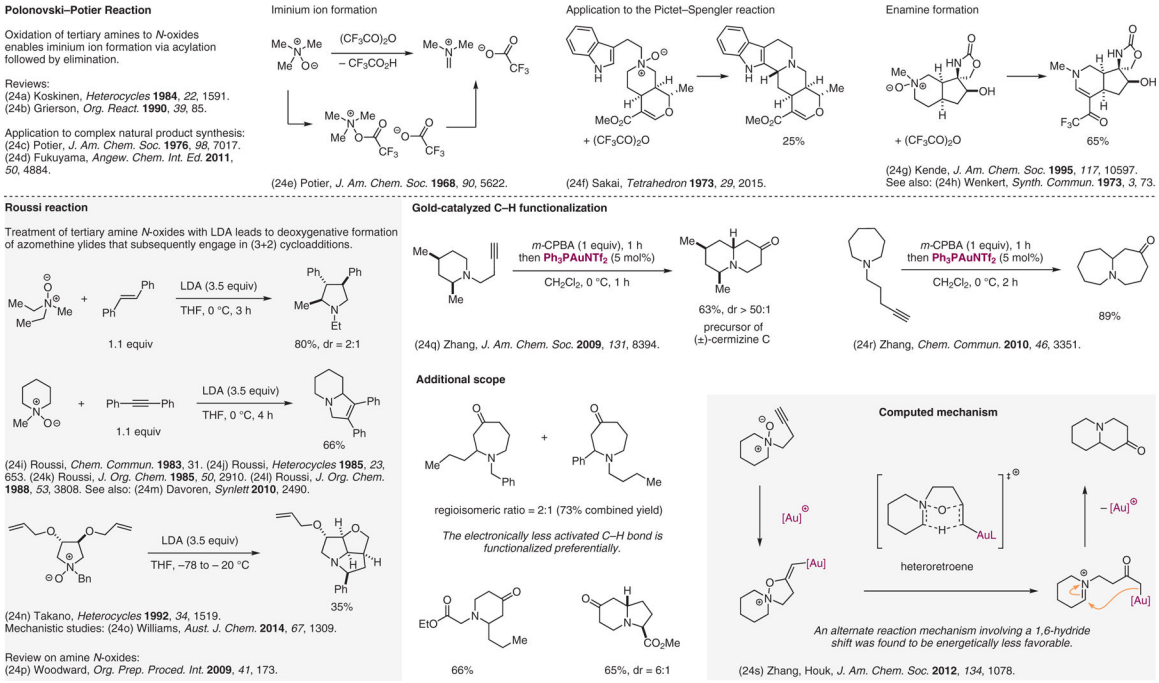


Figure 24.
Reactions involving amine *N*-oxides.[24]

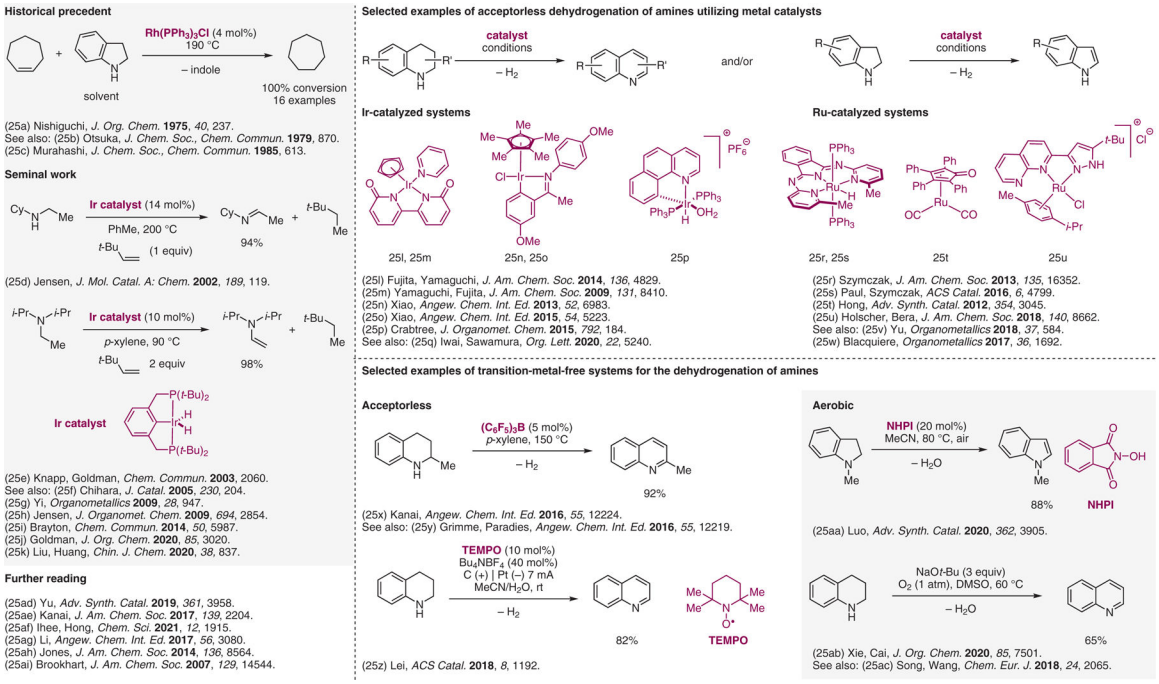


Figure 25.
Dehydrogenation/aromatization.[25]

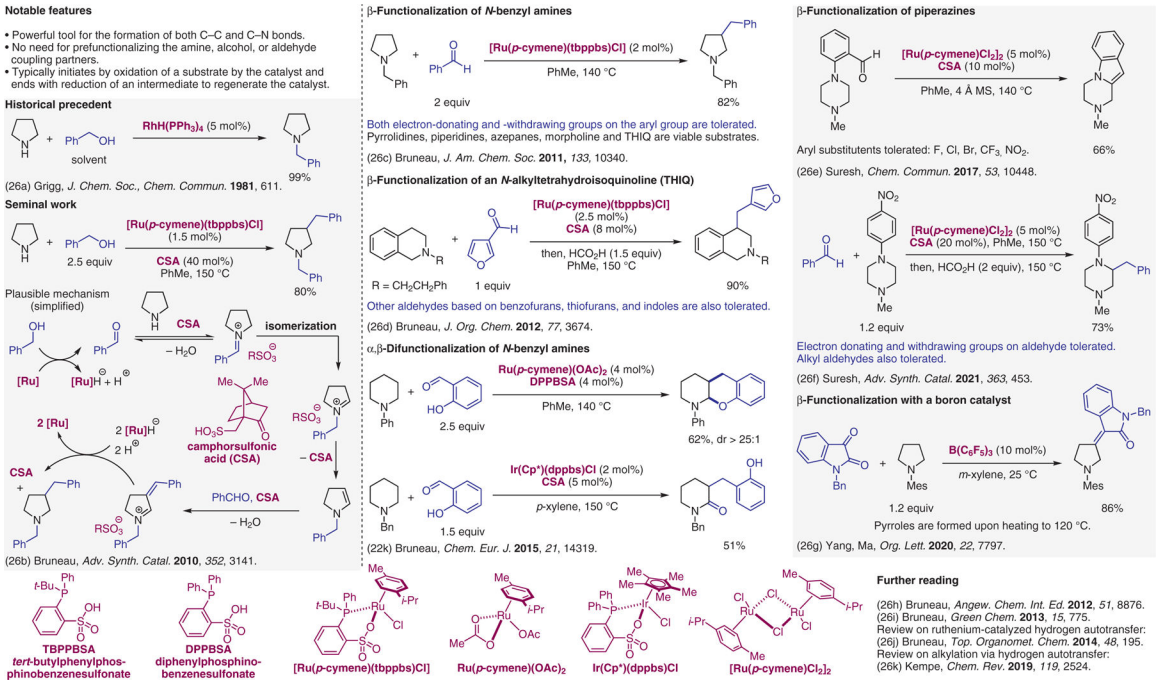


Figure 26.
Hydrogen borrowing.[26]

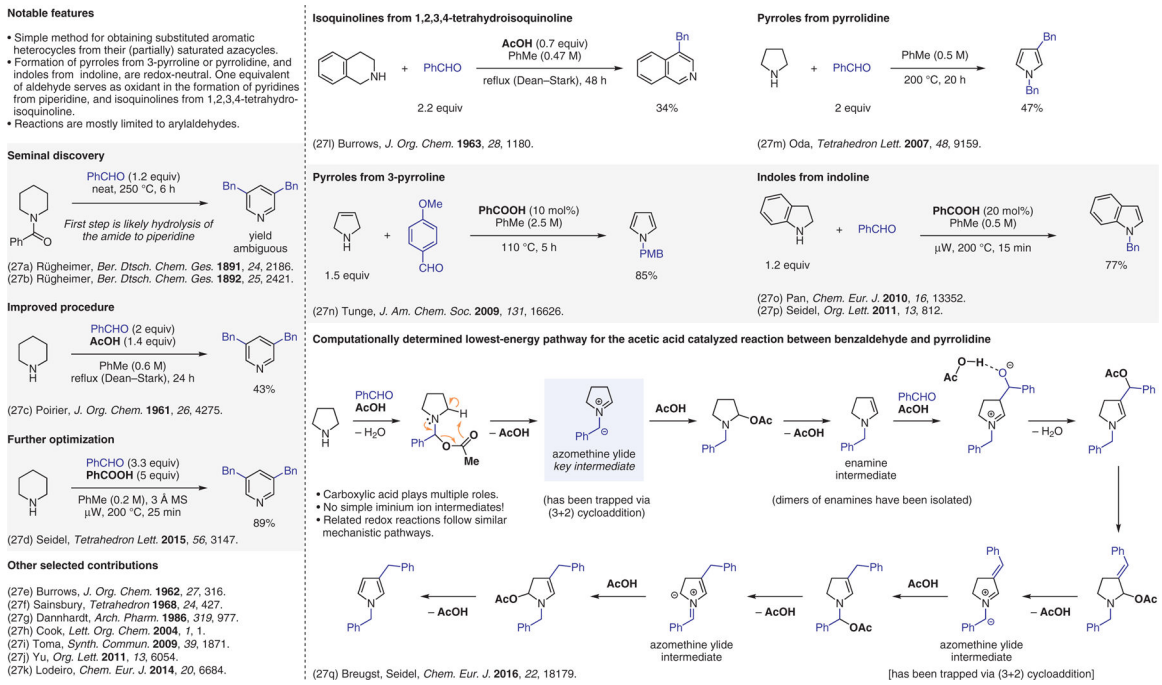


Figure 27.

Condensation-based methods involving azomethine ylide intermediates, aromatization.[27]

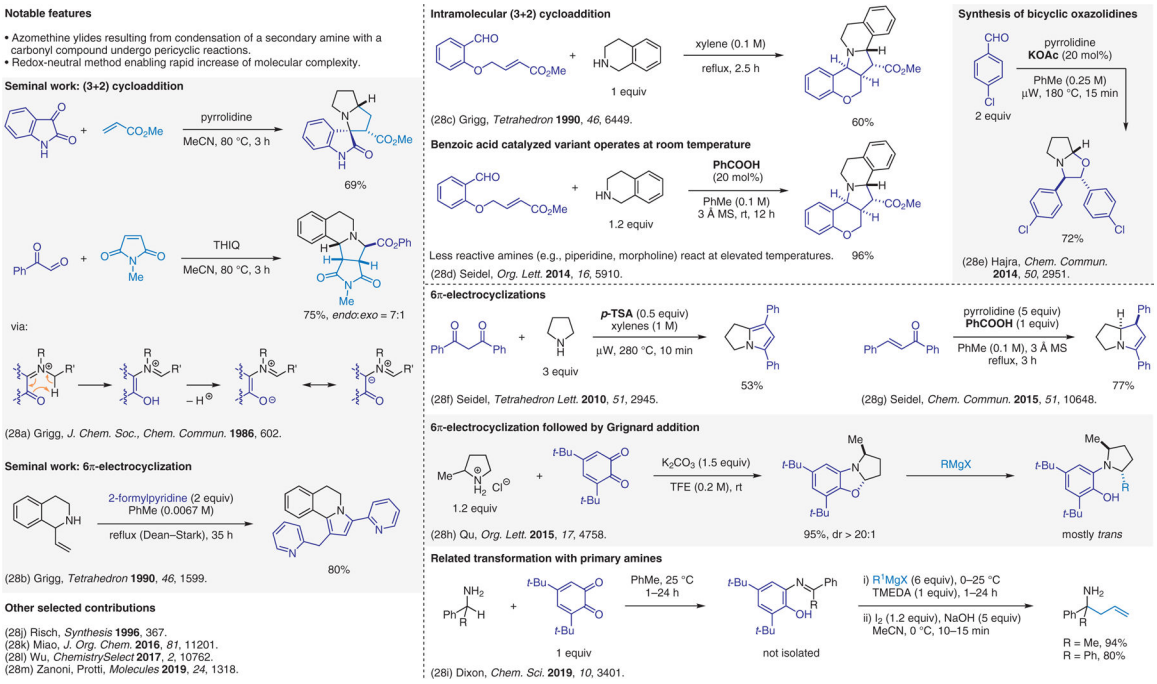


Figure 28.

Condensation-based methods involving azomethine ylide intermediates, pericyclic reactions.[28]

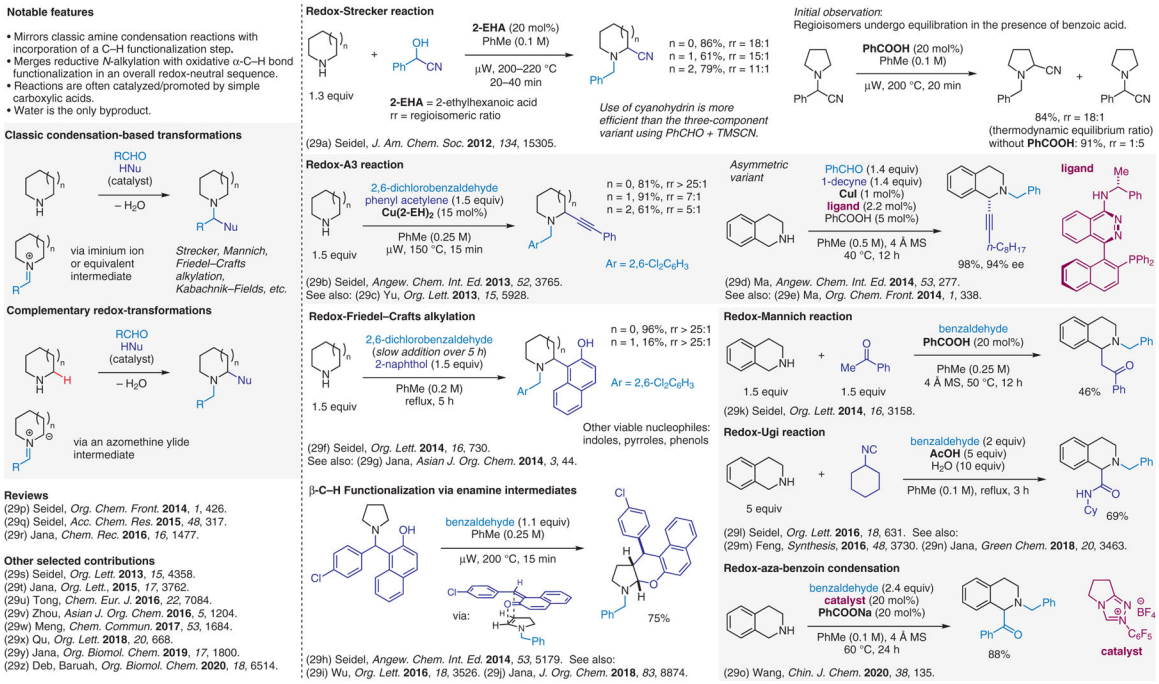


Figure 29.

Condensation-based methods involving azomethine ylide intermediates, redox-neutral 3-component coupling reactions.[29]

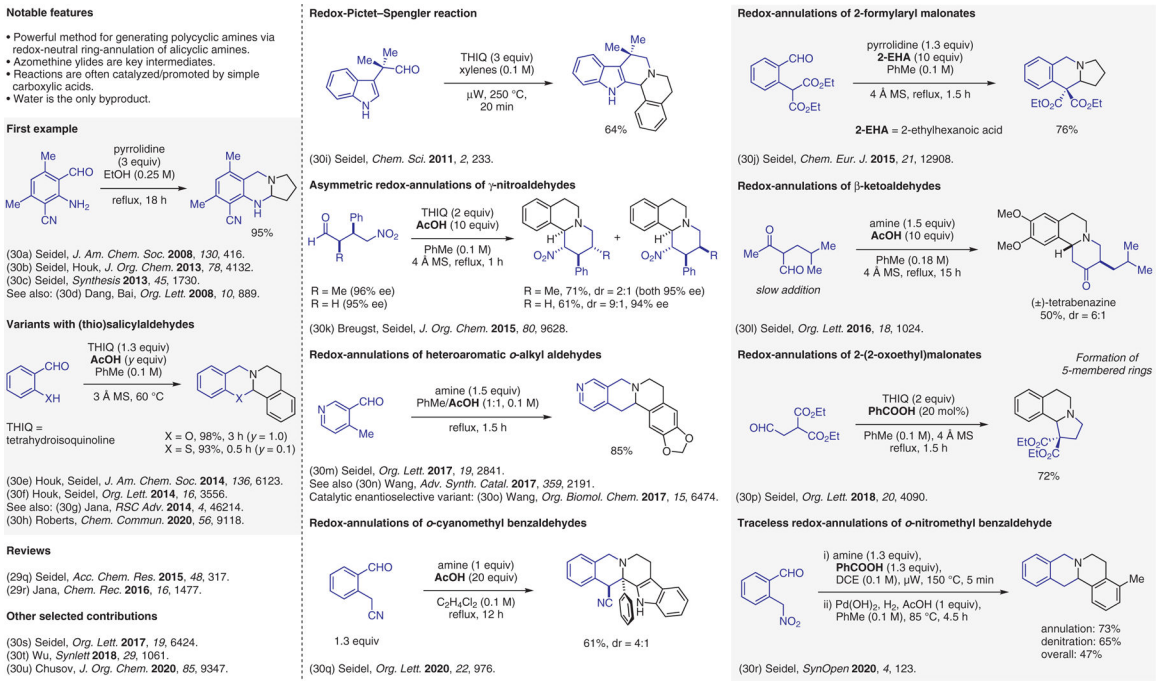


Figure 30.

Condensation-based methods involving azomethine ylide intermediates, redox-annulations.[30]

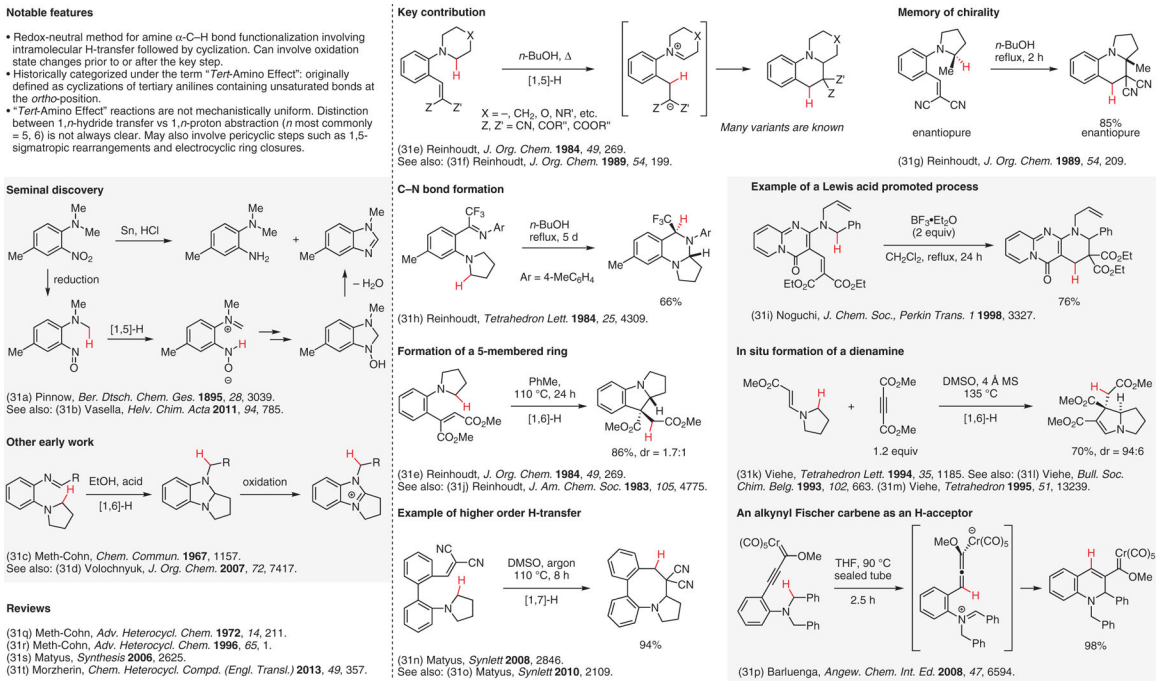


Figure 31.

Internal redox transformations involving [1,*n*]-H transfers, the '*tert*-amino effect'.[31]

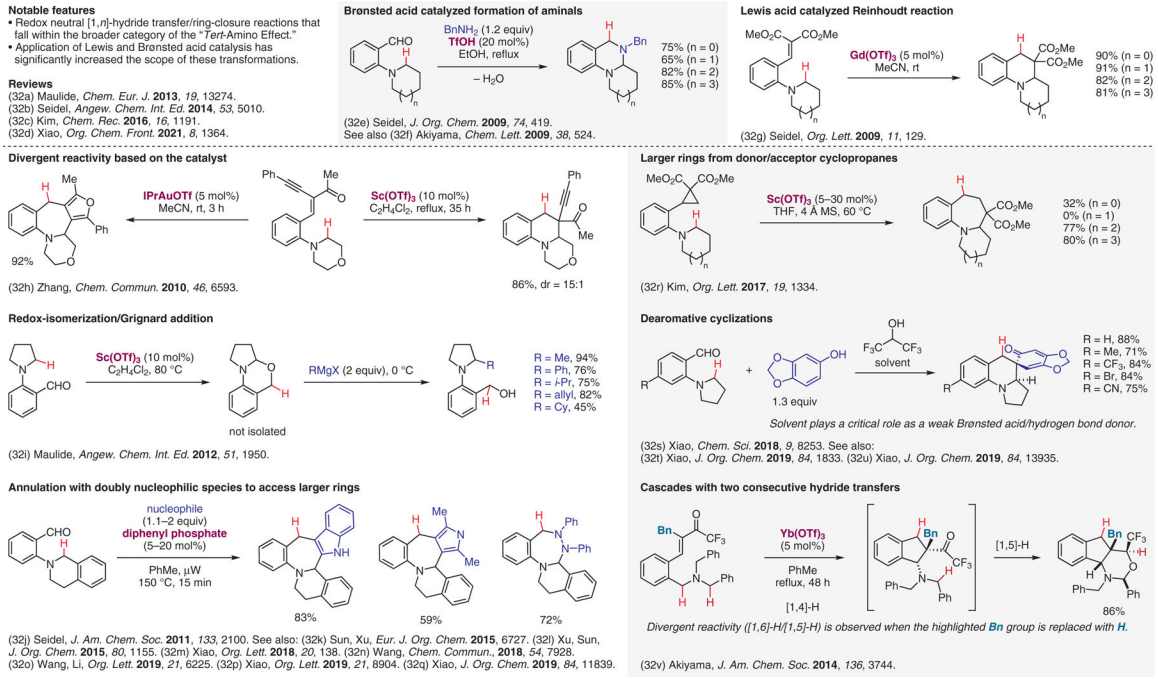


Figure 32.

Lewis and Brønsted acid catalyzed internal redox transformations involving [1,*n*]-H transfers.[32]

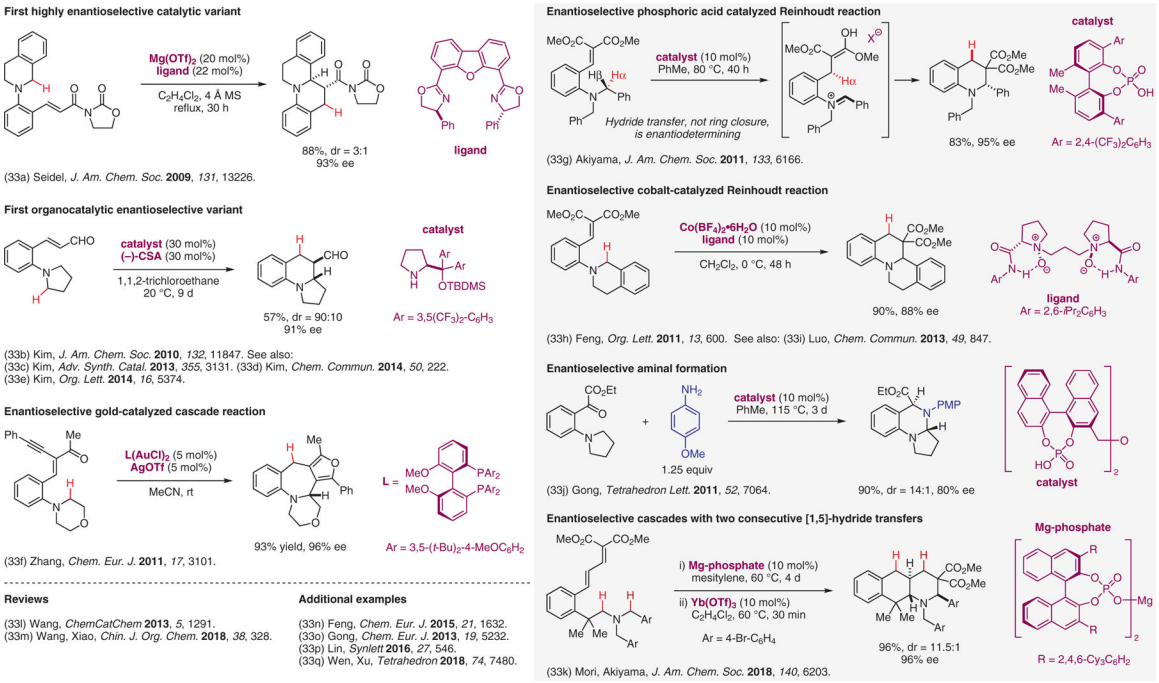


Figure 33.

Catalytic enantioselective internal redox transformations involving [1,*n*]-H transfers.[33]

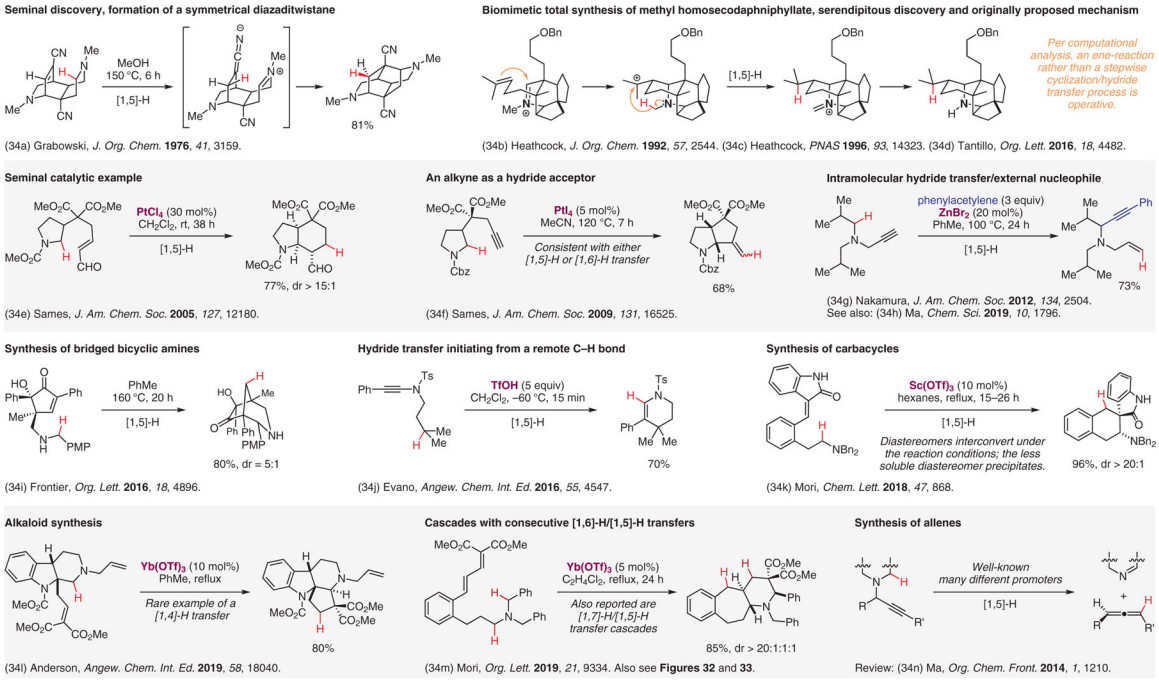


Figure 34.

Internal redox transformations involving [1,*n*]-H transfers in non-conjugated systems.[34]

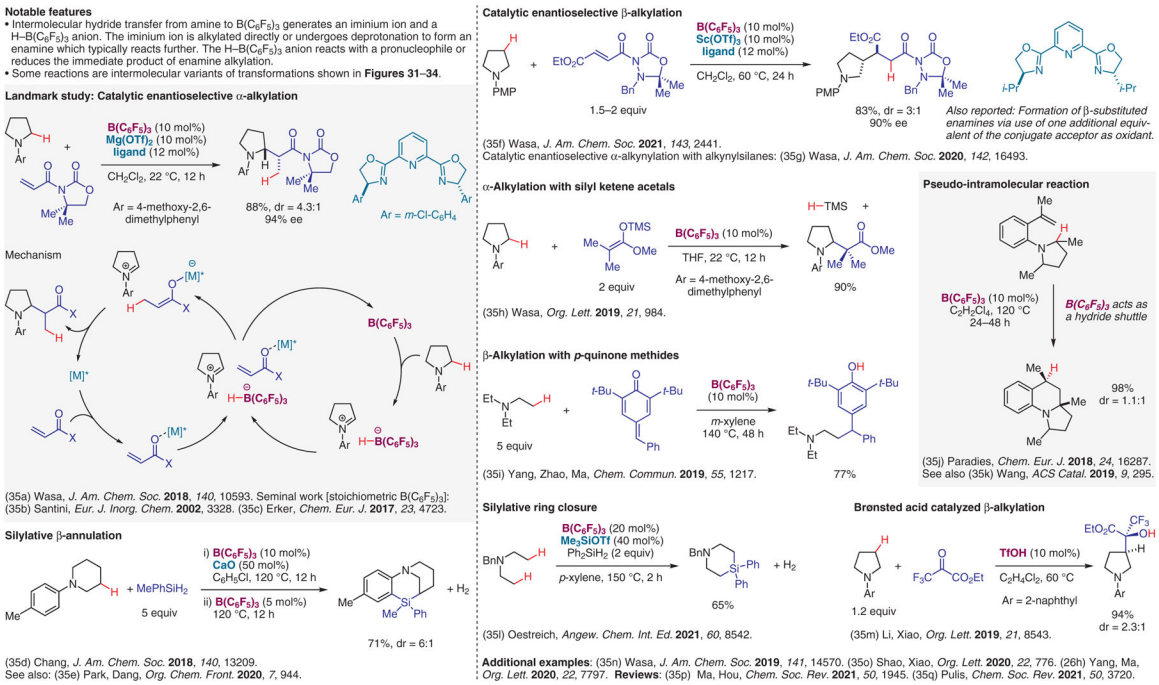


Figure 35.
(Redox-neutral) methods involving intermolecular hydride transfer.[35]

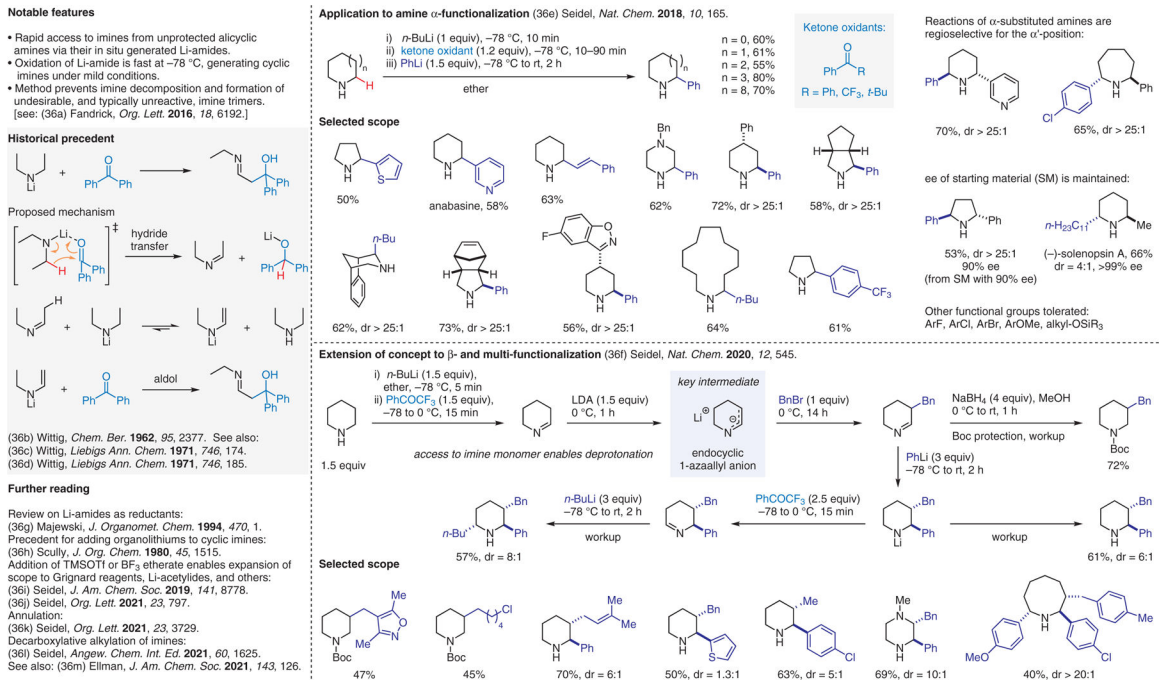
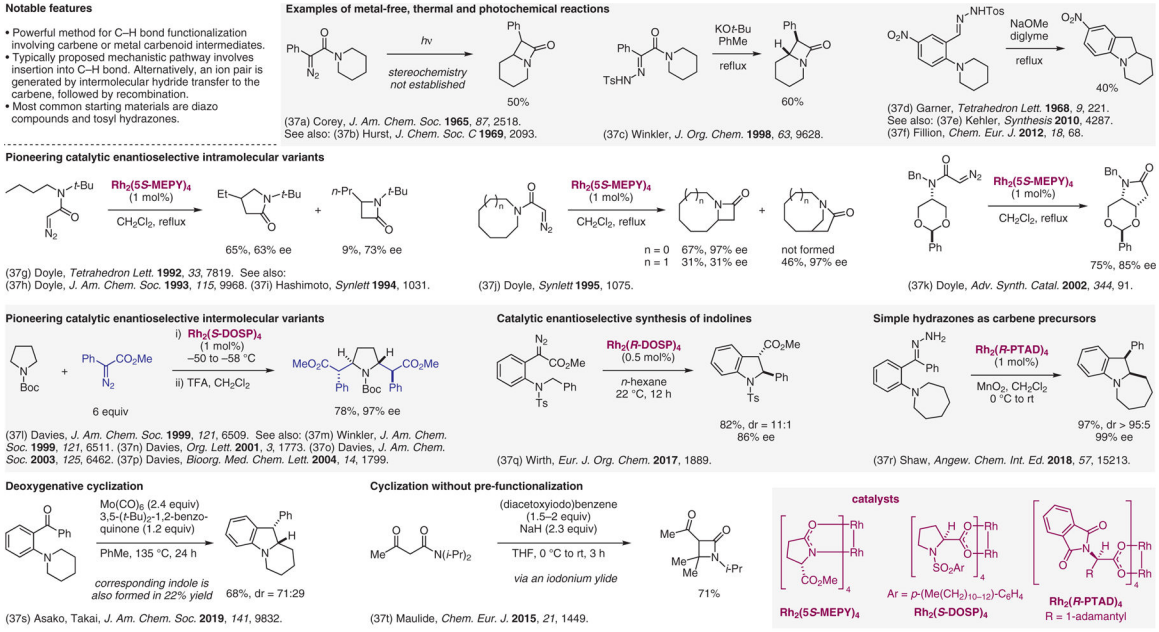


Figure 36.
Li-amide-based imine and 1-azaallyl anion generation from unprotected azacycles.[36]



Additional examples: (37u) Doyle, *Tetrahedron Lett.* **1996**, *37*, 1371. (37v) Sulikowski, *Tetrahedron* **1997**, *53*, 16521. (37w) Sulikowski, *Tetrahedron Lett.* **1999**, *40*, 8035. (37x) Compain, *Org. Lett.* **2006**, *8*, 4493. (37y) Compain, *Tetrahedron Lett.* **2007**, *48*, 8531. (37z) Davies, *Nat. Commun.* **2015**, *6*, 5943. (37aa) Chen, Arnold, *ACS Catal.* **2020**, *10*, 5393. **Reviews**: (37ab) Davies, *Chem. Rev.* **2003**, *103*, 2861. (37ac) Davies, *Nature* **2008**, *451*, 417. (37ad) Doyle, *Chem. Rev.* **2010**, *110*, 704. (37ae) Davies, *Chem. Soc. Rev.* **2011**, *40*, 1857. (37af) Sultanova, *Chem. Heterocycl. Compd. (Engl. Transl.)* **2015**, *51*, 775.

Figure 37.
Reactions involving carbenes or metal carbenoids.[37]

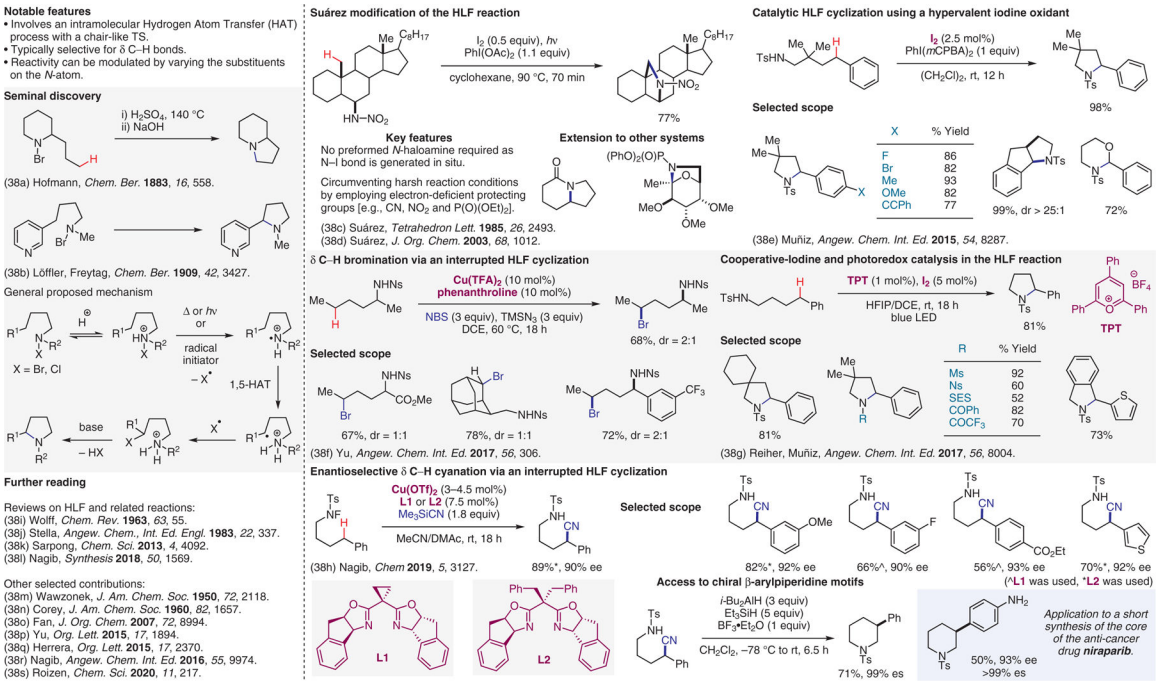


Figure 38.
Hofmann–Löffler–Freytag (HLF) reaction.[38]

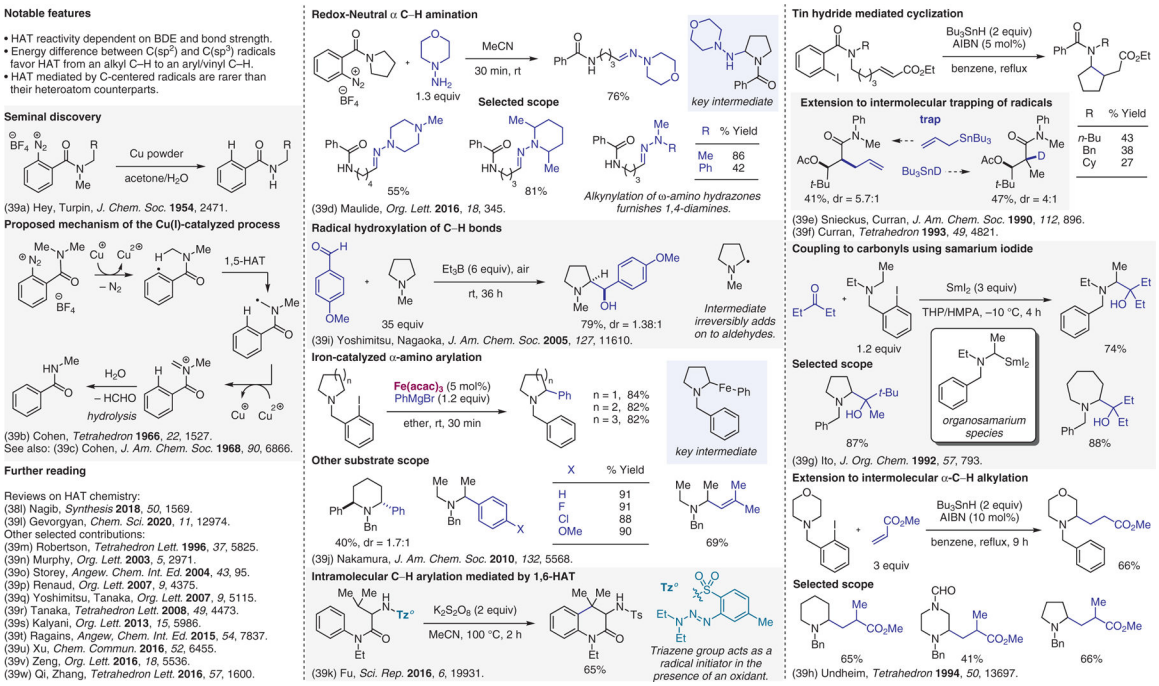


Figure 39.
Miscellaneous radical-based methods.[39]

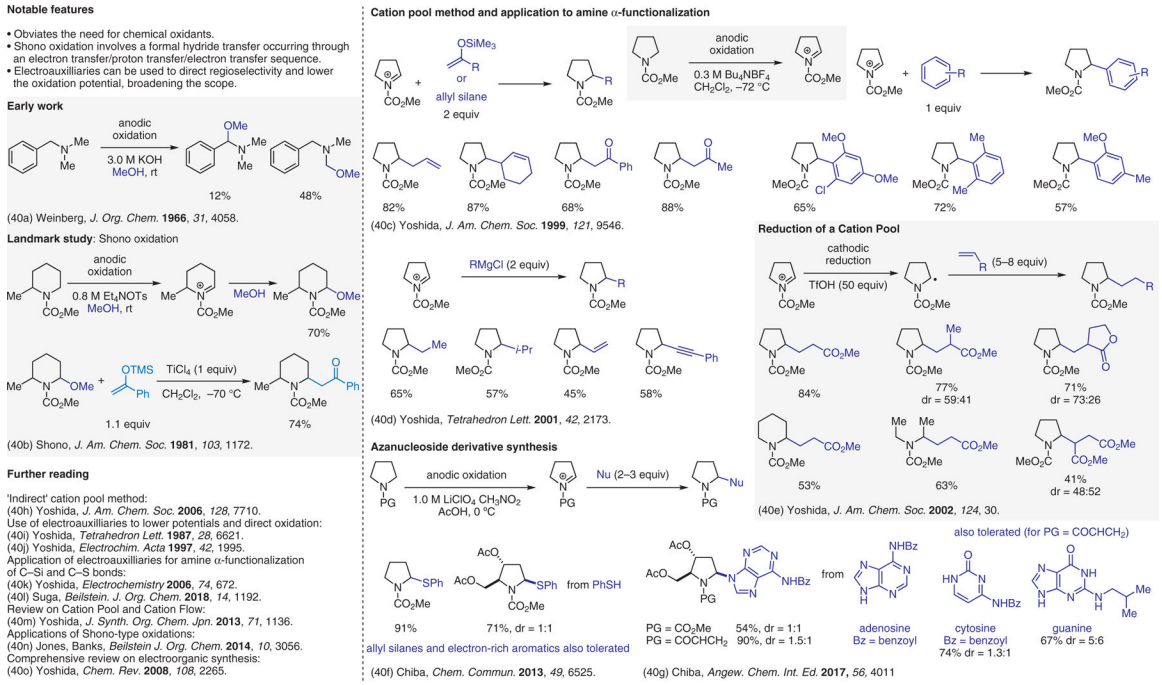


Figure 40.
Electrochemical approaches, cation pool method.[40]

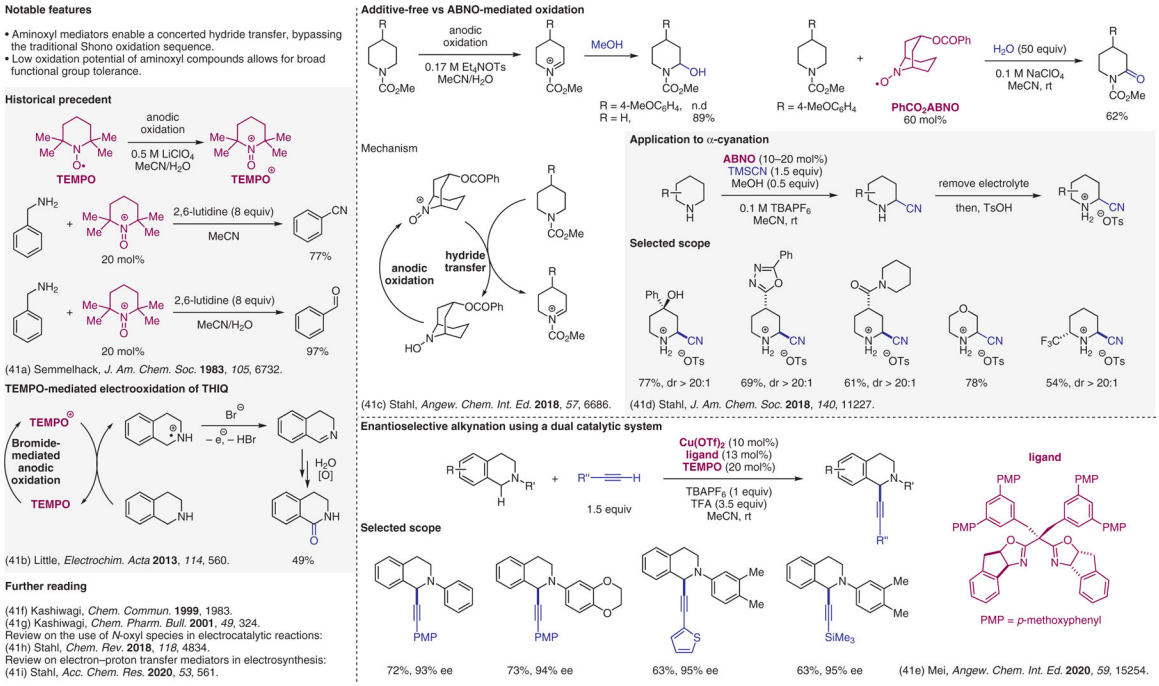


Figure 41.

Electrochemical approaches, 9-azabicyclo[3.3.1]nonane *N*-oxyl (ABNO) catalysis.[41]

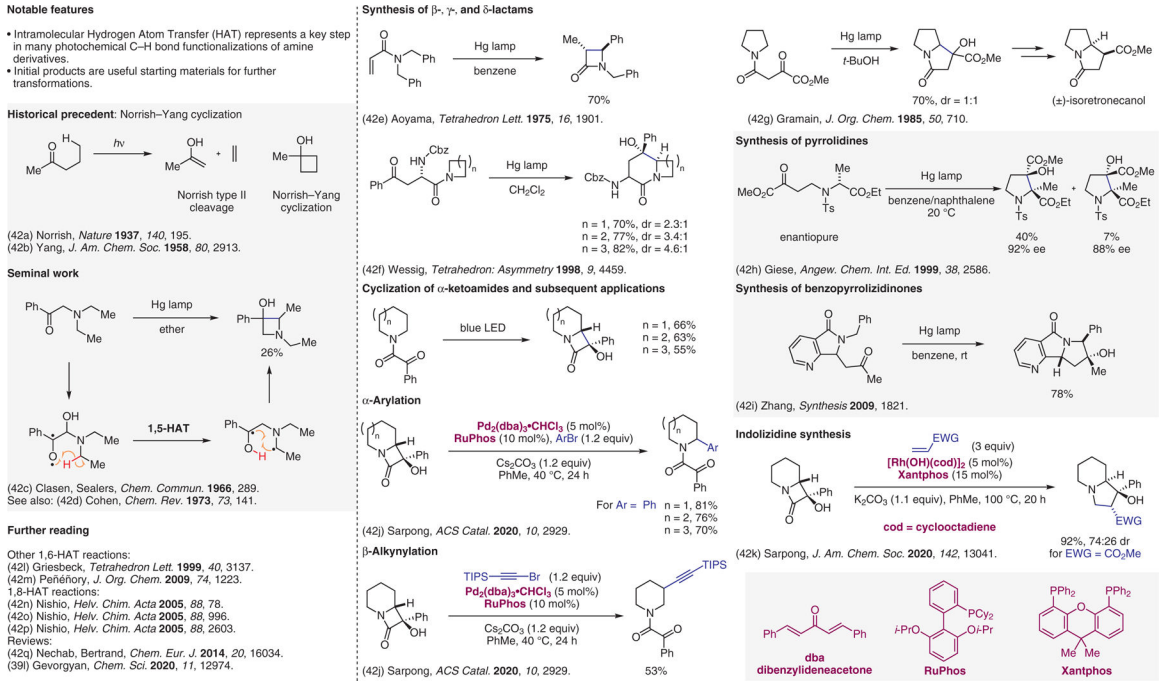


Figure 42.
Intramolecular hydrogen atom transfer (HAT).[42]

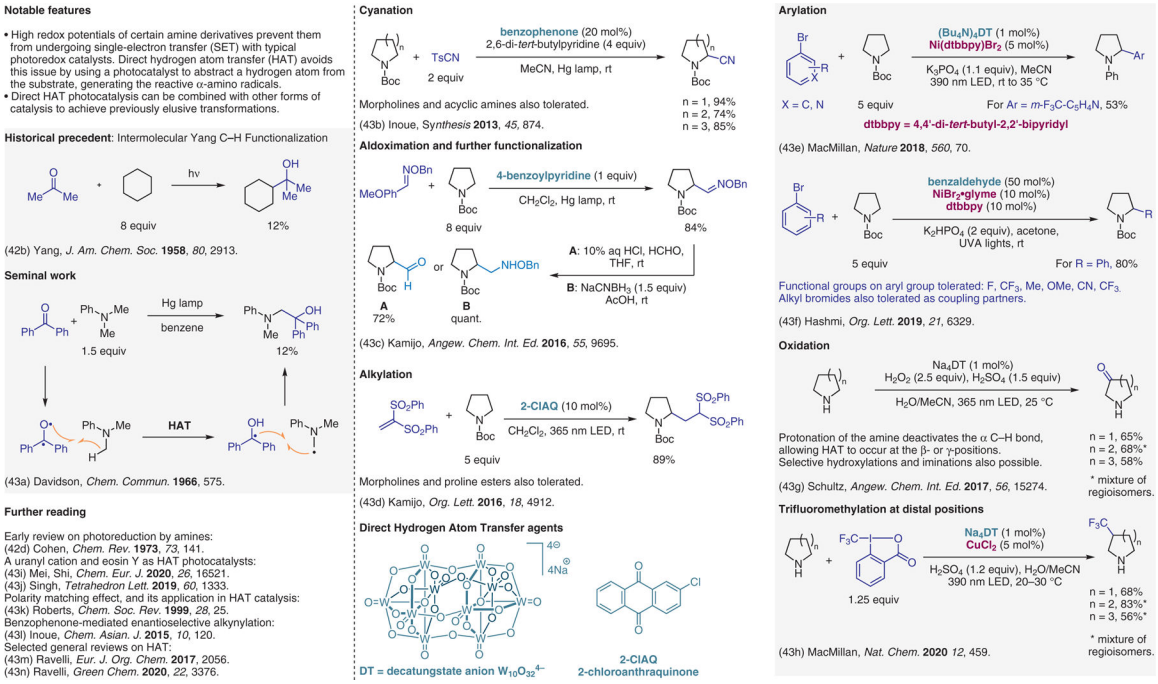


Figure 43.
Direct hydrogen atom transfer (HAT).[43]

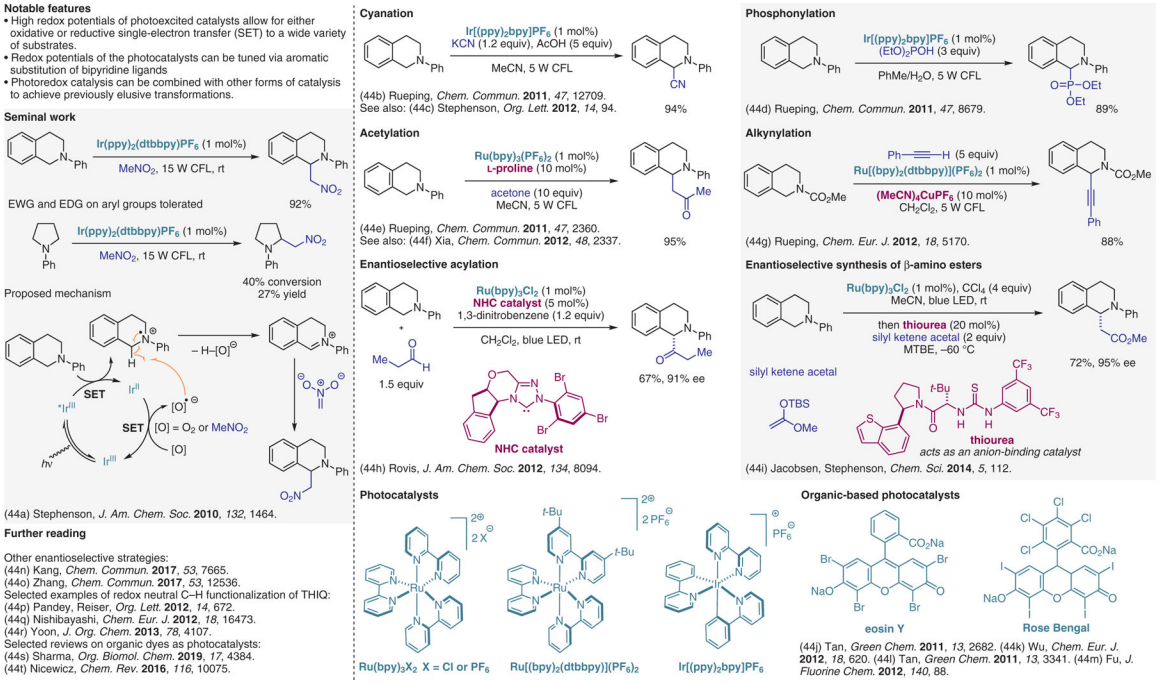


Figure 44.
Photoredox approaches, part I.[44]

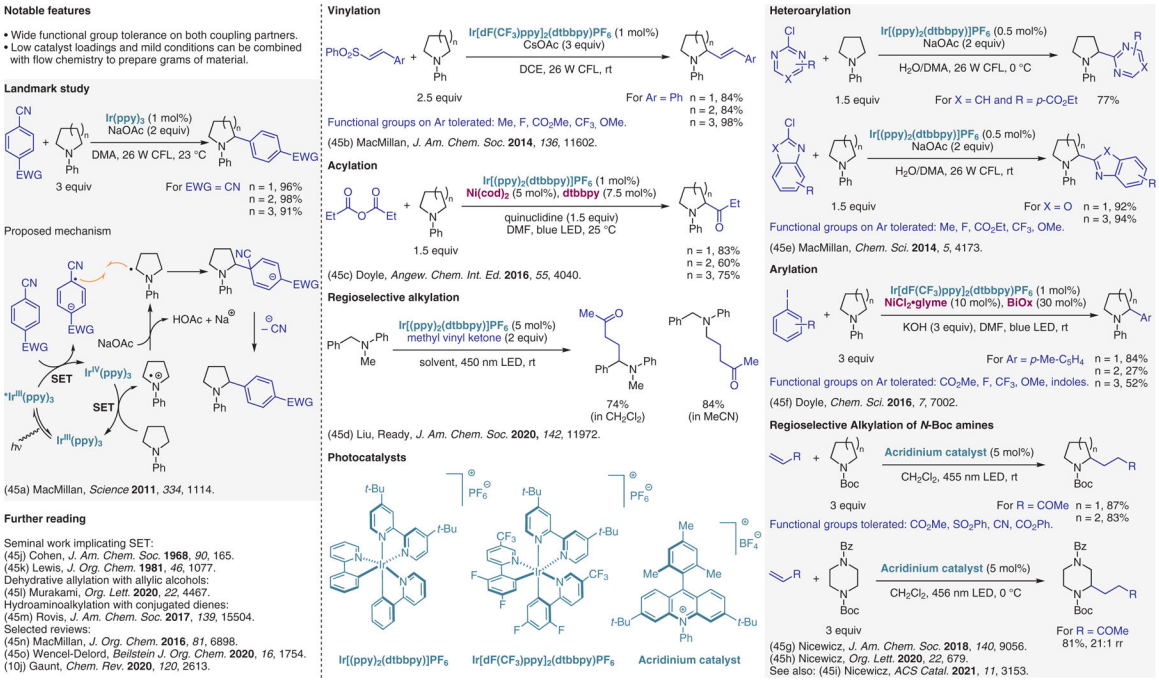


Figure 45.
Photoredox approaches, part II.[45]

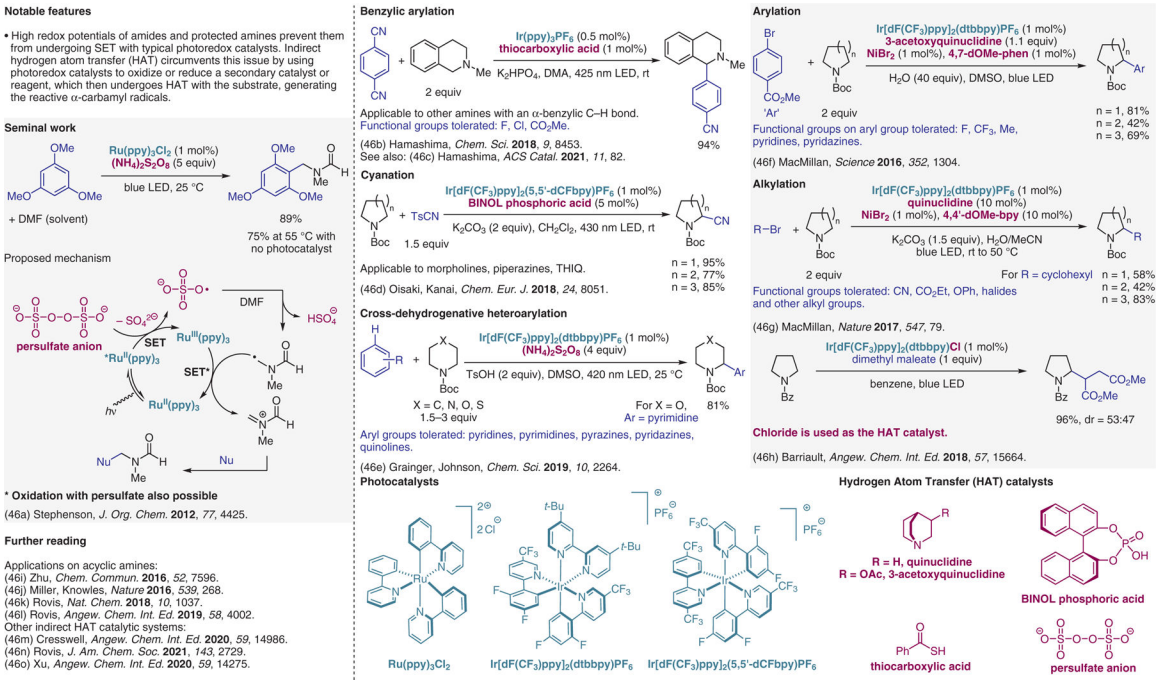


Figure 46.
Indirect hydrogen atom transfer (HAT).[46]

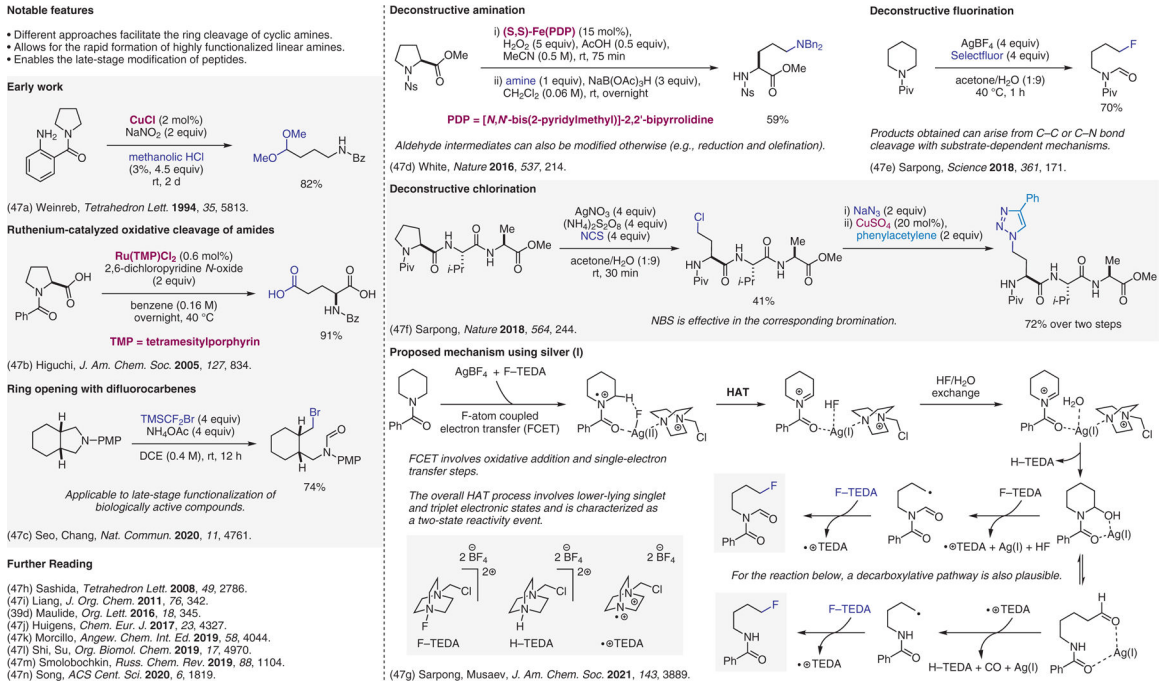


Figure 47.
Deconstructive functionalization.[47]