New Pyrazole-Based Ligands and Their Complexes for Application in Transfer Hydrogenation and Hydrosilylation

Iryna Alshakova

A thesis submitted to the Faculty of Graduate Studies in partial fulfillment of the requirements for the degree of Doctor of Philosophy

Chemistry Department
Faculty of Mathematics and Science
Brock University

St. Catharines, Ontario
April, 2019
© Iryna Alshakova, 2019
Abstract

A series of bidentate and tridentate ligands bearing pyrazolyl moiety in combination with phosphine, oxazoline, amine, and sulfide were synthesized. These ligands were applied for the synthesis of ruthenium complexes, that would be efficient in catalyzing transfer hydrogenation reaction in alcohol. From a number of obtained complexes, a mixture of two isomeric ruthenium complexes III-20/20’ was found to be the most efficient in reduction of acetophenone and N-benzylideneaniline, as model substrates, with 2-propanol. III-20/20’ was successfully applied in transfer hydrogenation of nitriles, heterocyclic compounds, olefins, and alkynes in 2-propanol. Activated esters can be reduced in the presence of III-20/20’, when ethanol was used as a hydrogen source.

III-20/20’ was also applied in the synthesis of secondary amines via hydrogen borrowing methodology. A number of primary amines and anilines were combined with primary alcohols under the conditions, optimized for transfer hydrogenation of nitriles, resulting in corresponding secondary amines. Furthermore, ammonium formate was used as a nitrogen source for alcohol amination. Thus, secondary and tertiary amines were obtained from primary alcohols.

Another project was focused on transfer hydrogenation of carbonyl compounds with lithium isopropoxide. Addition of various ligands and small molecules was found to improve the reaction efficiency for aromatic substrates. Further studies revealed that lithium cation forms stable adduct with aromatic alcohols, while different additives help to break this interaction, thus resulting in significant improvement of the conversion to alcohols. Another
strategy that was applied to improve the reaction yields was the addition of a cheap source of lithium cations, such as LiCl.

Finally, new zinc complex III-58 was synthesized and applied in catalytic hydrosilylation of carbonyl compounds. Reaction conditions optimization revealed that presence substoichiometric amounts of methanol in the system significantly accelerates the process. The reaction can proceed at very low catalyst load (down to 0.1mol%) under relatively mild reaction conditions. The substrate scope analysis showed the tolerance to carbon-carbon double bond. Thus, this procedure is efficient for the synthesis of allylic alcohols from α,β-unsaturated aldehydes and ketones.
Acknowledgements

Foremost, I would like to thank my supervisor Dr. Georgii Nikonov for the opportunity to work as a part of his research group. I am sincerely grateful for this valuable experience in my life. I have always admired your enthusiasm and devotion to chemistry. Thank you for your time, your support and encouragement.

I would like to express my gratitude to my graduate committee members Dr. Costa Metallinos and Dr. Travis Dudding for their helpful suggestions. I would also like to acknowledge Dr. Martin Lemaire and Dr. Tony Yan for participation in my candidacy examination. I want to express my appreciation to the excellent staff members at Brock. Many thanks to John Vandenhoff from the glassblowing shop, Steve Crumb from the machine shop, and Irene Palumbo, Alison Moffat, and Parthajit Mukherjee from the Science Stores, Marie Harris and Jenn Roberts. Special thanks to Razvan Simionescu for his invaluable assistance with all things related to NMR spectroscopy, Dr. Liqun Qiu for her help with GC-MS and HPLC-MS analysis, Dr. Bulat Gabidullin, Dr. Ilya Korobkov, and Dr. Lyudmila G. Kuzmina for their assistance in collecting and solving X-ray diffraction data.

Furthermore, I would like to thank the former and current members of the Nikonov lab for their support and friendship: Dr. Terry Chu, Dr. Van Hung Mai, Kostya Piatrou, Minh Tho Nyugen, Kayla Jakobsson, John Lortie, Jan-Willem Lamberink, Billy Petrushko, Josh Clarke, Anton Dmitrienko, Aisha Kassymbek, and Aliona Baradzenka. Since it is impossible to mention here everyone that I wish to, I want to thank all the research group members of the Chemistry department at Brock University, especially the Hudlicky, Lemaire, Dudding, Metallinos, Pilkington, Stamatatos and Yan groups.

Finally, I wish to thank my family, and especially my husband for his endless love and support.
Table of Contents

Abstract.................................................................................................................. i
Acknowledgements.................................................................................................. iii
Table of Contents.................................................................................................... iv
List of Abbreviations................................................................................................ vii
List of Figures.......................................................................................................... ix
List of Schemes........................................................................................................ xii
List of Tables........................................................................................................... xvi

I. Introduction....................................................................................................... 1

II. Historical........................................................................................................... 4
   II. 1. Transition metal-catalyzed transfer hydrogenation..................................... 4
       II. 1. 1. Introduction.......................................................................................... 4
       II. 1. 2. Milestones in transition metal-catalyzed transfer hydrogenation........ 5
       II. 1. 3. Ir, Rh and Ru catalysts for transfer hydrogenation of carbonyl compounds.............................................................................................................. 10
       II. 1. 4. Ir, Rh, and Ru catalysts for transfer hydrogenation of imines.......... 20
       II. 1. 5. Transfer hydrogenation of nitriles....................................................... 24
       II. 1. 6. Transfer hydrogenation of heterocyclic compounds.......................... 27
       II. 1. 7. Transfer hydrogenation of carboxylic acids and their derivatives..... 29
       II. 1. 8. Transfer hydrogenation of olefins and alkynes................................. 31
   II. 2. C-N bond-formation reactions by borrowing hydrogen catalysis for amine production...................................................................................................... 37
       II. 2. 1. Introduction.......................................................................................... 37
       II. 2. 2. Activation of alcohols........................................................................ 38
       II. 2. 3. Activation of amines......................................................................... 50
   II. 3. Reduction via direct hydrogen transfer..................................................... 53
       II. 3. 1. Meerwein-Ponndorf-Verley reduction............................................... 53
       II. 3. 2. Alkali metal-catalyzed transfer hydrogenation.................................. 57
   II. 4. Zinc-catalyzed hydrosilylation................................................................. 64
       II. 4. 1. Introduction.......................................................................................... 64
       II. 4. 2. Zinc-catalyzed hydrosilylation of carbonyl compounds.................. 65
V. 4. Transfer hydrogenation

V. 4. 1. Transfer hydrogenation of nitriles in 2-propanol

V. 4. 2. Transfer hydrogenation of nitriles in ethanol

V. 4. 3. Transfer hydrogenation of heterocyclic compounds

V. 4. 4. Transfer hydrogenation of olefins

V. 4. 5. Transfer hydrogenation of alkynes

V. 4. 6. Transfer hydrogenation of esters

V. 4. 7. Kinetic studies of transfer hydrogenation of cyclohexene

V. 4. 8. Z-E isomerization

V. 5. Amine alkylation via hydrogen borrowing methodology

V. 6. Transition metal-free transfer hydrogenation

V. 6. 1. Kinetic studies of transfer hydrogenation with LiO\textsubscript{i}Pr

V. 7. Hydrosilylation with zinc complex

VI. Appendix

VII. References
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^1$H</td>
<td>proton decoupled</td>
</tr>
<tr>
<td>°C</td>
<td>degrees Celsius</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>temperature coefficient</td>
</tr>
<tr>
<td>$\delta$</td>
<td>chemical shift</td>
</tr>
<tr>
<td>$\Delta H^\neq$</td>
<td>activation enthalpy</td>
</tr>
<tr>
<td>$\Delta S^\neq$</td>
<td>activation entropy</td>
</tr>
<tr>
<td>Å</td>
<td>Angström</td>
</tr>
<tr>
<td>A</td>
<td>Arrhenius constant</td>
</tr>
<tr>
<td>Alk</td>
<td>Alkyl</td>
</tr>
<tr>
<td>Ar</td>
<td>Aryl</td>
</tr>
<tr>
<td>atm</td>
<td>atmosphere (1 atm = 1 bar, 760 mm Hg, 101.3 kPa, 14.969 psi)</td>
</tr>
<tr>
<td>Bn</td>
<td>benzyl</td>
</tr>
<tr>
<td>br</td>
<td>broad (NMR)</td>
</tr>
<tr>
<td>Bu</td>
<td>butyl</td>
</tr>
<tr>
<td>cod</td>
<td>cyclooctadiene</td>
</tr>
<tr>
<td>coe</td>
<td>cyclooctene</td>
</tr>
<tr>
<td>Cp</td>
<td>$\eta^5$-C$_5$H$_5$</td>
</tr>
<tr>
<td>Cp*</td>
<td>$\eta^5$-C$_5$(Me)$_5$</td>
</tr>
<tr>
<td>Cy</td>
<td>cyclohexyl</td>
</tr>
<tr>
<td>d</td>
<td>doublet (NMR)</td>
</tr>
<tr>
<td>DCM</td>
<td>dichloromethane</td>
</tr>
<tr>
<td>Dipp</td>
<td>2,6-diisopropylphenyl</td>
</tr>
<tr>
<td>DMAP</td>
<td>4-dimethylaminopyridine</td>
</tr>
<tr>
<td>DME</td>
<td>1,2-dimethoxyethane</td>
</tr>
<tr>
<td>DMF</td>
<td>dimethylformamide</td>
</tr>
<tr>
<td>DMSO</td>
<td>dimethyl sulfoxide</td>
</tr>
<tr>
<td>dppe</td>
<td>1,2-Bis(diphenylphosphino)ethane</td>
</tr>
<tr>
<td>e</td>
<td>electron</td>
</tr>
<tr>
<td>Ea</td>
<td>activation energy</td>
</tr>
<tr>
<td>EA</td>
<td>elemental analysis</td>
</tr>
<tr>
<td>Et</td>
<td>ethyl</td>
</tr>
</tbody>
</table>
g  gram(s)
h  hour(s)
h  Planck constant
hept  heptet (NMR)
Hz  Hertz
Hex  hexyl
iPr  isopropyl
IR  infrared spectroscopy
J  coupling constant (NMR)
k_{obs}  observed reaction rate constant
K  Kelvin
M  central metal atom in a complex
m  meta
m  multiplet (NMR)
Me  methyl
Mes  mesityl
MPV  Meerwein-Ponndorf-Verley reaction
NacNac  \( \beta \)-diketiminate
NHC  N-heterocyclic carbene
NMR  nuclear magnetic resonance
o  ortho
p  para
Ph  phenyl
Py  pyridine
q  quartet (NMR)
RT  room temperature
s  singlet (NMR)
t  triplet (NMR)
tBu  tert-butyl
TH  transfer hydrogenation
THF  tetrahydrofuran
TMS  trimethylsilyl
TOF  turnover frequency
TON  turnover number
List of Figures

Figure 1. Molecular structure of complex III-14. Thermal ellipsoids are given at 30% probability. Hydrogen atoms and the molecule of CH₂Cl₂ solvate are omitted for clarity. ................................................................. 85
Figure 2. Molecular structure of complex III-19. Thermal ellipsoids are given at 30% probability. Hydrogen atoms are omitted for clarity. ................................. 89
Figure 3. Molecular structure of complex III-21. Thermal ellipsoids are shown at 30% probability. Hydrogen atoms are omitted for clarity. ................................. 92
Figure 4. Molecular structure of complex III-25. Thermal ellipsoids are shown at 30% probability. Hydrogen atoms are omitted for clarity. ................................. 96
Figure 5. The dependence of effective rate constant Keff on the catalyst load under the pseudo first order conditions ....................................................... 117
Figure 6. The effective rate constant vs the amount of 2-propanol ................... 118
Figure 7. The Hammett plot for the N-alkylation of anilines with different substituents in the para position of the benzene ring relative to the reaction with unsubstituted aniline ................................................................. 128
Figure 8. Kinetic profiles for transfer hydrogenation of acetophenone in 2-propanol catalyzed by LiOiPr, NaOiPr, and KOiPr ....................................................... 135
Figure 9. Kinetic profiles for transfer hydrogenation of cyclohexanone in 2propanol catalyzed by LiOiPr, NaOiPr, and KOiPr ....................................................... 132
Figure 10. Keff of transfer hydrogenation of cyclohexanone with various concentration of LiOiPr ................................................................. 144
Figure 11. Keff of transfer hydrogenation of cyclohexanone with various amounts of 2-propanol ................................................................. 144
Figure 12. Keff of transfer hydrogenation of cyclohexanone at temperatures between 70 and 90°C ................................................................. 145
Figure 13. Linearization of data in Arrhenius coordinates: ln(Keff) vs T⁻¹ ......... 146
Figure 14. Linearization of data in Eyring coordinates ln (KeffT⁻¹) vs T⁻¹ ......... 146
Figure 15. The Hammond plot for the transfer hydrogenation of acetophenones with different substituents in the para position of the benzene ring relative to the reaction with unsubstituted acetophenone ................................................................. 149
Figure 16. ¹H NMR spectrum of compound III-1a in CDCl₃ (*THF) ............... 222
Figure 17. ¹³C NMR spectrum of compound III-1a in CDCl₃ (*THF) ............... 222
Figure 18. ³¹P ¹H) NMR spectrum of compound III-1a in CDCl₃ ............... 222
Figure 19. ¹H NMR spectrum of compound III-1b in C₆D₆ ....................... 223
Figure 20. ¹³C NMR spectrum of compound III-1b in C₆D₆ ....................... 223
Figure 21. $^{31}$P $^{1}$H NMR spectrum of compound III-1b in C$_6$D$_6$ ......................... 223
Figure 22. $^1$H NMR spectrum of compound III-4a in CDCl$_3$ ................................. 224
Figure 23. $^{13}$C NMR spectrum of compound III-4a in CDCl$_3$ ................................. 224
Figure 24. $^1$H NMR spectrum of compound III-4b in CDCl$_3$ ................................. 225
Figure 25. $^{13}$C NMR spectrum of compound III-4b in CDCl$_3$ ................................. 225
Figure 26. $^1$H NMR spectrum of compound III-5a in CDCl$_3$ ................................. 226
Figure 27. $^{13}$C NMR spectrum of compound III-5a in CDCl$_3$ ................................. 226
Figure 28. $^1$H NMR spectrum of compound III-5b in CDCl$_3$ ................................. 227
Figure 29. $^{13}$C NMR spectrum of compound III-5b in CDCl$_3$ ................................. 227
Figure 30. $^1$H NMR spectrum of compound III-6 in CDCl$_3$ ................................. 228
Figure 31. $^{13}$C NMR spectrum of compound III-6 in CDCl$_3$ ................................. 228
Figure 32. $^1$H NMR spectrum of compound III-7 in CDCl$_3$ ................................. 229
Figure 33. $^{13}$C NMR spectrum of compound III-7 in CDCl$_3$ ................................. 229
Figure 34. $^1$H NMR spectrum of compound III-9 in CDCl$_3$ ................................. 230
Figure 35. $^{13}$C NMR spectrum of compound III-9 in CDCl$_3$ ................................. 230
Figure 36. $^1$H NMR spectrum of compound III-8 in CDCl$_3$ (*Et$_2$O) ....................... 231
Figure 37. $^{13}$C NMR spectrum of compound III-8 in CDCl$_3$ (*Et$_2$O) ....................... 231
Figure 38. $^1$H NMR spectrum of compound III-10 in CDCl$_3$ ................................. 232
Figure 39. $^{13}$C NMR spectrum of compound III-10 in CDCl$_3$ ................................. 232
Figure 40. $^1$H NMR spectrum of compound III-11a in CDCl$_3$ ................................. 233
Figure 41. $^{13}$C NMR spectrum of compound III-11a in CDCl$_3$ ................................. 233
Figure 42. $^1$H NMR spectrum of compound III-11b in CD$_3$CN .............................. 234
Figure 43. $^{13}$C NMR spectrum of compound III-11b in CD$_3$CN .............................. 234
Figure 44. $^1$H NMR spectrum of compound III-12 in CDCl$_3$ ................................. 235
Figure 45. $^{13}$C NMR spectrum of compound III-12 in CDCl$_3$ ................................. 235
Figure 46. $^1$H NMR spectrum of compound III-13 in CDCl$_3$ ................................. 236
Figure 47. $^{13}$C NMR spectrum of compound III-13 in CDCl$_3$ ................................. 236
Figure 48. $^1$H NMR spectrum of complex III-14 in CDCl$_3$ (*free DMSO) ............... 237
Figure 49. $^{13}$C NMR spectrum of complex III-14 in CDCl$_3$ ................................. 237
Figure 50. $^{31}$P $^{1}$H NMR spectrum of complex III-14 in CDCl$_3$ ............................ 237
Figure 51. $^1$H NMR spectrum of complex III-15 in CD$_2$Cl$_2$ ................................. 238
Figure 52. $^{13}$C NMR spectrum of complex III-15 in CD$_2$Cl$_2$ ................................. 238
Figure 53. $^{31}$P $^{1}$H NMR spectrum of complex III-15 in CD$_2$Cl$_2$ ............................ 238
Figure 54. $^1$H NMR spectrum of complexes III-16/16' in CD$_2$Cl$_2$ .......................... 239
Figure 55. $^{13}$C NMR spectrum of complexes III-16/16' in CD$_2$Cl$_2$ .......................... 239
Figure 56. $^{31}$P $[^1H]$ NMR spectrum of complexes III-16/16’ in CD$_2$Cl$_2$....................... 240
Figure 57. $^1$H NMR spectrum of complex III-17 in THF-d$_8$.............................................. 241
Figure 58. $^{31}$P $[^1H]$ NMR spectrum of complex III-17 in THF-d$_8$...................................... 241
Figure 59. $^1$H NMR spectrum of complex III-18 in CD$_2$Cl$_2$............................................. 242
Figure 60. $^{31}$P $[^1H]$ NMR spectrum of complex III-18 in CD$_2$Cl$_2$................................. 242
Figure 61. $^1$H NMR spectrum of complex III-19 in CD$_2$Cl$_2$............................................. 243
Figure 62. $^{13}$C NMR spectrum of complex III-19 in CDCl$_3$............................................. 243
Figure 63. $^{31}$P $[^1H]$ NMR spectrum of complex III-19 in CD$_2$Cl$_2$................................. 243
Figure 64. $^1$H NMR spectrum of complexes III-20/20’ in CDCl$_3$....................................... 244
Figure 65. $^1$H NMR spectrum (3.30-3.75 ppm) of complexes III-20/20’ in CDCl$_3$... 244
Figure 66. $^1$H NOE NMR spectrum of complexes III-20/20’ in CDCl$_3$, excitation
frequency 753.28 Hz................................................................................................................ 245
Figure 67. $^1$H NOE NMR spectrum of complexes III-20/20’ in CDCl$_3$, excitation
frequency 439.11 Hz................................................................................................................ 245
Figure 68. $^{13}$C NMR spectrum of complexes III-20/20’ in CDCl$_3$....................................... 246
Figure 69. $^{31}$P $[^1H]$ NMR spectrum of complexes III-20/20’ in CDCl$_3$............................. 246
Figure 70. $^1$H NMR spectrum of complex III-21 in C$_6$D$_5$Br.............................................. 247
Figure 71. $^{13}$C NMR spectrum of complex III-21 in C$_6$D$_5$Br.............................................. 248
Figure 72. $^{31}$P $[^1H]$ NMR spectrum of complex III-21 in C$_6$D$_5$Br...................................... 248
Figure 73. $^1$H NMR spectrum of complex III-22 in CD$_2$Cl$_2$............................................. 249
Figure 74. $^{13}$C NMR spectrum of complex III-22 in CD$_2$Cl$_2$............................................. 249
Figure 75. $^{31}$P $[^1H]$ NMR spectrum of complex III-22 in CD$_2$Cl$_2$................................. 249
Figure 76. $^1$H NMR spectrum of complexes III-24/24’ in CH$_2$Cl$_2$ (with D$_2$O
insert).......................................................................................................................................... 250
Figure 77. $^{13}$C-DEPT$_{135}$ NMR spectrum of complexes III-24/24’ in CH$_2$Cl$_2$ (with
D$_2$O insert).................................................................................................................................. 250
Figure 78. $^1$H NMR spectrum of complex III-25 in CD$_2$Cl$_2$.............................................. 251
Figure 79. $^{13}$C NMR spectrum of complex III-25 in CD$_2$Cl$_2$.............................................. 251
Figure 80. $^1$H NMR spectrum of complex III-26 in CDCl$_3$............................................. 252
Figure 81. $^{13}$C NMR spectrum of complex III-26 in CDCl$_3$............................................. 252
Figure 82. $^{31}$P $[^1H]$ NMR spectrum of complex III-26 in CDCl$_3$................................. 252
Figure 83. $^1$H NMR spectrum of complex III-58 in C$_6$D$_6$ (* toluene).................................. 253
Figure 84. $^{13}$C NMR spectrum of complex III-58 in C$_6$D$_6$.............................................. 253
Figure 85. $^1$H NMR spectrum of 5,6,7,8-tetrahydroisoquinoline III-33d in CDCl$_3$... 254
Figure 86. $^{13}$C NMR spectrum of 5,6,7,8-tetrahydroisoquinoline III-33d in CDCl$_3$. 254
Figure 87. $^1$H NMR spectrum of 1,2,3,4-tetrahydroacridine III-33fb in CDCl$_3$...... 255
Figure 88. $^{13}$C NMR spectrum of 1,2,3,4-tetrahydroacridine III-33fb in CDCl$_3$…… 255
Figure 89. $^1$H NMR spectrum of 1,4-dihydro-1,3,5-triazine III-33h in CDCl$_3$…… 256
Figure 90. $^{13}$C NMR spectrum of 1,4-dihydro-1,3,5-triazine III-33h in CDCl$_3$…… 256
Figure 91. $^1$H NMR spectrum of 1,2,3,4-tetrahydroanthracene III-35j in CDCl$_3$…… 257
Figure 92. $^{13}$C NMR spectrum of 1,2,3,4-tetrahydroanthracene III-35j in CDCl$_3$…… 257
Figure 93 $^1$H NMR spectrum of cis-stilbene III-37a in CDCl$_3$………………………… 258
Figure 94. $^{13}$C NMR spectrum of cis-stilbene III-37a in CDCl$_3$………………………… 258
Figure 95. $^1$H NMR spectrum of TH of 1-phenyl-1-propyne III-36c in 2-propanol (after 24 h)……………………………………………………………………………. 259
Figure 96. $^1$H NMR spectrum of TH of 1-phenyl-1-propyne III-36c in 2-propanol (after 72 h)……………………………………………………………………………. 259
Figure 97. Superimposed $^1$H NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol after 10min (blue) and after 4h (red) of heating at 80°C……………… 260
Figure 98. $^1$H COSY NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol………………………………………………………………………………… 260
Figure 99. Superimposed $^{19}$F NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol after 10min (blue) and after 4h (red) of heating at 80°C……………… 261
Figure 100. Superimposed $^1$H NMR spectrum of TH of ethyl pentafluoropropionate III-39b in ethanol after 10min (blue) and after 7.5h (black) of heating at 80°C……… 262
Figure 101. Superimposed $^{19}$F NMR spectra of TH of ethyl pentafluoropropionate III-39b in ethanol after 10min (blue) and after 4h (red) of heating at 80°C……………… 262
Figure 102. $^1$H NMR spectrum of cyclopropyl(phenyl)methanol III-55h in CDCl$_3$………… 263
Figure 103. $^{13}$C NMR spectrum of cyclopropyl(phenyl)methanol III-55h in CDCl$_3$………… 263
Figure 104. TH of cyclohexene III-34d with different amounts of catalyst III-20/20’………………………………………………………………………………………… 264
Figure 105. $^1$H NMR spectrum of E-stilbene in CDCl$_3$ as the product of Z-stilbene III-37aa isomerization in 2-propanol-d$_8$…………………………………………………………… 265
Figure 106. $^2$H NMR spectrum of E-stilbene in CHCl$_3$ as the product of Z-stilbene III-37aa isomerization in 2-propanol-d$_8$…………………………………………………………… 265
Figure 107. $^{31}$P {$^1$H} NMR spectrum of phosphonate product of (R)-1-phenylethanol in CDCl$_3$……………………………………………………………………………………… 266
Figure 108. $^{31}$P {$^1$H} NMR spectrum of phosphonate product of racemic 1-phenylethanol in CDCl$_3$……………………………………………………………………………………… 266
Figure 109. $^{31}$P {$^1$H} NMR spectrum of phosphonate product of 1-phenylethanol in CDCl$_3$ after racemization……………………………………………………………………………………… 267
Figure 110. Reduction of cyclohexanone with different amounts of LiOiPr……………… 267
List of Schemes

Scheme 1. Hydrogenation vs transfer hydrogenation ........................................... 1
Scheme 2. General scheme for the synthesis of secondary amines via the borrowing hydrogen methodology ................................................................. 2
Scheme 3. Monohydridic (A) and dihydridic (B) mechanisms of transfer hydrogenation ......................................................................................... 7
Scheme 4. Proposed mechanism of metal ligand bifunctional catalysis ............... 9
Scheme 5. Proposed mechanism of the metal ligand bifunctional catalysis with the pincer iridium catalyst II-22 ................................................................. 14
Scheme 6. Transfer hydrogenation of ketones via bifunctional mechanism on catalyst bearing hydroxypyridine ligand .............................................. 16
Scheme 7. Proposed mechanism of transfer hydrogenation of imines with Shvo catalyst II-57 ................................................................. 23
Scheme 8. Possible side reactions, accompanying transfer hydrogenation of nitriles ............................................................................................................. 25
Scheme 9. Ester metathesis in the presence of ruthenium complex II-73 .............. 30
Scheme 10. Proposed mechanism of semihydrogenation of alkynes, providing Z-selectivity ...................................................................................... 34
Scheme 11. General scheme for borrowing hydrogen methodology ................. 38
Scheme 12. Selected examples of transition metal catalysts for acceptorless dehydrogenation ....................................................................................... 39
Scheme 13. N- and C3-alkylation of pyrrolidine and morpholine in the presence of II-98 .............................................................................................. 43
Scheme 14. Synthesis of N-benzylpyperidine in the presence of II-105 .............. 46
Scheme 15. Synthesis of N-benzylaniline via indirect aza-Wittig reaction .......... 49
Scheme 16. Synthesis of secondary amines in the presence of II-111 ............... 51
Scheme 17. Representation of transalkylation of amines ................................... 52
Scheme 18. Accepted mechanism of the MPV reduction .................................. 54
Scheme 19. Accepted mechanism of Cannizzaro reaction .................................. 58
Scheme 20. Alkali base-catalyzed MPV reduction of quinine and quinidine ....... 58
Scheme 21. Suggested mechanism for deuterium redistribution catalyzed by sodium alkoxides .................................................................................... 60
Scheme 22. Proposed mechanism for NaOH-catalyzed transfer hydrogenation of carbonyl compounds ...................................................................... 62
Scheme 23. Proposed reaction sequence for alkali-mediated β-alkylation of secondary alcohols ...................................................................................... 63
Scheme 24. Lithium tert-butoxide-mediated synthesis of quinolines from (2-aminophenyl)methanol and ketones ................................................................. 64
Scheme 25. Proposed mechanisms of zinc catalyzed hydrosilylation ................................................................. 64
Scheme 26. Examples of chiral diamine-ligands ......................................................................................................................... 67
Scheme 27. Proposed reaction pathway for zinc-catalyzed reduction of activated imines ................................................................. 71
Scheme 28. Proposed reaction mechanism for zinc-catalyzed reduction of tertiary amides ................................................................. 73
Scheme 29. Proposed reaction mechanism for zinc-catalyzed monoreduction of benzonitrile ................................................................. 75
Scheme 30. The mechanism of ligand-metal-bifunctional hydrogenation with a catalyst containing pyrazole ................................................................. 79
Scheme 31. Synthesis of 3-tert-butyl-5-[(diphenylphosphanyl)methyl]-1H-pyrazole III-1a and 3-tert-butyl-5-[(di-iso-butylphosphanyl)methyl]-1H-pyrazole III-1b ................................................................................................................................. 81
Scheme 32. Synthesis of 2-[(3-tert-butyl-1H-pyrazol-5-yl)methyl]-4,4-dimethyl-4,5-dihydro-1,3-oxazole III-8 ........................................................................... 82
Scheme 33. Synthesis of N-[(3-phenyl-1H-pyrazol-5-yl)methyl]-2-(phenylsulfanyl)ethanamine III-10 ........................................................................... 83
Scheme 34. Transfer hydrogenation of imines ................................................................................................................................. 101
Scheme 35. Transfer hydrogenation of nitriles. Reaction conditions: 1 mol% III-20/20’, 5 mol% KOtBu in 2 ml of 2-propanol at 80°C .................................................................. 104
Scheme 36. Transfer hydrogenation of nitriles in ethanol. Reaction conditions: 1 mol% III-20/20’, 5 mol% KOtBu in 2 ml of ethanol at 80°C ................................................................................................................................. 105
Scheme 37. Transfer hydrogenation of heterocyclic compounds. Reduced bonds are highlighted in bold. Reaction conditions: 1 mol% III-20/20’, 10 mol% KOtBu in 3 ml of 2-propanol at 80°C ................................................................................................................................. 108
Scheme 38. Transfer hydrogenation of unsaturated hydrocarbons. Reduced bonds are highlighted in bold. Reaction conditions: 1 mol% III-20/20’, 4 mol% KOtBu in 2 ml of 2-propanol at 80°C ................................................................................................................................. 111
Scheme 39. Transfer hydrogenation of alkynes. Reaction conditions: 2 mol% III-20/20’, 2 mol% KOtBu in 2 ml of 2-propanol at 80°C ................................................................................................................................. 112
Scheme 40. Transfer hydrogenation of esters. Reaction conditions: 5 mol% III-20/20’, 20 mol% KOtBu in 3 ml of ethanol at 80°C ................................................................................................................................. 115
Scheme 41. Proposed catalytic cycle for transfer hydrogenation of olefins with III-20/20’ ................................................................................................................................. 120
Scheme 42. a) Isomerization of cis-stilbene under the catalytic conditions. b) the mechanism of H/D scrambling and the stilbene isomerization ................................................................................................................................. 121
Scheme 43. N-alkylation of anilines in the presence of III-20/20’. Reaction conditions: 1 mol% III-20/20’, 5 mol% KOrBu, 3 eq. hexan-1-ol in 1 ml tert-amyl alcohol. .................................................................................................................. 127

Scheme 44. Proposed mechanism of amine alkylation in the presence of III-20/20’. .................................................................................................................................. 129

Scheme 45. One-pot synthesis of dibenzylamine by the coupling of benzylamine and benzaldehyde and subsequent hydrogenation of N-(benzylidene)benzylamine. .................................................................................................................................. 129

Scheme 46. Amination of alcohols with ammonium formate. Reaction conditions: 100 mg NH4COOH, 2 mol% III-20/20’, 10 mol% KOtBu in 1 ml of corresponding alcohol at 100°C. .................................................................................................................................. 131

Scheme 47. Formation of intermediate product under the conditions of alcohol amination. .................................................................................................................................. 132

Scheme 48. a) No reaction is observed in the absence of catalyst; b) No reaction occurs between aldehyde and ammonium formate under the proposed catalytic conditions. .................................................................................................................................. 133

Scheme 49. Alternative route of alcohol amination under the proposed catalytic conditions. .................................................................................................................................. 133

Scheme 50. Racemization of (R)-1-phenylethanol in the presence of 10 mol% LiOiPr. .................................................................................................................................. 139

Scheme 51. Ligand-assisted transfer hydrogenation of ketones. .................................................................................................................................. 140

Scheme 52. a) Hydride mechanism and b) single electron mechanism for lithium-catalyzed transfer hydrogenation of cyclopropyl phenyl ketone. .................................................................................................................................. 148

Scheme 53. Proposed mechanism for transfer hydrogenation of ketones with LiOiPr. .................................................................................................................................. 150

Scheme 54. Reaction conditions: 10 mol% LiOiPr, 1 eq. LiCl in 2-propanol (1.5 ml). .................................................................................................................................. 154

Scheme 55. Reaction conditions: substrate (0.429 mmol), ZnMe2 (0.5 mol%), ligand III-10 (0.5 mol%), methanol (4.4 μL, 25 mol%), and triethoxysilane (158 μL, 0.858 mmol) in 1 ml of toluene. .................................................................................................................................. 160

Scheme 56. Proposed mechanism for the methanol assisted hydrosilylation with zinc catalyst. .................................................................................................................................. 161

Scheme 57. Proposed mechanism of hydrosilylation of carbonyl compounds with III-58. .................................................................................................................................. 162
List of Tables

Table 1. Transfer hydrogenation of acetophenone, catalyzed by ruthenium complexes ................................................................. 99
Table 2. Transfer hydrogenation of N-benzylideneaniline III-27a, catalyzed by III-20/20’ ................................................................. 101
Table 3. Optimization of the amount of base for transfer hydrogenation of benzonitrile with 1 mol% III-20/20’ in 2-propanol .................. 102
Table 4. Optimization of the amount of base for transfer hydrogenation of quinoline with 1 mol% load of III-20/20’ in 2-propanol .......... 107
Table 5. Optimization of the amount of base for transfer hydrogenation of 3,3-dimethylbutene-1 with 1 mol% load of III-20/20’ in 2-propanol .......... 110
Table 6. Transesterification of esters in the presence of III-20/20’ in 2-propanol ............................................................... 113
Table 7. Determination of kinetic isotope effect ............................................... 119
Table 8. Condition optimization for the synthesis of benzylethyl amine via borrowing hydrogen methodology ........................................... 123
Table 9. Condition optimization for the synthesis of dibenzylamine via borrowing hydrogen methodology ....................................... 125
Table 10. Alkylation of amines via borrowing hydrogen methodology .......... 126
Table 11. Alcohol amination via borrowing hydrogen methodology ............ 130
Table 12. Transfer hydrogenation of acetophenone with 10 mol% LiO\textsubscript{i}Pr in the presence of various ligands (10 mol%) .............. 137
Table 13. The effect of chiral ligands (10 mol%) on transfer hydrogenation of acetophenone catalyzed by 10 mol% LiO\textsubscript{i}Pr ............. 138
Table 14. Transfer hydrogenation of acetophenone with LiO\textsubscript{i}Pr in the presence of various additives ......................................................... 141
Table 15. Kinetic parameters found for transfer hydrogenation of cyclohexanone ................................................................. 147
Table 16. Determination of kinetic isotope effect .......................................... 148
Table 17. Hydrosilylation of acetophenone with III-58 formed \textit{in situ} ................. 157
Table 18. Hydrosilylation of acetophenone with III-58 with various amounts of methanol ................................................................. 158
Table 19. Crystal structure determination parameters for complex III-14 .......... 266
Table 20. Crystal structure determination parameters for complex III-19 .......... 267
Table 21. Crystal structure determination parameters for complex III-21 .......... 268
Table 22. Crystal structure determination parameters for complex III-25 .......... 269
I. Introduction

Reduction of functional groups of organic compounds is one of the fundamental transformations in chemistry, constantly performed both on small scale in academia and on large scale by the industry.\(^1\) There are several strategies for this type of transformation, including hydrogenation and hydrosilylation. These reactions can be performed under relatively mild conditions in the presence of efficient catalysts, based on transition metals and main group elements.

![Scheme 1. Hydrogenation vs transfer hydrogenation.](image)

Hydrogenation is the most atom-economic method for reduction of unsaturated bonds, however it often requires high pressures of hydrogen gas and high temperatures, and often suffers from the lack of chemoselectivity.\(^2\) Transfer hydrogenation, an alternative reduction strategy (Scheme 1), that utilizes other sources of hydrogen, such as alcohols or formate salts, has been extensively explored, as it allows reaction at milder conditions (low temperatures down to room temperature, no pressure) with application of general laboratory equipment.\(^3\) Transfer hydrogenation has shown its high efficiency in reduction of carbonyl
compounds and imines. Nitriles, heterocyclic compounds and esters are much less studied substrates in this type of reaction.

Hydrosilylation is another important reduction method in organic synthesis. Chemoselective catalytic hydrosilylation of aldehydes and ketones is an important transformation in organic synthesis, affording alkoxy silanes, that can be further hydrolyzed to achieve functionalized primary and secondary alcohols, important building blocks for pharmaceuticals, agrochemicals, polymers, in natural product syntheses, auxiliaries, and ligands. Furthermore alkoxy silanes have diverse application as valuable reagents in organic synthesis and material chemistry.

The content of the present thesis is divided into several sections. The major study was focused on the development of transition metal catalysts, bearing pyrazole-containing ligands, for transfer hydrogenation of various types of unsaturated substrates, such as nitriles, heterocyclic compounds, olefins, alkenes, and esters. This study also involves the synthesis of secondary and tertiary amines via a hydrogen borrowing strategy, which includes the step of transfer hydrogenation (Scheme 2).

Scheme 2. General scheme for the synthesis of secondary amines via the borrowing hydrogen methodology.
Transition metal catalysts for transfer hydrogenation have been thoroughly explored, much less attention has been given to alkali metal bases as promoters for this transformation.\(^\text{10}\) To broaden the application of main group elements for catalytic transfer hydrogenation, one of the sections of this thesis is dedicated to transition metal-free transfer hydrogenation of carbonyl compounds, performed on alkali metal cations.

The tendency of replacing expensive and toxic precious transition metal catalysts for different types of transformation, including hydrosilylation, by first-row transition metals (e.g. iron, cobalt, etc.) and main group elements (e.g. calcium, boron, aluminum, magnesium, etc.) has been currently observed. The final part of the thesis presents hydrosilylation of aldehydes and ketones with new zinc catalyst bearing tridentate ligand, containing pyrazolyl moiety.

The following historical section includes an overview of transition metal catalysts for transfer hydrogenation, as a solo transformation or as a step in hydrogen borrowing methodology. Further, the current progress in alkali metal-catalyzed transfer hydrogenation of carbonyl compounds is described. Lastly, zinc catalysts for hydrosilylation of different functional groups are reviewed.
II. Historical

II. 1. Transition metal-catalyzed transfer hydrogenation

II. 1. 1. Introduction

Hydrogenation is the most widely used method of reduction, and its application is spread from fine chemicals synthesis to the production of pharmaceuticals. Based on the hydrogen source, two types of hydrogenation can be recognized: direct hydrogenation (when hydrogen gas is involved) and transfer hydrogenation (when other sources are used, e.g. ethanol, 2-propanol, formic acid, etc.).

In the ideal scenario, direct hydrogenation falls under the majority of green chemistry principles. It provides high atom economy, minimizing the amount of by-products and derivatives. Moreover, in certain cases the reaction can proceed under neat conditions without any solvent. The process is generally performed under catalytic conditions and does not require stoichiometric loads of reducing reagents (i.e. LiAlH₄, Na(Hg), DIBAL-H, NaBH₄, etc.), which decreases the overall amount of toxic waste and makes the chemical synthesis less hazardous. All the above-mentioned benefits combined make the direct hydrogenation preferred over other methods of reduction. However, there are always two sides of the medal. One of the obvious drawbacks of this method is the application of a highly flammable hydrogen gas, often at very high pressures, which in turn requires expensive and elaborate experimental setups.

Transfer hydrogenation is an attractive alternative to direct hydrogenation and has hit the charts of research in the field of chemical reduction. It is usually performed under
ambient pressure, albeit elevated temperature is often required, thus making it accessible in the laboratories with general equipment, and depending on the catalyst sensitivity, it may or may not require inert atmosphere environment, while direct hydrogenation must be always conducted under oxygen-free conditions. Although transfer hydrogenation is less beneficial towards atom economy, comparing to direct hydrogenation, the hydrogen donors are readily available, safe, inexpensive and easy to handle, and the major by-products can be efficiently isolated and recycled. Simple alcohols, ethanol and 2-propanol, can be named among the most popular hydrogen donors.

However, it is known that transfer hydrogenation of carbonyl compounds with alcohols is a reversible process, and the rate of the reaction drops exponentially in parallel with accumulation of the products down to the full stop, sometimes resulting in limited conversions. To shift the equilibrium as far to the right as possible, the reaction is generally performed with a significant excess of the reducing agent. Another solution to drive the reaction may be the application of the Le Chatelier Principle. Thus, Thiel et al. showed that the efficiency of the reaction increases significantly, comparing to the process in a closed flask, if benzaldehyde, the product of ethanol oxidation, is removed at elevated temperature (40°C) under nitrogen flow.12 As an alternative, formic acid is another broadly used hydrogen donor that is capable of reduction with concurrent formation of CO₂ in the irreversible fashion, pushing the reaction to 100% conversion.

II. 1. 2. Milestones in transition metal-catalyzed transfer hydrogenation

Transfer hydrogenation was discovered more than a century ago. In 1903, Knoevenagel reported the disproportionation of dimethyl 1,4-dihydroterephthalate to
dimethyl terephthalate and dimethyl cis-hexahydroterephthalate in the presence of palladium black, when hydrogen transfer occurs between identical molecules.\textsuperscript{13} It was the first instance of a hydrogen transfer reaction that was reported. In 1912, Wieland showed a similar disproportionation for 1,2-dihydronaphthalene. He also observed a hydrogen transfer reaction of 1,2-diphenylhydrazine, which yielded phenylamine and azobenzene.\textsuperscript{14} In 1933, cyclohexadiene and cyclohexene were demonstrated to disproportionate in the presence of palladium or platina black,\textsuperscript{15} and in 1939, in the presence of nickel\textsuperscript{16}. An important breakthrough in transfer hydrogenation was made by the groups of Meerwein\textsuperscript{17} and Verley\textsuperscript{18} in 1925, and Ponndorf et al.\textsuperscript{19} in 1926. Hydrogen transfer from alcohols to aldehydes and ketones was observed to occur on aluminum alkoxide. This reaction, titled Meerwein-Ponndorf-Verley (MPV) reduction, had been the major reduction method until 1950s. MPV types of transformation are discussed in detail in the following section.

The milestone in transfer hydrogenation was the discovery of homogenous late transition metal complexes capable of catalyzing the reduction of carbonyl compounds in 2-propanol. One of the first examples was reported by Henbest and Mitchell. They observed transfer hydrogenation of cyclohexanone\textsuperscript{20} and $\alpha,\beta$-unsaturated ketones\textsuperscript{21} to alcohols with 2-propanol in the presence of a catalytic amount of iridium hydride complex.

In 1960s, the catalytic activity of Wilkinson’s catalyst, [RuCl\textsubscript{2}(PPh\textsubscript{3})\textsubscript{3}], in various organic transformations was explored.\textsuperscript{22-24} Sasson and Blum reported the transfer hydrogenation of saturated and $\alpha,\beta$-unsaturated ketones catalyzed by this ruthenium complex,\textsuperscript{25, 26} as well as by complexes of rhodium and iridium.\textsuperscript{27} Two decades later, Chowdhury and Bäckvall found the accelerating effect (by $10^3$-$10^4$ times) of the addition of a catalytic amount of NaOH to the [RuCl\textsubscript{2}(PPh\textsubscript{3})\textsubscript{3}]-promoted reactions.\textsuperscript{28} This discovery was
the key aspect in the investigation of the mechanism of transition metal-catalyzed transfer hydrogenation. Addition of a base leads to the formation of a metal-hydride complex that many studies revealed to be the active species.\textsuperscript{29, 30} These hydrides can be isolated in some cases and then applied in catalysis or can be formed \textit{in situ}. Bäckvall showed that two catalytic pathways for transfer hydrogenation are possible:\textsuperscript{31, 32} monohydridic A (Scheme 3A) and dihydridic B (Scheme 3B).

\begin{center}
\textbf{Scheme 3.} Monohydridic (A) and dihydridic (B) mechanisms of transfer hydrogenation.
\end{center}

In the pathway A, a metal-hydride complex is the active species. Substrate coordinates first to a vacant site of the metal, followed by the hydride shift from metal to the β-position. After that, the hydrogen transfer agent (e.g. alcohol) releases the reduced substrate by protonolysis. Subsequent β-hydride elimination recovers the metal-hydride species. This pathway was considered for iridium and rhodium catalysts.\textsuperscript{33}

A metal-dihydride complex is required in the mechanism B. Substrate insertion into the metal-hydride bond is followed by product release. Then the hydrogen transfer reagent coordinates to the metal with formation of a metal-hydride complex. After β-hydride
elimination, the metal-dihydride species is regenerated. This pathway was demonstrated for ruthenium complexes, for instance [RuH₂(PPh₃)₃], which can be added to the catalytic reaction or can be generated in situ from [RuCl₂(PPh₃)₃] or [RuHCl(PPh₃)₃].

Another breakthrough was made in 1980s, when early studies of ruthenium-catalyzed asymmetric transfer hydrogenation were reported. Since then asymmetric hydrogenation and transfer hydrogenation have received much attention and became an important tool in the synthesis of fragrances and pharmaceuticals, culminating with the awarding of the Nobel Prize in 2001 to Noyori and Knowles for their contribution to the field.

New horizons were discovered by Noyori and Ikariya with the introduction of efficient ruthenium catalysts II-1a-f for asymmetric transfer hydrogenation of ketones and imines in 1995. Few years later they were able to isolate and describe the key intermediates that allowed them to suggest the outer-sphere hydrogen transfer mechanism (Scheme 4), which was later supported by computational studies. Unlike the inner-sphere mechanisms, when the substrate is coordinated to the metal centre, the hydrogen transfer in the Noyori’s system was suggested to proceed via an outer-sphere pathway through a six-membered transition state.

According to the proposed mechanism, the amine group of the precatalyst II-2 is deprotonated with the formation of II-3. The transfer of hydrogens from alcohol (or the activation of dihydrogen) in the next step yields a ruthenium(II)-hydride complex II-4 and
the amide turns back to the amine. Thus, the hydrogen coordinated to the metal centre has a hydridic character and the hydrogen bound to the ligand has a protic character. The substrate coordinates through the hydrogens and hydrogen transfer occurs via a six-membered transition state (II-5 to II-6). Such a concerted hydrogen transfer, which involves ligand transformations, was coined the name of metal ligand bifunctional catalysis.

Scheme 4. Proposed mechanism of metal ligand bifunctional catalysis.

However, recently Dub et al. have revised the role of the ligand in bifunctional catalysis. More thorough calculations revealed that, although hydrogen transfer most likely occurs via an outer-sphere mechanism, the role of the N-H functionality in a close proximity to the metal centre comes down to the stabilization of the rate-determining transition state by a N-H···O hydrogen-bonding interaction rather than reversible proton transfer. The stronger this N-H···O bonding is, the more stabilization of the transition state can be achieved, and the faster process of hydrogen transfer becomes. Furthermore, the
presence of the N-H group is beneficial for asymmetric reduction in terms of orienting the substrate, when only two minimum energy Re- and Si-face transition states become possible.\textsuperscript{49}

II. 1. 3. Ir, Rh and Ru catalysts for transfer hydrogenation of carbonyl compounds

To date, a wide number of transition metal complexes, involving different kinds of ligands, hydrogen sources, and additives have been developed. The family of Ir, Rh and Ru complexes, bearing a variety of mono- and multidentate ligands, e. g. N-heterocyclic carbenes (NHC), phosphines, amines, aromatic $\pi$-systems, etc., is probably the most popular and expanded class of catalysts for transfer hydrogenation, although the horizon has been already pushed to earth-abundant and less toxic first-row transition metals, such as iron, nickel, manganese, etc. The classes of substrates that can be reduced under transfer hydrogenation conditions have also broadened: starting with the most explored carbonyls and imines and moving to more challenging substrates, such as nitriles, heterocyclic compounds and esters.\textsuperscript{3, 50}

Chelating bi- and multidentate ligands containing phosphorus, nitrogen, oxygen, and sulfur sites have been widely studied in the hydrogenation of carbonyl compounds. Such ligands can be readily synthesized and modified structurally and electronically, due to almost infinite possibilities of topological modifications, which provides a broad range of coordination behavior and structural features for the corresponding Ru, Ir, and Rh complexes through small variations of the bite angle, steric hindrance, fluxional behavior, etc.
Along with Noyori’s catalysts, bearing ligands with amine and N-tosylated amide groups, described above, Ir and Rh half-sandwich complexes **II-7a-b**, containing chiral diamines, have been developed by the Ikariya group\(^{51}\) and showed good catalytic activity in the asymmetric transfer hydrogenation of aromatic ketones. These successful results gave rise to a number of other Ru, Ir and Rh complexes for transfer hydrogenation of different types of substrates. A large variety of transfer hydrogenation catalysts, containing N,N-, N,O-, and N,P-bidentate ligands have been introduced. For instance, bidentate dinitrogen ligands **II-8–II-11**, containing pyridyl moiety, were studied in the course of development of new half-sandwich ruthenium complexes.\(^{52,53}\) Chiral amino alcohols have found their niche as ligands for asymmetric transfer hydrogenation catalysts, initiated by the successful studies of \(\beta\)-amino alcohols, in particular, ephedrine **II-12**, as substitutes of monotosylated diamines in Noyori’s catalysts.\(^{54}\) It was followed by a number of Ru, Ir and Rh complexes with various readily available chiral amino alcohol ligands (for instance **II-13, II-14, II-15**), which were applied in the catalysis of transfer hydrogenation reaction.\(^{46,55-59}\)
Combination of amino and phosphino groups to produce chelating ligands with pronounced hemilabile character and unusual electronic properties, due to the presence of two different binding sites, has opened even more opportunities for the design of transfer hydrogenation catalysts.\textsuperscript{60} Thus, one of the first highly efficient ruthenium catalysts were reported by Le Floch\textsuperscript{61} and Stradiotto\textsuperscript{62}. Ruthenium half-sandwich catalyst II-16, bearing 1-(2-methylpyridyl)phosphole ligand, exhibits very high TONs (up to $2\times10^7$) and TOF (up to $1.2\times10^6$ h\textsuperscript{-1}).\textsuperscript{61} Zwitterionic ruthenium complex II-17 was shown to be able to operate at a load as low as 0.05 mol\text%, while maintaining a high TOF up to $2.2\times10^5$ h\textsuperscript{-1}.\textsuperscript{62} Interestingly, that despite these complexes do not possess the N-H functionality within the ligands, which had previously been believed to be essential for providing high effectiveness of transfer hydrogenation catalysis,\textsuperscript{63} yet they were proven to be efficient catalysts.

A large family of transition metal pincer complexes that serve as catalysts for transfer hydrogenation, have been developed during the past two decades.\textsuperscript{64,65} A pincer ligand is a tridentate chelating ligand that generally binds to a metal within one plane, providing high thermal stability of complexes. Due to this chelating character of the ligand, transfer hydrogenation occurs in the plane perpendicular to the plane of the pincer.
One of the first transition metal pincer complexes, applied in transfer hydrogenation, were aryl ruthenium(II) complexes **II-18**, reported by van Koten *et al.* in 2000. In 2005, the Baratta group introduced the ruthenium pincer complex **II-19** that formed *in situ* a ruthenium-hydride species **II-20** in the presence of a base. This system was found to be a very efficient catalyst for transfer hydrogenation of aromatic and aliphatic ketones at loads down to 0.005 mol%, providing TOF up to $2.5 \times 10^6$ h$^{-1}$.66,67

A group of researchers in collaboration with Kanata Chemical Technologies Inc. investigated the possible bifunctional proton-hydride motif within the iridium pincer complex **II-21** bearing an aminodiphosphine ligand (Scheme 5).69 These workers were able to show that the amidodihydride complex **II-22** is quantitatively formed, when **II-21** is treated with a base in THF. Following reaction with hydrogen gas or 2-propanol leads to the aminotrihydride iridium complex **II-23**. Both **II-22** and **II-23**, as well as **II-21** in the presence of base, were applied to transfer hydrogenation of aliphatic and aromatic ketones and showed very similar activity with TOF up to 43 000 h$^{-1}$ at 60°C.
Scheme 5. Proposed mechanism of the metal ligand bifunctional catalysis with the pincer iridium catalyst II-22.69

One more example of a highly efficient pincer catalyst for transfer hydrogenation of carbonyl compounds was reported by Messerle et al.70 A series of ruthenium complexes bearing a pyridine-2,6-bis(thioether) ligand was synthesized and applied in the reduction of ketones in 2-propanol. The best result was observed for complex II-25 that provides as high TOF in transfer hydrogenation as 87 000 h⁻¹.

Pincer ligands can be also used in combination with chiral bidentate ligands to provide enantioselectivity. Thus, Barrata et al. modified the previously reported ruthenium complex II-19 with the chiral bisphosphine ligand (S,R)-JOSIPHOS that was applied in transfer hydrogenation of several acetophenones and aliphatic β-ketones to produce a number of chiral alcohols (70-98 ee%).71 Further optimization of the pincer ligand and
variation of the diphosphine ligand, including the chiral (S,R)-JOSIPHOS, in the ruthenium catalyst II-26 resulted in faster conversions, comparing to II-19, and lower catalyst loads (down to 0.0001 mol%).

Szymczak et al. reported the pincer ruthenium complex II-27 bearing a ligand with the hydroxypyridyl moiety. Hydroxypyridines are known to be involved in the equilibrium, accompanied by dearomatization of the pyridyl ring, demonstrated on Scheme 6. The hydroxypyridyl moiety, as a part of the ligand structure, contributes to substrate coordination and promotes transfer hydrogenation of aldehydes and ketones by presumably bifunctional mechanism. The complex provides exclusive chemoselectivity in the reduction of carbonyl compounds over other functionalities, including terminal alkenes, which are known to be active enough to compete with the carbonyl group. Gimeno et al. introduced the ruthenium
complex II-28 bearing chiral PyBox ligands, that exhibited good enantioselectivity in asymmetric transfer hydrogenation of ketones in 2-propanol.

![Scheme 6](image)

**Scheme 6.** Transfer hydrogenation of ketones via bifunctional mechanism on catalyst bearing hydroxypyridine ligand.

In 2012, Yu et al. reported new ruthenium complexes bearing pyridyl-based pyrazolyl-oxazolinyl complexes II-29 and II-30. Complex II-29 was found to be much more efficient in terms of catalytic activity and enantioselectivity in transfer hydrogenation of ketones than complex II-30 and provides excellent conversions within short times down to 5 min with catalyst load down to 0.3 mol% at slightly elevated temperature. This observation was attributed to the presence of the NH-functionality in the complex II-29, that may allow metal-ligand bifunctional mechanism of hydrogen transfer.

![Images of complexes II-29 to II-32](image)

Ruthenium pincer complex II-31, bearing pyridyl-based ligand with two pyrazolyl units, was shown to exhibit very high activity in transfer hydrogenation of ketones, reaching $7.2 \times 10^6 \text{ h}^{-1} \text{ TOF}$. The reaction was suggested to proceed via deprotonation of $1H$-pyrazolyl group and formation of amido-ruthenium species II-32, that can be produced independently when II-31 is treated with base. Another ruthenium catalyst II-33 with $1H$-benzimidazolyl-containing ligand was also shown to provide up to 23 times higher TOF values than complex
II-34, that has \( N \)-methylated benzimidazolyl unit, supporting the idea of essential N-H functionality for more efficient catalysis.\(^79\)

Another widely employed class of ligands for transfer hydrogenation catalysts is the family of NHC ligands,\(^80,81\) that became popular shortly after the first free NHC was isolated by Arduengo \textit{et al.} in 1991.\(^82\) They are strong \( \sigma \)-donors, with very broad possibilities for tuning their electronic and steric properties. NHC moieties are often incorporated into chelating, pincer, and chiral ligands.

The pioneering work on transition metal complexes bearing NHC ligands was done by Nolan \textit{et al.}, who designed and synthesized Ir complexes II-35a-c which were successfully applied in the transfer hydrogenation of ketones, while showing less activity in the case of olefins and nitroarenes.\(^83\) Following this results, many Ir-NHC complexes have been developed shortly,\(^84,85\) including the air-stable and moisture-insensitive Crabtree’s catalyst II-36, bearing chelating bis-(\( N \)-heterocyclic carbenes).\(^86\) The Royo group designed the first Cp*-functionalized NHC ligand and used it to prepare the iridium complex II-37.\(^87\) It was particularly active in transfer hydrogenation of ketones even at loads as low as 0.01 mol\%, showing a TON up to 9900. Iridium catalyst II-38, reported by Hahn and Oro, was shown to drive the transfer hydrogenation of cyclohexanone in 2-propanol with very fast
conversion within a few minutes (TOF above 6000 h\(^{-1}\)).\(^{88-90}\) The first triazole-based NHC was prepared by the Crabtree’s group and applied in the synthesis of the Ir catalyst \textbf{II-39} for transfer hydrogenation of imines and alkenes.\(^{91}\) Another iridium complex \textbf{II-40} bearing a 1,8-naphthyridine-NHC hybrid ligand, can catalyze transfer hydrogenation of carbonyl compounds at slightly elevated temperatures.\(^{92}\)

Shortly, a number of ruthenium catalysts with various multidentate ligands containing an NHC moiety were developed.\(^{93,94}\) The complexes demonstrated high catalytic activity in the transfer hydrogenation of carbonyl compounds in 2-propanol. Peris\(^{95}\) and Danopolous\(^{96}\) were the pioneers in the subfield of Ru-NHC complexes. Their catalysts \textbf{II-41} and \textbf{II-42}, respectively, could be readily prepared from 2,6-bis(imidazolium-3-yl)pyridine salts and widely used ruthenium precursors. Their catalytic activity in transfer hydrogenation was evaluated in the reduction of cyclohexanone in 2-propanol, which demonstrated remarkably high TONs of 126 000 and 8 800, for \textbf{II-41} and \textbf{II-42}, respectively.
The variation of the ligands has been only limited by researcher’s imagination. Thus, Yu et al. reported the ruthenium complex II-43 with a pincer ligand that combines NHC, pyridyl, and pyrazolyl units.\textsuperscript{97} Gabe’s group prepared the first half-sandwich ruthenium catalyst II-44, bearing an oxazolinyl-carbene ligand, applicable for transfer hydrogenation of carbonyl compounds.\textsuperscript{98} Another highly efficient ruthenium catalyst II-45 was prepared with a commercially available NHC derivative.\textsuperscript{99} Being applied to transfer hydrogenation, it showed particularly large TOFs of up to 120,000 h\textsuperscript{-1} for a broad scope of carbonyl substrates.

The first Rh-NHC catalysts II-46 for transfer hydrogenation of ketones were reported by Crabtree and Peris,\textsuperscript{100} followed by a number of other rhodium complexes bearing different types of NHC ligands, e. g. benzannulated NHCs \textbf{(II-47)}\textsuperscript{89}, bridged bis(NHC) \textbf{(II-48)}\textsuperscript{101}, amine-functionalized NHC \textbf{(II-49)}\textsuperscript{102}, and diether-functionalized NHC \textbf{(II-50)}\textsuperscript{103}. 
II. 1. 4. Ir, Rh, and Ru catalysts for transfer hydrogenation of imines

Catalytic transfer hydrogenation of imines to amines has been discovered in the late 1980s. In 1987, Jones et al. applied reduction of benzylideneaniline in 2-propanol for the study of ruthenium cluster catalytic species.\textsuperscript{104} \([\text{HRu}_3(\text{CO})_9(\text{PhN}=\text{CHC}_6\text{H}_4)]\) was isolated from the reaction mixture and was confirmed to be an active catalyst for the hydrogen transfer reaction of the imine. Later Wang and Bäckvall reported transfer hydrogenation of a wide scope of both aldimines and ketoimines in 2-propanol with \(\text{RuCl}_2(\text{PPh}_3)_3\) promoted by addition of a base.\textsuperscript{105} Thereafter, \(\text{RuH}_2(\text{PPh}_3)_3\) was found to be the actual catalyst that does not require activation with base.\textsuperscript{34,106}

One of the most important discoveries, made in mid 1990s, was the application of ruthenium complexes \textbf{II-1}, bearing monotosylated 1,2-diamines, in the asymmetric reduction of imines.\textsuperscript{40} Noyori et al. were able to broaden the substrate scope to dihydroisoquinolines (DHIQs) and dihydro-β-carbolines (DHBs), synchronously achieving good to excellent enantioselectivity. Formic acid/triethylamine buffer solution was used as a reducing reagent, and an organic co-solvent was required. Isoelectronic to the Noyori’s
catalyst, the rhodium catalyst II-7a was also applied in the transfer hydrogenation of imines, showing high efficiency for most of the substrates, although, comparing to catalyst II-1e, the reduction of aromatic-substituted and acyclic imines gave products of very low enantioselectivity.\(^{107}\)

![Chemical structures](image1)

Mechanistic studies of transfer hydrogenation of imines with the catalysts II-1e or II-7a did not confirmed the concerted mechanism claimed for the reduction of carbonyl compounds with Noyori’s catalyst.\(^{108, 109}\) It was observed that the suggested active catalyst, ruthenium-hydride complex II-51, capable of promoting the hydrogen transfer to ketones in 2-propanol without base activation, did not give any products under the same catalytic conditions with the imine substrate. However, protonated imines were readily reduced with stoichiometric amounts of II-51, which explained why formic acid/triethylamine reducing system was required instead of just 2-propanol. Thus, it was shown that formic acid is not just an essential hydrogen donor in this transformation but is required for imine activation. Furthermore, the reduction of iminium salts of other Brønsted acids with stoichiometric amounts of II-51 was demonstrated.

![Chemical structures](image2)
Interestingly, modification of monotosylated 1,2-diamines in the Noyori’s catalyst via \(N\)-alkylation resulted in a much higher activity towards the transfer hydrogenation of imines, comparing to the reduction of ketones. Thus, imine substrates were reduced within hours in the presence of a catalytic amount of \(N\)-alkylated derivatives II-52a-e, while transfer hydrogenation of ketones required one and more days under the same conditions.\(^{110}\) Moreover, fully \(N\)-alkylated 1,2-diamines were shown to be even more beneficial for the reduction of imines, increasing the activity of catalysts II-53a-b for this transformation, comparing to II-1e and II-52a-e, whilst almost cancelled transfer hydrogenation of ketones.\(^{111}\) This phenomenon confirmed that the NH-functionality is beneficial for transfer hydrogenation of ketones\(^{112}\), but not essential for the reduction of imines, signifying an “open” transition state in the case of imines, rather than a cyclic transition state proposed for carbonyl compounds.

Recently, the iridium complex II-54 has been applied in asymmetric transfer hydrogenation of acyclic imines with alcohols.\(^{113}\) A number of alcohols were screened as suitable hydrogen donors. Although, using 1-phenylethanol provides good enantioselectivity, meso-1,2-diphenyl-1,2-ethanediol was selected as the optimal choice, providing the highest e.r. (up to 95:5). Since the process also required an acid additive, catalytic amounts of chiral phosphoric acid II-55 were used to increase the efficiency.
Bäckvall and Samec applied the dimeric Shvo catalyst II-56 in transfer hydrogenation of imines in 2-propanol.\textsuperscript{114} In solution, II-56 dissociates into two species: 18e complex II-57 (reducing component) and 16e complex II-58 (oxidation component). Due to this unique behavior, it has been applied in a variety of catalytic processes.\textsuperscript{115-119} Unlike Noyori’s catalyst II-1e, active species II-57 catalyzes hydrogen transfer to imine via a stepwise metal-ligand bifunctional mechanism (Scheme 7).\textsuperscript{120, 121}

Scheme 7. Proposed mechanism of transfer hydrogenation of imines with Shvo catalyst II-57.

Asymmetric synthesis of chiral primary amines was achieved by means of transfer hydrogenation of \textit{N}-sulfinyl imines in 2-propanol in the presence of 2.5-5 mol\% of
[RuCl₂(\textit{para}-cymene)]₂ and 5-10 mol% of chiral 2-amino-alcohol.\textsuperscript{122-124} When (\textit{1S,2R})-1-amino-2-indanol was used as a chiral ligand, only aromatic \textit{N}-sulfinyl imines were reduced.\textsuperscript{122, 123} However, application of 2-amino-2-methylpropanol allowed the authors to broaden the scope of the substrates to aliphatic \textit{N}-sulfinyl imines as well.\textsuperscript{124}

One of the highly efficient ruthenium catalysts for asymmetric transfer hydrogenation of imines in 2-propanol were reported by Gamasa’s and Pizanno’s groups (\textbf{II-62} and \textbf{II-63}).\textsuperscript{125} Excellent enantioselectivities in the process were achieved by means of chiral PyBox ligands.

\begin{align*}
\text{II-62} & \quad \text{II-63}
\end{align*}

\textbf{II. 1. 5. Transfer hydrogenation of nitriles}

Hydrogenation of nitriles is considered to be a straightforward method for the production of amines, which are common building blocks for pharmaceutical and biochemical synthesis. However quite a few studies of catalytic transfer hydrogenation of nitriles have been reported to date. In addition, primary amines, initially formed in the reaction, are active enough and can readily undergo several further transformations (Scheme 8). In particular, reductive amination with the carbonyl compounds, which are formed as by-products in transfer hydrogenation with alcohols, is very hard to avoid.
Transfer hydrogenation of nitriles with HCO$_2$NH$_4$, promoted by heterogeneous palladium catalyst, was first reported by Brown et al. in 1982.\textsuperscript{126} Yamaguchi’s group applied RuH$_2$(PPh$_3$)$_4$ in the transfer hydrogenation of benzonitrile.\textsuperscript{34} However, the target product, benzylamine, was observed in a very low yield, whereas the major products were benzylidenbenzylamine, considered to be formed via transimination of the imine to benzylamine, and its reduced product, dibenzylamine.

In 2013, Beller et al. applied the readily available RuCl$_2$(PPh$_3$)$_3$ to catalytic transfer hydrogenation of nitriles in 2-propanol at 120\textdegree C.\textsuperscript{127} The ultimate product of this reaction was secondary amine formed from the coupling of the initial product, primary amine, with the co-product acetone (formed by dehydrogenation of 2-propanol), followed by transfer hydrogenation of the resultant ketimine. Thus, secondary $N$-\textit{iso}-propylamines were selectively produced under the proposed conditions. When a different ruthenium-based catalytic system was used, i.e. [Ru$_2$(para-cymene)Cl$_2$]$_2$ (1 mol\%) and DPPB (DPPH = 1,6-bis(diphenylphosphino)hexane) (2 mol\%), the desired primary amines could be produced with high selectivity, avoiding completely the reductive amination.\textsuperscript{128}
Recently 2-(2-pyridyl-2-ol)-1,10-phenanthroline based ruthenium complex II-64 was reported to serve as an efficient catalyst for transfer hydrogenation of ketones and nitriles.\textsuperscript{129} A wide scope of aromatic nitriles has been reduced under the proposed conditions with selective production of acetoneimines, which can be hydrolyzed under acidic conditions, yielding primary amines. Nikonov \textit{et al.} reported the half-sandwich ruthenium complex II-65 to be capable of catalyzing transfer hydrogenation of aromatic and aliphatic nitriles in 2-propanol at room temperature\textsuperscript{130} or in methanol with ammonium formate at 60°C.\textsuperscript{131} Another, NHC-supported, half-sandwich ruthenium complex II-66 was also applied as a catalyst for transfer hydrogenation of nitriles with 2-propanol at loads as low as 0.5 mol\%.\textsuperscript{132} Both aliphatic and aromatic nitriles can be reduced under the proposed conditions at 70°C, although long chain and branched aliphatic nitriles required more time and/or higher temperatures.

Cobalt pincer catalysts II-67 and II-68 were applied by the groups of Liu and Zhou to mild transfer hydrogenation of nitriles.\textsuperscript{133} Ammonia-borane was used as a hydrogen source. The selectivity of the catalytic process can be adjusted towards the production of primary amines, if the reaction is performed in hexane, or secondary amines via alkylation with a terminal amine, when 1,1,1,3,3,3-hexafluoro-2-propanol is used as a solvent.
II. 1. 6. Transfer hydrogenation of heterocyclic compounds

Saturated nitrogen heterocyclic motif can be found in a large number of pharmaceutical products.\textsuperscript{134} Most commonly they are obtained by hetero- and homogeneous hydrogenation of unsaturated heterocyclic compounds.\textsuperscript{135} Unfortunately, very few examples of transfer hydrogenation of heterocycles are known to date.

Yamaguchi and Fujita found that dimeric half-sandwich iridium complex $\text{[Cp}^*\text{IrCl}_2\text{]}_2$ II-69 catalyzes transfer hydrogenation of quinolines in refluxing 2-propanol.\textsuperscript{136} Screening catalysis with various additives revealed that acids enhance the rate of reaction by the activation of substrates via their protonation. Recently, II-69 was applied in the transfer hydrogenation of 1,10-phenanthrolines, while formic acid was used as a hydrogen donor.\textsuperscript{137} Furthermore, addition of monotosylated diamine ligands resulted in asymmetric reduction 2- or 2,9-substituted 1,10-phenanthrolines. In the case of symmetrical substituents, 1,2,3,4-tetrahydro-1,10-phenanthrolines were the only products. However, reduction of monosubstituted substrates or 2,9-substituted 1,10-phenanthrolines with different aliphatic groups resulted in hydrogenation of the less hindered heterocycle, although the products of the reduction of the other ring were present in the product mixture in significant amounts as well.
Crabtree et al. observed good conversions of quinoline and quinaldine to 1,2,3,4-tetrahydroquinalines and full conversion of pyrazine to piperazine in the presence of 1 mol% NHC-supported iridium catalyst II-70 in refluxing 2-propanol within 24 hours. The Xia group also reported the half-sandwich iridium complex II-71 that promotes transfer hydrogenation of a large scope of quinolines, including quinaldines, with aqueous solution of HCO$_2$H/NEt$_3$ at 30°C within 14 hours. Quinolinium and pyridinium salts were also hydrogenated under these conditions, although a longer time is required to achieve high yields (24-36 hours).

Frediani et al. reported cis-[Rh(bipy)$_2$Cl$_2$]Cl (bipy - bipyridine) in the application to transfer hydrogenation of quinoline, pyridine and 2-methylpyridine in 2-propanol (TOFs are 18.0, 17.0 and 8.2 h$^{-1}$ respectively). [Cp*RhCl$_2$]$_2$ was shown to be an efficient catalyst for a wide range of quinolines, isoquinolines and quinoxalines, as well as pyridinium salts in the presence of low catalyst load (down to 0.01 mol%) with the addition of KI at 40°C and utilizing HCOOH/NEt$_3$ as hydrogen source. Asymmetric transfer hydrogenation of a broad spectrum of 2-substituted quinolines was achieved with half-sandwich rhodium complex II-72 in the buffered aqueous solution of sodium formate (pH=5).

NHC-supported ruthenium complexes II-65 and II-66, reported by Nikonov’s group, catalyze transfer hydrogenation of heterocyclic compounds with ammonium formate and 2-propanol, respectively. Quinoline, quinoxaline and 1,5-naphtharidine were reduced to
1,2,3,4-tetrahydrogenated product, while only one of the C=N bonds of triazine was reduced under the same conditions. Phenanthridine and acridine underwent hydrogenation of the internal rings.

II. 1. 7. Transfer hydrogenation of carboxylic acids and their derivatives

Direct reduction of carboxylic acids and their derivatives, such as esters, anhydrides, amides, is one of the preferred methods to obtain corresponding alcohols and amines. This transformation can proceed with metal hydrides (LiAlH₄, NaBH₄, etc.). However, stoichiometric amounts of reagents, required in this case, lead to the formation of an equimolar quantity of waste and the whole process is considered to be poor from the atom-economical perspective.

Homogeneous catalytic hydrogenation and hydroxilalylation of carboxylic acid derivatives has been known since 1980s and extensively developed during the past decade, involving ruthenium-, osmium- and iron-based catalysts. Although it is a much more environmentally friendly process, often harsh conditions, e. g. high temperatures (100°C and more) and H₂ pressures (up to 50 atm), are required. Catalytic transfer hydrogenation usually allows for milder reduction conditions. However, generally, hydrogenation of carboxylic acid derivatives is much less kinetically favorable than that of the carbonyl compounds, which is of particular importance for the transfer hydrogenation process.

Only three examples of transfer hydrogenation of esters have been reported to date. Nikonov’s group reported the catalytic activity of half-sandwich ruthenium complex II-65 in reduction of some esters. Aliphatic and aromatic esters were studied in transfer
hydrogenation reaction with 5 mol% catalyst load in 2-propanol at 70°C. Alkyl esters were found to be inactive under these conditions, whereas moderate yields of benzylic alcohol were observed in the transfer hydrogenation of phenyl benzoates within 24 hours. It was considered that the larger electronegativity of the sp²-hybridized carbon atom in the phenyl group compared to the sp³-hybridized carbon atom activated the substrate electrophilically, which made possible the transfer hydrogenation reaction. It was proved with ethyl trifluoroacetate, which was reduced to 1,2,3-trifluoroethanol with 60% conversion at room temperature within 24 hours.

Dubey and Khaskin used Gusev’s ruthenium catalyst II-73 for transfer hydrogenation of esters. High yield of corresponding alcohols were obtained from aromatic and aliphatic esters, including lactones. The reaction proceeds in the presence of 20 and more equivalents of ethanol, which transforms into ethyl acetate upon oxidation. Catalyst II-73 was also shown to be responsible for ester metathesis in toluene at 80°C (Scheme 9), which led to the scrambling of one ester to a statistical equilibrium of the products.

![Scheme 9. Ester metathesis in the presence of ruthenium complex II-73.](image)

Recently, the first example of iron-catalyzed transfer hydrogenation of esters has been reported by de Vries et al. Iron catalyst II-74 was able to reduce esters with ethanol as a hydrogen source at 5 mol% catalyst loading at 100°C. Aliphatic and aromatic esters, as well as lactones were reduced with good to excellent yield in 24 hours. Furthermore, II-74
was successfully applied for degradation of polyester Dynacol 7360, made from adipic acid and 1,6-hexanediol.

\[
\text{\begin{center}
\includegraphics[width=0.3\textwidth]{image.png}
\end{center}}
\]

II. 1. 8. Transfer hydrogenation of olefins and alkynes

Homogeneous transfer hydrogenation of nonpolarized multiple C-C bonds is much less studied than transfer hydrogenation of C=O or C=N bonds. Moreover, the proposed catalytic systems are often applicable to the reduction of only activated C=C bonds\(^{156}\) (e.g. \(\alpha,\beta\)-unsaturated esters\(^{157}\), \(\alpha,\beta\)-unsaturated nitriles\(^{91}\), etc.). Even fewer catalytic systems have been developed for the transfer semihydrogenation of alkynes to alkenes, as the process is often accompanied by overreduction to alkanes\(^{157}\).

The NHC-supported iridium complex \textbf{II-39} was demonstrated to catalyze transfer hydrogenation of \textit{trans}-stilbene and 3-phenylacrylonitrile in cyclopentanol at 140\(^\circ\)\(^{91}\). 3-Phenylacrylonitrile was fully hydrogenated within 6 hours, while only 75\% conversion was achieved for \textit{trans}-stilbene under the same catalytic conditions.

\textit{Albrecht et al.} reported an olefin-tethered NHC-supported ruthenium complex \textbf{II-75} for catalytic transfer hydrogenation of unfunctionalized alkenes\(^{158}\). Several mono- and disubstituted alkenes could be reduced with 1 mol\% \textbf{II-75} and 10 mol\% KOH in 2-propanol at 80\(^\circ\)C, although the products of isomerization were observed in significant amounts in
some cases. α,β- Unsaturated ketones were also shown to be hydrogenated to the corresponding saturated secondary alcohols.\textsuperscript{159}

\[
\text{II-75}
\]

The Nikonov group demonstrated that the NHC-supported half-sandwich ruthenium complex II-66 promotes transfer hydrogenation of alkenes with 0.5 mol\% catalyst load in 2-propanol at 70°C.\textsuperscript{132} Mono- and 1,2-disubstituted olefins were reduced within 48 h, but very low conversion was observed for trisubstituted substrates, while four-substituted alkenes could not be reduced under the proposed conditions. α,β-Unsaturated esters, amides and acids were also transfer hydrogenated to the corresponding saturated esters, amides and acids under these conditions, although a considerable amount of side products of Michael addition of 2-propanol were also observed.

Nickel-based catalysts containing chiral bis(phosphine) ligands for asymmetric transfer hydrogenation of α,β-unsaturated esters were introduced by Zhou et al. The Ni(OAc)\textsubscript{2}/(S)-binapine system II-76 was employed in the asymmetric reduction of α,β-unsaturated α- and β-acetamidoesters with HCO\textsubscript{2}H/NEt\textsubscript{3}.\textsuperscript{160} Highly efficient and enantioselective (up to 99\% \textit{ee}) catalytic process may find further application in the synthesis of chiral aminoacids. Another catalytic system, NiBr\textsubscript{2}(DME)/(2R)-DuPhos II-77, was proven to catalyze asymmetric transfer hydrogenation of α,β-unsaturated 3-methylesters providing high yields and \textit{ee} (up to 98\%).\textsuperscript{161}
Recently, triazolylidene iridium complex II-78 was introduced by Albrecht’s and Dieguez’ groups. Its catalytic activity was studied for the reaction of transfer hydrogenation of ketones, imines, and olefins in 2-propanol. TOF of up to 260 h⁻¹ was recorded for alkene reduction. The catalyst demonstrated efficiency in transfer hydrogenation mono-, di- and trisubstituted olefins, as well as allylic alcohols and α,β-unsaturated ketones, although carbonyl group was also reduced in the latter case.

Iridium pincer catalyst II-79 was developed by Huang et al. and applied to transfer hydrogenation of alkenes and alkynes in ethanol. Substrates containing the terminal double C=C bond were shown to be reduced in 2–4 hours at 60°C, while internal di- and trisubstituted alkenes required 12 and more hours to reach high conversions under the same conditions. Remarkably, that reaction tolerates the carbonyl group in unsaturated ketones, and the product with only the C=C bond reduced can be isolated after a short time, although the C=O bond undergoes transfer hydrogenation as well if a longer reaction time is applied. Disubstituted alkynes can undergo transfer hydrogenation in the presence of 1 mol% II-79.
in ethanol. Full reduction to alkanes was observed for all substrates, although electron-deficient alkynes require large catalyst load and more reaction time.

Plietker et al. demonstrated that RuH$_2$(PPh$_3$)$_4$ can catalyze transfer hydrogenation of a series of internal alkynes in DMF/HCO$_2$H mixture, affording a variety of Z-alkenes.$^{164}$ According to the proposed mechanism, the Z-selectivity is established at the step of hydrometallation (Scheme 10). Upon alkyne insertion into the metal-hydride bond, which is a cis-addition process, the less sterically demanding Z-alkene forms.

![Scheme 10. Proposed mechanism of semihydrogenation of alkynes, providing Z-selectivity.](image)

The simple and commercially available complex Pd(OAc)$_2$ was found to catalyze transfer semihydrogenation of internal alkynes with the formation of Z-alkene, utilizing DMF/KOH as hydrogen source.$^{165}$ Although high conversions and selectivity for a wide substrate scope could be observed, the required high temperatures (145°C) might make it inapplicable for complicated substrates.

Elsevier et al. reported several palladium-based complexes for transfer hydrogenation of alkynes to Z-alkenes. NHC-supported palladium complex II-80 was one
of the first catalysts demonstrated to promote a stereoselective transfer semihydrogenation of a wide scope of aromatic and aliphatic internal alkynes, utilizing H$_3$CCO$_2$H/NEt$_3$ as a hydrogen source. Interestingly, the catalyst tolerates the carbonyl group under the transfer hydrogenation conditions. Mechanistic investigations proved a broken order in substrate and the first order in catalyst and hydrogen donor. The broken order in substrate describes linear acceleration of the reaction with the increasing of alkyne concentration, with the abrupt change to reverse dependence of the reaction rate, when the substrate concentration exceeds 0.15 M. This implies that the substrate coordinates to palladium before the rate-determining step and that an equilibrium is involved between the Pd(solvent)-complex + alkyne and the Pd(alkyne) complex. Measurements of the kinetic isotope effect revealed two rate-determining steps: the proton and hydride transfer. Another efficient palladium catalyst II-81 contains a pyrimidyl-NHC ligand and provides high selectivity toward Z-alkene upon transfer hydrogenation.

Zerovalent palladium complexes II-82 bearing bulky expanded-ring NHC ligands were also employed in the transfer hydrogenation of alkynes. Strong σ-donor NHCs in these cases were observed to enhance the catalytic activity that led to over-reduction to the corresponding alkane.
The Elsevier group has also proposed a convenient methodology for transfer semihydrogenation.\textsuperscript{170} They demonstrated the commercially available NHC-supported palladium complex \textbf{II-83} to be an excellent precatalyst that formed \textit{in situ} an active species with triphenylphosphine and provided high $Z$-selectivity for a wide scope of alkynes.

Recently, Swamy \textit{et al.} Pd(PPh$_3$)$_4$ can catalyze transfer semihydrogenation of ynamides and ynamines in ethanol, providing exceptional $E$-selectivity at 90$^\circ$C.\textsuperscript{171} No products of overreduction were observed even upon prolonged heating.

Iron-based catalytic system Fe(BF$_4$)$_2$·6H$_2$O/tetraphos was introduced by Beller \textit{et al.} for transfer hydrogenation of terminal alkynes with formic acid.\textsuperscript{172} Reaction affords the semireduction of aliphatic and aromatic alkynes, providing tolerance to a variety of functional groups, including halogens, hydroxyl and alkoxy groups, esters.

Zhang \textit{et al.} have recently reported cobalt complexes \textbf{II-84} bearing pincer-type PNP ligands. These complexes were demonstrated to promote transfer hydrogenation of styrene with 2-propanol.\textsuperscript{173} A wide range of mono- and disubstituted alkynes can be reduced with excellent yields at 100$^\circ$C within 24 hours. They also showed that transfer hydrogenation of diphenylacetylene yielded a mixture of $Z$- and $E$-alkenes in the ratio of 1:2.
II. 2. C-N bond-formation reactions by borrowing hydrogen catalysis for amine production

II. 2. 1. Introduction

The phenomenon of hydrogen transfer gave rise to a number of synthetic approaches that fall under the name “borrowing hydrogen methodology”.\textsuperscript{174} This is a powerful strategy that combines dehydrogenation/hydrogenation processes with one or more intermediate reactions in one pot. Borrowing hydrogen methodology utilizes readily accessible substrates for the synthesis of more complex molecules, which otherwise would require three or more synthetic steps. The strategy strongly benefits from the perspective of atom economy, as only a few side-products (e. g. H\textsubscript{2}O, NH\textsubscript{3}, etc.) are generated during the process, as compared to the amount of waste that would be produced if a step-by-step procedure were applied, utilizing large quantities of reducing/oxidizing reagents and solvents. It is also a much less time-consuming procedure, as it does not require tedious separation or isolation of intermediate products.

The key idea behind the strategy is that the hydrogen, obtained upon oxidation of a donor molecule, is stored on a catalytic metal species to be later accepted by the intermediate product in the final step. The general scheme for borrowing hydrogen catalysis is presented on Scheme 11. The circle process is launched by dehydrogenation of one of the substrates, resulting in the formation of a product able to react with another substrate to give an unsaturated compound that will be reduced by the metal-hydride species generated during the first step. Dehydrogenation step is a thermodynamically disfavoured process and
generally reversible. Nevertheless, the total process is shifted to products, due to the irreversibility of the hydrogenation step.

\[
R', R'', R''' = \text{H, Alkyl, or Aryl} \\
X = \text{CH}_2, \text{NH, O} \\
Y = \text{CH, N}
\]

**Scheme 11.** General scheme for borrowing hydrogen methodology.

Heterogeneous hydrogen borrowing catalysis has been known since 1930s.\(^{175-178}\) However, the intense development of this methodology was caused by the studies of homogeneous catalysts for hydrogenation and transfer hydrogenation. To date, different approaches have been established for the formation of C-N and C-C bonds by activation of alcohols,\(^ {179-183}\) amines,\(^ {184-186}\) and alkanes.\(^ {187-189}\)

**II. 2. 2. Activation of alcohols**

Alcohols are known to be poor nucleophiles and in the absence of a pre-activation, for instance by addition of a base or acid, possess limited reactivity. On the other hand, carbonyl compounds have a much broader spectrum of reactivity and can act both as nucleophile and electrophile. Therefore, temporary dehydrogenation of alcohols, involved in the borrowing hydrogen catalysis, has become an alternative way of their activation.\(^ {190}\)
Borrowing hydrogen strategy through the activation of alcohols has been developed in parallel with the expansion of the catalysts for oxidative dehydrogenation. Very often transition metal complexes that catalyze hydrogenation and/or transfer hydrogenation can also promote the reverse dehydrogenation process. Generally, secondary alcohols can undergo dehydrogenation to ketones in the presence of transition metal-based catalysts without any hydrogen acceptor, which is convenient and atom economical process. Dehydrogenation of primary alcohols usually leads to the formation of esters, as initially obtained aldehyde reacts with alcohol to give hemiacetal, which is then oxidized to ester. Ruthenium-, iridium-, osmium-, iron-, nickel-based complexes for acceptorless dehydrogenation of alcohols have been developed (Scheme 12).

Scheme 12. Selected examples of transition metal catalysts for acceptorless dehydrogenation.

**N-Alkylation of Amines.** Borrowing hydrogen methodology has provided benefits of chemoselective synthesis of secondary amines from alcohols and primary amines, although examples of formation of tertiary amines are also known and will be presented below. The process occurs via three steps: (1) dehydrogenation of alcohol to form
aldehyde/ketone; (2) coupling reaction of carbonyl compound and amine; (3) hydrogenation of the produced imine. The chemoselectivity under borrowing hydrogen conditions is explained by a faster reaction of primary amine during coupling with aldehyde or ketone, while secondary amines are known to be more reactive towards conventional alkylating agents, such as alkyl halides, resulting in the formation of tertiary amines.

First examples of homogeneous $N$-alkylation of amines were reported in early 1980s. Grigg et al. screened a number of readily available rhodium, iridium and ruthenium complexes for alkylation of pyrrolidine in boiling methanol.\textsuperscript{200} RhH(PPh$_3$)$_4$, which showed the highest catalytic activity, was further applied in alkylation of benzylamine, cyclohexylamine and pyrrolidine in methanol, ethanol or 2-propanol. \textsuperscript{3}$N$-(N-alkylamino)propan-1-ol also underwent cyclization to form $N$-alkylated pyrrolidine under proposed conditions. Watanabe’s group showed that RuCl$_2$(PPh$_3$)$_2$ can catalyze alkylation of aniline with simple alcohols, although mixtures of secondary and tertiary amines were obtained.\textsuperscript{201}

A large family of iridium catalysts has been developed for $N$-alkylation of aromatic and aliphatic amines. Half-sandwich iridium complex [Cp*IrCl$_2$]$_2$ was applied for the synthesis of ($N$-alkyl)anilines with primary and secondary alcohols with the catalyst load od 1-3 mol% at 110°C.\textsuperscript{202} A higher catalyst load was required in the case of aniline containing electron-withdrawing substituents. Few examples of aliphatic primary amines, involved in the reaction, were also reported to proceed with 3 mol% iridium catalyst. Secondary amines can undergo alkylation yielding tertiary amines, although even a larger amount of the catalyst (up to 5 mol%) was required to achieve good conversions. Later this iridium catalytic system was applied for the synthesis of piperazines, using vicinal diamines and diols.\textsuperscript{203} Although
the catalyst load could be reduced to 0.5 mol%, a much higher temperature (140°C) was required for the reaction. Analogous iridium complex \([\text{Cp}^*\text{IrI}_2]\) was found to be more suitable for amine alkylation in aqueous media.\(^{204}\) Primary terminal and \(\alpha\)-methylated amines were involved in the reaction, which resulted in the formation of secondary amines with good to excellent yields.

Kempe et al. reported two iridium complexes, \(\text{II-91}\) and \(\text{II-92}\), bearing bidentate N,P-ligands for alkylation of anilines with benzyl alcohol or hexanol at 70°C.\(^{205}\) Half-sandwich iridium complex \(\text{II-93}\) was studied in the alkylation of primary amines.\(^{206}\) In most cases secondary amines were predominantly produced, although a double alkylation was observed when simple linear alcohols were used. Tertiary amines were also produced when secondary amines were treated with 1-hexanol under the proposed conditions. NHC-supported iridium complex \(\text{II-94}\) was recently reported as an efficient catalyst for alkylation of anilines and cyclic amines with benzyl alcohol.\(^{207}\) Furthermore, anilines can be alkylated with a range of other alcohols as well. Chemosselectivity depends on the ratio of reactants, thus addition of a two-fold excess of aniline results in the production of secondary amines exclusively, however the reaction proceeds to tertiary amines if a two-fold excess of alcohol is used. Moreover, \(N\)-arylated cycloamines can be produced when anilines are involved in the reaction together with terminal diols.

![Image of chemical structures](image.png)
Ruthenium catalysts for alkylation of amines via borrowing hydrogen strategy have expanded exponentially since Beller et al. reported the activity of Ru$_3$(CO)$_{12}$ in this type of transformation in 2006. Primary amines were treated with primary and secondary alcohols in the presence of 2 mol% Ru$_3$(CO)$_{12}$ and 6 mol% tri-(o-tolyl)phenyl or n-butyl-di-1-adamantyl-phosphine. Later, another ruthenium complex, [Ru(p-cymene)Cl$_2$]$_2$, was studied by Williams et al. It was reported that addition of DPEphos ligand II-95 to the reaction mixture boosts the activity of the ruthenium catalyst towards alkylation of amines with alcohols. This was applied to a number of transformations, including the synthesis of secondary and tertiary amines from primary and secondary amines (or cycloamines), respectively. N-substituted saturated heterocyclic compounds were also obtained from primary amines and terminal diols under the proposed conditions.

![Chemical Structures](s3.lorrent.org/2021/09/1460440817_II-95.png)

Martín-Matute et al. proposed ruthenium pincer catalyst II-96 for selective alkylation of anilines and 2-aminopyridines. It was shown that 2-aminoalcohols can be used to alkylate aromatic amines, because the amino group of the alcohol does not undergo alkylation under this conditions. Ruthenium complex II-97, bearing a phosphine-functionalized hydrazone/thiosemicarbazone ligand, was applied to N-alkylation of 2-aminobenzothiazoles, 2-aminopyrimidines, 2-aminopyridines, anilines, and benzensulfonamides, although only benzyl alcohols were screened as alkylation agents.
Özdemir et al. prepared NHC-supported ruthenium complexes II-98a-e from [RuCl₂(p-cymene)]₂ and readily available 1,3-dialkylbenzimidazolium salts, functionalized with benzyl groups. The NHC ligand was found to provide π-interaction of the aromatic ring with metal centre. The obtained complexes were screened for the catalytic activity in N-alkylation of cyclic amines, pyrrolidine and morpholine, with benzyl alcohols (Scheme 13).

Scheme 13. N- and C3-alkylation of pyrrolidine and morpholine in the presence of II-98.

Besides the product of N-alkylation, further activation of the C3 position was also observed for both amines. Because the former product turns into a side-product of C3-alkylation upon prolonged heating, it can be isolated with good yield as an intermediate compound. Later [RuCl₂(p-cymene)]₂ in combination with benzimidazolium sulfonate salts was studied for catalytic N-alkylation of anilines and 2-aminopyridines. Compound II-99 provided the largest increase of catalytic efficiency of the reaction among the studied benzimidazolium sulfonate salts bearing different N-substituents.
Another NHC-supported ruthenium catalyst **II-100** can mediate dehydrogenative amidation or \(N\)-alkylation that can be controlled by the choice of solvent and base.\(^{214}\) Thus, \(N\)-alkylation of amines is a predominant process at 130°C under neat conditions with the addition of NaHCO\(_3\). Using molecular sieves helps in driving the reaction by removing water. The double alkylation can be achieved with a higher ratio of alcohol to amine (5:1) at 140°C. On the other hand, an amide is formed via dehydrogenation of intermediate hemiaminal when the reaction is conducted in toluene and NaH is used as a base.

Takacs et al. developed a new half-sandwich ruthenium complex **II-101** for the activation primary and secondary alcohols in the borrowing hydrogen methodology.\(^{215}\) Due to the easier activation of primary alcohols, compared to the secondary one, selective amination of diols, containing both types of hydroxyl groups, was achieved with the proposed catalytic system. Thus, primary alcohol reacts with amine first, yielding amino alcohol. Then another equivalent of same or different amine can be added to aminate the remaining secondary alcohol. Moreover, the developed catalytic system was applied for intra- and intermolecular cyclizations of aminoalcohols, diols, and diamines providing heterocyclic systems. In particular, piperazine was obtained by the reaction of intramolecular cyclization of two molecules of \(\beta\)-aminoalcohol or the reaction of diamines with diols.

An interesting application of the borrowing hydrogen strategy for glycerol upgrading was reported by Kann et al.\(^{216}\) Primary and secondary amines, including morpholine and
piperazine, was alkylated in the presence of 1.25 mol% [Ru(p-cymene)Cl₂]₂ and 2.5 mol% DPEphos or dppf at 130°C, with solketal (isopropylideneglycerol) employed as alkylating reagent. Deprotection under acidic conditions leads to glycerol aminated at the terminal carbon. The applicability of the catalytic system was demonstrated in the synthesis of dropropizine **II-102** (an antitussive agent included in a number of commercial cough suppressants) from solketal and N-phenylpiperazine.

Although iridium and ruthenium catalysts prevail in N-alkylation, catalysts based on other transition metals have recently also emerged. Thus, Kempe *et al.* reported cobalt-catalyzed N-alkylation of anilines and 3-aminopyridines.²¹⁷ A series of cobalt P,N,P-pincer complexes was screened for reactivity and showed enhanced reactivity compared to CoCl₂. Complex **II-103** demonstrated the best results.

First manganese pincer complex that can catalyze the amination of alcohols was reported by the Beller group.²¹⁸ These workers were able to alkylate a number of anilines and aminopyridines with benzyl alcohols in the presence of 3 mol% complex **II-104** and 75 mol% KOtBu. N-methylated anilines can be obtained if the reaction proceeds in methanol. Indole can be also synthesized by intramolecular condensation of 2-(2-aminophenyl)ethanol under the proposed catalytic conditions within 48 hours.

![Complex II-103](image)

**II-103**

Iron cyclopentadienone complex **II-105**, which has previously shown excellent activity in hydrogenation of ketones²¹⁹ and Oppenauer-type oxidation of alcohols²²⁰, was
also applied in the $N$-alkylation of amines with alcohols via borrowing hydrogen methodology.\textsuperscript{221, 222} Primary as well as secondary amines, including morpholine, can be alkylated with a variety of aliphatic and benzyl alcohols in the presence of 5 mol\% II-105 at 120-135°C. Saturated $N$-heterocycles can be produced by a reaction of benzylamine with terminal diol or benzyl alcohol with amino alcohol under the proposed conditions as well (Scheme 14).

\textbf{Scheme 14.} Synthesis of $N$-benzylpyperidine in the presence of II-105.

$N$-\textit{Alkylation of Ammonia.} Classic reductive amination of aldehydes is the most common industrial process for the production of lower alkyl amines.\textsuperscript{223} The wide application of this method is supported by high accessibility of carbonyl compounds and ammonia. However, one of the serious issues of this procedure is the possibility of side reactions due to the high concentration of electrophilic aldehydes. Borrowing hydrogen methodology allows one to circumvent this problem by providing conditions when aldehyde or ketone is produced \textit{in situ} and is immediately involved in the further reaction without significant accumulation in the reaction mixture.

Milstein \textit{et al.} were among the first who studied $N$-alkylation of ammonia by borrowing hydrogen catalysis.\textsuperscript{224} During their investigation of the role of metal-ligand cooperation, involving aromatization-dearomatization of the ligand\textsuperscript{147}, a pincer ruthenium complex II-106, bearing an acridine-based ligand, was found to act as an efficient catalyst for the production of primary amines from primary alcohols and ammonia. The reaction occurred under 7.5 atm NH$_3$ under reflux in toluene. It was mentioned that although a
primary amine is formed first, the reaction proceeds further to produce a secondary amine, as soon as all alcohol was consumed.

![Chemical structures II-106 and II-107]

Ruthenium cluster Ru$_3$(CO)$_{12}$ in combination with different mono- and bidentate phosphine ligands was applied for alkylation of ammonia by Beller’s group.$^{225}$ The catalytic system was found to benefit most from the addition of phosphine II-107. Secondary alcohols can be transformed into $\alpha$-substituted primary amines. However, a sufficient pressure of ammonia (18 atm) is required for chemoselective monoalkylation and high temperature ($150^\circ$C and higher) is necessary for the full conversion of alcohols. It was also highlighted that primary alcohols undergo transformation with a significantly lower conversion under the same conditions.

Almost at the same time Vogt et al. reported a similar study and came up with the same catalytic system Ru$_3$(CO)$_{12}$/II-107 for ammonia alkylation of secondary alcohols.$^{226}$ Interestingly, according to their observation, the secondary amine, produced during alkylation of ammonia with cyclohexanol as a side product, was consumed after all alcohol had reacted. It was suggested that dicyclohexylamine could be dehydrogenated with the formation of imine, with the following decomposition to primary amine and cyclohexanone under the reaction conditions. Following studies were mainly focused on the application of Ru$_3$(CO)$_{12}$ with different ligands for ammonia alkylation by bio monoalcohols and bioderived diols.$^{227}$
As an alternative to the use of ammonia gas for the reaction, requiring a high-pressure equipment, ammonium salts can be applied as a source of nitrogen. Fujita et al. used ammonia acetate and ammonia tetrafluoroborate for the chemoselective synthesis of tertiary or secondary amines in the presence of half-sandwich iridium catalyst \([\text{Cp}^*\text{IrCl}_2]_2\) \(^{228}\). Thus, exclusively tertiary amines were produced from primary and secondary alcohols with ammonia acetate, while the application of NH\(_4\)BF\(_4\) resulted in the formation of secondary amines, with only traces of tertiary amines in the case of primary alcohols.

However, the procedure described above suffers from the issue of production of stoichiometric amounts of waste salts. The solution can be the utilization of aqueous ammonia. Thus, a water-soluble half-sandwich iridium catalyst II-108 was developed for the amination of a series of primary and secondary alcohols in aqueous media.\(^{229}\) Chemoselectivity was shown to depend strongly on the structural parameters of the substrates, providing secondary amines in the case of secondary alcohols, while primary alcohols were transformed to tertiary amines.

![II-108](image1.png)

Another example of a catalytic system for ammonia alkylation of aqueous ammonia through borrowing hydrogen strategy is based on the platinum complex \([\text{Pt(cod)}\text{Cl}_2]\) with the addition of diphosphine ligand II-109.\(^{230}\) A broad range of primary allylic alcohols was involved in the reaction, resulting in chemoselective formation of primary amines with good yield. However, secondary allylic alcohols with a terminal double bond underwent 1,3-isomerization upon the reaction. It was also highlighted that aqueous ammonia is essential
for the procedure, and was demonstrated that a mixture of primary, secondary and tertiary amines was obtained if the ammonia gas was applied.

**Indirect Aza-Wittig Reaction.** Iminophosphoranes ("aza-Wittig reagents") can react with carbonyl compounds, analogously to the Wittig reagent, to produce imines.\(^{231}\) Borrowing hydrogen methodology allows one to combine hydrogenation/dehydrogenation process with the aza-Wittig reaction, as an alternative route for amine synthesis (Scheme 15), although this strategy is less preferable, as it generally requires an additional step of formation of iminophosphoranes from azides and triarylphosphines by the Staudinger reaction.\(^{232}\)

![Scheme 15. Synthesis of N-benzylaniline via indirect aza-Wittig reaction.](image)

Williams *et al.* reported that 2.5 mol\% [Ir(COD)Cl\(_2\)] in the presence of 5 mol\% dppf can catalyze the reaction of benzyl alcohol and *N*-{(triphenylphosphoranylidene)-aniline II-110 to produce *N*-benzylaniline at 110°C with 91% conversion in 24 hours.\(^{233}\) *N*-benzylaniline can be obtained by the reaction of aniline with benzyl alcohol under the same conditions, albeit with a much lower conversion (23%).
Commercially available Pd(OAc)$_2$ can be applied as a catalyst in the indirect aza-Wittig reaction as well, although simple $N$-alkylation of amines with alcohols proceeds faster under the same catalytic conditions.$^{182}$ Later Cu(OAc)$_2$ was reported to demonstrate catalytic activity in the indirect aza-Wittig reaction.$^{183, 234}$ However, both catalytic systems require an equivalent of base (CsOH and KO$_t$Bu, respectively), and the substrate scope is limited to primary alcohols.

II. 2. 3. Activation of amines

$N$-Alkylation of Amines. Primary amines can undergo dehydrogenation to give imines, which can serve as an activation step in the borrowing hydrogen methodology for amine synthesis. Nucleophilic attack of a second equivalent of amine produces aminoaminal, which is unstable, and upon elimination of ammonia secondary imine is formed. The latter can be hydrogenated in situ under the reaction conditions. However, the reaction generally proceeds at higher temperatures than the analogous $N$-alkylation with alcohols.

Beller $et$ $al.$ screened a number of ruthenium catalysts, previously found to be efficient catalysts for hydrogenation and/or transfer hydrogenation, for the activation of hexylamine in the reaction of $N$-alkylation of aniline.$^{235}$ The Shvo’s catalyst II-56 showed the best performance, leading to 94% conversion to secondary amine at 150°C in 24 hours. Substrate scope screening demonstrated good to excellent yields for an array of aromatic amines and alkylamines with high tolerance of the catalytic system to a variety of functional groups, with the exception of sterically hindered anilines.

Recently cobalt-based catalyst II-111 for amine coupling was introduced by Zhang $et$ $al.$.$^{186}$ A number of $N$-alkylanilines can be produced, using terminal and internal
primary amines as alkylationing agents, while heating same alkylamines in the presence of II-111 at 120°C affords asymmetrical secondary amines. Terminal diamines undergo intramolecular cyclization under the proposed conditions, leading to saturated heterocyclic products (Scheme 16).

**Scheme 16.** Synthesis of secondary amines in the presence of II-111.

*N-Alkyl Transfer.* While dehydrogenation of primary amines may be quite challenging, oxidation of secondary and tertiary amines to imines and iminium salts, respectively, can undergo much easier. In this case, it is the amine that eliminates from an intermediate aminoaminal, performing formal N-alkyl transfer (Scheme 17). In fact, N-alkyl exchange between tertiary amines in the presence of Ru₃(CO)₁₂, Os₃(CO)₁₂, and Ir₄(CO)₁₂ has been known since 1980s.²³⁶

**Scheme 17.** Representation of transalkylation of amines.
N-alkylation of anilines was performed with tetrabutyl ammonium bromide in the presence of 1 mol% RuCl₃·nH₂O/PPh₃ or Ru₃(CO)₁₂ at 180°C in dioxane. Addition of a catalytic amount of SnCl₂·2H₂O afforded mainly mono-alkylated products, albeit in moderate yields. Here the tertiary amines can be also considered as true alkylating agents, as quaternary ammonium salts has been shown to transform into tertiary amines by cleavage of the C-N bond in aqueous media.

Iridium dimer [Cp*IrI₂]₂ is capable to catalyze selective coupling of two different amines, even though both of them can be potentially dehydrogenated. Anilines, as well as benzyl amines, were treated with diisopropylamine in the presence of 1 mol% catalyst at 155°C in xylene to produce N-isopropyl derivatives, so that the overall process can be recognized as a formal transfer of isopropyl group. Wang et al. applied IrCl₃ in combination with the alanine triazole ligand II-112 to perform transfer of the ethyl group from triethylamine to anilines and 2-aminopyridines at 150°C with moderate to good yields.

New benzoazolyl iridium(III) complexes were developed by the Ding group. These complexes were screened for the activity in C-N formation reactions, with complex II-113 showing the best performance. Anilines can be chemoselectively mono-N-alkylated with triethylamine in the presence of 2 mol% II-113 at 155°C, providing good yields and demonstrating high tolerance to different functional groups. Addition of small amounts of
AgNTf$_2$ was found to be the most beneficial among a number of screened silver salts for the formation of an active catalytic species *in situ*.

II. 3. Reduction via direct hydrogen transfer

II. 3. 1. Meerwein-Ponndorf-Verley reduction

One of the important past breakthroughs in the reduction chemistry was the discovery of Meerwein-Ponndorf-Verley (MPV) reduction. In 1925, the groups of Meerwein$^{17}$ and Verley$^{18}$ independently reported the first examples of hydrogen transfer from alcohols (ethanol and geraniol) to aldehyde, utilizing aluminum ethoxide. In 1926, Ponndorf *et al.* observed the reduction of ketones by aluminum alkoxides of secondary alcohols, such as 2-propanol.$^{19}$ Later trialkylaluminum compounds, for instance triisobutylaluminum, also were demonstrated to be efficient reducing reagents for ketones and aldehydes.$^{242, 243}$ Oppenauer showed the reverse process of alcohol oxidation with aluminum butoxide in acetone (Oppenauer oxidation).$^{244}$ A number of cholestene-type products were produced by the reduction of cholesterol-type compounds.

Hydrogen transfer in the MPV reduction is commonly regarded to proceed by a direct mechanism via a six-membered cyclic transition state, in which hydrogen is symmetrically located between two carbon atoms (Scheme 1).$^{245, 246}$ DFT calculations confirmed that this route is much more energetically preferred over the hydridic mechanism, where an aluminum-hydride species forms.$^{247}$
Since simple aluminum alkoxide species showed competence in reduction, quite a few more complex aluminum compounds for the MPV reduction have been also developed. For instance, a dimeric aluminum biphenoxylalkoxide II-114 was reported by Lin et al. \(^{248}\) Benzaldehydes were screened in the MPV reduction with 10 mol% II-114 in 2-propanol, as hydrogen source, at room temperature with good conversion. However, a higher conversion can be achieved with two equivalents of the reducing alcohol. Maruoka et al. proposed an aluminum alkoxide II-115 bearing 2-hydroxy-2'-(perfluorooctanesulfonamino)biphenyl for the reduction of ketones with 2-propanol with 10 mol% catalyst load at room temperature.\(^{249}\) Bidentate aluminum alkoxide II-116 was applied as a catalyst in a formal intramolecular hydrogen transfer in substrates, containing both hydroxy and carbonyl groups.\(^{250}\)
A number of aluminum MPV catalysts bearing ligands other than alkoxide have been also developed. Huang et al. reported a series of aluminum species II-117 containing pyrrole–imine ligand, which exhibited activity in the MPV-type hydrogen transfer from 1-naphthalenemethanol to 2-naphthalenecarbaldehyde at room temperature.\textsuperscript{251} Krempner’s group introduced a well-defined and thermally robust aluminum isopropoxide II-118 that was found to be an efficient catalyst for MPV reduction of a broad range of aliphatic and aromatic carbonyl compounds. High TOFs up to 940 were observed for the cyclohexanone reduction at the catalyst load as low as\textsuperscript{252} 0.05 mol\%, albeit at 60°C. A series of asymmetric guanidinato aluminum complexes were prepared and screened for the MPV reduction of carbonyl compounds in 2-propanol by the group of Wei, with complex II-119 showing the best results.\textsuperscript{253}
Aluminum isopropoxide became a widespread reagent for MPV reduction, although the reaction is reversible, and the removal of acetone is required to move the equilibrium in the direction of product formation. Replacement of the alkoxy ligands with more electronegative substituents, such as anions of strong protic acids, was revealed to enhance the reaction rate by facilitating coordination of carbonyl compounds to the aluminum. Thus, the procedure for the MPV reduction was significantly improved by a simple addition of a catalytic amount of trifluoroacetic acid (TFA).\textsuperscript{254,255}

The first attempts of asymmetric MPV reduction were made in 1950s by Bothner-By, who applied LiAlH\textsubscript{4} in combination with D-camphor for the stoichiometric hydrogenation of 2-butane and pinacolone,\textsuperscript{256} although enantioselectivity reported in the paper was later shown to be erroneous and was provided by traces of camphor.\textsuperscript{257} In 1962, Landor \textit{et al.} were able to show that addition of 1,2-\textalpha-cyclohexylidene-\textalpha-D-glucofuranose or 4,6-\textalpha-benzylidene-\textalpha-D-glucopyranoside as chiral ligands in the MPV reduction of a number of ketones provided enantioselectivity, albeit it did not exceed 15\%.\textsuperscript{258} In subsequent years, LiAlH\textsubscript{4} was modified with a number of readily accessible and naturally occurring substances, such as alkaloids\textsuperscript{259}, sugars\textsuperscript{260}, alcohols\textsuperscript{261}, amino alcohols\textsuperscript{262,263}, etc.

Meerwein also showed the applicability of trialkylboranes for the reduction of aldehydes.\textsuperscript{242} Much later, boranes with alkyl groups that contain substituents on the \(\beta\)-
carbon, such as B-siamyl-9-BBN (II-120), were demonstrated to be highly effective and chemoselective towards aldehydes under mild conditions.\textsuperscript{264,265} Soon a wide variety of boron with chiral alkyl groups, e.g. (+)-\(\alpha\)-pinene II-121, (+)-\(\beta\)-pinene II-122, (-)-camphene II-123, and (+)-3-carene II-124, became available for asymmetric hydrogen transfer to ketones.\textsuperscript{266-270}

![Chemical structures](image)

In 1985, diisopinocampheylhaloboranes were found to reduce ketones at low temperatures as well.\textsuperscript{271,272} In the subsequent years, hydroxy-, alkoxy-, acetoxy- and methanesulfonyoxy-incorporated diisopinocampheylborane derivatives were prepared and explored towards hydrogen transfer.\textsuperscript{273-277} A number of MPV reagents, containing other metals, e.g. lanthanum\textsuperscript{278}, samarium\textsuperscript{279}, scandium\textsuperscript{280}, yttrium\textsuperscript{280}, tantalum\textsuperscript{281}, ytterbium\textsuperscript{282}, indium\textsuperscript{283,284} have been also introduced.

\textbf{II. 3. 2. Alkali metal-catalyzed transfer hydrogenation}

Although alkali metals are not generally considered as catalytic centres, but merely as innocent counter-cations, their role in catalysis is not negligible. In fact, the oldest alkali metal-mediated reaction, albeit usually not considered as such, is the classical Cannizzaro reaction,\textsuperscript{285} i.e. disproportionation of aldehydes under the action of alkali metal bases, e.g.
KOH. However, according to the mechanism of this reaction (Scheme 19), the alkali metal cation plays a minor role in the process, while the hydroxyl anion and its concentration is essential. Closely related Tishchenko reaction of aldehyde disproportionation requires aluminum or sodium alkoxide to produce esters, rather than free carboxylic acids.286

![Scheme 19. Accepted mechanism of Cannizzaro reaction.](image)

In 1945, Woodward et al. reported that alkali metal bases can catalyze the MPV reduction and Oppenauer oxidation, which was successfully applied to the transformation of cinchona alkaloids.287 Thus, a full conversion of quinine or quinidine to quininone was observed after 15 hours of reflux in benzene with 5 equivalents of benzophenone, as the hydrogen acceptor, and 3 equivalents of KOrBu (Scheme 20).

![Scheme 20. Alkali base-catalyzed MPV reduction of quinine and quinidine.](image)

If the oxidation is performed in the presence of one equivalent of benzophenone, only 80% conversion can be achieved, as the process is reversible. A number of other cinchona alkaloids were dehydrogenated under the same conditions, demonstrating the general applicability of the procedure. It is worth noting that aluminum alkoxides were inactive
towards Oppenauer-type oxidation of these substrates. The reason for this was suggested to be that aluminum alkoxides form stable adducts with amines. Quininone can be hydrogenated by sodium isopropoxide (10 equivalents) in refluxing toluene, leading to quinine and quinidine in 30% and 60% yield, respectively. Thus, it became possible to convert quinine to quinidine via successive Oppenauer oxidation and MPV reduction steps.

Later on, von Doering and Aschner studied the racemization of \((S)\)-methylbutanol-1 in the presence of sodium alkoxides and different additives.\(^{288}\) Racemization is possible through oxidation of alcohol to aldehyde, that can lose the optical activity via enolization, followed by hydrogenation with the formation of both enantiomers. A high level of racemization was observed when catalytic amounts (3-5 mol\%) of benzophenone or benzpinacol were applied. The latter is known to disproportionate to benzophenone and benzhydrol under basic conditions. Different experiments with the addition of benzhydrol did not lead to any changes. Addition of pinacol resulted in minor conversion, as this compound is stable and does not undergo disproportionation like benzpinacol. Thus, in both cases the presence of a carbonyl compound was beneficial. Addition of radical scavengers, such as diphenylamine or thiophenol, as well as \(p,p'\)-bis[2-(dimethylamino)phenyl]amine, known to form radical species capable of initiating the single electron transfer, under basic conditions neither enhanced the reaction nor retarded the process, already initiated by benzophenone. This led to the conclusion that radical intermediates did not form in this reaction. The fact of racemization via aldehyde enolization was demonstrated with deuterated substrates. Thus, the migration of deuterium from the hydroxyl group of the initial \((S)\)-methylbutanol-1 to the C2 position in the racemic product was demonstrated, while no deuterium was found on the C1 carbon (Scheme 21). Besides, the process with a deuterated
substrate proceeds slower than with protonated one by a factor of 2.5, which indicates the rate determining step as formation or cleavage of the C-H bond.

Scheme 21. Suggested mechanism for deuterium redistribution catalyzed by sodium alkoxides.

Despite this finding, the role of alkali metals in catalysis had been largely neglected until Bäckvall et al. discovered the accelerating effect of bases in transition metal-mediated transfer hydrogenation. After that, the application of excess alkali metal bases (in the form of hydroxides, alkoxides, carbonates, or phosphates) as promoters in catalytic transfer hydrogenation became very common. Nevertheless, the idea that alkali metals themselves can be the catalytic centres had been dormant until 2004, when Crabtree et al. studied iridium-catalyzed transfer hydrogenation of 2-naphthaldehyde with 2-propanol. Carbonates $\text{M}_2\text{CO}_3$ ($\text{M} = \text{Rb, Cs}$), applied at 50 mol% load as bases for producing active iridium species in situ, were observed to provide excellent conversion of the substrate in blank experiments without the iridium complex, albeit in a longer time.

Alkali metal catalysis was rediscovered again in 2007, when Adolfsson et al. reported reduction of an array of aryl and alkyl ketones in isopropanol mediated by lithium isopropoxide, albeit at elevated temperatures (180 °C). Later, while exploring the iron-catalyzed transfer hydrogenation of carbonyl compounds, the Ouali group observed that the
reaction rate raised consistently as the load of base was increased (10, 20, and 50 mol%).\textsuperscript{10} Moreover, blank experiments with either KO\textsubscript{t}Bu or NaOH in the absence of any iron salt or complex resulted in a significantly higher conversion of the substrate. Subsequent studies of employing lithium, sodium, and potassium alkoxides and hydroxides at 20 mol\% load in the transfer hydrogenation of acetophenone in refluxing 2-propanol revealed that the activity of alkali metal compounds follows the order Li < K < Na, which was explained by the balancing effect of alkali metal Lewis acidity on the carbonyl activation and product decomplexation steps. Phosphates, carbonates, as well as triethylamine showed no or significantly lower activity. Furthermore, there was found no correlation between the amount of transition metal traces, contained in NaOH and KO\textsubscript{t}Bu of different purity grade and coming from different sources, with the conversion of acetophenone, thus providing evidence that transition metal contaminants were not responsible for catalysis. Transfer hydrogenation catalyzed by alkali metal alkoxides was proposed to proceed via a direct hydrogen transfer, similar to the MPV reduction (Scheme 22).

\begin{center}
\textbf{Scheme 22.} Proposed mechanism for NaOH-catalyzed transfer hydrogenation of carbonyl compounds.
\end{center}
Almost at the same time Polshettiwar and Varma reported transfer hydrogenation of aldehydes and ketones with KOH. Aldehydes were shown to be reduced by 65-75% in the presence of 12 mol% KOH in 2-propanol at reflux within 30 minutes, while 25 mol% KOH is required to achieve similar conversions for ketones in 24 hours. Later, solid K$_3$PO$_4$ was applied as a heterogeneous catalyst for the reduction of carbonyl compounds in alcohols. Investigation of primary and secondary simple alcohols revealed 2-propanol to be the most efficient hydrogen source in this process. Excellent conversions of a number of aldehydes in 6-10 hours was demonstrated, however only moderate yields in the reduction of cyclohexanone and acetophenone can be achieved in 12 hours. Recently, Astruc et al. also applied NaOH in transfer hydrogenation of benzaldehydes and acetophenones in ethanol at 80°C, albeit 2 equivalents of base were used. They also demonstrated that the developed catalytic system is capable of reduction of nitroarenes with the formation of anilines and azobenzenes.

The closely related β-alkylation of secondary alcohols and ketones with primary alcohols has been also reported for alkalis and alkali metal salts as well. Allen and Crabtree reported that KOH can mediate β-alkylation of 1-arylethanols with primary aliphatic or benzyl alcohols in toluene at reflux. NaOH also shows activity towards this transformation, albeit significantly lower than KOH. The process is believed to proceed via dehydrogenation of alcohols, followed by aldol condensation, resulting in a α,β-unsaturated ketone II-125. It is then reduced, yielding allyl alcohol II-126, which can isomerize under the reaction conditions to give ketone II-127. Finally, its reduction leads to the product II-128 (Scheme 23). Full conversion to II-128 was observed only when aliphatic alcohols were
used as precursors for aldehydes, while up to 34% of ketones II-127 were left nonreduced in the case of benzylic alcohols, even though an equivalent of alkali was used.

\[
\begin{align*}
\text{II-128} & \quad \text{II-127} & \quad \text{II-126} & \quad \text{III-125}
\end{align*}
\]

**Scheme 23.** Proposed reaction sequence for alkali-mediated β-alkylation of secondary alcohols.

The procedure was further improved by addition of catalytic amounts of corresponding aldehydes (30 mol%), which triggers the process.\(^{297}\) This allowed the authors to reduce the KOH load down to 20 mol% while providing higher conversion to the fully reduced alcohol II-128. Lithium alkoxide was studied as a promoter for this kind of transformation as well.\(^{298}\) Acetophenones undergo α-alkylation with primary alcohols in the presence of an equivalent of LiOtBu in toluene at reflux. The above-mentioned conditions lead to high chemoselectivity towards ketones II-127 as the final products, with no further reduction to alcohol II-128. Furthermore, when (2-aminophenyl)methanol was heated with ketones in the presence of LiOtBu, quinolines were formed instead of the corresponding ketones (Scheme 24). Using excess ketones significantly improved the conversion, likely due to their ability to serve as hydrogen acceptors in this process.

\[
\begin{align*}
\text{Scheme 24.} & \quad \text{Lithium tert-butoxide-mediated synthesis of quinolines from (2-aminophenyl)methanol and ketones.}
\end{align*}
\]
II. 4. Zinc-catalyzed hydrosilylation

II. 4. 1. Introduction

Transition metal complexes are doubtlessly considered to be efficient reagents and catalysts in many organic syntheses. However, high prices, toxicity and low abundance of common catalytic transition metals are some urgent challenges that have to be overcome. One of the most commonly considered solutions is the application of first-row transition metals and main group elements (iron, cobalt, calcium, boron, aluminum, magnesium, etc.) in catalysis and replacement of classical transition metal complexes in this field.

Zinc has recently attracted attention in hydrosilylation as the catalyst core for the reduction of functional groups of organic substrates. It is relatively inexpensive, nontoxic, and earth abundant post-transition metal. Over the past few decades studies on zinc-catalyzed hydrosilylation have been focused mainly on the reduction of ketones, aldehydes, and imines, although a few catalytic systems for the hydrosilylation of more challenging substrates, such as nitriles, amides, esters and CO₂, have been recently discovered.

Several mechanisms of zinc-catalyzed hydrosilylation have been proposed. In the most typical, hydride mechanism, the substrate inserts into the zinc-hydride bond and the subsequent reaction with a silane yields the reduced product and regenerates the zinc-hydride moiety (Scheme 25a). Alternatively, the activation of substrate (Scheme 25b) or silane on a Lewis acidic zinc centre can be also assumed (Scheme 25c).
II. 4. 2. Zinc-catalyzed hydrosilylation of carbonyl compounds

First attempts of zinc catalyzed hydrosilylation were made by Noyori et al.\textsuperscript{303} It was claimed that an active zinc species was obtained 	extit{in situ} by the reaction of Zn(OSO$_2$CH$_3$)$_2$ with LiH, which was also used to generate a hydrosilane from a chlorosilane. Thus, LiH is the actual hydride source in this process. Later Mimoun\textsuperscript{304} developed a procedure for zinc-catalyzed hydrosilylation with PMHS. Zn(2-ethylhexanoate)$_2$ was treated with NaBH$_4$ to obtain a catalytically active zinc species, although its structure was not confirmed.

Carpentier et al. were able to improve a zinc-based catalytic system to perform the reduction of carbonyl compounds with PMHS at room temperature.\textsuperscript{305} According to their procedure, ZnEt$_2$ reacts rapidly with $N,N'$-dibenzylethlenediamine (dbea) with the formation of a dimeric zinc complex II-129, although $N,N'$-diphenylethlenediamine (ebpe) gives stable adducts ZnR$_2$(ebpe)$_2$ (R = Me, Et). II-129 was determined to be the only precursor that transforms rapidly in the presence of MeOH, PMHS, and substrate to an active, though unidentified species, which is effective at a load as low as 2 mol\%.

\begin{equation}
\begin{aligned}
\text{a.} & \quad \text{L}_n\text{Zn-H} \quad \xrightarrow{X=\text{CR}_2} \quad \text{L}_n\text{Zn-CHR}_2 \quad \xrightarrow{\text{H-SiR'}_3} \quad \left[\text{L}_n\text{Zn-XCHR}_2\right]_{\text{H-SiR'}_3} \quad \xrightarrow{R'_3\text{Si-XCHR}_2} \quad \text{L}_n\text{Zn-H} \\
\text{b.} & \quad \text{ZnL}_n \quad \xrightarrow{X=\text{CR}_2} \quad \text{L}_n\text{Zn-CHR}_2 \quad \xrightarrow{\text{H-SiR'}_3} \quad \text{ZnL}_n \\
\text{c.} & \quad \text{ZnL}_n \quad \xrightarrow{\text{H-SiR'}_3} \quad \text{L}_n\text{Zn}^+ \quad \xrightarrow{X=\text{CR}} \quad \text{ZnL}_n \\
\end{aligned}
\end{equation}

\textbf{Scheme 25.} Proposed mechanisms of zinc catalyzed hydrosilylation.
In the subsequent years, a relatively high efficiency of catalytic asymmetric hydrosilylation was demonstrated for zinc complexes modified by diamine chiral ligands (Scheme 26). Most of the procedures provide only moderate enantioselectivity and require up to 5 mol% catalyst load. Recently, Mlynarski et al. have reported that Zn(OAc)$_2$ with the addition of a chiral diamine ligand II-131 can catalyze the hydrosilylation of ketones at a load as low as 0.03 mol%. Good to excellent enantioselectivity was observed for most of acetophenones and α,β-unsaturated ketones in 6 and 16 hours, respectively, at room temperature. The procedure is claimed to be solvent-free, although enormous amount of triethoxysilane (20 equivalents) is used.

**Scheme 26.** Examples of chiral diamine-ligands.

Zinc complex II-134 bearing chiral (oxazolynyl)ferrocene ligands were synthesized by Riant et al. The complex was further applied in the asymmetric hydrosilylation of ketones with PMHS. A dimeric catalytic species was produced *in situ* by mixing II-134 with ZnEt$_2$. Full conversion of ketones to the corresponding alcohols can be achieved after 2-6
hours heating at 60°C with 10 mol% zinc catalyst, although the enantioselectivity does not exceed 55% ee.

In 2010, Driess and Enthaler reported new zinc complexes with tridentate (O,S,O)-ligand II-135 that possessed high catalytic activity in achiral hydrosilylation of ketones with triethoxysilane. A turnover frequency (TOF) up to 970 h⁻¹ was observed at 1 mol% catalyst load at 60°C. Zinc complexes, synthesized in situ from diethyl zinc and commercially available formamidine ligands II-136, were also demonstrated to be highly efficient catalysts for hydrosilylation of aryl and alkyl ketones with a TOF up to 1000 h⁻¹.

Lai et al. applied chiral Schiff bases as ligands for zinc-catalyzed asymmetric hydrosilylation of ketones. While investigating a series of imines, they concluded that the carboxylate unit in II-137 is essential for the good performance of the catalytic system, as it provides a tridentate coordination of the ligand. Furthermore, the presence of potassium cation leads to a significantly higher enantioselectivity than other alkali metal cations. The reaction has to be performed at -40°C to achieve high ee values, albeit at a loss of conversion.

Zinc hydride DippNacNacZnH II-138 was shown to catalyze the hydrosilylation of aldehyde and ketone at 3 mol% load at room temperature with the tolerance to cyano-,
amino-, nitro- and ester groups. Aldehydes can be reduced with triethoxysilane within 20 minutes at room temperature, while a significantly longer time 5-24 hours is required for ketones.

Later, the catalytic activity of diethylzinc and zinc acetate in the asymmetric hydrosilylation, promoted by the chiral PyBox-ligands II-139a-d, was demonstrated. Although the up to 85% ee can be achieved at room temperature in the presence of 5 mol% zinc complex with II-139d, 20-46 hours were required for 99% conversion.

Recently, a new type of heteroscorpionate zwitterionic terminal hydride zinc complex II-140 was reported to catalyze the hydrosilylation of aldehydes with phenylsilane at 1 mol% catalyst load. The reaction can be performed at room temperature, although a relatively long time is required (6-20 hours).

Zinc hydride complexes supported with NHC ligands have been also shown to act as efficient catalysts for the hydrosilylation of carbonyl compounds. Thus, benzophenone was rapidly reduced with an equimolar amount of methylphenylsilane at room temperature in the
presence of 0.1 mol% II-141. The reaction rate was observed to reach 475 h⁻¹ TOF. Zinc cluster II-142 can catalyze reduction of a number of aliphatic and aromatic carbonyl compounds with different hydrosilanes at room temperature in 1-3 hours, although up to 3.3 mol% catalyst load was required for some substrates.

II. 4. 3. Hydrosilylation of imines

For a long time transition metal (Ti, Ru, Rh, Cu, Re) complexes have dominated the field of enantioselective hydrosilylation of imines. The employment of zinc complexes has been intended to offer a cheaper and environmentally friendly solution. One issue that has to be addressed in this reaction is the formation of a relatively strong zinc-nitrogen bond after the insertion of imine into the zinc-hydrogen bond. However, this particular bond should be easily cleaved by an incoming silane to achieve considerable reactivity. Another issue, pertinent to the enantioselective version of this reaction, is that the formed amine product also can act as ligands to zinc, which may significantly reduce enantioselectivity. This is why proper conditions should be chosen to avoid this.

Yun’s group reported a highly enantioselective hydrosilylation of imines catalyzed by zinc catalysts bearing chiral diamines II-130a and II-143a, II-143b. They emphasized the importance of choosing the diphenylphosphinyl moiety as the substituent attached to the amine nitrogen of the substrate that would approach the above mentioned requirements. Their catalytic system promotes the hydrosilylation of diphenylphosphinyl ketoimines with excellent yields and up to 97% ee in 12 hours at room temperature. The diphenylphosphinyl group can be later removed under basic conditions. The Umani-Ronchi group synthesized diamino-bis(tert-thiophene) ligands II-144a and II-144b that improved zinc catalyzed
hydrosilylation of ketones and, in particular, ketoimines. Thus, diphenylposhinyl ketoimines could be reduced in 3 hours at 0°C with the enantioselectively with up to 97% ee.

Later Kwit and co-workers considered the mechanism of this reaction (Scheme 27). An active zinc species II-145 is obtained in situ from the diamine-ligand and diethyl zinc. It reacts with silane with the formation of zinc-hydrido complex II-146. The substrate is assumed to coordinate to the NH-functionality of II-147 via a hydrogen bond. This step provides the stereoselectivity of the process itself. After that, the hydride transfers from zinc to the imine-group. The last step is methanolysis that yields the zinc species II-145 and N-diphenylphosphanylamine.

Scheme 27. Proposed reaction pathway for zinc-catalyzed reduction of activated imines.
Recently diphenylposhinyl ketoimines were also reduced with triethoxysilane in the presence of 5 mol% Zn(OAc)$_2$ and 5 mol% diamine II-148. Good to excellent conversions and high enantioselectivities were achieved at room temperature in 24 hours.

Mlynarski and Adamkiewicz showed that sulfinylmines can be reduced diastereoselectively with triethoxysilanes in the presence of 5 mol% Zn(OAc)$_2$ at room temperature. The reaction is believed to proceed via a six-member transition state II-149 that provides stereoselectivity even without a chiral ligand. The reduction of a series of N-(tert-butylsulfinyl)imines under the proposed conditions shows high enantioselectivities, although moderate to good conversions could be achieved even after 72 hours.

II. 4. 4. Hydrosilylation of amides

Secondary and tertiary amines can be obtained by reduction of secondary and tertiary amides, respectively. In 2010, the Beller group reported the first efficient hydrosilylation of amides using the widely available Zn(OAc)$_2$, while other zinc salts (ZnCl$_2$, ZnF$_2$, Zn(OTf)$_2$) possessed a low catalytic activity. It was showed that quite a broad scope of tertiary amides can be reduced smoothly at room temperature in the presence of 10 mol% Zn(OAc)$_2$ and 3 equivalents of triethoxysilane. Furthermore, electron poor benzamides were observed to be reduced faster than those with electron donating substituents. In addition, an unprecedented functional group tolerance was demonstrated. For instance, amides can be reduced chemoselectively in the presence of ester, ether, nitro-, cyano- and azo-groups.
The proposed mechanism for zinc catalyzed reduction of amides is shown in Scheme 28. The active species II-150 is formed in situ by a reaction of ZnX₂ (X = OAc) with silane. Heterolytic splitting of the Si-H bond, followed by hydride transfer from the zinc centre yields the N,O-acetal II-152. After the release of the anionic zinc ether II-153, an iminium species II-154 is obtained. One more equivalent of silane is required for the conversion of II-154 to the amine.

Scheme 28. Proposed reaction mechanism for zinc-catalyzed reduction of tertiary amides.

Later, secondary amides were demonstrated to be reduced in the presence of Zn(OTf)₂, but surprisingly, in this case Zn(OAc)₂ did not show any catalytic activity. However, 20 mol% Zn(OTf)₂ and heating at 100°C for 24 hours were required to achieve good yields.
Xie et al. showed that Zn(OAc)\textsubscript{2}/TMEDA can also catalyze selective reduction of cyclic \textit{N}-substituted imides.\textsuperscript{330} \(\Omega\)-hydroxylactams can be obtained with moderate to high yields in the presence of 10 mol\% zinc catalyst and 3 equivalents of triethoxysilane or PMHS at 70°C.

### II. 4. 5. Hydrosilylation of esters

Reduction of esters provides a straightforward synthesis of functionalized alcohols, which are important for manufacture of pharmaceuticals, agrochemicals, dyes, and numerous bioactive compounds. In 1999, Mimoun reported hydrosilylation of esters and lactones with a zinc-hydride species generated \textit{in situ} from Zn(OAc)\textsubscript{2} and NaBH\textsubscript{4}.\textsuperscript{304} Alcohols with 90-95\% yields were obtained with PMHS in the presence of 2 mol\% Zn(OAc)\textsubscript{2} at 70°C in 4 hours.

Beller \textit{et al.} established a zinc-catalyzed reduction of esters with (EtO)\textsubscript{2}MeSiH without any other additives for the \textit{in situ} generation of an active Zn-H species.\textsuperscript{331} Although good conversions in 24 hours required 10 mol\% load of Zn(OAc)\textsubscript{2}, the operational simplicity and the high functional group tolerance made this procedure attractive for organic synthesis because there was no need for protection and deprotection steps.

Adolfsson and Kovalenko reported a procedure for mild hydrosilylation of aromatic and aliphatic esters.\textsuperscript{332} The reduction occurs in the presence of 3 equivalents of PMHS, 5 mol\% ZnEt\textsubscript{2} and 20 mol\% LiCl, which appeared to be crucial for the process, although the mechanism was not discussed in the paper. High conversions to alcohols can be achieved at room temperature within 6 hours.
II. 4. 6. Hydrosilylation of nitriles

Nitriles have always been regarded to be challenging substrates. The catalytic reduction of nitriles has been considered impossible without transition metals for a long time, until Nikonov et al. demonstrated zinc-catalyzed chemoselective monoreduction of aryl and alkyl nitriles.\textsuperscript{302} For instance, benzonitrile can be transformed to $N$-silyl imine at room temperature in 7 hours with 3 mol\% DippNacNacZnH $\text{II-138}$. The presence of electron donating groups in the aromatic ring leads to the slowdown of the reaction, whereas acceleration can be observed for aryl nitriles with electron withdrawing groups. Hydrosilylation can be also applied to alkyl nitriles that do not contain labile hydrogen on the $\alpha$-carbon atom. Otherwise the deactivation of zinc catalyst takes place. Kinetic studies revealed the mechanism shown in Scheme 29. Thus, after the silane activation by a Lewis acidic zinc centre, an out-of-sphere zinc hydride transfer occurs via a 6-membered cyclic transition state $\text{II-156}$.

\begin{center}
\textbf{Scheme 29.} Proposed reaction mechanism for zinc-catalyzed monoreduction of benzonitrile.
\end{center}
Okuda et al. showed that the zinc cluster II-142 (3.3 mol%) is able to catalyze hydrosilylation of a number of nitriles with triethoxysilane at room temperature.\textsuperscript{322} Benzonitriles can be reduced in 4-9 hours, and the time depends on the presence of electron-donating or electro-withdrawing groups, analogously to the previous example. Pivalonitrile required a significantly longer time (48 hours), while reduction of 4-pyridinecarbonitrile stopped at 41\% conversion, which was attributed to catalyst deactivation.

II. 4. 7. Hydrosilylation of heterocyclic compounds

Hydrosilylation as a method for selective reduction of heterocyclic compounds is of significant interest as an alternative to conventional methods that utilize hydrogen gas and have a strong tendency to overreduction.\textsuperscript{333} To date, there has been only one example of zinc-catalyzed hydrosilylation of heterocyclic compounds. Nikonov et al. investigated the catalytic activity of zinc hydride complexes II-138 and II-157 in this type of transformation.\textsuperscript{334} Catalyst 105 indeed possessed activity in the hydrosilylation of pyridine, although the efficiency was low. However, zinc complex II-157, as more sterically accessible, showed more promising results in the reduction of quinoline. Methylsilane and phenylsilane were found to be the most effective reducing agents for the selective production of 1,2-dihydroquinoline in high yield.
A number of different heterocyclic compounds were involved in the reaction with phenylsilane in the presence of 8 mol% catalyst II-157 at 70°C. Quinaldine can be selectively reduced to 1,2-dihydroquinaldine, albeit only a moderate conversion was achieved in 72 hours. 1,5-Naphthyridine undergoes complete hydrosilylation to 1,2- and 1,4-derivatives in the ratio 11:1. Hydrosilylation of acridine is significantly slower, and only 45% conversion can be reached in 3 days even at 80°C. Isoquinoline can be reduced with excellent conversion even in the presence of 5 mol% catalyst, albeit a longer time is required. However, only traces of product can be observed in the case of pyridine.
III. Results and Discussion

III. 1. Ruthenium complexes for transfer hydrogenation

III. 1. 1. Ligand design

Among numerous ligands used in transfer hydrogenation catalysts, compounds containing heterocyclic moieties (pyrazolyl, oxazolyl, imidazolyl, etc.) occupy a special niche because N-heterocycles have recently gained significant interest as components of non-innocent ligands. The pyrazolyl group, in particular, possesses an acidic proton on one of the nitrogen atoms, while the second nitrogen centre can coordinate to a metal centre, which makes the proton even more acidic. This geometry feature puts the NH-group in a proximity to a catalytic metal site and allows for potential cooperation in catalytic processes. A possible scheme for transfer hydrogenation of carbonyl compounds catalyzed by ruthenium complexes with pyrazole-containing ligands is presented in Scheme 30. The unprotected N-H functionality of the pyrazole ring in the pre-catalyst A can be deprotonated under basic conditions, thus releasing a catalytically active 16-electron metal species B. Transfer of hydrogen from a hydrogen source results in the formation of a metal-hydride species C, with protonated pyrazolyl group. Then the cooperative transfer of hydride and proton to an unsaturated substrate by a cyclic transition state (from D to B) yields the alcohol product. When the product is liberated, the active species B is regenerated.
The mechanism of ligand-metal-bifunctional hydrogenation with a catalyst containing pyrazole.

Scheme 30. The mechanism of ligand-metal-bifunctional hydrogenation with a catalyst containing pyrazole.

The proposed mechanism correlates with that one proposed for metal-ligand bifunctional hydrogenation by Noyori bis(amine)-ruthenium catalysts. However, recently Dub and Gordon demonstrated by DFT calculations the role of ligand in the Noyori system is to stabilize the rate determining transition state by means of N−H···O hydrogen bonding and not via reversible interconversion of amine to amide, thus behaving in a chemically intact manner within the productive cycle. Therefore, even if the bifunctional mechanism, in its original sense, may not operate in the case of pyrazolyl ligands either, the presence of the N-H moiety can be still beneficial for directing substrates through the formation of hydrogen bonds.

Transition metal catalyst containing pyrazolyl-based ligands have been only applied to the reduction of carbonyl compounds. Therefore, it is highly important to explore the
benefits of using such ligands in the transfer hydrogenation of other functional groups, such as nitriles, imines, esters, amides, heterocycles, etc.\(^{337,338}\)

**III. 1. 2. Ligand synthesis**

The synthetic scheme used to prepare the pyrazole/phosphine ligands **III-1** is shown in Scheme 31. The presence of a bulky group in the 3-position was expected to be important to prevent possible dimerization via the nitrogen atom in the 2-position. Therefore, pinacolone was chosen as the starting substrate. Claisen condensation of diethyl oxalate **III-2** with pinacolone **III-3** leads to diketone **III-4**. The latter reacts with hydrazine to form the pyrazole **III-5**. Reduction of the ester function with LiAlH\(_4\) in THF followed by substitution of the hydroxyl group in alcohol **III-6** with chloride leads to the 3-tert-butyl-5-(chloromethyl)-1\(H\)-pyrazole **III-7**. In the last step of preparing the pyrazole/phosphine ligand two equivalents of LiPPh\(_2\) or LiP\(_i\)Bu\(_2\) were required, as deprotonation of the pyrazole ring occurs first, followed by nucleophilic substitution of the chloride. As a result, 3-tert-butyl-5-[(diphenylphosphanyl)-methyl]-1\(H\)-pyrazole **III-1a** and 3-tert-butyl-5-[(di-iso-butyolphosphanyl)-methyl]-1\(H\)-pyrazole **III-1b** were obtained as colorless oils in the overall yields 47% and 39%, respectively. The \(^{31}\)P \(^1\)H NMR spectra of **III-1a** and **III-1b** show one singlet at \(\delta = -15.3\) and -37.7 ppm, respectively, consistent with the formation of an Alk-PR\(_2\) species. Carbone signals of the bridging methylene in both ligands appears at \(\delta = 27.3\) and 26.3 ppm as doublets with the coupling constant \(J_{CP} = 15.3\) and 14.4 Hz, respectively.
Scheme 31. Synthesis of 3-tert-butyl-5-[(diphenylphosphanyl)methyl]-1H-pyrazole III-1a and 3-tert-butyl-5-[(di-iso-butylphosphanyl)methyl]-1H-pyrazole III-1b.

The new NN-ligand III-8, with two heterocycles (pyrazole and oxazoline), was also synthesized. Both heterocycles contain nitrogen donors that can coordinate with a metal centre. The possibility to vary substituents on the 4C-atom gives the opportunity for the synthesis of chiral ligands for enantioselective catalytic hydrogenation. We studied several methods for the generation of oxazoline rings, and finally applied the following synthetic strategy (Scheme 32). Nucleophilic substitution of chloride in compound III-7 with cyanide yields (3-tert-butyl-1H-pyrazol-5-yl)acetonitrile III-9. Further reaction of compound III-9 with 2-amino-2-methyl-propan-1-ol with addition of ZnCl₂ in toluene under reflux gives the NN-ligand III-8, as a creamy solid with the overall yield 45%. ^1H NMR spectrum of the product shows signals at δ = 6.07 (for the pyrazole H), 4.25 (for the methylene in the oxazolinyl group), 3.90 (for the bridging methylene), 1.60 (for two methyls of the oxazolynyl moiety), and 1.37 (for the tert-butyl group).
Scheme 32. Synthesis of 2-[(3-tert-butyl-1H-pyrazol-5-yl)methyl]-4,4-dimethyl-4,5-dihydro-1,3-oxazole III-8.

The tridentate N,N,S-ligand III-10 was designed to include a sulfide moiety, which is less bulky than the phosphine groups in the ligands III-1a and III-1b. Sulfide is a mild nucleophile that can relatively easily coordinate to metal and dissociate to release the vacant site, thus providing hemilability. In addition, switching to sulfur containing ligands has the additional benefit of providing stability of the ligand to air, a feature that phosphine groups generally do not have.

Initially, ligands with tert-butyl and phenyl substituents in the pyrazolyl ring (Scheme 33). III-4b and III-5b were obtained analogously to III-4a and III-5a (Scheme 31). Amides III-11a and III-11b were obtained by the treatment of III-5a and III-5b, respectively, with 2-aminoethanol in the presence of K$_2$CO$_3$. The next step, the nucleophilic substitution of the hydroxyl group with chloride, was only successfully performed for the compound III-11b, while an attempted with III-11a under these conditions returned only the starting compound. Nucleophilic substitution in the chloride III-12 with sodium phenyl sulfide resulted in the sulfide III-13 that was further reduced by LiAlH$_4$ to give the target compound NNS ligand III-10 as a colourless semiliquid with the overall yield 55%. $^1$H NMR spectrum of III-10 contains five sets of multiplets in a lower
field, corresponding to aromatic protons (δ = 7.15-7.85 ppm), as well as singlets at δ = 6.47 and 3.92 ppm for the pyrazolyl proton and isolated methylene group, respectively, and two triplets at δ = 3.11 and 2.92 for the ethylene bridging group.

Scheme 33. Synthesis of N-[(3-phenyl-1H-pyrazol-5-yl)methyl]-2-(phenylsulfanyl)ethanamine III-10.

III. 1. 3. Ruthenium complexes supported by novel pyrazole-based ligands

A series of new Ru(II) pyrazole complexes were obtained by ligand substitution in the readily available precursors RuCl₂(DMSO)₄, RuHCl(CO)(PPh₃)₃, and RuCl₂(PPh₃)₃ with the ligand III-1a. Ligand III-1a replaces two molecules of DMSO in RuCl₂(DMSO)₄ affording complex III-14. Attempts to replace the two remaining DMSO
ligands in **III-14** by reactions with phosphines (PPh$_3$ and dppe) at 60°C were unsuccessful. Reaction of RuCl$_2$(DMSO)$_4$ with dppe first resulted in the substitution of two molecules of DMSO by dppe to give RuCl$_2$(DMSO)$_2$(dppe). But further attempts to displace the coordinated DMSO with the ligand **III-1a** resulted instead in the substitution of dppe, yielding the same complex **III-14**.

![III-14](image)

Compound **III-14** was fully characterized by NMR spectroscopy. The protons of the bridging methylene group become non-equivalent due to the bidentate complexation of **III-1a**. Two sets of multiplets appear in the $^1$H NMR spectra at $\delta = 3.64$ and 3.80 ppm with slightly different coupling constants to phosphorus ($J_{HP} = 8.4$ and 13.6 Hz, respectively). All four methyl groups of two DMSO ligands are also non-equivalent, giving rise to four singlets at $\delta = 3.58$, 3.46, 3.19, and 2.38 ppm. The $^{31}$P NMR signal of **III-14** is shifted to a significantly lower field (67.4 ppm) relative to the free ligand **III-1a** (-15.3 ppm).
Crystals suitable for X-ray diffraction analysis were obtained from a saturated solution in CH$_2$Cl$_2$ by slow diffusion of hexanes. The molecular structure of complex III-14 is shown in Figure 1. The compound has a pseudo-octahedral geometry, with the strong trans-influence phosphine ligand lying trans to one chloride and the strongly donating DMSO ligand being trans to the second chloride and to the nitrogen end of the pyrazole ring. Both DMSO ligands bind ruthenium via the sulfur end, in accordance with the soft base/soft acid complementarity. The two Ru-S distances of 2.276(3) Å and 2.258(3) Å are nearly the same. The slightly longer distance corresponds to the DMSO ligand located trans to the chloride. The latter chloride Cl(1) has the Ru-Cl distance of 2.419(3) Å that is noticeably
shorter than the Ru-Cl bond to the chloride lying trans to the phosphine (2.465(3) Å), suggesting that phosphine is a stronger trans influence ligand than DMSO.

Reaction of complex RuHCl(CO)(PPh₃)₃ with III-1a in refluxing CH₂Cl₂ yields the cationic complex III-15. All attempts to grow crystals suitable for X-ray study were unsuccessful. However, NMR data allow for unequivocal structural assignment. Thus, the $^{31}$P{¹H} NMR spectrum of III-15 shows a doublet at $\delta = 43.2$ ppm, integrated as 2P, coupled to a triplet at $\delta = 34.3$ ppm (1P) with a small coupling constant $J_{PP} = 13.7$ Hz. These data suggest that two PPh₃ phosphines are equivalent and are located trans to each other, whereas the unique phosphine of the ligand III-1a is in the cis-position. The $^1$H NMR signal of hydride shows up at $\delta = -5.31$ ppm as a doublet of triplets (dt, $J_{HP} = 95.5, 23.3$ Hz), and what is more, the larger coupling constant, corresponding to the doublet, indicates that the phosphine in the ligand III-1a and the hydride are in the trans arrangement. This disposition leaves the sixth position of a distorted octahedron, located trans to the pyrazole ring, for the CO ligand.

Related reaction of RuHCl(CO)(PPh₃)₃ with III-1a carried out in toluene at 100°C afforded a mixture of neutral isomers III-16 and III-16′, formed in the ratio 1:3 (based on
integration of $^1$H and $^1$P{$^1$H} NMR spectra). All attempts to separate these isomers by crystallization failed. Bidentate coordination mode of the ligand III-1a in both isomers can be concluded from the non-equivalent character of the protons of the bridging methylene, which give rise to two sets of multiplets in the $^1$H NMR spectrum ($\delta = 3.40$-4.10 ppm). The hydride signals of both complexes appear in $^1$H NMR as doublets of doublets at $\delta = -12.03$ (minor isomer) and -14.18 (major isomer) ppm. On the basis of observing the large P-P coupling constants ($J_{PP} = 290.9$ and 312.8 Hz) in the $^{31}$P{$^1$H} NMR spectrum, one can conclude that both isomers contain the PPh$_3$ ligand trans to the phosphine end of the NP-ligand III-1a, which means that III-16 and III-16' differ in the nature of the ligand located trans to the pyrazole ring. On the basis of trans influence, we suggest that these trans ligands are the carbonyl and hydride.

Monitoring the reaction by NMR spectroscopy showed intermediate formation of the bis(phosphine) complex III-17, in which the NP-ligand coordinates to the metal via a nitrogen atom of the pyrazole ring, whereas the phosphine moiety remains free. This unexpected coordination mode was confirmed by the observation of a $^{31}$P NMR singlet at $\delta = -20.7$ ppm, which is close to the $^{31}$P{$^1$H} NMR chemical shift of the free NP-ligand signal at $\delta = -15.3$ ppm. At the same time, another phosphorus signal that also appears as a singlet and is integrated as 2P, can be assigned to two equivalent PPh$_3$ ligands in the trans-position to each other. The hydride signal in the $^1$H NMR spectrum, observed at $\delta = -13.09$ ppm, is coupled to two phosphorus atoms with a small coupling constant ($J_{HP} = 19.2$ Hz), which suggests the cis-position of the hydride relatively to both phosphine ligands.

III-17 can be isolated from a mixture of RuHCl(CO)(PPh$_3$)$_3$ and the ligand III-1a in toluene, after stirring at room temperature for 1 hour. Complexes III-16 and III-16' can be
further obtained from III-17 after a suspension of the latter in toluene is heated under reflux for 3 hours. It can be assumed that III-16 and III-16’ are formed upon substitution of the second PPh₃ by the phosphine part of the ligand III-1a.

Treatment of RuCl₂(PPh₃)₃ with the NP-ligand III-1a in benzene under reflux furnished the symmetrical complex III-18 containing two NP moieties. Its structure was established by ¹H and ³¹P NMR spectroscopy. Thus, in the ¹H NMR spectrum III-18 gives rise to only one set of signals for the coordinated ligand III-1a, including two multiplets for the bridging methylenes at δ = 3.77-3.61 and 3.45-3.31 ppm, corresponding to non-equivalent protons within the single methylene group. Concurrently, the ³¹P{¹H} NMR spectrum shows one signal at δ = 67.9 ppm. These spectral data are consistent both with C₂ₕ (trans phosphines) and C₂ᵥ (cis phosphines) structures. Given the stronger trans effect of phosphine than pyrazole, we propose the C₂ᵥ structure III-18.

A crystal suitable for X-ray analysis was grown from a saturated acetonitrile solution. NMR data showed that one of the chloride ligands was substituted by acetonitrile molecule to give the cationic nitrile complex III-19. Although NMR spectra of III-18 and III-19 are quite similar, there are certain differences, such as the ¹H NMR signals of bridging methylene protons have much smaller difference in the chemical shifts (δ = 3.40-3.25 ppm), compared to III-18, and are shifted to a stronger field. The proton signal of acetonitrile is
observed at $\delta = 1.48$ ppm. The $^{31}\text{P}\{^1\text{H}\}$ NMR signal in **III-19** is also slightly shifted to a stronger field ($\delta = 63.7$ ppm), comparing to phosphorus signal in complex **III-18**.

The molecular structure of complex **III-19** is shown in Figure 2. The compound has a pseudo-octahedral geometry, with two NP ligands forming a base of the bipyramid. The phosphorus atoms are positioned *trans* to the pyrazole moieties, in agreement with the stronger *trans* influence of phosphines than amines. However, the two Ru-P distances (2.2885(1) and 2.2788(1) Å), as well as two Ru-N1 distances (2.166(3) Å and 2.159(3) Å) are slightly different. Interestingly, these Ru-N bonds are much longer than the related Ru-N bond in complex **III-14** (2.081(9) Å), again supporting the notion that the phosphine moiety of the ligand **III-1a** exerts a stronger *trans* influence than DMSO.

**Figure 2.** Molecular structure of complex **III-19**. Thermal ellipsoids are given at 30% probability. Hydrogen atoms are omitted for clarity.
Refluxing complex RuCl₂(PPh₃)₃ and the ligand III-1a in acetonitrile afforded a mixture of two isomeric complexes III-20/20'. The ³¹P{¹H} NMR spectrum of the mixture showed two pairs of doublets at δ = 61.8 and 42.7 ppm and at δ = 57.8 and 43.7 ppm, respectively. The cis position of the phosphorus atom of the NP-ligand III-1a with respect to triphenylphosphine in both isomers is assumed on the basis of small coupling constants $J_{PP} = 25.6$ and 27.4 Hz, respectively. The poor solubility of this compound in nonpolar solvents and the presence of two nitrile ligands suggest that it has the cationic structure III-20/20'.

Remarkably, two different patterns for the bridging methylene protons can be identified in the ¹H NMR spectrum. The methylene group in the major isomer III-20 has equivalent protons, which is represented by a doublet signal at δ = 3.56 ($J_{HH} = 9.98$ Hz). This means that the major isomer III-20 shows the C₃ symmetry, indicating the trans arrangement of the nitrile ligands. Moreover, III-20 gives rise to one unique signal for both acetonitrile
ligands at $\delta = 1.86$ ppm, which also confirms the symmetry. Another methylene proton signal in the same region ($\delta = 3.43$-$3.61$ ppm) is a multiplet (presumably two doublets of doublets), indicating non-equivalent protons due to the $C_1$ symmetry of complex III-20’. In addition, two singlets for each acetonitrile can be identified in $^1$H NMR at $\delta = 1.08$ and 2.01 ppm.

However, from the data obtained by NMR spectroscopy no definite structure for III-20’ can be assigned. Considering two phosphine ligands cis to each other, as well as two acetonitriles also in the cis position, four structures can be assumed: III-20’a, III-20’b, III-20’c, and III-20’d. To differentiate between the proposed structures, a NOE experiment was performed. The signals corresponding to acetonitriles were excited. Through space interaction was observed for the acetonitrile signal at $\delta = 1.86$ ppm in III-20 with the CH singlet of the pyrazole ring at $\delta = 6.39$ ppm, which supports the suggested structure. No similar interaction was found for the acetonitrile ligands in III-20’, which likely means that the ligands are trans to the pyrazolyl and phosphine groups, respectively (structure III-20’a). Additionally, one of the acetonitrile signals ($\delta = 1.08$ ppm) has NOE with the protons of the phenyl groups of the NP-ligand, whereas no such interactions were found for the other acetonitrile.

While obtaining X-ray quality crystals for either III-20 or III-20’ from acetonitrile failed, crystallization from chlorobenzene by hexanes layering led to the formation of dimer
III-21 that does not feature acetonitrile ligands. In solution, complex III-21 retains the \textit{cis} disposition of the phosphine ligands evinced by the small $J_{PP}$ constant of 37.6 Hz. $^1$H NMR spectrum shows distinctive non-equivalent character of protons of the bridging methylene group ($\delta = 3.54$-$3.73$ and $2.81$-$3.19$ ppm). When two equivalents of acetonitrile are added to a solution of III-21 in chlorobenzene, the dimer breaks down with the formation of complexes III-20 and III-20$^*$. 

![Molecular structure of complex III-21. Thermal ellipsoids are shown at 30% probability. Hydrogen atoms are omitted for clarity.](image)

**Figure 3.** Molecular structure of complex III-21. Thermal ellipsoids are shown at 30% probability. Hydrogen atoms are omitted for clarity.

The molecular structure of III-21 determined from X-ray analysis is shown in Figure 3. Although the quality of the crystal was rather low and a relatively high R factor was achieved, the quality of the data is sufficient to establish the connectivity of the molecule.
and discuss the key structural parameters. The molecule of III-21 is dimeric, with each ruthenium centre adopting a distorted octahedral geometry. The phosphine ligands are located cis to each other and trans to the bridging chloride ligands. Such a sterically unfavorable orientation is likely dictated by an electronic factor, that is the stronger trans influence of phosphine relative to chloride. The Ru(1)-P distances are comparable for the NP and PPh₃ ligands at 2.249(3) and 2.269(4) Å, respectively, and are close to the Ru-P bond length in the related complex III-14 (2.299(3) Å). The Ru(1)-Cl distances to the bridging chlorides are the same, 2.491(3) and 2.494(3) Å, whereas the terminal Ru(1)-Cl(3) distance is shorter (2.429(3) Å), as expected. This latter distance is also shorter than the Ru-Cl bond length in III-14 (2.465(3) Å) that also features the phosphine ligand located trans to a chloride. The positions of bridging chlorides in III-21 are symmetrical, with Ru(2)-Cl(1) being 2.497(3) Å and Ru(2)-Cl(2) being 2.498(3) Å. Other metrics associated with the second part of the dimer show trends similar to what is observed for the first part.

When RuCl₂(PPh₃)₃ was refluxed in acetonitrile with ligand III-1b, according to NMR spectroscopic analysis a single isomer III-22 was produced, possessing the Cₛ symmetry similar to III-20. There was only one signal for the bridging methylene protons in ¹H NMR at δ = 3.19 ppm (d, JPH = 9.72 Hz); likewise single peaks were observed for the N-H and C-H of pyrazolyl group (δ = 11.85 and 6.30 ppm, respectively). ³¹P{¹H} NMR shows two signals at δ = 43.5 and 57.6 ppm, coupled to each other with a relatively small
coupling constant $J_{PP}$ of 23.6 Hz, which corresponds to the relative $cis$ position of two phosphorus atoms of the ligand III-1b and PPh$_3$.

The NN-ligand III-8 does not substitute triphenylphosphine ligands either in RuCl$_2$(PPh$_3$)$_3$ or in RuHCl(CO)(PPh$_3$)$_3$, regardless of the polarity of solvent and temperature. Therefore, we opted to use different ruthenium precursors containing weaker ligands and easier to displace ligands, such as acetonitrile and pyridine, that is complexes [CpRu(CH$_3$CN)$_3$][PF$_6$] and [CpRu(Py)$_3$][PF$_6$].

It was expected that ligand III-8 would react with [CpRu(CH$_3$CN)$_3$][PF$_6$] to give complex III-23. But, in fact, a mixture of two substances with the 1:1 ratio was observed as the result of reaction. The $^1$H NMR spectrum of the mixture showed two N-H singlets ($\delta = 11.74$ and $10.70$ ppm), two pyrazolyl C-H singlets ($\delta = 6.08$ and $5.91$ ppm), two signals for the bridging methylene ($\delta = 3.91$ and $3.56$ ppm). The signal at $\delta = 4.10$ ppm (the Cp-H region) was integrated as 6.82, while the peak at $\delta = 4.14$ ppm was integrated as 3.39. Taking into account that all other peaks were in the ratio of 1:1, the peak at $\delta = 4.10$ ppm must be the result of overlap of Cp-H and CH$_2$ in oxazolinyl cycle of one of the isomers. This was also confirmed by correlation with two $^{13}$C NMR signals at $\delta = 67.4$ (Cp ligand) and 79.7 (methylen in oxazolinyl group) ppm in the $^1$H-$^{13}$C HSQC spectrum. Thus, there are two oxazolinyl methylene singlets at $\delta = 4.19$ and $4.10$ ppm and two Cp-H singlets at $\delta = 4.14$ and $4.10$ ppm. The spectrum also showed a singlet for the methyl groups of the oxazolinyl moiety of one of the products at $\delta = 1.40$ ppm and a multiplet ($\delta = 1.26$-1.23 ppm) that was integrated as 27.6 and must consist of signals for the methyl groups of oxazolinyl moiety of another product and protons of the tert-butyl groups of both isomers. The acetonitrile peaks
showed up at $\delta = 2.26$ and 2.03 ppm, and were found to be in exchange with each other according to a $^1$H NOESY NMR spectrum.

![Chemical structures](image)

Taking into account that the methyl groups of oxazolyl moiety are equivalent in $^1$H NMR, as are the protons of the bridging methylene, the NN-ligand III-8 more likely works as a monodentate ligand in this case and is bound to the metal either through the pyrazolyl nitrogen (III-24) or oxazolynyl nitrogen (III-24').

Yet, the NN-ligand III-8 substitutes two pyridine-ligands in [CpRu(Py)$_3$][PF$_6$], when refluxed in DCM within 1 hour, and yields the new complex III-25. A new Cp-H signal was observed at $\delta = 4.12$ ppm in the $^1$H NMR spectrum. The methyl groups of the oxazolynyl moiety became non-equivalent and showed up at $\delta = 0.70$ and 1.50 ppm, respectively. So did protons of methylene in the oxazolynyl ring as well, represented by two doublets at $\delta = 4.11$ and 4.34 ppm ($J_{HH} = 9.4$ Hz) in $^1$H NMR spectrum. The protons of the bridging methylene were non-equivalent too. Two doublets corresponding to these two protons can be observed at $\delta = 3.82$ and 3.55 ppm ($J_{HH} = 18.7$ Hz). Complex III-25 turns to a hydride complex when treated with KOtBu in 2-propanol at 80°C within 1 h. The $^1$H NMR spectrum shows the hydride singlet at $\delta = -12.19$ ppm.
The crystal of III-25 suitable for X-Ray spectroscopy was grown from a saturated DCM solution by slow diffusion of hexane (Figure 4). Interestingly, the Ru-N(3) and Ru-N(4) distances are similar, 2.155(3) and 2.157(3) Å, respectively, whereas the Ru-N(1) bond is noticeably shorter (2.107(3) Å) and correlates with the Ru-N distance in complex III-14 (2.081(9) Å).

Figure 4. Molecular structure of complex III-25. Thermal ellipsoids are shown at 30% probability. Hydrogen atoms are omitted for clarity.
RuCl₂(PPh₃)₃ reacts with the NNS-ligand III-10 in toluene within 1 hour under reflux with the formation of complex III-26. III-10 coordinates to ruthenium in a tridentate fashion, which was confirmed by ¹H NMR. Thus, two protons of the methylene bridge became non-equivalent and showed up as two multiplets at δ = 4.36 and 4.75 ppm, coupled to each other and to the proton of the nearby amine. The protons of the bridging ethylene, also shifted towards a weaker field with δ = 3.59-3.74 (2H), 3.50-3.59 (1H), and 3.24-3.39 (1H), as compared to the free ligand III-10 (δ = 3.11 and 2.92), can be characterized as non-equivalent. The NNS-ligand III-10 substitutes two triphenylphosphine molecules, according to ³¹P{¹H} NMR spectrum showing a singlet for the single remaining phosphine ligand at δ = 54.5 ppm, and the signal for free triphenylphosphine at δ = -5.4 ppm, with the ratio 1:2. Unfortunately, no crystals of III-26 suitable for X-ray study could be grown. Nevertheless, we can suggest the following structure of this compound. The bulkiest ligands, the NNS ligand and triphenylphosphine most likely occupy the equatorial positions of a distorted octahedron, whereas two chlorides are in the remaining axial positions. The coordinated amine unit is chiral and provides the observed asymmetry.

![Image of compound III-26]

III. 1. 4. Catalytic transfer hydrogenation of acetophenone

The new ruthenium complexes were evaluated for their ability to catalyze transfer hydrogenation of ketones. Acetophenone was chosen as a model carbonyl substrate. In the standard experiment, the ketone was dissolved in 2-propanol in the presence of 1 mol%
catalyst and 1 mol% base. The addition of a base is considered to be an important factor in
the transfer hydrogenation after the pioneering work of Bäckvall who showed that external
base mediates conversion of metal halide precursors into metal alkoxides which then
undergo β-H elimination with the formation of catalytically active hydride complexes.28,33

The reaction mixture was then heated in a closed NMR tube at 80°C for 1 hour. The results
are summarised in Table 1.

Among all ruthenium complexes that were tested, complexes **III-20/20**' shows the
best catalytic activity in the transfer hydrogenation of acetophenone (Table 1, entry 5).
Reducing the load of catalyst and base by half slows down the reaction significantly (Table
1, entry 6). If the experiment is performed at room temperature, while keeping all other
reaction conditions the same, the highest conversion of 90% (equilibrium under given
reaction conditions) is reached within 100 min (Table 1, entry 7). Only traces of the product
were observed in NMR spectrum, when no KOtBu was added (Table 1, entry 8), which
confirms the importance of a base for the formation of an active catalytic species. Increasing
the load of base to 2 mol% did not lead to any improvement (Table 1, entry 9).
Table 1. Transfer hydrogenation of acetophenone, catalyzed by ruthenium complexes in 2-propanol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst, mol%</th>
<th>KOtBu, mol%</th>
<th>Temperature, ºC</th>
<th>Time</th>
<th>Yielda, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>III-14, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>40</td>
</tr>
<tr>
<td>2</td>
<td>III-15, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>10</td>
</tr>
<tr>
<td>3</td>
<td>III-16/16*, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>III-18, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>25</td>
</tr>
<tr>
<td>5</td>
<td>III-20/20*, 1</td>
<td>1</td>
<td>80</td>
<td>35 min</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>III-20/20*, 0.5</td>
<td>0.5</td>
<td>80</td>
<td>2 h</td>
<td>52</td>
</tr>
<tr>
<td>7</td>
<td>III-20/20*, 1</td>
<td>1</td>
<td>rt</td>
<td>100 min</td>
<td>90</td>
</tr>
<tr>
<td>8</td>
<td>III-20/20*, 1</td>
<td>-</td>
<td>rt</td>
<td>1 h</td>
<td>traces</td>
</tr>
<tr>
<td>9</td>
<td>III-20/20*, 1</td>
<td>2</td>
<td>rt</td>
<td>100 min</td>
<td>90</td>
</tr>
<tr>
<td>10</td>
<td>III-21, 1b</td>
<td>1</td>
<td>80</td>
<td>35 min</td>
<td>90</td>
</tr>
<tr>
<td>11</td>
<td>III-22, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>21</td>
</tr>
<tr>
<td>12</td>
<td>III-25, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>5</td>
</tr>
<tr>
<td>13</td>
<td>III-26, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>23</td>
</tr>
<tr>
<td>14</td>
<td>III-26, 1</td>
<td>1</td>
<td>rt</td>
<td>2.5 h</td>
<td>90</td>
</tr>
<tr>
<td>15</td>
<td>III-26, 0.05</td>
<td>0.05</td>
<td>50</td>
<td>24 h</td>
<td>38</td>
</tr>
<tr>
<td>16</td>
<td>III-26, 0.05</td>
<td>0.05</td>
<td>rt</td>
<td>24 h</td>
<td>78</td>
</tr>
</tbody>
</table>

*a Yields are determined from 1H NMR spectra of the reaction mixture by relative integration of corresponding signals of substrate and product; b relative to the number of ruthenium catalytic centre equivalents.
Dimeric complex **III-21** (Table 1, entry 10) was found to be as effective, as **III-20/20′**. This fact most likely indicates the formation of the same active species in both cases either by acetonitrile elimination from **III-20/20′** or by splitting the dimeric **III-21**. Catalyst **III-22**, bearing NP-ligand **III-1b**, exhibits surprisingly low catalytic activity (Table 1, entry 11), relative to complexes **III-20/20′**. Application of NNS-supported catalyst **III-26** also resulted in a quite low conversion of acetophenone under the chosen conditions (Table 1, entry 13). However, in this case the reason appears to be the decomposition of the catalyst at elevated temperatures. Thus, 90% conversion of acetophenone in the presence of same amount of **III-26** (1%) can be reached in just 2.5 hours at room temperature (Table 1, entry 14). The catalyst **III-26** also operates at very small loads, down to 0.05 mol%, to give 78% conversion to the alcohol within 24 hours at room temperature (Table 1, entry 16).

**III. 1. 5. Catalytic transfer hydrogenation of imines**

Imines are analogues of carbonyl compounds that are used as substrates in hydrogenation for the synthesis of secondary amines (Scheme 34). We therefore were interested in the application of our catalytic systems in this important reaction. N-benzylideneaniline **III-27a** was treated under the catalytic conditions, optimized for the reduction of acetophenone. Gratifyingly, amine **III-28a** was produced in excellent yield in the presence of 1 mol% of **III-20/20′** and 1 mol% of KOrBu within 4.5 hours (Table 2, entry 2). However, unlike acetophenone reduction, this transfer hydrogenation can be improved by using higher load of base. Thus, the reaction time decreased down to 1 hour (Table 2, entry 4) when 4 mol% of KOrBu was added. Further increasing the base concentration did not bring any improvement (Table 2, entry 5).
Scheme 34. Transfer hydrogenation of imines.

Table 2. Transfer hydrogenation of N-benzylideneaniline III-27a, catalyzed by III-20/20’.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst, mol%</th>
<th>KOtBu, mol%</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Yielda, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>1</td>
<td>80</td>
<td>4 h</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>III-20/20’, 1</td>
<td>1</td>
<td>80</td>
<td>4.5 h</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>III-20/20’, 1</td>
<td>1</td>
<td>80</td>
<td>1 h</td>
<td>45</td>
</tr>
<tr>
<td>4</td>
<td>III-20/20’, 1</td>
<td>3</td>
<td>80</td>
<td>1 h</td>
<td>90</td>
</tr>
<tr>
<td>5</td>
<td>III-20/20’, 1</td>
<td>4</td>
<td>80</td>
<td>1 h</td>
<td>98</td>
</tr>
<tr>
<td>6</td>
<td>III-20/20’, 1</td>
<td>5</td>
<td>80</td>
<td>1 h</td>
<td>98</td>
</tr>
<tr>
<td>7</td>
<td>III-20/20’, 1</td>
<td>6</td>
<td>80</td>
<td>1 h</td>
<td>98</td>
</tr>
</tbody>
</table>

*a Yields are determined from 1H NMR spectra of the reaction mixture by relative integration of corresponding signals of substrate and product.

However, bulkier N-1-phenylethylideneaniline III-27b could not be reduced under the catalytic conditions even when the load of catalyst III-20/20’ and base was increased to 5 mol% and 10 mol%, respectively, most likely because of the steric hindrance of the substrate.

III. 1. 6. Catalytic transfer hydrogenation of nitriles

When benzonitrile was involved in the transfer hydrogenation under the conditions optimized for acetophenone no appreciable amount of the product was produced even after
24 hours. Remarkably, increasing the load of base had a positive effect on the catalyst activity, significantly accelerating the reaction (Table 3). Thus, 5 mol% of KOrBu was found to be the optimal amount of base that leads to 58% conversion of the substrate within 3 hours (Table 3, entry 4), and 75% after 24 hours (Table 3, entry 7).

Table 3. Optimization of the amount of base for transfer hydrogenation of benzonitrile with 1 mol% III-20/20’ in 2-propanol.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Base</th>
<th>Load, mol%</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Yielda, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KOrBu</td>
<td>1</td>
<td>80</td>
<td>3 h</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>KOrBu</td>
<td>3</td>
<td>80</td>
<td>3 h</td>
<td>12</td>
</tr>
<tr>
<td>3</td>
<td>KOrBu</td>
<td>4</td>
<td>80</td>
<td>3 h</td>
<td>26</td>
</tr>
<tr>
<td>4</td>
<td>KOrBu</td>
<td>5</td>
<td>80</td>
<td>3 h</td>
<td>58</td>
</tr>
<tr>
<td>5</td>
<td>KOrBu</td>
<td>6</td>
<td>80</td>
<td>3 h</td>
<td>61</td>
</tr>
<tr>
<td>6</td>
<td>KOrBu</td>
<td>7</td>
<td>80</td>
<td>3 h</td>
<td>61</td>
</tr>
<tr>
<td>7</td>
<td>KOrBu</td>
<td>5</td>
<td>80</td>
<td>24 h</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>NaOrBu</td>
<td>5</td>
<td>80</td>
<td>24 h</td>
<td>74</td>
</tr>
<tr>
<td>9</td>
<td>LiOrBu</td>
<td>5</td>
<td>80</td>
<td>24 h</td>
<td>72</td>
</tr>
<tr>
<td>10</td>
<td>KOrBu</td>
<td>5</td>
<td>80</td>
<td>3 h</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^a\) Yields are determined from \(^1\)H NMR spectra of reaction mixture by relative integration of corresponding signals of substrate and product; \(^b\) without III-20/20’.

The effect of alkali metal cation was also investigated, but using NaOrBu (Table 3, entry 8) or LiOrBu (Table 3, entry 9) instead of KOrBu did not result in any change in the activity of the catalyst. The use of a base alone, without any ruthenium complex, did not result in any reduction (Table 3, entry 10).
As it was previously observed for some other catalysts \(^{130, 132}\), the initially formed amine product reacts further with acetone, the by-product of transfer hydrogenation in 2-propanol, to yield ketoimine as the final product. No further reduction of the ketoimine to a secondary amine, which was observed by Beller et al. for the (Ph\(_3\)P)\(_3\)RuCl\(_2\) catalyst \(^{127}\), takes place under these conditions. The increased steric hindrance of the pre-catalysts III-20/20’ most likely prevents coordination of ketoimine, required for its further reduction, which correlates with the results for transfer hydrogenation of imines discussed in the previous above. The treatment of the imine products with HCl affords the corresponding primary ammonium salts.

Further substrate screening showed that aromatic nitriles with electron donating groups, such as amino and alkoxy, are reduced easier than benzonitrile, with full conversion in 24 hours, i.e. III-30b and III-30c in Scheme 35. This observation suggests that the rate determining step in reduction is not related to the electrophilicity of the nitrile carbon centre but to nucleophilicity of the nitrogen centre, such is its ability to coordinate to the catalyst. Full conversions were also observed for aliphatic nitriles, although the transfer hydrogenation of butyronitrile and valeronitrile requires more time than transfer hydrogenation of pivalonitrile (III-30f,g vs III-30e). The transfer hydrogenation of sterically hindered 2,6-dimethylbenzonitrile afforded a low yield of the imine product III-30d (29% after 24 hours). No reaction was observed in the transfer hydrogenation of 3-nitrobenzonitrile, likely because of poisoning of the catalyst by the nitro group of the substrate. \(m\)-Acetylbenzonitrile, featuring both the keto and nitrile functionalities, was selectively reduced at the keto group (III-30i in Scheme 35).
Scheme 35. Transfer hydrogenation of nitriles. Reaction conditions: 1 mol% III-20/20’, 5 mol% KOtBu in 2 mL of 2-propanol at 80°C. Conversions were determined by $^1$H NMR spectroscopy by relative integration of corresponding signals of substrate and product, isolated yields of the corresponding ammonium salts are shown in parentheses. a Heating for 36 h.

Considering the positive results obtained for transfer hydrogenation of aldimine N-benzylideneaniline III-27a in the above section, one can assume that reduction of nitriles with primary alcohols under the catalytic conditions should lead to the production of secondary amines. Indeed, when benzonitrile III-29a was heated in ethanol with 1 mol% III-20/20’ and 5 mol% base, stoichiometric amount of benzylethylamine III-31a was produced after 48 hours (Scheme 36). Two equivalents of ethanol are consumed for the reduction of each equivalent of nitrile. Another equivalent of ethanol is used for amine alkylation. Acetaldehyde, the initial by-product in transfer hydrogenation, instantly
undergoes further Tishchenko reaction to produce ethyl acetate. Thus, overall an equivalent of ester is produced per each equivalent of the product.

\[
\begin{align*}
\text{R-CN} & \quad \overset{1 \text{ mol}\% \text{ III-20/20'}, 5 \text{ mol}\% \text{ KOtBu}}{\text{ethanol, 80°C}} \quad \text{R-\text{N}} \\
\text{III-29a-g} & \quad \rightarrow \quad \text{III-31a-g}
\end{align*}
\]

III-31a, 99% (48 h)
III-31b, 18% (20 h)
III-31c, 76% (20 h)
III-31d, 23% (20 h)
III-31e, NR (20 h)
III-31f, 99% (10 h)

Chemoselective reduction of carbonyl group

III-31ga, 90% and III-31gb, 8% (20 h)
III-31gb, 99% (48 h)

Scheme 36. Transfer hydrogenation of nitriles in ethanol. Reaction conditions: 1 mol% III-20/20’, 5 mol% KOtBu in 2 mL of ethanol at 80°C. Conversions were determined by \(^1\)H NMR spectroscopy by relative integration of corresponding signals of substrate and product.

Unexpectedly, the cyano-group in 4-aminobenzonitrile III-29b was not reduced under these conditions. Instead, the amine function was alkylated to form 4-N-ethylaminobezonitrile III-31b, although ethyl acetate was also formed. Even though, the yield is quite low (18% in 20 hours), the alkylation of amine is certainly preferred over the transfer hydrogenation of nitrile. The production of ethyl acetate in the absence of an obvious reduction process indicates the occurrence of acceptorless dehydrogenation of ethanol.\(^{342}\) 4-Methoxybenzonitrile III-29c can be reduced within 20 hours with the formation of
secondary amine III-31c in good yield. Sterically hindered ortho-substituted benzonitrile III-29d shows low conversion to secondary amine III-32d, similar to the reduction in 2-propanol (Scheme 35). 4-Nitrobenzonitrile III-29e cannot be reduced under these conditions. Only carbonyl-group reduction is observed in the case of 4-cyanobenzophenone III-29f. Pivalonitrile III-29e is converted to secondary amine III-31ea in the first 20 hours of heating. However, III-31ea undergoes further alkylation and is fully transformed to diethyl-tert-butylamine III-31eb within the following 24 hours.

III. 1. 7. Catalytic transfer hydrogenation of heterocyclic compounds

Transfer hydrogenation of heterocyclic compounds was investigated next. As for nitriles, the dependence of the observed reaction rate on the base load was also observed (Table 4). Thus, it was found that transfer hydrogenation of quinoline accelerates when the amount of KOtBu increases up to 10 mol% (Table 4, entry 6). Further increase of the base load does not lead to any improvement (Table 4, entry 7). Thus, 84% conversion of quinoline can be reached in 24 hours (Table 4, entry 8).
The scope of N-heterocyclic substrates reduced by this catalytic system is shown in Scheme 37. Using the conditions optimized for quinoline, 1,5-naphthyridine III-32b and quinoxaline III-32c can be hydrogenated in good yields. Unexpectedly, reduction of isoquinoline III-32d and quinaldine III-32e resulted in hydrogenation of the all-carbon rings, although the conversion in the latter case was low. The exact reason for this unusual regioselectivity is unknown, although we can speculate that in the case of quinaldine the

<table>
<thead>
<tr>
<th>Entry</th>
<th>Base</th>
<th>Load, mol%</th>
<th>Temperature, ºC</th>
<th>Time</th>
<th>Yield&lt;sup&gt;a&lt;/sup&gt;, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KOrBu</td>
<td>1</td>
<td>80</td>
<td>10 h</td>
<td>5</td>
</tr>
<tr>
<td>2</td>
<td>KOrBu</td>
<td>3</td>
<td>80</td>
<td>10 h</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>KOrBu</td>
<td>4</td>
<td>80</td>
<td>10 h</td>
<td>25</td>
</tr>
<tr>
<td>4</td>
<td>KOrBu</td>
<td>6</td>
<td>80</td>
<td>10 h</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>KOrBu</td>
<td>8</td>
<td>80</td>
<td>10 h</td>
<td>44</td>
</tr>
<tr>
<td>6</td>
<td>KOrBu</td>
<td>10</td>
<td>80</td>
<td>10 h</td>
<td>55</td>
</tr>
<tr>
<td>7</td>
<td>KOrBu</td>
<td>12</td>
<td>80</td>
<td>10 h</td>
<td>55</td>
</tr>
<tr>
<td>8</td>
<td>KOrBu&lt;sup&gt;b&lt;/sup&gt;</td>
<td>50</td>
<td>80</td>
<td>24 h</td>
<td>84</td>
</tr>
<tr>
<td>9</td>
<td>NaOrBu</td>
<td>10</td>
<td>80</td>
<td>10 h</td>
<td>55</td>
</tr>
<tr>
<td>10</td>
<td>LiOrBu</td>
<td>10</td>
<td>80</td>
<td>10 h</td>
<td>54</td>
</tr>
<tr>
<td>11</td>
<td>KOrBu&lt;sup&gt;c&lt;/sup&gt;</td>
<td>10</td>
<td>80</td>
<td>10 h</td>
<td>0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Yields are determined from <sup>1</sup>H NMR spectra of reaction mixture by relative integration of corresponding signals of substrate and product. <sup>b</sup> 5 mol% III-20/20'; <sup>c</sup> without III-20/20'.

The scope of N-heterocyclic substrates reduced by this catalytic system is shown in Scheme 37. Using the conditions optimized for quinoline, 1,5-naphthyridine III-32b and quinoxaline III-32c can be hydrogenated in good yields. Unexpectedly, reduction of isoquinoline III-32d and quinaldine III-32e resulted in hydrogenation of the all-carbon rings, although the conversion in the latter case was low. The exact reason for this unusual regioselectivity is unknown, although we can speculate that in the case of quinaldine the
reduction of the N=C bond is not possible for steric reasons, analogous to ketoimine discussed in the above sections.

Scheme 37. Transfer hydrogenation of heterocyclic compounds. Reduced bonds are highlighted in red. Reaction conditions: 1 mol% III-20/20’, 10 mol% KOtBu in 3 ml of 2-propanol at 80°C. Conversions were determined by 1H NMR spectroscopy by relative integration of corresponding signals of substrate and product, isolated yields of selected products are shown in brackets; a 5 mol% III-20/20’, 50 mol% KOtBu; b 5h.

Acridine III-32f was hydrogenated with excellent yield in 21 hours to give a mixture of 9,10-dihydroacridine III-33fa and 1,2,3,4-tetrahydroacridine III-33fb, the latter species being the major product and having the all-carbon ring hydrogenated. For isoquinoline,
however, an electronic factor can be responsible. In the case of phenanthridine III-32g, the C-N double bond was hydrogenated with moderate conversion after 24 hours. Interestingly, the yield did not increase upon addition of a larger amount of the catalyst, suggesting that an equilibrium was reached. This observation can be attributed to the propensity of 5,6-dihydrophenanthridine III-33g to serve as a hydrogen source.\textsuperscript{343}

Attempted transfer hydrogenation of 1,10-phenanthroline III-32k returned only a very small amount of the product, with one of the external heterocycles being reduced, although the load of the catalyst was increased to 5 mol\%. The reason for the low yield is likely the ability of 1,10-phenanthroline to act as a bidentate ligand and thus poison the catalyst. In the case of triazine III-32h, only one of the C=N bonds can be reduced in moderate yield. The strongly aromatically stabilized pyrimidine III-32i and pyridine III-32j cannot be hydrogenated under these conditions, neither is the five-membered heterocycle in indole III-32l. In contrast, benzofuran III-32m was found to be more active in the transfer hydrogenation under these conditions, so that 66\% conversion can be achieved. Likewise, benzothiophene III-32n was fully converted to 2,3-dihydrothiophene III-33n with 1 mol\% catalyst load within 5 hours. The difference between the nitrogen-containing five-membered cycles on one side, and oxygen- and sulfur-containing cycles on the other, can be attributed to the presence of the NH bond in indole which may lead to an interaction with the catalyst and inhibition.

III. 1. 8. Transfer hydrogenation of C=C bonds

The application of complexes III-20/20' in transfer hydrogenation can be extended to the reduction of olefins and conjugated arenes. Treatment of 3,3-dimethylbutene-1 with 1
mol% of III-20/20’ and 1 mol% of KOtBu in 2-propanol did not give even traces of the reduced product after 1.5 hours at 80°C (Table 5, entry 1). However, an increase of base load to 2 mol% resulted in dramatic enhancement of the catalytic activity, so that 90% conversion was achieved after 1.5 hours (Table 5, entry 2). Experiments with 3 and 4 mol% KOtBu (Table 5, entries 3 and 4) showed only slight improvement of the catalyst performance. Controlled experiment without ruthenium complexes did not lead to any reduction of the double bond (Table 5, entry 5).

<table>
<thead>
<tr>
<th>Entry</th>
<th>Base</th>
<th>Load, mol%</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Yielda, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>KOtBu</td>
<td>1</td>
<td>80</td>
<td>1.5 h</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>KOtBu</td>
<td>2</td>
<td>80</td>
<td>1.5 h</td>
<td>90</td>
</tr>
<tr>
<td>3</td>
<td>KOtBu</td>
<td>3</td>
<td>80</td>
<td>1.5 h</td>
<td>96</td>
</tr>
<tr>
<td>4</td>
<td>KOtBu</td>
<td>4</td>
<td>80</td>
<td>1.5 h</td>
<td>98</td>
</tr>
<tr>
<td>5</td>
<td>KOtBu&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4</td>
<td>80</td>
<td>1.5 h</td>
<td>-</td>
</tr>
</tbody>
</table>

<sup>a</sup> Yields are determined from <sup>1</sup>H NMR spectra of reaction mixture. <sup>b</sup> Without III-20/20’.

With this catalytic system in hand, the substrate scope was screened (Scheme 38). Mono- and disubstituted alkenes were easily reduced. Moreover, no isomerization was observed in transfer hydrogenation of the terminal hexene III-34c, but more sterically encumbered tri- and tetra-substituted alkenes did not enter this reaction. Conjugated α,β-unsaturated esters, such as ethyl methacrylate III-34g and ethyl crotonate III-34h, were reduced to the corresponding saturated esters in high yield. Naphthalene underwent only
marginal reduction but the less aromatically stabilized anthracene III-34j was hydrogenated at one of the lateral rings to 1,2,3,4-tetrahydroanthracene in excellent yield within 21 hours.

Scheme 38. Transfer hydrogenation of unsaturated hydrocarbons. Reduced bonds are highlighted in bold. Reaction conditions: 1 mol% III-20/20’, 4 mol% KOrBu in 2 ml of 2-propanol at 80°C. Conversions were determined by ¹H NMR spectroscopy, isolated yields of selected products are shown in brackets; a 3 mol% III-20/20’, 12 mol% KOrBu.

III. 1.9. Transfer hydrogenation of alkynes

Semi-hydrogenation of alkynes is of significant current interest as it provides a route to valuable olefin products, but very little is known about the application of transfer hydrogenation in this reaction. Following the successful reduction of olefins, ruthenium complexes III-20/20’ were applied in the transfer hydrogenation of alkynes, although the catalyst load was increased to 2 mol% (Scheme 39).
Scheme 39. Transfer hydrogenation of alkynes. Reaction conditions: 2 mol% III-20/20', 2 mol% KOtBu in 2 ml of 2-propanol at 80°C. Conversions were determined by ¹H NMR spectroscopy, isolated yields of selected products are shown in brackets. " 1 mol% III-20/20', 4 mol% KOtBu.

Rewardingly, diphenylacetylene III-36a was selectively reduced to diphenylethylene III-37a with the unexpected E-selectivity evinced from the observation of the olefinic CH peak at δ = 7.16 ppm in the ¹H NMR spectrum in CDCl₃ and by comparison to literature data.⁵⁰ This fact is of significance because previous studies on the semi-transfer hydrogenation of alkynes showed Z-selectivity.¹⁶⁴, ¹⁷², ³⁵² Semi-hydrogenation was also observed for 1-chloro-4-(phenylethynyl)benzene III-36b with the preferential formation of the E-isomer (E:Z = 89:11). However, alkynes with less bulky substituents, such as methylphenylacetylene III-36c and 1-phenyl-1-pentyne III-36d, were first reduced to mixtures of Z and E alkenes III-37c and III-37d and then further hydrogenated to the corresponding aliphatics, propylbenzene III-38c and pentylbenezene III-38d, respectively. Attempted reduction of a terminal alkyne, phenylacetylene III-36e, resulted in a very low conversion. This behaviour can be attributed to the ability of monosubstituted alkynes to
poison the catalyst by formation of stable \( \pi \)-alkyne metal complexes or by C-H bond activation.

### III. 1. 10. Transfer hydrogenation of esters

The ethyl esters of acetic, benzoic and trifluoroacetic acids were tested under conditions, optimized for catalytic transfer hydrogenation of acetophenone. However ester reduction did not occur even with increased load of catalyst **III-20/20’**. Instead, only the products of transesterification with 2-propanol were observed (Table 6).

**Table 6. Transesterification of esters in the presence of **III-20/20’** in 2-propanol.**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Substrate</th>
<th>Product</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Yield(^a), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CH(_3)-COOPh</td>
<td>CH(_3)-COO\text{Pr}</td>
<td>80</td>
<td>3.5 h</td>
<td>78</td>
</tr>
<tr>
<td>2</td>
<td>Ph-COOPh</td>
<td>Ph-COO\text{Pr}</td>
<td>80</td>
<td>4 h</td>
<td>13</td>
</tr>
<tr>
<td>3</td>
<td>CF(_3)-COOPh</td>
<td>CF(_3)-COO\text{Pr}</td>
<td>80</td>
<td>2 h</td>
<td>91</td>
</tr>
</tbody>
</table>

Reaction conditions: 1 mol\% **III-20/20’**, 4 mol\% KO\text{tBu}, in 1 ml 2-propanol. \(^a\)Yields are determined from \(^1\)H NMR spectra of reaction mixture by relative integration of corresponding signals of substrate and product.

These results are quite predictable, considering that transfer hydrogenation is an equilibrium process, where acetone, formed by alcohol oxidation, accumulates in the system and can compete in the process of transfer hydrogenation, whereas the activation energy for ester reduction is quite high. As mentioned in the review above, transfer hydrogenation of esters is a just recently discovered phenomenon,\(^{130,154}\) as it is a very challenging process, likely because in this case the equilibrium of reduction by alcohols is usually shifted toward the side of starting compounds.
2-Propanol has been used as the reaction media in transfer hydrogenation since the pioneering work of Ponndorf.\textsuperscript{353} It quickly replaced ethanol as reductant\textsuperscript{354} because the oxidation of secondary alcohols to ketone is more thermodynamically favorable than the oxidation of primary alcohol to aldehyde because of the lower oxidation potential of the former,\textsuperscript{355} as well as to avoid complications arising from condensation reactions of the acetaldehyde product (in the case of ethanol) with the usual ketone and imine substrates. However, recently ethanol received renewed attention as a green, renewable reagent in the transfer hydrogenation\textsuperscript{157, 356-358}. Furthermore, the application of ethanol may be very beneficial, in particular for the reduction of esters, because acetaldehyde produced in the first step of transfer hydrogenation can undergo the Tishchenko reaction\textsuperscript{359} under basic conditions with the formation of ethyl acetate, resulting in the formal ester metathesis, i.e. a thermodynamically neutral process.

This idea prompted the research of transfer hydrogenation of esters in ethanol. Given the generally lower activity of esters in reduction processes, electrophilically activated esters were chosen as primary substrates. The results are summarized in Scheme 40. Ethyl trifluoroacetate \textit{III-39a} was reduced by 35\% with 1 mol\% \textit{III-20/20'} and 4 mol\% KO\textsubscript{t}Bu within 19 hours and no further conversion was observed. Gratifyingly, with 5 mol\% load of the catalyst \textit{III-20/20'}, full conversion of \textit{III-39a} to 1,2,3-trifluoroethanol was accomplished in 4 hours. As expected, ethyl acetate was identified as the co-product. Ethyl pentafluoropropionate \textit{III-39b} can be reduced in good yield, although a longer reaction time is required. In the case of methyl pentafluorobenzoate \textit{III-39c}, there was no reduction of the ester group. However, several products were observed that, on the basis of \textsuperscript{19}F{\textsuperscript{1}H} NMR
spectra, can be attributed to the products of defluorination\textsuperscript{360-362}; but more research is required to delineate their nature.

\[ \text{F}_3\text{C}-\text{CO}_2\text{Et} \quad \text{C}_2\text{H}_5-\text{CO}_2\text{Et} \quad \text{Ph}-\text{CO}_2\text{Et} \]

\[ \text{III-39a}, 35\% (19 \text{ h})^a \quad \text{III-39b} 78\% (7.5 \text{ h}) \quad \text{III-39c} \quad \text{III-39d}, \text{NR} \]

\[ \text{III-39e}, \text{NR} \quad \text{III-39f}, \text{NR} \quad \text{III-39g}, \text{NR} \]

\[ \text{NC}-\text{CO}_2\text{Et} \quad \text{C}_2\text{H}_5-\text{CO}_2\text{Et} \quad \text{COOEt} \quad \text{EtOOC}^\prime \]

\[ \text{III-39h}, 99 (98 \%) (3-15 \text{ h}) \quad \text{III-39i}, \text{NR} \quad \text{III-39j}, 99 (94 \%) (5 \text{ h}) \]

\textbf{Scheme 40.} Transfer hydrogenation of esters. Reaction conditions: 5 mol\% III-20/20\(^{\prime}\), 20 mol\% KOtBu in 3 ml of ethanol at 80°C. Conversions were determined by \(^1\text{H}\) NMR spectroscopy by relative integration of corresponding signals of substrate and product. \(^a\) 1 mol\% III-20/20\(^{\prime}\), 4 mol\% KOtBu.

Other aromatic substrates, having both electron-neutral (III-39d) and electron-poor aromatic systems (III-39e-g), were also unreactive. Ethyl 4-cyanobenzoate III-39h, however, reacted at the cyano-group affording an amine, which further underwent coupling with acetaldehyde to form an imine. Unlike the ketoimines formed in the transfer hydrogenation of nitriles in 2-propanol, this aldimine is more sterically accessible and can be further hydrogenated under the catalytic conditions to give a secondary amine. Likewise, \(\alpha,\beta\)-unsaturated ester III-34h (Scheme 38) was chemoselectively hydrogenated at the C-C double bond. Diethyl oxalate III-39j was chemoselectively reduced at one ester group in
excellent yield after only 5 hours. The product of the latter reaction is ethyl hydroxyacetate, which is not sufficiently activated for the subsequent reduction of the remaining ester group.

III. 1. 11. Kinetic studies of catalytic transfer hydrogenation of olefins

To shed light on the possible mechanism of catalytic transfer hydrogenation, kinetic studies were performed for the reduction of cyclohexene as a model substrate. Cyclohexene was chosen because of the relatively low rate of its hydrogenation in comparison with external alkenes. The fact that more than two equivalents of a base are required for the reaction (Table 5, entry 2) may indicate that the true catalyst is a dihydrido-ruthenium complex. However, no hydrido-complexes could be detected by NMR monitoring of the reaction mixture, likely because of their labile nature. Neither was any ruthenium hydride observed in the reactions of III-20/20′ with sodium tert-butoxide, lithium triethylborohydride or L-selectride in 2-propanol. A mercury drop test was performed to determine the heterogeneity of the catalytic system. Neither inhibition nor deceleration of the reaction, as compared to a reference reaction with the same catalyst and substrate under identical conditions, was observed, indicating the homogenic nature of the reaction mixture.

Reduction of cyclohexene was studied under pseudo first order conditions by using neat 2-propanol. The progress of the reaction was monitored by ¹H NMR spectroscopy. The kinetic analysis was done with the help of Dynamics Centre 2.4.5. The data were truncated at about 20% conversion, to minimize the effect of possible catalyst deactivation. Linearization of the data in coordinates –Ln(x/x₀) vs time revealed the first order in the substrate. A series of experiments were then performed by varying the amount of complexes III-20/20′ and the base (1, 2, 3, 4, 5 mol% of III-20/20′ and 4, 8, 12, 16, 20 mol% of KOtBu,
respectively). The effective rate constants obtained for each catalyst load were plotted against the amount of the catalyst, which revealed a linear dependence on the catalyst (Figure 5).

Similar experiments with different amounts of 2-propanol (10 to 40 equivalents) were performed. Toluene was added to maintain the concentration of all other reagents. A graph of the effective rate constant against the amount of 2-propanol showed linear dependence, indicating that the reaction is also first order in the alcohol (Figure 6). Based on these results, the following kinetic law can be derived:

\[
\text{Rate} = k_{\text{obs}} [\text{catalyst}][\text{cyclohexene}][\text{2-propanol}]
\] (1).

![Figure 5. The dependence of effective rate constant \( k_{\text{obs}} \) on the catalyst load under the pseudo first order conditions. \( k_{\text{obs}} \) values were derived from Dynamics Centre 2.4.5.](image)

\[
y = 1.48x \\
R^2 = 0.9828
\]
Figure 6. The effective rate constant vs the amount of 2-propanol. $k_{\text{obs}}$ values were derived with Dynamics Centre 2.4.5.

The reaction rate does not change when an O-labelled alcohol, $(\text{CH}_3)_2\text{CH-OD}$, was used as the solvent (Table 7). However, when the reaction was performed in the fully deuterated 2-propanol-d$_8$, a kinetic isotope effect of 3.2 was observed. This significant KIE is consistent with the cleavage of the C-H bond in the rate determining step. Moreover, we observed scrambling of deuterium over all positions in the product, as well as over the yet unreacted substrate, which indicates the reversibility of hydride transfer and intermediacy of a Ru-cyclohexyl complex.

Table 7. Determination of kinetic isotope effect.$^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>$k_{\text{obs}}$, min$^{-1}$</th>
<th>KIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$(\text{CH}_3)_2\text{-CH-OH}$</td>
<td>0.00419</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>$(\text{CH}_3)_2\text{-CH-OD}$</td>
<td>0.00408</td>
<td>1.0</td>
</tr>
<tr>
<td>3</td>
<td>$(\text{CD}_3)_2\text{-CD-OD}$</td>
<td>0.00131</td>
<td>3.2</td>
</tr>
</tbody>
</table>

$^a$ Reaction conditions: 1 mol% III-20/20’, 4 mol% KOtBu in 2 ml of solvent at 80°C.
III. 1. 12. The mechanism of transfer hydrogenation of olefins

The proposed mechanism of the transfer hydrogenation of olefins catalyzed by III-20/20’ is presented in Scheme 41. This is a conventional dihydride mechanism.\textsuperscript{30} A reaction of complexes III-20/20’ with alcohol in the presence of an external base produces the putative dihydride complex III-41. Replacement of the labile nitrile ligand by a substrate would give the adduct III-42. Alkene insertion into the Ru-H bond results in the alkyl complex III-43. This step should be reversible, which accounts for the observed D-scrambling. Subsequent coordination of alcohol to the created vacant site, followed by reductive elimination, releases the cyclohexane product. Proton shift would generate the alkoxide III-44, which after β-H shift would afford the dihydride complex III-45 with a π-coordinated ketone. Substitution of the latter by alkene closes the catalytic cycle.
Scheme 41. Proposed catalytic cycle for transfer hydrogenation of olefins with III-20/20’.

When applied to alkyne reduction, this mechanism predicts the formation of Z-alkenes, i.e. the products of cis-hydrogenation. However, our experiments revealed the preferential formation of the more thermodynamically stable E-alkenes. Fout et al. have recently shown by the application of para-hydrogen that Co-catalyzed hydrogenation of alkynes proceeds by the expected cis-addition followed by isomerization. We believe that a similar process occurs under our catalytic conditions. To test the possibility of a Ru-mediated Z-E isomerization, we heated cis-stilbene III-37aa, the possible product of initial
cis-hydrogenation of diphenylacetylene, under our catalytic conditions (Scheme 42a). Full conversion to the trans-stilbene III-37ab was observed after 3 hours.

Scheme 42. a) Isomerization of cis-stilbene under the catalytic conditions. b) the mechanism of H/D scrambling and the stilbene isomerization.

The way how Z-E isomerization takes place is also of interest. For the related Ru-catalyzed hydrogenation of alkynes to E-olefins, Fürstner suggested a mechanism based on the formation of alkylidene complexes. To understand better the isomerization process in the III-20/20’ mediated catalysis, a labelling experiment was conducted. Thus, cis-stilbene III-37aa was heated in 2-propanol-d$_8$ to yield the deuterated trans-stilbene III-37ac (Scheme 42b). The possible rationalization of this transformation is that Z-E isomerization occurs as a result of interrupted hydrogenation of olefin. Namely, insertion of alkene into the Ru-H bond affords an alkyl intermediate, which is a reversible process (e.g. see III-42 → III-43, Figure 7) and should lead to D-scrambling if the C-H elimination step is much
slower. Therefore, we believe that Z-E isomerisation may proceed via a sequence of migratory insertion, rotation around the C-C bond, and β-hydrogen elimination.

Alkynes with less bulky substituents also initially produce Z-alkenes which can be either further hydrogenated or isomerized to the E-alkene. The second hydrogenation is sterically allowed but it appears that Z-alkenes are hydrogenated easier than E-isomers. Z-alkenes are more accessible for transfer hydrogenation and reduced easier comparing to E-isomers. That is the reason why in the case of 1-phenyl-1-propyne III-36c or 1-phenyl-1-pentyne III-36d E-isomers remained in the reaction mixture, while Z-isomers were fully consumed.

III. 2. Synthesis of amines by borrowing hydrogen methodology

III. 2. 1. Alkylation of amines via alcohol activation

It was shown above that nitriles undergo reductive alkylation in ethanol in the presence of 1 mol% III-20/20’ and 5 mol% KOtBu at 80°C. Moreover, the alkylation of 4-aminobenzonitrile III-32b was observed instead of cyano group reduction under the same conditions. Thus, the study of catalytic activity of III-20/20’ in amine synthesis by borrowing hydrogen methodology was the next logical step.

First benzylamine was heated in ethanol with 1 mol% III-20/20’ and 5 mol% KOtBu at 80°C (Table 8, entry 1). Only 21% conversion was observed in 24 hours. When temperature is increased to 100°C, 81% of benzylamine can be converted into secondary amine within 24 hours (Table 8, entry 2), however benzylidethylamine, product of double alkylation, starts to form at this point and its amount grows under prolonged heating.
Interesting that upon reductive alkylation of benzonitrile in ethanol only secondary amine was produced and full conversion was reached in 48 hours (Scheme 4). The only difference between two reactions is the formation of an equivalent of ethyl acetate in the latter case, as product of ethanol oxidation. Indeed, when an equivalent of ester is added to the reaction with amine, 96% conversion to benzylethylamine occurs in 36 hours (Table 8, entry 3).

**Table 8.** Condition optimization for the synthesis of benzylethyl amine via borrowing hydrogen methodology.$^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Amine</th>
<th>Alcohol, eq</th>
<th>Temperature, °C</th>
<th>Yield, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Benzylamine</td>
<td>Ethanol, 35 eq</td>
<td>80</td>
<td>21</td>
</tr>
<tr>
<td>2</td>
<td>Benzylamine</td>
<td>Ethanol, 35 eq</td>
<td>100</td>
<td>81$^b$</td>
</tr>
<tr>
<td>3$^c$</td>
<td>Benzylamine</td>
<td>Ethanol, 35 eq</td>
<td>100</td>
<td>96$^d$</td>
</tr>
<tr>
<td>4$^c$</td>
<td>Benzylamine</td>
<td>Ethanol, 0.1 eq</td>
<td>100</td>
<td>_$^e$</td>
</tr>
<tr>
<td>5</td>
<td>Benzylamine</td>
<td>Ethanol, 1 eq</td>
<td>100</td>
<td>traces</td>
</tr>
<tr>
<td>6$^f$</td>
<td>Benzylamine</td>
<td>Ethanol, 1 eq</td>
<td>100</td>
<td>_$^g$</td>
</tr>
<tr>
<td>7$^f$</td>
<td>Benzylamine</td>
<td>Ethanol, 3 eq</td>
<td>100</td>
<td>87$^h$</td>
</tr>
</tbody>
</table>

$^a$ Reaction conditions: 1 mol% III-20/20°, 5 mol% KOtBu, neat. Yields of secondary amines after 24 hours were determined by $^1$H NMR spectroscopy; $^b$ 4% benzylidethylamine; $^c$ an equivalent of ethyl ester was added; $^d$ after 36 hours; $^e$ 20% of N-benzylacetamide was observed; $^f$ in THF; $^g$ 17% N-benzylidenethylamine; $^h$ after 48 hours.

To elucidate the role of ethyl acetate, a set of experiments was performed for determining whether the ester can be a source of ethyl group for amine alkylation. First of all, benzylamine was heated in THF with 0.1 equivalent of ethanol and an equivalent of ethyl ester in the presence of the catalyst (Table 8, entry 4). After 20 hours 20% of ester reacted with amine to give N-benzylacetamide. Subsequent addition of excess ethanol (4
equivalents) drives the reaction of alkylation of unreacted amine, while N-benzylacetamide is left in the solution as it is. Moreover, if benzylamine is alkylated in the presence of ethyl propionate, N-ethylated product forms exclusively. Thus, ester does not act as an alkyl source.

Meanwhile, some amount of ester, although less than equivalent, is consumed during the reaction, which is caused by hydrolyses. Free acetic acid likely forms benzylethalammonium acetate, which less tends to further alkylation, leading to chemoselective synthesis of secondary amine.

On the other hand, overalkylation, which is most likely provoked by the large excess of an alkylating agent, can be avoided if stoichiometric amounts of alcohol are used. However, if benzylamine/ethanol mixture (1:1) is heated with the ruthenium catalyst, only traces of N-alkylated product is obtained (Table 8, entry 5). When the reaction is performed in THF media, N-benzylidene(ethylamine) is formed (Table 8, entry 6), which is the product of N-ethylidene(benzylamine) isomerization, driven by the formation of more favorable π-conjugated system. Increasing amount of ethanol to 3 equivalents resulted in 63% conversion after 24 hours and 87% - after 48 hours (Table 8, entry 7).

Further, benzyl alcohol as an alkylating agent was studied. Complete alkylation of benzylamine with the excess benzyl alcohol is achieved after 48 hours of heating at 100℃ (Table 9, entry 1). When stoichiometric amounts of benzylamine and benzyl alcohol in THF solution were heated, no reaction was observed even after prolonged heating (Table 9, entry 2). Based on the consideration, that protic media may be more beneficial for the reaction, it was performed in methanol (Table 9, entry 3). Surprisingly, low conversion to N-methylated amine was observed, and no dibenzylamine formed. This result is unexpected, as
dehydrogenation of methanol is considered to be much more challenging, than benzyl alcohol, that should be more favorable due to creation of π-conjugated system. Thus, tertiary alcohol, uncapable of dehydrogenation, has to be used as a solvent. The simplest tertiary alcohols are tert-butanol and tert-amyl alcohol, the latter was chosen due to its low melting point, comparing to tert-butanol, which makes it easier in operating. However, heating benzylamine and benzyl alcohol in tert-amyl alcohol at 100°C resulting in formation of N-benzylidene(benzyl)amine (Table 9, entry 4).

**Table 9.** Condition optimization for the synthesis of dibenzylamine via borrowing hydrogen methodology.$^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Amine</th>
<th>Alcohol, eq</th>
<th>Temperature, °C</th>
<th>Yield, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 20 eq</td>
<td>100</td>
<td>99$^b$</td>
</tr>
<tr>
<td>2$^c$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 1 eq</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>3$^d$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 1 eq</td>
<td>100</td>
<td>-$^e$</td>
</tr>
<tr>
<td>4$^f$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 1 eq</td>
<td>100</td>
<td>-$^g$</td>
</tr>
<tr>
<td>5$^f$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 1 eq</td>
<td>120</td>
<td>49</td>
</tr>
<tr>
<td>6$^{f,h}$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 1 eq</td>
<td>120</td>
<td>52</td>
</tr>
<tr>
<td>7$^f$</td>
<td>Benzylamine</td>
<td>Benzyl alcohol, 2 eq</td>
<td>120</td>
<td>98$^i$</td>
</tr>
</tbody>
</table>

$^a$ Reaction conditions: 1 mol% III-20/20”, 5 mol% KOrBu, neat. Yield of secondary amine after 24 hours was determined by $^1$H NMR spectroscopy; $^b$ after 48 hours; 4% benzylidiethylamine; $^c$ in THF; $^d$ in MeOH; $^e$ 36% benzylmethylamine; $^f$ in tert-amyl alcohol; $^g$ 13% N-benzylidene(benzyl)amine; $^h$ 2 mol% III-20/20”, 10 mol% KOrBu; $^i$ isolated yield.

Reaction can be forced by increasing the temperature to 120°C, when 49% conversion to secondary amine is observed in 24 hours with no further change (Table 9, entry
5). Assuming that moderate yield was due to the catalyst decomposition, the reaction was performed with 2 mol% III-20/20’, 10 mol% KOtBu, however again only half on the amine was alkylated (Table 9, entry 6). Finally, it was found that at least 2-fold excess of alkylating agent is required to get full conversion to secondary amine within 24 hours in the presence of 1 mol% III-20/20’ and 5 mol% KOtBu at 120°C (Table 9, entry 7).

A number of alcohols and amines were involved in the reaction under optimized conditions (Table 9, entry 7). Thus, alkylbenzylamines can be obtained with excellent yields regardless of the reagent combinations: benzyl alcohol/alkylamine (Table 10, entries 1 and 2) or aliphatic alcohol/benzylamine (Table 10, entry 3).

**Table 10. Alkylation of amines via borrowing hydrogen methodology.**

<table>
<thead>
<tr>
<th>Entry</th>
<th>Amine</th>
<th>Alcohol, eq</th>
<th>Temperature, °C</th>
<th>Yield, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Benzylamine</td>
<td>Hexan-1-ol, 2 eq</td>
<td>120</td>
<td>99(96)</td>
</tr>
<tr>
<td>2</td>
<td>Benzylamine</td>
<td>Butan-1-ol, 2 eq</td>
<td>120</td>
<td>99(95)</td>
</tr>
<tr>
<td>3</td>
<td>Hexylamine</td>
<td>Benzyl alcohol, 2 eq</td>
<td>120</td>
<td>95(93)</td>
</tr>
<tr>
<td>4</td>
<td>Hexylamine</td>
<td>Butan-1-ol, 2 eq</td>
<td>120</td>
<td>98(91)</td>
</tr>
<tr>
<td>5</td>
<td>Butylamine</td>
<td>Hexan-1-ol, 2 eq</td>
<td>120</td>
<td>99(92)</td>
</tr>
<tr>
<td>6</td>
<td>Aniline</td>
<td>Hexan-1-ol, 3 eq</td>
<td>120</td>
<td>66</td>
</tr>
<tr>
<td>7</td>
<td>Morpholine</td>
<td>Hexan-1-ol, 2 eq</td>
<td>120</td>
<td>-</td>
</tr>
</tbody>
</table>

*a Reaction conditions: 1 mol% III-20/20’, 5 mol% KOtBu, in 1 ml tert-amyl alcohol. Conversions after 24 hours were determined by 1H NMR spectroscopy. Isolated yields of corresponding ammonium salts are in parentheses.

Unsymmetrical aliphatic secondary amines can be produced with high efficiency as well (Table 10, entries 4 and 5). Surprisingly, significantly lower efficiency was observed in case of aniline, although aromatic amines have been considered more active towards
alkylation. Only 66% conversion of aniline to \( N \)-hexylaniline was achieved after 24 hours at \( 120^\circ C \) even in the presence of 3 equivalents of alkylating agent (Table 10, entry 6). Secondary amine morpholine found to be totally inactive under proposed conditions (Table 10, entry 7).

Substituted anilines can be alkylated under the proposed condition with moderate yield, even if 3 equivalents of alcohol are used (Scheme 43). However, one can observe a little higher yields for substrates with electron-donating groups (III-46d and III-46e).

**Scheme 43.** \( N \)-alkylation of anilines in the presence of III-20/20'. Reaction conditions: 1 mol% III-20/20', 5 mol% KOtBu, 3 eq hexan-1-ol in 1 ml tert-amyl alcohol.

Conversions after 24 hours were determined by \( ^1H \) NMR spectroscopy by relative integration of corresponding signals of substrate and product. Isolated yields of corresponding ammonium salts are in parentheses.

It was also determined that the initial reaction rate is linearly dependant on the electronic properties of the \( para \)-substituents in aniline (Figure 7). The slope of the plot, which describes the relative reaction constant, is less than one, and thus the process is not much sensitive to the electronic properties of the substrates. However, a tendency of rate acceleration for the substrates bearing electron withdrawing substituents can be observed,
while the presence of electron donating groups results in rate suppression. The positive slope of the Hammett plot implies that a negative charge develops at the reaction centre in the rate determining step.\textsuperscript{565} The above described dependence, as well as observation of imine signals in \textsuperscript{1}H NMR spectrum during the reactions led to the conclusion that hydrogenation of imines should involve the rate determining step (Scheme 44), in particular hydrogen transfer from ruthenium-hydride species to imine, considering the positive slope of the Hammett plot.

\textbf{Figure 7.} The Hammett plot for the N-alkylation of anilines with different substituents in the para position of the benzene ring relative to the reaction with unsubstituted aniline.
Scheme 4. Proposed mechanism of amine alkylation in the presence of III-20/20'.

The process was confirmed to proceed via dehydrogenation-hydrogenation sequence according to hydrogen borrowing methodology (Scheme 44) by following experiments. Benzylamine was shown to react with benzaldehyde in 2-propanol even in the absence of ruthenium catalyst and/or base (Scheme 45). Full conversion to N-(benzylidene)benzylamine was reached after 1 hour of heating at 80°C. Subsequent addition of III-20/20' and KOtBu yielded 78% conversion to dibenzylamine in 24 hours, while 2-propanol was used as a hydrogen source.

Scheme 45. One-pot synthesis of dibenzylamine by the coupling of benzylamine and benzaldehyde and subsequent hydrogenation of N-(benzylidene)benzylamine.
III. 2. 2. Amination of alcohols with ammonium formate

Alcohols are readily available substrates for the synthesis of amines using simple ammonia sources, such as ammonia gas or aqueous ammonia. In our further study we wanted to optimize reaction conditions so that it would not require pressurized ammonia gas, and thus, could be performed using general laboratory equipment. The most obvious solution is to use aqueous ammonia, however complexes III-20/20' have very low solubility in water and would require degassed solution, as an active species formed in situ is very sensitive to oxygen. Further the reaction was performed with 0.5 M solution of ammonia in dioxane, where ethanol was in 10-fold excess in respect to ammonia content. After 24 hours of heating at 100°C 25% conversion to diethylamine was observed (Table 11, entry 1).

Table 11. Alcohol amination via borrowing hydrogen methodology. \(^a\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Aminating agent</th>
<th>Alcohol</th>
<th>Temperature, °C</th>
<th>Yield, %(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NH(_3) (0.5 M in dioxane)</td>
<td>Ethanol</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>2</td>
<td>NH(_3) (0.5 M in dioxane)</td>
<td>Benzyl alcohol</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>NH(_3) (0.5 M in dioxane)</td>
<td>Hexan-1-ol</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>NH(_4)COOH</td>
<td>Ethanol</td>
<td>100</td>
<td>97 (81)</td>
</tr>
<tr>
<td>5</td>
<td>NH(_4)COOCH(_3)</td>
<td>Ethanol</td>
<td>100</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^a\)Reaction conditions: 1.58 mmol ammonia equivalent, 2 mol% III-20/20', 5 mol% KOtBu, in 1 mL of corresponding alcohol. Conversions after 24 hours were determined by \(^1\)H NMR spectroscopy. Isolated yields of corresponding ammonium salts are in parentheses.

However, neither hexan-1-ol nor benzyl alcohol gave any products of amination (Table 11, entry 2 and 3). Then ammonium formate was tested as a nitrogen source for this
type of transformation. High results were observed for ethanol with the formation of diethylamine as a major product and traces of triethylamine after 24 hours of heating at 100°C (Table 11, entry 4). Tertiary amine can be produced after prolonged heating. Ammonium acetate when used as a nitrogen source gives only ethyl acetate as a product (Table 11, entry 5).

Next, a number of primary alcohols were screened under the optimized conditions (Scheme 46). Butan-1-ol III-48a and hexan-1-ol III-48b were transformed to corresponding secondary amines after 24 hours at 100°C. Tertiary amines were obtained when the reaction was heated for 72 hours. Benzyl alcohol III-48c also gave secondary amine, albeit 120°C was required to obtain high conversion in 24 hours. Tribenzylamine cannot be produced under these conditions even with prolonged heating. 2-Propanol III-48d was converted to secondary amine with a significantly lower conversion (45%) under the same catalytic conditions.

\[
\begin{align*}
\text{III-48a-e} & \quad \overset{2 \text{ mol} \% \text{III-20/20'}, 10 \text{ mol} \% \text{KOrBu}}{\longrightarrow} \quad \text{HCOONH}_4, 100^\circ \text{C} \quad (\text{in corresponding alcohol}) \quad \text{III-49a-e} \quad \text{or} \quad \text{III-50a-e}
\end{align*}
\]

\[
\begin{align*}
\text{III-49a} & \quad 97(81)\% \quad \text{(after 24 h)} \\
\text{III-49b} & \quad 93(89)\% \quad \text{(after 24 h)} \\
\text{III-50a} & \quad 99(91)\% \quad \text{(after 24 h)} \\
\text{III-49c} & \quad 96(90)\% \quad \text{(after 24 h)} \\
\text{III-50b} & \quad 98(95)\% \quad \text{(after 72 h)} \\
\text{III-49d} & \quad 99(94)\% \quad \text{(after 24 h)} \\
\text{III-49e} & \quad 45(41)\% \quad \text{(after 24 h)} \\
\end{align*}
\]

**Scheme 46.** Amination of alcohols with ammonium formate. Reaction conditions: 100 mg HCOONH\(_4\), 2 mol% III-20/20’, 10 mol% KOrBu in 1 mL of corresponding alcohol at 100°C. Conversions were determined by \(^1\)H NMR spectroscopy. Isolated yields are shown in parentheses.
The mechanism of alcohol amination under the proposed catalytic conditions turned out to be not so straightforward as it was expected. Initially, ammonia was suggested to release to the reaction by decomposition of ammonium formate, and it was supposed to be alkylated according to general hydrogen borrowing mechanism. However, reaction monitoring with $^1$H NMR spectroscopy revealed fast consumption (within 2 hours) of formate signal and simultaneous formation of free hydrogen gas and an intermediate with alkoxide signal shifted to a weaker field in respect to alcohol signal. Further heating led to the conversion of the intermediate into the secondary amine. Comparison to the standards showed that the intermediate compound is neither alkyl carbamate III-51 nor dialkyl carbonate III-52 (Scheme 47). However, proton and carbon signals of alkoxide group ($^1$H NMR $\delta = 3.83$ ppm and $^{13}$C NMR $\delta = 60.8$ ppm) have very close values to the later compound, hence the best suggestion is ammonium alkyl carbonate III-53.

![Scheme 47. Formation of intermediate product under the conditions of alcohol amination.](image)

The intermediate product is very unstable, and all attempts of isolation failed. Moreover, alkoxy group undergoes fast exchange even at room temperature when the volatiles are removed under reduced pressure and different alcohol is added. A control experiment with sodium formate resulted in formation of the same compound. III-53 does not form without ruthenium complex III-20/20' and KOtBu (Scheme 48a). Furthermore, hydrogen gas is produced via alcohol coupling with formate and not by the dehydrogenation
of alcohol, as no reaction can be observed between aldehyde and ammonium formate with or without catalyst III-20/20’ (Scheme 48b).

\[
\begin{align*}
\text{a)} & \quad \text{OH} + \text{NH}_4^+ \cdot \text{HOOH} \quad \text{100°C, 2 h} \quad \text{ethanol} \quad \rightarrow \quad \text{no reaction} \\
\text{b)} & \quad \text{O} + \text{NH}_4^+ \cdot \text{HOOH} \quad \text{2 mol\% III-20/20’} \quad \text{100°C, 2 h} \quad \text{toluene} \quad \rightarrow \quad \text{no reaction}
\end{align*}
\]

Scheme 48. a) No reaction is observed in the absence of catalyst; b) No reaction occurs between aldehyde and ammonium formate under the proposed catalytic conditions.

Although the intermediate product is consumed during the reaction and no other by-products is produced, it is not clear whether the amination occurs on free alcohol. Alternatively the reaction may proceed via the primary or secondary amination of alkoxide group of carbonate intermediate III-53 (Scheme 49). In this case carbonate group can act as an efficient leaving group.

\[
\begin{align*}
\text{NH}_4^+ \cdot \text{HOOH} \quad \rightarrow \quad \text{NH}_2 \quad \rightarrow \quad \text{OH} \quad \rightarrow \quad \text{N} \\
\text{III-53} \\
\text{NH}_2 \quad \rightarrow \quad \text{N} \\
\text{NH}_2 \quad \rightarrow \quad \text{N}
\end{align*}
\]

Scheme 49. Alternative route of alcohol amination under the proposed catalytic conditions.
III. 3. Transition Metal-Free Transfer Hydrogenation

III. 3. 1. Hydrogen transfer in the presence of alkali metal bases

Transition metal-free transfer hydrogenation with alkali metal bases is an attractive strategy, even though it generally requires relatively high loads of bases. As it was shown above, the procedures based on sodium and potassium containing bases has been developed so far, while lithium containing bases show significantly lower catalytic activity. This feature of lithium cation was puzzling, as being the strongest Lewis acid among alkali metals, it should have provided the highest reactivity in transfer hydrogenation. The following study is aimed at investigation of the phenomenon of low reactivity of lithium bases and the ways of its improvement.

First the relative activity of Li⁺, Na⁺, and K⁺ in transfer hydrogenation of ketones was evaluated. Corresponding isopropoxides were prepared and applied in the reaction of transfer hydrogenation of acetophenone with 10% MOiPr. Transfer hydrogenation of acetophenone with 2-propanol catalyzed by 10 mol% MOiPr was chosen as a model system. The kinetic profiles, presented in Figure 8, show that the efficiency increases in the order Li⁺ < K⁺ < Na⁺, which largely agrees with the catalytic activity documented for other alkali metal bases. Since transfer hydrogenation is an equilibrium process, the maximum conversion of about 90% is achieved for NaOiPr after about 8 h, whereas for KOiPr the curve is much less steep but gives the highest conversion of 54% (80% after 20 h). In contrast, a very different behaviour was observed for LiOiPr. The initial reaction is very fast, reaching 60% after 2 h vs 47% for NaOiPr, but then the reduction slows down and shows a saturation behaviour at about 68% conversion. These data clearly indicate that the lithium
cation is intrinsically more active than its heavier congeners but is also passivated by the product of this reaction, 1-phenylethanol.

![Figure 8](image.png)

**Figure 8.** Kinetic profiles for transfer hydrogenation of acetophenone in 2-propanol catalyzed by LiO\textsubscript{i}Pr, NaO\textsubscript{i}Pr, and KO\textsubscript{i}Pr.

To test this hypothesis, experiments were repeated with a substrate that is more resembling the HO\textsubscript{i}Pr/acetone redox pair in term of electronic properties, that is cyclohexanone. Kinetic profiles shown in Figure 9 conclusively prove that Li\textsuperscript{+} is the most active, reaching 94% conversion after only 2 hours. The activity now decreases in the order Li\textsuperscript{+} >> Na\textsuperscript{+} > K\textsuperscript{+}, consistent with the decreasing Lewis acidity of the alkali cation. The observation that cyclohexanone is more active than acetophenone is quite remarkable and counterintuitive, given the fact that dialkyl-substituted ketones have the highest reduction potential.
Figure 9. Kinetic profiles for transfer hydrogenation of cyclohexanone in 2-propanol catalyzed by LiOiPr, NaOiPr, and KOiPr.

The important conclusion from these two sets of experiments is that the catalytic activity may depend not only on the substrate and reductant but also on compounds being added to the mixture or formed during the reaction. This idea prompted the investigation of the ligand effect on alkali metal catalyzed transfer hydrogenation. Reduction of acetophenone in 2-propanol was again chosen as the model system. The efficiency of additives was gauged by the time required to reach the equilibrium. Gratifyingly, addition of simple chelating diamines, such as ethylenediamine and TMEDA, significantly improves the conversion after 12 hours (Table 12, entries 2 and 3 vs entry 1). Both a chelating diether, such as DME, and even a monoligating ether, 1,4-dimethoxybenzene, are more effective, as the equilibrium is reached in a much shorter time, 8h (Table 12, entries 4 and 5). Unexpectedly, soft donors, such as the chelating diphosphine dppe (Table 12, entry 6) and
monoligating phosphines (Table 12, entries 7 and 8) turned out to be even stronger promoters, whereas the N-heterocyclic carbene IMes (Table 12, entry 9) was just a bit weaker. The highest conversion in the shortest time was achieved for the chelating DalPhos ligand that features both hard amino and soft phosphine sites (Table 12, entry 10).

**Table 12.** Transfer hydrogenation of acetophenone with 10 mol% LiOiPr in the presence of various ligands (10 mol%).

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand</th>
<th>Time, h</th>
<th>Conversion(^b), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-</td>
<td>12</td>
<td>64</td>
</tr>
<tr>
<td>2</td>
<td>Ethylenediamine</td>
<td>12</td>
<td>83</td>
</tr>
<tr>
<td>3</td>
<td>TMEDA</td>
<td>12</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>DME</td>
<td>8</td>
<td>83</td>
</tr>
<tr>
<td>5</td>
<td>1,4-dimethoxybenzene</td>
<td>8</td>
<td>84</td>
</tr>
<tr>
<td>6</td>
<td>dppe</td>
<td>7</td>
<td>86</td>
</tr>
<tr>
<td>7</td>
<td>PPh(_3)</td>
<td>7</td>
<td>84</td>
</tr>
<tr>
<td>8</td>
<td>PEt(_3)</td>
<td>7</td>
<td>85</td>
</tr>
<tr>
<td>9</td>
<td>IMes</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>10</td>
<td>DalPhos</td>
<td>4</td>
<td>86</td>
</tr>
<tr>
<td>11</td>
<td>12-Crown-4 (10%)</td>
<td>10</td>
<td>84</td>
</tr>
<tr>
<td>12</td>
<td>12-Crown-4 (20%)</td>
<td>12</td>
<td>51</td>
</tr>
</tbody>
</table>

\(^a\) Reaction conditions: acetophenone (50 µL), LiOiPr (2.8 mg), ligand (0.043 mmol), and 2-propanol (1.5 ml), 100°C; \(^b\) reaction progress was monitored by 1H NMR spectroscopy by relative integration of corresponding signals of a substrate and a product.
Interestingly, using an equimolar amount (10%) of 12-crown-4 still has a beneficial effect on catalysis (Table 12, entry 11) and, in fact, this cyclic polyether is more effective that diamines (Table 12, entries 2 and 3) because the equilibrium is reached in a shorter time. However, using two equivalents of this crown ether per lithium results in sequestering the cation, likely in the form of a sandwich, and partial inhibition of catalysis (Table 12, entry 12).

Encouraged by the discovery of the ligand effect, we became interested in investigating the possibility of enantioselective reduction on alkali metal centres. Several chiral ligands have been tried and the results are garnered in Table 13. Unfortunately, in neither case was any asymmetric induction obtained as evinced by the Feringa’s chiral test. For example, (-)-sparteine, a naturally occurring alkaloid that is a common chiral inducer for asymmetric lithiation reactions, failed to bring about any asymmetric induction in this transfer hydrogenation (Table 13, entry 1).

**Table 13.** The effect of chiral ligands (10 mol%) on transfer hydrogenation of acetophenone catalyzed by 10 mol% LiOiPr.

<table>
<thead>
<tr>
<th>Entry</th>
<th>Ligand</th>
<th>Time, h</th>
<th>Conversion(^b), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-)-sparteine</td>
<td>7h</td>
<td>86(^c)</td>
</tr>
<tr>
<td>2</td>
<td>PyBox</td>
<td>4h</td>
<td>85(^c)</td>
</tr>
<tr>
<td>3</td>
<td>(S)-DTBM-SEGPHOS</td>
<td>8h</td>
<td>85(^c)</td>
</tr>
<tr>
<td>4</td>
<td>(S)-BINAP</td>
<td>10h</td>
<td>85(^c)</td>
</tr>
<tr>
<td>5</td>
<td>(S)-BINOL</td>
<td>12h</td>
<td>NR</td>
</tr>
</tbody>
</table>

\(^a\)Reaction conditions: acetophenone (50 µL), LiOiPr (2.8 mg), ligand (0.043 mmol), and 2-propanol (1.5 ml), 100°C; \(^b\) reaction progress was monitored by 1H NMR spectroscopy by relative integration of corresponding signals of a substrate and a product; \(^c\) no asymmetric induction.
In terms of efficiency, chelating nitrogen-based ligands, (-)-sparteine and PyBox, performed the best, reaching equilibrium in 7 and 4 hours (Table 13, entries 1 and 2), respectively. No reaction took place in the case of a chelating diphenol ligand, such as BINOL (Table 13, entry 5), likely because of the higher acidity of phenol comparing to aliphatic alcohols and increased stability of its dianionic form. This factors significantly decrease the concentration of the reactive isopropoxide in solution.

To elucidate whether the lack of enantioselectivity was due to fast racemization of the chiral product, racemization of (R)-1-phenylethanol with 10 mol% LiO\textsubscript{i}Pr as catalyst and 10 mol% of acetophenone as hydrogen acceptor was studied (Scheme 50). Very slow decrease of chirality from 98% ee to 77% ee after 24 hours was observed. This observation further substantiates the point that the transfer hydrogenation at lithium centre is impeded by 1-phenylethanol.

Scheme 50. Racemization of (R)-1-phenylethanol in the presence of 10 mol% LiO\textsubscript{i}Pr.

To demonstrate the synthetic utility of this catalytic system, reduction of a few substrates was screened with and without 10 mol% dppe (Scheme 51). Acetophenone III-\textsuperscript{54}a, p-chloroacetophenone III-\textsuperscript{54}b, p-acetylbenzonitrile III-\textsuperscript{54}c, and benzophenone III-\textsuperscript{54}e were reduced much faster in the presence of phosphine, whereas the ligand addition had no effect on the reduction of aliphatic ketones, cyclohexanone III-\textsuperscript{54}f and methyl tert-butyl ketone III-\textsuperscript{54}g. Surprisingly, transfer hydrogenation of p-methoxyacetophenone III-\textsuperscript{54}d was also insensitive to the addition of dppe.
Scheme 51. Ligand-assisted transfer hydrogenation of ketones. Conversions were determined by $^1$H NMR spectroscopy by relative integration of corresponding signals of a substrate and a product, isolated yields of selected products are shown in brackets. $^a$ No ligand was added.

III. 3. 2. Effect of additives

We were intrigued by the fact that quite a vast diversity of ligands containing oxygen, amine, phosphine, and aromatics serving as binding sites could significantly enhance the catalytic activity of LiOiPr. We thus decided to investigate further the effect of different additives, to understand whether the mere presence of a simple functional group, such as aromatic ring or oxygen atom, can have a beneficial effect on catalysis.

Remarkably, addition of benzene and methyl substituted benzenes also resulted in the enhancement of catalytic activity of LiOiPr. Thus, the presence of 0.5 equivalents (relatively to the substrate) of benzene, toluene, mesitylene, or hexamethylbenzene allowed the reaction to reach 81-83% conversion in 10 h (Table 14, entries 1-4), as compared to the
maximum 68% conversion observed in the absence of these additives (Table 14, entry 11). A similar enhancement effect was found upon addition of THF (Table 14, entry 5).

**Table 14.** Transfer hydrogenation of acetophenone with LiO\textsubscript{i}Pr in the presence of various additives.\textsuperscript{a}

<table>
<thead>
<tr>
<th>Entry</th>
<th>Additive</th>
<th>Load, eq.\textsuperscript{b}</th>
<th>Time, h</th>
<th>Conversion\textsuperscript{c}, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Benzene</td>
<td>0.5</td>
<td>10</td>
<td>83</td>
</tr>
<tr>
<td>2</td>
<td>Toluene</td>
<td>0.5</td>
<td>10</td>
<td>82</td>
</tr>
<tr>
<td>3</td>
<td>Mesitylene</td>
<td>0.5</td>
<td>10</td>
<td>81</td>
</tr>
<tr>
<td>4</td>
<td>Hexamethylbenzene</td>
<td>0.5</td>
<td>10</td>
<td>82</td>
</tr>
<tr>
<td>5</td>
<td>THF</td>
<td>0.5</td>
<td>10</td>
<td>82</td>
</tr>
<tr>
<td>6</td>
<td>Toluene</td>
<td>0.05</td>
<td>10</td>
<td>70</td>
</tr>
<tr>
<td>7</td>
<td>Toluene</td>
<td>0.1</td>
<td>10</td>
<td>81</td>
</tr>
<tr>
<td>8</td>
<td>Toluene</td>
<td>1</td>
<td>10</td>
<td>74</td>
</tr>
<tr>
<td>9</td>
<td>Toluene</td>
<td>3</td>
<td>10</td>
<td>72</td>
</tr>
<tr>
<td>10</td>
<td>Toluene</td>
<td>15</td>
<td>10</td>
<td>39</td>
</tr>
<tr>
<td>11</td>
<td>No additives</td>
<td>-</td>
<td>10</td>
<td>68</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Reaction conditions: acetophenone (50 µL), LiO\textsubscript{i}Pr (2.8 mg), and 2-propanol (1.5 ml), 100°C; \textsuperscript{b} relatively to the substrate; \textsuperscript{c} conversions were determined by \textsuperscript{1}H NMR analysis by relative integration of corresponding signals of a substrate and a product.

The dependence of the catalytic activity on toluene load was studied then (Table 14, entries, 2, 6-10). Thus, increasing the toluene amount up to 0.5 equivalent led to a steady advancement of the reaction to 82% conversion in 10 hours (Table 14, entry 2). However, addition of a larger amount of toluene (1 - 15 eq., entries 8-10) decreased the conversion down to 39% with a 15-fold excess of toluene after 10 hours (Table 14, entry 10). Even more
surprisingly, addition of toluene to the sodium or potassium cations catalyzed transfer hydrogenation had zero effect on the reaction rate, underlying the unique role of lithium in this catalysis.

III. 3. 3. Mechanistic studies

The mechanism of alkali metal catalysis is of interest. Foremost, checking whether a strong, metal-free base alone can mediate catalytic reduction needed to be investigated. Phosphorus ylides can subtract proton from alcohols to form an innocent phosphonium cation and alkoxide anion. Thus, catalytic amounts (10 mol%) of methylene(triphenyl)phosphorane (CH$_2$=PPh$_3$) and phenylmethylene(triphenyl)-phosphorane (PhCH=PPh$_3$) were added to the solution of acetophenone in 2-propanol, which was then heated at 100°C for 10 hours, but did not produce even traces of the product. However, addition of 10 mol% LiCl to a mixture of 10% Ph$_3$P=CH$_2$ and acetophenone in 2-propanol results in 68% conversion after reflux for 8 hours. Carrying out the reaction in the presence of catalytic LiOiPr (10 mol%) under or without hydrogen atmosphere (1 atm) showed the same activity.

The above data clearly show that alkali metal cations play the key role in the catalytic transfer hydrogenation and that ligands and additives can have significant impact on their performance, which is particularly noticeable in the case of lithium. For the traditional MPV reactions, three mechanistic pathways were considered: the hydridic route based on formation of a metal-hydride, a radical route, and a direct H-transfer from alkoxide to carbonyl via a six-membered transition state (most common).$^{290, 368, 369}$ For the alkali metal catalyzed reaction, the hydridic route can be reliably ruled out as the formation of a MH
species in alcohol solution is highly unlikely and because added hydrogen, the likely product of a reaction between the transient MH and isopropanol, had no impact on catalysis.

To get a further insight into the mechanism of catalytic action, kinetic studies under pseudo-first order conditions were performed by using large excess of 2-propanol (10-25 equivalents). Cyclohexanone was chosen as the model substrate because its transfer hydrogenation can be considered as a virtually irreversible process at the start of the reaction (before 20% conversion was reached). In all cases, rate measurements showed first order kinetics in the substrate. The dependence of the reaction rate on the catalyst was established by studying the variation of LiOiPr load from 2 to 10 mol% in 1 ml of 2-propanol. A linear plot of the effective reaction rate vs the amount of base was obtained (Figure 10), which shows that the reaction is also first order in the alkali metal catalyst. Further variation of the amount of 2-propanol at a fixed LiOiPr load (4 mol %) (Figure 11), established that the reaction is also first order in the reducing agent, and can be expressed with the following kinetic law:

\[
\text{rate} = k[\text{catalyst}][\text{ketone}][\text{alcohol}]
\]

(2).
Figure 10. $k_{obs}$ of transfer hydrogenation of cyclohexanone with various concentrations of LiO\textsubscript{i}Pr. Fitted function of cyclohexanone consumption in each reaction: $f(t)=I_0*\exp(-k_{obs}t)$ – first order.

Figure 11. $k_{obs}$ of transfer hydrogenation of cyclohexanone with various amounts of 2-propanol. Fitted function of cyclohexanone consumption: $f(t)=I_0*\exp(-k_{obs})$ – first order.
The effect of temperature was studied then. The measurements were taken between 70°C and 90°C (Figure 12). By using Van't Hoff equation (3), the temperature coefficient was found to be 2.7.

\[ r_2 = r_1 Q_{10}^{\frac{T_2 - T_1}{10}} \]  (3).

![Figure 12](image)

**Figure 12.** \( k_{obs} \) of transfer hydrogenation of cyclohexanone at temperatures between 70 and 90°C.

Linearization of the data in Arrhenius and Eyring coordinates (Figure 13 and 14), based on equations 4 and 5, respectively, allowed for the activation energy, enthalpy, and entropy be determined (Table 15). The relatively low enthalpy of activation and negative entropy of activation point to an organized transition state, which is consistent with a six-membered transition state commonly accepted for the aluminum-catalyzed MPV reaction.\(^{247}\)

\[ k = A e^{-\frac{E_a}{RT}} \]  (4);

\[ k = \frac{k_b T}{h} e^{-\frac{\Delta G^*}{RT}} \]  (5).
Figure 13. Linearization of data in Arrhenius coordinates: \( \ln(k_{\text{obs}}) \) vs \( T^{-1} \).

\[
y = -12394x + 25.965 \\
R^2 = 0.9999
\]

Figure 14. Linearization of data in Eyring coordinates \( \ln(k_{\text{obs}}T^{-1}) \) vs \( T^{-1} \).

\[
y = -12041x + 15.005 \\
R^2 = 0.9999
\]
Then the possibility of a radical mechanism was investigated by studying transfer hydrogenation of cyclopropyl phenyl ketone, employing the cyclopropyl group as a radical probe (a “radical clock”). Although earlier studies by von Doering and Aschner ruled out a radical mechanism, some later works supported the possibility of one electron transfer to substrates prone to stabilize radicals. Thus, the ketyl radical were detected in the MPV reduction of benzophenone. Cyclopropyl phenyl ketone would give different products, depending on the mechanism of the reduction process. When an MVP-like transfer of hydrogens occurs, only the C=O bond undergoes transformation to the hydroxyl functionality (Scheme 52a). But if a radical is generated during the reaction, it can cause intermolecular isomerization, which would be triggered by the steric tension of the cyclopropyl ring (Scheme 52b). In the reduction of cyclopropyl phenyl ketone under the catalytic conditions, solely cyclopropyl(phenyl)methanol was observed, which agrees well with the cyclic MPV mechanism, however, does not rule out the radical mechanism. If the radical quenching proceeds faster than isomerization, the result will be the same as in case hydride mechanism.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_a$</td>
<td>103.0 kJ mol$^{-1}$</td>
<td>0.5 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>$A$</td>
<td>26.0 sec$^{-1}$</td>
<td>1.2 sec$^{-1}$</td>
</tr>
<tr>
<td>$\Delta H^\ne$</td>
<td>100.1 kJ mol$^{-1}$</td>
<td>0.6 kJ mol$^{-1}$</td>
</tr>
<tr>
<td>$\Delta S^\ne$</td>
<td>-38.743 J mol$^{-1}$</td>
<td>1.600 J mol$^{-1}$K$^{-1}$</td>
</tr>
</tbody>
</table>

$^a$ Reaction conditions: cyclohexanone (0.250 mmol), LiO\text{ipr} (0.025 mmol), and 2-propanol (1.5 mL), 70-90°C
Scheme 52. a) Hydride mechanism and b) single electron mechanism for lithium-catalyzed transfer hydrogenation of cyclopropyl phenyl ketone.

Further insight into the mechanism of transfer hydrogenation of benzophenone was provided by kinetic isotope effect measurements carried out in 2-propanol with 10 mol% LiOiPr and 10% TMEDA (Table 16). Benzophenone, a non-enolizable ketone, was chosen as a substrate to avoid any side effects, which can be caused by enolization.

Table 16. Determination of kinetic isotope effect. $^a$

<table>
<thead>
<tr>
<th>Entry</th>
<th>Solvent</th>
<th>K, min$^{-1}$</th>
<th>KIE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(CH$_3$)$_2$-CH-OH</td>
<td>0.01713</td>
<td>—</td>
</tr>
<tr>
<td>2</td>
<td>(CH$_3$)$_2$-CH-OD</td>
<td>0.01529</td>
<td>1.1</td>
</tr>
<tr>
<td>3</td>
<td>(CD$_3$)$_2$-CD-OD</td>
<td>0.00475</td>
<td>3.6</td>
</tr>
</tbody>
</table>

$^{a}$ Reaction conditions: 10 mol% LiOiPr, 10 mol% TMEDA in 1.5 ml of 2-propanol at 80°C.

Comparison of rates obtained in (CH$_3$)$_2$CH-OH and (CH$_3$)$_2$CH-OD gave a small KIE of 1.1, indicating that proton transfer is not involved in the rate determining step. On the other hand, a significant KIE of 3.6 was obtained for the reaction carried out in the fully...
deuterated isopropanol (CD$_3$)$_2$CD-OD, which is consistent with the C-D bond cleavage in the rate determining step. This result corroborates further the suggestion that reaction proceeds via direct hydrogen transfer from the alkoxide to carbonyl.

When the reaction rates for acetophenones with different substituents are examined, a clear dependence on the electronic properties of the substrate can be observed. Thus, the reaction accelerates, when electron-withdrawing substituents in the para position are present in the benzene ring (Figure 15). This means that a negative charge is developed on the carbonyl during the rate determining step, which is more effectively stabilized with an electron-withdrawing, rather than electron-donating group.

![Hammett plot](image)

**Figure 15.** The Hammett plot for the transfer hydrogenation of acetophenones with different substituents in the para position of the benzene ring relative to the reaction with unsubstituted acetophenone.

Taken together, these kinetic data underpin the Woodward’s proposal$^{287}$ that alkali base-catalyzed transfer hydrogenation proceeds via a six-membered cyclic transition state
(Scheme 53) similar to the conventional mechanism of Meerwein–Ponndorf–Verley reduction mediated by aluminium alkoxides.

**Scheme 53.** Proposed mechanism for transfer hydrogenation of ketones with LiOiPr.

III. 3. 4. Discussion of the results

The understanding of alkali metal catalyzed reduction is very important in the context of development of more benign and sustainable synthetic processes that would circumvent the use of toxic and expensive transition metals and minimize the production of waste. The latter aspect is of great concern in the traditional aluminium-based MPV catalysis which usually requires stoichiometric amounts of aluminium alkoxide or alkyl reagents.\textsuperscript{290, 368, 369} So far, the use of alkali metals in the MPV reactions has been very limited because of the low activity and the need of using increased amounts of the catalyst.\textsuperscript{290} The research described above shows that this problem can be mitigated by the application of ligands and promoters.

Before discussing the alkali metal catalysis, one question should be addressed: is it possible that catalysis is triggered by traces of transition metals? The detailed study by Ouali
et al. shows that transition metals are not responsible for the observed base catalysis and, in fact, their addition has a detrimental effect. This finding may help to explain why large excess of alkali base is required in some “transition metal catalyzed” transfer hydrogenations.

The main puzzle of the alkali metal-catalyzed MPV reduction is that the reactivity order in the transfer hydrogenation of acetophenone, the most common model substrate for transfer hydrogenation, is Na⁺ > K⁺ > Li⁺. This order is counterintuitive because MPV requires the presence of a strong Lewis acid to polarize and activate the C=O, whereas the order of Lewis acidity of alkali metal is Li⁺ > Na⁺ > K⁺. Ouali et al. explained this reactivity order by the need to balance the substrate activation step with the rate of substrate decoordination, which requires a weaker Lewis acid, so that the maximum activity is observed with sodium. However, the ligand exchange for alkali metal ions is known to be very fast. The lack of reactivity by the application of ylide H₂C=günPH₃ alone versus the productive catalysis in the case of combined action of ylide and LiCl illustrates the need of a Lewis acid. Furthermore, the change of the reactivity order to the expected Li⁺ > Na⁺ > K⁺ in the case of cyclohexanone shows conclusively that the reactivity is substrate-dependent and therefore should be caused by the presence of the aromatic ring in acetophenone.

A seemingly obvious explanation is that the change of reactivity is caused by specific interactions between the alkali ion and the aromatic ring. Indeed, alkali metal cation-π interactions are very well established, so that alkali ions can be solvated by aromatic molecules through interaction with π-electrons. However, Kochi et al. conclusively demonstrated that the strength of alkali metal/aromatic interactions increases down Group 1, with the sodium cation (the smallest studied) showing no sign of Na⁺…π-interactions.
Therefore, it is unlikely to play any major role in the lithium catalysis and if this effect were operating, the activity in transfer hydrogenation should have changed monotonously down the group.

Since Lewis acidity of the lithium cation is not a decisive factor in impeding the reduction of acetophenone, it may be caused by the different stabilization of the product, 1-phenylethanol, in the solution and in the complex. Because 1-phenylethanol is a relatively large molecule, it disrupts the hydrogen bonding network of the solvent (2-propanol). On the other hand, placing two or more molecules of 1-phenylethanol in the coordination sphere of a lithium ion may allow for additional stabilization through the $\pi-\pi$ stacking interactions or charge-transfer interactions between the aromatic rings in the intermediates III-56 and III-57.

Support to this idea is the observation that lithium-catalyzed reduction noticeably slows down at about 40% conversion, which corresponds to four molecules of the product per the alkali metal ion (at the 10% catalyst load). On the other hand, the stabilizing aromatic interactions ($\pi-\pi$ stacking) should be weakened in the case of sodium and potassium because their larger size places the aromatic groups of ligated 1-phenylethanol farther away. This stabilizing effect is absent in the case of cyclohexanone which is reduced quicker on the
lithium centre because of its high Lewis acidity and stronger activation of the carbonyl function.

The ligand effect in the case of acetophenone is then explained by a dual phenomenon. First, strong ligands, and in particular chelate ligands, can coordinate to lithium, thus preventing the accumulation of 1-phenylethanol in the coordination sphere of the cation. The enhanced activity of soft ligands, phosphine and carbene, versus hard nitrogen- and oxygen-based donors is likely caused by the same reason: the former type of ligands are stabilized to a lesser extent by the polar media than the latter and tend to bind the lithium cation better. Second, the need to stabilize the product, 1-phenylethanol, in solution is nicely illustrated by the effect of aromatic additives. Small amounts of toluene and other aromatics (and likely Ph-containing ligands) solvate 1-phenylethanol more effectively than 2-propanol likely by means of π-π interactions and help the product leave the coordination sphere of lithium, thus regenerating the catalytic unit.

Another way to break the proposed arene/arene π-interactions is to increase the temperature. This allows for the need of very high temperature (180 °C) in the lithium isopropoxide-catalyzed reduction of aromatic ketones reported by Adolfsson et al.292 At such temperatures, high conversions to targeted alcohols (86-96%) was achieved in 20-40 min.

To test further this hypothesis, the reduction of acetophenone was carried out in the presence of 10 mol% LiOiPr and a stoichiometric amount of LiCl. Fast reduction of benzophenone 46a was observed, reaching 79% conversion after only 2 hours versus 50% conversion in the absence of additional LiCl (the equilibrium value was accomplished within 3 hours), and maximum of 83% conversion was achieved after 5 hours. In total, the tendency for the acceleration of transfer hydrogenation of other aromatic substrates (Scheme 54) was
similar to the one with the addition of dppe. At the same time, no reaction rate improvement was observed for cyclohexanone. This experiment proves that sufficient amount of Lewis acid in the reaction system is another successful strategy, that helps in protecting the catalytic centre from being poisoned with the product of transfer hydrogenation, thus improving the reaction efficiency.

**Scheme 54.** Reaction conditions: 10 mol% LiOiPr, 1 eq. LiCl in 2-propanol (1.5 ml). Conversions were determined by ¹H NMR spectroscopy by relative integration of corresponding signals of a substrate and a product, isolated yields of selected products are shown in brackets. " No LiCl was added.
III. 4. Novel zinc complexes for transfer hydrosilylation of carbonyl compounds

III. 4. 1. Synthesis of zinc complex

The mutual affinity of zinc and sulfur is well-recognized not only in general chemistry and mineralogy, but also in biologic systems. Thus, the coordination mode of zinc in hundreds of enzymes was proven to include not only nitrogen and oxygen (of aminoacids), but also sulfur atoms, so that the Zn-S bond is as much frequently occurring phenomenon in the bioorganic world, as in inorganic.\textsuperscript{373} This fact prompted us to use the NNS-ligand III-10 in the synthesis of zinc catalysts.

Zinc chloride was the first choice as a precursor, however, it did not react with compound III-10 in THF, even when heated to 100°C, which can be attributed to poor solubility of zinc salts in organic solvents. Thus, ligand III-10 was preliminary deprotonated by MeLi, to create a driving force for the reaction with ZnCl\textsubscript{2} by LiCl elimination in THF at 60°C. However, the experiment resulted in a complex mixture of products, with no opportunity to isolate and/or identify any of the major products.

![III-58](image)

Therefore, dimethylzinc, a more active metal precursor, was then reacted with ligand III-10 in toluene. Complex III-58 and methane (as the only by-product) formed almost instantly at room temperature. III-58 is a colourless semi-liquid, therefore we failed to grow crystals suitable for X-Ray analysis. Nevertheless, the coordination of the NNS-ligand III-
10 can be certainly confirmed by $^1$H NMR spectroscopy. Only one NH signal can be observed in the NMR spectrum. The assignment of this signal to the proton of amine group was supported by $^1$H-$^1$H COSY NMR that showed correlation of this signal with the nearby methylene protons. This signal is significantly shifted upfield ($\delta = 1.18$-$1.92$ ppm), comparing to the NH-amine signal in complex III-58 ($\delta = 6.18$ ppm). Given the fact that the reaction is accompanied by gas evolution (likely methane), one can conclude that the pyrazolyl group was most likely deprotonated, resulting in pyrazolide. The pyrazolyl CH signal ($\delta = 6.13$ ppm), as well as the resonances for the methylene ($\delta = 3.09$ ppm) and ethylene bridging groups ($\delta = 2.14$ and 2.31 ppm), were also shifted to a stronger field relative to the free ligand. The zinc-bond methyl group gives rise to a high-field $^1$H NMR signal at $\delta = -0.03$ ppm. Furthermore, an NOE experiment showed a through space interaction between the methyl group and the protons of amine, methylene, ethylene, and phenyl units, which supports the tridentate coordination mode of the deprotonated NNS ligand.

III. 4. 2. Hydrosilylation of carbonyl compounds

Considering the fact, that complex 27 is a semiliquid, it was decided to generate it in situ from the stock solutions of ZnMe$_2$ and ligand III-10, for further applications in catalysis. Formation of III-58 was confirmed by $^1$H NMR spectroscopy, after that a substrate and a hydrosilane were added. For the optimization of catalytic conditions acetophenone was chosen as a model substrate, and different hydrosilanes, containing alkyl, aryl, and/or alkoxy groups, were investigated for their reducing ability (Table 17). Triethoxysilane was found to have the best activity, providing full conversion of the substrate within 10 hours at room
temperature and in 1.5 hours when heated at 60°C (Table 17, entries 5 and 7, respectively).

To confirm the positive effect of III-10, the reaction was performed under the same conditions as in entry 5, but in the absence of the ligand, which resulted in a very low yield of the hydrosilylation product (Table 17, entry 6).

**Table 17.** Hydrosilylation of acetophenone with III-58 formed *in situ.*

<table>
<thead>
<tr>
<th>Entry</th>
<th>Hydrosilane</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Conversion(b), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PhMe(_2)SiH</td>
<td>RT</td>
<td>22 h</td>
<td>NR</td>
</tr>
<tr>
<td>2</td>
<td>PhMeSiH(_2)</td>
<td>RT</td>
<td>3 d</td>
<td>60</td>
</tr>
<tr>
<td>3</td>
<td>PMHS</td>
<td>RT</td>
<td>3 d</td>
<td>9</td>
</tr>
<tr>
<td>4</td>
<td>(EtO)(_2)MeSiH</td>
<td>RT</td>
<td>5 d</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>(EtO)(_3)SiH</td>
<td>RT</td>
<td>10 h</td>
<td>100</td>
</tr>
<tr>
<td>6(^c)</td>
<td>(EtO)(_3)SiH</td>
<td>RT</td>
<td>22 h</td>
<td>12</td>
</tr>
<tr>
<td>7</td>
<td>(EtO)(_3)SiH</td>
<td>60</td>
<td>1.5 h</td>
<td>97</td>
</tr>
</tbody>
</table>

\(\text{a}\) Reaction conditions: acetophenone (50 μL, 0.429 mmol), ZnMe\(_2\) (5 mol%, 0.022 mmol), ligand III-10 (5 mol%, 0.022 mmol), hydrosilane (2 eq.) in 1 ml of toluene; \(\text{b}\) conversions were determined by \(^1\)H NMR analysis by relative integration of the corresponding signals of substrate and product; \(\text{c}\) no ligand was added.

Carpentier *et al.* have previously reported that zinc-catalyzed hydrosilylation of carbonyl compounds can be accelerated in methanol/toluene (v/v = 80/20) media.\(^{307}\) They correlated this affect with the formation of a zinc-methoxide intermediate. The same idea was applied to the hydrosilylation with catalyst III-58 (Table 18). When 10 equivalents of methanol (relative to the substrate) were added, 27% conversion was reached almost instantly at room temperature, however, no further conversion was observed. Instead, all triethoxysilane was consumed by methanol in a concurrent alcoholysis reaction to give
methoxytriethoxysilane. (Table 18, entry 2). Nevertheless, the high initial rate of the hydrosilylation under these conditions served as a proof of principle. Remarkably, if one equivalent of methanol is added to the reaction mixture, almost full conversion of acetophenone can be reached within 5.5 hours at room temperature (Table 18, entry 3), which is about twice as fast as the reaction without addition of methanol (Table 18, entry 1).

Table 18. Hydrosilylation of acetophenone with III-58 with various amounts of methanol.\(^a\)

<table>
<thead>
<tr>
<th>Entry</th>
<th>Catalyst, mol%</th>
<th>Methanol, eq</th>
<th>Temperature, °C</th>
<th>Time</th>
<th>Conversion(^b), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5</td>
<td>-</td>
<td>RT</td>
<td>10 h</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>5</td>
<td>10</td>
<td>RT</td>
<td>0.5 h</td>
<td>27(^c)</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
<td>1.0</td>
<td>RT</td>
<td>5.5 h</td>
<td>98</td>
</tr>
<tr>
<td>4</td>
<td>5</td>
<td>0.75</td>
<td>RT</td>
<td>4.5 h</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>0.50</td>
<td>RT</td>
<td>3 h</td>
<td>99</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>0.25</td>
<td>RT</td>
<td>2.5 h</td>
<td>98</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>0.10</td>
<td>RT</td>
<td>4 h</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>5</td>
<td>0.05</td>
<td>RT</td>
<td>8.5 h</td>
<td>96</td>
</tr>
<tr>
<td>9</td>
<td>2</td>
<td>0.25</td>
<td>RT</td>
<td>10 h</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>0.25</td>
<td>60</td>
<td>0.5 h</td>
<td>98</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>0.25</td>
<td>60</td>
<td>1 h</td>
<td>96</td>
</tr>
<tr>
<td>12</td>
<td>0.5</td>
<td>0.25</td>
<td>60</td>
<td>2.5 h</td>
<td>97</td>
</tr>
<tr>
<td>13</td>
<td>0.1</td>
<td>0.25</td>
<td>60</td>
<td>5 h</td>
<td>84</td>
</tr>
</tbody>
</table>

\(a\) Reaction conditions: acetophenone (50 µL, 0.429 mmol), ZnMe\(_2\), ligand III-10, triethoxysilane (158 µL, 0.858 mmol) in 1 mL of toluene; \(b\) conversions were monitored by \(^1\)H NMR analysis by relative integration of the corresponding signals of substrate and product; \(c\) no further conversion.
Further decrease of the amount of methanol down to 0.25 equivalents leads to the increase of the reaction rate, with a nearly full conversion achieved in 2.5 hours (Table 18, entry 6). When a smaller amount of methanol is used, the reaction slows down again (Table 18, entry 7 and 8). This positive effect of methanol allowed us to reduce the load of the catalyst. Thus, if the reaction is performed in the presence of 2 mol% of **III-58**, it requires about 10 hours at room temperature for the quantitative conversion of the substrate (Table 18, entry 9). When heated with the same amount of the catalyst, the reaction time drops significantly to 0.5 hours (Table 18, entry 10). If the catalyst load is reduced further, the process slows down accordingly. Thus, considering the catalyst economy and time efficiency, conditions in the entry 12 were chosen as optimal.

Next, the catalytic system was studied for its applicability and limitations. It was observed that the reaction rate is highly dependent on the substrate (Scheme 55). Thus, the hydrosilylation of benzaldehyde **III-59a** under the optimized conditions was significantly slower than in case of acetophenone **III-59h**. However, when both an aldehyde and keto groups were present in the molecule (**III-59e**), the aldehyde is the one to be reduced first. Overall, the tendency for the faster reduction of benzaldehyde containing electron-withdrawing groups was observed. Thus, 4-cyano benzaldehyde **III-59b** and 4-bromobenzaldehyde **III-59c** can be fully converted to the primary alcohols **III-59d** and **III-59c** in 1 and 4 hours, respectively. Whereas, 4-methoxy benzaldehyde **III-59d** requires a much longer time, 19 hours. The reaction tolerates the C=C bonds in α,β-unsaturated aldehydes **III-59f** and **III-59g**, leading to primary allylic alcohols **III-59f** and **III-59g** in excellent yield. Here, cinnamaldehyde **III-59g** contains a more electron-donating group in
the \( \gamma \)-position, as compared to \( \text{crotonaldehyde III-59f} \), and requires about twice as much time as \( \text{III-59f} \) for full conversion. \( \text{Benzophenone III-59i} \) can be fully reduced within 9 hours that is significantly longer, compared to \( \text{acetophenone III-59h} \). This can be explained by more steric hindrance in \( \text{III-59i} \), as well as by the presence of two electron-donating phenyl groups.

**Scheme 55.** Reaction conditions: substrate \((0.429 \text{ mmol})\), \( \text{ZnMe}_2 \) \((0.5 \text{ mol\%})\), ligand \( \text{III-10} \) \((0.5 \text{ mol\%})\), methanol \((4.4 \mu\text{L}, 25 \text{ mol\%})\), and triethoxysilane \((158 \mu\text{L}, 0.858 \text{ mmol})\) in 1 ml of toluene. Conversions were determined by \( ^1\text{H} \) NMR spectroscopy, isolated yields are shown in parentheses.

The mechanism of the hydrosilylation with \( \text{III-58} \) and the role of methanol in the reaction acceleration remains unclear. No distinctive zinc species could be isolated or
determined in the $^1$H NMR spectrum when an alcohol was added to a solution of III-58. Carpentier et al. proposed a mechanism for their zinc-catalyzed system (Scheme 56), based on the formation of a zinc-methoxy species III-61, which reacts fast with hydrosilane producing a zinc-hydride complex III-62. However, this mechanism requires more than a stoichiometric (relative to the substrate) amount of alcohol, and no experiments with substoichiometric amount of methanol was performed.

Scheme 56. Proposed mechanism for the methanol assisted hydrosilylation with zinc catalyst.

At the same time only 25 mol% of methanol is the most beneficial for the catalytic system ZnEt$_2$/III-10, while more than stoichiometric load of alcohol stops the reaction completely. Thus, methanol in this case is only essential for starting the reaction by converting III-58 to III-63 (Scheme 53), which is more reactive towards the reaction with hydrosilane. Zinc alkoxide III-65, formed upon the reduction of carbonyl compound, drives the reaction further by completing the catalytic cycle.
Scheme 53. Proposed mechanism of hydrosilylation of carbonyl compounds with III-58.
IV. Conclusions and Future Work

A series of bidentate and tridentate ligands bearing the pyrazolyl moiety in combination with phosphine, oxazoline, amine, and sulfide were synthesized. These ligands were applied for the synthesis of ruthenium complexes having the potential to catalyze transfer hydrogenation in alcohol. From a number of obtained complexes, the mixture III-20/20’ was found to be the most efficient in the reduction of acetophenone and N-benzylideneaniline, as model substrates, with 2-propanol.

Further studies showed that III-20/20’ can be successfully applied in the transfer hydrogenation of other substrates as well. Thus, nitriles can be reduced to primary amines in 2-propanol, while reductive alkylation occurs in ethanol, providing secondary amines. Heterocyclic compounds can be also reduced in the presence of III-20/20’, resulting in saturated heterocycles in most cases, although an interesting phenomenon of the reduction of all-carbon rings in isoquinoline III-32d and quinaldine III-32e was also observed. III-20/20’ was also found to be an efficient catalyst for the transfer hydrogenation of mono- and disubstituted olefins and the aromatic ring in anthracene. The latter was reduced at the external carbon ring, whereas usually this substrates is hydrogenated at carbons 9 and 10. Further, III-20/20’ was applied in the transfer hydrogenation of alkynes. Sterically hindered diphenylacetylenes undergo monohydrogenation to E-stilbenes. This stereoselectivity is different from the Z-selectivity usually observed in direct hydrogenation and transfer hydrogenation with other transition metal catalysts and can be explained by fast E-Z isomerization. Meanwhile, full hydrogenation of the triple bond in alkyl substituted alkynes occurs under same conditions.
Significant results were achieved in the transfer hydrogenation of some activated esters. It was shown that switching the hydrogen source to ethanol allows for ester reduction by pushing the equilibrium to the side of products.

Following the above-mentioned positive results in the transfer hydrogenation of N-benzylideneaniline and reductive coupling of nitriles with ethanol, III-20/20’ was applied in the synthesis of secondary amines via hydrogen borrowing methodology. A number of primary amines and alcohols were coupled under the conditions optimized for transfer hydrogenation of nitriles, resulting in the corresponding secondary amines with excellent yields. Anilines can be alkylated under these conditions as well, albeit a large excess of the corresponding alcohols is required for high conversion. A Hammett plot for anilines with different substituents revealed a positive dependence of the reaction rate on the substituent constants, which suggest that the rate determining step is transfer of hydride to an imine intermediate. Furthermore, ammonium formate was used as the nitrogen source for alcohol amination, allowing for preparation of secondary and tertiary amines from primary alcohols.

Transfer hydrogenation of the above-mentioned substrates (e.g. nitriles, heterocyclic compounds, alkenes, and esters) is much less studied, comparing to the transfer hydrogenation of carbonyl compounds and imines. Thus, further investigation of catalytic systems based on ruthenium and other transition metals is required to improve the reaction conditions and to broaden the substrate scope. Furthermore, a combination of the pyrazolyl component with a chiral moiety can expand the library of chiral ligands for enantioselective catalysts applied in various types of transformations, including transfer hydrogenation.

Another project was focused on transfer hydrogenation of carbonyl compounds with lithium isopropoxide. Lithium cation was shown to possess strong bonding to aromatic
alcohols, obtained by transfer hydrogenation of aromatic ketones. Such cation complexation poisons the catalytic center, making high conversions inaccessible. However, our studies revealed that this interaction can be broken by addition of various ligands or other cheap sources of lithium cations, such as LiCl. Thus, transfer hydrogenation with lithium isopropoxide was shown to be more efficient than the transfer hydrogenation with other alkali metal bases, if suitable additive is added.

Currently, only aldehydes and ketones are known to undergo transfer hydrogenation in alcohols, catalyzed by alkali metal bases. However, it has been already shown that changing the hydrogen source can be beneficial for catalytic process, for which transfer hydrogenation of esters in ethanol, described above, serves as an example. Thus, further studies on alkali metal-catalyzed transfer hydrogenation should be more focused on finding a proper hydrogen source, whose oxidation would be more thermodynamically favourable to drive the whole process of hydrogen transfer.

Finally, a new zinc complex III-58 was synthesized and applied to catalytic hydrosilylation of carbonyl compounds. Reaction conditions optimization revealed that the presence of substoichiometric amounts of methanol in the system significantly accelerates the process. This behaviour was explained by fast formation of more catalytically active zinc alkoxide species, which are believed to be more prone to undergo metathesis with hydrosilane to produce a reactive zinc-hydride intermediate. The reaction can proceed at very low catalyst load (down to 0.1 mol%) under relatively mild reaction conditions. The substrate scope analysis showed tolerance to the carbon-carbon double bond, so this procedure is efficient in the synthesis of allylic alcohols from α,β-unsaturated aldehydes and ketones.
Future studies can be done to investigate the potential of zinc complex II-58 in catalytic hydrosilylation of other types of substrates, such as nitriles and heterocyclic compounds. As the reduction of these substrates is generally more challenging than reduction of carbonyl compounds, harsh conditions and/or more active hydrosilanes may be required, as well as further modification of the zinc complex.
V. Experimental Section

V. 1. General methods and instrumentation

All manipulations, required an inert atmosphere, were carried out using controlled atmosphere glove-box or nitrogen-line Schlenk techniques. All glassware was rinsed with acetone and stored in a 190 °C oven for a minimum of 2 hours before immediate transfer to the glovebox or assembly and evacuation on the vacuum line. Dry ice/acetone (−78°C) and water/ice (0°C) baths were used to maintain low temperature conditions during reactions, when required. Benzene, toluene, hexanes, diethyl ether, tetrahydrofuran, and dichloromethane were dried and purified using a Grubbs-type solvent purification system. Benzene-$d_6$ and toluene-$d_8$ were dried and distilled from K/Na alloy and stored in a glass vessel in the glovebox. Chloroform-$d_1$, dichloromethane-$d_2$, and bromobenzene-$d_5$ were dried and distilled from CaH$_2$ and stored in a glass vessel in the glovebox. All organic substrates were purchased from Sigma-Aldrich and Alfa Aesar. These reagents were used without further purification.

NMR spectra were obtained with a Bruker DPX-300, AVANCE III HD 400 MHz, and DPX-600 spectrometers ($^1$H, 300, 400, and 600 MHz; $^{13}$C, 75, 101, and 151 MHz; $^{19}$F, 282, 377, and 565 MHz; $^{31}$P, 121, 162, and 243 MHz) at room temperature, unless stated otherwise, then processed and analyzed with MestReNova software (v10.0.2-15465). IR spectra were measured on a Perkin-Elmer 1600 FT-IR spectrometer. HRMS and GC-MS analysis was carried out on Thermo Scientific DFS (Double Focusing Sector) mass spectrometer. Elemental analyses were performed by the ANALEST laboratory at the University of Toronto, the analytical laboratory of McMaster University, the analytical
laboratory of the London Metropolitan University, or the Elemental Analysis Service at the Université de Montréal. X-ray crystallographic analyses were performed on suitable crystals coated in perfluoropolyether oil and mounted on a glass fiber. Measurements were collected on a Bruker AXS SMART single crystal diffractometer equipped with a sealed Mo tube source and an APEX II CCD detector. Full details can be found in individual tables for each crystal structure (Appendix).

V. 2. Synthesis of ligands

**Preparation of III-4a.** Solid sodium (2.53 g; 0.110 mol) was dissolved in methanol (100 mL, cooled by ice bath) in a 500 ml round bottom flask equipped with a condenser. Pinacolone (12.5 mL; 0.100 mol) was added to this solution, followed by diethyl oxalate (13.6 mL; 0.100 mol). The mixture was stirred for 12 hours to produce a yellow precipitate, which was filtered, washed with water (20 mL) two times, and dried (20.3 g, 98%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = (s, 1H, CH), 3.67 (s, 3H, CH$_3$), 1.02 (s, 9H, CH$_3$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ = 206.2, 167.5, 93.4, 52.4, 42.1, 27.8 ppm; IR (KBr): $\tilde{\nu}$ = 1712.2 (C=O), 1632.4 (C=O), 1245.3 (C-O) cm$^{-1}$; HRMS-EI (positive mode): m/z calcd for C$_9$H$_{13}$NaO$_4$: 208.1869; found: 208.1269.

**Preparation of III-5a.** Methyl 2,4-dioxo-4-tert-butylbutanoate III-4a (10.0 g; 48.0 mmol) was dissolved in ethanol (200 mL) then acetic acid (3.50 mL) was added. The solution of hydrazine monohydrate (4.12 mL; 96.0 mmol) in ethanol (20.0 mL) was gently added dropwise while stirring the reaction system. After 1 day of stirring, the reaction mixture was
concentrated under reduced pressure. Toluene (100 mL) was added and the mixture was dried again under vacuum to remove the residual hydrazine monohydrate. Saturated aqueous solution of NaHCO₃ was added to the residue to remove acetic acid. The white solid was filtered and dried under vacuum. (7.96 g, 91%). ¹H NMR (400 MHz, CDCl₃): δ = 9.38 (s, 1H, NH), 6.65 (s, 1H, CH), 3.93 (s, 3H, OCH₃), 1.37 (s, 9H, CH₃); ¹³C NMR (101 MHz, CDCl₃): δ = 162.1, 157.9, 140.4, 104.7, 52.2, 31.6, 30.3 ppm; IR (KBr): ν = 3283.2 (N-H), 1735.5 (C=O), 1255.1 (C-O) cm⁻¹; HRMS-EI (positive mode): m/z calcd for C₉H₁₄N₂O₂: 182.2197; found: 182.1056.

**Preparation of III-6.** LiAlH₄ (1.50 g; 40.0 mmol) was dissolved in THF (75 mL) and cooled to 0°C under nitrogen atmosphere. Then III-5a (6.00 g; 33.0 mmol) was slowly added to the solution. The mixture was stirred overnight, then water (1.5 mL), aqueous NaOH (1.5 mL) and again water (4.5 mL) were added sequentially. The residue was filtered and washed with CH₂Cl₂ (30 mL) two times. The filtrate was dried under MgSO₄ and then volatiles were removed under reduced pressure. The white solid obtained was dried under vacuum. (4.38 g, 86%). ¹H NMR (400 MHz, CDCl₃) δ 6.67 (s, 1H, CH), 5.30 (s, 2H, CH₂), 1.92 (s, 9H, CH₂); ¹³C NMR (101 MHz, CDCl₃) δ 163.4, 102.2, 100.0, 57.3, 31.3, 30.3 ppm; IR (KBr): ν = 3332.5 (N-H and O-H) cm⁻¹; HRMS-EI (positive mode): m/z calcd for C₈H₁₄N₂O: 154.2096; found: 154.1545.

**Preparation of III-7.** The solution of III-6 (4.30 g; 27.9 mmol) in CH₂Cl₂ (100 mL) was cooled to 0°C. Sulfonyl chloride (5 mL) was added dropwise. After stirring overnight, the solvent and the excess of sulfonyl chloride were removed under reduced pressure. The residue was dispersed in
aqueous solution of NaHCO₃, filtered, washed with pentane, and dried under vacuum. A creamy solid was obtained. (5.72 g, 98%). ¹H NMR (400 MHz, CDCl₃): δ = 10.69 (s, 1H, NH), 6.14 (s, 1H, CH), 4.60 (s, 2H, CH₂), 1.33 (s, 9H, CH₃); ¹³C NMR (101 MHz, CDCl₃): δ = 155.5, 148.0, 101.2, 38.6, 31.2, 30.2 ppm; IR (KBr): ν = 3247 (N-H) cm⁻¹; HRMS-EI (positive mode): m/z calcd for C₈H₁₃ClN₂: 172.6552; found: 172.4582.

**Preparation of III-1a.** All manipulations were done under the nitrogen atmosphere. A solution of diphenylphosphine (1.57 mL; 8.61 mmol) in THF was cooled to -78°C. Then a solution of MeLi in ether (1.6 M; 5.62 mL; 8.99 mmol) was added gently. The reaction mixture turned orange and was stirred for 1 hour. A solution of III-7 in THF (495 mg, 2.87 mmol, 50.0 mL) was prepared under nitrogen atmosphere and gently added to the cooled solution of lithium diphenylphosphide described above. The reaction mixture was stirred for 12 hours while being slowly warmed up to room temperature. After that a concentrated aqueous solution of NH₄Cl (100 mL) was added. The reaction system was stirred for 10 min. The THF layer was collected and the solvent was removed under reduced pressure. The residual diphenylphosphine was distilled off under reduced pressure at 100-102°C (1.48 Torr), leaving a creamy semiliquid of clean compound III-1a (0.647 g, 70%). The stock solution of III-1a in dry THF (100 mg/ml) was prepared for the convenience of further use. ¹H NMR (400 MHz, CD₂Cl₂): δ = 9.52 (s, 1H, NH), 7.49 – 7.37 (m, 4H, ArH), 7.37 – 7.24 (m, 6H, ArH), 5.73 (s, 1H, CH), 3.38 (s, 2H, CH₂), 1.23 (s, 9H, CH₃); ¹³C NMR (101 MHz, CDCl₃): δ = 157.1 (s), 143.2 (d, J = 8.7 Hz), 138.3 (d, J = 14.3 Hz), 132.9 (d, J = 18.7 Hz), 128.9 (s), 128.5 (d, J = 6.5 Hz), 101.5 (d, J = 5.4 Hz), 31.4 (s), 30.3 (s), 27.3 (d, J = 15.3 Hz); ³¹P {¹H}
NMR (162 MHz, CD$_2$Cl$_2$): $\delta = -15.3$ (s) ppm; HRMS-EI (positive mode): m/z calcd for C$_{20}$H$_{23}$N$_2$P: 322.3838; found: 321.9938.

**Preparation of III-1b.** All manipulations were done under the nitrogen atmosphere. A solution of di-iso-butylphosphine (0.951 mL; 5.79 mmol) in THF was cooled to -78°C. Then a solution of MeLi in ether (1.6 M; 3.64 mL; 5.82 mmol) was added gently. The reaction mixture turned orange and was stirred for 1 hour. A solution of III-7 in ether (500 mg, 2.90 mmol, 50.0 mL) was prepared under nitrogen atmosphere and gently added to the cooled solution of lithium diisobutylphosphide described above. The reaction mixture was stirred for 12 hours while being slowly warmed up to room temperature. After that a concentrated aqueous solution of NH$_4$Cl (100 mL) was added. The reaction system was stirred for 10 min. The organic layer was collected, and the solvent was removed under reduced pressure. The residual diisobutylphosphine was distilled off under reduced pressure at 79-80°C (2.05 Torr), leaving a yellowish semiliquid of clean compound III-1b (0.480 g, 58%). The stock solution of III-1b in dry THF (100 mg/ml) was prepared for the convenience of further use. $^1$H NMR (400 MHz, C$_6$D$_6$): $\delta = 11.57$ (s, 1H, NH), 5.97 (s, 1H, CH), 2.76 (bs, 2H, CH$_2$), 1.59-1.73 (m, 2H, CH$_{3}^{tBu}$), 1.33-1.47 (m, 6H, CH$_3^{iBu}$), 1.30 (s, 9H, CH$_3$), 1.15-1.25 (m, 4H, CH$_2^{iBu}$), 0.99 (dd, $J = 9.5$, 6.7 Hz, 6H, CH$_3^{iBu}$); $^{13}$C NMR (101 MHz, C$_6$D$_6$): $\delta = 157.4$ (s), 142.3 (s), 100.7 (d, $J = 4.1$ Hz), 39.0 (d, $J = 15.1$ Hz), 31.2 (s), 30.4 (d, $J = 10.8$ Hz), 30.3 (s), 26.3 (d, $J = 14.4$ Hz), 24.2 (d, $J = 9.3$ Hz), 24.0 (d, $J = 9.6$ Hz); $^{31}$P {$^1$H} NMR (162 MHz, C$_6$D$_6$): $\delta = -37.7$ (s) ppm; HRMS-EI (positive mode): m/z calcd for C$_{16}$H$_{31}$N$_2$P: 282.4040; found: 282.2145.
Preparation of III-9. Aqueous solution of KCN (250 mg, 3.85 mmol) was added to the solution of compound III-7 (600 mg, 2.87 mmol) in 20 ml of ethanol. The reaction mixture was stirred for 1 hour at room temp. After that the solvent was evaporated. The residue was washed with water, hexane and dried. Brownish solid was obtained (561 mg, 98%). \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta = 6.11 \) (s, 1H, CH), 1.34 (s, 2H, CH\(_2\)), 1.37 (s, 9H, CH\(_3\)\(^{tBu}\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)): \(\delta = 155.5\) (s), 141.9 (s), 117.4 (s), 100.7 (s), 65.9 (s), 31.8 (s), 30.2 (s), 17.6 (s) ppm; HRMS-EI (positive mode): m/z calcd for C\(_9\)H\(_{13}\)N\(_3\): 163.2196; found: 163.1032.

Preparation of III-8. Compound III-9 (500 mg, 3.36 mmol) was dissolved in dry toluene under N\(_2\). ZnCl\(_2\) (45.8 mg, 0.336 mmol) was added. The mixture was heated at 110\(^\circ\)C. 2-amino-2-methylpropan-1-ol (320 mL, 3.36 mmol) was added to this boiling solution. The reaction mixture was stirred under reflux for 2 days. After the solution was cooled to room temperature the brine was added. Organic phase was separated, and the solvent was evaporated. The residual orange oil was washed with ether. Colorless crystals were obtained (364 mg, 46%). \(^1\)H NMR (400 MHz, CDCl\(_3\)): \(\delta = 6.07\) (s, 1H, CH), 4.25 (s, 2H, CH\(_2\)), 3.90 (s, 2H, CH\(_2\)), 1.60 (s, 6H, 2CH\(_2\)), 1.37 (s, 9H, CH\(_3\)\(^{tBu}\)); \(^{13}\)C NMR (101 MHz, CDCl\(_3\)): \(\delta = 167.9\) (s), 156.8 (s), 143.7 (s), 102.6 (s), 80.6 (s), 68.2 (s), 31.4 (s), 29.9 (s), 27.9 (s), 26.3 (s) ppm; HRMS-EI (positive mode): m/z calcd for C\(_{13}\)H\(_{21}\)N\(_3\)O: 235.3253; found: 235.1659.

Preparation of III-4b. Solid sodium (2.53 g; 0.110 mol) was dissolved in methanol (100 mL, cooled by ice bath) in a 500 mL round bottom flask equipped with a condenser. Acetophenone (11.7 mL; 0.100 mol) was added to this solution,
followed by diethyl oxalate (13.6 mL; 0.100 mol). The mixture was stirred for 12 hours to produce a yellow precipitate, which was filtered, washed with water (20 mL) two times, and dried (22.1 g, 98%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 8.00-8.07 (m, 2H, o-ArH), 7.60-7.68 (m, 1H, p-ArH), 7.50-7.57 (m, 2H, m-ArH), 7.12 (s, 1H, CH), 3.97 (s, 3H, OCH$_3$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ = 1779.7 (s), 178.1 (s), 165.7 (s), 137.0 (s), 133.1 (s), 128.6 (s), 128.4 (s), 92.5 (s), 52.8 (s) ppm; IR (KBr): $\tilde{\nu}$ = 1712.8 (C=O), 1633.1 (C=O), 1245.2 (C-O) cm$^{-1}$; HRMS-EI (positive mode): m/z calcd for C$_{11}$H$_9$NaO$_4$: 2228.1765; found: 228.0338.

**Preparation of III-5b.** Methyl 2,4-dioxo-4-phenylbutanoate III-4b (10.0 g; 43.8 mmol) was dissolved in ethanol (200 mL) then acetic acid (3.00 mL) was added. The solution of hydrazine monohydrate (3.76 mL; 96.0 mmol) in ethanol (20.0 mL) was gently added dropwise while stirring the reaction system. After 1 day of stirring, the reaction mixture was concentrated under reduced pressure. Toluene (100 mL) was added and the mixture was dried again under vacuum to remove the residual hydrazine monohydrate. Saturated aqueous solution of NaHCO$_3$ was added to the residue to remove acetic acid. The white solid was filtered and dried under vacuum. (8.50 g, 96%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 8.09 (bs, 1H, NH), 7.73-7.81 (m, 2H, o-ArH), 7.44-7.51(m, 2H, m-ArH), 7.37-7.44 (m, 1H, p-ArH), 7.15 (s, 1H, CH), 3.98 (s, 3H, OCH$_3$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ = 16.3 (s), 149.5 (s), 139.5 (s), 129.0 (s), 128.7 (s), 126.9 (s), 125.7 (s), 105.7 (s), 52.2 (s) ppm; IR (KBr): $\tilde{\nu}$ = 3282.9 (N-H), 1736.1 (C=O), 1255.9 (C-O) cm$^{-1}$; HRMS-EI (positive mode): m/z calcd for C$_{11}$H$_{10}$N$_2$O$_2$: 202.093; found: 202.0749.
Preparation of III-11a. Compound III-5a (5 g; 27.4 mmol) was dissolved in 100 mL of MeOH. 2-Aminoethanol (8.26 mL; 137 mmol) and K₂CO₃ (1.90 g; 13.7 mmol) were added to the solution. Reaction mixture was refluxed (90°C) for 24 hours. After that volatiles were removed on rotavap, and oily residue was treated with brine. The product crushed out of the solution as creamy solid, was separated and dried (4.11 g; 71%). ¹H NMR (400 MHz, CDCl₃): δ = 8.12 (bs, 1H, CONH), 6.58 (s, 1H, CH), 3.80-3.90 (m, 2H, CH₂), 3.52-3.62 (m, 2H, CH₂), 1.32 (s, 9H, CH₃tBu); ¹³C NMR (101 MHz, CDCl₃): δ = 163.3 (s), 155.3 (s), 146.3 (s), 102.1 (s), 61.9 (s), 41.6 (s), 30.0 (s), 29.8 (s) ppm; HRMS-EI (positive mode): m/z calcd for C₁₀H₁₇N₃O₂: 211.2609; found: 211.1249.

Preparation of III-11b. Compound III-5b (5 g; 24.7 mmol) was dissolved in 100 ml of MeOH. 2-Aminoethanol (7.48 mL; 137 mmol) and K₂CO₃ (1.71 g; 13.7 mmol) were added to the solution. Reaction mixture was refluxed (90°C) for 24 hours. After that volatiles were removed on rotovap, and oily residue was treated with brine. The product crushed out of the solution as creamy solid, was separated and dried (4.97 g; 87%). ¹H NMR (400 MHz, CD₃CN): δ = 7.73-7.81 (m, 2H, o-ArH), 7.47-7.54(m, 2H, m-ArH), 7.39-7.47 (m, 1H, p-ArH), 7.06 (s, 1H, CH), 3.69 (t, J = 5.49 Hz, 2H, CH₂), 3.50 (dt, J = 5.49, 5.67 Hz, 2H, CH₂), 2.36 (bs, 2NH and OH); ¹³C NMR (101 MHz, CD₃CN): δ = 161.4 (s), 146.0 (s), 142.3 (s), 134.9 (s), 134.4(s), 133.9(s), 130.9(s), 107.6 (s), 66.2 (s), 46.9 (s) ppm; HRMS-EI (positive mode): m/z calcd for C₁₂H₁₃N₃O₂: 231.3502; found: 231.0912.
Preparation of III-12. Thionyl chloride (1.62 mL; 22.7 mmol) was added to the suspension of compound III-11b (3.5 g; 15.1 mmol) in DCM (100 mL). The reaction mixture was stirred at room temperature for 24 hours. After that the solution was filtered and neutralized with saturated aqueous solution of NaHCO$_3$. Organic phase was separated, dried over MgSO$_4$ and the solvent was removed under reduced pressure. Product was obtained as white solid (3.39 g; 90%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta = 8.89$ (bs, 1H, CONH), 7.95-8.02 (m, 2H, o-ArH), 7.48-7.62 (m, 3H, m- and p-ArH), 7.44 (s, 1H, CH), 3.83-3.91 (m, 2H, CH$_2$), 3.74-3.82 (m, 2H, CH$_2$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta = 155.7$ (s), 147.1 (s), 143.0 (s), 132.3 (s), 130.1(s), 129.5(s), 127.0(s), 106.9 (s), 42.4 (s), 41.7 (s) ppm; HRMS-EI (positive mode): m/z calcd for C$_{12}$H$_{12}$ClN$_3$O: 249.6962; found: 249.0657.

Preparation of III-13. Reaction was performed under N$_2$ atmosphere. A solution of sodium thiophenolate (1.07 g, 8.10 mmol) in ethanol (50 mL) was carefully added to a solution of compound III-12 (2 g, 8.01 mmol) in ethanol (50 mL). The reaction mixture instantly turned dark grey, and was stirred at room temperature for 24 hours until the colour became pale yellow. After that the solution was filtered and ethanol was removed under reduced pressure. The product was obtained as creamy solid (2.49 g; 96%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta = 11.43$ (bs, 1H, CONH), 7.65 (d, $J = 7.3$ Hz, 2H, o-ArH), 7.36-7.50 (m, 5H, ArH), 7.26-7.34 (m, 2H, m-ArH), 7.17-7.24 (m, 1H, p-ArH), 7.05 (s, 1H, CH), 3.69 (q, $J = 6.41$ Hz, 2H, CH$_2$), 3.19 (t, $J = 6.56$ Hz, 2H, CH$_2$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta = 161.7$ (s), 146.5 (s), 146.1 (s), 135.0 (s), 130.0 (s), 129.9 (s), 129.2 (s), 129.1 (s), 128.9 (s), 128.7
(s), 126.5 (s), 125.6 (s), 103.1 (s), 38.5 (s), 33.6 (s) ppm; HRMS-EI (positive mode): m/z calcd for C$_{18}$H$_{17}$N$_3$OS: 323.4121; found: 323.1328.

**Preparation of III-10.** Reaction was performed under N$_2$ atmosphere. Compound III-13 (1.00 g, 3.09 mmol) was dispersed in dry THF and the mixture was cooled down on ice bath. LiAlH$_4$ (153 mg, 4.00 mmol) was added carefully in two potions. The reaction was stirred for 16 hours being warmed up to room temperature. The excess of LiAlH$_4$ was quenched with ethanol. The solution was filtered and the solvent was removed under reduced pressure. The product was purified by treatment with aqueous HCl. Crystalline product was filtered, washed with hexane and dried. Then it was suspended in DCM and the solution was treated with saturated aqueous solution of NaHCO$_3$. Organic phase was separated, dried over MgSO$_4$ and the solvent was removed under reduced pressure. The product was obtained as pale yellow semiliquid (746 mg, 78%). $^1$H NMR (400 MHz, CDCl$_3$): $\delta$ = 7.70-7.77 (m, 2H, o-ArH), 7.39-7.45 (m, 2H, ArH), 7.32-7.38 (m, 3H, ArH), 7.25-7.31 (m, 2H, m-ArH), 7.18-7.23 (m, 1H, p-ArH), 6.46 (s, 1H, CH), 3.91 (s, 2H, CH$_2$), 3.11 (t, $J$ = 6.34 Hz, 2H, CH$_2$), 2.92 (t, $J$ = 6.34 Hz, 2H, CH$_2$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta$ = 149.4 (s), 145.8 (s), 135.4 (s), 132.3 (s), 129.8 (s), 129.0 (s), 129.1 (s), 128.8 (s), 128.0 (s), 126.4 (s), 125.6 (s), 101.5 (s), 47.6 (s), 45.0 (s), 34.1 (s) ppm; HRMS-EI (positive mode): m/z calcd for C$_{18}$H$_{19}$N$_3$S: 309.4286; found: 309.1587.
Preparation of complex III-14. A solution of ligand III-1a (0.322 g; 1.00 mmol) in THF (3.7 mL) was added to a solution of RuCl₂(DMSO)₄ (0.450 g; 1.00 mmol) in CH₂Cl₂ (2 mL). The reaction mixture was stirred at room temperature under nitrogen atmosphere for 6 h. After that hexane (0.5 mL) was carefully layered on top of the solution and the mixture was left at room temperature for crystallization. Yellow crystals were obtained after 2 days (0.505 g; 78%). ¹H NMR (400 MHz, CDCl₃): δ = 11.52 (s, 1H, NH), 8.10 (ddd, J = 11.4, 7.8, 1.3 Hz, 2H, ArH), 7.54-7.44 (m, 3H, ArH), 7.29 (dt, J = 8.2, 1.7 Hz, 1H, ArH), 7.20 (td, J = 7.6, 2.0 Hz, 2H, ArH), 6.92 (dd, J = 10.1, 7.7 Hz, 2H, ArH), 6.37 (d, J = 2.2 Hz, 1H, CH), 3.80 (dd, J = 16.4, 13.6 Hz, 1H, CH₂), 3.64 (dd, J = 16.4, 8.4 Hz, 1H, CH₂), 3.58 (s, 3H, CH₃), 3.46 (s, 3H, CH₃), 3.19 (s, 3H, CH₃), 2.38 (s, 3H, CH₃), 1.41 (s, 9H, CH₃); ¹³C NMR (101 MHz, CDCl₃): δ = 157.9 (s), 134.8 (d, J = 10.7 Hz), 132.4 (d, J = 8.1 Hz), 131.2 (s), 129.66 (s), 128.2 (d, J = 10.7 Hz), 127.3 (d, J = 9.8 Hz), 100.8 (d, J = 8.8 Hz), 50.4 (s), 47.1 (s), 45.9 (s), 44.8 (s), 31.9 (s), 30.1 (s); ³¹P {¹H} NMR (162 MHz, CDCl₃): δ = 67.4 (s, 1P, ligand III-1a) ppm. IR (KBr): ν = 1107.0 (S=O), 1023.7 (S=O) cm⁻¹. El. Anal. for C₂₄H₃₅Cl₂N₂O₂PRuS₂ (+CH₂Cl₂): calcd. C 39.36, H 5.33, N 3.44, S 11.82; found C 40.03, H 5.66, N 3.33, S 12.43.

Preparation of complex III-15. A solution of RuHCl(CO)(PPh₃)₃ (0.100 g; 0.11 mmol) and ligand III-1a (0.034 g; 0.11 mmol) in CH₂Cl₂ (2 mL) was stirred at room temperature overnight. Volatiles were removed under reduced pressure. Recrystallization from THF (5 mL) gave colorless crystals (0.067 g; 62%). ¹H
NMR (600 MHz, CD₂Cl₂): δ = 11.69 (s, 1H, NH), 7.34 (t, J = 7.2 Hz, 6H, ArH), 7.30 (dd, J = 11.7, 6.0 Hz, 12H, ArH), 7.25-7.19 (m, 14H, ArH), 7.12 (dd, J = 7.8, 2.4 Hz, 8H, ArH), 6.06 (s, 1H, CH), 3.36 (d, J = 8.2 Hz, 2H, CH₂), 1.02 (s, 9H, CH₃), -5.31 (dt, J = 95.5, 23.3 Hz, 1H, RuH); ¹³C NMR (101 MHz, CD₂Cl₂): δ = 159.14 (s), 152.39 (s), 136.10 (d, J = 24.9 Hz), 134.34 (d, J = 21.9 Hz), 133.99 (m), 131.33 (d, J = 11.0 Hz), 130.26 (s), 129.86 (s), 128.98 (d, J = 9.0 Hz), 128.55 (m), 101.70 (d, J = 11.8 Hz), 31.39 (s), 30.27 (s), 30.00 (d, J = 21.0 Hz); ³¹P {¹H} NMR (162 MHz, CD₂Cl₂): δ = 42.6 (d, J = 14.2 Hz, 2P, PPh₃), 34.7 (t, J = 14.3 Hz, 1P, ligand III-1a) ppm. IR (KBr): v = 1932.20 (C=O) cm⁻¹. El. Anal. for C₅₇H₅₄ClN₂O₃Ru: calcd. C 67.62, H 5.38, N 2.77; found C 67.41, H 5.05, N 2.64.

**Preparation of complexes III-16/16'.** RuHCl(CO)(PPh₃)₃ (0.400 g, 0.41 mmol) was dispersed in toluene and ligand III-1a (0.133 g, 0.41 mmol) was added. The reaction mixture was stirred at room temperature for 1 h to produce the N-coordinated complex III-17 which was isolated by filtration. ¹H NMR (400 MHz, THF-d₈): δ = 12.33 (s, 1H, NH), 7.60-7.53 (m, 12H, ArH), 7.48-7.41 (m, 4H, ArH), 7.33-7.24 (m, 18H, ArH), 7.16-7.08 (m, 6H, ArH), 5.17 (s, 1H, CH), 3.11 (s, 2H, CH₂), 0.79 (s, 9H, CH₃), -13.09 (t, J = 19.2 Hz, 1H, RuH); ³¹P {¹H} NMR (162 MHz, THF): δ = 41.5 (s, 2P, PPh₃), -20.7 (s, 1P, ligand III-1a).

Complex III-17 produced above was dissolved in toluene and heated to 100°C for 3 h. Then the solvent was removed under reduced pressure and the residue was washed with ether. The remaining solid was recrystallized from chloroform/hexane. A yellowish powder
was obtained (0.199 g, 63% yield), which is a mixture of two isomers. $^1$H NMR (400 MHz, CD$_2$Cl$_2$) of the mixture of two isomers: $\delta = 8.66$ (s, NH, minor), 8.53 (s, 1H, NH, major), 7.85-7.71 (m, ArH, major), 7.53-7.40 (m, ArH, major), 7.39-7.20 (m, ArH, major), 6.23 (s, CH, minor), 6.08 (s, 1H, CH, major), 3.99 (dd, $J = 15.5, 7.8$ Hz, 1H, CH$_2$, major), 3.93-3.73 (m, CH$_2$, minor), 3.71-3.52 (m, 1H, CH$_2$, major), 1.09 (s, CH$_3$, minor), 0.92 (s, 9H, CH$_3$, major), -12.03 (dd, $J = 22.7, 14.0$ Hz, RuH, minor), -14.18 (dd, $J = 19.2, 17.7$ Hz, 1H, RuH, major); $^{13}$C NMR (101 MHz, CD$_2$Cl$_2$) of major isomer: $\delta = 156.0$ (s), 154.1 (d, $J = 2.8$ Hz), 135.1 (s), 134.1 (d, $J = 11.5$ Hz), 132.56 (d, $J = 11.5$ Hz), 129.4-128.9 (m), 101.4 (d, $J = 8.7$ Hz), 30.0 (s), 29.8 (s); $^{31}$P $^1$H NMR (162 MHz, CD$_2$Cl$_2$) of the mixture of two isomers: $\delta = 60.33$ (d, $J = 290.9$ Hz, 1P, ligand III-1a, major), 58.55 (d, $J = 312.8$ Hz, ligand III-1a, minor), 44.89 (d, $J = 312.8$ Hz, PPh$_3$, minor), 42.38 (d, $J = 290.9$ Hz, 1H, PPh$_3$, major) ppm. IR (KBr): $\tilde{\nu} = 1965.43$ (C=O) cm$^{-1}$. El. Anal. for C$_{39}$H$_{39}$ClN$_2$OP$_2$Ru: calcd. C 62.44, H 5.24, N 3.73; found C 62.23, H 4.98, N 3.83.

**Preparation of complex III-18.** A solution of RuCl$_2$(PPh$_3$)$_3$ (0.200 g; 0.21 mmol) and ligand III-1a (0.135 g; 0.42 mmol) in benzene (5 ml) was stirred at 60°C for 2 h under the nitrogen atmosphere. Yellow crystals formed. The precipitate was filtered, washed with a small portion of hexane and dried. (0.154 g; 90%). $^1$H NMR (400 MHz, CD$_2$Cl$_2$): $\delta = 11.45$ (s, 2H, NH), 7.71-7.60 (m, $J = 11.6, 7.9$ Hz, 4H, ArH), 7.60-7.51 (m, $J = 7.6$ Hz, 2H, ArH), 7.52-7.43 (m, $J = 6.5$ Hz, 4H, ArH), 7.39-7.33 (m, 8H, ArH and CH), 7.34-7.26 (m, 4H, ArH), 7.26-7.17 (m, $J = 7.3$ Hz, 4H, ArH), 7.03-6.92 (m, $J = 5.4$ Hz, 6H, ArH), 6.81-6.70 (m, $J = 7.3$ Hz, 4H, ArH), 6.40-6.28 (m, $J = 8.7$ Hz, 6H, ArH), 3.77-3.61 (m, 2H, CH$_2$), 3.45-3.31 (m, 2H, CH$_2$), 1.46 (s, 18H, CH$_3$); $^{13}$C
NMR spectrum was not obtained due to the low solubility of this complex; $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta = 67.9$ (s, 2P, ligand III-1a) ppm. El. Anal. for C$_{40}$H$_{46}$Cl$_2$N$_4$P$_2$Ru: calcd. C 58.82, H 5.68, N 6.86; found C 58.91, H 5.86, N 6.46.

Complex III-18 was dissolved in CH$_3$CN and crystals of complex III-19 were grown by slow diffusion of hexane. NMR data for III-19: $^1$H NMR (400 MHz, CD$_2$Cl$_2$): $\delta = 14.17$ (s, 2H, NH), 7.30-6.85 (m, 20H, ArH), 6.14 (s, 2H, CH), 3.40-3.25 (m, 4H, CH$_2$), 1.48 (s, 3H, CH$_3$CN), 1.37 (s, 18H, CH$_3$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta = 158.24$ (s), 153.23 (s), 135.37 (d, $J = 43.3$ Hz), 133.33 (d, $J = 9.8$ Hz), 131.92 (d, $J = 2.5$ Hz), 129.66 (d, $J = 19.1$ Hz), 126.18 (s), 101.73 (d, $J = 7.0$ Hz), 34.99 (d, $J = 29.7$ Hz), 32.69 (s), 30.13 (s), 4.03 (s); $^{31}$P NMR (162 MHz, CD$_2$Cl$_2$): $\delta = 63.7$ (s, 2P, ligand III-1a) ppm.

Preperation of complexes III-20/20'. RuCl$_2$(PPh$_3$)$_3$ (0.800 g, 0.836 mmol) was dissolved in acetonitrile. Compound III-1a (0.270 g, 0.836 mmol – in stock solution in THF) was added. The mixture was refluxed under the nitrogen atmosphere for 2 hours. After that acetonitrile was removed under reduced pressure, the yellow residue was recrystallized by slow diffusion of hexane into a saturated chloroform solution at -30°C. A yellow powder was obtained. Yield: 0.380 g, 57%. $^1$H NMR (CDCl$_3$; 400 MHz) for a mixture of two isomers III-20 (minor) and III-20' (major): $\delta = 12.12$ (s, NH, minor), 11.84 (s, 1 H, NH, major), 7.72-
7.79 (m, 6H, ArH, major), 7.58-7.65 (m, 2H, P ArH, major), 7.43-7.57 (m, 27H, ArH, major), 7.31-7.39 (m, 27H, ArH, major), 7.22-7.30 (m, 16H, ArH, major), 7.01-7.17 (m, 27H, ArH, major), 6.39 (s, 1H, CH, major), 6.18 (s, 1H, CH, minor), 3.56 (d, JPH = 9.98 Hz, 2H, CH2, major), 3.43-3.61 (m, CH2 - minor), 2.01 (s, CH3CN, minor), 1.86 (s, 6H, CH3CN, major), 1.44 (s, 9H, HtBu, major), 1.36 (s, HtBu, minor), 1.08 (s, CH3CN, minor); 13C NMR (CDCl3; 101 Hz) for a mixture of two isomers: δ = 172.8 (s, minor), 157.3 (s, major), 155.3 (s, minor), 152.0 (d, JPC = 4.5 Hz, major), 150.8 (d, JPC = 4.5 Hz, minor), 136.0 (d, JPC = 43.0 Hz, major), 134.6 (d, JPC = 10.1 Hz, minor), 134.0 (d, JPC = 9.0 Hz, major), 133.9 (s, minor), 133.7 (d, JPC = 41.5 Hz, major), 132.1 (d, JPC = 9.0 Hz, major), 131.6 (d, JPC = 9.0 Hz, major), 131.2 (d, JPC = 2.2 Hz, major), 130.1 (d, JPC = 9.0 Hz, major), 129.3 (d, JPC = 2.2 Hz, minor), 128.9 (d, JPC = 10.1 Hz, major), 128.7 (d, JPC = 2.2 Hz, minor), 128.1 (d, JPC = 9.6 Hz, major), 127.8 (d, JPC = 9.2 Hz, major), 127.2 (d, JPC = 9.2 Hz, minor), 127.5 (s, CH3CN, major), 119.94 (s, CH3CN, minor), 101.3 (d, JPC = 9.2 Hz, major), 100.0 (d, JPC = 9.8 Hz, minor), 34.9 (d, JPC = 28.2 Hz, minor), 34.8 (d, JPC = 28.9 Hz, major), 32.0 (s, major), 31.7 (s, minor), 31.2 (s, minor), 30.0 (s, major), 22.6 (s, CH3CN, minor), 4.3 (s, CH3CN, major), 3.11 (s, CH3CN, minor); 31P {1H} NMR (CDCl3; 162 MHz): δ = 62.9 (d, JPP = 24.9 Hz, 1P, ligand III-1a, major), 58.9 (d, JPP = 29.8 Hz, ligand III-1a, minor), 44.1 (d, JPP = 29.8 Hz, PPh3, minor), 42.6 (d, JPP = 29.8 Hz, 1P, PPh3, major) ppm. HRMS (EI) (positive mode): m/z 803.2385 (C42H44ClN4P2Ru). FTIR (KBr): v = 529.85 (S), 722.15 (s), 746.48 (m), 999.23 (w), 1028.05 (w), 1090.98 (m), 11.87.06 (w), 1288.42 (w), 1315.43 (w), 1367.15 (w), 1435.11 (s), 1483.36 (m), 1622.13 (m), 1668.45 (m), 22.53.71 (m), 2274.62 (m), 2973.90 (m), 3055.33 (m), 3399.98 (m, br) cm⁻¹. El. Anal. for C42H44Cl2N4P2Ru: calcd. C 60.14, H 5.29, N 6.68; found. C 60.25, H 5.04, N 7.03.
Preparation of complex III-21. Mixture of isomers III-20/20' was dissolved in chlorobenzene. Orange crystals were obtained by slow diffusion of hexanes at -30°C. \(^1\)H NMR (C\(_6\)D\(_5\)Br; 400 MHz): \(\delta = 13.37\) (s, 1 H, NH), 8.03-8.13 (m, 2H, ArH), 7.54-7.65 (m, 6H, ArH), 7.40-7.50 (m, overlapped with C\(_6\)D\(_5\)Br), 7.00-7.26 (m, overlapped with C\(_6\)D\(_5\)Br), 6.86-6.94 (m, 6H, ArH), 6.10 (d, \(J_{HP} = 1.49\) Hz, CH), 3.54-3.73 (m, 1H, CH\(_2\)), 2.81-3.19 (m, 1H, CH\(_2\)), 1.67 (s, 9H, CH\(_3\)tBu); \(^{13}\)C NMR (C\(_6\)D\(_5\)Br; 101 MHz): \(\delta = 157.1\) (s), 151.5 (s), 136.1 (d, \(J_{CP} = 43.7\) Hz), 134.5 (d, \(J_{CP} = 9.0\) Hz), 125.99-131.99 (overlapped with C\(_6\)D\(_5\)Br), 100.9 (d, \(J_{CP} = 14.5\) Hz), 32.0 (s), 30.3 (s), 30.6 (d, \(J_{CP} = 8.4\) Hz); \(^{31}\)P \(^1\)H NMR (C\(_6\)D\(_5\)Br; 162 MHz): \(\delta = 59.8\) (d, \(J_{PP} = 34.8\) Hz, 1P, ligand III-1a), 53.9 (d, \(J_{PP} = 37.6\) Hz, 1P, PPh\(_3\)) ppm. HRMS (EI) (positive mode): m/z calcd for C\(_{76}\)H\(_{76}\)Cl\(_4\)N\(_4\)P\(_4\)Ru\(_2\): 1479.9821; found: 1479.3498. FTIR (KBr): \(\nu = 518.85\) (s), 696.30 (s), 746.45 (m), 999.13 (w), 1028.06 (w), 1091.21 (m), 1159.22 (w), 1188.15 (w), 1288.45 (w), 1315.45 (w), 1367.53 (m), 1435.04 (s), 1483.26 (m), 1573.91 (w), 1622.13 (m), 1668.43 (m), 2960.73 (m), 3055.24 (m), 3396.64 (m, br) cm\(^{-1}\). El. Anal. for C\(_{76}\)H\(_{76}\)Cl\(_4\)N\(_4\)P\(_4\)Ru\(_2\): calcd. C 60.32, H 5.06, N 3.70; found C 60.58, H 5.20, N 4.38.

Preparation of complex III-22. RuCl\(_2\)(PPh\(_3\))\(_3\) (68.0 mg, 0.177 mmol) was dissolved in acetonitrile. Compound III-1b (20.0 mg, 0.177 mmol) was added. The mixture was heated under reflux for 2 hours. After that acetonitrile was evaporated. The yellow residue was washed with ether. Yellow powder was obtained (31.1 mg, 61%). \(^1\)H NMR (CD\(_2\)Cl\(_2\); 400
MHz): \( \delta = 11.85 \) (s, 1H, NH), 7.88-7.72 (m, 6H, o-ArH), 7.54-7.42 (m, 9H, m- and p-ArH), 6.30 (s, 1H, CH), 3.19 (d, \( J_{PH} = 9.72 \) Hz, 2H, CH\(_2\)), 2.14 (s, 6H, CH\(_3\)CN), 1.84-1.72 (m, 2H, CH\(_{PBu^2}\)), 1.42 (s, 9H, H\(_{PBU}\)), 1.24-1.36 (m, 4H, CH\(_2\)\(_{PBU^2}\)), 0.86 (dd, \( J_{HH} = 26.2 \) and 5.41 Hz, 8H, H\(_{tBU}\)); \(^{13}\)C NMR (CD\(_2\)Cl\(_2\); 101 Hz): \( \delta = 158.3 \) (s), 153.5 (s), 134.9 (d, \( J_{CP} = 45.5 \) Hz), 133.9 (d, \( J_{CP} = 10.64 \) Hz), 130.2 (d, \( J_{CP} = 2.2 \) Hz), 128.3 (d, \( J_{CP} = 8.9 \) Hz), 124.3 (CH\(_3\)CN), 101.4 (d, \( J_{CP} = 6.55 \) Hz), 35.5 (d, \( J_{CP} = 24.09 \) Hz), 29.9 (s), 29.7 (s), 27.7 (d, \( J_{CP} = 24.1 \) Hz), 25.23 (d, \( J_{CP} = 6.3 \) Hz), 24.69 (d, \( J_{CP} = 6.29 \) Hz), 15.15 (s, CH\(_3\)CN); \(^{31}\)P \( \{^1\)H\} NMR (CD\(_2\)Cl\(_2\); 162 MHz): \( \delta = 57.6 \) (d, \( J_{PP} = 23.6 \) Hz, ligand III-1b), 43.5 (d, \( J_{PP} = 23.6 \) Hz, PPh\(_3\)) ppm.

HRMS (EI) (positive mode): \( m/z \) 762.8975 (C\(_{38}\)H\(_{25}\)ClN\(_4\)P\(_2\)Ru).

**Preparation of complex III-24/24'.** The mixture of compound III-8 (100 mg, 0.429 mmol) and [CpRu(CH\(_3\)CN)\(_3\)][PF\(_6\)] (235 mg, 0.429 mmol) in DCM was stirred under reflux for 1 hour. Then the solvent was removed under reduced pressure and the residue was dried in vacuum. Pale orange solid was obtained (113 mg, 99%). NMR spectra for the mixture of isomers: \(^1\)H NMR (CH\(_2\)Cl\(_2\)/D\(_2\)O; 400 MHz): \( \delta = 11.75 \) (s, 1H, NH\(^a\)), 10.63 (s, 1H, NH\(^b\)), 6.03 (bs, 1H, CH\(^a\)), 5.88 (bs, 1H, CH\(^b\)), 4.15 (bs, 2H, CH\(_2^a\)), 4.10 (s, 5H, Cp\(^a\)), 4.06 (s, 7H, CH\(_2^b\) and Cp\(^b\)), 3.87 (bs, 2H, CH\(_2^a\)), 3.52 (bs, 2H, CH\(_2^b\)), 2.26 (s, 7H, CH3CNa), 2.03 (bs, 4H, CH\(_3\)CN\(^b\)), 1.38 (s, 6H, CH\(_3^a\)), 1.19-1.24 (m, 24H, \( tBu^a\), \( tBu^b\) and CH\(_3^b\)); \(^{13}\)C-DEPT\(_{135}\) NMR (CH\(_2\)Cl\(_2\)/D\(_2\)O; 101 MHz): \( \delta = 103.0 \) (s, negative), 101.7 (s, negative), 80.5 (s, positive), 79.7 (s, positive), 68.7 (s, negative), 67.4 (s, negative), 29.4
Preparation of complex III-25. The mixture of compound III-8 (100 mg, 0.429 mmol) and [CpRuPy₃][PF₆] (235 mg, 0.429 mmol) in DCM was stirred under reflux for 1 hour. Then the solvent was removed under reduced pressure and the residue was dried in vacuum. The solid was recrystallized from a saturated chloroform solution by slow diffusion of hexane at -30°C. Dark-orange crystals were obtained (113 mg, 42%). ¹H NMR (CCl₄D₂; 400 MHz): δ = 10.69 (s, 1H, NH), 8.52 (d, J_HH = 4.9 Hz, 2H, o-HPy), 7.87 (t, J_HH = 7.2 Hz, 1H, p-HPy), 7.31-7.40 (m, 2H, m-HPy), 6.18 (s, 1H, CH), 4.31 (d, J_HH = 9.4 Hz, 1H, CH₂), 4.29 (s, 5H, Cp), 4.11 (d, J_HH = 9.4 Hz, 1H, CH₂), 1.50 (s, 3H, CH₃), 1.35 (s, 9H, CH₃ tertBu), 0.70 (s, 3H, CH₃); ¹³C NMR (CCl₄D₂; 101 MHz): δ = 169.40 (s), 158.29 (s), 154.55 (s), 145.58 (s), 137.30 (s), 125.72 (s), 102.62 (s), 80.00 (s), 71.60 (s), 67.91 (s), 31.34 (s), 29.53 (s), 28.64 (s), 27.88 (s), 26.48 (s) ppm. HRMS-EI (positive mode): m/z 408.6187 (C₂₃H₃₁N₄O₃Ru).

Preparation of complex III-26. Compound III-10*HCl (150 mg, 0.429 mmol), and KOtBu (48.8 mg, 0.436 mmol) were dissolved in dry toluene and RuCl₂(PPh₃)₃ (400 mg, 0.418 mmol) was added. The reaction mixture was heated at 100°C in the closed flask for 1 hour. After that solution was filtered and toluene was removed under reduced pressure. The product was crystallized from saturated DCM solution by slow diffusion of hexane. Complex III-26 was obtained as a pale orange powder (221 mg, 72%). ¹H NMR
(400 MHz, CDCl$_3$): $\delta = 9.05$ (bs, 1H, NH), 7.65-7.75 (m, 6H, o-ArH), 7.50-7.59 (m, 2H, o-ArH), 7.25-7.38 (m, 12H, ArH), 7.12-7.20 (m, 1H, p-ArH), 7.01-7.08 (m, 2H, ArH), 6.92-7.00 (m, 2H, ArH), 6.47 (d, 1H, $J_{HH} = 1.8$ Hz, CH), 6.16 (bs, 1H, NH), 4.75 (t, $J_{HH} = 12.1$ Hz, 1H, CH$_2$), 4.36 (dt, $J_{HH} = 13.4$, 4.5 Hz, 1H, CH$_2$), 3.59-3.74 (m, 2H, CH$_2$), 3.50-3.59 (m, 1H, CH$_2$), 3.24-3.39 (m, 1H, CH$_2$); $^{13}$C NMR (101 MHz, CDCl$_3$): $\delta = 155.7$ (s), 145.2 (s), 144.7 (s), 134.7 (d, $J_{CP} = 10.8$ Hz), 129.2 (d, $J_{CP} = 2.1$ Hz), 128.9 (s), 128.8 (s), 128.4 (s), 127.7 (d, $J_{CP} = 9.0$ Hz), 125.0 (s), 100.7 (s), 77.2 (s), 49.0 (s), 48.3 (s), 47.8 (s) ppm; $^{31}$P NMR (162 MHz, CDCl$_3$): $\delta = 54.5$ (s, 1P, PPh$_3$) ppm. El. Anal. for C$_{36}$H$_{34}$Cl$_2$N$_3$PRuS: calcd. C 58.14, H 4.61, N 5.65 S 4.31; found. C 57.68, H 5.73, N 5.25 S 4.08.

**Preparation of complex III-58.** 0.400 ml of the stock solution of compound III-10 in toluene (100 mg, 0.320 mmol) and 0.267 ml of the stock solution of ZnMe$_2$ in toluene (0.320 mmol) were combined in toluene (2 ml). The solution was stirred at room temperature in the glovebox for 20 min. As the reaction was completed, the solvent was removed under reduced pressure. The product was obtained as colourless semiliquid (123 mg, 99%). $^1$H NMR (400 MHz, C$_6$D$_6$): $\delta = 7.99$-7.87 (m, 2H, o-ArH), 7.20-7.33 (m, 2H, o-ArH), 7.06-7.15 (m, 1H, p-ArH), 6.85-7.06 (m, 5H, ArH), 6.13 (s, 1H, CH), 3.09 (d, $J_{HH} = 6.9$ Hz, 2H, CH$_2$), 2.31 (bs, 2H, CH$_2$), 2.14 (bs, 2H, CH$_2$), 1.18-1.92 (m, 1H, NH), -0.03 (s, 3H, CH$_3$); $^{13}$C NMR (101 MHz, C$_6$D$_6$): $\delta = 214.2$ (s), 153.3 (s), 148.7 (s), 135.0 (s), 134.7 (s), 129.6 (s), 128.9 (s), 128.2 (s), 126.9 (s), 126.3 (s), 98.9 (s), 47.7 (s), 46.1 (s), 31.5 (s) ppm. HRMS (EI): m/z 386.8413 (C$_{19}$H$_{21}$N$_3$SZn).
V. 4. Transfer hydrogenation

**General procedure for transfer hydrogenation of acetophenone.** A Schlenk flask was charged with acetophenone (58.3 μL, 0.50 mmol), a catalyst (5.0 μmol), and a stock solution of KOtBu in 2-propanol (10 mg/mL, 0.056 mL), and 2-propanol (1.5 mL) under nitrogen atmosphere. The solution was stirred at room temperature or at 80°C. The progress of the reaction was monitored by NMR spectroscopy. 1-phenylethanol $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.75$ (d, $J_{HH} = 7.4$ Hz, ortho-ArH), 7.66 (t, $J_{HH} = 7.6$ Hz, meta-ArH), 7.57 (t, $J_{HH} = 7.3$ Hz, para-ArH), 5.23 (q, $J_{HH} = 6.5$ Hz, CH$_2$-OH), 1.84 (d, $J_{HH} = 6.5$ Hz, CH$_3$) ppm.

**Product Isolation.** The solvent was removed on rotary evaporator. 1-Phenylethanol was isolated on chromatographic column, eluted by hexane/ethyl acetate mixture (4:1, then 1:1). The product was obtained as a colourless liquid. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.26$ – 7.46 (m, 5ArH), 4.84 – 4.97 (m, CH$_2$-OH), 2.16 (s, OH), 1.52 (d, $J = 6.5$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 145.95$ (ipso-C$_{Ar}$), 128.59 (meta-C$_{Ar}$), 127.55 (para-C$_{Ar}$), 125.50 (ortho-C$_{Ar}$), 70.47 (CH$_2$-OH), 25.24 (CH$_3$) ppm.

**General procedure for transfer hydrogenation of imines.** A Schlenk flask was charged with N-benzylideneaniline (90.5 mg, 0.50 mmol), a stock solution of III-20/20’ in 2-propanol (10 mg/mL, 0.42 ml), a stock solution of KOtBu in 2-propanol (10 mg/mL, 0.056-0.336 ml), and 2-propanol (1.5 mL) under nitrogen atmosphere. The flask was heated at 80°C. The progress of the reaction was monitored by NMR spectroscopy. $N$-benzylaniline $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.70$ (d, $J_{HH} = 7.4$ Hz, ortho-ArH), 7.62 (t, $J_{HH} = 7.8$ Hz, meta-ArH), 7.54 (t, $J_{HH} = 6.9$ Hz, para-ArH), 7.40 (d, $J_{HH} = 8.0$ Hz, ortho-ArH),
6.89-7.00 (m, 3H, *meta*- and *ortho*-ArH), 5.69 (bs, 1H, NH), 4.65 (d, \(J_{HH} = 5.8\) Hz, 1H, CH\(_2\)) ppm.

V. 4. 1. Transfer hydrogenation of nitriles in 2-propanol

**General procedure.** A Schlenk flask was charged with a nitrile (0.50 mmol), a stock solution of **III-20/20’** in 2-propanol (10 mg/mL, 0.42 mL), a stock solution of KOtBu in 2-propanol (10 mg/mL, 0.28 mL), and 2-propanol (1.3 mL) under nitrogen atmosphere. The flask was heated at 80°C for 24 hours. The progress of the reaction was monitored by NMR spectroscopy. To isolate the product as an ammonium salt, the reaction mixture was treated with aqueous HCl (1M, 1.5 mL), and stirred for 1 hour at room temperature. The solvent was removed under the vacuum and water (5 mL) was added to the residual solid to dissolve the ammonium salt. It was crystallized then by hexane (1 mL) layering.

**NMR spectral data for the products.**

86\% conversion to **III-30a** in 24 hours: \(^1\)H NMR (2-propanol/D\(_2\)O, 400MHz): \(\delta = 7.74 – 7.53\) (m, 5ArH), 4.89 (s, CH\(_2\)), 2.51 (s, CH\(_3\)), 2.36 (s, CH\(_3\)) ppm.

The ammonium salt was isolated in 75\% yield: \(^1\)H NMR (D\(_2\)O, 400MHz): \(\delta = 7.49\) (5H, ArH), 4.20 (2H, CH\(_2\)); \(^{13}\)C NMR (D\(_2\)O, 101MHz): \(\delta = 132.6\) (*ipso*-C\(_{Ar}\)), 129.2 (*ortho*- and *para*-C\(_{Ar}\)), 128.8 (*meta*- C\(_{Ar}\)), 43.1 (CH\(_2\)) ppm.

99\% conversion to **III-30b** in 24 hours: \(^1\)H NMR (2-propanol/D\(_2\)O, 400MHz): \(\delta = 7.37\) (d, \(J_{HH} = 8.1\) Hz, 2ArH), 7.09
(d, $J_{HH} = 8.2$ Hz, 2ArH), 4.87 (s, NH$_2$), 4.77 (s, CH$_2$), 2.48 (s, CH$_3$), 2.34 (s, CH$_3$) ppm.

The ammonium salt was isolated in 77% yield: $^1$H NMR (D$_2$O, 400MHz): $\delta = 7.57$ (d, $J_{HH} = 8.37$ Hz, 2ArH), 7.42 (d, $J_{HH} = 8.37$ Hz, 2ArH), 4.22 (s, CH$_2$); $^{13}$C NMR (D$_2$O, 101MHz): $\delta = 148.4$ (C$_{Ar}$), 132.7 (C$_{Ar}$), 130.5 (C$_{Ar}$-H), 123.1 (C$_{Ar}$-H), 42.4 (CH$_2$) ppm.

99% conversion to III-30c in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.47$ (d, $J_{HH} = 8.5$ Hz, 2ArH), 7.15 (d, $J_{HH} = 8.5$ Hz, 2ArH), 4.73 (s, CH$_2$), 4.06 (s, OCH$_3$), 2.40 (s, CH$_3$), 2.25 (s, CH$_3$).

The ammonium salt was isolated in 77% yield: $^1$H NMR (D$_2$O, 400MHz): $\delta = 7.42$ (d, $J_{HH} = 8.70$ Hz, 2ArH), 7.06 (d, $J_{HH} = 8.14$ Hz, 2ArH), 4.14 (s, CH$_2$), 3.86 (s, OCH$_3$); $^{13}$C NMR (D$_2$O, 101MHz): $\delta = 163.3$ (C$_{Ar}$-OMe), 134.4 (C$_{Ar}$-H), 129.5 (Ar-CH$_2$NH$_3^+$), 115.5 (C$_{Ar}$-H), 56.1 (OCH$_3$), 42.4 (CH$_2$) ppm.

29% conversion to III-30d in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.43 - 7.34$ (m, 3ArH), 4.77 (s, CH$_2$), 2.69 (s, 2CH$_3$), 2.48 (s, CH$_3$), 2.47 (s, CH$_3$) ppm.

99% conversion to III-30e in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 3.45$ (s, CH$_2$), 2.47 (s, CH$_3$), 2.27 (s, CH$_3$), 1.38 (s, C(CH$_3$)$_3$) ppm.
99% conversion to **III-30f** in 36 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 3.69$ (t, $J_{HH} = 7.2$ Hz, NCH$_2$), 2.45 (s, CH$_3$), 2.30 (s, CH$_3$), 2.22-2.43 (m, CH$_2$), 1.39 (t, $J_{HH} = 7.1$ Hz, CH$_3$) ppm.

The ammonium salt was dissolved in water and aqueous solution of NaHCO$_3$ was added. Free amine was extracted with ether (3×2 mL). Solvent was removed under reduced pressure. 1-Butylamine was isolated in 80% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 2.65$ (t, $J_{HH} = 6.87$ Hz, CH$_2$), 1.35-1.44 (m, CH$_2$), 1.25-1.35 (m, CH$_2$), 1.09 (s, NH$_2$), 0.88 (t, $J_{HH} = 7.16$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 42.0$ (NH$_2$-CH$_2$), 36.1 (NH$_2$-CH$_2$-CH$_2$), 20.0 (NH$_2$-CH$_2$-CH$_2$-CH$_2$), 14.1 (CH$_3$) ppm.

99% conversion to **III-30g** in 36 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 3.59$ (t, $J_{HH} = 7.3$ Hz, CH$_2$), 2.36 (s, CH$_3$), 2.21 (s, CH$_3$), 1.92 – 2.00 (m, CH$_2$), 1.28 (t, $J_{HH} = 6.8$ Hz, CH$_3$).

The ammonium salt was isolated in 69% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 8.27$ (s, NH$_3^+$), 2.95-3.07 (m, CH$_2$), 1.35-1.44 (m, CH$_2$), 1.74-1.85 (m, CH$_2$), 1.37-1.47 (m, CH$_2$), 1.28-1.47 (m, 2CH$_2$), 0.90 (t, $J_{HH} = 6.63$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 40.1$ (NH$_2$-CH$_2$), 31.2 (CH$_2$), 27.7 (CH$_2$), 26.3 (CH$_2$), 22.5 (CH$_2$), 14.0 (CH$_3$) ppm.
99% conversion to III-30i in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta$ = 8.13 (s, ArH), 8.06 (d, $J_{HH} = 7.6$ Hz, ArH), 7.85-7.98 (m, 2ArH), 5.30 (q, $J_{HH} = 6.5$ Hz, CH$_2$OH), 1.86 (d, $J_{HH} = 6.5$ Hz, CH$_3$) ppm.

V. 4. 2. Transfer hydrogenation of nitriles in ethanol

**General procedure.** A Schlenk flask was charged with a nitrile (0.50 mmol), a stock solution of III-20/20' in ethanol (10 mg/mL, 0.42 mL), a stock solution of KOtBu in ethanol (10 mg/mL, 0.28 mL), and ethanol (1.3 mL) under nitrogen atmosphere. The flask was heated at 80°C. The progress of the reaction was monitored by NMR spectroscopy. To isolate the product as a free amine, the reaction mixture was treated with aqueous HCl (1M, 1.5 mL), and stirred for 1 hour at room temperature. The solvent was removed under the vacuum and water (5 mL) was added to the residual solid to dissolve the ammonium salt. Aqueous solution of NaHCO$_3$ was added and 1-butylamine was extracted with ether (3×2 mL). Solvent was removed under reduced pressure.

**NMR spectral data for the products.**

99% conversion to III-31a in 48 hours: $^1$H NMR (ethanol/D$_2$O, 400MHz): $\delta$ = 7.56 – 7.79 (m, 5ArH), 4.51 (q, $J = 7.3$ Hz, CH$_2$ – ethyl acetate), 4.15 (s, 1H, NH), 3.04 (q, $J = 7.2$ Hz, CH$_2$CH$_3$), 2.41 (s, 3H, CH$_3$ – ethyl acetate) ppm.

The product was isolated in 95% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta$ = 7.19-7.41 (m, 5H, ArH), 3.80 (s, 2H, CH$_2$), 2.70 (q, $J = 7.2$ Hz, CH$_2$), 1.56 (bs, 1H, NH), 1.15 (t, $J = 7.2$ Hz, CH$_3$) ppm.
Hz, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 139.9 (C Ar), 128.2 (C Ar), 128.0 (C Ar), 126.5 (C Ar), 53.1 (Ph-CH₂-NH), 43.5 (CH₂-NH), 15.2 (CH₃) ppm.

18% conversion to III-31b in 20 hours: ¹H NMR (ethanol/D₂O, 400MHz): δ = 7.81 (d, J = 8.8 Hz, 2ArH), 7.08 (d, J = 8.8 Hz, 2ArH), 3.54-3.66 (m, 2H, CH₂) ppm.

76% conversion to III-31c in 24 hours: ¹H NMR (ethanol/D₂O, 400MHz): δ = 7.54-7.67 (m, 2ArH), 7.16-7.27 (m, 2ArH), 4.18 (s, 2H, CH₂), 4.12 (s, 3H, OCH₃), 2.97 (q, J = 7.2 Hz, 2H, CH₂CH₃) ppm.

23% conversion to III-31d in 20 hours: ¹H NMR (ethanol/D₂O, 400MHz): δ = 7.30-7.40 (m, 3ArH), 4.13 (s, 2H, CH₂), 3.12 (q, J = 7.2 Hz, 2H, CH₂CH₃), 2.76 (s, 6H, CH₃) ppm.

90% conversion to III-31ea in 20 hours: ¹H NMR (ethanol/D₂O, 400MHz): δ = 3.05 (q, J = 7.2 Hz, 2H, CH₂CH₃), 1.36 (s, 9H, tBu) ppm.

99% conversion to III-31eb in 48 hours: ¹H NMR (ethanol/D₂O, 400MHz): δ = 3.02 (q, J = 7.1 Hz, 4H, CH₂CH₃), 1.49 (t, J = 7.1 Hz, 6H, CH₂CH₃) 1.37 (s, 9H, tBu) ppm.
V. 4. 3. Transfer hydrogenation of heterocyclic compounds

**General procedure.** A Schlenk flask was charged with a heterocyclic compound (0.50 mmol), a stock solution of III-20/20’ in 2-2-propanol (10 mg/mL, 0.42 mL), a stock solution of KOtBu in 2-propanol (10 mg/mL, 0.28 mL), and 2-propanol (1.3 mL) under N₂ atmosphere. The flask was heated at 80°C. The progress of the reaction was monitored by NMR spectroscopy. The product was isolated, after the solvent was removed under vacuum, and purified on a chromatographic column with silica gel, eluted with a mixture of hexane and ethyl acetate (4:1).
NMR spectral data for the products.

99% conversion to III-33a in 24 hours (with 5mol% III-20/20’):

$^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.23$ (dd, $J_{HH} = 13.7$, 7.2 Hz, 2ArH), 6.88 (dd, $J_{HH} = 14.7$, 7.6 Hz, 2ArH), 5.35 (s, NH), 3.69 – 3.57 (m, CH$_2$), 3.10 (t, $J_{HH} = 6.4$ Hz, CH$_2$), 2.34 – 2.23 (m, CH$_2$) ppm.

The product was isolated in 55% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.00$-7.10 (m, 2Ar-H), 6.68-6.74 (m, Ar-H), 6.55 (d, $J_{HH} = 7.85$ Hz, Ar-H), 3.83 (s, NH), 3.33-3.40 (m, CH$_2$), 2.82-2.89 (m, CH$_2$), 1.98-2.07 (m, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta =$ 144.9 (C$_{Ar}$), 129.6 (C$_{Ar}$-H), 126.7 (C$_{Ar}$-H), 121.5 (C$_{Ar}$), 117.0 (C$_{Ar}$-H), 114.3 (C$_{Ar}$-H), 42.1 (CH$_2$), 27.1 (CH$_2$), 22.3 (CH$_2$) ppm.

83% conversion to III-33b in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 8.05$ (d, $J_{HH} = 2.3$ Hz, Ar-H), 7.15–7.33 (m, 2Ar-H), 3.57–3.75 (m, CH$_2$), 3.29 (t, $J_{HH} = 6.4$ Hz, CH$_2$), 2.30-2.39 (m, CH$_2$) ppm.

The product was isolated in 79% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.80$ (dd, $J = 4.6$, 1.2 Hz, Ar-H), 6.83 (dd, $J = 8.0$, 4.7 Hz, Ar-H), 6.67 (dd, $J = 8.0$, 1.3 Hz, Ar-H), 3.28 – 3.17 (m, CH$_2$), 2.88 (t, $J = 6.5$ Hz, CH$_2$), 1.92 – 2.01 (m, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta =$ 142.73 (C$_{Ar}$), 140.99 (C$_{Ar}$), 137.83 (C$_{Ar}$-H), 121.90 (C$_{Ar}$-H), 120.17 (C$_{Ar}$-H), 41.34 (CH$_2$), 30.32 (CH$_2$), 21.75 (CH$_2$) ppm.
72% conversion to III-33c in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 6.84 - 6.69$ (m, ArH), 3.74 (s, CH$_2$) ppm.

The product was isolated in 70% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 6.54 - 6.63$ (m, 2ArH), 6.44 – 6.53 (m, 2ArH), 3.39 (s, 4CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 133.70$ (2C$_{Ar}$), 118.79 (2C$_{Ar}$-H), 114.74 (2C$_{Ar}$-H), 41.25 (2CH$_2$) ppm.

64% conversion to III-33d in 24 hours (with 5mol% III-20/20$^\circ$):

$^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 8.46$ (s, ArH), 8.43 (d, $J_{HH} = 5.0$ Hz, ArH), 7.30 (d, $J_{HH} = 5.0$ Hz, ArH), 2.95-3.06 (m, 2CH$_2$), 2.09 – 2.02 (m, 2CH$_2$) ppm.

The product was isolated in 56% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 8.29$ (s, ArH), 8.25 (d, $J = 5.0$ Hz, ArH), 6.96 (d, $J = 5.0$ Hz, ArH), 2.65 – 2.83 (m, 2CH$_2$), 1.69 – 1.91 (m, 2CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 150.44$ (C$_{Ar}$-H), 146.41 (C$_{Ar}$-H), 146.03 (C$_{Ar}$), 132.87 (C$_{Ar}$), 123.78 (C$_{Ar}$-H), 28.62 (CH$_2$), 26.21 (CH$_2$), 22.55 (2CH$_2$) ppm.

13% conversion to III-33e in 24 hours (with 5mol% III-20/20$^\circ$):

$^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.63$ (d, $J_{HH} = 7.9$ Hz, ArH), 7.27 (d, $J_{HH} = 7.9$ Hz, ArH), 3.23 (t, $J_{HH} = 5.7$ Hz, CH$_2$), 3.05 (t, $J_{HH} = 6.4$ Hz, CH$_2$), 2.82 (s, CH$_3$), 2.21 (m, CH$_2$), 2.13 (m, CH$_2$) ppm.
35% conversion to III-33fa in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta$ = 7.22-7.29 (m, 4ArH), 7.11 (d, $J_{HH}$ = 8.0 Hz, 2ArH), 6.99 (t, $J_{HH}$ = 7.4 Hz, 2ArH) ppm.

65% conversion to III-33fb in 24 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta$ = 8.29 (d, $J_{HH}$ = 8.5 Hz, ArH), 8.12 (s, ArH), 8.00 (d, $J_{HH}$ = 8.1 Hz, ArH), 7.88 (t, $J_{HH}$ = 7.7 Hz, ArH), 7.71 (t, $J_{HH}$ = 7.5 Hz, ArH), 3.39 (t, $J_{HH}$ = 6.5 Hz, CH$_2$), 3.23 (t, $J_{HH}$ = 6.3 Hz, CH$_2$), 2.32 – 2.22 (m, CH$_2$), 2.18 – 2.07 (m, CH$_2$) ppm.

The product was isolated in 64% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta$ = 8.08 (d, $J$ = 8.5 Hz, ArH), 7.90 (s, ArH), 7.80 (d, $J$ = 8.1 Hz, ArH), 7.76 – 7.67 (m, ArH), 7.58 – 7.49 (m, ArH), 3.24 (t, $J$ = 6.5 Hz, CH$_2$), 3.08 (t, $J$ = 6.3 Hz, CH$_2$), 2.14 – 2.05 (m, CH$_2$), 2.03 – 1.94 (m, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta$ = 159.44 (C$_{Ar}$), 146.74 (C$_{Ar}$), 135.07 (C$_{Ar}$-H), 131.08 (C$_{Ar}$), 130.41 (C$_{Ar}$), 128.58 (C$_{Ar}$-H), 128.40 (C$_{Ar}$-H), 127.00 (C$_{Ar}$-H), 125.63 (C$_{Ar}$-H), 33.70 (CH$_2$), 29.38 (CH$_2$), 23.35 (CH$_2$), 23.03 (CH$_2$) ppm.

36% conversion to III-33g in 18 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta$ = 7.87 (dd, $J_{HH}$ = 7.2, 5.2 Hz, 2ArH), 7.49 (t, $J_{HH}$ = 7.5 Hz, ArH), 7.40 (t, $J_{HH}$ = 7.4 Hz, ArH), 7.35 – 7.25 (m, 2ArH), 7.07 (d, $J_{HH}$ = 7.9 Hz, ArH), 7.02 (t, $J_{HH}$ = 7.5 Hz, ArH), 4.58 (s, CH$_2$) ppm.
The product was isolated in 31% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.68$ (dd, $J = 7.1$, 5.2 Hz, 2ArH), 7.31 (t, $J = 7.6$ Hz, ArH), 7.21 (t, $J = 7.4$ Hz, ArH), 7.10 (t, $J = 7.6$ Hz, 2ArH), 6.84 (t, $J = 7.5$ Hz, ArH), 6.67 (d, $J = 8.0$ Hz, ArH), 4.40 (s, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 145.01$ (C$_{Ar}$), 133.01 (C$_{Ar}$), 129.07 (C$_{Ar}$), 128.95 (C$_{Ar}$-H), 127.78 (C$_{Ar}$-H), 127.22 (C$_{Ar}$-H), 126.15 (C$_{Ar}$-H), 126.03 (C$_{Ar}$), 123.74 (C$_{Ar}$-H), 122.56 (2C$_{Ar}$-H), 119.43 (C$_{Ar}$-H), 115.26 (C$_{Ar}$-H), 46.53 (CH$_2$) ppm.

$^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.63$ (s, 2CH), 5.21 (s, CH$_2$) ppm.

The product was isolated in 36% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.63$ (s, 2CH), 5.21 (s, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 144.8$ (2CH), 44.9 (CH$_2$) ppm.

Traces of III-33k in 24 hours (with 5mol% III-20/20'): $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 8.90$ (d, $J_{HH} = 4.1$ Hz, ArH), 8.27 (d, $J_{HH} = 8.3$ Hz, ArH), 7.49 – 7.69 (m, 3ArH), 3.71 – 3.79 (m, CH$_2$), 3.13 (t, $J_{HH} = 6.3$ Hz, CH$_2$), 2.27 – 2.31 (m, CH$_2$) ppm.

62% conversion to III-33m in 24 hours (with 5mol% III-20/20'): $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.55$ (d, $J_{HH} = 7.3$ Hz, ArH), 7.44 (t, $J_{HH} = 7.7$ Hz, ArH), 7.18 (t, $J_{HH} = 7.3$ Hz, ArH), 7.10 (d, $J_{HH} = 8.0$ Hz, ArH), 4.90 (t, $J_{HH} = 8.7$ Hz, CH$_2$), 3.57 (t, $J_{HH} = 8.7$ Hz, CH$_2$) ppm.
The product was isolated in 59% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.19$ (d, $J = 6.5$ Hz, ArH), 7.08 – 7.13 (m, ArH), 6.81 – 6.86 (m, ArH), 6.79 (d, $J = 8.0$ Hz, ArH), 4.56 (t, $J = 8.7$ Hz, CH$_2$), 3.21 (t, $J = 8.7$ Hz, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 161.17$ (C$_{Ar}$), 127.87 (C$_{Ar}$-H), 27.76 (C$_{Ar}$), 124.90 (C$_{Ar}$-H), 120.35 (C$_{Ar}$-H), 109.33 (C$_{Ar}$-H), 71.01 (CH$_2$), 29.80 (CH$_2$) ppm.

99% conversion to III-33n in 5 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.44$ (t, $J_{HH} = 7.9$ Hz, 2ArH), 7.35 (d, $J_{HH} = 7.5$ Hz, ArH), 7.28 – 7.17 (m, ArH), 3.66 – 3.47 (m, 2CH$_2$) ppm.

The product was isolated in 98% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.16$ – 7.24 (m, 2ArH), 7.07 – 7.16 (m, ArH), 7.01 (td, $J = 7.4$, 1.1 Hz, ArH), 3.32 – 3.39 (m, CH$_2$), 3.25 – 3.31 (m, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 141.51$ (C$_{Ar}$), 140.03 (C$_{Ar}$), 127.31 (C$_{Ar}$-H), 124.39 (C$_{Ar}$-H), 124.09 (C$_{Ar}$-H), 122.14 (C$_{Ar}$-H), 36.21 (CH$_2$), 33.29 (CH$_2$) ppm.

V. 4. 4. Transfer hydrogenation of olefins

**General procedure.** A Schlenk flask was charged with an alkene (0.50 mmol), a stock solution of III-20/20 in 2-propanol (10 mg/mL, 0.42 mL), a stock solution of KOTBu in 2-propanol (10 mg/mL, 0.22 mL) and 2-propanol (1.3 mL) under N$_2$ atmosphere. The flask was heated at 80$^\circ$C. The progress of the reaction was monitored by NMR spectroscopy. Where applicable, the product was extracted with diethyl ether from aqueous solution.
NMR spectral data for the products.

99% conversion to **III-35a** in 1.5 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.63$ (t, $J = 7.6$ Hz, 2ArH), 7.49 – 7.59 (m, 3ArH), 3.03 (q, $J = 7.6$ Hz, CH$_2$CH$_3$) ppm. *NMR signal of CH$_3$-group is overlapped by solvent signal. GC/MS vs phenylethane standard was performed to confirm the product.

98% conversion to **III-35b** in 1.5 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 1.31$ (s, C(CH$_3$)$_3$), 1.28 (t, $J_{HH} = 7.6$ Hz, CH$_3$) ppm. *NMR signal of CH$_2$-group is likely overlapped by solvent signal. GC/MS vs 2,2-dimethylbutane standard was performed to confirm the product.

99% conversion to **III-35c** in 1 hour: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 1.72$-1.80 (m, CH$_2$), 1.38 (t, $J_{HH} = 6.8$ Hz, CH$_3$) ppm. GC/MS vs 1-hexane standard was performed to confirm the product.

85% conversion to **III-35d** in 5 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 1.89$ (s, 12H) ppm. GC/MS vs cyclohexane standard was performed to confirm the product.
99% conversion to \textbf{III-35g} in 1 hour: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 5.40$ (hept, $J_{HH} = 6.2$ Hz, OCH), 2.92 (hept, $J_{HH} = 7.1$ Hz, CHCOOR), 1.68 – 1.65 (d, $J_{HH} = 6.2$ Hz, C(CH$_3$)$_3$) ppm.

The product was isolated in 75% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 4.97$ (sep, $J_{HH} = 6.25$ Hz, OCH(CH$_3$)$_2$), 2.58 (t, $J_{HH} = 6.24$ Hz, CH$_2$COOR), 2.05 – 1.91 (m, CH$_3$CH$_3$), 1.58 (d, $J_{HH} = 6.3$ Hz, C(CH$_3$)$_2$), 1.30 (t, $J_{HH} = 7.4$ Hz, CH$_2$CH$_3$) ppm.

99% conversion to \textbf{III-35h} in 1 hour: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 5.33$ (hept, $J_{HH} = 6.2$ Hz, OCH), 2.58 (t, $J_{HH} = 7.3$ Hz, CH$_2$COOR), 2.05 – 1.91 (m, CH$_3$CH$_3$), 1.58 (d, $J_{HH} = 6.3$ Hz, C(CH$_3$)$_2$), 1.30 (t, $J_{HH} = 7.4$ Hz, CH$_2$CH$_3$) ppm.

The product was isolated in 79% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 4.97$ (sep, $J_{HH} = 6.24$ Hz, OCH(CH$_3$)$_2$), 2.21 (t, $J_{HH} = 6.16$ Hz, CH$_3$COOR), 1.52-1.65 (m, CH$_2$-CH$_3$), 1.19 (d, $J_{HH} = 6.25$ Hz, CH(CH$_3$)$_2$), 0.88 (t, $J_{HH} = 6.20$ Hz, CH$_2$-CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 173.8$ (COOR), 69.2 (CH(CH$_3$)$_2$), 36.3 (CH$_2$-COOR), 21.9 (CH(CH$_3$)$_2$), 18.5 (CH$_2$-CH$_3$), 13.6 (CH$_2$-CH$_3$) ppm.

5% conversion to \textbf{III-35i} in 21 hours (with 3mol% \textbf{III-20/20'}):

$^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.32 - 7.16$ (m, 4 ArH), 2.94-3.00 (m, 2CH$_2$), 1.99-2.03 (m, 2CH$_2$) ppm.
97% conversion to **III-35j** in 21 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 8.06$ (dd, $J_{HH} = 5.9$, 3.3 Hz, 2ArH), 7.88 (s, 2ArH), 7.71 (dd, $J_{HH} = 6.4$, 2.6 Hz, 2ArH), 3.28-3.41 (m, 2CH$_2$), 2.24-2.29 (m, 2CH$_2$) ppm.

The product was isolated in 95% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.72$ (dd, $J = 6.2$, 3.3 Hz, 2ArH), 7.55 (s, 2ArH), 7.36 (dd, $J = 6.3$, 3.2 Hz, 2ArH), 2.87 – 3.10 (m, 2CH$_2$), 1.78 – 1.94 (m, 2 CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 136.23$ (2C$_{Ar}$), 132.12 (2C$_{Ar}$), 126.98 (2C$_{Ar}$H), 126.65 (2C$_{Ar}$H), 124.89 (2C$_{Ar}$H), 29.79 (CH$_2$), 23.40 (CH$_2$) ppm.

V. 4. 5. Transfer hydrogenation of alkynes

**General procedure.** A Schlenk flask was charged with an alkyne (0.50 mmol), a stock solution of 20/20 in 2-propanol (10 mg/mL, 0.84 mL), a stock solution of KOtBu in 2-propanol (10 mg/mL, 0.44 mL) and 2-propanol (0.8 mL) under N$_2$ atmosphere. The flask was heated at 80°C. The progress of the reaction was monitored by NMR spectroscopy.

**NMR spectral data for the products.**

99% conversion to **III-37a** in 41 hours (with 1mol% **III-20/20**). The volume of the solvent was reduced by half under reduced pressure. The colourless crystals of the product were filtered and dried under vacuum. Yield 77%.

$^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.54$-7.59 (m, 4 ortho-ArH), 7.37-7.45 (m, 4 meta-ArH), 7.28-7.35 (m, 2 para-ArH), 7.16 (s, 2CH); $^{13}$C NMR (CDCl$_3$, 400MHz): $\delta = 137.4$ (ipso-C$_{Ar}$), 128.7 (meta-C$_{Ar}$), 127.6 (CH), 126.5 (ortho-C$_{Ar}$) ppm.
99% conversion to **III-37b** (Z:E 13:86) in 40 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.72$ (t, $J_{HH} = 8.3$ Hz, AH), 7.62 – 7.37 (m, ArH), 7.32 (d, $J = 4.6$ Hz, CH$_E$-isomer), 6.86 (d, $J_{HH} = 12.2$ Hz, CH$_Z$-isomer), 6.76 (d, $J_{HH} = 12.2$ Hz, CH$_Z$-isomer) ppm.

The major product was isolated in 83% yield: $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.54$-7.59 (m, 4 ortho-ArH), 7.37-7.45 (m, 4 meta-ArH), 7.28-7.35 (m, 2 para-ArH), 7.16 (s, 2CH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 137.4$ (ipso-C$_{Ar}$), 128.7 (meta-C$_{Ar}$), 127.6 (CH), 126.5 (ortho-C$_{Ar}$) ppm.

22% conversion to **III-37c** in 72 hour: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 6.68$ (d, $J_{HH} = 15.7$ Hz, CH), 6.50 (dq, $J_{HH} = 15.7$, 6.9 Hz, CH), 2.17 (d, $J_{HH} = 7.5$ Hz, CH$_3$) ppm.

77% conversion to **III-38c** in 72 hour: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.31$-7.70 (m, ArH), 2.88 (t, $J_{HH} = 7.6$ Hz, CH$_2$), 1.96 (h, $J_{HH} = 7.5$ Hz, CH$_2$), 1.25 (t, $J_{HH} = 7.5$ Hz, CH$_3$) ppm.

25% conversion to **III-37d** (Z:E 35:65) in 72 hours: $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.73 – 7.42$ (m, ArH), 6.82 (d, $J_{HH} = 11.6$ Hz, CH$_Z$-isomer), 6.76 (d, $J_{HH} = 15.8$ Hz, CH$_E$-isomer),
6.55-6.64 (m, CH\textsubscript{E}-isomer), 6.00-6.09 (m, CH\textsubscript{Z}-isomer), 2.70 (ddt, \(J_{HH} = 7.5, 7.1, 1.8\) Hz, CH\textsubscript{Z}-isomer), 2.62 – 2.56 (m, CH\textsubscript{E}-isomer), 1.85-1.94 (m, CH\textsubscript{2} \textit{Z- and E-isomers}) ppm.

\begin{align*}
\text{Ph} & \text{Pr} \\
\text{III-38d} & 74\% \text{ conversion to III-38d in 72 hour: } ^1\text{H NMR (2-propanol/D}_2\text{O, 400MHz): } \delta = 7.73 – 7.42 (\text{m, ArH}), 2.76 (t, J_{HH} = 7.0 \text{ Hz, CH}_2), 2.07 – 1.97 (m, CH_2) \text{ ppm. *Other NMR signals can not be assigned as they are overlapped by the solvent signals.}
\end{align*}

\begin{align*}
\text{Ph} & \text{H} \\
\text{III-37e} & 20\% \text{ conversion to III-37e in 20 hours: } ^1\text{H NMR (2-propanol/D}_2\text{O, 400MHz): } \delta = 8.31 (d, J_{HH} = 7.6 \text{ Hz, ortho-ArH}), 7.07 (d, J_{HH} = 11.9 \text{ Hz, CH}), 6.28 (d, J_{HH} = 11.9 \text{ Hz, CH}) \text{ ppm. *Other NMR signals can not be assigned as they are overlapped by the substrate’s signals.}
\end{align*}

V. 4. 6. Transfer hydrogenation of esters

**General procedure.** A Schlenk flask was charged with an ester (0.5 mmol), a stock solution of III-20/20' in ethanol (10 mg/mL, 2.1 mL), and a stock solution of KOrBu in ethanol (10 mg/mL, 1.1 mL) under N\textsubscript{2} atmosphere. The flask was heated at 80\textdegree C. The progress of the reaction was monitored by NMR spectroscopy.
NMR spectral data for the products.

**III-40a**

99% conversion to III-40a in 4 hours. $^1$H NMR (ethanol/D$_2$O, 400MHz): $\delta = 4.58$ (q, $J_{HH} = 7.1$ Hz, CH$_2$, ethyl acetate), 4.35 (q, $J_{HH} = 9.1$ Hz, CH$_2$, 2,2,2-trifluoroethanol), 2.49 (s, CH$_3$COOR, ethyl acetate), 1.72 (t, $J_{HH} = 7.1$ Hz, CH$_2$CH$_3$, ethyl acetate) ppm.

COSY NMR spectrum does not show interaction between signal at $\delta = 4.35$ ppm and any other proton signal. Based on that it was assigned to 2,2,2-trifluoroethanol. $^{19}$F {$^1$H} NMR (ethanol/D$_2$O, 400MHz): $\delta = -76.3$ (CF$_3$, residual trifluoroacetate), -77.7 (CF$_3$, 2,2,2-trifluoroethanol) ppm.

**III-40b**

78% conversion to III-40b in 7.5 hours: $^1$H NMR (ethanol/D$_2$O, 400MHz): $\delta = 4.37$ (tq, $J_{HF} = 13.9$, 0.9 Hz, CH$_2$) ppm. $^{19}$F {$^1$H} NMR (ethanol/D$_2$O, 400MHz): $\delta = -84.1$ (CF$_3$), -126.3 (CF$_2$) ppm.

**III-40h**

99% conversion to III-40h in 3 hour: $^1$H NMR (ethanol/D$_2$O, 400MHz): $\delta = 8.46$ (d, $J_{HH} = 8.3$ Hz, 2ArH), 7.94 (d, $J_{HH} = 8.3$ Hz, 2 ArH), 4.84 (q, $J_{HH} = 7.1$ Hz, OCH$_2$CH$_3$), 4.29 (s, NH), 3.11 (q, $J_{HH} = 7.2$ Hz, NCH$_2$CH$_3$), 1.86 (t, $J_{HH} = 7.1$ Hz, OCH$_2$CH$_3$) ppm.

To isolate the product, the solvent was removed under reduced pressure. The residue was dissolved in ether, filtered and dried under vacuum. Yield 98%. $^1$H NMR (CDCl$_3$,
(400MHz): $\delta = 7.93$ (d, $J = 8.3$ Hz, 2ArH), 7.42 (d, $J = 8.3$ Hz, 2ArH), 4.30 (q, $J = 7.1$ Hz, OCH$_2$CH$_3$), 3.76 (s, CH$_2$), 2.58 (q, $J = 7.2$ Hz, NHCH$_2$CH$_3$), 1.34 (t, $J = 7.1$ Hz, OCH$_2$CH$_3$), 1.29 (t, $J = 7.2$ Hz, NHCH$_2$CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 165.96$ (COOR), 146.71 (C$_{Ar}$), 129.70 (C$_{Ar}$-H), 126.41 (C$_{Ar}$-H), 126.36 (C$_{Ar}$), 61.01 (OCH$_2$CH$_3$), 56.95 (CH$_2$), 46.65 (NHCH$_2$CH$_3$), 14.34 (CH$_3$), 14.29 (CH$_3$) ppm.

99% conversion to III-40j in 5 hours: $^1$H NMR (ethanol/D$_2$O, 400MHz): $\delta = 4.60$ (q, $J_{HH} = 7.2$ Hz, OCH$_2$CH$_3$), 4.59 (s, CH$_2$OH); $^1$H COSY NMR (ethanol/D$_2$O, 400MHz): $\delta = 4.60$ (q, OCH$_2$CH$_3$) – 1.74 (t, OCH$_2$CH$_3$) ppm.

To isolate the product, the solvent was removed on rotary evaporator. The residue was dissolved in ether, filtered and carefully dried under reduced pressure. Ethyl glycolate was obtained as a colourless liquid. Yield 94%. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 4.26$ (q, $J = 7.1$ Hz, CH$_2$), 4.16 (s, CH$_2$), 2.63 (s, OH), 1.31 (t, $J = 7.2$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 173.49$ (COOR), 61.66 (CH$_2$), 60.72 (CH$_2$), 14.25 (CH$_3$) ppm.

V. 4. 7. Kinetic studies of transfer hydrogenation of cyclohexene

**General procedure for kinetic analysis under pseudo-first order conditions.** A low-pressure NMR sample tube was charged with cyclohexene (25.3 µL, 0.25 mmoL), a stock solution of III-20/20' in 2-propanol (20 mg/mL), a stock solution of KOrBu in 2-propanol (20 mg/mL) and 2-propanol under N$_2$ atmosphere. Toluene was added to equalize volumes in the experiments with different amounts of 2-propanol. The NMR sample tube
was placed in NMR spectrometer and heated at 80°C. The spectra were taken every 2 or 3 minutes. The data were uploaded to Dynamics Centre 2.4.5, where the signals of cyclohexene were integrated and processed to provide a best-fit curve. Then the data derived from the program was used to determine the order of the reaction. Only points before 20% conversion of the substrate were used in further calculations. The graphs of the logarithm of the substrate concentration vs time was created. The slopes of the curves for each experiments equal the initial rates of the reaction under the corresponding conditions.

V. 4. 8. Z-E isomerization

**General procedure for isomerization of cis-stilbene.** A Schlenk flask was charged with cis-stilbene (89.2 μL, 0.50 mmol), a stock solution of III-20/20’ in 2-propanol (10 mg/ml, 0.42 mL), a stock solution of KOrBu in 2-propanol (10 mg/mL, 0.22 mL) and 2-propanol (1.3 mL) under N₂ atmosphere. The flask was heated at 80°C for 3 hours. 99% conversion to trans-stilbene was reached. The volume of the solvent was reduced by half under reduced pressure. The colourless crystals of the product were filtered and dried under vacuum. Yield 85%. ¹H NMR (CDCl₃, 400MHz): δ = 7.54-7.59 (m, 4 ortho-ArH), 7.37-7.45 (m, 4 meta-ArH), 7.28-7.35 (m, 2 para-ArH), 7.16 (s, 2CH); ¹³C NMR (CDCl₃, 400MHz): δ = 137.4 (ipso-C₆H₅), 128.7 (meta-C₆H₅), 127.6 (CH), 126.5 (ortho-C₆H₅) ppm.

V. 5. Amine alkylation via hydrogen borrowing methodology

**General procedure for amine alkylation with alcohols.** A Schlenk flask was charged with an amine (0.50 mmol) and alcohol (1.00 mmol), a stock solution of III-20/20’ in t-amyl alcohol (10 mg/mL, 0.42 mL), a stock solution of KOrBu in t-amyl alcohol (10
mg/mL, 0.28 mL), and in t-amyl alcohol (0.8 mL) under nitrogen atmosphere. The flask was heated at 120°C for 24 hours. To isolate the product as a free amine, the reaction mixture was treated with aqueous HCl (1M, 1.5 mL), and stirred for 1 hour at room temperature. The solvent was removed under the vacuum. Aqueous solution of NaHCO$_3$ and CDCl$_3$ (1 mL) were added to the residue. Organic phase was separated and dried over MgSO$_4$.

**NMR spectral data for the products.**

Yield of ammonium chloride salt - 113 mg, 97% (via the reaction of benzylamine with benzyl alcohol): $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.36 – 7.49$ (m, 8H, ArH), 7.28 – 7.36 (m, 2H, ArH), 3.87 (s, 4H, CH$_2$), 2.06 (bs, 1H, NH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 140.2$ (C$_{Ar}$), 128.5 (C$_{Ar}$), 128.3 (C$_{Ar}$), 127.1 (C$_{Ar}$), 53.1 (Ph-CH$_2$-NH) ppm.

Yield of ammonium chloride salt - 111 mg, 96% (via the reaction of benzylamine with hexan-1-ol) and 107 mg, 93% (via the reaction of hexylamine with benzyl alcohol): $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.32 – 7.39$ (m, 4H, ArH), 7.24 – 7.31 (m, 1H, ArH), 3.82 (s, 2H, Ph-CH$_2$-NH), 2.65 (t, $J = 7.2$ Hz, C$_5$H$_{11}$-CH$_2$-NH), 2.27 (bs, 1H, NH), 1.49 – 1.58 (m, 2H, CH$_2$), 1.29 – 1.36 (m, 6H, CH$_2$), 0.90 (t, $J = 6.5$ Hz, 3H, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 140.0$ (C$_{Ar}$), 128.4 (C$_{Ar}$), 128.3 (C$_{Ar}$), 127.0 (C$_{Ar}$), 53.9 (Ph-CH$_2$-NH), 49.4 (C$_5$H$_{11}$-CH$_2$-NH), 31.76 (CH$_2$), 29.84 (CH$_2$), 27.03 (CH$_2$), 22.62 (CH$_2$), 14.05 (CH$_3$) ppm.
Yield of ammonium chloride salt – 94.8 mg, 95% (via the reaction of benzylamine with butan-1-ol).\textsuperscript{1}H NMR (CDCl\textsubscript{3}, 400MHz): \(\delta = 7.34 – 7.42\) (m, 4H, ArH), 7.24 – 7.33 (m, 1H, ArH), 3.86 (s, 2H, Ph-CHO-NH), 3.03 (bs, 1H, NH), 2.60 – 2.72 (m, 2H, C\textsubscript{3}H\textsubscript{7}-CH\textsubscript{2}-NH), 1.51 – 1.65 (m, 2H, CH\textsubscript{2}), 1.30 – 1.42 (m, 2H, CH\textsubscript{2}), 1.25 – 1.39 (m, 8H, CH\textsubscript{2}), 0.93 (t, \(J = 7.3\) Hz, 3H, CH\textsubscript{3}), 0.89 (t, \(J = 6.9\) Hz, 3H, CH\textsubscript{3}); \textsuperscript{13}C NMR (CDCl\textsubscript{3}, 101MHz): \(\delta = 138.4\) (C\textsubscript{Ar}), 128.6 (C\textsubscript{Ar}), 128.5 (C\textsubscript{Ar}), 127.4 (C\textsubscript{Ar}), 53.4 (Ph-CHO-NH), 48.5 (C\textsubscript{3}H\textsubscript{7}-CHO-NH), 31.3 (CH\textsubscript{2}), 20.4 (CH\textsubscript{2}), 13.9 (CH\textsubscript{3}) ppm.

Yield of ammonium chloride salt – 88.2 mg, 91% (via the reaction of hexylamine with butan-1-ol) and 89.1 mg, 92% (via the reaction of butylamine with hexan-1-ol).\textsuperscript{1}H NMR (CDCl\textsubscript{3}, 400MHz): \(\delta = 3.61\) (bs, 1H, NH), 2.61 – 2.72 (m, 4H, CH\textsubscript{2}-NH), 1.53 – 1.66 (m, 4H, CH\textsubscript{2}), 1.25 – 1.39 (m, 8H, CH\textsubscript{2}), 0.93 (t, \(J = 7.3\) Hz, 3H, CH\textsubscript{3}), 0.89 (t, \(J = 6.9\) Hz, 3H, CH\textsubscript{3}); \textsuperscript{13}C NMR (CDCl\textsubscript{3}, 101MHz): \(\delta = 49.5\) (CH\textsubscript{2}-NH), 49.2 (CH\textsubscript{2}-NH), 31.6 (CH\textsubscript{2}), 31.1 (CH\textsubscript{2}), 29.0 (CH\textsubscript{2}), 27.0 (CH\textsubscript{2}), 22.6 (CH\textsubscript{2}), 20.4 (CH\textsubscript{2}), 14.0 (CH\textsubscript{3}), 13.9 (CH\textsubscript{3}) ppm.

**General procedure for alkylation of anilines.** A Schlenk flask was charged with an amine (0.50 mmol) and hexanol (90 mL, 1.50 mmol), a stock solution of III-20/20° in \(t\)-amyl alcohol (10 mg/mL, 0.42 mL), a stock solution of KOtBu in \(t\)-amyl alcohol (10 mg/mL, 0.28 mL), and in \(t\)-amyl alcohol (0.8 mL) under nitrogen atmosphere. The flask
was heated at 120°C for 24 hours. Corresponding amines were isolated by column chromatography (n-hexanes/ethyl acetate mixture).

**NMR spectral data for the products.**

---

66% conversion to secondary amine was reached after 24 hours. Yield of free amine is 54%. \(^1\)H NMR (CDCl\(_3\), 400MHz): δ = 7.17 – 7.23 (m, 2H, ArH), 6.75 – 6.81 (m, 1H, ArH), 6.64 – 6.69 (m, 2H, ArH), 3.11 (t, \(J = 7.0\) Hz, 2H, CH\(_2\)-NH), 1.58 – 1.68 (m, 2H, CH\(_2\)), 1.28 – 1.45 (m, 6H, CH\(_2\)), 0.90 (t, \(J = 6.9\) Hz, 3H, CH\(_3\)); \(^13\)C NMR (CDCl\(_3\), 101MHz): δ = 147.6 (C\(_{Ar}\)), 129.3 (C\(_{Ar}\)), 118.0 (C\(_{Ar}\)), 113.5 (C\(_{Ar}\)), 44.7 (CH\(_2\)-NH), 31.6 (CH\(_2\)), 29.2 (CH\(_2\)), 26.8 (CH\(_2\)), 22.6 (CH\(_2\)), 14.0 (CH\(_3\)) ppm.

---

47% conversion to secondary amine was reached after 24 hours. Yield of free amine is 46%. \(^1\)H NMR (CDCl\(_3\), 400MHz): δ = 7.40 (d, \(J = 8.4\) Hz, 2H, ArH), 6.38 (d, \(J = 8.8\) Hz, 2H, ArH), 3.06 (t, \(J = 7.1\) Hz, 2H, CH\(_2\)-NH), 1.55 – 1.66 (m, 2H, CH\(_2\)), 1.21 – 1.37 (m, 6H, CH\(_2\)), 0.89 (d, \(J = 6.7\) Hz, 3H, CH\(_3\)); \(^13\)C NMR (CDCl\(_3\), 101MHz): δ = 148.2 C\(_{Ar}\)), 137.8 (C\(_{Ar}\)), 115.0 (C\(_{Ar}\)), 77.6 (C\(_{Ar}\)), 43.9 (CH\(_2\)-NH), 31.7 (CH\(_2\)), 29.5 (CH\(_2\)), 26.9 (CH\(_2\)), 22.7 (CH\(_2\)), 14.2 (CH\(_3\)) ppm.
54% conversion to secondary amine was reached after 24 hours. Yield of free amine is 50%. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 6.87 - 7.01$ (m, 2H, ArH), 6.53 – 6.65 (m, 2H, ArH), 3.14 (t, $J = 7.1$ Hz, 2H, CH$_2$-NH), 1.71– 1.82 (m, 2H, CH$_2$), 1.43 – 1.58 (m, 6H, CH$_2$), 0.98 (t, $J = 6.7$ Hz, 3H, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 155.8$ (d, $J = 234.4$ Hz, C$_{Ar}$), 145.0 (C$_{Ar}$) 115.7 (d, $J = 22.3$ Hz, C$_{Ar}$), 113.6 (d, $J = 7.3$ Hz, C$_{Ar}$), 44.8 (CH$_2$-NH), 31.8 (CH$_2$), 29.6 (CH$_2$), 26.9 (CH$_2$), 22.7 (CH$_2$), 14.1 (CH$_3$) ppm.

68% conversion to secondary amine was reached after 24 hours. Yield of free amine is 65%. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.00$ (d, $J = 8.1$ Hz, 2H, ArH), 6.55 (d, $J = 8.4$ Hz, 2H, ArH), 3.10 (t, $J = 7.1$ Hz, 2H, CH$_2$-NH), 2.26 (s, 3H, CH$_3$), 1.78 – 1.63 (m, 2H, CH$_2$), 1.35 – 1.15 (m, 6H, CH$_2$), 0.93 (t, $J = 6.8$ Hz, 3H, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 146.4$ (C$_{Ar}$), 129.8 (C$_{Ar}$), 126.3 (C$_{Ar}$), 113.0 (C$_{Ar}$), 44.5 (CH$_2$-NH), 31.8 (CH$_2$), 29.7 (CH$_2$), 27.0 (CH$_2$), 22.7 (CH$_2$), 14.1 (CH$_3$) ppm.

69% conversion to secondary amine was reached after 24 hours. Yield of free amine is 65%. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 6.78$ (d, $J = 8.9$ Hz, 2H, ArH), 6.58 (d, $J = 8.9$ Hz, 2H, ArH), 3.75 (s, 3H, OCH$_3$), 3.06 (t, $J = 7.2$ Hz, 2H, CH$_2$-NH), 1.67 –
1.50 (m, 2H, CH₂), 1.47 – 1.23 (m, 6H, CH₂), 0.90 (t, J = 6.9 Hz, 3H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 152.0 (C₆), 142.9 (C₆), 114.9 (C₆), 114.1 (C₆), 55.9 (OCH₃), 45.1 (CH₂-NH), 31.7 (CH₂), 29.7 (CH₂), 26.9 (CH₂), 22.6 (CH₂), 14.1 (CH₃) ppm.

**General procedure for amination of alcohols with ammonium formate.** A Schlenk flask was charged with ammonium formate (0.60 mmol, 37.8 mg), III-20/20’ (0.012 mmol, 10.0 mg), KOrBu (0.06 mmol, 6.8 mg), and alcohol (1.5 mL) under nitrogen atmosphere. The flask was heated at 110°C for 24-72 hours. To isolate the product as a free amine, the reaction mixture was treated with aqueous HCl (1M, 1.5 mL), and stirred for 1 hour at room temperature. The solvent was removed under the vacuum. Aqueous solution of NaHCO₃ and CDCl₃ (1 mL) were added to the residue. Organic phase was separated and dried over MgSO₄.

**NMR spectral data for the products.**

Yield of the ammonium chloride salt is 81% after 24 hours of reflux.

¹H NMR (CDCl₃, 400 MH): δ = 2.70 (q, J = 7.2 Hz, 4H, CH₂-NH), 2.30 (s, 1H, NH), 1.15 (t, J = 7.2 Hz, 6H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 43.9 (CH₂-NH), 14.9 (CH₃) ppm.

Yield of the ammonium chloride salt is 85% after 72 hours of reflux.

¹H NMR (CDCl₃, 400 MH): δ = 2.56 (q, J = 7.2 Hz, 6H, CH₂-N),
1.05 (t, J = 7.2 Hz, 9H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 46.4 (CH₂-N), 11.5 (CH₃) ppm.

Yield of the ammonium chloride salt is 89% after 24 hours of reflux.

¹H NMR (CDCl₃, 400 MH): δ = 2.59 – 2.65 (m, 4H, CH₂-NH), 2.19 (s, 1H, NH), 1.51 (dt, J = 15.0, 7.3 Hz, 4H, CH₂), 1.26 – 1.36 (m, 4H, CH₂), 0.92 (d, J = 7.3 Hz, 6H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 49.7 (CH₂-NH), 31.9 (CH₂), 20.6 (CH₂), 14.1 (CH₃) ppm.

Yield of the ammonium chloride salt is 95% after 72 hours of reflux.

2.37 – 2.44 (m, 6H, CH₂-N), 1.41 (dd, J = 16.7, 9.2 Hz, 6H, CH₂), 1.27 (dt, J = 19.0, 5.9 Hz, 6H, CH₂), 0.90 (t, J = 7.3 Hz, 9H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 54.0 (CH₂-N), 29.1 (CH₂), 20.9 (CH₂), 14.2 (CH₃) ppm.

Yield of the ammonium chloride salt is 90% after 24 hours of reflux.

¹H NMR (CDCl₃, 400MHz): δ = 2.53 – 2.64 (m, 4H, CH₂-NH), 1.79 (bs, 1H, NH), 1.40 – 1.52 (m, 4H, CH₂), 1.22 – 1.35 (m, 12H, CH₂), 0.88 (t, J = 6.8 Hz, 6H, CH₃); ¹³C NMR (CDCl₃, 101MHz): δ = 50.1 (CH₂-NH), 31.8 (CH₂), 30.1 (CH₂), 27.1 (CH₂), 22.6 (CH₂), 14.0 (CH₃) ppm.
Yield of the ammonium chloride salt is 95% after 72 hours of reflux. 
$^1$H NMR (CDCl$_3$, 400MHz): $\delta = 2.38 - 2.49$ (m, 6H, CH$_2$-N), 1.38 – 1.49 (m, 6H, CH$_2$), 1.21 – 1.30 (m, 18H, CH$_2$), 0.87 (t, $J = 7.1$ Hz, 9H, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 54.2$ (CH$_2$-N), 31.9 (CH$_2$), 27.4 (CH$_2$), 27.1 (CH$_2$), 22.8 (CH$_2$), 14.2 (CH$_3$) ppm.

Yield of the ammonium chloride salt is 94% after 24 hours heating at 120°C. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.36 - 7.49$ (m, 8H, ArH), 7.28 – 7.36 (m, 2H, ArH), 3.87 (s, 4H, CH$_2$), 2.06 (bs, 1H, NH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 140.2$ (C$_{Ar}$), 128.5 (C$_{Ar}$), 128.3 (C$_{Ar}$), 127.1 (C$_{Ar}$), 53.1 (Ph-CH$_2$-NH) ppm.

Yield of the ammonium chloride salt is 41% after 24 hours of reflux. 
$^1$H NMR (CDCl$_3$, 400MHz): $\delta = 2.93$ (hept, $J = 6.3$ Hz, 2H, CH-NH), 1.77 (bs, 1H, NH), 1.06 (d, $J = 6.3$ Hz, 12H, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 45.4$ (CH-NH), 23.3 (CH$_3$) ppm.

V. 6. Transition metal-free transfer hydrogenation

**General procedure for transfer hydrogenation with alkali metal isopropoxides.**

A Schlenk flask was charged with acetophenone (58.3 µL, 0.50 mmol) or cyclohexanone (51.8 µL, 0.50 mmol), alkali metal isopropoxide (0.05 mmol), and dry 2-propanol (1.5 mL) under nitrogen atmosphere. The solution was stirred at 100°C. The progress of the reaction was monitored by NMR spectroscopy.
NMR spectral data for the products.

\[
\begin{align*}
\text{1H NMR (2-propanol/D}_2\text{O, 400MHz): } & \delta = 7.75 \text{ (d, } J_{HH} = 7.4 \text{ Hz, ortho-} \\
& \text{ArH), 7.66 (t, } J_{HH} = 7.6 \text{ Hz, meta-} \text{ArH), 7.57 (t, } J_{HH} = 7.3 \text{ Hz, para-} \text{ArH),} \\
& 5.23 (q, J_{HH} = 6.5 \text{ Hz, CH-OH), 1.84 (d, } J_{HH} = 6.5 \text{ Hz, CH}_3 \text{) ppm.}
\end{align*}
\]

\[
\begin{align*}
\text{1H NMR (2-propanol/D}_2\text{O, 400MHz): } & \delta = 3.79-3.94 \text{ (m, 1H, CH-} \\
& \text{OH), 2.19-2.26 (m, 2H, CH}_2 \text{), 2.03-2.13 (m, 2H, CH}_2 \text{), 1.84-1.93 (m, 1H,} \\
& \text{CH}_2 \text{) ppm. *Other NMR signals can not be assigned as they are} \\
& \text{overlapped by the solvent signals.}
\end{align*}
\]

**General procedure for transfer hydrogenation with different additives.** A Schlenk flask was charged with acetophenone (58.3 μL, 0.50 mmol), lithium isopropoxide (3.3 mg, 0.05 mmol), ligand/additive (0.50 mmol), and dry 2-propanol (1.5 mL) under nitrogen atmosphere. The solution was stirred at 100°C. The progress of the reaction was monitored by NMR spectroscopy.

**General procedure for transfer hydrogenation of ketones.** A Schlenk flask was charged with a ketone (0.50 mmol), lithium isopropoxide (3.3 mg, 0.05 mmol), dppe (19.9 mg, 0.05 mmol) or LiCl (21.2 mg, 0.5 mmol), and dry 2-propanol (1.5 mL) under nitrogen atmosphere. The solution was stirred at 100°C. The progress of the reaction was monitored by NMR spectroscopy.

**Product Isolation.** 1M HCl aqueous solution (50 μL) was added. Then the solvent was removed on rotary evaporator. 1-Phenylethanol was isolated on chromatographic column, eluted by hexane/ethyl acetate mixture (4:1, then 1:1).
The product was isolated in 79% yield (with dppe) and 80% yield (with LiCl) after 5 hours of reflux. $^1$H NMR (CDCl$_3$, 400MHz): δ = 7.26 – 7.46 (m, 5ArH), 4.84 – 4.97 (m, CH$_3$-OH), 2.16 (s, OH), 1.52 (d, $J = 6.5$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): δ = 146.0 (C$_{Ar}$), 128.6 (C$_{Ar}$), 127.6 (C$_{Ar}$), 125.5 (C$_{Ar}$), 70.5 (CH-OH), 25.2 (CH$_3$) ppm.

The product was isolated in 80% yield (with dppe) and 86% yield (with LiCl) after 2 hours of reflux. $^1$H NMR (CDCl$_3$, 400MHz): δ = 7.18 – 7.25 (m, 4H, ArH), 4.77 (q, $J = 6.5$ Hz, CH$_2$-OH), 3.56 (s, 1H, OH), 1.38 (d, $J = 6.5$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): δ = 144.4 (C$_{Ar}$), 132.7 (C$_{Ar}$), 128.3 (C$_{Ar}$), 126.9 (C$_{Ar}$), 69.26 (CH-OH), 25.17 (CH$_3$) ppm.

The product was isolated in 88% yield (with dppe) and 87% yield (with LiCl) after 1 hour of reflux. $^1$H NMR (CDCl$_3$, 400MHz): δ = 7.57 (d, $J = 8.2$ Hz, 2ArH), 7.45 (d, $J = 8.2$ Hz, 2ArH), 4.90 (q, $J = 6.4$ Hz, CH$_2$-OH), 2.64 (s, 1H, 1H), 1.44 (d, $J = 6.5$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): δ = 151.5 (C$_{Ar}$), 132.3 (C$_{Ar}$), 126.1 (C$_{Ar}$), 118.9 (CN), 110.8 (C$_{Ar}$), 69.4 (CH-OH), 25.4 (CH$_3$) ppm.
Conversion of 63% was reached with dppe, and 66% - with LiCl after 12 hours of reflux. $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 7.40$ (d, $J = 8.6$ Hz, 2ArH), 6.95 (d, $J = 8.7$ Hz, 2ArH), 4.93 (q, $J = 6.5$ Hz, CH-OH), 3.87 (s, 3H, OCH$_3$), 1.56 (d, $J = 6.5$ Hz, 3H, CH$_3$) ppm.

The product was isolated in 89% yield (with dppe) and 85% yield (with LiCl) after 3 hours of reflux. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.70$ (d, $J = 7.5$ Hz, 4H, o-ArH), 7.64 – 7.54 (m, 6H, ArH), 6.42 (s, 1H, CH$_2$-OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 141.1$ (C$_{Ar}$), 128.6 (C$_{Ar}$), 128.1 (C$_{Ar}$), 127.8 (C$_{Ar}$), 64.3 (CH-OH) ppm.

Conversion of 93% was reached with dppe, and 95% - with LiCl after 2 hours of reflux. $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 3.79$-3.94 (m, 1H, CH-OH), 2.19-2.26 (m, 2H, CH$_2$), 2.03-2.13 (m, 2H, CH$_2$), 1.84-1.93 (m, 1H, CH$_2$) ppm. *Other NMR signals can not be assigned as they are overlapped by the solvent signals.

The highest conversion of 56% was achieved with dppe in 42 hours. $^1$H NMR (2-propanol/D$_2$O, 400MHz): $\delta = 3.86$ (q, $J = 6.4$ Hz, 1H, CH-OH), 1.33 (s, 9H, tBu) ppm. *Other NMR signals can not be assigned as they are overlapped by the solvent signals.
The product was isolated in 59% yield with dppe after 30 hours of reflux. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 6.97$ (d, $J = 7.5$ Hz, 2H, ArH), 6.90 (t, $J = 7.5$ Hz, 2H, ArH), 6.86 – 6.81 (m, 1H, ArH), 3.55 (d, $J = 8.2$ Hz, 1H, CH-OH), 1.80 (s, 1H, OH), 0.78 – 0.66 (m, 1H, CH), 0.25 – 0.14 (m, 1H, CH$_2$), 0.14 – 0.04 (m, 1H, CH$_2$), 0.05 – 0.03 (m, 1H, CH$_2$), -0.02 – -0.15 (m, 1H, CH$_2$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta =$ 143.9 (C$_{Ar}$), 128.5 (C$_{Ar}$), 127.5 (C$_{Ar}$), 126.1 (C$_{Ar}$), 78.5 (CH-OH), 19.2 (CH), 3.6 (CH$_2$), 2.8 (CH$_2$) ppm.

**General procedure for racemization.** (S)-1-phenylethanol (100 mL, 0.827 mmol), LiOiPr (5.46 mg, 0.083 mmol) and acetophenone (9.64 mL, 0.083 mmol) were dissolved in 10ml of 2-propanol. The solution was heated in close flask at 100°C for 24 hours. After that solvent was removed under reduced pressure and ee of the product was studied by Feringa’s procedure, described above.

**Ee determination.** 1 ml aliquots were taken to determine enantiomeric excess of (S)-1-phenylethanol by Feringa’s procedure.\textsuperscript{374} 2-propanol was removed under low pressure. The residue was dissolved in CDCl$_3$. Pyridine (6.70 mL, 0.083 mmol) and PCl$_3$ (2.40 mL, 0.083 mmol) were added. Ee was determined based on the ratio of the phosphonate products (two diastereoisomers and two meso forms). $^{31}$P NMR (400MHz, CDCl$_3$): $\delta = 5.23$ (meso form), 4.68 (two diastereomers), 4.37 (meso form) ppm.
V. 6. 1. Kinetic studies of transfer hydrogenation with LiOiPr

**General procedure for kinetic analysis under pseudo-first order conditions.** A low-pressure NMR sample tube was charged with cyclohexanone (25.5 μL, 0.25 mmol), a stock solution of lithium isopropoxide in 2-propanol (1 mg/mL), and dry 2-propanol (filled to 1.5 mL) under nitrogen atmosphere. Toluene was added to equalize volumes in the experiments with different amounts of 2-propanol. The NMR sample tube was placed in NMR spectrometer and heated at 80°C. The spectra were taken every 2 or 3 minutes. The data were uploaded to Dynamics Centre 2.4.5, where the signals of cyclohexene were integrated and processed to provide a best-fit curve. Then the data derived from the program was used to determine the order of the reaction. Only points before 20% conversion of the substrate were used in further calculations. The graphs of the logarithm of the substrate concentration vs time was created. The slopes of the curves for each experiments equal the initial rates of the reaction under the corresponding conditions.

**General procedure for variable temperature analysis.** A low-pressure NMR sample tube was charged with cyclohexanone (25.5 μL, 0.25 mmol), a stock solution of lithium isopropoxide in 2-propanol (0.66 mL, 1 mg/mL, 0.01 mmol), and dry 2-propanol (filled to 0.4 mL) under nitrogen atmosphere. The NMR sample tube was placed in NMR spectrometer and heated at 70-90°C. The spectra were taken every 2 or 3 minutes. The data were uploaded to Dynamics Centre 2.4.5, where the signals of cyclohexene were integrated and processed to provide a best-fit curve. Then the data derived from the program was used to determine the order of the reaction. Only points before 20% conversion of the substrate were used in further calculations. The graphs of the logarithm of the substrate concentration
vs time was created. The slopes of the curves for each experiments equal the initial rates of the reaction under the corresponding conditions.

**General procedure for measurement of kinetic isotope effect.** A low-pressure NMR sample tube was charged with benzophenone (45.5 mg, 0.25 mmol), a stock solution of lithium isopropoxide in 2-propanol (1.5 mg, 0.025 mmol), TMEDA (3.8 µL, 0.025 mmol) and dry 2-propanol, 2-propanol-OD or 2-propanol-d₈ (1 mL) under nitrogen atmosphere. The NMR sample tube was placed in NMR spectrometer and heated at 100°C. The spectra were taken every 2 or 3 minutes. The data were uploaded to Dynamics Centre 2.4.5, where the signals of cyclohexene were integrated and processed to provide a best-fit curve. Then the data derived from the program was used to determine the order of the reaction. Only points before 20% conversion of the substrate were used in further calculations. The graphs of the logarithm of the substrate concentration vs time was created. The slopes of the curves for each experiments equal the initial rates of the reaction under the corresponding conditions.

V. 7. Hydrosilylation with zinc complex

**General procedure for hydrosilylation.** All manipulations were done under N₂ atmosphere. A stock solution of ZnMe₂ in toluene (1.2 M) and a stock solution of ligand III-10 in toluene (1.0 M) were added to 1 mL of benzene in a low-pressure NMR sample tube. One minute later aldehyde or ketone (0.429 mmol) was injected in the toluene solution, followed by silane (0.858 mmol) and methanol (4.4 mL, 0.107 mmol). Sealed NMR tube was heated at 60°C. The progress of the reaction was monitored by ¹H NMR spectroscopy.
Product Isolation. Methanol solution of KOH (1 mL, 0.5 M) was added to the reaction solution on air. The mixture was stirred at room temperature for 20 minutes, and then solvent was removed under reduced pressure. HCl aqueous solution (2 mL, 1 M) was added to the residue and 1-phenylethanol was extracted twice with DCM (1 mL). Combined organic solution was dried over MgSO$_4$ and the solvent was removed on rotary evaporator.

NMR spectral data for the products.

98% conversion was reached in 10 hours. The product was isolated in 91% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.85 - 7.93$ (m, 4H, $o$- and $m$-ArH), 7.79 – 7.84 (m, 1H, $p$-ArH), 5.22 (s, 2H, CH$_2$-OH), 2.78 (s, 1H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 141.0$ (C$_{Ar}$), 128.5 (C$_{Ar}$), 127.6 (C$_{Ar}$), 127.0 (C$_{Ar}$), 65.3 (CH$_2$-OH) ppm.

99% conversion was reached in 1 hour. The product was isolated in 94% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.63$ (d, $J = 7.9$ Hz, 2H, ArH), 7.47 (d, $J = 7.8$ Hz, 2H, ArH), 4.76 (s, 2H, CH$_2$-OH), 1.88 (s, 1H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 146.3$ (C$_{Ar}$), 132.3 (C$_{Ar}$), 127.0 (C$_{Ar}$), 118.8 (CN), 111.1 (C$_{Ar}$), 64.2 (CH$_2$-OH) ppm.

99% conversion was reached in 4 hours. The product was isolated in 93% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.47$ (d, $J = 8.4$ Hz, 2H, ArH), 7.23 (d, $J = 8.3$ Hz, 2H, ArH), 4.63 (s, 2H, CH$_2$-OH), 1.88 (s, 3H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 139.8$ (C$_{Ar}$), 131.6 (C$_{Ar}$), 128.6 (C$_{Ar}$), 121.5 (C$_{Ar}$), 64.6 (CH$_2$-OH) ppm.
98% conversion was reached in 19 hours. The product was isolated in 94% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.30$ (d, $J = 8.7$ Hz, 2H, ArH), 6.87 (d, $J = 8.7$ Hz, 2H, ArH, 4.56 (s, 2H, CH$_2$-OH), 3.80 (s, 3H, OCH$_3$), 2.20 (s, 1H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta =$ 159.7 (C$_{Ar}$), 130.0 (C$_{Ar}$), 129.3 (C$_{Ar}$), 114.1 (C$_{Ar}$), 55.2 (CH$_2$-OH), 46.2 (OCH$_3$) ppm.

98% conversion was reached in 2.5 hours. The product was isolated in 92% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.94$ (s, 1H, ArH), 7.86 (d, $J = 7.7$ Hz, 1H, ArH), 7.56 (d, $J = 7.6$ Hz, 1H, ArH), 7.44 (t, $J =$ 7.7 Hz, 1H, ArH), 4.74 (s, 2H, CH$_2$-OH), 2.59 (s, 3H, CH$_3$), 2.21 (s, 1H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta =$ 198.3 (CO), 141.6 (C$_{Ar}$), 137.3 (C$_{Ar}$), 131.6 (C$_{Ar}$), 128.8 (C$_{Ar}$), 127.5 (C$_{Ar}$), 126.6 (C$_{Ar}$), 64.6 (CH$_2$-OH), 26.7 (CH$_3$) ppm.

99% conversion was reached in 9 hours. $^1$H NMR (C$_6$H$_6$/D$_2$O, 400MHz): $\delta =$ 5.50 – 5.74 (m, 2H, -CH=CH-), 4.31 – 4.40 (m, 1H, CH$_2$-OSi), 4.22 – 4.31 (m, 1H, CH$_2$-OSi), 1.49 – 1.63 (m, 3H, CH$_3$) ppm.
97% conversion was reached in 20 hours. The product was isolated in 89% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 6.96 - 7.26$ (m, 5H, ArH), 6.42 (d, $J = 15.6$ Hz, 1H, CH), 6.09 (dt, $J = 14.8, 7.2$ Hz, 1H, CH), 4.01 (d, $J = 7.2$ Hz, 2H, CH$_2$-OH), 2.38 (s, 1H, OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 135.8$ (C$_{Ar}$), 134.0 (C$_{Ar}$), 128.6 (C$_{Ar}$), 128.2 (C$_{Ar}$), 126.6 (CH), 124.9 (CH), 45.2 (CH$_2$-OH) ppm.

97% conversion was reached in 2.5 hours. The product was isolated in 92% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.26 - 7.46$ (m, 5ArH), 4.84 – 4.97 (m, CH$_2$-OH), 2.16 (s, OH), 1.52 (d, $J = 6.5$ Hz, CH$_3$); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 146.0$ (C$_{Ar}$), 128.6 (C$_{Ar}$), 127.6 (C$_{Ar}$), 125.5 (C$_{Ar}$), 70.5 (CH-OH), 25.2 (CH$_3$) ppm.

99% conversion was reached in 9 hours. The product was isolated in 93% yield. $^1$H NMR (CDCl$_3$, 400MHz): $\delta = 7.70$ (d, $J = 7.5$ Hz, 4H, $\alpha$-ArH), 7.64 – 7.54 (m, 6H, ArH), 6.42 (s, 1H, CH$_2$-OH); $^{13}$C NMR (CDCl$_3$, 101MHz): $\delta = 141.1$ (C$_{Ar}$), 128.6 (C$_{Ar}$), 128.1 (C$_{Ar}$), 127.8 (C$_{Ar}$), 64.3 (CH-OH) ppm.
VI. Appendix

Figure 16. $^1$H NMR spectrum of compound III-1a in CDCl$_3$ (*THF).

Figure 17. $^{13}$C NMR spectrum of compound III-1a in CDCl$_3$ (*THF).

Figure 18. $^{31}$P $^1$H NMR spectrum of compound III-1a in CDCl$_3$. 
Figure 19. $^1H$ NMR spectrum of compound III-1b in C$_6$D$_6$.

Figure 20. $^{13}C$ NMR spectrum of compound III-1b in C$_6$D$_6$.

Figure 21. $^{31}P$ {$^1H$} NMR spectrum of compound III-1b in C$_6$D$_6$. 
Figure 22. $^1$H NMR spectrum of compound III-4a in CDCl$_3$.

Figure 23. $^{13}$C NMR spectrum of compound III-4a in CDCl$_3$. 


Figure 24. $^1$H NMR spectrum of compound III-4b in CDCl$_3$.

Figure 25. $^{13}$C NMR spectrum of compound III-4b in CDCl$_3$. 


Figure 26. $^1$H NMR spectrum of compound III-5a in CDCl$_3$.

Figure 27. $^{13}$C NMR spectrum of compound III-5a in CDCl$_3$.
Figure 28. $^1$H NMR spectrum of compound III-5b in CDCl$_3$.

Figure 29. $^{13}$C NMR spectrum of compound III-5b in CDCl$_3$. 
Figure 30. $^1$H NMR spectrum of compound III-6 in CDCl$_3$.

Figure 31. $^{13}$C NMR spectrum of compound III-6 in CDCl$_3$. 
Figure 32. $^1$H NMR spectrum of compound III-7 in CDCl$_3$.

Figure 33. $^{13}$C NMR spectrum of compound III-7 in CDCl$_3$. 
Figure 34. $^1$H NMR spectrum of compound III-8 in CDCl$_3$ (*Et$_2$O).

Figure 35. $^{13}$C NMR spectrum of compound III-8 in CDCl$_3$ (*Et$_2$O).
Figure 36. $^1$H NMR spectrum of compound III-9 in CDCl$_3$.

Figure 37. $^{13}$C NMR spectrum of compound III-9 in CDCl$_3$. 
Figure 38. $^1$H NMR spectrum of compound III-10 in CDCl$_3$.

Figure 39. $^{13}$C NMR spectrum of compound III-10 in CDCl$_3$. 
Figure 40. $^1$H NMR spectrum of compound III-11a in CDCl$_3$. 

Figure 41. $^{13}$C NMR spectrum of compound III-11a in CDCl$_3$. 
Figure 42. $^1$H NMR spectrum of compound III-11b in CD$_3$CN.

Figure 43. $^{13}$C NMR spectrum of compound III-11b in CD$_3$CN.
Figure 44. $^1$H NMR spectrum of compound III-12 in CDCl$_3$.

Figure 45. $^{13}$C NMR spectrum of compound III-12 in CDCl$_3$. 
Figure 46. $^1$H NMR spectrum of compound III-13 in CDCl$_3$.

Figure 47. $^{13}$C NMR spectrum of compound III-13 in CDCl$_3$. 
Figure 48. $^1$H NMR spectrum of complex III-14 in CDCl$_3$ (*free DMSO).

Figure 49. $^{13}$C NMR spectrum of complex III-14 in CDCl$_3$.

Figure 50. $^{31}$P {$^1$H} NMR spectrum of complex III-14 in CDCl$_3$. 
Figure 51. $^1$H NMR spectrum of complex III-15 in CD$_2$Cl$_2$.

Figure 52. $^{13}$C NMR spectrum of complex III-15 in CD$_2$Cl$_2$.

Figure 53. $^{31}$P {$^1$H} NMR spectrum of complex III-15 in CD$_2$Cl$_2$. 
Figure 54. $^1$H NMR spectrum of complexes III-16/16$'$ in CD$_2$Cl$_2$.

Figure 55. $^{13}$C NMR spectrum of complexes III-16/16$'$ in CD$_2$Cl$_2$. 
Figure 56. $^{31}\text{P} \{^1\text{H}\}$ NMR spectrum of complexes III-16/16’ in CD$_2$Cl$_2$. 
**Figure 57.** $^1$H NMR spectrum of complex III-17 in THF-d$_8$.

**Figure 58.** $^{31}$P {$^1$H} NMR spectrum of complex III-17 in THF-d$_8$. 
Figure 59. $^1$H NMR spectrum of complex III-18 in CD$_2$Cl$_2$.

Figure 60. $^{31}$P {$^1$H} NMR spectrum of complex III-18 in CD$_2$Cl$_2$. 
Figure 61. $^1$H NMR spectrum of complex III-19 in CD$_2$Cl$_2$.

Figure 62. $^{13}$C NMR spectrum of complex III-19 in CDCl$_3$.

Figure 63. $^{31}$P {$^1$H} NMR spectrum of complex III-19 in CD$_2$Cl$_2$. 
Figure 64. $^1$H NMR spectrum of complexes III-20/20' in CDCl$_3$.

Figure 65. $^1$H NMR spectrum (3.30-3.75 ppm) of complexes III-20/20' in CDCl$_3$. 


Figure 66. $^1$H NOE NMR spectrum of complexes III-20/20' in CDCl$_3$, excitation frequency 753.28 Hz.

Figure 67. $^1$H NOE NMR spectrum of complexes III-20/20' in CDCl$_3$, excitation frequency 439.11 Hz.
Figure 68. $^{13}$C NMR spectrum of complexes III-20/20’ in CDCl$_3$.

Figure 69. $^{31}$P {$^1$H} NMR spectrum of complexes III-20/20’ in CDCl$_3$. 
Figure 70. $^1$H NMR spectrum of complex III-21 in C$_6$D$_5$Br.
Figure 71. $^{13}$C NMR spectrum of complex III-21 in C$_6$D$_5$Br.

Figure 72. $^{31}$P {$^1$H} NMR spectrum of complex III-21 in C$_6$D$_5$Br.
Figure 73. $^1$H NMR spectrum of complex III-22 in CD$_2$Cl$_2$.

Figure 74. $^{13}$C NMR spectrum of complex III-22 in CD$_2$Cl$_2$.

Figure 75. $^{31}$P $^1$H NMR spectrum of complex III-22 in CD$_2$Cl$_2$.
Figure 76. $^1$H NMR spectrum of complexes III-24/24' in CH$_2$Cl$_2$ (with D$_2$O insert).

Figure 77. $^{13}$C-DEPT$_{135}$ NMR spectrum of complexes III-24/24' in CH$_2$Cl$_2$ (with D$_2$O insert).
Figure 78. $^1$H NMR spectrum of complex III-25 in CD$_2$Cl$_2$.

Figure 79. $^{13}$C NMR spectrum of complex III-25 in CD$_2$Cl$_2$. 

250
Figure 80. $^1$H NMR spectrum of complex III-26 in CDCl$_3$.

Figure 81. $^{13}$C NMR spectrum of complex III-26 in CDCl$_3$.

Figure 82. $^{31}$P {$^1$H} NMR spectrum of complex III-26 in CDCl$_3$. 
Figure 83. $^1\text{H}$ NMR spectrum of complex III-58 in C$_6$D$_6$ (* toluene).

Figure 84. $^{13}\text{C}$ NMR spectrum of complex III-58 in C$_6$D$_6$. 
NMR data for selected products

**Figure 85.** $^1$H NMR spectrum of 5,6,7,8-tetrahydroisoquinoline III-33d in CDCl$_3$.

**Figure 86.** $^{13}$C NMR spectrum of 5,6,7,8-tetrahydroisoquinoline III-33d in CDCl$_3$. 
Figure 87. $^1$H NMR spectrum of 1,2,3,4-tetrahydroacridine III-33fb in CDCl$_3$.

Figure 88. $^{13}$C NMR spectrum of 1,2,3,4-tetrahydroacridine III-33fb in CDCl$_3$. 
Figure 89. $^1$H NMR spectrum of 1,4-dihydro-1,3,5-triazine III-33h in CDCl$_3$.

Figure 90. $^{13}$C NMR spectrum of 1,4-dihydro-1,3,5-triazine III-33h in CDCl$_3$. 
**Figure 91.** $^1$H NMR spectrum of 1,2,3,4-tetrahydroanthracene III-35j in CDCl$_3$.

**Figure 92.** $^{13}$C NMR spectrum of 1,2,3,4-tetrahydroanthracene III-35j in CDCl$_3$. 
**Figure 93** $^1$H NMR spectrum of \textit{cis}-stilbene III-37a in CDCl$_3$.

**Figure 94.** $^{13}$C NMR spectrum of \textit{cis}-stilbene III-37a in CDCl$_3$. 
Figure 95. $^1$H NMR spectrum of TH of 1-phenyl-1-propyne III-36c in 2-propanol (after 24 h).

Figure 96. $^1$H NMR spectrum of TH of 1-phenyl-1-propyne III-36c in 2-propanol (after 72 h).
Figure 97. Superimposed $^1$H NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol after 10min (blue) and after 4h (red) of heating at 80°C.

Figure 98. $^1$H COSY NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol.
Figure 99. Superimposed $^{19}$F NMR spectrum of TH of ethyl trifluoroacetate III-39a in ethanol after 10min (blue) and after 4h (red) of heating at 80°C.
Figure 100. Superimposed $^1$H NMR spectrum of TH of ethyl pentafluoropropionate III-39b in ethanol after 10min (blue) and after 7.5h (black) of heating at 80°C.

Figure 101. Superimposed $^{19}$F NMR spectra of TH of ethyl pentafluoropropionate III-39b in ethanol after 10min (blue) and after 4h (red) of heating at 80°C.
Figure 102. $^1$H NMR spectrum of cyclopropyl(phenyl)methanol III-55h in CDCl$_3$.

Figure 103. $^{13}$C NMR spectrum of cyclopropyl(phenyl)methanol III-55h in CDCl$_3$. 
Kinetic studies of transfer hydrogenation of cyclohexene with III-20.

Figure 104. Reduction of cyclohexene III-34d with different amounts of catalyst III-20/20*.
Isomerization of Z-stilbene in 2-propanol-d$_8$

**Figure 105.** $^1$H NMR spectrum of $E$-stilbene in CDCl$_3$ as the product of Z-stilbene III-$37aa$ isomerization in 2-propanol-d$_8$.

**Figure 106.** $^2$H NMR spectrum of $E$-stilbene in CHCl$_3$ as the product of Z-stilbene III-$37aa$ isomerization in 2-propanol-d$_8$. 
Ee determination by Feringa’s procedure.

**Figure 107.** $^{31}\text{P} \left\{ ^1\text{H} \right\}$ NMR spectrum of phosphonate product of (R)-1-phenylethanol in CDCl$_3$.

**Figure 108.** $^{31}\text{P} \left\{ ^1\text{H} \right\}$ NMR spectrum of phosphonate product of racemic 1-phenylethanol in CDCl$_3$. 
Figure 109. $^{31}$P $^1$H NMR spectrum of phosphonate product of 1-phenylethanol in CDCl$_3$ after racemization.

Kinetic studies of transfer hydrogenation of cyclohexanone with LiO$i$Pr

![Graph showing the reduction of cyclohexanone with linear fits for different amounts of LiO$i$Pr.]

Figure 110. Reduction of cyclohexanone with different amounts of LiO$i$Pr.
Table 19. Crystal structure determination parameters for complex III-14.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Empirical formula</td>
<td>C_{24.20}H_{34.40}Cl_{2.40}N_{2}O_{2}PRuS_{2}</td>
</tr>
<tr>
<td>Formula weight</td>
<td>666.58</td>
</tr>
<tr>
<td>Temperature, K</td>
<td>200(2)</td>
</tr>
<tr>
<td>Color, habit</td>
<td>Yellow, plate</td>
</tr>
<tr>
<td>Wavelength, Å</td>
<td>0.71073</td>
</tr>
<tr>
<td>Crystal system</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Space group system</td>
<td>C2/c</td>
</tr>
<tr>
<td>a, Å</td>
<td>37.785(4)</td>
</tr>
<tr>
<td>a, °</td>
<td>90</td>
</tr>
<tr>
<td>b, Å</td>
<td>9.2026(9)</td>
</tr>
<tr>
<td>b, °</td>
<td>90.052(4)</td>
</tr>
<tr>
<td>c, Å</td>
<td>17.5220(16)</td>
</tr>
<tr>
<td>c, °</td>
<td>90</td>
</tr>
<tr>
<td>Volume, Å³</td>
<td>6092.8(10)</td>
</tr>
<tr>
<td>Z</td>
<td>8</td>
</tr>
<tr>
<td>Density (calcd), Mg/m³</td>
<td>1.453</td>
</tr>
<tr>
<td>Absorption coefficient, mm⁻¹</td>
<td>0.938</td>
</tr>
<tr>
<td>F(000)</td>
<td>2731</td>
</tr>
<tr>
<td>Crystal size, mm³</td>
<td>0.140 × 0.120 × 0.080</td>
</tr>
<tr>
<td>Theta range for data collection (°)</td>
<td>1.162 to 24.709</td>
</tr>
<tr>
<td>Index ranges</td>
<td>-44 ≤ h ≤ 44, -10 ≤ k ≤ 10, -20 ≤ l ≤ 20</td>
</tr>
<tr>
<td>Reflections collected</td>
<td>24972</td>
</tr>
<tr>
<td>Independent reflections</td>
<td>4922 [R(int) = 0.0469]</td>
</tr>
<tr>
<td>Completeness to θ</td>
<td>99.9 %</td>
</tr>
<tr>
<td>Absorption correction</td>
<td>Semi-empirical from equivalents</td>
</tr>
<tr>
<td>Max. and min. transmission</td>
<td>0.7457 and 0.5310</td>
</tr>
<tr>
<td>Refinement method</td>
<td>Full-matrix least-squares on F²</td>
</tr>
<tr>
<td>Data / restraints / parameters</td>
<td>4922 / 150 / 362</td>
</tr>
<tr>
<td>Goodness-of-fit on F²</td>
<td>1.055</td>
</tr>
<tr>
<td>Final R indices [I&gt;2sigma(I)]</td>
<td>R₁ = 0.0848, wR₂ = 0.2270</td>
</tr>
<tr>
<td>R indices (all data)</td>
<td>R₁ = 0.0993, wR₂ = 0.2365</td>
</tr>
</tbody>
</table>
Table 20. Crystal structure determination parameters for complex III-19.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empirical formula</strong></td>
<td>C_{42}H_{49}N_{5}P_{2}Cl_{2}Ru</td>
</tr>
<tr>
<td><strong>Formula weight</strong></td>
<td>857.77</td>
</tr>
<tr>
<td><strong>Temperature, K</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Color, habit</strong></td>
<td>Yellow, plate</td>
</tr>
<tr>
<td><strong>Wavelength, Å</strong></td>
<td>0.71073</td>
</tr>
<tr>
<td><strong>Crystal system</strong></td>
<td>Monoclinic</td>
</tr>
<tr>
<td><strong>Space group</strong></td>
<td>C2/c</td>
</tr>
<tr>
<td><strong>a, Å</strong></td>
<td>41.660(3)</td>
</tr>
<tr>
<td><strong>b, Å</strong></td>
<td>10.1941(7)</td>
</tr>
<tr>
<td><strong>c, Å</strong></td>
<td>24.0706(17)</td>
</tr>
<tr>
<td><strong>Volume, Å^3</strong></td>
<td>10142.2(12)</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>Density (calcd), Mg/m^3</strong></td>
<td>1.124</td>
</tr>
<tr>
<td><strong>Absorption coefficient, mm^-1</strong></td>
<td>0.507</td>
</tr>
<tr>
<td><strong>F(000)</strong></td>
<td>3552.0</td>
</tr>
<tr>
<td><strong>Crystal size, mm^3</strong></td>
<td>0.18 × 0.14 × 0.08</td>
</tr>
<tr>
<td><strong>Theta range for data collection (°)</strong></td>
<td>1.98 to 52</td>
</tr>
<tr>
<td><strong>Index ranges</strong></td>
<td>-51 ≤ h ≤ 51, -12 ≤ k ≤ 12, -29 ≤ l ≤ 29</td>
</tr>
<tr>
<td><strong>Reflections collected</strong></td>
<td>43305</td>
</tr>
<tr>
<td><strong>Independent reflections</strong></td>
<td>9970 [R_{int} = 0.0694]</td>
</tr>
<tr>
<td><strong>Completeness to θ</strong></td>
<td>100 %</td>
</tr>
<tr>
<td><strong>Absorption correction</strong></td>
<td>Multi-scan (SADABS)</td>
</tr>
<tr>
<td><strong>Max. and min. transmission</strong></td>
<td>0.7461 and 0.6451</td>
</tr>
<tr>
<td><strong>Refinement method</strong></td>
<td>Full-matrix least-squares on F^2</td>
</tr>
<tr>
<td><strong>Data / restraints / parameters</strong></td>
<td>9970 / 0 / 476</td>
</tr>
<tr>
<td><strong>Goodness-of-fit on F^2</strong></td>
<td>1.022</td>
</tr>
<tr>
<td><strong>Final R indices [I&gt;2sigma(I)]</strong></td>
<td>R_1 = 0.0509, wR_2 = 0.1203</td>
</tr>
<tr>
<td><strong>R indices (all data)</strong></td>
<td>R_1 = 0.0747, wR_2 = 0.1284</td>
</tr>
</tbody>
</table>
### Table 21. Crystal structure determination parameters for complex III-21.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empirical formula</strong></td>
<td>C_{76}H_{76}Cl_{4}N_{4}P_{4}Ru_{2}</td>
</tr>
<tr>
<td><strong>Formula weight</strong></td>
<td>1513.22</td>
</tr>
<tr>
<td><strong>Temperature, K</strong></td>
<td>200(2) K</td>
</tr>
<tr>
<td><strong>Color, habit</strong></td>
<td>orange, plate</td>
</tr>
<tr>
<td><strong>Wavelength, Å</strong></td>
<td>0.71073</td>
</tr>
<tr>
<td><strong>Crystal system</strong></td>
<td>Monoclinic</td>
</tr>
<tr>
<td><strong>Space group</strong></td>
<td>P 21/n</td>
</tr>
<tr>
<td>a, Å</td>
<td>22.2100(8)</td>
</tr>
<tr>
<td>a, °</td>
<td>90</td>
</tr>
<tr>
<td>b, Å</td>
<td>12.7915(5)</td>
</tr>
<tr>
<td>b, °</td>
<td>113.185(2)°</td>
</tr>
<tr>
<td>c, Å</td>
<td>27.9520(11)</td>
</tr>
<tr>
<td>c, °</td>
<td>90</td>
</tr>
<tr>
<td><strong>Volume, Å³</strong></td>
<td>7299.8(5)</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>4</td>
</tr>
<tr>
<td><strong>Density (calcd), Mg/m³</strong></td>
<td>1.377</td>
</tr>
<tr>
<td><strong>Absorption coefficient, mm⁻¹</strong></td>
<td>0.692</td>
</tr>
<tr>
<td><strong>F(000)</strong></td>
<td>3104</td>
</tr>
<tr>
<td><strong>Crystal size, mm³</strong></td>
<td>0.960 x 0.790 x 0.190</td>
</tr>
<tr>
<td><strong>Theta range for data collection (°)</strong></td>
<td>1.778 to 25.249</td>
</tr>
<tr>
<td><strong>Index ranges</strong></td>
<td>-26&lt;=h&lt;=26, -15&lt;=k&lt;=13, -32&lt;=l&lt;=33</td>
</tr>
<tr>
<td><strong>Reflections collected</strong></td>
<td>60653</td>
</tr>
<tr>
<td><strong>Independent reflections</strong></td>
<td>13172 [R(int) = 0.0730]</td>
</tr>
<tr>
<td><strong>Completeness to θ</strong></td>
<td>99.7</td>
</tr>
<tr>
<td><strong>Absorption correction</strong></td>
<td>SADABS, Bruker (2003)</td>
</tr>
<tr>
<td><strong>Max. and min. transmission</strong></td>
<td>0.5994 and 0.5994</td>
</tr>
<tr>
<td><strong>Refinement method</strong></td>
<td>Full-matrix least-squares on F²</td>
</tr>
<tr>
<td><strong>Data / restraints / parameters</strong></td>
<td>13172 / 597 / 812</td>
</tr>
<tr>
<td><strong>Goodness-of-fit on F²</strong></td>
<td>1.153</td>
</tr>
<tr>
<td><strong>Final R indices [I&gt;2sigma(I)]</strong></td>
<td>R₁ = 0.0979, wR₂ = 0.2105</td>
</tr>
<tr>
<td><strong>R indices (all data)</strong></td>
<td>R₁ = 0.1381, wR₂ = 0.2354</td>
</tr>
</tbody>
</table>
**Table 22.** Crystal structure determination parameters for complex III-25.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Empirical formula</strong></td>
<td>$\text{C}<em>{23}\text{H}</em>{30}\text{F}<em>{6}\text{N}</em>{3}\text{OPRu}$</td>
</tr>
<tr>
<td><strong>Formula weight</strong></td>
<td>610.54</td>
</tr>
<tr>
<td><strong>Temperature, K</strong></td>
<td>200(2)</td>
</tr>
<tr>
<td><strong>Color, habit</strong></td>
<td>orange, plate</td>
</tr>
<tr>
<td><strong>Wavelength, Å</strong></td>
<td>0.71073</td>
</tr>
<tr>
<td><strong>Crystal system</strong></td>
<td>orthorhombic</td>
</tr>
<tr>
<td><strong>Space group</strong></td>
<td>$\text{P2}_1\text{2}_1\text{2}_1$</td>
</tr>
<tr>
<td><strong>a, Å</strong></td>
<td>8.2323(4)</td>
</tr>
<tr>
<td><strong>b, Å</strong></td>
<td>16.0006(7)</td>
</tr>
<tr>
<td><strong>c, Å</strong></td>
<td>19.9255(9)</td>
</tr>
<tr>
<td><strong>Volume, Å$^3$</strong></td>
<td>2624.6(2)</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>8</td>
</tr>
<tr>
<td><strong>Density (calcd), Mg/m$^3$</strong></td>
<td>3.090</td>
</tr>
<tr>
<td><strong>Absorption coefficient, mm$^{-1}$</strong></td>
<td>1.443</td>
</tr>
<tr>
<td><strong>F(000)</strong></td>
<td>2480.0</td>
</tr>
<tr>
<td><strong>Crystal size, mm$^3$</strong></td>
<td>$0.23 \times 0.14 \times 0.09$</td>
</tr>
<tr>
<td><strong>Theta range for data collection (°)</strong></td>
<td>3.26 to 56.68</td>
</tr>
<tr>
<td><strong>Index ranges</strong></td>
<td>$-10 \leq h \leq 10, -21 \leq k \leq 21, -26 \leq l \leq 26$</td>
</tr>
<tr>
<td><strong>Reflections collected</strong></td>
<td>85269</td>
</tr>
<tr>
<td><strong>Independent reflections</strong></td>
<td>6540 [$R_{\text{int}} = 0.0698, R_{\text{sigma}} = 0.0361$]</td>
</tr>
<tr>
<td><strong>Completeness to θ</strong></td>
<td>100</td>
</tr>
<tr>
<td><strong>Absorption correction</strong></td>
<td>None</td>
</tr>
<tr>
<td><strong>Max. and min. transmission</strong></td>
<td>0.8787 and 0.7326</td>
</tr>
<tr>
<td><strong>Refinement method</strong></td>
<td>Full-matrix least-squares on $F^2$</td>
</tr>
<tr>
<td><strong>Data / restraints / parameters</strong></td>
<td>6540 / 0 / 362</td>
</tr>
<tr>
<td><strong>Goodness-of-fit on $F^2$</strong></td>
<td>1.020</td>
</tr>
<tr>
<td><strong>Final R indices [I&gt;2sigma(I)]</strong></td>
<td>$R_1 = 0.0356, wR_2 = 0.0762$</td>
</tr>
<tr>
<td><strong>R indices (all data)</strong></td>
<td>$R_1 = 0.0514, wR_2 = 0.0824$</td>
</tr>
</tbody>
</table>
VII. References


(212) Sahin, Z.; Gurbuz, N.; Ozdemir, I.; Sahin, O.; Buyukgungor, O.; Achar, M.; Bruneau, C., Organometallics 2015, 34 (11), 2296-2304.
(222) Yan, T.; Feringa, B. L.; Barta, K., ACS Catal. 2016, 6 (1), 381-388.
(244) Oppenauer, R. V., Recueil des Travaux Chimiques des Pays-Bas banner 1937, 56, 137-144.


Meerwein, H.; Schmidt, R., *Justus Liebig's Annalen Der Chemie* 1925, 444, 221-238.


