

Editorial

# From Mechanisms in Homogeneous Metal Catalysis to Applications in Chemical Synthesis

Axel Klein <sup>1,\*</sup> , Bernd Goldfuss <sup>2</sup> and Jarl-Ivar van der Vlugt <sup>3</sup>

<sup>1</sup> University of Cologne, Department of Chemistry, Institute for Inorganic Chemistry, Greinstrasse 6, D-50939 Cologne, Germany

<sup>2</sup> University of Cologne, Department of Chemistry, Institute for Organic Chemistry, Greinstrasse 4, D-50939 Cologne, Germany; goldfuss@uni-koeln.de

<sup>3</sup> Homogeneous, Bioinspired, and Supramolecular Catalysis, van't Hoff Institute for Molecular Sciences University of Amsterdam Science Park 904, 1098 XH Amsterdam, The Netherlands; J.I.vanderVlugt@uva.nl

\* Correspondence: axel.klein@uni-koeln.de; Tel.: +49-221-470-4006; Fax: +49-221-470-4899

Received: 30 December 2017; Accepted: 19 January 2018; Published: 24 January 2018

**Abstract:** Man-made homogeneous catalysis with the aid of transition metal compounds looks back on a long history of almost one hundred years. Still, more detailed insight into the underlying mechanisms is warranted. The knowledge of how transition metals with their specific/characteristic properties, such as oxidation states, redox chemistry, spin states, kinetics, and coordination preference will contribute to these processes paving the way to optimize existing processes, and to finding new exciting organic, inorganic, and organometallic transformations and to broaden the substrate scope through catalyst design. This special issue collects very recent mechanistic insight from experimental, theoretical, and mixed experimental–theoretical approaches.

At the very end of the 19th century, Alfred Werner established the basis of our modern understanding of (transition) metal complexes [1]. When Otto Roelen discovered and developed the hydroformylation reaction (or Oxo Process) in the late 1930s, probably the first milestone in homogeneous catalysis, serendipity played an important role [2,3]. A deeper understanding of the specific interactions of ligands and metals came only later with the development of binding concepts such as the ligand field theory and the molecular orbital theory, e.g., the Dewar–Chatt–Duncanson model, which was developed in the 1950s for the binding of olefins to transition metals [4]. Originally dedicated to the binding situation of the complex anion of the Zeise salt  $[\text{PtCl}_3(\text{ethene})]^-$ , it soon became clear that homogeneously metal-catalyzed transformations of olefins can be described and understood using this concept [4–7]. Probably the most prominent examples of such olefin complexes are the Pd derivatives of the Zeise anion  $[\text{PdCl}_3(\text{olefin})]^-$ , which were the pivotal species of today's technically most important organocatalytic process, the Wacker Process (or Wacker Oxidation), which was developed starting in the 1950s [7–10].

About 80 years after Roelen's hydroformylation, on a list of recently identified “holy grails” in chemistry “perfect catalysis” is prominently in the top ten [11] and homogeneous transition metal catalysis provides the basis for many desired transformations, e.g., in C–H aminations, in site-selective bond activations, for the functionalization of alkanes or in oxidative couplings yielding complex target molecules. Even since the rise of “metal-free” organo-catalysis at the beginning of our millennium and its enormous impact on organic transformations, the meanwhile established “classical” (transition) metal mediated applications reside as solid pillars in the toolbox for chemical synthesis [12–14]. Recent Nobel Prizes in chemistry, i.e., 2010 to Richard F. Heck, Ei-ichi Negishi and Akira Suzuki, 2005 to Yves Chauvin, Robert H. Grubbs and Richard R. Schrock, as well as 2001 to William S. Knowles, Ryoji Noyori and K. Barry Sharpless [14,15] clearly highlight homogeneous transition metal catalysis as an outstanding discipline, crucial for various areas of chemical synthesis.

Mechanistic insights are crucial for understanding and in this way important for the further development of multifaceted transition metal mediated transformations [16–21]. Short-living, sensitive and highly reactive intermediates as well as different oxidation- and spin-states [17,20,21] often complicate mechanistic analyses. Steadily advancing experimental techniques (spectroscopy, electrochemical methods, X-ray analysis, etc.) as well as more and more powerful computers applicable to a growing arsenal of modern theoretical methods (e.g., DFT with dispersion corrections) [22] today provide unforeseen tools to explore and conquer the mechanistic conundrum of transition metal mediated processes. This special issue “Revealing Reaction Mechanisms in Homogeneous Transition Metal Catalysis” provides highlights of this exciting chemistry in two reviews and five original papers.

Budnikova, Dudkina and Khrizanforov reviewed the use, desirable properties and complementarity of oxidants for non-redox-neutral palladium-catalyzed aromatic oxidative C–H functionalizations, in order to arrive at effective and waste-free processes [23]. In a separate contribution, displaying a multi-national collaborative effort, Budnikova, Vicic and Klein comprehensively review the mechanisms that are relevant in the nickel(tpy)-catalyzed C–C cross-coupling, wherein tpy is the 2,2':6'-2'' terpyridine ligand [24]. This contribution centers around Negishi-type coupling reactions to illustrate studies describing the role of low-valent as well as trivalent Ni(tpy)-systems. The second part of the review illustrates advances in the use of Ni(tpy) complexes for electrochemical cross-coupling. It is clear that further progress in this field is highly desired, given the anticipated switch to a more electron-driven chemical industry.

This review nicely connects to the article by Iffland, Petuker, van Gastel and Apfel on mechanistic implications for the Ni(I)-catalyzed Kumada cross-coupling [25]. Ni(I) is slowly emerging as a very important oxidation state for nickel, particularly with respect to its involvement in carbon–carbon bond formation protocols. This article describes the chemistry of Ni(I)–Triphos for the coupling of phenylmagnesium bromide with aryl halides. A mechanistic study using UV and EPR spectroscopy in combination with DFT calculations suggests that Ni(I) rather than Ni(II) is the active species for this cross-coupling reaction.

Metz, Heck, Gohlke, Kröckert, Louven, McKeown, Hoffmann, Jones and Herres-Pawlis describe the use of structurally characterized chiral Zn-catalysts bearing two different N-donor ligands (amine-guanidine) for the solvent-free polymerization of *rac*-lactide, including kinetic studies using *in situ* IR and NMR spectroscopy and complemented by DFT calculations [26]. All three complexes showed activity for the formation of polylactide, although stereo information is not transferred from the ligand to the polymeric materials, resulting in an atactic polymer.

The work by van de Watering, Heijtebrink, van der Vlugt, Dzik, de Bruin and Reek describes the coordination chemistry of a series of tripodal tetraphosphane ligands (tris-(3-methylindolephosphane)phosphanes = PP<sub>3</sub>) with ruthenium(II) [27]. The reduction of these species under an N<sub>2</sub> atmosphere led to isolable Ru–N<sub>2</sub> complexes. Using chlorotrimethylsilane, superstoichiometric formation of ammonia was achieved but likely involving a species that does not bear any PP<sub>3</sub> ligand, as indicated by control experiments. The Ru(II) species did prove stable and active for the dehydrogenation of formic acid, which is a relevant reaction in the context of renewable hydrogen storage and CO<sub>2</sub> valorization.

Nguyen, Tashima, (the late) Ikariya and Kuwata report on the room temperature dimerization of 1,1-diphenylpropargyl alcohol mediated by the organometallic Ru(II) complex [Ru(Cp\*)Cl(diene)]—diene = 1,5-cyclooctadiene (cod) or isoprene, leading to the new crystalline product alkylidenebenzocyclobutenyl alcohol [28]. This product is formed via the intermediacy of facile selective aromatic C–H activation on one of the arene rings within the substrate, as revealed by labelling studies and control experiments to exclude other pathways. The reaction of the related complex [Ru(Cp\*)(H)(cod)] with the same substrate resulted in the formation of a novel ruthenocene containing one triply-substituted Cp-analog.

Eliasson, Chatterjee, Occhipinti and Jensen published a comprehensive computational study on the mechanism of the Rh-mediated decarbonylative dehydration of fatty acids to provide linear

terminal alkenes (LAO) and carboxylic acid, with anhydride as the co-reagent [29]. Furthermore, the authors investigated the mechanism of Pd-systems for the same reaction in order to find similarities and differences between both catalyst types, to draw conclusions regarding the relative rates and to provide avenues for catalyst optimization. Linear terminal alkenes or linear alpha olefins are key commodity chemicals and petrochemical intermediates that are e.g., used in the large-scale technical synthesis of oxo alcohols to give detergents and plasticizers [29], using e.g., the hydroformylation reaction [2].

## References

1. Constable, E.C.; Housecroft, C.E. Coordination chemistry: The scientific legacy of Alfred Werner. *Chem. Soc. Rev.* **2013**, *42*, 1429–1439. [[CrossRef](#)] [[PubMed](#)]
2. Franke, R.; Selent, D.; Börner, A. Applied Hydroformylation. *Chem. Rev.* **2012**, *112*, 5675–5732. [[CrossRef](#)] [[PubMed](#)]
3. Chikkali, S.H.; van der Vlugt, J.I.; Reek, J.N.H. Hybrid diphosphorus ligands in rhodium catalysed asymmetric hydroformylation. *Coord. Chem. Rev.* **2014**, *262*, 1–15. [[CrossRef](#)]
4. Frenking, G. The Dewar–Chatt–Duncanson bonding model of transition metal–olefin complexes examined by modern quantum chemical methods. In *Modern Coordination Chemistry: The Legacy of Joseph Chatt*; Leigh, G.J., Winterton, N., Eds.; RSC Publishing: Cambridge, UK, 2002; Volume 221, ISBN 978-1-84755-148-1.
5. Nyholm, R.S. Synthesis, Structure and Reactions of Chelate Metal–Olefin Complexes. *Pure Appl. Chem.* **1971**, *27*, 127–144. [[CrossRef](#)]
6. Nyholm, R.S. Electron Configuration and Structure of Transition-Metal Complexes. *Proc. Chem. Soc.* **1961**, *1961*, 273–296.
7. McDonald, R.I.; Liu, G.; Stahl, S.S. Palladium(II)-Catalyzed Alkene Functionalization via Nucleopalladation: Stereochemical Pathways and Enantioselective Catalytic Applications. *Chem. Rev.* **2011**, *111*, 2981–3019. [[CrossRef](#)] [[PubMed](#)]
8. Keith, J.A.; Henry, P.M. The Mechanism of the Wacker Reaction: A Tale of Two Hydroxypalladations. *Angew. Chem. Int. Ed.* **2009**, *48*, 9038–9049. [[CrossRef](#)] [[PubMed](#)]
9. Jira, R. Acetaldehyde from ethylene—A Retrospective on the Discovery of the Wacker Process. *Angew. Chem. Int. Ed.* **2009**, *48*, 9034–9037. [[CrossRef](#)] [[PubMed](#)]
10. Baiju, T.V.; Gravel, E.; Doris, E.; Namboothiri, I.N.N. Recent developments in Tsuji–Wacker oxidation. *Tetrahedron Lett.* **2016**, *57*, 3993–4000. [[CrossRef](#)]
11. Burrows, C.J. Holy Grails in Chemistry, Part II—Editorial. *Acc. Chem. Res.* **2017**, *50*, 445. [[CrossRef](#)] [[PubMed](#)]
12. Behr, A.; Vorholt, A.J. Homogeneous catalysis with renewables. In *Catalysis by Metal Complexes*; Cole-Hamilton, D.J., van Leeuwen, P.W.N.M., Eds.; Springer: Cham, Switzerland, 2017; Volume 39, ISBN 978-3-319-54161-7.
13. Echevarren, A.M.; Homs, A. *Metal-Catalyzed Cross-Coupling Reactions and More*, 1st ed.; de Meijere, A., Bräse, S., Oestreich, M., Eds.; Wiley-VCH: Weinheim, Germany, 2014; ISBN 978-3-52765-560-1.
14. Johansson Seechurn, C.C.C.; Deangelis, A.; Colacot, T.J. *New Trends in Cross-Coupling: Theory and Applications*; Colacot, T.J., Ed.; RSC Publishing: Cambridge, UK, 2015; ISBN 978-1-78262-025-9.
15. Colacot, T.J. The 2010 Nobel Prize in Chemistry: Palladium-Catalysed Cross-Coupling. *Plat. Met. Rev.* **2011**, *55*, 84–90. [[CrossRef](#)]
16. Choi, J.; Fu, G.C. Transition metal-catalyzed alky–alkyl bond formation: Another dimension, in cross-coupling chemistry. *Science* **2017**, *356*, 152.
17. Fürstner, A. Iron catalysis in organic synthesis: A critical assessment of what it takes to make this base metal a multitasking champion. *ACS Cent. Sci.* **2016**, *2*, 778–789. [[CrossRef](#)] [[PubMed](#)]
18. Souillart, L.; Cramer, N. Catalytic C–C Bond Activations via Oxidative Addition to Transition Metals. *Chem. Rev.* **2015**, *115*, 9410–9464. [[CrossRef](#)] [[PubMed](#)]
19. Labinger, J.A. Tutorial on Oxidative Addition. *Organometallics* **2015**, *34*, 4784–4795. [[CrossRef](#)]
20. Shang, R.; Ilies, L.; Nakamura, E. Iron-Catalyzed C–H Bond Activation. *Chem. Rev.* **2017**, *117*, 9086–9139. [[CrossRef](#)] [[PubMed](#)]

21. Holland, P.L. Distinctive Reaction Pathways at Base Metals in High-Spin, Organometallic Catalysts. *Acc. Chem. Res.* **2015**, *48*, 1696–1702. [[CrossRef](#)] [[PubMed](#)]
22. Sperger, T.; Sanhueza, I.A.; Kalvet, I.; Schoenebeck, F. Computational Studies of Synthetically Relevant Homogeneous Organometallic Catalysis Involving Ni, Pd, Ir, and Rh: An Overview of Commonly Employed DFT Methods and Mechanistic Insights. *Chem. Rev.* **2015**, *115*, 9532–9586. [[CrossRef](#)] [[PubMed](#)]
23. Budnikova, Y.H.; Dudkina, Y.B.; Khrizanforov, M.N. Redox-Induced Aromatic C–H Bond Functionalization in Metal Complex Catalysis from the Electrochemical Point of View. *Inorganics* **2017**, *5*, 70. [[CrossRef](#)]
24. Budnikova, Y.H.; Vivic, D.A.; Klein, A. Exploring Mechanisms in Ni Terpyridine Catalyzed C–C Cross-Coupling Reactions—A Review. *Inorganics* **2018**, *6*, 18. [[CrossRef](#)]
25. Iffland, L.; Petuker, A.; van Gastel, M.; Apfel, U.-P. Mechanistic Implications for the Ni(I)-Catalyzed Kumada Cross-Coupling Reaction. *Inorganics* **2017**, *5*, 78. [[CrossRef](#)]
26. Metz, A.; Heck, J.; Gohlke, C.M.; Kröckert, K.; Louven, Y.; McKeown, P.; Hoffmann, A.; Jones, M.D.; Herres-Pawlis, S. Reactivity of Zinc Halide Complexes Containing Camphor-Derived Guanidine Ligands with Technical *rac*-Lactide. *Inorganics* **2017**, *5*, 85. [[CrossRef](#)]
27. Van de Watering, F.F.; Heijbrink, N.; van der Vlugt, J.I.; Dzik, W.I.; de Bruin, B.; Reek, J.N.H. Methylindole-Based Tripodal Tetrakisphosphine Ruthenium Complexes in N<sub>2</sub> Coordination and Reduction and Formic Acid Dehydrogenation. *Inorganics* **2017**, *5*, 73. [[CrossRef](#)]
28. Nguyen, H.N.; Tashima, N.; Ikariya, T.; Kuwata, S. Ruthenium-Catalyzed Dimerization of 1,1-Diphenylpropargyl Alcohol to a Hydroxybenzocyclobutene and Related Reactions. *Inorganics* **2017**, *5*, 80. [[CrossRef](#)]
29. Hopen Eliasson, S.H.; Chatterjee, A.; Occhipinti, G.; Jensen, V.R. The Mechanism of Rh-Catalyzed Transformation of Fatty Acids to Linear Alpha olefins. *Inorganics* **2017**, *5*, 87. [[CrossRef](#)]



© 2018 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).