Homogeneous Hydroformylation

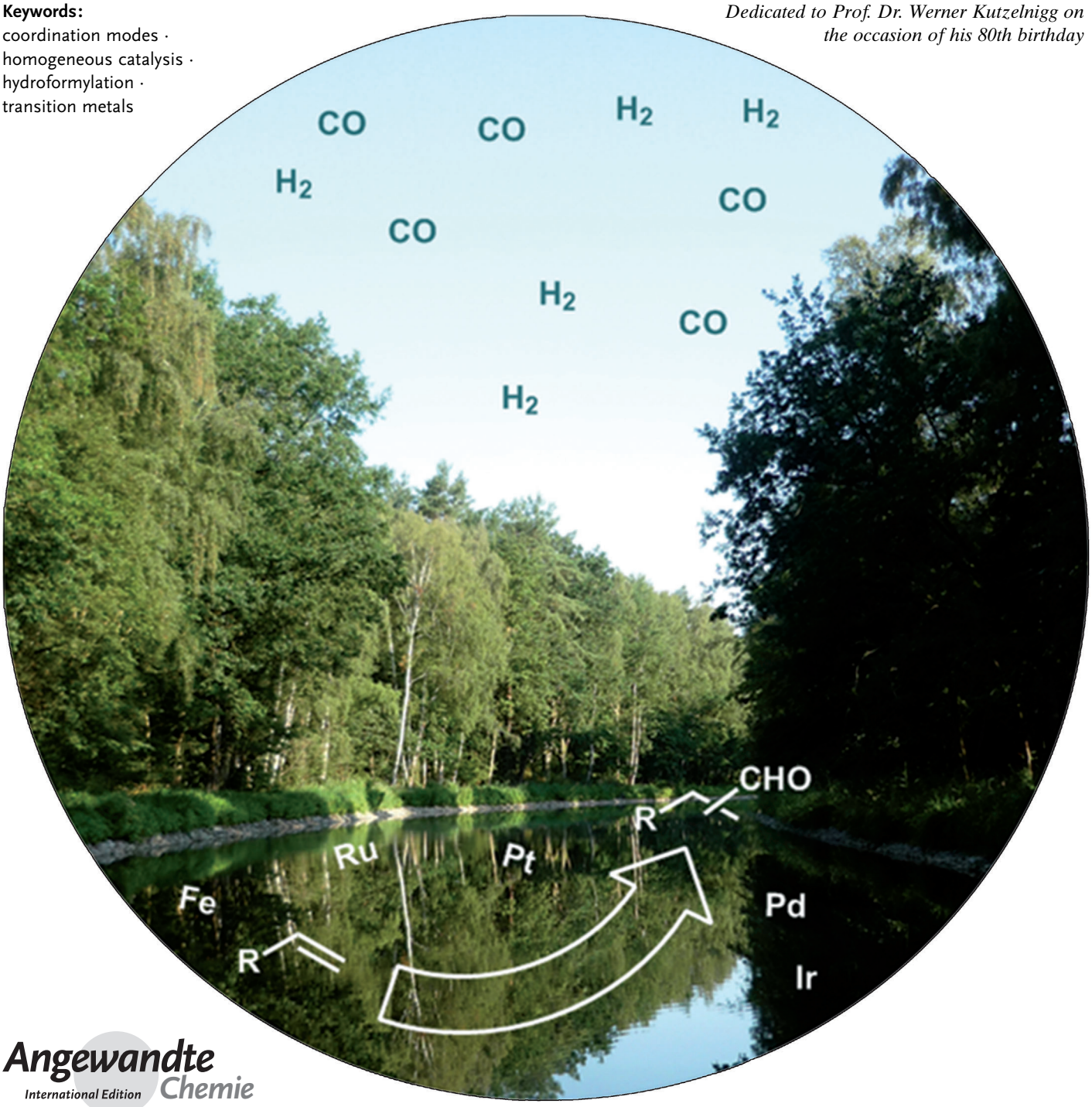
DOI: 10.1002/anie.201208330

# Alternative Metals for Homogeneous Catalyzed Hydroformylation Reactions

*Jola Pospech, Ivana Fleischer, Robert Franke,* Stefan Buchholz, and Matthias Beller**

**Keywords:**
coordination modes · homogeneous catalysis · hydroformylation · transition metals

*Dedicated to Prof. Dr. Werner Kutzelnigg on the occasion of his 80th birthday*



*Transition-metal-catalyzed hydroformylation reactions constitute one of the most powerful tools for C–C bond formation in organic synthesis and represent an outstanding example of the application of homogeneous catalysis on an industrial scale. This process allows for the straightforward conversion of inexpensive chemical feedstock into broadly applicable aldehydes, which serve as major building blocks for numerous chemical products. These products are highly valuable for the chemical industry and used as plasticizers, detergents, and surfactants on a million ton scale. Moreover, aldehydes serve as versatile chemical intermediates for the production of fine chemicals and pharmaceuticals. Currently, most of the bulk hydroformylation processes rely on rhodium-based catalysts. The increasing demand and resulting high cost of this precious metal has resulted in alternative transition-metal catalysts becoming highly desirable. The following Review summarizes the progress achieved utilizing Ru, Ir, Pd, Pt, and Fe catalysts in hydroformylation reactions.*

## From the Contents

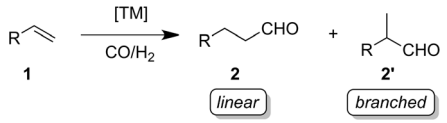
1. General and Background 2853

2. Alternative Metals in Homogeneous Hydroformylation Reactions 2854

3. Summary and Outlook 2869

## 1. General and Background

The transition-metal-catalyzed carbonylation of alkenes with carbon monoxide and hydrogen is generally known as hydroformylation or the oxo synthesis (Scheme 1). This

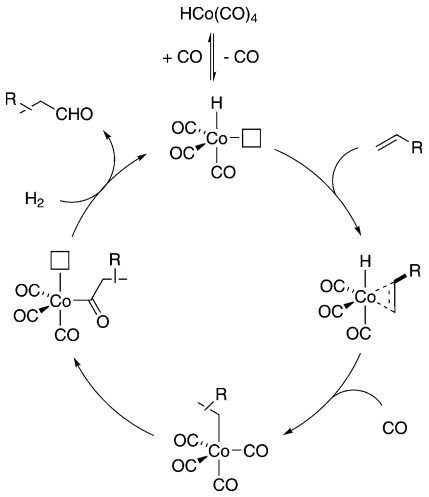



***Scheme 1.*** Transition-metal-catalyzed hydroformylation. TM = transition metal.

procedure is a powerful and valuable process for C–C bond formation to yield higher aldehydes, and is employed in numerous industrial applications on a large scale.[1] Besides catalytic activity and chemoselectivity, a key parameter for hydroformylation reactions is regioselectivity. Immense effort has been invested in the development of selective syntheses of linear aldehydes **2**, which are desired products for bulk applications; for example, butyraldehyde is the starting material for the production of phthalates.[2] On the other hand, the synthesis of branched aldehydes **2′** is of interest for the synthesis of pharmaceuticals and fine chemicals because of the potential formation of a stereogenic center.[3]

The hydroformylation reaction was discovered by the German industrial chemist Otto Roelen as early as 1938 during the course of his studies on the oxygenated side products of cobalt-catalyzed Fischer–Tropsch reactions.[4] The observation of the pressure-dependent transformation of ethene into propanal and diethyl ketones in the presence of CO and $H_2$, respectively, marked a major breakthrough of homogeneous catalysis in synthetic chemistry and represents the birth of hydroformylation chemistry. The first generation of cobalt-catalyzed hydroformylation processes (BASF, ICI, Ruhrchemie) was performed at a relatively high temperature (150–180 °C) and pressure (200–350 bar).[5] In the 1950s, Shell introduced a phosphine-modified catalyst system for the synthesis of detergent alcohols, which is still in use today.[6] The first generally accepted mechanism from Heck and Breslow[7] of the reaction using the original cobalt catalyst is depicted in Scheme 2.

Unfortunately, the cobalt-based processes suffer from low chemo- and regioselectivity. Hence, significant amounts of




***Scheme 2.*** Heck–Breslow mechanism for the Co-catalyzed hydroformylation reaction.[7]

[*] J. Pospech, Dr. I. Fleischer, Prof. Dr. M. Beller
Leibniz-Institut für Katalyse e.V. an der Universität Rostock
Albert-Einstein-Strasse 29a, 18059 Rostock (Germany)
E-mail: matthias.beller@catalysis.de
Homepage: http://www.catalysis.de
Prof. Dr. R. Franke, Prof. Dr. S. Buchholz
Evonik Industries AG
Paul-Baumann-Strasse 1, 45772 Marl (Germany)
E-mail: robert.franke@evonik.com
Prof. Dr. R. Franke
Lehrstuhl für Theoretische Chemie, Ruhr-Universität Bochum
44780 Bochum (Germany)

undesired by-products, for example, alkanes, are produced. In 1965, Wilkinson reported studies on the $[RhCl(PPh_3)_3]$-catalyzed hydroformylation under mild conditions, which proceeded with superior chemo- and regioselectivity.[8,9] Rhodium-based systems subsequently gained considerable attention, and substantial progress in terms of chemo- and regioselectivity has been made to date.[10] As a consequence of the technical and economic success of the homogeneous low-pressure oxo processes (LPO) by Union Carbide and Celanese in the mid-1970s, the cobalt catalysts were replaced by rhodium catalysts. Nevertheless, a significant amount of oxo products (> 2.5 million tons per annum) is still produced using cobalt catalysts, in particular $[HCo(CO)_4]$ and $[HCo(CO)_3PR_3]$.

An important industrial development in the 1980s was the realization of the Ruhrchemie/Rhône–Poulenc process, whereby a water-soluble rhodium catalyst is employed in a two-phase hydroformylation process.[11] Based on the original idea of Kuntz, a Rh/TPPTS complex (TPPTS = trisodium salt of *meta*-trisulfonated triphenylphosphine) is used as the catalyst.[12] Despite the advantages of the Rh/TPPTS catalyst, such as simple separation, it is not possible to efficiently hydroformylate internal olefins or longer chain olefins. These limitations were later overcome by the introduction of bulky bidentate diphosphines.[13]

## 2. Alternative Metals in Homogeneous Hydroformylation Reactions

As a consequence of the technical success of rhodium-based hydroformylations, it is understandable why the vast majority of academic and industrial investigations in this area since the 1970s focused on rhodium catalysts. However, the increased worldwide demand for rhodium for chemical and technical processes elevated the price of this already expensive precious metal.[14] This situation led to the search for more readily available alternative transition-metal catalysts. Indeed, a number of other complexes based on transition metals (e.g. Ru, Ir, Pd, Pt, Fe) are generally capable of forming complexes that catalyze hydroformylation reactions. Recent research demonstrates that the substrate scope and catalyst activity of these complexes have, until now, tended to be underestimated. As a result of the increasing interest in so-called "alternative" hydroformylation catalysts (non-Rh- and non-Co-based complexes), the present Review summarizes the decisive studies in this industrially important and scientifi-

*Jola Pospech received her MSc (with distinction) from the University of Göttingen in 2011. In the course of her undergraduate studies she worked on research projects concerning palladium- and ruthenium-catalyzed direct arylation through C–H bond activation under the supervision of Prof. Dr. Lutz Ackermann. She is currently a graduate student in the group of Prof. Dr. Matthias Beller at the Leibniz-Institute for Catalysis in Rostock.*

*Ivana Fleischer studied chemistry at the Commenius University, Bratislava, Slovakia, where she obtained her MSc under the direction of Prof. Stefan Toma. She received her PhD from the University of Basel, Switzerland, under the guidance of Prof. Dr. Andreas Pfaltz for research focused on mass-spectrometric screening of organocatalysts. As a postdoctoral fellow of the Swiss National Science Foundation, she joined the group of Prof. Dr. Matthias Beller at the Leibniz-Institute for Catalysis in Rostock, Germany, where she is now an independent researcher investigating novel carbonylation reactions.*

*Matthias Beller earned his PhD in 1989 under the supervision of Prof. Lutz F. Tietze at the University of Göttingen. After postdoctoral research at MIT with Prof. Barry Sharpless, he gained industrial experience at Hoechst AG in Frankfurt from 1991 until 1995. Subsequently, he started his independent career at TU Munich as C3 professor for inorganic chemistry. In 1998 he relocated to the University of Rostock, where since 2006 he has been director. His research concerns applied homogeneous catalysis for the synthesis of fine and large-scale chemicals, as well as for energy technology.*

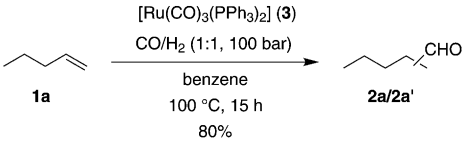
*Robert Franke studied chemistry with a focus on industrial and theoretical chemistry at Bochum University in Germany. He earned his PhD in 1994 in the field of relativistic quantum chemistry under Prof. W. Kutzelnigg. After working for a period as a research assistant, in 1998 he joined the process engineering department of Hüls AG, a predecessor company of Evonik Industries AG. He is now Director of Innovation Management Hydroformylation. He completed his Habilitation in 2002, and since then has taught at the University of Bochum. In 2011 he was made adjunct professor.*

*Stefan Buchholz studied chemistry at the Philipps-University in Marburg and earned his PhD with Prof. G. Wegner at the Max-Planck-Institute of Polymer Research. After postdoctoral research with Prof. George Whitesides at Harvard University, he joined Degussa AG, a predecessor company of Evonik Industries AG in 1993. He held numerous positions in research and development, before becoming Vice President of Innovation Management of the business unit Advanced Intermediates in 2008. Since October 2012 he has been Head of Creavis Technologies & Innovation. He became Honorary Professor at Stuttgart University in 2011.*

cally interesting area. These research efforts are ordered by the respective metal catalysts.

### 2.1. Ruthenium-Catalyzed Hydroformylation

Key pioneering experiments for the application of ruthenium catalysts in homogeneous hydroformylation reactions were initially reported by Wilkinson and co-workers in 1965.[15] They found that the well-defined complex $[Ru(CO)_3(PPh_3)_2]$ (**3**) is capable of hydroformylating 1-pentene to $C_6$ aldehydes in the presence of $CO/H_2$ (1:1) in benzene solution at 100 bar total pressure and 100 °C (Scheme 3). Wilkinson

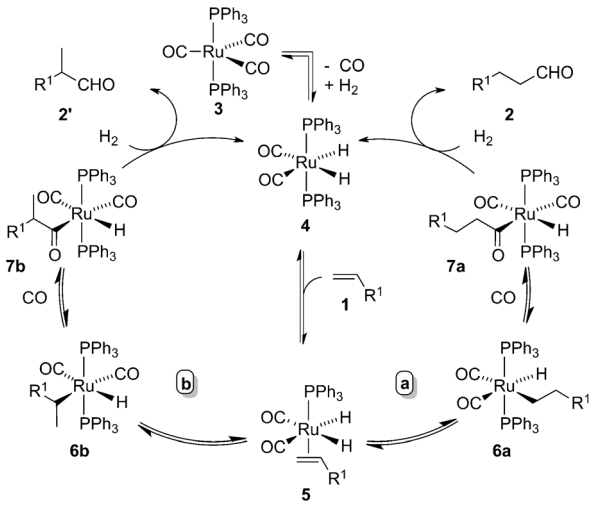



***Scheme 3.*** First example of Ru-catalyzed hydroformylation by Wilkinson and co-workers.[15]

and co-workers pointed out that the $Ru^{III}$ species $[RuCl_3(PPh_3)_2]$·MeOH is also moderately active, whereas the related $[RuCl_2(PPh_3)_3]$ complex rapidly reacts to form an insoluble $[RuCl_2(CO)_2(PPh_3)_2]$ species.[9]

Later on, Schulz and Bellstedt pursued intensive studies aimed at identifying critical reaction parameters in the Ru-catalyzed hydroformylation of propene.[16] Direct comparison of the ruthenium system with unmodified cobalt and rhodium catalysts revealed the ruthenium catalysts to have a medium reactivity and selectivity in the hydroformylation. Although the authors observed slightly better linear to branched ratios compared to the rhodium-based systems, the high hydrogenation activity of $[Ru(CO)_3(PPh_3)_2]$ results in higher yields of the alcohols and alkanes. Furthermore, the stability of the carbonylruthenium complexes allowed the hydroformylation to be carried out below 100 bar.

Further attempts to investigate ruthenium–phosphine complexes in the catalytic hydroformylation of alkenes led to a mechanistic proposal involving $[Ru(H)_2(CO)_2(PPh_3)_2]$ (**4**) as the postulated active catalytic species formed at the outset of the catalytic cycle (Scheme 4).[17] The oxidative addition of hydrogen to the metal center is accompanied by dissociation of one carbonyl ligand, and this appears to be the rate-determining step of the reaction. Dissociation of a phosphine ligand allows for coordination of the alkene to form complex **5**. Subsequent insertion of CO into the metal–alkyl bond leads to the corresponding acyl species **7**. Eventually, transfer of a second hydrogen atom results in the formation of the desired product and regeneration of the active complex **4**. The coordination of phosphine ligands increases the electron density on the metal center and enforces the polarization of the M–H bond. As a consequence, anti-Markovnikov addition is favored, thereby leading to increased *n* selectivity (path a). Hence, both electronic and steric effects of the phosphine ligand favor the formation of the linear alkyl–metal complex **6a**. An excess of CO is helpful for accelerating

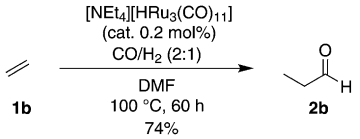



***Scheme 4.*** Proposed catalytic cycle for $[Ru(CO)_3(PPh_3)_2]$-catalyzed hydroformylation.[17]

the CO migration step (**6**→**7**), which is considerably faster than the competitive β-hydride elimination. Indeed, when mononuclear $[Ru(CO)_3(PPh_3)_2]$ was used, the alkenes were only isomerized to a minor extent.

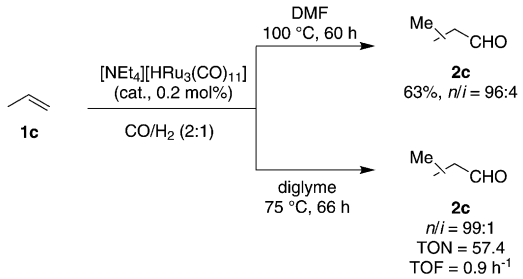
The same authors observed that, under similar reaction conditions, the dodecacarbonylruthenium complex $[Ru_3(CO)_{12}]$ produced only modest yields and low linear-to-branched-chain ratios.[17] The authors, therefore, assumed that polynuclear ruthenium complexes might interact differently with the alkene substrate, and that competitive ligands may result in suppressed hydroformylation activity. In following studies, $[Ru_3(CO)_{12}]$ was widely used as the precatalyst in hydroformylation reactions.[18]

Süss-Fink further investigated the catalytic activity of the trinuclear cluster anion $[HRu_3(CO)_{11}]^-$ in the hydroformylation of ethylene and propylene.[19] An experimental setup comprising $[NEt_4][HRu_3(CO)_{11}]$ and synthesis gas ($CO/H_2$, 1:2 ratio) in DMF converted ethylene (**1b**) into propionaldehyde (**2b**) in a yield of 74% of the isolated product (Scheme 5). Under similar reaction conditions, propylene




***Scheme 5.*** Ru-catalyzed hydroformylation of ethylene in DMF.[19]

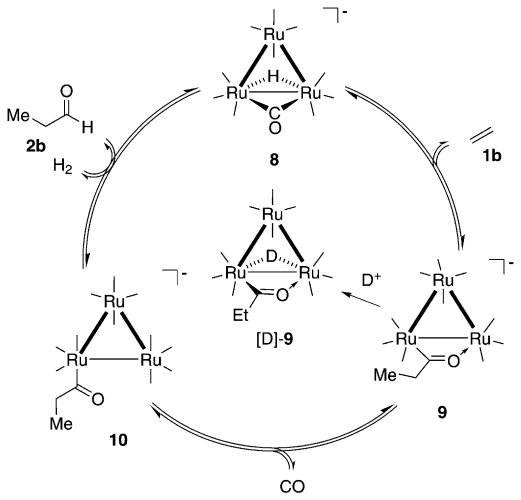
(**1c**) was also effectively converted into the corresponding higher aldehydes **2c** in a slightly diminished yield of 63% (Scheme 6). More detailed selectivity studies on the hydroformylation of propylene revealed that the regioselectivity of the reaction is influenced significantly by the solvent used, and is also highly pressure and temperature dependent.[20] In contrast, the chemoselectivity remained unaltered irrespective of the solvent, temperature, or pressure. For example, the




***Scheme 6.*** Ru-catalyzed hydroformylation of propylene in DMF and diglyme.[19,20] TON = turnover number, TOF = turnover frequency.

highest linear to branched selectivities were obtained in ethereal solvents rather than DMF. The maximum regioselectivity of 72.5 (98.6 % *n*-butanal, 1.4 % methylpropanal) was obtained at a temperature of 75 °C by using 1,5-dimethoxy-3-oxapentane (diglyme) as the solvent ($CO/H_2 = 2:1$, 10 bar) with a catalyst turnover number of 57 (Scheme 6). These results mark the highest *n* selectivity that has been achieved in the presence of Ru catalysts to date. Although the authors did not reveal a close correlation between the catalytic turnover and the *n*/*i* ratio (*n*/*i* = linear/branched, with *n* = normal, *i* = *iso*), high regioselectivities are in accord with the lower turnover numbers. As a consequence of its ionic character, the catalyst $[HRu_3(CO)_{11}]^-$ (**8**) can be recovered from the reaction mixture and recycled with no loss of its hydroformylation activity. Furthermore, in contrast to other ruthenium precursors, the hydrogenation of alkenes is almost completely suppressed in the presence of carbon monoxide.[21] Thus, it seems that the cluster anion $[HRu_3(CO)_{11}]^-$ is a potent catalyst for hydroformylation reactions, even though the catalyst productivity is still too low to be competitive with industrial cobalt or rhodium catalysts.

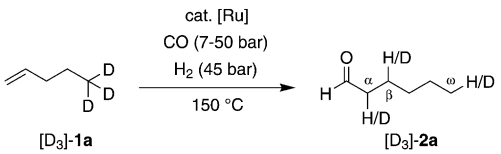
Isotope labeling studies allowed a closer insight into the reaction sequence. On the basis of spectroscopic analysis, Süss-Fink and Herrmann disclosed that the hydroformylation of ethylene catalyzed by the cluster anion $[HRu_3(CO)_{11}]^-$ (**8**) proceeds through an intermediary intact trinuclear metal cluster.[22] The authors thus proposed a catalytic cycle commencing with the transfer of the hydride ligand to the incoming ethylene molecule, accompanied by the electrophilic attack of the carbon atom of the carbonyl bridge. This sequence results in the formation of the $\mu_2$-$\eta^2$(C,O)-propionyl ligand in intermediate **9** (Scheme 7). Subsequent coordination of another carbonyl ligand leads to intermediate **10**, which readily reacts with hydrogen to form propionaldehyde and the original cluster **8**. Although isolation of the anionic intermediates **9** and **10** was not feasible, intermediate **9** could be trapped by acidification, and was successfully identified as the known neutral complex structure $[Ru_3(\mu_2\text{-}D)(\mu_2\text{-}\eta^2\text{-}OCCH_2CH_3)(CO)_{10}]$ ([D]-**9**), thus providing indirect evidence for the presence of the anion **9**. Replacement of hydrogen by $D_2$, resulted in clean deuteration of the aldehyde at the formyl position. Nevertheless, as a result of the overall reversibility of the elementary steps in the catalytic cycle, deuterium incorporation was also detected in minor quantities at other positions.




***Scheme 7.*** Proposed catalytic cycle for the hydroformylation of ethene by the cluster anion $[Ru_3H(CO)_{11}]^-$.[22]

A major drawback of trinuclear ruthenium precatalyts becomes apparent when higher aliphatic olefins are employed. In these cases (especially at lower temperature), 1-olefins are predominantly isomerized to the less-reactive 2-alkenes. Comparing the catalytic activity of the polynuclear catalysts $[HRu_3(CO)_{11}]^-$ and $[Ru_3(CO)_{12}]$ to that of mononuclear anionic $[HRu(CO)_4]^-$ revealed that only $[HRu(CO)_4]^-$ serves as a potent catalyst for the hydroformylation of 1-pentene, styrene, and ethyl acrylate.[23] Of the three catalyst precursors, $[HRu(CO)_4]^-$ demonstrated superior selectivity in the case of 1-pentene for the linear carbonylation product. As a result of its strong reduction ability, however, minor amounts of hexanol were also detected. In addition, the mononuclear precatalyst was the most regioselective in converting styrene into 2-phenylpropionaldehyde and 2-phenylpropanol, with a total yield of 95 % and up to 96 % selectivity in favor of the branched product. It must be mentioned, however, that the carbonylation activity drops drastically at a decreased temperature of 100 °C.

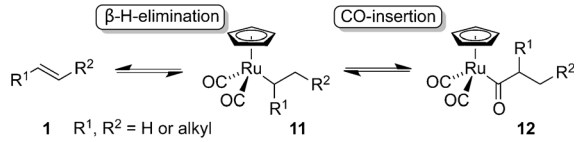
To deduce the extent of rearrangements over the course of the catalytic reaction, Frediani and co-workers examined the hydroformylation of [5-$D_3$]pent-1-ene ([$D_3$]-**1a**) catalyzed by the polynuclear catalysts $[Ru_3(CO)_{12}]$ and $[\{H_4Ru_4(CO)_8[(-)\text{-diop}]\}_2]$ (diop = (−)-1,4-bis(diphenylphosphino)-1,4-dideoxy-2,3-*O*-isopropyliden-L-threitol; Scheme 8).[24] The two catalysts resulted in a different pattern of deuterium distribution in the product. At high CO pressure, complex $[\{H_4Ru_4(CO)_8[(-)\text{-diop}]\}_2]$ transformed the substrate [$D_3$]-**1a** with complete deuterium retention at C-6. In contrast, a pressure-independent deuterium migration in the α-, β-, and




***Scheme 8.*** Deuterium migration under hydroformylation conditions.[21]

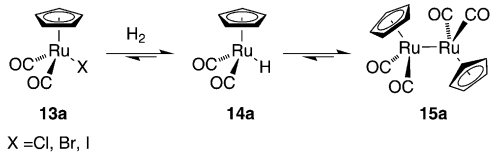
ω-positions of the corresponding hexanoate [$D_3$]-**2a** has been observed in the presence of [$Ru_3(CO)_{12}$].[25]

Attempts to use ruthenium sources other than [$Ru(CO)_3(PPh_3)_2$] or [$HRu(CO)_4$]$^-$ initially did not show any promising results. For example, [{$\eta^5$-$C_5H_5Ru(CO)_2$}$_2$] (**15a**) demonstrated only a marginal hydroformylation capability.[26] Although it might be assumed that the cyclopentadienyl ring can easily be displaced to form an active hydroformylation catalyst, the ligand still remains strongly bound to the metal at temperatures up to 150 °C. Hence, olefin isomerization was found to be predominant under the applied reaction conditions. This side reaction formally indicates the formal generation of a metal–alkyl species **11** and a rather inhibited formation of an acyl compound **12**. Considering the necessity of an adequate number of vacant coordination sites for substrates, the authors hypothesized a mononuclear species to be operative in the course of the catalytic transformation (Scheme 9).




***Scheme 9.*** β-H Elimination versus CO insertion in cyclopentadienylruthenium complexes.[26]

Consecutive studies focusing on the hydroformylation activity of the mono- and dinuclear cyclopentadienyl–metal complexes [$\eta^5$-CpM(CO)$_2$X] (**13**) and [{$\eta^5$-CpM(CO)$_2$}$_2$] (**15**: M = Ru, Fe; X = Cl, Br, I), respectively, emphasized a significant influence of the nuclearity of the complex on both the overall activity and selectivity of the hydroformylation process (Scheme 10).[27] The monomeric hydride complex




***Scheme 10.*** Generation of the catalytically active species [$\eta^5$-$C_5H_5Ru(CO)_2H$] (**14a**).[27]

[$\eta^5$-CpRu(CO)$_2$H] (**14a**) was identified as the catalytically active species that is preferentially formed starting from complex **13a**. On the other hand, the formation of **14a** from dimer **15a** was retarded. Consequently, the poor reaction outcome was attributed to the fact that only a minor amount of the active monomeric species **14a** is formed from the dimer [{$\eta^5$-CpRu(CO)$_2$}$_2$]. Unexpectedly, the corresponding iron complexes ([$\eta^5$-CpFe(CO)$_2$X] and [{$\eta^5$-CpFe(CO)$_2$}$_2$]) exhibited the reverse behavior in hydroformylation reactions.

In 1985, Suarez and Fontal published a protocol for the use of polydentate phosphine ligands in ruthenium-catalyzed hydrogenation and hydroformylation.[28] They showed that tripodal ruthenium–phosphine complex **16** and ruthenium

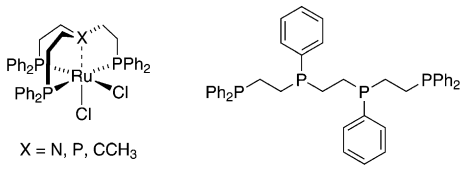



***Figure 1.*** Tripodal ruthenium chloride complex **16** and tetraphos ligand **17**.[28]

complexes bearing the tetraphos ligand **17** (Figure 1) are capable of hydrogenating unsaturated compounds such as alkenes, aldehydes, and ketones in ethanol at 100 °C and 80 bar hydrogen pressure. It was found that ammonium and silver salts have a positive effect on the catalyst activity, whereas higher pressure or elevated temperatures diminish the amount of hydrogenated product. Moreover, these complexes were found to be active towards the hydroformylation of ethylene and 1-hexene at 150 °C and 100 bar CO/$H_2$ in 1,4-dioxane. Unfortunately, these rather harsh conditions merely produced moderate yields of the corresponding aldehydes, in addition to a substantial amount of reduced products.

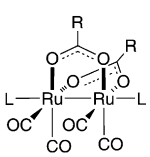
After Mirbach et al. had examined the influence of UV irradiation on cobalt- and rhodium-catalyzed hydroformylations,[29,30] Gordon and Eisenberg studied photochemical hydroformylation reactions in the presence of ruthenium catalysts.[31] The authors revealed that photogeneration of the catalytically active species is more efficient than the thermal activation of $Ru^0$ precatalysts. UV irradiation, in other words, accelerates the abstraction of a carbonyl ligand from the tetracarbonyl complex [$Ru(CO)_4PPh_3$] to generate the presumably catalytically active, coordinatively unsaturated, 16-valence electron ruthenium species [$Ru(CO)_3PPh_3$]. The experiments were performed in NMR tubes, sealed under 0.7–0.8 bar of $H_2$/CO (1:1) and irradiated with a 200 W Hg-Xe lamp through a pyrex filter at ambient temperature. When aliphatic olefins such as ethylene or propylene were used, hydroformylation products were obtained in addition to an extensive amount of hydrogenated products. Alternative irradiation sources and storage in the absence of light showed that the reaction only occurs during photolysis. Thus, the system is photoassisted and not merely photoinitiated. However, the total catalyst turnover numbers were not higher than nine. Aromatic olefins proved to be inert towards hydroformylation under these reaction conditions.

Although the main focus thus far had been primarily on the carbonylation of 1-olefins, important contributions towards the transformation of internal alkenes were reported by Knifton (Texaco Chemical Co).[32] They showed that the so-called ruthenium "melt" catalysts, in which carbonylruthenium complexes are dispersed in low-melting quaternary phosphonium salts, are capable of converting internal alkenes into linear alcohols. Improved linear-to-branched ratios were achieved by adding chelating N- and P-donor ligands as well as by careful choice of the quaternary phosphonium salt. The highest linear selectivity (69%) was obtained through the addition of 2,2′-bipyridine (bipy). In addition, the use of mixed Ru-Co catalysts suppressed the hydrogenation reaction

and yielded the corresponding aldehydes as the main products. Catalyst systems containing $[Ru_3(CO)_{12}]$ with bidentate nitrogen- and phosphorus-containing ligands are more extensively explored in the following.[33]

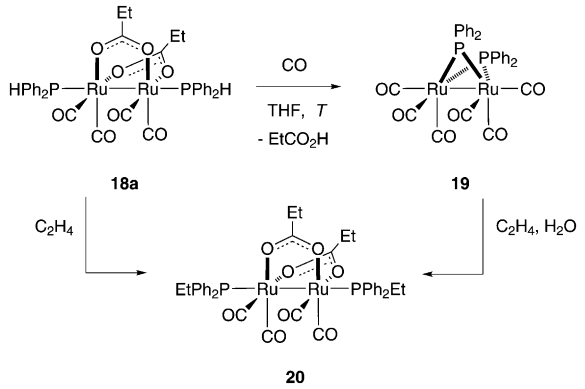
Inspired by the performance of trinuclear ruthenium catalysts in hydroformylation reactions, Kalck and co-workers focused on the use of dinuclear ruthenium complexes by starting from di-$\mu$-acetatocarbonyldiruthenium complexes.[34] The authors successfully demonstrated a selective low-pressure hydroformylation reaction of alkenes by applying $[Ru_2(\mu\text{-}O_2CR)_2(CO)_4L_2]$ (**18**; Figure 2). The presence of excess amounts of $NEt_3$ or $PPh_3$ turned out to be mandatory for the process, and superior results were achieved by adding small amounts of water. The aliphatic alkenes 1-heptene and 1-octene were efficiently converted under these reaction conditions with moderate regioselectivity (up to 80% *n* selectivity). Interestingly, the use of triphenylphosphite ($P(OPh)_3$) instead of $PPh_3$ resulted in minor amounts of hydrogenated substrate and internal alkenes along with high yields of the corresponding aldehydes. In contrast, the addition of the more basic $PtBu_3$ disrupted the hydroformylation almost entirely. The latter study revealed that excess phosphine (P/Ru = 5:1) is not only a requirement for achieving clean conversion into the oxo product, it also favors *anti*-Markovnikov addition of the alkene to the metal–alkyl bond, thus resulting in enhanced *n* selectivity. Additionally, higher phosphine concentrations prevented isomerization of the starting material. Similar results had previously been reported for rhodium-based systems, whereas the carboxylate ligand present in the catalyst did not have a significant effect.[1g] In agreement with this observation, subsequent studies led to a mechanism being proposed in which the $\mu^2$-carboxylate ligand is abstracted over the course of the hydroformylation reaction (Scheme 11).[35] Complex **20** is the catalytically active species that produces propionaldehyde, propanol, and diethyl ketone instead of propionic acid.[35a]



**18**

***Figure 2.*** Dinuclear ruthenium carboxylate complex **18**.[34]

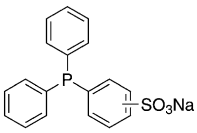
Cost-effective processing is a crucial factor for meeting the requirements of an industrial process, and thus laborious separation of miscellaneous ingredients ought to be avoided. In catalytic reactions, especially if only low TONs can be achieved and thus a relatively large amount of the metal catalyst is required, the efficient separation and recycling of the catalyst from the reaction mixture is highly desirable.



**18a** **19** **20**

***Scheme 11.*** Interplay of phosphido and phosphine ligands in dinuclear ruthenium complexes.[35]

Diverse methods have been envisioned to solve this problem. For example, Borowski et al. prepared a variety of metal complexes bearing the monosulfonated triphenylphosphine ligand **21** (Figure 3), which imparts water solubility to the resulting metal complex and makes it possible to separate the catalyst by simple extraction.[36] The complex $[RuH(\mathbf{21})_3Cl]$ exhibited moderate hydroformylation activity. Within 24 h, 30% of the 1-hexene was converted into the corresponding $C_7$ aldehydes at 90 °C and a total pressure of 60 bar. The ratio of linear-to-branched aldehydes was typically 75:25.



**21**

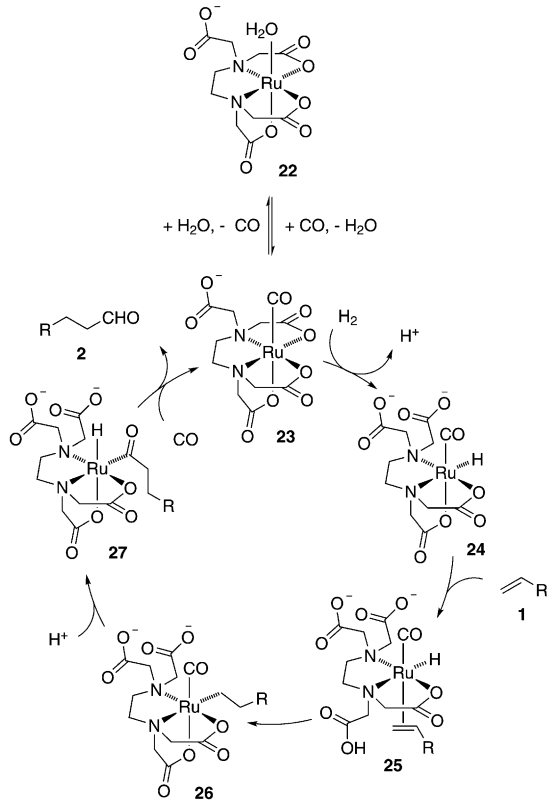
***Figure 3.*** Monosulfonated triphenylphosphine ligand **21** (tppms) for the formation of water-soluble hydroformylation catalysts.[36]

Similarly, Gao et al. studied the same ligand in combination with the well-defined dodecacarbonylruthenium complex.[37] The performance of the resulting water-soluble and air-stable catalyst system $[Ru_3(CO)_9(tppms)_3]$ was moderate. Hydrocarbonylation of propylene to butylaldehyde occurred with a catalytic turnover of 490 and a rate of 61 $h^{-1}$ in water as reaction medium. The excellent *n* selectivity of 94% makes this catalyst system one of the best ruthenium catalysts known, and is competitive with rhodium catalysts.

Another approach towards water-soluble ruthenium-based hydroformylation catalysts was disclosed by the Khan research group in the late 1980s.[38–40] Ligation of ethylenediaminetetraacetate (edta) to a ruthenium metal center yielded an efficient water-soluble catalyst precursor. The catalyst was tested in hydroformylation reactions of aliphatic[38] and cyclic olefins[36] as well as allylic alcohols.[40] The best results were achieved by starting with the anionic ruthenium(III)–aqua complex $[Ru(edta)H_2O]^-$ (**22**), which is readily carbonylated under CO pressure to yield the presumably catalytically active species $[Ru(edta)CO]^-$ (**23**). $[Ru(edta)(CO)H]^{2-}$ (**24**) is subsequently formed by heterolytic splitting of dihydrogen (Scheme 12). The authors reported that this system performed remarkably well, with 1-hexene fully converted into 1-heptanal within 12 h (TOF $\approx 12\ h^{-1}$) in EtOH/$H_2O$ (80:20) under 50 bar syngas pressure at 130 °C.

As a result of the reasonable success of polyfluorinated compounds and their unique physiological activities in bioactive substances,[41] Ojima and Fuchikami were interested in the hydroformylation of olefins bearing perfluoroalkyl or perfluoraryl substituents.[42] Prior to their efforts, only one example had been reported, namely for the hydrocarbonylation of perfluorinated heptadecafluorodecene to yield the corresponding alcohols and aldehydes, and this was performed in the presence of the cobalt catalyst $[Co_2(CO)_8]$.[43] Unfortunately $[Ru_3(CO)_{12}]$ showed rather low catalytic

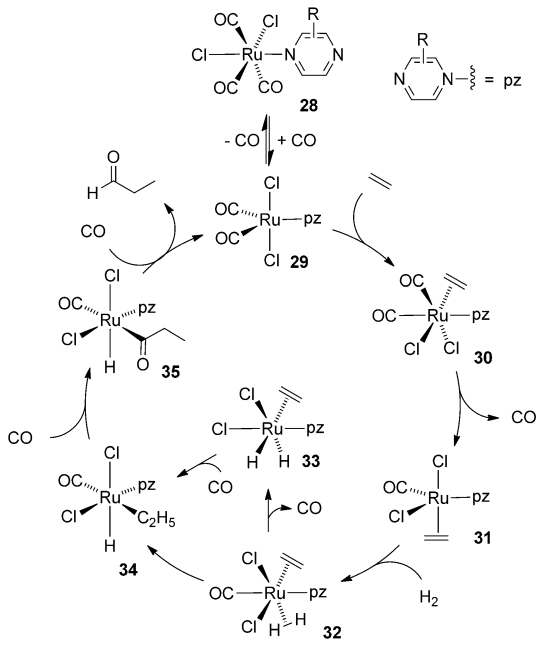


***Scheme 12.*** Proposed catalytic cycle for EDTA complex **22**.[38]

activity, and yielded isoaldehyde as the major isomer accompanied by a large amount of hydrogenated product.

Haukka and co-workers tested a variety of monomeric carbonylruthenium complexes containing 2-substituted pyrazines (pz) as catalysts for the hydroformylation of 1-hexene for mechanistic studies.[44] The authors concluded that the reactivity of the pyrazinylruthenium complexes **28** was closely related to the intrinsic electronic properties of the substituents attached to the heterocycle. Thus, strong electron-donating substituents increased the catalytic activity of the metal complex, while electron-withdrawing substituents decreased the activity. The introduction of a substituent in the 2-position has a positive influence on the hydroformylation compared to unsubstituted pyrazine. The authors postulated that the increased steric bulk in the 2-position leads to a stabilization of the monomeric species and suppression of the formation of catalytically less-reactive Ru-pz-Ru dimers.[45] As frequently described, the aldehydes appeared to be partially hydrogenated throughout the course of the reaction, whereas no hexane resulting from the hydrogenation of the substrate was detected. Based on computational and spectroscopic data, the authors provided a plausible route for the hydroformylation of alkenes catalyzed by the ruthenium–pyrazine complex (Scheme 13).

To simplify the geometry of the system, ethene was used instead of 1-hexene as a model substrate in the calculations. Density functional theory (DFT) calculations revealed that the release of the carbonyl ligand in the *cis* position with respect to the pyrazine ring constitutes the key step in the



***Scheme 13.*** Possible routes for the hydroformylation of ethylene by $[Ru(CO)_3Cl_2(pz)]$.[44]

formation of the active species **29** and is energetically favored over the release of the *trans*-coordinated carbonyl ligand. The DFT studies conducted also disclosed that the activation of the ruthenium dimer $[\{Ru(CO)_3Cl_2\}_2]$ and its corresponding acetonitrile complexes proceeds by exchange of the solvent molecule instead of release of a carbonyl ligand.

The same authors also conducted theoretical and practical investigations into the effect of *ortho*-substituted phosphine ligands **36**.[46] These studies examined the possibility that potentially chelating *ortho* substituents, such as dimethylamino, methylthio, or methoxy substituents, inhibit the catalytic activity of the resultant ruthenium complexes **37** (Figure 4). Indeed, the catalytic activity diminishes with the

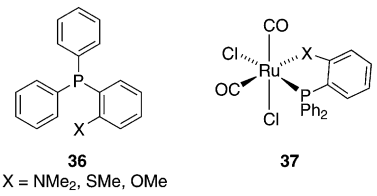


***Figure 4.*** Carbonylruthenium complexes containing *ortho*-substituted triphenylphosphine ligands.[46]

enhanced affinity of the *ortho* substituent to form a Ru–X bond and thus increases in the following order: OR > SR > $NR_2$. It is worth noting that triphenylphosphine ligands bearing noncoordinating alkyl substituents showed moderate activity towards the formation of oxo products (up to 78% hydroformylation products).

$[RuH(CO)(NCMe)_2(PPh_3)_2]BF_4$, which can be easily obtained by treating $[RuHCl(CO)(PPh_3)_3]$ with acetonitrile in the presence of $NaBF_4$ was also found to trigger the

hydrocarbonylation of 1-hexene.[47] However, the catalytic system was not selective for the synthesis of heptanal (10% yield); instead, reduction of the carbonyl functionality to the corresponding $C_7$ alcohols and a 30% yield of internal olefins and hexane has been observed.

Most recently, Kontkanen and Haukka envisioned the application of a microencapsulated ruthenium catalyst prepared from $[\{Ru(CO)_3Cl_2\}_2]$ encased in poly(4-vinylpyridine) (P4VP) and cross-linked with 25% divinylbenzene (DVB).[48] The hydroformylation of 1-hexene proceeded using synthesis gas ($CO/H_2 = 1:1$) at 150 °C in a solution of *N*-methylpyrrolidine (NMP). Although a high conversion rate of 93% was obtained, the desired aldehydes were formed in only 44% yield. In addition, 26% of the corresponding alcohol and hexene isomers were formed as major by-products. The microencapsulated catalyst could be reused with only a minor loss in hydroformylation activity. Unfortunately, almost no regiocontrol was found ($n/i \leq 1.1:1$) and the reaction only showed a slow overall conversion (TON = 2.1–2.8, TOF = 0.13–0.17 $h^{-1}$).

Rosales et al. undertook a brief study on ruthenium– and osmium–hydridocarboxylate complexes that exhibited reasonable activity for the hydroformylation of 1-hexene to heptanal and 2-methylpentanal under milder reaction conditions (120 °C, 15 atm $H_2/CO$) in toluene.[49] Ruthenium complexes of the general type $[RuH(CO)(\kappa^3\text{-}OCOR)(PPh_3)_2]$ (**38**) showed modest turnover frequencies, which depended on the carboxylate. Generally, carboxylate complexes with electron-donating substituents performed better in the hydroformylation (Figure 5). The highest TOFs were achieved with

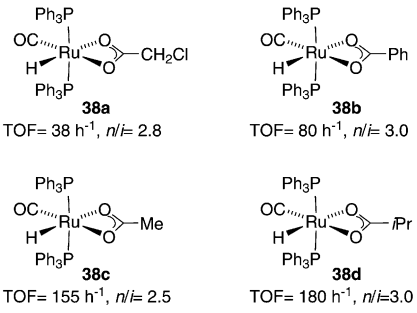
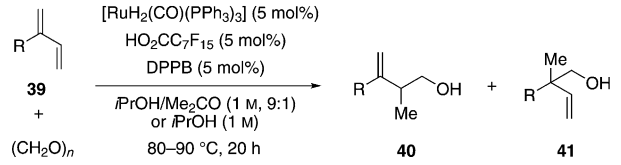



***Figure 5.*** Turnover frequencies and *n*/*i* ratios obtained in the hydroformylation of 1-hexene with different complexes $[RuH(CO)(\kappa^3\text{-}OCOR)(PPh_3)_2]$ (R = $CH_2Cl$ **38a**, Ph **38b**, Me **38c**, *i*Pr **38d**).[49]

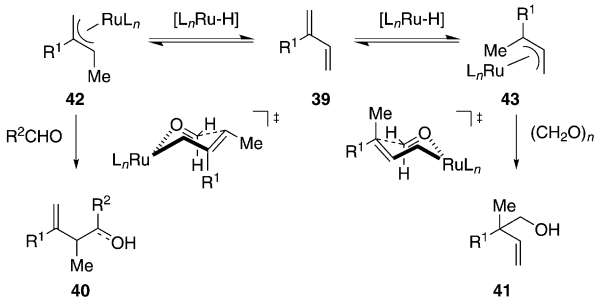
the isobutyrate complex **38d** (TOF = 180 $h^{-1}$) and acetate complex **38c** (TOF = 155 $h^{-1}$). Presumably, the observed differences in activity are a result of the different rates of preformation of the active catalyst species. The linear-to-branched ratios for the product vary in the range from 2.5:1 to 3.0:1.

In addition to activating simple alkenes, the hydroformylation of conjugated dienes represents an attractive but challenging task. Although not a classical hydroformylation reaction, it is reasonable to mention a study by Breit, Krische, and co-workers. The authors described the interesting development of the ruthenium-catalyzed reductive coupling of 2-



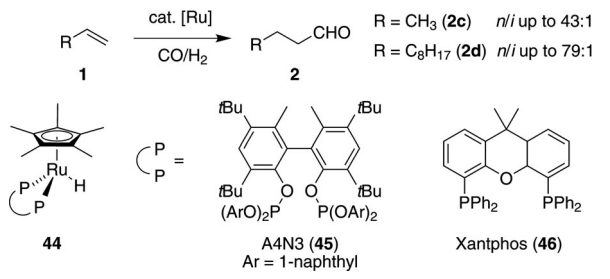

***Scheme 14.*** Formaldehyde-mediated Ru-catalyzed hydroformylation of 2-substituted butadienes.[50] DPPB = 1,1′-bis(diphenylphosphanyl)-butane.

substituted butadienes **39** with paraformaldehyde, which allowed the synthesis of hydroxymethylation products with all-carbon quaternary centers (Scheme 14).[50] This catalytic system promotes the interconversion of the stabilized π-allyl complex **42** to the π-allyl complex **43** by reversible β-H elimination. The ultimate driving force for the selective formation of neopentyl alcohol **41** was attributed to the favorable equatorial bias of the substituent in the 2-position (Scheme 15).




***Scheme 15.*** Proposed mechanism for the formation of neopentyl alcohols **41** from conjugated dienes **39** and paraformaldehyde.[50]

Very recently, in 2012, Yamashita, Nozaki, and co-workers revisited the application of cyclopentadienylruthenium complexes in the hydroformylation of aliphatic olefins. Drawing conclusions from conventional rhodium-catalyzed hydroformylation complexes, in which a monohydridorhodium(I) species acts as a key intermediate, the authors aimed to synthesize a corresponding monohydridoruthenium complex.[51] As the cylopentadienyl ligands proved to be constantly attached to a ruthenium metal center, the authors were able to demonstrate the synthesis and application of [RuCp*] (Cp* = $C_5Me_5$) complexes with biphosphine and biphosphite ligands **45** and **46** (Scheme 16). Indeed, the




***Scheme 16.*** Ru/Cp*/bisphosphino- or bisphophite-based catalysts for *n*-selective hydroformylation.[51]

approach successfully suppressed undesired site reactions, such as hydrogenation and isomerization, and yielded linear aldehydes almost exclusively, albeit with low activity.

In a further development of this method, the same authors crafted a tandem hydroformylation/hydrogenation sequence of terminal alkenes to generate the corresponding higher linear alcohol.[52] The initial attempt concentrated on a sequential one-pot Rh-catalyzed hydroformylation/Ru-catalyzed hydrogenation upon utilization of Shvo's catalyst **47**. On the basis of an intensive mechanistic investigation, the authors successfully combined the salient features of both ruthenium catalysts. Hence, a combination of the previously utilized Cp*Ru/bisphosphine system for *n*-selective hydroformylation and Shvo's catalyst **47** resulted in a bifunctional catalyst **48** that was active for both transformations (Figure 6).

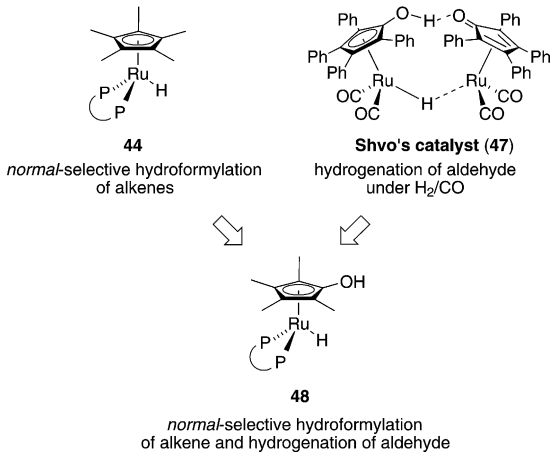



***Figure 6.*** Conceptual explanation of Ru-based hydroformylation/hydrogenation catalysts.[52]

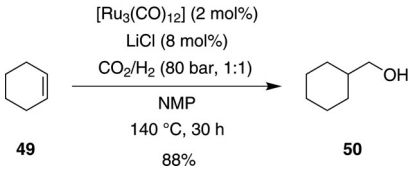
The utilization of carbon dioxide as a nontoxic and inexpensive C-1 building block is of widespread interest in the chemical industry. Several approaches have demonstrated the considerable potential of $CO_2$ as a valuable alternative to CO.[53] Independently published studies by Pettit et al.[54] and Laine et al.[55] on Ru-catalyzed hydroformylation and hydrohydroxymethylation under Reppe-type[56] reaction conditions (water-gas shift reaction, WGSR; Scheme 17) initially showed that the use of $CO_2$ was promising, because it is formed under the reaction conditions together with $H_2$. Here, the ability of polynuclear ruthenium complexes ($[Ru_3(CO)_{12}]$ and


***Scheme 17.*** Water-gas shift reaction.

$[H_4Ru_4(CO)_{12}]$) was exploited to promote the water-gas shift reaction in an alkaline solution.

Both $[Ru_3(CO)_{12}]$ and $[H_4Ru_4(CO)_{12}]$ efficiently catalyzed the hydroformylation of 1-pentene to hexanal and 2-methylpentanal with a high degree of *normal* selectivity (97%) under WGSR conditions.[55a] Unfortunately, the basic reaction conditions also catalyzed a subsequent aldol condensation, thus significantly diminishing the yield of 1-hexanal. The catalytic activity was attributed to the formation of $[H_3Ru_4(CO)_{12}]^-$ from $[Ru_3(CO)_{12}]$. To validate this presumption, the related tetranuclear compound $[H_4Ru_4(CO)_{12}]$ was used as a catalyst precursor. Under basic conditions this complex readily formed the presumed active $[H_3Ru_4(CO)_{12}]^-$ species, and resulted in a reduced induction period with otherwise identical product ratios.

Later on, Tominaga, Sasaki et al. reported substantial progress in the field of hydroformylation sequences under reverse water-gas shift conditions.[57,58] They found that halide anions promote the hydroformylation process under the pressure of carbon dioxide and hydrogen. The promoting effect decreased in the following order: $I^- < Br^- < Cl^-$, which correlates with their proton affinities.[59] As an example, $[Ru_3(CO)_{12}]$/LiCl catalyzed the hydroformylation of cyclohexene (**49**) to give an 88% yield of the corresponding alcohol **50** (Scheme 18). Under the same reaction conditions, competitive hydrogenation of the substrates limited the hydroformylation of terminal alkenes and vinyl arenes, thus providing low yields of the corresponding alcohols (32–56%).




***Scheme 18.*** Hydroformylation of cyclohexene (**49**) with $CO_2$.[58]

The concomitant hydrogenation of terminal alkenes was significantly suppressed by utilizing immobilized Ru complexes in the mixed ionic liquid [bmim][Cl+$NTf_2$] (bmim = 1-butyl-3-methylimidazolium).[60] The catalytic system was easily separated from the reaction mixture and recovered with only a minor loss of activity and chemoselectivity. However, this promising transformation still suffers from harsh conditions, narrow substrate scope, and a deficient in the understanding of its mechanism.[61]

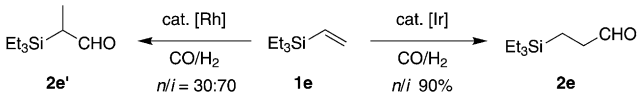
The majority of the Ru cataylsts employed in hydroformylations are based on polynuclear carbonyl complexes. However, it has been shown that mononuclear complexes exhibit higher activity.[23,27] The modification of such complexes with different phosphine ligands could lead to significant rewards in terms of activity and selectivity in the future.

### *2.2 Iridium-Catalyzed Hydroformylation*

Iridium and rhodium exhibit closely related chemical properties and coordination geometries. Iridium complexes provide elegant models for rhodium complexes, which tend to be unstable under certain conditions.[10e] It is, therefore, likely that the similar chemical properties of carbonyliridium complexes may result in comparable hydroformylation activity. This has led to the development of alternative iridium catalysts for homogeneous hydroformylation.[62]

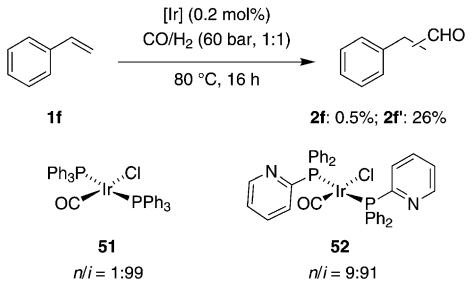
  

Research efforts by Crudden and Alper to develop regioselective hydroformylation reactions of vinylsilanes revealed remarkable differences in the selectivity of cobalt, rhodium, and iridium catalysts.[63] Whereas [Rh(cod)$BPh_4$] (cod = 1,5-cyclooctadienyl) resulted in branched aldehyde **2e′** with 70% selectivity, all the tested iridium complexes yielded the linear 3-(trialkylsilyl)propanal (**2e**) as the main product (Scheme 19). The best *n* selectivity (> 98%) was reported




***Scheme 19.*** Rh- and Ir-catalyzed regioselective formylation of vinylsilanes.[63]

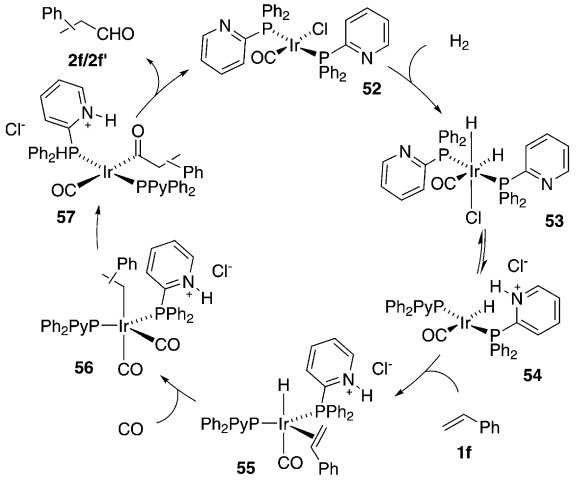
when $IrCl_3$ was used as the metal source. Likewise, cationic [$Ir(cod)_2$]$BF_4$ was able to produce linear aldehydes with up to 97% *n* selectivity and 75–80% yield. It is noteworthy that excess carbon monoxide ($CO/H_2 = 7:1$) appeared necessary to prevent unwanted olefin hydrogenation reactions. The addition of excess $PPh_3$ completely suppressed any hydroformylation ability of the iridium-based system, which had not been the case with the rhodium catalysts. Consistent observations have been made concerning a related reaction sequence catalyzed by iridium siloxide complexes.[64] It is important to note that phosphine ligands do not possess a general inhibiting effect. Although Vaska's complex *trans*-[Ir(CO)Cl-($PPh_3$)$_2$] (**51**) showed negligible reactivity, the analogues *trans*-[Ir(CO)Cl($PPyPh_2$)$_2$] (**52**; Py = pyridyl) significantly increased the rate of the catalytic hydroformylation of styrene (TOF up to 10 $h^{-1}$; Scheme 20).[65] Consequently, the signifi-




***Scheme 20.*** Vaska's complex, *trans*-[Ir(CO)Cl($PPh_3$)$_2$] (**51**) and *trans*-[Ir(CO)Cl($PPyPh_2$)$_2$] (**52**).[65]

cant change in the catalytic activity was attributed to the inherently basic nitrogen atom in the pyridine ring.

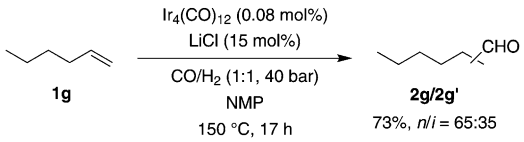
The authors showed that catalyst **52** is quantitatively transformed into dihydridoiridium species **53** upon treatment with hydrogen. Furthermore, pyridinium ions were detected under acidic conditions. On the basis of these observations, a catalytic cycle was proposed (Scheme 21). The catalytic cycle commences with hydrogenation of precatalyst **52**. The resulting dihydrido species **53** was found to react readily to form **54** under equilibrium conditions. Reductive elimination of HCl and generation of the vacant coordination site might be assisted by the neighboring pyridine nitrogen atom. The vacant coordination site allows for coordination of an incoming styrene molecule, which inserts into the metal–hydride bond. This, in conjunction with coordination of an additional carbonyl molecule, yields complex **56**. The adjacent CO ligand then migrates into the iridium—alkyl bond to give the corresponding acyl complex **57**. The final protonolysis of the acyl ligand was again thought to be supported by the proximate pyridium group. Eventually, recoordination of a chloride ligand to the metal center regenerates the active $Ir^I$ catalyst **52**. Notably, ethylbenzene was formed during the reaction in a yield ranging from 38 to 46%. This hydrogenated product is presumably formed due to protonolysis of the σ-bonding iridium–alkyl species **56** by means of the protonated $PPh_2PyH^+$ ligand.




***Scheme 21.*** Proposed mechanism for the *trans*-[Ir(CO)Cl($PPyPh_2$)$_2$] (**52**) catalyzed hydroformylation of styrene.[65]

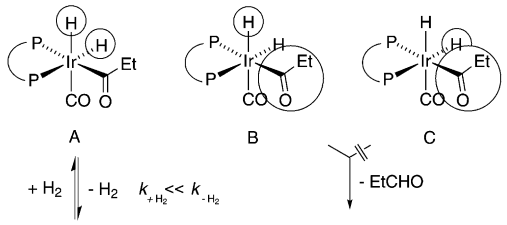
In the process of evaluating the promoting effect of metal salts on hydroformylation,[57b,66] the Haukka research group also examined the effect of such additives on the catalytic activity of iridium-based systems.[67] It has been shown that both the halide anion and the alkali metal cation have an impact on the activity and selectivity of the organometallic catalyst. The observed increased chemoselectivity may correlate with the size of the alkali cations, increasing in the order $K^+ < Na^+ < Ca^{2+} < Li^+$. It is thought that the cation stabilizes the most active oxidation state of the organometallic complex. The proper choice of the anion ($CO_3^{2-} < Br^- < Cl^-$) proved to be crucial for the effective formation of the catalytically active species and for decreasing the amount of hydrogenated side products. Consequently, the addition of LiCl resulted in significantly suppressed the hydrogenation and promoted an enhanced selectivity for the aldehyde. IR-spectroscopic analysis of the recovered catalysts provided evidence of the formation of a carbonylchloroiridium complex. This species was most efficiently prepared from [$Ir_4(CO)_{12}$]. Hence, a slight excess of LiCl relative to the catalyst afforded the best results (Scheme 22).

Whilst studying the synthesis and reactivity of the complexes [Ir($\eta^2$-$C_2H_4$)(Et)(CO)(dppe)] and [$IrH_2$(Et)(CO)-(dppe)] (dppe = ethane-1,2-diylbis(diphenylphosphane)),




***Scheme 22.*** Lithium chloride promoted Ir-catalyzed hydroformylation.[67]

Deutsch and Eisenberg detected the competitive reductive elimination of ethane and hydrogen.[68] The authors then focused on the competitive reductive elimination of acetaldehyde and hydrogen from alkyl and acyl iridium hydride complexes.[69] Two possible pathways for the formation of aldehydes (paths B and C) are available when starting from the Ir(III) species, for example, and one path for dihydride abstraction (path A, Scheme 23).

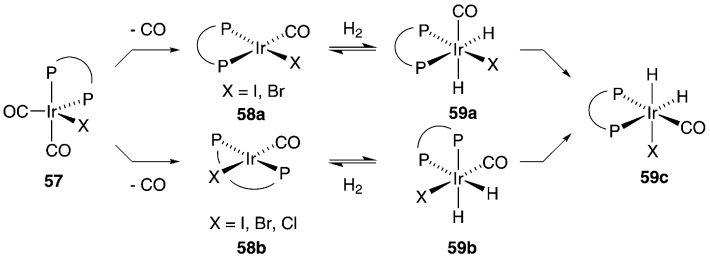



***Scheme 23.*** Possible pathways for reductive elimination of C–H and H–H bonds.[69]

Nevertheless, path C is unlikely to proceed through a concerted mechanism because the one-step elimination of the acyl and hydride ligands result in a *trans* coordination of the bidentate ligand, which is unprecedented for dppe, and was therefore excluded. Kinetic studies revealed that dihydride elimination proceeds considerably faster than the reductive C(O)H elimination. It follows that shifting the equilibrium in favor of aldehyde formation would require elevated temperatures and an excess of $H_2$.

Since xantphos, a ligand with a large bite angle, had received considerable attention and allowed for superior regioselectivity in rhodium-based hydroformylations, Eisenberg and co-workers prepared the corresponding iridium complexes.[70] Their studies included careful examination of the complex structure after exposure of $Ir^I$–xantphos complexes to parahydrogen. PHIP spectroscopy (parahydrogen induced polarization) is a powerful tool for investigating the coordination pattern of hydrogen to a metal catalyst.[71] This experiment is useful if the residence time of $H_2$ at the catalyst exceeds the NMR time scale. Coordination of parahydrogen in magnetically inequivalent positions breaks the high nuclear symmetry of the singlet state ($S_0$) and initiates an admixture of triplet states. This results in significantly enhanced signals and an altered pattern, thus allowing for precise assignment of the ligand coordination.

Consequently, treatment of [IrX(CO)$_2$(xantphos)] (**57**; X = I, Br, Cl) with parahydrogen revealed the formation of two different dihydride complexes, **59a** and **59b** (Scheme 24).



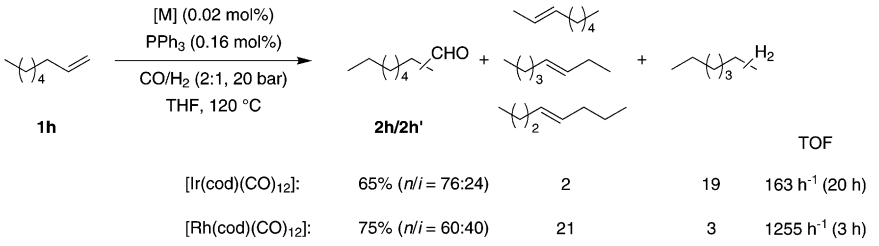

***Scheme 24.*** Different pathways for the formation of iridium dihydride **59**.[70]

Complex **59a** is formed when $H_2$ inserts in the P-M-CO bonds, whereas complex **59b** was thought to result from $H_2$ insertion in the P-M-P bonds of a *trans*-chelated $Ir^I$ complex (**58b**)—possible only because of its extremely wide bite angle.[72] The last complexes were exclusively formed from [IrCl(CO)$_2$-(xantphos)] and were only formed in small amounts from the Br and I analogues. The complexes were carefully analyzed by NMR and X-ray spectroscopy. Both structures were cleanly converted into the more stable complex **59c** at elevated temperatures. The hydroformylation of 1-hexene produced the corresponding higher aldehydes with an NMR yield of about 10% and an *n* selectivity of 4:1. The results are consistent with those of the dppe analogue indicated above. An unusual linear-to-branched product ratio of 3.3:1 has been observed in the hydroformylation of styrene. Here, the preference of the ligand for the linear product overrules the formation of the typically favored branched product, which is formed during the course of the formation of the thermodynamically more-stable benzyliridium complex. The overall diminished hydroformylation activity of iridium–xantphos complexes compared to the rhodium analogue was attributed to the inhibited formation of the iridium–acyl species.

Over the course of a large number of studies on the kinetics and mechanisms of homogeneous catalytic reactions, Rosales et al. investigated the hydroformylation of 1-hexene catalyzed by the cationic rhodium and iridium complexes [M(cod)(PPh$_3$)$_2$]PF$_6$.[73] Precatalysts bearing nonchelating phosphine ligands resulted in a chemoselective reaction to form the corresponding aldehydes. Direct comparison of the kinetics of these cationic systems revealed the Ir catalyst to be initially less active. Although the rhodium precatalyst was active at 60 °C and 3 bar syngas in toluene, the corresponding Ir-based system required an elevated temperature of 100 °C.

Despite previous reservations regarding the applicability of iridium–monophosphine complexes in hydroformylation reactions, our research group succeeded in devising a broadly applicable Ir/PPh$_3$-based hydroformylation catalyst (Scheme 25).[74] The catalyst was able to convert various terminal olefins with an average regioselectivity of 3:1 in favor of the linear aldehyde. Cooling the reaction mixture after a preliminary run led to precipitation of a metal salt, which was successfully characterized (by X-ray analysis) as dinuclear [Ir$_2$(CO)$_6$(PPh$_3$)$_2$]. This complex still showed moderate hydroformylation activity (46%), with no change in the linear-to-branched ratio (74:26). To evaluate the catalyst's performance in terms of cost efficiency, a corresponding Rh-




***Scheme 25.*** Ir versus Rh catalysts for the hydroformylation of 1-octene.[74]

based system was subjected to the same reaction conditions and the regioselectivity was found to be superior to the Ir-based system, although a slightly diminished yield was produced. In addition, unlike rhodium, iridium appeared to suppress alkene isomerization significantly. The overall TOF of the Rh-catalyzed hydroformylations (1255 $h^{-1}$) remained remarkable. However, when the high cost of the rhodium precursor is considered, the iridium catalysts may represent a worthwhile alternative for industrial applications.

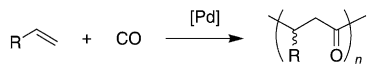
It is noteworthy that the superior stability of carbonyliridium complexes results in the overall activity of such catalysts in hydroformylation reactions remaining considerably lower than those of the rhodium congeners.

### 2.3. Palladium-Catalyzed Hydroformylation

Palladium(II) diphosphine complexes bearing weakly or noncoordinating anions proved to be valuable catalysts for hydroformylation reactions. In recent years, palladium catalysts have found widespread use in hydrocarboxylation and hydroesterification processes[75] as well as for the copolymerization of olefins with carbon monoxide.[73] Far fewer studies have, however, been conducted on palladium-catalyzed hydroformylation.

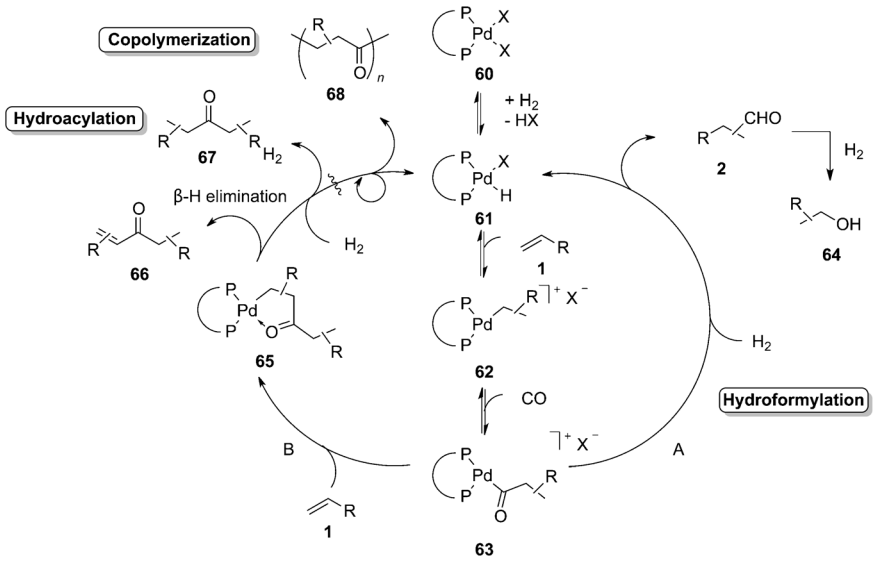
The recent interest in palladium-based carbonylation catalysts was sparked by a discovery of Drent et al. at Shell. They demonstrated the excellent catalytic performance of cationic palladium catalysts in highly efficient alternating copolymerizations of olefins with carbon monoxide (Scheme 26).[76,77]

Subsequent research efforts focused on the selective interruption of the polymerization process so as to target the efficient formation of aldehydes and ketones. Indeed, within the last decade, reasonable progress has been achieved in regard to chemoselectivity. The contribution made by




***Scheme 26.*** Palladium-catalyzed olefin/CO copoloymerization.[76,77]

alcohols, aldehydes, ketones, or oligoketones to the product is highly dependent on the intrinsic steric and electronic properties of the metal complex, which can be generally described as $[PdL_2X_2]$ ($L_2$ = bidentate ligand). The characteristics of the catalysts can be readily influenced by the appropriate choice of ligands and counterions.[78,79] It follows that strongly coordinating counterions and basic ligands favor the hydroformylation (pathway A), whereas a combination of noncoordinating anions and aryl phosphine ligands promotes the formation of (oligo)ketones (pathway B; Scheme 27). The elementary steps of the catalytic cycle are




***Scheme 27.*** Proposed catalytic cycle for Pd-catalyzed hydrocarbonylation reactions.

basically similar to the previously described hydroformylation processes. The Pd–hydride complex $[PdL_2HX]$ **61** is generally thought to serve as a catalytically active species, and is presumably formed through an anion-assisted heterolytic cleavage of dihydrogen. Subsequent coordination of the olefin and its migration into the Pd–hydride bond forms the Pd–alkyl species **62**. The resulting Pd–acyl complex **63** is formed when carbon monoxide inserts into the Pd–alkyl bond and serves as the key intermediate of the hydrocarbonylation sequence. Various pathways may be followed when starting from **63**. In the case of hydroacylation, insertion of a second olefin leads to the well-defined complex **65**[80] in which the carbonyl group coordinates to the metal center (path B). Regeneration of the active catalyst can occur through of β-hydride elimination that results in α,β-unsaturated ketone **66**, hydrogenolysis to form saturated ketones **67**, or after olefin/CO copolymerization. On the other hand, direct hydrogenolysis of the Pd–acyl species **63** leads to aldehydes **2** through a hydroformylation pathway (path A).

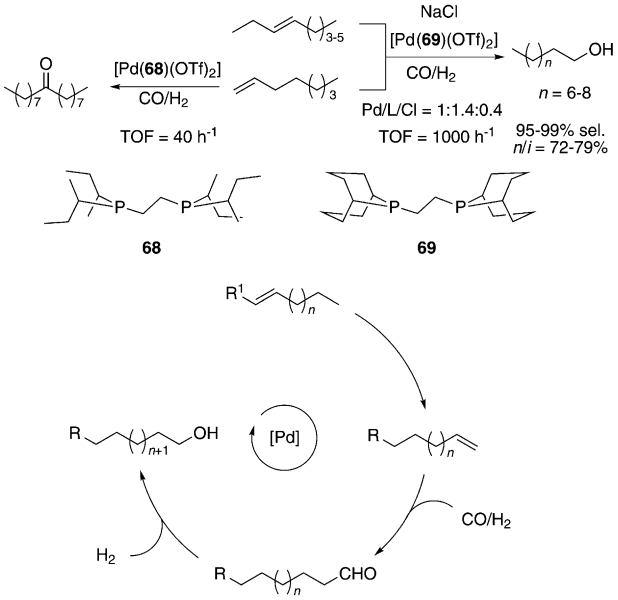
In further developments, Drent et al. published groundbreaking studies on chemoselective palladium-catalyzed for-

mylation.[78] Proper adjustment of the chelating phosphine ligands with the general formula $R_2P(CH_2)_nPR_2$ and the appropriate choice of counteranions $X^-$ allowed the authors to selectively address either the hydroformylation or hydroacylation pathway. The active complexes were generated in situ through a facile ligand complexation/anion displacement sequence starting from $Pd(OAc)_2$. The reaction was performed at 30 bar total syngas pressure ($CO/H_2 = 1:1$) at temperatures ranging between 80 and 125 °C. Initial turnover frequencies of up to 800 $h^{-1}$ have been achieved under these reaction conditions. Higher rates consistently resulted in poor chemoselectivity, which was largely affected by the nature of the acid used. For example, TFA (trifluoroacetic acid, $pK_a = -0.7$) allowed for the selective synthesis of aldehydes, whereas the selectivity was significantly shifted towards the formation of ketones when TfOH (trifluormethanesulfonic acid, $pK_a = -5.1$) was used. The concomitant use of *p*-TsOH (*para*-toluenesulfonic acid, $pK_a = -2.7$) and an increased hydrogen pressure altered the chemoselectivity in favor of the alcohol products. The regioselectivity was affected by the use of weaker acids, which result in a reduced electrophilicity of the metal center upon coordination. The resultant proximity of the anion to the metal center resulted in enhanced regiocontrol. Basic *cis*-chelating phosphine ligands led support to this effect, and led to enhanced regioselectivity in favor of the linear hydroformylation product. Stronger acids and less basic ligands, on the other hand, decreased the *n* selectivity. Since the coordination strength of anions depends greatly on the solvent, the best results were obtained in less polar solvents, e.g., diglyme solution.

The selective conversion of miscellaneous internal alkenes to linear carbonylation products is of considerable interest to the chemical industry. Although well developed, a severe lack in chemoselectivity remains evident. For example, simple carbonylcobalt complexes are suitable for isomerization/hydroformylation sequences but suffer from the formation of significant amounts of alkane by-products. On the other hand high, regioselectivity can be achieved with rhodium-based catalysts, but often requires expensive and sophisticated ligands.[81]

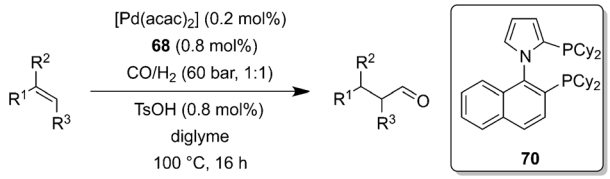
In 2006, Konya et al. reported a highly selective anion-promoted palladium-catalyzed isomerization/hydroformylation sequence that allowed for the efficient conversion of internal alkenes into linear aldehydes and alcohols, respectively (Scheme 28).[82] The combination of a [Pd(OTF)$_2$-(bcope)] (bcope = bis(cyclooctyl)phosphine ethane; **69**) catalysts and a substochiometric amount of halide anion (with respect to the catalyst, Pd/L/Hal = 1:1.4:0.4) promoted the efficient conversion of a conglomerate of $C_8$–$C_{10}$ internal olefins into terminal alcohols through an all-metal-catalyzed domino isomerization/hydrocarbonylation/hydrogenation reaction sequence. The authors were able to show that halide anions exert a significant influence on the thermal equilibration of internal alkenes. Chloride anions from an NaCl source led to an enhanced regioselectivity and increased the overall reaction rate. Furthermore, the authors also identified that the Pd–acyl species specifically underwent an accelerated hydrogenolysis. Chemoselectivity, in contrast, was severely ligand-dependent, but not influenced by the addition




***Scheme 28.*** Efficient halide anion promoted Pd-catalyzed hydroformylation of internal alkenes to linear aldehydes or alcohols.[81]

of an anion. Hence, the structurally closely related ligand **68** mainly yielded hydroacylation products from 1-octene and showed no activity in terms of the conversion of internal olefins. An equilibrated mixture of internal $C_8$–$C_{10}$ alkenes was, therefore, successfully converted into the corresponding higher linear alcohols. This was followed by a comprehensive study of the structure and properties of potentially reactive intermediates.[83,84]

In 2009, our research group investigated the palladium-catalyzed hydroformylation sequence using a catalytic system comprising [Pd(acac)$_2$] (acac = acetylacetonato), a bidentate ligand derived from 1-(naphthalen-1-yl)-1*H*-pyrrole (**70**), and *p*-TsOH at 60 bar total pressure in diglyme solution (Scheme 29).[85] Reactions in degassed water or methanol




***Scheme 29.*** Pd-catalyzed hydroformylation.[84] Cy = cyclohexyl.

resulted in concomitant hydroxy and methoxy alkylation products, respectively. However, a system that was originally optimized for converting 1-octene into nonanal afforded good to excellent regioselectivity when applied to numerous substrates. Although 1-octene underwent isomerization to internal olefins, the system demonstrated impressive regioselectivity for linear aldehydes when vinyl substrates were used. For example, *N*-vinylphthalimide (**71**) was hydroformylated to the corresponding aldehyde **72** in 95% yield with 98% *n* selectivity, which sets a benchmark for this substrate (Scheme 30).

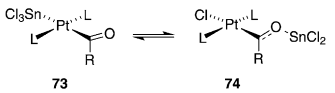
  


***Scheme 30.*** Highly *n*-selective Pd-catalyzed hydroformylation of *N*-vinylphthalimide (**71**).[85]

In conclusion, more-potent Pd catalysts for hydroformylation can be formed from basic, bidentate phosphine ligands in combination with an acid co-catalyst. Nevertheless, palladium-catalyzed hydroformylation reactions have received merely minor attention compared to other hydrocarbonylation reactions. In contrast, the corresponding hydrocarboxylation and hydroesterification processes have been studied and addressed much more frequently.

### *2.4. Platinum-Catalyzed Hydroformylation*

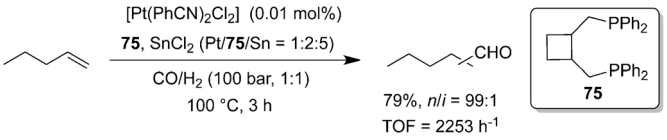
Platinum is another potent metal for hydroformylation catalysis. The first examples of the application of platinum metals in hydroformylation appeared in the patent literature at an early stage (in 1966).[86] Initial doubts concerning the benefit of this precious metal catalyst were soon disregarded when Schwager and Knifton[87] and Kehoe and Schell[88] discovered the fundamental impact of tin(II) chloride as a co-catalyst on the process. The regioselectivity exhibited by bimetallic Pt/Sn systems for linear aldehydes was significantly higher than that of rhodium- or cobalt-based systems under mild reaction conditions. In the following years, the influence of this additive was investigated in numerous studies. Nevertheless, the actual role of tin chloride has not been fully elucidated, as $SnCl_3^-$ may interact with the platinum catalyst in a number of different ways. The addition of trichlorostannate proved advantageous and led to significantly increased activity and selectivity. In addition to its Lewis acid character, tin chloride may also act as a counterion or as a directly coordinated ligand.[89] Furthermore, an exceptional ability of stannates to stabilize five-coordinated platinum centers was suggested.[90] The inherent *trans* effect of the $SnCl_3^-$ ligand seems to be prevalent in the first step of the catalytic cycle upon activation of the Pt–H bond to facilitate the insertion of the olefin (**80**→**82**, see Scheme 34).[91] The same effect, but less pronounced, was observed in the migration of CO into the Pt–alkyl bond (**82**→**83**; see Scheme 34).[90d,92] Two different complexes are formed after CO migration into the Pt–alkyl bond: *trans*-[Pt($SnCl_3$)(COR)$L_2$] (**73**) and *trans*-[PtCl(COR)$L_2$] (**74**), in which the Lewis acidic $SnCl_2$ coordinates to the acyl oxygen atom (Scheme 31).[93] Notably, the structure was found to be formed predominately under hydroformylation conditions. The hemilabile stannate ligand can easily be abstracted from a metal–hydride species through the addition of strong bases. The resulting $HSnCl_3$ is not capable of further coordination, thus completely inhibiting the catalytic activity.[94]




***Scheme 31.*** $SnCl_2$ as a ligand or Lewis acid.[93]

In addition to its essentially promoting character, $SnCl_2$ proved necessary for the final reaction step, that is, hydrogenolysis of the metal acyl intermediate **83** (see Scheme 34).[95] Tin chloride has a twofold effect on the oxidative addition of dihydrogen to the metal center. These were attributed to the weak σ-donor and strong π-acceptor properties of $SnCl_2$.[93a] On the one hand, the σ-donor function increases the electron density of the metal center and thus facilitates its oxidative addition. Additionally, accumulation of dihydrogen at the bonding π orbitals of the Sn–Pt bond increases the electron density in the antibonding σ* bond, which facilitates H–H bond cleavage.[92a] Similar ligand effects have previously been noted in iridium–carbonyl[96] and rhodium–chloride systems.[97]

Platinum–phosphine catalysts activated by tin chloride demonstrated remarkable catalytic activity in the hydroformylation of both terminal and internal alkenes.[98] During the course of numerous studies, a strong influence of ligand flexibility became apparent. The situation is similar to rhodium-based systems, where steric constraints permit increased regioselectivity. In the case of hydroformylation by platinum catalysts, this influence was initially reported by Kawabata et al., who recognized significant improvement in terms of the *n*/*i* ratio when rigid diphosphine ligands, in particular *trans*-1,2-bis((diphenylphosphino)methyl)cyclobutane (**75**), was used.[99] The optimal ratio of catalyst to phosphine and additive was found to be Pt/Sn/L = 1:5:2. The hydroformylation of 1-pentene proceeded with a remarkable *n*/*i* selectivity of 99:1 in benzene solution at 100 °C and an initial syngas pressure of 100 bar (Scheme 32). The formation of by-products could be reduced by using lower temperatures or higher syngas pressures.

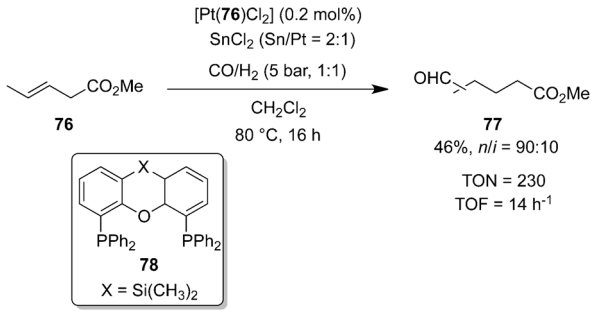



***Scheme 32.*** Pt/Sn-catalyzed hydroformylation with rigid phosphine ligands.[99]

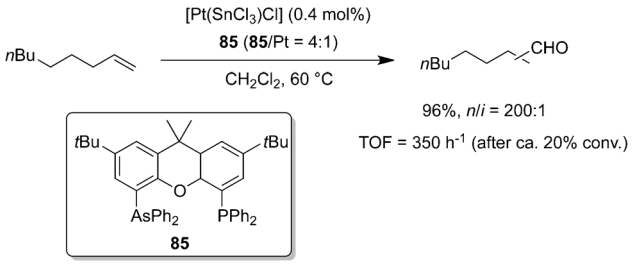
Vogt and co-workers disclosed a protocol for the highly regioselective hydroformylation of internal, functionalized olefins by using ligands with large bite angles.[98e] Si-xantphos (**78**) displayed high regioselectivities for linear aldehydes **77** through an isomerization/hydrocarbonylation sequence (Schemes 33 and 34). The resulting products are of considerable industrial interest as potential intermediates for polyesters and polyamides.

The pressure dependence of the reaction was examined during the course of the optimization studies. As expected, a decreased syngas pressure lowered the hydrogenation activity. However, an elevated pressure resulted in superior

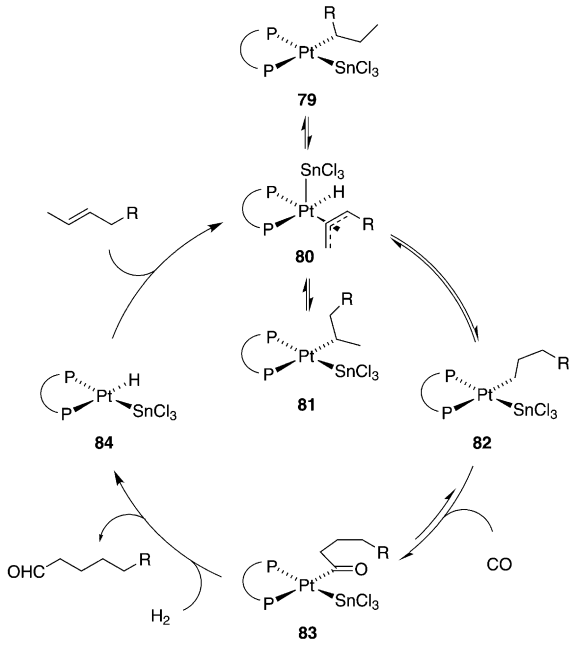
  




***Scheme 33.*** Pt/Sn-catalyzed hydroformylation of methyl pentenoates.[98e]




***Scheme 35.*** Xanthphosarsine **85** in Pt/Sn-catalyzed hydroformylation.[101]

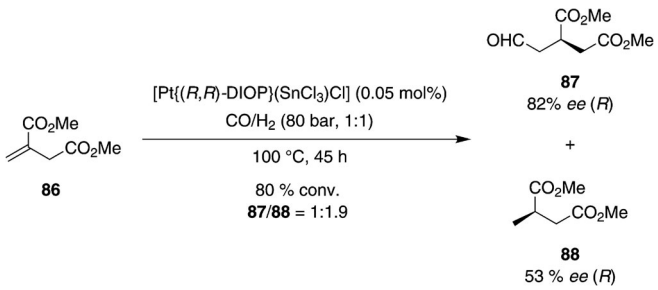



***Scheme 34.*** Isomerization versus carbonyl migration.

regioselectivity. At low CO concentration, isomerization to the thermodynamically favored *n*-alkyl complex was achieved at a rate faster than CO insertion. It is worth mentioning that the pressure dependence was studied at a constant $CO/H_2$ ratio of 1:1; the partial pressures were not, however, varied.

Hydroformylations with alternative metals are not merely promoted by phosphine ligands—arsine-, amine-, and sulfur-containing analogues were also found to be effective in this reaction.[100] Indeed, studies on the synthetic application of wide-bite-angle arsine ligands by van Leeuwen and co-workers emphasized that the activity and selectivity of mixed xantphosarsine ligands **85** in the Pt/Sn-catalyzed hydroformylation of 1-octene (Scheme 35) were higher than had previously been observed.[101] The conversion of the terminal olefin into its corresponding $C_1$-extended aldehyde was catalyzed by 0.4 mol% Pt, with an initial TOF of 350 $h^{-1}$. The addition of **85** led to excellent chemo- and regioselectivity for the linear aldehyde (96%, $n/i = 200:1$) along with negligible amounts of undesired by-products.

Despite the exceptional linear-to-branched ratios induced by platinum–tin complexes, attention soon focused primarily on asymmetric reaction sequences. This interest evolved largely from the progression made in rhodium-catalyzed asymmetric hydroformylations.[3] Initial studies likewise addressed Pt/Sn-diop complexes, and resulted in a series of publications describing the enantioselective hydroformylation of butenes[102] and vinyl arenes.[103] It is noteworthy that the hydroformylation of dimethyl itaconoate using chiral Pt/Sn catalysts proceeded with 82% *ee* (Scheme 36), but rarely exceeded 50% for other substrate classes.[104]



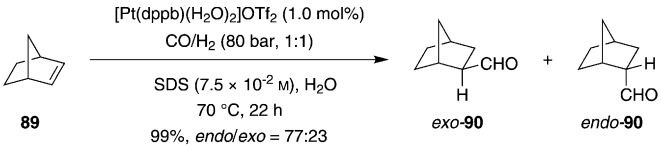

***Scheme 36.*** Enantioselective Pt/Sn-catalyzed hydroformylation of dimethyl itaconoate.[104]

A detailed study of the chiral induction by enantiomerically pure diop showed a temperature-dependent reversal of enantioselectivity over the course of the addition of platinum hydride to prochiral substrates.[105] It became apparent that the reversibility may be affected by the choice of the solvent. A polar reaction medium of triethyl formate led to a significant decrease in product racemization, thereby resulting in high enantiomeric excess (>96%; compared to 70% *ee* in benzene solution). However, a diminished catalyst activity needed to be taken into account under these conditions.[106] These findings were then applied to the asymmetric platinum/tin-catalyzed hydroformylation of a variety of prochiral vinyl arenes in the presence of well-defined platinum–diphosphine complexes derived from 4-hydroxy-L-proline.[107] The use of triethyl formate significantly increased the chemoselectivity (>90%), thus yielding an excess of valuable aryl propanals; prolonged reaction times of up to several days were, however, required for these reactions.

While most initial investigations of platinum-catalyzed hydroformylation focused on platinum–tin complexes, some

tin-free hydroformylation catalysts have also been discussed in detail.[108] Noteworthy among these is the study by Gottardo et al., who elaborated an elegant procedure for the hydroformylation of terminal and internal alkenes by cationic platinum triflate complexes in a micellar medium.[108b] The addition of sodium dodecylsulfonate (SDS) ensured high dissolution of the substrate and catalyst. Aggregation of the catalyst on the micellar surface allowed for convenient separation of the catalyst as well as recycling with only a minor loss of activity and unaltered regioselectivity. The authors presented a large array of substrates in which terminal alkenes demonstrated high *n* selectivities. Under the optimal conditions, the internal double bond of norbornene (**89**) was transformed to give a quantitative yield of the corresponding aldehyde, according to $^1$H NMR measurements. The *endo*/*exo* ratio of the product was 77:23 (Scheme 37).




***Scheme 37.*** Pt$^{II}$-catalyzed tin-free hydroformylation of norbornene.[108]

The importance of sterically constrained ligands in Pt/Sn systems was further demonstrated by Pongrácz et al. as part of a systematic investigation of the effect of five- and six-membered phosphorus heterocycles in styrene hydroformylation.[109,110] The hydroformylation of vinyl arenes in the presence of platinum catalysts containing mostly planar tetra- and hexahydrophosphine ligands (**91** and **92**; Figure 7),

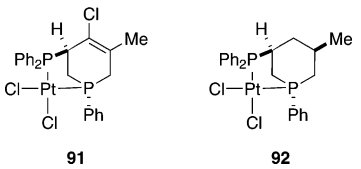


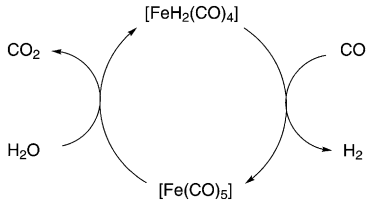

***Figure 7.*** Platinum catalyst precursors **91** and **92** for the hydroformylation of styrene derivatives.[110]

respectively, provided excellent results in terms of chemo- and regioselectivity in favor of the branched aldehydes.

### *2.5. Iron-Catalyzed Hydroformylation*

Iron constitutes one of the most prevalent metals, with a worldwide occurrence of roughly 6 wt% in the lithosphere. The facile availability and worthwhile physicochemical properties render iron a key commodity in the manufacturing industry. In addition, the global demand for more economical and sustainable chemical processes led to an increased interest in the application of iron in transition-metal catalysis.[111]

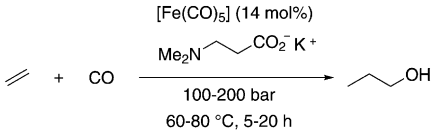
The general reactivity of carbonylhydridoiron complexes was studied by Reppe and Vetter in 1953 (Scheme 38).[56] They identified the formation of hydrogen and $[Fe(CO)_5]$




***Scheme 38.*** General scheme for hydrogen evolution under Reppe conditions.[56]

upon treatment of $[Fe(CO)_4H_2]$ with carbon monoxide in alkaline solution. This reaction was found to be in equilibrium with the Hieber base reaction, in which the pentacarbonyliron complex undergoes nucleophilic attack by excess alkali metal hydroxides, thus allowing for regeneration of the metal carbonyl hydride species and evolution of $CO_2$.

The authors attempted to convert the evolving hydrogen with alkenes and acetylene derivatives in the presence of water and different amines. The introduction of ethylene in an aqueous alkaline solution of $[Fe(CO)_5]$ predominantly yielded higher boiling alcohols, resulting from the condensation of the initially formed propionaldehyde, along with minor amounts of propanol. The undesired formation of alkaline formates and carbonates in alkaline solution prevented practical applications of this process. The substitution of alkali metal hydroxides with tertiary amine bases ensured continuous evolution of $CO_2$ and facilitated the reduction of the aldehydes, thereby resulting in enhanced alcohol formation.[54,112] Eventually, a recyclable system comprising a potassium dimethyl glycine solution and catalytic amounts of $[Fe(CO)_5]$ permitted the selective conversion of ethylene with CO and in situ generated hydrogen into *n*-propanol at 60–80 °C at 100–200 bar total pressure (ethylene/CO = 1:3; Scheme 39).



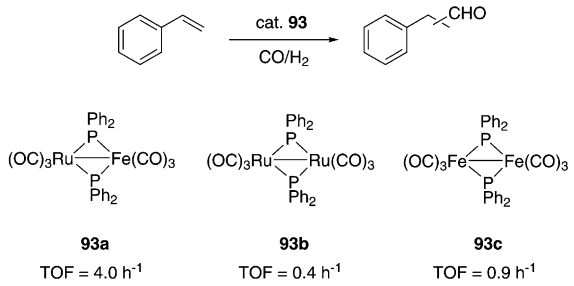

***Scheme 39.*** First example of the Fe-catalyzed hydroformylation of ethylene by Reppe and Vetter.

Almost 30 years after the initial discovery of the Reppe hydroformylation, the process was revisited by Pálágyi and Markó, but this time with styrene.[113] The hydroformylation proceeded in the presence of $[Fe_3(CO)_{12}]$, $NEt_3$, and NaOH at an elevated temperature of 140 °C and 100 bar CO pressure in $H_2O$/MeOH solution. The authors found a strong dependence of the product distribution on the $H_2O$/MeOH ratio. Thus, the formation of linear and branched alcohols was favored in a 3:1 $H_2O$/MeOH mixture, whereas hydrogenation was

predominant at lower water concentrations ($H_2O$/MeOH = 1:2). It is noteworthy that the total conversion into the desired oxygenated products did not exceed 30%.

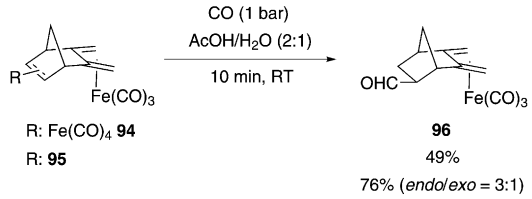
Since then, research efforts in this area predominantly evolved towards the applicability of mixed iron–metal clusters for hydroformylation reactions,[114] with Fe–Rh cluster complexes having received the most attention. However, catalyst degradation was observed in most cases.[115] Nevertheless, He et al. observed a rate-accelerating effect on the hydroformylation of styrene when phosphine-bridged heterobimetallic Fe–Ru clusters were employed.[116] Thus, the oxygenation of styrene in the presence of complex **93a** proceeded up to ten and four times faster (TOF = 4.0 $h^{-1}$) than the corresponding Ru–Ru (**93b**; 0.4 $h^{-1}$) and Fe–Fe (**93c**; 0.9 $h^{-1}$) analogues, respectively (Scheme 40). A similar effect was later observed in the hydroformylation of propylene.[117]




***Scheme 40.*** Hydroformylation of styrene catalyzed by phosphine-bridged homo- and heterobimetallic complexes **93a–c**.[116]

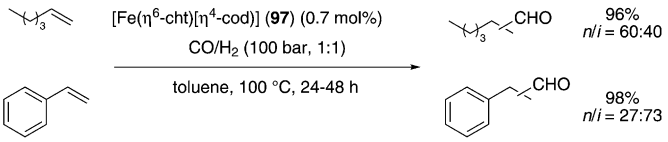
Della Pergola et al. synthesized and characterized the mixed-metal Fe–Rh and Fe–Ir nitrido carbonyl clusters $[Fe_5RhN(CO)_{15}]^{2-}$, $[Fe_5IrN(CO)_{15}]^{2-}$, and $[Fe_5Rh_2N(CO)_{15}]^{-}$.[115b] The Fe–Rh nitrido clusters exhibited higher stability than the corresponding carbides,[115a] and showed moderate activity towards the hydroformylation of 1-pentene. However, the mixed-metal cluster also suffered from degradation under the applied reaction conditions. The dianion $[Fe_5RhN(CO)_{15}]^{2-}$ was found to be less prone to fragmentation, but only marginal conversion of 1-pentene into hexanal (10%, $n/i$ = 66:33, TOF = 26 $h^{-1}$) has been achieved. The related monoanion $[Fe_5Rh_2N(CO)_{15}]^{-}$ demonstrated superior hydroformylation abilities, and allowed for an improved and accelerated conversion of 1-pentene into hexanal (>70%, $n/i$ = 36:64, TOF = 351 $h^{-1}$). The inverse regioselectivity was not further elaborated upon by the authors. IR spectroscopic studies and specific chemical properties gave evidence for the prevalent formation of rhodium-rich clusters of high nuclearity, which predominantly accounted for the high catalytic activity.

An interesting but stochiometric application of a direct carbonylation of an iron–olefin complex was presented by Loset and Roulet in 1985.[118] Therein a rapid carbonylation of the *exo*-(1*R*,4*S*)-5,6-dimethylenebicyclo[2.2.1]hept-2-ene-derived carbonyliron complexes **94** and **95** at atmospheric CO pressure and ambient temperature in AcOH/$H_2O$ (2:1) was reported. Monocarbonylation products were isolated in moderate yields and good *endo* selectivity by following this protocol (Scheme 41).




***Scheme 41.*** Direct carbonylation of iron–olefin complexes reported by Loset and Roulet.[118]

In 2000, Pertici and co-workers disclosed an interesting protocol for the application of a readily accessible iron(0) catalyst precursor in which the metal center is exclusively coordinated by cycloolefins (Scheme 42).[119] The complex




***Scheme 42.*** Hydroformylation of 1-hexene and styrene catalyzed by [Fe($\eta^6$-cht)( $\eta^4$-cod)] (**97**) as a catalyst precursor.[119]

[Fe($\eta^6$-cht)($\eta^4$-cod)] (**97**; cht = 1,3,5-cycloheptatriene) showed a respectable catalytic activity in the hydroformylation of 1-hexene and styrene as well as in [2+2+2] cycloadditions. The hydroformylation activity was examined in toluene at 100 °C and 100 atm $CO/H_2$ (1:1) total pressure in the presence of 0.7 mol% of the catalyst precursor. Under the hydroformylation conditions, 1-hexene was chemoselectively converted into 1-heptanal and the branched aldehyde 2-methylhexanal in a 60:40 ratio. The hydroformylation of styrene was achieved with 98% conversion after 48 h. The formation of the branched aldehyde as the main component is commonly attributed to the increased stability of the respective metal–alkyl intermediates. The applied precatalysts **97** showed significantly increased hydroformylation activity compared to the parent complex [Fe(CO)$_5$], and allowed the clean, high-yielding hydroformylation of aliphatic alkenes and vinyl arenes, without occurrence of hydrogenative side reactions. The unusually high activity of complex **97** became most evident in the hydroformylation of styrene, in which a superior TOF of 4.1 $h^{-1}$ compared to 0.6 $h^{-1}$ for [Fe(CO)$_5$] was found.

## 3. Summary and Outlook

Cobalt- and rhodium-based catalysts have dominated hydroformylations, both in laboratories and on an industrial scale, for more than 60 years. However, comparison of these classic hydroformylation processes with those subsequently developed that are based on "alternative" metals such as ruthenium, iridium, palladium, platinum, and iron catalysts reveal the latter to have weaknesses in terms of productivity and activity. The activity of the catalyst is a crucial factor, particularly for bulk industrial applications. Realistically, the TOFs of these "alternative" systems have to be improved by one to two orders of magnitude before they will become

economical viable. The understanding of the rate-limiting elementary reaction steps in "alternative" metal-catalyzed hydroformylation has to be significantly increased to achieve this challenging goal. In this regard, one ought to consider that the substantial progress that has been achieved in rhodium-based hydroformylations is owed to a large part to its beneficial NMR spectroscopic properties. However, it took more than 30 years to gain a fundamental understanding of this process. Unfortunately, the spectroscopic properties of the other metals are limited. Despite the significant progress that has been achieved in fields such as in situ spectroscopy (IR, ESI-MS, PHIP NMR, etc.) and computational chemistry, which impart a deeper insight into the mechanisms, extensive further research will be indispensable.

However, there is a growing awareness that the diversification of organometallic complexes offers new opportunities for hydroformylation reactions. New catalyst systems may become particularly rewarding for the transformation of more challenging or industrially interesting substrates, such as internal olefins or olefins from renewable feedstocks. Further research should certainly exploit the beneficial features that are provided by the "alternative" metal catalysts, for example, selective formation of higher alcohols (Ru), isomerization (Pd), and asymmetric carbonylation (Pt/Sn). Indisputably, the use of organometallic complexes from more readily available biorelevant metals attracts increasing interest in homogeneous catalysis. On this basis, the most promising solution in terms of price and availability of the metal would be the use of efficient iron-based carbonylation systems.

Tremendous endeavors in comprehensive ligand screening have been made in other research areas. In comparison, most of the reports summarized herein lack any such investigations. Nevertheless, we expect that considerable improvements ought to be achieved through judicious choice of the ligand for each of the metals mentioned herein. However, one should also keep in mind that the ligand always contributes significantly to the overall price of the catalyst system. Hence, novel easy-to-synthesize ligand systems represent another auspicious challenge. We believe that bio-inspired catalysts might pave the way for the future development of enzymatic hydroformylation.

*The financial support by Evonik Industries AG, the Bundesministerium, für Bildung und Forschung (the German Federal Ministry of Education and Research) under the PROFORMING project (no. 03X3559), the state Mecklenburg Vorpommern, and Swiss National Science Foundation (SNSF, grants for I.F.) is gratefully acknowledged.*

Received: October 16, 2012
Published online: February 21, 2013

[1] a) K.-D. Wiese, D. Obst in *Catalytic Carbonylation Reactions* (Ed.: M. Beller), Springer, Berlin, **2010**, pp. 1 – 33; b) K. Weissermel, H.-J. Arpe in *Industrial Organic Chemistry*, Wiley-VCH, Weinheim, **2008**, pp. 127 – 144; c) B. Breit, W. Seiche, *Synthesis* **2001**, 1 – 36; d) B. Breit in *Metal Catalyzed Reductive C-C Bond Formation* (Ed.: M. Krische), Springer, Berlin, **2007**, pp. 139 – 172; e) C. P. Casey, J. F. Hartwig in *Organotransition Metal Chemistry: From Bonding to Catalysis* (Ed.: J. F. Hartwig), University Science Books, Sausalitos, **2010**, pp. 751 – 769; f) R. Franke, D. Selent, A. Börner, *Chem. Rev.* **2012**, *112*, 5675 – 5732; g) P. W. N. M. van Leeuwen, *Homogeneous Catalysis—Understanding the Art*, Kluwer Academic Publisher, Dodrecht, **2004**.

[2] P. M. Lorz, F. K. Towae, W. Enke, R. Jäckh, N. Bhargava, W. Hillesheim in *Ullmann's Encyclopedia of Industrial Chemistry*, Wiley-VCH, Weinheim, **2007**, DOI: 10.1002/14356007.a20_181.pub2.

[3] For selected reviews on branched-selective hydroformylations, see a) J. Klosin, C. R. Landin, *Acc. Chem. Res.* **2007**, *40*, 1251 – 1259; b) M. L. Clarke, *Curr. Org. Chem.* **2005**, *9*, 701 – 718; c) B. Breit, *Acc. Chem. Res.* **2003**, *36*, 264 – 275; d) F. Agbossou, J.-F. Carpentier, A. Mortreux, *Chem. Rev.* **1995**, *95*, 2485 – 2506.

[4] a) O. Roelen (Chemische Verwertungsgesselschaft Oberhausen), DE849548, **1938/52**; US2327066 **1943**; b) B. Cornils, W. A. Herrmann, M. Rasch, *Angew. Chem.* **1994**, *106*, 2219 – 2238; *Angew. Chem. Int. Ed. Engl.* **1994**, *33*, 2144 – 2163.

[5] a) G. Dümbgen, D. Neubauer, *Chem. Ing. Tech.* **1969**, *41*, 974 – 980; b) H.-W. Bohnen, B. Cornils, *Advances in Catalysis*, *Vol. 47*, Academic Press, New York, **2002**, pp. 1 – 64.

[6] E. F. Lutz, *J. Chem. Educ.* **1986**, *63*, 202.

[7] R. F. Heck, D. S. Breslow, *J. Am. Chem. Soc.* **1961**, *83*, 4023 – 4027.

[8] J. A. Osborn, G. Wilkinson, J. F. Young, *Chem. Commun.* **1965**, 17.

[9] D. Evans, J. A. Osborn, G. Wilkinson, *J. Chem. Soc. A* **1968**, 3133 – 3142.

[10] a) *Rhodium Catalyzed Hydroformylation* (Eds.: C. Claver, P. W. N. M. van Leeuwen), Springer, Berlin, **2008**; b) L. A. van der Veen, M. D. K. Boele, F. R. Bregman, P. C. J. Kamer, P. W. N. M. van Leeuwen, K. Goubitz, J. Fraanje, H. Schenk, C. Bo, *J. Am. Chem. Soc.* **1998**, *120*, 11616 – 11626; c) M. Kranenburg, Y. E. M. van der Burgt, P. C. J. Kamer, P. W. N. M. van Leeuwen, K. Goubitz, J. Fraanje, *Organometallics* **1995**, *14*, 3081 – 3089; d) C. P. Casey, E. L. Paulsen, E. W. Beuttenmueller, B. R. Proft, B. A. Matter, D. R. Powell, *J. Am. Chem. Soc.* **1999**, *121*, 63 – 70, and references therein.

[11] C. W. Kohlpaintner, R. W. Fischer, B. Cornils, *Appl. Catal. A* **2001**, *221*, 219 – 225.

[12] B. Cornils, E. G. Kuntz, *J. Organomet. Chem.* **1995**, *502*, 177 – 186.

[13] L. A. van der Veen, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Angew. Chem.* **1999**, *111*, 349 – 351; *Angew. Chem. Int. Ed.* **1999**, *38*, 336 – 338.

[14] J. Butler in *PLATINUM 2011*, Johnson Mattey Public Limited Company, Hertfordshire, **2011**.

[15] D. Evans, J. A. Osborn, F. H. Jardine, G. Wilkinson, *Nature* **1965**, *208*, 1203 – 1204.

[16] H. F. Schulz, F. Bellstedt, *Ind. Eng. Chem. Prod. Res. Dev.* **1973**, *12*, 176 – 183.

[17] R. A. Sanchez-Delgado, J. S. Bradley, G. Wilkinson, *J. Chem. Soc. Dalton Trans.* **1976**, 399 – 404.

[18] L. Alvila, T. A. Pakkanen, T. T. Pakkanen, O. Krause, *J. Mol. Catal.* **1992**, *73*, 325 – 334.

[19] a) G. Süss-Fink, *J. Organomet. Chem.* **1980**, *193*, C20 – C22; b) B. F. G. Johnson, J. Lewis, P. R. Raithby, G. Suss, *J. Chem. Soc. Dalton Trans.* **1979**, 1356 – 1361.

[20] G. Süss-Fink, G. F. Schmidt, *J. Mol. Catal.* **1987**, *42*, 361 – 366.

[21] G. Süss-Fink, J. Reiner, *J. Mol. Catal.* **1982**, *16*, 231 – 242.

[22] G. Süss-Fink, G. Herrmann, *J. Chem. Soc. Chem. Commun.* **1985**, 735 – 737.

[23] T. Hayashi, Z. Hui Gu, T. Sakakura, M. Tanaka, *J. Organomet. Chem.* **1988**, *352*, 373 – 378.

[24] M. Bianchi, G. Menchi, P. Frediani, U. Matteoli, F. Piacenti, *J. Organomet. Chem.* **1983**, *247*, 89 – 94.

[25] For further insight on the effect of Ru–phosphine complexes on the isomerization of aliphatic olefins, see A. Salvini, F. Piacenti, P. Frediani, A. Devescovi, M. Caporali, *J. Organomet. Chem.* **2001**, *625*, 255–267.
[26] E. Cesarotti, A. Fusi, R. Ugo, G. M. Zanderighi, *J. Mol. Catal.* **1978**, *4*, 205–216.
[27] A. Fusi, E. Cesarotti, R. Ugo, *J. Mol. Catal.* **1981**, *10*, 213–221.
[28] T. Suarez, B. Fontal, *J. Mol. Catal.* **1985**, *32*, 191–199.
[29] a) M. J. Mirbach, M. F. Mirbach, A. Saus, N. Topalsavoglou, P. Tuyet Nhu, *J. Am. Chem. Soc.* **1981**, *103*, 7594–7601; b) M. J. Mirbach, M. F. Mirbach, A. Saus, N. Topalsavoglou, P. Tuyet Nhu, *J. Am. Chem. Soc.* **1981**, *103*, 7590–7594.
[30] A. Saus, T. N. Phu, M. J. Mirbach, M. F. Mirbach, *J. Mol. Catal.* **1983**, *18*, 117–125.
[31] E. M. Gordon, R. Eisenberg, *J. Organomet. Chem.* **1986**, *306*, C53–C57.
[32] J. F. Knifton, *J. Mol. Catal.* **1987**, *43*, 65–77.
[33] For additional examples of the application of *N,N*-chelating ligands, see J. F. Knifton, *J. Mol. Catal.* **1988**, *47*, 99–116.
[34] a) J. Jenck, P. Kalck, E. Pinelli, M. Siani, A. Thorez, *J. Chem. Soc. Chem. Commun.* **1988**, 1428–1430; b) P. Kalck, M. Siani, J. Jenck, B. Peyrille, Y. Peres, *J. Mol. Catal.* **1991**, *67*, 19–27.
[35] a) A. Béguin, H.-C. Böttcher, G. Süss-Fink, B. Walther, *J. Chem. Soc. Dalton Trans.* **1992**, 2133–2134; b) A. Salvini, P. Frediani, D. Rovai, M. Bianchi, F. Piacenti, *J. Mol. Catal.* **1994**, *89*, 77–91.
[36] A. F. Borowski, D. J. Cole-Hamilton, G. Wilkinson, *Nouv. J. Chim.* **1978**, *2*, 137–144 [*Chem. Abstr.* **1978**, 509734].
[37] J.-x. Gao, P.-p. Xu, X.-d. Yi, H.-l. Wan, K.-r. Tsai, *J. Mol. Catal. A* **1999**, *147*, 99–104.
[38] M. M. T. Khan, S. B. Halligudi, S. H. R. Abdi, *J. Mol. Catal.* **1988**, *48*, 313–317.
[39] M. M. T. Khan, S. B. Halligudi, S. H. R. Abdi, S. Shukla, *J. Mol. Catal.* **1990**, *60*, 275–281.
[40] a) M. M. T. Khan, S. B. Halligudi, S. H. R. Abdi, *J. Mol. Catal.* **1988**, *45*, 215–224; b) M. M. T. Khan, S. B. Halligudi, S. H. R. Abdi, *J. Mol. Catal.* **1988**, *48*, 7–9.
[41] R. Peters, *Carbon-fluorine compounds: Chemistry, biochemistry, and biological activities*, Associated Scientific Publishers, Amsterdam, **1972**, p. 55–76.
[42] T. Fuchikami, I. Ojima, *J. Am. Chem. Soc.* **1982**, *104*, 3527–3529.
[43] F. Roehrscheid (Farbwerke Hoechst A.-G.), DE2163752, **1973**.
[44] M. A. Moreno, M. Haukka, A. Turunen, T. A. Pakkanen, *J. Mol. Catal. A* **2005**, *240*, 7–15.
[45] C. Dragonetti, M. Pizzotti, D. Roberto, S. Galli, *Inorg. Chim. Acta* **2002**, *330*, 128–135.
[46] M. A. Moreno, M. Haukka, S. Jääskeläinen, S. Vuoti, J. Pursiainen, T. A. Pakkanen, *J. Organomet. Chem.* **2005**, *690*, 3803–3814.
[47] R. A. Sanchez-Delgado, M. Rosales, A. Andriollo, *Inorg. Chem.* **1991**, *30*, 1170–1173.
[48] M.-L. Kontkanen, M. Haukka, *Catal. Commun.* **2012**, *23*, 25–29.
[49] M. Rosales, B. Alvarado, F. Arrieta, C. De La Cruz, Á. González, K. Molina, O. Soto, Y. Salazar, *Polyhedron* **2008**, *27*, 530–536.
[50] T. Smejkal, H. Han, B. Breit, M. J. Krische, *J. Am. Chem. Soc.* **2009**, *131*, 10366–10367.
[51] K. Takahashi, M. Yamashita, Y. Tanaka, K. Nozaki, *Angew. Chem.* **2012**, *124*, 4459–4463; *Angew. Chem. Int. Ed.* **2012**, *51*, 4383–4387.
[52] K. Takahashi, M. Yamashita, K. Nozaki, *J. Am. Chem. Soc.* **2012**, *134*, 18746–18757.
[53] a) M. Peters, B. Köhler, W. Kuckshinrichs, W. Leitner, P. Markewitz, T. E. Müller, *ChemSusChem* **2011**, *4*, 1216–1240; b) K. Huang, C.-L. Sun, Z.-J. Shi, *Chem. Soc. Rev.* **2011**, *40*, 2435–2452.
[54] H. C. Kang, C. H. Mauldin, T. Cole, W. Slegeir, K. Cann, R. Pettit, *J. Am. Chem. Soc.* **1977**, *99*, 8323–8325.
[55] a) R. M. Laine, *J. Am. Chem. Soc.* **1978**, *100*, 6451–6454; b) R. M. Laine, R. G. Rinker, P. C. Ford, *J. Am. Chem. Soc.* **1977**, *99*, 252–253.
[56] W. Reppe, H. Vetter, *Justus Liebigs Ann. Chem.* **1953**, *582*, 133–161.
[57] a) K.-i. Tominaga, Y. Sasaki, M. Kawai, T. Watanabe, M. Saito, *J. Chem. Soc. Chem. Commun.* **1993**, 629–631; b) K.-i. Tominaga, Y. Sasaki, *Catal. Commun.* **2000**, *1*, 1–3.
[58] T.-a. Mitsudo, T. Kondo, *Ruthenium in Organic Synthesis*, Wiley-VCH, Weinheim, **2005**, pp. 277–307.
[59] K.-i. Tominaga, Y. Sasaki, K. Hagihara, T. Watanabe, M. Saito, *Chem. Lett.* **1994**, 1391–1394.
[60] K.-i. Tominaga, *Catal. Today* **2006**, *115*, 70–72.
[61] a) M.-L. Kontkanen, L. Oresmaa, M. A. Moreno, J. Jänis, E. Laurila, M. Haukka, *Appl. Catal. A* **2009**, *365*, 130–134; b) S.-i. Fujita, S. Okamura, Y. Akiyama, M. Arai, *Int. J. Mol. Sci.* **2007**, *8*, 749–759; c) S. Jääskeläinen, M. Haukka, *Appl. Catal. A* **2003**, *247*, 95–100.
[62] a) L. Benzoni, A. Andreetta, C. Zanzottera, M. Camia, *Chim. Ind.* **1966**, *48*, 1076–1078 [*Chem. Abstr.* **1967**, 22601]; b) N. S. Imyanitov, D. M. Rudkovskii, *Zh. Prikl. Khim.* **1967**, *40*, 2020–2024 [*Chem. Abstr.* **1968**, 95367]; c) M. Yamaguchi, *Shokubai* **1969**, *11*, 179–195 [*Chem. Abstr.* **1970**, 413787]; d) L. A. Oro, M. T. Pinillos, M. Royo, E. Pastor, *J. Chem. Res. Synop.* **1984**, 206–207 [*Chem. Abstr.* **1984**, 591096]; e) S. S. C. Chuang, *Appl. Catal.* **1990**, *66*, L1–L6; f) J. Z. Zhang, Z. Li, C. Y. Wang, *Studies in Surface Science and Catalysis*, *Vol. 75* (Eds.: L. Guczi, F. Solimosi, P. Ténényi), Elsevier, **1993**, pp. 919–925; g) S. Rojas, J. L. G. Fierro, R. Fandos, A. Rodriguez, P. Terreros, *J. Chem. Soc. Dalton Trans.* **2001**, 2316–2324.
[63] C. M. Crudden, H. Alper, *J. Org. Chem.* **1994**, *59*, 3091–3097.
[64] E. Mieczyńska, A. M. Trzeciak, J. J. Ziółkowski, I. Kownacki, B. Marciniec, *J. Mol. Catal. A* **2005**, *237*, 246–253.
[65] G. Franciò, R. Scopelliti, C. G. Arena, G. Bruno, D. Drommi, F. Faraone, *Organometallics* **1998**, *17*, 338–347.
[66] Z. Csók, G. Keglevich, G. Petöcz, L. Kollár, *J. Organomet. Chem.* **1999**, *586*, 79–84.
[67] M. A. Moreno, M. Haukka, T. A. Pakkanen, *J. Catal.* **2003**, *215*, 326–331.
[68] P. P. Deutsch, R. Eisenberg, *J. Am. Chem. Soc.* **1990**, *112*, 714–721.
[69] P. P. Deutsch, R. Eisenberg, *Organometallics* **1990**, *9*, 709–718.
[70] D. J. Fox, S. B. Duckett, C. Flaschenriem, W. W. Brennessel, J. Schneider, A. Gunay, R. Eisenberg, *Inorg. Chem.* **2006**, *45*, 7197–7209.
[71] C. R. Bowers, D. P. Weitekamp, *Phys. Rev. Lett.* **1986**, *57*, 2645–2648.
[72] For references on the *trans*-binding mode of xantphos, see a) M. A. Zuideveld, B. H. G. Swennenhuis, M. D. K. Boele, Y. Guari, G. P. F. van Strijdonck, J. N. H. Reek, P. C. J. Kamer, K. Goubitz, J. Fraanje, M. Lutz, A. L. Spek, P. W. N. M. van Leeuwen, *J. Chem. Soc. Dalton Trans.* **2002**, 2308–2317; b) A. J. Sandee, L. A. van der Veen, J. N. H. Reek, P. C. J. Kamer, M. Lutz, A. L. Spek, P. W. N. M. van Leeuwen, *Angew. Chem.* **1999**, *111*, 3428–3432; *Angew. Chem. Int. Ed.* **1999**, *38*, 3231–3235; c) P. Nieczypor, P. W. N. M. van Leeuwen, J. C. Mol, M. Lutz, A. L. Spek, *J. Organomet. Chem.* **2001**, *625*, 58–66.
[73] M. Rosales, J. A. Durán, Á. González, I. Pacheco, R. A. Sánchez-Delgado, *J. Mol. Catal. A* **2007**, *270*, 250–256.
[74] I. Piras, R. Jennerjahn, R. Jackstell, A. Spannenberg, R. Franke, M. Beller, *Angew. Chem.* **2011**, *123*, 294–298; *Angew. Chem. Int. Ed.* **2011**, *50*, 280–284.

[75] a) C. Claver, C. Godard, A. Ruiz, O. Pàmies, M. Diéguez, *Modern Carbonylation Methods* (Ed.: L. Kollár), Wiley-VCH, Weinheim, **2008**, pp. 65 – 92; b) G. Kiss, *Chem. Rev.* **2001**, *101*, 3435 – 3456.
[76] E. Drent, P. H. M. Budzelaar, *Chem. Rev.* **1996**, *96*, 663 – 682.
[77] E. Drent, J. A. M. Van Broekhoven, M. J. Doyle, *J. Organomet. Chem.* **1991**, *417*, 235 – 251.
[78] E. Drent, P. H. M. Budzelaar, *J. Organomet. Chem.* **2000**, *593 – 594*, 211 – 225.
[79] J. Scheele, P. Timmerman, D. N. Reinhoudt, *Chem. Commun.* **1998**, 2613 – 2614.
[80] G. P. C. M. Dekker, C. J. Elsevier, K. Vrieze, P. W. N. M. van Leeuwen, C. F. Roobeek, *J. Organomet. Chem.* **1992**, *430*, 357 – 372.
[81] a) H. Klein, R. Jackstell, K.-D. Wiese, C. Borgmann, M. Beller, *Angew. Chem.* **2001**, *113*, 3505 – 3508; *Angew. Chem. Int. Ed.* **2001**, *40*, 3408 – 3411; b) R. P. J. Bronger, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Organometallics* **2003**, *22*, 5358 – 5369.
[82] D. Konya, K. Q. Almeida Leñero, E. Drent, *Organometallics* **2006**, *25*, 3166 – 3174.
[83] M. Baya, J. Houghton, D. Konya, Y. Champouret, J.-C. Daran, K. Q. Almeida Leñero, L. Schoon, W. P. Mul, A. B. v. Oort, N. Meijboom, E. Drent, A. G. Orpen, R. Poli, *J. Am. Chem. Soc.* **2008**, *130*, 10612 – 10624.
[84] For the synthesis of bcope derivatives, see M. R. Eberhard, E. Carrington-Smith, E. E. Drent, P. S. Marsh, A. G. Orpen, H. Phetmung, P. G. Pringle, *Adv. Synth. Catal.* **2005**, *347*, 1345 – 1348.
[85] R. Jennerjahn, I. Piras, R. Jackstell, R. Franke, K.-D. Wiese, M. Beller, *Chem. Eur. J.* **2009**, *15*, 6383 – 6388.
[86] a) L. H. Slaugh, R. D. Mullineaux (Shell Oil Company), US 3239571, **1966**; b) M. G. Wilkinson (Johnson Matthey Co. Ltd.), FR 1459643, **1966**.
[87] I. Schwager, J. F. Knifton (Texaco Development Corp.), DE2322751, **1973**.
[88] L. J. Kehoe, R. A. Schell, *J. Org. Chem.* **1970**, *35*, 2846 – 2848.
[89] a) A. Scrivanti, C. Botteghi, L. Toniolo, A. Berton, *J. Organomet. Chem.* **1988**, *344*, 261 – 275; b) M. Gomez, G. Muller, D. Sainz, J. Sales, X. Solans, *Organometallics* **1991**, *10*, 4036 – 4045.
[90] a) R. V. Lindsey, G. W. Parshall, U. G. Stolberg, *J. Am. Chem. Soc.* **1965**, *87*, 658 – 659; b) W. R. Rocha, W. B. DeAlmeida, *Int. J. Quantum Chem.* **1997**, *65*, 643 – 650; c) D. Fernández, M. I. García-Seijo, T. Kégl, G. Petöcz, L. Kollár, M. E. García-Fernández, *Inorg. Chem.* **2002**, *41*, 4435 – 4443; d) I. Toth, T. Kegl, C. J. Elsevier, L. Kollar, *Inorg. Chem.* **1994**, *33*, 5708 – 5712.
[91] a) R. P. Dias, W. R. Rocha, *Organometallics* **2011**, *30*, 4257 – 4268; b) T. G. Appleton, H. C. Clark, L. E. Manzer, *Coord. Chem. Rev.* **1973**, *10*, 335 – 422; c) W. R. Rocha, W. B. DeAlmeida, *Organometallics* **1998**, *17*, 1961 – 1967.
[92] W. R. Rocha, W. B. DeAlmeida, *J. Comput. Chem.* **2000**, *21*, 668 – 674.
[93] a) A. Scrivanti, A. Berton, L. Toniolo, C. Botteghi, *J. Organomet. Chem.* **1986**, *314*, 369 – 383; b) H. J. Ruegg, P. S. Pregosin, A. Scrivanti, L. Toniolo, C. Botteghi, *J. Organomet. Chem.* **1986**, *316*, 233 – 241.
[94] L. Kollár, P. Sándor, G. Szalontai, B. Heil, *J. Organomet. Chem.* **1990**, *393*, 153 – 158.
[95] a) R. Bardi, A. M. Piazzesi, G. Cavinato, P. Cavoli, L. Toniolo, *J. Organomet. Chem.* **1982**, *224*, 407 – 420; b) R. Bardi, A. M. Piazzesi, A. Del Pra, G. Cavinato, L. Toniolo, *J. Organomet. Chem.* **1982**, *234*, 107 – 115; c) G. Cavinato, L. Toniolo, *J. Organomet. Chem.* **1983**, *241*, 275 – 279; d) G. K. Anderson, H. C. Clark, J. A. Davies, *Organometallics* **1982**, *1*, 64 – 70.
[96] C. E. Johnson, B. J. Fisher, R. Eisenberg, *J. Am. Chem. Soc.* **1983**, *105*, 7772 – 7774.
[97] A. Dedieu, A. Strich, *Inorg. Chem.* **1979**, *18*, 2940 – 2943.
[98] a) I. Schwager, J. F. Knifton, *J. Catal.* **1976**, *45*, 256 – 267; b) C.-Y. Hsu, M. Orchin, *J. Am. Chem. Soc.* **1975**, *97*, 3553 – 3553; c) T. Hayashi, Y. Kawabata, T. Isoyama, I. Ogata, *Bull. Chem. Soc. Jpn.* **1981**, *54*, 3438 – 3446; d) F. Ancillotti, M. Lami, M. Marchionna, *J. Mol. Catal.* **1990**, *63*, 15 – 30; e) P. Meessen, D. Vogt, W. Keim, *J. Organomet. Chem.* **1998**, *551*, 165 – 170; f) G. Muller, D. Sainz, J. Sales, *J. Mol. Catal.* **1990**, *63*, 173 – 180; g) R. van Duren, J. I. van der Vlugt, H. Kooijman, A. L. Spek, D. Vogt, *Dalton Trans.* **2007**, 1053 – 1059.
[99] Y. Kawabata, T. Hayashi, I. Ogata, *J. Chem. Soc. Chem. Commun.* **1979**, 462 – 463.
[100] a) H. C. Clark, J. A. Davies, *J. Organomet. Chem.* **1981**, *213*, 503 – 512; b) A. Lofù, P. Mastrorilli, C. F. Nobile, G. P. Suranna, P. Frediani, J. Iggo, *Eur. J. Inorg. Chem.* **2006**, 2268 – 2276; c) L. A. van der Veen, P. K. Keeven, P. C. J. Kamer, P. W. N. M. van Leeuwen, *J. Chem. Soc. Dalton Trans.* **2000**, 2105 – 2112.
[101] L. A. van der Veen, P. K. Keeven, P. C. J. Kamer, P. W. N. M. van Leeuwen, *Chem. Commun.* **2000**, 333 – 334.
[102] a) G. Consiglio, P. Pino, *Helv. Chim. Acta* **1976**, *59*, 642 – 645; b) P. Haelg, G. Consiglio, P. Pino, *J. Organomet. Chem.* **1985**, *296*, 281 – 290; c) Y. Kawabata, T. M. Suzuki, I. Ogata, *Chem. Lett.* **1978**, 361 – 362; d) G. Consiglio, S. C. A. Nefkens, A. Borer, *Organometallics* **1991**, *10*, 2046 – 2051.
[103] a) C. U. Pittman, Y. Kawabata, L. I. Flowers, *J. Chem. Soc. Chem. Commun.* **1982**, 473 – 474; b) S. Paganelli, U. Matteoli, A. Scrivanti, *J. Organomet. Chem.* **1990**, *397*, 119 – 125; c) G. Petöcz, G. Rangits, M. Shaw, H. d. Bod, D. B. G. Williams, L. Kollár, *J. Organomet. Chem.* **2009**, *694*, 219 – 222; d) P. Pongrácz, G. Petöcz, M. Shaw, D. B. G. Williams, L. Kollár, *J. Organomet. Chem.* **2010**, *695*, 2381 – 2384.
[104] L. Kollár, G. Consiglio, P. Pino, *J. Organomet. Chem.* **1987**, *330*, 305 – 314.
[105] a) L. Kollár, P. Sándor, G. Szalontai, *J. Mol. Catal.* **1991**, *67*, 191 – 198; b) C. P. Casey, S. C. Martins, M. A. Fagan, *J. Am. Chem. Soc.* **2004**, *126*, 5585 – 5592.
[106] a) G. Parrinello, J. K. Stille, *J. Am. Chem. Soc.* **1987**, *109*, 7122 – 7127; b) G. Parrinello, R. Deschenaux, J. K. Stille, *J. Org. Chem.* **1986**, *51*, 4189 – 4195.
[107] J. K. Stille, H. Su, P. Brechot, G. Parrinello, L. S. Hegedus, *Organometallics* **1991**, *10*, 1183 – 1189.
[108] a) L. Jánosi, T. Kégl, L. Kollár, *J. Organomet. Chem.* **2008**, *693*, 1127 – 1135; b) M. Gottardo, A. Scarso, S. Paganelli, G. Strukul, *Adv. Synth. Catal.* **2010**, *352*, 2251 – 2262.
[109] P. Pongrácz, L. Kollár, A. Kerényi, V. Kovács, V. Ujj, G. Keglevich, *J. Organomet. Chem.* **2011**, *696*, 2234 – 2237.
[110] L. Kollár, G. Keglevich, *Chem. Rev.* **2010**, *110*, 4257 – 4302.
[111] *Iron Catalysis Fundamentals and Applications*, (Ed.: B. Plietker), Springer, Berlin, **2011**.
[112] H. W. Sternberg, R. Markby, I. Wender, *J. Am. Chem. Soc.* **1957**, *79*, 6116 – 6121.
[113] J. Palágyi, L. Markó, *J. Organomet. Chem.* **1982**, *236*, 343 – 347.
[114] a) S. Attali, R. Mathieu, *J. Organomet. Chem.* **1985**, *291*, 205 – 211; b) M. G. Richmond, *J. Mol. Catal.* **1989**, *54*, 199 – 204.
[115] a) M. K. Alami, F. Dahan, R. Mathieu, *J. Chem. Soc. Dalton Trans.* **1987**, 1983 – 1987; b) R. Della Pergola, A. Cinquantini, E. Diana, L. Garlaschelli, F. Laschi, P. Luzzini, M. Manassero, A. Repossi, M. Sansoni, P. L. Stanghellini, P. Zanello, *Inorg. Chem.* **1997**, *36*, 3761 – 3771.
[116] Z. He, N. Lugan, D. Neibecker, R. Mathieu, J.-J. Bonnet, *J. Organomet. Chem.* **1992**, *426*, 247 – 259.
[117] V. I. Kovalchuk, N. M. Mikova, N. V. Chesnokov, L. V. Naimushina, B. N. Kuznetsov, *J. Mol. Catal. A* **1996**, *107*, 329 – 337.
[118] J. Loset, R. Roulet, *Helv. Chim. Acta* **1985**, *68*, 236 – 247.
[119] C. Breschi, L. Piparo, P. Pertici, A. Maria Caporusso, G. Vitulli, *J. Organomet. Chem.* **2000**, *607*, 57 – 63.