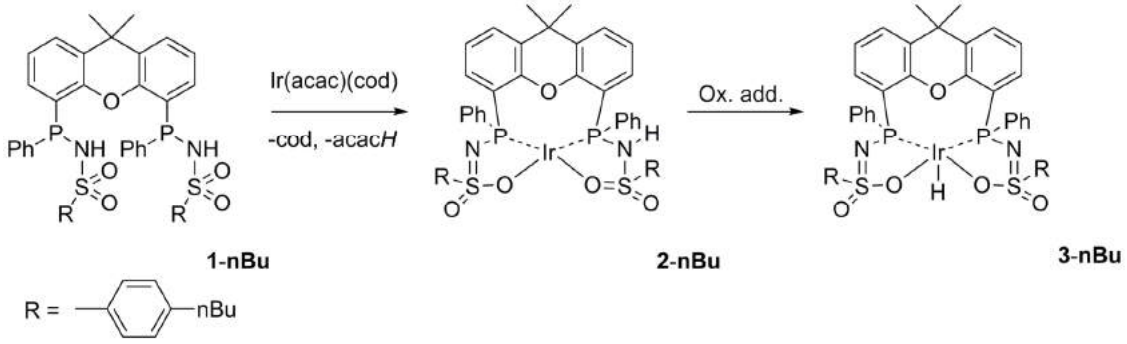
Summary

Catalysis plays a key role in the prosperity of our society, as catalysts are applied in the majority of chemical processes that provide us in our daily needs in food, energy, medicine etc. Continued advancement in scientific knowledge is required in order to develop new catalysts that can be used to improve existing catalytic processes and to explore currently unknown chemical transformations. In the field of homogeneous catalysis, catalyst properties and reactivities are determined by the nature of the metal applied in combination with the ligands surrounding the metal center. Therefore ligand exploration is an important and very active field of research. Traditionally, ligands functioned merely as spectators and affected the reactivity of a metal center via their electronic donating/accepting abilities and steric properties. However, the role of ligands can be broadened and they can be designed such that they are actively involved during catalysis via for instance hydrogen bonding interactions, redox non-innocence or proton responsiveness leading to so called bifunctional ligands. METAMORPhos, a novel (bifunctional) ligand type was developed in 2008 by Reek et al. at the University of Amsterdam. These ligands form the common thread throughout this manuscript wherein their coordination behavior and reactivity to several transition metals (Ir, Rh and Pd) is described. Also, they have been applied in the Ir-catalyzed dehydrogenation of HCOOH and their bifunctional role was thoroughly investigated. In **Chapter 1** the preparation and different coordination modes of this ligand type to transition metals and applications in catalysis are detailed. Furthermore, the general concepts of hydrogen bonding ligands, proton responsive ligands and bimetallic complexes in catalysis are introduced, supported by illustrative examples from literature. These concepts will play an important role throughout this manuscript. In **Chapter 2** the preparation of a bisMETAMORPhos ligand (**1**-**nBu**) and its coordination to Ir^{I}(acac)(cod) is described (see Scheme 1). Coordination of **1**-**nBu** to Ir^{I}(acac)(cod) leads to the formation of an Ir^{I} complex



Scheme 1. BisMETAMORPhos ligand **1**-**nBu** generates Ir^{I} complex **2**-**nBu** upon coordination to Ir(acac)(cod). Complex **2**-**nBu** over time converts to $Ir^{III}H$ complex **3**-**nBu** via oxidative addition of an NH group of the ligand.

(**2**-**nBu**), wherein the ligand is mono-deprotonated by $acac^-$, generating one anionic and one neutral ligand arm. Over time, oxidative addition of the ligand in complex **2**-**nBu**, takes place, generating an $Ir^{III}H$ complex (**3**-**nBu**) with the ligand coordinated as a dianionic P_2O_2 fragment. Importantly, complex **3**-**nBu** was applied in the (base-free) dehydrogenation of HCOOH, an interesting reaction in the context of the development of a hydrogen storage/release system based on CO_2/HCOOH, see Figure 1. Base-free dehydrogenation is important as it increases the hydrogen content from 2.3 wt% (in a typical 5:2 HCOOH/NEt_3 mixture) to 4.4 wt% (in pure HCOOH). The ligand in **3**-**nBu** was found to function as internal base and the catalyst was proven to be selective and robust. Catalytic activities of up to 3090 turnovers per hour were obtained at 80 °C.

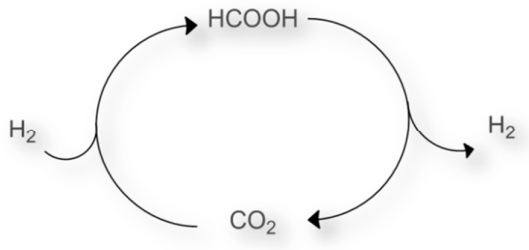


Figure 1. H_2 storage release cycle based on CO_2-HCOOH.

In **Chapter 3** the preparation of two new bisMETAMORPhos ligands with different steric and electronic properties (**1**-$\mathbf{CF_3}$, **1**-$^{\mathbf{i}}$**Pr**) is presented. Their coordination to Ir(acac)(cod) led to Ir-^{III}hydride complexes (**3**-$\mathbf{CF_3}$ and **3**-$^{\mathbf{i}}$**Pr**) similar to complex **3**-**nBu** as detailed in Chapter 2. Complexes **3**-$\mathbf{CF_3}$ and **3**-$^{\mathbf{i}}$**Pr** were also found to be active in the base-free dehydrogenation of formic acid and turnover frequencies of 877 and 1791 h^{-1} were obtained for **3**-$\mathbf{CF_3}$ and **3**-$^{\mathbf{i}}$**Pr**, respectively. The role of the ligand during catalysis was investigated by variable temperature ^1H and ^{31}P NMR spectroscopy which points to the formation of a **3**-HCOOH adduct. DFT calculations indicate that the hydrogen bonding ability and proton responsive property of the ligand play an important role during catalysis and result in an uncommon direct hydride-transfer mechanism instead of the more commonly proposed β-hydride elimination (see Figure 2). The mechanism proposed involves initial coordination of HCOOH to the catalyst forming an HCOOH-adduct (**3I**, exergonic by -3.1 kcal·mol^{-1}). The next step involves rotation of HCOOH, positioning the formate hydrogen *H*COOH in a favorable position for direct hydride-transfer (**3II**, endergonic by 12.8 kcal·mol^{-1}), which takes place via transition state **3III** (exergonic by 20.2 kcal·mol^{-1}). The release of CO_2 generates Ir-dihydride complex **3IV**, which is slightly endergonic (0.1 kcal·mol^{-1}). From **3IV**, H_2 is released with the aid of an exogenous HCOOH equivalent, which is involved in protonation of the Ir-H while simultaneously being protonated by the ligand, see transition state **3V** (endergonic by 10.3 kcal·mol^{-1}). This regenerates complex **3** and completes the catalytic cycle. Direct hydride transfer (**3II** to **3IV**) was found to be the rate determining step of the catalytic cycle, which is in agreement with kinetic isotope effects described in Chapter 2. Interestingly, these findings

show that the ligand not only functions as an internal base but also assists in the pre-assembly of HCOOH within the Ir-coordination sphere and aids in stabilizing (rate-determining) transition states through hydrogen-bonding.

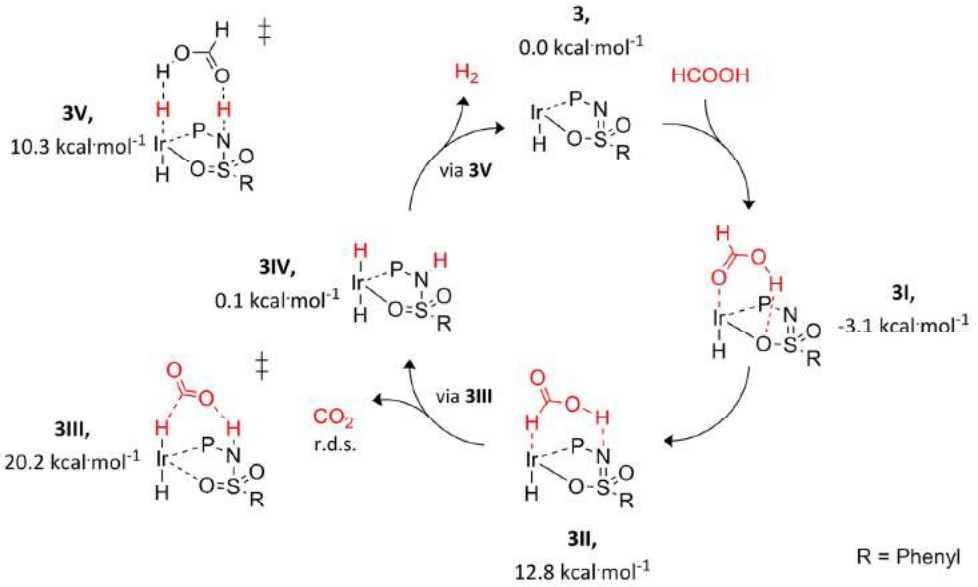


Figure 2. Proposed mechanism for the dehydrogenation of HCOOH with Ir^{III}-hydride complex **3** based on NMR and DFT calculations, which confirm the bifunctional role of the ligand as internal base *and* hydrogen bond acceptor/donor.

In **Chapter 4** the micro-reverse reaction of HCOOH dehydrogenation, i.e. hydrogenation of CO_2, with **3-nBu** is described. Hydrogenation experiments were performed in a high pressure (sapphire) NMR tube and were monitored in time by ^1H NMR spectroscopy. Under base-free conditions, complex **3-nBu** was found to hydrogenate CO_2 with a TOF of 18 h^{-1} in DMSO-d_6 at 373 K under 50 bar of CO_2/H_2 (1:1). The addition of DBU resulted in a significant increase in catalytic activity (TOF of 636 h^{-1}). An *in situ* NMR study showed that under CO_2/H_2 atmosphere (50 bar, 1:1) at 373 K, **3-nBu** is converted to *fac*-trihydride complex **4-nBu** (see Figure 3). DFT calculations suggest that complex **4-nBu** likely is a dormant species, as the energy barriers for hydride transfer to CO_2 from **4-nBu** were found to be high for both the axial and the equatorial hydrides (65.6 and 44.2 kcal·mol^{-1}, respectively).

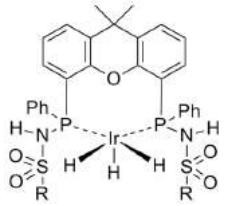
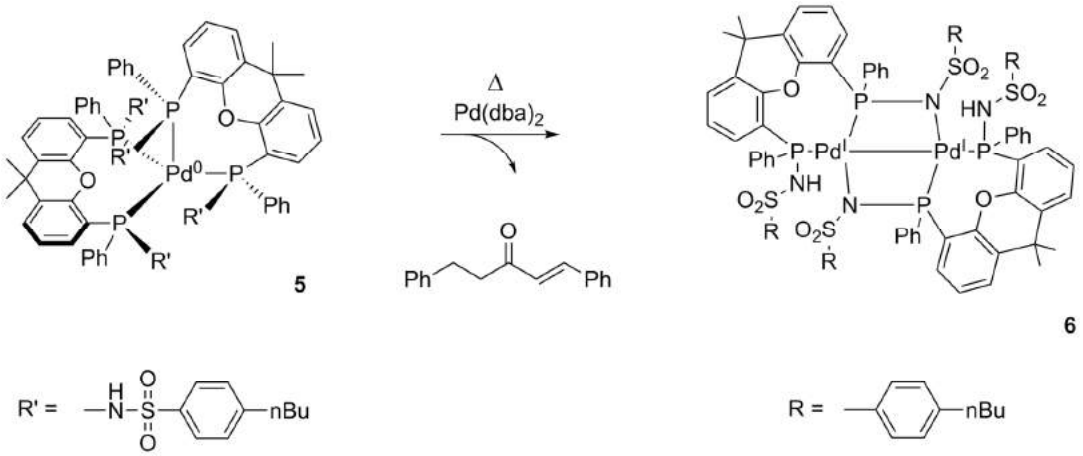


Figure 3. Complex **4-nBu** generated under high pressure of CO_2/H_2 (50 bar) at 373 K from **3-nBu**.

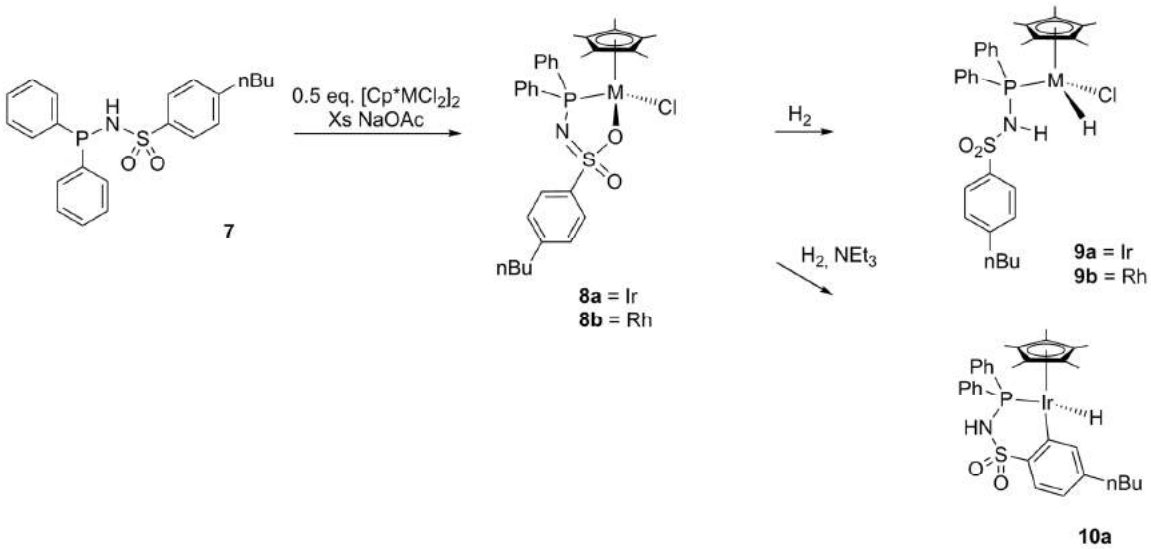
In **Chapter 5** the coordination chemistry of bisMETAMORPhos ligand **1** to $Pd(dba)_2$ is described. Initially, displacement of the dba results in formation of **1_2Pd** complex (**5**), with a highly distorted tetrahedral Pd^0 center (see Scheme 2). Upon heating, complex **5** converts to a unique PN-bridged dinuclear Pd^I complex (**6**) that encompasses a completely flat $Pd_2N_2P_2$ core (see Scheme 2). The formation of complex **6** is suggested to proceed via an *in situ*

comproportionation pathway that involves: 1) decoordination of one equivalent **1** in **5**, followed by oxidative addition of one coordinated ligand arm to generate a **1**-Pd^{II}-hydride complex; 2) reaction of this **1**-Pd^{II}-hydride species with free dba to yield a **1**-Pd^{II}dba complex, which was detected by ^1H NMR and mass spectrometry; 3) intra- or intermolecular protonolysis of the Pd-dba bond to release 1,5-diphenylpent-1-en-3-one, which is observed by ^1H NMR spectroscopy and GC-MS, concomitant with comproportionation of **1**-Pd^0 to generate **6** (see Scheme 2). Complex **6** was successfully applied in the Suzuki–Miyaura coupling reaction of *p*-chloroacetophenone with phenylboronic acid, resulting in good conversion to the hetero-coupled product. Complex **6** is most likely not directly involved as active species during catalysis, but rather serves as a pre-catalyst for formation of the catalytically active species.



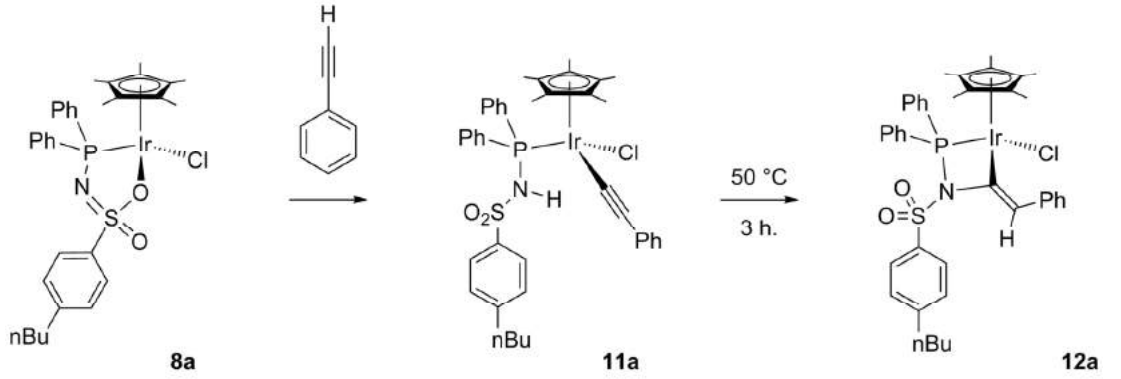
Scheme 2. Coordination of **1** (2 eq.) to $Pd(dba)_2$ generates complex **5** from which dinuclear Pd^I complex **6** forms via an *in situ* comproportionation pathway.

In **Chapter 6** the coordination of METAMORPhos ligand **7** with iridium and rhodium piano-stool complexes ($[Cp^*MCl_2]_2$, M = Ir or Rh) and bifunctional activation of H_2 and phenylacetylene with the obtained complexes is described. Complex **8a** (Ir) and **8b** (Rh), wherein the ligand is a deprotonated P,O-chelate, are formed by the addition of **7** and 0.5 equivalent of $[Cp^*MCl_2]_2$ (M = Ir or Rh) to a suspension of NaOAc in CH_2Cl_2 (see Scheme 3). These complexes were found to be active in the bifunctional activation of H_2, generating monohydride complexes **9a**-**b**. Complex **8a** further reacts with H_2 in the presence of NEt_3, leading to complex **10a** that is formed via intramolecular C-H activation of the sulfonamide phenyl ring. The formation of **10a** likely proceeds via the formation of an Ir-dihydride species, which releases H_2 to create a highly reactive Ir^I intermediate, prior to C-H oxidative addition.



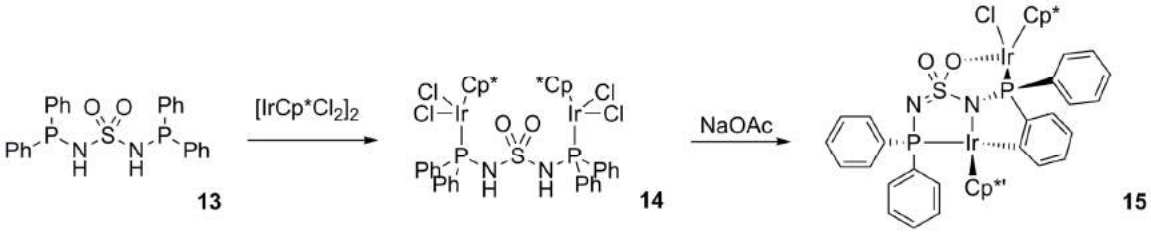
Scheme 3. P,O-chelate complexes **8a**-**b** are formed from the reaction of **7** with $[Cp^*MCl_2]_2$ and an excess of NaOAc. Complexes **8a**-**b** heterolytically cleave H_2, generating monohydride complexes **9a**-**b**. Under basic conditions, i.e. in the presence of NEt_3, **8a** was found to further react and form **10a** via intramolecular C-H activation.

Complex **8a** is also active in the bifunctional intermolecular activation of phenylacetylene, which initially results in Ir-acetylide complex **11a** (see Scheme 4). This complex rearranges to the unusual Ir-P-N-C ring complex **12a**. DFT calculations suggest that formation of this species proceeds via proton transfer from the ligand to the β-carbon of **11a**, generating an Ir^V-vinylidene intermediate. Subsequent nucleophilic attack of the nitrogen onto the electrophilic α-carbon results in the formation of **12a**, bearing a unique exo-cyclic vinyl unit.



Scheme 4. The reaction of **8a** with phenylacetylene initially generates Ir-acetylide **11a**, which rearranges to complex **12a** consisting of a four-membered Ir-P-N-C ring.

In **Chapter 7** the preparation of a new bisMETAMORPhos ligand (**13**) is described. Upon coordination of one equivalent of **13** to $[Cp^*IrCl_2]_2$ P,P-coordinated complex **14** is formed (see Scheme 5). Deprotonation of the novel bisMETAMORPhos ligand in bimetallic iridium complex **14** using NaOAc led to an unexpected intramolecular C-H activation of a phenyl ring of the ligand, resulting in the selective formation of complex **15** (see Scheme 5). Interestingly, complex **15** contains two distinctly different iridium centers with dissimilar coordination environments (P,N,C and P,O,Cl). Complex **15** reacts cleanly and selectively at the Ir-POCl center with a single equivalent of H_2 via heterolytic cleavage of the H-H bond, which reprotonates the ligand, confirming the bifunctional applicability of the ligand. A similar P,P-coordinated complex was obtained with the reaction of **13** and $[Cp^*RhCl_2]_2$, but ill-defined products were obtained upon reaction of with NaOAc.



Scheme 5. Bimetallic complex **14** is generated by the addition of ligand **13** to $[Cp^*IrCl_2]_2$. Addition of NaOAc to complex **14** in CH_2Cl_2 formed complex **15** via intramolecular C-H activation.

Throughout this manuscript the role of METAMORPhos ligands in the formation Ir, Rh and Pd complexes and follow-up reactivity has been outlined. It has been shown that this versatile ligand can lead to very diverse bonding modes and it has great potential as hydrogen bonding and proton responsive (bifunctional) ligand. The obtained knowledge described in this manuscript can be used as a guideline to further explore the possibilities with METAMORPhos ligands. It would be interesting to investigate whether the reactivity described, in particular the dehydrogenation of HCOOH, can be translated to first row transition metals like iron and cobalt. Other interesting reactivity to further explore is the intermolecular C-H activation using complex **8a** and the generation of hetero bimetallic complexes with ligand **13**.