Nature inspired catalytic systems using sulfonamido-phosphorus based complexes: Increasing complexity in transition metal catalysis

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Chapter 2

Ligand Self-sorting and Nonlinear Effects in Dinuclear Asymmetric Hydrogenation*

2.1 Introduction

Nature has been a source of inspiration for scientists as billion years of evolution have resulted in magnificent examples of how processes can be controlled efficiently. In the field of supramolecular catalysis, enzymes have been the major source of inspiration. As such, many synthetic systems have been prepared to mimic certain aspects of enzymes, with a strong focus on connecting catalytically active sites to cavities or binding sites having affinity for the substrate.\textsuperscript{1,2} Although such approaches have resulted in interesting new tools to control selectivity\textsuperscript{3–5}, we are not nearly close to the abilities of Nature to control chemical transformations. One of the major differences between Nature and synthetic approaches is that in biological systems, chemical processes take place in a complex out-of-equilibrium environment.\textsuperscript{6} In a cell, many chemical transformations occur simultaneously or in controlled sequence, involving an impressive number of different components. An important challenge for biologists is to understand how this organized complexity leads to emerging properties. As a result, new fields such as systems biology\textsuperscript{7} including non-equilibrium thermodynamics\textsuperscript{8} have been developed. Synthetic chemists traditionally aim for systems that are as clean and pure as possible\textsuperscript{9}, and it is only recently that complexity in chemical systems received attention.\textsuperscript{10–12} Despite the interesting perspectives, complexity in homogeneous catalysis has not been a research focus in itself, although many aspects related to complexity have been reported. Product inhibition and catalyst poisoning are relevant to complex chemistry as they imply processes with feedback loops. Dynamic catalyst libraries and combinatorial catalysis require selection procedures\textsuperscript{6,13}, and nonlinear effect (NLE) in asymmetric catalysis\textsuperscript{14–16} can lead to emerging properties. With this in mind we decided to study in detail NLE using dinuclear hydrogenation catalyst C that has four chiral ligands. Application of non-enantiopure ligands can lead to formation of heterochiral complexes (with more than 2 chiral ligands) with different properties and these complexes can theoretically be more active and selective than their homochiral analogues.\textsuperscript{16} Catalytically active complexes with 4 chiral ligands are rare, and complex C is, to the best of our knowledge, the only example for hydrogenation. The use of a racemic ligand could lead to the formation of 10 stereoisomers of C (Figure 1).

![Figure 1](image-url)

**Figure 1.** The [Rh\(_2\)(L)\(_4\)] complex C and a schematic representation of the 10 potential complexes forming from a racemic mixture (pink represents the ligand in R configuration and blue the S). For L1, R= 4-n-butylphenyl, for L2, R=CF\(_3\) and for L3, R=CH\(_3\).
Herein we report the self-sorting of chiral ligands at these bimetallic complexes and the in situ enantiopurification of the system caused by the relative insolubility of the racemate of homochiral complexes. As a result, in asymmetric hydrogenation using non-pure ligands (S:R=70:30) the product can be formed in high enantiopurity (90% ee). The outcome, however, is strongly dependent on starting conditions (concentration, incubation, substrate) as intermediate complexes towards the formation of C are not self-sorted and yet active in hydrogenation.

The METAMORPhos family, a new class of sulfonamide-phosphorus ligand was recently disclosed. Their coordination to rhodium gives rise to unique complexes consisting of two metal centers and four METAMORPhos ligands [Rh$_2$L$_4$] (C). Two deprotonated ligands form a bridge between the two metals and two ligands coordinate in a P-O chelating fashion. These complexes display unrivaled high selectivity in asymmetric hydrogenation of benchmark substrates and challenging cyclic enamides.

2.2 Results and Discussions

2.2.1 Coordination Studies

Studies on the coordination chemistry of enantiopure ligands revealed that C is formed from the precursor [Rh(nbd)$_2$]BF$_4$ in three steps (Scheme 1). One equivalent of ligand (L$_1$, L$_2$ or L$_3$) reacts with the rhodium precursor to yield A [Rh$_2$L$_2$(nbd)$_2$], a bimetallic complex where two METAMORPhos ligands form a bridge between the metals, and each rhodium atom is chelated by an nbd ligand. This dimeric complex reacts with two additional ligands (one per rhodium) to give the monomeric complex B [Rh$_2$L$_2$(nbd)]. The monomeric nature of this complex is evident from the mass spectrum and the doublet in the $^{31}$P NMR spectrum, indicating a symmetric complex with one rhodium and two ligands. The structure of this complex is similar to the precatalyst synthesized from monodentate phosphorus ligands, such as the well-studied MONOPhos. The final dimeric complex C [Rh$_2$L$_4$] quantitatively forms when 5 bars of hydrogen is applied to this monomer, which effectively removes the nbd ligands.

Scheme 1.
Coordination of the METAMORPhos ligands to rhodium in three steps to form the final dinuclear complex C.

† In this Chapter, the protonation state of the ligands (coordinated or not) is sometimes ambiguous. Conventionally, B and C will be considered as neutral. This matter is thoroughly discussed in Chapter 3.
We explored the coordination of racemic ligands under the same conditions for the formation of the three complexes A-C. When a racemic mixture of the ligand is used, three diastereomers of A can be formed: [Rh$_2$((R)-L)$_2$(nbd)$_2$], [Rh$_2$((S)-L)$_2$(nbd)$_2$] and [Rh$_2$((R)-L)((S)-L)(nbd)$_2$]. Surprisingly, the $^{31}$P NMR of A is identical for complexes based on (R)-L1 and (rac)-L1, suggesting that only homocomplexes [Rh$_2$((R)-L)$_2$(nbd)$_2$] and [Rh$_2$((S)-L)$_2$(nbd)$_2$] are formed. Indeed the diastereoisomer is expected to give a different signal in the NMR. To confirm this self-sorting behaviour, the experiment was repeated using pseudo-enantiomers ((S)-L1 and (R)-L2), mirror image ligands that have a different R group on the sulfur atom. In this experiment also only homochiral complexes [Rh$_2$((S)-L)$_2$(nbd)$_2$] and [Rh$_2$((R)-L)$_2$(nbd)$_2$] can be seen in the phosphorus NMR spectra (Figure 2). Control experiments show that the substituents on the sulfur are not responsible for this chiral self-recognition.\textsuperscript{19, 21}

![Figure 2. $^{31}$P NMR spectrum of A synthesized from (a) (S)-L1, (b) (R)-L2 and (c) a mixture of (S)-L1 and (R)-L2](image)

The reaction of [Rh(nbd)$_2$]BF$_4$ and (rac)-L2 also resulted in the formation of self-sorted homochiral complexes, as showed by $^{31}$P NMR and further confirmed by X-ray analysis (Figure 3). The homocomplexes A [Rh$_2$((R)-L)$_2$(nbd)$_2$] and [Rh$_2$((S)-L)$_2$(nbd)$_2$] crystallize as racemate of homochiral complexes. Notably, the ligands have the same coordination mode and the complex has the same conformation as previously established by NMR studies and DFT calculation.\textsuperscript{19}

In contrast to what is observed for complex A, if (rac)-L1 (or (rac)-L2) is used to form complex B, $^{31}$P NMR shows two doublets in a 1:1 ratio indicating the formation of two diastereomeric complexes. One of the doublets corresponds to the previously observed homochiral complex [Rh(L)$_2$(nbd)], whereas the other indicates the formation of a meso heterochiral complex. X-ray diffraction confirmed the monomeric nature of the complex. Just as observed for complex A, B crystallizes as racemate of homochiral complexes (crystals of the heterochiral complex were not obtained).

When two equivalents of (rac)-L1 were reacted with [Rh(nbd)$_2$]BF$_4$ under hydrogen pressure to form complex C, the $^{31}$P NMR spectrum of the solution was identical to the very characteristic AA’BB’XX’ pattern observed for the homochiral complex C prepared from (R)-L1 (see experimental section.). This suggests that C forms with a high fidelity chiral self-
sorting: only [Rh\(_2\)((R)-L1)\(_4\)] and [Rh\(_2\)((S)-L1)\(_4\)] are present in solution. To confirm these findings, we used pseudo-enantiomers consisting of (S)-L1 and (R)-L2. This strategy allowed us to distinguish the pseudo-diastereomers by mass spectrometry and to have a better separation of the \(^{31}\)P NMR signals. Again, mostly homochiral complexes were formed, but now the self-sorting was not perfect and at least three doublets of doublets could be distinguished as minor side-products (see Figure 13 in the experimental section). Control experiments show that the substituent on the sulfur is not responsible for self-sorting. Using a mixture of (S)-L1 and (S)-L2 to form complex C leads to a multitude of signals in \(^{31}\)P NMR consistent with a statistical mixture of complexes (see Figure 7c). The use of the structurally more similar ligands (R)-L2 and (S)-L3 showed strong self-sorting behaviour, as only homochiral complexes could be seen in the \(^{31}\)P NMR spectrum (Figure 3). In line with this, in the MS-spectra only homocomplexes could be identified.

![Figure 3](image.png)

**Figure 3.** \(^{31}\)P NMR spectrum of Rh\(_4\) (C) synthesized from (a) (R)-L2, (b) (S)-L3 and (c) a mixture of (R)-L2 and (S)-L3.

The reaction of 2 equivalents of (rac)-L2 with [Rh(nbd)\(_2\)]BF\(_4\) under hydrogen pressure yielded a compound that is very poorly soluble in dichloromethane. Analysis by NMR was prohibited by the low solubility, but X-ray structure determinations on isolated crystals demonstrated that the solid state consisted of the racemate of the homochiral complexes C (see Figure 4). Like for complex A, these crystal structures confirmed the coordination mode of the ligands, previously established by NMR studies, as well as the boat-shaped conformation, previously proposed on the basis of DFT calculations. A noticeable difference between the previously proposed structure and the crystallized complex is that the P-O coordinated ligands are deprotonated by triethylamine in the solid state (see Chapter 3 for a better insight into this matter).

![Figure 4](image.png)

**Figure 4.** Crystal structures\(^{22}\) of A, B and C synthesized from (rac)-L2. Hydrogen atoms, solvent and, in the case of C, triethylamonium counterion are omitted for clarity.
2.2.2 Mechanism and Driving Force of the Self-sorting of A and C

Self-sorting processes are driven by several “molecular codes” such as size and shape complementarity, steric effects and stabilizing weak interactions. Most of the time, fast exchange of the building blocks leads to the formation of the most thermodynamically stable products. However, kinetic self-sorting and competition between kinetic and thermodynamic self-sorting have been reported.

To investigate what leads to the self-sorting of A, we checked first if the ligands are in fast exchange. It had been reported that by using (R)-L1 and (R)-L2, a statistical mixture consisting of [Rh2((R)-L1)2(nbd)2], [Rh2((R)-L2)2(nbd)2] and [Rh2((R)-L2)((R)-L2)(nbd)2] is obtained. The same complexes are observed in the same proportions when preformed [Rh2((R)-L1)2(nbd)2] and [Rh2((R)-L2)2(nbd)2] are mixed. This observation points towards a thermodynamic self-sorting.

![Figure 5](image)

**Figure 5.** $^{31}$P NMR spectrum of [RhL2(nbd)2] synthesized (a) from (R)-L1, (b) from (R)-L2 and (c) by mixing [Rh2((R)-L1)2(nbd)2] and [Rh2((R)-L2)2(nbd)2].

In the crystal structure of A, the binaphthol (BINOL) moieties and the Rh-P-N-Rh-P-N ring are pseudo-coplanar (Figure 4): the BINOLs are as far as possible from the nbd ligands, which minimizes steric repulsion.

Importantly, the Rh-P-N-Rh-P-N ring of the crystallized structure is in a twist boat conformation. The boat itself can be chiral: α and β (depicted in Figure 6) are not superimposable and interconversion by ring flipping is expected to be high in energy. In addition to that, the twist induces chirality: even in the simple case of cyclohexane, a twist boat is chiral (however, at room temperature, the ring flips rapidly, and the chair conformation is the most stable). In Figure 6, the twists are noted 1 and 2. Combined with the R/S chirality of the two BINOL moieties of the two bridging ligands, the boat-shaped complex A has 4 elements of symmetry: it represents 16 structures that can be reduced to 6 diastereomers (8 enantiomeric relations and 2 meso structures).

![Figure 6](image)

**Figure 6.** Chiral elements of the Rh-P-N-Rh-P-N ring.
We modeled all the possible diastereomeric boat-shaped complexes A (with L2 as a ligand) plus the chair conformations γ and we evaluated their relative energy by DFT calculations (see structures in Figure 16 and energy values in Table 1). As expected, the complex corresponding to the crystallized structure (β1RR) has the lowest energy. The energy of structure β2RR (with the opposite twist) could not be determined as it converged to β1RR; this result suggests that the energy barrier between 1 and 2 is very low. The β structures with S configurations at each BINOL are > 7 kcal/mol higher in energy: this is due to steric repulsion between the BINOL moieties and the nbd ligands for β1SS and steric repulsion between both BINOL moieties for β2SS. As reported previously,19 the chair conformation γRR is 11 kcal/mol higher in energy than the most stable structure. γRS is only 1.3 kcal/mol higher in energy: like for β1RR, the naphtyl cycles point away from the Rh-P-N-P-Rh cycle. The boat-shaped complexes with BINOL moieties of opposite chirality are > 6 kcal/mol higher in energy: it explains the self-sorting behavior of A.

**Table 1.** Relative (uncorrected) free energy of each diastereomer of A.

<table>
<thead>
<tr>
<th>structure (enantiomer)</th>
<th>ΔG (kcal/mol)</th>
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<tr>
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</tr>
<tr>
<td>γRS[a]</td>
<td>1.3</td>
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</tbody>
</table>

[a] meso structures, [b] not determined: converged to β1RR.

We were curious to know if C presents a fast exchange too. If a 1:1 homochiral mixture of L1 and L2 is used for the synthesis of C, 10 combinations are possible (Figure 7 (i)). 31P NMR supports this number, as a very complicated spectrum was recorded (Figure 7 (c)). In a separate experiment, preformed [Rh2((R)-L1)4] and [Rh2((R)-L2)4] were mixed. For mixtures of phosphoramidite-rhodium complexes, ligand exchange is usually fast and reversible.28 Thus we expected either a complete scrambling leading to the 10 combinations (Figure 7 (ii)) or an exchange of the chelating ligands leading to 6 combinations (Figure 7 (iii)). The resulting 31P NMR was much less complicated, as only the complex [Rh2((R)-L1)2((R)-L2)2] is present, together with the starting complexes (Figure 7 (d), assignment in the experimental section). This is in agreement with a rearrangement which involves the dissociation of the dimer into a monomer (Figure 7 (iv) and (v)) due to the breaking of the Rh-N bonds of the dinuclear complex.
Figure 7. top: $^{31}$P NMR spectrum of [Rh-L$_4$] complexes synthesized (a) from (R)-L$_2$, (b) from (R)-L$_1$, (c) from a mixture of (S)-L$_1$ and (S)-L$_2$, and (d) by mixing [Rh$_2$((R)-L$_1$)$_4$] and [Rh$_2$((R)-L$_2$)$_4$]; right: schematic representation of the possible outcomes by mixing [Rh$_2$((R)-L$_1$)$_4$] and [Rh$_2$((R)-L$_2$)$_4$]: (ii) complete scrambling, (iii) exchange of the chelate ligand, (iv)-(v) dissociation-reassociation of the dimer.

<table>
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<th>smallest d(C-O)</th>
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</tr>
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<td>3.15</td>
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<tr>
<td>sum of O and C vdW radii</td>
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</tr>
</tbody>
</table>

Figure 8. Left: lone-pair-$\pi$ interactions between neighbouring BINOLs in the crystal structure of C; right: distances in the structures and comparison with data from the literature (in Å). [a] Complex C crystallized in nitromethane (procedure A in exp. section); [b] complex C crystallized in dichloromethane (procedure B in exp. section); [c] since C has a pseudo-$C_2$ symmetry in the solid state, two values for each distance are given (except for A due to disorder).
As the phosphorus atoms of the ligands are bound to the rhodium centers in a cis-position, the BINOL moieties are very close to each other. We initially thought that the only reason why heterochiral complexes do not form is because it would lead to steric repulsion. A careful study of the two X-ray structures of A not only confirmed that the steric factors are necessary for the self-sorting, but also revealed outstanding lone-pair–π interactions between the neighbouring BINOL moieties (Figure 8). The distance between the oxygen of one BINOL and the centroid of the aryl ring of the neighbouring BINOL are among the smallest reported. The smallest C-O distance is significantly lower than the sum of the van der Waals radii (Figure 8, table). When the complex was modeled by DFT calculations, the oxygen-aryl distance was much longer than in the crystal structure as DFT calculations do not take into account van der Waals interactions. Using empirical dispersion correction allowed us to satisfactorily model this weak interaction (see values in Table 2 in section 2.4.3).

If significant in solution, the lone-pair–π interactions may be responsible for the absence of ligand exchange at the same rhodium. As C has 8 elements of symmetry (ring β and α, twist 1 and 2, chirality of the sulfur of the 2 P-O chelated ligands and chirality of each four BINOLs), the number of diastereomeric complexes is too big to allow the modelling of each of them. However, the relative energies of the diastereoisomers of A and the obvious steric incompatibility between neighbouring heterochiral ligands tend to indicate that the crystallized diastereoisomer of C is the lowest in energy. In that respect, the self-sorting of C is essentially thermodynamic, even if all the components of the system are not in fast exchange.

2.2.3 Effect of the Self-sorting on Asymmetric Hydrogenation

Before evaluating nonlinear effects in the hydrogenation of the benchmark substrates dimethyl itaconate 4 and methyl 2-acetamido acrylate 5 we first determined the solubility of the racemate of homochiral complexes based on the ligand L2 in pure dichloromethane and in the presence of typical amounts of the substrates (substrate/Rh ratio of 25 and initial Rh concentration of 25 mM), as this plays a role in the anticipated nonlinear effects. In the absence of substrate, the solubility of the racemic self-sorted complex is 0.64 mM. Interestingly, the presence of substrate 4 reduces this solubility to 0.41 mM whereas 5 increases it to 1.58 mM. We first hydrogenated 4 using complexes based on ligands L2 with an enantiopurity of the ligand varying between 0 and 100%. At high catalyst concentration ([Rh]=25mM), when the complexes are preformed prior to substrate addition, precipitation of the racemate occurs, leaving in solution homochiral complexes of the ligand that is in excess. Subsequent addition of substrate 4 enhances this enantiopurification of the reaction mixture by lowering the solubility of the racemate even further. This explicit reservoir effect leads to a very strong positive nonlinear effect. Lowering of the enantiomeric excess of the ligand from 100 to 40%, leads to a drop of the ee of the product of only 7% (Figure 9). Importantly, the same experiments but without incubation, which allows this self-sorting process and precipitation to occur, result in the opposite effect. Instead of a positive nonlinear effect, a strong negative nonlinear effect is observed. This suggests that under these conditions, catalysis happens before self-sorting and subsequent precipitation has completed. The kinetic
complexes formed before the metal-ligand system reaches a thermodynamic equilibrium are responsible for most of the conversion.

![Figure 9](image_url)  
**Figure 9.** NLE curves for the hydrogenation of 4 with 2 as a ligand (20 bars H₂, 14h at RT in CH₂Cl₂).

Similar hydrogenation experiments of 4 were done under more diluted conditions ([Rh] = 2mM), again with and without complex preformation prior to substrate addition. The same results are obtained in both these experiments, as expected, as under these dilute conditions no precipitation spontaneously occurs after incubation. The small deviation from linearity for the curve of $ee_{product}$ as a function of $ee_{ligand}$ may be due to imperfect self-sorting (as also observed in the NMR experiment using (S)-L₁ and (R)-L₂). We attempted to record the $^{31}$P NMR of the reaction mixture (with a racemic ligand) under these catalysis conditions to see these heterocomplexes arising from incomplete self-sorting. Unfortunately, even after an overnight acquisition, the signal-to-noise ratio was too small and only the signals for the homochiral complexes could be observed. In the NMR tube, crystals of the self-sorted racemate had appeared during the NMR experiment, of which the nature was confirmed by X-ray crystal structure determination. Apparently, the amount of non-self-sorted complexes is very small, yet they have an influence on the outcome of the reaction.

Similar studies on the nonlinear behaviour of the complexes were performed using substrate 5. For [Rh]=25mM the results were comparable as those observed for 4. However, the nonlinear effect observed after incubation is less pronounced (Figure 10), likely due to the substrate induced higher solubility of the racemate of self-sorted complexes. This shows that a feedback loop operates, wherein the substrate, by influencing the solubility of complexes, affects the outcome of its own hydrogenation. For [Rh]=2mM, the results with and without complex preformation were significantly different showing that for this substrate, hydrogenation is significantly faster than the formation of the self-sorted complexes (see Figure 18 in the experimental section). Like observed for the hydrogenation of 4 (at [Rh]=25mM) the kinetically formed active complexes give different selectivity than the thermodynamic self-sorted complexes. The exact nature of those complexes remains elusive, as they convert very fast to the stable dimer and no direct observation could be made. In analogy with well-known systems, we expect solvated bis-coordinated monomers to be active.
intermediates. As they are formed from the non-self-sorted intermediate B, they are not self-sorted either, and the weakly coordinated solvent molecules make them very reactive towards hydrogen and substrates.

Figure 10. NLE curves for the hydrogenation of 5 with 2 as a ligand (20 bars H₂, 14h at RT in CH₂Cl₂).

2.3 Conclusion

We studied in detail a catalytic system for asymmetric hydrogenation based on METAMORPhos ligands and rhodium as a complex chemical system. These studies revealed self-sorting of ligands at dinuclear complexes leading to homochiral complexes, which is not observed for the mononuclear complexes that form during the incubation phase of hydrogenation experiments. We confirmed the nature of the dimeric and mononuclear complexes with their X-ray structure. An uncommon lone-pair-π interaction between neighbouring BINOL moieties was observed in the crystal structures of [Rh₂(L₂)₄]. Experimental work and computational modelling show that the self-sorting of the dimers is thermodynamically driven. The racemate of the self-sorted homochiral complex [Rh₂(L₂)₄] synthesized from the racemic ligand was found to be very insoluble. This property leads to a very strong positive nonlinear effect in asymmetric hydrogenation, with a high ee obtained for the product while the ligand is present in low enantiopurity (40%). This is, however, only observed when the substrate is introduced after an incubation time in which the self-sorted complexes are formed. Addition of the substrates from the beginning of the experiment gives completely different effects showing that intermediate complexes, which form before the thermodynamic equilibrium of the ligand-metal system is reached, are catalytically active. The complexity of the system was further demonstrated by showing a feedback loop: the substrate influences the solubility of the racemate of homochiral complexes, which is important for the nonlinear effects observed. The substrate thus influences the extent of nonlinear effect. This is the first example of self-sorted ligation at dinuclear complexes that are active in asymmetric hydrogenation. Detailed information as presented here is relevant for process optimization and development of more complex catalytic systems that may play an important role in future processes.
2.4 Experimental Section

Methyl-2-acetamidoacrylate (MAA), phosphorustrichloride and methanesulfonamide were purchased from Aldrich; R(+)-1,1'-Bi-2-naphtol ((R)-BINOL) and S(+)-1,1'-Bi-2-naphtol ((S)-BINOL) from Reuter Chemische Apparabau; (rac)-1,1'-Bi-2-naphtol ((rac)-BINOL) from Acros; dimethyl itaconate (DMI) and bis(norbormadiene)rhodium(I) tetrafluoroborate ([Rh(nbd)]BF₄) from Alfa-Aesar; 4-butylbenzene-1-sulfonamide from Maybridge.

All reactions were carried out in dry glassware under nitrogen atmosphere. Every solution addition or transfer was performed via syringes or in a glovebox. The ligands and the metal precursor were weighed under air.

All solvents were dried and distilled according to standard procedures.

Nuclear Magnetic Resonance experiments were performed on a Varian Inova spectrometer (1H: 500 MHz, 31P: 202.3 MHz) or a Bruker AMX 400 (1H: 400.1 MHz, 13C: 100.6 MHz and 19F: 162.0 MHz). 

19F NMR experiments were performed on a Varian Mercury (1H: 300 MHz, 19F: 282.4 MHz). Chemical shifts are referenced to the solvent signal (5.320 ppm in 1H and 54.00 ppm in 13C NMR for CD₂Cl₂).

Conversions and enantiomeric excess for the asymmetric hydrogenation of Methylacetamidoacrylate were determined by Gas Chromatography (GC) on an Interscience Focus GC Ultra (FID detector) with a Supelco β-DEX 225 column (30 m x 0.25 mm).

2.4.1 Ligand Synthesis

Ligands (S)-L1, (R)-L2 and (S)-L3 were synthesized according to reported procedures. The same procedure was used for the synthesis of (rac)-L1, (rac)-L2 and (S)-L3.

(rac)-L1 and (rac)-L2 have identical characterization spectra as (S)-L1 and (R)-L2 respectively, except for the proton NMR: H⁺ and HΦ are equivalent when racemic BINOL is employed.

(rac)-L1

1H NMR (400 MHz, CD₂Cl₂, r.t.) δ (ppm): 10.194 (broad s., 1H, Et₃NH⁺); 7.981-6.776 (aromatic area); 2.731 (t., 7.6 Hz, 2H, CH₃-CH₂-CH₂-CH₂-Ar); 2.436 (q., 3JCH₂-CH₃ = 7.3 Hz, 6H, CH₃CH₂-NH of Et₃NH⁺); 1.678 (m., 2H, CH₃-CH₂-CH₂-CH₂-Ar); 1.413 (m., 2H, CH₃-CH₂-CH₂-CH₂-Ar); 0.969 (t., 7.4 Hz, 3H, CH₃-CH₂-CH₂-CH₂-Ar); 0.741 (t., 3JCH₂-CH₃ = 7.3 Hz, 9H, CH₃CH₂-NH of Et₃NH⁺)

(rac)-L2

1H NMR (400 MHz, CD₂Cl₂, r.t.) δ (ppm): 8.669 (broad s., 1H, Et₃NH⁺); 8.016-7.244 (aromatic area); 2.439 (q., 3JCH₂-CH₃ = 7.3 Hz, 6H, CH₃CH₂-NH of Et₃NH⁺); 0.755 (t., 3JCH₂-CH₃ = 7.3 Hz, 9H, CH₃CH₂-NH of Et₃NH⁺)

(S)-L3

31P{1H} NMR (162 MHz, CD₂Cl₂, r.t.) δ (ppm): +172.19 (broad s)

1H NMR (400 MHz, CD₂Cl₂, r.t.) δ (ppm): 10.042 (broad s., 1H, Et₃NH⁺); 7.992-7.234 (aromatic area); 3.030 (s., 3H, SO₂CH₃); 2.605 (broad d., 3JHa-Hb = 7.3 Hz, 3JHb-Ha = 13.9 Hz, 3H, CH₂CH₃H⁺-NH of Et₃NH⁺); 2.260 (broad d., 3JHb-Ha = 7.3 Hz, 3JHb-Ha = 13.9 Hz, 3H, CH₂CH₃H⁺-NH of Et₃NH⁺); 0.790 (d., 3JCH₃-Ha = 1JCH₃-Hb = 7.3 Hz, 9H, CH₃CH₂H⁺-NH of Et₃NH⁺)

H⁺ and HΦ are unequal because of the chiral environment, like in the case of L1 and L2.

31C{1H} NMR (101 MHz, CD₂Cl₂, r.t.): δ (ppm): 150.285 (broad s., aromatic C quar-O-P); 150.001 (d., 3JCP = 3.9 Hz, C quar-O-P); 133.435 (C quad); 133.319 (C quad); 131.850 (C quad); 131.175 (C quad); 130.593 (CH); 129.508 (CH); 128.893 (CH); 128.724 (CH); 127.115 (CH); 126.741 (CH); 126.617 (CH); 126.570 (CH); 125.196 (CH); 125.019 (CH); 124.897 (d., JCP = 5 Hz, C quad); 124.659 (CH); 124.329 (d., JCP = 2.3 Hz, C quad); 122.769 (CH); 45.528 (d., 3JCP = 3.1 Hz, CH₃); 45.107 (s.; CH₂ of NH-CH₂-CH₃ of Et₃NH⁺); 8.293 (s. CH₃ of NH-CH₂-CH₃ of Et₃NH⁺). Note: because of rotational constraints around the P-N bond, the ligand is not C₂ symmetric and each carbon (of the the BINOL moiety) have a distinct signal.

MS (FAB+): m/z calcd. for C₂₁H₁₇NO₄PS (no triethylamine adduct): [MH]+: 410.0616; obsd.: 410.0606 (Δ = - 2.4 ppm).
2.4.2 Complex Preparation and Characterization, Complexation Experiments

Complex A [Rh$_2$(L$_2$(nbd)$_2$)]

Ligand L$_1$, L$_2$ or a mixture of ligands (0.0175 mmol in total, 1 eq.) was dissolved in 0.7 mL of CD$_2$Cl$_2$ and mixed with [Rh(nbd)$_2$]BF$_4$ (0.0175 mmol, 1 eq.) resulting immediately in the formation of a very dark purple solution.

31P NMR yield: quantitative in every case

[ Rh$_2$((R)-L$_1$(nbd)$_2$) ] and [ Rh$_2$((R)-L$_2$(nbd)$_2$) ] were fully characterized previously.$^{19}$

**Self-sorted [ Rh$_2$((S)-L$_1$(nbd)$_2$) ] + [ Rh$_2$((R)-L$_1$(nbd)$_2$) ]**

Prepared with 1 eq (rac)-L$_1$.

This mixture has identical characterization spectra as [ Rh$_2$((S)-L$_1$(nbd)$_2$) ] prepared from (S)-L$_1$, except for the proton NMR: CH$_2$ of the triethylammonium is a simple quadruplet when racemic BINOL is employed. The multiplicity of this signal of [ Rh$_2$((R)-L$_1$(nbd)$_2$) ] has been previously explained by a coupling with NEt$_3^+$. The spectrum of [ Rh$_2$((R)-L$_1$(nbd)$_2$) ] + [ Rh$_2$((S)-L$_1$(nbd)$_2$) ] shows that the chiral environment is responsible for this pattern.

$^1$H NMR (500 MHz, CD$_2$Cl$_2$, r.t.) δ (ppm): 8.170 – 6.679 (aromatic area); 6.261 (broad s.); 5.914 (broad s.); 4.628 (broad s.); 3.985 (broad s.); 3.538 (broad s.); 3.387 (broad s.); 3.095 (q., J = 7.2 Hz, CH$_2$ from triethylammonium); 2.557 (broad s.); 2.421 (m.); 1.956 (broad s.); 1.428 – 1.333 (alkyl area); 1.292 (t., J = 7.2 Hz, CH$_3$ from triethylammonium); 1.090 (m.), 0.696 (t, J = 7.4 Hz).

**Self-sorted [ Rh$_2$((S)-L$_2$(nbd)$_2$) ] + [ Rh$_2$((R)-L$_2$(nbd)$_2$) ]**

Prepared with 0.5 eq (S)-L$_1$ and 0.5 eq (R)-L$_2$ (for 1 eq [Rh(nbd)$_2$]BF$_4$)

$^3$P NMR showed a 1:1 mixture of [ Rh$_2$((S)-L$_2$(nbd)$_2$) ] and [ Rh$_2$((R)-L$_2$(nbd)$_2$) ] (see Figure 2)

Self-sorted [ Rh$_2$((S)-L$_2$(nbd)$_2$) ] + [ Rh$_2$((R)-L$_2$(nbd)$_2$) ]

Prepared with 1 eq (rac)-L$_2$.

All characterization data were identical to [ Rh$_2$((S)-L$_2$(nbd)$_2$) ] prepared from (S)-L$_2$ (even the $^1$H NMR signals of the triethylammonium).

No heterochiral complexes could be detected by $^31$P NMR ($^31$P [$^1$H] NMR (162 MHz, CD$_2$Cl$_2$, r.t.).

**Crystallization procedure**

The solvent of the solution used for the NMR experiment (self-sorted [ Rh$_2$((S)-L$_2$(nbd)$_2$) ] + [ Rh$_2$((R)-L$_2$(nbd)$_2$) ], with an initial Rh concentration of 25 mM) was slowly evaporated. After 1 week at room temperature, very dark violet crystals formed.

**X-ray crystal structure determination**

C$_{36}$H$_{45}$F$_{39}$O$_9$P$_3$Rh$_2$S$_2$ · 1.5CH$_2$Cl$_2$, Fw = 1442.17, dark needle, 0.89 x 0.28 x 0.18 mm$^3$, monoclinic, C2/c (no. 15), a = 23.2816(18), b = 12.8308(10), c = 19.4444(8) Å, β = 97.263(4) °, V = 5761.9(7) Å$^3$, Z = 4, D$_x$ = 1.663 g/cm$^3$, μ = 0.92 mm$^{-1}$. The diffraction experiment was performed on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (λ = 0.71073 Å) at a temperature of 150(2) K. The crystal appeared to be cracked into two fragments and was consequently integrated with two orientation matrices. 50948 Reflections were measured up to a resolution of (sin θ/λ)$_{max}$ = 0.65 Å$^{-1}$. Intensity data were integrated with the Eval15 software.$^{29}$ Absorption correction and scaling was performed based on multiple measured reflections with TWINABS$^{30}$ (correction range 0.55-0.75). 6639 Reflections were unique (R$_{int}$ = 0.050), of which 5358 were observed (I>2σ(I)).

The structure was solved with Direct Methods using the program SHELXS-97$^{31}$. Least-squares refinement was performed with SHELXL-97$^{32}$ against F$^2$ of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. Hydrogen atoms were introduced in calculated positions and refined with a riding model. The CH$_2$Cl$_2$ solvent molecule was refined with a partial occupancy of 0.75. 380 Parameters were refined with one restraint for the C-Cl distances in the solvent molecule. R1/wR2 [I > σ(I)]: 0.0421 / 0.1091. R1/wR2 [all refl.]: 0.0552 / 0.1166. S = 1.067. Residual electron density between -0.59 and 1.60 e/Å$^3$. Geometry calculations and checking for higher symmetry was performed with the PLATON program.$^{32}$

[Rh$_2$((R)-L$_1$(nbd)$_2$)]

[Rh$_2$((R)-L$_1$(nbd)$_2$)] and [ Rh$_2$((R)-L$_2$(nbd)$_2$)] in CD$_2$Cl$_2$ are prepared in two separate shlenk flasks. The two solutions are mixed.

$^3$P NMR shows the immediate formation of a statistical mixture: [ Rh$_2$((R)-L$_2$)((R)-L$_2$(nbd)$_2$)] / [ Rh$_2$((R)-L$_1$(nbd)$_2$)] / [ Rh$_2$((R)-L$_1$(nbd)$_2$)] (50:25:25). [ Rh$_2$((R)-L$_2$)((R)-L$_2$(nbd)$_2$)] has been previously characterized.$^{19}$
Complex B [RhL_2(nbd)]

Ligand L1, L2, or a mixture of ligands (0.0125 mmol, 2 eq.) was dissolved in 0.5 mL of CD_2Cl_2 and mixed with [Rh(nbd)]_2BF_4 (0.0125 mmol, 1 eq.). The solution becomes purple and then orange-yellow within 1 to 5 minutes. 1^3P NMR yield: quantitative in every case

[Rh(S)-L1](nbd)]

^1H NMR (500 MHz, CD_2Cl_2, r.t.) δ (ppm): 8.041-6.749 (aromatic region); 5.223 (broad s.); 4.788 (broad s.); 3.566 (broad s.); 3.510 (broad s.); 2.762 (d.q., J = 14.4, 7.2 Hz); 2.635 (d.q., J = 14.2, 7.2 Hz); 2.509 (t., J = 7.8 Hz); 1.962 (broad s.); 1.499 (m.); 1.402 (broad s.); 1.292 (m.); 0.925-0.883 (alkyl region)

^31P{^1H} NMR (202 MHz, CD_2Cl_2, r.t.) δ (ppm): 136.56 (d, J_{P,Rh} = 247.5 Hz)

MS (FAB\^+): m/z calcd. for C_{37}H_{50}O_8P_2RhS_2N_2 ([Rh(S)-L1](nbd)] minus nbd): [M]^+): 1157.1695; obsd.: 1157.1703 +0.6ppm). m/z calcd. for C_{37}H_{50}O_8P_2RhS_2N_3 ([Rh(S)-L1](nbd)] plus triethylammonium): [MHNOne]^+): 1351.3604; obsd.: 1351.3616 +0.9ppm).

[Rh(S)-L2](nbd)]

^1H NMR (400 MHz, CD_2Cl_2, r.t.) δ (ppm): 8.083 - 7.179 (aromatic region); 6.749 (m.); 5.112 (broad s.); 4.786 (broad s.); 3.663 (broad m.); 3.566 (m.); 2.830 (broad m.); 1.961 (t., J = 1.7 Hz); 1.444 (broad s.); 1.011 (t., J = 7.3 Hz)

^31P{^1H} NMR (202 MHz, CD_2Cl_2, r.t.) δ (ppm): 134.73 (d, J_{P,Rh} = 251.3 Hz)

MS (FAB\^+): m/z calcd. for C_{37}H_{50}O_8P_2RhS_2N_2 ([Rh(S)-L2](nbd)] minus nbd): [M]^+): 1028.96; obsd.: 1028.95 (-4.1ppm). m/z calcd. for C_{37}H_{50}O_8P_2RhS_2N_3 ([Rh(S)-L2](nbd)] plus triethylammonium): [MHNOne]^+): 1222.14; obsd.: 1222.14 (-0.8ppm).

[Rh(S)-L1](R)-L1](nbd)]

Synthesized from 2 eq (rac)-L1.

^3P NMR shows the formation of a statistical mixture: [Rh((R)-L1)(S)-L1](nbd)] / [Rh((S)-L1)(nbd)] / [Rh((R)-L1)(nbd)] (50:25:25).

^1H NMR (500 MHz, CD_2Cl_2, r.t.) δ (ppm): 8.045-6.747 (aromatic region); 5.229 (broad s.); 4.794 (broad s.); 4.517 (broad s.); 3.566 (broad m.); 3.519 (broad m.); 3.043 (broad s.); 2.773 (q., J = 7.3 Hz); 2.638 (t., J = 7.8 Hz); 2.515 (t., J = 7.7 Hz); 1.961 (broad s.); 1.601 (m.); 1.503 (m.); 1.409 (broad s.); 1.386-1.270 (alkyl region); 1.052 (broad s.); 0.984-0.878 (alkyl region)

^31P{^1H} NMR (202 MHz, CD_2Cl_2, r.t.) δ (ppm): 136.56 (broad d., J = 246.3 Hz, homochiral complexes), 128.55 (broad s., heterochiral complex)

[Rh(S)-L2](R)-L2](nbd)]

Synthesized from 2 eq (rac)-L2.

^3P NMR shows the formation of a statistical mixture: [Rh((S)-L2)(S)-L2](nbd)] / [Rh((S)-L2)(nbd)] / [Rh((R)-L2)(nbd)] (50:25:25).

^1H NMR (400 MHz, CD_2Cl_2, r.t.) δ (ppm): 8.082-7.210 (aromatic region); 6.749 (broad s.); 5.512 (broad s.); 5.170 (broad s.); 4.779 (broad s.); 3.662 (broad m.); 3.568 (m., J = 1.8 Hz); 2.827 (q., J = 7.3 Hz); 1.961 (broad s.); 1.435 (broad m.); 0.994 (t., J = 7.3 Hz)

^31P{^1H} NMR (162 MHz, CD_2Cl_2, r.t.) δ (ppm): 137.45 (d, J_{P,Rh} = 247.5 Hz, heterochiral ligand), 134.73 (d, J_{P,Rh} = 251.3 Hz, homochiral ligands)

Crystallization procedure

Under nitrogen atmosphere, 1 mL of diethyl ether was layered on the solution used for the NMR measurements (Initial Rh concentration of 25 mM in the NMR tube. After 2 weeks at room temperature, orange crystals formed.

X-ray crystal structure determination

[C_{37}H_{50}O_8P_2RhS_2][C_{6}H_{8}N]+ disordered solvent, Fw = 1221.93[^{11}], red needle, 0.70 x 0.30 x 0.28 mm\(^3\), monoclinic, P2_1/c (no. 14), a = 13.7706(7), b = 23.0956(7), c = 18.5506(6) Å, β = 103.595(2) °, V = 5734.5(4) Å\(^3\), Z = 4, D_\text{c} = 1.415 g/cm\(^3\)[^{11}], μ = 0.50 mm\(^{-1}\)[^{11}], 79791 Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (λ = 0.71073 Å) at a temperature of 150(2) K up to a resolution of (sin θ/λ)\(^{\text{max}}\) = 0.65 Å\(^{-1}\). Intensity data were integrated with the Eval15 software.\[^{20}\] Absorption correction and scaling was performed based on multiple measured reflections with SADABS\[^{30}\] (correction range 0.38-0.43). 13136 Reflections were unique (R_{int} = 0.022), of which 11219 were observed [I>2σ(I)]. The structure was solved with Direct Methods using the program SHELXS-97\[^{31}\]. Least-squares refinement was performed with SHELXL-97\[^{31}\] against F^2 of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement
parameters. Hydrogen atoms were located in difference Fourier maps and refined with a riding model. The structure contains large voids (795 Å³ / unit cell) filled with severely disordered CH₂Cl₂ solvent molecules. Their contribution to the structure factors was secured by back-Fourier transformation using the SQUEEZE routine of the PLATON software. 697 Parameters were refined with no restraints. R1/wR2 [I > 2σ(I)]: 0.0331 / 0.0878. R1/wR2 [all refl.]: 0.0391 / 0.0905. S = 1.073. Residual electron density between -0.46 and 0.94 e/Å³. Geometry calculations and checking for higher symmetry was performed with the PLATON program.

**Complex C [Rh₂L₄]**

Ligand L₁, L₂, L₃ or a mixture of ligands (0.0125 mmol in total, 2eq.) was dissolved in 0.5 mL of CD₂Cl₂ and mixed with [Rh(nbd)]₂BF₄ (0.0125 mmol, 1 eq.). The solution becomes purple and then brownish immediately to (the) bimetallic species [Rh₂L₄] as the only complex present in solution (red to brownish-red solution). ³¹P NMR yield: quantitative in every case.

[Rh₂((R)-L₁)] has been fully characterized previously.

**[Rh₂((R)-L₂)]**

Synthesized from 2 eq (R)-L₂

$^1$H NMR (400 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 8.258 - 6.229 (aromatic region); 4.606 (s.); 2.744 (m.); 2.187 (broad m.); 1.944 - 1.452 (alkyl region); 1.191 - 1.154 (alkyl region); 1.004 (t, $J = 7.3$ Hz)

$^{31}$P{¹H} NMR (126 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 140.84 (dd, $J_{P,RO} = 288.7$, $J_{P,P} = 35.0$ Hz, P of the chelating ligands), 116.91 (AA'BB'XX' broad half spectrum, $J_{P-RO} \approx 332$ Hz, other couplings not extractable, $P'$ of the bridging ligands).

MS (FAB+): m/z calcd. for C₅₀H₄₈O₁₆P₄Rh₂S₄ [Rh₂((S)-L₃)]⁻: [M]⁻: 2055.8974; obsd.: 2055.9062 ($\Delta = +0.4$ ppm). m/z calcd. for C₆₀H₅₀N₁₄O₁₈P₄Rh₂S₄ [NEt₃,Rh₂((S)-L₃)]⁻: [NEt₃,M]⁻: 2157.0178; obsd.: 2157.0212 ($\Delta = +0.16$ ppm). m/z calcd. for C₆₀H₅₀N₁₄O₁₈P₄Rh₂S₄ [NEt₃,Rh₂((S)-L₃)]⁻: [NEt₃,M]⁻: 2259.1414; obsd.: 2259.1409 ($\Delta = 0.2$ ppm).

**[Rh₂((S)-L₃)]**

Synthesized from 2 eq (S)-L₃

$^1$H NMR (400 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 8.375 - 6.442 (aromatic region); 5.990 (t, $J = 1.9$ Hz); 5.925 (d, $J = 8.8$ Hz); 4.605 (s); 3.511 (s); 3.004 (s); 2.607 (m); 2.184 (broad m.); 1.610 (m); 1.485 - 1.458 (alkyl region); 1.293 (m); 1.191 - 1.072 (alkyl region); 0.930 (t, $J = 7.2$ Hz)

$^{31}$P{¹H} NMR (126 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 142.81 (dd, $J_{P,RO} = 276.1$, $J_{P,P} = 43.7$ Hz, P of the chelating ligands); 114.9 (AA'BB'XX' broad half spectrum, $J_{P-RO} \approx 327$ Hz, other couplings not extractable, $P'$ of the bridging ligands).

MS (FAB+): m/z calcd. for C₅₀H₄₈O₁₆P₄Rh₂S₄ [Rh₂((S)-L₃)]⁻: [M]⁻: 1840.0104; obsd.: 1840.0184 ($\Delta = +0.2$ ppm). Note: The chelating ligands are here in their protonated form.

**Self-sorted [Rh₂((R)-L₁)] + [Rh₂((S)-L₁)]**

Synthesized from (rac)-L₁

This mixture has identical characterization spectra as [Rh₂((S)-L₁)] prepared from (S)-L₁, except for the proton NMR: CH₂ of the triethylammonium is a simple quadruplet when racemic BINOL is employed.

$^1$H NMR (500 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 8.94 - 6.40 (aromatic area); 6.359 (d, $J = 8.8$ Hz); 6.258 (m); 5.903 (broad d, $J = 8.2$ Hz); 5.756 (d, $J = 8.8$ Hz); 4.606 (s); 3.050 (t, $J = 7.6$ Hz); 2.664 (q, $J = 7.3$ Hz); 2.401 (m); 2.342 (broad s); 2.281 - 2.222 (alkyl region); 2.189 (m); 1.963 (m); 1.628 (m); 1.486 - 1.122 (alkyl region); 0.932 - 0.886 (alkyl region).

Full conversion and no traces of other complexes could be detected by $^{31}$P NMR ($^{31}$P{¹H} NMR (162 MHz, CD₂Cl₂, r.t.).

**Partial self-sorting: formation of [Rh₂((S)-L₁)] + [Rh₂((R)-L₂)] + other complexes**

Synthesized from 1 eq (R)-L₁ and 1 eq (S)-L₂ (for 1 eq [Rh(nbd)]₂BF₄)

$^{31}$P{¹H} NMR (202 MHz, CD₂Cl₂, r.t.) $\delta$ (ppm): 151.86 (d, $J = 46.5$ Hz); 150.30 (d, $J = 47.2$ Hz); 148.35 (d, $J = 86.9$ Hz); 146.93 (d, $J = 83.5$ Hz); 145.39 (d.d, $J_{P,RO} = 286.9$, $J_{P,P} = 38.8$ Hz, chelating ligands of [Rh₂((S)-L₁)]) 140.84 (d.d, $J_{P,RO} = 288.7$, $J_{P,P} = 35.0$ Hz, chelating ligands of [Rh₂((R)-L₂)]); 140.83 (d, $J = 47.1$ Hz); 139.42 (d, $J = 46.7$ Hz); 133.79 (d.m.); 132.05 (d.m.); 116.9 (AA'BB'XX' broad half spectrum, $J_{P-RO} \approx 332$ Hz bridging ligands of [Rh₂((S)-L₁)]) 116.1 (AA'BB'XX' broad half spectrum, $J_{P-RO} \approx 325$ Hz bridging ligands of [Rh₂((S)-L₁)])

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The ratio self-sorted species / non self-sorted species were found to be in the range of 80:20, according to the integration in phosphorus NMR. See experimental profile ($^{31}$P{$^{1}$H} NMR (202 MHz, CD$_2$Cl$_2$, r.t.)).

**Figure 13.** Top: $^{31}$P{$^{1}$H} NMR of [Rh$_2$((R)-L2)$_4$]; middle: $^{31}$P{$^{1}$H} NMR of [Rh$_2$((S)-L1)$_4$]; bottom spectrum: partial self-sorting.

Mixture of complexes [Rh$_2$((R)-L1)$_6$((R)-L2)($n_0$)]; $n = 0$ to 4
Synthesized from 1 eq (R)-L1 and 1 eq (R)-L2 (for 1 eq [Rh(nbd)$_2$]BF$_4$)
Control experiment showing that the substituent on the sulfur is not responsible for the self-sorting. No complex could be clearly identified. However, the signals in the region 140 – 146 ppm can be assigned to chelating ligands; the signals in the region 111 – 121 ppm to bridging ligands. The large quantity of signals is coherent with a mixture of 10 different complexes. The experimental profile corresponds to Figure 7(c).

Self-sorted [Rh$_2$((R)-L2)$_4$] + [Rh$_2$((S)-L3)$_4$]
Synthesized from 1 eq (R)-L2 and 1 eq (S)-L3 (for 1 eq [Rh(nbd)$_2$]BF$_4$)
$^{31}$P{$^{1}$H} NMR (202 MHz, CD$_2$Cl$_2$, r.t.) δ (ppm): 142.81 (d.d., $^1$J$_{P2-Rh}$ = 276.1, $^3$J$_{P2-P2'}$ = 43.7 Hz, chelating ligands of [Rh$_2$((R)-L2)$_4$]); 140.84 (d.d., $^1$J$_{P1-Rh}$ = 288.7, $^3$J$_{P1-P1'}$ = 35.0 Hz, chelating ligands of [Rh$_2$((S)-L3)$_4$]); 116.9 (AA'$\text{BB}'$XX' broad half spectrum, $^1$J$_{P2-Rh}$ $\approx$ 332 Hz bridging ligands of [Rh$_2$((R)-L2)$_4$]); 114.9 (AA'$\text{BB}'$XX' broad half spectrum, $^1$J$_{P3-Rh}$ $\approx$ 332 Hz bridging ligands of [Rh$_2$((S)-L3)$_4$]).
Mass spectroscopy showed only homochiral complexes (FAB+), as displayed on the experimental profile below.

**Figure 14.** Mass spectrum of [Rh$_2$((R)-L2)$_4$] + [Rh$_2$((S)-L3)$_4$] and assignment.
**Mixture of complexes** \([\text{Rh}_2 ((S)-L2)_n ((S)-L3)_{4-n})]\); \(n = 0\) to 4

Synthesized from 1 eq (S)-L2 and 1 eq (S)-L3 (for 1 eq \([\text{Rh}({nbd})_2]\)BF_4)

Mass spectroscopy (FAB+) showed all the possible combinations, as displayed on the experimental profile below.

![Mass spectrum of \([\text{Rh}_2 ((S)-L2)_n ((S)-L3)_{4-n})]\); \(n = 0\) to 4.](image)

**Signals assignment:**

- a \([\text{Rh}_2 (L3)_4]\): [M]^+
- b \([\text{Rh}_2 (L2)(L3)_3]\): [M]^+
- c \([\text{Rh}_2 (L2)(L3)_3]\) minus H^+ plus Na^+: [MNa]^+
- d \([\text{Rh}_2 (L2)(L3)_3]\): [M]^+
- e \([\text{Rh}_2 (L2)(L3)_3]\) minus H^+ plus Na^+: [MNa]^+
- f \([\text{Rh}_2 (L2)(L3)_3]\): [M]^+
- g \([\text{Rh}_2 (L2)(L3)_3]\) minus H^+ plus Na^+: [MNa]^+
- h \([\text{Rh}_2 (L2)(L3)_3]\) plus triethylamine: [MNa]^+
- i \([\text{Rh}_2 (L2)(L3)_3]\) plus triethylamine minus H^+ plus Na^+: [MNa]^+
- j \([\text{Rh}_2 (L2)(L3)_3]\) plus triethylamine: [MNa]^+
- k \([\text{Rh}_2 (L2)(L3)_3]\) plus triethylamine minus H^+ plus Na^+: [MNa]^+
- l \([\text{Rh}_2 (L2)_2]\): [M]^+
- m \([\text{Rh}_2 (L2)_2]\) minus H^+ plus Na^+: [MNa]^+

**Self-sorted** \([\text{Rh}_2 ((R)-L2)_4] + [\text{Rh}_2 ((S)-L2)_4]\)

Synthesized from (rac)-L2

The complex immediately precipitated after formation and no NMR was possible.

**Crystallization procedure A**

The solvent was removed using a syringe and the precipitate was washed with 1 mL of dry dichloromethane. It was dissolved in 0.5 mL of nitromethane at 80°C. When the solution cooled down, big red crystals formed that were found suitable for X-ray diffraction.

**X-ray crystal structure determination**

\([C_{49}H_{38}F_{21}O_{18}P_2\text{Rh}_2S_2](C_6H_{16}N)_2 \cdot 2\text{CH}_3\text{NO}_2 + \text{disordered solvent, Fw = 2381.68}[^*] \), red block, 0.75 x 0.29 x 0.21 mm³, triclinic, P 1̅ (no. 2), \(a = 13.8434(3), b = 16.9625(5), c = 28.6470(6)\) Å, \(\alpha = 80.878(1), \beta = 86.264(1), \gamma = 66.980(1)°, V = 6112.9(2)\) Å³, \(Z = 2, D_x = 1.294 \text{ g/cm}^3[^*] \), \(\mu = 0.47\) mm⁻¹
241328 Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (\(\lambda = 0.71073 \text{ Å}\)) at a temperature of 150(2) K up to a resolution of \((\sin \theta / \lambda)_{\text{max}} = 0.65 \text{ Å}^{-1}\). Intensity data were integrated with the Eval15 software\(^{29}\). Absorption correction and scaling was performed based on multiple measured reflections with SADABS\(^{30}\) (correction range 0.36-0.43). 28035 Reflections were unique \((R_{\text{int}} = 0.023)\), of which 24121 were observed \([I>2\sigma(I)]\). The structure was solved with the program SHELXT\(^{31}\). Least-squares refinement was performed with SHELXL-97\(^{31}\) against \(F^2\) of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. Hydrogen atoms were included in calculated positions and refined with a riding model. One binaphthyl group was refined with a disorder model. Additionally to the ordered CH\(_3\)NO\(_2\) molecules, the structure contains large voids (1503 Å\(^3\) / unit cell) filled with severely disordered solvent molecules. Their contribution to the structure factors was secured by back-Fourier transformation using the SQUEEZE routine of the PLATON software\(^{32}\) (427 electrons / unit cell). 1514 Parameters were refined with 1008 restraints (flatness, distances and angles in the naphthyl groups; distances and angles in CH\(_3\)NO\(_2\) and isotropic behaviour of disordered groups). R1/wR2 \([I > 2\sigma(I)]: 0.0346 / 0.0947. R1/wR2 [all refl.]: 0.0417 / 0.0998. S = 1.040. Residual electron density between -1.75 and 0.68 e/Å\(^3\). Geometry calculations and checking for higher symmetry was performed with the PLATON program\(^{32}\). [*] Derived parameters do not contain the contribution of the disordered solvent molecules.

Crystallization procedure

A high pressure NMR tube were charged with 1 mmol \([\text{Rh(nbd)}]_2\text{BF}_4\) (1 eq), 2 mmol \((\text{rac})-\text{L2}\) and 25 mmol substrate 4. The powders were dissolved in 0.5 mL CD\(_2\)Cl\(_2\) and the solution was submitted to 5 bars of hydrogen; no spontaneous precipitation was observed. The NMR tube was placed in the NMR machine for an overnight acquisition \((^{31}\text{P})\). Only self-sorted products could be observed, with a mediocre signal to noise ratio. In the bottom of the tube, red crystals had formed that were found suitable for X-ray diffraction.

X-ray crystal structure determination

\([\text{Cp}_2\text{IrCl}_2\text{F}_2\text{N}_{2}\text{O}_{2}\text{P}_{2}\text{Rh}_2\text{S}_2\text{l}_2(\text{C}_6\text{H}_5\text{N})]\cdot 2.5\text{CH}_2\text{Cl}_2 \ + \ \text{disordered solvent}, F_w = 2471.91^{\text{[1]}}\), red block, 0.38 x 0.18 x 0.11 mm\(^3\), triclinic, \(P\bar{1}\) (no. 2), a = 19.4282(11), b = 24.6321(17), c = 25.8679(19) Å, \(\alpha = 108.856(2), \beta = 93.042(1), \gamma = 107.766(2)\) \(^\circ\), \(V = 10997.1(13) \text{ Å}^3\), \(Z = 4, D_\text{x} = 1.493 \text{ g/cm}^3\)\(^{[1]}\), \(\mu = 0.64 \text{ mm}^{-1}\)\(^{[1]}\). 296820 Reflections were measured on a Bruker Kappa ApexII diffractometer with sealed tube and Triumph monochromator (\(\lambda = 0.71073 \text{ Å}\)) at a temperature of 150(2) K up to a resolution of \((\sin \theta / \lambda)_{\text{max}} = 0.61 \text{ Å}^{-1}\). Intensity data were integrated with the Eval15 software\(^{29}\). Absorption correction and scaling was performed based on multiple measured reflections with SADABS\(^{30}\) (correction range 0.64-0.75). 41433 Reflections were unique \((R_{\text{int}} = 0.071)\), of which 26928 were observed \([I>2\sigma(I)]\). The structure was solved with the program SHELXS-97\(^{31}\). Least-squares refinement was performed with SHELXL-97\(^{31}\) against \(F^2\) of all reflections. Non-hydrogen atoms were refined freely with anisotropic displacement parameters. Hydrogen atoms were included in calculated positions and refined with a riding model. The refinement was hampered by disorder and correlations due to pseudo-translational symmetry. Additionally to the ordered CH\(_2\)Cl\(_2\) molecules, the structure contains large voids (1458 Å\(^3\) / unit cell) filled with severely disordered solvent molecules. Their contribution to the structure factors was secured by back-Fourier transformation using the SQUEEZE routine of the PLATON software\(^{32}\) (539 electrons / unit cell). 2656 Parameters were refined with 2643 restraints (flatness, distances and angles in the naphthyl groups; distances, angles, and isotropic behaviour in CH\(_2\)Cl\(_2\)/C\(_6\)H\(_5\)N). R1/wR2 \([I > 2\sigma(I)]: 0.0750 / 0.2031. R1/wR2 [all refl.]: 0.1133 / 0.2317. S = 1.043. Residual electron density between -1.35 and 2.73 e/Å\(^3\). Geometry calculations and checking for higher symmetry was performed with the PLATON program\(^{32}\). [*] Derived parameters do not contain the contribution of the disordered solvent molecules.

\[\text{[R}_{\text{h}_2}(\text{R}-\text{L3})_4(\text{R}-\text{L2})_4]\]

\[\text{[R}_{\text{h}_2}(\text{R}-\text{L1})_4(\text{R}-\text{L2})_4]\] and \[\text{[R}_{\text{h}_2}(\text{R}-\text{L2})_4]\] in CD\(_2\)Cl\(_2\) are prepared in two separate high pressure NMR tubes. The two solutions are mixed.

\(^{31}\text{P}\) NMR shows the immediate formation of a mixture of \[\text{[R}_{\text{h}_2}(\text{R}-\text{L1})_4]\], \[\text{[R}_{\text{h}_2}(\text{R}-\text{L2})_4]\] and \[\text{[R}_{\text{h}_2}(\text{R}-\text{L1})_4(\text{R}-\text{L2})_4]\]. Upon keeping the reaction mixture at room temperature for 3 days, no new signals appeared.

In addition to the signals of \[\text{[R}_{\text{h}_2}(\text{R}-\text{L1})_4]\] and \[\text{[R}_{\text{h}_2}(\text{R}-\text{L2})_4]\]:

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$^{31}$P$^{[1]}$H NMR (202 MHz, CD$_2$Cl$_2$, r.t.) $\delta$ (ppm): 144.2 (dd, $^1J_{P-Rh} = 281$ Hz, $^1J_{PL1(chelate)-PL1(bridging)} = 35$ Hz, chelate $L1$), 141.9 (dd, $^1J_{PL2(chelate)-PL2(bridging)} = 293$ Hz, $^1J_{P-Rh} = 33$ Hz, chelate $L2$), 117.7 (dm, $^1J_{P-Rh} = 327$ Hz, bridging $L2$), 114.6 (dm, $^1J_{P-Rh} = 323$ Hz, bridging $L1$).

### 2.4.3 Computational Modeling

All geometry optimizations were carried out with the Turbomole program$^{34}$ coupled to the PQS Baker optimizer.$^{35}$ Geometries were fully optimized as minima at the (ri-)$BP86$ level using the SV(P) basis set$^{37}$ on all atoms. All stationary points (minima) were characterized by vibrational analysis (analytical frequencies). To optimize C ([Rh(L3)$_4$]), empirical dispersion corrections (disp3)$^{38}$ have been applied when indicated. C has been modelled as a neutral complex.

Figure 16. Model of the diastereomeric structures of [Rh$_2$(nbd)$_2$(L3)$_2$].
Table 2. Distances extracted from the models of [Rh₂(L₃)₄] and comparison with experimental values.

<table>
<thead>
<tr>
<th></th>
<th>d(O-centroid) (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O_chelating ligand</td>
</tr>
<tr>
<td>values for the X-ray structure of C (procedure B)</td>
<td>3.04</td>
</tr>
<tr>
<td>Model with dispersion correction</td>
<td>2.97</td>
</tr>
<tr>
<td>Δd</td>
<td>-0.07</td>
</tr>
<tr>
<td>Model without dispersion correction</td>
<td>4.00</td>
</tr>
<tr>
<td>Δd</td>
<td>+0.96</td>
</tr>
</tbody>
</table>

2.4.4 Solubility Evaluation by UV-Vis

Solution preparation and measurements were done at r.t. under N₂ atmosphere. The path length was 2 mm; the wavelength used was 460 nm. The solvent used was dichloromethane. The calibration curve was done with the homochiral complex [Rh₂((R)-L₂)₄].

Figure 17. Calibration curve for the determination of the concentration of [Rh₂(L₃)₄].

Solutions preparation
Saturated solution of self-sorted [Rh₂((R)-L₂)₄] + [Rh₂((S)-L₂)₄]: the complexes were synthesized as described previously. The solution was shaken for 12h and then filtered with a HPLC filter. Saturated solution of self-sorted [Rh₂((R)-L₂)₄] + [Rh₂((S)-L₂)₄] in the presence of substrate: the complexes were synthesized as described previously (same amount in mmol but in 0.3 mL dichloromethane). After 1h, the H₂ pressure was released and the solution was further degased by sonication for 15min. 25 eq of substrate (for 1 eq of [Rh(nbd)₂]BF₄) were added and the volume of the solution were adjusted to 0.5 mL by adding solvent. The solution was shaken for 12 h, filtered with a HPLC filter and dissolved by a factor x.

Table 3. Concentration of [Rh₂(L₃)₄] in the presence or absence of substrates 4 and 5.

<table>
<thead>
<tr>
<th>entry</th>
<th>solution</th>
<th>x</th>
<th>absorbance</th>
<th>concentration (mmol/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>saturated solution</td>
<td>1</td>
<td>0.2815</td>
<td>0.6382</td>
</tr>
<tr>
<td>B</td>
<td>saturated solution + 4</td>
<td>2.5</td>
<td>0.1063</td>
<td>0.4102</td>
</tr>
<tr>
<td>C</td>
<td>saturated solution + 5</td>
<td>6.25</td>
<td>0.0929</td>
<td>1.5769</td>
</tr>
</tbody>
</table>

2.4.5 Asymmetric Hydrogenation

The hydrogenation experiments were carried out in a stainless steel autoclave (250 ml) charged with an insert suitable for 14 reaction vessels (2 mL vials equipped with Teflon mini stirring bars) for conducting parallel reactions. The charged autoclave was purged three times with 20 bar of dihydrogen and then pressurized at 20 bar H₂.

General procedure for the asymmetric hydrogenation with incubation
A 2 mL vial equipped with a stirring bar was charged in a glovebox under N₂ atmosphere. First, a volume V_R of a solution S_R of ligand (R)-L₂ at a concentration C_R in dichloromethane and a volume V_rac of a solution S_rac of ligand (rac)-L₂ at a concentration C_rac in dichloromethane are introduced in the vial (V_R + V_rac = 0.8 mL; V_R / V_rac is chosen according to the ee_ligand required (see Figure 5 and 6)). The content of the vial was stired for 5 min.
Then 0.1 mL of a solution $S_{Rh}$ of $[\text{Rh(nbd)}_2]\text{BF}_4$ at a concentration $C_{Rh}$ in dichloromethane was added to the vial. The content of the vial was stirred for 5 min. Then the solution was stirred under a 20 bars atmosphere of $\text{H}_2$ at room temperature for 1h. After depressurization, under a stream of $\text{N}_2$, 0.1 mL of a solution $S_{Sub}$ of the substrate at a concentration $C_{Sub}$ in dichloromethane was added to the vial. The content of the vial was stirred for 5 min. Then the solution was stirred under a 20 bars atmosphere of $\text{H}_2$ at room temperature for 14h.

**General procedure for the asymmetric hydrogenation without incubation**

A 2 mL vial equipped with a stirring bar was charged in a glovebox under $\text{N}_2$ atmosphere. First, a volume $V_R$ of a solution $S_R$ of ligand $(\text{R})$-$L_2$ at a concentration $C_R$ in dichloromethane and a volume $V_{rac}$ of a solution $S_{rac}$ of ligand $(\text{rac})$-$L_2$ at a concentration $C_{rac}$ in dichloromethane are introduced in the vial ($V_R + V_{rac} = 0.8$ mL; $V_R / V_{rac}$ is chosen according to the $ee_{\text{ligand}}$ required (see Figure 5 and 6)). The content of the vial was stirred for 5 min. Then 0.1 mL of a solution $S_{Rh}$ of $\text{Rh(nbd)}_2\text{BF}_4$ at a concentration $C_{Rh}$ in dichloromethane was added to the vial. The content of the vial was stirred for 5 min. Then 0.1 mL of a solution $S_{Sub}$ of the substrate at a concentration $C_{Sub}$ in dichloromethane was added to the vial. The content of the vial was stirred for 5 min. Then the solution was stirred under a 20 bars atmosphere of $\text{H}_2$ at room temperature for 14h.

**General remarks**

Conversions and $ee_{\text{product}}$ were determined by chiral GC (equipped with Supelco $\beta$-dex 225 column). Full conversion were observed in all cases. For methyl-2-acetamido acrylate (with a 140°C plateau), the retention times for the substrate, the $(S)$-product and the $(R)$-product were, respectively 5.6 min, 6.1 min and 6.6 min. For dimethyl itaconate (with a 92°C plateau), the retention times for the $(+)$-product, the $(-)$-product and the substrate were, respectively 15.4 min, 16.0 min and 18.3 min. Calibrated micropipette were used to transfer the solutions and measure the volumes. All the vials corresponding to the same curve (in Figure 5 and 6) were prepared and hydrogenated simultaneously.

Concentration were chosen as followed:

$$(C_R + C_{rac}) / C_{Rh} = 2.2$$

$C_{Sub} / C_{Rh} = 25$

$C_{Rh} = 250$ mM for “high concentration hydrogenation” and $C_{Rh} = 20$ mM for “low concentration hydrogenation” (so that the final concentration in the vial is respectively 25 mM and 2 mM for a reaction mixture volume of 1 mL).

![Figure 18](image-url)  
*Figure 18. NLE curves for substrate 5 (MAA)*
2.5 References


21. Usually, narcissistic self-sorting and self-recognition are used indifferently. In the case of chiral self-sorting, the term “narcissistic” is misleading as Narcissus fell in love with his reflection (his mirror image).
CCDC 931393 [i0242], 931394 [i0296], 931395 [i0224], and 931396 [i0244] contain the supplementary crystallographic data for this paper. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif.


Average O-centroid distance of 2451 structures in the CSD presenting a close contact between a benzene ring and a R-O-R' moiety; see ref [25]


G. M. Sheldrick, 1999. SADABS and TWINABS. Universität Göttingen, Germany.


(a) PQS version 2.4, 2001, Parallel Quantum Solutions, Fayetteville, Arkansas, USA (the Baker optimizer is available separately from PQS upon request); (b) J. Baker, J. Comput. Chem. 1986, 7, 385-395.

